④

AD

MODELLING SEASONALLY FREEZING GROUND CONDITIONS

Final Technical Report

by

K.M.Sambles and M.G.Anderson

May 1989

European Research Office
U.S. Corps of Engineers
London England

CONTRACT NUMBER 45-87-C-0036

Dr.M.G.Anderson

Approved for Public Release : Distribution Unlimited

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE

REPORT DOCUMENTATION PAGE

Form Approved
OMB No 0704-0188
Exp Date Jun 30, 1986

1a. REPORT SECURITY CLASSIFICATION
UNCLASSIFIED

1b. RESTRICTIVE MARKINGS

2a. SECURITY CLASSIFICATION AUTHORITY

2b. DECLASSIFICATION / DOWNGRADING SCHEDULE

3. DISTRIBUTION / AVAILABILITY OF REPORT
APPROVED FOR PUBLIC DISTRIBUTION
UNLIMITED

4. PERFORMING ORGANIZATION REPORT NUMBER(S)

5. MONITORING ORGANIZATION REPORT NUMBER(S)
R&D 5806-EN-01

6a. NAME OF PERFORMING ORGANIZATION
University of Bristol

6b. OFFICE SYMBOL (If applicable)

7a. NAME OF MONITORING ORGANIZATION
EUROPEAN RESEARCH OFFICE
USARDSG-UK

6c. ADDRESS (City, State, and ZIP Code)
Department of Geography,
University of Bristol,
BRISTOL, BS8 1SS, England

7b. ADDRESS (City, State, and ZIP Code)
BOX 65, FPO-09510-1500 NY

8a. NAME OF FUNDING / SPONSORING ORGANIZATION
EUR. R&D
USARDSG-UK

8b. OFFICE SYMBOL (If applicable)
AMXSN-UK-RE

9. PROCUREMENT INSTRUMENT IDENTIFICATION NUMBER
DAJA 45-87-C-0036

8c. ADDRESS (City, State, and ZIP Code)
BOX 65, FPO-09510-1500 NY

10. SOURCE OF FUNDING NUMBERS

PROGRAM ELEMENT NO.	PROJECT NO.	TASK NO.	WORK UNIT ACCESSION NO
61102A	IL16110 2BH57	01	

11. TITLE (Include Security Classification)
(U) Modelling Seasonally Freezing Ground Conditions

12. PERSONAL AUTHOR(S)
K M Sambles and M G Anderson

13a. TYPE OF REPORT
FINAL

13b. TIME COVERED
FROM Aug 1987 TO Mar 1989

14. DATE OF REPORT (Year, Month, Day)
May 1989

15. PAGE COUNT
176

16. SUPPLEMENTARY NOTATION

17. COSATI CODES

FIELD	GROUP	SUB-GROUP
08 12		

18. SUBJECT TERMS (Continue on reverse if necessary and identify by block number)

19. ABSTRACT (Continue on reverse if necessary and identify by block number)

A prototype catchment scale distributed snow melt model (SNOMO) is developed for areas experiencing seasonally freezing ground conditions. SNOMO is based on the energy budget approach and is designed to account for variation in slope aspect and slope angle.

This report contains the background to the development of SNOMO as well as a code listing of the prototype model. Validation in the complete sense has yet to be undertaken, although data for this purpose was obtained from 2 field seasons at W3 Research Watershed in Vermont through collaboration with CRREL. [illegible]

[illegible] soils, Seasonal [illegible], Snow [illegible] distribution, watershed drainage, [illegible] computer programs, [illegible] Great Britain (EOARD)

20. DISTRIBUTION / AVAILABILITY OF ABSTRACT
☐ UNCLASSIFIED/UNLIMITED ☐ SAME AS RPT. ☐ DTIC USERS

21. ABSTRACT SECURITY CLASSIFICATION
UNCLASSIFIED

22a. NAME OF RESPONSIBLE INDIVIDUAL
J.C. COMATI

22b. TELEPHONE (Include Area Code)
01-402-7331

22c. OFFICE SYMBOL
AMXSN-UK-RE

DD FORM 1473, 84 MAR

83 APR edition may be used until exhausted.
All other editions are obsolete.

SECURITY CLASSIFICATION OF THIS PAGE

UNCLASSIFIED

CONTENTS

LIST OF PHOTOGRAPHS

Photograph

I INTRODUCTION

I. INTRODUCTION

1.1 Background

Snow accumulation and melt are an important subsystem within the hydrological cycle. In the USA, snowfall and snowcover are of economic importance (Lichfield, 1989), with possible economic hardship resulting from abnormally low seasonal snowfalls. Figures 1 and 2 show that in the USA the mean maximum length of snowcover duration is eight and a half months (September 15 - June 1) and the mean minimum duration two weeks (January 15 - February 1), with only seven states experiencing less than 30% of the sample years without snowcover. The snowfall area extends over many different climatic zones, each with a characteristic topography and vegetation, e.g. tundra, prairie, high mountain and desert. These, with their accompanying differences in snowcover duration, result in characteristic snow environments. A detailed knowledge of and ability to simulate the processes occurring in these snow environments are specifically required for:

1) Prediction of streamflows. Predictions are usually short-term (1 day - 1 week), concerned with flood flows, and long-term concerned with seasonal water yield for domestic, agricultural and energy supply purposes.

2) Assessment of the impact of land use changes. For example, these can be caused by silvicultural changes (Swanson, 1972, Berris and Harr, 1987, and De Walle et al. 1977), and leisure related activities, Simons (1988).

3) An understanding of the action of snow and snowmelt as a pollutant carrier and concentrator, e.g. acid snow flushes, Goodison et al. (1986).

4) A research tool for use in hydrology, botany, zoology, ecology, geomorphology, agricultural studies (e.g. crop protection) and as a consideration in the context of possible global climatic change.

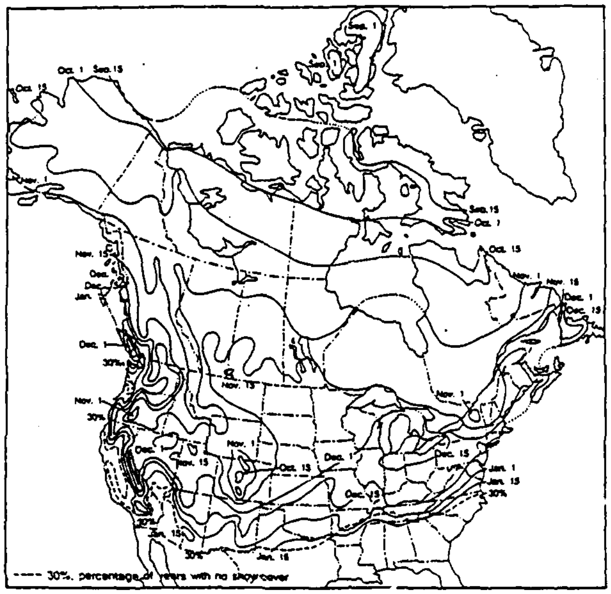


Figure 1: Mean date of snowcover formation (North America) McKay and Gray (1981).

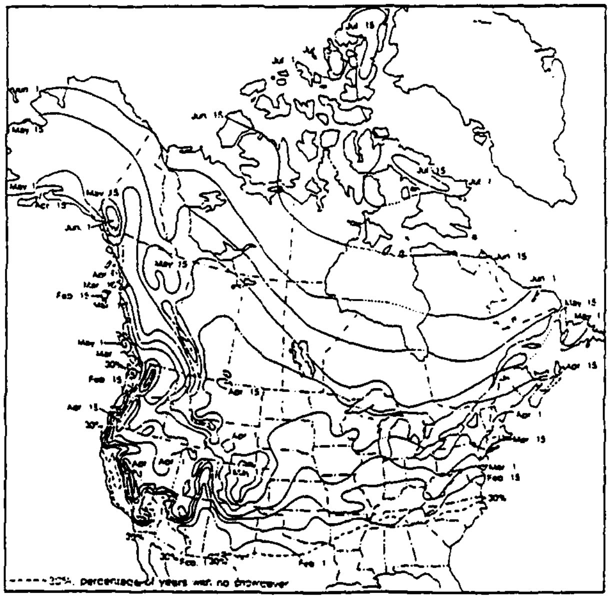


Figure 2: Mean date of snowcover disappearance (North America), McKay and Gray (1981).

This report is concerned with the development of a model to reach these requirements. First the current models available are considered in the context of the above requirements and the objectives and scope of the model to be developed are evolved. The snow environment to be modelled is then considered. The remainder of the report discusses the resultant model and its development.

1.2 Current modelling methods

This report is primarily concerned with the modelling of snowmelt and therefore this review will consider only snowmelt models, or those which by default have to involve snow accumulation, i.e. those in which the snow system is modelled throughout the season. Unless specified, the term 'snowmelt models' will include those modelling the whole season and involving accumulation. There are many snowmelt models in operation today, IAHS (1986). Morris (1985) presents a classification based on the operational scale (point or catchment) and the melt calculation method. Classification can however, sometimes lead to confusion. To avoid this, three main aspects of snowmelt models have been identified: snowmelt model development, scale and melt volume calculation, and these are discussed below.

1.2.1 Snowmelt model development

The wide range of snow environments (table 1 and section 1.1) has tended to result in the development of environment specific models, especially those for high mountain and prairie environments rather than one all-encompassing snowmelt model (Male and Gray, 1975). The historical development of snowmelt models mirrors that of rainfall-runoff models, i.e. developing in complexity from basic equations, e.g. Darcy's Law to complex distributed, multiple equations models (Anderson and Sambles, 1989). Snowmelt model development has followed three paths:

(i) Models developed as snow accumulation and melt subroutines within larger hydrological models which call subroutines relating to all the processes of the hydrological cycle, e.g. infiltration and evapotranspiration. Pangburn (1987), for example, is concerned with the development of the snow 'box' within the larger MILHY

Table 1 : Snow environments and related models

Snow environment type	Pack depth	Vegetation cover	Melt characteristics	Example
Prairie/steppe	Shallow	Grassland cultivated	Rapid	Male & Gray (1975) Kuz'min (1961)
High mountain	Deep plus alpine permafrost	Forest	Prolonged	Leaf & Brink (1973a & b)
Temperate lowlands	Deep	Mixed/deciduous forest, pasture, cultivated mix	Prolonged	Dunne & Black (1971)
Tundra	Shallow plus permafrost	Tundra vegetation - low, sparse	Rapid	Everett & Ostendorf (1988)

Military Hydrological) model. Morris (1982) considers various models for inclusion into the SHE (Systeme Hydrologique Europeen) model.

(ii) Independent snowmelt models, e.g. Anderson (1976).

(iii) Detailed process specific models. These are concerned with aspects of snowmelt, e.g. snow metamorphism or capillary water movement (Colbeck, 1974). These models are physically-based and aim to mathematically simulate the environmental process as accurately as possible, e.g. Bohren and Barkstrom (1979) and Colbeck (1977). The model output and scale are specific to the process being modelled (figure 3). These models can be used as 'building blocks' of more complex models that model the whole melt process.

1.2.2 The scale of snowmelt models

There are two basic scales of snowmelt model, those that simulate snowmelt at a point (Obled and Rosse, 1977) and those that simulate snowmelt over an area, i.e. a catchment (Price et al., 1976). Point snowmelt models are usually extended to form areal snowmelt models by a consideration of areal snowfall, this and other variables are assumed homogeneous over the area. Ferguson and Morris (1987) consider that all areal snowmelt models consist of a basic structure, as shown in figure 4. There are four sub-units to this structure.

(i) A meteorological submodel. This enables meteorological data from possibly distant point sources to be extrapolated to the snowpack surface (as in the case of remoter catchment sites). Ferguson (1984) uses lapse rate to calculate air temperatures at a maximum height of 1265 masl from a meteorological station at 400 masl. Other variables, e.g. precipitation totals and evaporation, can be calculated in a similar way (Reiners et al. 1984). In mountainous areas temperature and precipitation changes with altitude will be important. In other environments, e.g. prairies, other factors, e.g. wind (snow drifting) will be important spatial variants. A

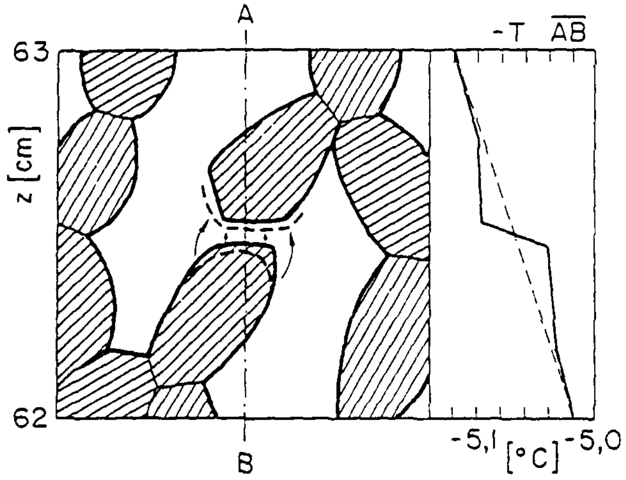


Figure 3: De Quervain (1972), a schematic diagram of the local variation of temperature gradient and mass flux in a snow structure. Small scale, detailed mass flux model.

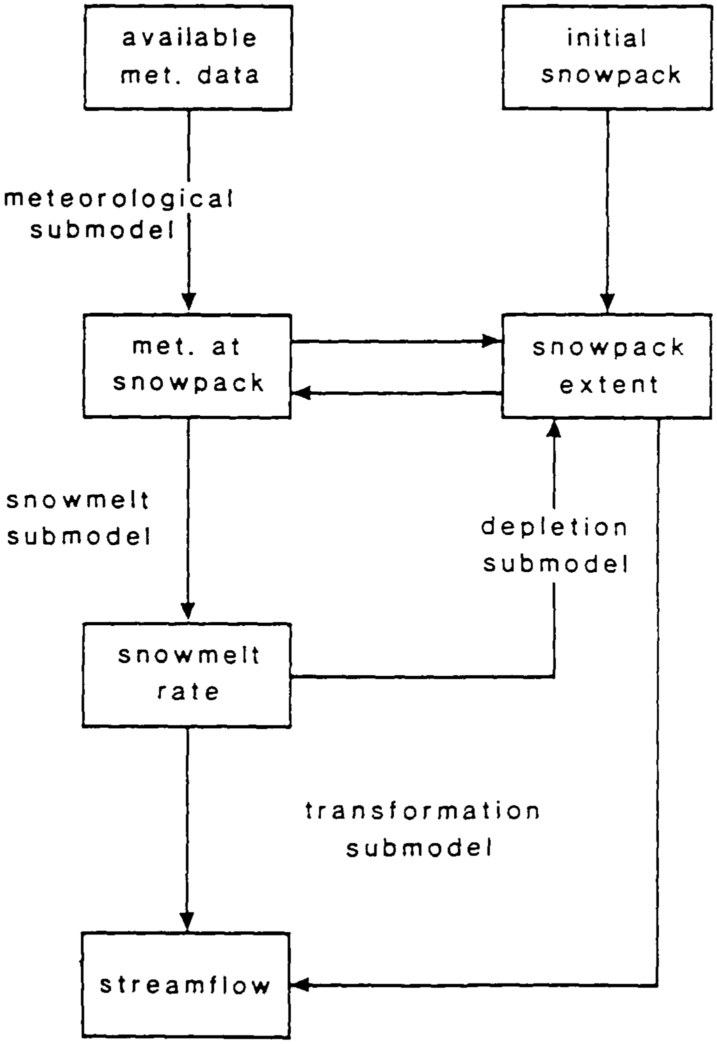


Figure 4: Components of a snowmelt runoff model, Ferguson and Morris (1987)

sophisticated meteorological submodel would, in reality, be an areal snow accumulation model. In many areal snowmelt models initial snowpack extent is important. Errors in the estimation of initial snowpack extent can manifest themselves in the depletion submodel rendering the melt output, however accurately calculated by the snowmelt submodel, inaccurate.

(ii) A snowmelt submodel. This calculates the volume of meltwater reaching the ground. There are two main methods used to calculate this, the index method and the energy-budget method. These are discussed further below.

(iii) A transformation submodel. This routes the estimated meltwater to the outflow stream. These vary in complexity, reflecting the variation in current hillslope-runoff modelling techniques (e.g. figure 5). Some transformation submodels are included with the snowmelt submodel, and the meltwater movement through the snowpack and the hillslope are considered together (Dunne et al. 1976).

(iv) A depletion submodel. In a point model this is implicit in the snowmelt submodel. In an areal snowmelt model, the depletion submodel is important as it effectively attempts to describe the pattern of snowmelt and the resultant snowcover pattern. Buttle and McDonnell (1987) evaluate five such models (figures 6, 7 and 8). Depletion models are in an early stage of development, and most treat the areal snowcover they represent in a lumped approach, i.e. the percentage of bare ground may be calculated but there is no indication of the distribution of that bare ground. Unless the depletion model is operated in smaller homogeneous areas, e.g. Buttle and McDonnell (1987), or Leaf and Brink (1973), no indication of spatial melt patterns can be obtained.

1.2.3 The calculation of melt-snowmelt submodel

Snowmelt models can be classified on the basis of the method they use to calculate melt. Older models used simple regression techniques (Hendrick and DeAngelis, 1976). These regressed snowmelt volume against a number

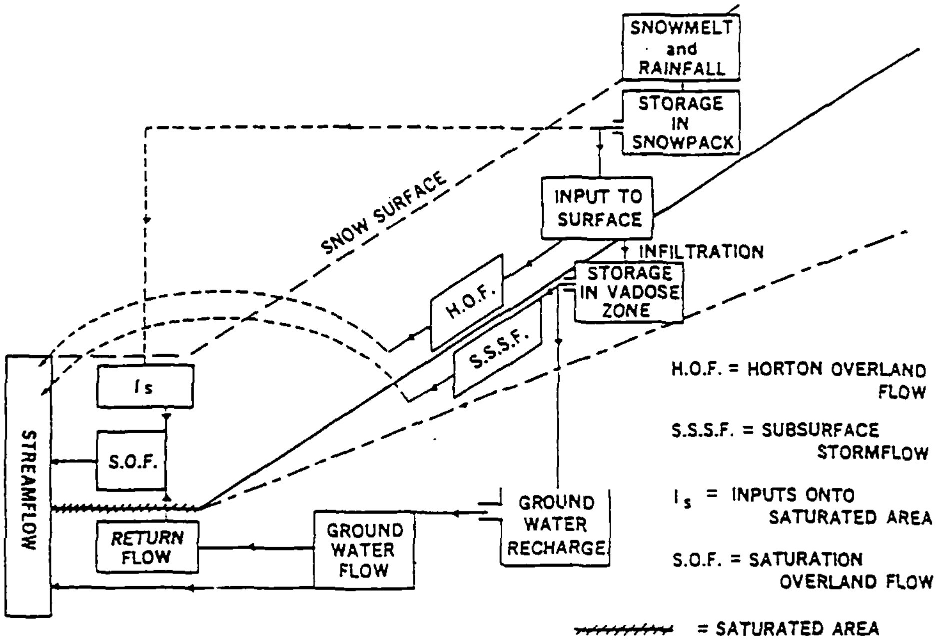


Figure 5: Meltwater pathways, Price and Hendrie (1983).

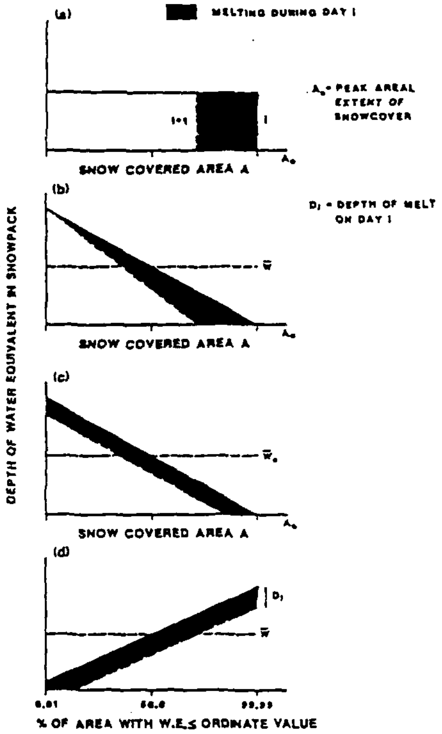


Figure 6: Schematic representation of four models of snowcover depletion: (a) spatially uniform water-equivalent, melt at snowpack margins (model 1); (b) spatially non-uniform water-equivalent, melt at snowpack margins (model 2); (c) spatially non-uniform water-equivalent, spatially uniform melt (model 3); (d) observed pattern of peak water-equivalent, spatially uniform melt (model 4).

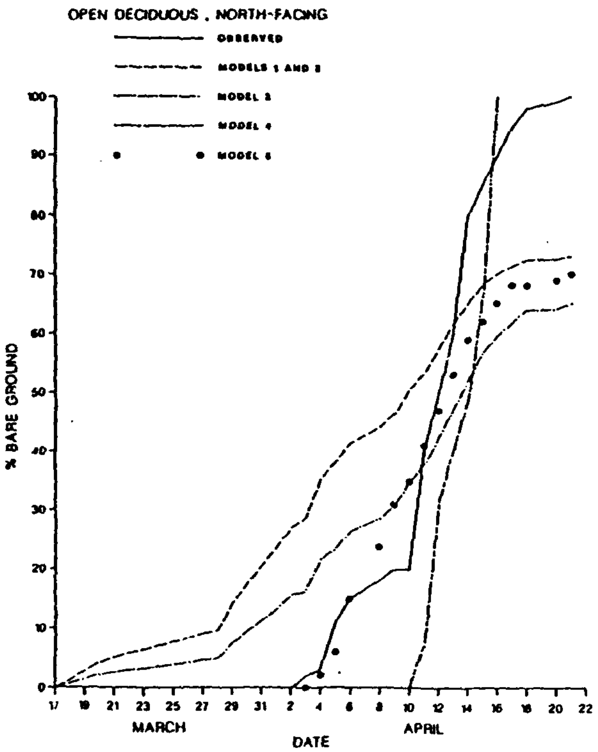


Figure 7: Observed and predicted trends in % bare ground development. Model 5 was developed by Buttle and McDonnell (1987).

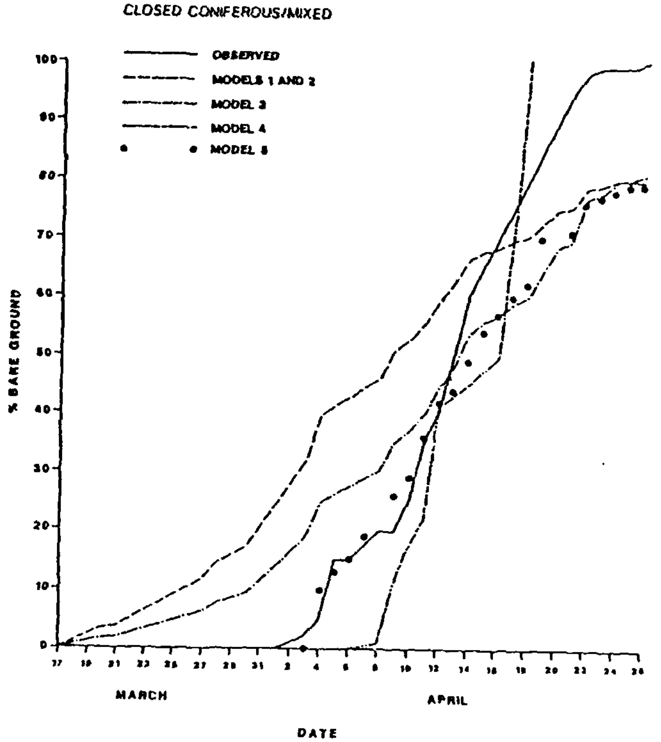


Figure 8: Observed and predicted trends in % bare ground development.

of variables, e.g. air temperature, windspeed and precipitation. However, there are two main methods of calculating snowmelt volume today:

i) Index models. In these models meltrate is expressed empirically as a function of one or more variables. The most commonly used index variable is air temperature, often in the form of a degree-day index. Other index variables, e.g. vegetation and solar radiation can be used (Male and Gray, 1981 and Martinec and Rango 1986) can be used. An example of a typical index model is Ferguson (1984). Melt volume is calculated by:

$$V_i = A_i D_i M \qquad (1)$$

where

V_i melt volume, $10^3 m^3$

D_i degree days above snowline (degree-day index)

M constant, mm $^oC^{-1}$ day^{-1}

A_i snowpack area, km^2

where D_i is given by:

$$D_i = \frac{\max^2(0,y) - \max^2(0,x)}{4(y-x)} + \frac{\max^2(0,y) - \max^2(0,z)}{4(y-z)} \qquad (2)$$

where

x minimum air temperature in the 24 hours to 0900 GMT on day i

y maximum air temperature in the next 24 hours

z minimum air temperature in the next 24 hours

(see figure 9)

A_i is calculated using the areal feedback equation:

$$A_{i+1} = (A_i^{\,2} - V_i\, A_o/W_o)^{1/2} \qquad (3)$$

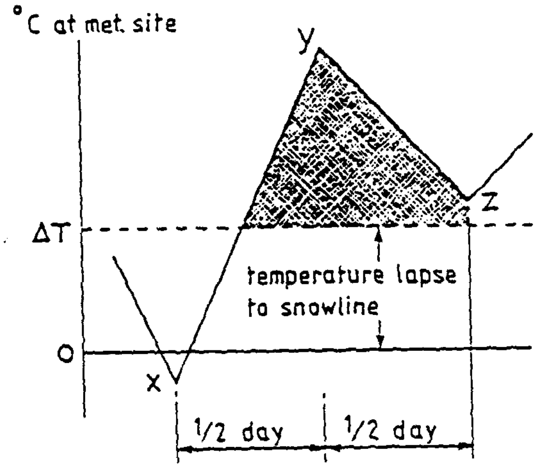


Figure 9: Definition diagram for calculation of degree-days above 0°C at snow line.

where

A_o initial snowpack area, km^2
W_o initial mean water equivalent depth, mm.

It can be seen from this typical example that index models do not require detailed meteorological inputs and they can operate on very basic meteorological and snow area data. This is an advantage in the more remote areas where only basic meteorological and snow condition coverage exist. Snow area data can be collected by remote means, i.e. satellite (Rango, 1988, and Merry et al. 1977), or estimated using snow-area elevation curves. Areal index models have a primary output, melt volume and a secondary output, snow covered area. Index models are the models that are used most commonly for operational forecasting purposes (Roberge et al., 1988) and are also most often used as the 'snow input' in the larger hydrological models, e.g. Pangburn (1987). The most advanced index model is Anderson's (1973) model. This bases the calculation of melt on the snowpack energy budget but uses index methods to calculate each of these components. For example, net radiation, Q*, is calculated by:

$$Q^* = 0.007\ (T_a - 32) \qquad (4)$$

where

T_a ambient air temperature, ^oF
Q^* net radiation, inches/6 hr

The internal energy exchanges in the pack are not modelled on a physically based criterion. Index models do not attempt to simulate the physical processes occurring during melt. They are concerned with the manipulation of index variables to produce the correct melt volume.

(ii) Energy-budget models. Energy-budget models use the equation for the energy-budget of a melting snowpack as the basis of the calculation of melt and they use physically-based equations to calculate the components of this equation (this distinguishes them from the Anderson (1973) type of index model). The energy budget equation is given in Male and Gray (1981):

$$Q_m = Q^* + Q_e + Q_h + Q_g + Q_p - dU/dt \qquad (5)$$

where

Q_m	energy flux available for melt
Q^*	net radiation transfer
Q_e	latent heat (evaporation, sublimation, condensation) transfer at snow-air interface
Q_h	convective or sensible heat transfer at snow-air interface
Q_g	heat introduced to pack by rain
Q_p	heat introduced to pack by rain
dU/dt	rate of change of internal (or stored)energy per unit area of snowcover

Meltrate is then calculated from Q_m:

$$M = Q_m / (\rho h_f \beta) \qquad (6)$$

where

M	snowmelt water equivalent, cm day^{-1}
h_f	latent heat of fusion, kJ kg^{-1}
ρ	density of water, kgm^{-3}
β	thermal quality or the friction of ice in a unit mass of wet snow

Anderson (1976) has a very strict definition of energy-budget models restricting them to fully-distributed physically-based models able to simulate snowpack characteristics (density, thermal conductivity, temperature changes) as well as incoming radiation, etc. Obled and Rosse (1977) and Anderson (1976) are examples of these true energy-budget models. There is yet no catchment-scale fully distributed energy-budget model. Most energy-budget models are point models, the exception being Leaf and Brink (1973). This is an energy-budget model but presents a very simplistic calculation of the snowpack characteristics (Anderson, 1973). Energy-budget models, because they are physically based, are much more flexible in their output, i.e. snowpack temperatures, radiation totals, etc., can be obtained as output in addition to meltwater volume. However, they do require more input data in order to operate. Anderson (1976) lists a minimum of five inputs.

There are advantages and disadvantages in both the index and the energy-budget methods of melt volume calculation. Anderson (1976) tested his energy budget model, presented in that report, with his previous temperature index model (Anderson, 1973), figure 10. He concluded the following:

(i) The minimum input data required for the operation of an energy-budget model are a good estimate of incoming solar radiation and measurements of air temperature, vapour, pressure and wind speed.

(ii) Energy-budget models perform better than index models when applied to open areas, because of the greater ability of the energy-budget model to operate under variable meteorological conditions.

(iii) Under the stable meteorological conditions of the forest floor, index models give similar results to those of energy-budget models.

(iv) Physiographic factors, i.e. topography, vegetation cover and climatic factors, should be considered when choosing between energy-budget and index models. Generally, the more varied the physiography and climate, the better the performance of the energy-budget model when compared to the index model.

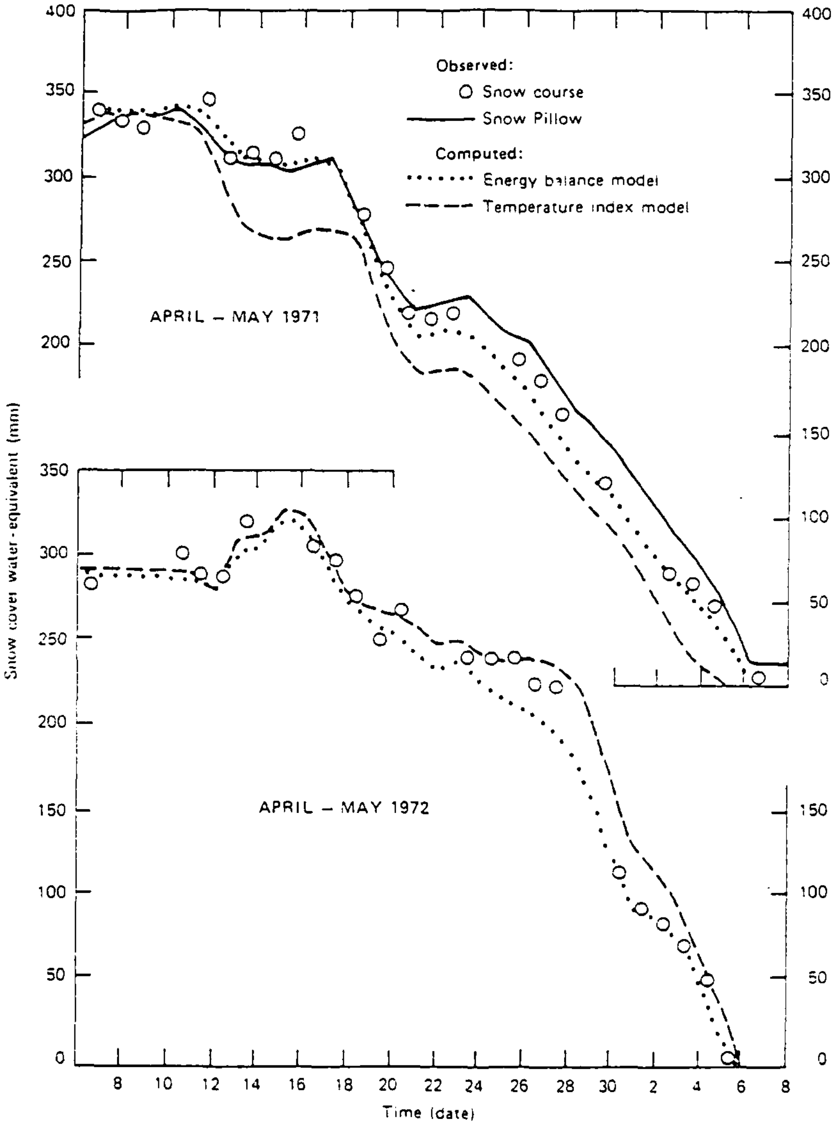


Figure 10: Comparison of energy balance and temperature index models during the 1971 and 1972 melt seasons (Anderson, 1976).

(v) When extreme conditions need to be modelled, energy-budget models should be used.

Anderson (1976) also considered the demands upon computing time of the model and concluded (in 1976) that the energy budget model was too large and time consuming to be of much practical use, but that with some modification, not at the expense of accuracy, it could be made more manageable.

There are therefore many snowmelt models in operation today. In order to fulfill *all* of the requirements for snow modelling outlined in the introduction (i.e. streamflow prediction, environmental changes, research tool, etc.) a snowmelt model *must* be of the *energy-budget type*, and at the *catchment scale*. There is a need for a catchment scale, energy-budget based model that is able to simulate the effects of slope angle, aspect and vegetation cover impact on snowmelt volume, snowpack characteristics and subsequent areal snow patterns.

1.3 Objectives and scope

The aim of this project is to *develop a catchment-scale distributed snowmelt model for areas experiencing seasonally frozen ground*.

The model that has been developed is SNOMO (SNOw MOdel) and has been designed to meet five basic requirements:

1) the primary output from SNOMO is the spatial pattern of snowcover over a catchment and subsequent volume of snowmelt

2) SNOMO is based on the energy-budget approach to snowmelt modelling and is designed so as not to require calibration

3) SNOMO can account for the effects of spatial variance in aspect and slope angle on snowmelt

4) SNOMO can account for the effects of spatial variance in vegetation on snowmelt

5) SNOMO is flexible enough to allow for choice of input and output, and manipulation of environmental conditions. In accordance with the spatial nature of SNOMO, output is graphical as well as numerical

Requirements (4) and (5) will be met in the period May 1989 - May 1990.

The requirements are achieved by:

1) development of the FORTRAN-77 code at Bristol University, U.K., on a SUN-360 workstation

2) validation of SNOMO using field data supplied from and collected at Sleepers River Research Watershed, Danville, Vermont.

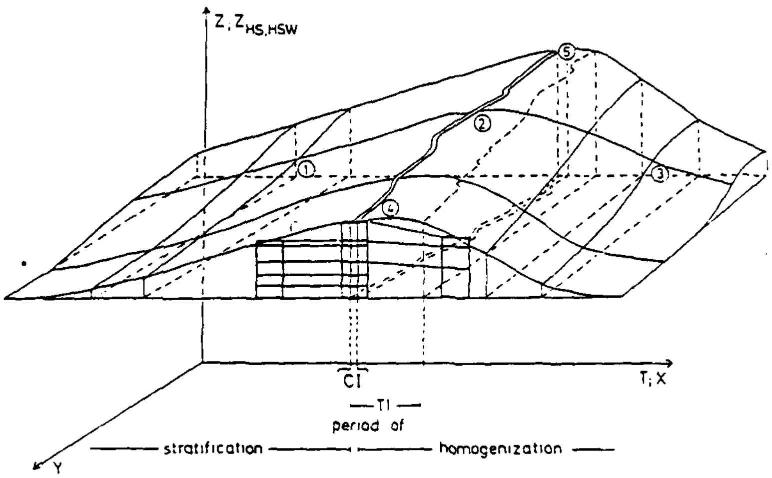
3) evaluation of SNOMO against Leaf and Brinks' (1973a and b) existing spatial snow model

1.4 The snow environment

The snow environment is a complex system of inter-related factors. The primary outputs on the catchment scale are snowmelt discharge and the distribution of residual snowcover. These melt outputs, the energy budget components that result in melt and the internal properties of the snowpack, are considered in general terms.

1.4.1 Residual snowcover pattern

Snowpack area and depth vary due to the accumulation pattern of the snowpack (itself dependent upon factors such as drifting, topography, etc.) and the variation of the energy budget components (variation caused by differing slope angle, aspect, vegetation cover and the prevailing meteorological conditions). Rau and Herrmann (1982) present a simplified version of this spatial and temporal variability (fig. 11). This is a graphical representation of the snowcover distribution with elevation



HS	Snowdepth
HSW	Water equivalent of snowdepth
CI	Critical Interval, meltwater production is initiated
TI	Transition Interval, runoff formation is initiated

Figure 11: Schematic model of an Alpine snowcover store (Rau and Herrmann, 1982)

over the snow season and considers a plane model slope, the position and elevation of which are defined by the coordinates of X, Y and Z. X and Z are the axes of rotation for variations of slope angles and azimuths. The evolution in time of a snow profile at a given point (Xy/Yy) on the slope is drawn along the T-axis (points 1,2 and 3). Snow profile variation with elevation is demonstrated for any time along the y axis (points 4,2 and 5). Figure 11 implies differential melt upslope. The pattern of snowcover retreat is dependent upon the scale of the area over which melt is occurring. There are three general scales:

i) Large ($>10km^2$), e.g. Rango (1988). Snowmelt patterns relate to regional meteorological patterns, e.g. localised precipitation and major altitudinal changes, e.g. mountain "snow-lines". Snowcover is usually categorized as 100% or 0% cover.

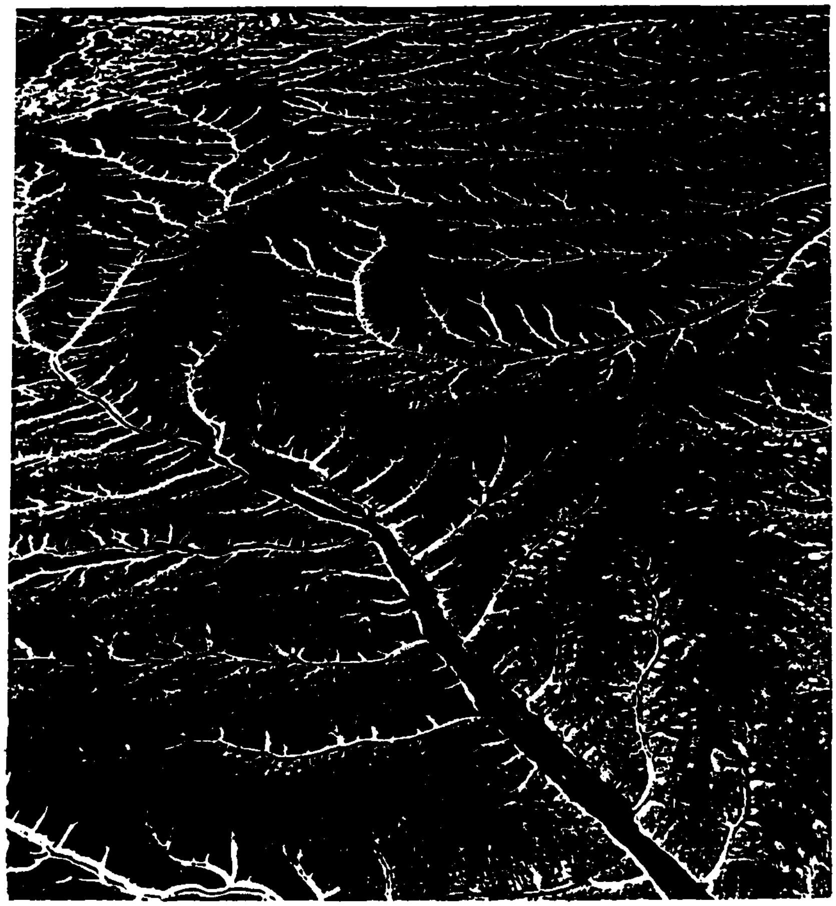
ii) Medium ($1\text{-}10km^2$), e.g. Leaf and Brink (1973a and b). Snowmelt patterns relate to major topographic features, e.g. hills and river valleys (photo 1), valley orientation and vegetation changes, e.g. coniferous forest, pasture boundaries.

iii) Small ($<1km^2$), e.g. Dunne and Black (1971). Snowmelt patterns relate to smaller topographic features, e.g. hillocks, drumlins, individual hillslopes (aspect and angle), field boundaries (drifting and shading) and individual objects, e.g. telegraph poles, trees. Snowcover at this scale is very patchy and discontinuous.

Therefore, in the development of a spatial snowmelt model, the resolution that is required for the modelling of the residual snowcover is very important.

1.4.2 Snowmelt discharge

This follows a diurnal pattern reflecting the decrease or cessation of meltflows during the night. Snowmelt is facilitated by rain. Rain during melt is more common in some snow environments, e.g. Oregon (Berris and Harr, 1987) than in others, e.g. prairies (Male and Gray,



Photograph 1 : The drainage network is highlighted by the distribution of the snowcover, which is concentrated in the channels, Hamelin and Cook (1967).

1975). Flooding during snowmelt is faciliated by rainfall, abnormally high air temperatures and the topographic and vegetational homogeneity of the catchment (Hendrick et al. 1971). Meltflow occurs through the snowpack and on the surface of the snowpack and as throughflow (through the soil) and overland flow (over the soil surface). Snowmelt can cause soil saturation due to the presence of an impermeable frost layer in the soil at depth preventing infiltration or rapid melt releasing a large volume of water in a short time and exceeding the infiltration capacity of the soil.

