CLASS – THE CANADIAN LAND SURFACE SCHEME (VERSION 3.4)

Technical Documentation (Version 1.1)

WRITTEN BY DIANA VERSEGHY

CLIMATE RESEARCH DIVISION, SCIENCE AND TECHNOLOGY BRANCH

January 2009

TECHNICAL DOCUMENTATION – VERSION 3.4

The Canadian Land Surface Scheme

Table of Contents

Notice to users:

Please read carefully the Licence/Disclaimer agreement provided in Appendix C. It sets out the terms and conditions associated with use of any Environment Canada copyright software, including CLASS.

In general, no updates, technical support etc. are provided to outside users who download EC software. However, any users wishing to be involved in CLASS development and its evolution beyond version 3.4 may contact Dr. Diana Verseghy at diana.verseghy@ec.gc.ca, with a view to entering into a collaborative research agreement.

Part

1

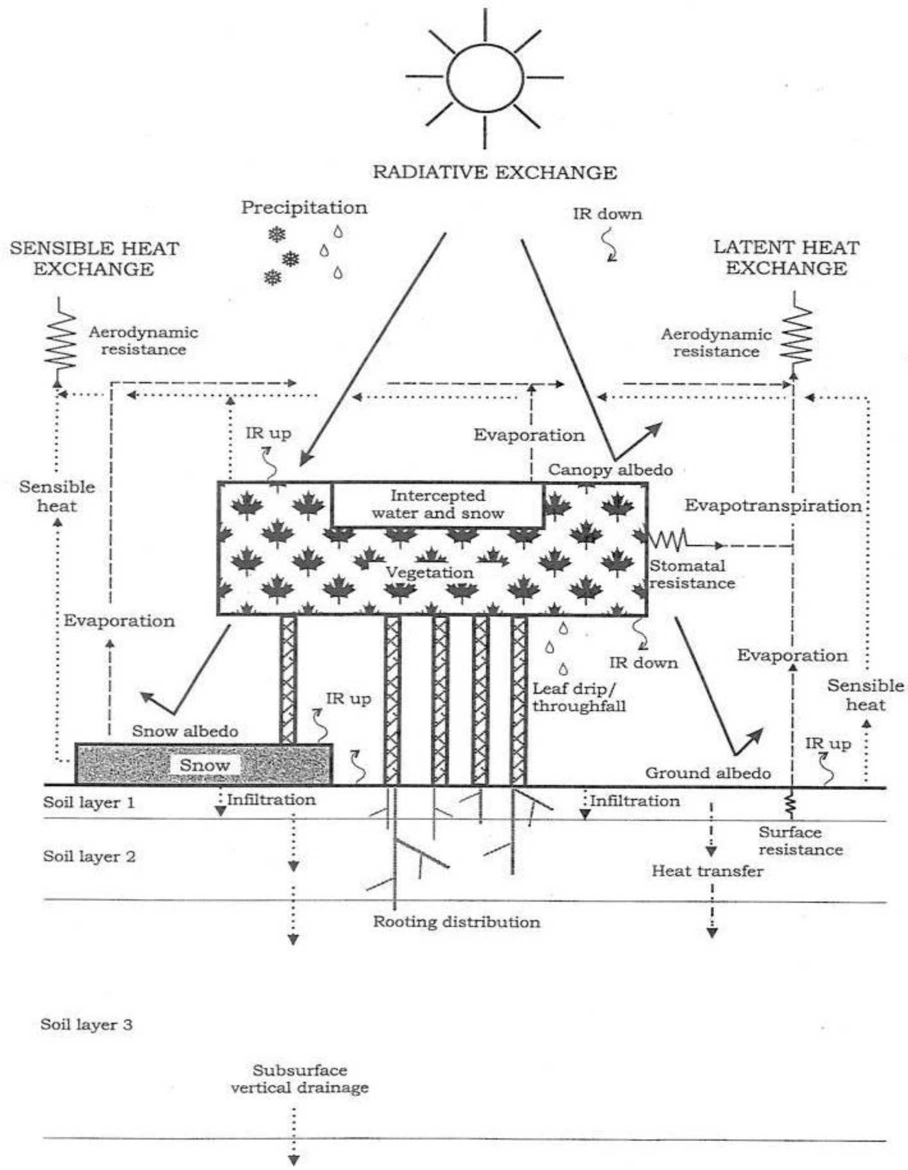
Overview of CLASS

The Canadian Land Surface Scheme, CLASS, was originally developed for use with the Canadian Global Climate Model or GCM (Verseghy, 1991; Verseghy et al., 1993). This documentation describes version 3.4 of CLASS, which was released in April of 2008. The table at the end of this overview summarizes the development of CLASS from the late 1980's to the present.

The basic function of CLASS is to integrate the energy and water balances of the land surface forward in time from an initial starting point, making use of atmospheric forcing data to drive the simulation. When CLASS is run in coupled mode with an atmospheric model, the forcing data are passed to it at each time step from the parallel atmospheric model simulation. CLASS then produces surface parameters such as albedo and surface radiative and turbulent fluxes, which are in turn passed back to the atmospheric model. CLASS can also be run in uncoupled or offline mode, with forcing data derived from a separate atmospheric model run or from field measurements, and its output fluxes and the values of its prognostic variables can then be validated against measured values. Version 3.4 includes an offline driver which can be used for this purpose.

CLASS models separately the energy and water balances of the soil, snow, and vegetation canopy if present (see the diagram below). The basic prognostic variables consist of the temperatures and the liquid and frozen moisture contents of the soil layers; the mass, temperature, density and albedo of the snow pack if present; the temperature and intercepted rain and snow on the vegetation canopy; the temperature and depth of ponded water on the soil surface; and an empirical vegetation growth index. These variables must be initialized, and a set of soil parameters describing the soil and vegetation present on the modelled area must be assigned values, at the beginning of the simulation (see the section on "Data Requirements").

At each time step, CLASS calculates the bulk characteristics of the vegetation canopy on the basis of the vegetation types present over the modelled area. In a pre-processing step, the vegetation types present are assigned background values of parameters such as albedo, roughness length, annual maximum and minimum plant area index, rooting depth and so on (see the section on "Data Requirements"). These values are then aggregated over four main vegetation categories identified by CLASS: needleleaf trees, broadleaf trees, crops, and grass (i.e. short vegetation). The physiological characteristics of the vegetation in each category are determined at the current time step using the aggregated background parameters and assumed annual or diurnal variation functions. These physiological characteristics are then aggregated to produce the bulk canopy characteristics for the current time step.



Schematic diagram of CLASS

In performing the surface flux calculations the surface is divided into up to four subareas: bare soil, vegetation over soil, snow over bare soil, and vegetation over snow. The fractional snow coverage is determined using the concept of a threshold snow depth. If the calculated snow depth is less than this value, the snow depth is set to the threshold value and the fractional snow cover is calculated on the basis of conservation of snow mass. The fluxes are calculated for each of the four subareas, and these and the prognostic variables are then areally averaged before being passed back to the atmospheric model.

Originally CLASS performed only one set of these calculations for each grid cell of the model domain. In more recent versions, a “mosaic” option has been added to handle sub-grid scale heterogeneity more effectively, in which each grid cell is in turn divided into a user-specified number of mosaic “tiles”, and the CLASS calculations are performed over each. The prognostic variables are kept separate for each of the tiles of the mosaic between time steps.

The section on the CLASS offline driver, RUNCLASS, provides information on how a CLASS run is typically performed, from assigning the background and initial values of variables, through calling the high-level CLASS subroutines, to calculating values of diagnostic and output variables. A gather-scatter operation is included in the driver, mimicking the practice in atmospheric models of “gathering” land surface points on latitude circles onto long vectors prior to the calculations, for improved computational efficiency on vector supercomputers. For CLASS, the mosaic tiles on each of the modelled grid cells are “gathered” onto long arrays of mosaic tiles prior to calling the CLASS subroutines (thus collapsing the first two dimensions of the arrays into one), and subsequently “scattered” back onto the grid cells before performing the diagnostic averaging calculations.

The sections following the one that describes the driver provide detailed descriptions first of the common block and other preliminary routines that are called before the run is launched, and then of the pre- and post-processing routines that are called at the beginning and end of each time step. The next three sections detail the three main CLASS subroutines together with the auxiliary subroutines that they call: CLASSA, which handles the calculation of the albedos and other surface parameters; CLASST, which addresses the evaluation of the surface energy balance and related variables; and CLASSW, which performs the surface water balance calculations and the re-aggregation of the prognostic variables. The sub-section on each subroutine contains a dictionary of the variables passed into and out of it, with units. The final section provides a list of references cited.

Developmental history of CLASS

Version	*Release date*	*Features and enhancements*
1.0	April 1989	Basic thermal and hydrological model of snow and soil.
2.0	August 1991	Addition of vegetation thermal and hydrological model.
2.1	May 1993	Full vectorization of code to enable efficienr running on vector supercomputers.
2.2	April 1994	Augmentation of diagnostic calculations; incorporation of in-line comments throughout; development of a parallel stand-alone version of the model for use with field data.
2.3	December 1994	Revisions to diagnostic calculations; new near-surface atmospheric stability functions.
2.4	August 1995	Complete set of water budget diagnostic calculations; parametrizations of organic soils and rock soils; allowance for inhomegeneity between soil layers; incorporation of variable surface detention capacity.
2.5	January 1996	Completion of energy budget diagnostic calculations.
2.6	August 1997	Revisions to surface stability function calculations.
2.7	December 1997	Incorporation of variable soil permeable depth; calculation of soil thermal and hydraulic properties based on textural

		composition; modified surface temperature iteration scheme.
3.0	December 2002	Improved treatment of soil evaporation; complete treatment of organic soils; new canopy conductance formulation; preliminary routines for lateral movement of soil water; enhanced snow density and snow interception; improved turbulent transfer from vegetation; mosaic formulation.
3.1	April 2005	Faster surface temperature iteration scheme; refinements to leaf boundary resistance formulation; improved treatment of snow sublimation and interception; transition to Fortran 90 and single precision variables.
3.2	May 2006	Option for multiple soil layers at depth; additional liquid water content of snow pack; revised radiation transmission in vegetation.
3.3	December 2006	Separate temperature profile curve fit for snow and soil; multiple-layer option for ice sheets; water and energy balance checks for each time step; modifications to soil hydraulic conductivity calculations.
3.4	April 2008	Streamline and clean up code; updated soil thermal conductivity calculations; revisions to handling of water stored on vegetation.

Part

2

Data Requirements

This section describes the three types of data that are required to run CLASS: atmospheric forcing data, surface vegetation data, soil data and initial values for prognostic variables.

Forcing Data

At each time step, for each grid cell or modelled area, the following atmospheric forcing data are required:

FCLOGRD	Fractional cloud cover [ ]
FDLGRD	Downwelling longwave sky radiation [W m^{-2}]
FSIHGRD	Near infrared shortwave radiation incident on a horizontal surface [W m^{-2}]
FSVHGRD	Visible shortwave radiation incident on a horizontal surface [W m^{-2}]
PREGRD	Surface precipitation rate [kg m^{-2} s^{-1}]
PRESGRD	Surface air pressure [P_a]
QAGRD	Specific humidity at reference height [kg kg^{-1}]
TAGRD	Air temperature at reference height [K]
ULGRD	Zonal component of wind velocity [m s^{-1}]
VLGRD	Meridional component of wind velocity [m s^{-1}]
ZBLDGRD	Atmospheric blending height for surface roughness length averaging [m]
ZRFHGRD	Reference height associated with forcing air temperature and humidity [m]
ZRFMGRD	Reference height associated with forcing wind speed [m]

When assembling the forcing data from model output files or field measurements, the following recommendations are provided:

1) CLASS ordinarily requires that the forcing incoming shortwave radiation be partitioned into the visible and near-infrared components. If these are not available, however, they can each be roughly estimated as approximately half of the total incoming solar radiation.

2) The fractional cloud cover is used to calculate the direct and diffuse components of the incoming shortwave radiation. If it is not available it can be estimated on the basis of the solar zenith angle and the occurrence of precipitation (see the section on the RUNCLASS driver).

3) For atmospheric models, the air temperature supplied to CLASS should be the potential temperature, extrapolated using the dry adiabatic lapse rate to the bottom of the atmosphere, i.e. where the wind speed is zero and the pressure is equal to the surface pressure P_a. In the case of field data, the actual measured air temperature at the reference height should be supplied, since in this case the adiabatic extrapolation is performed within CLASS.

4) Atmospheric models provide the zonal and meridional components of the wind velocity, but CLASS does not actually require information on wind direction. Thus, if only the scalar wind speed is available, either ULGRD or VLGRD can be set to it, and the other to zero.

5) In atmospheric models the forcing wind speed, air temperature and relative humidity are typically obtained from the lowest modelled atmospheric layer, and thus the reference height will be the height above the "surface" (i.e. the location where the wind speed is zero and the pressure is equal to the surface pressure P_a) corresponding to that lowest layer. Some atmospheric models use a vertical co-ordinate system in which the momentum and thermodynamic levels are staggered, and if so, ZFRMGRD and ZRFHGRD will have different values. If that is the case, the switch ISLFD in the CLASS driver should be set to 2, so that the subroutines FLXSURFZ and DIASURF are called (see the RUNCLASS documentation), since the other options do not support different reference heights. In the case of field data, the reference height is the height above the ground surface at which the variables are measured. If the measurement height for wind speed is different from that for the air temperature and relative humidity, again the ISLFD switch in the CLASS driver should be set to 2. (Note that neither ZRFHGRD nor ZRFMGRD may be smaller than the vegetation canopy height, as this will cause the model run to crash.)

6) If the surface being modelled is a heterogeneous one, care must be taken to ensure that the reference heights are greater than the "blending height", the distance above the surface at which the atmospheric variables are not dominated by any one surface type. In principle this height depends on the length scale of the roughness elements; it is usually of the order of 50-100 m. In CLASS the blending height is used in averaging the roughness lengths over the modelled area, and is read in separately from ZRFMGRD and ZRFHGRD as ZBLDGRD.

7) CLASS normally runs with total incoming precipitation, and partitions it into rainfall and snowfall on the basis of empirically derived equations. If the rainfall rate (RPREGRD) and snowfall rate (SPREGRD) are available, they should be used instead. The READ statement in the CLASS driver should be modified accordingly, and the switch IPCP should be set to 4.

8) The length of the time step should be carefully considered in assembling the forcing data. CLASS has been designed to run at a time step of 30 minutes or less, and the explicit prognostic time stepping scheme used for the soil, snow and vegetation variables is based on this assumption. Longer time steps may lead to the appearance of numerical instabilities in the modelled prognostic variables.

Vegetation Data

For each of the four main vegetation categories (needleleaf trees, broadleaf trees, crops and grass), the following data are required for each mosaic tile over each grid cell or modelled area:

ALICROW	Average near-IR albedo of vegetation category when fully-leafed [ ]
ALVCROW	Average visible albedo of vegetation category when fully-leafed [ ]
CMASROW	Annual maximum canopy mass for vegetation category [kg m^{-2}]
FCANROW	Annual maximum fractional coverage of modelled area [ ]
LNZ0ROW	Natural logarithm of maximum vegetation roughness length [ ]
PAMNROW	Annual minimum plant area index of vegetation category [ ]
PAMXROW	Annual maximum plant area index of vegetation category [ ]
PSGAROW	Soil moisture suction coefficient (used in stomatal resistance calculation) [ ]
PSGBROW	Soil moisture suction coefficient (used in stomatal resistance calculation) [ ]
QA50ROW	Reference value of incoming shortwave radiation (used in stomatal resistance calculation) [W m^{-2}]
ROOTROW	Annual maximum rooting depth of vegetation category [m]
RSMNROW	Minimum stomatal resistance of vegetation category [s m^{-1}]
VPDAROW	Vapour pressure deficit coefficient (used in stomatal resistance calculation) [ ]
VPDBROW	Vapour pressure deficit coefficient (used in stomatal resistance calculation) [ ]

CLASS models the physiological characteristics of trees as remaining constant throughout the year except for the leaf area index and plant area index, which vary seasonally between the limits defined by PAMXROW and PAMNROW. The areal coverage of crops varies from zero in the winter to FCANROW at the height of the growing season, and their physiological characteristics undergo a corresponding cycle. Grasses remain constant year-round. (For full details of these calculations, see the documentation for subroutine APREP). Urban areas are also treated as "vegetation" in the CLASS code, and have associated values for FCANROW, ALVCROW, ALICROW and LNZ0ROW. Thus these arrays have a third dimension of 5 rather than 4.

Ideally the above vegetation parameters should be measured at the modelled location. Of course this is not always possible, especially when running over a large modelling domain. As a guide, the table in Appendix A provides representative values for the 20 vegetation types recognized by the Canadian GCM. If more than one type of vegetation in a given category is present on the modelled area, the parameters for the category should be areally averaged over the vegetation types present. For the stomatal resistance parameters, typical values of these for the four principal vegetation types are given below:

	RSMN	QA50	VPDA	VPDB	PSGA	PSGB
Needleleaf trees	200.0	30.0	0.65	1.05	100.0	5.0
Broadleaf trees	125.0	40.0	0.50	0.60	100.0	5.0
Crops	85.0	30.0	0.50	1.00	100.0	5.0
Grass	100.0	30.0	0.50	1.00	100.0	5.0

Soil Data

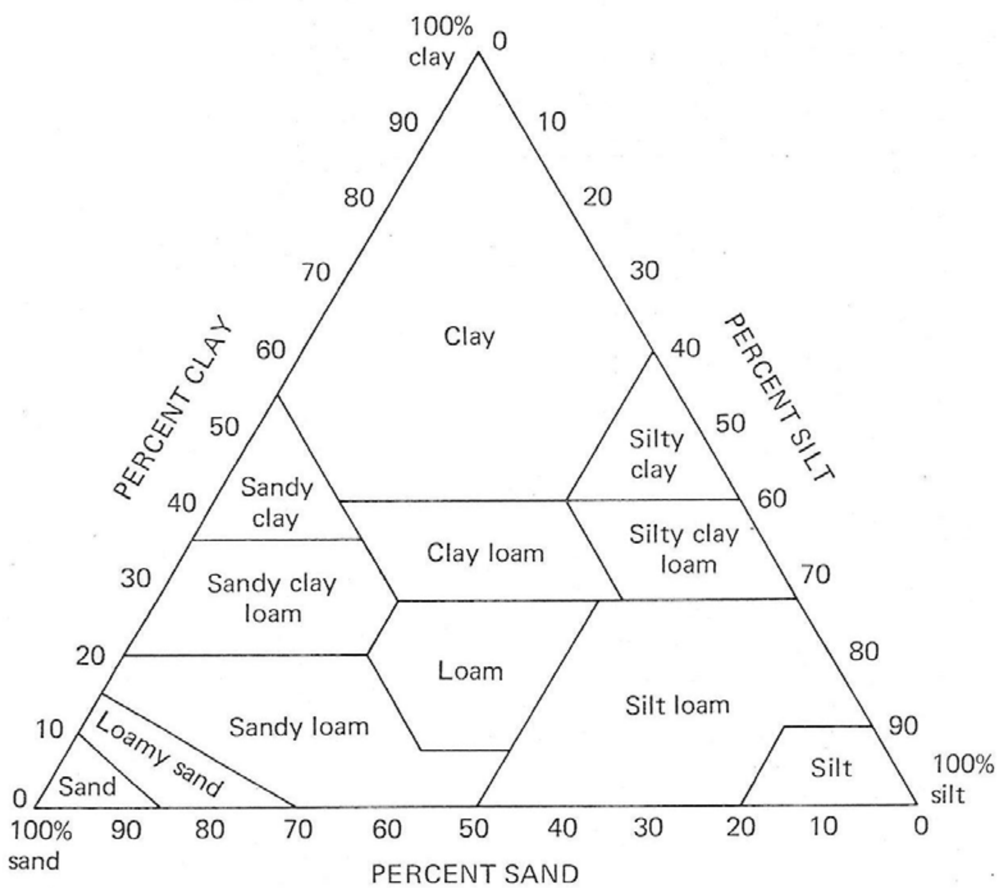
For the model run, the following information is required for each modelled soil layer:

DELZ	Layer thickness [m]
ZBOT	Depth of bottom [m]

The standard operational configuration for CLASS consists of three soil layers, of thicknesses 0.10 m, 0.25 m and 3.75 m, and thus of bottom depths 0.10, 0.35 and 4.10 m respectively. CLASS versions 3.2 and higher support other options: the third soil layer may be replaced with a larger number of thinner layers, and/or the bottom of the soil profile may be extended below 4.10 m. However, because the temperature stepping scheme used in CLASS is of an explicit formulation, care must be taken not to make the layers too thin, since this may lead to numerical instability problems. As a rule of thumb, layer thicknesses should be limited to $\geq$ 0.25 m.

For each of the modelled soil layers on each of the mosaic tiles, the following texture data are required:

CLAYROW	Percentage clay content
ORGMROW	Percentage organic matter content
SANDROW	Percentage sand content



1) For mineral soils, the percentages of sand, clay and organic matter content need not add up to 100%, since the residual is assigned to silt content. If the exact sand, clay and organic matter contents are not known, estimates can be made from the general soil type on the basis of the standard USDA texture triangle shown above. Organic matter contents in mineral soils are typically not more than a few percent.

2) If the soil layer is a fully organic one, SANDROW, CLAYROW and ORGMROW are used differently. The sand content is assigned a flag value of -2, and the organic matter content is assigned a flag value of 1, 2 or 3 depending on whether the peat texture is fibric, hemic or sapric (see Letts *et al.*, 2000). CLAYROW is not used and is set to zero.

3) If the layer consists of rock, SANDROW is assigned a flag value of -3. If it is part of a continental ice sheet, it is assigned a flag value of -4. In both cases, CLAYROW and ORGMROW are not used and are set to zero.

SANDROW, CLAYROW and ORGMROW are used to calculate the soil layer thermal and hydraulic properties in subroutine CLASSB. If the measured values of these properties are available, they should be used instead.

For each of the mosaic tiles over the modelled area, the following surface parameters must be specified:

DRNROW	Soil drainage index
FAREROW	Fractional coverage of mosaic tile on modelled area
MIDROW	Mosaic tile type identifier (1 for land surface, 0 for inland lake)
SDEPROW	Soil permeable depth [m]

1) The soil permeable depth, i.e. the depth to bedrock, may be less than the modelled thermal depth of the soil profile. This permeable depth is indicated by the variable SDEP. If the depth to bedrock occurs within a soil layer rather than at the interface between two layers, CLASS assigns the specified mineral or organic soil characteristics to the part of the layer above bedrock, and values corresponding to rock to the portion below.

2) The drainage index, DRN, is set to 1 except in cases of deep soils where it is desired to suppress drainage from the bottom of the soil profile (*e.g.* in bogs, or in deep soils with a high water table). In this case it is set to 0.

When the standard three-layer soil configuration is used, CLASS provides a means of accounting for the possibility of the depth to bedrock falling within the thick third layer, and therefore of phase changes of water taking place in only the upper part of the layer, by introducing the variable TBAS, which refers to the temperature of the lower part of the layer containing the bedrock. At the beginning of the time step the temperature of the upper part of the layer is disaggregated from the overall average layer temperature using the saved value of TBAS. The heat flow between the upper part of the soil layer and the lower part is diagnosed from the heat flux at the top of the layer. The upper layer temperature and TBAS are stepped ahead separately, and the net heat flux in the upper part of the layer is used in the phase change of water if appropriate. The upper layer temperature and TBAS are re-aggregated at the end of the time step to yield once again the overall average layer temperature.

Two variables, assumed to be constant over the grid cell, are provided if required for atmospheric model runs:

GGEOGRD	Geothermal heat flux [W m^{-2}]
Z0ORGRD	Orographic roughness length [m]

Unless the soil depth is very large and/or the run is very long, the geothermal heat flux can be set to zero. Z0ORGRD is the surface roughness length representing the contribution of orography or other terrain effects to the overall roughness, which becomes important when the modelled grid cell is very large (*e.g.* in a GCM). For field studies it can be set to zero.

Finally, four parameters are required for modelling lateral movement of soil water: GRKFROW, WFCIROW, WFSFROW and XDEPROW. However, the routines for interflow and streamflow modelling are still under development, so unless the user is involved in this development, these parameters can be set to arbitrary values, since they will not be used.

Initialization of Prognostic Variables

CLASS requires initial values of the land surface prognostic variables, either from the most recent atmospheric model integration or from field measurements. These are listed below, with guidelines for specifying values for each.

ALBSROW	Snow albedo [ ]
CMAIROW	Aggregated mass of vegetation canopy [kg m^{-2}]
GROROW	Vegetation growth index [ ]
QACROW	Specific humidity of air within vegetation canopy space [kg kg^{-1}]
RCANROW	Intercepted liquid water stored on canopy [kg m^{-2}]
RHOSROW	Density of snow [kg m^{-3}]
SCANROW	Intercepted frozen water stored on canopy [kg m^{-2}]
SNOROW	Mass of snow pack [kg m^{-2}]
TACROW	Temperature of air within vegetation canopy [K]
TBARROW	Temperature of soil layers [K]
TBASROW	Temperature of bedrock in third soil layer [K]
TCANROW	Vegetation canopy temperature [K]
THICROW	Volumetric frozen water content of soil layers [m^3 m^{-3}]
THLQROW	Volumetric liquid water content of soil layers [m^3 m^{-3}]
TPNDROW	Temperature of ponded water [K]
TSFSROW	Ground surface temperature over subarea [K]
TSNOROW	Snowpack temperature [K]
WSNOROW	Liquid water content of snow pack [kg m^{-2}]
ZPNDROW	Depth of ponded water on surface [m]

1) TBARROW, THLQROW and THICROW are required for each of the modelled soil layers. Thin soil layers near the surface equilibrate quickly, but thicker, deeper layers respond more slowly, and

long-term biases can be introduced into the simulation if their temperatures and moisture contents are not initialized accurately. For the moisture contents, it is better to err on the low side, since soil moisture recharge typically takes place on shorter scales than soil moisture loss. Very deep soil temperatures do not have a large effect on surface fluxes, but errors in their initial values can adversely effect hydrological simulations. If the standard three-layer soil configuration is being used, TBASROW should be set to the third soil layer temperature; otherwise it can be arbitrarily set to zero. For rock or ice layers, THLQROW and THICROW should both be set to zero.

2) It is best to begin a simulation in snow-free conditions, so that the snow simulation can begin from the simplest possible state where SNOROW, TSNOROW, ALBSROW, RHOSROW and WSNOROW are all initialized to zero. If erroneous values of the snow variables are specified as initial conditions, this can lead to a persistent bias in the land surface simulation.

3) The vegetation canopy has a relatively small heat capacity and water storage capacity relative to the soil, so its temperature and intercepted water stores equilibrate quite quickly. TCANROW and TACROW can be initialized to the air temperature and QACROW to the air specific humidity or to an arbitrary value. RCANROW and SCANROW can be initialized to zero. CMAIROW, which is used only in the diagnostic energy balance check during the time step, can also be set to zero.

4) GROROW should be initialized to 1 during the growing season and to 0 otherwise.

5) Surface ponded water is a small term and is ephemeral in nature, so ZPNDROW and TPNDROW can both be initialized to zero. TSFSROW is included simply to provide a first guess for the surface temperature iteration in the next time step, so it can be initialized to an arbitrary value. For the snow-covered subareas of the surface (the first and second levels of the third dimension of the array) it can be set to the freezing point of water; for the snow-free subareas (the third and fourth levels) it can be set to the temperature of the first soil layer.

Part 3

The CLASS Stand-Alone Driver

This section outlines the structure of the stand-alone driver RUNCLASS used for running CLASS offline with specified model or field data.

Integer constants, variables, flags and counters:

IALC	Flag to enable use of user-specified canopy albedo
IALG	Flag to enable use of user-specified ground albedo
IALS	Flag to enable use of user-specified snow albedo
ICAN	Number of vegetation categories being modelled
ICP1	ICAN + 1
IDAY	Julian day of the year
IDISP	Flag governing treatment of vegetation displacement height
IGND	Number of soil layers being modelled
IHGT	Flag to enable use of user-specified vegetation height
IHOUR	Hour of day
ILG	Product of NLAT and NMOS
IMIN	Minutes elapsed in current hour
IPAI	Flag to enable use of user-specified plant area index
IPCP	Flag indicating approach to be used for partitioning precipitation into rainfall and snowfall
ISLFD	Flag governing options for surface stability functions and diagnostic calculations
ITC	Flag to select iteration scheme for canopy temperature
ITCG	Flag to select iteration scheme for surface under canopy
ITG	Flag to select iteration scheme for ground or snow surface
IWF	Flag governing lateral soil water flow calculations
IYEAR	Year of run
IZREF	Flag governing treatment of surface roughness length

JLAT	Integer value of latitude of grid cell
NCOUNT	Counter for daily averaging
NICE	Counter representing number of modelled areas that are sea ice
NLANDC	Number of modelled areas that contain subareas of canopy over bare ground
NLANDCS	Number of modelled areas that contain subareas of canopy over snow
NLANDG	Number of modelled areas that contain subareas of bare ground
NLANDGS	Number of modelled areas that contain subareas of snow over bare ground
NLANDI	Number of modelled areas that are ice sheets
NLAT	Maximum number of grid cells to be modelled
NLTEST	Number of grid cells being modelled for this run
NML	Counter representing number of mosaic tiles on modelled domain thar are land
NMW	Counter representing number of mosaic tiles on modelled domain thar are water
NMOS	Maximum number of mosaic tiles being modelled for each grid cell
NMTEST	Number of mosaic tiles being modelled for this run
NSUM	Timestep sum for daily averaging
NWAT	Counter representing number of modelled areas that are ocean

Land surface prognostic variables

(Before gathering, these have the suffix ROW, and the first two dimensions of the arrays are NLAT and NMOS. After gathering, the new variables have the suffix GAT, and the first dimension of the array is ILG.)

ALBS	Snow albedo [ ]
CMAI	Aggregated mass of vegetation canopy [kg m^{-2}]
GRO	Vegetation growth index [ ]
QAC	Specific humidity of air within vegetation canopy space [kg kg^{-1}]
RCAN	Intercepted liquid water stored on canopy [kg m^{-2}]
RHOS	Density of snow [kg m^{-3}]
SCAN	Intercepted frozen water stored on canopy [kg m^{-2}]
SNO	Mass of snow pack [kg m^{-2}]
TAC	Temperature of air within vegetation canopy [K]
TBAR	Temperature of soil layers [K]
TBAS	Temperature of bedrock in third soil layer [K]
TCAN	Vegetation canopy temperature [K]
THIC	Volumetric frozen water content of soil layers [m^3 m^{-3}]
THLQ	Volumetric liquid water content of soil layers [m^3 m^{-3}]
TPND	Temperature of ponded water [K]
TSFS	Ground surface temperature over subarea [K]
TSNO	Snowpack temperature [K]
WSNO	Liquid water content of snow pack [kg m^{-2}]
ZPND	Depth of ponded water on surface [m]

Gather-scatter index arrays

IICE	Index of grid cell corresponding to current element of gathered vector of sea ice

	variables [ ]
ILMOS	Index of grid cell corresponding to current element of gathered vector of land surface variables [ ]
IWAT	Index of grid cell corresponding to current element of gathered vector of ocean variables [ ]
IWMOS	Index of grid cell corresponding to current element of gathered vector of inland water body variables [ ]
JLMOS	Index of mosaic tile corresponding to current element of gathered vector of land surface variables [ ]
JWMOS	Index of mosaic tile corresponding to current element of gathered vector of inland water body variables [ ]

Canopy and soil information arrays

(As with the land surface prognostic variables, before gathering these have the suffix ROW, and the first two dimensions of the arrays are NLAT and NMOS. After gathering, the new variables have the suffix GAT, and the first dimension of the array is ILG.)

ACID	Optional user-specified value of canopy near-infrared albedo to override CLASS-calculated value [ ]
ACVD	Optional user-specified value of canopy visible albedo to override CLASS-calculated value [ ]
AGID	Optional user-specified value of ground near-infrared albedo to override CLASS-calculated value [ ]
AGVD	Optional user-specified value of ground visible albedo to override CLASS-calculated value [ ]
ALGD	Reference albedo for dry soil [ ]
ALGW	Reference albedo for saturated soil [ ]
ALIC	Background average near-infrared albedo of vegetation category [ ]
ALVC	Background average visible albedo of vegetation category [ ]
ASID	Optional user-specified value of snow near-infrared albedo to override CLASS-calculated value [ ]
ASVD	Optional user-specified value of snow visible albedo to override CLASS-calculated value [ ]
BI	Clapp and Hornberger empirical “b” parameter [ ]
CLAY	Percentage clay content of soil
CMAS	Maximum canopy mass for vegetation category [kg m^{-2}]
DLZW	Permeable thickness of soil layer [m]
DRN	Drainage index at bottom of soil profile [ ]
FARE	Fractional coverage of mosaic tile on modelled area
FCAN	Maximum fractional coverage of modelled area by vegetation category [ ]
GRKF	WATROF parameter used when running MESH code [ ]
GRKS	Saturated hydraulic conductivity of soil layers [m s^{-1}]
HCPS	Volumetric heat capacity of soil particles [J m^{-3}]
HGTD	Optional user-specified values of roughness lengths of vegetation categories to override CLASS-calculated values [m]

IORG	Integer identifier associated with organic matter content
ISND	Integer identifier associated with sand content
LNZ0	Natural logarithm of maximum roughness length of vegetation category [ ]
MID	Mosaic tile type identifier (1 for land surface, 0 for inland lake)
ORGM	Percentage organic matter content of soil
PAID	Optional user-specified value of plant area indices of vegetation categories to override CLASS-calculated values [ ]
PAMN	Minimum plant area index of vegetation category [ ]
PAMX	Maximum plant area index of vegetation category [ ]
PSGA	Soil moisture suction coefficient for vegetation category (used in stomatal resistance calculation) [ ]
PSGB	Soil moisture suction coefficient for vegetation category (used in stomatal resistance calculation) [ ]
PSIS	Soil moisture suction at saturation [m]
PSIW	Soil moisture suction at wilting point [m]
QA50	Reference value of incoming shortwave radiation for vegetation category (used in stomatal resistance calculation) [W m^{-2}]
SDEP	Depth to bedrock in the soil profile
ROOT	Maximum rooting depth of vegetation category [m]
RSMN	Minimum stomatal resistance of vegetation category [s m^{-1}]
SAND	Percentage sand content of soil
TCS	Thermal conductivity of soil particles [W m^{-1} K^{-1}]
THFC	Field capacity [m^3 m^{-3}]
THM	Residual soil liquid water content remaining after freezing or evaporation [m^3 m^{-3}]
THP	Pore volume in soil layer [m^3 m^{-3}]
THR	Liquid water retention capacity for organic soil [m^3 m^{-3}]
THRA	Fractional saturation of soil behind the wetting front [ ]
VPDA	Vapour pressure deficit coefficient for vegetation category (used in stomatal resistance calculation) [ ]
VPDB	Vapour pressure deficit coefficient for vegetation category (used in stomatal resistance calculation) [ ]
WFCI	WATROF parameter used when running MESH code [ ]
WFSF	WATROF parameter used when running MESH code [ ]
XSLP	Surface slope (used when running MESH code) [degrees]
ZBTW	Depth to permeable bottom of soil layer [m]
ZPLG	Maximum water ponding depth for snow-free subareas (user-specified when running MESH code) [m]
ZPLS	Maximum water ponding depth for snow-covered subareas (user-specified when running MESH code) [m]
ZSNL	Limiting snow depth below which coverage is < 100% [m]

Atmospheric and grid-constant input variables

(These variables are constant over each grid call; they have the suffix GRD and a dimension of NLAT before the gather operation. In the gather subroutine CLASSG they are assigned to vectors with dimension ILG, with the suffix GAT.)

CSZ	Cosine of solar zenith angle [ ]
DLON	Longitude of grid cell (east of Greenwich) [degrees]
FCLO	Fractional cloud cover [ ]
FDL	Downwelling longwave radiation at bottom of atmosphere (i.e. incident on modelled land surface elements [W m^{-2}]
FSIH	Near-infrared radiation incident on horizontal surface [W m^{-2}]
FSVH	Visible radiation incident on horizontal surface [W m^{-2}]
GC	Type identifier for grid cell (1 = sea ice, 0 = ocean, -1 = land)
GGEO	Geothermal heat flux at bottom of soil profile [W m^{-2}]
PADR	Partial pressure of dry air [Pa]
PRE	Surface precipitation rate [kg m^{-2} s^{-1}]
PRES	Surface air pressure [Pa]
QA	Specific humidity at reference height [kg kg^{-1}]
RADJ	Latitude of grid cell (positive north of equator) [rad]
RHOA	Density of air [kg m^{-3}]
RHSI	Density of fresh snow [kg m^{-3}]
RPCP	Rainfall rate over modelled area [m s^{-1}]
RPRE	Rainfall rate over modelled area [kg m^{-2} s^{-1}]
SPCP	Snowfall rate over modelled area [m s^{-1}]
SPRE	Snowfall rate over modelled area [kg m^{-2} s^{-1}]
TA	Air temperature at reference height [K]
TADP	Dew point temperature of air [K]
TRPC	Rainfall temperature [K]
TSPC	Snowfall temperature [K]
UL	Zonal component of wind velocity [m s^{-1}]
UV	Wind speed [m s^{-1}]
VL	Meridional component of wind velocity [m s^{-1}]
VPD	Vapour pressure deficit [mb]
Z0OR	Orographic roughness length [m]
ZBLD	Atmospheric blending height for surface roughness length averaging [m]
ZDH	User-specified height associated with diagnosed screen-level variables [m]
ZDM	User-specified height associated with diagnosed anemometer-level wind speed [m]
ZRFH	Reference height associated with forcing air temperature and humidity [m]
ZRFM	Reference height associated with forcing wind speed [m]

Land surface diagnostic variables

(As with the land surface prognostic variables, before gathering these have the suffix ROW, and the first two dimensions of the arrays are NLAT and NMOS. After gathering, the new variables have the suffix GAT, and the first dimension of the array is ILG. After the scatter operation has been performed, grid-cell average values for each of these variables are calculated and stored in new variables with the suffix GRD and a first dimension of NLAT.)

ALIR	Diagnosed total near-infrared albedo of land surface [ ]
ALVS	Diagnosed total visible albedo of land surface [ ]
CDH	Surface drag coefficient for heat [ ]
CDM	Surface drag coefficient for momentum [ ]

DR	Surface drag coefficient under neutral stability [ ]
EF	Evaporation efficiency at ground surface [ ]
FLGG	Diagnosed net longwave radiation at soil surface [W m^{-2}]
FLGS	Diagnosed net longwave radiation at snow surface [W m^{-2}]
FLGV	Diagnosed net longwave radiation on vegetation canopy [W m^{-2}]
FSGG	Diagnosed net shortwave radiation at soil surface [W m^{-2}]
FSGS	Diagnosed net shortwave radiation at snow surface [W m^{-2}]
FSGV	Diagnosed net shortwave radiation on vegetation canopy [W m^{-2}]
FSNO	Diagnosed fractional snow coverage [ ]
GA	Diagnosed product of drag coefficient and wind speed over modelled area [m s^{-1}]
GFLX	Heat conduction between soil layers [W m^{-2}]
GT	Diagnosed effective surface black-body temperature [K]
HBL	Height of the atmospheric boundary layer [m]
HEVC	Diagnosed latent heat flux on vegetation canopy [W m^{-2}]
HEVG	Diagnosed latent heat flux at soil surface [W m^{-2}]
HEVS	Diagnosed latent heat flux at snow surface [W m^{-2}]
HFS	Diagnosed total surface sensible heat flux over modelled area [W m^{-2}]
HFSC	Diagnosed sensible heat flux on vegetation canopy [W m^{-2}]
HFSG	Diagnosed sensible heat flux at soil surface [W m^{-2}]
HFSS	Diagnosed sensible heat flux at snow surface [W m^{-2}]
HMFC	Diagnosed energy associated with phase change of water on vegetation [W m^{-2}]
HMFG	Diagnosed energy associated with phase change of water in soil layers [W m^{-2}]
HMFN	Diagnosed energy associated with phase change of water in snow pack [W m^{-2}]
HTC	Diagnosed internal energy change of soil layer due to conduction and/or change in mass [W m^{-2}]
HTCC	Diagnosed internal energy change of vegetation canopy due to conduction and/or change in mass [W m^{-2}]
HTCS	Diagnosed internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}]
ILMO	Inverse of Monin-Obukhov roughness length (m^{-1}]
ISUM	Total number of iterations required to solve surface energy balance for the elements of the four subareas for the current run
ITCT	Counter of number of iterations required to solve surface energy balance for the elements of the four subareas
PCFC	Diagnosed frozen precipitation intercepted by vegetation [kg m^{-2} s^{-1}]
PCLC	Diagnosed liquid precipitation intercepted by vegetation [kg m^{-2} s^{-1}]
PCPG	Diagnosed precipitation incident on ground [kg m^{-2} s^{-1}]
PCPN	Diagnosed precipitation incident on snow pack [kg m^{-2} s^{-1}]
PET	Diagnosed potential evapotranspiration [kg m^{-2} s^{-1}]
QEVP	Diagnosed total surface latent heat flux over modelled area [W m^{-2}]
QFC	Diagnosed vapour flux from transpiration over modelled area [W m^{-2}]
QFCF	Diagnosed vapour flux from frozen water on vegetation [kg m^{-2} s^{-1}]
QFCL	Diagnosed vapour flux from liquid water on vegetation [kg m^{-2} s^{-1}]
QFG	Diagnosed water vapour flux from ground [kg m^{-2} s^{-1}]
QFN	Diagnosed water vapour flux from snow pack [kg m^{-2} s^{-1}]
QFS	Diagnosed total surface water vapour flux over modelled area [kg m^{-2} s^{-1}]
QFX	Product of surface drag coefficient, wind speed and surface-air specific humidity

difference [m s^{-1}]
QG Diagnosed surface specific humidity [kg kg^{-1}]
ROF Total runoff from soil [kg m^{-2} s^{-1}]
ROFB Base flow from bottom of soil column [kg m^{-2} s^{-1}]
ROFC Liquid/frozen water runoff from vegetation [kg m^{-2} s^{-1}]
ROFN Liquid water runoff from snow pack [kg m^{-2} s^{-1}]
ROFO Overland flow from top of soil column [kg m^{-2} s^{-1}]
ROFS Interflow from sides of soil column [kg m^{-2} s^{-1}]
ROVG Diagnosed liquid/frozen water runoff from vegetation to ground surface [kg m^{-2} s^{-1}]
SFCQ Diagnosed screen-level specific humidity [kg kg^{-1}]
SFCT Diagnosed screen-level air temperature [K]
SFCU Diagnosed anemometer-level u-wind [m s^{-1}]
SFCV Diagnosed anemometer-level v-wind [m s^{-1}]
TFX Product of surface drag coefficient, wind speed and surface-air temperaturedifference [K m s^{-1}]
TROB Temperature of base flow from bottom of soil column [K]
TROF Temperature of total runoff [K]
TROO Temperature of overland flow from top of soil column [K]
TROS Temperature of interflow from sides of soil column [K]
TSF Average ground/snow surface temperature over modelled area [K]
UE Friction velocity of air [m s^{-1}]
WTAB Depth of water table in soil [m]
WTRC Diagnosed residual water transferred on or off the vegetation canopy [kg m^{-2} s^{-1}]
WTRG Diagnosed residual water transferred into or out of the soil [kg m^{-2} s^{-1}]
WTRS Diagnosed residual water transferred into or out of the snow pack [kg m^{-2} s^{-1}]

Time averaging arrays

(These have the suffix "ACC", and represent grid-averaged, daily averaged values of selected prognostic and diagnostic variables.)

ALIR Diagnosed total near-infrared albedo of land surface [ ]
ALVS Diagnosed total visible albedo of land surface [ ]
EVAP Diagnosed total surface water vapour flux over modelled area [kg m^{-2}]
FSIN Downwelling shortwave radiation above surface [W m^{-2}]
FLIN Downwelling longwave radiation above surface [W m^{-2}]
FLUT Upwelling longwave radiation from surface [W m^{-2}]
GRO Vegetation growth index [ ]
GT Diagnosed effective surface black-body temperature [K]
HFS Diagnosed total surface sensible heat flux over modelled area [W m^{-2}]
HMFN Diagnosed energy associated with phase change of water in snow pack [W m^{-2}]
OVR Overland flow from top of soil column [kg m^{-2}]
PRE Surface precipitation rate [kg m^{-2}]
PRES Surface air pressure [Pa]
QA Specific humidity at reference height [kg kg^{-1}]
QEVP Diagnosed total surface latent heat flux over modelled area [W m^{-2}]

RCAN	Intercepted liquid water stored on canopy [kg m^{-2}]
RHOS	Density of snow [kg m^{-3}]
ROF	Total runoff from soil [kg m^{-2}]
SCAN	Intercepted frozen water stored on canopy [kg m^{-2}]
SNO	Mass of snow pack [kg m^{-2}]
TA	Air temperature at reference height [K]
TBAR	Temperature of soil layers [K]
THAL	Total volumetric water content of soil layers [m^3 m^{-3}]
THIC	Volumetric frozen water content of soil layers [m^3 m^{-3}]
THLQ	Volumetric liquid water content of soil layers [m^3 m^{-3}]
TCAN	Vegetation canopy temperature [K]
TSNO	Snowpack temperature [K]
UV	Wind speed [m s^{-1}]
WSNO	Liquid water content of snow pack [kg m^{-2}]
WTBL	Depth of water table in soil [m]

This section describes the structure of RUNCLASS, the stand-alone driver designed to run CLASS offline. The benchmark version of RUNCLASS for CLASS version 3.4 has been set up to run a test using measured field data, at a single location and with only one mosaic tile, for the standard configuration of three soil layers. When using RUNCLASS for other applications, modifications to the code may be required, and these locations are flagged in the following discussion.

The first requirement is to consider whether the values of the integer constants specified on lines 37 and 38 should be changed. The maximum number of grid cells being modelled, NLAT, can be left at 3 and the maximum number of mosaic tiles, NMOS., can be left at 8 unless the particular application being run involves more of either one. ICAN should retain a value of 4, since the standard approach of four main vegetation categories is hard-coded into CLASS. ILG should be set to the product of NLAT and NMOS, and ICP1 should be set to ICAN + 1. IGND is set to the number of soil layers that the user wishes to model.

After the DIMENSION statements and variable declarations, the common blocks are defined and the values of the variables are assigned through the external BLOCK DATA routine CLASSBD and a call to the subroutine CLASSD (see the appropriate section.) The grid-average height for the momentum diagnostic variables ZDMGRD and the energy diagnostic variables ZDHGRD are hard-coded to the standard anemometer height of 10 m and the screen height of 2 m respectively.

A number of switches are assigned flag values depending on the user's application:

1) IDISP. This switch controls the calculation of the vegetation displacement height. In most atmospheric models a "terrain-following" coordinate system is used, in which the vegetation displacement height is considered to be part of the "terrain", and is therefore neglected. For such applications IDISP is set to 0. For all other applications, such as studies making use of field data, it is set to 1.

2) IZREF. This switch indicates where the bottom of the atmosphere is conceptually located. In most atmospheric models the bottom is assumed to lie at the local surface roughness length, i.e. where the horizontal wind speed is zero; for such simulations IZREF is set to 2. For all other cases it is set to 1.

3) ISLFD. This switch indicates which surface layer flux stability correction and screen-level diagnostic subroutines are to be used. If ISLFD=0, the CCCma stability correction subroutine DRCOEF is used with the original GCM screen-level diagnostic calculations. If ISLFD=1, DRCOEF is used for the stability corrections and the RPN subroutine SLDIAG is used for the screen level diagnostic calculations. If ISLFD=2, the RPN stability correction subroutine FLXSURFZ is used with the companion RPN subroutine DIASURF for the screen level diagnostics. (When running CLASS coupled to an atmospheric model with staggered vertical thermodynamic and momentum levels, ISLFD is to be set to 2, since FLXSURFZ allows inputs on staggered levels.)

4) IPCP. This switch is used to specify which approach is to be used in subroutine CLASSI for the partitioning of precipitation between rainfall and snowfall. If IPCP=1, precipitation is assumed to be all rainfall at air temperatures above 0 C and all snowfall at air temperatures ≤ 0 C. If IPCP=2, the partitioning between rainfall and snowfall varies linearly between all rainfall at temperatures above 2 C, and all snowfall at temperatures below 0 C. If IPCP=3, rainfall and snowfall are partitioned according to a polynomial curve, from all rainfall at temperatures above 6 C to all snowfall at temperatures below 0 C. If IPCP=4, the rainfall and snowfall rates, RPREGRD and SPREGRD, are read in directly at each time step, and the total precipitation is calculated as their sum. (Note that if the latter option is used, the READ and FORMAT statements for the forcing variables in loop 250 must be modified.)

5) ITC, ITCG and ITG. These switches refer to the iteration schemes to be used for the solution of the surface energy balance and the calculation of the surface temperature for the vegetation canopy, the ground under the canopy, and the bare ground respectively. If the switch is set to 1, the bisection method of iteration is used; if it is set to 2 the Newton-Raphson scheme is used.

6) IWF. This switch indicates whether interflow and streamflow calculations are to be performed. If IWF=0 no lateral flow calculations are done. (Note that the interflow and streamflow parts of the code are still under development, so unless the user is engaged in this development, this switch should be set to 0.)

7) IPAI, IHGT, IALC, IALS, IALG. These switches allow values of plant area index, vegetation height, canopy albedo, snow albedo and ground albedo to be specified by the user at each time step. If the switch is set to 0, the value calculated by CLASS is used; if it is set to 1 the user-specified value is used. (Note that if this option is utilized, the user must provide the necessary files and insert the required READ statements into the RUNCLASS code.)

Next, files are opened for reading and writing. The CLASS input data are organized into two parts: an "ini" file containing background and initialization data, and a "met" file containing meteorological forcing data (for further details, see the section on "Data Requirements"). A third file, "Soil_3lev", contains information on the depth and spacing of the soil layers. (A different file should be created and read here if it is desired to use a soil configuration other than the standard three layers; again, see the section on

"Data Requirements".) Nine other files with the suffixes "of1" to "of9" are opened to store output data. Title lines are written to the nine output files using information from the "ini" file.

In loop 25 the thickness and depth to the bottom of each of the soil layers is read from the file "Soil_3lev". Next the first data line in the "ini" file is read, which contains several basic pieces of information:

1) DEGLAT and DEGLON, the latitude (positive northward, negative southward) and longitude (east of Greenwich).

2) ZRFMGRD and ZRFHGRD, the reference height at which the momentum variables (wind speed) and energy variables (temperature and specific humidity) are provided. In a run using atmospheric model forcing data, these heights would vary by time step, but since this version of the driver is set up to use field data, ZRFMGRD and ZRFHGRD refer to the measurement height of these variables.

3) ZBLDGRD, the atmospheric blending height. Technically this variable depends on the length scale of the patches of roughness elements on the land surface, but this is difficult to ascertain. Here it is assigned a value of 50 m.

4) GCGRD, the GCM surface descriptor variable. For land surfaces (including inland water) it has a value of -1.

5) NLTEST and NMTEST, the number of grid cells or modelled areas and the number of mosaic tiles for this test run. As noted above, the benchmark version of the driver is set up to handle one grid cell with one mosaic tile, so NLTEST and NMTEST are each assigned values of 1 in the "ini" file, and all of the GRD input variables have only one entry. If it were desired to run different data sets with more tiles or grid cells, a loop or loops would have to be introduced into the READ statements, and additional lines in the "ini" file, to read in the necessary information.

In the following lines of code the parameter JLAT is calculated from DEGLAT as the nearest integer value, and DEGLON is converted to radians and stored in the array RADJGRD. DEGLON is stored as is in DLONGRD. The orographic roughness length, Z0ORGRD, and the geothermal heat flux, GGEOGRD, are set to zero for this application.

In the 50 loop, vegetation and soil information are read over each of the NLTEST x NMTEST modelled areas and mosaic tiles (one in the benchmark simulation). The first twelve lines deal with background data. The last three lines deal with initialization data for the CLASS prognostic variables. (For further details on these data see the section on "Data Requirements").

In the 100 and 150 loops, further initial calculations are done. In the 100 loop the temperatures that were read from the "ini" file are converted to degrees C, and initial values are assigned to secondary prognostic variables. The limiting snow depth, ZSNL, is assigned its operational value of 0.10 m. An option is included to extrapolate soil information to layers below the third layer, if more are being modelled and if no measured data are available for them. (This loop is to be commented out or deleted if data are actually available.) In the 150 loop, the daily average accumulator arrays are initialized to zero.

As the last step in the initialization sequence, the subroutine CLASSB is called, to assign soil thermal and hydraulic properties on the basis of the textural information read in for each of the soil layers. The timestep counter N for the run is initialized to 0, the daily averaging counter NCOUNT is set to 1, and the total number of timesteps in the day NDAY is calculated as the number of seconds in a day (86400) divided by the timestep length DELT.

The 200 continuation line marks the beginning of the time stepping loop for the actual run. N is incremented by 1, and the atmospheric forcing data for the current time step are read in for each grid cell or modelled area (see the section on "Data Requirements"). In the dataset associated with the benchmark run, only the total incoming shortwave radiation FSDOWN is available; it is partitioned approximately into the incoming visible (FSVHGRD) and near-infrared (FSIHGRD) radiation by dividing it in half. The air temperature TAGRD is converted from degrees C to K. The zonal (ULGRD) and meridional (VLGRD) components of the wind speed are not available at the benchmark site; only the overall wind speed UVGRD is measured. However, CLASS does not require wind direction for its calculations, so UVGRD is arbitrarily assigned to ULGRD and VLGRD is set to zero for this run. The cosine of the solar zenith angle COSZ is calculated from the day of the year, the hour, the minute and the latitude using basic radiation geometry, and (avoiding vanishingly small numbers) is assigned to CSZGRD. The fractional cloud cover FCLOGRD is not available at the benchmark site; a rough estimate is obtained by setting it to 1 when precipitation is occurring, and to the fraction of incoming diffuse radiation XDIFFUS otherwise (assumed to be 1 when the sun is at the horizon, and 0.10 when it is at the zenith).

The core CLASS subroutines are now called in sequence:

- CLASSI evaluates a series of derived atmospheric variables;
- GATPREP assigns values to vectors governing the gather-scatter operations;
- CLASSG performs the gather operation, gathering variables from their positions as mosaic tiles within the modelled areas to long vectors of mosaic tiles;
- CLASSZ does the initial calculations for the energy and water balance checks;
- CLASSA manages the calculation of albedos and other surface parameters;
- CLASST calls the subroutines associated with the surface energy balance calculations;
- CLASSW calls the subroutines associated with the surface water balance calculations;
- CLASSZ completes the energy and water balance checks for the current time step;
- CLASSS performs the scatter operation, scattering the variables from the long vectors of mosaic tiles back onto the configuration of mosaic tiles within grid cells.

In the remaining sections of RUNCLASS the output variables are processed, and selected ones are written to the nine "of" files. In the 450 loop several high-level diagnostic variables are calculated for the current time step, and a wide variety of variables are written to the "of4" to "of9" files. In loops 525 to 600 grid-cell average values are calculated for the mosaic diagnostic variables. In loops 675 to 800 daily average values are calculated for selected diagnostic variables, for the CLASS prognostic variables and for the forcing data, and are written to the "of1" to "of3" files; the accumulator arrays are subsequently reset to zero.

At the end of the 200 loop NCOUNT is incremented by 1, and is reset to 1 if it exceeds NDAY. After exiting the loop, sums over the whole run are calculated for the components of the surface temperature iteration counter ITCTGAT, and the program is terminated.

Part

4

Common Block and Other Preliminary Routines

CLASSBD and CLASSD

Purpose: Assign values to variables in CLASS common blocks. CLASS uses several kinds of variables in its common blocks. Some are defined specifically for use in the CLASS code; some are used in the code of the atmospheric model as well.

a) *Common block variables defined in subroutine CLASSD*

In subroutine CLASSD, some variables in CLASS common blocks are set equal to their corresponding values in the common blocks PARAMS, PARAM1, PARAM3 and TIMES which are used in the GCM, and some variables in the common blocks SURFCON and PHYCON which are used in the RPN subroutines DIASURF and FLXSURFZ are set equal to their values defined in the GCM or in the block data routine CLASSBD, so that consistency is maintained throughout the code. The variables in question are as follows:

CLASS/RPN name	GCM name	Definition	Units
DELT	DELTIM	Time step	s
TFREZ	CELZRO	Freezing point of water	K
RGAS	GAS	Gas constant	$J\ kg^{-1}\ K^{-1}$
RGASV	GASV	Gas constant for water vapour	$J\ kg^{-1}\ K^{-1}$
GRAV	G	Acceleration due to gravity	$m\ s^{-1}$
CGRAV	G	Acceleration due to gravity	$m\ s^{-1}$

SBC	SIGMA	Stefan Bolzmann constant	W m^{-2} K^{-4}
CKARM	VKC	Von Karman constant	-
SPHAIR	CPRES	Specific heat of air	J kg^{-1} K^{-1}
CPD	CPRES	Specific heat of air	J kg^{-1} K^{-1}
PI	CPI	Pi	-

b) CLASS common block variables defined in block data routine CLASSBD

In routine CLASSBD, values are primarily assigned to the variables that are specific to the CLASS code, and are passed through it via common blocks CLASS1 through CLASS8. The table below lists the scalar variables, their definitions, and their designated values with units.

Name	**Definition**	**Value**	**Units**
VKC	Von Karman constant	0.40	-
CT	Drag coefficient for water	1.15×10^{-3}	-
VMIN	Minimum wind speed	0.1	m s-1
TCW	Thermal conductivity of water	0.57	W m^{-1} K^{-1}
TCICE	Thermal conductivity of ice	2.24	W m^{-1} K^{-1}
TCSAND	Thermal conductivity of sand	2.5	W m^{-1} K^{-1}
TCCLAY	Thermal conductivity of clay	2.5	W m^{-1} K^{-1}
TCOM	Thermal conductivity of organic matter	0.25	W m^{-1} K^{-1}
TCDRYS	Thermal conductivity of dry mineral soil	0.275	W m^{-1} K^{-1}
RHOSOL	Density of soil mineral matter	2.65×10^{3}	kg m^{-3}
RHOOM	Density of soil organic matter	1.30×10^{3}	kg m^{-3}
HCPW	Volumetric heat capacity of water	4.187×10^{6}	J m^{-3} K^{-1}
HCPICE	Volumetric heat capacity of ice	1.9257×10^{6}	J m^{-3} K^{-1}
HCPSOL	Volumetric heat capacity of mineral matter	2.25×10^{6}	J m^{-3} K^{-1}
HCPOM	Volumetric heat capacity of organic matter	2.50×10^{6}	J m^{-3} K^{-1}
HCPSND	Volumetric heat capacity of sand	2.13×10^{6}	J m^{-3} K^{-1}
HCPFIN	Volumetric heat capacity of fine mineral soil	2.38×10^{6}	J m^{-3} K^{-1}
SPHW	Specific heat of water	4.186×10^{3}	J kg^{-1} K^{-1}
SPHICE	Specific heat of ice	2.10×10^{3}	J kg^{-1} K^{-1}
SPHVEG	Specific heat of vegetation matter	2.70×10^{3}	J kg^{-1} K^{-1}
RHOW	Density of water	1.0×10^{3}	kg m^{-3}
RHOICE	Density of ice	0.917×10^{3}	kg m^{-3}
TCGLAC	Thermal conductivity of ice sheets	2.24	W m^{-1} K^{-1}
CLHMLT	Latent heat of freezing of water	0.334×10^{6}	J kg^{-1}
CLHVAP	Latent heat of vaporization of water	2.501×10^{6}	J kg^{-1}
ZOLNG	Natural log of roughness length of soil	-4.605	-
ZOLNS	Natural log of roughness length of snow	-6.908	-
ZOLNI	Natural log of roughness length of ice	-6.215	-
ZORATG	Ratio of soil roughness length for momentum to roughness length for heat	3.0	-
ALVSI	Visible albedo of ice	0.95	-

ALIRI	Near-infrared albedo of ice	0.73	-
ALVSO	Visible albedo of organic matter	0.05	-
ALIRO	Near-infrared albedo of organic matter	0.30	-
ALBRCK	Albedo of rock	0.27	-

Values are also assigned to several non-scalar variables, as follows:

1) The crop growth descriptor array GROWYR (see the documentation for subroutine APREP);
2) Three parameters for the four main vegetation categories recognized by CLASS (needleleaf trees, broadleaf trees, crops and grass): ZORAT, the ratio of the roughness length for momentum to the roughness length for heat (currently set to 1); CANEXT, an attenuation coefficient used in calculating the sky view factor for vegetation canopies (variable c in the documentation for subroutine CANALB); and XLEAF, a leaf dimension factor used in calculating the leaf boundary resistance (variable C_l in the documentation for subroutine APREP);
3) Six hydraulic parameters associated with the three basic types of organic soils (fibric, hemic and sapric): THPORG, THRORG, THMORG, BORG, PSISORG and GRKSORG (see the documentation for subroutine CLASSB). The table below lists their values alongside the symbols used in the CLASSB documentation.

Name	**Symbol**	**Fibric peat**	**Hemic peat**	**Sapric peat**
THPORG	θ_p	0.93	0.88	0.83
BORG	b	2.7	6.1	12.0
GRKSORG	K_{sat}	2.8×10^{-4}	2.0×10^{-6}	1.0×10^{-7}
PSISORG	ψ_{sat}	0.0103	0.0102	0.0101
THMORG	θ_{min}	0.04	0.15	0.22
THRORG	θ_{ret}	0.275	0.62	0.705

Finally, if CLASS is being run offline, values must be assigned to the variables listed in the first table which would normally be assigned in the GCM:

GCM name	**Definition**	**Value**	**Units**
DELTIM	Time step	Varies by run	s
CELZRO	Freezing point of water	273.16	K
GAS	Gas constant	287.04	$J\ kg^{-1}\ K^{-1}$
GASV	Gas constant for water vapour	461.50	$J\ kg^{-1}\ K^{-1}$
G	Acceleration due to gravity	9.80616	$m\ s^{-1}$
SIGMA	Stefan Bolzmann constant	5.66796×10^{-8}	$W\ m^{-2}\ K^{-4}$
CPRES	Specific heat of air	1.00464×10^{3}	$J\ kg^{-1}\ K^{-1}$
CPI	Pi	3.14159265	-

The variables in common blocks SURFCON and PHYCON that do not have corresponding values assigned in the GCM are assigned their RPN values, and the remaining variables in the GCM common blocks PARAMS, PARAM1, PARAM3 and TIMES are assigned dummy values.

CLASSB

Purpose: Assign thermal and hydraulic properties to soil layers based on sand/clay content, or soil type. Also calculate permeable thickness of soil layers, and wet and dry surface albedo for mineral soils.

Output variables:

ALGDRY	All-wave albedo of dry soil for modelled area [ ]
ALGWET	All-wave albedo of wet soil for modelled area [ ]
BI	Clapp and Hornberger empirical parameter [ ] (b)
DELZW	Thickness of permeable part of soil layer [m]
GRKSAT	Hydraulic conductivity of soil at saturation [m s^{-1}] (K_{sat})
HCPS	Volumetric heat capacity of soil matter [J m^{-3} K^{-1}] (C_g)
IORG	Organic matter content flag
ISAND	Sand content flag
PSISAT	Soil moisture suction at saturation [m] (ψ_{sat})
PSIWLT	Soil moisture suction at wilting point [m] (ψ_{wilt})
TCS	Thermal conductivity of soil [W m^{-1} K^{-1}] (τ_g)
THFC	Field capacity [m^3 m^{-3}] (θ_{fc})
THLMIN	Residual soil liquid water content remaining after freezing or evaporation [m^3 m^{-3}] (θ_{min})
THLRAT	Fractional saturation of soil at half the saturated hydraulic conductivity [ ] (f_{inf})
THLRET	Liquid water retention capacity for organic soil [m^3 m^{-3}] (θ_{ret})
THPOR	Pore volume [m^3 m^{-3}] (θ_p)
ZBOTW	Depth of bottom of permeable part of soil layer [m]

Input variables:

CLAY	Percent clay content of soil layer [%] (X_{clay})
DELZ	Thickness of soil layer [m]
ORGM	Percent organic matter content of soil layer [%]
SAND	Percent sand content of soil layer [%] (X_{sand})
SDEPTH	Permeable depth of soil column (depth to bedrock) [m] (z_b)
ZBOT	Depth of bottom of soil layer [m]

The thermal and hydraulic properties of each of the modelled soil layers are determined differently for different ground types. The percentage sand and organic matter contents are first converted into integer flags, and based on the value of the sand flag ISAND, the appropriate part of the code is executed.

CLASS allows the permeable depth of the soil profile z_b, i.e. the depth to bedrock, to be less than the modelled thermal depth. In loop 200 calculations are done to identify the soil layer in which this depth occurs, and to determine the permeable thickness DELZW of this layer (the distance from the top of the layer to z_b). The depth of the bottom of this permeable thickness, ZBOTW, is z_b. For layers above this soil layer, DELZW is set equal to DELZ, the standard thickness of the corresponding thermal layer, and ZBOTW is set equal to ZBOT, the standard depth of the bottom of the corresponding thermal layer. For layers below this soil layer, DELZW is set equal to zero, and ZBOTW to the depth of the top of the layer, and the ISAND flag is set to the rock soil flag -3. If the land cover is an ice sheet (indicated by an ISAND value of -4 in the top layer), the value of DELZW in each layer is set to DELZ and the soil flag to -4.

At the bottom of the loop, if the soil is a mineral one, the wet and dry albedo values are calculated using simple empirical functions derived from values given in Wilson and Henderson-Sellers (1985).

In loop 300, various thermal and hydraulic soil properties are assigned. Values of ISAND greater than zero indicate mineral soil. The pore volume θ_p, the saturated hydraulic conductivity K_{sat}, and the soil moisture suction at saturation ψ_{sat} are calculated from the percentage sand content X_{sand}, and the hydraulic parameter b is calculated from the percentage clay content X_{clay}, based on empirical relationships given in Cosby *et al.* (1984):

$$\theta_p = (-0.126\ X_{sand} + 48.9)/100.0$$
$$b = 1.59\ X_{clay} + 2.91$$
$$\psi_{sat} = 0.01 \exp(-0.0302\ X_{sand} + 4.33)$$
$$K_{sat} = 7.0556 \times 10^{-6} \exp(0.0352\ X_{sand} - 2.035)$$

The fractional saturation of the soil at half the saturated hydraulic conductivity, f_{inf}, is calculated by inverting the Clapp and Hornberger (1978) expression relating hydraulic conductivity K to liquid water content of the soil θ_l :

$$K = K_{sat}\ (\theta_l/\theta_p)^{(2b + 3)}$$

Thus,

$$f_{inf} = 0.5^{\ 1/(2b+3)}$$

The residual soil liquid water content remaining after evaporation or freezing, θ_{min}, and the liquid water retention capacity, θ_{ret}, are both set for mineral soils to a textbook value of 0.04.

The volumetric sand, silt/clay and organic matter components of the soil matrix are derived by converting the percent values to volume fractions. The overall volumetric heat capacity of the soil material, C_g, is then calculated as a weighted average:

$$C_g = \Sigma\ (C_{sand}\theta_{sand} + C_{fine}\theta_{fine} + C_{org}\theta_{org})/(1 - \theta_p)$$

where the subscript "fine" refers to the silt and clay particles taken together. The thermal conductivity of the soil material, τ_g, is likewise calculated as a weighted average over the thermal conductivities of the components:

$$\tau_g = \Sigma\ (\tau_{sand}\theta_{sand} + \tau_{fine}\theta_{fine} + \tau_{org}\theta_{org})/(1 - \theta_p)$$

The field capacity θ_{fc}, that is, the liquid water content of the soil at which gravitational drainage effectively ceases, is calculated by setting the expression for K above to a value of 0.1 mm d^{-1}, and solving for the liquid water content:

$$\theta_{fc} = \theta_p \,(1.157 \times 10^{-9}/K_{sat})^{1/(2b+3)}$$

The soil moisture suction ψ_{wilt} at the wilting point (the liquid water content at which plant roots can no longer draw water from the soil) is calculated from the saturated soil moisture suction using the Clapp and Hornberger (1978) expression, with the value for θ_l approximated as 0.5 θ_{fc}:

$$\psi_{wilt} = \psi_{sat}\,(0.5\,\theta_{fc}/\theta_p)^{-b}$$

Organic soils are flagged with an ISAND value of -2. For these soils, the variables θ_p, b, K_{sat}, ψ_{sat}, θ_{min}, and θ_{ret} area determined based on the peat texture (fibric, hemic or sapric), reflecting its degree of decomposition. These are indicated by flags of 1, 2 and 3 respectively in IORG. Values are assigned as indicated below, following the work of Letts *et al.* (2000).

	Fibric peat	Hemic peat	Sapric peat
θ_p	0.93	0.88	0.83
b	2.7	6.1	12.0
K_{sat}	2.8×10^{-4}	2.0×10^{-6}	1.0×10^{-7}
ψ_{sat}	0.0103	0.0102	0.0101
θ_{min}	0.04	0.15	0.22
θ_{ret}	0.275	0.62	0.705

The volumetric heat capacity and thermal conductivity are set to textbook values for organic matter; the field capacity is set equal to the retention capacity; f_{inf} is obtained as above; and ψ_{wilt} is assume to apply at a liquid water content of θ_{min}.

In the cases of rock soils and ice sheets (respectively flagged with ISAND values of -3 and -4), all of the above variables are set to zero except for the volumetric heat capacity and the thermal conductivity, which are assigned values representative of rock or ice.

Part

5

Pre- and Post-Processing Routines

CLASSI

Purpose: Evaluate atmospheric variables and rainfall/snowfall rates over modelled area.

Input/output variables:

IPCP	Flag indicating which option is to be used for partitioning precipitation into rainfall and snowfall
PADRY	Partial pressure of dry air [Pa] (p_{dry})
PCPR	Precipitation rate over modelled area [kg m^{-2} s^{-1}]
PRESSG	Surface atmospheric pressure [Pa] (p)
QA	Specific humidity at reference height [kg kg^{-1}] (q_a)
RHOAIR	Density of air [kg m^{-3}] (ρ_a)
RHOSNI	Density of fresh snow [kg m^{-3}] ($\rho_{s,i}$)
RPCP	Calculated rainfall rate over modelled area [m s^{-1}]
RRATE	Input rainfall rate over modelled area [kg m^{-2} s^{-1}]
SPCP	Calculated snowfall rate over modelled area [m s^{-1}]
SRATE	Input snowfall rate over modelled area [kg m^{-2} s^{-1}]
TA	Air temperature at reference height [K] (T_a)
TADP	Dew point temperature of air [K]
TRPCP	Rainfall temperature over modelled area [C]
TSPCP	Snowfall temperature over modelled area [C]

VPD Vapour pressure deficit of air [mb] (e_d)

In the first section, the air vapour pressure deficit, dry air pressure, air density and dew point temperature are calculated. The vapour pressure deficit e_d (in units of mb) is obtained from the saturated and actual vapour pressures of the air, e_a and $e_{a,sat}$ respectively (in units of Pa), as

$$e_d = [e_{a,sat} - e_a] / 100.0$$

The air vapour pressure is obtained from the specific humidity q_a using the formula

$$e_a = q_a p / [0.622 + 0.378 q_a]$$

where p is the surface atmospheric pressure. For the saturated vapour pressure, a standard empirical equation is utilized relating $e_{a,sat}$ to the temperature T_a and the freezing point T_f:

$$e_{a,sat} = 611.0 \exp[17.269(T_a - T_f)/(T_a - 35.86)] \qquad T_a \geq T_f$$
$$e_{a,sat} = 611.0 \exp[21.874(T_a - T_f)/(T_a - 7.66)] \qquad T_a < T_f$$

The partial pressure of dry air, p_{dry}, is obtained by subtracting e_a from p, and the density of the air is calculated as the sum of the densities of the dry air and the water vapour:

$$\rho_a = p_{dry}/R_d T_a + e_a/R_v T_a$$

where R_d and R_v are the gas constants for dry air and water vapour respectively. The dew point temperature of the air is evaluated by substituting e_a for $e_{a,sat}$ on the left-hand side of the appropriate equation above, and solving for T_a.

In the next section, the density of fresh snow $\rho_{s,i}$ is determined as an empirical function of the air temperature. For temperatures below 0 C, an equation presented by Hedstrom and Pomeroy (1998) is used. For temperatures ≥ 0 C, a relation following Pomeroy and Gray (1995) is used, with an upper limit of 200 kg m^{-3}:

$$\rho_{s,i} = 67.92 + 51.25 \exp[(T_a - T_f)/2.59] \qquad T_a < T_f$$
$$\rho_{s,i} = 119.17 + 20.0(T_a - T_f) \qquad T_a \geq T_f$$

In the last section, the partitioning of precipitation between rainfall RPCP and snowfall SPCP is addressed. Four options for doing so are provided; the user's selection is indicated by the flag IPCP. In each case the rainfall and snowfall rates are converted to units of m s^{-1}, by dividing by the density of water in the case of rain and by $\rho_{s,i}$ in the case of snow. The rainfall temperature is set to the maximum of 0 C and T_a, and the snowfall temperature to the minimum of 0 C and T_a. If IPCP = 1, the precipitation is simply diagnosed as rain if the air temperature is greater than 0 C, and as snow otherwise. If IPCP = 2, an empirical relation developed by Brown (2001) is used, where the precipitation is entirely snowfall when T_a ≤ 0 C, and entirely rainfall when T_a ≥ 2.0 C, and varies linearly between the two, with an equal mix of rain and snow at T_a = 1.0 C. If IPCP = 3, the precipitation is assumed to be entirely snowfall when T_a ≤ 0 C, and entirely rainfall when $T_a \geq 6.0$ C, and between the two a polynomial function presented by Auer (1974) is used, relating the fraction of the precipitation that is snowfall, X_{sf}, to T_a:

$$X_{sf} = [0.0202T_a^6 - 0.3660T_a^5 + 2.0399T_a^4 - 1.5089T_a^3 - 15.038T_a^2 + 4.6664T_a + 100.0]/100.0$$

Finally, if IPCP = 4, this indicates that the partitioning between rainfall and snowfall has been done outside of CLASS. The rainfall and snowfall rates RRATE and SRATE that have been passed into the subroutine are therefore assigned to RPCP and SPCP, and their sum PCPR is calculated for diagnostic purposes.

GATPREP

Purpose: Assign values to pointer vectors relating the location of elements on the "gathered" variable vectors to elements on the original two-dimensional arrays (latitude circle x mosaic tiles) for land grid cells, and to elements on the latitude circle for sea ice and ocean grid cells.

Input/output variables:

FAREA	Fractional coverage of mosaic tile on grid cell [ ]
GCGRD	Real number identifier indicating whether the grid cell is land (-1.0), sea ice (+1.0), or ocean (0.0)
IICE	Index of grid cell corresponding to current element of gathered vector of sea ice variables [ ]
ILG	Hard-coded maximum number of elements in the gathered vectors
ILMOS	Index of grid cell corresponding to current element of gathered vector of land surface variables [ ]
IM	Maximum number of mosaic tiles within the grid cells in the array under consideration
IWAT	Index of grid cell corresponding to current element of gathered vector of ocean variables [ ]
IWMOS	Index of grid cell corresponding to current element of gathered vector of inland water body variables [ ]
JLMOS	Index of mosaic tile corresponding to current element of gathered vector of land surface variables [ ]
JWMOS	Index of mosaic tile corresponding to current element of gathered vector of inland water body variables [ ]
MOSID	Mosaic tile type identifier (1 for land surface, 0 for inland lake)
NICE	Total number of grid cells in sea ice gather vectors
NLAT	Hard-coded maximum number of grid cells
NML	Total number of mosaic tiles in land surface gather vectors
NMOS	Hard-coded maximum number of mosaic tiles
NMW	Total number of mosaic tiles in inland lake gather vectors
NWAT	Total number of grid cells in ocean gather vectors

A looping operation is performed over the latitude circle, or array of grid cells, under consideration. If the grid cell is a land one (GCGRD = -1.0), an additional internal loop is performed over all the mosaic tiles present. For each mosaic tile, if its fractional coverage is greater than zero, then if the mosaic type identifier MOSID is equal to 1 (indicating a land surface tile), the counter of total mosaic tiles in the land surface gather vectors, NML, is incremented by one, and the elements of the vectors ILMOS and JLMOS corresponding to NML are set to the indices of the current grid cell and mosaic tile respectively. If MOSID is equal to zero (indicating an inland lake tile), the counter of total mosaic tiles in the inland lake gather vectors, NMW, is incremented by one, and the elements of the vectors IWMOS and JWMOS corresponding to NMW are set to the indices of the current grid cell and mosaic tile respectively.

If the grid cell is a sea ice one (GCGRD = 1.0), the counter of total grid cells in the sea ice gather vectors, NICE, is incremented by one, and the element of the vector IICE corresponding to NICE is set to the index of the current grid cell. If the grid cell is an ocean one (GCGRD = 0.0), the counter of total grid cells in the ocean gather vectors, NWAT, is incremented by one, and the element of the vector IWAT corresponding to NWAT is set to the index of the current grid cell.

CLASSG

Purpose: Gather variables from two-dimensional arrays (latitude circle x mosaic tiles) onto long vectors for optimum processing efficiency on vector supercomputers.

Input/output variables:

(Suffix GAT refers to variables on gathered long vectors; suffix ROW refers to variables on original two-dimensional arrays.)

ACID	Optional user-specified value of canopy near-infrared albedo to override CLASS-calculated value [ ]
ACVD	Optional user-specified value of canopy visible albedo to override CLASS-calculated value [ ]
AGID	Optional user-specified value of ground near-infrared albedo to override CLASS-calculated value [ ]
AGVD	Optional user-specified value of ground visible albedo to override CLASS-calculated value [ ]
ALBS	Snow albedo [ ]
ALGD	Reference albedo for dry soil [ ]
ALGW	Reference albedo for saturated soil [ ]
ALIC	Background average near-infrared albedo of vegetation category [ ]
ALIR	Diagnosed total near-infrared albedo of land surface [ ]
ALVC	Background average visible albedo of vegetation category [ ]
ALVS	Diagnosed total visible albedo of land surface [ ]
ASID	Optional user-specified value of snow near-infrared albedo to override CLASS-calculated value [ ]
ASVD	Optional user-specified value of snow visible albedo to override CLASS-calculated value [ ]
BI	Clapp and Hornberger empirical "b" parameter [ ]
CDH	Surface drag coefficient for heat [ ]
CDM	Surface drag coefficient for momentum [ ]
CMAI	Aggregated mass of vegetation canopy [kg m^{-2}]
CMAS	Maximum canopy mass for vegetation category [kg m^{-2}]
CSZ	Cosine of solar zenith angle [ ]
DLON	Longitude of grid cell (east of Greenwich) [degrees]
DLZW	Permeable thickness of soil layer [m]
DR	Surface drag coefficient under neutral stability [ ]
DRN	Drainage index at bottom of soil profile [ ]
EF	Evaporation efficiency at ground surface [ ]
FCAN	Maximum fractional coverage of modelled area by vegetation category [ ]
FCLO	Fractional cloud cover [ ]
FDL	Downwelling longwave radiation at bottom of atmosphere [W m^{-2}]

FLGG	Diagnosed net longwave radiation at soil surface [W m^{-2}]
FLGS	Diagnosed net longwave radiation at snow surface [W m^{-2}]
FLGV	Diagnosed net longwave radiation on vegetation canopy [W m^{-2}]
FSGG	Diagnosed net shortwave radiation at soil surface [W m^{-2}]
FSGS	Diagnosed net shortwave radiation at snow surface [W m^{-2}]
FSGV	Diagnosed net shortwave radiation on vegetation canopy [W m^{-2}]
FSIH	Near-infrared radiation incident on horizontal surface [W m^{-2}]
FSNO	Diagnosed fractional snow coverage [ ]
FSVH	Visible radiation incident on horizontal surface [W m^{-2}]
GA	Diagnosed product of drag coefficient and wind speed over modelled area [m s^{-1}]
GFLX	Heat conduction between soil layers [W m^{-2}]
GGEO	Geothermal heat flux at bottom of soil profile [W m^{-2}]
GRKF	WATROF parameter used when running MESH code [ ]
GRKS	Saturated hydraulic conductivity of soil layers [m s^{-1}]
GRO	Vegetation growth index [ ]
GT	Diagnosed effective surface black-body temperature [K]
HCPS	Volumetric heat capacity of soil particles [J m^{-3}]
HEVC	Diagnosed latent heat flux on vegetation canopy [W m^{-2}]
HEVG	Diagnosed latent heat flux at soil surface [W m^{-2}]
HEVS	Diagnosed latent heat flux at snow surface [W m^{-2}]
HFS	Diagnosed total surface sensible heat flux over modelled area [W m^{-2}]
HFSC	Diagnosed sensible heat flux on vegetation canopy [W m^{-2}]
HFSG	Diagnosed sensible heat flux at soil surface [W m^{-2}]
HFSS	Diagnosed sensible heat flux at snow surface [W m^{-2}]
HGTD	Optional user-specified values of roughness lengths of vegetation categories to override CLASS-calculated values [m]
HMFC	Diagnosed energy associated with phase change of water on vegetation [W m^{-2}]
HMFG	Diagnosed energy associated with phase change of water in soil layers [W m^{-2}]
HMFN	Diagnosed energy associated with phase change of water in snow pack [W m^{-2}]
HTC	Diagnosed internal energy change of soil layer due to conduction and/or change in mass [W m^{-2}]
HTCC	Diagnosed internal energy change of vegetation canopy due to conduction and/or change in mass [W m^{-2}]
HTCS	Diagnosed internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}]
ILMOS	Index of latitude grid cell corresponding to current element of gathered vector of land surface variables [ ]
IWMOS	Index of latitude grid cell corresponding to current element of gathered vector of inland water body variables [ ]
ISND	Sand content flag
ITCT	Counter of number of iterations required to solve surface temperature balance for the elements of the four subareas
JLMOS	Index of mosaic tile corresponding to current element of gathered vector of land surface variables [ ]
JWMOS	Index of mosaic tile corresponding to current element of gathered vector of inland water body variables [ ]
LNZ0	Natural logarithm of maximum roughness length of vegetation category [ ]

NL	Number of latitude points in land surface variable vectors
NM	Number of mosaic points in land surface variable vectors
NML	Total number of mosaic tiles in land surface gather vectors
PADR	Partial pressure of dry air [Pa]
PAID	Optional user-specified value of plant area indices of vegetation categories to override CLASS-calculated values [ ]
PAMN	Minimum plant area index of vegetation category [ ]
PAMX	Maximum plant area index of vegetation category [ ]
PCFC	Diagnosed frozen precipitation intercepted by vegetation [kg m^{-2} s^{-1}]
PCLC	Diagnosed liquid precipitation intercepted by vegetation [kg m^{-2} s^{-1}]
PCPG	Diagnosed precipitation incident on ground [kg m^{-2} s^{-1}]
PCPN	Diagnosed precipitation incident on snow pack [kg m^{-2} s^{-1}]
PET	Diagnosed potential evapotranspiration [kg m^{-2} s^{-1}]
PRE	Surface precipitation rate [kg m^{-2} s^{-1}]
PRES	Surface air pressure [Pa]
PSGA	Soil moisture suction coefficient for vegetation category (used in stomatal resistance calculation) [ ]
PSGB	Soil moisture suction coefficient for vegetation category (used in stomatal resistance calculation) [ ]
PSIS	Soil moisture suction at saturation [m]
PSIW	Soil moisture suction at wilting point [m]
QA	Specific humidity at reference height [kg kg^{-1}]
QA50	Reference value of incoming shortwave radiation for vegetation category (used in stomatal resistance calculation) [W m^{-2}]
QAC	Specific humidity of air within vegetation canopy [kg kg^{-1}]
QEVP	Diagnosed total surface latent heat flux over modelled area [W m^{-2}]
QFC	Diagnosed vapour flux from transpiration over modelled area [W m^{-2}]
QFCF	Diagnosed vapour flux from frozen water on vegetation [kg m^{-2} s^{-1}]
QFCL	Diagnosed vapour flux from liquid water on vegetation [kg m^{-2} s^{-1}]
QFG	Diagnosed water vapour flux from ground [kg m^{-2} s^{-1}]
QFN	Diagnosed water vapour flux from snow pack [kg m^{-2} s^{-1}]
QFS	Diagnosed total surface water vapour flux over modelled area [kg m^{-2} s^{-1}]
QFX	Product of surface drag coefficient, wind speed and surface-air specific humidity difference [m s^{-1}]
QG	Diagnosed surface specific humidity [kg kg^{-1}]
RADJ	Latitude of grid cell (positive north of equator) [rad]
RCAN	Intercepted liquid water stored on canopy [kg m^{-2}]
RHOA	Density of air [kg m^{-3}]
RHOS	Density of snow [kg m^{-3}]
RHSI	Density of fresh snow [kg m^{-3}]
ROF	Total runoff from soil [kg m^{-2} s^{-1}]
ROFB	Base flow from bottom of soil column [kg m^{-2} s^{-1}]
ROFC	Liquid/frozen water runoff from vegetation [kg m^{-2} s^{-1}]
ROFN	Liquid water runoff from snow pack [kg m^{-2} s^{-1}]
ROFO	Overland flow from top of soil column [kg m^{-2} s^{-1}]
ROFS	Interflow from sides of soil column [kg m^{-2} s^{-1}]
ROOT	Maximum rooting depth of vegetation category [m]

ROVG	Diagnosed liquid/frozen water runoff from vegetation to ground surface [kg m^{-2} s^{-1}]
RPCP	Rainfall rate over modelled area [m s^{-1}]
RSMN	Minimum stomatal resistance of vegetation category [s m^{-1}]
SCAN	Intercepted frozen water stored on canopy [kg m^{-2}]
SFCQ	Diagnosed screen-level specific humidity [kg kg^{-1}]
SFCT	Diagnosed screen-level air temperature [K]
SFCU	Diagnosed anemometer-level u-wind [m s^{-1}]
SFCV	Diagnosed anemometer-level v-wind [m s^{-1}]
SNO	Mass of snow pack [kg m^{-2}]
SPCP	Snowfall rate over modelled area [m s^{-1}]
TA	Air temperature at reference height [K]
TAC	Temperature of air within vegetation canopy [K]
TADP	Dew point temperature of air [K]
TBAR	Temperature of soil layers [K]
TBAS	Temperature of bedrock in third soil layer [K]
TCAN	Vegetation canopy temperature [K]
TCS	Thermal conductivity of soil particles [W m^{-1} K^{-1}]
TFX	Product of surface drag coefficient, wind speed and surface-air temperature difference [K m s^{-1}]
THFC	Field capacity [m^3 m^{-3}]
THIC	Frozen water content of soil layers under vegetation [m^3 m^{-3}]
THLQ	Volumetric liquid water content of soil layers [m^3 m^{-3}]
THM	Residual soil liquid water content remaining after freezing or evaporation [m^3 m^{-3}]
THP	Pore volume in soil layer [m^3 m^{-3}]
THR	Liquid water retention capacity for organic soil [m^3 m^{-3}]
THRA	Fractional saturation of soil behind the wetting front [ ]
TPND	Temperature of ponded water [K]
TROB	Temperature of base flow from bottom of soil column [K]
TROF	Temperature of total runoff [K]
TROO	Temperature of overland flow from top of soil column [K]
TROS	Temperature of interflow from sides of soil column [K]
TRPC	Rainfall temperature [K]
TSPC	Snowfall temperature [K]
TSF	Average ground/snow surface temperature over modelled area [K]
TSFS	Ground surface temperature over subarea [K]
TSNO	Snowpack temperature [K]
UL	Zonal component of wind speed [m s^{-1}]
VL	Meridional component of wind speed [m s^{-1}]
VPD	Vapour pressure deficit [mb]
VPDA	Vapour pressure deficit coefficient for vegetation category (used in stomatal resistance calculation) [ ]
VPDB	Vapour pressure deficit coefficient for vegetation category (used in stomatal resistance calculation) [ ]
WFCI	WATROF parameter used when running MESH code [ ]
WFSF	WATROF parameter used when running MESH code [ ]
WSNO	Liquid water content of snow pack [kg m^{-2}]
WTRC	Diagnosed residual water transferred on or off the vegetation canopy [kg m^{-2} s^{-1}]

WTRG	Diagnosed residual water transferred into or out of the soil [kg m^{-2} s^{-1}]
WTRS	Diagnosed residual water transferred into or out of the snow pack [kg m^{-2} s^{-1}]
XSLP	Surface slope (used when running MESH code) [degrees]
Z0OR	Orographic roughness length [m]
ZBLD	Atmospheric blending height for surface roughness length averaging [m]
ZBTW	Depth to permeable bottom of soil layer [m]
ZDH	User-specified height associated with diagnosed screen-level variables [m]
ZDM	User-specified height associated with diagnosed anemometer-level wind speed [m]
ZPLG	Maximum water ponding depth for snow-free subareas (user-specified when running MESH code) [m]
ZPLS	Maximum water ponding depth for snow-covered subareas (user-specified when running MESH code) [m]
ZPND	Depth of ponded water on surface [m]
ZRFH	Reference height associated with forcing air temperature and humidity [m]
ZRFM	Reference height associated with forcing wind speed [m]
ZSNL	Limiting snow depth below which coverage is < 100% [m]

The prognostic, background and input variables are gathered into long arrays (collapsing the latitude and mosaic dimensions into one, but retaining the soil level and canopy category dimensions) using the pointer vectors generated in subroutine GATPREP. Diagnostic, surface-average arrays are initialized to zero.

CLASSS

Purpose: Scatter variables from long, gathered vectors back onto original two-dimensional arrays (latitude circle x mosaic tiles).

Input/output variables:

(Suffix GAT refers to variables on gathered long vectors; suffix ROW refers to variables on original two-dimensional arrays.)

ALBS	Snow albedo [ ]
ALIR	Diagnosed total near-infrared albedo of land surface [ ]
ALVS	Diagnosed total visible albedo of land surface [ ]
CDH	Surface drag coefficient for heat [ ]
CDM	Surface drag coefficient for momentum [ ]
CMAI	Aggregated mass of vegetation canopy [kg m^{-2}]
DR	Surface drag coefficient under neutral stability [ ]
EF	Evaporation efficiency at ground surface [ ]
FLGG	Diagnosed net longwave radiation at soil surface [W m^{-2}]
FLGS	Diagnosed net longwave radiation at snow surface [W m^{-2}]
FLGV	Diagnosed net longwave radiation on vegetation canopy [W m^{-2}]
FSGG	Diagnosed net shortwave radiation at soil surface [W m^{-2}]
FSGS	Diagnosed net shortwave radiation at snow surface [W m^{-2}]
FSGV	Diagnosed net shortwave radiation on vegetation canopy [W m^{-2}]
FSNO	Diagnosed fractional snow coverage [ ]
GA	Diagnosed product of drag coefficient and wind speed over modelled area [m s^{-1}]
GFLX	Heat conduction between soil layers [W m^{-2}]
GRO	Vegetation growth index [ ]
GT	Diagnosed effective surface black-body temperature [K]
HBL	Height of the atmospheric boundary layer [m]
HEVC	Diagnosed latent heat flux on vegetation canopy [W m^{-2}]
HEVG	Diagnosed latent heat flux at soil surface [W m^{-2}]
HEVS	Diagnosed latent heat flux at snow surface [W m^{-2}]
HFS	Diagnosed total surface sensible heat flux over modelled area [W m^{-2}]
HFSC	Diagnosed sensible heat flux on vegetation canopy [W m^{-2}]
HFSG	Diagnosed sensible heat flux at soil surface [W m^{-2}]
HFSS	Diagnosed sensible heat flux at snow surface [W m^{-2}]
HMFC	Diagnosed energy associated with phase change of water on vegetation [W m^{-2}]
HMFG	Diagnosed energy associated with phase change of water in soil layers [W m^{-2}]
HMFN	Diagnosed energy associated with phase change of water in snow pack [W m^{-2}]
HTC	Diagnosed internal energy change of soil layer due to conduction and/or change in mass [W m^{-2}]
HTCC	Diagnosed internal energy change of vegetation canopy due to conduction and/or change in mass [W m^{-2}]

HTCS	Diagnosed internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}]
ILMO	Inverse of Monin-Obukhov roughness length (m^{-1}]
ILMOS	Index of latitude grid cell corresponding to current element of gathered vector of land surface variables [ ]
IWMOS	Index of latitude grid cell corresponding to current element of gathered vector of inland water body variables [ ]
ITCT	Counter of number of iterations required to solve surface energy balance for the elements of the four subareas
JLMOS	Index of mosaic tile corresponding to current element of gathered vector of land surface variables [ ]
JWMOS	Index of mosaic tile corresponding to current element of gathered vector of inland water body variables [ ]
NL	Number of latitude points in land surface variable vectors
NM	Number of mosaic points in land surface variable vectors
NML	Total number of mosaic tiles in land surface gather vectors
PCFC	Diagnosed frozen precipitation intercepted by vegetation [kg m^{-2} s^{-1}]
PCLC	Diagnosed liquid precipitation intercepted by vegetation [kg m^{-2} s^{-1}]
PCPG	Diagnosed precipitation incident on ground [kg m^{-2} s^{-1}]
PCPN	Diagnosed precipitation incident on snow pack [kg m^{-2} s^{-1}]
PET	Diagnosed potential evapotranspiration [kg m^{-2} s^{-1}]
QAC	Specific humidity of air within vegetation canopy space [kg kg^{-1}]
QEVP	Diagnosed total surface latent heat flux over modelled area [W m^{-2}]
QFC	Diagnosed vapour flux from transpiration over modelled area [W m^{-2}]
QFCF	Diagnosed vapour flux from frozen water on vegetation [kg m^{-2} s^{-1}]
QFCL	Diagnosed vapour flux from liquid water on vegetation [kg m^{-2} s^{-1}]
QFG	Diagnosed water vapour flux from ground [kg m^{-2} s^{-1}]
QFN	Diagnosed water vapour flux from snow pack [kg m^{-2} s^{-1}]
QFS	Diagnosed total surface water vapour flux over modelled area [kg m^{-2} s^{-1}]
QFX	Product of surface drag coefficient, wind speed and surface-air specific humidity difference [m s^{-1}]
QG	Diagnosed surface specific humidity [kg kg^{-1}]
RCAN	Intercepted liquid water stored on canopy [kg m^{-2}]
RHOS	Density of snow [kg m^{-3}]
ROF	Total runoff from soil [kg m^{-2} s^{-1}]
ROFB	Base flow from bottom of soil column [kg m^{-2} s^{-1}]
ROFC	Liquid/frozen water runoff from vegetation [kg m^{-2} s^{-1}]
ROFN	Liquid water runoff from snow pack [kg m^{-2} s^{-1}]
ROFO	Overland flow from top of soil column [kg m^{-2} s^{-1}]
ROFS	Interflow from sides of soil column [kg m^{-2} s^{-1}]
ROVG	Diagnosed liquid/frozen water runoff from vegetation to ground surface [kg m^{-2} s^{-1}]
SCAN	Intercepted frozen water stored on canopy [kg m^{-2}]
SFCQ	Diagnosed screen-level specific humidity [kg kg^{-1}]
SFCT	Diagnosed screen-level air temperature [K]
SFCU	Diagnosed anemometer-level u-wind [m s^{-1}]
SFCV	Diagnosed anemometer-level v-wind [m s^{-1}]
SNO	Mass of snow pack [kg m^{-2}]

TAC	Temperature of air within vegetation canopy [K]
TBAR	Temperature of soil layers [K]
TBAS	Temperature of bedrock in third soil layer [K]
TCAN	Vegetation canopy temperature [K]
TFX	Product of surface drag coefficient, wind speed and surface-air temperature difference [K m s^{-1}]
THIC	Volumetric frozen water content of soil layers [m^3 m^{-3}]
THLQ	Volumetric liquid water content of soil layers [m^3 m^{-3}]
TPND	Temperature of ponded water [K]
TROB	Temperature of base flow from bottom of soil column [K]
TROF	Temperature of total runoff [K]
TROO	Temperature of overland flow from top of soil column [K]
TROS	Temperature of interflow from sides of soil column [K]
TSF	Average ground/snow surface temperature over modelled area [K]
TSFS	Ground surface temperature over subarea [K]
TSNO	Snowpack temperature [K]
UE	Friction velocity of air [m s^{-1}]
WTAB	Depth of water table in soil [m]
WSNO	Liquid water content of snow pack [kg m^{-2}]
WTRC	Diagnosed water transferred on or off the vegetation canopy [kg m^{-2} s^{-1}]
WTRG	Diagnosed water transferred into or out of the soil [kg m^{-2} s^{-1}]
WTRS	Diagnosed water transferred into or out of the snow pack [kg m^{-2} s^{-1}]
ZPND	Depth of ponded water on surface [m]

The prognostic and diagnostic variables are scattered from the long, gathered arrays (collapsing the latitude and mosaic dimensions into one) back onto the original arrays using the pointer vectors generated in subroutine GATPREP.

CLASSZ

Purpose: Check for energy and water balance closure over modelled area.

Input/output variables:

CMAI	Current mass of vegetation canopy [kg m^{-2}] (W_c)
CT1STP	Change in internal energy of first soil layer over current time step [W m^{-2}]
CT2STP	Change in internal energy of second soil layer over current time step [W m^{-2}]
CT3STP	Change in internal energy of third soil layer over current time step [W m^{-2}]
CTSSTP	Change in internal energy of snow pack over current time step [W m^{-2}]
CTVSTP	Change in internal energy of vegetation over current time step [W m^{-2}]
DELZ	Total thickness of soil layer [m] (Δz)
DELZW	Permeable thickness of soil layer [m] (Δz_w)
FC	Fractional coverage of vegetation over bare ground on modelled area [ ]
FCS	Fractional coverage of vegetation over snow on modelled area [ ]
FG	Fractional coverage of bare ground on modelled area [ ]
FGS	Fractional coverage of snow over bare ground on modelled area [ ]
FLGG	Diagnosed net longwave radiation at soil surface [W m^{-2}] ($L_{*,g}$)
FLGS	Diagnosed net longwave radiation at snow surface [W m^{-2}] ($L_{*,s}$)
FLGV	Diagnosed net longwave radiation on vegetation canopy [W m^{-2}] ($L_{*,c}$)
FSGG	Diagnosed net shortwave radiation at soil surface [W m^{-2}] ($K_{*,g}$)
FSGS	Diagnosed net shortwave radiation at snow surface [W m^{-2}] ($K_{*,s}$)
FSGV	Diagnosed net shortwave radiation on vegetation canopy [W m^{-2}] ($K_{*,c}$)
HCPS	Volumetric heat capacity of soil particles [J m^{-3}] (C_g)
HEVC	Diagnosed latent heat flux on vegetation canopy [W m^{-2}] ($Q_{E,c}$)
HEVG	Diagnosed latent heat flux at soil surface [W m^{-2}] ($Q_{E,g}$)
HEVS	Diagnosed latent heat flux at snow surface [W m^{-2}] ($Q_{E,s}$)
HFSC	Diagnosed sensible heat flux on vegetation canopy [W m^{-2}] ($Q_{H,c}$)
HFSG	Diagnosed sensible heat flux at soil surface [W m^{-2}] ($Q_{H,g}$)
HFSS	Diagnosed sensible heat flux at snow surface [W m^{-2}] ($Q_{H,s}$)
HMFC	Diagnosed energy associated with phase change of water on vegetation [W m^{-2}] ($Q_{M,c}$)
HMFG	Diagnosed energy associated with phase change of water in soil layers [W m^{-2}] ($Q_{M,g}$)
HMFN	Diagnosed energy associated with phase change of water in snow pack [W m^{-2}] ($Q_{M,s}$)
HTC	Diagnosed internal energy change of soil layer due to conduction and/or change in mass [W m^{-2}] ($Q_{I,g}$)
HTCC	Diagnosed internal energy change of vegetation canopy due to conduction and/or change in mass [W m^{-2}] ($Q_{I,c}$)
HTCS	Diagnosed internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}] ($Q_{I,s}$)
ISTEP	Flag indicating position at beginning or end of time step
PCFC	Diagnosed frozen precipitation intercepted by vegetation [kg m^{-2} s^{-1}] ($P_{f,c}$)
PCLC	Diagnosed liquid precipitation intercepted by vegetation [kg m^{-2} s^{-1}] ($P_{l,c}$)

PCPG	Diagnosed precipitation incident on ground [kg m^{-2} s^{-1}] (P_g)
PCPN	Diagnosed precipitation incident on snow pack [kg m^{-2} s^{-1}] (P_s)
QFC	Diagnosed vapour flux from transpiration over modelled area [W m^{-2}] (E_c)
QFCF	Diagnosed vapour flux from frozen water on vegetation [kg m^{-2} s^{-1}] ($E_{f,c}$)
QFCL	Diagnosed vapour flux from liquid water on vegetation [kg m^{-2} s^{-1}] ($E_{l,c}$)
QFG	Diagnosed water vapour flux from ground surface [kg m^{-2} s^{-1}] (E_g)
QFN	Diagnosed water vapour flux from snow pack [kg m^{-2} s^{-1}] (E_s)
RCAN	Intercepted liquid water stored on canopy [kg m^{-2}] ($W_{l,c}$)
ROF	Total runoff from soil [kg m^{-2} s^{-1}] (R_g)
ROFC	Liquid/frozen water runoff from vegetation [kg m^{-2} s^{-1}] (R_c)
ROFN	Liquid water runoff from snow pack [kg m^{-2} s^{-1}] (R_s)
SCAN	Intercepted frozen water stored on canopy [kg m^{-2}] ($W_{f,c}$)
SNO	Mass of snow pack [kg m^{-2}] (W_s)
TBAR	Temperature of soil layers [K] (T_g)
TCAN	Vegetation canopy temperature [K] (T_c)
THICE	Volumetric frozen water content of soil layers [m^3 m^{-3}] (θ_f)
THLIQ	Volumetric liquid water content of soil layers [m^3 m^{-3}] (θ_l)
THPOR	Pore volume in soil layer [m^3 m^{-3}]
TPOND	Temperature of ponded water [K] (T_p)
TSNOW	Snowpack temperature [K] (T_s)
WSNOW	Liquid water content of snow pack [kg m^{-2}] ($W_{l,s}$)
WTGSTP	Change in soil water storage over current time step [kg m^{-2}]
WTRC	Diagnosed water transferred on or off the vegetation canopy [kg m^{-2} s^{-1}] (A_c)
WTRG	Diagnosed water transferred into or out of the soil [kg m^{-2} s^{-1}] (A_g)
WTRS	Diagnosed water transferred into or out of the snow pack [kg m^{-2} s^{-1}] (A_s)
WTSSTP	Change in snow mass over current time step [kg m^{-2}]
WTVSTP	Change in vegetation mass over current time step [kg m^{-2}]
ZPOND	Depth of ponded water on surface [m] (z_p)

In this subroutine, checks are carried out to ensure that the change in energy storage in each of the components of the modelled area (canopy, snow and soil) is equal to the sum of the energy fluxes into and out of them; and that the change in moisture storage in each of the components is equal to the sum of the water fluxes into and out of them. The subroutine is called twice, once at the beginning (ISTEP=0) and once at the end (ISTEP=1) of each time step. At the beginning, the instantaneous energy and moisture storage terms are evaluated, and at the end the differences over the time step are calculated:

Change in canopy energy storage = $\Delta[(c_c W_c + c_w W_{l,c} + c_i W_{f,c}) T_c]/\Delta t$

Change in snow energy storage = $\Delta[(C_i W_s/\rho_i + C_w W_{l,s}/\rho_w) T_s]/\Delta t$

Change in soil layer energy storage =

$$\Delta\{[(C_w\theta_l + C_i\theta_f + C_g\theta_g)\Delta z_w + C_b(\Delta z - \Delta z_w)]T_j\}/\Delta t$$

(For the first soil layer, the numerator contains the additional term $C_w z_p T_p$.)

Change in canopy moisture storage = $\Delta[W_{l,c} + W_{f,c}]$

Change in snow moisture storage = $\Delta[W_s + W_{l,s}]$

Change in soil moisture storage = $\Delta[(\theta_l \rho_w + \theta_f \rho_i)\Delta z_w + z_p \rho_w]$

In these equations the W terms refer to masses, the c terms to specific heat capacities, the C terms to volumetric heat capacities, the T terms to temperatures, the ρ terms to densities, the θ terms to volume fractions and the z terms to depths. For the subscripts, c refers to vegetation canopy, s to snow, g to ground, l to liquid water content, f to frozen water content, w to water, i to ice, p to pond, and j to a generalized soil layer. The variable Δt refers to the time step length, Δz_w refers to the permeable thickness of the soil layer, Δz refers to the total thickness of the soil layer, and C_b refers to the heat capacity of the impermeable part of the soil layer.

The net energy and moisture fluxes are also evaluated at the end of the time step:

Net energy flux for canopy = $K_{*,c} + L_{*,c} - Q_{H,c} - Q_{E,c} - Q_{M,c} + Q_{I,c}$

Net energy flux for snow = $K_{*,s} + L_{*,s} - Q_{H,s} - Q_{E,s} - Q_{M,s} + Q_{I,s}$

Net energy flux for first soil layer = $K_{*,g} + L_{*,g} - Q_{H,g} - Q_{E,g} - Q_{M,1} + Q_{I,1}$

Net energy flux for other soil layers = $- Q_{M,j} + Q_{I,j}$

Net moisture flux for canopy = $P_{l,c} + P_{f,c} - E_{l,c} - E_{f,c} - R_c + A_c$

Net moisture flux for snow = $P_s - E_s - R_s + A_s$

Net moisture flux for soil = $P_g - E_g - R_g + A_g - E_c$

In these equations the K_* terms refer to net shortwave radiation, the L_* terms to net longwave radiation, the Q_H terms to sensible heat flux, the Q_E terms to latent heat flux, the Q_M terms to heat associated with melting or freezing of water, and the Q_I terms to changes in heat storage caused by conduction or redistribution of water. The P terms refer to precipitation, the E terms to evaporation, the R terms to runoff and the A terms to water transferred between different components of the landscape. The subscript 1 refers to the first soil layer, and j to a generalized other layer as above.

Finally, each change in energy or moisture storage is compared in turn with the corresponding net flux of energy or moisture, and if the difference is greater than 1 or 2 W m^{-2} or 10^{-3} kg m^{-2} respectively, an error message is printed out and the run is stopped.

Part

6

CLASSA

Purpose: Organize calculation of radiation-related and other surface parameters.