1.4.3 Energy-budget components

The energy-budget of a melting snowpack in the absence of rain is shown in figure 12 , Oke (1987). The energy balance in the absence of rain, is described as:

$$\Delta Q_s = Q^* + Q_h + Q_e + Q_g + \Delta Q_m \qquad (7)$$

where

ΔQ_s net heat storage term (ie. dU/dt)

Q^* net radiation

Q_h sensible heat flux

Q_e latent heat flux

Q_g heat introduced to the pack from the ground

ΔQ_m latent heat storage change due to melting or freezing

The daily energy totals relating to the energy balance components of figure 12 are given in table 2. Meltwater runoff rate per unit area, Δr, is calculated by:

$$\Delta r = \frac{\Delta Q_m}{L_f \rho} . 1000 \qquad (8)$$

where

Δr meltwater runoff rate, mm day^{-1}

L_f latent heat of fusion, Jkg^{-1}

ρ density of water, kgm^{-3}

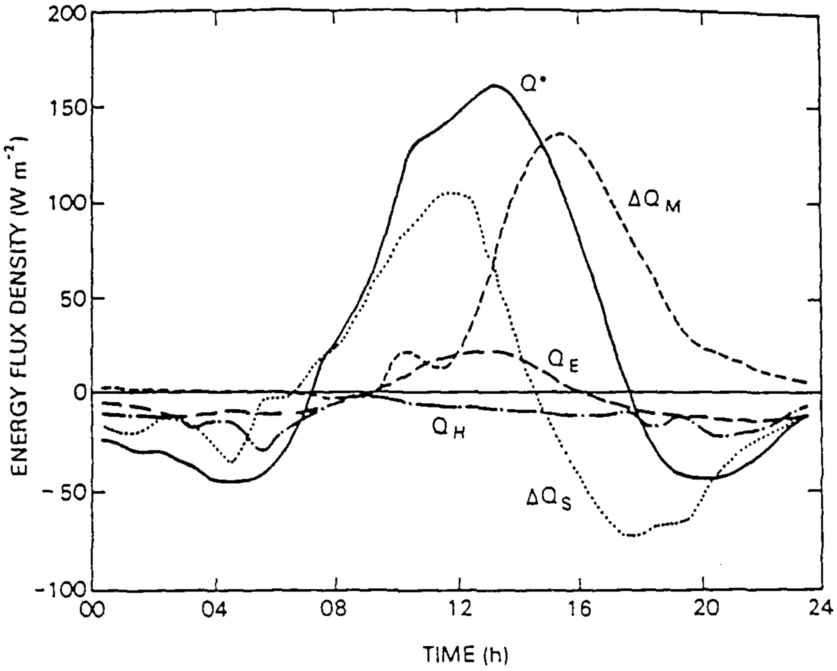


Figure 12: Energy budget components for a melting snow cover at Bad Lake Saskatchewan (51°N) on 10 April 1978, Oke (1987).

Energy components (MJm^{-2} day $^{-1}$)

Q^*	2.02
ΔQ_m	2.97
ΔQ_s	-0.11
Q_h	-0.84
Q_e	-0.07
Q_g	0.11

Δr = 8.92 mmh^{-1}

Table 2 : Daily energy totals for energy components and the derived term Δr for fig. 2 (Oke, 1987)

Table 3

SELECTED DAILY ENERGY FLUX TRANSFER (kJ/m^2)[a] DURING THE MELT PERIOD IN THE ABSENCE OF VEGETATION (BAD LAKE, SASKATCHEWAN).

Date (Day/Mon/Yr)	Q_{sn}	Q_{ln}	Q_n[b]	Q_h	Q_e	Q_g
11-4/75	8090	-6320	1770	186	-855	- 45
12-4/75	9620	-8480	1140	782	26	- 22
14-4/75	12290	-9430	2860	13	-395	- 4
17-3/76	4630	-4500	130	1830	-555	64
27-3/76	7200	-7720	- 520	1517	-208	-237
28-3/76	7790	-7120	670	70	-201	-111
29-3/76	9070	-7660	1410	532	- 60	-180
30-3/76	9290	-6040	3250	827	140	-270

[a] positive values indicate an energy gain by the snow.

[b] the daily net radiation flux transfer: $Q_n = Q_{sn} + Q_{ln}$.

(Male and Gray, 1981)

Table 3 shows some comparable results for other years at the same station (Bad Lake, Saskatchewan). A discussion of the energy-balance of a melting snowpack can be found in Oke (1987). The energy-budget components and the factors that affect them are now considered in turn.

(i) Net radiation, Q*

Q* is composed of a short-wave component and a long-wave component and can be described as:

$$Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow \tag{9}$$

where

$K\downarrow$	incoming solar radiation
$K\uparrow$	reflected solar radiation
$L\downarrow$	incoming longwave radiation
$L\uparrow$	reflected longwave radiation

(a) Short-wave component. This consists of incoming ($K\downarrow$) and outgoing ($K\uparrow$) components. $K\downarrow$ can be divided into diffuse and direct components. Diffuse radiation in the portion of $K\downarrow$ that is reflected and scattered (i.e. by clouds) reflected between the surface and the atmosphere (back-scattered), and reflected global (direct and diffuse $K\downarrow$) radiation from the surrounding terrain, figure 13. In mountainous terrain the diffuse radiation input is affected by:

i) decreased sky dome due to surrounding topography
ii) angle of slope
iii) reflected radiation from surrounding surfaces
iv) anisotropic distribution of diffuse radiation in the sky dome (concentrated nearer the solar disc and the horizon).
v) altitude

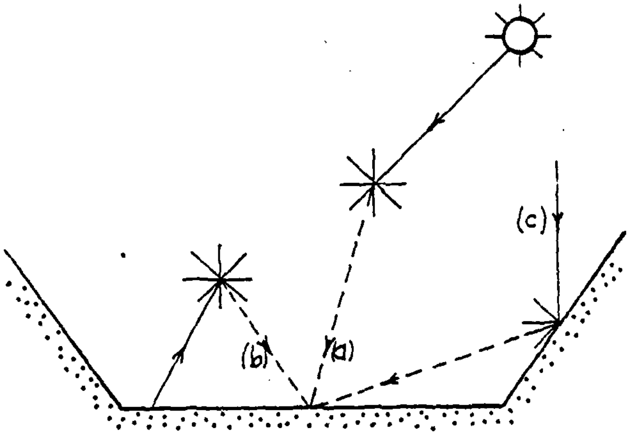


Figure 13: Sources of diffuse radiation:
(a) scattered incoming solar radiation
(b) back-scattered radiation
(c) reflected global radiation

Obled and Harder (1978)

Direct beam shortwave radiation is the portion of $K\downarrow$ that reaches the earth's surface without being absorbed or diffused. Direct beam radiation on a slope can be calculated using spherical geometry if the slope angle, azimuth (aspect), latitude, date and hour of the day are known. Direct beam radiation also increases with altitude due to the decrease in optical air mass with the decreased thickness of the atmosphere. Figure 14 shows the effect of slope angle and aspect on the amount of direct solar radiation received. Tables 4 and 5 and figure 15 show some of the results from Wendler and Ishikawa's (1974) calculations on the effect of slope, aspect ('exposure') and mountain screening on the direct beam radiation received at the surface of the McCall glacier, Alaska (69^{o} 19'N). Here, screening and aspect effects resulted in a loss in duration and energy content of the incoming direct solar radiation. On a slope the upper portion will receive the most incoming solar radiation, due to its longer exposure to the sun, than the base of the slope. This is demonstrated in Dunne and Black (1971), fig. 16).

Snow allows some transmission of incident short-wave radiation. The decay of the flux into the snow follows an exponential curve. The amount of short-wave radiation reaching any depth z is given by Beer's Law:

$$K\downarrow_z = K\downarrow_0 e^{-az} \qquad (10)$$

where

$K\downarrow_z$ short wave radiation incident at depth z

e base of natural logarithms

a extinction coefficient, m-1

The extinction coefficient, a, is dependent upon the nature of the transmitting medium (figure 17) and the wavelength of the radiation. The depth of shortwave penetration can be as much as 1 metre in snow, Oke (1987).

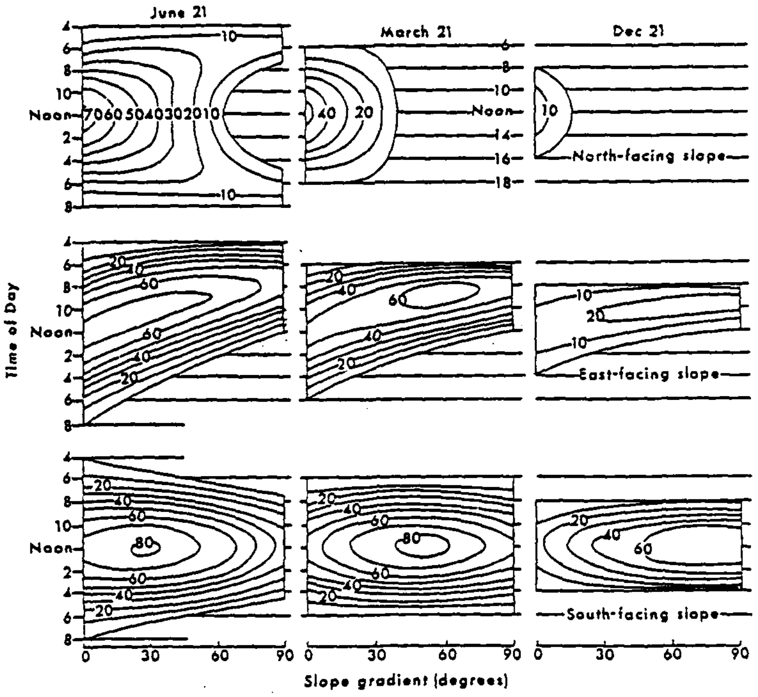


Figure 14: Direct solar radiation (cal,cm^{-2} hr^{-1}) received on different slopes during clear weather at 50°N. lat. Three slopes are shown: north, south, and east-facing (west would be a mirror image of east), for summer and winter solstice and equinox (vernal is a mirror image of autumnal). The lefthand side of each diagram shows the distribution of solar energy on a horizontal surface (0° gradient). The righthand side of each diagram represents a vertical wall (90° gradient). The top of each diagram shows sunrise and the bottom shows the sunset, Price (1981).

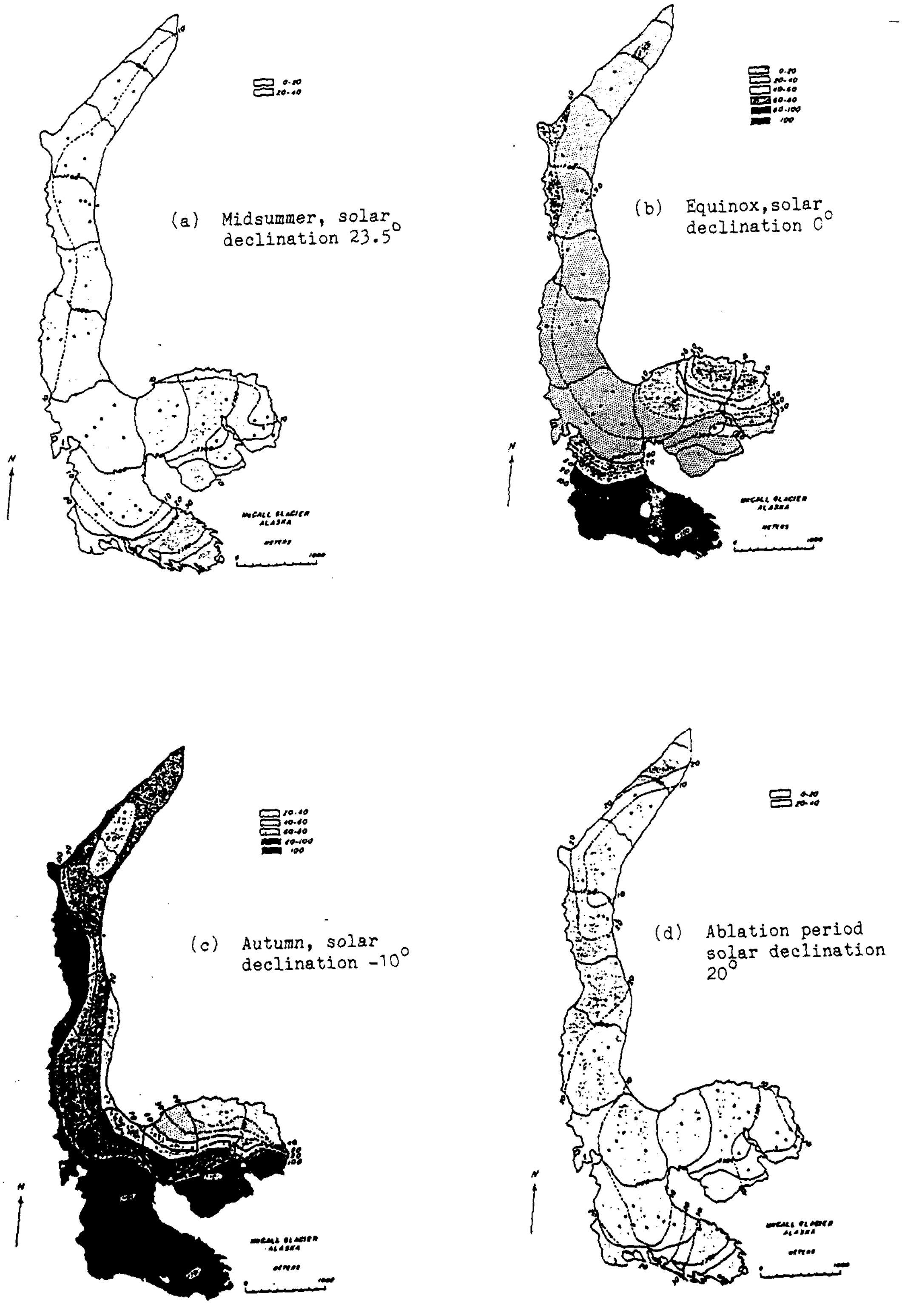
TABLE 4 LOSS IN DURATION AND ENERGY FOR THE WHOLE McCALL GLACIER OWING TO THE SCREENING EFFECT OF THE SURROUNDING MOUNTAINS FOR DIFFERENT SOLAR DECLINATIONS

Solar declination deg	*Loss in duration* %	*Loss in energy* %
23.5	32.6	10.1
20	39.9	13.4
0	67.6	55.7
−10	93.6	87.8

TABLE 5 ENERGY RECEIVED ON THE McCALL GLACIER FOR DIFFERENT SOLAR DECLINATIONS

A horizontal surface without any screening of the sun is considered to receive 100% energy

Solar declination deg	*Exposure* %	*Screening* %	*Total* %
23.5	98.7	89.9	88.8
20	98.3	86.6	85.1
0	75.2	44.3	33.3
−10	67.4	12.2	8.2

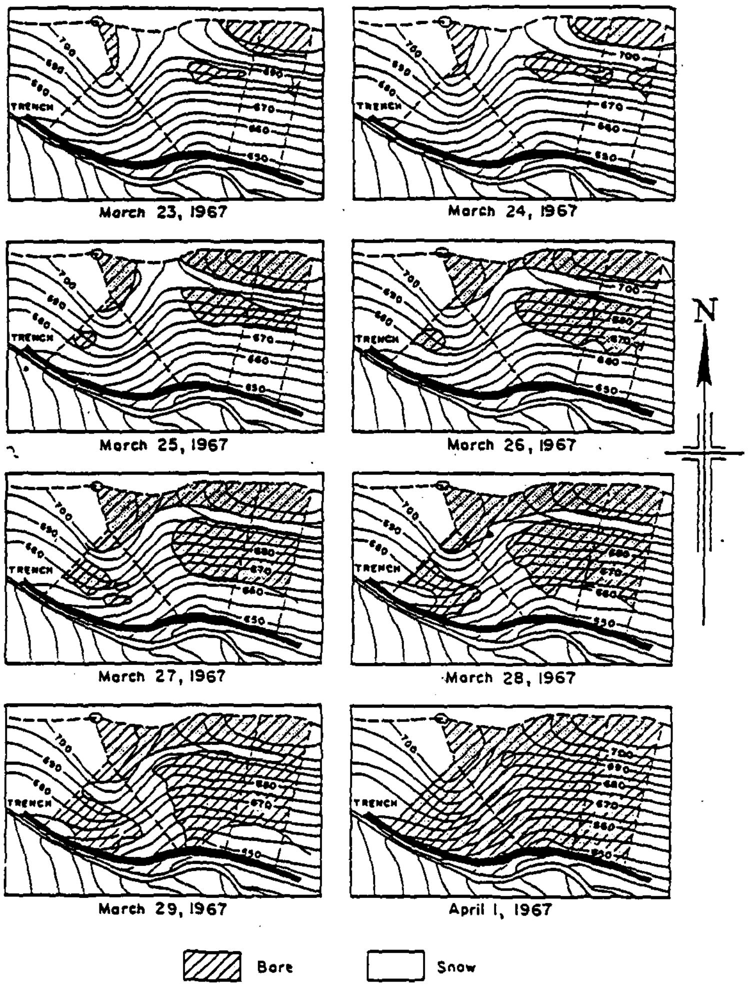

(a) Midsummer, solar declination 23.5°

(b) Equinox, solar declination 0°

(c) Autumn, solar declination -10°

(d) Ablation period solar declination 20°

Figure 15: The loss in energy of direct solar radiation of McCall Glacier, Wendler and Ishikawa (1974)



March 23, 1967

March 24, 1967

March 25, 1967

March 26, 1967

March 27, 1967

March 28, 1967

March 29, 1967

April 1, 1967

Figure 16: Distribution of snow cover on a hillside at noon each day during the melt period of March 1967, Dunne and Black (1971).

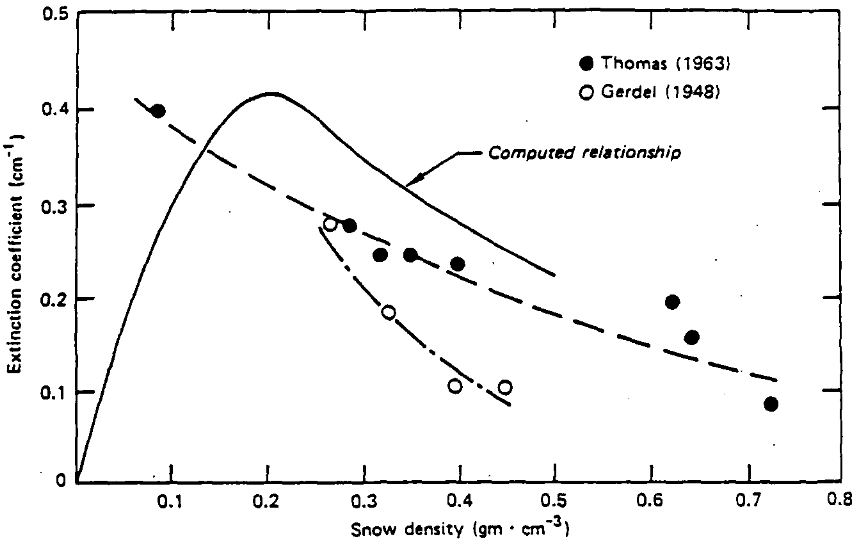


Figure 17: Extinction coefficient versus snow density, Anderson (1976).

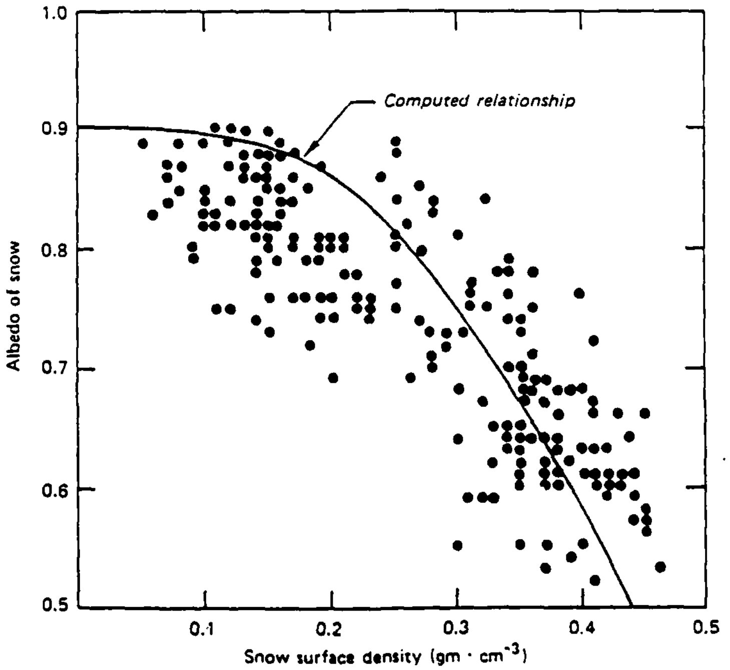


Figure 18: Albedo versus snow surface density, Anderson (1976).

Reflected shortwave radiation ($K\uparrow$) is dependent upon the amount of incoming shortwave radiation ($K\downarrow$) and the surface albedo (α):

$$K\uparrow = K\downarrow(\alpha) \tag{11}$$

Net shortwave radiation (K^*) can therefore be expressed as:

$$K^* = K\downarrow(1 - \alpha) \tag{12}$$

The albedo of snow varies with:

1) Contamination of the snow by dust (leading to occurrences of 'red snow' in the Alps, i.e. contamination by red Saharan dust), forest litter, etc. This increases with the age of the snow and reduces the albedo.

2) Density. This is again related to the age of the snowpack and the amount of metamorphism and compression it has undergone. Density increases as albedo decreases (fig. 18). Albedo is also related to snow grain size (which is related to density), Bergen (1975).

3) The nature of the surface. The albedo of a surface will change dramatically when the snowcover is removed or conversely once snowfall occurs. Price (1988) mentions overnight albedo changes from 0.40 to 0.90 at Perch Lake, Ontario (Canada), due to snowfall on deciduous forest. Figure 19 demonstrates a similar situation, i.e. snowcover on open fields has a high albedo whereas the albedo of bare-tree cover with understorey snowcover is much lower. Figure 20 shows the close relationship between point albedo and snowfall.

Density and contamination changes increase with age, as mentioned above, and cause a reduction in the albedo of snow.

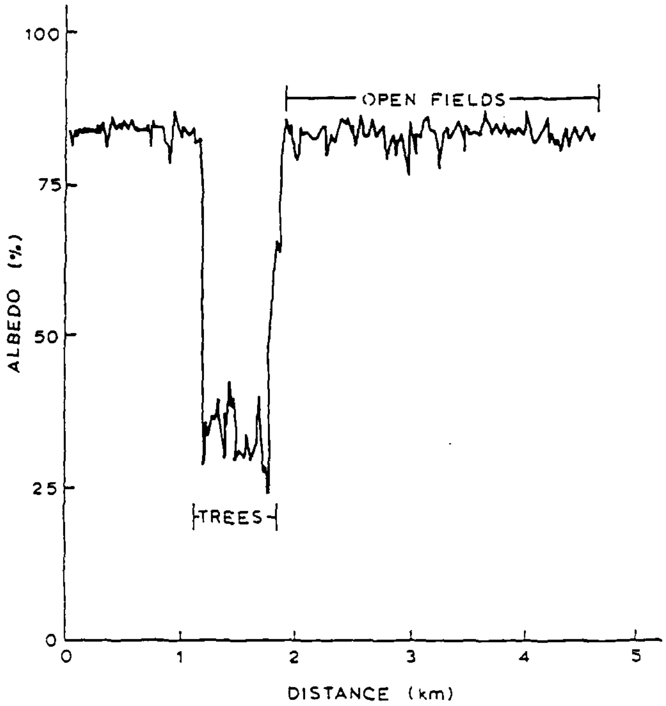


Figure 19: Albedo variation with vegetation cover, 6 January 1971, O'Neill and Gray (1972).

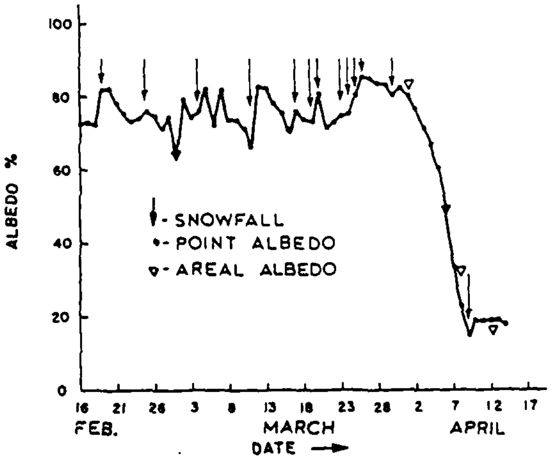


Figure 20: Albedo variance in response to snowfall, O'Neill and Gray (1972).

O'Neill and Gray (1972) summarize these changes (fig. 21). Average values for the albedo of snow are found in Male and Gray (1981), Oke (1987) and Balick et al. (1981).

Increased absorption of $K\downarrow$ will occur around dark objects contained within the snowpack, i.e. tree trunks, leaves, twigs, fence posts, etc. This is because of their lower albedo, greater thermal conductivity and, therefore, greater ability to absorb shortwave radiation than snow. Localised melting will therefore occur around these objects.

(b) Long-wave component

This consists of incoming ($L\downarrow$) and outgoing ($L\uparrow$) components. Net longwave radiation (L^*) is:

$$L^* = L\downarrow - L\uparrow \tag{13}$$

$L\downarrow$ is dependent, in the absence of cloud, upon the bulk atmospheric temperature and emissivity (which depends upon distributions of temperature, water vapour and carbon dioxide) following the Stephan-Boltzmann Law. Neither atmospheric temperature or emissivity fluctuate rapidly and, therefore, $L\downarrow$ is almost constant throughout the day. $L\uparrow$ is also dependent upon temperature (surface temperature) and emissivity (surface emissivity). If the surface is a full radiator, i.e. $\varepsilon_0 = 1$, then:

$$L\uparrow = \sigma T_0^4 \tag{14}$$

where

σ Stephan - Boltzmann constant

T_0 surface temperature

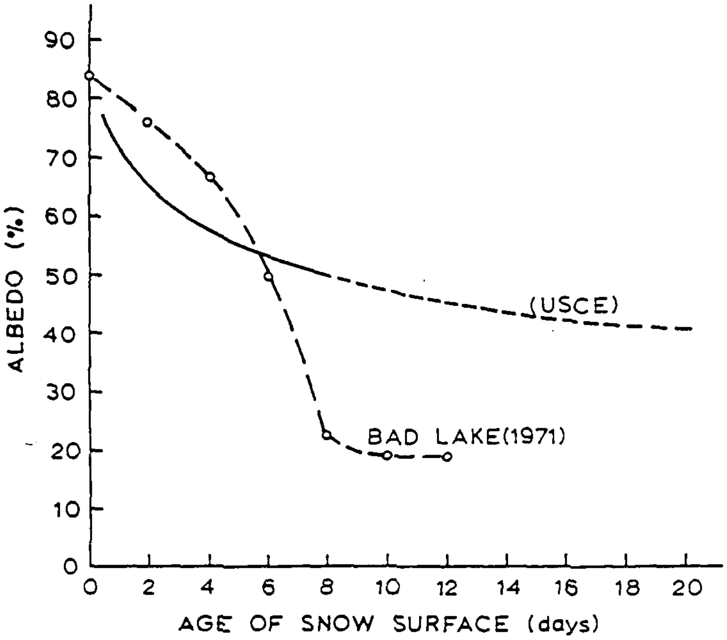


Figure 21: Variation in albedo with time over a melting Prairie snowpack (Bad Lake, 1971) and a deep mountain snowpack (U.S. Corps of Engineers, 1956), O'Neill and Gray (1972).

However, in reality ε_0 is rarely 1 and equation (14) becomes

$$L\uparrow = \varepsilon \sigma T_0^4 + (1 - \varepsilon_0) L\downarrow \tag{15}$$

where

ε_0 surface emissivity

ε atmospheric emissivity

The values of T_0 and ε_0 are greater than their atmospheric equivalents and because T_0 varies considerably during the day L↑ is larger and more variable than L↓. L↑ has a maximum value. This is when the snowpack is melting, i.e. $T_0 = 0^\circ C$ and $\varepsilon_0 = 1$ and, therefore, L↑ equals 316 Wm^{-2}, the black body emittance at $0^\circ C$. During forest snowmelt L may become large because the canopy absorbs a large proportion of the K↓ incident on it, heats up and radiates in the longwave (Price and Petzold, 1984). This can result in a large L* which, although K* at the forest floor may be small, will result in a large Q*.

More detailed accounts of the net radiation exchanges can be found in Obled and Harder (1978), Oke (1987) and Male and Gray (1981). Q* can and has been used as an index for melt, instead of air temperature.

Price (1988) relates Q* to K↓ and T_a in order to use Q* as an index for melt. Olyphant (1986) table 6, demonstrates the relative importance of the components of Q* during the melt of a mid-latitude alpine snowpack. Ambach (1974) discusses the effect of cloudiness on Q*.

ii) Sensible and latent heat exchanges, Q_h and Q_e

Tables 2 and 3 indicate that the sensible and latent heat exchanges are usually of secondary importance when compared with net radiation during snowmelt. There are,

TABLE 6

Simulated radiation totals for individual partial areas of snow cover in upper Green Lakes Valley[a]

Snowfield[b]	N[c]	$S\downarrow$ (MJ m^{-2} d^{-1})	$D\downarrow$ (MJ m^{-2} d^{-1})	$K\uparrow$ (MJ m^{-2} d^{-1})	$L\downarrow$ (MJ m^{-2} d^{-1})	$L\uparrow$ (MJ m^{-2} d^{-1})
Arikaree	11	14.90	7.70	1.63	19.38	5.44
		8.37–17.50	4.94–8.67	0.80–3.68	13.23–21.22	2.85–13.90
Green Lake 5	8	17.20	7.66	1.63	19.17	5.65
		15.90–17.79	7.28–7.91	1.38–2.01	18.33–19.63	5.02– 7.03
Kiowa	8	14.78	8.04	1.42	19.88	4.77
		13.06–15.91	7.87–8.25	1.00–1.76	19.38–20.89	3.52– 5.53
Rock Glacier	3	12.01	8.08	1.59	19.46	5.11
		11.05–13.22	8.00–8.20	1.42–1.80	19.30–19.80	4.64– 5.40
Green Lake 4	4	16.03	7.87	1.26	19.97	4.77
		15.70–16.41	7.24–8.67	0.38–2.05	17.80–22.23	1.63– 7.49
Unobstructed ridge top		15.57	9.21	–	23.02	–

[a] Upper entry represents the mean and lower entries represent the range of simulated irradiance totals.
[b] Individual snowfields are identified in Figure 1.
[c] Number of sites evaluated.

(Olyphant, 1986)

however, certain environments in which these exchanges increase in importance, e.g. Golding (1978). Table 7 gives some of the results of Golding's study of the importance of evaporation during chinooks in Alberta (Canada) and demonstrates that in most of the sites investigated snowpack loss due to evaporation was greater than that due to melt.

iii) Ground heat flux, Q_g

This is a negligible energy-budget component when compared to the others (tables 2 and 3). Q_g is more important in shallow snowpacks than deep snowpacks. Q_g affects the state of the soil, i.e. frozen, partially frozen or unfrozen, which affects the state of the base of the snowpack and the infiltration of meltwater during melt. The distribution of frozen soil will vary areally. The forest litter present under deciduous forest protects the soil from frost penetration prior to the major winter snowfalls. Therefore frost penetration is usually much less under deciduous forest than coniferous and non-forested areas. Frost penetration in the open is dependent upon the timing of the first major winter snows and the preceding meteorological conditions. If the snowfalls are late and preceding temperatures are very low, then frost penetration will be great. If the soil is frozen when snowfall occurs, the snow will tend to freeze, especially if at the start of winter the temperatures oscillate around zero, or there is an early winter thaw to the soil resulting in a snowpack with a frozen base. Included in Q_g may also be the heat evolved from the decomposition of organic matter present between the base of the snowpack and the soil.

Table 7 : Mean daily snowpack evaporation and melt during chinooks, January - March 1975 and 1976. (Golding, 1978).

Site	Elevation	1975 Daily snowpack Evap (mm)	 Melt (mm)	1976 Daily snowpack Evap (mm)	 Melt (mm)
1	1740	0.9	0.9	1.9	1.3
2	1700	1.0	0.6	1.7	1.5
3	1890	0.8	0.2	1.6	0
4	2190	-	-	4.0	0
5	2360	2.4	0	-	-
6	1280	1.0	0.5	2.4	2.4
7	1520	0.9	0.5	2.1	2.0
8	1690	1.0	1.7	2.0	3.2
9	1430	1.2	0.1	-	-
10	1580	1.1	1.6	1.9	5.5
11	1520	1.4	0.4	1.8	4.0
12	1520	1.1	0.5	0.8	3.7
13	1600	-	-	0.8	0.6
14	1120	1.4	0.1	1.0	3.9
15	1410	1.0	0.4	0.8	1.5
16	1630	0.8	0.2	1.0	0.4
17	2020	1.0	0	2.2	0
18	2200	2.3	0	3.0	0
19	2320	0.8	0	3.8	0

iv) Rain-on-snow. Q_p

Rainfall on snow, commonly called rain-on-snow, can be a contributary factor in snowmelt flooding by increasing meltrate and adding to total discharge. The energy transferred by rain to the snow is the difference between the energy content of the rain directly above the snow surface and its energy content upon reaching thermal equilibrium within the back. Two situations occur:

a) rainfall on a melting isothermal pack where the rain does not freeze

b) rainfall on a pack with a temperature below $0^{o}C$, where the water freezes and releases its latent heat of fusion and the pack warms up

v) Latent and sensible heat storage fluxes, ΔQ_m and ΔQ_s

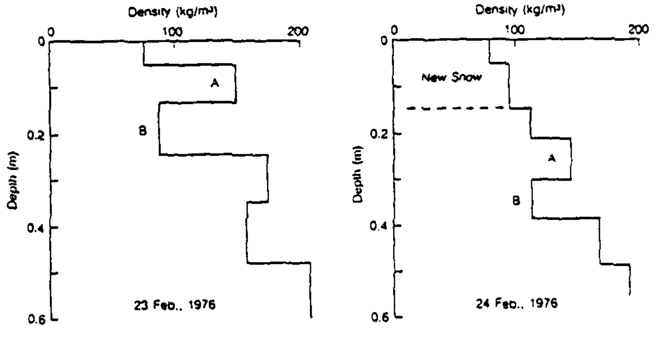
ΔQ_s represents the convergence or divergence of sensible heat fluxes within the snowpack, i.e. the changes in internal energy of the pack. ΔQ_m is the latent heat storage change due to melting or freezing. In order for the melt to occur, the pack first has to reach $0^{o}C$ and then the latent heat change can occur, i.e. melt. This is demonstrated in figure 12. In the morning, the heat input into the pack is almost entirely put into storage, ΔQ_s. This warms the pack to $0^{o}C$ from its overnight temperature (below $0^{o}C$). Only when the pack is homogeneous at $0^{o}C$ can the heat input into the pack be used to change the proportions of ice and water in the pack, i.e. melt. Melt peaks in the afternoon and declines as the pack cools. This cooling is retarded by the meltwater freezing within the pack, so releasing its latent heat of fusion.

1.4.4 Internal characteristics of the snowpack

Snow, once fallen, undergoes metamorphosis. This involves a change in the shape of the snow crystals and an accompanying change in the physical properties of the snow, e.g. density, hardness, thermal conductivity and thermal diffusivity. At its extreme metamorphism is responsible for the conversion of fresh snow to glacial ice. Therefore a snowpack composed from freshly fallen snow (e.g. an early winter pack) will have different physical properties from one consisting of old snow (e.g. a spring pack) or one consisting of layerrs of snow of variable ages.

Density changes result in a compression of the pack height. Density within a pack is usually greatest at the base and least in the surface layers, i.e. density increases with depth. Snow density increases with the age of the snow. Fresh snow will have a density value of around $0.130gm^{-3}$ whereas old snow exposed by melt will have a value around $0.400gm^{-3}$. The density of the top of the pack can be increased by the action of wind. Figure 22a shows the effect of wind on increasing the density of the top of the snowpack, A. Figure 22b shows the same profile a day later, after a snowfall. Layer A has effectively moved down the pack and the fresh, less dense snow, sits on top of the wind affected dense layer. Layer B has been compressed and density increases as depth increases overall. Figures 22a and 22b also demonstrate the layering of the pack that results from density changes. Figure 23 presents a simple layered snowpack where the 'new' snow (less dense is easily distinguished from the 'old' snow (more dense). Hardness is directly related to density, e.g. ice is harder than fresh snow.

Figure 24 relates the change in density to the change in effective thermal conductivity. Snow density is directly proportional to snow effective thermal conductivity. The thermal conductivity of snow is very low, which makes snow a good insulator (of houses, soil, crops, instruments, etc.). Thermal conductivity is also dependent upon the temperature and micro-structure of the snow.



a) b)

Figure 22: Density versus depth measured at a Whistler Mountain, B.C. ski run (elev. 1800 m), Perla and Glenne (1981).

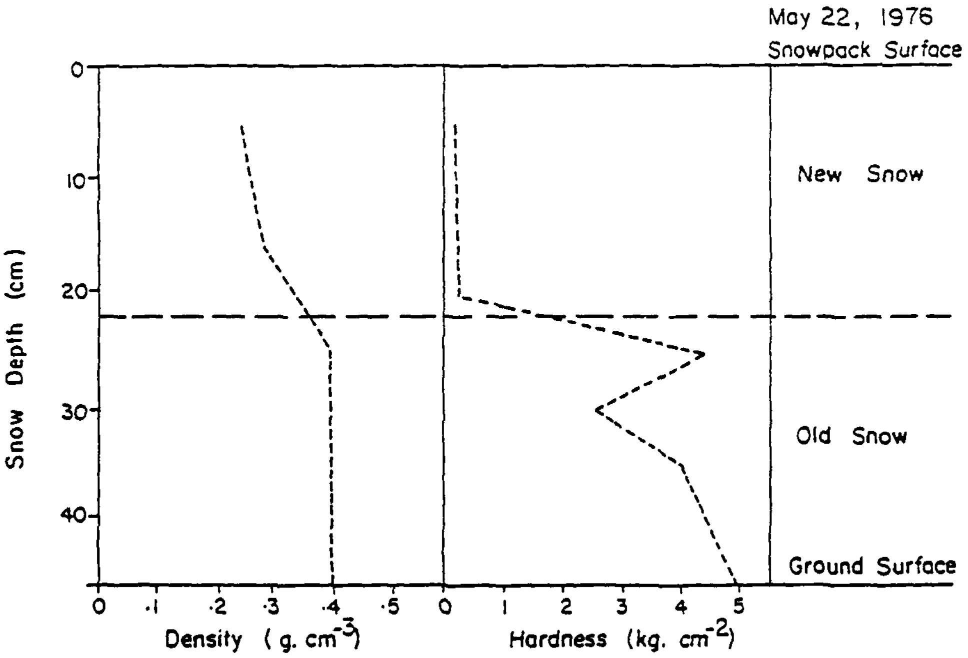


Figure 23: Differences in snow hardness and density distinguish new snow from old snow layers within the snowpack, Woo and Marsh (1977).

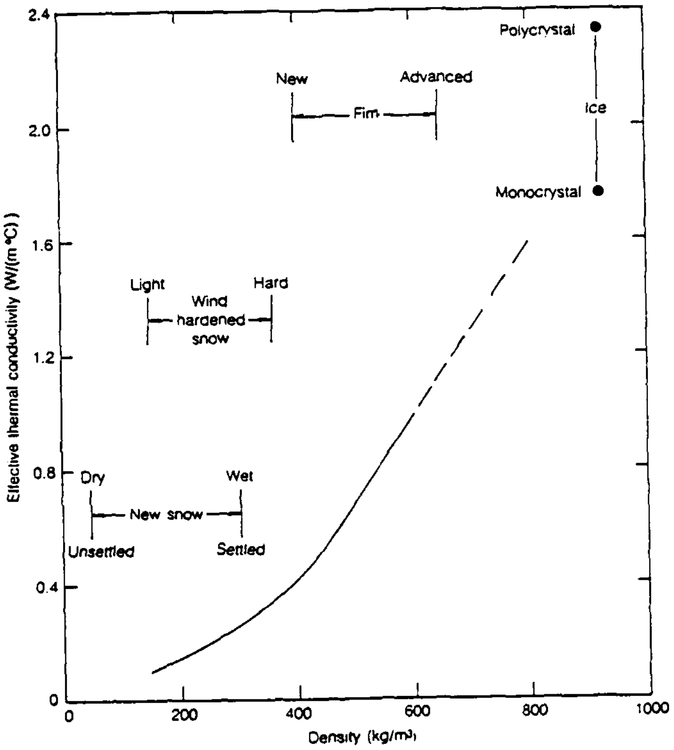


Figure 24: Approximate relation between effective thermal conductivity of snow and ice and density, Langham (1981).

The thermal diffusivity of snow is also low and directly related to density. The variations of snow density, thermal conductivity and thermal diffusivity that can occur in the snowpack result in variations of the snowpack temperature profile. When melt occurs the pack has a homogeneous temperature profile at $0^{o}C$ and is said to be 'ripe'. Usually temperatures warm from the top to the base of the pack. Inversions, when the centre or base of the pack is colder than the top, do sometimes occur. Snowpack layering can also occur due to the refreezing of melt water within the pack and the formation of extremely dense layers (by compaction under a large snowpack or wind action at the surface). This results in ice layers or ice lenses within the snowpack.

Therefore, snowpack physical properties, e.g. density, hardness, crystål shape, thermal conductivity and thermal diffusivity change with snowpack, age and depth due to metamorphosis. These changes result in compression of the snowpack, layers within the snowpack and a variable temperature profile. Metamorphosis begins as soon as the freshly fallen snow reaches the ground and increases with time and snow overburden pressure. Fresh snow and old snow have characteristic values for these physical properties. Ice layers can form because of metamorphosis and also because of the refreezing of melt water.