Input/output variables:

ACIDAT	Optional user-specified value of canopy near-infrared albedo to override CLASS-calculated value [ ]
ACVDAT	Optional user-specified value of canopy visible albedo to override CLASS-calculated value [ ]
AGIDAT	Optional user-specified value of ground near-infrared albedo to override CLASS-calculated value [ ]
AGVDAT	Optional user-specified value of ground visible albedo to override CLASS-calculated value [ ]
ALBSNO	Snow albedo [ ]
ALGDRY	Reference albedo for dry soil [ ]
ALGWET	Reference albedo for saturated soil [ ]
ALIR	Diagnosed total near-infrared albedo of land surface [ ]
ALIRC	Background average near-infrared albedo of vegetation category [ ]
ALVS	Diagnosed total visible albedo of land surface [ ]
ALVSC	Background average visible albedo of vegetation category [ ]
ALVSCN/ALIRCN	Visible/near-IR albedo of vegetation over bare ground [ ]
ALVSCS/ALIRCS	Visible/near-IR albedo of vegetation over snow [ ]
ALVSG/ALIRG	Visible/near-IR albedo of open bare ground [ ]
ALVSGC/ALIRGC	Visible/near-IR albedo of bare ground under vegetation [ ]
ALVSSC/ALIRSC	Visible/near-IR albedo of snow under vegetation [ ]
ALVSSN/ALIRSN	Visible/near-IR albedo of open snow cover [ ]
ASIDAT	Optional user-specified value of snow near-infrared albedo to override CLASS-calculated value [ ]

ASVDAT	Optional user-specified value of snow visible albedo to override CLASS-calculated value [ ]
BI	Clapp and Hornberger empirical “b” parameter [ ]
CHCAP	Heat capacity of canopy over bare ground [J m^{-2} K^{-1}]
CHCAPS	Heat capacity of canopy over snow [J m^{-2} K^{-1}]
CMAI	Aggregated mass of vegetation canopy [kg m^{-2}]
CMASSC	Mass of canopy over bare ground [kg m^{-2}]
CMASCS	Mass of canopy over snow [kg m^{-2}]
COSZS	Cosine of solar zenith angle [ ]
CWFCAP	Storage capacity of canopy over bare ground for frozen water [kg m^{-2}]
CWFCPS	Storage capacity of canopy over snow for frozen water [kg m^{-2}]
CWGTMX	Maximum canopy mass for vegetation category [kg m^{-2}]
CWLCAP	Storage capacity of canopy over bare ground for liquid water [kg m^{-2}]
CWLCPS	Storage capacity of canopy over snow for liquid water [kg m^{-2}]
DELZ	Soil layer thickness [m]
DELZW	Permeable thickness of soil layer [m]
DISP	Displacement height of vegetation over bare ground [m]
DISPS	Displacement height of vegetation over snow [m]
DLON	Longitude of grid cell (east of Greenwich) [degrees]
FC/G/CS/GS	Subarea fractional coverage of modelled area [ ]
FCANMX	Maximum fractional coverage of modelled area by vegetation category [ ]
FCLOUD	Fractional cloud cover [ ]
FRAICS	Fractional coverage of canopy by liquid water over snow-covered subarea [ ]
FRAINC	Fractional coverage of canopy by liquid water over snow-free subarea [ ]
FROOT	Fraction of total transpiration contributed by soil layer [ ]
FSNOW	Diagnosed fractional snow coverage [ ]
FSNOCS	Fractional coverage of canopy by frozen water over snow-covered subarea [ ]
FSNOWC	Fractional coverage of canopy by frozen water over snow-free subarea [ ]
FSVF	Sky view factor for bare ground under canopy [ ]
FSVFS	Sky view factor for snow under canopy [ ]
GROWTH	Vegetation growth index [ ]
HCPS	Volumetric heat capacity of soil particles [J m^{-3}]
HGTDAT	Optional user-specified values of roughness lengths of vegetation categories to override CLASS-calculated values [m]
HTC	Diagnosed internal energy change of soil layer due to conduction and/or change in mass [W m^{-2}]
HTCC	Diagnosed internal energy change of vegetation canopy due to conduction and/or change in mass [W m^{-2}]
HTCS	Diagnosed internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}]
IALC	Flag to enable use of user-specified canopy albedo
IALG	Flag to enable use of user-specified ground albedo
IALS	Flag to enable use of user-specified snow albedo
IDAY	Julian day of the year

IDISP	Flag governing treatment of vegetation displacement height
IHGT	Flag to enable use of user-specified vegetation height
IPAI	Flag to enable use of user-specified plant area index
ISAND	Sand content flag
IWF	Flag governing lateral soil water flow calculations
IZREF	Flag governing treatment of surface roughness length
JL	Integer value of latitude of grid cell [ ]
PAIDAT	Optional user-specified value of plant area indices of vegetation categories to override CLASS-calculated values [ ]
PAIMAX	Maximum plant area index of vegetation category [ ]
PAIMIN	Minimum plant area index of vegetation category [ ]
PSIGA	Soil moisture suction coefficient for vegetation category (used in stomatal resistance calculation) [ ]
PSIGB	Soil moisture suction coefficient for vegetation category (used in stomatal resistance calculation) [ ]
PSISAT	Soil moisture suction at saturation [m]
PSIWLT	Soil moisture suction at wilting point [m]
QA50	Reference value of incoming shortwave radiation for vegetation category (used in stomatal resistance calculation) [W m^{-2}]
QSWINV	Visible radiation incident on horizontal surface [W m-2]
RADJ	Latitude of grid cell (positive north of equator) [rad]
RAICAN	Intercepted liquid water stored on canopy over bare ground [kg m^{-2}]
RAICNS	Intercepted liquid water stored on canopy over snow [kg m^{-2}]
RBCOEF	Parameter for calculation of leaf boundary resistance
RC	Stomatal resistance of vegetation over bare ground [s m^{-1}]
RCAN	Intercepted liquid water stored on canopy [kg m^{-2}]
RCS	Stomatal resistance of vegetation over snow [s m^{-1}]
RHOAIR	Density of air [kg m^{-3}]
RHOSNI	Density of fresh snow [kg m^{-3}]
RHOSNO	Density of snow [kg m^{-3}] (ρ_s)
RSMIN	Minimum stomatal resistance of vegetation category [s m^{-1}]
SNCAN	Intercepted frozen water stored on canopy [kg m^{-2}]
SNO	Mass of snow pack [kg m^{-2}] (W_s)
SNOCAN	Intercepted frozen water stored on canopy over bare soil [kg m^{-2}]
SNOCNS	Intercepted frozen water stored on canopy over snow [kg m^{-2}]
SNOLIM	Limiting snow depth below which coverage is < 100% [m] ($z_{s,lim}$)
TA	Air temperature at reference height [K]
TBAR	Temperature of soil layers [K]
TCAN	Vegetation canopy temperature [K]
THICE	Volumetric frozen water content of soil layers [m^3 m^{-3}]
THLIQ	Volumetric liquid water content of soil layers [m^3 m^{-3}]
THLMIN	Residual soil liquid water content remaining after freezing or evaporation [m^3 m^{-3}]
THPOR	Pore volume in soil layer [m^3 m^{-3}]
TRVSCN/TRIRCN	Visible/near-IR transmissivity of vegetation over bare ground [ ]
TRVCSCS/TRIRCS	Visible/near-IR transmissivity of vegetation over snow [ ]
TRSNOW	Short-wave transmissivity of snow pack [ ]

TSNOW	Snowpack temperature [K]
VPD	Vapour pressure deficit of air [mb]
VPDA	Vapour pressure deficit coefficient for vegetation category (used in stomatal resistance calculation) [ ]
VPDB	Vapour pressure deficit coefficient for vegetation category (used in stomatal resistance calculation) [ ]
WSNOW	Liquid water content of snow pack [kg m^{-2}]
WTRC	Diagnosed residual water transferred on or off the vegetation canopy [kg m^{-2} s^{-1}]
WTRG	Diagnosed residual water transferred into or out of the soil [kg m^{-2} s^{-1}]
WTRS	Diagnosed residual water transferred into or out of the snow pack [kg m^{-2} s^{-1}]
Z0ORO	Orographic roughness length [m]
ZBLEND	Atmospheric blending height for surface roughness length averaging [m]
ZBOTW	Depth to permeable bottom of soil layer [m]
ZOELCS	Logarithm of roughness length for heat of vegetation over snow [ ]
ZOELNC	Logarithm of roughness length for heat of vegetation over bare ground [ ]
ZOELNG	Logarithm of roughness length for heat of bare ground [ ]
ZOELNS	Logarithm of roughness length for heat of snow [ ]
ZOLN	Natural logarithm of maximum roughness length of vegetation category [ ]
ZOMLCS	Logarithm of roughness length for momentum of vegetation over snow [ ]
ZOMLNC	Logarithm of roughness length for momentum of vegetation over bare ground [ ]
ZOMLNG	Logarithm of roughness length for momentum of bare ground [ ]
ZOMLNS	Logarithm of roughness length for momentum of snow [ ]
ZPLIMC	Maximum water ponding depth for ground under canopy [m]
ZPLIMG	Maximum water ponding depth for bare ground [m]
ZPLMG0	Maximum water ponding depth for snow-free subareas (user-specified when running MESH code) [m]
ZPLMS0	Maximum water ponding depth for snow-covered subareas (user-specified when running MESH code) [m]
ZPLMCS	Maximum water ponding depth for ground under snow under canopy [m]
ZPLMGS	Maximum water ponding depth for ground under snow [m]
ZRTMAX	Maximum rooting depth of vegetation category [m]
ZSNOW	Depth of snow pack [m] (z_s)

In the first loop, the depth of snow z_s is calculated from the snow mass W_s and density ρ_s as:

$$z_s = W_s / \rho_s.$$

If the calculated value of z_s is less than the limiting snow depth $z_{s,lim}$, the snow cover is deemed to be discontinuous. The fractional snow coverage X_s of the modelled area is evaluated as

$$X_s = z_s / z_{s,lim}$$

and the snow depth is reset to $z_{s,lim}$. The water content of the snow pack is corrected according to the new snow fractional area.

The subarea albedo and transmissivity arrays (for canopy, bare ground, canopy over snow and snow over bare ground) are next initialized to zero, and the four CLASSA subsidiary subroutines are called in turn: APREP to evaluate various model parameters for the four subareas, SNOALBA to calculate the snow albedo and transmissivity, GRALB to calculate the ground surface albedo, and CANALB to calculate the canopy albedo, transmissivity and stomatal resistance. Finally, the overall visible and near-infrared albedos for the modelled area are determined as weighted averages over the four subareas.

APREP

Purpose: Calculate various land surface parameters.

Output variables:

AIL	Leaf area index of vegetation category over bare ground [ ]
CHCAP	Heat capacity of canopy over bare ground [J m^{-2} K^{-1}]
CHCAPS	Heat capacity of canopy over snow [J m^{-2} K^{-1}]
CMAI	Aggregated mass of vegetation canopy [kg m^{-2}]
CMASSC	Mass of canopy over bare ground [kg m^{-2}]
CMASCS	Mass of canopy over snow [kg m^{-2}]
CWFCAP	Storage capacity of canopy over bare ground for frozen water [kg m^{-2}] ($W_{f,max}$)
CWFCPS	Storage capacity of canopy over snow for frozen water [kg m^{-2}] ($W_{f,max}$)
CWLCAP	Storage capacity of canopy over bare ground for liquid water [kg m^{-2}] ($W_{l,max}$)
CWLCPS	Storage capacity of canopy over snow for liquid water [kg m^{-2}] ($W_{l,max}$)
DISP	Displacement height of vegetation over bare ground [m] (d)
DISPS	Displacement height of vegetation over snow [m] (d)
FC/G/CS/GS	Subarea fractional coverage of modelled area [ ] (X)
FCAN	Fractional coverage of vegetation category over bare ground[ ] (X_i)
FCANS	Fractional coverage of vegetation category over snow [ ] (X_i)
FRAICS	Fractional coverage of canopy by liquid water over snow-covered subarea [ ]
FRAINC	Fractional coverage of canopy by liquid water over snow-free subarea [ ]
FROOT	Fraction of total transpiration contributed by soil layer [ ]
FSNOCS	Fractional coverage of canopy by frozen water over snow-covered subarea [ ]
FSNOWC	Fractional coverage of canopy by frozen water over snow-free subarea [ ]
FSVF	Sky view factor for bare ground under canopy [ ] (χ)
FSVFS	Sky view factor for snow under canopy [ ] (χ)
HTC	Diagnosed internal energy change of soil layer due to conduction and/or change in mass [W m^{-2}]
HTCC	Diagnosed internal energy change of vegetation canopy due to conduction and/or change in mass [W m^{-2}]
HTCS	Diagnosed internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}]
PAI	Plant area index of vegetation category over bare ground [ ]
PAICAN	Plant area index of canopy over bare ground [ ] (Λ_p)
PAICNS	Plant area index of canopy over snow [ ] (Λ_p)
PAIS	Plant area index of vegetation category over snow [ ]
PSIGND	Minimum liquid moisture suction in soil layers [m]
RAICAN	Intercepted liquid water stored on canopy over bare ground [kg m^{-2}] (W_l)
RAICNS	Intercepted liquid water stored on canopy over snow [kg m^{-2}] (W_l)
RBCOEF	Parameter for calculation of leaf boundary resistance (C_{rb})
SNOCAN	Intercepted frozen water stored on canopy over bare soil [kg m^{-2}] (W_f)

SNOCNS	Intercepted frozen water stored on canopy over snow [kg m^{-2}] (W_f)
WTRC	Diagnosed residual water transferred on or off the vegetation canopy [kg m^{-2} s^{-1}]
WTRG	Diagnosed residual water transferred into or out of the soil [kg m^{-2} s^{-1}]
WTRS	Diagnosed residual water transferred into or out of the snow pack [kg m^{-2} s^{-1}]
ZOELCS	Logarithm of roughness length for heat of vegetation over snow [ ]
ZOELNC	Logarithm of roughness length for heat of vegetation over bare ground [ ]
ZOELNG	Logarithm of roughness length for heat of bare ground [ ]
ZOELNS	Logarithm of roughness length for heat of snow [ ]
ZOMLCS	Logarithm of roughness length for momentum of vegetation over snow [ ]
ZOMLNC	Logarithm of roughness length for momentum of vegetation over bare ground [ ]
ZOMLNG	Logarithm of roughness length for momentum of bare ground [ ]
ZOMLNS	Logarithm of roughness length for momentum of snow [ ]
ZPLIMC	Maximum water ponding depth for ground under canopy [m]
ZPLIMG	Maximum water ponding depth for bare ground [m]
ZPLMCS	Maximum water ponding depth for ground under snow under canopy [m]
ZPLMGS	Maximum water ponding depth for ground under snow [m]

Input variables:

BI	Clapp and Hornberger empirical "b" parameter [ ]
CWGTMX	Maximum canopy mass for vegetation category [kg m^{-2}]
DELZ	Soil layer thickness [m]
DELZW	Permeable thickness of soil layer [m]
DLON	Longitude of grid cell (east of Greenwich) [degrees]
FCANMX	Maximum fractional coverage of modelled area by vegetation category [ ]
FSNOW	Diagnosed fractional snow coverage [ ]
GROWTH	Vegetation growth index [ ]
HCPS	Volumetric heat capacity of soil particles [J m^{-3}]
HGTDAT	Optional user-specified values of roughness lengths of vegetation categories to override CLASS-calculated values [m]
IDAY	Julian day of the year
IDISP	Flag governing treatment of vegetation displacement height
IHGT	Flag to enable use of user-specified vegetation height
IPAI	Flag to enable use of user-specified plant area index
ISAND	Sand content flag
IWF	Flag governing lateral soil water flow calculations
IZREF	Flag governing treatment of surface roughness length
JL	Integer value of latitude of grid cell
PAIDAT	Optional user-specified value of plant area indices of vegetation categories to override CLASS-calculated values [ ]
PAIMAX	Maximum plant area index of vegetation category [ ]
PAIMIN	Minimum plant area index of vegetation category [ ]
PSISAT	Soil moisture suction at saturation [m] (ψ_{sat})
PSIWLT	Soil moisture suction at wilting point [m] (ψ_w)
RADJ	Latitude of grid cell (positive north of equator) [rad]
RCAN	Intercepted liquid water stored on canopy [kg m^{-2}] (W_l)

RHOAIR	Density of air [kg m^{-3}]
RHOSNI	Density of fresh snow [kg m^{-3}] ($\rho_{s,f}$)
RHOSNO	Density of snow [kg m^{-3}] (ρ_s)
SNCAN	Intercepted frozen water stored on canopy [kg m^{-2}] (W_f)
SNO	Mass of snow pack [kg m^{-2}] (W_s)
TA	Air temperature at reference height [K]
TBAR	Temperature of soil layers [K]
TCAN	Vegetation canopy temperature [K]
THICE	Frozen water content of soil layers under vegetation [m^3 m^{-3}]
THLIQ	Volumetric liquid water content of soil layers [m^3 m^{-3}] (θ_l)
THLMIN	Residual soil liquid water content remaining after freezing or evaporation [m^3 m^{-3}]
THPOR	Pore volume in soil layer [m^3 m^{-3}] (θ_p)
TSNOW	Snowpack temperature [K]
Z0ORO	Orographic roughness length [m]
ZBLEND	Atmospheric blending height for surface roughness length averaging [m] (z_b)
ZBOTW	Depth to permeable bottom of soil layer [m]
ZOLN	Natural logarithm of maximum roughness length of vegetation category [ ]
ZPLMG0	Maximum water ponding depth for snow-free subareas (user-specified when running MESH code) [m]
ZPLMS0	Maximum water ponding depth for snow-covered subareas (user-specified when running MESH code) [m]
ZRTMAX	Maximum rooting depth of vegetation category [m]
ZSNOW	Depth of snow pack [m] (z_s)

This subroutine is hard-coded to handle the standard four vegetation categories recognized by CLASS (needleleaf trees, broadleaf trees, crops and grass), so a call to abort is performed if the number of vegetation classes, IC, is not equal to 4. A set of diagnostic and accumulator arrays is then initialized to zero, and the liquid water suction in the soil is set to an arbitrarily high value.

In the 120 loop, the growth index for crops, GROWA, is calculated. This is done by referring to the three-dimensional array GROWYR, which contains values corresponding to the four Julian days of the year on which crops are planted, on which they reach maturity, on which harvesting begins, and on which the harvest is complete, for each ten-degree latitude half-circle in each hemisphere. These are generic, average dates, approximated using information gleaned from annual UN FAO (Food and Agriculture Organization) reports. (In the tropics, it is assumed that areas classified as agricultural are constantly under cultivation, so all four values are set to zero.)

First, the latitude of the modelled area is converted from a value in radians to a value from 1 to 18, IN, corresponding to the index of the latitude circle (1 for latitudes 80-90° S, 18 for latitudes 80-90° N). Then the hemisphere index, NL, is set to 1 for the Eastern Hemisphere, and 2 for the Western Hemisphere. If the planting date for the modelled area is zero (indicating a location in the tropics), GROWA is set to 1. Otherwise, GROWA is set to 1 if the day of the year lies between the maturity date and the start of the harvest, and to zero if the day of the year lies between the end of the harvest and the planting date. For dates in between, the value of GROWA is interpolated between 0 and 1. Checks are performed at the end to ensure that GROWA is not less than 0 or greater than 1. If the calculated value of GROWA is vanishingly small, it is set to zero.

In the 150 loop the other three growth indices are evaluated, as well as the vegetation heights and plant area indices for the four vegetation categories over snow-covered and snow-free ground. The background growth index for trees, GROWTH, is evaluated separately in subroutine CGROW. It varies from a value of 0 for dormant or leafless periods to 1 for fully-leafed periods, with a sixty-day transition between the two. When senescence begins, it is set instantaneously to -1 and thereafter increases over a sixty-day period back to 0. (The onset of spring budburst and fall senescence are triggered by near-zero values of the air temperature and the first soil layer temperature.) For needleleaf trees, the growth index GROWN is simply set to the absolute value of GROWTH. For broadleaf trees, the transition period is assumed to last thirty days instead of sixty, and so the growth index GROWB is set to the absolute value of double the value of GROWTH, with upper and lower limits of 1 and 0. Finally, the growth index of grasses is set to 1 all year round.

A branch in the code occurs next, depending on the value of the flag IHGT. If IHGT=0, the values of vegetation height calculated by CLASS are to be used. For trees and grass, the vegetation height under snow-free conditions is assumed to be constant year-round, and is calculated as 10 times the exponential of ZOLN, the logarithm of the maximum vegetation roughness length. For crops, this maximum height is multiplied by GROWA. If IHGT=1, vegetation heights specified by the user are utilized instead. This height H for each of the four vegetation categories is used to calculate the height HS over snow-covered areas. For needleleaf and broadleaf trees, HS is set to H. For crops and grass, HS is calculated by subtracting the snow depth ZSNOW from H, to take into account the burying of short vegetation by snow.

A second branch now occurs, depending on the value of the flag IPAI. If IPAI=0, the values of plant area index calculated by CLASS are to be used. For all four vegetation categories, the plant area index over snow-free ground, PAI, is determined by interpolating between the annual maximum and minimum plant area indices using the growth index. If IPAI=1, plant area index values specified by the user are utilized instead. For trees, the plant area index over snow-covered ground, PAIS, is set to PAI. For crops and grass, if H>0, PAIS is set to PAI scaled by the ratio of HS/H; otherwise, it is set to zero. Lastly, the leaf area indices for the four vegetation categories over snow-free ground, AIL, are determined from the PAI values. For needleleaf trees, AIL is estimated as 0.90 PAI; for broadleaf trees it is estimated as the excess PAI over the annual minimum value. For crops and grass AIL is assumed to be equal to PAI.

In the 175 loop, the fractional coverage of the modelled area by each of the four vegetation categories is calculated, for snow-free (FCAN) and snow-covered ground (FCANS). For needleleaf and broadleaf trees, FCAN is set to the maximum coverage FCANMX of the vegetation category, scaled by the snow-free fraction of the modelled area, 1-FSNOW. For crops and grass, this calculation is modified for cases where the plant area index has been calculated as falling below 1 owing to growth stage or burying by snow. In such cases the vegetation coverage is assumed to become discontinuous, and so an additional multiplication by PAI is performed to produce a reduced value of FCAN, and PAI is reset to 1. An identical procedure is followed to determine the FCANS values.

The areal fractions of each of the four CLASS subareas, vegetation over bare soil (FC), bare soil (FG), vegetation over snow (FCS) and snow (FGS) are then calculated, using the FCAN and FCANS values and FSNOW. Checks are carried out, and adjustments performed if necessary, to ensure that none of the four subareas is vanishingly small. The values of FSNOW and of the four FCANs and FCANSs are recalculated accordingly. Finally, checks are carried out to ensure that each of the four subareas is greater than zero, and that their sum is unity. If this is not the case, a call to abort is performed.

In the last part of the 175 loop, the limiting ponding depth for surface water is determined for each of the four subareas. If the flag IWF is zero, indicating that lateral flow of water within the soil is to be neglected, the values are assigned within CLASS. If the index ISAND of the first soil layer is -2, indicating organic soil, the four ponding limits are set to 10 cm. Otherwise, if ISAND=-4 or -3, indicating an ice sheet or a rock surface, the bare soil ponding limit, ZPLIMG, is set to 1 mm. If ISAND is zero or positive, indicating mineral soil, ZPLIMG is set to 2 mm. If the fractional area of snow on bare soil area is greater than zero, the subarea ponding limit ZPLMGS is set to the weighted average of ZPLIMG over the areas where snow has not buried vegetation and where it has buried crops, and to 3 mm over areas where it has buried grass; otherwise to zero. If the fractional area of canopy over bare soil is greater than zero, the subarea ponding depth ZPLIMC is set to the weighted average of 1 cm under trees and 3 mm under crops and grass; otherwise to zero. If the fractional area of canopy over snow is greater than zero, the subarea ponding depth ZPLMCS is also currently set to the weighted average of 1 cm under trees and 3 mm under crops and grass; otherwise to zero. Finally, if the flag IWF is greater than zero, indicating that lateral flow of soil water is being modelled, user-specified values of the ponding limit for the four subareas are assigned.

In loop 200, calculations are done related to the interception of water on vegetation. First, the plant area indices of the composite vegetation canopy over the snow-free and snow-covered subareas are calculated as weighted averages of the plant area indices of the four vegetation categories over each subarea. The liquid water interception capacity $W_{l,max}$ on each of the two subareas is calculated as

$$W_{l,max} = 0.20\Lambda_p$$

where Λ_p is the plant area index of the composite canopy. This simple relation has been found to work well for a wide range of canopy types and precipitation events (see Verseghy et al, 1993). If either the average amount of liquid water on the canopy, RCAN, or the total cancpy coverage, FC+FCS, is less than a small threshold value, the value of RCAN is stored in a residual water array RRESID, and RCAN is set to zero. Next the intercepted liquid water is partitioned between FC and FCS. First RCAN is re-evaluated as an average value over the canopy-covered area only, rather than over the whole modelled area. Then the intercepted liquid water amounts on vegetation over snow-free (RAICAN) and snow-covered areas (RAICNS) are calculated by making use of the relations

$$W_{L,0}/\Lambda_{p,0} = W_{L,s}/\Lambda_{p,s} \quad \text{and}$$
$$W_l(X_0+X_s) = W_{l,0}X_0 + W_{l,s}X_s$$

where W_l is the liquid water on the canopy, X is the fractional area, and the subscripts $_0$ and $_s$ refer to snow-free and snow-covered areas respectively.

For snow interception on the canopy, a modified calculation of the plant area indices $\Lambda_{p,0}$ and $\Lambda_{p,s}$ is performed, assigning a weight of 0.7 to the plant area index of needleleaf trees, to account for the effect of needle clumping. The interception capacity for snow, $W_{f,max}$, is calculated following Bartlett et al. (2006), using a relation developed by Schmidt and Gluns (1991):

$$W_{f,max} = 6.0\ \Lambda_p\ [0.27 + 46.0\ \rho_{s,f}]$$

where $\rho_{s,f}$ is the density of fresh snow. As was done for the intercepted liquid water, if either the average amount of snow on the canopy, SNCAN, or the total cancpy coverage is less than a small threshold value, the value of SNCAN is stored in a residual water array SRESID, and SNCAN is set to zero. Next the intercepted snow is partitioned between FC and FCS. First SNCAN is recalculated as an average over the canopy-covered area only, rather than over the whole modelled area. Then the intercepted snow amounts on vegetation over snow-free (SNOCAN) and snow-covered areas (SNOCNS) are calculated in the same way as for RAICAN and RAICNS.

The fractional canopy coverages of snow and liquid water are calculated as the ratio of the intercepted snow or liquid water to their respective interception capacities. Separate values are determined for the snow-covered (FSNOCS, FRAICS) and snow-free (FSNOWC, FRAINC) subareas. If intercepted snow and liquid water are both present on the canopy, part of the liquid water cover is assumed to underlie the snow cover, so the fractional liquid water coverage is decreased by the fractional snow coverage, to yield the fractional coverage of liquid water that is exposed to the air.

Next, tests are performed to ascertain whether the liquid water and snow on the canopy exceed their respective interception capacities. If so, the excess is assigned to RRESID for liquid water and SRESID for snow, and the intercepted liquid water or snow is reset to the respective interception capacity. The sum of RRESID and SRESID is added to WTRC, the diagnosed residual water transferred on or off the canopy, and the diagnosed change in internal energy of the canopy, HTCC, is updated. If the fractional coverage of snow on the modelled area is greater than zero, SRESID is added to the snow pack; the snow depth, mass, and temperature are recalculated, the diagnosed change in internal energy of the snow pack HTCS is updated, and SRESID is added to WTRS, the diagnosed residual water transferred to or from the snow pack. The remaining amounts of RRESID and SRESID are added to the soil. For each layer in turn whose permeable depth is greater than zero, if the sum of RRESID, SRESID and the ambient soil liquid and frozen moisture contents is less than the pore volume THPOR, RRESID is added to the liquid water content and SRESID is added to the frozen moisture content. The layer temperature is recalculated, the diagnosed change in internal energy HTC is updated, and RRESID and SRESID are added to WTRG, the diagnosed residual water transferred into or out of the soil, and are then set to zero.

In loops 250 and 275, calculations of the displacement height and the logarithms of the roughness lengths for heat and momentum are performed for the vegetated subareas. The displacement height d_i and the roughness length $z_{0,i}$ for the separate vegetation categories are obtained as simple ratios of the canopy height H:

$$d_i = 0.70\ H$$
$$z_{0,i} = 0.10\ H$$

The averaged displacement height d over the vegetated subareas is only calculated if the flag IDISP has been set to 1. If IDISP = 0, this indicates that the atmospheric model is using a terrain-following coordinate system, and thus the displacement height is treated as part of the "terrain". If DISP = 1, d is calculated as a logarithmic average over the vegetation categories:

$$X \ln(d) = \Sigma\ [X_i \ln(d_i)]$$

where X is the fractional coverage of the subarea. The averaged roughness length for momentum z_{0m} over the subarea is determined based on the assumption that averaging should be performed on the basis of the drag coefficient formulation. Thus, following Delage et al. (1999), and after Mason (1988):

$$X/\ln^2(z_b/z_{0m}) = \Sigma\ [X_i/\ln^2(z_b/z_{0i})]$$

The averaged roughness length for heat z_{0e} over the subarea is calculated as a geometric mean over the vegetation categories:

$$z_{0e}z_{0m}{}^{X} = \Pi\ (\ z_{0i}{}^{2Xi}\ )$$

In loop 300, calculations of the logarithms of the roughness lengths for heat and momentum are performed for the bare ground and snow-covered subareas. Background values of $\ln(z_{om})$ for soil, snow cover, ice sheets and urban areas are passed into the subroutine through common blocks. In CLASS, urban areas are treated very simply, as areas of bare soil with a high roughness length. The subarea values of $\ln(z_{om})$ for bare soil and snow are therefore adjusted for the fractional coverage of urban area. Values for the ratio between the roughness lengths for momentum and heat for bare soil and snow are also passed in via common blocks. These are used to derive subarea values of $\ln(z_{oe})$ from $\ln(z_{om})$.

In loop 325, an adjustment is applied to $\ln(z_{om})$ if the effect of terrain roughness needs to be taken into account. If the surface orographic roughness length is not vanishingly small, its logarithm, LZ0ORO, is calculated. If it is greater than the calculated logarithm of the roughness length for momentum of any of the subareas, these are reset to LZ0ORO.

In loop 350, the canopy mass is calculated as a weighted average over the vegetation categories, for canopy over bare soil (CMASSC) and over snow (CMASCS). (For crops over bare soil, the mass is adjusted according to the growth index; for crops and grass over snow, the mass is additionally adjusted to take into account burying by snow.) If IDISP = 0, indicating that the vegetation displacement height is part of the "terrain", the mass of air within the displacement height is normalized by the vegetation heat capacity and added to the canopy mass. If IZREF = 2, indicating that the bottom of the atmosphere is taken to lie at the local roughness length rather than at the ground surface, the mass of air within the roughness length is likewise normalized by the vegetation heat capacity and added to the canopy mass. The canopy heat capacities over bare soil (CHCAP) and over snow (CHCAPS) are evaluated from the respective values of canopy mass and of intercepted liquid water and snow. The aggregated canopy mass CMAI is recalculated, and is used to determine the change in internal energy of the canopy, HTCC, owing to growth or disappearance of the vegetation.

In the 450 and 500 loops, the fraction of plant roots in each soil layer is calculated. For each vegetation category the rooting depth ZROOT is set to the background maximum value, except in the case of crops, for which it is set to the maximum scaled by GROWA. If the soil permeable depth is less than ZROOT, ZROOT is set to this depth instead. Values are then assigned in the matrix RMAT, which stores the fraction of roots in each vegetation category for each soil layer. According to Feddes et al. (1974), the fractional root volume R(z) below a depth z is well represented for many varieties of plants by the following exponential function:

$$R(z) = a_1\exp(-3.0z) + a_2.$$

Making use of the boundary conditions $R(0) = 1$ and $R(z_r) = 0$, where z_r is the rooting depth ZROOT, it can be seen that the fraction of roots within a soil depth interval Δz can be obtained as the difference between $R(z)$ evaluated at the top (z_T) and bottom (z_B) of the interval:

$$R(\Delta z) = [\exp(-3.0z_T) - \exp(-3.0z_B)] / [1 - \exp(-3.0z_r)]$$

The total fraction of roots in each soil layer, FROOT, can then be determined as a weighted average over the four vegetation categories.

In loop 450, a leaf boundary resistance parameter C_{rb}, incorporating the plant area indices of the four vegetation subareas, is also calculated for later use in subroutine TSOLVC:

$$C_{rb} = C_l \Lambda_{p,i}^{0.5} / 0.75 \cdot [1 - \exp(-0.75\Lambda_{p,i}^{0.5})]$$

where C_l is a parameter that varies with the vegetation category. The aggregated value of C_{rb} is obtained as a weighted average over the four vegetation categories over bare ground and snow cover.

In loop 600, the sky view factor χ of the ground underlying the canopy is calculated for the vegetated subareas. The standard approach is to determine χ as an exponential function of the plant area index Λ_p:

$$\chi = \exp[-c\Lambda_p]$$

where c is a constant depending on the vegetation category. The subarea values of χ are obtained as weighted averages over the four vegetation categories.

In the 650 loop, the fraction of the total transpiration of water by plants that is extracted from each soil layer is determined. This is done by weighting the values of FROOT calculated above by the relative soil moisture suction in each layer:

$$(\psi_w - \psi_i) / (\psi_w - \psi_{sat})$$

where ψ_i, the soil moisture suction in the layer, is obtained as

$$\psi_i = \psi_{sat} (\theta_{l,i} / \theta_p)^{-b}$$

In these equations ψ_w is the soil moisture suction at the wilting point, ψ_{sat} is the suction at saturation, $\theta_{l,i}$ is the volumetric liquid water content of the soil layer, θ_p is the pore volume, and b is an empirical parameter developed by Clapp and Hornberger (1978). The layer values of FROOT are then re-normalized so that their sum adds up to unity. In this loop, the representative soil moisture suction PSIGND is also calculated for later use in the vegetation stomatal resistance formulation, as the minimum value of ψ_i and ψ_w over all the soil layers.

Finally, in loop 800 the aggregated canopy plant area indices PAICAN and PAICNS are set back to their original values, from the modified values used for the snow interception calculations above.

SNOALBA

Purpose: Diagnose snowpack visible and near-IR albedos given the all-wave albedo at the current time step. Calculate snowpack transmissivity for shortwave radiation.

Output variables:

ALIRSC	Near-IR albedo of snow on ground under vegetation canopy [ ]
ALVSSC	Visible albedo of snow on ground under vegetation canopy [ ]
ALIRSN	Near-IR albedo of snow pack on bare ground [ ] ($\alpha_{s,NIR}$)
ALVSSN	Visible albedo of snow pack on bare ground [ ] ($\alpha_{s,VIS}$)
TRSNOW	Transmissivity of snow to shortwave radiation [ ] (τ_s)

Input variables:

ALBSNO	All-wave albedo of snow pack [ ] ($\alpha_{s,T}$)
ASIDAT	Assigned value of near-IR albedo of snow pack – optional [ ]
ASVDAT	Assigned value of visible albedo of snow pack – optional [ ]
FSNOW	Fractional coverage of snow on grid cell [ ]
IALS	Flag indicating whether snow albedo is to be calculated or assigned
ZSNOW	Depth of snow [m] (z_s)

In subroutine SNOALBW, called at the end of CLASSW, the change of total snow albedo over the current time step is calculated using an empirical exponential decay function, which has different coefficients depending on whether the snow is dry or melting. In this subroutine, the visible and near-IR components of the snow albedo are diagnosed from the total albedo. According to the literature (Aguado, 1985; Robinson and Kukla, 1984; Dirmhirn and Eaton, 1975), the following represent typical snow albedos for fresh snow, old dry snow and melting snow:

	Total albedo	Visible albedo	Near-IR albedo
Fresh snow	0.84	0.95	0.73
Old dry snow	0.70	0.84	0.56
Melting snow	0.50	0.62	0.38

The same decay function is assumed to apply to all three albedo ranges, so the relative location of the visible and near-IR albedos, $\alpha_{s,VIS}$ and $\alpha_{S,NIR}$, on the decay curve will be analogous to that of the total albedo, $\alpha_{s,T}$. Thus, for dry snow:

$$[\alpha_{s,VIS} - 0.84]/[0.95-0.84] = [\alpha_{s,T} -0.70]/[0.84-0.70]$$

$$[\alpha_{s,NIR} - 0.56]/[0.73-0.56] = [\alpha_{s,T} - 0.70]/[0.84-0.70]$$

or, simplifying:

$$\alpha_{s,VIS} = 0.79[\alpha_{s,T} - 0.70] + 0.84$$
$$\alpha_{s,NIR} = 1.21[\alpha_{s,T} - 0.70] + 0.56$$

For melting snow:

$$[\alpha_{s,VIS} - 0.62]/[0.95-0.62] = [\alpha_{s,T} - 0.50]/[0.84-0.50]$$
$$[\alpha_{s,NIR} - 0.38]/[0.73-0.38] = [\alpha_{s,T} - 0.50]/[0.84-0.50]$$

or, simplifying:

$$\alpha_{s,VIS} = 0.97[\alpha_{s,T} - 0.50] + 0.62$$
$$\alpha_{s,NIR} = 1.03[\alpha_{s,T} - 0.50] + 0.38$$

The above calculations are performed if the flag IALS is set to zero. If IALS is set to one, indicating that assigned snow albedos are to be used instead of calculated values, $\alpha_{s,VIS}$ and $\alpha_{s,NIR}$ are set to the assigned values ASVDAT and ASIDAT respectively. The sub-canopy values of visible and near-IR albedo are currently set equal to the open snowpack values (this is expected to change if a canopy litterfall parametrization is developed).

The transmissivity of snow τ_s is calculated from the snow depth z_s using Beer's law, with an empirical extinction coefficient of 25.0 m^{-1} derived from the literature (Grenfell and Maykut, 1977; Thomas, 1963):

$$\tau_s = \exp[-25.0\, z_s]$$

GRALB

Purpose: Calculate visible and near-IR ground albedos.

Output variables:

ALIRG	Near-IR albedo of bare ground [ ] ($\alpha_{g,NIR}$)
ALVSG	Visible albedo of bare ground [ ] ($\alpha_{g,VIS}$)
ALIRGC	Near-IR albedo of ground under vegetation canopy [ ]
ALVSGC	Visible albedo of ground under vegetation canopy [ ]

Input variables:

AGIDAT	Assigned value of near-IR albedo of ground – optional [ ]
AGVDAT	Assigned value of visible albedo of ground – optional [ ]
ALGDRY	All-wave albedo of dry soil for modelled area [ ] ($\alpha_{g,dry}$)
ALGWET	All-wave albedo of wet soil for modelled area [ ] ($\alpha_{g,wet}$)
ALIRU	Near-IR albedo of urban part of modelled area [ ] ($\alpha_{u,NIR}$)
ALVSU	Visible albedo of urban part of modelled area [ ] ($\alpha_{u,VIS}$)
FCMXU	Fractional coverage of urban part of modelled area [ ] (X_u)
FSNOW	Fractional coverage of snow on modelled area [ ]
IALG	Flag indicating whether snow albedo is to be calculated or assigned
ISAND	Soil type flag based on sand content, assigned in subroutine CLASSB
THLIQ	Volumetric liquid water content of soil layers [m^3 m^{-3}]

If the ISAND flag for the surface soil layer is greater than zero (indicating mineral soil), the visible and near-IR open ground albedos, $\alpha_{g,VIS}$ and $\alpha_{g,NIR}$, are calculated on the basis of the wet and dry ground albedos $\alpha_{g,wet}$ and $\alpha_{g,dry}$ which were assigned for the modelled area in CLASSB. Idso *et al.* (1975) found a correlation between the soil liquid moisture content in the top 10 cm of soil (represented in CLASS by that of the first soil layer, $\theta_{l,1}$) and the total surface albedo $\alpha_{g,T}$: for liquid water contents less than 0.22 m^3 m^{-3}, $\alpha_{g,T}$ took on the value of $\alpha_{g,dry}$; for liquid water contents greater than 0.26 m^3 m^{-3}, $\alpha_{g,T}$ took on the value of $\alpha_{g,wet}$. For values of $\theta_{l,1}$ between these two limits, a linear relationship is assumed:

$$[\alpha_{g,T} - \alpha_{g,dry}]/[\theta_{l,1} - 0.22] = [\alpha_{g,wet} - \alpha_{g,dry}]/[0.26 - 0.22]$$

Thus, in GRALB $\alpha_{g,T}$ is calculated as follows:

$$\alpha_{g,T} = \alpha_{g,dry} \qquad \theta_{l,1} \leq 0.22$$
$$\alpha_{g,T} = \theta_{l,1} [\alpha_{g,wet} - \alpha_{g,dry}]/0.04 - 5.50 [\alpha_{g,wet} - \alpha_{g,dry}] + \alpha_{g,dry} \qquad 0.22 < \theta_{l,1} < 0.26$$
$$\alpha_{g,T} = \alpha_{g,wet} \qquad 0.26 \leq \theta_{l,1}$$

The total albedo is partitioned into values for the visible and near-IR albedo by making use of the observation that in the case of mineral soils, the near-IR albedo is typically twice that of the visible albedo (*e.g.* Dickinson, 1983). Since the partitioning of incoming shortwave radiation into visible and near-IR can be approximated as 50:50 on average, $\alpha_{g,VIS}$ and $\alpha_{g,NIR}$ can be calculated as

$$\alpha_{g,VIS} = 2.0\ \alpha_{g,T}\ /3.0$$
$$\alpha_{g,NIR} = 2.0\ \alpha_{g,VIS}$$

Finally, a correction is applied to $\alpha_{g,VIS}$ and $\alpha_{g,NIR}$ in order to account for the possible presence of urban areas over the modelled area. Visible and near-IR albedos are assigned for local urban areas, $\alpha_{u,VIS}$ and $\alpha_{u,NIR}$, as part of the background data (see the section on "Data Requirements"). A weighted average is calculated from the fractional urban area X_u as:

$$\alpha_{g,VIS} = X_u\ \alpha_{u,VIS} + [1.0\text{-}X_u]\ \alpha_{g,VIS}$$
$$\alpha_{g,NIR} = X_u\ \alpha_{u,NIR} + [1.0\text{-}X_u]\ \alpha_{g,NIR}$$

If the soil on the modelled area is not mineral, *i.e.* if the ISAND flag is less than zero, $\alpha_{g,VIS}$ and $\alpha_{g,NIR}$ are determined as follows:

- If ISAND = -2, indicating organic soil, $\alpha_{g,VIS}$ and $\alpha_{g,NIR}$ are assigned values of 0.05 and 0.30 respectively from the lookup tables in the block data subroutine CLASSBD, corresponding to average measured values reported in Comer *et al.* (2000).

- If ISAND = -3, indicating rock at the surface, $\alpha_{g,T}$ is given a value of 0.27 from CLASSBD, based on typical literature values (*e.g.* Sellers, 1974), and this is partitioned into values of $\alpha_{g,VIS}$ and $\alpha_{g,NIR}$ as above.

- If ISAND = -4, indicating continental ice sheet or glacier, $\alpha_{g,VIS}$ and $\alpha_{g,NIR}$ are assigned values of 0.95 and 073 from CLASSBD, reflecting values reported for Antarctica (*e.g.* Sellers, 1974).

The above calculations are all performed if the flag IALG is set to zero. If IALG is set to one, indicating that assigned ground albedos are to be used instead of calculated values, $\alpha_{g,,VIS}$ and $\alpha_{g,NIR}$ are set to the assigned values AGVDAT and AGIDAT respectively.

Lastly, the ground values of visible and near-IR albedo under the vegetation canopy are currently set equal to the open values (this approach is currently under review).

CANALB

Purpose: Calculate vegetation albedos, transmissivities and stomatal resistances.

Output variables:

ALVSCN/ALIRCN	Visible/near-IR albedo of vegetation over bare ground [ ]
ALVSCS/ALIRCS	Visible/near-IR albedo of vegetation over snow [ ]
RC	Stomatal resistance of vegetation over bare ground [s m^{-1}] (r_c)
RCS	Stomatal resistance of vegetation over snow [s m^{-1}]
TRVSCN, TRIRCN	Visible/near-IR transmissivity of vegetation over bare ground [ ] (τ_c)
TRVCSCS, TRIRCS	Visible/near-IR transmissivity of vegetation over snow [ ] (τ_c)

Input variables:

ACIDAT	Optional user-specified value of canopy near-infrared albedo to override CLASS-calculated value [ ]
ACVDAT	Optional user-specified value of canopy visible albedo to override CLASS-calculated value [ ]
AIL	Leaf area index of vegetation category over bare ground [ ] (Λ)
ALIRC	Background average near-infrared albedo of vegetation category [ ]
ALVSC	Background average visible albedo of vegetation category [ ]
ALVSGC/ALIRGC	Visible/near-IR albedo of bare ground under vegetation [ ]
ALVSSC/ALIRSC	Visible/near-IR albedo of snow under vegetation [ ]
ASIDAT	Optional user-specified value of snow near-infrared albedo to override CLASS-calculated value [ ]
ASVDAT	Optional user-specified value of snow visible albedo to override CLASS-calculated value [ ]
COSZS	Cosine of solar zenith angle [ ]
FC	Fractional coverage of canopy over bare ground [ ]
FCS	Fractional coverage of canopy over snow [ ]
FCAN	Fractional coverage of vegetation category over bare ground [ ] (X_i)
FCANS	Fractional coverage of vegetation category over snow [ ]
FCLOUD	Fractional cloud cover [ ] (X_i)
FROOT	Fraction of water-accessing vegetation roots in soil layer [ ]
FSNOW	Diagnosed fractional snow coverage [ ]
FSNOCS	Fractional coverage of canopy by frozen water over snow-covered subarea [ ]
FSNOWC	Fractional coverage of canopy by frozen water over snow-free subarea [ ]
IALC	Flag to enable use of user-specified canopy albedo
PAI	Plant area index of vegetation category over bare ground [ ] (Λ_p)
PAIS	Plant area index of vegetation category over snow [ ] (Λ_p)

PSIGA	Soil moisture suction coefficient for vegetation category (used in stomatal resistance calculation) [ ] ($c_{\psi 1}$)
PSIGB	Soil moisture suction coefficient for vegetation category (used in stomatal resistance calculation) [ ] ($c_{\psi 2}$)
PSIGND	Minimum liquid moisture suction in soil layers [m] (ψ_s)
QA50	Reference value of incoming shortwave radiation for vegetation category (used in stomatal resistance calculation) [W m^{-2}] ($K{\downarrow}_{1/2}$)
QSWINV	Visible radiation incident on horizontal surface [W m^{-2}] ($K{\downarrow}$)
RSMIN	Minimum stomatal resistance of vegetation category [s m^{-1}] ($r_{s,min}$)
TA	Air temperature at reference height [K] (T_a)
VPD	Vapour pressure deficit of air [mb] {Δe }
VPDA	Vapour pressure deficit coefficient for vegetation category (used in stomatal resistance calculation) [ ] (c_{v1})
VPDB	Vapour pressure deficit coefficient for vegetation category (used in stomatal resistance calculation) [ ] (c_{v2})

The transmissivity τ_c of a vegetation canopy to shortwave radiation is obtained by applying a form of Beer's law of radiation transfer in non-scattering media:

$$\tau_c = \exp[-\varkappa\Lambda_p]$$

where $\varkappa$ is the canopy extinction coefficient and Λ_p is the plant area index. The extinction coefficient is calculated after Goudriaan (1988) as

$$\varkappa = \varepsilon O/\cos Z$$

where ε is a correction factor less than or equal to 1, accounting for forward-scattering of radiation and non-random leaf distributions (i.e. clumping), O represents the mean projected leaf area fraction perpendicular to the incoming radiation, and Z is the zenith angle of the incoming radiation. For crops, grass and needleleaf trees, the distribution of leaf angles is assumed to be spherical, and thus O = 0.5. For broadleaf trees, the preferred leaf orientation tends to be horizontal; thus O = cosZ.

In the clear-sky case, incoming shortwave radiation is dominated by the direct beam; thus, the transmissivity for clear skies $\tau_{c,\circ}$ is evaluated by simply setting Z to Z_s, the solar zenith angle. An extensive search of the literature for values of ε appropriate to the four vegetation categories yielded the following results for the extinction coefficient:

$\varkappa = 0.3/\cos Z_s$	(needleleaf trees)
$\varkappa = 0.4$	(broadleaf trees, full canopy)
$\varkappa = 0.4/\cos Z_s$	(broadleaf trees, leafless)
$\varkappa = 0.4/\cos Z_s$	(crops and grass)

In the visible range of the shortwave spectrum, scattering is less important because of high leaf absorptivities. The following results were obtained for visible radiation:

$\varkappa = 0.4/\cos Z_s$ (needleleaf trees)
$\varkappa = 0.7$ (broadleaf trees, full canopy)
$\varkappa = 0.4/\cos Z_s$ (broadleaf trees, leafless)
$\varkappa = 0.5/\cos Z_s$ (crops and grass)

In the case of overcast skies, the hemispherical distribution of incoming shortwave radiation is modelled using the generally accepted "standard overcast sky" distribution (e.g. Steven and Unsworth, 1980), where the shortwave radiation D(Z) emanating from a sky zenith angle Z is approximated as

$$D(Z) = D(0)\ [(1 + 1.23\cos Z)/2.23].$$

Integration of the cloudy-sky transmissivity $\tau_{c,\bullet}$ over the sky hemisphere is performed using a simple weighting function proposed by Goudriaan (1988):

$$\tau_{c,\bullet} = 0.3\ \tau_c(Z=15^o) + 0.5\ \tau_c(Z=45^o) + 0.2\ \tau_c(Z=75^o)$$

The albedo α_c of a vegetation canopy is, like the transmissivity, dependent in principle on the zenith angle Z of the incoming radiation and the mean projected leaf area fraction O. However, in practice the observed diurnal and seasonal variation of vegetation albedo tends to be slight for closed canopies or for radiation zenith angles larger than a few degrees. Since the former is generally true in the tropics and the latter in the extratropics, the diurnal variation of visible and near-infrared canopy albedo is neglected in CLASS.

Corrections are applied to the average albedos to account for the effects of intercepted snow on the canopy and incomplete canopy closure. The presence of snow on the canopy will tend to increase the albedo; this increase will be larger in the visible range of the spectrum, since the visible albedo of vegetation is typically very small. Making use of data presented by Leonard and Eschner (1968), the visible albedo of snow-covered vegetation is set to 0.17. The near-infrared albedo, being larger in magnitude, will be affected to a lesser degree, and is therefore set to the background near-infrared albedo plus 0.04.

If the canopy closure is incomplete, a fraction χ of the ground or snow under the canopy will be visible through gaps in it. This fraction is equal to the sky view factor of the underlying surface, which is calculated using an equation analogous to that for the canopy transmissivity, as an exponential function of the plant area index Λ_p:

$$\chi = \exp[-c\Lambda_p]$$

where c is a constant depending on the vegetation category. The overall albedo α_T is calculated as a weighted average of the canopy albedo and the underlying ground or snow albedo (the latter weighted by the canopy transmissivity, to account for the decreased downwelling shortwave radiation at the surface):

$$\alpha_T = (1 - \chi)\ \alpha_c + \chi\tau_c\alpha_0$$

where α_0 is the albedo of the surface under the canopy.

At the beginning of the subroutine, a series of work arrays is initialized to zero. Then the transmissivity and albedo of each vegetation category are calculated in turn, first over bare soil and then over a snow pack. After each of the latter sets of calculations, consistency checks are carried out to ensure that the calculated albedos and transmissivities are not less than 0 or greater than 1, and that the transmissivity is not greater than 90% of the non-reflected radiation.

The clear-sky and cloudy-sky transmissivities in the visible range are calculated first, and then the clear-sky and cloudy-sky transmissivities in the total shortwave spectrum, using the extinction coefficient equations above. (For broadleaf trees, the minimum of the full-canopy and leafless calculated values is used.) The overall transmissivity in the visible range at the current time step is obtained as an average of the clear and cloudy-sky values, weighted according to the fractional cloud cover. The effective overall extinction coefficient CXTEFF in the visible range is computed for use later on in the stomatal resistance calculation. The overall transmissivity for the entire shortwave spectrum at the current time step is similarly obtained as an average of the clear and cloudy-sky values, weighted according to the fractional cloud cover. The near-infrared transmissivity is calculated from the total and visible transmissivities, making use of the assumption that visible and near-infrared radiation each typically comprise 50% of the incoming shortwave radiation. Lastly, the aggregated visible and near-infrared transmissivities for the bulk canopy are incremented using the current values weighted by the fractional coverage of the vegetation category. At the end, the sum is normalized by the total fractional vegetation coverage in the subarea.

For the albedos, first the sky view factor and the near-infrared albedo of snow-covered vegetation are calculated. Next, a branch directs further processing depending on the value of the flag IALC. If IALC = 0, the CLASS-calculated visible and near-infrared vegetation albedos are used. These albedos are corrected for the presence of intercepted snow, using an average of the snow-covered and background snow-free albedos weighted according to FSNOWC over snow-free, and FSNOCS over snow-covered subareas (representing the ratio of the amount of snow present on the canopy relative to the interception capacity). The correction for incomplete canopy closure is applied to the resulting visible and near-infrared albedos as described above. If IALC = 1, user-specified albedos for the vegetation canopy are used instead of the CLASS values. These are assumed to incorporate the effects of incomplete canopy closure, but not of the presence of snow. Thus the CLASS values for the albedo of snow-covered vegetation and the albedo of snow under the canopy are still used in the averaging. Finally, the aggregated visible and near-infrared albedos for the bulk canopy are incremented using the current values weighted by the fractional coverage of the vegetation category. At the end, the sum is normalized by the total fractional vegetation coverage in the subarea.

In the final section, the stomatal resistance r_c of the vegetation canopy is determined. Based on the analysis of Schulze et al. (1995), the unstressed stomatal resistance $r_{c,u}$ for a given vegetation category can be calculated as a function of the incoming visible shortwave radiation $K\downarrow$:

$$r_{c,u} = r_{s,min}\varkappa_e / \ln[\{K\downarrow + K\downarrow_{1/2}/\varkappa_e)/\{ K\downarrow \exp(-\varkappa_e \Lambda) + K\downarrow_{1/2}/\varkappa_e)]$$

where $r_{s,min}$ is the minimum stomatal resistance for the vegetation category, $\varkappa_e$ is the extinction coeffient for visible radiation (CXTEFF above), Λ is the leaf area index, and $K\downarrow_{1/2}$ is the value of $K\downarrow$ at which $r_{c,u} = 2r_{s,min}$.

Suboptimum environmental conditions for transpiration may lead to stresses on the plant, causing the stomatal resistance to be greater than its unstressed value. The effects of these stresses are modelled by defining functions of the air temperature T_a, the air vapour pressure deficit Δe, and the soil moisture suction ψ_s. These functions are used to derive $r_{c,i}$ of each vegetation category on the basis of $r_{c,u,i}$:

$$r_{c,i} = f(T_a)\, f(\Delta e)\, f(\psi_s) \cdot r_{c,u,i}$$

The air temperature function $f(T_a)$ has a value of 1 for temperatures between 5° C and 40° C, and an arbitrary large value of 250 for temperatures less than -5° C and greater than 50° C. Between these points it varies in a linear fashion. For the vapour pressure deficit function $f(\Delta e)$, two alternate forms are provided, after Oren et al. (1999) and Wu et al. (2000) respectively:

$$f(\Delta e) = (\Delta e/10.0)^{cv2}/c_{v1} \quad \text{and}$$
$$f(\Delta e) = 1/\exp(-c_{v1}\, \Delta e/10.0)$$

where c_{v1} and c_{v2} are parameters depending on the vegetation category. If c_{v2} is greater than zero, the first form is used; if not, the second form is used. The soil moisture suction function $f(\psi_s)$ is expressed, following Choudhury and Idso (1985) and Fisher et al. (1981), as:

$$f(\psi_s) = 1 + (\psi_s / c_{\psi 1})^{c\psi 2}$$

where $c_{\psi 1}$ and $c_{\psi 2}$ are parameters depending on the vegetation category. Finally, the aggregated stomatal resistance for the canopy over the bare ground subarea is obtained as a weighted average over the vegetation categories. (It is assumed that transpiration is suppressed when snow is present under the canopy, so r_c for this subarea is set to a large number). Since, following the electrical analogy, resistances act in parallel, the aggregated resistance for the subarea of canopy over bare ground is obtained as an average of inverses:

$$X/r_c = \Sigma\, (X_i/r_{c,i})$$

The calculations described above pertaining to stomatal resistances are performed in loops 850, 900 and 950. In the 850 loop, $f(T_a)$ is evaluated. In the 900 loop, for each vegetation category in turn, $f(\Delta e)$, $f(\psi_s)$ and $r_{c,i}$ are determined. $r_{c,i}$ is assigned upper and lower limits of 5000 and 10 s m^{-1} respectively, and the accumulated stomatal resistance for the canopy is incremented by $X_i/r_{c,i}$. In loop 950, FRMAX, the maximum value of FROOT, the fraction of transpiration apportioned to each soil layer, is determined. If FRMAX is vanishingly small, transpiration is suppressed by setting the stomatal resistances over the vegetated subareas to a large number. If the incoming visible radiation is small, the stomatal resistances are likewise set to a large number. Otherwise, the stomatal resistance of vegetation over snow is set to a large number, and the normalized, aggregated stomatal resistance of vegetation over soil is obtained by inverting the accumulated value.

XIT

Purpose: Print the name of the subroutine and an error code when an error condition is encountered.

Input/Output variables:

N	Error code
NAME	Name of the subroutine in which the error was found

In CLASS, this subroutine is called when a test of ambient values of selected variables is performed and an abnormal condition is encountered. The name of the subroutine in which the condition arose is passed in, and is printed together with an error code, flagging the location of the error in the subroutine. A call to abort is then executed.

Part

7

CLASST

Purpose: Call subroutines to perform surface energy budget calculations.

Output variables:

(In composite definitions, suffix C or CO = vegetation over ground; G or GO = bare ground; CS = vegetation over snow cover; GS = bare snow cover.)

ACOND	Diagnosed product of drag coefficient and wind speed over modelled area [m s^{-1}]
CDH	Surface drag coefficient for heat [ ] (C_{DH})
CDM	Surface drag coefficient for momentum [ ] (C_{DM})
CHCAP	Heat capacity of canopy over bare ground [J m^{-2} K^{-1}]
CHCAPS	Heat capacity of canopy over snow [J m^{-2} K^{-1}]
DRAG	Surface drag coefficient under neutral stability [ ]
EVAP	Diagnosed total surface water vapour flux over modelled area [kg m^{-2} s^{-1}]
EVAPB	Evaporation efficiency at ground surface [ ]
EVAPC	Evaporation from vegetation over ground [m s^{-1}]
EVAPCS	Evaporation from vegetation over snow [m s^{-1}]
EVAPCG	Evaporation from ground under vegetation [m s^{-1}]
EVAPG	Evaporation from bare ground [m s^{-1}]
EVAPGS	Evaporation from snow on bare ground [m s^{-1}]
EVPCSG	Evaporation from snow under vegetation [m s^{-1}]
EVPPOT	Diagnosed potential evapotranspiration [kg m^{-2} s^{-1}] (E_p)
FLGG	Diagnosed net longwave radiation at soil surface [W m^{-2}]
FLGS	Diagnosed net longwave radiation at snow surface [W m^{-2}]
FLGV	Diagnosed net longwave radiation on vegetation canopy [W m^{-2}]
FSGG	Diagnosed net shortwave radiation at soil surface [W m^{-2}]

FSGS	Diagnosed net shortwave radiation at snow surface [W m^{-2}]
FSGV	Diagnosed net shortwave radiation on vegetation canopy [W m^{-2}]
G12C/G/CS/GS	Subarea heat flux between first and second soil layers [W m^{-2}]
G23C/G/CS/GS	Subarea heat flux between second and third soil layers [W m^{-2}]
GT	Diagnosed effective surface black-body temperature [K] ($T_{0,eff}$)
GZEROC/G, GZROCS/GS	Subarea heat flux at soil surface [W m^{-2}]
HBL	Height of the atmospheric boundary layer [m]
HCPC	Heat capacity of soil layers under vegetation [J m^{-3} K^{-1}]
HCPG	Heat capacity of soil layers in bare areas [J m^{-3} K^{-1}]
HEVC	Diagnosed latent heat flux on vegetation canopy [W m^{-2}]
HEVG	Diagnosed latent heat flux at soil surface [W m^{-2}]
HEVS	Diagnosed latent heat flux at snow surface [W m^{-2}]
HFSC	Diagnosed sensible heat flux on vegetation canopy [W m^{-2}]
HFSG	Diagnosed sensible heat flux at soil surface [W m^{-2}]
HFSS	Diagnosed sensible heat flux at snow surface [W m^{-2}]
HMFC	Diagnosed energy associated with phase change of water on vegetation [W m^{-2}]
HMFN	Diagnosed energy associated with phase change of water in snow pack [W m^{-2}]
HTC	Diagnosed internal energy change of soil layer due to conduction and/or change in mass [W m^{-2}]
HTCC	Diagnosed internal energy change of vegetation canopy due to conduction and/or change in mass [W m^{-2}]
HTCS	Diagnosed internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}]
ILMO	Inverse of Monin-Obukhov roughness length (m^{-1}]
ITERCT	Counter of number of iterations required to solve surface energy balance for the elements of the four subareas
QAC	Specific humidity of air within vegetation canopy space [kg kg^{-1}]
QEVAP	Diagnosed total surface latent heat flux over modelled area [W m^{-2}]
QFCF	Sublimation from frozen water on vegetation [kg m^{-2} s^{-1}]
QFCL	Evaporation from liquid water on vegetation [kg m^{-2} s^{-1}]
QFLUX	Product of surface drag coefficient, wind speed and surface-air specific humidity difference [m s^{-1}]
QFREZC	Heat sink to be used for freezing water on ground under canopy [W m^{-2}]
QFREZG	Heat sink to be used for freezing water on bare ground [W m^{-2}]
QG	Diagnosed surface specific humidity [kg kg^{-1}]
QMELTC	Heat to be used for melting snow under canopy [W m^{-2}]
QMELTG	Heat to be used for melting snow on bare ground [W m^{-2}]
QSENS	Diagnosed total surface sensible heat flux over modelled area [W m^{-2}]
RAICAN	Intercepted liquid water stored on canopy over ground [kg m^{-2}]
RAICNS	Intercepted liquid water stored on canopy over snow [kg m^{-2}]
RHOSCS	Density of snow under vegetation [kg m^{-3}]
RHOSGS	Density of snow in bare areas [kg m^{-3}]
SNOCAN	Intercepted frozen water stored on canopy over ground [kg m^{-2}]
SNOCNS	Intercepted frozen water stored on canopy over snow [kg m^{-2}]
SQ	Diagnosed screen-level specific humidity [kg kg^{-1}]

ST	Diagnosed screen-level air temperature [K]
SU	Diagnosed anemometer-level zonal wind [m s^{-1}]
SV	Diagnosed anemometer-level meridional wind [m s^{-1}]
TAC	Temperature of air within vegetation canopy [K]
TBARC/G/CS/GS	Subarea temperatures of soil layers [C]
TCANO	Temperature of canopy over ground [K]
TCANS	Temperature of canopy over snow [K]
TCBOTC/G	Thermal conductivity of soil at bottom of layer [W m^{-1} K^{-1}]
TCTOPC/G	Thermal conductivity of soil at top of layer [W m^{-1} K^{-1}]
TFLUX	Product of surface drag coefficient, wind speed and surface-air temperature difference [K m s^{-1}]
THICEC	Frozen water content of soil layers under vegetation [m^3 m^{-3}]
THICEG	Frozen water content of soil layers in bare areas [m^3 m^{-3}]
THLIQC	Liquid water content of soil layers under vegetation [m^3 m^{-3}]
THLIQG	Liquid water content of soil layers in bare areas [m^3 m^{-3}]
TPONDC/G, TPNDCS/GS	Subarea temperature of surface ponded water [C]
TSNOCS	Temperature of snow pack under vegetation [K]
TSNOGS	Temperature of snow pack in bare areas [K]
TSURF	Average ground/snow surface temperature over modelled area [K]
UE	Friction velocity of air [m s^{-1}]
WSNOCS	Liquid water content of snow pack under vegetation [kg m^{-2}]
WSNOGS	Liquid water content of snow pack in bare areas [kg m^{-2}]
WTABLE	Depth of water table in soil [m]
WTRG	Diagnosed residual water transferred into or out of the soil [kg m^{-2} s^{-1}]

Input variables:

ALVSCN/ALIRCN	Visible/near-IR albedo of vegetation over bare ground [ ]
ALVSCS/ALIRCS	Visible/near-IR albedo of vegetation over snow [ ]
ALVSG/ALIRG	Visible/near-IR albedo of open bare ground [ ]
ALVSGC/ALIRGC	Visible/near-IR albedo of bare ground under vegetation [ ]
ALVSSC/ALIRSC	Visible/near-IR albedo of snow under vegetation [ ]
ALVSSN/ALIRSN	Visible/near-IR albedo of open snow cover [ ]
CMASSC	Mass of canopy over bare ground [kg m^{-2}]
CMASCS	Mass of canopy over snow [kg m^{-2}]
DELZ	Overall thickness of soil layer [m]
DELZW	Permeable thickness of soil layer [m]
DISP	Displacement height of vegetation over bare ground [m] (d)
DISPS	Displacement height of vegetation over snow [m] (d)
FC/G/CS/GS	Subarea fractional coverage of modelled area [ ]
FRAICS	Fractional coverage of canopy by liquid water over snow-covered subarea [ ]
FRAINC	Fractional coverage of canopy by liquid water over snow-free subarea [ ]
FSNOCS	Fractional coverage of canopy by frozen water over snow-covered subarea [ ]
FSNOWC	Fractional coverage of canopy by frozen water over snow-free subarea [ ]

FSVF	Sky view factor for bare ground under canopy [ ]
FSVFS	Sky view factor for snow under canopy [ ]
HCPS	Heat capacity of soil material [J m^{-3} K^{-1}]
ISAND	Sand content flag
ISLFD	Flag governing options for surface stability functions and diagnostic calculations
ITC	Flag to select iteration scheme for canopy temperature
ITCG	Flag to select iteration scheme for surface under canopy
ITG	Flag to select iteration scheme for ground or snow surface
IZREF	Flag governing treatment of surface roughness length
NLANDC/G/CS/GS	Number of modelled areas that contain subareas of canopy over bare ground / bare ground / canopy over snow /snow
NLANDI	Number of modelled areas that are ice sheets [ ]
PADRY	Partial pressure of dry air [Pa] (p_{dry})
PCPR	Surface precipitation rate [kg m^{-2} s^{-1}]
QA	Specific humidity at reference height [kg kg^{-1}]
QLWIN	Downwelling longwave radiation at bottom of atmosphere [W m^{-2}]
QSWINI	Near-infrared radiation incident on horizontal surface [W m^{-2}]
QSWINV	Visible radiation incident on horizontal surface [W m^{-2}]
RADJ	Latitude of grid cell (positive north of equator) [rad] (φ)
RBCOEF	Parameter for calculation of leaf boundary resistance
RC	Stomatal resistance of vegetation over bare ground [s m^{-1}]
RCS	Stomatal resistance of vegetation over snow [s m^{-1}]
RHOAIR	Density of air [kg m^{-3}] (ρ_a)
RHOSNO	Density of snow [kg m^{-3}]
TA	Air temperature at reference height [K] (T_a)
TADP	Dew point temperature of air [K]
TBAR	Temperature of soil layers [K]
TBASE	Temperature of bedrock in third soil layer [K]
TCAN	Vegetation canopy temperature [K]
TCS	Thermal conductivity of soil particles [W m^{-1} K^{-1}]
THFC	Field capacity [m^3 m^{-3}]
THICE	Volumetric frozen water content of soil layers [m^3 m^{-3}]
THLIQ	Volumetric liquid water content of soil layers [m^3 m^{-3}]
THLMIN	Residual soil liquid water content remaining after freezing or evaporation [m^3 m^{-3}]
THLRET	Liquid water retention capacity for organic soil [m^3 m^{-3}]
THPOR	Pore volume in soil layer [m^3 m^{-3}]
TPOND	Temperature of ponded water [K]
TRSNOW	Short-wave transmissivity of snow pack [ ]
TRVSCN/TRIRCN	Visible/near-IR transmissivity of vegetation over bare ground [ ]
TRVCSCS/TRIRCS	Visible/near-IR transmissivity of vegetation over snow [ ]
TSFSAV	Ground surface temperature over subarea [K]
TSNOW	Snowpack temperature [K]
UWIND	Zonal component of wind speed [m s^{-1}] (U_a)
VPD	Vapour pressure deficit [mb]
VWIND	Meridional component of wind speed [m s^{-1}] (V_a)

WSNOW	Liquid water content of snow pack [kg m^{-2}]
ZBOTW	Depth to permeable bottom of soil layer [m]
ZDIAGH	User-specified height associated with diagnosed screen-level variables [m]
ZDIAGM	User-specified height associated with diagnosed anemometer-level wind speed [m]
ZOELCS	Logarithm of roughness length for heat of vegetation over snow [ ]
ZOELNC	Logarithm of roughness length for heat of vegetation over bare ground [ ]
ZOELNG	Logarithm of roughness length for heat of bare ground [ ]
ZOELNS	Logarithm of roughness length for heat of snow [ ]
ZOMLCS	Logarithm of roughness length for momentum of vegetation over snow [ ]
ZOMLNC	Logarithm of roughness length for momentum of vegetation over bare ground [ ]
ZOMLNG	Logarithm of roughness length for momentum of bare ground [ ]
ZOMLNS	Logarithm of roughness length for momentum of snow [ ]
ZPOND	Depth of ponded water on surface [m]
ZREFH	Reference height associated with forcing air temperature and humidity [m]
ZREFM	Reference height associated with forcing wind speed [m]
ZSNOW	Depth of snow pack [m]

First, two parameters are calculated for later use in the CLASST subroutines: the wind speed v_a at the reference height, and the Coriolis parameter f_{cor} (describing the effect of the earth's rotation on the movement of air according to the reference frame of the earth's surface). The wind speed is obtained by the vector addition of the zonal wind speed U_a (along latitude bands) and the meridional wind speed V_a (along longitude circles):

$$v_a = [U_a^2 + V_a^2]^{1/2}$$

It is assumed that air is never completely still, so v_a is assigned a limiting lower value of 0.1 m s^{-1}. The Coriolis parameter is calculated from the angular velocity Ω of the earth's rotation (7.29 x 10^{-5} radians/s), and the latitude φ:

$$f_{cor} = 2\ \Omega \sin \varphi$$

The packing and unpacking of binary files may cause small shifts in the values of variables at certain points in the model run, so checks are performed on the depth of ponded water and on the soil liquid and frozen moisture contents to ensure that unphysical values have not occurred. If the ponded water depth is vanishingly small or less than zero, it is set to zero. If the soil liquid water content falls below the set minimum value, it is set to the minimum value. If the soil frozen water content is less than zero, it is set back to zero. If the sum of the liquid water content and frozen water content converted to an equivalent liquid amount is greater than the pore volume, both are re-normalized by the pore volume. (This treatment of frozen water is employed in recognition of the fact that water expands upon freezing and can therefore occupy a greater volume than the nominal pore volume of the soil.) The small changes in internal energy and water content of the soil layers resulting from these operations are accounted for by updating the diagnostic variables HTC and WTRG.

Subroutine TPREP is now called, to carry out the initialization of a number of variables and to do preparatory calculations of various parameters associated with the energy and water budget calculations.

The energy budget calculations that follow are performed over the four subareas, of canopy over snow (CS), snow over ground (GS), canopy over bare ground (C) and bare ground (G). First, a counter NLANDx is defined for each subarea, containing the number of modelled areas in which the subarea occurs. The subarea calculations are only done if the relevant counter is greater than zero. A counter NLANDI is also set to the number of modelled areas that are ice sheets (indicated by ISAND = -4). (This is used later in subroutine CLASSW to toggle the call to subroutine ICEBAL.)

For each subarea, the roughness lengths for momentum and heat, ZOM and ZOH, are obtained from their logarithms, and are then used to determine various height intervals in the atmosphere for subsequent calculations. These heights are derived from the input variables ZREFM and ZREFH, the reference heights corresponding to the input values of wind speed and of air temperature and humidity respectively, and ZDIAGM and ZDIAGH, the heights at which the diagnostic values of anemometer wind speed and screen level temperature and humidity are to be determined. The form of the calculations depends on the value of the flag IZREF. If IZREF = 1, the zero plane is taken to lie at the physical ground surface (as with field measurements); if IZREF = 2, the zero plane is taken to lie at the local roughness height for momentum(as with atmospheric models). The variables ZRSLDM and ZRSLDH are the height differences used in subroutine DRCOEF to express the interval between the conceptual bottom of the atmosphere and the reference heights for wind speed and for temperature and humidity respectively; the variables ZRSLFM and ZRSLFH are the corresponding height differences used in subroutine FLXSURFZ. If IZREF = 1, ZRSLDM and ZRSLDH are set to ZREFM and ZREFH minus the displacement height DISP or DISPS, and ZRSLFM and ZRSLFH are set to ZREFM and ZREFH minus the roughness length ZOM and DISP or DISPS. If IZREF = 2, ZRSLDM and ZRSLDH are set to ZREFM and ZREFH plus the roughness height ZOM, and ZRSLFM and ZRSLFH are set to ZREFM and ZREFH minus DISP or DISPS. (In the absence of a vegetation canopy, the displacement height is zero.) The variables ZDSLM and ZDSLH are the heights above the bottom of the modelled atmosphere at which the diagnostic values are to be calculated. If IZREF = 1, they are set to ZDIAGM and ZDIAGH minus ZOM; if IZREF = 2 they are simply set to ZDIAGM and ZDIAGH. At the end of the branch in the code, the ratios ZOSCLM and ZOSCLH, which are used in subroutine DRCOEF, are calculated as ZOM/ZRSLDM and ZOH/ZRSLDH respectively.

Several other local parameters are also calculated. The potential temperature is the temperature that air would have if brought adiabatically (without addition or removal of heat) to a given height. The potential temperature of the air at the reference height, $T_{a,pot}$, is calculated relative to the height at which the horizontal wind speed goes to zero, using the dry adiabatic lapse rate, $dT/dz = -g/c_p$, where g is the acceleration due to gravity and c_p is the specific heat at constant pressure:. Thus,

$$T_{a,pot} = T_a + z_{ref,h}\, g/c_p$$

where T_a is the temperature of the air at the reference height and $z_{ref,h}$ is the height interval, equivalent to ZRSLFH defined above. If CLASS is being run coupled to an atmospheric model, i.e. if IZREF=2, the air temperature at the reference height has already been adiabatically extrapolated before being passed to CLASS. Otherwise, the correction is performed using the above equation.

The virtual potential temperature of the air at the reference height, $T_{a,v}$, is the potential temperature adjusted for the reduction in air density due to the presence of water vapour. This is applied in order to enable the use of the equation of state for dry air. $T_{a,v}$ can be approximated as:

$$T_{a,v} = T_{a,pot} [1 + 0.61 q_a]$$

where q_a is the specific humidity of the air at the reference height.

The bulk Richardson number Ri_B, used in the calculations of the atmospheric stability functions in subroutine DRCOEF, is formulated as:

$$Ri_B = [T_0 – T_{a,v}] [–g (z_{ref} – d\}]/[T_{a,v} v_a^2]$$

where T_0 is the surface temperature and d is the displacement height. For ease of calculation later on, the factor multiplying $[T_0 – T_{a,v}]$ on the right-hand side of the above equation is evaluated and assigned to a coefficient CRIB, using ZRSLDM for z_{ref}. The drag coefficient under neutral stability, C_{DN}, is expressed using basic flux-gradient analysis as:

$$C_{DN} = k^2/[\ln(z_{ref} – d) – \ln(z_0)]^2$$

where k is the von Karman constant and z_0 is the roughness length. ZRSLDM is used for z_{ref} and the logarithm of the local roughness length for $\ln(z_0)$ and the neutral drag coefficient DRAG over the modelled area is obtained as a weighted average over the four subareas.

For the two subareas with canopy cover, the wind speed of the air at the canopy top, $v_{a,c}$, is obtained by applying the classic logarithmic wind law for the wind speed v(z) at a height z:

$$kv(z)/v_* = \ln[(z – d)/z_0]$$

Thus, $v_{a,c}$ at the canopy height H can be related to v_a at the reference height z_{ref} as:

$$v_{a,c} = v_{a,c} [\ln(H – d) – \ln(z_0)]/[\ln(z_{ref} – d) – \ln(z_0)]$$

The vegetation height is calculated as $10z_0$. Local values of the temperature of the canopy air TAC and the humidity of the canopy air QAC are assigned to variables TACCS/TACCO and QACCS/QACCO respectively.

At this point calls are made to a series of subroutines addressing the calculation of the energy balance components of the subarea in question. The calls are summarized in the table below.

		CS	GS	C	G
CWCALC	Freezing/thawing of liquid/frozen water on canopy	√		√	
TNPREP	Set coefficients for temperature calculations in soil	√	√	√	√

TSPREP	Set coefficients for temperature calculations of snow	√	√		
TSOLVC	Calculate components of canopy energy balance	√		√	
TSOLVE	Calculate components of ground or snow energy balance		√		√
TSPOST	Heat conduction in snow pack	√	√		
TNPOST	Heat conduction in soil	√	√	√	√

After these calls, various diagnostic calculations are performed. First the screen-level temperature and humidity, and the anemometer-level zonal and meridional wind speeds, are calculated. Three options are provided for doing this, indicated by the flag ISLFD. If ISLFD = 0, the simple approach used in the Canadian GCM is selected. The ratio of the square root of the surface drag coefficient for momentum, C_{DM}, to that of the neutral drag coefficient C_{DN}, is calculated for the screen height z_s (RATFC1) and the anemometer height (RATFCA1), to give a measure of the degree of atmospheric instability. If the bulk Richardson number RIB is positive (indicating stable conditions), RATFC1 is adopted for the screen-level calculations; if RIB is negative (indicating unstable conditions), the ratio used is the minimum of the ratio of the drag coefficient for heat C_{DH} to C_{DN}, and $(z_s/z_{ref})^{1/3}$, a measure of the depth of the convection. These ratios are applied to the calculation of the screen and anemometer level variables. If the ratios are large, indicating strong coupling with the atmosphere, the screen level variables tend to the values at the reference height; if the ratio is small, they tend to the values at the surface. If ISLFD= 1 or 2, the more rigorous calculations in subroutines SLDIAG and DIASURF are followed. The calculations done in SLDIAG are consistent with the modelling approach used in subroutine DRCOEF to determine the atmospheric stability functions, so when ISLFD = 1, DRCOEF and SLDIAG are called. The calculations done in DIASURF are consistent with the modelling approach used in subroutine FLXSURFZ for the atmospheric stability functions, so when ISLFD = 2, FLXSURFZ and DIASURF are called.

A number of additional diagnostic variables are calculated as weighted averages over the four subareas. For the most part, these calculations are straightforward; only the calculation of the porential evapotranspiration E_p (EVPPOT) involves some complexity. E_p is defined as the evapotranspiration that would occur under ambient atmospheric conditions if the soil were completely saturated and the vegetation canopy were completely water-covered, i.e. if there were no surface resistances to evaporation:

$$E_p = \rho_a C_{DH} v_a [q_{0,sat} - q_a]$$

where ρ_a is the density of air and $q_{0,sat}$ is the saturated specific humidity at the surface. For the ground or snow surface $q_{0,sat}$ was calculated in subroutine TSOLVE. For the canopy, the saturated specific humidity at the canopy air temperature, $q_{ac,sat}$, is used. This is obtained from the mixing ratio at saturation, $w_{ac,sat}$:

$$q_{ac,sat} = w_{ac,sat}/[1 + w_{ac,sat}]$$

The mixing ratio is a function of the saturation vapour pressure $e_{ac,sat}$ at the canopy air temperature:

$$w_{ac,sat} = 0.622\ e_{ac,sat}/(p_{dry})$$

A standard empirical equation for the saturation vapour pressure dependence on the temperature T is used:

$$e_{sat} = 611.0 \exp[17.269(T - T_f)/(T - 35.86)] \qquad T \geq T_f$$
$$e_{sat} = 611.0 \exp[21.874(T - T_f)/(T - 7.66)] \qquad T < T_f$$

where T_f is the freezing point. At the end of the code dealing with the four subareas, several more diagnostic variables are evaluated. Again, these calculations are generally straightforward. The effective black-body surface temperature $T_{0,eff}$ is obtained by inverting the Stefan-Boltzmann equation:

$$L\uparrow = \sigma T_{0,eff}^{4}$$

where $L\uparrow$ is the outgoing longwave radiation and σ is the Stefan-Boltzmann constant. The evaporation efficiency parameter EVAPB is calculated as the ratio of the actual evapotranspiration to the potential evapotranspiration, and the effective surface humidity QG is obtained by inverting the evaporation equation.

TPREP

Purpose: Initialize subarea variables and calculate various parameters for surface energy budget calculations.

Output variables:

(Suffix CS = vegetation over snow cover; GS = bare snow cover; C or CO = vegetation over ground; G or GO = bare ground.)

ACOND	Diagnosed product of drag coefficient and wind speed over modelled area [m s^{-1}]
CDH	Surface drag coefficient for heat [ ]
CDM	Surface drag coefficient for momentum [ ]
CEVAP	Soil evaporation efficiency coefficient [ ] (β)
DRAG	Surface drag coefficient under neutral stability [ ]
EVAPC	Evaporation from vegetation over ground [m s^{-1}]
EVAPCS	Evaporation from vegetation over snow [m s^{-1}]
EVAPCG	Evaporation from ground under vegetation [m s^{-1}]
EVAPG	Evaporation from bare ground [m s^{-1}]
EVAPGS	Evaporation from snow on bare ground [m s^{-1}]
EVPCSG	Evaporation from snow under vegetation [m s^{-1}]
EVPPOT	Diagnosed potential evapotranspiration [kg m^{-2} s^{-1}]
FLGG	Diagnosed net longwave radiation at soil surface [W m^{-2}]
FLGS	Diagnosed net longwave radiation at snow surface [W m^{-2}]
FLGV	Diagnosed net longwave radiation on vegetation canopy [W m^{-2}]
FSGG	Diagnosed net shortwave radiation at soil surface [W m^{-2}]
FSGS	Diagnosed net shortwave radiation at snow surface [W m^{-2}]
FSGV	Diagnosed net shortwave radiation on vegetation canopy [W m^{-2}]
GSNOWC	Heat flux at top of snow pack under canopy [W m^{-2}]
GSNOWG	Heat flux at top of snow pack over bare ground [W m^{-2}]
GZEROC/G, GZROCS/GS	Subarea heat flux at soil surface [W m^{-2}]
HBL	Height of the atmospheric boundary layer [m]
HBLX	Height of the atmospheric boundary layer over each subarea [m]
HCPC	Heat capacity of soil layers under vegetation [J m^{-3} K^{-1}] (C_g)
HCPG	Heat capacity of soil layers in bare areas [J m^{-3} K^{1}] (C_g)
HCPSCS	Heat capacity of snow pack under vegetation canopy [J m^{-3} K^{1}] (C_s)
HCPSGS	Heat capacity of snow pack in bare areas [J m^{-3} K^{1}] (C_s)
HEVC	Diagnosed latent heat flux on vegetation canopy [W m^{-2}]
HEVG	Diagnosed latent heat flux at soil surface [W m^{-2}]
HEVS	Diagnosed latent heat flux at snow surface [W m^{-2}]
HFSC	Diagnosed sensible heat flux on vegetation canopy [W m^{-2}]
HFSG	Diagnosed sensible heat flux at soil surface [W m^{-2}]
HFSS	Diagnosed sensible heat flux at snow surface [W m^{-2}]

HMFC	Diagnosed energy associated with phase change of water on vegetation [W m^{-2}]
HMFN	Diagnosed energy associated with phase change of water in snow pack [W m^{-2}]
IEVAP	Flag indicating whether soil evaporation is occurring or not
ILMO	Inverse of Monin-Obukhov roughness length [m^{-1}]
ILMOX	Inverse of Monin-Obukhov roughness length over each subarea [m^{-1}]
QACCO	Specific humidity of air within vegetation canopy space over bare ground [kg kg^{-1}]
QACCS	Specific humidity of air within vegetation canopy space over snow [kg kg^{-1}]
QEVAP	Diagnosed total surface latent heat flux over modelled area [W m^{-2}]
QEVAPC	Latent heat flux from vegetation canopy over subarea [W m^{-2}]
QEVAPG	Latent heat flux from ground over subarea [W m^{-2}]
QLWAVG	Upwelling longwave radiation over modelled area [W m^{-2}]
QMELTC	Heat to be used for melting snow under canopy [W m^{-2}]
QMELTG	Heat to be used for melting snow on bare ground [W m^{-2}]
QSENS	Diagnosed total surface sensible heat flux over modelled area [W m^{-2}]
QSENSC	Sensible heat flux from vegetation canopy over subarea [W m^{-2}]
QSENSG	Sensible heat flux from ground over subarea [W m^{-2}]
RHOSCS	Density of snow pack under vegetation canopy [kg m^{-3}]
RHOSGS	Density of snow pack in bare areas [kg m^{-3}]
SQ	Diagnosed screen-level specific humidity [kg kg^{-1}]
ST	Diagnosed screen-level air temperature [K]
SU	Diagnosed anemometer-level zonal wind [m s^{-1}]
SV	Diagnosed anemometer-level meridional wind [m s^{-1}]
TACCO	Temperature of air within vegetation canopy space over bare ground [K]
TACCS	Temperature of air within vegetation canopy space over snow [K]
TBAR1P	Lumped temperature of ponded water and first soil layer [K]
TBARC/G/CS/GS	Subarea temperatures of soil layers [C]
TCBOTC	Thermal conductivity of soil at bottom of layer in canopy-covered subareas [W m^{-1} K^{-1}] (λ)
TCBOTG	Thermal conductivity of soil at bottom of layer in bare ground subareas [W m^{-1} K^{-1}] (λ)
TCANO	Temperature of canopy over ground [K]
TCANS	Temperature of canopy over snow [K]
TCSNOW	Thermal conductivity of snow [W m^{-1} K^{-1}]
TCTOPC	Thermal conductivity of soil at top of layer in canopy-covered subareas [W m^{-1} K^{-1}] (λ)
TCTOPG	Thermal conductivity of soil at top of layer in bare ground subareas [W m^{-1} K^{-1}] (λ)
THICEC	Frozen water content of soil layers under vegetation [m^3 m^{-3}]
THICEG	Frozen water content of soil layers in bare areas [m^3 m^{-3}]
THLIQC	Liquid water content of soil layers under vegetation [m^3 m^{-3}]
THLIQG	Liquid water content of soil layers in bare areas [m^3 m^{-3}]
TPONDC/G, TPNDCS/GS	Subarea temperature of surface ponded water [C]
TSNOCS	Temperature of snow pack under vegetation canopy [K]

TSNOGS	Temperature of snow pack in bare areas [K]
TSURF	Average ground/snow surface temperature over modelled area [K]
UE	Friction velocity of air [m s^{-1}]
UEX	Friction velocity of air over each subarea [m s^{-1}]
WSNOCS	Liquid water content of snow pack under vegetation [kg m^{-2}]
WSNOGS	Liquid water content of snow pack in bare areas [kg m^{-2}]
WTABLE	Depth of water table in soil [m] (z_{wt})
ZERO	Dummy vector containing all zeros

Input variables:

DELZ	Overall thickness of soil layer [m]
DELZW	Permeable thickness of soil layer [m] (Δz_w)
FC	Fractional coverage of canopy over bare ground for modelled area [ ]
FCS	Fractional coverage of canopy over snow for modelled area [ ]
HCPS	Heat capacity of soil material [J m^{-3} K^{-1}] (C_m)
ISAND	Sand content flag
RHOSNO	Density of snow [kg m^{-3}] (ρ_s)
TA	Air temperature at reference height [K]
TBAR	Temperature of soil layers [K]
TCAN	Vegetation canopy temperature [K]
TCS	Thermal conductivity of soil particles [W m^{-1} K^{-1}] (λ_s)
THFC	Field capacity [m^3 m^{-3}] (θ_{fc})
THICE	Volumetric frozen water content of soil layers [m^3 m^{-3}] (θ_i)
THLIQ	Volumetric liquid water content of soil layers [m^3 m^{-3}] (θ_l)
THLMIN	Residual soil liquid water content remaining after freezing or evaporation [m^3 m^{-3}]
THLRET	Liquid water retention capacity for organic soil [m^3 m^{-3}] (θ_{ret})
THPOR	Pore volume in soil layer [m^3 m^{-3}] (θ_p)
TPOND	Temperature of ponded water [K]
TSNOW	Snowpack temperature [K]
WSNOW	Liquid water content of snow pack [kg m^{-2}] (w_s)
ZBOTW	Depth to permeable bottom of soil layer [m] ($z_{b,w}$)
ZPOND	Depth of ponded water on surface [m]
ZSNOW	Depth of snow pack [m] (z_s)

In the first two loops, various subarea arrays and internal CLASST variables are initialized. The initial temperatures of the vegetation canopy above snow and above bare ground (TCANS and TCANO) are set to the temperature of the vegetation over the whole modelled area (TCAN) if TCAN is not effectively 0 K (the value it is assigned if vegetation is not present). Otherwise, the canopy temperatures are initialized to the air temperature TA.

In loop 200 the soil surface evaporation flag IEVAP and the evaporation efficiency coefficient CEVAP are assigned. If the liquid water content of the first soil layer is effectively equal to the minimum water content THLMIN, IEVAP and CEVAP are set to zero. If the liquid water content of the first soil layer is greater than the field capacity THFC, IEVAP and CEVAP are set to unity. Otherwise, IEVAP is set to 1 and CEVAP (or β as it is typically symbolized in the literature) is calculated using a relation presented by Lee and Pielke 1992:

$$\beta = 0.25\ [1 - \cos(\theta_l \pi / \theta_{fc})]^2$$

where θ_l is the liquid water content of the first soil layer and θ_{fc} is its field capacity.

In loop 300 the volumetric heat capacities C_g of the soil layers under a bare surface (HCPG) and under vegetation (HCPC) are calculated, from their respective liquid and frozen water contents θ_l and θ_i:

$$C_g = C_w \theta_l + C_i \theta_i + C_m (1 - \theta_p)$$

where C_m is the heat capacity of the soil matter and θ_p is the pore volume. (The heat capacity of air is neglected.)

In loop 400, the thermal properties of the snow pack under the vegetation canopy and over bare soil are assigned on the basis of the properties of the snow pack over the whole modelled area. The heat capacity of the snow pack C_s is calculated from the volume fractions of snow particles and liquid water in the pack. The former is obtained from the ratio of the densities of the snow pack and ice, and the latter from the ratio of the liquid water content, normalized by the snow depth, and the density of water:

$$C_s = C_i [\rho_s / \rho_i] + C_w w_s / [\rho_w\ z_s]$$

The thermal conductivity of snow λ_s is obtained from the snow density using an empirical relationship derived by Mellor (1977):

$$\lambda_s = 2.576 \times 10^{-6} \rho_s^{\ 2} + 0.074$$

In loop 500, the thermal conductivities of the soil layers are assigned. If the ISAND flag for the first soil layer is -4 (indicating glacier or ice sheet), or if the ISAND flag is -3 (indicating rock), then literature values for glacier ice or sand particles respectively are assigned. If the ISAND flag is equal to -2, indicating organic soil, the depth of the water table z_{wt} is first calculated. This is taken to lie within the first layer, counting from the bottom of the soil profile, in which the soil water content is larger than the retention capacity θ_{ret}. The water table depth is deduced by assuming that the soil is saturated below the water table, and that the water content is at the retention capacity above it. Thus, if $\theta_l + \theta_i = \theta_p$ for the soil layer, the water table is located at the top of the soil layer; if $\theta_l + \theta_i = \theta_{ret}$, it is located at the permeable bottom of the soil layer; and if $\theta_l + \theta_i$ is between these two values, its location is given by:

$$z_{wt} = z_{b,w} - \Delta z_w [(\theta_l + \theta_i - \theta_{ret}) / (\theta_p - \theta_{ret})]$$

where Δz_w is the permeable thickness of the soil layer.

The thermal conductivities of organic and mineral soils are calculated following the analysis of Côté and Konrad (2005). They model the soil thermal conductivity λ using the concept of a relative thermal conductivity λ_r which has a value of 0 for dry soils and 1 at saturation:

$$\lambda = [\lambda_{sat} - \lambda_{dry}]\lambda_r + \lambda_{dry}$$

The relative thermal conductivity is obtained from the degree of saturation (the water content divided by the pore volume) S_r, using the following generalized relationship:

$$\lambda_r = \varkappa S_r/[1 + (\varkappa-1)S_r]$$

The empirical coefficient $\varkappa$ takes the following values:

Unfrozen coarse mineral soils:	$\varkappa = 4.0$
Frozen coarse mineral soils:	$\varkappa = 1.2$
Unfrozen fine mineral soils:	$\varkappa = 1.9$
Frozen fine mineral soils:	$\varkappa = 0.85$
Unfrozen organic soils:	$\varkappa = 0.6$
Frozen organic soils:	$\varkappa = 0.25$

The dry thermal conductivity λ_{dry} is calculated using an empirical relationship based on the pore volume θ_p, with different coefficients for mineral and organic soils:

$$\lambda_{dry} = 0.75 \exp(-2.76\,\theta_p) \qquad \text{(mineral)}$$
$$\lambda_{dry} = 0.30 \exp(-2.0\,\theta_p) \qquad \text{(organic)}$$

The saturated thermal conductivity λ_{sat} is calculated by Côté and Konrad as a geometric mean of the conductivities of the soil components. However, other researchers (e.g. Zhang et al., 2008) have found the linear averaging used by de Vries (1963) to be more generally accurate:

$$\lambda_{sat} = \lambda_w\theta_p + \lambda_s(1 - \theta_p) \qquad \text{(unfrozen)}$$
$$\lambda_{sat} = \lambda_i\theta_p + \lambda_s(1 - \theta_p) \qquad \text{(frozen)}$$

where λ_w is the thermal conductivity of water, λ_i is that of ice and λ_s is that of the soil particles.

In the 500 loop, thermal conductivities are calculated for the top and bottom of each soil layer. The degree of saturation SATRAT is calculated as the sum of liquid and frozen water contents, θ_w and θ_i, divided by the pore volume. In organic soils, if the liquid water content of the soil layer is above the retention capacity θ_{ret}, θ_w at the top of the soil layer is assumed to be equal to θ_{re} and S_r at the bottom of the layer is assumed to be 1. The relative liquid and frozen water contents, THLSAT and THISAT, are calculated from θ_w and θ_i normalized by $\theta_w + \theta_i$. The dry thermal conductivity, and the saturated thermal conductivity for unfrozen and frozen conditions, are evaluated using the equations above. The unfrozen and frozen relative thermal conductivity, TCRATU and TCRATF, are obtained from SATRAT and the appropriate values of the empirical coefficient $\varkappa$. For mineral soils, $\varkappa$ is obtained as a weighted average over the percent sand content (ISAND converted to a real value) and the percentage of fine material (assumed to be 100-ISAND). The unfrozen and frozen soil thermal conductivities, TCSOLU and TCSOLF, are then calculated from TCRATU, TCRATF, and the dry and saturated thermal conductivities; and the actual thermal conductivity of the soil, TCSOIL, is determined as the average of TCSOLU and TCSOLF, weighted according to the relative liquid and frozen water contents THLSAT and THISAT. If the permeable thickness of the layer, DELZW, is greater than zero, the thermal conductivity at the top of the layer is set to TCSOIL; otherwise it is set to the rock value, TCSAND. If DELZW is less than the thermal thickness of the layer DELZ, the thermal conductivity at the bottom of the layer is set to TCSAND; otherwise it is set to TCSOIL. (In the case of organic soils in the latter branch, if θ_w was greater than θ_{ret}, the thermal conductivity at the bottom of the layer is set to the average of the saturated unfrozen and frozen values, weighted by THLSAT and THISAT.) Finally, if there is ponded water present on the soil surface, the thermal conductivity at the top of the first soil layer is treated as varying linearly from the calculated soil thermal conductivity if the pond depth ZPOND is zero, to the thermal conductivity of water if ZPOND $\geq 10^{-2}$ m.

Finally, in loop 600, a variable TBAR1P is evaluated, representing the weighted average value of the first layer soil temperature and the ponded water, if any. (The heat capacity of the soil is determined as the weighted average of HCPG over the permeable thickness DELZW, and the heat capacity of rock, HCPSND, over the impermeable thickness, DELZ-DELZW.)

CWCALC

Purpose: Check for freezing or thawing of liquid or frozen water on the vegetation canopy, and adjust canopy temperature and intercepted water stores accordingly.

Input/Output variables:

CHCAP	Heat capacity of vegetation canopy [J m^{-2} K^{-1}] (C_c)
CMASS	Mass of vegetation canopy [kg m^{-2}]
FI	Fractional coverage of subarea in question on modelled area [ ] (X_i)
FRAINC	Fractional coverage of canopy by liquid water [ ]
FSNOWC	Fractional coverage of canopy by frozen water [ ]
HMFC	Energy associated with freezing or thawing of water in canopy interception stores [W m^{-2}]
HTCC	Internal energy change of canopy due to changes in temperature and/or mass [W m^{-2}] (I_c)
RAICAN	Intercepted liquid water stored on the canopy [kg m^{-2}]
SNOCAN	Intercepted frozen water stored on the canopy [kg m^{-2}]
TCAN	Temperature of vegetation canopy [K] (T_c)

The change of internal energy I_c of the vegetation canopy as a result of the phase change processes treated here is calculated as the difference in I_c between the beginning and end of the subroutine:

$$\Delta I_c = X_i \Delta[C_c T_c]/\Delta t$$

where C_c represents the volumetric heat capacity of the canopy, T_c its temperature, Δt the length of the time step, and X_i the fractional coverage of the subarea under consideration relative to the modelled area.

If there is liquid water stored on the canopy and the canopy temperature is less than 0 C, the available energy sink HFREZ is calculated from CHCAP and the difference between TCAN and 0 C, and compared with HCONV, calculated as the energy sink required to freeze all of the liquid water on the canopy. If HFREZ ≤ HCONV, the amount of water that can be frozen is calculated using the latent heat of melting. The fractional coverages of frozen and liquid water FSNOWC and FRAINC and their masses SNOCAN and RAICAN are adjusted accordingly, TCAN is set to 0 C, and the amount of energy involved is subtracted from the internal energy HTCC and added to HMFC. Otherwise all of the intercepted liquid water is converted to frozen water, and the energy available for cooling the canopy is calculated as HCOOL = HFREZ – HCONV. This available energy is applied to decreasing the temperature of the canopy, using the specific heat of the canopy elements, and the amount of energy that was involved in the phase change is subtracted from HTCC and added to HMFC.

If there is frozen water stored on the canopy and the canopy temperature is greater than 0 C, the available energy for melting, HMELT, is calculated from CHCAP and the difference between TCAN and 0 C, and compared with HCONV, calculated as the energy required to melt all of the frozen water on the canopy.

If HMELT ≤ HCONV, the amount of frozen water that can be melted is calculated using the latent heat of melting. The fractional coverages of frozen and liquid water FSNOWC and FRAINC and their masses SNOCAN and RAICAN are adjusted accordingly, TCAN is set to 0 C, and the amount of energy involved is subtracted from HTCC and added to HMFC. Otherwise, all of the intercepted frozen water is converted to liquid water, and the energy available for warming the canopy is calculated as HWARM = HMELT – HCONV. This available energy is applied to increasing the temperature of the canopy, using the specific heats of the canopy elements, and the amount of energy that was involved in the phase change is subtracted from HTCC and added to HMFC.

In the final cleanup, the canopy heat capacity is recomputed and the remaining internal energy calculations are completed.

TNPREP

Purpose: Calculate coefficients for solution of heat conduction into soil.

Input/output variables:

A1, A2, B1, B3, C2	Work arrays used in calculation of GCONST and GCOEFF
CPHCHG	Latent heat of sublimation [J kg^{-1}]
DELZ	Overall thickness of soil layer [m] (Δz)
FI	Fractional coverage of subarea in question on modelled area [ ]
GCOEFF	Multiplier used in equation relating ground surface heat flux to surface temperature [W m^{-2} K^{-1}]
GCONST	Intercept used in equation relating ground surface heat flux to surface temperature [W m^{-2}]
GDENOM	Work array used in calculation of GCONST and GCOEFF
ISAND	Sand content flag
IWATER	Flag indicating condition of surface (dry, water-covered or snow-covered)
TBAR	Temperatures of soil layers, averaged over modelled area [K]
TBAR1P	Lumped temperature of ponded water and first soil layer [K]
TCBOT	Thermal conductivity of soil at bottom of layer [W m^{-1} K^{-1}] (λ_b)
TCSNOW	Thermal conductivity of snow [W m^{-1} K^{-1}]
TCTOP	Thermal conductivity of soil at top of layer [W m^{-1} K^{-1}] (λ_t)
ZPOND	Depth of ponded water on surface [m]
ZSNOW	Depth of snow pack [m]

In this subroutine, coefficients are derived for an equation relating the heat flux at the ground surface to the ground surface temperature, using the average temperatures and the thermal conductivities of the underlying first three soil layers. It is assumed that the variation of temperature T with depth z within each soil layer can be modelled by using a quadratic equation:

$$T(z) = \frac{1}{2} a z^2 + bz + c$$

By substituting 0 for z in the above equation and in the expressions for its first and second derivatives, it can be shown that $a = T''(0)$, $b = T'(0)$, and $c = T(0)$. The term $T''(0)$ can be evaluated from the expression for the first derivative evaluated at the bottom of the soil layer, $T(\Delta z)$:

$$T''(0) = [T'(\Delta z) - T'(0)]/\Delta z$$

The temperature gradient $T'(0)$ at the top of each layer is related to the heat flux $G(0)$ through the thermal conductivity λ_t; and the temperature gradient and heat flux at the bottom of the layer, $G(\Delta z)$ and $T(\Delta z)$, are similarly related through the bottom thermal conductivity λ_b:

$$G(0) = -\lambda_t T'(0)$$
$$G(\Delta z) = -\lambda_b T'(\Delta z)$$

The average soil layer temperature, $T_{av}(\Delta z)$, can be obtained by integrating the resulting equation for $T(z)$ between 0 and Δz. Making use of all of the above expressions, recognizing that the heat fluxes and temperatures at the bottoms of layers 1 and 2 must equal the heat fluxes and temperatures at the tops of layers 2 and 3 respectively, and neglecting as a first approximation the heat flux at the bottom of the third layer, a linear equation can be derived relating $G(0)$ to $T(0)$ at the soil surface, where the slope and intercept of the equation are functions only of the average temperatures, thicknesses, and top and bottom thermal conductivities of the three soil layers.

In the subroutine loop, first the depth corresponding to TBAR1P (the lumped temperature of the first soil layer and the ponded water) is calculated, as the sum of the first soil layer thickness and the ponded water depth. If the ponded water depth is not vanishingly small, the surface water flag IWATER is set to 1; otherwise it is set to 0 for soils and 2 for ice sheets (indicated by ISAND = -4). If IWATER = 2, indicating a frozen water surface, the latent heat of vaporization, CPHCHG, is set to the value for sublimation (by adding the latent heat of melting to the latent heat of vaporization). If there is a snow pack present, the thermal conductivity at the top of the ground surface is calculated as the harmonic mean of the thermal conductivity at the top of the first soil layer and that of the snow pack. Finally, a series of work arrays is evaluated and is used to calculate the slope and intercept, GCOEFF and GCONST, of the equation relating $G(0)$ to $T(0)$ at the ground surface.

TSPREP

Purpose: Calculate coefficients for solution of snow pack heat conduction.

Input/output variables:

CPHCHG	Latent heat of sublimation [J kg^{-1}]
FI	Fractional coverage of subarea in question on modelled area [ ]
GCOEFFS	Multiplier used in equation relating snow surface heat flux to snow surface temperature [W m^{-2} K^{-1}]
GCONSTS	Intercept used in equation relating snow surface heat flux to snow surface temperature [W m^{-2}]
IWATER	Flag indicating condition of surface (dry, water-covered or snow-covered
TCSNOW	Thermal conductivity of snow [W m^{-1} K^{-1}]
TSNOW	Snowpack temperature [K] ($T_s(\Delta z_s)$)
ZSNOW	Depth of snow pack [m] (Δz_s)

In this subroutine, coefficients are derived for an equation relating the heat flux at the snow surface to the snow surface temperature. It is assumed that the variation of temperature T with depth z in the snow pack can be modelled by using a quadratic equation:

$$T(z) = \tfrac{1}{2} az^2 + bz + c$$

By substituting 0 for z in the above equation and in the expressions for its first and second derivatives, it can be shown that $a = T''(0)$, $b = T'(0)$, and $c = T(0)$. The term $T''(0)$ can be evaluated from the expression for the first derivative evaluated at the bottom of the snow pack, $T(\Delta z_s)$:

$$T''(0) = [T'(\Delta z_s) - T'(0)]/\Delta z_s$$

The temperature gradient $T'(0)$ at the snow surface is related to the surface heat flux $G(0)$ by the snow thermal conductivity λ_s:

$$G(0) = -\lambda_s T'(0)$$

The average snow temperature, $T_s(\Delta z_s)$, can be obtained by integrating the resulting equation for $T(z)$ between 0 and Δz_s. Making use of all of the above expressions, and assuming as a first approximation that the heat flux at the bottom of the snow pack is zero, a linear equation can be derived relating $G(0)$ to $T(0)$:

$$G(0) = 3\lambda_s/\Delta z_s\ [T(0) - T_s(\Delta z_s)]$$

Just four calculations are performed in this subroutine. The slope and intercept of the G(0) vs. T(0) relation, GCOEFF and GCONST, are evaluated as $3\lambda_s/\Delta z_s$ and $-3\lambda_s T_s(\Delta z_s)/\Delta z_s$ respectively; the flag IWATER is set to 2, indicating a snow surface; and the latent heat of vaporization at the surface, CPHCHG, is set to the value for sublimation (by adding the latent heat of melting to the latent heat of vaporization).

TSOLVC

Purpose: Solution of surface energy balance for vegetated subareas.