1.4.5 Summary

Figure 25 summarizes the energy exchanges and environmental factors operating in an idealised snow environment during the start of the melt season. Precipitation falls as snow or rain with associated snow accumulation or melt enhancement. Snow accumulation is not areally homogeneous, drifting causing greater snow depths next to obstacles (the fence) and at the base of slopes. Snow accumulation will also be less under the forest, especially the conifers, than in the open. Snow interception also results in albedo variation. This and other factors result in the variation in the energy-budget between the forested and the open area. The slope aspect and angle, cloudiness, wind speed and

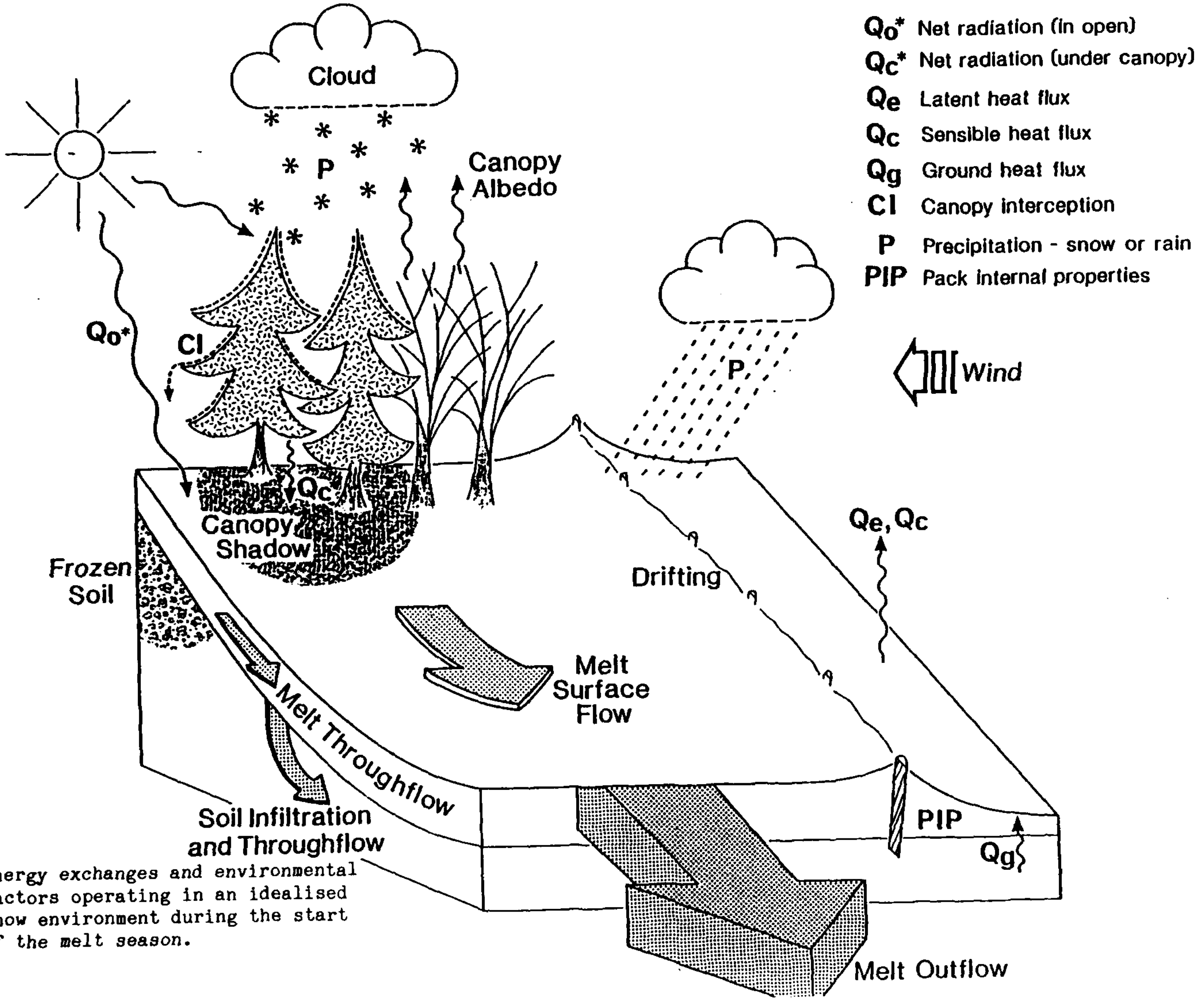


Figure 25: Energy exchanges and environmental factors operating in an idealised snow environment during the start of the melt season.

other factors affect the energy-budget for the whole area. Snowpack internal properties, e.g. density, thermal conductivity and thermal diffusivity vary with age of the pack, pack history, i.e. wind hardened layers and pack depth. The pack can be multi-layered and contain ice layers and lenses. Melt occurs as snow surface and snow throughflow and as throughflow within the soil.

The residual melt pattern on the small-scale is shown in figure 26. Snowcover remains in areas where there was a deeper pack initially, i.e. at the slope base, surface hollows, and by the fence, where shading retards melt, i.e. at forest margins and where the energy-budget is less, i.e. under forest cover. This diagram demonstrates the variation and hierarchy in the importance of various factors in influencing residual melt patterns. As explained, melt is usually initiated at the top of slopes. However, in this case, the upper part of the slope is forest covered. Field observations (photos 2 and 3) have shown that in this situation vegetation cover takes precedence over slope in determining the residual melt pattern. Under homogeneous vegetation cover, photo, slope determines melt pattern. Under different snow environments, e.g. the prairies, other factors (e.g. accumulation patterns) may take precedence. Snowmelt flow is as the start of melt situation (figure 25) but the presence of bare ground and saturated soils results in overland flow.

The snowmelt environment is therefore a complex interrelated system operating under variable ground, topographic, vegetation and meteorological conditions. The effects of the variance of these factors on the energy-budget of the snowpack is known and when melt occurs there is a corresponding residual snowpack distribution.

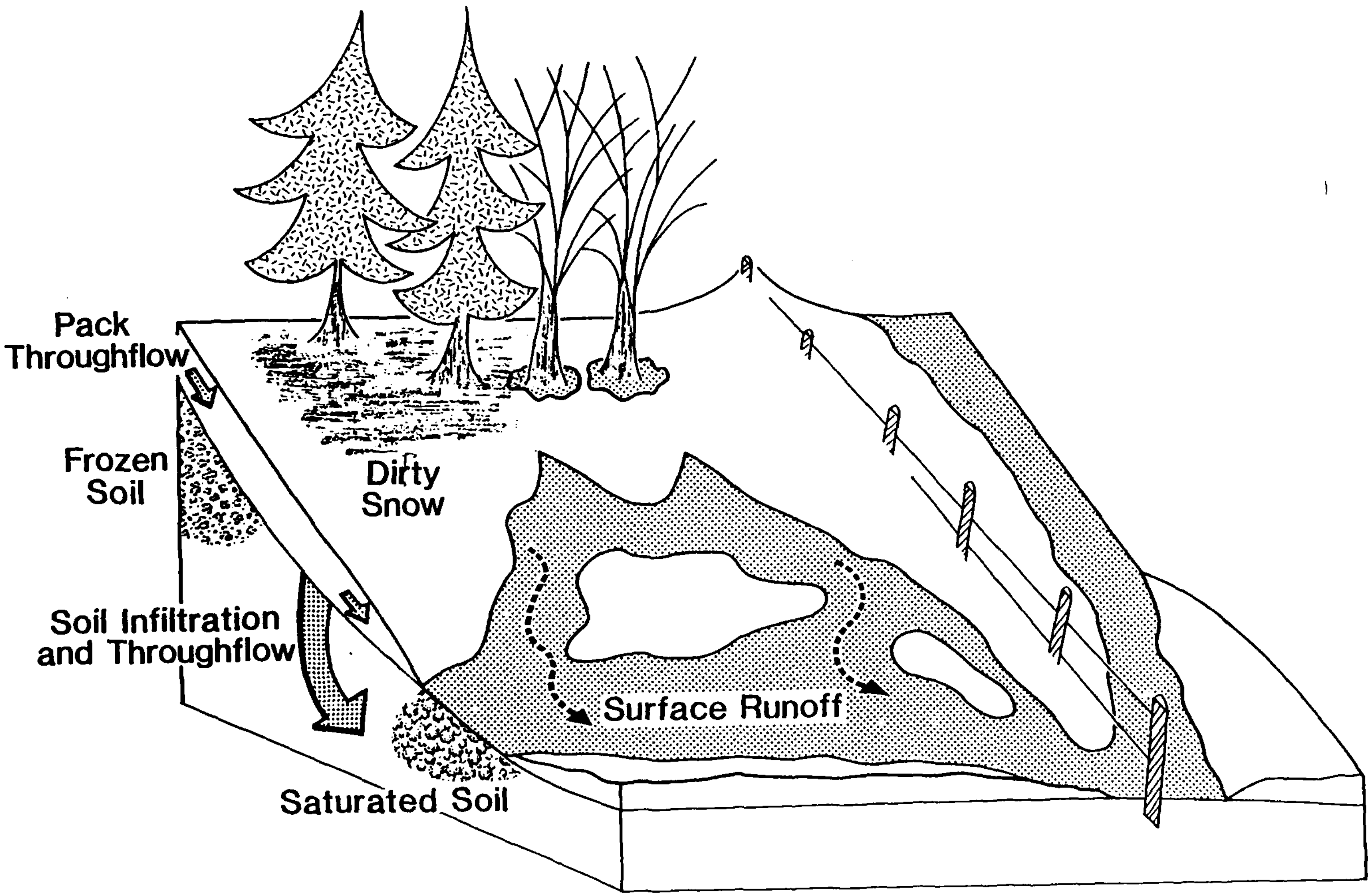
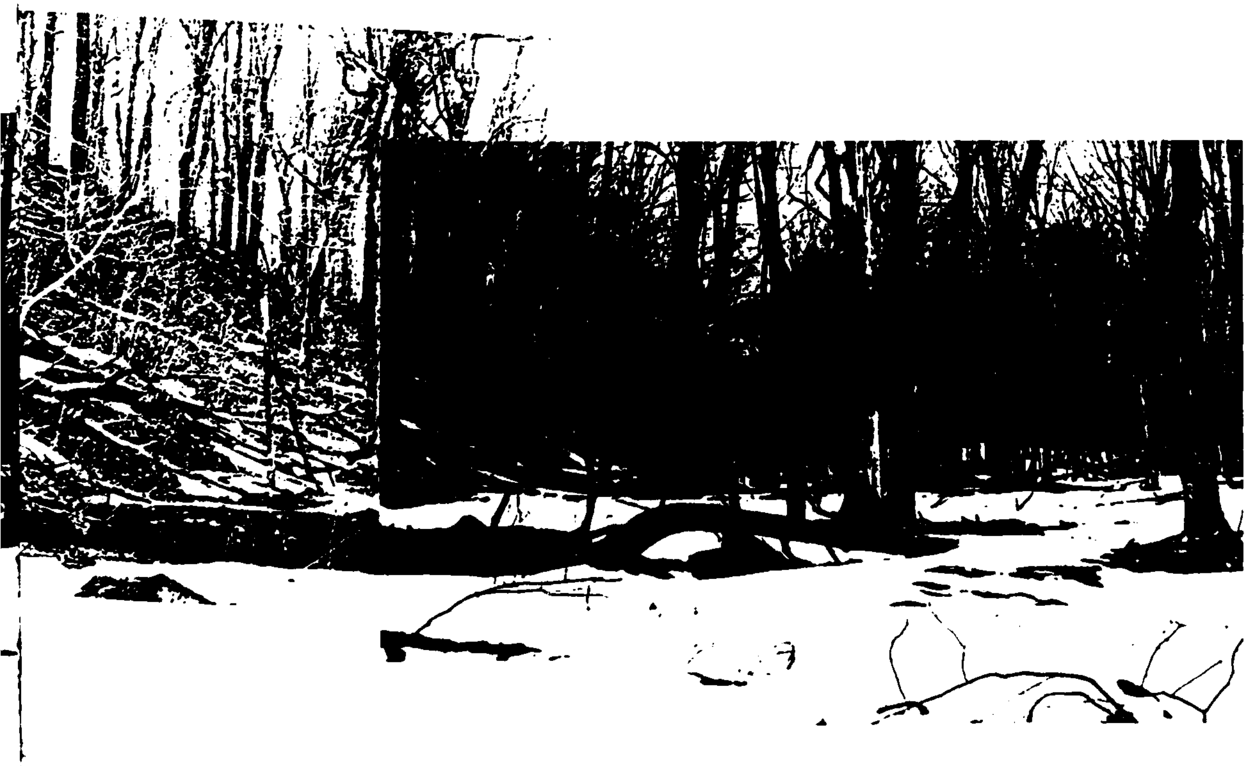


Figure 26: The idealised snow environment towards the end of the melt season.

Photograph 2

Photograph 3



II RESEARCH DESIGN

II. RESEARCH DESIGN

The design of SNOMO involves three stages:

(1) development of the model structure, i.e. logic pathways and source code

(2) validation of the model with data from the field

(3) evaluation of the model by comparison with a relevant existing model

The emphasis of this project is on the development of SNOMO, therefore roughly 80% of the project time is spent on stages (1) and (2) and the remaining 20% on stage (3).

2.1 Development of model structure

The basic structure of SNOMO is shown in figure 27. The catchment area that is to be modelled is subdivided into cells. The subdivision criteria are slope, aspect, vegetation cover and altitude. Each cell is assumed areally homogeneous in respect of these four factors. Obviously, there are intra-cell variations and these increase with the size of the cell, but it is left to the discretion of the user as to the resolution required. The energy-budget of the snowpack in each cell is calculated at the mid-point of the cell (i.e. mean altitude). The melt volume for each cell is then calculated by multiplying the calculated point melt depth by the area of the cell.

SNOMO is written in FORTRAN-77 and developed on a SUN-360 at Bristol University. The program is divided into a main 'control' section which governs snowpack characteristics, melt, and handles input and output and a large subroutine, TSTM, which calculates the energy-budget components

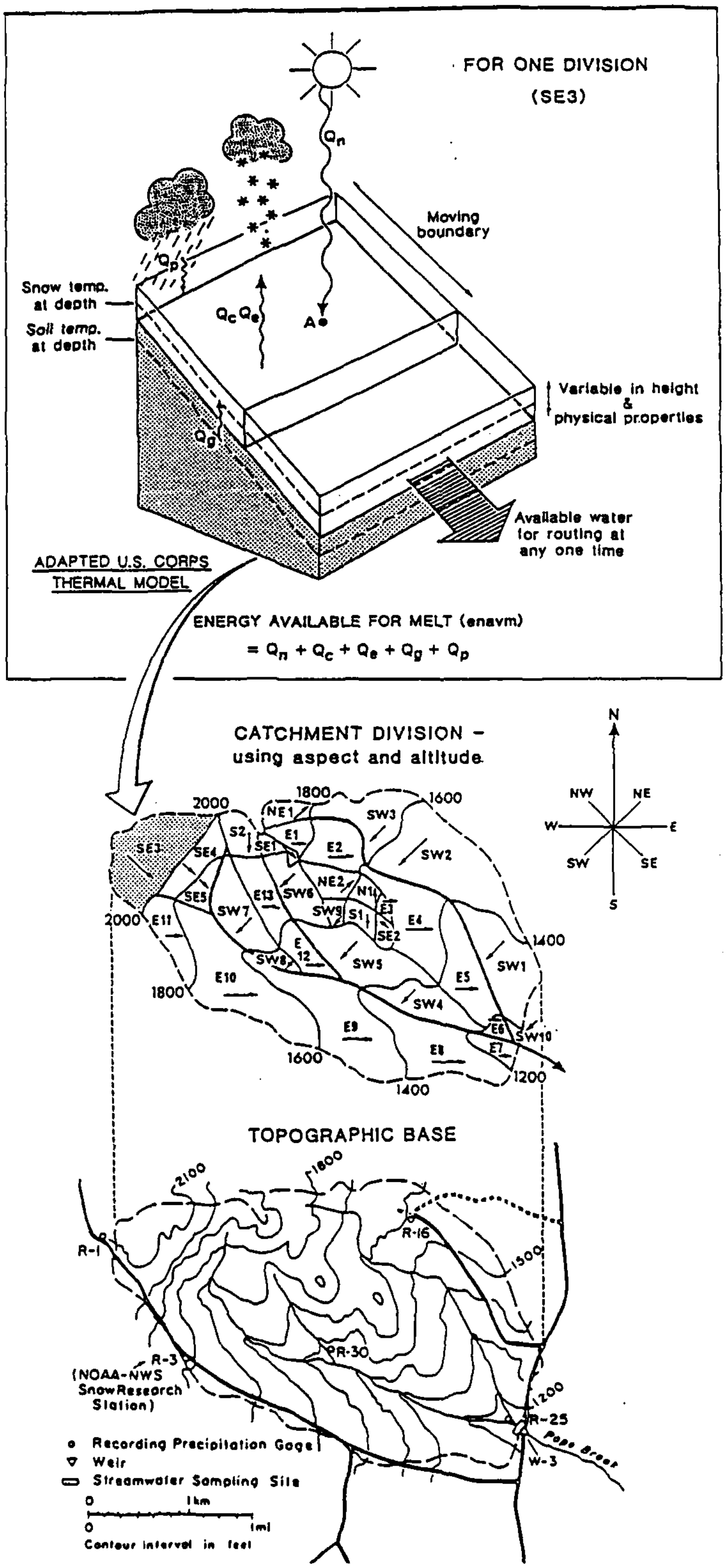


Figure 27: Basic structure of SNOMO.

and the temperature of the snow. The subroutine TSTM is adapted from the Terrain Surface Temperature Model (Balick et al., 1981a). Mr Randy Scoggins (WES) helped in the conversion of TSTM into a subroutine. Appendix I shows the main logic structure of the current SNOMO. Individual subroutines and equations used are considered in Section III.

The data required for the present operation of SNOMO is given in table 8. This appears extensive when compared to that required for an Index model. However, the meteorological inputs, with the exception of cloud cover type and amount, are those that are usually measured at meteorological stations even in the remoter sites. Cloud cover type and amount could be estimated from synoptic conditions if required. Snow absorptivity ($1 - \alpha$), emissivity, diffusivity, conductivity and density all have recognised values corresponding to their age, contamination, etc. The remaining inputs can be obtained from a good topographic map and a vegetation map. If a vegetation map is not available and a ground survey impossible, then aerial or satellite information could be used.

Subroutine TSTM, calculates incoming (direct) solar radiation for any slope, angle or aspect. This makes SNOMO different from most other snowmelt models which either require a measured solar radiation input, or calculate solar radiation using empirical relationships and parameters. There is also no pre-melt areal snow input. This is because, at present, SNOMO is designed to accumulate the snowpack from pre-snow conditions in the autumn or early winter. Accumulation is coarsely modelled using snow precipitation and densities. It is hoped to develop SNOMO to enable the initiation of modelling on any day, but in order to do this snowpack depth for that day will need to be known.

2.2 Model validation

Model validation is necessary to ensure that a model is operating correctly, i.e. the physical equations used and the processes they represent are, as far as is possible, representing reality. Validation is therefore not a proof or disproof of the utility and

Table 8 : SNOMO operational data requirements

- Instrument shelter height
- Latitude
- Altitude
- Vegetation cover type

For each cell:

- Air pressure
- Cloud cover type
- Cloud cover amount
- Air temperature
- Wind speed
- Relative humidity
- Surface emissivity
- Surface absorptivity
- Surface moisture content
- Thermal diffusivity at depth
- Heat conductivity at depth
- Slope aspect
- Slope angle
- Julian day
- Precipitation amount
- Snow density

accuracy of a model but a useful tool in its development. SNOMO is at present a prototype, the development of which will be aided by validation data. The main aim of this project (section 1.3) is to develop a new model, SNOMO. Once fully developed using the validation data, it can then be 'proved' or 'disproved' by application to many different catchments. The development alone will take three years.

The data required for the validation of SNOMO is shown in table 9. This data is detailed and there are few snow meteorlogical stations that have adequate data coverage of this type. Validation coverage of this type, over a catchment, is currently unavailable. The W3 catchment, part of the Sleepers River Research Watershed, Danville, Vermont, USA (figure 28) will be used for the validation of SNOMO. Snow accumulation depths are not as great in New England as elsewhere, but the area experiences variable meteorological conditions during melt and has a variable vegetation cover, both of which present a good test to the modelling ability of SNOMO. Snow is guaranteed from mid-November to late March.

2.2.1 Catchment description - W3, Sleepers River Research Watershed Danville, Vermont

Research began at W3 in 1965 with the initiation of a NOAA-NWS cooperative snow research project, the aim of which was to improve the data base available to snow researchers. The main meteorlogical station, Townline, began operation in 1968. Data from Townline enabled Eric Anderson to develop his point energy-budget snow model (Anderson, 1976). The data from Townline is comprehensive and reliable. Research at W3 has continued since the 1970s. At one stage nine snow course sites, four basic meteorological sites, and three weirs were in operation over W3, now only three meteorological and two weir sites remain in operation. Research at W3 is now conducted by CRREL (US Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire) Mr Hugh Greenan and Dr Timothy Pangburn, and the UVM (University of Vermont), Mr Bill Roberts. UVM initiated a ground temperature project in 1985. A series of frost tubes measuring the depth from the surface of frozen ground, is in operation under various vegetation cover types over W3. Weekly

Table 9 : SNOMO validation data requirements

Net shortwave radiation
Net longwave radiation
Sensible heat exchange
Latent heat exchange
Areal distribution and depth of the snowpack
Volume of snowmelt and river discharge over the snowmelt period
Density of the snowpack
Surface emissivity and albedo
Precipitation type and amount

Snow/soil saturation, thermal diffusivity and heat conductivity
Soil profile temperatures

Any additional information, e.g. snowpack stratification, snow profile temperatures, or unusual meteorological conditions.

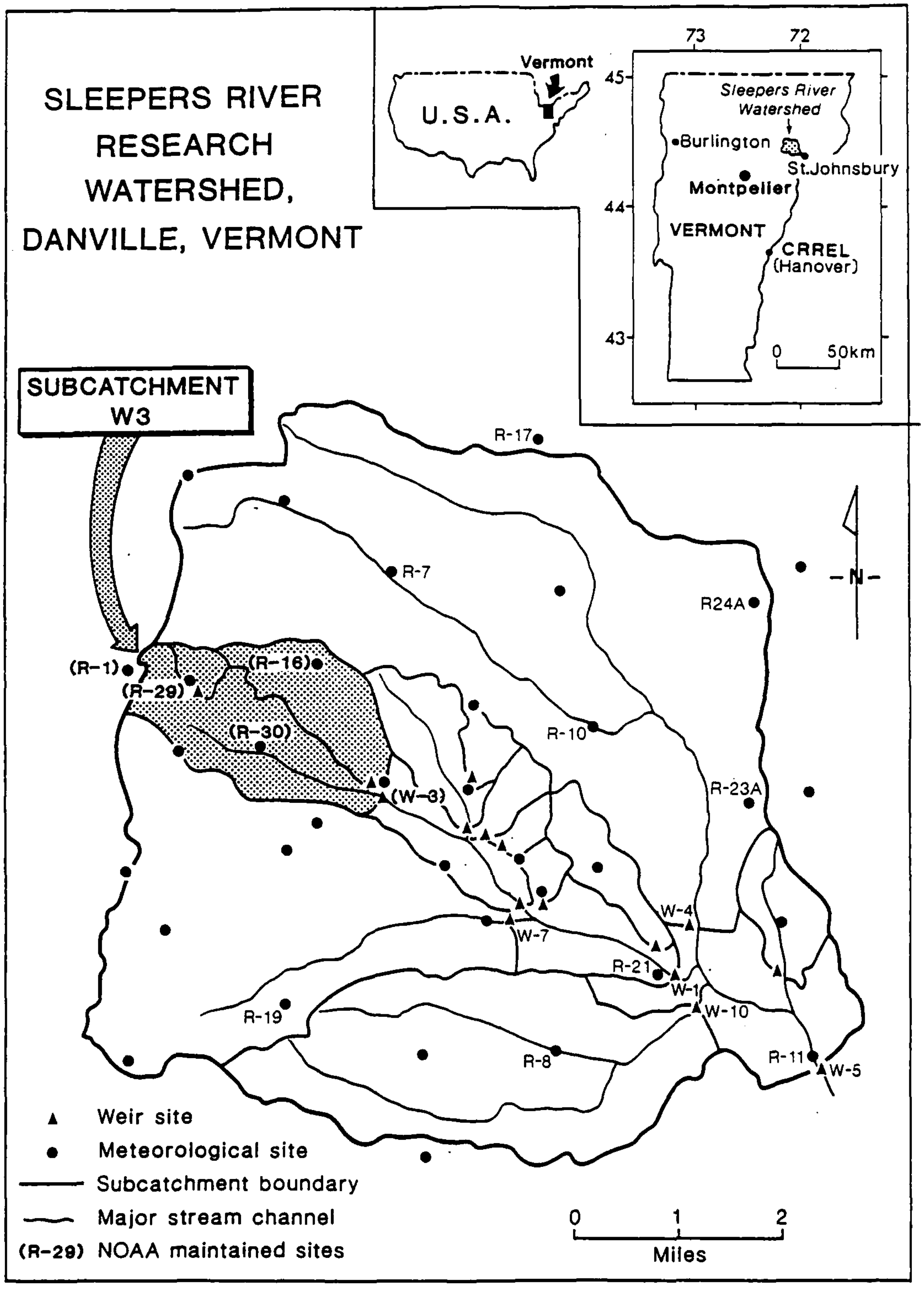


Figure 28: Location of the W3 watershed.

readings are made of the frost depths.

The W3 catchment is considered representative of the land use cover, soil and topographic conditions found in the northern areas of the New England States and southern Quebec. Photograph 2 is typical of this New England environment, rolling wooded hills, with small areas of pasture land. A more detailed description of W3 is given in Anderson, et al. (1977) and Pionke, et al. (1978).

The basin has an area of 8.4 km^2 and varies in altitude from 1135 to 2280 feet above mean sea level (figures 29 and 30). Vegetation cover is predominantly forest, coniferous, deciduous and mixed with some areas of open pasture (figure 31). There is no arable land at W3. The main deciduous species are Birch (yellow - *Betula allegheniensis*, white - *B. papyrifera* and grey - *B. populifolia.* Beech (*Fagus americana*) and Maple (sugar - *Acer saccharum* and red - *A. rubrum*). The major coniferous species are Red Spruce (*Picea rubra*) and Balsam Fir (*Abies balsamea*).

There has been and continues to be forestry activity in certain areas of W3, mainly in the coniferous areas, which has resulted in large tracts of clearcut. A lot of this activity occurred in the early 1980s, with the result that any new tree growth in these areas is still relatively young and light-loving shrubs, e.g. Dogwood, tend to predominate.

The Waits River formation forms the underlying solid geology of W3. The Waits River formation consists of calcareous granulites and calcareous schists (composed of quartz, calcite, muscovite and biotite), quartz mica schist and minor micaceous quartzite. Superficial deposits are a till with a clay-silt matrix with small patches of poorly-sorted horizontally stratified (lenticular bedded) and crossbedded sand, pebbly sand and pebble gravel.

Soils are in general fairly shallow and are variable in depth over small areas, i.e. from zero to several inches over exposed rock outcrops to 4 to 6 feet between these outcrops. The distribution of soils as mapped

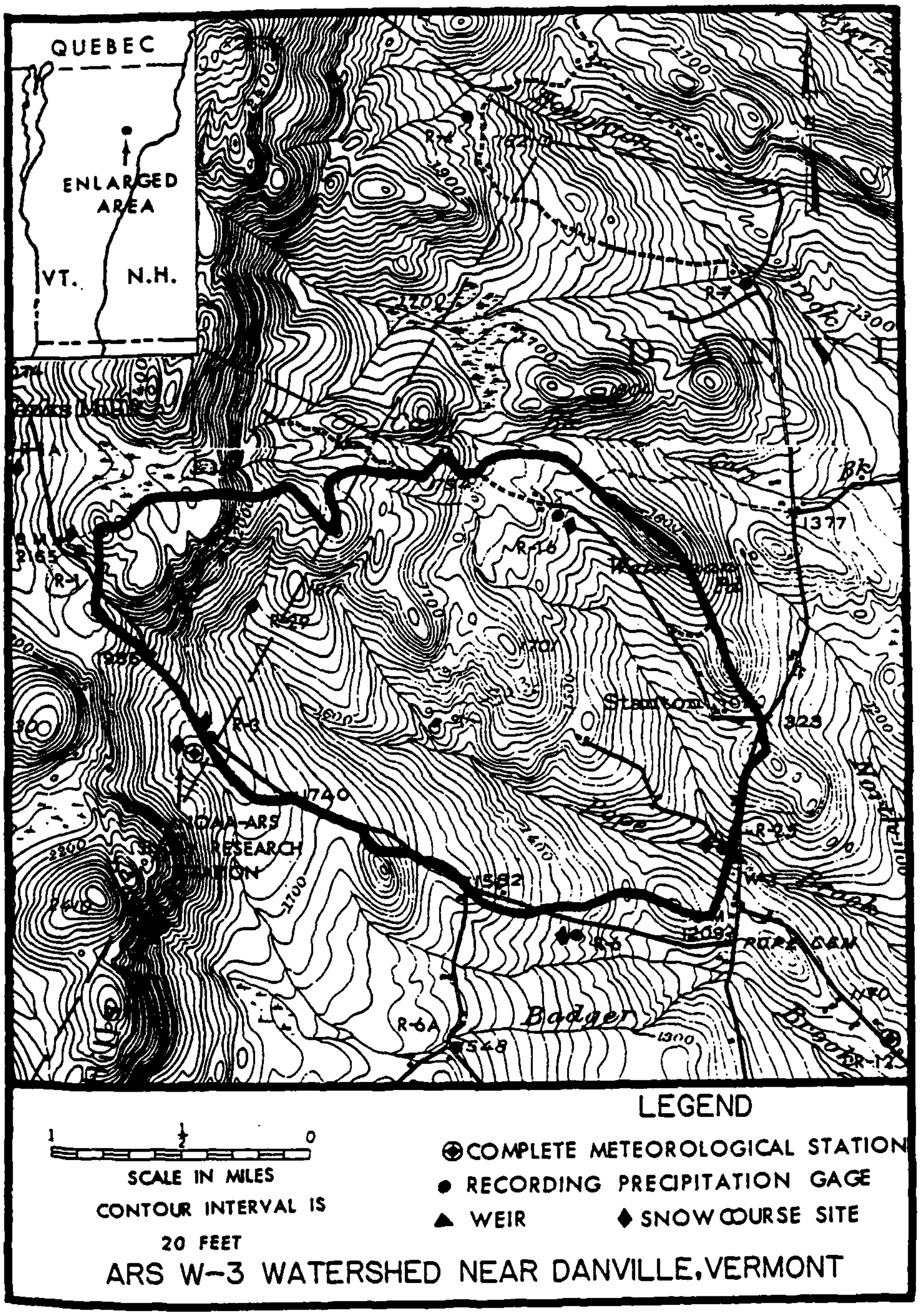


Figure 29: Topographic map of the W3 watershed, Anderson et al. (1977)

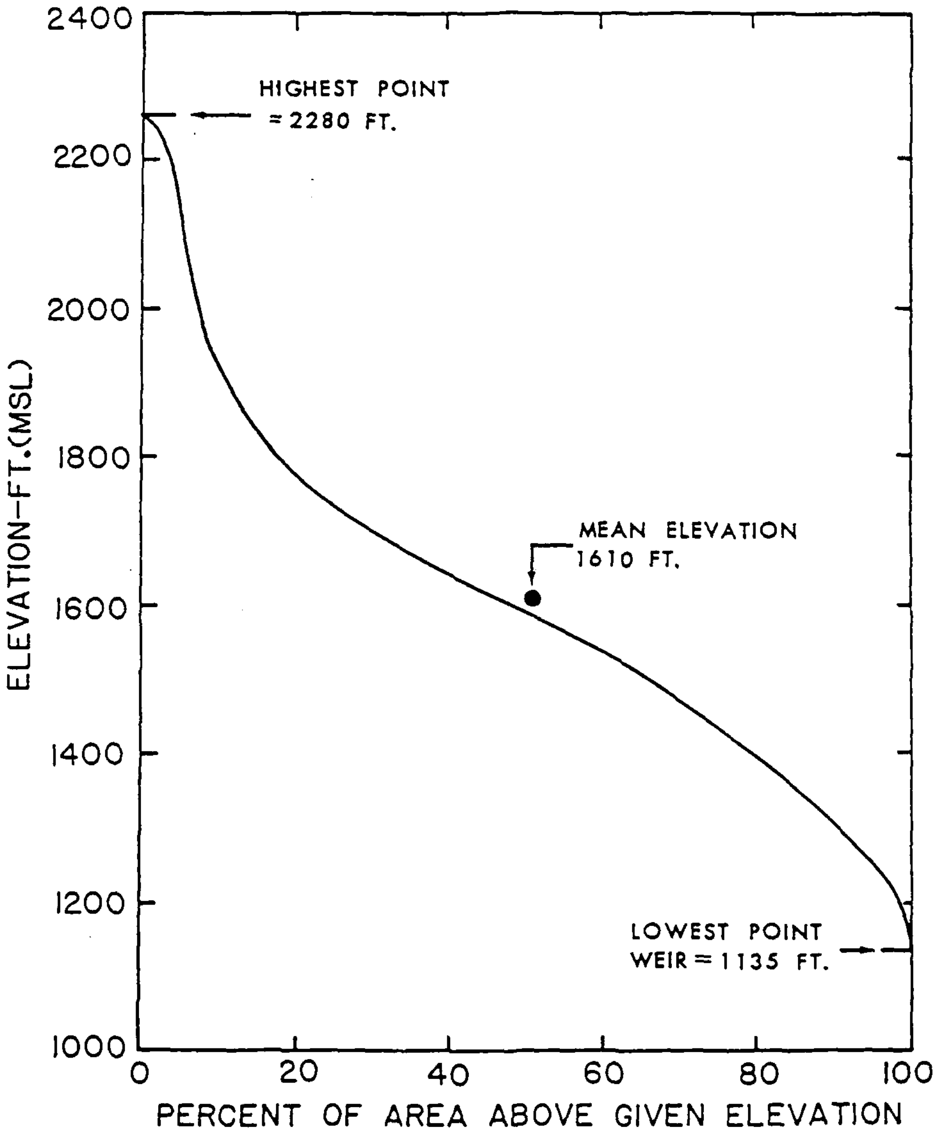


Figure 30: Area-elevation curve for the W3 watershed Anderson ^t al. (1977).

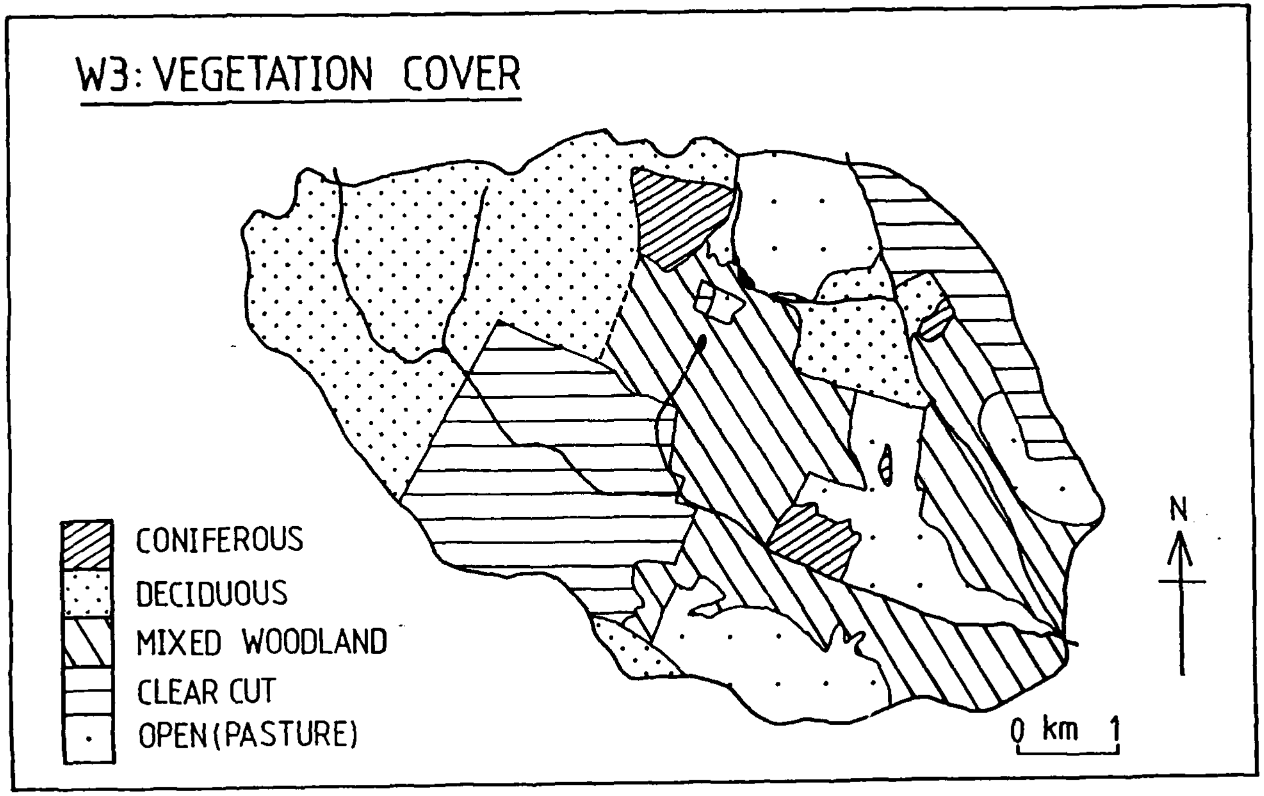


Figure 31: Vegetation cover, W3, 1988

and classified by SCS Soil Surveys 1960-64, compiled in 1969, (Pionke et al., 1978) and the dominant slope angles of W3 (from the same source as the soils) is shown in figures 32 and 33. Table 10 shows the percentage areas of Hydrologic Soil Groups, Land Use and Slope Distribution for W3 in 1978 (Pionke et al., 1978). It is probable that the figures for the Hydrologic Soils Group and the slope distribution have changed relatively little. Land use has, however, changed, there now being no arable land and a decrease in forest due to clearcutting.

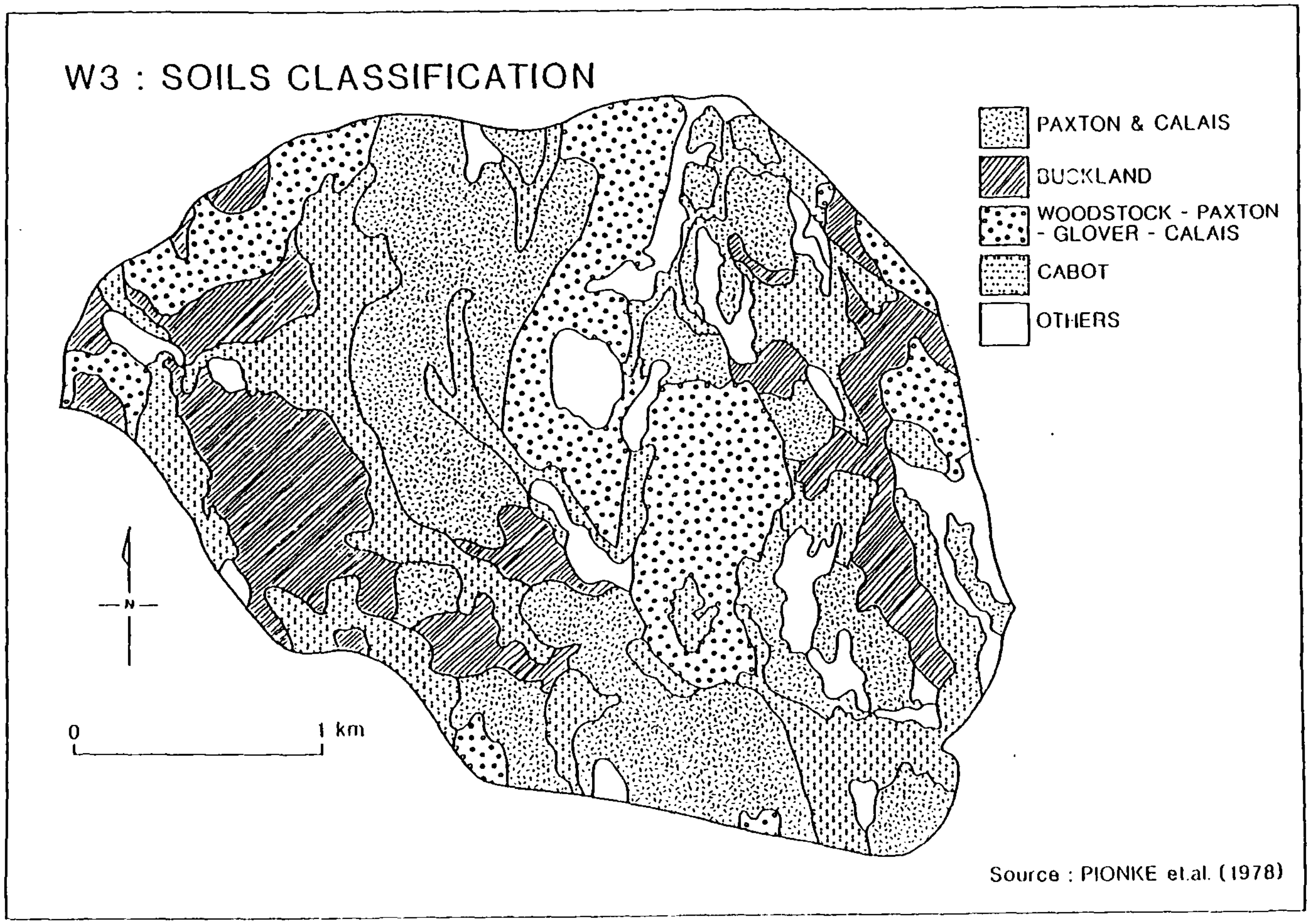
2.3 Model evaluation

It is necessary to compare the results from SNOMO with the results from a model which most closely resembles SNOMO, as an indication of the relative performance of SNOMO. SNOMO will be evaluated against Leaf and Brinks' (1973a and b) model, WATBAL, figure 34. In a review of models developed for forest hydrology (USFS, 1980), WATBAL was selected as the most "readily useful", along with PROSPER (a non-snow environment model). The aims and model structure of WATBAL most closely resemble that of SNOMO because WATBAL is specifically a catchment model. Anderson's (1976) point model most closely resembles the radiation computations and layering structures used in SNOMO, but it is a point model and does not allow for vegetation.

WATBAL models (1) winter snow accumulation, (2) the energy balance, (3) snowpack condition, and (4) resultant melt in time and space under a variety of conditions. WATBAL can model the effects of three watershed management practices:

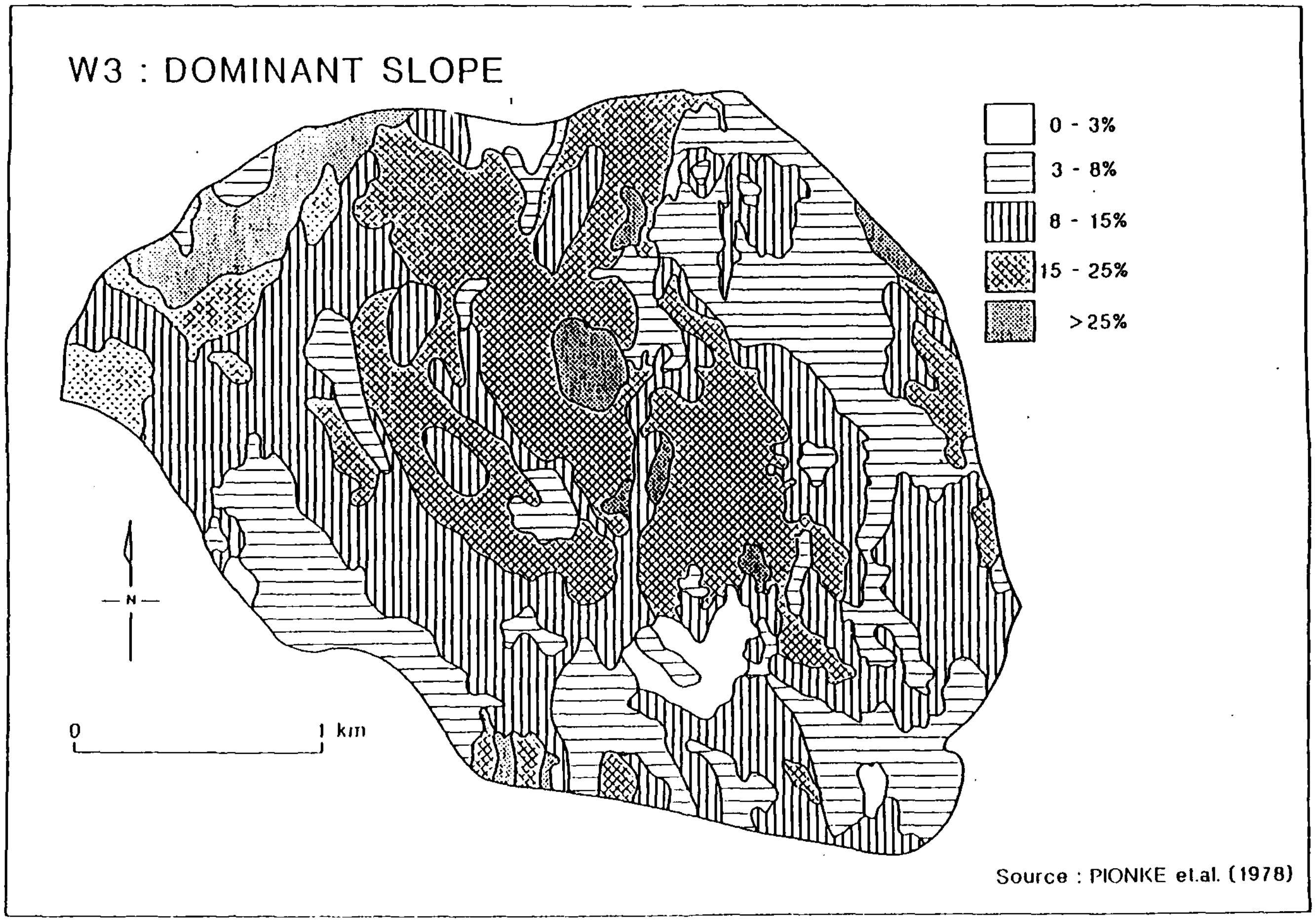
i) clearcutting in patches
ii) selective cutting (thinning)
iii) weather modification (cloud seeding)

Figure 35 is a diagrammatic comparison of SNOMO and WATBAL. There are similarities between the two models. They are both energy-budget models and subdivide the catchment into computational cells. Differences in the two models are listed in table 11.



Source : PIONKE et.al. (1978)

Figure 32: Soil distribution, W3



Source : PIONKE et.al. (1978)

Figure 33: Slope distribution, W3

Table 10: Percentage areas of Hydrologic Soil Groups, Land Use and Slope Distribution over W3 (Pionke et al., 1978)

Parameter	Mapping Unit	% Area
Hydrologic Soils Group*	A	0
	B	3
	C	75
	D	22
Land Use	Cultivated	11
	Forest	67
	Pasture	19
	Idle	3
Slope Distribution	0-3%	1
	3-8	27
	8-15	38
	15-25	22
	25	12

* A = (low runoff potential). High infiltration rates. Well to excessively well drained sands or gravels. High rate of water transmission.

B = Moderate infiltration rates. Moderate rate of water transmission.

C = Low infiltration rates. Slow rate of water transmission.

D = (High runoff potential). Very slow infiltration rates. Clay soils, soils with a permanent high water table, soils with a claypan or clay layer at or near the surface and shallow soils over nearly impervious material. Very slow rate of water transmission.

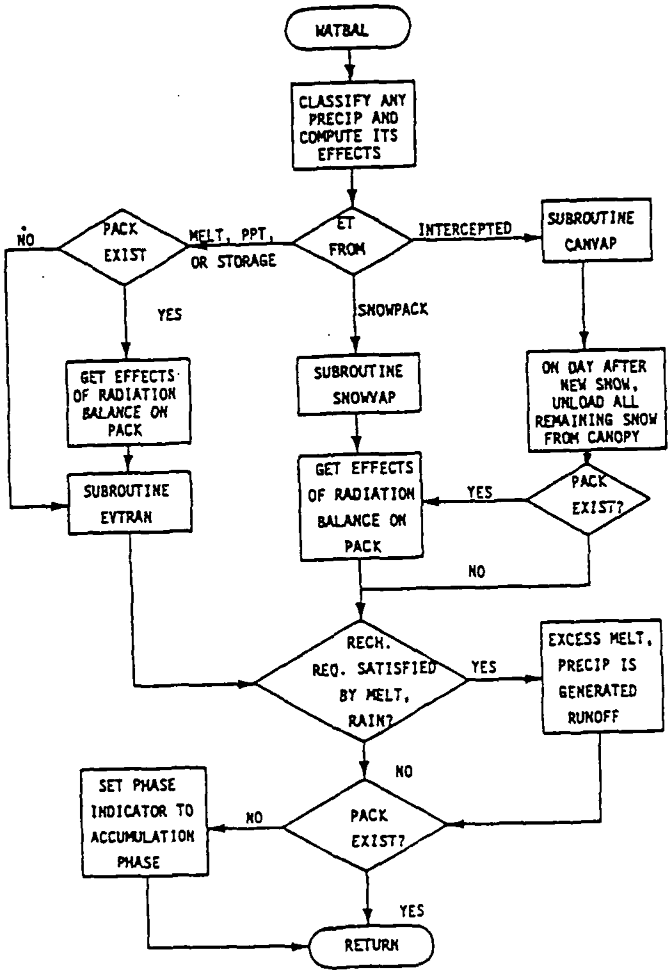


Figure 34: Flow diagram to show the structure of WATBAL, Leaf and Brink (1973b).

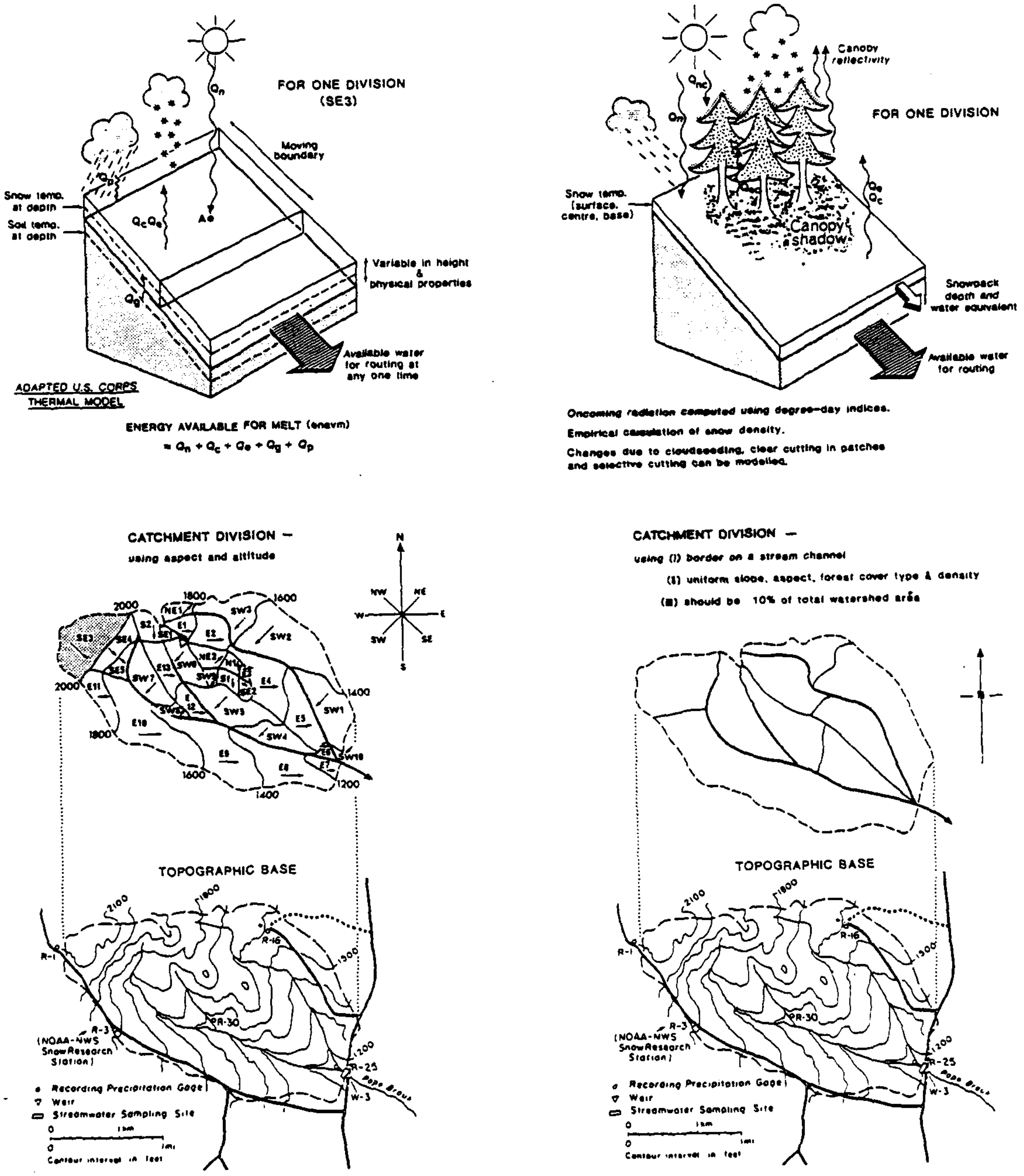


Figure 35: Comparison of SNOMO with WATBAL.

Table 11 : Comparison between SNOMO and WATBAL

Variable	SNOMO	WATBAL
Application	Catchments with a wide range of vegetation cover, elevation and meteorological conditions.	The North-American sub-alpine environment, i.e. high elevations with almost continuous coniferous tree cover are relatively stable meteorological conditions. An application of WATBAL to the Wolf Creek watershed (Oregon) showed problems in applying WATBAL to a sub-alpine area with a maritime climate (USFS, 1980).
Catchment division	Meltwater is routed through soil and therefore the position of the cells is unconstrained. Variable size of cell.	Meltwater is not routed through the soil, therefore the cells must border on a stream. Cell size is an average of 10% of the catchment area.
Calculation of shortwave radiation	See section III.1	Generated empirically as a function of maximum temperature and slope/aspect characteristics.
Calculation of longwave radiation	See section III.1	Empirically adjusted for the snow environment *with/without cloud* cover
Calculation of cell precipitation values	Cell precipitation values are assumed identical to that of the nearest meteorological station.	Base station is at a lower elevation than the catchment. Base station precipitation is adjusted until the specified peak water equivalent at each station is reached. Requires a knowledge of the peak WE of each cell and implies retrospective modelling
Calculation of cell temperature values	Cell temperatures are assumed identical to that of the nearest meteorological station	Base station is at a lower elevation than the catchment. $T_{subunit} = A + B\,(T_{base})$ where A and B are empirical coefficients.
Snowpack layering	Maximum of 6 layers, each layer with individual properties.	The snowpack is treated as a single homogeneous layer.

A copy of WATBAL and an operational data set have been obtained from Charles Troendle, U.S. Forest Service, Fort Collins, Colorado.

III MODEL DETAILS

III. MODEL DETAILS

3.1 Introduction

SNOMO consists of a 'control' program and various subroutines, figure I (appendix I). This section considers the various elements of figure I in detail as follows:

(a) snowpack characteristics and structure.
(b) data input and initialization of the model.
(c) calculation of the snow/soil energy budget variables, snow surface, and internal temperature
(d) rain-on-snow
(e) calculation of meltrate
(f) snowfall and compaction changes to pack characteristics
(g) melt changes to pack characteristics
(h) output

3.2 Snowpack characteristics and structure

The snowpack is modelled as either a 2-layered or 1-layered system. The snow is described as either 'old' or 'new' (fresh snow). The single layered pack is therefore either all old snow or new snow on top of old snow. The pack characteristics and temperature are held in two matrices, DEPMX and THKMX. There are four matrices in total, DEPMX1 (DEPMX1 for 1 layer pack), DEPMX2 (DEPMX for 2 layer pack), THKMX1 (THKMX for 1 layer pack) and THKMX2 (THKMX for 2 layer pack), see fig. 36. The matrices are also defined by two variables, NOMATL (number of layers) and NIPTS (number of iteration points, i.e. the layer boundaries), as detailed below:

1 layer system : DEPMX1

DEPMX1 (1,1): Depth of surface, i.e. 0	DEPMX1 (1,2): Surface temperature
DEPMX1 (2,1): Depth of base of pack	DEPMX1 (2,2): Temperature at base of pack

2 layer system : DEPMX2

DEPMX2 (1,1): Depth of surface, i.e. 0	DEPMX2 (1,2): Surface temperature
DEPMX2 (2,1): Depth of top of 2nd layer	DEPMX2 (2,2): Temperature at top of 2nd layer
DEPMX2 (3,1): Depth of base of pack	DEPMX2 (3,2): Temperature at base of pack

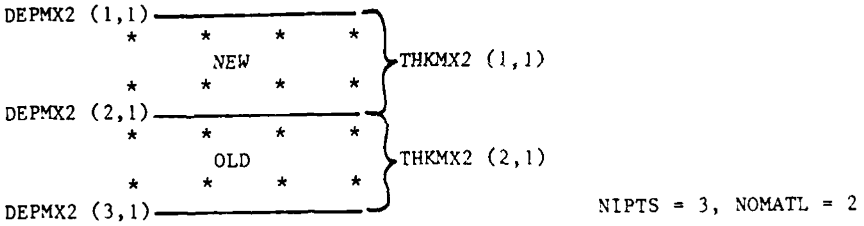


Figure 36 : SNOMO pack layering structure

i) DEPMX (depth matrix)
DEPMX1 is a 2 x 2 matrix and DEPMX2 is a 3 x 2 matrix
1st column: depth of the layer boundaries, centimetres
2nd column: corresponding temperature, $_{o}$C

ii) THKMX (thickness matrix)
THKMX1 is a 1 x 6 matrix and THKMX2 is a 2 x 6 matrix
1st column: thickness of the layer, centimetres
2nd column: thermal diffusivity, cal cm^2 min^{-1}
3rd column: heat conductivity, cal cm^2 min^{-1} k^{-1}
4th column: surface emissivity, decimal
5th column: surface albedo, decimal
6th column: density, gm^{-3}

The 5 physical variables in (ii) above refer to the snowpack and vary with the age and depth of the snowpack. Fresh snow and old snow have characteristic values (table 12). At present the extreme values for old and new snow (i.e. old, dirty and end-of-melt snow and freshly fallen, clean snow) are used in SNOMO. These characteristics are held in two vectors, VNEWSN (fresh snow values) and VOLDSN (old snow values). These vectors are 1 x 6 and the first column is 0.0. This is where the thickness of the pack is held in THKMX1 and THKMX2. The remaining 5 columns are the same as THKMX1 and THKMX2. The vectors VOLDSN and VNEWSN are substituted into the thickness matrix when and where appropriate. There is a third vector, VSOIL, which contains the same variables as VNEWSN and VOLDSN but for the soil (see table 12) VSOIL is used when snow disappears due to melt or compaction, or when SNOMO is at the start of a run and the snow has yet to fall. The values used in VSOIL depend upon soil type; if this is known then the values are obtainable from various sources such as those used for snow.

There is a threshold snowpack depth, the critical depth of 5cm which demarks the presence and absence of the snowpack. A depth of 5cm was chosen as snowpack depths under 5cm are difficult to measure accurately and the loss of less than 5cm of snow to the water input of SNOMO was deemed negligible, or, in the case of melt, could always be added.

Table 12 : Values for the physical characteristics of snow

	New snow	Old snow	Sandy soil	Clay soil
Density (gm^{-3})	0.10	0.48	1.60^{+}	1.60^{+}
Thermal diffusivity (cm^{2} min^{-1})	0.06	0.24	0.36*	0.39*
Heat 0.03 conductivity ($calcm^{-2}$ min^{-1} K^{-1})	0.08	0.08	0.09*	0.13*
Emissivity (decimal)	0.82	0.99	0.91-0.93*	0.88-0.97*
Albedo (decimal)	0.95	0.40	0.43-0.33*	0.60*

Sources: Oke (1987), Balick et al. (1981a) and Gray and Male (1981)

* frozen

\+ dry

3.3 Data input and model initialization

Data is input into SNOMO in a file SNOMO.DAT and is also present in DATA statements in the SNOMO code. The file SNOMO.DAT contains physical and computational data and variable daily data, see table 13. The data file SNOMO.DAT is considered below:

LINES 1-3 : discussed in section 3.2

LINE 4

C1 Air pressure: This is input in millibars and measured on site or taken from synoptic charts

C2 Cloud type: Index values ranging from 1 to 8 are used to determine cloud type, see table 14. If cloud type data is unavailable, then it is estimated from known synoptic conditions, precipitation, etc.

C3 Observation instrument height: This is the height of the meteorological instruments from the ground or, in the case of wind speed, from the snow surface.

LINE 5

C1 Slope angle: Angle of the slope from the horizontal measured in degrees. This is assumed homogeneous for each cell and can either be measured in the field or estimated from topographic maps.

C2 Slope aspect: Measured in degrees from south with positive values increasing westwards to north and negative values increasing eastwards to north, i.e. south = 0°, north = 180°, due east = -90° and due west = $+90^{\circ}$. Slope aspect is assumed homogeneous for each cell and can be measured in the field or estimated from topographic maps.

C3 Start date: The date, Julian calendar, of the first day modelled.

Table 13 : SNOMO.DAT.

LINE 1,	VNEWSN
LINE 2,	VOLDSN
LINE 3,	VSOIL
C1	0.0
C2	thermal diffusivity ($cm^2\ min^{-1}$)
C3	heat conductivity (cal $cm^{-2}\ min^{-1}\ K^{-1}$)
C4	surface emissivity (decimal)
C5	surface albedo (decimal)
C6	snow density (VNEWSN, VOLDSN, gm^{-3})
	soil density (VSOILgm^{-3})
LINE 4	
C1	air pressure (mb)
C2	cloud type (index)
C3	observation instrument height (cm)
LINE 5	
C1	slope angle (degrees)
C2	slope aspect (degrees)
C3	start date (Julian calendar)
C4	latitude (decimal)
LINE 6	
C1	area of cell (metres)
C2	critical snow depth (cm)
C3	number of seconds in a day
C4	bcoefficient (decimal)
C5	saturation (decimal)
LINE 7	
C1	soil depth (cm)
C2	start soil temperature at known depth (^{o}C)
C3	start soil surface temperature (^{o}C)
LINE 8	
C1	Number of days to be modelled plus one.
LINE 9	(Daily data)
C1	Julian date
C2	time of observation (24 hour notation)
C3	air temperature (^{o}C)
C4	relative humidity (%)
C5	cloud cover (tenths)
C6	wind speed (ms^{-1})
C7	precipitation (mm water)

Table 14 : Cloud Genera and Cloud Type Indices*

Cloud Genera	Abbreviation	Index Value	Comments
Cirrus	Ci	1	High clouds composed of white delicate filaments, patches of narrow bands, elements often curved or slanted and smaller than Cs, never overcast or precipitating
Cirrostratus	Cs	2	High clouds appearing as whitish veil usually fibrous, often produces halo phenomena, thinner than As, does not appear to move, nonprecipitating
Altocumulus	Ac	3	Midlevel clouds, patches, usually broken, lee wave clouds, elements smaller than Sc, nonprecipitating
Altostratus	As	4	Midlevel grey sheet or layer of striated, fibrous or uniform appearance, large horizontal extent; thicker than Cs, thinner than Ns, precipitation generally light and continuous (if any)
Stratocumulus	Sc	5	Grey and/or whitish layer or patch, nearly always has dark spots and is nonfibrous; elements larger than AC, nonprecipitating
Stratus	St	6	Grey rather uniform base, patches ragged if present, precipitation unusual but light and contnuous if present, lower and more uniform than Sc, less dense and less "wet" than Ns
Nimbostratus	Ns	7	Grey often dark, diffuse, large horizontal and vertical extent, thicker than As, more uniform than Sc, often precipitating, precipitation continuous
Fog	FG	8	

---

* Cloud genera; Cumulus (Cu), Cirrocumulus (Cc), and Cumulonimbus (Cb) are not treated here. At low cloud covers (0.3), Cu and Cc may be approximated with Ac.

C4 Latitude: The latitude of the cell expressed as a decimal.

LINE 6

C1 Cell area: This is calculated by a manual subdivision of the catchment. Subdivision criteria are slope aspect, vegetation cover and altitude.

C2 Critical snowdepth: This is the snowdepth, 5 cm, which demarks the presence and absence of snow, as discussed in section 3.2.

C3 DELTS: The number of seconds in a day, used in SNOMO calculations.

C4 Beta coefficient: Part of the energy budget melt equation (equation 6).

C5 Saturation: Percentage saturation of the snow or soil expressed as a decimal.

LINE 7

C1 Soil depth : This is either measured in the field or taken from soil maps.

C2 & C3 Soil and surface soil temperature: The soil temperature at either the base of the profile or at a known depth, which is then designated as the base of the soil profile. Soil temperatures are measured in the field (soil probe or frost tube). Soil temperatures at depth are required only if SNOMO is initiated from a bare ground situation. Soil temperature could be roughly estimated from the air temperature and preceding air temperatures if necessary. SNOMO operates on the extrapolation of the daily input data on a daily basis. Thus, for the extrapolation to occur the current day's and the next day's data has to be input. Therefore, for the number of days of daily data input (n) there are always n-1 days modelled by SNOMO.

LINE 8

C1 n, the number of days to be modelled plus one. The additional day allows for the data extrapolation routines in SNOMO.

LINE 9 - daily data

C1 Julian date

C2 Time of observation. This is input in the 24-hour clock format. Time of observation is used as this allows for flexibility in time input, useful for remote manual sites.

C3 Air temperature.

C4 Relative humidity.

C5 Cloud cover is measured in tenths and input as a decimal. If observation data is unavailable then, as with cloud type, it is estimated from synoptic conditions.

C6 Precipitation is that which is collected in a standard snow/rain gauge, i.e. it is measured in millimetres of water and not snow depth. SNOMO distinguishes between rain and snow precipitation after the precipitation data is input.

Data is also included in the SNOMO code in DATA statements. This is physical constants and computational control data:

(a) Density of water, 1000 kgm^{-3}.
(b) Heat capacity of water, 4.21×10^6 Jm^{-3} k^{-1}.
(c) Heat capacity of snow, 0.21×10^6 Jm^{-3} k^{-1}
(d) Latent heat of fusion, 0.334×10^6 Jkg^{-1}.
(e) TOTTIM: Total number of 24 hr repetitions used in solving the TSTM heat flow calculation. This is set to 1.
(f) TFRQ: Time step in minutes, used in solving the TSTM heat flow calculation, set at 5 minutes.

(g) TPRNT: Output time frequency in minutes. This refers to the TSTM outputs of surface temperature (°C), greybody radiation (Wm^{-2}) solar insolation (WM^{-2}), surface absorption (Wm^{-2}), atmospheric infra-red emission (Wm^{-2}), sensible heat (Wm^{-2}) and latent heat (Wm^{-2}).

Appendix I summarises the logic and operational structure followed by SNOMO. The logic and operational structure followed by TSTM is contained in Appendix II.

3.4 Calculation of the snow/soil energy budget

SNOMO is being developed to model the snow system and, therefore, unless specified, the remainder of this section is concerned with the snow system rather than the soil system. To avoid confusion and repetition TSTM(1) will be used to indicate the original TSTM program (Balick et al. 1981a) and TSTM(2) to indicate the converted TSTM subroutine used in SNOMO. When TSTM is used, it will refer to TSTM(1) and TSTM(2).

The snow energy budget is calculated using the subroutine TSTM. This, as stated previously, was converted from the Terrain Surface Temperature Model (Balick et al. 1981a) with the help of Mr Randy Scoggins (WES).

Figure 37 shows the concept for TSTM. TSTM predicts surface temperatures for a multilayered (1-6 layers) system by determining energy transfer in and out of the system. The model assumes that the layers and the environment above them are horizontally uniform, i.e. the most significant heat fluxes are vertical. Therefore, the temperature T estimates result from solving the one-dimensional heat equation.

$$\frac{\partial T(z,t)}{\partial t} = \alpha(z) \frac{\partial^2 T(z,t)}{\partial z^2} \qquad (16)$$

Subject to the boundary conditions.

$$\sum_{i=1}^{n} b_{it} = 0 \quad \text{at } z = 0 \qquad (17)$$

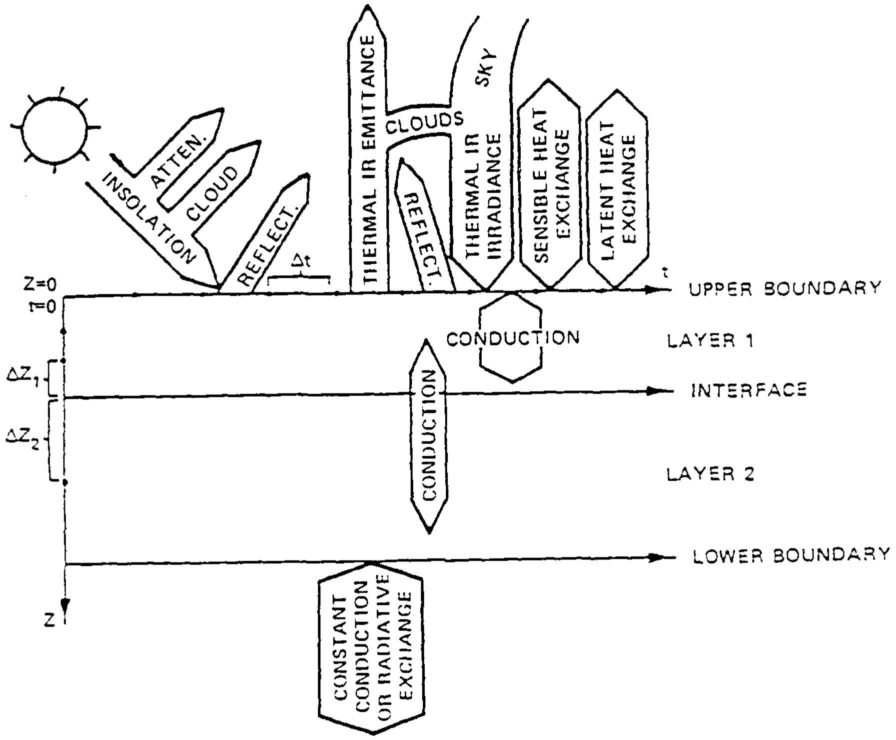


Figure 37: Terrain Surface Temperature Model, Balick et al. (1981).

and

$$\sum_{i=1}^{n} B_{it} = 0 \quad \text{at } z = b \tag{18}$$

Where the observable surface is z = b, lower surface is z = B, (z) is the diffusivity and both b_{it} and B_{it}, i = 1,2,.., n denote heat fluxes and at time t. Reliability of the results depends upon the extent to which the thermal characteristics in each of the layers can be approximated by constant values and is strongly dependent upon the approximation of b_{it}, i = 1,2,...,n, taking place at the surface which is exposed to environmental heat fluxes. TSTM calculates and outputs at any desired time interval within 24 hours (in TSTM(2) this has been changed to any time interval between one observation time and the next) the surface temperature (°C), greybody radiation ($L\uparrow$, Wm^{-2}), solar insolation ($K\downarrow$, Wm^{-2}), surface absorption ($K\downarrow - K\uparrow$, Wm^{-2}), atmospheric infra-red emission ($L\downarrow$, Wm^{-2}), sensible heat loss (ΔQ_h, Wm^{-2}) and latent heat loss (ΔQ_e, Wm^{-2}) of the snowpack.

TSTM(1) was designed to operate on a larger data base than TSTM(2). TSTM(1) was designed to allow the input of solar insolation but with the calculation of this if unavailable. The input of measured solar insolation values was preferred. TSTM(2) has been modified so that only calculation of solar insolation occurs but with little modification TSTM(2) could revert back to the input of solar insolation values. This could possibly be incorporated into an initial user menu.

3.4.1 Calculation of incoming solar radiation, $K\downarrow$

TSTM calculates only the direct incoming solar radiation. The solar radiation incident at the top of the atmosphere, the solar constant, S_o, is depleted by the atmosphere depending upon the length of its path and the vertical transmissivity of the air. The path length (or optical air mass number, M) is the ratio of the slant path, taken by the beam to the zenith distance, so that M = secz = 1/cosz. The effects of altitude are allowed for. Atmospheric transmissivity depends upon the concentrations of gases, droplets and particles in the atmosphere.

Therefore, S, the direct beam solar radiation on a horizontal surface (excluding the effect of clouds and optical air mass number) is:

$$S = (1-\alpha_g)\left[1-A(u^*, z)\right](0.349)S_0 \cos z + (1-\alpha_g)\left[(1-\alpha_0)/(1-\alpha_0 \bar{\alpha}_g)\right](0.651)S_0 \cos z \qquad (19)$$

where

α_g surface albedo

$A(u^*, z)$ Mugge-Moller absorption function, equal to $0.271\,(u^* \sec z)^{0.303}$

u^* effective water vapour content of atmosphere

$(0.349)S_0$ amount of solar radiation of wavelength greater than 0.9 um

S_0 solar radiation incident on top of the atmosphere

z zenith angle of the sun as a function of time of the day and time of the year

α_0 atmospheric albedo for Rayleigh scattering, equal to $0.085-0.247 \log_{10}\left[(\rho_s/\rho_0)\cos z\right]$

ρ_s surface pressure

ρ_0 1000mb

$\bar{\alpha}_g$ area average ground albedo

$(0.651)S_0$ amount of solar radiation of wavelength less than 0.9 um

The effective water vapour content, U^*, is the total precipitable water excluding clouds. Precipitable water is estimated from surface air temperature and relative humidity

$$u^* = \exp\left(0.07074\,T_d + \tau\right) \qquad (20)$$

where

T_d dew point temperature (°C)

τ -0.02290 April - June

0.02023 July - March

The effect upon S of cloudy skies is calculated in two stages. First, a cloud adjustment, factor, CA, is calculated which is dependent upon cloud type. This is then related to cloud cover to result in S_c.

$$CA = (a/94.4) \times \exp\left[-m \times (b-0.059)\right] \qquad (21)$$

where

a and b = empirical coefficients dependent upon cloud type (table 15)
m = optical air mass number

$$S_c = S - \left\{\left[S - (S \times CA)\right] \times CC^2\right\} \qquad (22)$$

where
CC visual cloud cover in tenths
S_c is then modified for slope and aspect by the calculation of a slope factor, SF

$$K\downarrow = S_c \times SF \qquad (23)$$

Spherical trigonometry gives the following relationships, figure 38.

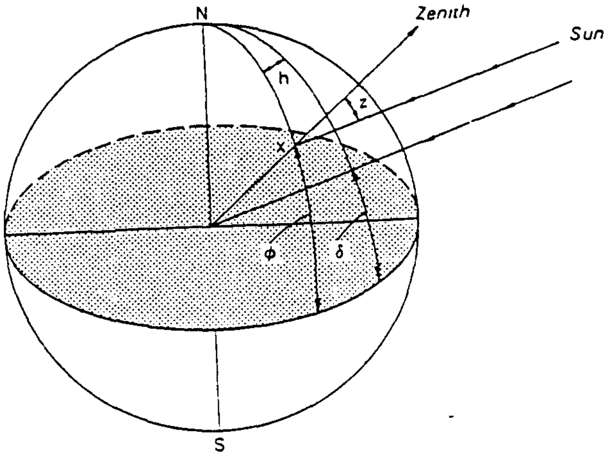
$$\cos z = \sin\phi \sin\delta + \cos\phi \cos\delta \cos h = \sin\beta \qquad (24)$$

$$\cos \Omega = (\sin\delta \cos\phi - \cos\delta \sin\phi \cos h) / \sin z \quad , t<12 \qquad (25)$$

$$= 360° - (\sin\delta \cos\phi - \cos\delta \sin\phi \cos h)/\sin z \, , t>12 \qquad (26)$$

Table 15 : Coefficients used in SNOMO energy budget calculations

Cloud type	Coefficient		
	a	b	CIR
Cirrus	82.2	0.079	0.04
Cirrostratus	87.1	0.148	0.08
Altocumulus	52.5	0.112	0.17
Altostratus	39.0	0.063	0.20
Stratocumulus	34.7	0.104	0.22
Stratus	23.8	0.159	0.24
Nimbostratus	11.2	-0.167	0.24
Fog	15.4	0.028	0.25



t	Apparent solar time
z	Solar zenith angle
ϕ	Latitude of location
δ	Solar declination
Ω	Solar azimuth angle
h	Hour angle

Figure 38: Geometrical relations between the Earth and the solar beam. The angles are defined with reference to the equatorial plane (shaded) and the point of interest (X), Oke (1987).

where

t	apparent solar time
z	solar zenith angle
ϕ	latitude of location
δ	solar declination
Ω	solar azimuth angle
h	hour angle

For a slope, the solar radiation incident on the slope, S, can be calculated using spherical trigonometry. figure 39.

$$\cos\hat{\Theta} = \cos\hat{\beta}\,\cos z + \sin\hat{\beta}\,\sin z\,\cos(\Omega - \hat{\Omega}) \qquad (27)$$

where

$\hat{\beta}$	slope angle
$\hat{\Omega}$	slope azimuth angle
$\cos\hat{\Theta}$	slope factor

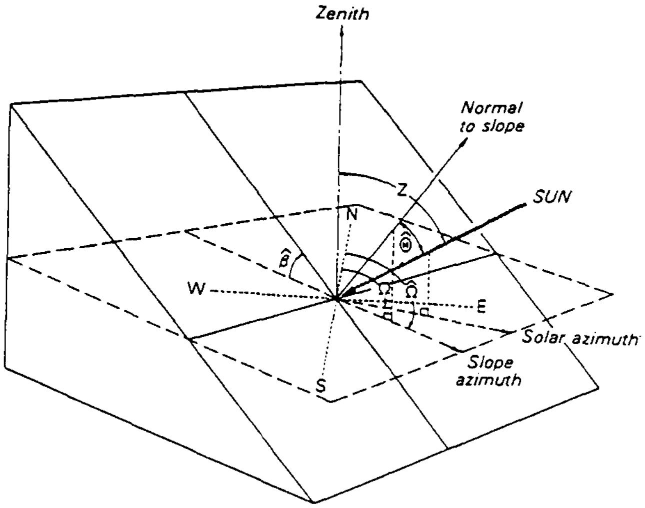
3.4.2 Calculation of reflected solar radiation, $K\uparrow$

TSTM calculates the amount of direct incoming solar radiation, $K\uparrow$, that is absorbed at the snow surface, K_{ab}:

$$K_{ab} = K\downarrow(1-\alpha) \qquad (28)$$

where

α	surface albedo
$(1-\alpha)$	absorptivity of the surface



Z	Zenith angle
$\hat{\beta}$	Slope angle
Ω	Solar azimuth angle
$\hat{\Theta}$	Angle of incidence (between sun and the normal to the slope

Figure 39: Geometry for solar beam irradiance of a sloping plane, Oke (1987).

The reflected solar radiation, K↑, can therefore be calculated:

$$K\uparrow = K\downarrow - K_{ab} \tag{29}$$

or alternatively,

$$K\uparrow = K\downarrow \alpha \tag{30}$$

3.4.3 Calculation of incoming longwave radiation (atmospheric infra-red emission) L↓

The Brunt equation is used to calculate atmospheric IR radiation on the surface, $I\downarrow_o$:

$$I\downarrow_0 = \varepsilon \sigma T_a^4 \left[c + b\left(e_a^{0.5}\right)\right] \tag{31}$$

where

ε	emissivity, assumed equal to 1
σ	Stephan-Boltzmann constant (0.813×10^{-10} Cal cm^{-2} min^{-1} $^{o}K^{-4}$)
T_a	shelter air temperature, ^{o}K
e_a	water vapour pressure, mb
b & c	empirical constants = c = 0.61, b = 0.05

The value of C_a is obtained from Teten's equation:

$$e_a = RH \times 6.108 \times \exp(A \times T_a) / (T_a + 273.15 - B) \tag{32}$$

where

RH	relative humidity (decimal)
A	17.269
B	35.86

Clouds also contribute to L$\downarrow$:

$$L\downarrow = I_0\downarrow\left(1 + CIR \times CC^2\right) \tag{33}$$

Where

CIR	coefficient dependent upon cloud type (see table 15).

3.4.4 Calculation of reflected longwave (greybody radiation, L$\uparrow$

$$L\uparrow = \varepsilon_g \sigma \left(T_g\right)^4 \tag{34}$$

where

ε_g	emissivity of ground
T_g	current surface temperature as predicted by the model

3.4.5 Calculation of sensible heat flux, ΔQ_h

$$\Delta Q_h = -\rho C_p K^2 z^2 \frac{\partial \theta}{\partial z} \frac{\partial v}{\partial z} SCF \tag{35}$$

where

$$SCF \begin{cases} 1.175(1-15Ri)^{0.75} & Ri \leq 0 \\ (1.5Ri)^2 & 0 < Ri \leq 0.2 \\ 0 & Ri > 0.2 \end{cases}$$

ρ	air density
C_p	specific heat of dry air at constant pressure
K	von Karman's constant (0.40)
z	observation height
$\frac{\partial \theta}{\partial z}$	partial derivative of potential temperature with respect to height z
$\partial v/\partial z$	partial derivative of wind speed with respect to height z
Ri	Richardson number
θ	potential temperature

Potential temperature, θ, is defined by:

$$\theta = T_a \left(\frac{1000}{P}\right)^{0.286} \tag{36}$$

where

T_a air temperature

P air pressure

The Richardson number, Ri, is defined by:

$$Ri = \left(\frac{g}{\bar{\theta}} \frac{\partial \theta}{\partial z}\right) \Big/ \left(\frac{\partial v}{\partial z}\right)^2 \tag{37}$$

where

g acceleration due to gravity

$\bar{\theta}$ average potential temperature between the surface and height z

In TSTM $\partial\theta/\partial z$ and $\partial v/\partial z$ are approximated by first order differences and it is assumed that the air temperature at the surface equals temperature of the surface and that wind velocity at the surface is zero.

3.4.6 Calculation of latent heat flux, ΔQ_e

$$\Delta Q_e = -\rho L K^2 z^2 (W \partial q/\partial z)(\partial v/\partial z)\, SCF \tag{38}$$

where

L latent heat of evaporation, 597.3 cal g^{-1}

q specific humidity

W decimal relative saturation of the top surface

3.4.7 Calculation of surface temperature and solution of heat flow equations

At present, TSTM(2) assumes a constant temperature at the bottom boundary (the snow/soil interface). TSTM(1) allows one of the following three options:

(a) Option 1: A constant temperature at the bottom boundary.
(b) Option 2: A constant heat flux at the bottom boundary.
(c) Option 3: A constant heat flux at the bottom boundary and an additional constant temperature radiating surface below the bottom boundary.

Option 3 requires additional input data: (i) bottom boundary thermal IR emissivity; (ii) bottom boundary geometric shape factor; (iii) under surface thermal IR emissivity; (iv) under surface geometric shape factor; and (v) under surface temperature. The bottom boundary *condition is kept constant in time regardless of the option chosen.*

The complicated nonlinear boundary conditions require that the heat conduction equation

$$\frac{\partial T(z,t)}{\partial t} = \frac{\alpha(z)\,\partial^2 T(z,t)}{\partial z^2} \qquad (39)$$

be solved numerically. In this equation, α is the diffusivity. Each layer is assumed to be homogeneous, and it is assumed that the thermal characteristics can be taken to be constant; specifically, the thermal conductivity and diffusivity for each layer are assumed to be a constant.

3.4.8 Solution within a layer

Within each layer, an explicit scheme is employed to solve the one-dimensional heat equation. In particular, given the temperature profile at time t, the temperature at time $t+\Delta t$ at the node z is given by

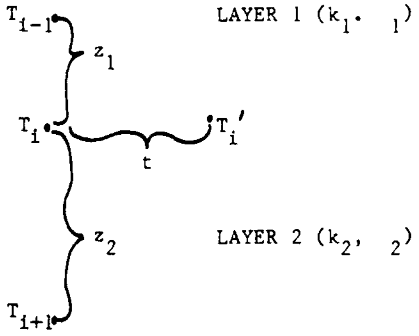
$$T(t+\Delta t,z) = T(t,z) + \alpha(\Delta t/\Delta z^2)\left[T(t,z+\Delta z) - 2T(t,z) + T(t,z-\Delta z)\right] \qquad (40)$$

where Δt is the time increment and Δz denotes the spatial increment. It should be noted that numerical stability requires $\alpha \Delta t / \Delta z^2 < 1/2$ The problem of numerical stability is critical for thin highly conductive layers.

3.4.9 Solution at the interface of two layers

The following derivation of an explicit finite difference scheme to handle the interface between layers is a modification of that presented in Carnahan, Luther, and Wilkes (1964). The derivation assumes perfect thermal contact at the interface, i.e. continuity of the heat flux and temperatures at the interfaces.

Let layer 1 have thermal conductivity, k_1, and diffusivity α_1, and layer 2 have thermal conductivity and diffusivity, k_2, and α_2, respectively.