Output variables:

CDH	Surface drag coefficient for heat [ ]
CDM	Surface drag coefficient for momentum [ ]
CFLUX	Product of surface drag coefficient and wind speed [$m\ s^{-1}$]
EVAPC	Evaporation rate from vegetation [$kg\ m^{-2}\ s^{-1}$] (E_c)
EVAPG	Evaporation rate from underlying surface [$kg\ m^{-2}\ s^{-1}$] ($E(0)$)
FTEMP	Product of surface-air temperature gradient, drag coefficient and wind speed [$K\ m\ s^{-1}$]
FVAP	Product of surface-air humidity gradient, drag coefficient and wind speed [$kg\ kg^{-1}\ m\ s^{-1}$]
GZERO	Heat flux into surface [$W\ m^{-2}$] ($G(0)$)
H	Height of the atmospheric boundary layer [m]
HTCC	Internal energy change of canopy due to changes in temperature and/or mass [$W\ m^{-2}$]
ILMO	Inverse of Monin-Obukhov roughness length (m^{-1}]
ITERCT	Counter of number of iterations required to solve energy balancefor four subareas
QCAN	Saturated specific humidity at canopy temperature [$kg\ kg^{-1}$] (q_c)
QAC	Specific humidity of air within vegetation canopy space [$kg\ kg^{-1}$] (q_{ac})
QEVAP	Latent heat flux from canopy and underlying surface [$W\ m^{-2}$] (Q_E)
QEVAPC	Latent heat flux from vegetation canopy [$W\ m^{-2}$] ($Q_{E,c}$)
QEVAPG	Latent heat flux from underlying surface [$W\ m^{-2}$] ($Q_{E,g}$)
QFCF	Sublimation from frozen water on vegetation [$kg\ m^{-2}\ s^{-1}$]
QFCL	Evaporation from liquid water on vegetation [$kg\ m^{-2}\ s^{-1}$]
QLWOC	Upwelling longwave radiation from vegetation canopy [$W\ m^{-2}$] ($L\uparrow_c$, $L\downarrow_c$)
QLWOG	Upwelling longwave radiation from underlying surface [$W\ m^{-2}$] ($L\uparrow_g$)
QLWOUT	Upwelling longwave radiation from canopy and underlying surface [$W\ m^{-2}$]
QMELTC	Heat available for melting snow or freezing water on the vegetation [$W\ m^{-2}$]
QMELTG	Heat available for melting snow or freezing water on the underlying surface [$W\ m^{-2}$]
QSENS	Sensible heat flux from canopy and underlying surface [$W\ m^{-2}$] (Q_H)
QSENSC	Sensible heat flux from vegetation canopy [$W\ m^{-2}$] ($Q_{H,c}$)
QSENSG	Sensible heat flux from underlying surface [$W\ m^{-2}$] ($Q_{H,g}$)
QSWNC	Net shortwave radiation on vegetation canopy [$W\ m^{-2}$] (K_{*c})
QSWNG	Net shortwave radiation at underlying surface [$W\ m^{-2}$] (K_{*g})
QSWNET	Total net shortwave radiation of canopy and underlying surface [$W\ m^{-2}$]
QTRANS	Shortwave radiation transmitted into surface [$W\ m^{-2}$]
QZERO	Specific humidity at surface [$kg\ kg^{-1}$] ($q(0)$)
RAICAN	Intercepted liquid water stored on vegetation canopy [$kg\ m^{-2}$]
RIB	Bulk Richardson number at surface [ ]

SNOCAN	Intercepted frozen water stored on vegetation canopy [kg m^{-2}]
TAC	Temperature of air within vegetation canopy [K] (T_{ac})
TCAN	Vegetation canopy temperature [K] (T_c)
TZERO	Temperature at surface [K] (T(0))
UE	Friction velocity of air [m s^{-1}]

Input variables:

ALNIRC	Near-IR albedo of vegetation canopy [ ] (α_c)
ALVISC	Visible albedo of vegetation canopy [ ] (α_c)
ALNIRG	Near-IR albedo of underlying surface [ ] (α_g)
ALVISG	Visible albedo of underlying surface [ ] (α_g)
CEVAP	Soil evaporation efficiency coefficient [ ]
CHCAP	Heat capacity of vegetation canopy [J m^{-2} K^{-1}] (C_c)
CMASS	Mass of vegetation canopy [kg m^{-2}]
CPHCHC	Latent heat of vaporization on vegetation canopy [J kg^{-1}] (L_v)
CPHCHG	Latent heat of vaporization on underlying ground [J kg^{-1}] (L_v)
CRIB	Richardson number coefficient [K^{-1}]
FCOR	Coriolis parameter [s^{-1}]
FI	Fractional coverage of subarea in question on modelled area [ ]
FRAINC	Fractional coverage of canopy by liquid water [ ] (F_l)
FSNOWC	Fractional coverage of canopy by frozen water [ ] (F_s)
FSVF	Sky view factor of ground underlying canopy [ ] (χ)
GCOEFF	Multiplier used in equation relating surface heat flux to surface temperature [W m^{-2} K^{-1}]
GCONST	Intercept used in equation relating surface heat flux to surface temperature [W m^{-2}]
IEVAP	Flag indicating whether surface evaporation is occurring or not
ISNOW	Flag indicating presence or absence of snow
IWATER	Flag indicating condition of surface (dry, water-covered or snow-covered)
PADRY	Partial pressure of dry air [Pa] (p_{dry})
PCPR	Surface precipitation rate [kg m^{-2} s^{-1}]
QA	Specific humidity at reference height [kg kg^{-1}] (q_a)
QLWIN	Downwelling longwave radiation at bottom of atmosphere [W m^{-2}] ($L\downarrow$)
QSWINI	Near-infrared radiation incident on horizontal surface [W m^{-2}] ($K\downarrow$)
QSWINV	Visible radiation incident on horizontal surface [W m^{-2}] ($K\downarrow$)
RBCOEF	Parameter for calculation of leaf boundary resistance
RC	Stomatal resistance of vegetation [s m-1] (r_c)
RHOAIR	Density of air [kg m^{-3}] (ρ_a)
TADP	Dew point of air at reference height [K]
TGND	Starting point for surface temperature iteration [K]
TPOTA	Potential temperature of air at reference height [K] ($T_{a,pot}$)
TRNIRC	Near-IR transmissivity of vegetation canopy [ ] (τ_c)
TRSNOW	Short-wave transmissivity of snow pack [ ]
TRVISC	Visible transmissivity of vegetation canopy [ ] (τ_c)
TVIRTA	Virtual potential temperature of air at reference height [K] ($T_{a,v}$)

VA	Wind speed at reference height [m s^{-1}]
VAC	Wind speed within vegetation canopy space [m s^{-1}] (v_{ac})
ZOH	Surface roughness length for heat [m]
ZOM	Surface roughness length for momentum [m] ($z_{0,m}$)
ZOSCLH	Ratio of roughness length for heat to reference height for temperature and humidity [ ]
ZOSCLM	Ratio of roughness length for momentum to reference height for wind speed [ ]
ZRSLFH	Difference between reference height for temperature and humidity and height at which extrapolated wind speed goes to zero [m]
ZRSLFM	Difference between reference height for wind speed and height at which extrapolated wind speed goes to zero [m]

For the subcanopy surface temperature iteration, two alternative schemes are offered: the bisection method (selected if the flag ITCG = 1) and the Newton-Raphson method (selected if ITCG = 2). In the first case, the maximum number of iterations ITERMX is set to 12, and in the second case it is set to 5. An optional windless transfer coefficient EZERO is made available, which can be used, following the recommendations of Brown et al. (2006), to prevent the sensible heat flux over snow packs from becoming vanishingly small under highly stable conditions. If the snow cover flag ISNOW is zero (indicating bare ground), EZERO is set to zero; if ISNOW=1, EZERO is set to 2.0 W m^{-2} K^{-1}. The surface transfer coefficient under conditions of free convection, RAGCO, is set to 1.9 x 10^{-3} (see the calculation of RAGINV below).

In the 50 loop, some preliminary calculations are done. The shortwave transmissivity at the surface, TRTOP, is set to zero in the absence of a snow pack, and to the transmissivity of snow, TRSNOW, otherwise. The net shortwave radiation at the surface, QSWNG, is calculated as the sum of the net visible and net near-infrared shortwave radiation. Each of these is obtained as:

$$K_{*g} = K\downarrow \tau_c [1 - \alpha_g]$$

where K_{*g} is the net radiation at the surface, $K\downarrow$ is the incoming shortwave radiation above the canopy, τ_c is the canopy transmissivity and α_g is the surface albedo. This average value is corrected for the amount of radiation transmitted into the surface, QTRANS, obtained using TRTOP. The net shortwave radiation for the vegetation canopy, QSWNC, is calculated as the sum of the net visible and net near-infrared shortwave radiation. Each of these is determined as:

$$K_{*c} = K\downarrow[1 - \alpha_c] - K_{*g}$$

where K_{*c} is the net radiation on the canopy and α_c is the canopy albedo. If the canopy temperature is essentially 0 K, indicating that a canopy was not present in the previous time step but has now appeared, the canopy temperature is initialized to the potential temperature of the air, TPOTA. The outgoing longwave radiation emitted upward ($L\uparrow_c$) or downward ($L\downarrow_c$) from the canopy is calculated using the standard Stefan-Boltzmann equation:

$$L\uparrow_c = L\downarrow_c = \sigma T_c^4$$

where σ is the Stefan-Boltzmann constant and T_c is the canopy temperature.

Virtual temperature is defined as temperature adjusted for the reduction in air density due to the presence of water vapour. This is applied in order to enable the use of the equation of state for dry air. The virtual temperature can be approximated by multiplying the actual temperature by a factor [1 + 0.61 q], where q is the specific humidity of the air in question. Thus, the virtual temperature of air at the vegetation canopy temperature, $T_{c,v}$, is obtained as:

$$T_{c,v} = T_c [1 + 0.61 q_c]$$

where q_c is the saturated specific humidity at the canopy temperature. This is determined from the saturation mixing ratio at the canopy temperature, w_c:

$$q_c = w_c/[1 + w_c]$$

The saturation mixing ratio is a function of the saturation vapour pressure e_c at the canopy temperature:

$$w_c = 0.622\, e_c/(p_{dry})$$

where p_{dry} is the partial pressure of dry air. A standard empirical equation for the saturation vapour pressure dependence on the temperature T is used:

$$e_{sat} = 611.0 \exp[17.269(T - T_f)/(T - 35.86)] \qquad T \geq T_f$$
$$e_{sat} = 611.0 \exp[21.874(T - T_f)/(T - 7.66)] \qquad T < T_f$$

where T_f is the freezing point. The virtual temperature of the air in the canopy space, $T_{ac,v}$, is likewise calculated from the canopy air temperature T_{ac} and the specific humidity in the canopy air space, q_{ac}, as

$$T_{ac,v} = T_{ac} [1 + 0.61 q_{ac}]$$

If the Newton-Raphson method is being used for the canopy temperature iteration (pre-selected by setting the flag ITC to 2), the temperature of the air in the canopy space is approximated as the canopy temperature, and the specific humidity in the canopy air space is approximated as the specific humidity of the air above the canopy.

If there is intercepted snow on the vegetation, the latent heat associated with water flux from the canopy, CPHCHC, is set to the latent heat of sublimation (the sum of the heat of vaporization and the heat of melting). Otherwise the latent heat is set to that of vaporization alone. The leaf boundary layer resistance RB, and its inverse RBINV, are calculated using the wind speed in the canopy air space, VAC, and a coefficient RBCOEF evaluated in subroutine APREP. This coefficient is formulated after Bartlett (2004), who developed an expression for the inverse of the leaf boundary resistance, $1/r_b$, drawing on the analysis of Bonan (1996) and McNaughton and van den Hurk (1995), of the form:

$$1/r_b = v_{ac}^{1/2}\, \Sigma\, f_i \gamma_i \Lambda_i^{1/2}/0.75\, [1 - \exp(-0.75\, \Lambda_i^{1/2})]$$

where v_{ac} is the wind speed in the canopy air space, f_i is the fractional coverage of each vegetation type i over the subarea in question, Λ_i is its leaf area index, and γ_i is a vegetation-dependent parameter which incorporates the effects of leaf dimension and sheltering. The initial value of the surface temperature TZERO is set to TGND, which contains the value of TZERO from the previous time step, and the initial temperature of the canopy, TCANO, is set to the current canopy temperature. The first step in the iteration sequence, TSTEP, is set to 1.0 K. The flag ITER is set to 1 for each element of the set of modelled areas, indicating that its surface temperature has not yet been found. The iteration counter NITER is initialized to 1 for each element. Initial values are assigned to other variables.

The 100 continuation line marks the beginning of the surface temperature iteration sequence. First the flag NUMIT (indicating whether there are still locations at the end of the current iteration step for which the surface temperature has not yet been found) is set to zero. Loop 125 is then performed over the vector of modelled areas. If ITER=1, the saturated specific humidity at the ground surface temperature, $q(0)_{sat}$, is calculated using the same method as that outlined above for the saturated specific humidity at the canopy temperature. If there is a snow cover or ponded water present on the surface (IWATER > 0), the surface evaporation efficiency EVBETA is set to 1 and the surface specific humidity q(0) is set to $q(0)_{sat}$. Otherwise EVBETA is set to CEVAP, the value obtained in subroutine TPREP on the basis of ambient conditions, and q(0) is calculated from $q(0)_{sat}$ by making use of the definition of the surface evaporation efficiency β:

$$\beta = [q(0) - q_{ac}]/[q(0)_{sat} - q_{ac}]$$

which is inverted to obtain an expression for q(0). If $q(0) > q_{ac}$ and the evaporation flag IEVAP has been set to zero, EVBETA is reset to zero and q(0) is reset to q_{ac}.

Next, the potential temperature of air at the ground surface temperature, $T(0)_{pot}$, is calculated relative to the sum of the displacement height d and the roughness length for momentum $z_{0,m}$, the height at which the canopy temperature is assumed to apply. (This is also the height corresponding to the potential temperature of the air at the reference height above the canopy). $T(0)_{pot}$ is found using the dry adiabatic lapse rate, $dT/dz = -g/c_p$, where g is the acceleration due to gravity and c_p is the specific heat at constant pressure. Since the displacement height d is assumed to lie at 0.7 of the canopy height, and the roughness length for momentum is assumed to lie at 0.1 of the canopy height, the displacement height can be calculated as 8.0 $z_{0,m}$. Thus,

$$T(0)_{pot} = T(0) - 8.0\, z_{0,m}\, g/c_p$$

The virtual potential temperature at the surface is obtained using the same expression as above:

$$T(0)_v = T(0)_{pot} [1 + 0.61\, q(0)]$$

Since wind speeds under the canopy are expected to be relatively small, it is assumed that under stable or neutral conditions, turbulent fluxes are negligible. If the virtual potential temperature of the surface is more than 1 K greater than that of the canopy air, free convection conditions are assumed. Townsend's (1964) equation for the surface-air transfer coefficient, or the inverse of the surface resistance $r_{a,,g}$, is used in a form derived from the analysis of Deardorff (1972):

$$1/r_{a,,g} = 1.9 \times 10^{-3} [T(0)_v - T_{ac,v}]^{1/3}$$

The first derivative of the transfer coefficient with respect to the surface temperature is calculated for use with the Newton-Raphson iteration scheme:

$$d(1/r_{a,,g})/dT = 1.9 \times 10^{-3} [T(0)_v - T_{ac,v}]^{-2/3}/3$$

If the virtual potential temperature of the surface is between 0.001 and 1 K greater than that of the canopy air, a simple diffusion relation is assumed:

$$1/r_{a,,g} = 1.9 \times 10^{-3} [T(0)_v - T_{ac,v}]$$

Thus,

$$d(1/r_{a,,g})/dT = 1.9 \times 10^{-3}$$

The remaining terms of the surface energy balance are now evaluated. The energy balance equation is expressed as:

$$K_{*g} + L_{*g} - Q_{H,g} - Q_{E,g} - G(0) = 0$$

where K_{*g} is the net surface shortwave radiation, L_{*g} is the net longwave radiation, $Q_{H,g}$ is the sensible heat flux, $Q_{E,g}$ is the latent heat flux, and G(0) is the conduction into the surface. K_{*g} was evaluated earlier in loop 50. L_{*g} is calculated as the difference between the downwelling radiation $L\downarrow_g$ at the surface and the upwelling radiation $L\uparrow_g$. The downwelling radiation incident on the surface is determined from the downwelling sky radiation above the canopy $L\downarrow$ and the downwelling radiation from the canopy itself, $L\downarrow_c$, weighted according to the sky view factor χ:

$$L\downarrow_g = \chi L\downarrow + [1 - \chi] L\downarrow_c$$

The upwelling radiation is obtained using the Stefan-Boltzmann equation:

$$L\uparrow_g = \sigma T(0)^4$$

The sensible heat flux is given by

$$Q_{H,g} = \varrho_a c_p [T(0)_{pot} - T_{a,c}]/r_{a,,g}$$

where ϱ_a is the density of the air and c_p is its specific heat. (The windless transfer coefficient defined at the beginning of the subroutine is currently not used under vegetation canopies.) The evaporation rate at the surface, E(0), is calculated as

$$E(0) = \varrho_a [q(0) - q_{a,c}]/r_{a,,g}$$

If precipitation is occurring, E(I) is set to zero. Q_E is obtained by multiplying E(0) by the latent heat of vaporization at the surface. The heat flux into the surface G(0) is determined as a linear function of T(0) (see documentation for subroutines TNPREP and TSPREP). It can be seen that each of the terms of the surface energy balance is a function of a single unknown, T(0) or TZERO. The residual RESID of the energy balance is now evaluated on the basis of the current estimation for TZERO. If the absolute value of RESID is less than 5.0 W m^{-2}, or if the absolute value of the iteration step TSTEP most recently used is less than 0.01 K, the surface temperature is deemed to have been found and ITER is set to 0. If the iteration counter NITER is equal to the maximum number and ITER is still 1, ITER is set to -1.

In the following section, the iteration sequence is moved ahead a step. If ITCG = 1, the calculations for the bisection method of solution in loop 150 are performed, over each of the modelled areas for which ITER = 1. If NITER = 1 (indicating that this is the first step in the iteration), then if RESID > 0 (indicating that the current value for TZERO had undershot the correct value), TZERO is incremented by 1 K; otherwise it is decremented by 1 K. If this is not the first step in the iteration, then if RESID >0 and TSTEP < 0 (indicating that TZERO has undershot the correct value and the last temperature increment had been a negative one) or if RESID < 0 and TSTEP > 0 (indicating that TZERO has overshot the correct value and the last temperature increment had been a positive one), TSTEP is divided in half and its sign changed. TSTEP is then added to TZERO. The iteration counter NITER and the flag NUMIT are each incremented by one. Finally, if NUMIT > 0, the iteration cycle is repeated from line 100 on.

If ITCG = 2, the calculations for the Newton-Raphson method of iteration in loop 175 are performed, over each of the modelled areas for which ITER = 1. In this approach, the value x_{n+1} used at each iteration step is obtained from the value x_n at the previous step as follows:

$$x_{n+1} = x_n - f(x_n)/f'(x_n)$$

Identifying x_n with TZERO and $f(x_n)$ with the surface energy balance equation, it can be seen that the second term on the right-hand side corresponds to TSTEP; the numerator is equal to RESID and the denominator to the first derivative of the energy balance equation evaluated at TZERO, which in turn is equal to the sum of the derivatives of the individual terms:

$$d(L\uparrow_g)/dT = -4\sigma T(0)^3$$

$$d(Q_{H,g})/dT = \rho_a c_p\{1/r_{a,,g} + [T(0)_{pot} - T_{ac}]\ d(1/r_{a,,g})/dT\}$$

$$d(Q_{E,g})/dT = L_v\rho_a\{1/r_{a,,g}\ dq(0)/dT + [q(0) - q_{ac}]\ d(1/r_{a,,g})/dT\}$$

and dG(0)/dT is equal to the coefficient multiplying TZERO in the equation for G(0). (L_v is the latent heat of vaporization at the surface.) At the end of the calculations the iteration counter NITER and the flag NUMIT are each incremented by one, and upon exiting the loop, if NUMIT > 0, the iteration cycle is repeated from line 100 on.

After the iteration has been completed, if the Newton-Raphson method has been used, a check is carried out in loop 200 to ascertain whether convergence has not been reached (i.e. whether ITER = -1) for any location. In such cases it is assumed that conditions of near-neutral stability at the surface are the cause of the difficulty in finding a solution. A trial value of TZERO is calculated using the virtual potential temperature of the canopy. If this temperature is within 5.0 K of the last guess, and if the absolute value of RESID is > 15 W m^{-2}, TZERO is set to this trial value. The values of q(0) and the components of the surface energy balance are recalculated as above, except that $Q_{H,g}$ and $Q_{E,g}$ are assumed as a first approximation to be zero. RESID is determined on this basis, and is then partitioned between $Q_{H,g}$ and

$Q_{E,g}$ on the basis of the Bowen ratio B, the ratio of $Q_{H,g}$ over $Q_{E,g}$. Setting the residual R equal to $Q_{H,g}$ + $Q_{E,g}$, and substituting for $Q_{H,g}$ using $B = Q_{H,g}/Q_{E,g}$, results in:

$$Q_{E,g} = R/(1 + B)$$

(If precipitation is occurring, $Q_{E,g}$ is set to zero.) $Q_{H,g}$ is then obtained as R – $Q_{E,g}$, the residual is reset to zero, and E(0) is recalculated from $Q_{E,g}$.

At this point a check is performed for unphysical values of the surface temperature, i.e. for values greater than 100 C or less than -100 C. If such values are encountered, an error message is printed and a call to abort is carried out.

Finally, clean-up calculations are performed in loop 250. A check is carried out to ensure that TZERO is not less than 0 C if ponded water is present on the surface (IWATER = 1) or greater than 0 C if snow is present on the surface (IWATER = 2). If either is the case, TZERO is reset to the freezing point, and q(0), $T(0)_{pot}$ and $T(0)_v$ are re-evaluated. The components of the surface energy balance are recalculated using the above equations. The residual of the energy balance equation is assigned to the energy associated with phase change of water at the surface, QMELTG, and RESID is set to zero.

In the last part of the loop, some final adjustments are made to a few other variables. If the evaporation flux is vanishingly small, it is added to RESID and reset to zero. If both RESID and $Q_{E,g}$ are not small, and if the precipitation rate is vanishingly small, RESID is added to $Q_{E,g}$; otherwise RESID is added to $Q_{H,g}$. Lastly, the iteration counter ITERCT is updated for the level corresponding to the subarea type and the value of NITER.

In the 300 loop, preliminary calculations are done in preparation for the canopy temperature iteration. The sensible heat flux from the surface is treated differently if ITC = 1 (bisection method of solution) and ITC = 2 (Newton-Raphson method of solution). In the first instance the surface sensible heat flux is applied to heating the air in the canopy space; in the second, the canopy and the air space within it are treated as one aggregated mass, and the sensible heat flux from below is assumed to be added to its energy balance. Thus, if ITC = 1, the sensible heat flux that is added to the canopy, QSGADD, is set to 0. If ITC = 2, it is set to $Q_{H,g}$; and T_{ac} is set to T_c, q_{ac} to q_c, and $T_{ac,v}$ to $T_{c,v}$. The flag ITER is set to 1 for each element of the set of modelled areas, indicating that its surface temperature has not yet been found. The iteration counter NITER is initialized to 1 for each element. The first step in the iteration sequence, TSTEP, is set to 1.0 K. Initial values are assigned to other variables. After exiting the loop, the maximum number of iterations ITERMX is set to 12 if ITC = 1, and to 5 if ITC = 2.

The 400 continuation line marks the beginning of the canopy temperature iteration sequence. First the flags NIT (indicating whether there are still locations at the beginning of the current iteration step for which the surface temperature has not yet been found) and NUMIT (indicating whether there are still locations at the end of the current iteration step for which the surface temperature has not yet been found) are set to zero. Loop 450 is then performed over the set of modelled areas. If ITER=1, NIT is incremented by one; if ITC = 1, the vegetation virtual temperature $T_{c,v}$ is recalculated.

If NIT > 0, a subroutine is called to evaluate the stability-corrected surface drag coefficients for heat and momentum. The subroutine selection is made on the basis of the flag ISLFD. If ISLFD=1, indicating that the calculations are to be consistent with CCCma conventions, subroutine DRCOEF is called; if

ISLFD=2, indicating that the calculations are to be consistent with RPN conventions, subroutine FLXSURFZ is called.

Next, canopy parameters and turbulent transfer coefficients are calculated prior to evaluating the terms of the surface energy balance equation. If ITC = 1, the analysis of Garratt (1992) is followed. The sensible and latent heat fluxes from the canopy air to the overlying atmosphere, Q_H and Q_E, are obtained as the sums of the sensible and latent heat fluxes from the canopy to the canopy air, $Q_{H,c}$ and $Q_{E,c}$, and from the underlying surface to the canopy air, $Q_{H,g}$ and $Q_{E,g}$:

$$Q_H = Q_{H,c} + Q_{H,g}$$
$$Q_E = Q_{E,c} + Q_{E,g}$$

where

$$Q_H = \rho_a c_p [T_{a,c} - T_{a,pot,}]/r_a$$
$$Q_{H,c} = \rho_a c_p [T_c - T_{a,c,}]/r_b$$

and

$$Q_E = L_v \rho_a [q_{a,c} - q_{a,}]/r_a$$
$$Q_{E,c} = L_v \rho_a [q_{,c} - q_{a,c,}]/(r_b + r_c)$$

The equations for the sensible and latent heat fluxes from the surface were presented above. In these expressions, $T_{a,pot}$ and q_a are the potential temperature and specific humidity of the air overlying the canopy, r_a is the aerodynamic resistance to turbulent transfer between the canopy air and the overlying air, and r_c is the stomatal resistance to transpiration. (The term CFLUX that is generated by the subroutines DRCOEF and FLXSURFZ is equivalent to $1/r_a$.) Thus, $T_{a,c}$ and $q_{a,c}$ can be evaluated as

$$T_{a,c} = [T_{a,pot}/r_a + T_c/r_b + T(0)_{pot}/r_{a,,g}]/[1/r_a + 1/r_b + 1/r_{a,,g}]$$
$$q_{a,c} = [q_a/r_a + q_c/(r_b + r_c) + q(0)/r_{a,,g}]/[1/r_a + 1/(r_b + r_c) + 1/r_{a,,g}]$$

If the water vapour flux is towards the canopy leaves, or if the canopy is snow-covered or rain-covered, r_c is zero. If the water vapour flux is away from the canopy leaves and the fractional snow or water coverage on the canopy, F_s or F_l, is less than 1, the term $1/(r_b + r_c)$ adjusted for the presence of intercepted snow or water, X_E (XEVAP in the code) is calculated as a weighted average, as follows. If $F_s > 0$, the canopy must be at a temperature of 0 C or less, and so it is deduced that no transpiration can be occurring. Thus,

$$X_E = (F_s + F_l)/r_b.$$

Otherwise, X_E is calculated on the assumption that the resistance is equal to r_b over the water-covered area and $r_b + r_c$ over the rest:

$$X_E = F_l/r_b + [1 - F_l]/[r_b + r_c]$$

In the 450 loop, XEVAP is first set as a trial value to RBINV (neglecting stomatal resistance), and QAC is calculated using this value. If $q_{a,c} < q_c$, indicating that the vapour flux is away from the canopy leaves, XEVAP is recalculated as above and QAC is re-evaluated. Otherwise, if $F_s > 0$, XEVAP is scaled by F_s, since it is assumed that snow on the canopy will be at a lower temperature than the canopy itself, and deposition via sublimation will occur preferentially onto it. $T_{a,c}$ and $T_{ac,v}$ are calculated as above, and the canopy-air turbulent transfer coefficients for sensible and latent heat flux, CFSENS and CFEVAP, are set to RBINV and XEVAP respectively.

If ITC = 2, the canopy parameters and turbulent transfer coefficients are calculated, as noted above, on the basis of the assumption that the vegetation canopy and the air space within it can be treated as one aggregated mass, with a single representative temperature. Thus, the resistances r_a and r_b are considered as acting in series upon the sensible and latent heat fluxes between the canopy and the overlying air:

$$Q_{H,c} = \rho_a c_p [T_{,c} - T_{a,pot,}]/(r_a + r_b)$$
$$Q_{E,c} = L_v \rho_a [q_{,c} - q_{a,}]/(r_a + r_b + r_c)$$

In loop 500 the term $1/(r_a + r_b)$ is calculated from the variables CFLUX (the inverse of r_a) and RBINV (the inverse of r_b), and assigned to the temporary variable CFLX. If the incoming visible shortwave radiation QSWINV is greater than or equal to 25 W m^{-2}, the calculated value of CFLX is retained; if QSWINV is zero, it is reset to CFLUX; and between these two limits it varies linearly between the two. Thus the effect of the calculated leaf boundary resistance is suppressed during conditions of zero or low solar heating. (This is done to avoid unrealistically low calculated turbulent fluxes at night, which can lead to anomalously low canopy temperatures.) The overall aerodynamic resistance $r_A = r_a + r_b$ is obtained as 1/CFLX and assigned to the variable RA. As with ITC = 1, if $q_a < q_c$, XEVAP is recalculated as above (except that r_A is substituted for r_b). If $F_s > 0$, XEVAP is again scaled by F_s.

In the approach used here, the specific humidity of the aggregated canopy $q_{0,c}$ is not assumed to be equal to the saturated specific humidity at the canopy temperature, but is rather determined using X_E. If the two methods of calculating $Q_{E,c}$ are assumed to be analogous:

$$Q_{E,c} = L_v \rho_a X_E [q_{,c} - q_{a,}]$$
$$Q_{E,c} = L_v \rho_a [q_{,0,c} - q_{a,}]/r_A$$

then solving for $q_{0,c}$ leads to the expression

$$q_{0,c} = r_A X_E q_c + [1 - r_A X_E] q_a$$

In the second part of the 500 loop the saturated specific humidity of the canopy is calculated as before and adjusted using the above equation to obtain the specific humidity of the aggregated canopy. This is then used to calculate $T_{c,v}$. The canopy-air turbulent transfer coefficients for sensible and latent heat flux, CFSENS and CFEVAP, are both set to CFLX, and for calculation purposes in the following loop $T_{a,c}$ is set to the potential temperature of the air above the canopy, and $q_{a,c}$ to the specific humidity of the air above the canopy.

In the 525 loop, the terms of the canopy energy balance are evaluated. The energy balance is expressed as:

$$K_{*c} + L_{*c} - Q_{H,c} + Q_{H,g+} - Q_{E,c} - \Delta Q_{S,c} = 0$$

(The term $Q_{H,g+}$ corresponds to the variable QSGADD discussed above; the term $\Delta Q_{S,c}$ represents the change of energy storage in the canopy.) The net shortwave radiation K_{*c} was evaluated earlier in the 50 loop. The net longwave radiation is obtained as:

$$L_{*c} = (1 - \chi)\ [L\downarrow + L\uparrow_g - 2\ L\downarrow_c]$$

$Q_{H,c}$ is calculated as above. If there is intercepted liquid or frozen water on the canopy, or if the vapour flux is downward, or if the stomatal resistance is less than a limiting high value of 5000 s m^{-1}, the canopy vapour flux E_c (that is, $Q_{E,c}/L_v$) is calculated as above and the flag IEVAPC is set to 1; otherwise, and also if precipitation is occurring, E_c and IEVAPC are both set to zero and q_c is set to q_a. If the water vapour flux is towards the canopy and the canopy temperature is greater than the air dew point temperature, the flux is set to zero. If there is intercepted water on the canopy, a limiting evaporation flux EVPWET is calculated as the rate required to sublimate all of the intercepted snow if $F_s > 0$, or all of the intercepted rain otherwise. If the canopy is more than half covered by intercepted water and the calculated canopy vapour flux is greater than EVPWET, it is reset to EVPWET and IEVAPC is set to zero. $Q_{E,c}$ is calculated from E_c and $\Delta Q_{S,c}$ is obtained as

$$\Delta Q_{S,c} = C_c\ [T_c - T_{c,o}]/\Delta t$$

where C_c is the canopy heat capacity, $T_{c,o}$ is the canopy temperature from the previous time step and Δt is the length of the time step. The residual RESID of the energy balance is evaluated on the basis of the current estimation for the canopy temperature TCAN. If the absolute value of RESID is less than 5.0 W m^{-2}, or if the absolute value of the iteration step TSTEP most recently used is less than 0.01 K, the surface temperature is deemed to have been found and ITER is set to 0. If the iteration counter NITER is equal to the maximum number and ITER is still 1, ITER is set to -1.

In the following section, the iteration sequence is moved ahead a step. If ITC = 1, the calculations for the bisection method of solution in loop 550 are performed, over each of the modelled areas for which ITER = 1. If NITER = 1 (indicating that this is the first step in the iteration), then if RESID > 0 (indicating that the current value for TCAN had undershot the correct value), TCAN is incremented by 1 K; otherwise it is decremented by 1 K. If this is not the first step in the iteration, then if RESID >0 and TSTEP < 0 (indicating that TCAN has undershot the correct value and the last temperature increment had been a negative one) or if RESID < 0 and TSTEP > 0 (indicating that TCAN has overshot the correct value and the last temperature increment had been a positive one), TSTEP is divided in half and its sign changed. TSTEP is then added to TCAN. If TCAN is vanishingly close to 0 C, it is reset to that value. The iteration counter NITER and the flag NUMIT are each incremented by one. Finally, if NUMIT > 0, the iteration cycle is repeated from line 400 on.

If ITC = 2, the calculations for the Newton-Raphson method of iteration in loop 575 are performed, over each of the modelled areas for which ITER = 1. As outlined above, in this approach the value x_{n+1} used at each iteration step is obtained from the value x_n at the previous step as follows:

$$x_{n+1} = x_n - f(x_n)/f'(x_n)$$

Identifying x_n with TCAN and $f(x_n)$ with the surface energy balance equation, it can be seen that the second term on the right-hand side corresponds to TSTEP; the numerator is equal to RESID and the denominator to the first derivative of the energy balance equation evaluated at TCAN, which in turn is equal to the sum of the derivatives of the individual terms:

$$d(L_{*c})/dT = -8\sigma T_c^3(1 - \chi)$$

$$d(Q_{H,c})/dT = \rho_a c_p\{1/r_A + [T_c - T_{a,pot}]\ d(1/r_A)/dT\}$$

$$d(Q_{E,c})/dT = L_v\rho_a\{X_E dq_c/dT + [q_c - q_a]\ dX_E/dT\}$$

$$d\Delta Q_{S,c}/dT = C_c/\Delta t$$

The term $d(1/r_A)/dT$ is represented by the variable DCFLXM, which is approximated as the difference between CFLX and its value for the previous iteration, CFLUXM, divided by TSTEP. The term dX_E/dT is represented by the variable DXEVAP, which is approximated as the difference between XEVAP and its value for the previous iteration, XEVAPM, divided by TSTEP. The calculated value of TSTEP obtained from the above calculations is constrained to be between -10 and 5 K to dampen any spurious oscillations, and is then added to TCAN. If the resulting value of TCAN is vanishingly close to 0 C, it is reset to that value. At the end of the calculations the iteration counter NITER and the flag NUMIT are each incremented by one. The values of $T_{a,c}$, $q_{a,c}$ and $T_{ac,v}$ are reset to T_c, q_c and $T_{c,v}$ respectively. Upon exiting the loop, if NUMIT > 0, the iteration cycle is repeated from line 400 on.

After the iteration has been completed, if the Newton-Raphson method has been used, a check is carried out in loop 600 to ascertain whether convergence has not been reached (i.e. whether ITER = -1) for any location. In such cases it is assumed that conditions of near-neutral stability at the surface are the cause of the difficulty in finding a solution. The flags NUMIT and IEVAPC are set to zero, and a trial value of TCAN is calculated using the virtual potential temperature of the air and the canopy specific humidity. If this temperature is within 5.0 K of the last guess, and if the absolute value of RESID is > 100 W m^{-2}, TCAN is set to this trial value. The values of $q_{0,c}$ and the components of the surface energy balance are recalculated as above, except that $Q_{H,c}$ and $Q_{E,c}$ are assumed as a first approximation to be zero. RESID is determined on this basis, and is then assigned to $Q_{H,c}$ and $Q_{E,c}$. If RESID > 0, $Q_{E,c}$ is set to this value; otherwise it is equally divided between $Q_{H,c}$ and $Q_{E,c}$. (If precipitation is occurring, $Q_{E,c}$ is set to zero.) The residual is then reset to zero, and E(0) and $T_{v,c}$ are recalculated. NUMIT is incremented by 1, and the flag IEVAPC for the current location is set to 1.

After loop 600, calls to DRCOEF or FLXSURFZ are performed to re-evaluate the surface turbulent transfer coefficients for any locations for which the fluxes were modified in the previous loop, i.e. for any locations for which IEVAPC was set to 1. After this a check is performed for unphysical values of the canopy temperature, i.e. for values greater than 100 C or less than -100 C. If such values are encountered, an error message is printed and a call to abort is carried out.

Next a check is carried out to determine whether freezing or melting of intercepted water has occurred over the current time step. If this is the case, adjustments are required to the canopy temperature, the intercepted liquid and frozen water amounts and fractional coverages, and to C_c and $\Delta Q_{S,c}$. In loop 650, if there is liquid water stored on the canopy and the canopy temperature is less than 0 C, the first half of the adjustment to $\Delta Q_{S,c}$ is performed, and the flags ITER and NIT are set to 1. The available energy sink HFREZ is calculated from CHCAP and the difference between TCAN and 0 C, and compared with HCONV, calculated as the energy sink required to freeze all of the liquid water on the canopy. If

HFREZ ≤ HCONV, the amount of water that can be frozen is calculated using the latent heat of melting. The fractional coverages of frozen and liquid water FSNOWC and FRAINC and their masses SNOCAN and RAICAN are adjusted accordingly, TCAN is set to 0 C, and the amount of energy involved is stored in the diagnostic variable QMELTC. Otherwise all of the intercepted liquid water is converted to frozen water, and the energy available for cooling the canopy is calculated as HCOOL = HFREZ – HCONV. This available energy is applied to decreasing the temperature of the canopy, using the specific heat of the canopy elements, and the amount of energy that was involved in the phase change is stored in the diagnostic variable QMELTC. In both cases q_c and $T_{c,v}$ are recalculated, and at the end of the loop C_c and $\Delta Q_{S,c}$ are re-evaluated.

In loop 675, if there is frozen water stored on the canopy and the canopy temperature is greater than 0 C, the first half of the adjustment to $\Delta Q_{S,c}$ is performed, and the flags ITER and NIT are set to 1. The available energy for melting, HMELT, is calculated from CHCAP and the difference between TCAN and 0 C, and compared with HCONV, calculated as the energy required to melt all of the frozen water on the canopy. If HMELT ≤ HCONV, the amount of frozen water that can be melted is calculated using the latent heat of melting. The fractional coverages of frozen and liquid water FSNOWC and FRAINC and their masses SNOCAN and RAICAN are adjusted accordingly, TCAN is set to 0 C, and the amount of energy involved is stored in the diagnostic variable QMELTC. Otherwise, all of the intercepted frozen water is converted to liquid water, and the energy available for warming the canopy is calculated as HWARM = HMELT – HCONV. This available energy is applied to increasing the temperature of the canopy, using the specific heats of the canopy elements, and the amount of energy that was involved in the phase change is stored in the diagnostic variable QMELTC. In both cases q_c and $T_{c,v}$ are recalculated, and at the end of the loop C_c and $\Delta Q_{S,c}$ are re-evaluated.

For the locations over which melting or freezing of water on the canopy has occurred, the surface fluxes must now be recalculated to reflect the modified canopy temperature and humidity. If NIT > 0, first DRCOEF or FLXSURFZ is called to re-evaluate the surface turbulent transfer coefficients over all locations where ITER has been set to 1. Loops 700 and 750 repeat the calculations done in loops 475 and 500, to obtain the surface transfer coefficients. Loop 800 repeats the calculations of the surface fluxes done in loop 525.

At the end of the subroutine, some final diagnostic and clean-up calculations are performed. If the evaporation rate from the canopy, EVAPC, is very small, it is added to the residual of the canopy energy balance equation, RESID, and then reset to zero. The overall residual is added to the sensible heat flux from the canopy. The energy balance of the surface underlying the canopy is then re-evaluated to take into account the new value of the canopy longwave radiation. If the surface temperature is close to 0 C, the residual of the equation is assigned to QMELTG, representing the energy associated with melting or freezing of water at the surface; otherwise it is assigned to the ground heat flux. If the water vapour flux is towards the canopy, the water sublimated or condensed is assigned to interception storage: to SNOCAN if SNOCAN > 0 (for consistency with the definition of CPHCHC), and to RAICAN otherwise. The diagnostic water vapour flux variables QFCF and QFCL, and the diagnostic change of canopy heat storage HTCC, are updated accordingly, and the canopy heat capacity CHCAP is recalculated. Finally, the net shortwave radiation, outgoing longwave radiation, sensible and latent heat fluxes are calculated for the whole canopy-ground surface ensemble; the evaporation rates are converted to m s^{-1}; and the iteration counter ITERCT is updated for the level corresponding to the subarea type and the value of NITER.

TSOLVE

Purpose: Solution of surface energy balance for non-vegetated subareas.

Output variables:

CDH	Surface drag coefficient for heat [ ] (C_{DH})
CDM	Surface drag coefficient for momentum [ ]
CFLUX	Product of surface drag coefficient and wind speed [m s^{-1}]
EVAP	Evaporation rate at surface [kg m^{-2} s^{-1}] (E(0))
FTEMP	Product of surface-air temperature gradient, drag coefficient and wind speed [K m s^{-1}]
FVAP	Product of surface-air humidity gradient, drag coefficient and wind speed [kg kg^{-1} m s^{-1}]
H	Height of the atmospheric boundary layer [m]
ILMO	Inverse of Monin-Obukhov roughness length (m^{-1}]
ITERCT	Counter of number of iterations required to solve energy balance for four subareas
GZERO	Heat flux into surface [W m^{-2}] (G(0))
QEVAP	Latent heat flux from surface [W m^{-2}] (Q_E)
QLWOUT	Upwelling longwave radiation at surface [W m^{-2}] (L↑)
QMELT	Heat available for melting snow or freezing water at the surface [W m^{-2}]
QSENS	Sensible heat flux from surface [W m^{-2}] (Q_H)
QSWNET	Net shortwave radiation at surface [W m^{-2}]
QTRANS	Shortwave radiation transmitted into surface [W m^{-2}]
QZERO	Specific humidity at surface [kg kg^{-1}] (q(0))
RIB	Bulk Richardson number at surface [ ]
TZERO	Temperature at surface [K] (T(0))
UE	Friction velocity of air [m s^{-1}]

Input variables:

ALNIRG	Near-IR albedo of ground surface [ ]
ALVISG	Visible albedo of ground surface [ ]
CEVAP	Soil evaporation efficiency coefficient [ ] (β)
CPHCH	Latent heat of vaporization at surface [J kg^{-1}]
CRIB	Richardson number coefficient [K^{-1}]
FCOR	Coriolis parameter [s^{-1}]
FI	Fractional coverage of subarea in question on modelled area [ ]
GCOEFF	Multiplier used in equation relating surface heat flux to surface temperature [W m^{-2} K^{-1}]
GCONST	Intercept used in equation relating surface heat flux to surface temperature [W m^{-2}]
IEVAP	Flag indicating whether surface evaporation is occurring or not

ISAND	Sand content flag
ISNOW	Flag indicating presence or absence of snow
IWATER	Flag indicating condition of surface (dry, water-covered or snow-covered)
PCPR	Surface precipitation rate [kg m^{-2} s^{-1}]
QA	Specific humidity at reference height [kg kg^{-1}] (q_a)
QLWIN	Downwelling longwave radiation at bottom of atmosphere [W m^{-2}]
QSWINI	Near-infrared radiation incident on horizontal surface [W m^{-2}]
QSWINV	Visible radiation incident on horizontal surface [W m^{-2}]
PADRY	Partial pressure of dry air [Pa] (p_{dry})
RHOAIR	Density of air [kg m^{-3}] (ρ_a)
TPOTA	Potential temperature of air at reference height [K] ($T_{a,pot}$)
TRSNOW	Short-wave transmissivity of snow pack [ ]
TSTART	Starting point for surface temperature iteration [K]
TVIRTA	Virtual potential temperature of air at reference height [K]
VA	Wind speed at reference height [m s^{-1}] (v_a)
ZOH	Surface roughness length for heat [m]
ZOM	Surface roughness length for momentum [m]
ZOSCLH	Ratio of roughness length for heat to reference height for temperature and humidity [ ]
ZOSCLM	Ratio of roughness length for momentum to reference height for wind speed [ ]
ZRSLFH	Difference between reference height for temperature and humidity and height at which extrapolated wind speed goes to zero [m]
ZRSLFM	Difference between reference height for wind speed and height at which extrapolated wind speed goes to zero [m]

For the surface temperature iteration, two alternative schemes are offered: the bisection method (selected if the flag ITG = 1) and the Newton-Raphson method (selected if ITG = 2). In the first case, the maximum number of iterations ITERMX is set to 12, and in the second case it is set to 5. An optional windless transfer coefficient EZERO is available, which can be used, following the recommendations of Brown et al. (2006), to prevent the sensible heat flux over snow packs from becoming vanishingly small under highly stable conditions. If the snow cover flag ISNOW is zero (indicating bare ground), EZERO is set to zero; if ISNOW=1, EZERO is set to 2.0 W m^{-2} K^{-1}.

In the 50 loop, some preliminary calculations are done. The shortwave transmissivity at the surface, TRTOP, is set to zero in the absence of a snow pack, and to the transmissivity of snow TRSNOW otherwise. The net shortwave radiation at the surface, QSWNET, is calculated as the sum of the incoming visible and near-infrared shortwave radiation, weighted according to one minus their respective albedos. This average value is corrected for the amount of radiation transmitted into the surface, obtained using TRTOP. The initial value of the surface temperature TZERO is set to TSTART, which contains the value of TZERO from the previous time step, and the first step in the iteration sequence, TSTEP, is set to 1.0 K. The flag ITER is set to 1 for each element of the set of modelled areas, indicating that its surface temperature has not yet been found. The iteration counter NITER is initialized to 1 for each element. Initial values are assigned to several other variables.

The 100 continuation line marks the beginning of the surface temperature iteration sequence. First the flags NIT (indicating that there are still locations at the beginning of the current iteration step for which the surface temperature has not yet been found) and NUMIT (indicating that there are still locations at the end of the current iteration step for which the surface temperature has not yet been found) are set to zero. Loop 150 is then performed over the set of modelled areas. If ITER=1, NIT is incremented by one, and the initial value of the surface transfer coefficient CFLUXM for this iteration pass is set to its value from the previous pass. The virtual temperature at the surface, $T(0)_v$, is obtained using the standard expression (see documentation for subroutine CLASST):

$$T(0)_v = T(0) [1 + 0.61 q(0)]$$

where T(0) is the surface temperature and q(0) is the specific humidity at the surface. The surface humidity can be obtained from the saturated specific humidity $q(0)_{sat}$ by making use of the definition of the surface evaporation efficiency β:

$$\beta = [q(0) - q_a]/[q(0)_{sat} - q_a]$$

where q_a is the specific humidity of the air at the reference height. This expression is inverted to obtain an expression for q(0). The saturated specific humidity $q(0)_{sat}$ is determined from the mixing ratio at saturation, $w(0)_{sat}$:

$$q(0)_{sat} = w(0)_{sat}/[1 + w(0)_{sat}]$$

The saturation mixing ratio is a function of the saturation vapour pressure $e(0)_{sat}$ at the surface:

$$w(0)_{sat} = 0.622\, e(0)_{sat}/(p_{dry})$$

where p_{dry} is the partial pressure of dry air. A standard empirical equation for the saturation vapour pressure dependence on the temperature T is used:

$$e_{sat} = 611.0 \exp[17.269(T - T_f)/(T - 35.86)] \qquad T \geq T_f$$
$$e_{sat} = 611.0 \exp[21.874(T - T_f)/(T - 7.66)] \qquad T < T_f$$

where T_f is the freezing point. If there is a snow cover or ponded water present on the surface (IWATER > 0), the surface evaporation efficiency EVBETA is set to 1 and q(0) is set to $q(0)_{sat}$. Otherwise EVBETA is set to CEVAP, the value obtained in subroutine TPREP on the basis of ambient conditions, and q(0) is calculated as above. If $q(0) > q_a$ and the evaporation flag IEVAP has been set to zero, EVBETA is reset to zero and q(0) is reset to q_a. Finally, $T(0)_v$ is determined using the equation above.

If NIT > 0, a subroutine is called to evaluate the stability-corrected surface drag coefficients for heat and momentum. The subroutine selection is made on the basis of the flag ISLFD. If ISLFD=1, indicating that the calculations are to be consistent with CCCma conventions, subroutine DRCOEF is called; if ISLFD=2, indicating that the calculations are to be consistent with RPN conventions, subroutine FLXSURFZ is called.

In loop 175, the terms of the surface energy balance are evaluated. The energy balance equation is written as:

$$K_* + L_* - Q_H - Q_E - G(0) = 0$$

where K_* is the net shortwave radiation, L_* is the net longwave radiation, Q_H is the sensible heat flux, Q_E is the latent heat flux, and G(0) is the conduction into the surface. K_* was evaluated earlier in loop 50. L_* is obtained as the difference between the downwelling radiation L↓ and the upwelling radiation L↑, which in turn is determined using the Stefan-Boltzmann equation:

$$L\uparrow = \sigma\, T(0)^4$$

where σ is the Stefan-Boltzmann constant. (It is assumed that natural surfaces, because of their radiative complexity, act as effective black bodies, so that their emissivity can be taken to be 1.) The sensible heat flux is given by

$$Q_H = [\varrho_a c_p C_{DH} v_a + \varepsilon_0][T(0) - T_{a,pot}]$$

where ϱ_a is the density of the air, c_p is its specific heat, C_{DH} is the surface drag coefficient for heat, and v_a and $T_{a,pot}$ are the wind speed and potential temperature respectively at the reference height. (Note in the code that the variable CFLUX, evaluated in subroutine DRCOEF or FLXSURFZ, represents the product of C_{DH} and v_a.) The windless transfer coefficient ε_0, evaluated at the beginning of the subroutine, is used only under stable conditions, i.e. if $T(0) < T_{a,pot}$. The evaporation rate at the surface, E(0), is calculated as

$$E(0) = \varrho_a C_{DH} v_a\, [q(0) - q_a]$$

If precipitation is occurring, E(0) is set to zero. Q_E is obtained by multiplying E(0) by the latent heat of vaporization at the surface. The ground heat flux G(0) is determined as a linear function of T(0) (see documentation for subroutines TNPREP and TSPREP). It can be seen that each of the terms of the surface energy balance is a function of a single unknown, T(0) or TZERO. The residual RESID of the energy balance is now evaluated on the basis of the current estimation for TZERO. If the absolute value of RESID is less than 5.0 W m^{-2}, or if the absolute value of the iteration step TSTEP most recently used is less than 0.01 K, the surface temperature is deemed to have been found and ITER is set to 0. If the iteration counter NITER is equal to the maximum number and ITER is still 1, ITER is set to -1.

In the following section, the iteration sequence is moved ahead a step. If ITG = 1, then if NIT > 0 and if ITER for the array element in question is 1, the calculations for the bisection method of solution are performed. If NITER = 1 (indicating that this is the first step in the iteration), then if RESID > 0 (indicating that the current value for TZERO had undershot the correct value), TZERO is incremented by 1 K; otherwise it is decremented by 1 K. If this is not the first step in the iteration, then if RESID >0 and TSTEP < 0 (indicating that TZERO has undershot the correct value and the last temperature increment had been a negative one) or if RESID < 0 and TSTEP > 0 (indicating that TZERO has overshot the correct value and the last temperature increment had been a positive one), TSTEP is divided in half and its sign changed. TSTEP is then added to TZERO. The iteration counter NITER and the flag NUMIT are each incremented by one. The next loop contains an optional set of print statements that are executed if ITER=-1, that is if a solution for the surface temperature has not been found within the prescribed maximum number of iteration steps. Finally, if NUMIT > 0, the iteration cycle is repeated from line 100 on.

If ITG = 2, then if NIT > 0 and if ITER for the array element in question is 1, the calculations for the Newton-Raphson method of iteration are performed. In this approach, the value x_{n+1} used at each iteration step is obtained from the value x_n at the previous step as follows:

$$x_{n+1} = x_n - f(x_n)/f'(x_n)$$

Identifying x_n with TZERO and $f(x_n)$ with the surface energy balance equation, it can be seen that the second term on the right-hand side corresponds to TSTEP; the numerator is equal to RESID and the denominator to the first derivative of the energy balance equation evaluated at TZERO, which in turn is equal to the sum of the derivatives of the individual terms:

$$d(L\uparrow)/dT = -4\sigma T(0)^3$$

$$d(Q_H)/dT = \varrho_a c_p \{C_{DH} v_a + [T(0) - T_{a,pot}]\ d(C_{DH} v_a)/dT\}$$

$$d(Q_E)/dT = L_v \varrho_a \{C_{DH} v_a\ dq(0)/dT + [q(0) - q_a]\ d(C_{DH} v_a)/dT\}$$

and $dG(0)/dT$ is equal to the coefficient multiplying TZERO in the equation for G(0). (L_v is the latent heat of vaporization at the surface.) At the end of the calculations the iteration counter NITER and the flag NUMIT are each incremented by one, and upon exiting the loop, if NUMIT > 0, the iteration cycle is repeated from line 100 on.