Knowing the temperature T_{i-1}, T_i, and T_{i+1} at the node points i - 1, i, and i + 1, the problem is to calculate the new temperature T_i at the interface. Employing the truncated Taylor series, T_{i-1} is approximated by

$$T_{i-1} = T_i - \Delta z_1 \left(\frac{\partial T}{\partial z}\right)_{i1} + \frac{\Delta z_1^2}{2} \left(\frac{\partial^2 T}{\partial z^2}\right)_{i1} \qquad (41)$$

where i1 denotes the partial derivative in layer 1 at the interface. Thus,

$$\left(\frac{\partial^2 T}{\partial z^2}\right)_{i1} = \frac{2}{\Delta z_1^2}\left[T_{i-1} - T_i + \Delta z_1 \left(\frac{\partial T}{\partial z}\right)_{i1}\right] \tag{42}$$

Also, the first order approximation to   is given by

$$\left(\frac{\partial T}{\partial t}\right)_{i1} = \frac{T_i' - T_i}{\Delta t} \tag{43}$$

Since $\partial T/\partial t = \alpha_1 \left(\partial^2 T/\partial z^2\right)$ one obtains

$$\frac{T_i' - T_i}{\Delta t} = \frac{2\alpha_1}{\Delta z_1^2}\left[T_{i-1} - T_1 + \Delta z_1 \left(\frac{\partial T}{\partial z}\right)_{i1}\right] \tag{44}$$

or

$$\frac{k_1 \Delta z_1^2 \; T_i' - T_i}{2\alpha_1 \Delta z_1 \, \Delta t} - k_1 \frac{T_{i-1}}{\Delta z_1} + \frac{k_1 T_i}{\Delta z_1} = k_1 \left(\frac{\partial T}{\partial z}\right)_{i1} \tag{45}$$

i.e.

$$k_i \left(\frac{\partial T}{\partial z}\right)_{i1} = \frac{k_1}{2\Delta z_1 \alpha_1 (\Delta t/\Delta z_1^2)}\left[T_i' - T_i\right] - \frac{k_1}{\Delta z_1} T_{i-1} + \frac{k_1 T_1}{\Delta z_1} \tag{46}$$

In a similar fashion for layer 2, one obtains

$$k_2 \left(\frac{\partial T}{\partial z}\right)_{i2} = \frac{-k_2}{2\Delta z_2 \alpha_2 (\Delta t/\Delta z_2)^2}\left[T_i' - T_i\right] + \frac{k_2 T_{i+1}}{\Delta z_2} - \frac{k_2 T_i}{\Delta z_2} \tag{47}$$

Continuity of the heat flux implies that Equation 46 equals Equation 47; thus, after simplification, the final equation used to calculate T_i is:

$$\left[\frac{k_1}{2\Delta z_1 \alpha_1 (\Delta t/\Delta z_1^2)} + \frac{k_2}{2\Delta z_2 \alpha_2 (\Delta t/\Delta z_2^2)}\right] T_i' = \frac{k_1}{2\Delta z_1 \alpha_1 (\Delta t/\Delta z_1^2)} \tag{48}$$

$$+ \frac{k_2}{2\Delta z_2 \alpha_2 (\Delta t/\Delta z_2^2)}\Bigg] T_i + \frac{k_1}{\Delta z_1} T_{i-1} - \left(\frac{k_1}{\Delta z_1} \div \frac{k_2}{\Delta z_2}\right) T_i + \frac{k_2}{\Delta z_2} T_{i+1}$$

3.4.10 <u>Upper boundary</u>

The new or updated value of the surface temperature $T(t + \ t,0)$ is calculated by solving the surface heat balance equation for the surface temperature, T_g. The heat balance equation is

$$K^* + L\downarrow + L\uparrow + \Delta Q_h + \Delta Q_e + \Delta Q_g = 0 \tag{49}$$

where ΔQ_g denotes the heat flux into the surface; i.e. $\Delta Q_g = k(\partial T/\partial z)$ and is approximated by $k\,(T_1 - T_g/\Delta z)$ where k denotes the conductivity of the surface layer and T_1 denotes the temperature at the present time for the first node point below the surface. Letting $D = K^* + L\downarrow - \Delta Q_h - \Delta Q_e$, the heat balance equation becomes

$$-\varepsilon\sigma T_g^4 + k\left(\frac{T_1 - T_g}{\Delta z}\right) + D = 0 \tag{50}$$

or upon rewriting

$$T_g^4 - \frac{kT_1}{\varepsilon\sigma\Delta z} + \frac{kT_g}{\varepsilon\sigma\Delta z} - \frac{D}{\varepsilon\sigma} = 0 \tag{51}$$

The function F is defined by

$$F(T_g) = T_g^4 + \frac{k}{\varepsilon\sigma\Delta z} - \frac{dD/dT_g}{\varepsilon\sigma} \tag{52}$$

It is seen that the updated surface temperature is a root of F. The Newton Raphson algorithm has been employed to locate a value of T_g such that F vanishes. In employing the Newton-Raphson scheme, the derivative of F with respect to T_g is needed:

$$\frac{dF(T_g)}{dT_g} = 4T_g^3 + \frac{k}{\varepsilon\sigma\Delta z} - \frac{dD/dT_g}{\varepsilon\sigma} \tag{53}$$

Numerical considerations have resulted in the approximation of dD/dT_g by the following expression

$$\frac{dD}{dT_g} = \frac{(D_N - D_o)}{-\Delta T} \tag{54}$$

where D_N is the value of D using the latest estimate of T_g, D_0 is the value of D obtained by using the previous estimate of T_g, and T denotes the change in temperature. The starting value for the Newton-Raphson scheme is taken to be the surface temperature at the previous time step. It appears that three to five iterations yield satisfactory convergence to the new surface temperature.

3.4.11 Bottom boundary

The bottom boundary condition is the heat flux through the bottom of the lowest layer and can be specified with one of three options. The requirement of a constant temperature results in a straightforward boundary condition.

For options 2 and 3, it is required that the following equation be satisfied:

$$R\downarrow - \Delta Q_g - R\uparrow - D = 0 \tag{55}$$

where $R\downarrow$ denotes the radiative energy loss through the bottom boundary, G denotes the heat flux into the lower surface and is given by $G = k(\partial T/\partial x)$ where k denotes the conductivity of the bottom layer, $R\uparrow$ denotes the radiative energy from the constant temperature radiating surface below the bottom boundary, and D is the constant heat flux at the bottom boundary. G is approximated by $k(T_B - T_1)/\Delta z$ where T_B is the temperature of the bottom surface and T_1 is the temperature at the first node point above the bottom surface.

The following equation results from substituting the appropriate energy components into Equation 55:

$$\varepsilon_B \delta b_{kB} T_B^4 - k\left(\frac{T_B - T_1}{\Delta z}\right) - \varepsilon_R \delta b_{kR} T_R^4 - D = 0 \qquad (56)$$

where ε_B denotes the bottom boundary thermal IR emissivity, b_{kB} denotes the bottom geometric shape factor, ε_R is the under surface thermal IR emissivity, b_{kR} is the under surface geometric shape factor, and T_R denotes the under surface temperature. Equation 56 is solved by employing the Newton-Raphson iterative scheme.

3.5 Rain-on-snow

The heat transferred to the snow by rainwater is the difference between its energy content before falling on the snow and its energy content on reaching thermal equilibrium within the pack. Depending upon the thermal state of the pack, the energy produced by the rain will heat up the pack or melt the pack.

i) Rainfall on a melting pack where the rainwater does not freeze

$$Q_p = \rho_w C_p (T_r - T_s) P/1000 \qquad (57)$$

where

Q_p	energy supplied to the pack by rain, kJm^{-2} day^{-1}
ρ_w	density of water
C_p	heat capacity of water, $kJkg^{-1}{}^{0}C^{-1}$
T_r	temperature of the rain, ^{o}C
T_s	temperature of the snow, ^{o}C
P	precipitation rate, mm day^{-1}

(from Male and Gray 1981)

In SNOMO T_r is taken to be the same as the air temperature T_A. In a melting pack, the pack should be isothermal at $0^{o}C$, therefore the working equation for SNOMO is:

$$Q_p = (\rho_w C_p T_A P)/1000 \qquad (58)$$

ii) Rainfall on a pack with a temperature below $0^{o}C$, where the rainfall freezes and releases its latent heat of fusion resulting in a warming of the pack. The rate of change in snow temperature, dT_M/dt is calculated from Male and Granger (1978):

$$\frac{dT_m}{dt} = \frac{P\rho_w(C_p T_p + L_f - C_{pi} T_m)}{C_{pi}\rho_i D} \qquad (59)$$

where

P	precipitation rate, mm day^{-1}
ρ_w	density of water, kgm^{-3}
C_p	heat capacity of water, $kJkg^{-1}$ $^{o}C^{-1}$
T_p	temperature of rain, taken to equal air temperature, ^{o}C
L_f	latent heat of fusion, $kJkg^{-1}$
C_{pi}	heat capacity of snow, $kJkg^{-1}$ $^{o}C^{-1}$
T_m	average snow temperature, ^{o}C
ρ_i	snow density, kgm^{-3}
D	depth, m.

3.6 Calculation of meltrate

The calculation of meltrate occurs within the two subroutines CMELT and C1MELT. CMELT and C1MELT are identical except that CMELT uses daily energy flux totals and C1MELT uses average daily energy fluxes in the calculation of the energy available for melt, ΔQ_m. CMELT and C1MELT are used for comparative purposes in the development of SNOMO. The meltrate calculation involves five stages:

i) Calculation of snow density, ρ_{sn}
If the snowpack is single layered then the snow density is the value in THKMX1 (1,6). If the snowpack is two-layered then the average snow density is calculated allowing for differing layer thicknesses.

ii) Calculation of the average temperature of the snowpack, T_M
This is calculated using the daily average surface and base temperatures of the snowpack.

iii) Calculation of the snowpack internal energy change, dU/dt

$$dU/dt = D(\rho_i C_{p_i} + \rho_l C_{p_l} + \rho_v C_{p_v})/T_M \qquad (60)$$

where

dU/dt	snowpack internal energy change, $kJm^{-2}\ day^{-1}$
D	snowdepth, m
ρ	density, kgm^{-3}
C_p	specific heat, $kJkg^{-1}\ {}^oC^{-1}$
T_m	Mean snow temperature, ^oC

and i, l, v refer to ice, liquid and vapour

(from Male and Gray, 1981)

If it is assumed that the humidity of the air in the snowpack is 100% then the contribution to dU/dt by the vapour phase term is negligible and is ignored in the calculation of du/dt. During non-melt periods, there is no liquid component to the pack and, therefore, terms and are not required. The working equation for a melting pack is therefore:

$$dU/dt = D(\rho_i Cp_i + \rho_l Cp_l)/T_M \qquad (61)$$

iv) *Calculation of the energy available for melt,* ΔQ_M

This calculation is based on equation (5) and occurs in 4 stages. Daily totals or averages are used.

a) $Q^* = K\downarrow - K\uparrow + L\downarrow - L\uparrow$ (62)

where

Q^*	net radiation
$K\downarrow$	incoming shortwave radiation
$K\uparrow$	reflected shortwave radiation
$L\downarrow$	incoming longwave radiation
$L\uparrow$	reflected longwave radiation

Units: Wm^{-2}

$K\downarrow$, $L\downarrow$ and $L\uparrow$ are calculated by TSTM and $K\downarrow$ is solved from the TSTM term XABSOR

b) Using equation (5):

$$ENAVM = Q^* + Q_h + Q_e + Q_g \qquad (63)$$

where

ENAVM	energy available for melt, intermediate term
Q_h	sensible heat flux, ATERM
Q_e	latent heat flux, BTERM
Q_g	ground heat flux, set to zero at present

Units: Wm^{-2}

ENAVM is converted from Wm^{-2} to Jm^{-2} day^{-1} by multiplying by 8.64×10^4.

c) For the completion of equation (5):

$$\Delta Q_M = ENAVM + Q_p - dU/dt \tag{64}$$

where

ΔQ_M energy available for melt, Jm^{-2} day^{-1}

Q_p energy introduced to the pack by rain, Jm^{-2} day^{-1}

v) Calculation of the meltrate, M

The meltrate is calculated from equation (6) in both millimetres of water equivalent and centimetres of snow,

$$M_{we} = \left[\Delta Q_M / (L_f \rho_w)\right] \cdot 1000 \tag{65}$$

where

M_{we} meltrate, mm water day^{-1}

L_f latent heat of fusion, Jkg^{-1}

ρ_w density of water, kgm^{-3}

$$M_{sn} = \left[\Delta Q_M / (L_f \rho_{sn})\right] \cdot 100 \tag{66}$$

where

M_{sn} meltrate, cm snow day-1

ρ_{sn} density of snow, kgm^{-3}

3.7 Snowfall and compaction changes to pack characteristics

This section of SNOMO models the effects of snowfall, or absence of snowfall, on the snowpack. SNOMO models the effects of three snowfall intervals:

i) No snowfall for 3 days or longer.

If 3 days after snowfall, no snow has fallen on the fourth day any 'new' snow in the pack becomes 'old' snow.

ii) Snowfall for 2 consecutive days.

Snow falling on any 2 consecutive days is considered to belong to the same snow event. Therefore, snowfall on day 2 is simply added to the 'new' snow total that fell on day 1.

iii) Time interval of 1 or 2 days between snowfalls.

This is demonstrated by the situation when there is a snowfall on day 1, no snowfall on day 2, and snowfall on day 3. Here the 'new' snow that fell on day 1 is converted to 'old'snow on day 3. The two snowfalls are considered as separate events.

Each change in the snowpack layering results in a change in the physical characteristics of the snowpack, due to the substitution of VNEWSN and VOLDSN values in to THKMX1 or THKMX2. Therefore, the pack characteristics of thermal diffusivity, heat conductivity, emissivity, albedo, and density are modelled as changing with time and snowfall (frequency and amount). When 'new' snow is converted to 'old' snow the resultant 'old' snow layer is thinner than the original 'new' snow layer. This is because of the higher density of the 'old' snow (0.48 gm^{-3}) compared to the 'new' snow (0.10 gm^{-3})

SNOMO at present uses the extreme values for the physical characteristics of the pack, i.e. the values for freshly fallen snow and very old, dirty snow. When the 'new' to 'old' snow or 'old' to 'new' snow conversion occurs, this creates large changes in the snowpack characteristics overnight. A situation not replicated, except for albedo, in reality. However, this method is sufficient for SNOMO at present. It would not be very difficult to introduce a seasonal variation in certain values, e.g. density, and to lessen the effect of overnight changes.

3.8 Melt changes to pack characteristics

This section of SNOMO models the effect of melt on the snowpack. Meltrate in cm snow day^{-1} and mm water day^{-1} (where day refers to a SNOMO operational day) is calculated by SNOMO. The depth of snow subtracted from the pack if melt occurs is measured in centimetres (i.e. calculated using snow density, equation 66) and operates over one operational day. A threshold melt depth of 1 cm is used below which no melt is said to have occurred. The subtraction of any melt is dependent upon the layer structure of the pack with substraction always from the surface of the pack downwards. Therefore if melt occurs in:

i) a 1-layer pack
   - SNOMO stops if the melt depth is greater than the pack depth
   - subtraction of the melt depth occurs and the pack remains single-layered

ii) a 2-layered pack
   - SNOMO stops if the melt depth is greater than the pack depth
   - if the melt depth is greater than the thickness of the top layer, then the melt depth is subtracted from the surface resulting in a single-layered pack
   - if the melt depth is less than the thickness of the top layer then subtraction occurs and the pack remains double-layered

3.9 Output

At present, the output from SNOMO reflects the current phase of development. Once fully operational, the output of SNOMO will be manipulated so that it is menu driven, or at least offers the operator a choice of outputs. The output could be produced in graphical form.

IV CURRENT RESEARCH

IV. CURRENT RESEARCH

4.1 Areas of current research

There are four areas of current research:

- layering and the manipulation of snowpack characteristics have been introduced to SNOMO and are now operational. Initial comparisons between calculated radiation results and measured results at Townline (W3, Danville, Vt.) are favourable.

- SNOMO currently calculates melt depth at the cell scale but the timing of the melt requires further modification.

- WES visit (27 February - 3rd March 1989).

  i) VEGIE (Balick et al. 1981b) was incorporated into SNOMO and made operational with the help of Mr Randy Scoggins. The inclusion of VEGIE enables the modelling of the effects of vegetation (up to one metre in height) on the snowpack.

  ii) The interpolation routine used by TSTM2 to calculate air temperature from the two input points was improved. The interpolation now reflects the diurnal temperature cycle.

  iii) The TSTM(2) code was optimized removing any unused remnants of TSTM(1).

- CRREL visit (6th March - 7th April 1989).

  i) Discussed SNOMO with Dr Rachel Jordan (CRREL) who suggested various improvements.

  ii) Field program conducted at W3, Danville, Vermont. The object of the field program was to maximize the collection of spatial snow depth and water equivalent data over W3 during the snowmelt period. A series of trails were laid across W3 and snow courses set at points on the trails to reflect the vegetation, aspect and altitude differences over W3. In addition pre-existing sites and sites used in 1988 were also included. Every Tuesday for 4 weeks data from 40 snow courses (usually 5 sampling points per snow course) was collected. In addition to Dr Timothy Pangburn, Mr Bill Roberts and Mr Hugh Greenan, extra researchers came from CRREL. The data collected will be used to validate SNOMO but will also be used at CRREL (Dr Timothy Pangburn and Dr Ike Mackim) and at UVM (Dr Alan Cassell).

V SUMMARY OF RESEARCH PROJECT ACHIEVEMENTS

V. SUMMARY OF RESEARCH PROJECT ACHIEVEMENTS

5.1 Development of a phototype distributed snowmelt model, SNOMO, based on the energy-budget approach to snowmelt calculation. The development has involved:

i) development of the SNOMO operational logic allowing for the manipulation of the TSTM subroutine and the effect of melt and snowfall on the temporal and spatial variations of the snowpack characteristics

ii) implementation of this logic into a 'control' program and the conversion of TSTM into a subroutine within SNOMO

iii) incorporation of VEGIE, an addition to the original TSTM, to SNOMO. This enables the modelling of the energy-budget of a snow-covered vegetated surface (the vegetation is less than 1 m high)

5.2 Fieldwork conducted during the 1988 and 1989 melt seasons has resulted in the collection of spatial snow depth and water equivalent data for use in the validation of SNOMO. The data has also been used for other research projects at CRREL.

VI REFERENCES

VI. REFERENCES

Ambach, W. (1974). The influence of cloudiness on the radiation balance of a snow surface with high albedo. J. of Glaciology, Vol. 13, No. 67, 73-84.

Anderson, E.A. (1973). National Weather Service River Forecast System - Snow Accumulation and Ablation Model. NOAA Technical Memorandum NWS HYDRO-17, US Dept. Commerce, National Oceanic and Atmospheric Admin. National Weather Service.

Anderson, E.A. (1976). A Point Energy and Mass Balance Model of a Snow Cover. NOAA Technical Report NWS 19, US Dept. of Commerce, Silver Spring, MD, 150pp.

Anderson, E.A., Whipkey, R.Z., Greenan, H.J. and Machell, C.T. (1977). NOAA-ARS Cooperative Snow Research Project - Watershed Hydro-Climatology and Data for Water Years 1960-1974, US Dept. of Commerce, Silver Spring, MD, 304pp.

Anderson, M.G. and Sambles, K.M. (1988). A review of the basis of geomorphological modelling, in Modelling of Geomorphological Systems, M.G. Anderson (ed.), John Wiley & Sons Ltd., 1-32.

Balick, L.K., Link, L.E., Scoggins, R.K., and Solomon, J.L. (1981a). Thermal Modelling of Terrain Surface Elements. Technical Report EL-81-2 prepared by the Environmental Laboratory, Waterways Experiment Station. in collaboration with Mississippi State University, for the US Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Balick, L.K., Scoggins, R.K., Link, L.E.Jr. (1981b). Inclusion of a simple vegetation layer in terrain temperature models for thermal infrared (IR) signature prediction, Miscellaneous Paper EL-81-4, US Army Engineer Waterways Experiment Station, CE, Vicksburg, Miss.

Bergen, J.D. (1975). A possible relation of albedo to the density and grain size of natural snow cover. Water Res. Res., 11, 5, 745-746.

Berris, S.N. and Harr, R.D. (1987). Comparative snow accumulation and melt during rainfall in forested and clear-cut plots in the Western Cascades of Oregon. Water Res. Res., 23, 1, 135-142.

Bohren, C.F. and Barkstrom, B.R. (1974). Theory of the optical properties of snow. J. Geophysical Research, 79, 4527-4535.

Buttle, J.M. and McDonnell, J.J. (1987). Modelling the areal depletion of snowcover in a forested catchment. J. of Hydrology, 90, 43-60.

Colbeck, S.C. (1974). The capillary effects on water percolation in homogeneous snow. J. of Glaciology, 13, 67; 85-97.

Colbeck, S.C. (1977). Thermodynamic deformation of wet snow. Proc. of the 34th Annual Eastern Snow Conf., Belleville, Ontario, 130-146.

DeWalle, D.R., Parrott, H.A. and Peters, J.G. (1977). Effect of clearcutting deciduous forest on radiation exchange and snow-melt in Pennsylvania. Proc. of the 34th Annual Eastern Snow Conf., Belleville, Ontario, 105-117.

Dunne, T. and Black, R.D. (1971). Runoff processes during snowmelt. Water Res. Res. 7, 5, 1160-1172.

Dunne, T., Price, A.G. and Colbeck, S.C. (1976). The generation of runoff from subarctic snowpacks. Water Res. Res., 12, 4, 677-685.

Everett, K.R. and Ostendorf, B. (1988). Hydrology and geochemistry of a small drainage basin in upland tundra, northern Alaska, in Proc. of the Vth Int. Permafrost Conf., Trondheim, Norway, August 2-5, 1988, 574-580.

Ferguson, R.I. (1984). Magnitude and modelling of snowmelt runoff in the Cairngorm Mountains, Scotland. Hydrol. Sciences J., 29, 1, 3/1984, 49-62.

Ferguson, R.I. and Morris, E.M. (1987). Snowmelt modelling in the Cairngorms, N.E. Scotland. Trans. Royal Soc. Edinburgh; Earth Sci., 78, 261-267.

Golding, D.L. (1978). Calculated snowpack evaporation during Chinooks along the Eastern slopes of the Rocky Mountains in Alberta. J. Applied Meteorology, 17, 1647-1651.

Goodison, B.E., Louie, P.Y.T. and Metcalfe, J.R. (1986). Investigations of snowmelt acidic shock potential in south central Ontario, Canada, in Proc. of Symp. on Modelling Snowmelt-Induced Processes, IAHS, Publ. No. 155, 297-310.

Hamelin, L-E. and Cook, F.A. (1967). Le periglaciare par l'image - Illustrated glossary of periglacial phenomena. Les presses de l'universite Laval, Quebec.

Hendrick, R.L., Filgate, B.D. and Adams, W.P. (1971). Application of environmental analysis to watershed snowmelt. J. Applied Meteor., 10, 3, 418-429.

Hendrick, R.L. and DeAngelis, R.J. (1976). Seasonal snow accumulation melt and water input - a New England model. J. Applied Meteorology, 15, 7, 717-727.

IAHS (1986). Modelling snowmelt-induced processes. Proc. Budapest Symp., July, E.M. Morris (ed.). Publ. No. 155, pp.382.

Kuz'min, P.P. (1961). Protsess tayaniya shezhnogo pokrova, Gidrometeorologicheskoe Izdatalstvo, Leningrad. (English translation: "Melting of Snow Cover". Israel program for scientific translations, Jerusalem, 1972, 290pp.

Langham, E.J. (1981). Physics and properties of snowcover, in Handbook of Snow, Gray, D.M. and D.H. Male (eds.) Pergamon Press, Oxford, 275-337.

Leaf, C.F. and Brink, G.E. (1973a). Computer simulation of snowmelt within a Colorado Subalpine Watershed. USDA For Serv Res. Pap. RM-99, Rocky Mt. For. and Range Exp. Stn., Fort Collins, Colo., pp22.

Leaf, C.F. and Brink, G.E. (1973b). Hydrologic simulation model of Colorado Subalpine Forest. USDA For. Serv. Res. Pap. RM-107, pp23.

Lichfield, J. (1989). Rethinking the politics of plenty. The Independant, Saturday, 28th January, 10.

Male, D.H. and D.M. Gray (1975). Problems in developing a physically based snowmelt model. Can. J. Civ. Eng., 2, 474-488.

Male, D.H. and Gray, D.M. (1981). Snowcover ablation and runoff, in Handbook of Snow, Gray, D.M. and D.H. Male (eds.), Pergamon Press, Oxford, 360-436.

Martinec, J. and Rango, A. (1986). Parameter values for snowmelt runoff modelling. J. of Hydrology, 84, 197-219.

McKay, G.A. and Gray, D.M. (1981). The distribution of snowcover, in Handbook of Snow, Gray, D.M. and D.H. Male, (eds.), Pergamon Press, Oxford, 153-191.

Merry, C.J., McKim, H.L. Cooper, S. and Ungar, S.G. (1977). Preliminary analysis of water equivalent/snow characteristics using LANDSAT digital processing techniques. Proc. of the 34th Annual Eastern Snow Conf., Belleville, Ontario, 39-54.

Morris, E.M. (1982). Sensitivity of the European Hydrological System snow models. Hydrological Aspects of Alpine and High Mountain Areas (Proc. of Exeter Symposium, July 1982). IAHS Publ. No. 138, 221-231.

Morris, E.M. (1985). Snow and Ice, in Hydrological Forecasting (ed.) M.G. Anderson and T.P. Burt, J. (eds.), Wiley & Sons Ltd., 153-182.

Obled, C. and Harder, H. (1978). A review of snowmelt in the mountain environment. Proc. Modelling of Snow Cover Runoff, S.C. Colbeck and Mr. Ray (eds.). US Army Cold Regions Research and Eng. Lab., Hanover, New Hampshire.

Obled, C. and Rosse, B. (1977). Mathematical models of a melting snowpack at an index plot. J. of Hydrology, 32, 139-163.

Oke, T.R. (1987). Boundary Layer Climates. 2nd ed., Methuen and Co. Ltd. (London).

Olyphant, G.A. (1986. The components of incoming radiation within a mid-latitude alpine watershed during the snowmelt season. Arctic and Alpine Res. 18, 2, 163-169.

O'Neill, A.D.J. and Gray, D.M. (1972). Spatial and temporal variations of the albedo of prairie snowpack, in The Role of Snow and Ice in Hydrology, IAHS Publ. No. 107, Vol. 1, Proc. Banff. Symp., Sept, 1972, 176-186.

Pangburn, T. (1987). Documentation of the Cold Regions Modification to the MILHY (Military Hydrology) Model. Unpub. CRREL (US Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire).

Perla, R. and Glenne, B. (1981). Skiing, in Handbook of Snow, Gray, D.M. and D.H. Male (eds.), Pergamon Press, Oxford, 709-740.

Pionke, H.B., Bahleda, K. and Chamberlain, B.J. (1978). Data directory, data and data collection site characteristics for the Sleepers River Watershed, N. Danville, Vermont. Northeast Watershed Research Centre, USDA-SEA-FR, 111 Research Building A, University Park, Pennsylvania 16802.

Price, A.G. (1988). Prediction of snowmelt rates in a deciduous forest. J. of Hydrology, 101, 145-157.

Price, A.G. and Hendrie, L.K. (1984). Water motion in a deciduous forest during snowmelt. J. of Hydrology, 64, 339-356.

Price, A.G. and Petzold, D.E. (1984). Surface emissivities in a boreal forest during snowmelt. Arctic and Alpine Research, 16(1), 45-51.

Price, A.G., Dunne, T. and Colbeck, S.C. (1976). Energy balance and runoff from a subarctic snowpack. US Army Cold Regions Research and Engineering Laboratory, Report 76-27, pp.40.

Price, L.W. (1981). Mountains and Man. Univ. of California Press, London.

de Quervain, M.R. (1972). Snow structure, heat and mass flux through snow, Symp. on Role of Snow and Ice in Hydrology, IAHS Publ. No. 107, Vol. 1, 203-226.

Rango, A. (1988). Progress in developing an operational snowmelt-runoff forecast model with remote sensing input. Nordic Hydrology, 19, 65-76.

Rau, R.G. and Herrmann, A. (1982). Variations in the properties of Alpine snow-cover stores. Hydrol. Aspects of Alpine and High Mt. Areas, IAHS Publ. No. 138, 91-100.

Reiners, W.A., Hollinger, D.Y. and Lang, G.E. (1984). Temperature and evapotranspiration gradients of the White Mountains, New Hampshire, USA. Arctic and Alpine Res., 16, 1, 31-36.

Roberge, J., Stein, J. amd Plamondon, A. (1988). Evaluation d'un modele de fonte nivale en foret boreale (Evaluation of a snowmelt model in a boreal forest environment). J. Hydrol., 97, 161-179.

Simons, P. (1988). Apres ski de deluge. New Scientist, 14 Jan. 1988, 1595, 49-52.

Swanson, R.H. (1972). Small openings in poplar forest increase snow accumulation. Symp. on Role of Snow and Ice in Hydrology, IAHS Publ. No. 107, Vol. 2, 1382-1389.

U.S. Army Corps of Engineers (1956). Snow hydrology. U.S. Army Corps of Engineers, Portland, Oreg., 437pp.

USFS (US Forest Service) (1980). An Approach to Water Resources Evaluation of Non-Point Silvicultural Sources (A Procedural Handbook). USFS, Dept. Agric., EPA-600/8-80-012, 173pp.

Wendler, G. and Ishikawa, N. (1974). The effect of slope exposure and mountain screening on the solar radiation of McCall glacier, Alaska: a contribution to the International Hydrological Decade. J. of Glaciology, 13, 68, 213-226.

Woo, M-K. and Marsh, P. (1977). Determination of snow storage for small eastern High Arctic basins. Proc. of the 34th Annual Eastern Snow Conf., Belleville, Ontario, 147-162.

VII APPENDICES

APPENDIX I

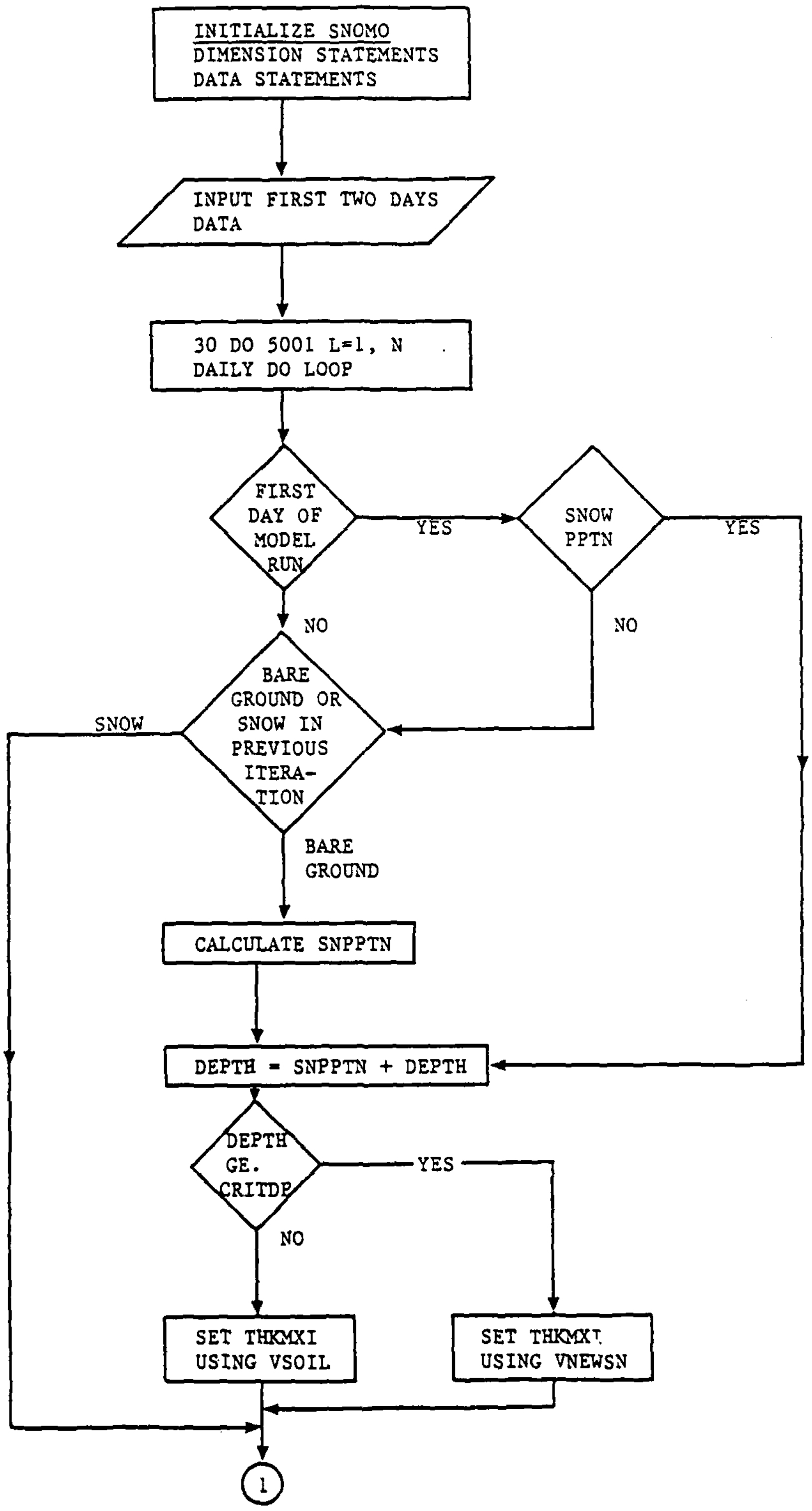


Figure I : Simplified flowchart for SNOMO(Sheet 1 of 4)

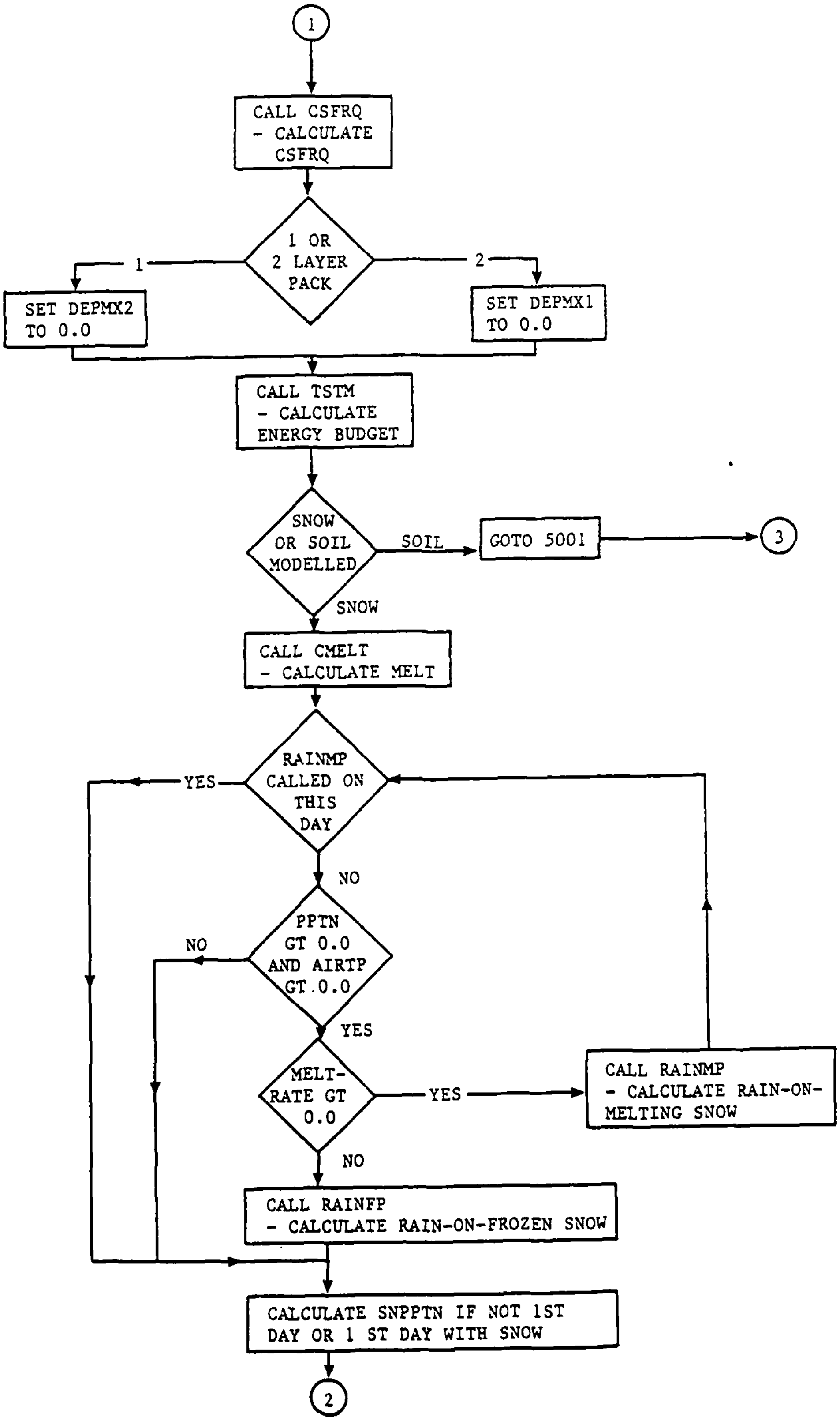


Figure I : (Sheet 2 of 4)

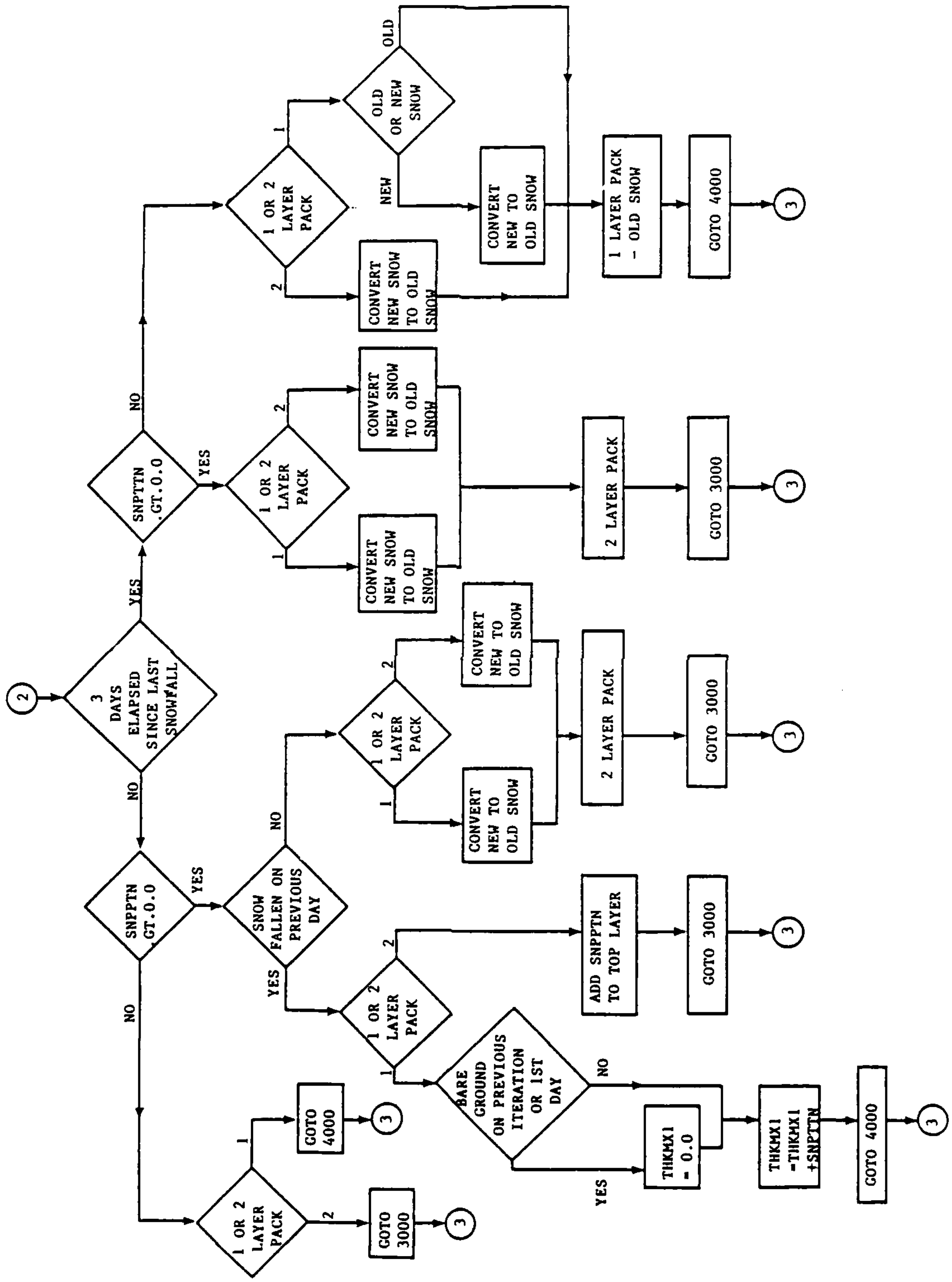


Figure I : (Sheet 3 of 4)

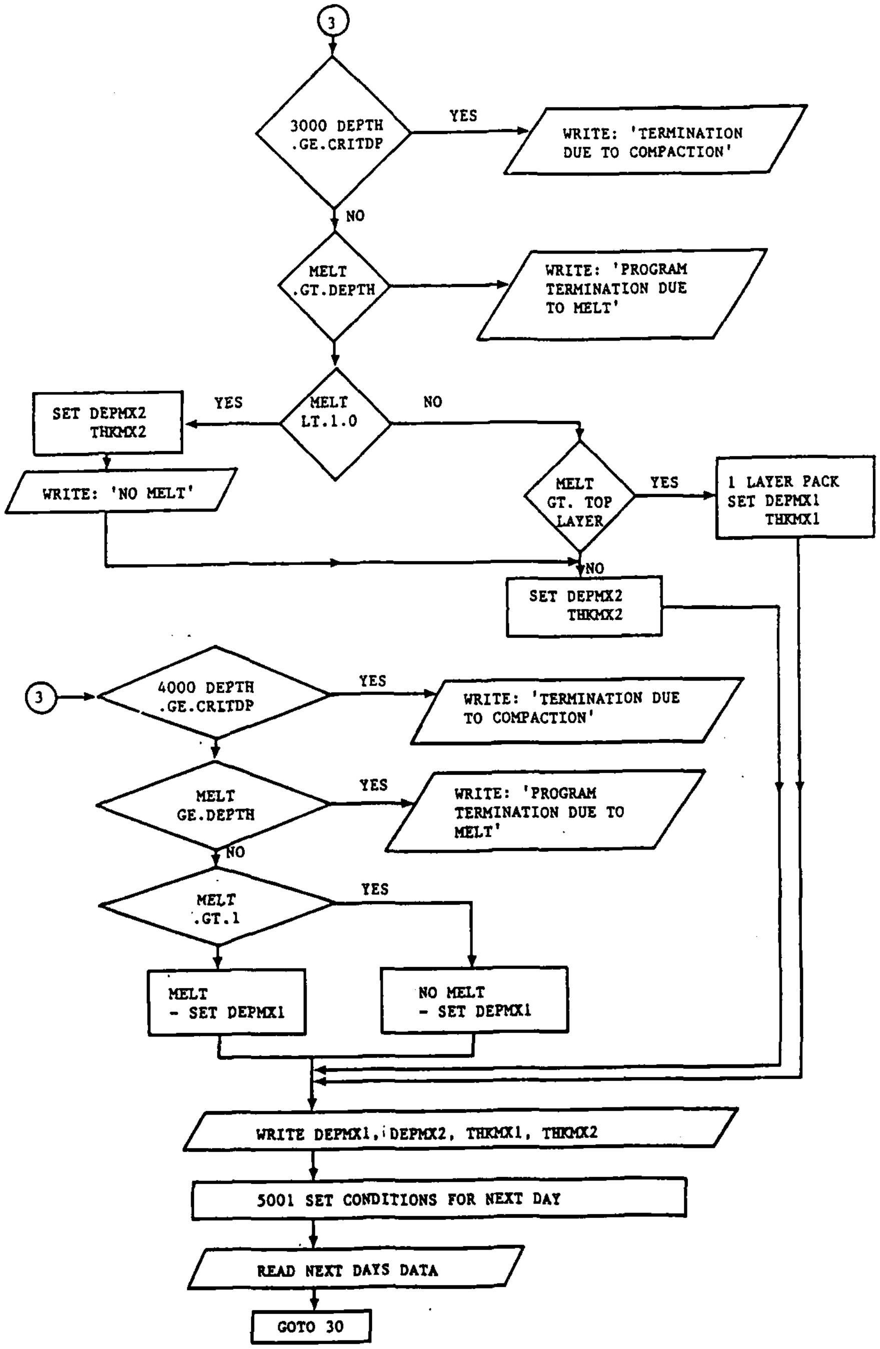


Figure I : (Sheet 4 of 4)

APPENDIX II

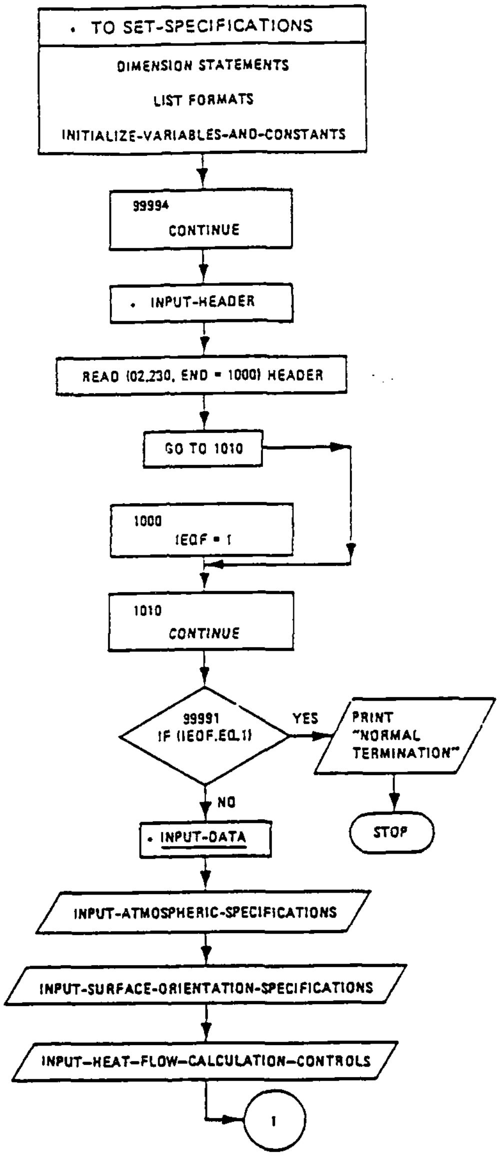


Figure II : Simplified flowchart for TSTM subroutine,
Balick et al., 1981a. (Sheet 1 of 5).