After the iteration has been completed, NUMIT is reset to zero and a check is carried out to ascertain whether convergence has not been reached (i.e. whether ITER = -1) for any location. In such cases it is assumed that conditions of near-neutral stability at the surface are the cause of the difficulty in finding a solution. A trial value of TZERO is calculated using the virtual potential temperature of the air. If this temperature is within 5.0 K of the last guess, and if RESID > 50 W m^{-2}, TZERO is set to this trial value. The values of q(0) and the components of the surface energy balance are recalculated as above, except that Q_H and Q_E are assumed as a first approximation to be zero. RESID is determined on this basis. If RESID is positive, it is assigned to Q_E; otherwise RESID is divided equally between Q_H and Q_E. (If precipitation is occurring, Q_E is set to zero.) RESID is reset to zero, E(0) is obtained from Q_E, and $T(0)_v$ is recalculated. The flag JEVAP for the location is set to 1, and NUMIT is incremented by 1. If NUMIT > 0 at the end of this loop, DRCOEF or FLXSURF are called again, and their calculations are performed for any location where JEVAP is 1, to ensure consistency with the new surface temperature and humidity.

At this point a check is performed for unphysical values of the surface temperature, i.e. for values greater than 100 C or less than -100 C. If such values are encountered, an error message is printed and a call to abort is carried out.

Finally, a check is performed to ensure that TZERO is not less than 0 C if ponded water is present on the surface (IWATER = 1) or greater than 0 C if snow is present on the surface (IWATER = 2), or greater than zero if the surface is an ice sheet (ISAND = -4). If any of these cases is true, TZERO is reset to the freezing point, and q(0) and $T(0)_v$ are recalculated. DRCOEF or FLXSURFZ are called, and their calculations are performed for all locations meeting these criteria. The components of the surface energy balance are recalculated; the residual amount is assigned to the energy associated with phase change of water at the surface, QMELT, and RESID is set to zero. If QMELT < 0, i.e. if there is freezing taking place, the evaporation flux QEVAP is added to it and then reset to zero (since if ponded water is freezing, it is unavailable for evaporation).

In the last half of the loop, some final adjustments are made to a few variables. If the evaporation flux is vanishingly small, it is added to RESID and reset to zero. If an anomalous case has arisen in which QMELT < 0 over a snow-covered surface or QMELT > 0 over a snow-free surface, QMELT is added to the heat flux into the surface and then reset to zero. Any remaining residual flux is added to Q_H. The shortwave radiation transmitted into the surface is added back to the net shortwave radiation for diagnostic purposes. The surface vapour flux is converted into units of m s^{-1}. Lastly, the iteration counter ITERCT is updated for the level corresponding to the subarea type and the value of NITER.

TSPOST

Purpose: Snow temperature calculations and cleanup after surface energy budget calculations.

Input/output variables:

DELZ	Overall thickness of soil layer [m]
FI	Fractional coverage of subarea in question on modelled area [ ] (X_i)
GCOEFF	Multiplier used in equation relating snow surface heat flux to snow surface temperature [W m^{-2} K^{-1}]
GCOEFFS	Multiplier used in equation relating snow surface heat flux to snow surface temperature [W m^{-2} K^{-1}]
GCONST	Intercept used in equation relating snow surface heat flux to snow surface temperature [W m^{-2}]
GCONSTS	Intercept used in equation relating snow surface heat flux to snow surface temperature [W m^{-2}]
GSNOW	Heat conduction into surface of snow pack [W m^{-2}] (G(0))
GZERO	Heat conduction into soil surface [W m^{-2}] ($G(\Delta z_s)$)
HCPSNO	Heat capacity of snow [J m^{-3} K^{1}] (C_s)
HMFN	Energy associated with phase change of water in snow pack [W m^{-2}]
HTCS	Internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}] (I_s)
QMELTG	Available energy to be applied to melting of snow [W m^{-2}]
QTRANS	Shortwave radiation transmitted through the snow pack [W m^{-2}]
RHOSNO	Density of snow [kg m^{-3}] (ρ_s)
TBAR	Temperatures of soil layers, averaged over modelled area [K]
TCSNOW	Thermal conductivity of snow [W m^{-1} K^{-1}]
TSNBOT	Temperature at bottom of snow pack [K]
TSNOW	Snowpack temperature [K/C] (T_s)
TSURF	Snow surface temperature [K]
WSNOW	Liquid water content of snow pack [kg m^{-2}] (w_s)
ZSNOW	Depth of snow pack [m] (Δz_s)

In the 100 loop, the heat flux into the snow surface (without adjustments that may have been applied relating to partitioning of the residual of the surface energy balance among the surface flux terms) is calculated from the snow surface temperature TSURF, using the GCOEFFS and GCONSTS terms (see documentation of subroutine TSPREP). The temperature at the bottom of the snow pack, TSNBOT, is then calculated. Currently TSNBOT is determined as a simple average of the temperatures of the snow and the first soil layer, weighted according to their respective depths, but this is currently under review. The heat flux into the soil surface is then evaluated from TSNBOT and the GCOEFF and GCONST terms (see documentation of subroutine TNPREP). If the energy to be applied to the melting of snow, QMELTG, is negative (indicating an energy sink), QMELTG is added to the heat flux into the ground, GZERO, and reset to zero. The temperature of the snow pack is then stepped forward using the heat fluxes at the top and bottom of the snow pack, G(0) and $G(\Delta z_s)$:

$$\Delta T_s = [G(0) - G(\Delta z_s)]\Delta t/(C_s \Delta z_s)$$

where C_s is the snow heat capacity, Δt the time step and Δz_s the snow depth. If the new snow temperature is greater than zero, the excess amount of heat is calculated and added to QMELTG and subtracted from GSNOW, and TSNOW is reset to 0 C. Finally, the shortwave radiation transmitted through the snow pack, QTRANS, is added to GZERO.

In the 200 loop, since liquid water is assumed only to exist in the snow pack if it is at 0 C, a check is carried out to determine whether the liquid water content WSNOW > 0 at the same time as the snow temperature TSNOW < 0. If so, the change of internal energy I_s of the snow pack as a result of this phase change is calculated as the difference in I_s between the beginning and end of the loop:

$$\Delta I_s = X_i \Delta[C_s T_s]/\Delta t$$

where X_i represents the fractional coverage of the subarea under consideration relative to the modelled area. The total energy sink HADD available to freeze liquid water in the snow pack is calculated from TSNOW, and the amount of energy HCONV required to freeze all the available water is calculated from WSNOW. If HADD < HCONV, only part of WSNOW is frozen; this amount WFREZ is calculated from HADD and subtracted from WSNOW, the snow temperature is reset to 0 C, the frozen water is used to update the snow density, and the snow heat capacity is recalculated:

$$C_s = C_i[\rho_s/\rho_i] + C_w w_s/[\rho_w \Delta z_s]$$

where C_i and C_w are the heat capacities of ice and snow respectively, w_s is the snow water content and ρ_s, ρ_i and ρ_w are the densities of snow, ice and water respectively. If HADD > HCONV, the available energy sink is sufficient to freeze all of WSNOW. HADD is recalculated as HADD – HCONV, WFREZ is set to WSNOW and added to the snow density, WSNOW is set to zero, the snow heat capacity is recalculated and HADD is used to determine a new value of TSNOW. Finally, WFREZ is used to update the diagnostic variables HMFN describing phase changes of water in the snow pack, and the change in internal energy HTCS.

TNPOST

Purpose: Soil heat flux calculations and cleanup after surface energy budget calculations.

Input/output variables:

A1, A2, B1, B3, C2	Work arrays used in calculation of GCONST and GCOEFF
DELZ	Overall thickness of soil layer [m] (Δz)
DELZW	Permeable thickness of soil layer [m]
FI	Fractional coverage of subarea in question on modelled area [ ]
G12	Heat conduction between first and second soil layers [W m^{-2}] ($G(\Delta z_{1p})$)
G23	Heat conduction between second and third soil layers [W m^{-2}]
GCOEFF	Multiplier used in equation relating ground surface heat flux to surface temperature [W m^{-2} K^{-1}]
GCONST	Intercept used in equation relating ground surface heat flux to surface temperature [W m^{-2}]
GZERO	Heat conduction into soil surface [W m^{-2}] ($G(0)$)
HCP	Heat capacity of soil layer [J m^{-3} K^{-1}]
ISAND	Sand content flag
IWATER	Flag indicating condition of surface (dry, water-covered or snow-covered)
QFREZG	Energy sink to be applied to freezing of ponded water [W m^{-2}]
TBAR	Temperatures of soil layers, averaged over modelled area [K]
TBAR1P	Lumped temperature of ponded water and first soil layer [K] (T_{1p})
TBARPR	Temperatures of soil layers for subarea [C]
TBASE	Temperature of bedrock in third soil layer [K]
TCBOT	Thermal conductivity of soil at bottom of layer [W m^{-1} K^{-1}] (λ)
TCTOP	Thermal conductivity of soil at top of layer [W m^{-1} K^{-1}] (λ)
TPOND	Temperature of ponded water [C] (T_p)
TSURF	Ground surface temperature [K]
ZPOND	Depth of ponded water on surface [m] (Δz_p)

In the 100 loop, the heat flux into the ground (without adjustments that may have been applied owing to phase changes of water at the surface or partitioning the residual of the surface energy balance among the surface flux terms) is calculated from the ground surface temperature TSURF, using the GCOEFF and GCONST terms (see documentation of subroutine TNPREP). This flux is then used to back-calculate the heat conduction between the first and second, and the second and third soil layers.

If the depth of water ponded on the surface is greater than zero, the total thickness of the lumped layer consisting of the first soil layer and the ponded water, Δz_{1p}, is calculated as the sum of the two depths. The temperature of the ponded water over the subarea in question is disaggregated from the temperature of the lumped layer, T_{1p}, by making use of the calculated heat fluxes at the top and bottom of the layer, and the assumption (discussed in the documentation of subroutine TNPREP) that that the variation of temperature T with depth z within a soil layer can be modelled using a quadratic equation:

$$T(z) = \tfrac{1}{2} T''(0)z^2 + T'(0)z + T(0)$$

Integrating this equation separately over the ponded water depth Δz_p and over the thickness of the lumped layer produces expressions for the ponded water temperature T_p and the temperature of the lumped layer. Making use of the fact that

$$T''(0) = [T'(\Delta z) - T'(0)]/\Delta z$$

where Δz is a depth interval, and

$$G(z) = - \lambda(z)T'(z)$$

where λ represents the thermal conductivity, an expression for T_p can be derived:

$$T_p = [G(0)/\lambda(0) - G(\Delta z_{1p})/\lambda(\Delta z_{1p})][\Delta z_p^{\,2} - \Delta z_{1p}^{\,2}]/6\Delta z_{1p} - G(0)[\Delta z_p - \Delta z_{1p}]/2\lambda(0) - T_{1p}$$

The temperature TBARPR of the first soil layer over the subarea in question can then be obtained by disaggregating the ponded water temperature from the lumped layer temperature using the respective heat capacities of the ponded water and the soil layer. (The heat capacity of the soil is determined as the weighted average of HCP over the permeable thickness DELZW, and the heat capacity of rock, HCPSND, over the impermeable thickness, DELZ-DELZW.) Both the ponded water temperature and the soil layer temperature are converted to C. Lastly, if there is ponded water on the surface (IWATER = 1) and QFREZG, the surface energy available for phase change of water, is positive (indicating an energy source), or if there is snow on the ground (IWATER = 2) and QFREZG is negative (indicating an energy sink), or if there is no liquid or frozen water on the surface (IWATER = 0), QFREZG is added to the heat flux into the ground, GZERO, and then reset to zero.

In loop 200, the subarea soil layer temperatures TBARPR are set for the remaining soil layers. In all cases the temperature of the layer is set to that for the modelled area, TBAR, converted to C, except in the case of the third soil layer if the standard three-layer configuration is being modelled (with a very thick third soil layer of 3.75 m). In this case TBARPR and the layer heat capacity HCP are considered to apply to the permeable depth DELZW of the layer, and the bedrock temperature TBASE and the rock heat capacity HCPSND apply to the remainder, DELZ-DELZW. The disaggregation of TBARPR from TBAR and TBASE is carried out on this basis. TBARPR for this layer is also converted to C.

Part

8

CLASSW

Purpose: Call subroutines to perform surface water budget calculations.

Output variables:

ALBSNO	Snow albedo [ ]
BASFLW	Base flow from bottom of soil column [m or kg m^{-2} s^{-1}]
EVAP	Diagnosed total surface water vapour flux over modelled area [kg m^{-2} s^{-1}]
GFLUX	Heat flux at interfaces between soil layers [W m^{-2}]
GROWTH	Vegetation growth index [ ]
HMFC	Diagnosed energy associated with phase change of water on vegetation [W m^{-2}]
HMFG	Diagnosed energy associated with phase change of water in soil layers [W m^{-2}]
HMFN	Diagnosed energy associated with phase change of water in snow pack [W m^{-2}]
HTC	Diagnosed internal energy change of soil layer due to conduction and/or change in mass [W m^{-2}]
HTCC	Diagnosed internal energy change of vegetation canopy due to conduction and/or change in mass [W m^{-2}]
HTCS	Diagnosed internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}]
OVRFLW	Overland flow from top of soil column [m or kg m^{-2} s^{-1}]
PCFC	Frozen precipitation intercepted by vegetation [kg m^{-2} s^{-1}]
PCLC	Liquid precipitation intercepted by vegetation [kg m^{-2} s^{-1}]
PCPG	Precipitation incident on ground [kg m^{-2} s^{-1}]
PCPN	Precipitation incident on snow pack [kg m^{-2} s^{-1}]
QFC	Water removed from soil layers by transpiration [kg m^{-2} s^{-1}]
QFCF	Sublimation from frozen water on vegetation [kg m^{-2} s^{-1}]

QFCL	Evaporation from liquid water on vegetation [kg m^{-2} s^{-1}]
QFG	Evaporation from ground [kg m^{-2} s^{-1}]
QFN	Sublimation from snow pack [kg m^{-2} s^{-1}]
RCAN	Intercepted liquid water stored on canopy [kg m^{-2}]
RHOSNO	Density of snow [kg m^{-3}]
ROFC	Liquid/frozen water runoff from vegetation [kg m^{-2} s^{-1}]
ROFN	Liquid water runoff from snow pack [kg m^{-2} s^{-1}]
ROVG	Liquid/frozen water runoff from vegetation to ground surface [kg m^{-2} s^{-1}]
RUNOFF	Total runoff from soil [m or kg m^{-2} s^{-1}]
SNCAN	Intercepted frozen water stored on canopy [kg m^{-2}]
SNO	Mass of snow pack [kg m^{-2}]
SUBFLW	Interflow from sides of soil column [kg m^{-2} s^{-1}]
TBAR	Temperature of soil layers [K]
TBASE	Temperature of bedrock in third soil layer [K]
TBASFL	Temperature of base flow from bottom of soil column [K]
TCAN	Vegetation canopy temperature [K]
THICE	Volumetric frozen water content of soil layers [m^3 m^{-3}]
THLIQ	Volumetric liquid water content of soil layers [m^3 m^{-3}]
TOVRFL	Temperature of overland flow from top of soil column [K]
TPOND	Temperature of ponded water [K]
TRUNOF	Temperature of total runoff [K]
TSNOW	Snowpack temperature [K]
TSUBFL	Temperature of interflow from sides of soil column [K]
WSNOW	Liquid water content of snow pack [kg m^{-2}]
WTRG	Diagnosed residual water transferred into or out of the soil [kg m^{-2} s^{-1}]
WTRS	Diagnosed residual water transferred into or out of the snow pack [kg m^{-2} s^{-1}]
ZPOND	Depth of ponded water on surface [m]

Input variables:

(In composite definitions, suffix C or CO = vegetation over ground; G or GO = bare ground; CS = vegetation over snow cover; GS = bare snow cover.)

ALBSNO	Albedo of snow [ ]
BI	Clapp and Hornberger empirical "b" parameter [ ]
CHCAP	Heat capacity of canopy over bare ground [J m^{-2} K^{-1}]
CHCAPS	Heat capacity of canopy over snow [J m^{-2} K^{-1}]
CMASSC	Mass of canopy over bare ground [kg m^{-2}]
CMASCS	Mass of canopy over snow [kg m^{-2}]
CWFCAP	Storage capacity of canopy over bare ground for frozen water [kg m^{-2}]
CWFCPS	Storage capacity of canopy over snow for frozen water [kg m^{-2}]
CWLCAP	Storage capacity of canopy over bare ground for liquid water [kg m^{-2}]
CWLCPS	Storage capacity of canopy over snow for liquid water [kg m^{-2}]
DELZ	Overall thickness of soil layer [m]
DELZW	Permeable thickness of soil layer [m]

EVAPC	Evaporation from vegetation over ground [m s^{-1}]
EVAPCS	Evaporation from vegetation over snow [m s^{-1}]
EVAPCG	Evaporation from ground under vegetation [m s^{-1}]
EVAPG	Evaporation from bare ground [m s^{-1}]
EVAPGS	Evaporation from snow on bare ground [m s^{-1}]
EVPCSG	Evaporation from snow under vegetation [m s^{-1}]
FC/G/CS/GS	Subarea fractional coverage of modelled area [ ]
FROOT	Fraction of total transpiration contributed by soil layer [ ]
FSVF	Sky view factor of ground under vegetation canopy [ ]
FSVFS	Sky view factor of snow under vegetation canopy [ ]
G12C/G/CS/GS	Subarea heat flux between first and second soil layers [W m^{-2}]
G23C/G/CS/GS	Subarea heat flux between second and third soil layers [W m^{-2}]
GGEO	Geothermal heat flux at bottom of soil profile [W m^{-2}]
GRKFAC	WATROF parameter used when running MESH code [ ]
GRKSAT	Saturated hydraulic conductivity of soil layer [m s^{-1}]
GZEROC/G, GZROCS/GS	Subarea heat flux at soil surface [W m^{-2}]
HCPC	Heat capacity of soil layers under vegetation [J m^{-3} K^{-1}]
HCPG	Heat capacity of soil layers in bare areas [J m^{-3} K^{-1}]
HCPS	Heat capacity of soil material [J m^{-3} K^{-1}]
ISAND	Sand content flag
IWF	Flag governing lateral soil water flow calculations
NLANDC/G/CS/GS	Number of modelled areas that contain subareas of canopy over bare ground / bare ground / canopy over snow /snow
NLANDI	Number of modelled areas that are ice sheets [ ]
PCPR	Surface precipitation rate [kg m^{-2} s^{-1}]
PSISAT	Soil moisture suction at saturation [m]
QFREZC	Heat sink to be used for freezing water on ground under canopy [W m^{-2}]
QFREZG	Heat sink to be used for freezing water on bare ground [W m^{-2}]
QMELTC	Heat to be used for melting snow under canopy [W m^{-2}]
QMELTG	Heat to be used for melting snow on bare ground [W m^{-2}]
RAICAN	Intercepted liquid water stored on canopy over ground [kg m^{-2}]
RAICNS	Intercepted liquid water stored on canopy over snow [kg m^{-2}]
RHOSCS	Density of snow under vegetation [kg m^{-3}]
RHOSGS	Density of snow in bare areas [kg m^{-3}]
RHOSNI	Density of fresh snow [kg m^{-3}]
RPCP	Rainfall rate over modelled area [m s^{-1}]
SNOCAN	Intercepted frozen water stored on canopy over ground [kg m^{-2}]
SNOCNS	Intercepted frozen water stored on canopy over snow [kg m^{-2}]
SPCP	Snowfall rate over modelled area [m s^{-1}]
TA	Air temperature at reference height [K]
TBARCS/GS/C/G	Subarea temperatures of soil layers [C]
TBASE	Temperature of bedrock in third soil layer [K]
TCANO	Temperature of canopy over ground [K]
TCANS	Temperature of canopy over snow [K]
TCBOTC/G	Thermal conductivity of soil at bottom of layer [W m^{-1} K^{-1}]
TCTOPC/G	Thermal conductivity of soil at top of layer [W m^{-1} K^{-1}]

THFC	Field capacity [m^3 m^{-3}]
THICEC	Frozen water content of soil layers under vegetation [m^3 m^{-3}]
THICEG	Frozen water content of soil layers in bare areas [m^3 m^{-3}]
THLIQC	Liquid water content of soil layers under vegetation [m^3 m^{-3}]
THLIQG	Liquid water content of soil layers in bare areas [m^3 m^{-3}]
THLMIN	Residual soil liquid water content remaining after freezing or evaporation [m^3 m^{-3}]
THLRAT	Fractional saturation of soil behind the wetting front [ ]
THLRET	Liquid water retention capacity for organic soil [m^3 m^{-3}]
THPOR	Pore volume in soil layer [m^3 m^{-3}]
TPONDC/G, TPNDCS/GS	Subarea temperature of surface ponded water [C]
TRPCP	Rainfall temperature over modelled area [C]
TSFSAV	Ground surface temperature over subarea [K]
TSNOCS	Temperature of snow pack under vegetation [K]
TSNOGS	Temperature of snow pack in bare areas [K]
TSPCP	Snowfall temperature over modelled area [C]
WFCINT	WATROF parameter used when running MESH code [ ]
WFSURF	WATROF parameter used when running MESH code [ ]
WSNOCS	Liquid water content of snow pack under vegetation [kg m^{-2}]
WSNOGS	Liquid water content of snow pack in bare areas [kg m^{-2}]
XDRAIN	Drainage index at bottom of soil profile [ ]
XSLOPE	Surface slope (used when running MESH code) [degrees]
ZBOTW	Depth to permeable bottom of soil layer [m]
ZPLIMC/G, ZPLMCS/GS	Subarea maximum ponding depth [m]
ZPOND	Depth of ponded water on surface [m]
ZSNOW	Depth of snow pack [m]

First, subroutine WPREP is called to initialize various arrays and produce parameters for the four subareas of canopy over snow (CS), snow on ground (GS), canopy over ground (C) and bare ground (G). Then, for each of the four subareas, if the number of modelled areas containing that subarea is greater than zero, a series of subroutines is called. The subroutines associated with each subarea are listed in the table below.

		CS	GS	C	G
CANVAP	Evaporation/sublimation of water from vegetation canopy	√		√	
CANADD	Addition of rainfall/snowfall to canopy; throughfall and drip	√		√	
CWCALC	Freezing/thawing of liquid/frozen water on canopy	√		√	
SUBCAN	Precipitation and condensation under canopy	√		√	
TWCALC	Freezing/thawing of liquid/frozen water in soil	√	√	√	√
SNOVAP	Sublimation from snow pack	√	√	√	√
TFREEZ	Freezing of ponded water on soil	√	√	√	√

TMELT	Melting of snow pack	√	√		
SNOADD	Accumulation of snow on ground	√	√	√	√
SNINFL	Infiltration of rain into snow pack	√	√		
ICEBAL	Energy and water budget of ice sheets		√		√
GRINFL	Infiltration of water into soil	√	√	√	√
GRDRAN	Soil water movement in response to gravity and suction forces	√	√	√	√
TMCALC	Step ahead soil layer temperatures, check for freezing/thawing	√	√	√	√
CHKWAT	Check subarea moisture balances for closure	√	√	√	√
SNOALBW	Temporal variation of snow albedo and density	√	√		

After these calls have been done, average values of the main prognostic variables over the modelled area are determined by performing weighted averages over the four subareas, and checks are carried out to identify and remove vanishingly small values. First the bedrock temperature in the third soil layer, the total runoff and the runoff temperature are calculated. Then the total runoff and the overland flow, interflow and baseflow are converted from units of m to kg m^{-2} s^{-1}. The total surface water vapour flux over the modelled area is updated to account for the residual amounts of evaporative demand over the four subareas that could not be supplied by surface stores (WLSTCS, WLSTGS, WLOSTC and WLOSTG, variables that are defined internally in this subroutine).

The temperature of the vegetation canopy TCAN and the amount of intercepted liquid water RCAN are calculated as weighted averages over the two canopy subareas. A flag is set to trigger a call to abort if TCAN is less than -100 C or greater than 100 C. If RCAN is vanishingly small, it is added to the overland flow and to the total runoff, and their respective temperatures are recalculated. The diagnostic arrays ROFC, ROVG, PCPG and HTCC are updated, and RCAN is set to zero. The amount of intercepted snow SNCAN is likewise calculated as a weighted average over the two canopy subareas. If SNCAN is vanishingly small, it is added to the overland flow and to the total runoff, and their respective temperatures are recalculated. The diagnostic arrays ROFC, ROVG, PCPG and HTCC are updated, and SNCAN is set to zero. If there is no canopy present, TCAN is set to zero.

At the end of the 600 loop, the depth of ponded water ZPOND and its temperature TPOND over the modelled area are calculated as weighted averages over the four subareas. If ZPOND is vanishingly small, then as in the case of intercepted water, it is added to the overland flow and to the total runoff, and their respective temperatures are recalculated. The diagnostic array HTC is updated, and ZPOND and TPOND are set to zero.

In the 650 loop, values of the snow prognostic variables are calculated as weighted averages over the four subareas. The weightings for the subareas include the four internally-defined CLASSW variables XSNOCS, XSNOGS, XSNOWC and XSNOWG, which are set in subroutine CHKWAT to 1 if the subarea snow depth is greater than zero, and to zero otherwise. If the snow depth over the CS and GS subareas is greater than zero (meaning that there was a pre-existing snow cover at the beginning of the time step), the average snow albedo ALBSNO is preferentially set to the average over these two subareas. Otherwise ALBSNO is set to the average over the C and G subareas (where snow has just been added in the current time step). The snow temperature TSNOW and density RHOSNO are set to weighted averages over the four subareas, using the internally-defined subarea volumetric heat capacities HCPSCS/GS/C/G and RHOSCS/GS/C/G. Finally the snow depth ZSNOW is calculated from the subarea depths; the liquid water content of the snow pack WSNOW is obtained as a weighted average over the CS and GS subareas (assuming that freshly fallen snow does not yet contain liquid water); and the snow mass is determined from ZSNOW and RHOSNO. As in the case of intercepted and ponded water, if the snow mass is vanishingly small it and its liquid water content are added to the overland flow and to the total runoff, and their respective temperatures are recalculated. The diagnostic arrays ROFN, PCPG and HTCS are updated, and TSNOW, RHOSNO, SNO and WSNOW are set to zero. Flags are set to trigger calls to abort if TSNOW is less than 0 K or greater than 0.001 C. Finally, the three abort flags set thus far are checked, and calls to abort are performed if they are greater than zero.

In the 700 loop, the temperature of each soil layer is calculated as a weighted average over the four subareas. In the case of the third soil layer., if the standard three-layer configuration is being modelled (with a very thick third soil layer of 3.75 m), the subarea layer temperatures TBARCS/GS/C/G and the layer heat capacities HCPCS/GS/C/G apply to the permeable depth DELZW of the layer, and the bedrock temperature TBASE and the rock heat capacity HCPSND to the remainder, DELZ-DELZW. The averaging is carried out accordingly. In all other soil layers, the layer temperature applies to the whole thickness, whose heat capacity is a weighted average of HCPCS/GS/C/G over DELZW and HCPSND over DELZ-DELZW. The volumetric liquid water content THLIQ, the volumetric frozen water content THICE, and the heat flux at the soil layer interfaces GFLUX are calculated as simple weighted averages over the subareas. A flag is set to trigger a call to abort if the soil layer temperature is less than -100 C or greater than 100 C, and after the end of the loop, a call to abort is performed if the flag is greater than zero.

Finally, subroutine CGROW is called to update the vegetation growth index.

WPREP

Purpose: Initialize subarea variables for surface water budget calculations, and perform preliminary calculations for diagnostic variables.

Output variables:

(Suffix CS = vegetation over snow cover; GS = bare snow cover; C or CO = vegetation over ground; G or GO = bare ground.)

ALBSCS/GS/C/G	Subarea snow albedo [ ]
BASFLW	Base flow from bottom of soil column [m]
DELZZ	Soil layer depth variable used in TWCALC/TMCALC [m]
DT	Time stepping variable used in GRINFL/GRDRAN [s]
EVPICS/GS/C/G	Subarea evapotranspiration rate going into CLASSW [m s^{-1}]
GFLXCS/GS/C/G	Subarea heat flux between soil layers [W m^{-2}]
GRKSCS/GS/C/G	Subarea saturated hydraulic conductivity [m s^{-1}] (K_{sat})
HCPCS/GS/CO/GO	Subarea heat capacity of soil layers [J m^{-3} K^{-1}]
HCPSCS/GS/CO/GO	Subarea heat capacity of snow [J m^{-3} K^{-1}] (C_s)
HMFG	Energy associated with phase change of water in soil layers [W m^{-2}]
IZERO	Zero integer flag used in GRINFL
OVRFLW	Overland flow from top of soil column [m]
PCFC	Frozen precipitation intercepted by vegetation [kg m^{-2} s^{-1}]
PCLC	Liquid precipitation intercepted by vegetation [kg m^{-2} s^{-1}]
PCPG	Precipitation incident on ground [kg m^{-2} s^{-1}]
PCPN	Precipitation incident on snow pack [kg m^{-2} s^{-1}]
QFC	Water removed from soil layers by transpiration [kg m^{-2} s^{-1}]
QFCF	Sublimation from frozen water on vegetation [kg m^{-2} s^{-1}]
QFCL	Evaporation from liquid water on vegetation [kg m^{-2} s^{-1}]
QFG	Evaporation from ground [kg m^{-2} s^{-1}]
QFN	Sublimation from snow pack [kg m^{-2} s^{-1}]
RHOSCS/GS/C/G	Subarea snow density [kg m^{-3}]
RPCCS/GS/C/G	Subarea rainfall rate [m s^{-1}]
RACS/C	Subarea liquid water on canopy going into CLASSW [kg m^{-2}]
RDUMMY	Dummy variable
ROFC	Liquid/frozen water runoff from vegetation [kg m^{-2} s^{-1}]
ROFN	Liquid water runoff from snow pack [kg m^{-2} s^{-1}]
ROVG	Liquid/frozen water runoff from vegetation to ground surface [kg m^{-2} s^{-1}]
RUNFCS/GS/C/G	Subarea total runoff [m]
SNCS/C	Subarea frozen water on canopy going into CLASSW [kg m^{-2}]
SPCCS/GS/C/G	Subarea snowfall rate [m s^{-1}]
SUBFLW	Interflow from sides of soil column [m]
SUBLCS/C	Subarea sublimation rate from vegetation [m s^{-1}]
TBASCS/GS/C/G	Subarea temperature of bedrock in third soil layer [C]

TBASFL	Temperature of base flow from bottom of soil column [K]
THICEX	Internal CLASSW work array for soil frozen water [m^3 m^{-3}]
THICCS/GS/CO/GO	Subarea volumetric frozen water content of soil layers [m^3 m^{-3}] (θ_i)
THIDUM	Internal CLASSW dummy variable for soil frozen water [m^3 m^{-3}]
THLDUM	Internal CLASSW dummy variable for soil frozen water [m^3 m^{-3}]
THLIQX	Internal CLASSW work array for soil frozen water [m^3 m^{-3}]
THLQCS/GS/CO/GO	Subarea volumetric liquid water content of soil layers [m^3 m^{-3}]
TOVRFL	Temperature of overland flow from top of soil column [K]
TRPCCS/GS/C/G	Subarea rainfall temperature [K/C]
TRUNFCS/GS/C/G	Subarea total runoff temperature [K]
TRUNOF	Temperature of total runoff [K]
TSNOWC/G	Subarea snowpack temperature [K]
TSPCCS/GS/C/G	Subarea snowfall temperature [K/C]
TSUBFL	Temperature of interflow from sides of soil column [K]
WLSTCS/GS, WLOSTC/G	Subarea residual water not met by surface stores [kg m^{-2}]
XSNOCS/GS, XSNOWC/G	Subarea fractional snow coverage [ ]
ZERO	Zero vector used in several subroutines [ ]
ZPNDCS/GS, ZPONDC/G	Subarea depth of surface ponded water [m]
ZSNOCS/GS, ZSNOWC/G	Subarea depth of snow pack

Input variables:

(Suffix CS = vegetation over snow cover; GS = bare snow cover; C or CO = vegetation over ground; G or GO = bare ground.)

ALBSNO	Albedo of snow [ ]
DELZ	Overall thickness of soil layer [m]
DELZW	Permeable thickness of soil layer [m]
EVAPC	Evaporation from vegetation over ground [m s^{-1}]
EVAPCS	Evaporation from vegetation over snow [m s^{-1}]
EVAPCG	Evaporation from ground under vegetation [m s^{-1}]
EVAPG	Evaporation from bare ground [m s^{-1}]
EVAPGS	Evaporation from snow on bare ground [m s^{-1}]
EVPCSG	Evaporation from snow under vegetation [m s^{-1}]
FCS/GC/C/G	Subarea fractional coverage of modelled area [ ]
FSVF	Sky view factor of ground under vegetation canopy [ ]
FSVFS	Sky view factor of snow under vegetation canopy [ ]
GRKSAT	Saturated hydraulic conductivity of soil layers [m s^{-1}]
HCPC	Heat capacity of soil layers under vegetation [J m^{-3} K^{-1}]
HCPG	Heat capacity of soil layers in bare areas [J m^{-3} K^{-1}]
HCPS	Heat capacity of soil material [J m^{-3} K^{-1}]
ISAND	Sand content flag
RAICAN	Intercepted liquid water stored on canopy over ground [kg m^{-2}]
RAICNS	Intercepted liquid water stored on canopy over snow [kg m^{-2}]
RHOSCS	Density of snow under vegetation [kg m^{-3}] (ρ_s)
RHOSGS	Density of snow in bare areas [kg m^{-3}] (ρ_s)

RPCP	Rainfall rate over modelled area [m s^{-1}]
RHOSNI	Density of fresh snow [kg m^{-3}]
SNOCAN	Intercepted frozen water stored on canopy over ground [kg m^{-2}]
SNOCNS	Intercepted frozen water stored on canopy over snow [kg m^{-2}]
SPCP	Snowfall rate over modelled area [m s^{-1}]
TBARCS/GS/C/G	Subarea temperatures of soil layers [C] (T_g)
TBASE	Temperature of bedrock in third soil layer [K]
THICEC	Frozen water content of soil layers under vegetation [m^3 m^{-3}]
THICEG	Frozen water content of soil layers in bare areas [m^3 m^{-3}]
THLIQC	Liquid water content of soil layers under vegetation [m^3 m^{-3}]
THLIQG	Liquid water content of soil layers in bare areas [m^3 m^{-3}]
THPOR	Pore volume in soil layer [m^3 m^{-3}] (θ_p)
TRPCP	Rainfall temperature over modelled area [C]
TSPCP	Snowfall temperature over modelled area [C]
TSURX	Ground surface temperature over subarea [K]
WSNOCS	Liquid water content of snow pack under vegetation [kg m^{-2}] (w_s)
WSNOGS	Liquid water content of snow pack in bare areas [kg m^{-2}] (w_s)
ZPOND	Depth of ponded water on surface [m]
ZSNOW	Depth of snow pack [m] (z_s)

In the first three loops, various subarea arrays and internal CLASSW variables are initialized. At the end of the 100 loop, a preliminary calculation of the precipitation diagnostics is carried out, as follows.

The rainfall incident on the vegetation, PCLC, is summed over the vegetated subareas FC and FCS, minus the fraction that falls through the gaps in the canopy (denoted by the sky view factors FSVF and FSVFS respectively). The rainfall incident on the snowpack PCPN is the sum of the rainfall on the snow-covered bare area FGS, and that on the snow under the gaps in the canopy in subarea FCS. The rainfall incident on bare ground, PCPG, is the sum of the rainfall on the snow-free bare area FG, and that on the ground under the gaps in the canopy in subarea FC.

The snowfall incident on the vegetation, PCFC, as in the case of rainfall, is summed over the vegetation subareas FC and FCS, minus the fraction that falls through the gaps in the canopy. The remaining amount is assigned to snowfall incident on the snow pack, PCPN.

In loops 200 to 550, each of the four subareas is addressed in turn. Additional variables are initialized, and an empirical correction is applied to the saturated hydraulic conductivity in each of the soil layers over the subarea, to account for the viscosity of water at the layer temperature (Dingman, 2002):

$$K_{sat}' = 1.7915 \times 10^{-3} K_{sat} / [2.0319 \times 10^{-4} + 1.5883 \times 10^{-3} \exp(-T_g^{\ 0.9}/22.0)]$$

Over the vegetated subareas, following the approach used in subroutine TSOLVC, the canopy evaporative flux is assigned to the sublimation diagnostic variable QFCF if there is snow present on the canopy (since it is assumed that any water present exists within or underneath the snow), and to the evaporation diagnostic variable QFCL if no snow is present. (A correction is later applied in subroutine CANVAP if it is determined that the evaporative flux should be applied to transpiration instead.) The evaporative flux at the ground surface is assigned to QFN over the snow-covered subarea, and to QFG over the bare soil subarea.

The subarea snowfall and rainfall rates, and snowfall and rainfall temperatures, are assigned from the precipitation information over the modelled area. For the GS and G subareas, if surfaceward vapour flux is occurring it is assigned to the snowfall or the rainfall rate respectively for the subarea; the temperature of the water flux is assigned the value of the surface temperature TSURX. (Condensation onto vegetation is handled by augmenting the intercepted water stores in subroutine TSOLVC, and water fluxes at the ground surface under the vegetation are addressed in subroutine SUBCAN.)

Finally, ponded water and snow pack physical characteristics are set, including the snow heat capacity, which is calculated from the heat capacities of ice and water C_i and C_w, the snow, ice and water densities ρ_s ρ_i, and ρ_w, and the water content and depth of the snow pack w_s and z_s, as follows:

$$C_s = C_i[\rho_s/\rho_i] + C_w w_s/[\rho_w z_s]$$

CANVAP

Purpose: Update liquid and frozen water stores on canopy and in soil in response to calculated sublimation, evaporation and transpiration rates.

Input/Output variables:

CHCAP	Heat capacity of vegetation canopy [J m^{-2} K^{-1}] (C_c)
CMASS	Mass of vegetation canopy [kg m^{-2}]
DELZW	Permeable depth of soil layer [m] ($\Delta z_{g,w}$)
EVAP	Evapotranspiration rate from vegetation canopy [m s^{-1}]
FI	Fractional coverage of subarea in question on modelled area [ ] (X_i)
FROOT	Fractional contribution of soil layer to transpiration [ ]
HCPSNO	Heat capacity of snow pack [J m^{-3} K^{-1}] (C_s)
HTC	Internal energy change of soil layer due to conduction and/or change in mass [W m^{-2}] (I_g)
HTCC	Internal energy change of canopy due to changes in temperature and/or mass [W m^{-2}] (I_c)
HTCS	Internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}] (I_s)
QFC	Transpired water removed from soil layer [kg m^{-2} s^{-1}]
QFCF	Sublimation from frozen water in canopy interception store [kg m^{-2} s^{-1}]
QFCL	Evaporation from liquid water in canopy interception store [kg m^{-2} s^{-1}]
QFN	Sublimation from snow pack [kg m^{-2} s^{-1}]
RAICAN	Intercepted liquid water stored on the canopy [kg m^{-2}]
RHOSNO	Density of snow pack [kg m^{-3}]
SNOCAN	Intercepted frozen water stored on the canopy [kg m^{-2}]
SUBL	Calculated sublimation rate from vegetation canopy [m s^{-1}]
TBAR	Temperature of soil layer [K] (T_g)
TCAN	Temperature of vegetation canopy [K] (T_c)
THLIQ	Volumetric liquid water content of soil layer [m^3 m^{-3}] (θ_l)
THLMIN	Residual soil liquid water content remaining after freezing or evaporation [m^3 m^{-3}]
THPOR	Pore volume in soil layer [m^3 m^{-3}]
TSNOW	Temperature of the snow pack [C]
WLOST	Residual amount of water that cannot be supplied by surface stores [kg m^{-2}]
ZSNOW	Depth of snow pack [m] (z_g)

The calculated fluxes of liquid and frozen water from the canopy to the overlying air, obtained as outputs of WPREP, are applied to the liquid and frozen intercepted water stores on the vegetation canopy, and to the liquid and frozen moisture stores at the surface and in the soil. Since there may not be sufficient water in one or more of these stores to sustain the calculated rate over the whole time step, a hierarchy of operations is followed as described below. The change of internal energy I in the canopy, snow and soil layers as a result of these processes is calculated as the difference in I between the beginning and end of the subroutine:

$$\Delta I_c = X_i \Delta(C_c T_c)/\Delta t$$
$$\Delta I_s = X_i \Delta(C_s T_s z_s)/\Delta t$$

where the C terms represent volumetric heat capacities and the T terms temperatures of the canopy and snow pack, Δt is the length of the time step, z_s the snow depth, and X_i the fractional coverage of the subarea under consideration relative to the modelled area. For the soil layers, since only the liquid water content is affected by these calculations, the change in internal energy of each layer is calculated from the change in liquid water content θ_l as:

$$\Delta I_g = X_i C_w \Delta z_{g,w} \Delta(T_g \theta_l)/\Delta t$$

Sublimation is addressed first. The predicted mass of sublimated water SLOST is calculated and compared to the frozen water in the canopy interception store, SNOCAN. If SLOST ≤SNOCAN, all of the sublimated water is subtracted from SNOCAN. If not, the excess sublimation is calculated as SLOST-SNOCAN, QFCF is corrected for the canopy sublimation difference, and SNOCAN is set to zero. Next, the new value of SLOST is compared to the snowpack mass, calculated as ZSNOW*RHOSNO. If SLOST≤ ZSNOW*RHOSNO, all of the remaining sublimated water is taken from the snow pack, and QFN is modified to reflect this loss. Otherwise, the excess sublimation is calculated as SLOST - ZSNOW*RHOSNO, QFN is adjusted accordingly, and ZSNOW is set to zero. There now remain no further frozen moisture stores from which sublimated water can be taken (frozen water in the soil is assumed to be immobile), so the remaining energy that had been assigned to sublimation is assigned to canopy evaporation instead, and QFCL is duly recalculated. This means, however, that a small imbalance will arise in the water budget owing to the difference between the latent heats of sublimation and evaporation. This imbalance is assigned to the housekeeping variable WLOST.

Now canopy evaporation is addressed. It is assumed that all intercepted liquid water evaporates before transpiration begins, since there is a canopy stomatal resistance associated with transpiration and there is none associated with evaporation. The predicted mass of evaporated water RLOST is calculated and compared to the liquid water in the canopy interception store, RAICAN. If RLOST≤RAICAN, all of the evaporated water is subtracted from RAICAN. If not, the excess evaporation is calculated as RLOST-RAICAN, and QFCL is corrected for the canopy evaporation difference. This excess evaporation is now treated as transpiration. An initial check is done by referring to the diagnostic flag IROOT, which was set to 1 at the beginning of the subroutine if there was water available for transpiration in any of the soil layers. If IROOT is zero, no transpiration can occur and the excess evaporation is stored in the temporary variable EVLOST.

The next loop is performed if IROOT=1, i.e. if transpiration is possible. For each soil layer, the volumetric water content that is removed by transpiration, THTRAN, is calculated from RLOST (converted to a volumetric content by dividing by the density of water and the permeable thickness of the soil layer), and the fractional contribution of the soil layer FROOT. If there is enough liquid water in the soil layer to supply THTRAN, the diagnostic transpiration flux QFC for the layer is updated using THTRAN, and the liquid water content of the layer is updated as THLIQ-THTRAN. If not, QFC is updated using the available water in the soil layer, THLIQ is set to THLMIN, and the residual untranspired water is added to EVLOST.

In the final cleanup, the canopy heat capacity is recalculated, the contents of EVLOST are added to WLOST, and the remaining internal energy calculations are completed.

CANADD

Purpose: Calculate canopy interception of rainfall and snowfall, and determine rainfall/snowfall rates at ground surface as a result of throughfall and unloading.

Input/Output variables:

CHCAP	Heat capacity of vegetation canopy [J m^{-2} K^{-1}] (C_c)
CMASS	Mass of vegetation canopy [kg m^{-2}]
CWFCAP	Interception storage capacity of vegetation for frozen water [kg m^{-2}] ($W_{f,max}$)
CWLCAP	Interception storage capacity of vegetation for liquid water [kg m^{-2}]
FI	Fractional coverage of subarea in question on modelled area [ ] (X_i)
FSVF	Sky view factor of surface under vegetation canopy [ ]
HTCC	Internal energy change of canopy due to changes in temperature and/or mass [W m^{-2}] (I_c)
IWATER	Integer flag indicating whether surface is snow or soil
PCPG	Precipitation incident on ground [kg m^{-2} s^{-1}]
PCPN	Precipitation incident on snow pack [kg m^{-2} s^{-1}]
R	Rainfall rate over subarea in question [m s^{-1}]
RAICAN	Intercepted liquid water stored on the canopy [kg m^{-2}] ($W_{l,c}$)
RHOSNI	Density of fresh snow [kg m^{-3}]
ROFC	Liquid/frozen water runoff from vegetation [kg m^{-2} s^{-1}]
ROVG	Liquid/frozen water runoff from vegetation to ground surface [kg m^{-2} s^{-1}]
S	Snowfall rate over subarea in question [m s^{-1}]
SNOCAN	Intercepted frozen water stored on the canopy [kg m^{-2}] ($W_{f,c}$)
TCAN	Temperature of vegetation canopy [K] (T_c)
TR	Temperature of rainfall [C]
TS	Temperature of snowfall [C]
TSURX	Ground or snow surface temperature of subarea [K]

The calculations in this subroutine are performed if the rainfall or snowfall rates over the modelled area are greater than zero, or if the intercepted liquid water RAICAN or frozen water SNOCAN is greater than zero (to allow for unloading). The throughfall of rainfall or snowfall incident on the canopy, RTHRU or STHRU, is calculated from FSVF, the canopy gap fraction or sky view factor. The remaining rainfall or snowfall is assigned to interception, as RINT and SINT. The resulting temperature of liquid water on the canopy, TRCAN, is calculated as a weighted average of RAICAN at the canopy temperature TCAN, and RINT at the rainfall temperature TR. The resulting temperature of frozen water on the canopy, TSCAN, is calculated as a weighted average of SNOCAN at the canopy temperature TCAN, and SINT at the snowfall temperature TS.

Calculations are now done to ascertain whether the total liquid water on the canopy exceeds the liquid water interception capacity CWLCAP. If such is the case, this excess is assigned to RDRIP, water dripping off the canopy. The rainfall rate reaching the surface under the canopy is calculated as RDRIP + RTHRU, and the temperature of this water flux is calculated as a weighted average of RDRIP at a temperature of TRCAN, and RTHRU at the original rainfall temperature TR. The remaining intercepted water becomes CWLCAP. Otherwise, the rainfall rate reaching the surface under the canopy is set to RTHRU, and the liquid water on the canopy RAICAN is augmented by RINT.

Interception and unloading of snow on the canopy is calculated using a more complex method. The amount of snow intercepted during a snowfall event over a time step, $\Delta W_{f,i}$, or SLOAD, is obtained from the initial intercepted snow amount $W_{f,c}$ and the interception capacity $W_{f,max}$, following Hedstrom and Pomeroy (1998), as:

$$\Delta W_{f,i} = (W_{f,max} - W_{f,c}) \; [1 - \exp(-S_{int}/W_{f,max})]$$

where S_{int} is the amount of snow incident on the canopy during the time step (SINT above). The amount of snow not stored by interception, SWXCES, is calculated as SINT – SLOAD. Between and during precipitation events, snow is unloaded from the canopy through wind gusts and snow densification. These effects of these processes are estimated using an empirical exponential relationship for the snow unloading rate $W_{f,u}$ or SNUNLD, again following Hedstrom and Pomeroy (1998):

$$W_{f,u} = \{W_{f,c} + \Delta W_{f,i}) \exp(-U \, \Delta t)$$

where U is a snow unloading coefficient, assigned a value of 0.1 d^{-1} or 1.157 x 10^{-6} s^{-1}. The sum of SWXCES and SNUNLD is assigned to SDRIP, the snow or frozen water falling off the canopy. The snowfall rate reaching the surface under the canopy is calculated as SDRIP + STHRU, and the temperature of this water flux is calculated as a weighted average of SDRIP at a temperature of TSCAN, and STHRU at the original snowfall temperature TS. The frozen water stored on the canopy is recalculated as SNOCAN + SINT – SWXCES - SNUNLD. Otherwise, the snowfall rate reaching the surface under the canopy is set to STHRU, and SNOCAN is augmented by SINT.

In the final section of the subroutine, the initial heat capacity and temperature of the canopy are saved in temporary variables. The new canopy heat capacity is calculated as a weighted average over the specific heats of the liquid and frozen water stored on the canopy and the canopy mass. The canopy temperature is calculated as a weighted average over the stored liquid and frozen water at the updated temperatures TRCAN and TSCAN, and the vegetation mass at the original temperature TCAN. Then the change in internal energy I_c of the vegetation canopy as a result of the water movement above is calculated as the difference in I_c before and after these processes:

$$\Delta I_c = X_i \Delta[C_c T_c]/\Delta t$$

where C_c represents the canopy heat capacity, T_c the canopy temperature, Δt the length of the time step, and X_i the fractional coverage of the subarea under consideration relative to the modelled area.

Finally, the rainfall and snowfall temperatures are converted to degrees C. (In the absence of precipitation, both are set equal to the surface temperature of the subarea to avoid floating point errors in later subroutines.) For subareas with a snow cover (IWATER = 2), the water running off the canopy and the precipitation incident on the snow pack are updated using RDRIP and SDRIP. For subareas without snow cover (IWATER = 1), the water running off the canopy is updated using RDRIP and SDRIP, the precipitation incident on the snow pack is augmented by SDRIP, and the precipitation incident on bare ground is augmented by RDRIP.

SUBCAN

Purpose: Assess water flux elements at the ground surface under the vegetation canopy.

Input/Output variables:

EVAPG	Evaporation rate from surface [$m\ s^{-1}$]
FI	Fractional coverage of subarea in question on modelled area [ ]
IWATER	Integer flag indicating whether surface is snow or soil
PCPG	Precipitation incident on ground [$kg\ m^{-2}\ s^{-1}$]
PCPN	Precipitation incident on ground [$kg\ m^{-2}\ s^{-1}$]
QFG	Evaporation from ground [$kg\ m^{-2}\ s^{-1}$]
QFN	Sublimation from snow pack [$kg\ m^{-2}\ s^{-1}$]
R	Rainfall rate incident on ground [$m\ s^{-1}$]
RHOSNI	Density of fresh snow [$kg\ m^{-3}$]
S	Snowfall rate incident on ground [$m\ s^{-1}$]
TR	Temperature of rainfall [C]
TS	Temperature of snowfall [C]

This subroutine starts with the precipitation rate under the canopy (a result of throughfall and unloading) and calculates the resulting overall evaporation or deposition rates.

For IWATER = 2 (snow on the ground under the canopy), the water vapour flux EVAPG at the ground surface is in the first instance assumed to be sublimation. Thus the first step is to compare it to the snowfall rate. The sum of the snowfall rate and the evaporation rate, SADD, is calculated as S – EVAPG, with EVAPG converted from a liquid water flux (the standard output from TSOLVC) to a snow flux. If SADD is greater than zero (indicating a downward flux) the snowfall rate is set to SADD and EVAPG is set to zero. Otherwise EVAPG is set to -SADD (converted back to a liquid water flux), and S and TS are set to zero.

After this section, any remaining evaporative flux is compared to the rainfall rate. The sum RADD is calculated as R – EVAPG. If RADD is greater than zero, the rainfall rate is set to RADD and EVAPG is set to zero. Otherwise EVAPG is set to –RADD, and R and TR are set to zero.

Analogous calculations are done for IWATER = 1 (bare ground under the canopy). In this case EVAPG is assumed in the first instance to be evaporation or condensation. Thus the first step is to compare it to the rainfall rate, and the same steps are followed as in the paragraph above. Afterwards, any remaining vapour flux is compared to the snowfall rate. If SADD is positive (downward), EVAPG, which is now considered to be absorbed into the snowfall rate, is subtracted from the ground vapour flux QFG and added to the snow vapour flux QFN. If SADD is negative (upward), S, which has now been absorbed into the evaporative flux, is subtracted from the snow precipitation flux PCPN and added to the ground precipitation flux PCPG.

TWCALC

Purpose: Check for freezing or thawing of liquid or frozen water in the soil layers, and adjust layer temperatures and water stores accordingly.

Input/Output variables:

DELZW	Permeable thickness of soil layer [m] ($\Delta z_{g,w}$)
DELZZ	Soil layer thicknesses to bottom of permeable depth for standard three-layer configuration, or to bottom of thermal depth for multiple layers [m] ($\Delta z_{g,z}$)
EVAP	Calculated evaporation rate from soil surface [m s^{-1}]
FI	Fractional coverage of subarea in question on modelled area [ ] (X_i)
HCP	Heat capacity of soil layer [J m^{-3} K^{-1}] (C_g)
HCPS	Heat capacity of soil material [J m^{-3} K^{-1}] (C_m)
HMFG	Energy associated with freezing or thawing of water in soil layer [W m^{-2}]
HTC	Internal energy change of soil layer due to conduction and/or change in mass [W m^{-2}] (I_g)
ISAND	Sand content flag
TBAR	Temperature of soil layer [C] (T_g)
TBARW	Temperature of water in soil layer [C]
THICE	Volumetric frozen water content of soil layer [m^3 m^{-3}] (θ_i)
THLIQ	Volumetric liquid water content of soil layer [m^3 m^{-3}] (θ_l)
THLMIN	Residual soil liquid water content remaining after freezing or evaporation [m^3 m^{-3}] (θ_r)
THPOR	Pore volume in soil layer [m^3 m^{-3}] (θ_p)

The adjustments of soil layer temperature and water content in this routine are done over the whole soil profile in the case of multiple soil layers (see the section on assignment of background data), but only to the bottom of the permeable depth in the case of the standard three-layer configuration (0.10, 0.25 and 3.75 m). This is because if the permeable depth lies within the thick third soil layer, it is recognized as desirable to apply the temperature changes only to that upper part of the layer in which the phase change is occurring, in order to avoid systematic damping of the temperature response of the layer. Thus the local array DELZZ (set in subroutine WPREP) is used here instead of DELZ when referring to the total thermal thickness of the soil layer, where DELZZ=DELZW for the third soil layer when the three-layer configuration is being used, but DELZZ=DELZ for all other cases.

The heat capacity C_g of the permeable part $\Delta z_{g,w}$ of the soil layer under consideration is calculated here and in various other places in the subroutine as the weighted average of the heat capacities of the liquid water content θ_l, the frozen water content θ_i, and the soil material (taken to apply to the volume fraction not occupied by the pore volume θ_p). The heat capacity of air in the pores is neglected:

$$C_g = C_w \theta_l + C_i \theta_i + C_m(1 - \theta_p)$$

Over the impermeable portion of the layer, the heat capacity of rock C_r is assumed to apply. Thus an effective heat capacity $C_{g,e}$ (in units of J m^{-2} K^{-1}) over the soil layer in question, $\Delta z_{g,z}$, can be calculated as:

$$C_{g,e} = C_g \Delta z_{g,w} + C_r(\Delta z_{g,z} - \Delta z_{g,w})$$

The change of internal energy I in the soil layers as a result of freezing and thawing is calculated as the difference in I between the beginning and end of the subroutine:

$$\Delta I_j = X_i \Delta(C_{g,e} T_g)/\Delta t$$

where T_g is the temperature of the layer, Δt the length of the time step, and X_i the fractional coverage of the subarea under consideration relative to the modelled area.

If the soil layer temperature is less than 0 C and the volumetric liquid water content θ_l of the layer is greater than the residual water content θ_r, the water content THFREZ that can be frozen by the available energy sink is calculated from C_e and T_g. The volumetric water content THEVAP of the first layer that is required to satisfy the surface evaporative flux is determined. For each layer, if THLIQ is found to exceed THLMIN + THEVAP, THFREZ is compared to the available water. If THFREZ ≤ THLIQ – THLMIN – THEVAP, all of the available energy sink is used to freeze part of the liquid water content in the permeable part of the soil layer, the amount of energy involved is subtracted from HTC and added to HMFG, C_g is recalculated and the layer temperature is set to 0 C. Otherwise, all of the liquid water content of the layer above THLMIN + THEVAP is converted to frozen water, and HMFG and HTC are recalculated to reflect this. Then C_g is recomputed, and the remaining energy sink is applied to decreasing the temperature of the soil layer (both the permeable and impermeable portions) using C_e.

If the soil layer temperature is greater than 0 C and the volumetric ice content θ_i of the layer is greater than zero, the ice content THMELT that can be melted by the available energy is calculated from C_e and T_g. For each layer, if THMELT ≤ THICE, all of the available energy is used to melt part of the frozen water content of the permeable part of the layer, the amount of energy involved is subtracted from HTC and added to HMFG, C_g is recalculated and the layer temperature is set to 0 C. Otherwise, all of the frozen water content of the layer is converted to liquid water, and HMFG and HTC are recalculated to reflect this. Then C_g is recomputed, and the remaining energy is applied to increasing the temperature of the soil layer (both the permeable and impermeable portions) using C_e.

In the final cleanup, the internal energy calculations for this subroutine are completed, and the first half of a new set of internal energy calculations is done to span the subroutines treating ground water movement, which will be completed in subroutine TMCALC. Lastly, TBARW, the liquid water temperature of each soil layer, is assigned using TBAR.

SNOVAP

Purpose: Sublimation calculations for the snow pack on the ground.

Input/Output variables:

EVAP	Sublimation rate from snow surface at start of subroutine [m s^{-1}]
FI	Fractional coverage of subarea in question on modelled area [ ] (X_i)
HCPSNO	Heat capacity of snow pack [J m^{-3} K^{-1}] (C_s)
HTCS	Internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}] (I_s)
OVRFLW	Overland flow from top of soil column [m s^{-1}]
QFG	Evaporation from ground [kg m^{-2} s^{-1}]
QFN	Sublimation from snow pack [kg m^{-2} s^{-1}]
R	Rainfall rate incident on snow pack [m s^{-1}]
RHOSNI	Density of fresh snow [kg m^{-3}]
RHOSNO	Density of snow pack [kg m^{-3}] (ρ_s)
RUNOFF	Total runoff [m s^{-1}]
S	Snowfall rate incident on snow pack [kg m^{-2} s^{-1}]
TOVRFL	Temperature of overland flow [K]
TRUNOF	Temperature of total runoff [K]
TSNOW	Temperature of the snow pack [C] (T_s)
WLOST	Residual amount of water that cannot be supplied by surface stores [kg m^{-2}]
WSNOW	Liquid water content of snow pack [kg m^{-2}] (w_s)
ZSNOW	Depth of snow pack [m] (z_g)

These calculations are done if a snowpack is present and there is no rainfall or snowfall occurring. The change of internal energy I_s of the snow pack as a result of the change in its mass is calculated as the difference in I_s between the beginning and end of the subroutine:

$$\Delta I_s = X_i \Delta[C_s z_s T_s]/\Delta t$$

where C_s represents the volumetric heat capacity of the snow pack, T_s its temperature, Δt the length of the time step, and X_i the fractional coverage of the subarea under consideration relative to the modelled area.

If the sublimation rate EVAP over the snow pack is negative (downward), the deposited depth of snow ZADD is calculated from EVAP by converting it from a liquid water flux to a fresh snow depth using RHOSNI, the fresh snow density. The snowpack density is updated as a weighted average of the original snow density RHOSNO and RHOSNI. The new snow depth is calculated as the sum of the old snow depth ZSNOW and ZADD. The new volumetric heat capacity of the snow pack is obtained from the heat capacities of ice and water C_i and C_w, the snow, ice and water densities ρ_s ρ_i, and ρ_w, and the water content and depth of the snow pack w_s and z_s, as:

$$C_s = C_i[\rho_s/\rho_i] + C_w w_s/[\rho_w z_s]$$

If the sublimation rate is positive, the depth of the snow pack ZLOST that is sublimated over the time step is calculated from EVAP using RHOSNO. If ZLOST ≤ ZSNOW, the snow depth is reduced and HCPSNO is recalculated. Otherwise the deficit amount ZREM is calculated from ZLOST – ZSNOW and converted to a depth of water. This amount is further converted to an evaporation rate by applying a correction factor of $(L_m + L_v)/L_v$, where L_m is the latent heat of melting and L_v is the latent heat of vaporization (to account for the fact that the energy is now being used to evaporate water instead of sublimate snow). This necessarily leads to a small discrepancy between the overall vapour flux for the subarea that was originally calculated in CLASST, and the actual change of water storage in the subarea, and therefore this discrepancy is added to the housekeeping variable WLOST for use in the water balance checks done later in CHKWAT. If there was liquid water in the snow pack, WSNOW, it is assigned to overall runoff RUNOFF, and to overland flow OVRFLW. The resulting temperatures of the runoff and overland flow, TRUNOF and TOVRFL, are recalculated as weighted averages using the original runoff amounts and temperatures, and the original snow temperature TSNOW for WSNOW. The snow depth, heat capacity, temperature and water content are all set to zero. Finally, since ZREM now becomes soil evaporation rather than snow sublimation, the diagnostic variables QFN and QFG, representing the vapour flux from snow and soil respectively, are adjusted to reflect this.

TFREEZ

Purpose: Address freezing of water ponded on ground surface.

Input/Output variables:

ALBSNO	Albedo of snow [ ]
FI	Fractional coverage of subarea in question on modelled area [ ] (X_i)
GZERO	Heat flow into soil surface [W m^{-2}]
HCPSNO	Heat capacity of snow pack [J m^{-3} K^{-1}] (C_s)
HMFG	Energy associated with phase change of water in soil layers [W m^{-2}]
HTC	Internal energy change of soil layer due to conduction and/or change in mass [W m^{-2}] (I_g)
HTCS	Internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}] (I_s)
ISAND	Sand content flag
QFREZ	Energy sink for freezing of water at the ground surface [W m^{-2}]
RHOSNO	Density of snow pack [kg m^{-3}] (ρ_s)
TA	Air temperature [K]
TBAR	Temperature of soil layer [C] (T_g)
TPOND	Temperature of ponded water [C] (T_p)
TSNOW	Temperature of the snow pack [C] (T_s)
WSNOW	Liquid water content of snow pack [kg m^{-2}] (w_s)
WTRG	Water transferred into or out of the soil [kg m^{-2} s^{-1}]
WTRS	Water transferred into or out of the snow pack [kg m^{-2} s^{-1}]
ZPOND	Depth of ponded water [m] (z_p)
ZSNOW	Depth of snow pack [m] (z_g)

Freezing of water ponded on the ground surface occurs if an energy sink QFREZ is produced as a result of the solution of the surface energy balance, or if the pond temperature at the beginning of the subroutine has been projected to be below 0 C. The change of internal energy I in the snow and first soil layer (which for the purposes of diagnostic calculations includes the ponded water) as a result of these processes is calculated as the difference in I between the beginning and end of the subroutine:

$$\Delta I_s = X_i \Delta(C_s T_s z_s)/\Delta t$$
$$\Delta I_g = X_i \Delta(C_w T_p z_p)/\Delta t$$

where the C terms represent volumetric heat capacities, the T terms temperatures, and the z terms depths of the snow pack and the ponded water respectively, Δt is the length of the time step, and X_i the fractional coverage of the subarea under consideration relative to the modelled area.

The energy sink HADD to be applied to the ponded water is calculated from QFREZ and the pond temperature TPOND (if it is below 0 C). Two diagnostic variables, HCOOL and HCONV, are calculated as the energy sink required to cool the ponded water to 0 C, and that required both to cool and to freeze the ponded water, respectively. If HADD ≤ HCOOL, the available energy sink is only sufficient to decrease the temperature of the ponded water. This decrease is applied, and the energy used is added to the internal energy HTC of the first soil layer.

If HADD > HCOOL but HADD ≤ HCONV, the available energy sink is sufficient to decrease the ponded water temperature to 0 C and to freeze part of it. The energy used in freezing is calculated as HADD – HCOOL, and is used to calculate the depth of frozen water ZFREZ, which is then subtracted from the ponded water depth ZPOND. HCOOL is added to HTC, and ZFREZ is converted from a depth of water to a depth of ice and added to the snow pack. If there is not a pre-existing snow pack, the snow albedo is set to the background value for old snow, 0.50. The temperature, density and heat capacity of the snow pack are recalculated.

If HADD > HCONV, the available energy sink is sufficient to cool and freeze the whole depth of ponded water, and also to decrease the temperature of the ice thus formed. The ponded water depth is converted to a depth of ice ZFREZ, and HCOOL is added to HTC. In order to avoid unphysical temperature decreases caused by the length of the time step and the small ponding depth, a limit is set on the allowable decrease. The theoretical temperature of the newly formed ice, TTEST, is calculated from HADD – HCONV. If there is a pre-existing snow pack, the limiting temperature TLIM is set to the minimum of the snow pack temperature TSNOW, the first soil layer temperature, and 0 C; otherwise it is set to the minimum of the air temperature, the first soil layer temperature and 0 C. If TTEST < TLIM, the new ice is assigned TLIM as its temperature in the recalculation of TSNOW, the excess heat sink HEXCES is calculated from HADD and TLIM and assigned to the ground heat flux GZERO, and HADD – HEXCES is used to update HTC. Otherwise the new ice is assigned TTEST as its temperature in the recalculation of TSNOW, and HADD is used to update HTC. If there is not a pre-existing snow pack, the snow albedo is set to the background value. The density, depth and heat capacity of the snow pack are recalculated, and the pond depth and temperature are set to zero.

At the end of the subroutine, the internal energy calculations are completed, and ZFREZ is used to update the diagnostic variable HMFG describing the energy associated with phase changes of water in soil layers, and also the diagnostic variables WTRS and WTRG describing transfers of water into or out of the snow and soil respectively. Finally, the initial step in the calculation of the internal energy change for the ponded water over the following subroutines GRINFL and GRDRAN is performed (the calculation is completed in subroutine TMCALC).

TMELT

Purpose: Address melting of the snow pack.

Input/Output variables:

FI	Fractional coverage of subarea in question on modelled area [ ]
GZERO	Heat flow into soil surface [W m^{-2}]
HCPSNO	Heat capacity of snow pack [J m^{-3} K^{-1}]
HMFN	Energy associated with freezing or thawing of water in the snow pack [W m^{-2}]
HTC	Internal energy change of soil layer due to conduction and/or change in mass [W m^{-2}]
HTCS	Internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}]
ISAND	Sand content flag
QMELT	Energy available for melting of snow [W m^{-2}]
R	Rainfall rate [m s^{-1}]
RALB	Rainfall rate saved for snow albedo calculations [m s^{-1}]
RHOSNO	Density of snow pack [kg m^{-3}]
TR	Temperature of rainfall [C]
TSNOW	Temperature of the snow pack [C]
WSNOW	Liquid water content of snow pack [kg m^{-2}]
ZSNOW	Depth of snow pack [m]

Melting of the snow pack occurs if a source of available energy QMELT is produced as a result of the solution of the surface energy balance, or if the snow pack temperature is projected to go above 0 C in the current time step (the available energy thus produced is added to QMELT in subroutine TSPOST). The change in internal energy in the snow pack is calculated at the beginning and end of the subroutine, and stored in diagnostic variable HTCS (see notes on subroutine SNOADD).

The calculations in the 100 loop are performed if QFREZ and the snow depth ZSNOW are both greater than zero. The available energy HADD to be applied to the snow pack is calculated from QMELT. The amount of energy required to raise the snow pack temperature to 0 C and melt it completely is calculated as HCONV. If HADD ≤ HCONV, the depth of snow ZMELT that is warmed to 0 C and melted is calculated from HADD. (It is assumed that melting of an upper layer of snow can occur even if the lower part of the snow pack is still below 0 C.) The amount of water generated by melting the snow, RMELTS, is calculated from ZMELT, and the temperature of the meltwater TRMELT is set to 0 C. ZMELT is subtracted from ZSNOW, the heat capacity of the snow is recalculated, and HTCS is corrected for the amount of heat used to warm the removed portion of the snow pack.

If HADD > HCONV, the amount of available energy is sufficient to warm and melt the whole snow pack, with some energy left over. The amount of water generated by melting the snow, RMELTS, is calculated from ZSNOW, and the total amount of water reaching the soil, RMELT, is obtained by adding the liquid water content of the snow pack, WSNOW, to RMELTS. HADD is recalculated as HADD –

HCONV, and used to calculate TRMELT. The snow depth, heat capacity, temperature and water content are set to zero, and HTCS is corrected for the amount of heat that was used to warm the snow pack to 0 C.

After the IF block, the diagnostic variable HMFN describing melting or freezing of water in the snow pack is updated using RMELTS, the temperature of the rainfall rate reaching the soil is updated using TRMELT, and RMELT is added to the rainfall rate R. QMELT is set to zero, and a flag variable RALB, used later in subroutine SNOALBW, is set to the rainfall rate reaching the ground.

In the 200 loop, a check is performed to see whether QMELT is still greater than zero and the modelled area is not an ice sheet (ISAND > -4). In this case QMELT is added to the ground heat flux GZERO, and the internal energy diagnostics HTCS and HTC for the snow and soil respectively are corrected. The flag variable RALB is evaluated as above.

SNOADD

Purpose: Add snow incident on the ground surface to the snow pack.

Input/Output variables:

ALBSNO	Albedo of snow [ ]
FI	Fractional coverage of subarea in question on modelled area [ ] (X_i)
HCPSNO	Heat capacity of snow pack [J m^{-3} K^{-1}] (C_s)
HTCS	Internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}] (I_s)
RHOSNI	Density of fresh snow [kg m^{-3}]
RHOSNO	Density of snow pack [kg m^{-3}] (ρ_s)
S	Snowfall rate incident on snow pack [m s^{-1}]
TS	Temperature of snowfall [C]
TSNOW	Temperature of the snow pack [C] (T_s)
WSNOW	Liquid water content of snow pack [kg m^{-2}] (w_s)
ZSNOW	Depth of snow pack [m] (z_g)

The change of internal energy I_s of the snow pack as a result of the snowfall added to it is calculated as the difference in I_s between the beginning and end of the subroutine:

$$\Delta I_s = X_i \Delta[C_s z_s T_s]/\Delta t$$

where C_s represents the volumetric heat capacity of the snow pack, T_s its temperature, Δt the length of the time step, and X_i the fractional coverage of the subarea under consideration relative to the modelled area.

The amount of snow incident at the given time step, SNOFAL, is calculated from S and the timestep length DELT. If SNOFAL ≥ 0.005 m, the snow albedo is set to the fresh snow value of 0.84. Otherwise, if the snow is falling on bare ground, its initial albedo is set to the old snow value of 0.50. The heat capacity of the precipitating snow, HCPSNP, is calculated from the fresh snow density RHOSNI and the heat capacity and density of ice. The new temperature of the snow pack is calculated as a weighted average of its old temperature, weighted by the snow depth ZSNOW and heat capacity HCPSNO, and the snowfall temperature, weighted by SNOFAL and HCPSNP. The new density of snow is calculated as a weighted average of the original density RHOSNO and RHOSNI, and the new snow depth is calculated as ZSNOW + SNOFAL. Finally, the new heat capacity of the snow pack is obtained from the heat capacities of ice and water C_i and C_w, the snow, ice and water densities ρ_s ρ_i, and ρ_w, and the water content and depth of the snow pack w_s and z_s, as:

$$C_s = C_i[\rho_s/\rho_i] + C_w w_s/[\rho_w z_s]$$

SNINFL

Purpose: Address infiltration of rain and meltwater into snow pack, and snow ripening.

Input/Output variables:

FI	Fractional coverage of subarea in question on modelled area [ ] (X_i)
HCPSNO	Heat capacity of snow pack [J m^{-3} K^{-1}] (C_s)
HMFN	Energy associated with freezing or thawing of water in the snow pack [W m^{-2}]
HTCS	Internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}] (I_s)
PCPG	Precipitation incident on ground [kg m^{-2} s^{-1}]
R	Rainfall rate incident on snow pack [m s^{-1}]
RHOSNO	Density of snow pack [kg m^{-3}] (ϱ_s)
ROFN	Runoff reaching the ground surface from the bottom of the snow pack [kg m^{-2} s^{-1}]
TSNOW	Temperature of the snow pack [C] (T_s)
TR	Temperature of rainfall [C]
WSNOW	Liquid water content of snow pack [kg m^{-2}] (w_s)
ZSNOW	Depth of snow pack [m] (z_g)

The rainfall rate, i.e. the liquid water precipitation rate incident on the snow pack from the atmosphere, from canopy drip and/or from melting of the top of the snow pack, may cause warming and/or melting of the snow pack as a whole. The overall change of internal energy of the snow pack as a result of the rainfall added to it, I_s or HTCS, is calculated as the difference in I_s between the beginning and end of the subroutine:

$$\Delta I_s = X_i \Delta[C_s z_s T_s]/\Delta t$$

where C_s represents the volumetric heat capacity of the snow pack, T_s its temperature, Δt the length of the time step, and X_i the fractional coverage of the subarea under consideration relative to the modelled area.

Four diagnostic variables are evaluated at the outset. HRCOOL, the energy sink required to cool the whole rainfall amount to 0 C, is calculated from the rainfall rate and temperature, and the heat capacity of water. HRFREZ, the energy sink required to freeze all the rainfall, is obtained from the latent heat of melting, the density of water and the rainfall rate. HSNWRM, the energy required to warm the whole snow pack to 0 C, is calculated from the temperature, heat capacity and depth of the snow pack. HSNMLT, the energy required to melt all the snow, is obtained from the latent heat of melting and the heat capacity and depth of the snow pack.

If HRCOOL $\geq$ (HSNWRM + HSNMLT), the energy contributed by the temperature of the rainfall is sufficient to warm to 0 C and melt the whole snow pack. HRCOOL is recalculated as the difference between HRCOOL and (HSNWRM + HSNMLT), and the snow depth is converted to a water depth

ZMELT. The energy used to melt the snow is added to the diagnostic variables HMFN, representing the energy associated with water phase changes in the snow pack, and HTCS. The new temperature of the rainfall is calculated by applying HRCOOL over the new rainfall rate reaching the soil, which now includes the original rainfall rate, the melted snow pack and the liquid water that was contained in the snow pack. The depth, temperature, density and heat capacity of the snow pack are set to zero.

If HRCOOL ≥ HSNWRM but HRCOOL < (HSNWRM + HSNMLT), the energy contributed by the temperature of the rainfall is sufficient to warm the whole snowpack to 0 C but not to melt all of it. HSNMLT is therefore recalculated as HRCOOL - HSNWRM, and used to determine a melted depth of the snowpack ZMELT, which is subtracted from the snow depth ZSNOW. The energy used to melt this depth of snow is added to HMFN and HTCS. The total water now available for retention in the snowpack, WAVAIL, is obtained as the sum of the mass of melted water and the mass of water originally retained in the snow pack, WSNOW. This amount is compared to the water retention capacity of the snow pack, calculated from the maximum retention percentage by weight, WSNCAP (currently set to 4%). If WAVAIL is greater than the water retention capacity, WSNOW is set to the capacity value and the excess is reassigned to ZMELT. Otherwise WSNOW is set to WAVAIL and ZMELT is set to zero. The temperature of the snow and the temperature TR of the rainfall reaching the ground surface are each set to 0 C, HCPSNO is recalculated, and ZMELT is added to the rainfall rate R.

If HSNWRM ≥ (HRCOOL + HRFREZ), the energy sink of the snow pack is sufficient to cool to 0 C and freeze all of the rainfall. HSNWRM is recalculated as the difference between HSNWRM and (HRCOOL + HRFREZ). The energy used in the freezing, HRFREZ, is added to HMFN and HTCS. The rainfall is applied to increasing the density of the snow pack RHOSNO; if the new density is greater than the density of ice, RHOSNO is reset to the ice density and ZSNOW is recalculated. HCPSNO is also recalculated, and the new snow temperature is obtained from HSNWRM, HCPSNO and ZSNOW. R and TR are set to zero.

If HSNWRM > HRCOOL and HSNWRM < (HRCOOL + HRFREZ), the energy sink of the snow pack is sufficient to cool the rainfall to 0 C, but not to freeze all of it. HRFREZ is therefore recalculated as HSNWRM – HRCOOL, and used to determine a depth of rain to be frozen, ZFREZ. The energy used in the freezing is added to HMFN and HTCS. The frozen rainfall is applied to increasing the density of the snow pack as above; if the calculated density exceeds that of ice, RHOSNO and ZSNOW are recalculated. The water available for retention in the snow pack, WAVAIL, is obtained as the sum of the unfrozen rainfall and WSNOW, and compared to the water retention capacity of the snow pack. If WAVAIL is greater than the water retention capacity, WSNOW is set to the capacity value and WAVAIL is recalculated. Otherwise WSNOW is set to WAVAIL and WAVAIL is set to zero. The heat capacity of the snow is recalculated, R is calculated from WAVAIL, and TR and TSNOW are set to zero.

Finally, the calculation of the change in internal energy is completed, and the rainfall rate leaving the bottom of the snow pack and reaching the soil is added to the diagnostic variables PCPG and ROFN.

ICEBAL

Purpose: Perform temperature stepping and surface runoff calculations over ice sheets.

Input/output variables:

ALBSNO	Albedo of snow [ ]
DELZ	Overall thickness of ice layer [m] (Δz)
EVAP	Evaporation rate from ice surface [m s^{-1}]
FI	Fractional coverage of subarea in question on modelled area [ ] (X)
G12	Heat flow between first and second ice layers [W m^{-2}] ($G(\Delta z_1)$)
G23	Heat flow between second and third ice layers [W m^{-2}] ($G(\Delta z_2)$)
GFLUX	Heat flow between ice layers [W m^{-2}] ($G(\Delta z)$)
GGEO	Geothermal heat flux at bottom of modelled ice profile [W m^{-2}]
GZERO	Heat flow into ice surface [W m^{-2}] ($G(0)$)
HCP	Heat capacity of ice layer [J m^{-3} K^{-1}]
HCPSNO	Heat capacity of snow pack [J m^{-3} K^{-1}]
HMFG	Energy associated with freezing or thawing of water in ice layer [W m^{-2}]
HTC	Internal energy change of ice layer due to conduction and/or change in mass [W m^{-2}] (I_j)
HTCS	Internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}]
ISAND	Sand content flag
OVRFLW	Overland flow from top of ice column [m]
QMELT	Energy available for melting of ice [W m^{-2}]
R	Rainfall rate at ice surface [m s^{-1}]
RHOSNO	Density of snow pack [kg m^{-3}]
RUNOFF	Total runoff from ice column [m]
TBAR	Temperature of ice layer [C] ($T_{av}(\Delta z)$)
TOVRFL	Temperature of overland flow from top of ice column [K]
TPOND	Temperature of ponded water [C]
TR	Temperature of rainfall [C]
TRUNOF	Temperature of total runoff from ice column [K]
TSNOW	Temperature of the snow pack [C]
WSNOW	Liquid water content of snow pack [kg m^{-2}]
WTRG	Water transferred into or out of the ice [kg m^{-2} s^{-1}]
WTRS	Water transferred into or out of the snow pack [kg m^{-2} s^{-1}]
ZPLIM	Limiting depth of ponded water [m]
ZPOND	Depth of ponded water [m]
ZSNOW	Depth of snow pack [m]

In the 100 loop, any rainfall or snowmelt R reaching the ice surface is added to the ponded water on the surface. The ponded water temperature is calculated as the weighted average of the existing pond and the rainfall or snowmelt added, and the change in internal energy HTC of the first ice layer is updated using the temperature of the added water.

If a full-scale hydrological modelling application is not being run, that is, if only vertical fluxes of energy and moisture are being modelled, the flag IWF will have been pre-set to zero. In this case, overland flow of water is treated using a simple approach: if the ponded depth of water on the soil surface ZPOND exceeds a pre-determined limiting value ZPLIM, the excess is assigned to overland flow. The total runoff from the ice sheet, RUNOFF, is incremented by the excess of the ponded water, and the overland flow for the whole grid cell OVRFLW is incremented by the product of the excess ponded water and the fractional area of the grid cell. The temperature of the overall runoff from the modelled area TRUNOF, and the temperature of the overland flow for the grid cell TOVRFL, are calculated as weighted averages over their previous values and the ponded water temperature TPOND. The internal energy change HTC of the first soil layer is adjusted for the amount of water lost, and ZPOND is set to ZPLIM.

If the temperature of the remaining ponded water is greater than 0 C, the sink of energy required to cool it to 0 C, HCOOL, is calculated and compared with the amount of energy required to warm the first ice layer to 0 C, HWARM. If HWARM > HCOOL, the energy sink of the first layer is used to cool the ponded water to 0 C, and the layer temperature is updated accordingly. Otherwise, the ponded water temperature and the temperature of the first ice layer are both set to 0 C, and the excess energy source given by HCOOL-HWARM is added to the heat available for melting ice, QMELT.

In loop 125, if the temperature of the first ice layer is less than -2 C after the above operations (i.e. if it is not very close to 0 C), and if the ponded water depth is not vanishingly small, freezing of the ponded water can take place. The energy sink required to freeze all of the ponded water, HFREZ, is calculated and compared with HWARM, the amount of energy required to raise the temperature of the first ice layer to 0 C. If HWARM > HFREZ, then HFREZ is converted into an equivalent temperature change using the heat capacity of ice, and added to the temperature of the first ice layer. HFREZ is also used to update HMFG, the diagnosed energy used for phase changes of water in the first ice layer. The internal energy of the first soil layer, HTC, is adjusted to account for the loss of the ponded water, which is assumed to be added to the snow pack. The ponded water is converted into a frozen depth ZFREZ, which is used to update the internal energy of the snow pack, HTCS. If there is not a pre-existing snow pack, the snow albedo is set to the limiting low value of 0.50. The temperature and density of the snow pack are recalculated as weighted averages over the original values and the frozen amount that has been added. ZFREZ is added to the snow depth ZSNOW. The snow heat capacity is recalculated using the new value of the snow density. Finally, the diagnostic amounts of water transferred to the snow pack, WTRS, and from the ice, WTRG, are updated using ZFREZ.

In the 150 loop the heat fluxes between the ice layers are calculated for the optional multiple-layer configuration, in which the standard third layer, normally with a thickness of 3.75 m, can be subdivided into smaller layers and extended to a greater depth if desired. (The heat fluxes at the ice surface, and between the first and second and the second and third layers, were already calculated in the CLASST subroutines.) The remaining fluxes are calculated by using a simple linearization of the soil temperature profile. The expression for the ground heat flux at a depth z, G(z), which depends on the thermal conductivity λ(z) and the temperature gradient, is written as:

$$G(z) = \lambda(z)\, dT(z)/dz$$

The linearized form is thus:

$$G_j = 2\lambda_i\{T_{j-1} - T_j)/(\Delta z_{j-1} + \Delta z_j)$$

where G_j is the heat flux at the top of layer j, T_j and Δz_j refer to the temperature and thickness of the layer, and λ_i is the thermal conductivity of ice.

In the 200 loop a value is assigned to the temperature at the bottom of the ice profile, TBOT, and the temperatures for the first three ice layers are stepped ahead. If the standard three-layer configuration is being used, TBOT is obtained by making use of the assumption (see documentation for subroutine TNPREP) that the variation of temperature T with depth z within each soil layer can be modelled using a quadratic equation:

$$T(z) = \tfrac{1}{2} az^2 + bz + c$$

It can be shown that the temperature at the bottom of a given soil layer, $T(\Delta z)$, is related to the temperature at the top of the layer T(0) and the heat fluxes at the top and bottom of the layer, G(0) and $G(\Delta z)$, as follows:

$$T(\Delta z) = T(0) - (\Delta z/2\lambda_i)[G(0) + G(\Delta z)]$$

Making use of the continuity requirement that the heat flux and temperature at the bottom of a given layer must be equal to the heat flux and temperature at the top of the layer beneath it, an expression for the temperature at the bottom of the third ice layer can be obtained as a function of the temperature at the surface and the fluxes between the ice layers:

$$T(\Delta z_3) = T(0) - \{G(\Delta z_2)[\Delta z_3 + \Delta z_2] + G(\Delta z_1)[\Delta z_2 + \Delta z_1] + G(0)\Delta z_{21}\}/2\lambda_i$$

The surface temperature T(0) is obtained by integrating the equation for T(z) to obtain an expression for the average layer temperature $T_{av}(\Delta z)$, and then inverting this to solve for T(0):

$$T(0) = T_{av}(\Delta z_1) + (\Delta z_1/3\lambda_i)[G(0) + \tfrac{1}{2}G(\Delta z_1)]$$

The third layer temperature is then updated using the geothermal flux GGEO. If the optional multiple-layer configuration is used, TBOT is simply set to the temperature of the lowest layer. In either the standard or the multiple-layer case, the first three layer temperatures are updated using the heat fluxes at the surface, between the first and second layers and between the second and third layers, which were determined in the CLASST subroutines. Finally, the latter fluxes are assigned to the appropriate levels in the diagnostic GFLUX vector.

In the 250 loop, the GFLUX values determined in the 150 loop are used to update the temperatures in the third and lower ice layers for the multiple-layer configuration. The calculations are bracketed by a determination of the change of internal energy I_j of the ice layers as a result of the heat fluxes, obtained as the difference in I_j between the beginning and end of the calculations:

$$\Delta I_j = X_i\Delta[C_i\Delta z_j T_{av}(\Delta z_j)]/\Delta t$$

where C_i is the heat capacity of ice, Δt is the length of the time step, and X_i is the fractional coverage of the subarea under consideration relative to the modelled area.

In the 300 loop, checks are carried out to determine whether any of the ice layer temperatures has overshot 0 C as a result of the calculations in the previous loop. If so, the excess energy is assigned to a temporary variable QADD and is also added to the total heat available for melting of the ice, QMELT. QADD is subtracted from the internal energy of the layer in questions and is added to the internal energy of the first layer, since melting is assumed to proceed from the top downwards. The temperature of the layer is reset to 0 C. Finally, the first half of a calculation of the change of internal energy of each ice layer is performed, to be completed at the end of the subroutine.

In the next three loops, the ice layers are adjusted downward to account for the removal of mass at the surface by melting or sublimation. First, the temperature TMOVE of the ice into which the layer is moving is set to the temperature of the layer below it. TMOVE for the bottom layer is set to TBOT. A depth of ice ZMELT is calculated as the amount of ice for which QMELT is sufficient to both raise its temperature to 0 C (if necessary) and melt it. The temperature of the overall runoff and the overland flow are updated as averages of the original temperature and the meltwater temperature (assumed to be at the freezing point), weighted according to their respective amounts, and the overall runoff and overland flow are incremented by ZMELT (with ZMELT converted to an equivalent water depth). The energy used for the melting of ice is calculated from ZMELT and added to HMFG for the first layer, and the amount of energy used to raise the layer temperature to 0 C is added to HTC for the first layer. The total depth of downward adjustment of the ice layers, ZMOVE, is obtained as the sum of ZMELT and the sublimation depth, calculated from EVAP. This amount is added to the diagnostic variable WTRG. Finally, the new temperature of each ice layer is calculated over the layer thickness DELZ as the average of the original temperature weighted by DELZ-ZMOVE and TMOVE weighted by ZMOVE.

In the next loops, the ice layers are adjusted upward to account for addition of mass at the surface by conversion of snow to ice. Snow is converted to ice if the mass of the snow pack exceeds 100 kg m^{-2}, or if the density exceeds 900 kg m^{-3} (approaching that of ice). In the first case the excess over and above 100 kg m^{-2} is converted; in the second, the whole snow pack is converted. These calculations are performed in the 500 loop, bracketed by a calculation of the change in internal energy of the snow pack, HTCS. In both cases the first level of the ice level movement matrix WMOVE is set to the amount of snow that is converted, expressed as a depth of ice, and the first level of the temperature matrix TMOVE is set to the snow temperature. The amount of converted snow is added to the diagnostic variables WTRS and WTRG. The depth, density and heat capacity of the snow are recalculated. If the entire snow pack is being converted and the water content WSNOW was non-zero, WSNOW is subtracted from WTRS and added to WTRG, and is also added to the total runoff and the overland flow. The runoff and overland flow temperatures are updated accordingly. The snow temperature and water content are reset to zero. The amount of ice that is lost to the bottom of the profile is added to the total runoff, and the runoff temperature is updated accordingly.

In the remaining parts of the code, the actual adjustment of ice layer positions is performed. First the levels of the available depth matrix ZRMDR are set to the ice layer thicknesses; the matrix ZMAT is initialized to zero; and each level J of WMOVE and TMOVE from 2 to the bottom of the ice profile is set to the value of DELZ and TBAR respectively of the J-1 ice level. The ZMAT matrix represents the depth of each ice layer J that is occupied by ice from level K in the layer movement matrix WMOVE after the layer adjustments are complete. In the 700 loop, starting at the top of the ice profile, an attempt is made to assign each layer of WMOVE in turn to the K,J level of ZMAT. If the calculated value of ZMAT is greater than the available depth ZRMDR of the layer, ZMAT is set to ZRMDR, WMOVE is decremented by ZRMDR, and ZRMDR is set to zero. Otherwise the calculated value of ZMAT is accepted, ZRMDR is decremented by ZMAT, and WMOVE is set to zero. Finally, the 900 loop is performed over each ice layer J to determine the new layer temperature. The temperature adjustment variable TADD is initialized to zero, and then incremented by the temperature TMOVE of each level K weighted by the corresponding K,J level of ZMAT, and finally by the original layer temperature weighted by the corresponding level of ZRMDR. The layer temperature is reset to TADD normalized by DELZ, and the updating of HTC, begun at the end of the 300 loop, is completed.

GRINFL

Purpose: Quantify movement of liquid water between soil layers under conditions of infiltration.

Input/Output variables:

BASFLW	Base flow from bottom of soil column [m]
BI	Clapp and Hornberger empirical "b" parameter [ ] (b)
DELZW	Permeable depth of soil layer [m] ($\Delta z_{g,w}$)
DT	Time period over which water movement takes place [s]
EVAP	Evaporation rate from ground surface [m s^{-1}]
FDT	Water flow at soil layer interfaces during current time step [m]
FI	Fractional coverage of subarea in question on modelled area [ ]
GRKSAT	Hydraulic conductivity of soil at saturation [m s^{-1}] (K_{sat})
IGRD	Flag to indicate whether calculations in subroutine GRDRAN are to be done
IGRN	Flag to indicate whether calculations in this subroutine are to be done
ISAND	Sand content flag
IVEG	Subarea type flag
LZFAV	Soil layer index in which the average position of the wetting front occurs
PSISAT	Soil moisture suction at saturation [m] (ψ_{sat})
QFG	Evaporation from soil surface (diagnostic) [kg m^{-2} s^{-1}]
R	Rainfall rate at ground surface [m s^{-1}]
RUNOFF	Total runoff from soil column [m]
THICE	Volumetric frozen water content of soil layer [m^3 m^{-3}] (θ_i)
THLIQ	Volumetric liquid water content of soil layer [m^3 m^{-3}] (θ_l)
TBARW	Temperature of water in soil layer [C]
TBASFL	Temperature of base flow from bottom of soil column [K]
TFDT	Temperature of water flowing between soil layers [C]
THFC	Field capacity [m^3 m^{-3}]
THLINV	Liquid water content behind the wetting front [m^3 m^{-3}]
THLMIN	Residual soil liquid water content remaining after freezing or evaporation [m^3 m^{-3}] ($\theta_{l,min}$)
THLRAT	Fractional saturation of soil behind the wetting front [ ] (f_{inf})
THLRET	Liquid water retention capacity for organic soil [m^3 m^{-3}] ($\theta_{l,ret}$)
THPOR	Pore volume in soil layer [m^3 m^{-3}] (θ_p)
TPOND	Temperature of ponded water [C]
TR	Temperature of rainfall [C]
TRUNOF	Temperature of total runoff from soil column [K]
WLOST	Residual amount of water that cannot be supplied by surface stores [kg m^{-2}]
XDRAIN	Drainage index for water flow at bottom of soil profile [ ]
ZBOTW	Depth to permeable bottom of soil layer [m]
ZFAV	Average depth of wetting front over current time step [m]
ZPOND	Depth of ponded water on soil surface [m]

In loop 50, the flag IGRN is first set to 1 for all grid cells where the calculations in this subroutine are to be performed. The necessary conditions are: that the surface being modelled is not a glacier or ice sheet (ISAND > -4); that the time period DT is greater than zero; and that either the rainfall rate is greater than zero or that ponded water exists on the surface. If any of these conditions is not met, IGRN is set to zero.

In loops 100 and 150, a series of local arrays THLIQX, THICEX, TBARWX, DELZX and ZBOTX are defined for use in the subsequent infiltration calculations, with a "y" dimension of IG+1, where IG is the number of soil layers. The entries from 1 to IG are set equal to the corresponding values in THLIQ, THICE, TBARW, DELZW and ZBOTW. The last entry is set equal to the values for the last soil layer in the case of THLIQX, THICEX and TBARWX; for DELZX and ZBOTX they are set to large positive numbers, unless the drainage index at the bottom of the soil profile is zero, in which case DELZX is set to zero. An effective saturated hydraulic conductivity GRKSATF is calculated for each soil layer, applying an empirical correction for the presence of ice. This ice content factor, f_{ice}, is calculated from Zhao and Gray (1997) as:

$$f_{ice} = [1.0 - \min(1.0, \theta_i/\theta_p)]^2$$

To further account for the presence of ice, a modified pore volume THPORF for the soil layer is calculated as the maximum of the available pore volume $\theta_p - \theta_i$ (where θ_p is the total pore volume and θ_i is the ice content of the layer), the actual liquid water content θ_l, and the minimum residual liquid water content $\theta_{l,min}$. (The last two conditions are required because in the case of a saturated soil undergoing freezing, since water expands when frozen, the sum of the liquid and frozen volumetric water contents may be greater than the pore volume, and thus θ_l or $\theta_{l,min}$ may be greater than $\theta_p - \theta_i$.) Finally, the water content THLINF and the hydraulic conductivity GRKINF behind the wetting front are evaluated, following the analysis of Green and Ampt (1911) and treating the change in soil moisture due to infiltration as a downward-propagating square wave. THLINF is calculated as the maximum of $f_{inf}(\theta_p - \theta_i)$, θ_l, and $\theta_{l,min}$, where f_{inf} represents the fractional saturation of the soil behind the wetting front, corresponding to a hydraulic conductivity of half the saturated value (this correction is applied in order to account for the fact that as infiltration occurs, a small amount of air is usually trapped in the soil). GRKINF is calculated from GRKSATF, THLINF and THPORF, using the classic Clapp and Hornberger (1978) equation

$$K(z) = K_{sat} (\theta_l/\theta_p)^{(2b + 3)}$$

where K(z) is the hydraulic conductivity at a depth z, K_{sat} is the hydraulic conductivity at saturation, θ_p is the pore volume and b is an empirical coefficient.

In loop 200, the soil water suction across the wetting front ψ_f is calculated for each soil layer, using equation 25 in Verseghy (1991)

$$\psi_f = b[\psi_{inf}K_{inf} - \psi(z)K(z)]/[K_{inf}(b+3)]$$

where ψ_{inf} and K_{inf} are the soil moisture suction and the hydraulic conductivity behind the wetting front, and $\psi(z)$ and K(z) are the soil moisture suction and the hydraulic conductivity ahead of the wetting front. The soil moisture suction values are obtained using the classic Clapp and Hornberger (1978) equation:

$$\psi(z) = \psi_{sat} (\theta_l/\theta_p)^{(-b)}$$

where ψ_{sat} is the soil moisture suction at saturation.

In loop 400, a test is carried out to determine whether saturated conditions are already present in the soil. Generally it is assumed that a period of unsaturated flow occurs initially, so the flag IFILL is set to 1, the depth of the wetting front ZF is set to zero, and the flag LZF indicating the index of the soil layer in which the wetting front occurs is set to 1. If a pond is present on the soil surface or if the hydraulic conductivity if the first soil layer is very small, it is deemed that saturated flow begins immediately, so IFILL is set to zero. Then each soil layer is checked in turn, to ascertain whether the liquid water content is greater than THLINF. If so, it is concluded that saturated flow is occurring in this layer; ZF is set to ZBOTW, the depth of the bottom of the soil layer, LZF is set to the index of the next layer, and IFILL is set to zero. For each layer found to be undergoing saturated flow, its water content is stored in the J+1 level of the water movement matrix WMOVE, and its water temperature is stored in the J+1 level of the matrix TMOVE. The counter NINF is set to the number of soil layers behind and including the one with the wetting front, plus 2.

A series of subroutines is called to complete the infiltration calculations. Subroutine WFILL treats the period of unsaturated flow up the point when saturated flow begins. Subroutine WFLOW treats the period of saturated flow. Subroutine WEND reassigns liquid water contents and temperatures at the conclusion of the infiltration period. THLIQ, THICE and TBARW are then set to the corresponding updated values of THLIQX, THICEX and TBARWX. The average depth of the wetting front in the soil layer in which it occurs, the index of the soil layer, and the moisture content behind the wetting front are stored in output variables ZFAV, LZFAV and THLINV respectively. Finally, if there is any time remaining in the current time step following the infiltration period, subroutine GRDRAN is called to treat the movement of soil water over the remainder of the time step.

WFILL

Purpose: Evaluate infiltration of water into soil under unsaturated conditions.

Input/Output variables:

DELZX	Permeable depth of soil layer [m] ($\Delta z_{g,w}$)
GRKINF	Hydraulic conductivity of soil behind the wetting front [m s^{-1}]
IFILL	Flag indicating whether unsaturated infiltration is occurring
LZF	Index of soil layer in which wetting front is located
NINF	Number of levels involved in water movement
PSIF	Soil water suction across the wetting front [m]
R	Rainfall rate at ground surface [m s^{-1}]
TBARWX	Temperature of water in soil layer [C]
THLINF	Volumetric liquid water content behind the wetting front [m^3 m^{-3}]
THLIQX	Volumetric liquid water content of soil layer [m^3 m^{-3}]
TMOVE	Temperature matrix associated with ground water movement [C}
TR	Temperature of rainfall [C]
TRMDR	Remainder of time step after unsaturated infiltration ceases [s]
WMOVE	Water movement matrix [m^3 m^{-2}]
ZBOTX	Depth of bottom of soil layer [m]
ZF	Depth of the wetting front [m]

The infiltration rate F_{inf} under conditions of a constant water supply can be expressed, e.g. in Mein and Larson (1973), as

$$F_{inf} = K_{inf} [(\psi_f + z_f)/z_f]$$

where K_{inf} is the hydraulic conductivity of the soil behind the wetting front, ψ_f is the soil moisture suction across the wetting front, and z_f is the depth of the wetting front. It can be seen that F_{inf} decreases with increasing z_f to an asymptotic value of K_{inf}. Thus, if the rainfall rate r is less than K_{inf}, the actual infiltration rate is limited by r, i.e. $F_{inf} = r$. Otherwise, F_{inf} will be equal to r until the right-hand side of the above equation becomes less than r, after which point the above equation applies and ponding of excess water begins on the surface. The depth of the wetting front at this time t_p can be calculated by setting F_{inf} equal to r in the above equation and solving for z_f. This results in:

$$z_f = \psi_f /[r/K_{inf} - 1]$$

The amount of water added to the soil up to the time of ponding is $t_p r$, or $z_f(\theta_{inf} - \theta_l)$, where θ_l and θ_{inf} are respectively the liquid water content of the soil before and after the wetting front has passed. Setting these two equal and solving for t_p results in

$$t_p = z_f (\theta_{inf} - \theta_l)/r$$

In the 100 loop, a check is done for each successive soil layer to compare the infiltration rate in the layer with the rainfall rate. If $K_{inf} < r$, a test calculation is performed to determine where the depth of the wetting front would theoretically occur at the ponding time t_p. If the calculated value of z_f is less than the depth of the top of the soil layer, z_f is set to the depth of the top of the layer; if z_f falls within the soil layer, that value of z_f is accepted. In both cases, the index LZF is set to the index of the layer, and the flag IFIND, indicating that z_f, has been successfully located, is set to 1. If the infiltration rate in the soil layer is greater than the rainfall rate, z_f is provisionally set to the bottom of the current layer, and LZF to the index of the next layer. IFIND remains zero. If the infiltration rate in the layer is vanishingly small, z_f is set to the depth of the top of the current layer, LZF to the index of the overlying layer, and IFIND to 1.

If LZF is greater than 1, some adjustment to the equation for t_p above is required to account for the fact that the values of θ_{inf} and θ_l in the layer containing the wetting front may differ from those in the overlying layers. The equation for t_p above can be rewritten as

$$t_p = [z_f [\theta_{inf}(z_f) - \theta_l(z_f)] + w_{adj}]/r$$

where w_{adj} is calculated as

$$w_{adj} = \sum_{i=1}^{LZF-1} [(\theta_{inf,i} - \theta_{l,i}) - (\theta_{inf}(z_f) - \theta_l(z_f))] \Delta z_{g,w}$$

The adjusting volume WADJ is calculated in loop 200, and the time to ponding TIMPND in loop 250. If TIMPND is greater than the amount of time remaining in the current time step TRMDR, then unsaturated infiltration is deemed to be occurring over the entire time step. In this case, the amount of water infiltrating over the time step is assigned to the first level of the water movement matrix WMOVE and to the accounting variable WADD, and the temperature of the infiltrating water is assigned to the first level of the matrix TMOVE. In loop 300 WADD is partitioned over the soil profile by comparing in turn the liquid water content of each soil layer with the calculated liquid water content behind the wetting front THLINF, and decrementing WADD layer by layer until a layer is reached in which the remainder of WADD is insufficient to raise the liquid water content to THLINF. If this condition is reached, LZF is set to the index of the soil layer; the depth of the wetting front DZF within the layer, obtained as WADD/(THLINF-THLIQX), is added to the depth of the bottom of the overlying layer to obtain ZF. In loop 400, the water content in each soil layer J existing above ZF is assigned to the J+1 level of the water movement matrix WMOVE, and the respective water temperatures are assigned to TMOVE.

If TIMPND < TRMDR, the amount of water infiltrating between the start of the time step and TIMPND is again assigned to the first level of the water movement matrix WMOVE, and the temperature of the infiltrating water is assigned to the first level of the matrix TMOVE. The depth DZF of the wetting front within the layer containing it is calculated by subtracting the depth of the bottom of the overlying layer from ZF. In loop 500, the water content in each soil layer J existing above ZF is assigned to the J+1 level of the water movement matrix WMOVE, and the respective water temperatures are assigned to TMOVE. Finally, the time remaining in the current time step after the period of unsaturated infiltration is recalculated, and the counter NINF is set to LZF+1.

WFLOW

Purpose: Evaluate infiltration of water into soil under saturated conditions.

Input/Output variables:

DELZX	Permeable depth of soil layer [m] ($\Delta z_{g,w}$)
EVAP	Surface evaporation rate [m s^{-1}]
GRKINF	Hydraulic conductivity of soil behind the wetting front [m s^{-1}] (K_{inf})
IGRN	Flag to indicate whether infiltration is occurring
LZF	Index of soil layer in which wetting front is located
NINF	Number of levels involved in water movement
PSIF	Soil water suction across the wetting front [m] (ψ_f)
R	Rainfall rate at ground surface [m s^{-1}]
TBARWX	Temperature of water in soil layer [C]
THLINF	Volumetric liquid water content behind the wetting front [m^3 m^{-3}]
THLIQX	Volumetric liquid water content of soil layer [m^3 m^{-3}]
TMOVE	Temperature matrix associated with ground water movement [C}
TPOND	Temperature of ponded water [C]
TR	Temperature of rainfall [C]
TRMDR	Time remaining in current time step [s]
WMOVE	Water movement matrix [m^3 m^{-2}]
ZBOTX	Depth of bottom of soil layer [m]
ZF	Depth of the wetting front [m] (z_f)
ZPOND	Depth of ponded water [m] (z_p)

The infiltration rate F_{inf} under saturated conditions is calculated as

$$F_{inf} = K_{inf} [(\psi_f + z_f + z_p)/z_f]$$

where K_{inf} is the hydraulic conductivity of the soil behind the wetting front, ψ_f is the soil moisture suction across the wetting front, z_f is the depth of the wetting front, and z_p is the depth of water ponded on the surface. Since ψ_f will vary by soil layer, and z_f and z_p will vary with time, the period of infiltration is divided into two-minute segments. A maximum iteration flag NEND is defined as the number of iteration segments plus 10, as a safeguard against runaway iterations. Since the surface infiltration rate will be limited by the lowest infiltration rate encountered, a maximum infiltration rate FMAX is defined as the minimum value of GRKINF, the hydraulic conductivity behind the wetting front, in all of the soil layers above and including that containing the wetting front.

In loop 200, a check is performed to determine whether the liquid water content of the current soil layer, THLIQX, equals or exceeds that behind the wetting front, THLINF. If so, the depth of the wetting front is reset to the depth of the soil layer. The water content of the soil layer is assigned to the level of the water movement matrix WMOVE corresponding to the soil layer index plus 1, and the temperature of the water in the layer is assigned to the same level of the matrix TMOVE. FMAX is recalculated, and the flags LZF and NINF are each incremented by 1. The flag ISIMP is set to 1, indicating that the following calculations are to be bypassed for this iteration.

If ISIMP is not 1, the time period DTFLOW applying to the current iteration loop is set to two minutes or to the remainder of the time step, whichever is less. If GRKINF for the current soil layer is not vanishingly small, the flag ISIMP is set to -2. Otherwise, it is deemed that infiltration is suppressed, and the temperature and depth of water ponded on the surface are simply updated. The temperature of the ponded water is calculated as the weighted average of the current pond temperature and the rainfall added to it. The ponded water remaining after rainfall and evaporation have taken place is calculated as ZPTEST. If ZPTEST is less than zero, it is deduced that evaporation must have removed the ponded water before the end of the current iteration loop. If this is the case, the time period of the current iteration loop is recalculated as the amount of time required for the difference between the evaporation and the rainfall rates to consume the ponded water, and the pond depth ZPOND is set to zero. Otherwise, ZPOND is set to ZPTEST. Finally, ISIMP is set to -1.