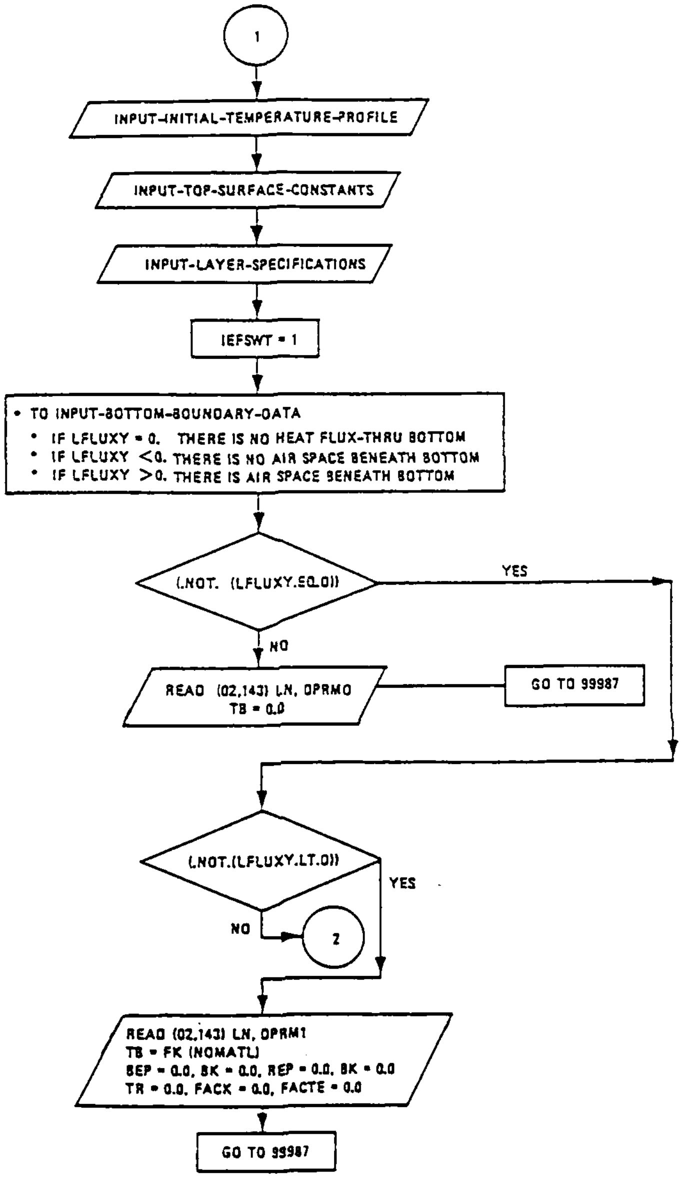


Figure II : (Sheet 2 of 5)

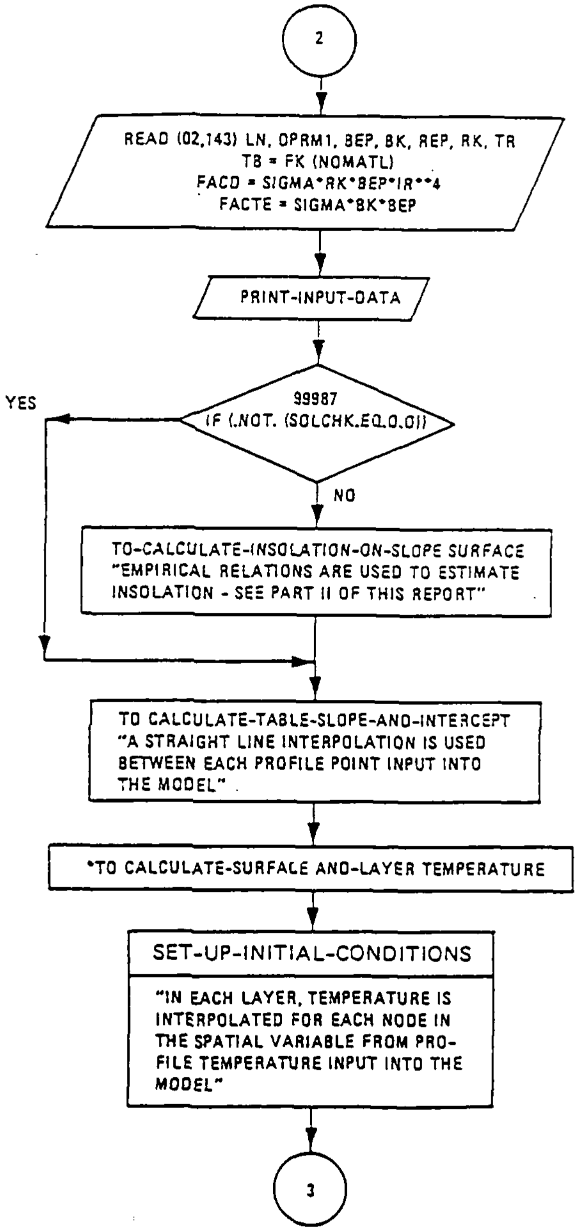


Figure II : (Sheet 3 of 5)

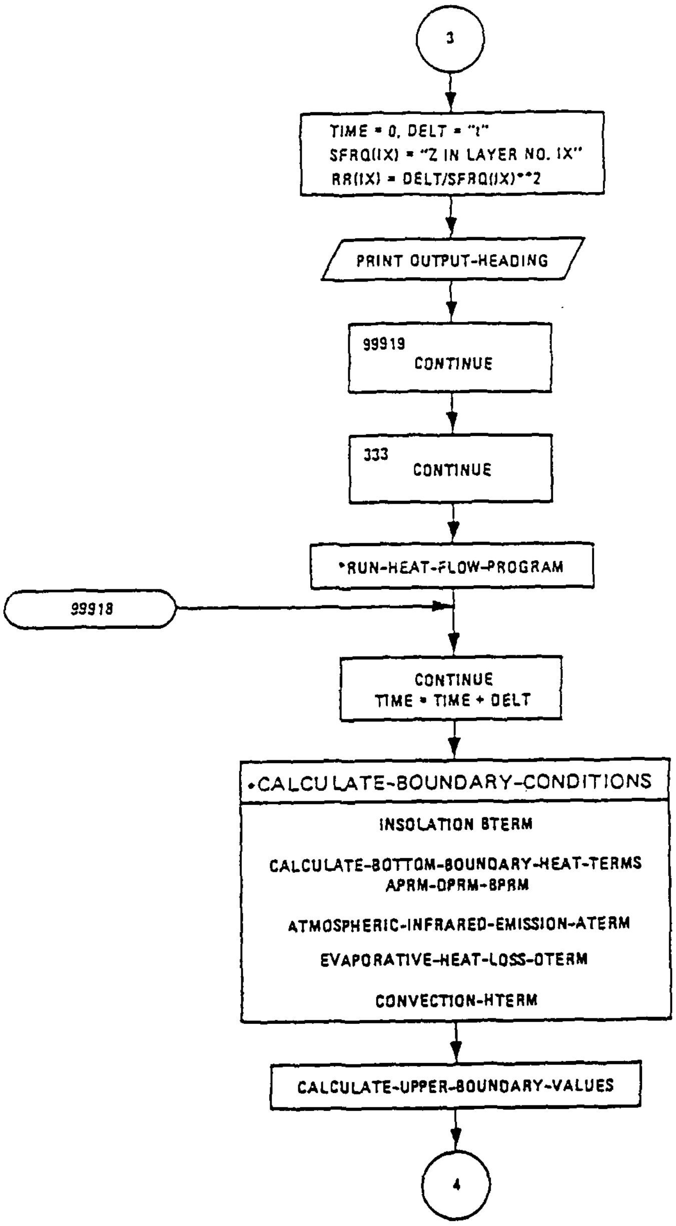


Figure II : (Sheet 4 of 5)

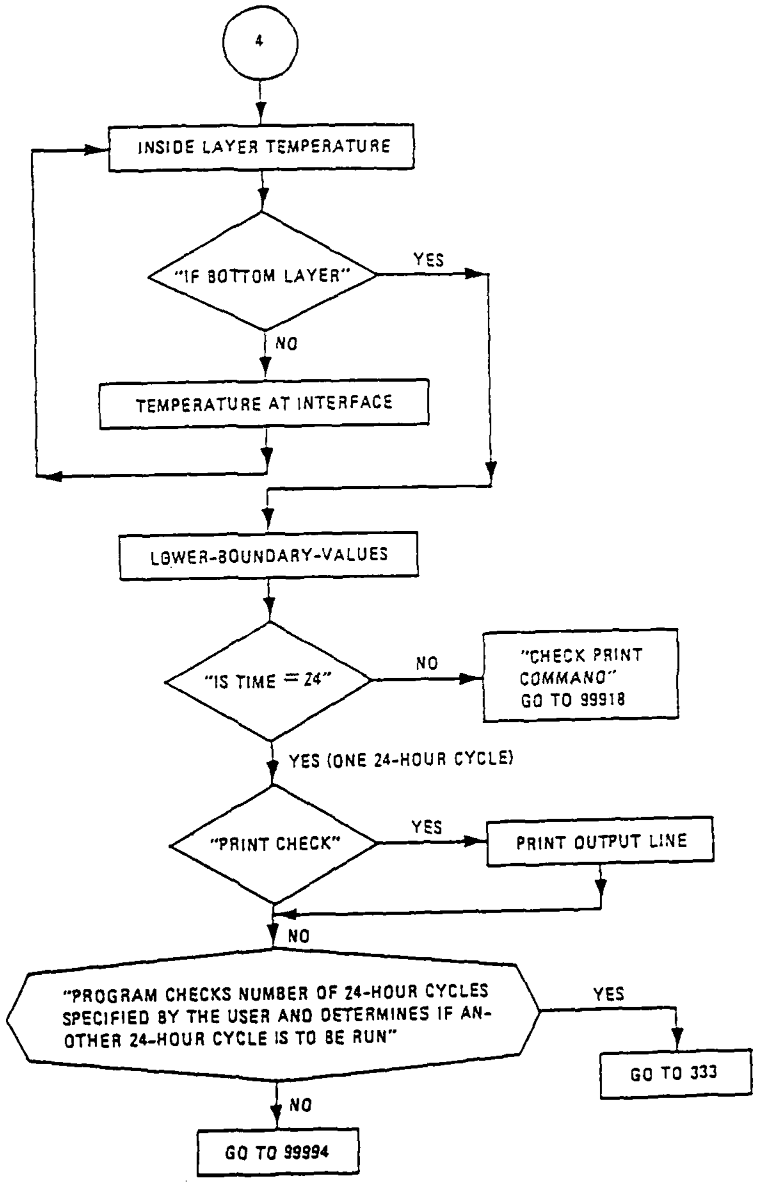


Figure II : (Sheet 5 of 5)

APPENDIX III

Table I : Variable definitions : SNOMO

Variable	Definition
AIRTP	Air temperature, °C
AREA	Area of cell, m^2
AVABSOR	Average daily shortwave radiation absorbed at the surface, Wm^{-2}
AVATERM	Average daily incoming longwave radiation, Wm^{-2}
AVBOTTP	Average daily temperature at the base of the snowpack, °C
AVDTERM	Average daily evaporative heat flux, Wm^{-2}
AVGBR	Average daily reflected longwave radiation, Wm^{-2}
AVHTERM	Average daily sensible heat flux, Wm^{-2}
AVSOL	Average daily incoming shortwave radiation, Wm^{-2}
AVSTP	Average snow temperature, °C
COEFB	Substitute constant for du/dt can be used in melt calculation
CRITDP	Critical snowdepth, 5cm
CUMTM	Cumulative time, i.e. length of computational day
DAY1	Julian date of day of SNOMO initiation
DDATE	Julian date of day being modelled
DENSN	Snow density, gm^{-3}
DENW	Density of water, kgm^{-3}
DEPMX1	Depth matrix for 1 layer pack
DEPMX2	Depth matrix for 2 layered pack
DEPTH	Snowpack depth, cm.
DEPTH1	Used in calculation of DEPTH when converting new snow to old snow, cm.

/cont...

(Sheet 1 of 3)

DUDT	du/dt, part of the energy budget equation
ENAVM	Energy available for melt Q_m. Calculated using energy totals, Wm^{-2}
ENAVM1	As ENAVM but calculated using energy averages
GTERM	Ground heat flux, Wm^{-2}
HCAPSN	Heat capacity of snow, kJ kg^{-1} $^{o}C^{-1}$
HCAPW	Heat capacity of water, kJ kg-^{1} $^{o}C^{-1}$
K1	Count of the number of days modelled, i.e. no. times DO 5001 loop called
K2	k2-1 indicates that SNOMO modelled soil in the previous day or is modelling the first day
K3	k3-1 indicates that soil was modelled in the previous day
K10	Count of the number of internal iterations of TSTM in order to calculate daily averages of TSTM calculated values.
K25	Count of the days elapsed since last snowfall
KELVIN	Air temperature converted to degrees
CONTROL	Counts of the number of days modelled and terminates SNOMO when necessary
LHEAF	Latent heat of fusion, MJ kg^{-1}
MRSN	Meltrate in cm of snow per 'day', calculated using ENAVM
MRWE	Meltrate in mm of water per 'day, calculated using ENAVM1.
MRSN1	As MRSN, but using ENAVM1
MRWE1	As MREW, but using ENAVM1
NETRAD	Net radiation, Wm^{-2}
NKONT	Used with KONTROL to terminate SNOMO
PPTN	Precipitation amount, MM water
PTERM	Heat input to pack by rain-on-melting snow, Wm^{-2}

/cont...

(Sheet 2 of 3)

RH	Relative humidity, %
RSTPC	Rate of surface temperature change due to rainfall on a frozen pack, °C
SNPPTN	Snow precipitation amount, cm snow.
SNVOL	AREA * DEPTH, m^3
SOILDP	Soil depth of base of soil profile of depth taken as base of profile, cm.
SOILTP	Soil temperature at depth, taken at the SOILDP, °C
SSOILTP	Surface soil temperature, °C
TABSOR	Total daily shortwave radiation absorbed at the surface, Wm^{-2}
TATERM	Total daily incoming longwave radiation, Wm^{-2}
TSTERM	Total daily evaporative heat flux, Wm^{-2}
TGBR	Total daily reflected longwave radiation, Wm^{-2}
THKMX1	Thickness matrix for a 1 layer pack
THKMX2	Thickness matric for a 2 layer pack
THTERM	Total daily sensible heat flux, Wm^{-2}
TSOL	Total daily incoming shortwave radiation, Wm^{-2}
VNEWSN	Vector holding new snow values of thermal diffusivity, heat conductivity emissivity, albedo and density
VOLDSN	Vector holding old snow values of thermal diffusivity, heat conductivity, emissivity, albedo and density
VSOIL	Vector holding soil values of thermal diffusivitv, heat conductivity, emissivity, albedo and density
WE1	Used in calculation of DEPTH when converting new snow to old snow, cm.

(Sheet 3 of 3)

APPENDIX IV

Table II : Variable definitions : TSTM

AB	MUGGE-MOLLER ABSORPTION FUNCTION.
ACL(8)	COEFFICIENT,a, DEPENDANT ON CLOUD TYPE, USED IN THE CALCULATION OF CTF.
ALPH(IX)	THERMAL DIFFUSIVITY OF LAYER IX IN CM**2/MIN
AO	ATMOSPHERIC ALBEDO FOR RAILEIGH SCATTERING.
APRM	FACTE*TEMP**3 IN CAL/CM**2-MIN-C
ATERM	ENERGY CONTRIBUTED BY ATMOSPHERIC IR EMISSION CAL CM**2-MIN
AVABSOR	AVERAGE DAILY SHORTWAVE RADIATION ABSORBED AT THE SURFACE, Wm-2.
AVATERM	AVERAGE DAILY INCOMING LONGWAVE RADIATION,Wm-2.
AVDTERM	AVERAGE DAILY EVAPORATIVE HEAT FLUX, Wm-2.
AVGBR	AVERAGE DAILY GREYBODY RADIATION, ie. REFLECTED LONGWAVE RADIATION, Wm-2.
AVHTERM	AVERAGE SENSIBLE HEAT FLUX, Wm-2.
AVSOL	AVERAGE DAILY INCOMING SHORTWAVE RADIATION, Wm-2.
AVSTP	AVERAGE SNOW TEMPERATURE, oC.
B	HEAT CONDUCTIVITY OF SURFACE CAL/CM**2-MIN-C
BBB(J,I)	Y INTERCEPT OF LINEAR EQUATION, USED FOR TABLE INTERPOLATION.
BC	CONSTANT USED IN THE CALCULATION OF WATER VAPOUR PRESSURE.
BCL(8)	COEFFICIENT, b, DEPENDANT ON CLOUD TYPE, USED IN THE CALCULATION OF CTF.
BEP	BOTTOM BOUNDARY THERMAL IR EMISSIVITY.
BK	BOTTOM SURFACE GEOMETRIC SHAPE IN FRACTION(0.0-1.0)
BPRM	HEAT CONDUCTIVITY OF BOTTOM BOUNDARY LAYER

/cont...

(Sheet 1 of 8)

BTERM	ENERGY CONTRIBUTED BY INSOLATION AFTER ADJUSTMENT USING SURFACE ABSORPTIVITY. IN CAL/CM**2-MIN
CC	CLOUD*CLOUD.
CCOEF	PART OF CALCULATION OF INTERFACE VALUES.
CLR(8)	COEFFICIENT DEPENDANT ON CLOUD TYPE, USED IN THE CALCULATION OF INCOMING LONGWAVE RADIATION.
COE1	USED IN CALCULATION OF SCF, DETERMINED BY THE RICHARDSON NUMBER.
COE2	USED IN CALCULATION OF SCF, DETERMINED BY THE RICHARDSON NUMBER.
CLOUD	CLOUD COVER IN FRACTION OF 0.1-1.0.
CP	SPECIFIC HEAT OF DRY AIR AT CONSTANT PRESSURE.
CTEMA	AIR TEPERATURE IN DEGREES KELVIN, USED IN CALCULATION OF EVAPORATIVE HEAT FLUX.
CTF	CLOUD ADJUSTMENT FACTOR.
DATMX	MATRIX HOLDING TSTM OUTPUT VALUES FOR MANIPULATION.
DAY	JULIAN DAY USED IN SOLVING INSOLATION
DCOEF	PART OF CALCULATION-OF-INTERFACE VALUES.
DDDT	dT/dTg, PART OF UPPER-BOUNDARY-CALCULATION.
DECL	SOLAR DECLINATION ANGLE
DELT	TIME STEP IN HOURS
DEPTH(IY)	MATRIX HOLDING LAYER DEPTHS.
DEPTH(450)	DEPTH OF SNOW OR SOIL PROFILE.
DIST	DEPTH IN CM OF INITIAL SOIL PROFILE AT WHICH CORRESPONDING SOIL TEMPERATURE IN DEGREE C IS INTERPOLATED.(TABLE 5).
DNEW	D VALUE USING LATEST ESTIMATE OF GROUND TEMPERATURE.
DOWNIR	INCOMING LONGWAVE RADIATION, CM-2 MIN-1.
DPRM	HEAT FLUX IN CAL/CM**2-MIN AT BOTTOM BOUDARY OR

/cont...

	TEMPERATURE IN RANKINS AT BOTTOM BOUNDARY.
DPRMO	TEMPERATURE OF BOTTOM MATERIAL IN DEGREE CELSIUS.USED WHEN LFLUXY=0
DPRM1	HEAT FLUX OF BENEATH BOTTOM MATERIAL, IN CAL/CM**2-MIN, USED WHEN LFLUXY NOT EQUAL 0.
DTERM	ENERGY LOSS DUE TO EVAPORATION.
DUST	ATMOSPERIC DUST IN POUNDS/CUBIC CENTIMETERS (LBS/CC)USED IN SOLVING INSOLATION.
ELF	LATITUDE IN RADIANS
EPSN	EMISSIVITY OF SURFACE MATERIAL
ES	
ESAT(T)	SATURATED VAPOUR PRESSURE AT TEMPERATURE T.
E(T)	VAPOUR PRESSURE AT TEMPERATURE T.
EX	USED IN CALCULATION OF SCF, DETERMINED BY THE RICHARDSON NUMBER.
F2	PART OF CALCULATION-OF-BOTTOM BOUNDARY VALUES.
FACTA	SIGMA*EPSN
FACTD	FACTD=SIGMA*BK*BEP*TR**4 USED IN BOTTOM BOUNDARY CALCULATION WHEN THERE IS AIRSPACE BENEATH THE BOTTOM
FACTE	FACTE=SIGMA*BK*BEP USED IN BOTTOM BOUNDARY CALCULATION WHEN THERE IS AIRSPACE BENEATH THE BOTTOM
FACTH	USED IN SOLVING CONVECTION TERM (HTERM) (1000.0/PRESS)**0.286
FK(IX)	HEAT CONDUCTIVITY OF LAYER IX IN CAL/MIN-CM-K
FMM(J,I)	SLOPE OF LINEAR EQUATION,USED FOR TABLE INTERPOLATION
G	ACCELERATION DUE TO GRAVITY.
GTERM	GROND HEAT FLUX, Wm-2

/cont...

HEADER	72 CHARCTER INPUT VARIABLE USED TO PRINT COMMENTS ON OUTPUT.
HTERM	ENERGY LOSS OF GAIN DUE TO CONVECTION CAL/CM**2-MIN
IABSOR	INCOMING SHORTWAVE RADIATION, Wm-2.
IATERM	INCOMING LONGWAVE RADIATION, Wm-2.
ICNT	TSTM INTERNAL ITERATION COUNT.
IDTERM	EVAPORATIVE HEAT FLUX, Wm-2.
IEFSWT	SWITCH WHEN =0 WILL PRINT OUTPUT ONLY AT SPECIFIED TIME IF NOT =0 WILL PRINT OUTPUT AT EVERY ITERATIONS.
IEOF	SET FROM 0 TO 1 WHEN AN EOF IS ENCOUNTERED. USED TO TERMINATE PROGRAM
IHTERM	SENSIBLE HEAT FLUX, Wm-2.
III	COUNT OF NUMBER OF INTERNAL ITERATIONS IN CALCULATION OF UPPER-BOUNDARY-VALUES.
IMATL	BACKWARD COUNTER OF LAYERS. STARTING WITH THE NUMBER OF LAYERS.
INTR(IX)	BEGINNING SUB-LAYER DEPTH NUMBER FOR LAYER NUMBER IX
IPRNT	BACKWARD COUNTER SET=NPRNT. WHEN EQUAL TO 1 OUTPUT IS PRINTED.
ITER	ITERATION COUNTER USED IN FINITE DIFFERENCE CALCULATION OF HEAT FLOW EQUATION
ITIME	BACKWARD COUNTER INITIALIZE AS TOTAL TIME STEPS IN HOUR
IX	LAYER NUMBER STARTING WITH TOP LAYER
IY	SUB-LAYER DEPTH NUMBER
JMAX	THE TOTAL NUMBER OF SUB-LAYERS
K10	TSTM INTERNAL ITERATION COUNT.
KSQ	VON KARMAN'S CONSTANT SQUARED.
KTEMPA	AIR TEMPERATURE IN DEGREES KELVIN.
KTEMPG	SURFACE TEMPERATURE IN DEGREES KELVIN.
LAYERS	COUNT OF THE PROFILE LAYERS.
LAT	LATITUDE USED IN SOLVING INSOLATION

/cont...

LFLUXY	INPUT BOTTOM BOUNDARY DATA CONTROL SWITCH. IF-0, THERE IS NO HEAT FLUX THROUGH BOTTOM OF MATERIAL, IF NEGATIVE THERE IS NO AIR SPACE BENEATH BOTTOM MATERIAL, IF POSITIVE THERE IS AIR SPACE BENEATH BOTTOM MATERIAL.
LN	DUMMY VARIABLE TO READ LINE NUMBER FROM INPUT FILE
M	SECANT OF SOLAR ZENITH ANGLE IN RADIANS
MAX(J)	NUMBER OF INPUT TABLE VALUES USED IN TABLE INTERPOLATION MODULE.
NCLOUD	CLOUD TYPE INDEX NUMBER (1-9) USED IN SOLVING INSOLATION, INFRARED EMISSION.
NIT	NUMBER OF ITERATIONS USED IN HEAT FLOW CALCULATIONS
NIPTS	NUMBER OF COMPUTATIONAL POINTS WITHIN PROFILE.
NOMATL	NUMBER OF MATERIAL LAYERS USED IN SOLVING HEAT FLOW
NPRNT	NUMBER OF TIMES OUTPUT TIME PRINT FREQUENCY IS DIVISIBL BY TIME STEPS. USED TO DETERMINED WHEN TO PRINT OUTPUT.
NTABL	TABLE NUMBER
NX(IX)	NUMBER OF SUBLAYER OF EACH LAYER, NX(IX)-THK(IX)/SFRQ(IX
OUTCD	OUTPUT MANIPULATION VARIABLE.
PI	3.141593
PPTN	PRECIPITATION, MM OF WATER.
PRESS	ATMOSPHERIC PRESSURE IN MILLIBAR(MB) USED IN SOLVING INSOLATION
PTYME	BEGINNING TIME OF OUTPUT-TOTAL NUMBER OF HOURS MINUS 24 USED IN PRINT-OUTPUT MODULE 2
QSAT(T)	SATURATED SPECIFIC HUMIDITY AT TEMPERATURE T.
Q(T)	SPECIFIC HUMIDITY AT TEMPERATURE T.
REP	EMISSIVITY BENEATH AIRSPACE
RH	RELATIVE HUMIDITY, %
RHOA	AIR DENSITY, CALCULATED AS PART OF SENSIBLE HEAT CALCULATION.

/cont...

RHOC(IX)	FK(IX)/ALPH(IX) IN CAL/CM**2-K
RI	RICHARDSON INDEX NUMBER USE IN SOLVING CONVECTION ENERGY LOSS.
RK	SURFACE BENEATH AIRSPACE GEOMETRIC SHAPE IN FRACTION (0.0 - 1.0)
RR(IX)	RR(IX)-DELT/SFREQ**2.(PART OF HEAT FLOW EQUATION)
SAZ	SOLAR AZIMUTH IN RADIANS. SAZ-ATAN(-COS(DECL)*SIN(TIMER (COS(ELF*SIN(DECL)-SIN(ELF)*COS(TIMER)))
SCF	USED IN CALCULATION OF SENSIBLE HEAT FLUX, DETERMINED BY THE RICHARDSN NUMBER.
SFRQ(IX)	VERTICAL GRID SPACING IN CM IN EACH LAYER IX IN CM**2/M
SICF	INSOLATION ADJUSTMENT DUE TO ZENITH ANGLE,SURFACE SLOPE AND SURFACE ASPECT ANGLE. SICF-COS(Z)*COS(SLOPE)+SIN(Z) SIN(SLOPE)*COS(SAZ-SURFAC)
SIGMA	STEPHAN-BOLTZMAN CONSTANT, 8.12E-11
SLOPE	SURFACE SLOPE IN DEGREES WITH HORIZONTAL-0 DEGREE, USED IN SOLVING INSOLATION
SMALLA	ABSORBTIVITY OF SURFACE MATERIAL
SPEED	WIND SPEED IN CM/SEC
STOR(1,IY)	ESTIMATE SUB-LAYER TEMPERATURE IN DEGREE RANKINE
STOR(2,IY)	FK;HEAT CONDUCTIVITY OF SUB-LAYER IY IN CAL/MIN-CM-K
STOR(3,IY)	RHOC,FK/ALPH IN CAL/CM**2-K
STOR(4,IY)	CONSTANT DIMENSIONLESS.
STOR(5,IY)	INITIAL SOIL TEMPERATURE IN DEGREE RANKINS OF INITIAL SOIL PROFILE
STOR(6,IY)	SAME AS STOR(2,IY)
STOR(7,IY)	SAME AS STOR(3,IY)
SUN	CALCULATED INSOLATION VALUE.
SURFAC	SURFACE AZIMUTH IN DEGREE WITH SOUTH -0 DEGREE,USED IN SOLVING INSOLATION
T	SAME AS TIME
TA	AIR TEMPERATURE IN DEGREE RANKINE
TATERM	TOTAL DAILY INCOMING LONGWAVE RADIATION, Wm-2.

/cont...

TABSOR	TOTAL DAILY SHORTWAVE RADIATION ABSORBED AT THE SURFACE, Wm-2.
TAC	AIR TEMPERATURE IN DEGREE CELSIUS
TAK	AIR TEMPERATURE IN DEGREE KELVIN
TAL	CONSTANT USED IN THE CALCULATION OF WATER.
TB	THERMAL CONDUCTIVITY OF BOTTOM MATERIAL CAL/CM**2-DEG C-MIN
TD	DEW POINT TEMPERATURE USED IN THE CALCULATION OF WATER.
TDTERM	TOTAL DAILY EVAPORATIVE HEAT FLUX, Wm-2.
TEML	SURFACE TEMPERATURE OF MATERIAL IN DEGREES RANKINE.
TEMR	BOTTOM LAYER TEMPERATURE OF MATERIAL IN DEGREES RANKINE.
TFRQ	TIME STEP IN MINUTES USED IN SOLVING HEAT FLOW
TGBR	TOTAL DAILY REFLECTED RADIATION, Wm-2.
THK(IX)	LAYER THICKNESS IN CM OF LAYER IX
THTERM	TOTAL DAILY SENSIBLE HEAT FLUX, Wm-2.
TIME	TIME IN HOURS IN WHICH MATERIAL TEMPERATURES ARE ESTIMATED
TIMER	SUN'S HOUR ANGLE IN RADIANS
TOTTIM	TOTAL NUMBER OF 24 HOUR REPETITIONS USED IN SOLVING HEAT FLOW
TPRNT	OUTPUT TIME PRINT FREQUENCY IN MINUTES
TR	TEMPERATURE OF AIRSPACE BENEATH BOTTOM MATERIAL.
TSK	MATERIAL SUB-LAYER TEMPERATURE IN DEGREES KELVIN
TSOL	TOTAL DAILY INCOMING SHORTWAVE RADIATION, Wm-2.
TYME	TIME IN HOURS USE INSOLATION CALCULATION
WATER	THE AMOUNT OF PRECIPIPAL WATER IN MILLIMETERS (MM) USED IN SOLVING INSOLATION.
WET	MOISTURE CONTENT OF SURFACE MATERIAL

/cont...

(Sheet 7 of 8)

XXX(J,1)	TIME IN HOURS FOR TABLE 1 (AIR TEMPERATURE)
XXX(J,2)	TIME IN HOURS FOR TABLE 2 (RELATIVE HUMIDITY)
XXX(J,6)	TIME IN HOURS FOR TABLE 6 (WIND SPEED)
XXX(J,3)	TIME IN HOURS FOR TABLE 3 (AMOUNT OF CLOUD COVER)
XXX(J,4)	TIME IN HOURS FOR TABLE 4
XXX(J,5)	DEPTH IN CENTIMERERS FOR TABLE (5)(TEMPERATURE PROFILE) INITIAL TEMPERATURE PROFILE IN DEGREES CELSIUS
YYY(J,1)	AIR TEMPERATURE IN DEGREES CELSIUS TABLE 1
YYY(J,2)	RELATIVE HUMIDITY INPUT FRACTION,USED IN TABLE 2 SOLVIN INFARED EMISSIONS,(ATERM) EVAPORATIVE HEAT LOSS (DTERM)
YYY(J,6)	WIND SPEED INPUT IN METERS/SECOND AND CONVERTED TO CENTIMETER/SECOND TABLE 6
YYY(J,3)	AMOUNT OF CLOUD COVER IN FRACTION (0 TO 1) USED IN SOLVING INSOLATION TABLE 3 INFARED EMISSION (ATERM)
YYY(J,4)	INSOLATION IN CAL/CM**2-MIN,IF 0.0 AT 1200 HOURS, INSOLATION VALUES WILL CACULATED TABLE 4
Z	SOLAR ZENITH ANGLE. Z=SIN(DECL)*SIN(ELF)+COS(DECL)* COS(ELF)*COS(TIMER)
ZA	SHELTER HEIGHT IN CENTIMETERS(CM)
ZASH	SHELTER HEIGHT IN CENTIMETRES(CM).
ZZA	SURFACE TEMPERATURE OF MATERIAL IN DEGREE RANKINE
ZZB	BOTTOM LAYER TEMPERATURE OF MATERIAL IN DEGREE RANKINE

(Sheet 8 of 8)

APPENDIX V

```
c
c  ************ PROGRAM SNOMO.F *************
c
c  **SNOMO.F IS A DISTRIBUTED SNOWMELT MODEL. THE MODEL OPERATES IN
c  CELLS, EACH CELL IS A SUBDIVISION OF THE CATCHMENT THAT IS BEING
c  MODELLED AND IS ASSUMED TO HAVE A HOMOGENEOUS VEGETATION COVER,
c  ALTITUDE AND ASPECT. THE SNOWMELT RATE IS DERIVED FROM THE
c  CALCULATION OF THE SNOWPACK ENERGY BUDGET. THE EFFECTS OF MELT
c  AND SNOWFALL ON THE SNOWPACK ARE MODELLED.
c
c
c  **Initialise variables, constants, matrices etc..
c  **Data is input from 2 files. Veg.dat contains only vegetation
data
c  and is called when iveg is 1. Snomo.dat contains daily
meteorological
c  data,physical constants and computational controls for both
vegetation
c  and non-vegetation situations.
c
        common/matrix1/xxx(30,10),yyy(30,10)
        common/matrix2/depmx1(2,2),depmx2(3,2)
        common/matrix3/thkmx1(1,6),thkmx2(2,6)
        common/tstm1/press,ncloud,za,slope,surfac,day,lat,wet
        common/tstm2/nomat1
        common/tstm3/tottim,tfrq,tprnt,nipts
        common/vegi/iveg,sigf,state,epf,fola,hfol
        common/rain/airtp
        common/sfrq/sfrq(6)
        common/phycons/lheatf,hcapsn,hcapw
        real area,surftp,snpptn,snvol,critdp,
     &  enavm,delts,hcapsn,densn,rstpc,denw,hcapw,lheatf,
     &  avsndp,depth,coefb,pterm,netrad,
     &  avbottp,pptn,dayl,lat,tgbr,tsol,tabsor,taterm,
     &  thterm,tdterm,vsoil(1,6),vnewsn(1,6),voldsn(1,6),
     &  wel,depth1,mrwe,mrsn,mrlwe,mrlsn,enavm1
        integer i,j,n,k1,k2,k3,k10,kontrol
        data denw,hcapw,hcapsn,lheatf/1000.0,4.21,2.09,0.334e+6/
        data tottim,tfrq,tprnt/1,1.,60./
        nin=10
        nveg=11
        nout=9
        open(unit=nin,file='snomo.dat',status='old')
        rewind nin
        open(unit=nveg,file='veg.dat',status='old')
        rewind nveg
        open(unit=nout,file='SNOMO.RES')
        rewind nout
```

```
      read(10,*)((vnewsn(i,j),j=1,6),i=1,1)
      read(10,*)((voldsn(i,j),j=1,6),i=1,1)
      read(10,*)((vsoil(i,j),j=1,6),i=1,1)
      read(10,*)press,ncloud,za
      read(10,*)slope,surfac,dayl,lat
      read(10,*)iveg
      if(iveg.eq.1)then
      read(11,*)sigf,state,epf,fola,hfol
      end if
      read(10,*)area,critdp,delts,coefb,wet
      read(10,*)soildp,soiltp,ssoiltp
      read(10,*)n
c
c** n  number of days to be modelled ie. no. of days in data file
c      minus one.
c** xxx(1,8)= Julain date
c   xxx(1,1)= observation time, 24hr clock
c   yyy(1,1)= air temperature, oC
c   yyy(1,2)= relative humidity, %
c   yyy(1,3)= cloud cover, 0-1
c   yyy(1,6)= wind speed, m/s
c   yyy(1,7)= precipitation, mm water
c
      read(10,*)xxx(1,8),xxx(1,1),yyy(1,1),yyy(1,9),yyy(1,2),
     & yyy(1,3),
     & yyy(1,6),yyy(1,7)
      read(10,*)xxx(2,8),xxx(2,1),yyy(2,1),yyy(2,9),yyy(2,2),
     & yyy(2,3),
     & yyy(2,6),yyy(2,7)
      write(9,*)'input matrix '
      write(9,*)xxx(1,8),xxx(1,1),yyy(1,1),yyy(1,9),yyy(1,2),
     & yyy(1,3),
     & yyy(1,6),yyy(1,7)
      write(9,*)xxx(2,8),xxx(2,1),yyy(2,1),yyy(2,9),yyy(2,2),
     & yyy(2,3),
     & yyy(2,6),yyy(2,7)
c
c
      do 20 i=1,2
       do 10 j=1,6
       thkmx2(i,j)=0.0
       depmx2(i,j)=0.0
10     continue
20    continue
      kontrol=0
      snvol=0.0
      depth=0.0
      k1=0
      k2=0
```

```
c
c  **The daily computational loop is do 5001
c
        do 5001 l=1,n
         kl=kl+1
         kelvin=yyy(1,1)+273.15
         pptn=yyy(1,7)
         airt =yyy(1,1)
         ddate=xxx(1,8)
         time2=xxx(2,1)
c
c**If statement to determine if is the first day of model run
c  and if the has been any snowfall.
c
         if(kl.eq.1)then
         write(9,*)'FLAG 20'
         write(9,*)'1 PPTN,AIRTP= ',snpptn,airtp
         k2=0
           if(pptn.gt.0.0.and.airtp.lt.0.0)then
           goto 50
           end if
         end if
c
c**If statement to determine if there was a snowcover present in the
c  previous iteration.
c
         if(k3.eq.1)then
         k2=0
         goto 57
         else
         depth=0.0
         goto 50
         end if
c
50       write(9,*)'FLAG 21'
c**Calculate snow precipitation.
         snpptn=(pptn/vnewsn(1,6))/10
         write(9,*)'snpptn(cm),pptn(mm)= ',snpptn,pptn
         depth=snpptn+depth
c
c**Snow present: set depth matrix using surface soil and air
c                temperatures as snow surface and basal temperatures.
c                snow state is 'new'.
c**Snow absent: set depth matrix using the known soil depth, soil
c               temperature at depth and air temperature as the
c               soil surface temperature.
c
```

```
         if(depth.ge.critdp)then
         write(9,*)'FLAG 22'
         nomatl=1
         nipts=2
         depmxl(1,1)=0.0
         depmxl(1,2)=airtp
         depmxl(2,1)=depth
         depmxl(2,2)=ssoiltp
         do 52 i=1,2
          write(9,555)(depmxl(i,j),j=1,2)
52       continue
         do 54 j=1,6
          thkmxl(1,j)=vnewsn(1,j)
54       continue
         thkmxl(1,1)=depth
         write(9,*)'THICKNESS MATRIX:'
         write(9,*)((thkmxl(i,j),j=1,6),i=1,1)
         write(9,*)'FLAG 23'
         k25=1
         k3=1
         k2=1
         goto 57
         else
         write(9,*)'FLAG 24'
         nomatl=1
         nipts=2
         do 56 j=1,6
          thkmxl(1,j)=vsoil(1,j)
56       continue
         thkmxl(1,1)=soildp
         depmxl(1,1)=0.0
         depmxl(1,2)=airtp
         depmxl(2,1)=soildp
         depmxl(2,2)=soiltp
         k3=0
         k2=0
         end if
c
c**Calculation of sfrq using subroutine csfrq.
c  sfrq(ix) is the vertical grid spacing in cm in each layer ix
c  in cm**2/m. sfrq is variable because layer size is variable.
c
57      call csfrq(i,n)
c
c**2-layered pack: set depth matrix for 1-layered pack to 0.0
c  1-layered pack: set depth matrix for 2-layered pack to 0.0
c
```

```
        if(nomatl.eq.1)then
        do 59 i=1,3
         do 58 j=1,2
          depmx2(i,j)=0.0
58       continue
59      continue
        else
        do 61 i=1,3
         do 60 j=1,2
          depmx1(i,j)=0.0
60       continue
61      continue
        end if
c
        do 62 i=1,3
         write(9,555)(depmx2(i,j),j=1,2)
62      continue
        do 63 i=1,2
         write(9,555)(depmx1(i,j),j=1,2)
63      continue
c
c**Set some variables to zero before calling TSTM
c  The write statements are a program developement check.
c  The format statements are for the output.
         write(9,*)'FLAG 25'
         write(9,*)'sfrq= ',sfrq
         k10=0
         avstp=0.0
         avsol=0.0
         avgbr=0.0
         avabsor=0.0
         avaterm=0.0
         avhterm=0.0
         avdterm=0.0
         avbottp=0.0
         write(9,*)'ALBEDO 1= ',thkmx1(1,5)
         write(9,*)'ALBEDO 2= ',thkmx2(2,5)
         write(9,*)'**DATA MATRIX PASSED TO TSTM**'
         write(9,64)xxx(1,8),xxx(1,1),yyy(1,1),yyy(1,2),yyy(1,3),
     &   yyy(1,6),yyy(1,7)
         write(9,64)xxx(2,8),xxx(2,1),yyy(2,1),yyy(2,2),yyy(2,3),
     &   yyy(2,6),yyy(2,7)
64       format(7f6.1)
310    FORMAT(11X,'TOTAL GRAYBODY   EFFECTIVE      GROUND   FOLIAGE',
     &          4X,'SOLAR')
320    FORMAT(14X,'RADIANCE        TEMP',10X,'TEMP     TEMP'
     & ,4X,'INSOLATION')
330    FORMAT(5X,'HR',7X,'(W/M**2)',9X,'(C)',11X,'(C)'
     & ,6X,'(C)     (W/M**2)')
340    FORMAT(9X,'-----REFL-NREFL----REFL----NREFL',30(1H-))
270
FORMAT(3X,F5.2,5X,I4,2X,I4,3X,F6.1,2X,F6.1,3X,F6.1,3X,F6.1,7X,I4)
355    FORMAT(57X,'SENSIBLE LATENT')
360    FORMAT(5X,'HRS SURFACE  GRAYBODY   SOLAR     SURFACE  ATMOS',
     & ' IR   HEAT    HEAT')
370    FORMAT(11X,'TEMP   RADIANCE INSOLATION   ABSORP  EMISSION',
     &  '    LOSS     LOSS')
380    FORMAT(11X,'DEG C',23(1H-),'(W/M**2)',24(1H-))
```

```
390     FORMAT(3X,'TIME',18X,'DEPTH, TEMPERATURE'/4X,'HR',21X,'CM',
     & 9X,'C'/2X,65(1H-))
        if(iveg.eq.0)then
          WRITE(9,355)
          WRITE(9,360)
          WRITE(9,370)
          WRITE(9,380)
        else
          WRITE(9,310)
          WRITE(9,320)
          WRITE(9,330)
          WRITE(9,340)
        endif
          write(6,*)'**ENTERING TSTM SUBROUTINE**'
c
c**Call the subroutine TSTM. TSTM calculates the shortwave, longwave,
c  latent heat and sensible heat energy exchanges at the surface of
the
c  snowpack and the heat transport through the pack. TSTM calculates
most
c  of the variables used in the calculation of snowmelt.
c  In SNOMO TSTM can model either snow or non-snow covered ground.
c
          call tstm(i,'Y','N',k10,avstp,avsol,avgbr,avabsor,avaterm,
     &    avhterm,avdterm,k2,avbottp,tgbr,tsol,tabsor,
     &    taterm,thterm,tdterm)
          write(6,*)'**EXITED TSTM SUBROUTINE**'
          write(9,*)'avstp,avgbr,avsol etc. '
          write(9,*)avstp,avgbr,avsol,avabsor,avaterm,avhterm,avdterm
          write(9,*)'average base temp.= ',avbottp
c
          if(k3.eq.0)then
          write(9,*)'TSTM with SOIL characteristics was called'
          goto 9000
          else
          k3=1
          write(9,*)'TSTM with SNOW characteristics was called'
          goto 65
          end if
c
65        pterm=0.0
c
c**Call subroutine cmelt. This calculates meltrate and volume of snow
c  melted. Clmelt is identical except that daily averages of the
c  energy exchanges are used, not totals. Meltrate is calculated in
c  cm of snow and mm of water equivalent.
c
          call cmelt(i,n,enavm,netrad,pterm,tsol,tgbr tabsor,
     &    taterm,thterm,tdterm,pptn,densn,mrwe,mrsn,gterm,denw,depth,
     &    avstp,avbottp)
          write(9,*)'1 ENAVM= ',enavm
          write(9,*)'1 MRWE(mm.water),MRSN(cm.snow)= ',mrwe,mrsn
          write(9,*)'**'
          call clmelt(i,n,enavml,netrad,pterm,avsol,avgbr,avabsor,
     &    avaterm,avhterm,avdterm,pptn,densn,mrlwe,mrlsn,gterm,denw,
     &    depth,avstp,avbottp)
          write(9,*)'2 ENAVM1= ',enavml
          write(9,*)'2 MR1WE(mm.water),MR1SN(cm.snow)= ',mrlwe,mrlsn
```

```
         write(9,*)' '
c
c**Rain and melting pack: call subroutine rainmp. Meltrate has to be
c  recalculated.
c  Rain and frozen pack: call subroutine rainfp
c
         if(pptn.gt.0.0.and.airtp.gt.0.0)then
           if(mrwe.gt.0.0)then
           call rainmp(i,n,pptn,pterm,denw)
           call cmelt(i,n,enavm,netrad,pterm,tsol,tgbr,tabsor,
     &     taterm,thterm,tdterm,pptn,densn,mrwe,mrsn,gterm,denw,
     &     depth,avstp,avbottp)
           write(9,*)'8 ENAVM= ',enavm
           write(9,*)'8 MRWE(mm.water),MRSN(cm.snow)= ',mrwe,mrsn
           write(9,*)'**'
           call clmelt(i,n,enavml,netrad,pterm,avsol,avgbr,avabsor,
     &     avaterm,avhterm,avdterm,pptn,densn,mrlwe,mrlsn,gterm,
     &     denw,depth,avstp,avbottp)
           write(9,*)'9 ENAVMl= ',enavml
           write(9,*)'9 MR1WE(mm.water),MR1SN(cm.snow)= ',mrlwe,mrlsn
           write(9,*)' '
           goto 66
           else
           write(9,*)'**RAIN-ON-FROZEN PACK CALLED**'
           call rainfp(i,n,pptn,rstpc,denw,avstp,depth,densn)
           end if
         end if
c
c**Calculate snow precipitation if is not the first SNOMO run or
c  the first day with snowfall.
66       if(k2.eq.0)then
           if(pptn.gt.0.0.and.airtp.lt.0.0)then
           snpptn=(pptn/vnewsn(1,6))/10
           write(9,*)'2 pptn(mm)= ',pptn
           write(9,*)'2 snpptn(cm)= ',snpptn
           else
           snpptn=0.0
           write(9,*)'3 snpptn(cm)= ',snpptn
           end if
         goto 68
         end if
c
c**Manipulation of the snowpack to allow for the effects of snowfall.
c
68       if(k25.ge.3)then
           if(snpptn.gt.0.0)then
             if(nomatl.eq.1)then
             write(9,*)'thkmxl(1,1)= ',thkmxl(1,1)
             wel=(thkmxl(1,1)*10)*vnewsn(1,6)
             depthl=(wel/voldsn(1,6))/10
             depth=depthl
             write(9,*)'10 wel= ',wel
             write(9,*)'10 depth= ',depth
             write(9,*)'FLAG 2'
             goto 125
             end if
```

```
           write(9,*)'FLAG 3'
c          depth=depth-snpptn
           wel=(thkmx2(1,1)*10)*vnewsn(1,6)
           depth1=(wel/voldsn(1,6))/10
           depth=depth1
           depth=thkmx2(2,1)+depth
125        nomatl=2
           nipts=3
           do 150 j=1,6
            thkmx2(1,j)=vnewsn(1,j)
            thkmx2(2,j)=voldsn(1,j)
150        continue
           thkmx2(1,1)=snpptn
           thkmx2(2,1)=depth
           depth=depth+snpptn
           depmx2(1,2)=avstp
           depmx2(3,2)=avbottp
           depmx2(3,1)=depth
           depmx2(2,1)=thkmx2(1,1)
           depmx2(2,2)=((depmx2(2,1)/depth)*(avbottp-avstp))+avstp
           k25=1
           write(9,*)'FLAG 4'
           goto 3000
           else
             if(nomatl.eq.1)then
               if(thkmx1(1,2).eq.vnewsn(1,2))then
               wel=(thkmx1(1,1)*10)*vnewsn(1,6)
               depth1=(wel/voldsn(1,6))/10
               depth=depth1
c              write(9,*)'wel,depth1,depth= ',wel,depth1,depth
               end if
             write(9,*)'FLAG 5'
             goto 200
             else
             wel=(thkmx2(1,1)*10)*vnewsn(1,6)
             depth1=(wel/voldsn(1,6))/10
             depth=thkmx2(1,1)+depth1
200          nomatl=1
             nipts=2
             do 250 j=1,6
              thkmx1(1,j)=voldsn(1,j)
250          continue
             thkmx1(1,1)=depth
             k25=k25+1
             write(9,*)'FLAG 6'
             goto 4000
             end if
           end if
         else
           if(snpptn.gt.0.0)then
             if(k25.eq.1)then
               if(nomatl.eq.1)then
               write(9,*)'1 thkmx1(1,1)= ',thkmx1(1,1)
               write(9,*)'1 snpptn= ',snpptn
                 if(k2.eq.1)then
                 thkmx1(1,1)=0.0
                 end if
```

```
              thkmxl(1,1)=thkmxl(1,1)+snpptn
              write(9,*)'6 depmxl(2,1)= ',depmxl(2,1)
              write(9,*)'2 thkmxl(1,1)= ',thkmxl(1,1)
              k25=1
              write(9,*)'FLAG 7'
              goto 4000
              else
              thkmx2(1,1)=thkmx2(1,1)+snpptn
              depth=thkmx2(1,1)+thkmx2(2,1)
              k25=1
              write(9,*)'FLAG 8'
              goto 3000
              end if
            else
              if(nomatl.eq.1)then
              wel=(thkmxl(1,1)*10)*vnewsn(1,6)
              depthl=(wel/voldsn(1,6))/10
              depth=depthl
              write(9,*)'FLAG 9'
              goto 300
              end if
c           vnewsn(1,6)=0.280
            wel=(thkmx2(1,1)*10)*vnewsn(1,6)
c           vnewsn(1,6)=0.280
            depthl=(wel/voldsn(1,6))/10
            depth=depthl+thkmx2(2,1)
300         nomatl=2
            nipts=3
            do 350 j=1,6
             thkmx2(1,j)=vnewsn(1,j)
             thkmx2(2,j)=voldsn(1,j)
350         continue
            thkmx2(1,1)=snpptn
            thkmx2(2,1)=depth+snpptn
            depth=thkmx2(2,1)
            depmx2(1,2)=avstp
            depmx2(3,2)=avbottp
            depmx2(3,1)=depth
            depmx2(2,1)=thkmx2(1,1)
            depmx2(2,2)=((depmx2(2,1)/depth)*(avbottp-avstp))+avstp
            k25=1
            write(9,*)'FLAG 10'
            goto 3000
            end if
           else
             if(nomatl.eq.1)then
             k25=k25+1
             write(9,*)'FLAG 11'
             goto 4000
             else
             k25=k25+1
             write(9,*)'FLAG 12'
             goto 3000
             end if
           end if
          end if
c
```

```
c**Manipulation of the snowpack to allow for the effects of snowmelt.
c
3000    if(depth.le.5.0)then
        write(9,*)'TERMINATION DUE TO COMPACTION'
        goto 5002
        else
        goto 3001
        end if
3001    if(mrsn.ge.depth)then
        write(9,*)'FLAG 13'
        goto 5002
        else
          if(mrsn.lt.1.0)then
          depmx2(1,2)=avstp
          depmx2(3,2)=avbottp
          depmx2(3,1)=depth
          depmx2(2,1)=thkmx2(1,1)
          depmx2(2,2)=((depmx2(2,1)/depth)*(avbottp-avstp))+avstp
          write(9,*)'NO MELT, DEPTH MATRIX:'
          do 375 i=1,3
           write(9,555)(depmx2(i,j),j=1,2)
375       continue
          write(9,*)'FLAG 14'
          goto 3500
          else
            if(mrsn.ge.thkmx2(1,1))then
            nomatl=1
            nipts=2
            do 400 j=1,6
             thkmx1(1,j)=voldsn(1,j)
400         continue
            depth=depth-mrsn
            thkmx1(1,1)=depth
            depmx1(1,2)=avstp
            depmx1(2,2)=avbottp
            depmx1(2,1)=thkmx1(1,1)
            write(9,*)'****************'
            write(9,*)'Post melt-depth matrix'
            do 410 i=1,2
             write(9,555)(depmx1(i,j),j=1,2)
410         continue
            write(9,*)'FLAG 15'
            goto 4500
            else
            thkmx2(1,1)=thkmx2(1,1)-mrsn
            depth=thkmx2(1,1)+thkmx2(2,1)
            depmx2(1,2)=avstp
            depmx2(3,2)=avbottp
            depmx2(3,1)=depth
            depmx2(2,1)=thkmx2(1,1)
            depmx2(2,2)=((depmx2(2,1)/depth)*(avbottp-avstp))+avstp
```

```
                write(9,*)'****************'
                write(9,*)'Post-melt depth matrix'
                do 415 i=1,3
                 write(9,555)(depmx2(i,j),j=1,2)
415             continue
                end if
3500            write(9,*)'****************'
                write(9,*)'THICKNESS MATRIX'
                do 420 i=1,2
                 write(9,550)(thkmx2(i,j),j=1,6)
                 write(6,550)(thkmx2(i,j),j=1,6)
420             continue
                write(9,*)'FLAG 16'
                goto 5000
              end if
            end if
4000        if(depth.le.5.0)then
            write(9,*)'TERMINATION DUE TO COMPACTION'
            goto 5002
            else
            goto 4001
            end if
4001        if(mrsn.ge.depth)then
            write(9,*)'FLAG 17'
            goto 5002
            else
              if(mrsn.lt.1.0)then
              depmx1(1,2)=avstp
              depmx1(2,2)=avbottp
              depmx1(2,1)=thkmx1(1,1)
              write(9,*)'NO MELT, DEPTH MATRIX:'
              do 425 i=1,2
               write(9,555)(depmx1(i,j),j=1,2)
425           continue
              write(9,*)'FLAG 18'
              goto 4500
              else
              depth=depth-mrsn
              thkmx1(1,1)=depth
              depmx1(1,2)=avstp
              depmx1(2,2)=avbottp
              depmx1(2,1)=thkmx1(1,1)
              write(9,*)'******************'
              write(9,*)'Post-melt matrix:'
              do 430 i=1,2
               write(9,555)(depmx1(i,j),j=1,2)
430           continue
              end if
            end if
```

```
4500      write(9,*)'*********************'
          write(9,*)'THICKNESS MATRIX:'

write(9,550)thkmxl(1,1),thkmxl(1,2),thkmxl(1,3),thkmxl(1,4),
     &    thkmxl(1,5),thkmxl(1,6)
          write(6,550)thkmxl(1,1),thkmxl(1,2),thkmxl(1,3),thkmxl(1,4),
     &    thkmxl(1,5),thkmxl(1,6)
5000      write(6,*)'nomatl,nipts= ',nomatl,nipts
          write(9,*)'nomatl,nipts= ',nomatl,nipts
          write(6,*)'k25,kl,k2,k3= ',k25,kl,k2,k3
          write(9,*)'k25,kl,k2,k3= ',k25,kl,k2,k3
          write(6,*)'depth= ',depth
          write(9,*)'depth= ',depth
          write(6,*)'snowfall,meltrate(cm snow)= ',snpptn,mrsn
          write(9,*)'snowfall,meltrate(cm snow)= ',snpptn,mrsn
          write(9,*)'avstp,avbottp= ',avstp,avbottp
550       format(6f6.2)
555       format(2f6.2)
c
c**Read in next daily data line, shift existing bottom data line to
c  the top.
c
9000      yyy(2,6)=yyy(2,6)/100.0
          yyy(2,2)=yyy(2,2)*100
          cumtm=xxx(2,1)
          write(9,*)'******cumulative time= ',cumtm
          xxx(1,8)=xxx(2,8)
          xxx(1,1)=time2
          yyy(1,1)=yyy(2,1)
          yyy(1,2)=yyy(2,2)
          yyy(1,9)=yyy(2,9)
          yyy(1,3)=yyy(2,3)
          yyy(1,6)=yyy(2,6)
          yyy(1,7)=yyy(2,7)
          xxx(2,8)=0
          xxx(2,1)=0
          yyy(2,1)=0
          yyy(2,9)=0
          yyy(2,2)=0
          yyy(2,3)=0
          yyy(2,6)=0
          yyy(2,7)=0
          nkont=n-kontrol
          if(nkont.eq.1)then
          goto 5002
          end if
          read(10,*)xxx(2,8),xxx(2,1),yyy(2,1),yyy(2,9),yyy(2,2),
     &              yyy(2,3),
     &              yyy(2,6),yyy(2,7)
```

```
        write(9,*)'shifted matrix to read next line '
        write(6,88)xxx(1,8),xxx(1,1),yyy(1,1),yyy(1,9),yyy(1,2),
     &            yyy(1,3),
     &            yyy(1,6),yyy(1,7)
        write(9,88)xxx(1,8),xxx(1,1),yyy(1,1),yyy(1,9),yyy(1,2),
     &            yyy(1,3),
     &            yyy(1,6),yyy(1,7)
        write(6,88)xxx(2,8),xxx(2,1),yyy(2,1),yyy(2,9),yyy(2,2),
     &            yyy(2,3),
     &            yyy(2,6),yyy(2,7)
        write(9,88)xxx(2,8),xxx(2,1),yyy(2,1),yyy(2,9),yyy(2,2),
     &            yyy(2,3),
     &            yyy(2,6),yyy(2,7)
88      format(7f6.1)
        airtp=yyy(1,1)
        yyy(1,1)=yyy(1,1)-273.15
        yyy(1,9)=yyy(1,9)-273.15
        kelvin=yyy(1,1)+273.15
        pptn=yyy(1,7)
        ddate=xxx(1,8)
        kontrol=kontrol+1
        snpptn=0.0
        write(9,*)'CALL NEXT L'
        write(9,*)' '
        write(9,*)' '
        write(9,*)'FLAG 30'
5001    continue
5002    write(9,*)'PROGRAM TERMINATION'
        stop
        end
c
c8*********************************************************************
**********
c
```

```
c*******subroutine cmelt********
c  This calculates the meltrate in cm of snow and mm of water
equivalent.
c  The density of the snowpack is calculated if the pack is a 2-
layered pack.
c  Melt is calculated using the snow energy budget. The components of
the
c  snow energy budget are calculated by TSTM, rainmp and dU/dtis
calculated
c  within cmelt.
c
          subroutine cmelt(i,n,enavm,netrad,pterm,tsol,tgbr,tabsor,
     &    taterm,thterm,tdterm,pptn,densn,mrwe,mrsn,gterm,denw,depth,
     &    avstp,avbottp)
          common/matrix2/depmx1(2,2),depmx2(3,2)
          common/matrix3/thkmx1(1,6),thkmx2(2,6)
          common/tstm2/nomatl
          common/phycons/lheatf,hcapsn,hcapw
          real lheatf,netrad,mrwe,mrsn,depth,densn,A,B,C,D,avsntp,dudt
c
c**calculation of the density of the snow.
          if(nomatl.eq.1)then
          densn=thkmx1(1,6)
          else
          A=thkmx2(1,1)/depth
          B=thkmx2(2,1)/depth
          C=A*thkmx2(1,6)
          D=B*thkmx2(2,6)
c         write(9,*)'A,B,C,D,depth= ',A,B,C,D,depth
c         write(9,*)'thkmx2(1,1),thkmx2(2,1)= ',thkmx2(1,1),thkmx2(2,1)
c         write(9,*)'thkmx2(1,6),thkmx2(2,6)= ',thkmx2(1,6),thkmx2(2,6)
          densn=C+D
          end if
          write(9,*)' '
          write(9,*)'1 density of snow= ',densn
c
c**Calculation of dU/dt, J/m**2.day
          avsntp=(avstp+avbottp)/2
          dudt=depth*(((densn*1000)*hcapsn)+hcapw)*avsntp
          write(9,*)'dU/dt= ',dudt
c
c**Calculation of meltrate.
          netrad=tsol-(tsol-tabsor)+taterm-tgbr
          enavm=netrad+thterm+tdterm+gterm
          enavm=enavm*8.64e+4
c 1W/m**2 = 8.64e+4 J/m**2.day
          write(9,*)'ENAVM 1= ',enavm
          write(9,*)'TSOL,TABSOR,TATERM,TGBR= ',tsol,tabsor,taterm,tgbr
          write(9,*)'NETRAD,THTERM,TDTERM= ',netrad,thterm,tdterm
          write(9,*)'GTERM,PTERM= ',gterm,pterm
          enavm=enavm+pterm-dudt
          write(9,*)'ENAVM 2= ',enavm
          mrwe=(enavm/(lheatf*denw))*1000
          mrsn=(enavm/(lheatf*(densn*1000)))*100
c Multiply mrwe by 1000, so that result is in mm water.
c Multiply mrsn by 100, so that result is in cm snow.
          return
          end
```

```
c*******subroutine clmelt********
c This is identical to cmelt except that daily averages are used in
the
c calculation of melt not totals.
c
      subroutine
clmelt(i,n,enavml,netrad,pterm,avsol,avgbr,avabsor,
     &
avaterm,avhterm,avdterm,pptn,densn,mrlwe,mrlsn,gterm,denw,depth,
     & avstp,avbottp)
      common/matrix2/depmxl(2,2),depmx2(3,2)
      common/matrix3/thkmxl(1,6),thkmx2(2,6)
      common/tstm2/nomatl
      common/phycons/lheatf,hcapsn,hcapw
      real lheatf,netrad,mrlwe,mrlsn,depth,A,B,C,D,avsntp,dudt
c
      if(nomatl.eq.1)then
      densn=thkmxl(1,6)
      else
      A=thkmx2(1,1)/depth
      B=thkmx2(2,1)/depth
      C=A*thkmx2(1,6)
      D=B*thkmx2(2,6)
      write(9,*)'A,B,C,D,depth= ',A,B,C,D,depth
      write(9,*)'thkmx2(1,1),thkmx2(2,1)= ',thkmx2(1,1),thkmx2(2,1)
      write(9,*)'thkmx2(1,6),thkmx2(2,6)= ',thkmx2(1,6),thkmx2(2,6)
      densn=C+D
      end if
      write(9,*)' '
      write(9,*)'2 densn= ',densn
c
      avsntp=(avstp+avbottp)/2
      dudt=depth*(((densn*1000)*hcapsn)+hcapw)*avsntp
      write(9,*)'dU/dt= ',dudt
c
      netrad=avsol-(avsol-avabsor)+avaterm-avgbr
      enavml=netrad+avaterm+avdterm+gterm
      enavml=enavml*8.64e+4
      write(9,*)'ENAVM 3= ',enavml
      write(9,*)'AVSOL,AVABSOR,AVATERM= ',avsol,avabsor,avaterm
      write(9,*)'NETRAD,AVHTERM,AVDTERM= ',netrad,avhterm,avdterm
      write(9,*)'GTERM,PTERM,AVGBR= ',gterm,pterm,avgbr
      enavml=enavml+pterm-dudt
      write(9,*)'ENAVM 4= ',enavml
      mrlwe=(enavml/(lheatf*denw))*1000
      mrlsn=(enavml/(lheatf*(densn*1000)*0.96))*100
      return
      end
c
c
*********************************************************************
*******
```

```
c
c********************************************************************
*********
c
c*******subroutine rainmp*******
c This calculates the energy input to the pack by rain falling on
c a melting pack at 0 oc.
c
        subroutine rainmp(i,n,pptn,pterm,denw)
        common/rain/airtp
        common/phycons/lheatf,hcapsn,hcapw
        real pterm
        pterm=(denw*hcapw*airtp*pptn)/1000
        return
        end
c
c
*********************************************************************
*******
c
```

```
c*******subroutine rainfp*******
c This calculates the warming effect of rainfall on a snowpack with
c a temperature <0 oC.
c lheatf converted from MJ/kg to kJ/kg, rstpc calculates in kJ/kg
c densn converted from g/m**2 to kg/m**2
c depth converted from cm to m
c
        subroutine rainfp(i,n,pptn,rstpc,denw,avstp,depth,densn)
        common/rain/airtp
        common/phycons/lheatf,hcapsn,hcapw
        common/matrix2/depmx1(2,2),depmx2(3,2)
        common/matrix3/thkmx1(1,6),thkmx2(2,6)
        common/tstm2/nomatl
        real rstpc,rstpc1,rstpc2,rstpc3,lheatf,depth,densn
        depth=depth/100
        densn=densn*1000
        lheatf=333.4
        rstpc1=(hcapw*airtp)+lheatf-(hcapsn*avstp)
        rstpc2=hcapsn*densn*depth
        rstpc3=(((pptn/1000)*denw)*rstpc1)/rstpc2
        rstpc=rstpc3
        avstp=avstp+rstpc
c       write(9,*)'rstpc1,rstpc2,rstpc3,avstp= ',rstpc1,rstpc2,
c    &  rstpc3,avstp
        lheatf=0.334e+6
        densn=densn/1000
        depth=depth*100
        return
        end
c
c
*********************************************************************
*******
c
```

```
c*******subroutine csfrq*******
c  This calculates sfrq. Sfrq(ix) is the vertical grid spacing in
c  cm in each layer ix in cm**2/m. A minimum value for sfrq of
c  5cm is used. Numerical instability results if smaller values
c  are used.
c
        subroutine csfrq(i,n)
        common/matrix3/thkmx1(1,6),thkmx2(2,6)
        common/tstm2/nomatl
        common/vegi/iveg,sigf,state,epf,fola,hfol
      common/sfrq/sfrq
        common/tstm3/tottim,tfrq,tprnt,nipts
        real sfrq(6),sfrq1,sfrq2
        if(nomatl.eq.1)then
        sfrq1=(thkmx1(1,1))/2
        else
        sfrq1=(thkmx2(1,1))/2
        end if
100     if(sfrq1.le.5.0)then
        goto 200
        else
          if(sfrq1.le.10.0)then
          goto 200
          else
          sfrq1=sfrq1/2
          goto 100
          end if
        end if
200     sfrq(1)=sfrq1
        if(nomatl.eq.2)then
        sfrq2=thkmx2(2,1)/2
300       if(sfrq2.le.5.0)then
          goto 400
          else
            if(sfrq2.le.10.0)then
            goto 400
            else
            sfrq2=sfrq2/2
            goto 300
            end if
          end if
400     sfrq(2)=sfrq2
        end if
      timesp1=0.5*(sfrq(1)*sfrq(1)/thkmx1(1,2))
      print *,'time ',timesp1,sfrq(1),thkmx1(1,2)
      if(nomatl.gt.1) then
            timesp1=0.5*(sfrq(1)*sfrq(1)/thkmx2(1,2))
            timesp2=0.5*(sfrq(2)*sfrq(2)/thkmx2(2,2))
            timesp1=min(timesp1,timesp2)
      endif
```

```
      itime=int(timespl)
      print *,'itime ',itime
      if(itime.eq.0)itime=1
      if(itime.gt.5)itime=5
      if(iveg.eq.1)itime=1
      tfrq=real(itime)
       return
        end
c
c*******************************************************************************
*********
c
```

```
c******Subroutine TSTM*******
c This calculates the longwave, shortwave, latent heat and sensible
c heat exchanges over the snowpack or soil surface, and the heat
c transport through the snowpack or soil pack. TSTM has been
converted
c to a subroutine from BALICK, L.K.,LINK, L.E., SCOGGINS, R.K. and
c SOLOMAN,J,1.(1981)Thermal Modelling of Terrain Surface
Elements.,U.S.
c Army, Tech. Report No. EL-81-2, Washington D.C. and BALICK, L.K.,
c SCOGGINS, R.K. and LINK, L.E.(1981)Inclusion of a simple vegetation
c layer in terrain temperature models for thermal infrared(IR)
c signature prediction.,Miscellaneous Paper EL-81-4, U.S. Army
c Engineer Waterways Experiment Station,CE,Vicksberg,Miss. Conversion
c to a subroutine was facilitated by the help of Mr. Randy
Scoggins(WES).
c
       SUBROUTINE TSTM(i,an1,an,k10,avstp,avgbr,avsol,avabsor,
     & avaterm,avhterm,avdterm,k2,avbottp,tgbr,tsol,
     & tabsor,taterm,thterm,tdterm)
C      TSTM:VEGIE----- BARE OR VEGETATED SURFACE TEMPERATURE MODEL
C---------------------------------------------------------------
C-                                                             -
C      THE FUNCTION OF THIS PROGRAM IS TO PREDICT SURFACE      -
C      TEMPERATURE.                                            -
C                                                              -
C---------------------------------------------------------------
C      PARAMETER (ND=30)
       INTEGER OUTCD
       DIMENSION datmx(100,10)
       DIMENSION RHOC(6),MAX(10),DEPTH(450),PROF(2,450),
     & FMM(30,10),BBB(30,10)
       DIMENSION TITLE(7)
       DIMENSION CLR(8),NX(6),ATF(2),FEB(2)
       DIMENSION RR(6),INTR(7)
       dimension thk(6),alph(6),f[illegible](6),stor(7,450),stabn(6)
       REAL KTEMPG,KTEMPA,LAT,ACL(8),BCL(8),M,KSQ,bottp
          CHARACTER DATE*8,HEADER*72,AN*1,AN1*1
          CHARACTER*30 FNAME
```

```
       common/matrix1/xxx(30,10),yyy(30,10)
       common/matrix2/depmx1(2,2),depmx2(3,2)
       common/matrix3/thkmx1(1,6),thkmx2(2,6)
       common/tstm1/press,ncloud,za,slope,surfac,day,lat,wet
       common/tstm2/nomatl
       common/tstm3/tottim,tfrq,tprnt,nipts
       common/vegi/iveg,sigf,state,epf,fola,hfol
       common/sfrq/sfrq(6)
        DATA CLR/0.04,0.08,0.17,0.20,0.22,0.24,0.24,0.25/
        DATA OUTCD/0/
        DATA  ACL/82.2,87.1,52.5,39.0,34.7,23.8,11.2,15.4/
        DATA  BCL/.079,.148,.112,.063,.104,.159,-.167,.028/
        DATA SIGMA,PI,AC,BC/8.12E-11,3.141593,17.269,35.86/
        DATA CC/0.261/
        DATA LAST,G,KSQ,CP/2,980.0,0.16,0.24/
C      SET-SPECIFICATIONS
C      STATEMENT FUNCTIONS FOR USE IN VEGETATION SECTION
        E(T)=RH*6.108*EXP(AC*(T-273.15)/(T-BC))
        ESAT(T)=6.108*EXP(AC*(T-273.15)/(T-BC))
        Q(T)=0.622/(PRESS/E(T)-.378)
        QSAT(T)=0.622/(PRESS/ESAT(T)-.378)
      print *,' Inside tstm'
        SOLCHK=0
        iflag2=0
        iretrn=0
        iprnt=0
        sun=0.0
        write(9,*)'data matrix received by tstm '
        write(9,60)xxx(1,8),xxx(1,1),yyy(1,1),yyy(1,9),yyy(1,2),
     &  yyy(1,3),
     &  yyy(1,6),yyy(1,7)
        write(9,60)xxx(2,8),xxx(2,1),yyy(2,1),yyy(1,9),yyy(2,2),
     &  yyy(2,3),
     &  yyy(2,6),yyy(2,7)
60      format(7f6.1)
        if(nomatl.eq.1)then
        xxx(1,5)=depmx1(1,1)
        yyy(1,5)=depmx1(1,2)
        xxx(2,5)=depmx1(2,1)
        yyy(2,5)=depmx1(2,2)
        thk(1)=thkmx1(1,1)
        alph(1)=thkmx1(1,2)
        fk(1)=thkmx1(1,3)
c       write(9,*)'sfrq 1 =',sfrq
        epsn=thkmx1(1,4)
        smalla=(1-thkmx1(1,5))
c       write(9,*)'TPRNT= ',tprnt
c       write(9,*)'ABSORPTIVITY= ',smalla
c**smalla=1-albedo(see Balick et. al. original)
        else
```

```
        xxx(1,5)=depmx2(1,1)
        yyy(1,5)=depmx2(1,2)
        xxx(2,5)=depmx2(2,1)
        yyy(2,5)=depmx2(2,2)
        xxx(3,5)=depmx2(3,1)
        yyy(3,5)=depmx2(3,2)
        thk(1)=thkmx2(1,1)
        thk(2)=thkmx2(2,1)
        alph(1)=thkmx2(1,2)
        alph(2)=thkmx2(2,2)
        fk(1)=thkmx2(1,3)
        fk(2)=thkmx2(2,3)
        write(9,*)'sfrq= 2',sfrq
        epsn=thkmx2(1,4)
        smalla=(1-thkmx2(1,5))
        write(9,*)'**2 LAYER SYSTEM INPUT INTO TSTM**'
c       write(9,*)'xxx(1,5),yyy(1,5)= ',xxx(1,5),yyy(1,5)
c       write(9,*)'xxx(2,5),yyy(2,5)= ',xxx(2,5),yyy(2,5)
c       write(9,*)'xxx(3,5),yyy(3,5)= ',xxx(3,5),yyy(3,5)
c       write(9,*)'thk(1),thk(2),alph(1)= ',thk(1),thk(2),alph(1)
c       write(9,*)'alph(2),fk(1),fk(2),epsn=
',alph(2),fk(1),fk(2),epsn
c       write(9,*)'TPRNT= ',tprnt
c       write(9,*)'ABSORBTIVITY= ',smalla
        end if
C----------------------------------------------------------------
C     INITIALIZE-VARIABLES-AND-CONSTANTS
99996   ASSIGN 99994 TO I99995
        GO TO 99995
99994   CONTINUE
C----------------------------------------------------------------
C     INPUT-DATA
        ASSIGN 99989 TO I99990
        GO TO 99990
C---------------------------------------------------------------
C     PRINT-INPUT-DATA
99989   ASSIGN 99987 TO I99988
        IF(AN1.EQ.'Y')GO TO 99988
99987   CONTINUE
C----------------------------------------------------------------
C     CALCULATE-TABLE-SLOPE-AND-INTERCEPT
99986   ASSIGN 99982 TO I99983
        GO TO 99983
C----------------------------------------------------------------
C     CALCULATE-SURFACE-AND-LAYER-TEMPERATURE
99982   CONTINUE
        ASSIGN 99980 TO I99981
        GO TO 99981
C----------------------------------------------------------------
```

```
99980   CONTINUE
       PPTN=(YYY(1,7)+YYY(2,7))/2
       sumc2=0
       sumc3=0
       sumc4=0
       sumc5=0
       sumc6=0
       sumc7=0
       sumc8=0
       sumc9=0
       do 99 i=1,k10
       sumc2=sumc2+datmx(i,2)
       sumc3=sumc3+datmx(i,3)
       sumc4=sumc4+datmx(i,4)
       sumc5=sumc5+datmx(i,5)
       sumc6=sumc6+datmx(i,6)
       sumc7=sumc7+datmx(i,7)
       sumc8=sumc8+datmx(i,8)
       sumc9=sumc9+datmx(i,9)
99     continue
       tgbr=sumc3
       tsol=sumc4
       tabsor=sumc5
       taterm=sumc6
       thterm=sumc7
       tdterm=sumc8
       avstp=sumc2/k10
       avgbr=sumc3/k10
       avsol=sumc4/k10
       avabsor=sumc5/k10
       avaterm=sumc6/k10
       avhterm=sumc7/k10
       avdterm=sumc8/k10
       avbottp=sumc9/k10
       WRITE(*,*)'NORMAL TERMINATION'
C---------------------------------------------------------------
C       STOP
        RETURN
C---------------------------------------------------------------
C---------------------------------------------------------------
99997   CONTINUE
C   FORMATS
 90     FORMAT(' BOTTOM BOUNDRY INDEX=',I3)
 92     FORMAT(' BOTTOM BOUNDRY TEMPERATURE=',F6.1,' DEG C')
 95     FORMAT(' BOTTOM BOUNDRY HEAT FLUX=',F6.1,'W/M**2')
 97     FORMAT(F11.2,F11.1,F13.2,F13.1,F8.2)
 120    FORMAT(A8,F6.1)
 140    FORMAT(F5.1,F10.1,F6.1,F12.1,F12.1,F13.1)
 145    FORMAT(F6.1,F7.1)
 150    FORMAT(F12.1,I12,F11.2)
 160    FORMAT(F11.2,F13.2,F8.1,F10.1)
 170    FORMAT(F9.4,F12.1)
 180    FORMAT(I7,F16.1,F11.0,F12.0)
 190    FORMAT(4X,F5.2,F6.1,2X,I8,I9,I11,I9,I9,I8)
 260    FORMAT(9X,F8.1,F11.2,F9.2,F9.2,F8.2,F10.2,F8.2)
 200    FORMAT(F6.2,F8.2,F17.2)
 210    FORMAT(I6,F11.1,F12.1,F14.2,F14.2)
 220    FORMAT(1H1)
```

```
 230    FORMAT(A72)
 240    FORMAT(4X,F7.2,3X,F5.0,5X,F6.2,10X,F6.2,9X,F7.2)
 250    FORMAT(6X,F6.1,13X,F4.1,12X,F5.1)
 310   FORMAT(11X,'TOTAL GRAYBODY   EFFECTIVE      GROUND   FOLIAGE',
     &          4X,'SOLAR')
 320   FORMAT(14X,'RADIANCE        TEMP',10X,'TEMP     TEMP'
     & ,4X,'INSOLATION')
 330   FORMAT(5X,'HR',7X,'(W/M**2)',9X,'(C)',11X,'(C)'
     & ,6X,'(C)     (W/M**2)')
 340   FORMAT(9X,'-----REFL-NREFL----REFL----NREFL',30(1H-))
 270
FORMAT(3X,F5.2,5X,I4,2X,I4,3X,F6.1,2X,F6.1,3X,F6.1,3X,F6.1,7X,I4)
 350   FORMAT(57X,'SENSIBLE LATENT')
 360   FORMAT(5X,'HRS SURFACE  GRAYBODY   SOLAR     SURFACE  ATMOS',
     & ' IR   HEAT    HEAT')
 370    FORMAT(11X,'TEMP   RADIANCE INSOLATION   ABSORP  EMISSION',
     &    '    LOSS    LOSS')
 380   FORMAT(11X,'DEG C',23(1H-),'(W/M**2)',24(1H-))
 390   FORMAT(3X,'TIME',18X,'DEPTH, TEMPERATURE'/4X,'HR',21X,'CM',
     & 9X,'C'/2X,65(1H-))
  400  FORMAT(2H0 ,F5.2,4(3X,F5.1,' ',F5.2))
  410  FORMAT(10X,F5.1,1X,F5.2,3X,F5.1,1X,F5.2,3X,F5.1,1X,F5.2,
     & 3X,F5.1,1X,F5.2)
       GO TO I99997
C--------------------------------------------------------------
99995  CONTINUE
C    TO INITIALIZE-VARIABLES-AND-CONSTANTS
       BB=-2.4E-4
       MAX(1)=2
       MAX(2)=2
       MAX(3)=2
       MAX(4)=2
       MAX(5)=NIPTS
       MAX(6)=2
       MAX(7)=2
       MAX(8)=0
       MAX(9)=0
       MAX(10)=3
       IBUG=0
       IEOF=0
       GO TO I99995
C--------------------------------------------------------------
```

```
99990  CONTINUE
C   TO INPUT-DATA
C
C       INPUT-ATMOSPHERIC-SPECIFICATIONS
       ASSIGN 99978 TO I99979
       GO TO 99979
C
C       INPUT-SURFACE-ORIENTATION-SPECIFICATIONS
99978  ASSIGN 99976 TO I99977
       GO TO 99977
C
C     INPUT-HEAT-FLOW-CACULATION-CONTROLS
99976  ASSIGN 99974 TO I99975
       GO TO 99975
C
C     INPUT-INITIAL-TEMPERATURE-PROFILE
99974  ASSIGN 99972 TO I99973
       GO TO 99973
C
C     INPUT-TOP-SURFACE-CONSTSNTS
99972  ASSIGN 99970 TO I99971
       GO TO 99971
C
C     INPUT-LAYER-SPECIFICATIONS
99970  ASSIGN 99968 TO I99969
       GO TO 99969
C
C     INPUT-BOTTOM-BOUNDRY-DATA
99968  ASSIGN 99966 TO I99967
       GO TO 99967
C
C     INPUT-VEGETATION-PARAMETERS
99966  ASSIGN 99798 TO I99799
       GO TO 99799
C
99798  GO TO I99990
C-------------------------------------------------------------
99979  CONTINUE
C     TO INPUT-ATMOSPHERIC-SPECIFICATIONS
C
C      LINE   TIME    AIR TEMP RH  CLOUD COVER WIND SPEED,INSOLATION
C      NO.    HR     DEG C    %   (0-1)       M/3        CAL/CM**2-
MIN
C
       xxx(2,1)=xxx(2,1)+2400*(xxx(2,8)-xxx(1,8))
  860  DO 99965 J=1,2
       ixxx=int(xxx(j,1)/100.0)*100
       axxx=(xxx(j,1) - real(ixxx))/60.0
       xxx(j,1)=real(ixxx)/100.0+axxx
       XXX(J,7)=XXX(J,1)
       XXX(J,2)=XXX(J,1)
       XXX(J,3)=XXX(J,1)
       XXX(J,4)=XXX(J,1)
       XXX(J,6)=XXX(J,1)
       YYY(J,1)=YYY(J,1)+273.1
       YYY(J,9)=YYY(J,9)+273.15
       YYY(J,2)=YYY(J,2)*0.01
       YYY(J,6)=YYY(J,6)*100.0
```

```
       YYY(J,4)=YYY(J,4)/697.6
99965  CONTINUE
      XXX(3,10)=XXX(2,1)
        XXX(2,10)=14.0
        XXX(1,10)=XXX(1,1)
        YYY(3,10)=YYY(2,1)
        YYY(2,10)=YYY(1,9)
      YYY(1,10)=YYY(1,1)
      PRINT*,'10s ',XXX(1,10),XXX(2,10),XXX(3,10),YYY(1,10),
     &    YYY(2,10),YYY(3,10)
C
  840  FACTH=(1000.0/PRESS)**0.286
       GO TO I99979
C-------------------------------------------------------------
99977  CONTINUE
C    TO INPUT-SURFACE-ORIENTATION-SPECIFICATIONS
C
C         LINE SFC SLOPE   SFC AZIMUTH  DAY     LATITUDE
C         NO.  DEG-HORIZ=0 DEG S=0      JULIAN  DEG
C
       SLOPE=SLOPE*PI/180.0
       SURFAC=SURFAC*PI/180.
       GO TO I99977
C-------------------------------------------------------------
99975  CONTINUE
C    TO INPUT-HEAT-FLOW-CACULATION-CONTROLS
C
C         LINE NO. OF NO. OF 24 HRS TIME STEP PRINT  FRE       Q
C         NO.  LAYERS REPITIONS      MIN       MIN
C                    1-6    2-5
C
             TOTTIM=XXX(2,1) - XXX(1,1)
       GO TO I99975
C-------------------------------------------------------------
99973  CONTINUE
C    TO INPUT-INITIAL-TEMPERATURE-PROFILE
C
C         LINE NO. OF
C         NO.  PROFILE POINTS
C
C
C         LINE DEPTH TEMP
C         NO.  CM    DEG C
C
       MAX(5)=NIPTS
       DO 99964 J3=1,NIPTS
       YYY(J3,5)=YYY(J3,5)+273.15
99964  CONTINUE
       GO TO I99973
C-------------------------------------------------------------
99971  CONTINUE
C    TO INPUT-TOP-SURFACE-CONSTANTS
C         LINE EMISSIVITY ABSORBTIVITY MOISTURE
C         NO.                          CONTENT DRY WT.
C
       FACTA=SIGMA*EPSN
C
       GO TO I99971
```

```
C------------------------------------------------------------
99967  CONTINUE
C    TO INPUT-BOTTOM-BOUNDRY-DATA
C
C       IF LFLUXY=0, THERE IS NO HEAT FLUX THRU BOTTOM
C       IF IFLUXY LT 0, THERE IS NO AIRSPACE BENEATH BOTTOM
C       IF IFLUXY GT 0, THERE IS AIRSPACE BENEATH BOTTOM
C
       LFLUXY=-1
       IF(.NOT.(LFLUXY.EQ.0)) GO TO 99962
       DPRM0=YYY(NIPTS,5)
       TB=0.
       GO TO 99963
99962  IF(.NOT.(LFLUXY.LT.0)) GO TO 99961
C
       DPRM1=-0.5
       TB=FK(NOMATL)
       BEP=0.0
       BK=0.
       REP=0.
       TR=0.0
       FACTD=0.
       FACTE=0.
       RK=0.
       DPRM1=DPRM1/697.6
       GO TO 99963
99961   CONTINUE
99963  GO TO I99967
C------------------------------------------------------------
99969  CONTINUE
C    TO INPUT-LAYER-SPECIFICATIONS
C
C          LINE THICKNESS VERT. GRID THERMAL DIFF HEAT COND
C          NO.  CM        SPACE-CM   CM**2/MIN    CAL/MIN-CM-K
C
       DO 99960 J4=1,NOMATL
       RHOC(J4)=FK(J4)/ALPH(J4)
99960  CONTINUE
C^^^^^^^CONTROL SWITHCHES SPECIFIED^^^^^^^^^
       NIT=1
       IEFSWT=1
       GO TO I99969
C------------------------------------------------------------
```

```
99799  CONTINUE
C    TO INPUT-VEGITATION-PARAMETERS
       if(iveg.eq.0) go to 1120
      print *,'iveg,sigf,epf,fola,hfol ',iveg,sigf,epf,fola,hfol
      IF(SIGF.LE.0.0)GO TO I99799
       TF=YYY(1,1)
       IVEG=1
       EP1=EPF+EPSN-EPF*EPSN
       Z0=0.131*HFOL**0.997
       CH0=KSQ/(ALOG(ZA/Z0)**2)
       ZDSP=0.701*HFOL**0.979
       CHH=KSQ/(ALOG((ZA-ZDSP)/Z0)**2)
       CHG=(1.-SIGF)*CH0+SIGF*CHH
       DELTMP=1.
       QAF=QSAT(TF)
1120   GO TO I99799
C----------------------------------------------------------------
99988  CONTINUE
C    TO PRINT-INPUT-DATA
c      WRITE(*,139)
       WRITE(*,220)
C      WRITE(*,120)DATE,TTIME
       WRITE(*,*)' '
       WRITE(*,230)HEADER
       WRITE(*,*)' '
       WRITE(*,*)' ATMOSPHERIC-SPECIFICATIONS'
       WRITE(*,*)' '
       WRITE(*,*)' ATMOS PRESS  CLOUD TYPE  SHELTER'
       WRITE(*,*)' MB           INDEX       HEIGHT-CM'
       WRITE(*,150)PRESS,NCLOUD,ZA
       WRITE(*,*)' '
       WRITE(*,*)' TIME  AIR TEMP  RH  CLOUD COVER  WIND SPEED'
     &    ,'  SOLAR IRRAD'
       WRITE(*,*)' HRS   DEG C     %  (0-1)         M/S
W/M**2'
       MMAX=2
       WRITE(*,140)(XXX(J,1),YYY(J,1)-273.15,
     &
YYY(J,2)*100.0,YYY(J,3),YYY(J,6)*0.01,YYY(J,4)*697.6,J=1,MMAX)
       WRITE(*,*)' '
       WRITE(*,*)' SURFACE-ORIENTATION-SPECIFICATIONS'
       WRITE(*,*)' '
       WRITE(*,*)' SFC SLOPE    SFC AZIMUTH  DAY     LATITUDE'
       WRITE(*,*)' DEG-HORIZ=0  DEG S=0      JULIAN  DEG'
       WRITE(*,160)SLOPE*180/PI,SURFAC*180.0/PI,DAY,LAT
       WRITE(*,220)
       WRITE(*,*)' HEAT-FLOW-CACULATION-CONTROLS'
       WRITE(*,*)' '
       WRITE(*,*)' NO. OF  NO. OF 24 HRS TIME STEP  PRINT FREQ'
       WRITE(*,*)' LAYERS  REPETITIONS    MIN        MIN'
       WRITE(*,*)' 1-6'
       WRITE(*,180)NOMATL,TOTTIM/24.0,TFRQ,TPRNT
       WRITE(*,*)' '
       WRITE(*,*)' INITIAL-TEMPERATURE-PROFILE'
       WRITE(*,*)' '
       WRITE(*,145)(XXX(J,5),YYY(J,5)-273.15,
     &       J=1,NIPTS)
       WRITE(*,*)' '
```

```
       WRITE(*,*)' TOP-SURFACE-CONSTANTS'
       WRITE(*,*)' '
       WRITE(*,*)' EMISS  ABSORB   SATURATION'
       WRITE(*,200)EPSN,SMALLA,WET
       WRITE(*,*)' '
       WRITE(*,*)' INPUT-LAYER-SPECIFICATIONS'
      WRITE(*,*)' LAYER  THICKNESS  VERT. GRID  THERMAL DIFF  HEAT
COND'
       WRITE(*,*)' NO.    CM        SPACE-CM    CM**2/MIN'
     &    ,'     CAL/MIN-CM-K'
       DO 99956 J4=1,NOMATL
       WRITE(*,210)J4,THK(J4),SFRQ(J4),
     &    ALPH(J4),FK(J4)
99956  CONTINUE
       WRITE(*,*)' '
       WRITE(*,*)' INPUT BOTTOM BOUNDRY DATA'
       WRITE(*,*)' '
       IF(.NOT.(LFLUXY.EQ.0)) GO TO 99958
       WRITE(*,90)LFLUXY
       WRITE(*,92)DPRM0-273.15
       WRITE(*,*)' '
       WRITE(*,*)' '
       GO TO 99959
99958  IF(.NOT.(LFLUXY.LT.0)) GO TO 99957
       WRITE(*,90)LFLUXY
       WRITE(*,95)DPRM1*697.6
       WRITE(*,*)' '
       GO TO 99959
99957  WRITE(*,90)LFLUXY
       WRITE(*,95)DPRM1*697.6
      WRITE(*,*)' ---BOTTOM SURFACE-----  SURFACE BENEATH AIRSPACE
TEMP'
      WRITE(*,*)' EMISSIVITY GEOM SHAPE  EMISSIVITY GEOM SHAPE  DEG
C'
       WRITE(*,*)'            FACT(0.-1.)            FACT(0.-1.)'
       WRITE(*,97)BEP,BK,REP,RK,TR-273.15
       WRITE(*,*)' '
99959  WRITE(*,*)' '
       IF(IVEG.EQ.0) GO TO I99988
       WRITE(*,*)' VEGETATION PARAMETERS'
       WRITE(*,*)' '
       WRITE(*,*)'  COVERAGE   STATE   EMISSIVITY   ABSORBTIVITY
     & FOLIAGE HEIGHT'
       WRITE(*,*)  (0.0 -1.0)           (0.0 -1.0)    (0.0-1.0)
     &      (CM)'
       WRITE(*,240)SIGF,STATE,EPF,FOLA,HFOL
       WRITE(*,*)' '
       WRITE(*,*)' '
       WRITE(*,*)' '
       GO TO I99988
C--------------------------------------------------------------
99985  CONTINUE
C     TO CALCULATE-INSOLATION-ON-SLOPE-SURFACE
C
C
C      SOLVE-SOLAR-ZENITH
       ASSIGN 99951 TO I99952
       GO TO 99952
```

```
C
C       SOLVE-SOLAR-AZIMUTH
99951   ASSIGN 99949 TO I99950
        GO TO 99950
C
C       CALCULATE-SLOPE-ATMOS-ATTEN-AND-CLOUD-ADJUSTMENTS
99949   ASSIGN 99947 TO I99948
        GO TO 99948
C
99947   CONTINUE
C
99953   GO TO I99985
C------------------------------------------------------------
99955 CONTINUE
C     TO ZERO-VARIABLES
C
        I=0
        GO TO I99955
C------------------------------------------------------------
99952   CONTINUE
C     TO SOLVE-SOLAR-ZENITH
C
        TYME=AMOD(TIME,24.0)
        T0=2.0*PI*(DAY-1.0)/365.0
        DECL=0.006918-0.399912*COS(T0)+0.070257*SIN(T0)
     &      -0.006758*COS(2.0*T0)+0.000907*SIN(2.0*T0)
     &      -0.002697*COS(3.0*T0)+0.001480*SIN(3.0*T0)
        ELF=(LAT/180*PI)
        TIMER=(TYME/12*PI)+PI
        IF(TIMER.GT.2.*PI)TIMER=TIMER-2.*PI
        AA=COS(DECL)*COS(ELF)*COS(TIMER)
        BB=SIN(DECL)*SIN(ELF)
        C=AA+BB
        Z=ACOS(C)
        GO TO I99952
C------------------------------------------------------------
```

```
99950 CONTINUE
C    TO SOLVE-SOLAR-AZIMUTH
C
      XNUM=-COS(DECL)*SIN(TIMER)
      XDNOM=COS(ELF)*SIN(DECL)-SIN(ELF)*COS(TIMER)
      SAZ=ATAN(XNUM/XDNOM)
      IF(.NOT.(XNUM.LT.0.0.AND.XDNOM.GT.0.0)) GO TO 99944
      SAZ=SAZ+PI
      GO TO 99945
99944 IF(.NOT.(XNUM.GT.0.0.AND.XDNOM.GT.0.0)) GO TO 99943
      SAZ=SAZ-PI
99943 CONTINUE
99945 GO TO I99950
C------------------------------------------------------------
99948 CONTINUE
C    TO CALCULATE-SLOPE-ATMOS-ATTEM-AND-CLOUD-ADJUSTMENTS
C
      SICF=COS(Z)*COS(SLOPE)+SIN(Z)*SIN(SLOPE)
     &  *COS(SAZ-SURFAC)
      IF(.NOT.(SICF.LT.0.0.OR.COS(Z).LE.0.0)) GO TO 99941
      SUN=0.0
      GO TO 99942
99941 M=1/COS(Z)
      IF(.NOT.(M.GE.0.0)) GO TO 99939
      TAL=0.02023
      IF(DAY.GE.92.0 .AND. DAY.LE.152.0)TAL=-0.02290
      TD=5352.2/(21.4-ALOG(RH*ESAT(TA)))
      WATER=EXP(0.07074*(TD-273.15)+TAL)
      AB=0.271*(WATER*M)**0.303
      A0=0.085-0.247*ALOG10(PRESS/1000.*1./M)
      ARG1=((1.-AB)*0.349+(1.-A0)/(1.-A0*0.2)*0.651)
      GO TO 99940
99939 ARG1=1.0
99940 QP=2.0*ARG1
      QO=QP*SICF
      IF(.NOT.(NCLOUD.EQ.0)) GO TO 99937
      SUN=QO
      GO TO 99938
99937 CONTINUE
      ARG2=-(BCL(NCLOUD)-.059)*M
      CTF=(ACL(NCLOUD)/94.4)*EXP(ARG2)
      SUN=QO-((CLOUD*CLOUD)*(QO-QO*CTF))
99938 CONTINUE
99942 CONTINUE
      GO TO I99948
C------------------------------------------------------------
99983 CONTINUE
C    TO CALCULATE-TABLE-SLOPE-AND-INTERCEPT
      I=1
      GO TO 99935
99936 IF(I.GT.10) GO TO 99934
99935 IMAX=MAX(I)
      IF(IMAX.EQ.0)GO TO 99931
      J=1
      GO TO 99932
99933 IF(J.EQ.IMAX) GO TO 99931
99932 FMM(J,I)=(YYY(J+1,I)-YYY(J,I))/(XXX(J+1,I)-XXX(J,I))
      BBB(J,I)=YYY(J,I)-FMM(J,I)*XXX(J,I)
```

```
      J=J+1
      GO TO 99933
99931 I=I+1
      GO TO 99936
99934 GO TO I99983
C------------------------------------------------------------
99930 CONTINUE
C    TO GET-TABLE-VALUES
C
      IMAX=MAX(NTABL)
      IJ=1
      IF(.NOT.(XN.GE.XXX(IMAX,NTABL))) GO TO 99928
      YN=YYY(IMAX,NTABL)
      GO TO 99929
99928 IF(IJ.EQ.IMAX+1) GO TO 99927
      JJ=IJ
      IF(.NOT.(XXX(IJ,NTABL).LT.XN)) GO TO 99925
      IJ=IJ+1
      GO TO 99928
99925 IF(.NOT.(XXX(IJ,NTABL).EQ.XN)) GO TO 99924
      YN=YYY(JJ,NTABL)
      IJ=IMAX+1
      GO TO 99928
99924 IF(.NOT.(XXX(IJ,NTABL).GT.XN)) GO TO 99923
      JJ=JJ-1
      YN=FMM(JJ,NTABL)*XN+BBB(JJ,NTABL)
      IJ=IMAX+1
99923 CONTINUE
      GO TO 99928
99927 CONTINUE
99929 GO TO I99930
C------------------------------------------------------------
99981 CONTINUE
C    TO CALCULATE-SURFACE-AND-LAYER-TEMPERATURE
C
C     SET-UP-INITIAL-CONDITIONS
      ASSIGN 99921 TO I99922
      GO TO 99922
C
C     PRINT-OUTPUT-HEADING
99921 ASSIGN 99919 TO I99920
      GO TO 99920
C
99919 CONTINUE
C
C     RUN-HEAT-FLOW-PROGRAM
      ASSIGN 99917 TO I99918
      GO TO 99918
C
```

```
C      SET-UP-AND-PRINT-OUTPUT
99917  ASSIGN 99915 TO I99916
       GO TO 99916
C
99915  IF(IRETRN.EQ.1) GO TO 4100
       GO TO 99919
 4100  CONTINUE
       GO TO I99981
C------------------------------------------------------------
99922  CONTINUE
C    TO SET-UP-INITIAL-CONDITIONS
C
       PTYME=TOTTIM-24.0
       TIME=XXX(1,1)
       DIST=0.
       IFLAG=0
       IF (TFRQ.LE.0) TFRQ=TOTTIM
       DELT=TFRQ/60.
       ITIME=MAX1(TOTTIM/DELT+.9,1.1)
       IX=1
       IY=1
       GO TO 99913
99914  IF(IX.GT.NOMATL) GO TO 99912
99913  INTR(IX)=IY
       IF (SFRQ(IX).LE.0.) SFRQ(IX)=THK(IX)/10.
       NX(IX)=MAX1(THK(IX)/SFRQ(IX)+.9,1.1)
c      write(9,*)'sfrq(ix),nx(ix)= ',sfrq(ix),nx(ix)
       RR(IX)=60.0*DELT/(SFRQ(IX)*SFRQ(IX))
       stabn(ix)=alph(ix)*rr(ix)
c      write(9,*)'stabn(ix)= ',stabn(ix)
       if(stabn(ix).gt.0.5)then
         stabn(ix)=0.5
c        write(9,*)'stabn(ix)= ',stabn(ix)
       end if
       LAYERS=0
       GO TO 99910
99911  IF(LAYERS.GT.NX(IX)) GO TO 99909
99910  XN=DIST
       NTABL=5
       DEPTH(IY)=XN
C
C      GET-TABLE-VALUES
       ASSIGN 99908 TO I99930
       GO TO 99930
C
99908 TEMP=YN
       STOR(1,IY)=TEMP
       STOR(5,IY)=TEMP
       STOR(6,IY)=FK(IX)
       STOR(7,IY)=RHOC(IX)
       STOR(4,IY)=0.
       STOR(2,IY)=FK(IX)
       STOR(3,IY)=RHOC(IX)
c      write(9,*)'STOR MATRIX= ',stor(1,iy),stor(5,iy),stor(6,iy),
c    & stor(7,iy),stor(4,iy),stor(2,iy),stor(3,iy)
```

```
      IY=IY+1
      DIST=DIST+SFRQ(IX)
      LAYERS=LAYERS+1
      GO TO 99911
99909 IX=IX+1
      DIST=DIST-SFRQ(IX-1)
      GO TO 99914
99912 JMAX=IY-1
      INTR(IX)=JMAX
      NPRNT=MAX1(TPRNT/TFRQ+.9,1.1)
      IPRNT=NPRNT
      GO TO I99922
C-----------------------------------------------------------------
99920 CONTINUE
C    TO PRINT-OUTPUT-HEADING
C
      IF(OUTCD.EQ.1)GO TO 1610
      IF(IVEG.GT.0)  GO TO 1420
      WRITE(*,350)
      WRITE(*,360)
      WRITE(*,370)
      WRITE(*,380)
      GO TO I99920
 1420 WRITE(*,310)
      WRITE(*,320)
      WRITE(*,330)
      WRITE(*,340)
      GO TO I99920
 1610 WRITE(*,390)
      GO TO I99920
C-----------------------------------------------------------------
99918 CONTINUE
C    TO RUN-HEAT-FLOW-PROGRAM
C
c     write(9,*)'iflag2= ',iflag2
      IF(.NOT.(IFLAG2.EQ.0)) GO TO 99907
      ITER=NIT
c     write(9,*)'iter,time,delt= ',iter,time,delt
      TIME=TIME+DELT
99907 ZZA=STOR(5,1)
      ZZB=STOR(5,JMAX)
      TEML=ZZA
      TEMR=ZZB
C

C     CALCULATE-BOUNDRY-CONDITIONS  calculate energy budget terms
      IF(IVEG.EQ.0)GO TO 930
      ASSIGN 99905 TO I99800
      GO TO 99800
 930  ASSIGN 99905 TO I99906
      GO TO 99906
C
```

```
C       CALCULATE-UPPER-BOUNDARY-VALUES  using energy budget, find top
tmp
99905   IF(IVEG.EQ.0) GO TO 900
        ASSIGN 99903 TO I99797
        GO TO 99797
 900    ASSIGN 99903 TO I99904
        GO TO 99904
C
99903   IX=1
        J=2
C ***    NOMAT CHANGED TO NOMATL NOV 22 85 ***
        IMATL=NOMATL
        IF(.NOT.(NOMATL.EQ.1)) GO TO 99901
        IZ=NX(IX)-1
        IF(.NOT.(IZ.GT.0)) GO TO 99900
C
C       CALCULATE-INSIDE-MATERIAL-VALUES
        ASSIGN 99898 TO I99899
        GO TO 99899
C
99898   CONTINUE
99900   GO TO 99902
99901   GO TO 99896
99897   IF(IMATL.LT.1) GO TO 99895
99896   IF(.NOT.(IMATL.GT.1)) GO TO 99893
        IZ=NX(IX)-1
c       write(9,*)'**FLAG 51**iz=',iz
        IF(.NOT.(IZ.GT.0)) GO TO 99892
C
C       CALCULATE-INSIDE MATERIAL-VALUES
        ASSIGN 99891 TO I99899
        GO TO 99899
C
99891   CONTINUE
C
C       CALCULATE-INTERFACE-VALUES
99892   ASSIGN 99889 TO I99890
        GO TO 99890
99889   GO TO 99894
99893   IZ=NX(IX)-1
        IF(.NOT.(IZ.GT.0)) GO TO 99888
C
C       CALCULATE-INSIDE-MATERIAL-VALUES
        ASSIGN 99887 TO I99899
C
        GO TO 99899
99887   CONTINUE
99888   CONTINUE
99894   IMATL=IMATL-1
        GO TO 99897
99895   CONTINUE
C
C       CALCULATE-LOWER-BOUNDARY-VALUES
99902   ASSIGN 99883 TO I99886
        GO TO 99886
C
99883   GO TO I99918
C--------------------------------------------------------------
```

```
99906  CONTINUE
C    TO CALCULATE-BOUNDRY-CONDITIONS
       B = -FK(1)
       T=TIME
C
C      CALCULATE-BOTTOM-BOUNDRY-HEAT-TERMS-APRM-DPRM-BPRM
       ASSIGN 99880 TO I99881
       GO TO 99881
C
C
C      ATMOSPHERIC-INFRARED-EMISSION-ATERM
99880  ASSIGN 99878 TO I99879
       GO TO 99879
C
99878  CONTINUE
C   CALCULATE-SOLAR-INSOLATION-FOR-DAY-AND-TIME
       DAY=XXX(1,8)
       ASSIGN 42 TO I99985
       GO TO 99985
 42    BTERM=SUN
       IF(BTERM.GT.0)BTERM=BTERM*SMALLA
C
C      CALCULATE-CONVECTION-HTERM
       ASSIGN 99876 TO I99877
       GO TO 99877
C
C
C      CALCULATE-EVAPORATIVE-HEAT-LOSS-DTERM
99876  ASSIGN 99874 TO I99875
       GO TO 99875
C
99874  D = ATERM + BTERM - HTERM-DTERM
 521   CONTINUE
       GO TO I99906
C--------------------------------------------------------------
99881 CONTINUE
C    TO CALCULATE-BOTTOM-BOUNDRY-HEAT-TERMS-APRM-DPRM-BPRM
C
       BPRM=TB
       IF(.NOT.(TB.EQ.0.0)) GO TO 99872
       APRM=1.0
       DPRM=DPRM0
       GO TO 99873
99872  APRM=FACTE*TEMR*TEMR*TEMR
       DPRM=DPRM1
99873  GO TO I99881
C--------------------------------------------------------------
99879  CONTINUE
C    TO ATMOSPHERIC-INFRARED-EMISSION-ATERM
       XN=TIME
       NTABL=2
C
```

```
C       GET-TABLE-VALUES
        ASSIGN 99867 TO I99930
        GO TO 99930
C
99867   RH=YN
        XN=TIME
        NTABL=10
C
C       GET-TABLE-VALUES
        ASSIGN 99866 TO I99930
        GO TO 99930
C
99866   TA=YN
        XN=TIME
        NTABL=3
C
C       GET-TABLE-VALUES
        ASSIGN 99865 TO I99930
        GO TO 99930
C
99865   CLOUD=YN
        TAK=TA
        TAC=(TAK-273.15)
        EA=6.108*RH*EXP((AC*TAC)/(TAK-BC))
        ALPHI=(0.61+0.05*SQRT(EA))*(1.0+(CLR(NCLOUD)*(CLOUD**2)))
        DOWNIR=0.8132E-10*TAK**4*ALPHI
        ATERM=DOWNIR
        GO TO I99879
C-------------------------------------------------------------
99877   CONTINUE
C     TO CALCULATE-CONVECTION-HTERM
C
        XN=TIME
        NTABL=6
C
C       GET-TABLE-VALUES
        ASSIGN 99862 TO I99930
        GO TO 99930
C
99862   SPEED=YN
        TAK=TA
        ZASH=ZA
        TSK=TEML
        RHOA=-0.001*0.348*PRESS/TAK
 1200   THETAZ=TAK*FACTH
        THETAS=TSK*FACTH
        DTHETA=(THETAZ-THETAS)/ZASH
        DU=SPEED/ZASH
        THETAV=(THETAZ+THETAS)/2.0
        RI=G*DTHETA/(THETAV*DU**2)
        COE1=15.0
        COE2=1.175
        EX=.75
```

```
      IF(TSK.GT.TAK)GO TO 31
      IF(RI.GT.0.2)RI=.19999
      COE1=5.0
      COE2=1.0
      EX=2.0
   31 HTER=RHOA*KSQ*ZASH**2*DU
     & *(COE2*(1.0-COE1*RI)**EX)
      HTERM=HTER*CP*DTHETA
c     write(9,*)'tak,zash,tsk,rhoa= ',tak,zash,tsk,rhoa
c     write(9,*)'thetaz,thetas,dtheta= ',thetaz,thetas,dtheta
c     write(9,*)'du,thetav,ri= ',du,thetav,ri
c     write(9,*)'hter,hterm= ',hter,hterm
c     write(9,*)'ksq,coe2,coel,ex= ',ksq,coe2,coel,ex
99864 GO TO I99877
C---------------------------------------------------------------
99875 CONTINUE
C    TO CALCULATE-EVAPORATIVE-HEAT-LOSS-DTERM
C
      IF(.NOT.(TEML.GT.TA)) GO TO 99860
      XN=TIME
      NTABL=2
C
C     GET-TABLE-VALUES
      ASSIGN 99859 TO I99930
      GO TO 99930
C
99859 RH=YN
      XN=TIME
      NTABL=10
C
C     GET-TABLE-VALUES
      ASSIGN 99858 TO I99930
      GO TO 99930
C
99858 CTEMA=YN
      KTEMPA=CTEMA
      CTEMA=CTEMA-273.15
      KTEMPG=TEML
      ES=EXP((AC*(KTEMPG-273.15))/(KTEMPG-BC))*6.1071
      EA=EXP((AC*CTEMA)/(KTEMPA-BC))*6.1071*RH
      DG=0.622/PRESS*(EA-ES)*WET/ZA
      XL=597.3-0.566*(CTEMA+KTEMPG-273.15)/2.0
      DTERM=HTER*XL*DG
      GO TO 99861
99860 DTERM=0.0
99861 GO TO I99875
C---------------------------------------------------------------
```

```
99904  CONTINUE
C    TO CALCULATE-UPPER-BOUNDARY-VALUES
       T1=stabn(1)*(STOR(1,3)-2.*STOR(1,2)+STOR(1,1))+STOR(1,2)
c      write(9,*)'stor1,2,3= ',stor(1,1),stor(1,2),stor(1,3)
c      write(9,*)'alph(1),rr(1)= ',alph(1),rr(1)
       III=0
  830  III=III+1
c      write(9,*)'iii= ',iii
       T2=STOR(5,1)**4*FACTA*SFRQ(1)+FK(1)*STOR(5,1)
     &   -(FK(1)*T1+D*SFRQ(1))
c      write(9,*)'facta,sfrq(1),fk(1)= ',facta,sfrq(1),fk(1)
c      write(9,*)'t1,d,stor3a= ',t1,d,stor(5,1)
       T2=T2/(4.*FACTA*SFRQ(1)*STOR(5,1)**3+FK(1)-SFRQ(1)*DDDT)
       STOR(5,1)=STOR(5,1)-T2
c      write(9,*)'stor4,t2= ',stor(5,1),t2
       TEML=STOR(5,1)
       GTERM=-FK(1)*(STOR(5,1)-T1)/SFRQ(1)
       ASSIGN 825 TO I99877
       GO TO 99877
  825  ASSIGN 810 TO I99875
       GO TO 99875
  810  DNEW=ATERM+BTERM-HTERM-DTERM
       IF(ABS(T2).LT.0.005 .OR. III.GT.30)GO TO I99904
       DDDT=-(DNEW-D)/T2
       D=DNEW
       GO TO 830
C
C-----------------------------------------------------------
99899  CONTINUE
C    TO CALCULATE-INSIDE-MATERIAL-VALUES
C
       GO TO 99856
99857  IF(IZ.LE.0) GO TO 99855
99856  CONTINUE
       STOR(5,J)=STOR(1,J)+stabn(ix)*(STOR(1,J-1)-2.*STOR(1,J)
     &      +STOR(1,J+1))
       J=J+1
       IZ=IZ-1
       GO TO 99857
99855  GO TO I99899
C-----------------------------------------------------------
C    TO CALCULATE-INTERFACE-VALUES
C
99890  CONTINUE
       BCOEF=STOR(6,J-1)/SFRQ(IX)
       DCOEF=STOR(6,J+1)/SFRQ(IX+1)
c      write(9,*)'stor9,10= ',stor(6,j-1),stor(6,j+1)
       CCOEF=BCOEF+DCOEF
       ACOEF=BCOEF/(2.*stabn(ix))+DCOEF/(2.*stabn(ix+1))
```

```
      STOR(5,J)=STOR(1,J)+(BCOEF*STOR(1,J-1)-CCOEF*STOR(1,J)+DCOEF*
    &      STOR(1,J+2))/ACOEF
c     write(9,*)'stor11,12,13= ',stor(1,j),stor(1,j-1),stor(1,j+2)
c     write(9,*)'stor14= ',stor(5,j)
      STOR(5,J+1)=STOR(5,J)
      IX=IX+1
      J=J+2
      GO TO I99890
C-------------------------------------------------------------
C    TO CALCULATE-LOWER-BOUNDARY-VALUES
99886 IF(LFLUXY.EQ.0) GO TO 880
      I=1
      R2=FACTD
  870 CONTINUE
      R1=SIGMA*BEP*BK*STOR(5,J)**4
      G1=-FK(NOMATL)*(STOR(5,J)-STOR(1,J-1))/SFRQ(NOMATL)
      F2=4.0*SIGMA*BEP*BK*STOR(5,J)**3-FK(NOMATL)/SFRQ(NOMATL)
      F2= - (R2-R1+G1+DPRM)/F2
      STOR(5,J)=STOR(5,J) + F2
c     write(9,*)'stor15= ',stor(5,j)
      I=I+1
      IF(ABS(F2).GT.0.01 .AND. I.LE.30) GO TO 870
 880  IF(LFLUXY.EQ.0) STOR(5,J)=STOR(5,J)
      GO TO I99886
C-------------------------------------------------------------
99916 CONTINUE
C    TO SET-UP-AND-PRINT-OUTPUT
C
      IFLAG2=0
      IRETRN=0
      IF(ITER.LE.1) GO TO 1245
      ITER=ITER-1
      IF (IEFSWT.NE.0) GO TO 1328
      IF (IPRNT.LE.1) GO TO 1244
      IF (ITIME.GT.1) GO TO 1328
 1244 CONTINUE
C
C     PRINT-OUTPUT
      ASSIGN 99846 TO I99847
      GO TO 99847
C
99846 GO TO 1328
 1245 IF (ITIME.GT.1) GO TO 1269
C
C     PRINT-OUTPUT
      ASSIGN 99845 TO I99847
      GO TO 99847
C
```

```
99845  IRETRN=1
       GO TO 1335
 1269  ITIME=ITIME-1
       IF (IPRNT.LE.1) GO TO 1279
       IPRNT=IPRNT-1
       GO TO 1303
 1279  CONTINUE
C
C      PRINT-OUTPUT
       ASSIGN 99844 TO I99847
       GO TO 99847
C
99844  IPRNT=NPRNT
 1303  J=1
       IZ=NOMATL
 1306  IX=NX(IZ)+1
 1311  STOR(1,J)=STOR(5,J)
       STOR(2,J)=STOR(6,J)
       STOR(3,J)=STOR(7,J)
       J=J+1
       IF (IX.LE.1) GO TO 1329
       IX=IX-1
       GO TO 1311
 1329  IF(IZ.LE.1) GO TO 1335
       IZ = IZ-1
       GO TO 1306
 1328  IFLAG2=1
 1335  CONTINUE
       GO TO I99916
C-------------------------------------------------------------
99847   CONTINUE
C      TO PRINT-OUTPUT
C
        TFACK=1.0
        IF(.NOT.(TIME.GT.PTYME)) GO TO 99843
        DO 99842 JKX=1,NOMATL+1
        IJ=INTR(JKX)
        TITLE(JKX)=(STOR(5,IJ)-273.15)
99842   CONTINUE
        NDX=TIME
        IF(NDX.EQ.0)NDX=1
        bottp=stor(5,j)-273.15
        k10=k10+1
        IF(IVEG.EQ.1) GO TO 1110
        IGBR=5.67E-8*EPSN*STOR(5,1)**4
c       write(9,*)'**-IGBR-epsn,stor(5,1)= ',epsn,stor(5,1)
        ISOL=BTERM/SMALLA*697.6+0.5
        IABSOR=ISOL*SMALLA
        IATERM=ATERM*697.6
        IHTERM=HTERM*697.6+0.5
        IDTERM=DTERM*697.6+0.5
1110   continue
```

```
c       write(9,*)'Bottom temp.= ',stor(5,j)
        datmx(k10,1)=time
        datmx(k10,2)=title(1)
        ASSIGN 1400 TO I1410
        if(iveg.eq.1) GO TO 1410
1400  continue
        if(iveg.eq.0) then
          WRITE(9,190)AMOD(TIME,24.),TITLE(1),IGBR,ISOL,IABSOR,
     &          IATERM,IHTERM,IDTERM
          datmx(k10,3)=igbr
          datmx(k10,4)=isol
          datmx(k10,5)=iabsor
          datmx(k10,6)=iaterm
          datmx(k10,7)=ihterm
          datmx(k10,8)=idterm
          datmx(k10,9)=bottp
      else
         WRITE(9,270)AMOD(TIME,24.),ISURFG+IREFRA,ISURFG,TEFFR-
273.15,
     &      TEFF-273.15,TEML-273.15,TF-273.15,ISOL
          datmx(k10,3)=rlu*697.6
          datmx(k10,4)=sol*697.6
          datmx(k10,5)=smalla*sg*697.6
          datmx(k10,6)=rld*697.6
          datmx(k10,7)=hsg*697.6
          datmx(k10,8)=elg*xll*697.6
          datmx(k10,9)=bottp
      endif
        IF(AN.EQ.'Y')THEN
           WRITE(6,190)TIME,TITLE(1),IGBR,ISOL,IABSOR,
     &     IATERM,IHTERM,IDTERM
c          write(9,*)'Bottom temp.= ',stor(5,j)
        ENDIF
      PRINT *,'TIME, AIR TEMP ',TIME, TA-273.15
99843   GO TO I99847
C------------------------------------------------------------
99800  CONTINUE
C      TO CALCULATE-BOUNDARY-CONDITIONS-WITH-VEG
         T=TIME
         XN=TIME
         NTABL=6
C
C        GET-TABEL-VALUES
         ASSIGN 960 TO I99930
         GO TO 99930  .
C
 960     UA=YN
         XN=TIME
         NTABL=4
C
C        ATMOSPHERIC-INFRARED-EMISSION-ATERM
         ASSIGN 980 TO I99879
         GO TO 99879
C
```

```
C    Calculate solar
 980      CONTINUE
          DAY=XXX(1,8)
          ASSIGN 43 TO I99985
          GO TO 99985
 43       SOL=SUN
C
          IF(UA.LT.10.0)UA=10.0
          UAF=0.83*SIGF*UA*SQRT(CHH)+(1.-SIGF)*UA
          DELTMP=5.
          CF=0.01*(1.+30.0/UAF)
          DU=(UA-UAF)/ZA
          RS=1/(.05+.0021*(SOL*697.0))
          RC=RS*STATE/(7.0*SIGF)
          ATF(1)=TF
          ASSIGN 1210 TO I950
          GO TO 950
1210      CONTINUE
          FEB(1)=FENB
          NDEX=0
1240      TF=TF+DELTMP
          NDEX=NDEX+1
          ASSIGN 1220 TO I950
          GO TO 950
1220      CONTINUE
          FEB(2)=FENB
          IF(FEB(1)*FEB(2).LT.0.0) GO TO 1230
          IF(ABS(FEB(2)).GT.ABS(FEB(1)))DELTMP=-5.
          IF(NDEX.LT.100)GO TO 1240
          WRITE(*,*)'FOLIAGE ENERGY BUDGET HAS NOT CROSSED X-AXIS'
          WRITE(*,*)'AFTER 100 SEARCH STEPS. CHECK INPUT DATA.'
          STOP
1230      CONTINUE
          ATF(2)=TF
1270      SLOPE1=(FEB(2)-FEB(1))/(ATF(2)-ATF(1))
          BINT=FEB(1)-SLOPE1*ATF(1)
          TF0=-BINT/SLOPE1
          IF(ABS(TF-TF0).LE.0.001)GO TO 1260
          TF=TF0
          ASSIGN 1250 TO I950
          GO TO 950
1250      CONTINUE
          IF(FENB*FEB(2).GT.0.0)IP=2
          IF(FENB*FEB(1).GT.0.0)IP=1
          ATF(IP)=TF
          FEB(IP)=FENB
          GO TO 1270
1260      GO TO I99800
C-----------------------------------------------------------------
```

```
C       TO CALCULATE-UPPER-BOUNDARY-VALUES-FOR-FOLAGE
99797     CONTINUE
          DELTMP=5.
          ATF(1)=TEML
          ASSIGN 1310 TO I1300
          GO TO 1300
1310      CONTINUE
          FEB(1)=FENB
          NDEX=0
1340      TEML=TEML+DELTMP
          NDEX=NDEX+1
          ASSIGN 1320 TO I1300
          GO TO 1300
1320      CONTINUE
          FEB(2)=FENB
          IF(FEB(1)*FEB(2).LT.0.0) GO TO 1330
          IF(ABS(FEB(2)).GT.ABS(FEB(1)))DELTMP=-5.
          IF(NDEX.LT.100)GO TO 1340
          WRITE(*,*)'GROUND ENERGY BUDGET HAS NOT CROSSED X-AXIS'
          WRITE(*,*)'AFTER 100 SEARCH STEPS. CHECK INPUT DATA.'
          STOP
1330      CONTINUE
          ATF(2)=TEML
1370      SLOPE1=(FEB(2)-FEB(1))/(ATF(2)-ATF(1))
          BINT=FEB(1)-SLOPE1*ATF(1)
          TFO=-BINT/SLOPE1
          IF(ABS(TEML-TFO).LE.0.001)GO TO 1360
          TEML=TFO
          ASSIGN 1350 TO I1300
          GO TO 1300
1350      CONTINUE
          IF(FENB*FEB(2).GT.0.0)IP=2
          IF(FENB*FEB(1).GT.0.0)IP=1
          ATF(IP)=TEML
          FEB(IP)=FENB
          GO TO 1370
1360      STOR(5,1)=TEML
          GO TO I99797
C-------------------------------------------------------------
C      TO CALCULATE-ENERGY-BUDGET
 950      TAF=(1.-SIGF)*TA+SIGF*(0.3*TA+0.6*TF+0.1*TEML)
          DTHETA=(TA-TF)*FACTH/ZA
          THETAV=(TA+TF)*FACTH/2.0
          RI=G*DTHETA/(THETAV*DU**2)
          RHOAF=-0.001*.348*PRESS/((TF+TA)/2.)
          COE1=15.
          COE2=1.175
          EX=.75
          IF(RI.LE.0.)GO TO 1280
          IF(RI.GT.0.2)RI=0.199
          COE1=5
          COE2=1.
          EX=2.0
```

```
1280      CONTINUE
          HTER=RHOAF*KSQ*ZA**2*DU
     &    *COE2*(1.-COE1*RI)**EX
C         HSF=1.1*7.*SIGF*CP*CF*UAF*(TF-TAF)*60.
          HSF=HTER*CP*DTHETA*60.
          XL=597.3-0.566*TAF
          RA=(ALOG((ZA-ZDSP)/Z0)*COE2*((1.-COE1*RI)**EX))**2
     &    /(.16*UA)
         RDP=RA/(RS+RA)
         QF=RDP*QSAT(TF)+(1.-RDP)*QAF
         QAF=(1.-SIGF)*Q(TA)+SIGF*(Q(TA)*0.3+QF*0.6+QG*0.1)
         EF=-(RHOAF*CP/0.66)*(ESAT(TF)-E(TA))/(RA+RC)*60.
         IF(EF.LT.0.0)EF=0.0
         SHRW=FOLA*SOL
         XLNGW=EPF*ATERM
         TG4=EPF*EPSN/EP1*SIGMA*TEML**4
         TF4=(EP1+EPSN)/EP1*EPF*SIGMA*TF**4
         FENB=SIGF*(SHRW+XLNGW+TG4-TF4)-HSF-EF
         GO TO I950
C-----------------------------------------------------------------
C       TO CALCULATE-ENERGY-BUDGET-FOR-GROUND
 1300    CONTINUE
         T1=ALPH(1)*RR(1)*(STOR(1,3)-2.*STOR(1,2)+STOR(1,1))
     &   +STOR(1,2)
         TF4=SIGMA*TF**4
         TG4=SIGMA*TEML**4
         QG=WET*QSAT(TEML)+(1.-WET)*QAF
         RHOAG=0.001*0.348*PRESS/TAF
         XL1=597.3-0.566*(TAF+TEML-2.0*273.15)/2.
         SG=(1.-SIGF)*SOL
         RLU=(1.-SIGF)*(EPSN*TG4+(1.-EPSN)*ATERM)
     &   +SIGF*(EPSN*TG4+(1.-EPSN)*EPF*TF4)/EP1
         RLD=(1.-SIGF)*ATERM+SIGF*(EPF*TF4+(1.-EPF)*EPSN*TG4)/EP1
         HSG=RHOAG*CP*CHG*UAF*(TEML-TAF)*60.
         ELG=RHOAG*CHG*UAF*(QG-QAF)*60.
         FENB=SMALLA*SG-RLU+RLD-HSG-ELG*XL1+(T1-TEML)/SFRQ(1)*FK(1)
         GO TO I1300
C----------------------------------------------------------------
C     TO CALCULATE-RADIANCE-VALUES
 1410     CONTINUE
          REFRAD=((1.-SIGF)*(1-EPSN)+SIGF*(1-EPF))*DOWNIR*697.6
          FOLGB=EPF*5.67E-8*TF**4
          GRNDGB=EPSN*5.67E-8*TEML**4
          SURFGB=SIGF*FOLGB+(1.-SIGF)*GRNDGB
          EEF=SIGF*EPF+(1.-SIGF)*EPSN
          TEFF=(SURFGB/5.67E-8)**.25
          ISURFG=SURFGB+.5
          TEFFR=((SURFGB+REFRAD)/(5.67E-8))**.25
          IREFRA=REFRAD+0.5
          ISOL=SOL*697.6+0.5
          GO TO I1410
C
        END
```

FILMED
8-91
DTIC