The 400 loop addresses the infiltration process under saturated conditions. Such infiltration is modelled as "piston flow". First the current infiltration rate FINF is calculated using the equation given above. If the wetting front has passed the bottom of the lowest soil layer, ψ_f is neglected. If FINF is greater than the rainfall rate R, FINF is set equal to R; if FINF is greater than FMAX, FINF is set equal to FMAX. If the wetting front has not passed the bottom of the lowest soil layer, the change in depth of the wetting front DZF over the current time interval is calculated from the amount of infiltrating water WINF and the volumetric water content behind the wetting front, THLINF. The amount of soil water WDISP displaced by this movement of the wetting front is calculated from DZF and THLIQX, and the depth to which this water penetrates, DZDISP, is calculated as WDISP/(THLINF – THLIQX). The amount of soil water WABS entrained by the movement of WDISP itself is calculated as the product of DZDISP and THLIQX. The change in depth of the wetting front, behind which the liquid water content of the soil layer is THLINF, is now the sum of the depth represented by infiltration of water at the surface, DZF, and the depth represented by displacement of the pre-existing soil water, DZDISP. If this change in depth causes the wetting front to move beyond the bottom of the current soil layer, DTFLOW is recalculated as the amount of time required for the composite wetting front to reach the bottom of the soil layer, and DZF, WDISP, DZDISP and WABS are likewise recalculated. As in the case for ISIMP = -1, the temperature of the ponded water on the surface is calculated as the weighted average of the current pond temperature and the rainfall added to it. The ponded water remaining after rainfall, infiltration and evaporation have taken place is calculated as ZPTEST. If ZPTEST is less than zero, it is deduced that infiltration and evaporation must have removed the ponded water before the end of the current iteration loop. If this is the case, the time period of the current iteration loop is recalculated as the amount of time required for the infiltration and evaporation minus the rainfall to consume the ponded water. The pond depth ZPOND is set to zero; if the wetting front has not passed the bottom of the lowest soil layer, DZF, WDISP, DZDISP and WABS are recalculated. Otherwise, ZPOND is set to ZPTEST. Finally, the first layer of the water movement matrix WMOVE is incremented with the amount of the infiltrated water, and the first layer of the matrix TMOVE with the temperature of the infiltrated water. The last layer of WMOVE is incremented by WDISP+WABS, and the depth of the wetting front by DZF+DZDISP.

In the 500 loop, if ISIMP < 0 (i.e. water movement has occurred), the time remaining in the current time step is recalculated. If the wetting front is at a soil layer boundary, if the time remaining is non-zero, if the wetting front is still within the modelled soil column, and if the calculated water content behind the wetting front is greater than zero, FMAX is updated, and LZF and NINF are incremented by 1. The NINF level of the TMOVE matrix is set to the water temperature of the new soil layer.

At the end of the iteration pass, checks are done in the 600 loop to ascertain whether the number of iteration passes is still less than NEND, whether either ponded water still exists or rain is still falling, and whether there is still time remaining in the current time step. If these conditions are all fulfilled, the counter NPNTS representing the number of points in the current vector of mosaic tiles for which infiltration is still occurring is incremented by 1. Otherwise, the iteration flag for the current tile is changed from 1 to 0, signaling the end of the saturated infiltration calculations for that tile.

WEND

Purpose: Recalculate liquid water content of soil layers after infiltration, and evaluate baseflow.

Input/Output variables:

BASFLW	Base flow from bottom of soil column [kg m^{-2}]
DELZX	Permeable depth of soil layer [m]
FI	Fractional coverage of subarea in question on modelled area [ ]
IGRN	Flag to indicate whether infiltration is occurring
LZF	Index of soil layer in which wetting front is located
NINF	Number of levels involved in water movement
RUNOFF	Total runoff from soil column [m]
TBARWX	Temperature of water in soil layer [C]
TBASFL	Temperature of base flow from bottom of soil column [K]
THLINF	Volumetric liquid water content behind the wetting front [m^3 m^{-3}]
THICEX	Volumetric frozen water content of soil layer [m^3 m^{-3}]
THLIQX	Volumetric liquid water content of soil layer [m^3 m^{-3}]
THLMIN	Residual soil liquid water content remaining after freezing or evaporation [m^3 m^{-3}]
TMOVE	Temperature matrix associated with ground water movement [C}
TPOND	Temperature of ponded water [C]
TRMDR	Time remaining in current time step [s]
TRUNOF	Temperature of total runoff from soil column [K]
WMOVE	Water movement matrix [m^3 m^{-2}]
ZPOND	Depth of ponded water [m]

At levels in the soil profile lower than the bottom of the wetting front, redistribution of soil liquid water proceeds in response to normal gravity and suction forces. Subroutine GRDRAN is called to calculate these redistributions, making use of dummy variables THLDUM, THIDUM and TDUMW which are set equal to the liquid water content, the frozen water content and the water temperature of the soil layers respectively. The time period TUSED that is passed to GRDRAN is set to the time period over which infiltration was occurring during the current time step, except if the wetting front has passed the bottom of the lowest soil layer, in which case TUSED is set to zero (since the flows calculated by GRDRAN are not required).

After GRDRAN has been called, the maximum value of the water movement index NINF is set to the number of soil layers plus 1. The values in the matrix ZRMDR, representing for each soil layer the depth that has not been affected by infiltration, are initialized to the soil permeable layer thicknesses DELZX. The water flows FDT coming out of GRDRAN are set to zero at the soil layer interfaces above the wetting front. For the layer containing the wetting front, if the flow at the bottom of the layer is upward, it is set to zero (to avoid possible overflows in liquid water content).

The values in the three-dimensional matrix ZMAT are initialized to zero. This matrix contains the depth of each soil layer J (including the dummy soil layer below the lowest layer) that is filled by water from level K in the water movement matrix WMOVE. In WMOVE, the first level contains the amount of water that has infiltrated at the surface during the time period in question, and each successive level K contains the amount of water in soil layer K-1 that has been displaced during the infiltration, down to the soil layer containing the wetting front. Thus, the number of levels in WMOVE that are used in the current infiltration calculations, NINF, is equal to LZF+1, where LZF is the index of the soil layer containing the wetting front; or to IGP1, the number of soil layers IG plus 1, if LZF is greater than IG, i.e. if the wetting front has penetrated below the bottom of the lowest soil layer into the underlying dummy layer. In the 400 loop, starting at the top of the soil profile, an attempt is made to assign each layer of WMOVE, converted into a depth by using the volumetric water content THLINF behind the wetting front for the soil layer, in turn to the K,J level of ZMAT. If the calculated value of ZMAT is greater than the available depth ZRMDR of the layer, ZMAT is set to ZRMDR, WMOVE is decremented by ZRMDR converted back to a water amount, and ZRMDR is set to zero. Otherwise the calculated value of ZMAT is accepted, ZRMDR is decremented by ZMAT, and WMOVE is set to zero. At the end of these calculations, any remaining residual amounts in the WMOVE matrix are assigned to ponded water, and the ponded water temperature is updated accordingly.

As a result of the above processes, the liquid water content and temperature of each soil layer (excluding the bottom, dummy layer) will be a combined result of infiltration processes (WADD, TADD), redistribution processes (WDRA, TDRA), and water in the layer that has remained unaffected (WREM, TREM). For each layer, WADD is calculated by summing over the respective ZMAT values corresponding to that layer multiplied by THLINF, and TADD by summing over the ZMAT and THLINF values multiplied by the respective TMOVE values. WREM is obtained as the product of the original water content THLIQX multiplied by ZRMDR, and TREM as the product of the water temperature TBARWX, THLIQX and ZRMDR. For the soil layer containing the wetting front, a check is carried out to determine whether the liquid moisture content resulting from the infiltration and drainage processes, THINFL, is less than the residual liquid moisture content THLMIN. If so, the flow FDT at the bottom of the layer is recalculated as the value required to keep THLIQX at THLMIN. WDRA is obtained from the difference between the water fluxes FDT at the top and bottom of the layer, supplied by GRDRAN, and TDRA is obtained from the water fluxes FDT and their corresponding temperatures TFDT. Finally, THLIQX is calculated as the sum of WADD, WREM and WDRA normalized by DELZX, and TBARWX as the sum of TADD, TREM and TDRA normalized by the product of THLIQX and DELZX.

Lastly, the base flow BASFLW at the bottom of the soil profile and its temperature TBASFL are calculated. If the wetting front is located in the dummy soil layer below the soil profile, BASFLW is obtained by summing over the ZMAT values for the IGP1 level, multiplied by the dummy layer THLINF value and the fractional coverage FI of the modelled subarea. TBASFL is similarly obtained as the weighted average of the original TBASFL and the values of TMOVE corresponding to the ZMAT values. The overall subarea runoff RUNOFF and its temperature TRUNOF are calculated in the same manner without the FI weightings. If the wetting front has not reached the bottom of the soil profile, the baseflow and total runoff are obtained from the value of FDT at the top of the dummy layer, and their temperatures from the values of TFDT and FDT at the top of the dummy layer.

GRDRAN

Purpose: Quantify movement of liquid water between soil layers under non-infiltrating conditions, in response to gravity and tension forces.

Input/Output variables:

BASFLW	Base flow from bottom of soil column [m]
BI	Clapp and Hornberger empirical "b" parameter [ ] (b)
DELZW	Permeable depth of soil layer [m] ($\Delta z_{g,w}$)
DT	Time period over which water movement takes place [s]
EVAP	Evaporation rate from ground surface [m s^{-1}]
FDT	Water flow at soil layer interfaces during current time step [m]
FI	Fractional coverage of subarea in question on modelled area [ ] (X_i)
GRKSAT	Hydraulic conductivity of soil at saturation [m s^{-1}] (K_{sat})
IGRD	Flag to indicate whether calculations in this subroutine are to be done
IGRN	Flag to indicate whether calculations in subroutine GRINFL are done
ISAND	Sand content flag
IVEG	Subarea type flag
PSISAT	Soil moisture suction at saturation [m] (ψ_{sat})
QFG	Evaporation from soil surface (diagnostic) [kg m^{-2} s^{-1}]
R	Rainfall rate at ground surface [m s^{-1}]
RUNOFF	Total runoff from soil column [m]
THICE	Volumetric frozen water content of soil layer [m^3 m^{-3}] (θ_i)
THLIQ	Volumetric liquid water content of soil layer [m^3 m^{-3}] (θ_l)
TBARW	Temperature of water in soil layer [C]
TBASFL	Temperature of base flow from bottom of soil column [K]
TFDT	Temperature of water flowing between soil layers [C]
THFC	Field capacity [m^3 m^{-3}]
THLMIN	Residual soil liquid water content remaining after freezing or evaporation [m^3 m^{-3}] ($\theta_{l,min}$)
THLRET	Liquid water retention capacity for organic soil [m^3 m^{-3}] ($\theta_{l,ret}$)
THPOR	Pore volume in soil layer [m^3 m^{-3}] (θ_p)
TRUNOF	Temperature of total runoff from soil column [K]
WLOST	Residual amount of water that cannot be supplied by surface stores [kg m^{-2}]
XDRAIN	Drainage index for water flow at bottom of soil profile [ ]
ZPOND	Depth of ponded water on soil surface [m]

In loop 50, the flag IGRD is first set to 1 for all grid cells where the calculations in this subroutine are to be performed. The necessary conditions are: that the surface being modelled is not a glacier or ice sheet (ISAND > -4); that the time period DT is greater than zero; that the infiltration calculations in subroutine GRINFL are not simultaneously being performed (IGRN = 0); and that the rainfall rate and the depth of ponded water are both vanishingly small. If any of these conditions is not met, IGRD is set to zero.

In loop 100, if the surface being modelled is not an ice sheet (ISAND = -4) and if the soil layer in question is not completely rock (ISAND = -3), the maximum possible water content of each soil layer, THLMAX, is calculated as the maximum of the available pore volume $\theta_p - \theta_i$ (where θ_p is the total pore volume and θ_i is the ice content of the layer), the actual liquid water content θ_l, and the minimum residual liquid water content $\theta_{l,min}$. The last two conditions are required because in the case of a saturated soil undergoing freezing, since water expands when frozen, the sum of the liquid and frozen volumetric water contents may be greater than the pore volume, and thus θ_l or $\theta_{l,min}$ may be greater than $\theta_p - \theta_i$. An effective saturated hydraulic conductivity GRKSATF of the soil layer is also defined, applying an empirical correction for the presence of ice. This ice content factor, f_{ice}, is calculated from Zhao and Gray (1997) as:

$$f_{ice} = [1.0 - \min((\theta_p - \theta_{l,min})/\theta_p, \theta_i/\theta_p)]^2$$

Finally, the pore volume of the soil layer is corrected for the presence of ice by defining the effective pore volume THPORF as equivalent to THLMAX.

In loops 150 and 200, the theoretical amounts of water FDT flowing across the soil layer boundaries are calculated. FDT is calculated as the product of the flow rate F(z) at the given depth z, and the period of time (DT) over which the flow is occurring. At z=0, the water flux is simply equal to the soil surface evaporation rate. Within the soil, the flow rate F at a given depth z is obtained using equation 21 from Verseghy (1991):

$$F(z) = K(z)\ [-b\psi(z)/\theta_l(z) \cdot d\theta_l/dz + 1]$$

where K(z) is the hydraulic conductivity and $\psi(z)$ is the soil moisture suction at depth z, and b is an empirical parameter developed by Clapp and Hornberger (1978). K(z) and $\psi(z)$ are calculated following Clapp and Hornberger as

$$K(z) = K_{sat}\ (\theta_l/\theta_p)^{(2b + 3)}$$

and

$$\psi(z) = \psi_{sat}\ (\theta_l/\theta_p)^{(-b)}$$

where K_{sat} and ψ_{sat} are the values of K and ψ respectively at saturation. At the bottom of the soil profile it is assumed that $d\theta_l/dz$ is effectively zero, so F(z) = K(z), multiplied by a drainage parameter XDRAIN, which is set to 0 if the soil is underlain by an impermeable layer (as in a bog), and to 1 otherwise.

Between soil layers, values of K(z) and $\psi(z)$ must be determined. This requires the estimation of soil properties at the layer interfaces. For θ_l, θ_p and $d\theta_l/dz$, slightly different approaches are followed if the permeable soil layer thickness DELZW increases with depth (the normal case), or if it decreases between one soil layer and the next (indicating the presence of an impermeable barrier at some depth in the second layer). In the first case, the pore volume THPBND, liquid water content THLBND, and liquid water gradient DTHLDZ are simply calculated as arithmetic averages of the values above and below the interface. This has the effect of weighting the interface values towards the upper layer values, roughly emulating a surfaceward exponential decay curve of liquid water content. In the second case, in order to avoid a spurious weighting towards the lower layer, the gradients of liquid water content and pore volume between the upper and lower layers are calculated as linear relations, and then solved for the values at the interface.

The Clapp and Hornberger b parameter at the interface is calculated as a simple average of the values in the upper and lower soil layers. The saturated hydraulic conductivity $K_{sat,bnd}$ is calculated as a harmonic mean, and the saturated soil moisture suction $\psi_{sat,bnd}$ as a geometric mean, of the top and bottom layer values:

$$K_{sat,bnd} = K_{sat,t}\, K_{sat,b}\, (\Delta z_{g,w,,t} + \Delta z_{g,w,,b})/(K_{sat,t}\, \Delta z_{g,w,b} + K_{sat,b}\, \Delta z_{g,w,t})$$

$$\psi_{sat,bnd} = \psi_{sat,t}^{\Delta zg,w,t/(\Delta zg,w,t + \Delta zg,w,b)}\, \psi_{sat,b}^{\Delta zg,w,b/(\Delta zg,w,t + \Delta zg,w,b)}$$

Finally, K(z), ψ(z) and F(z) at the interface are calculated from the equations given above.

In the next several loops, checks are carried out to ascertain whether the theoretically determined flow rates at the soil layer interfaces can be supported by the water contents in the layers. At the beginning of loop 250, the soil surface evaporation rate is addressed. A trial liquid water content THTEST is calculated for the first soil layer, reflecting the removal of the evaporated water. If THTEST is less than the minimum soil water content, F(0) is set to zero and θ_l is set to $\theta_{l,min}$. The excess surface flux that was not met by the removed liquid water is converted to a frozen water content, and an attempt is made to remove it from the frozen water in the layer. (The energy involved in converting the required frozen water mass to liquid water is obtained by decreasing the water temperature of the layer.) The frozen water content of the layer is adjusted to reflect the removal of the required amount. If the demand exceeds the supply of frozen water available, the frozen water content is set to zero, the diagnostic evaporative flux QFG at the soil surface is adjusted, and the remaining water flux not able to be met by the first soil layer is assigned to the variable WLOST.

In the remainder of the 250 loop, checks are carried out for soil layers with liquid water contents already effectively equal to $\theta_{l,min}$. If the flux at the top of the layer is upward and that at the bottom of the layer is downward, both are set to zero. If both are downward, only the flux at the bottom is set to zero; if both are upward, only the flux at the top is set to zero. If the soil layer is an organic one and the liquid water content is less than the layer retention capacity $\theta_{l,ret}$ and the flux at the bottom of the layer is downward, it is set to zero.

In the 300 loop, checks are carried out for soil layers with liquid water contents already effectively equal to THLMAX. If the flux at the top of the layer is downward and that at the bottom of the layer is upward, both are set to zero. If both are downward, then if the top flux is greater than the bottom flux, it is set equal to the bottom flux. If both are upward, then if magnitude of the bottom flux is greater than that of the top flux, it is set equal to the top flux.

In the 400 loop, for each soil layer THTEST is recalculated as the liquid water content resulting from the updated boundary fluxes, and is compared with a residual value THLTHR. For organic soil layers deeper than the first layer, THLTHR is set to the minimum of $\theta_{l,ret}$ and θ_l, since only evapotranspiration can cause the soil moisture to fall below the retention capacity. (The first layer is excepted because surface evaporation can drive its moisture content below $\theta_{l,ret}$.) For mineral soils, THLTHR is set to $\theta_{l,min}$. If THTEST < THLTHR, then if the flow at the bottom of the soil layer is downward, it is recalculated as the sum of the flow at the top of the layer plus the amount of water that must be removed to make the liquid water content of the layer equal to THLTHR. If the flow at the bottom of the layer is upward, the flow at the top of the layer is recalculated as the sum of the flow at the bottom of the layer minus the amount of water that must be removed to make the liquid water content of the layer equal to THLTHR. THTEST of the current layer is then reset to THLTHR, and THTEST of the overlying and underlying layers (if any) are recalculated using the new interface fluxes.

In the 500 loop, for each soil layer THTEST is compared with THLMAX. If THTEST > THLMAX, two temporary variables are defined: WLIMIT as the amount of water required to raise the liquid water content of the soil layer to THLMAX, and WEXCES as the amount of water representing the excess of THTEST over THLMAX. If the flux at the top of the layer is downward and the flux at the bottom of the layer is upward, then if the flux at the top of the layer is greater than WLIMIT, it is set equal to WLIMIT and the flux at the bottom is set to zero. If the flux at the top of the layer is less than WLIMIT, the flux at the bottom is set to the difference between the flux at the top and WLIMIT. If both the flux at the top and the flux at the bottom are downward, then WEXCES is subtracted from the flux at the top. If both are upward, then WEXCES is added to the flux at the bottom, and a correction is applied to the flux at the bottom of the underlying layer. Finally, THTEST is recalculated for all the soil layers using the new interface fluxes.

In the first part of the 600 loop, a correction is performed in the unlikely event that as a result of the above adjustments, the flux at the bottom of the last soil layer has become upward. If this occurs, all of the fluxes are corrected by the inverse of this same amount. However, this will result in a small spurious upward water flux at the surface. Since the liquid water flows are now accounted for, an attempt is made, as in loop 250, to remove the required water from the frozen water store in the first layer. The excess that cannot be supplied from this source is assigned to WLOST.

In the second part of the 600 loop, the temperatures TFDT of the water fluxes at the top and bottom of the soil profile are set equal to the temperatures of the water in the first and last soil layers respectively. The flow at the bottom of the soil profile and the temperature of the flow are used to update BASFLW and TBASFL, the baseflow from the current subarea and its temperature, and RUNOFF and TRUNOF, the total runoff from the grid cell in question and its temperature.

In the 700 loop, for each successive soil layer the temperature of the water flux at the bottom of the layer is first assigned. If the flux is downward, TFDT is set to the temperature of the water in the current layer; if it is upward, TFDT is set to the temperature of the water in the layer below. The temperature of the water in the current layer is then updated using the FDT and TFDT values at the top and bottom of the layer, and the liquid water content of the layer is set to THTEST.

TMCALC

Purpose: Calculate overland flow; step ahead pond and soil layer temperatures, and check for freezing of the pond and freezing or thawing of liquid or frozen water in the soil layers. Adjust pond temperature, soil layer temperatures and water stores accordingly.

Input/Output variables:

ALBSNO	Albedo of snow [ ]
DELZ	Overall thickness of soil layer [m]
DELZW	Permeable thickness of soil layer [m] ($\Delta z_{g,w}$)
DELZZ	Soil layer thicknesses to bottom of permeable depth for standard three-layer configuration, or to bottom of thermal depth for multiple layers [m] ($\Delta z_{g,z}$)
FI	Fractional coverage of subarea in question on modelled area [ ] (X_i)
G12	Heat flow between first and second soil layers [W m^{-2}]
G23	Heat flow between second and third soil layers [W m^{-2}]
GFLUX	Heat flow between soil layers [W m^{-2}]
GGEO	Geothermal heat flux at bottom of soil profile [W m^{-2}]
GZERO	Heat flow into soil surface [W m^{-2}]
HCP	Heat capacity of soil layer [J m^{-3} K^{-1}] (C_g)
HCPS	Heat capacity of soil material [J m^{-3} K^{-1}] (C_m)
HCPSNO	Heat capacity of snow pack [J m^{-3} K^{-1}] (C_s)
HMFG	Energy associated with freezing or thawing of water in soil layer [W m^{-2}]
HTC	Internal energy change of soil layer due to conduction and/or change in mass [W m^{-2}] (I_g)
HTCS	Internal energy change of snow pack due to conduction and/or change in mass [W m^{-2}] (I_s)
ISAND	Sand content flag
OVRFLW	Overland flow from top of soil column [m]
RHOSNO	Density of snow pack [kg m^{-3}] (ρ_s)
RUNOFF	Total runoff from soil column [m]
TA	Air temperature [K]
TBAR	Temperature of soil layer [C] (T_g)
TBARW	Temperature of water in soil layer [C]
TBASE	Temperature of bedrock in third soil layer, if only three layers are being modelled [K]
TCBOT	Thermal conductivity of soil at bottom of soil layer [W m^{-1} K^{-1}]
TCTOP	Thermal conductivity of soil at top of soil layer [W m^{-1} K^{-1}]
THICE	Volumetric frozen water content of soil layer [m^3 m^{-3}] (θ_i)
THLIQ	Volumetric liquid water content of soil layer [m^3 m^{-3}] (θ_l)
THLMIN	Residual soil liquid water content remaining after freezing or evaporation [m^3 m^{-3}] (θ_r)
THPOR	Pore volume in soil layer [m^3 m^{-3}] (θ_p)
TOVRFL	Temperature of overland flow from top of soil column [K]
TPOND	Temperature of ponded water [C] (T_p)
TRUNOF	Temperature of total runoff from soil column [K]
TSNOW	Temperature of the snow pack [C] (T_s)

WSNOW	Liquid water content of snow pack [kg m^{-2}] (w_s)
WTRG	Water transferred into or out of the soil [kg m^{-2} s^{-1}]
WTRS	Water transferred into or out of the snow pack [kg m^{-2} s^{-1}]
ZPLIM	Limiting depth of ponded water [m]
ZPOND	Depth of ponded water [m] (z_p)
ZSNOW	Depth of snow pack [m] (z_g)

If a full-scale hydrological modelling application is not being run, that is, if only vertical fluxes of energy and moisture are being modelled, the flag IWF is pre-set to zero. In this case, overland flow of water is treated using a simple approach: if the ponded depth of water on the soil surface ZPOND exceeds a limiting value ZPLIM (which varies by land surface type), the excess is assigned to overland flow. These calculations are carried out in loop 100, for all modelled areas except ice sheets (which are handled in subroutine ICEBAL). The overall runoff from the modelled area in question, RUNOFF, is incremented by the excess ponded water, and the overland flow for the whole grid cell OVRFLW is incremented by the product of the excess ponded water and the fractional area of the grid cell. The temperature of the overall runoff from the modelled area TRUNOF, and the temperature of the overland flow for the grid cell TOVRFL, are calculated as weighted averages over their previous values and the ponded water temperature TPOND. Finally, ZPOND is set to ZPLIM.

In loop 200, the calculation of the change in internal energy HTC within the soil layers due to movement of soil water (addressed in the preceding subroutines GRINFL and GRDRAN) is completed. (The initial step was performed at the end of subroutine TWCALC.) The volumetric heat capacity of the soil layers HCP is recalculated as a weighted average over the volumetric contents of liquid water, frozen water and soil particles. The temperature TBAR of each soil layer is recalculated as a weighted average of the liquid water temperature TBARW resulting from soil water movement, and the previous soil layer temperature. As noted in the documentation for subroutine TWCALC., TBARW and HCP apply only over the permeable depth of the soil layer, DELZW, whereas TBAR applies over the whole depth, DELZZ, and is associated with HCPSND, the volumetric heat capacity assigned to rock, in the interval DELZZ-DELZW. (For the default three-layer version of CLASS, DELZZ=DELZW in the third soil layer; see the documentation of loop 550 below.)

In loop 300 the calculation of the change of internal energy within the first soil layer due to changes in the surface ponded water is completed (for diagnostic purposes, the first level of HTC includes the internal energy of both the ponded water and the first soil layer). (The initial step of this calculation was performed at the end of subroutine TFREEZ.) The flow of heat between the bottom of the ponded water and the top of the first soil layer, GP1, is calculated by assuming a linear variation with depth of the heat flux between the top of the pond, GZERO, and between the first and second soil layers, G12. Since the heat flux G(z) varies directly with the temperature gradient dT(z)/dz, it can be seen that this approach is consistent with the assumption made in the CLASST subroutines that T(z) is a quadratic function of depth (and therefore that its first derivative is a linear function of depth). The temperature of the ponded water is stepped ahead using GZERO and GP1, and GZERO is reset to GP1 for use in the later soil temperature calculations.

In the 400 loop, a check is performed to ascertain whether the ponded water temperature has fallen below 0 C as a result of the above temperature change. If so, calculations are carried out analogous to those done in TFREEZ. A recalculation of the available energy in the snow pack, HTCS, is initiated. The available energy sink HADD is calculated from TPOND and ZPOND, and TPOND is set to 0 C. The amount of energy required to freeze the whole depth of ponded water is calculated as HCONV. An update of the first level value of HTC, reflecting the freezing of ponded water, is initiated. If HADD < HCONV, the available energy sink is sufficient to freeze only part of the ponded water. This depth ZFREZ is calculated from HADD, and subtracted from ZPOND. ZFREZ is then converted from a depth of water to a depth of ice, and is reassigned as part of the snow pack. The snow temperature, density, heat capacity and depth are recalculated as weighted averages of the pre-existing snow properties and those of the frozen water. If there was no snow on the ground to begin with, the snow albedo is initialized to its minimum background value of 0.50.

If HADD > HCONV, the available energy sink is sufficient to freeze the whole depth of ponded water and then to decrease the frozen water temperature to below 0 C. ZFREZ is evaluated as ZPOND converted to a depth of ice, and the remaining energy sink HADD-HCONV is used to calculated a test temperature TTEST of the newly formed ice. In order to avoid unphysical overshoots of the frozen water temperature, a limiting temperature TLIM is determined as the minimum of the snow temperature and the first level soil temperature if there is pre-existing snow, and as the minimum of the air temperature and the first level soil temperature if not. If TTEST < TLIM, the excess energy sink required to decrease the frozen water temperature from TLIM to TTEST is calculated and added to GZERO, and the new frozen water temperature is assigned as TLIM; otherwise it is assigned as TTEST. The energy sink used to cool the frozen water from 0 C to TLIM or TTEST is decremented from the first level of HTC, and the snow temperature is recalculated as the weighted average of the pre-existing snow temperature and the frozen water temperature. If there was no pre-existing snow, the snow albedo is initialized to the background value of 0.50. The density, heat capacity and depth of the snow are recalculated as above. Finally, the recalculations of the internal energy diagnostic variables HTC and HTCS are completed; and ZFREZ is used to update the diagnostic variable HMFG describing the energy associated with phase changes of water in soil layers, and the diagnostic variables WTRS and WTRG describing transfers of water into or out of the snow and soil respectively.

In the 500, 550 and 600 loops, the heat fluxes between soil layers and the updated temperatures for the soil layers are calculated according to the discretization approach that has been selected for the model run. It is assumed that the first two layer thicknesses are always set to 0.10 and 0.25 m respectively, but two possible options exist for the treatment of deeper layers. In the operational, "three-layer" configuration, a single third soil layer is modelled of thickness 3.75 m, with a user-specified permeable thickness DELZW. TBAR of the third layer is taken to apply to this permeable thickness, whereas a separate bedrock temperature, TBASE, is carried for the impermeable thickness, represented by DELZ-DELZW. This strategy is adopted so that temperature variations caused by melting and freezing of water are confined to the permeable thickness. In the "multi-layer" configuration, there can be any number of deeper layers, of thicknesses specified by the user (with the proviso that the thicknesses not be small enough to lead to numerical instability in the forward explicit time-stepping scheme). In this configuration it is deemed unnecessary to carry a separate calculation of TBASE.

In the CLASST subroutines, the heat fluxes at the top of the first soil layer, and between the first and second and the second and third soil layers, were determined. In loop 500, the fluxes between the remaining soil layers are calculated for the multi-layer configuration, and assigned to the heat flux vector GFLUX. Since the temperature variation is increasingly damped with depth, a simple linearization of the temperature profile is used. The expression for the ground heat flux at depth z, G(z), which depends on the thermal conductivity λ(z) and the temperature gradient, is given as:

$$G(z) = \lambda(z)\ dT(z)/dz$$

The linearized form is written as:

$$G_j = (\lambda_{j-1} + \lambda_j)\ \{T_{j-1} - T_j)/(\Delta z_{j-1} - \Delta z_j)$$

where G_j is the heat flux at the top of layer j, and λ_j, T_j and Δz_j refer to the thermal conductivity, temperature and heat capacity of the layer.

In the 550 loop, the first and second soil layer temperatures are stepped ahead using GZERO, G12 and G23. (Recall that the calculated heat capacity HCP applies to the permeable thickness DELZW, and the heat capacity of rock HCPSND applies to the rest of the layer thickness, DELZZ-DELZW.) If the three-layer configuration is being used, then a check is carried out to ascertain whether the permeable thickness DELZZ of the third layer is greater than zero. If so, and if DELZZ is not effectively equal to DELZ, the heat flow G3B at the interface between the permeable thickness and the underlying bedrock is calculated using the linearized heat flow equation given above; TBAR is updated using the difference between G23 and G3B, and TBASE is updated using the difference between G3B and GGEO, the geothermal heat flux at the bottom of the soil profile. If DELZZ is equal to DELZ, the whole layer is permeable and TBAR is updated using the difference between G23 and GGEO. If DELZZ is zero, the whole layer is impermeable, and TBASE is updated using the difference between G23 and GGEO. HTC for the third layer is updated with the GGEO value. Finally, if the multi-layer configuration is being used, TBAR of the third layer is updated using G23, the flux at the top of the layer. For diagnostic purposes, the first three levels of the GFLUX vector are assigned as GZERO, G12 and G23 respectively.

In the 600 loop, the remaining soil layer temperature calculations are done for layers 3 and deeper, for the multi-layer configuration. At the beginning and end of the loop an updated calculation of HTC for the layer in question is initiated and completed respectively. For the third layer, TBAR is updated using the heat flux at the bottom of the layer; for the last layer, TBAR is updated using the difference between GFLUX at the top of the layer and GGEO at the bottom. For the intermediate layers, TBAR is calculated using the difference between the GFLUX values at the top and bottom of the layer.

In the 700 loop, checks are carried out to determine whether, as a result of the forward stepping of the temperature, TBAR has fallen below 0 C while liquid water still exists in the layer, or risen above 0 C while frozen water still exists in the layer. If either occurs, adjustments to the water content are performed analogous to those done in subroutine TWCALC. Again, at the beginning and end of the loop an updated calculation of HTC for each layer in turn is initiated and completed respectively.

If the soil layer temperature is less than 0 C and the volumetric liquid water content THLIQ of the layer is greater than the residual water content THLMIN, the water content THFREZ that can be frozen by the available energy sink is calculated from TBAR and the weighted average of HCP and HCPSND. If THFREZ ≤ THLIQ – THLMIN, all of the available energy sink is used to freeze part of the liquid water content in the permeable part of the soil layer. The amount of energy involved is subtracted from HTC and added to HMFG. THFREZ is subtracted from THLIQ, converted to an ice volume and added to THICE. HCP is recalculated, and the layer temperature is set to 0 C. Otherwise, all of the liquid water content of the layer above THLMIN is converted to frozen water, and HMFG and HTC are recalculated to reflect this. HCP is recomputed, and the remaining energy sink HADD is applied to decreasing the temperature of the soil layer.

If the soil layer temperature is greater than 0 C and the volumetric ice content THICE of the layer is greater than zero, the ice content THMELT that can be melted by the available energy is calculated from TBAR and the weighted average of HCP and HCPSND. If THMELT ≤ THICE, all of the available energy is used to melt part of the frozen water content of the permeable part of the layer. The amount of energy involved is subtracted from HTC and added to HMFG. THMELT is subtracted from THICE, converted to a liquid water volume and added to THLIQ; HCP is recalculated and the layer temperature is set to 0 C. Otherwise, all of the frozen water content of the layer is converted to liquid water, and HMFG and HTC are recalculated to reflect this. HCP is recomputed, and the remaining energy HADD is applied to increasing the temperature of the soil layer.

CHKWAT

Purpose: Check for closure of surface water budget, and for unphysical values of certain variables.

Input variables:

DELZW	Permeable depth of soil layer [m]
EVAP	Evapotranspiration rate over modelled subarea [kg m^{-2} s^{-1}]
FCS	Fractional coverage of canopy over snow on modelled area [ ]
FGS	Fractional coverage of snow over bare ground on modelled area [ ]
FI	Fractional coverage of subarea in question on modelled area [ ]
ISAND	Sand content flag
ISFC	Flag identifying which subarea is being considered
PCPR	Precipitation rate over modelled subarea [kg m^{-2} s^{-1}]
RAICAN	Intercepted liquid water on canopy at end of time step [kg m^{-2}]
RAICNI	Intercepted liquid water on canopy at beginning of time step [kg m^{-2}]
RHOSNO	Density of snow pack [kg m^{-3}]
RUNOFF	Total runoff over modelled subarea [kg m^{-2} s^{-1}]
SNOCAN	Intercepted frozen water on canopy at end of time step [kg m^{-2}]
SNOCNI	Intercepted frozen water on canopy at beginning of time step [kg m^{-2}]
SNOWI	Snow pack mass at beginning of time step [kg m^{-2}]
THICE	Volumetric frozen water content of soil layers at end of time step [m^3 m^{-3}]
THICEI	Volumetric frozen water content of soil layers at beginning of time step [m^3 m^{-3}]
THLIQ	Volumetric liquid water content of soil layers at end of time step [m^3 m^{-3}]
THLIQI	Volumetric frozen water content of soil layers at beginning of time step [m^3 m^{-3}]
THLMIN	Residual soil liquid water content remaining after freezing or evaporation [m^3 m^{-3}]
THPOR	Pore volume in soil layer [m^3 m^{-3}]
WLOST	Residual amount of water that cannot be supplied by surface stores [kg m^{-2}]
WSNOW	Liquid water content of snow pack at end of time step [kg m^{-2}]
WSNOWI	Liquid water content of snow pack at beginning of time step [kg m^{-2}]
XSNOW	Switch to indicate presence of snow cover [ ]
ZPOND	Depth of ponded water on ground at end of time step [m]
ZPONDI	Depth of ponded water on ground at beginning of time step [m]
ZSNOW	Depth of snow pack [m]

This subroutine is called from CLASSW to perform water balance checks for each of the four subareas. The flag ISFC indicates which subarea is being addressed: ISFC=1 for vegetation over snow, ISFC=2 for snow over bare ground, ISFC=3 for vegetation over bare ground, and ISFC=4 for bare ground. If a problem is discovered, a flag is set to the index of the modelled area, and a call to XIT is performed with an error message. Checks are performed against a standard accuracy limit ACCLMT, currently set to 1 x 10^{-3} kg m^{-2}.

In loop 100, for canopy-covered subareas, the intercepted rain RAICAN and snow SNOCAN are checked to ensure that if they are negative, they are vanishingly small. A similar check is done for the runoff. In the 150 loop, for all areas that are not continental ice sheets (ISAND=-4), the liquid water content in each soil layer is checked to ensure that it is not larger than the pore volume and that it is not smaller than the minimum liquid water content (except for rock layers). The ice content is similarly checked to ensure that the sum of it, converted to an equivalent liquid water content, plus the minimum water content, is not greater than the pore volume (except for rock layers). It is also checked to ensure that if it is negative, it is vanishingly small. Finally, in loop 300, the overall water balance BAL is calculated and compared to ACCLMT. BAL is evaluated as the residual of the precipitation, the evaporation, the runoff, the water loss term WLOST, the change in canopy intercepted liquid and frozen water (for vegetation-covered areas), the change in surface ponded water, the change in snow pack and snow liquid water content (for snow-covered areas), and the changes in the soil layer liquid and frozen water contents. If the absolute value of BAL is greater than ACCLMT, a flag is set, all of the terms entering BAL are printed out, and a call to XIT is performed.

SNOALBW

Purpose: Calculate decrease in snow albedo and increase in density due to aging.

Input/Output variables:

ALBSNO	Albedo of snow [ ] (α_s)
FI	Fractional coverage of subarea in question on modelled area [ ]
HCPSNO	Heat capacity of snow pack [J m^{-3} K^{-1}]
ISAND	Sand content flag
RHOMAX	Maximum density of snow pack [kg m^{-3}] ($\rho_{s,max}$)
RHOSNO	Density of snow pack [kg m^{-3}] (ρ_s)
RMELT	Melt rate at top of snow pack [m s^{-1}]
S	Snowfall rate [m s^{-1}]
TSNOW	Temperature of the snow pack [C]
WSNOW	Liquid water content of snow pack [kg m^{-2}]
ZSNOW	Depth of snow pack [m] (z_s)

The albedo and density of snow are modelled using empirical exponential decay functions. In the absence of any fresh snowfall the snow albedo α_s is assumed to decrease exponentially with time from a fresh snow value of 0.84 to a background old snow value $\alpha_{s,old}$ using an expression based on data given in Aguado (1985), Robinson and Kukla (1984) and Dirmhirn and Eaton (1975):

$$\alpha_s(t+1) = [\alpha_s(t) - \alpha_{s,old}] \exp [-0.01\Delta t/3600] + \alpha_{s,old}$$

where Δt is the length of the time step. If the melt rate RMELT at the top of the snow pack is non-negligible or if the temperature of the snow is close to 0 C, $\alpha_{s,old}$ is assigned a value of 0.50; otherwise $\alpha_{s,old}$ is assigned a value of 0.70.

The maximum snow density $\rho_{s,max}$ is estimated as a function of snow depth z_s, after Tabler et al. (1990):

$$\rho_{s,max} = A_s - [204.70/z_s] [1.0 - \exp(-z_s/0.673)]$$

The empirical constant A_s is assigned a value of 450.0 for cold snow packs, and 700.0 for snow packs near the melting point, following Brown et al. (2006).

The density of snow ρ_s increases exponentially with time from its fresh snow value to the background old snow density calculated above, according to an expression analogous to that for albedo, derived from the field measurements of Longley (1960) and Gold (1958):

$$\rho_s(t+1) = [\rho_s(t) - \rho_{s,max}] \exp [-0.01\Delta t/3600] + \rho_{s,max}$$

The snow depth and heat capacity are adjusted (see notes on subroutine SNOVAP), and a check is performed with a call to abort if for unphysical albedo values are encountered.

CGROW

Purpose: Evaluate growth index used in calculating vegetation parameters for forests.

Input/Output variables:

FC	Fractional coverage of vegetation without snow on modelled area [ ]
FCS	Fractional coverage of vegetation with underlying snow pack on modelled area [ ]
GROWTH	Tree growth index [ ]
TA	Air temperature [K]
TBAR	Temperature of soil layers [K]

The growth index that is calculated here varies from a value of 1 for periods when the trees are mature and fully leaved, to 0 for dormant and leafless periods, with a linear transition between the two. The transition periods are assumed to last for sixty days; therefore during these periods the growth index is incremented by $\Delta t/5.184 \times 10^6$ where Δt is the time step in seconds.

The transition period from dormant to fully leafed is triggered when both the air temperature and the temperature of the first soil layer are above 2 C. If one of these conditions is not met afterwards, the growth index is reset back to 0. Increments are added continuously thereafter until the index reaches 1.

The transition from fully leafed to dormant is triggered when either the air temperature or the temperature of the first soil layer falls below 2 C. When this first happens at the end of the fully-leafed period, the growth index is set instantaneously to -1 and increments are continuously added from that point until the index reaches 0.

The absolute value of this growth index is utilized for performing calculations of various forest vegetation parameters in subroutine APREP; thus its shape as used there is that of a symmetrical trapezoidal function.

Appendix A

Land Cover Lookup Table

Parameters associated with land cover categories used in CLASS

	Code	Visible albedo [ ]	Near-IR albedo [ ]	Roughness length [m]	Maximum LAI	Minimum LAI	Max. mass [kg m^{-2}]	Rooting depth [m]
Evergreen needleleaf forest	1	0.03	0.19	1.5	2.0	1.6	25.0	1.0
Evergreen broadleaf forest	2	0.03	0.23	3.5	10.0	10.0	50.0	5.0
Deciduous needleleaf forest	1	0.03	0.19	1.0	2.0	0.5	15.0	1.0
Deciduous broadleaf forest	2	0.05	0.29	2.0	6.0	0.5	20.0	2.0
Tropical broadleaf forest	2	0.03	0.23	3.0	10.0	10.0	40.0	5.0
Drought deciduous trees	2	0.05	0.29	0.8	4.0	4.0	15.0	5.0
Evergreen broadleaf shrub	4	0.03	0.19	0.05	2.0	2.0	2.0	0.2
Deciduous shrub	2	0.05	0.29	0.15	4.0	0.5	8.0	1.0
Thorn shrub	2	0.06	0.32	0.15	3.0	3.0	8.0	5.0
Short grass and forbs	4	0.06	0.34	0.02	3.0	3.0	1.5	1.2
Long grass	4	0.05	0.31	0.08	4.0	4.0	3.0	1.2
Arable	3	0.06	0.34	0.08	4.0	0.0	2.0	1.2
Rice	3	0.06	0.36	0.08	6.5	0.0	2.0	1.2
Sugar	3	0.05	0.31	0.35	5.0	0.0	5.0	1.0
Maize	3	0.05	0.31	0.25	4.0	0.0	5.0	1.5
Cotton	3	0.07	0.43	0.10	5.0	0.0	2.0	2.0
Irrigated crop	3	0.06	0.36	0.08	4.0	0.0	2.0	5.0
Urban	5	0.09	0.15	1.35	-	-	-	-
Tundra	4	0.05	0.29	0.01	1.5	1.5	0.2	0.1
Swamp	4	0.03	0.25	0.05	1.5	1.5	1.0	5.0

("Code" refers to the vegetation group to which the land cover is assigned: 1=needleleaf tree, 2=broadleaf tree, 3=crops, 4=grass.)

Appendix

B

References

Aguado, E., 1985: "Radiation balances of melting snow covers at an open site in the central Sierra Nevada, California", *Water Resour. Res.* **21**, 1649-1654.

Auer, A.H., 1974: "The rain versus snow threshold temperatures", *Weatherwise* **27**, 67.

Bartlett, P.A., Mackay, M.D. and Verseghy, D.L., 2006: "Modified snow algorithms in the Canadian Land Surface Scheme: model runs and sensitivity analysis at three boreal forest stands", *Atmosphere-Ocean* **44**, 207-222.

Bartlett, P.A., 2004: "Report on the formulation of r_b, the boundary-layer resistance", unpublished report, Meteorological Service of Canada, 19 p.

Bonan, G.B., 1996: "A land surface model (LSM version 1.0) for ecological, hydrological and atmospheric studies: technical description and user's guide", NCAR TN-417+STR, National Center for Atmospheric Research, Boulder, CO, 150 p.

Brady, N.C. (1974): The Nature and Properties of Soils (8th edition), Macmillan, 639 p.

Brown, R., 2001: Contribution to Climate Change Action Fund Final Report on *Improved parameterization of land surface snow processes for Canadian climate models*, unpublished manuscript, Meteorological Service of Canada, 11 p.

Brown, R., Bartlett, P., Mackay, M. and Verseghy, D., 2006: "Estimation of snow cover in CLASS for SnowMIP", *Atmosphere-Ocean* **44**, 223-238.

Choudhury, B.J. and Idso, S.B., 1985: "An empirical model for stomatal resistance of field-grown wheat", *Agric. For. Meteorol.* **36**, 65-82.

Clapp, R.B., and Hornberger, G.M., 1978: "Empirical equations for some soil hydraulic properties", *Water Resour. Res.* **14**, 601-604.

Comer, N.T., Lafleur, P.M., Roulet, N.T., Letts, M.G., Skarupa, M. and Verseghy, D.L., 2000: "A test of the Canadian Land Surface Scheme (CLASS) for a variety of wetland types", *Atmosphere-Ocean* **38**, 161-179.

Cosby, B.J., Hornberger, G.M., Clapp, R.B., and Ginn, T.R., 1984: "A statistical exploration of the relationships of soil moisture characteristics to the physical properties of soils", *Water Resour. Res.* **20**, 682-690.

Côté, J., and Konrad, J.-M., 2005. "A generalized thermal conductivity model for soils and construction materials", *Can. Geotech. J.* **42**, 443-458.

De Vries, D.A., 1963: "Thermal properties of soils", in Physics of Plant Environment, ed. W.R. van Wijk, North-Holland Publishing Company, Amsterdam.

Deardorff, J.W., 1972: "Parameterization of the planetary boundary layer for use in general circulation models", *Mon. Wea. Rev.* **100**, 93-106.

Delage, Y.D., Wen, L. and Bélanger, J.-M., 1999: "Aggregation of parameters for the land surface model CLASS", *Atmosphere-Ocean* **37**, 157-178.

Dickinson, R.E., 1983: "Land-surface processes and climate-surface albedos and energy balance", in *Advances in Geophysics*, **25**, 305-353.

Dingman, S.L (2002): Physical Hydrology (2nd Edition). Prentice-Hall.

Dirmhirn, I., and Eaton, F.D., 1975: "Some characteristics of the albedo of snow", *J. Appl. Meteorol.* **14**, 375-379.

Farouki, O.T., 1981: "The thermal properties of soils in cold regions", *Cold Regions Sci. Technol.* **5**, 67-75.

Feddes, R.A., Bresler, E., and Neuman, S.P., 1974: Field test of a modified numerical model for water uptake by root systems", Water Resour. Res., 10, 1199-206.

Fisher, M.J., Charles-Edwards, D.A. and Ludlow, M.M., 1981: "An analysis of the effects of repeated short-term water deficits on stomatal conductance to carbon dioxide and leaf photosynthesis by the legume *Macroptilium atropurpureum cv. Sirato*", *Austral. J. Plant Physiol.* **8**, 347-357.

Garratt, J.R., 1992: The Atmospheric Boundary Layer, Cambridge University Press, 316 p.

Gold, L.W., 1958: "Changes in a shallow snow cover subject to a temperate climate", *J. Glaciol.* **3**, 218-222.

Goudriaan, J, 1988: "The bare bones of leaf angle distribution in radiation models for canopy photosynthesis and energy exchange", *Agric. For. Meteorol.* **43**, 155-169.

Green, W.H., and Ampt, G.A., 1911: "Studies on soil physics: I. Flow of air and water throught soils", *J. Agr. Sci.* **4**, 1-24.

Grenfell, T.C., and Maykut, G.A., 1977. "The optical properties of ice and snow in the Arctic Basin", *J. Glaciol.* **18**, 445-463.

Hedstrom, N.R., and Pomeroy, J.W, 1998: "Measurements and modelling of snow interception in the boreal forest", *Hydrol. Proc.* **12**, 1611-1625.

Idso, S.B., Jackson, R.D., Reginato, R.J., Kimball, B.A., and Nakayama, F.S., 1975: The dependence of bare soil albedo on soil water content", *J. Appl. Meteorol.* **14**, 109-113.

Lee, T.J., and Pielke, R.A., 1992: "Estimating the soil surface specific humidity", *J. Appl. Meteorol.* **31**, 480-484.

Leonard, R.E., and Eschner A.R., 1968: "Albedo of intercepted snow", *Water Resour. Res.* **4**, 931-935.

Letts, M.G., Roulet, N.T., Comer, N.T., Skarupa, M.R., and Verseghy, D.L., 2000: "Parametrization of peatland hydraulic properties for the Canadian Land Surface Scheme", *Atmosphere-Ocean* **38**, 141-160.

Longley, R.W., 1960: "Snow depth and snow density at Resolute, Northwest Territories", *J. Glaciol.* **3**, 733-738.

Mason, P.J., 1988: "The formation of areally-averaged roughness lengths", *Q. J. R. Meteorol. Soc.* **114**, 399-420.

McNaughton, K.G, and van den Hurk, B.J.J.M., 1995: "A Lagrangian revision of the resistors in the two-layer model for calculating the energy budget of a plant canopy", *Boundary-Layer Meteorol.* **74**, 261-288.

Mein, R.G., and Larson, C.L., 1973: "Modeling infiltration during a steady rain", *Water Resour. Res.* **9**, 384-394.

Mellor, M., 1977: "Engineering properties of snow", *J. Glaciol.* **19**, 15-66.

Oren, R., Sperry, J.S., Katul, G.G., Pataki, D.E., Ewers, B.E., Phillips, N. and Schafer. K.V.R., 1999: "Survey and synthesis of intra- and interspecific variation in stomatal sensitivity to vapour pressure deficit", *Plant Cell and Environ.* **22**, 1515-1526.

Pomeroy, J.W., and Gray, D.M., 1995: "Snowcover accumulation, relocation and management", National Hydrology Research Institute Science Report No. 7, Saskatoon, Environment Canada, 144 p.

Robinson, D.A., and Kukla, G., 1984: "Albedo of a disappearing snow cover", *J. Clim. Appl. Meteorol.* **23**, 1626-1634.

Schmidt, R.A., and Gluns, D.R., 1991: "Snowfall interception on branches of three conifer species", *Can. J. Forest Res.* **21**, 1262-1269.

Schulze, E.D., Leuning, R., and Kelliher, F.M., 1995: Environmental regulation of surface conductance for evaporation from vegetation", *Vegatatio* **121**, 79-87.

Sellers, W.D., 1974: *Physical Climatology*, University of Chicago Press, 272 p.

Steven, M.D., and Unsworth, M.H., 1980: "The angular distribution and interception of diffuse solar radiation below overcast skies", *Q. J. R. Meteorol. Soc.* **106**, 57-61.

Tabler, R.D., Benson, C.S., Santana, B.W. and Ganguly, P., 1990: "Estimating snow transport from wind speed records: estimates versus measurements at Prudhoe Bay, Alaska. In *Proc. 58th Western Snow Conf.*, 17-19 April 1990, Sacramento, CA., pp. 61-78.

Thomas, C.W., 1963: "On the transfer of visible radiation through sea ice and snow", *J. Glaciol.* **34**, 481-484.

Townsend, A.A., 1964: "Natural convection in water over an ice surface", *Q. J. R. Meteorol. Soc.* **90**, 248-259.

Verseghy, D.L., 1991: "CLASS – a Canadian land surface scheme for GCMs, I. Soil model", *Int. J. Climatol.* 11, 111-133.

Verseghy, D.L., McFarlane, N.A., and Lazare, M., 1993: "CLASS – a Canadian land surface scheme for GCMs, II. Vegetation model and coupled runs", *Int. J. Climatol.* 13, 347-370.

Wilson, M.F., and Henderson-Sellers, A., 1985: "A global archive of land cover and soils data for use in general circulation climate models", *J. Climatol.* **5**, 119-143.

Wu, A., Black, T.A., Verseghy, D.L., Novak, M.D., and Bailey, W.G., 2000, "Testing the α and β methods of estimating evaporation from bare and vegetated surfaces in CLASS", *Atmosphere–Ocean* **38**, 15–35.

Zhang, Y., Carey, S.K., and Quinton, W.L., 2008: "Evaluation of the simulation algorithms and parameterization methods for ground thawing and freezing in permafrost regions", submitted to *J. Geophys. Res. – Atmospheres.*

Zhao, L and D. M. Gray, 1997: "A parametric expression for estimating infiltration into frozen soils", *Hydrological Processes* **11**, 1761-1775.

Appendix

C

Licence/Disclaimer

Environment Canada – Atmospheric Science and Technology Licence/Disclaimer draft version 3 – May 7, 2008

Acceptance of this Agreement. Permission is hereby granted to install and use this Software subject to the terms and conditions set forth in this License Agreement. The Software refers to any copyrightable work of Environment Canada ("EC") as herein licensed. Downloading, installing and/or using the Software, as developed by EC will indicate your acceptance to enter into a license agreement with Her Majesty the Queen in Right of Canada, acting through and represented by the Minister of the Environment. If you do not wish to be bound by those terms and conditions, do not download and/or use the Software.

Access and use of the Software shall impose the following obligations on you and the organization you represent ("User"):

Grant of Rights. The User is granted the non-exclusive, perpetual, royalty-free right, to use, copy, modify, alter, enhance and distribute the Software, and any derivative works thereof (including Software outputs), and its supporting documentation for any purpose whatsoever, except commercial sales.

Redistribution Restrictions. Redistribution to any other third party is only permitted when that third party has been informed by the User of the terms and conditions on the usage of the Software as described herein, and that accessing and using the redistributed Software and/or derivative work imply their acceptance of those conditions. Furthermore the following notice shall be included in every distributed source file: