METEO FRANCE
Centre national de recherches météorologiques
Centre d'études de la neige

The snow cover model

CROCUS

User's Guide

version 2.4

January 2008

CNRM/CEN, 1441 rue de la piscine, 38400 St Martin d'Hères , France

Contents

1. Introduction

The development of the CROCUS code is the result of a modelling effort since the 70's at the CEN in the framework of the operational avalanche forecasting. This model has been developed in two steps : first energy and mass, then stratigraphy (evolution of snow grains). It is described in two papers in the Journal of Glaciology : Brun et al, 1989 et 1992 (see references).

Because of the numerous versions of this code at the Centre d'études de la neige and the interest of other researchers in CROCUS, the code has been completely re-written (FORTRAN77) with the norm DOCTOR. The version 2.1 was the first used by external users. The version 2.2 contains some improvements. These improvements come from several ongoing projects : polar snow modelling (POLAR SNOW), coupling between ARPEGE and CROCUS, simulation of the Sarennes glacier mass-balance, modelling of snow cover over ice pack (LEADEX92). The version 2.3 only include technical modifications, the 2 main changes are the use of the International System units and the FORTRAN90 language. The version 2.4 include studies realised for the GELCRO project (see references, Bouilloud and Martin in JAM 2006). It mainly concerns the possibility to couple Isba (SVAT model) and Crocus with the objective to improve the simulation of the energetic flux between the soil and the snow. This version also allows to simulate saturated layer (no air) at the bottom of the snow. Changes between the version 2.2 and the version 2.4 are described in the chapter 2.

This documentation includes some appendix which give a technical description of the model.

CROCUS runs in a UNIX environment and needs a FORTRAN90 compiler. CROCUS was tested on HP and Linux workstation.

If you have any question or remark, please contact Jean-Marie Willemet at the Centre d'Etudes de la Neige.

Jean-Marie Willemet
Météo-France/Centre d'Etudes de la Neige
1441 rue de la piscine
38400 St Martin d'Hères
FRANCE

Tél : +33 (0)4 76 63 79 00
Fax : +33 (0)4 76 51 53 46
Email : jean-marie.willemet@meteo.fr

2. Changes 2.2 > 2.4

Several aspects of the model are improved. In most cases, they are activated by logical keys in the namelist **NVSIMU**.

- Use of the International Units System in the source code. PRO files may be saved in SI units or in the old units (logical LVPROSI)
- Use of the Fortran90 language (free format, modules, dynamical allocation, …)
- Possibility to use CROCUS with a SVAT model (ISBA). The objective is to improve heat tranfert between the snow and the ground (logical LISBA)
- Possibility to create a saturated layer at the bottom of the snowpack (logical LCOUCHSAT)
- Possibility to be more precise in the repartition of the snowfall in a hour. It may be useful in case of shallow snow cover (logical LSNOWFALL)
- Solar radiation penetration is neglected when depth is sufficient
- Wet metamorphim (routine metamo). The calculation of the Liquid Water Content is improved and a threshold is introduced in the size increase of the wet grains.
- Aggregation or splitting of layers is modified in case of use of the logical LCOUCHESAT or LISBA.
- Possibility to follow marker initially placed on the snow surface (logical LVDISK)
- Correction of an error in the calculation of the size grain (function fzdangl.f90)
- 2 possibilities of format are proposed for the output files QUOT, TSURF and FLUX (logical LVNEWFMT)

Rem : To be in a configuration as close as possible to the 2.2 version, LISBA, LSNOWFALL, and LCOUCHSAT must be .F.. The results will not be identical because metamo.f90 and fzdangl.f90 have been modified .

3. Description of the files

The version 2.4 of Crocus is available as a compressed archive file crocus_v24.tar.gz. CROCUS is installed with the following commands :

```
$ gunzip crocus_v24.tar.gz
$ tar xvf crocus_v24.tar
```

A directory crocus is created and looks like :

```
exemples/
Doc/
outils/
progs/
lib/
compilv24
lib/
BIN/
RUN/
```

exemples/ :	contains examples of snow profiles and file GEO. Directory Col_de_Porte contains files allowing a simulation of snow cover at the Col de Porte laboratory of the Centre d'études de la neige (see § 8).
Doc/ :	contains the documentation (microsoft word files). Source code in html is also present in this directory.
outils/ :	contains programs for the initialisation of snow profiles, visualisation of snow profiles and visualisation of meteorological data.
progs/ :	contains the code of the models CROCUS, and include files (.H).
compilv24 :	procedure for the compilation of the model (usage : compilv24 crocus)
lib/ :	will contain crocus library
BIN/ :	directory for the procedure compil. Will contain object and module files.
RUN/ :	will contain executable file of the model

4. Model overview

CROCUS is a one-dimensional model : the snow cover is a pile of layers parallel to the ground. Energy and mass exchanges are projected orthogonally to the slope. Only, with the knowledge of initial profile and hour meteorological data, snow cover evolves in the model.

The model inputs are the initial snow profile (**PROi** file) and the evolution of the meteorological conditions (**MET** file). As output, one may obtain several files :

- a file containing daily values (**QUOT** file) with the snow depth, snow water equivalent at a fixed hour and the bottom runoff during the last 24 hours,
- snow profiles (**PRO** file),
- the surface temperature (**TSURF** file)
- the hourly or daily fluxes (**FLUX** files)

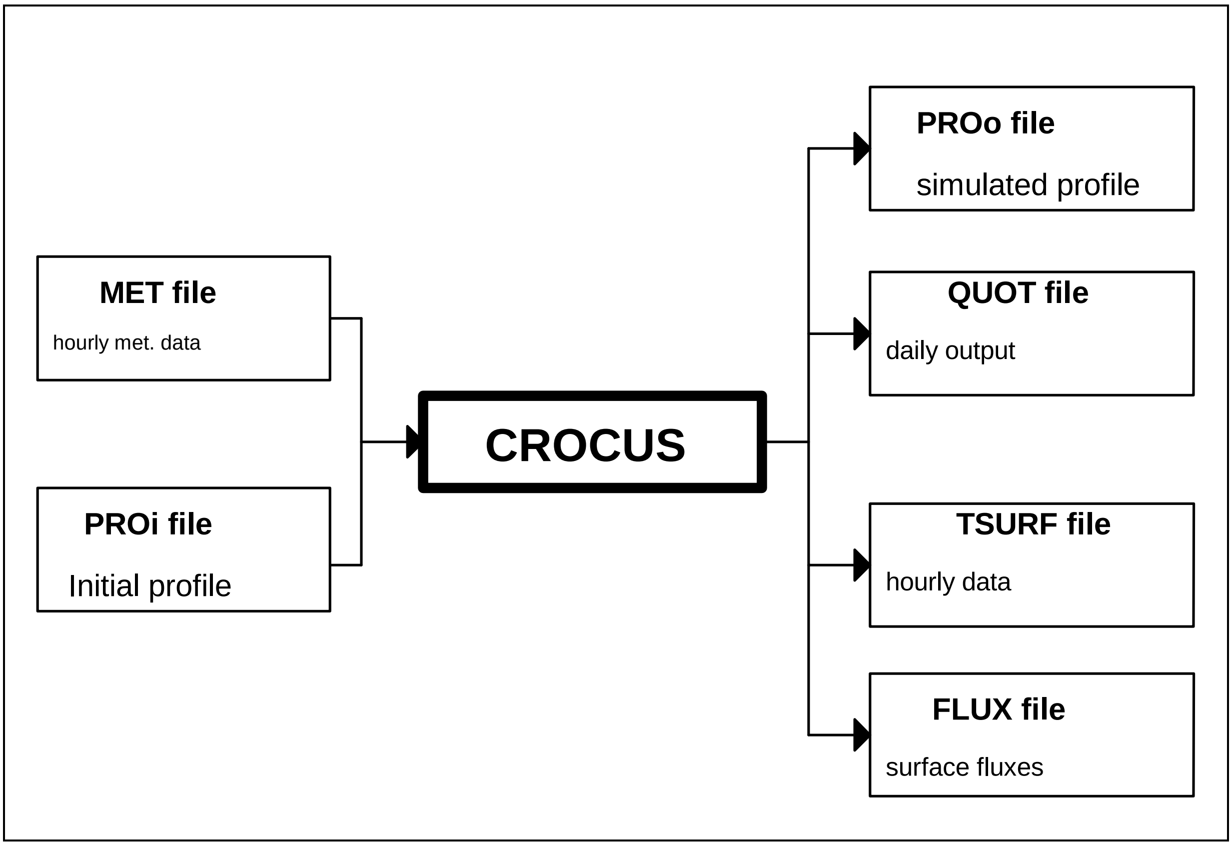


fig 1 : Input and output files for CROCUS

The input meteorological variables(file **MET**) are :

- air temperature
- air humidity
- wind speed
- incoming direct solar radiation

- incoming scattered solar radiation
- incoming longwave radiation
- cloudiness
- amount and phase of precipitation

The variables describing the snow profile (file **PRO**) and used in the model are :

Name of the variable in CROCUS	Variable
MSNST	- total number of layer
	and for each layer
SDZ	- thickness
ST1	- temperature
SRO	- dry density
SCW	- liquid water content
SGRAN1, SGRAN2 et MSDAST	- grain types (dendricity, sphericity, size and age)
MSHIST	- historical variable indicating if there were water or faceted crystals before

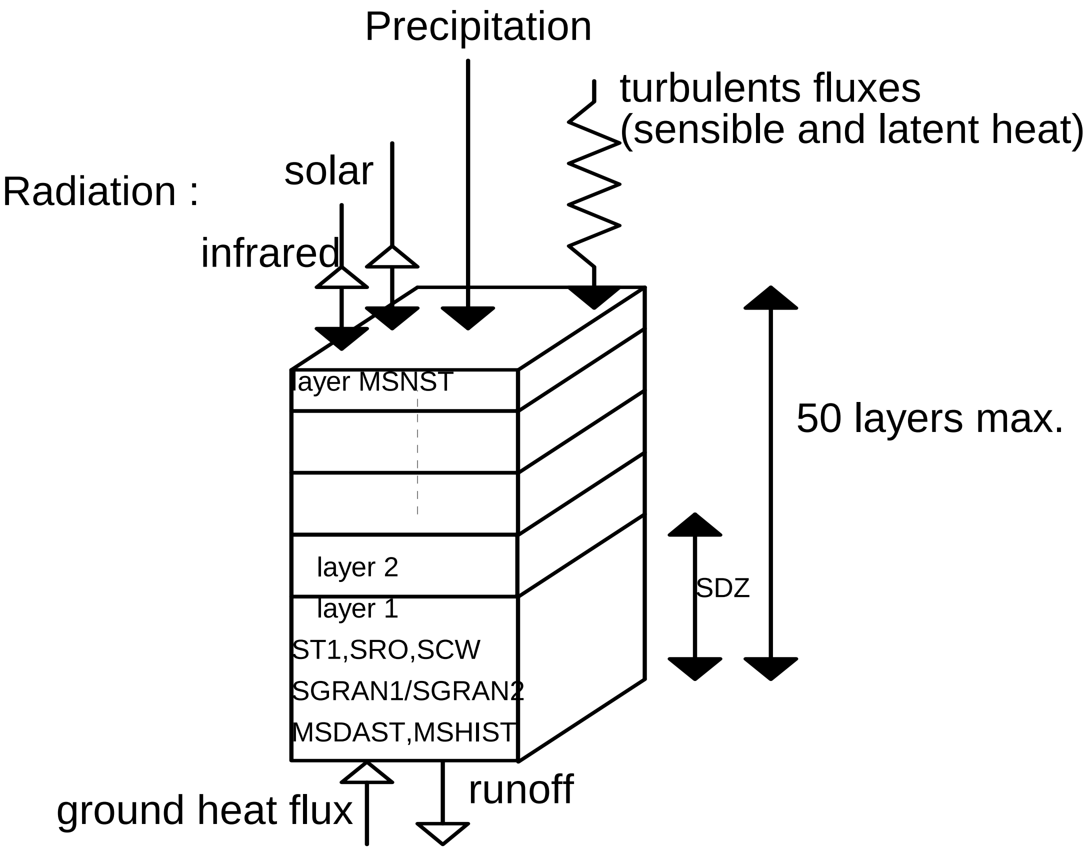


fig 2 :Schematic diagram of the N layer scheme

5. Input and output files

Rem : all time and dates in Crocus are in UTC time (Universal Time coordinated). It is roughly the same as GMT.

5.1 The file MET

It is the file containing the input meteorological data of CROCUS. It is a binary file, with direct access (one record per hour). Each record contains 9 variables and its length is 36 bytes (all variables have the type Real 4 bytes). The variables for the hour H are :

Variable	Unit	Validity	Comment
Air temperature	K	H (instantaneous)	
Wind speed	m/s	H (instantaneous)	
Air humidity	%	H (instantaneous)	
Precipitation	mm	between H-1 and H	water equivalent
Phase	0 : rain 1 : snow	between H-1 and H	intermediate values possible
Incoming longwaves radiation	W/m^2	between H-1 and H	
Incoming direct solar radiation	W/m^2	between H-1 and H	
Incoming scattered solar radiation	W/m^2	between H-1 and H	
Cloudiness	0 : clear sky 1 : overcast	between H-1 and H	intermediate values possible

5.2 The input and output files PRO

This type of file is used both as input and output file. It contains snow profiles at the CROCUS format. Usually, in the output PRO file, the initial profile is in the record 1, simulated profiles are in the others.

Output file may be the same than input file, for that it is necessary to modify CRO_LANC.F90 (the user must define the same file for input and output files CLPRI=CLPRO). The user indicates the profiles he wants to save with the variable MNFREQPRO (namelist NVSIMU).

Logical LVPROSI (namelist NVSIMU) indicates the unit of the variables in the files.

The 2 files are binary file, with direct access (record length : 1524 bytes for Crocus 50 layers). The variables in each record are :

NAME:	TYPE:	DIMENSION:	COMMENTS:
SDZ	REAL 32BITS	MNMAXST (=50)	layer thickness.
ST1	REAL 32BITS	MNMAXST (=50)	layer temperature.
SRO	REAL 32BITS	MNMAXST (=50)	layer dry snow density.
SCW/SDZ	REAL 32BITS	MNMAXST (=50)	layer liquid water density
SGRAN1	REAL 32BITS	MNMAXST (=50)	layer 1st variable for grain description
SGRAN2	REAL 32BITS	MNMAXST (=50)	layer 2nd variable for grain description
ZZSHTN	REAL 32BITS	1	snow depth
XECOU-XECOUV	REAL 32BITS	1	daily runoff.
MSDAST	INTEGER 32BITS	MNMAXST (=50)	date of the layer
MDATSI	INTEGER 16BITS	JPNDAT (=4)	Date of the profile YYYYMMDDHH.
MNHSI	INTEGER 16BITS	1	Number of hours since the beginning of the simulation.
INT(XALTI)	INTEGER 16BITS	1	Altitude.
MINCLI	INTEGER 16BITS	1	slope.
MSNST	INTEGER 16BITS	1	Number of layers
MSHIST	INTEGER 16BITS	MNMAXST (=50)	History of the snow layers.

Units :

NAME:	LVPROSI = TRUE:	LVPROSI=FALSE:	COMMENTS:
SDZ	meter	centimeter	layer thickness.
ST1	Kelvin	Kelvin	layer temperature.
SRO	Kg/m3	g/cm3	layer dry snow density.
SCW/SDZ	Kg/m3	G/cm3	liquid water density
SGRAN1	Between –99 and 0 Between 0 and 99	Between –99 and 0 Between 0 and 99	1st variable for grain description
SGRAN2	> 0 and < 99 (SGRAN1 <0) meter (SGRAN1 >=0)	> 0 and < 99 (SGRAN1 <0) 1/10mm (SGRAN1 >=0)	2nd variable for grain description
ZZSHTN	meter	Centimetre	snow depth
XECOU-XECOUV	mm (kg/m2)	mm (kg/m2)	daily runoff.
MSDAST	YYYYMMDDHH	YYYYMMDDHH	date of the layer
MDATSI	YEAR, MONTH, DAY, HOUR	YEAR, MONTH, DAY, HOUR	Date of the profile.
MNHSI			Number of hours since the beginning of the simulation.
INT(XALTI)	meter	meter	Altitude.
MINCLI	degree	degree	slope.
MSNST			Number of layers
MSHIST	0 –1 – 2 – 3 – 4 or 5	0 –1 – 2 – 3 – 4 or 5	History of the snow layers.

5.3 The file QUOT

It is a daily output file. This output is validated by the logical variable **LVQUOT** in the namelist **NVSIMU**. Each day of the simulation, at a given hour (**MHQ** in the namelist **NVSIMU**), CROCUS writes a new record containing the following variables :

Variable	Unit
Date	YYMMDD (LVNEWFMT=F) or YYYYMMDDHH (LVNEWFMT=T)
Snow depth	cm
Snow water equivalent	mm
runoff cumulated over the last 24 hours	mm

Comments : It is an ASCII file, but treated by Crocus as a direct acces file. Logical LVNEWFMT (namelist NVSIMU) modifies date format, insert a space between the variables and allows very thick snow cover

5.4 The file TSURF

It is an ASCII, hourly, direct access file (record length 14 bytes, 17 bytes if LVNEWFMT=T). It can also be edited as it contains the "return" character. This output is validated by the logical variable **LVSTS** in the namelist **NVSIMU**. Each hour, CROCUS writes a new record containing the following variables :

Variable	Unit
Date	YYMMDDHH (LVNEWFMT=F) or YYYYMMDDHH (LVNEWFMT=T)
snow surface temperature	1/100ème de K

Comments : if there is no snow on the ground, 99999 is written. It is an ASCII file, but treated by Crocus as a direct acces file. Logical LVNEWFMT (namelist NVSIMU) modifies date format and insert a space between the variables.

5.5 The file FLUX

It is an ASCII file with contains, for a given date the main fluxes during the past hour (LVFLUH=.T.) or day (LVFLUH=.F.) at the surface or at the bottom of the snow cover. Each line contains the following parameters :

Parameter	Unit	Format (F90)
Date	AAAAMMJJHH	A10
Net solar radiation	$W.m^{-2}$	F7.2
Net infrared radiation	$W.m^{-2}$	F7.2
Sensible heat flux	$W.m^{-2}$	F7.2

Latent heat flux	$W.m^{-2}$	F7.2
Rain heat flux	$W.m^{-2}$	F7.2
Snowfall Heat flux	$W.m^{-2}$	F7.2
Correction term due to sublimation and solid condensation	$W.m^{-2}$	F7.2
Ground heat flux	$W.m^{-2}$	F7.2
snow Albedo		F7.2
Surface solid condensation	$kg.m^{-2}$	F10.4
Surface condensation	$kg.m^{-2}$	F10.4
Surface sublimation	$kg.m^{-2}$	F10.4
Surface evaporation	$kg.m^{-2}$	F10.4
Rain	mm	F7.2
Snowfall	mm	F7.2
Bottom runoff	mm	F7.2

Comments Logical LVNEWFMT (namelist NVSIMU) insert a space between the variables

6. Description of the sources

6.1 Overview

Subroutines and modules can be visualized with a browser. For that, open the file "main.html" under the directory : Doc/html/WWW/v24/progs.

Most of the numerical parameters of the model are in Namelist FORTRAN, in a file called PARAM to avoid editing the source itself. The model is in fact the subroutine CROCUS. The main program (cro_lanc.f90) reads the namelist (subroutine param.f90), opens the input/output files (subroutine suopen.f90) before calling the model itself.

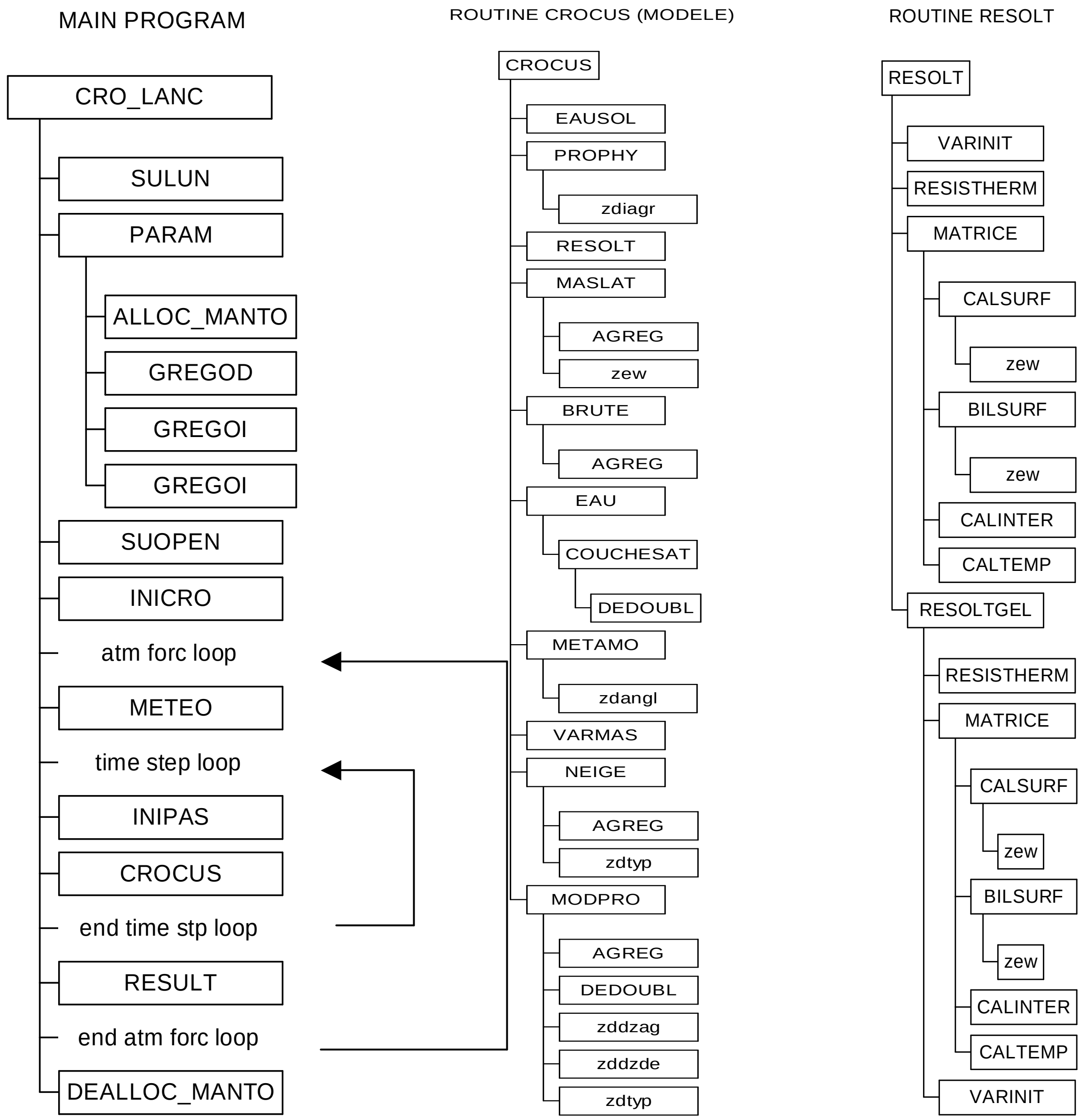
One "include" file NAMELIST.H contains variables declarations. It is included in the code by the compiler.
Global variables are defined in modules. A module is defined for every namelist. For example, the namelist NVSIMU is associated to the module YOMSIMU which realise the declaration of the namelist variables. You will find in the module (for example YOMSIMU) a short description of the variables.

Before a simulation, you need to build the file MET (meteorological data) and PRI (initial profile of the snow cover), copy a namelist PARAM from Outils/Exemples, modify it, eventually modify the file cro_lanc.f90 (files names for example), and compile the model.

6.2 Scheme

Scheme of the model

(Subroutines are in upper cases, functions in lower cases)



6.3 DOCTOR norm

Source code Crocus follows the DOCTOR norm. All variables have a prefix, depending on its type and use.

Words in italics are CROCUS conventions

Type Status	Integer	Real	Logical	Character	Dbl. precis	Complex
Common	*MA* *MS* *MX*	*A : atmosphere* *S : snow* *X : other*	L (but not LD, LL, LP,*LU*,*LV*)	C (but not CD, CL, CP, *CU*, *CV*)	D (but not DD, DL, DP, *DU*, *DV*)	Y (but not YD, YL, YP, *YU*, *YV*)
Dummy arguments	K	P	LD	CD	DD	YD
Local variables	I	Z	LL	CL	DL	YL
Loop control	J (but not JP)					
Parameter	JP	PP	LP	CP	DP	YP
Constants *(namelists)*	*NU* *NV*	*U: universal* *V: calibration*	*LU* *LV*			

7. Other tools (visumet, ascii2met, visupro, inipro)

These four programs are in the directory outils and are written in FORTRAN. A compilation is necessary before any use. **Compilation must be realised after the compilation of the Crocus code** (see § 8.1). File "compilf90" under the directory "outils" may be used.
For example, to create inipro tool, execute the command :
"compilf90 inipro" under the directory outils. Executable file, named inipro, will be built under the directory outils/inipro.

7.1 The program visumet

It prints the data of the file **MET**. It asks first the name of the file **MET**. It is then possible to print the data by giving dates (in this case you must also enter the date of the first record), or by giving record numbers (there will be no date indication in the outputs). The data are printed on the screen and in the file **res_visumet**.

Example of output :

```
----------------------------------------------------------------------
 Date       ART.   T  Vent  Hum RRtot SS/RRtot IR   Soldr Soldf  Neb
            REC.      Wind                    IR   Soldr Soldf  Cld
                  (C)  (m/s) (%) (mm)          -----W/m2------
----------------------------------------------------------------------
1993123000   1201   1.2  1.1  99 0.10 0.00    314.7   0.0   0.0 1.00
1993123001   1202   1.4  0.5  99 0.10 1.00    319.2   0.0   0.0 1.00
1993123002   1203   2.9  0.8  99 0.00 1.00    322.2   0.0   0.0 1.00
1993123003   1204   1.9  0.7  99 0.30 0.00    318.6   0.0   0.0 1.00
1993123004   1205   1.2  0.8  99 1.10 0.00    313.9   0.0   0.0 1.00
1993123005   1206   1.1  0.6  99 0.00 1.00    304.2   0.0   0.0 0.97
1993123006   1207   1.1  0.6  99 0.00 1.00    314.7   0.0   0.0 1.00
1993123007   1208   1.2  0.3  99 0.30 0.00    313.3   0.0   0.3 1.00
1993123008   1209   1.3  0.4  99 0.10 1.00    298.3   0.0   1.4 0.94
1993123009   1210   1.8  0.5  99 0.20 0.00    311.1   0.0  23.3 1.00
1993123010   1211   1.5  0.1  99 0.00 1.00    313.9   0.0  80.6 1.00
1993123011   1212   3.9  0.0  84 0.00 1.00    284.4  76.6 102.6 0.78
----------------------------------------------------------------------
```

7.2 The program ascii2met

It builts a meteorological file that will be used by crocus (binary file). The name of the output file is MET_YYYYMMDDHH, the date is the date of the first article. The input file is an ASCII file (named METASCII).
Two formats for the input file are recognised. The reading of the input file may be without format and in this case a space must separate the different fields.
For the non formatted reading, the fields are :

Variable	Unit
DATE	YYYYMMDDHH
Air temperature	Degree Celcius
Wind speed	m/s
Air humidity	%
Precipitation	mm

Phase	0 : rain 1 : snow
Incoming longwaves radiation	W/m^2
Incoming direct solar radiation	W/m^2
Incoming scattered solar radiation	W/m^2
Cloudiness	0 : clear sky 1 : overcast

The second possibility is the reading of a file built by visumet.

The first field (the field date) must be correct even if this field is not saved in the output file.

7.3 The program visupro

It prints data from the file PRO. It asks first the name of the file PRO. The record length of the file depends of the maximum number of layers (it is the MNMAXST variable in the namelist NVSIMU), so the user must give this information, the user must also give the units used when the PRO file has been created (SI or not, logical LVPROSI in the namelists Crocus).
Then it is possible to print data from this file by giving a date or a record number. The data are printed on the screen and in the file **res_visupro**.
The units in the output do not depend on the units in the PRO file.

Example of output :

```
================================================================================
 Date : 1994 09 02 12 H,  Snow depth :   25.7 cm   (15 layers) Rec :   66
 Altitude : 3600 m  inclinaison :    0 deg  Ecoulement :   .04 mm
--------------------------------------------------------------------------------
     H      DZ      T     RO   TEL/LWC     G1      G2      HIST    DATE
    cm      cm    deg C  g/cm3  g/cm3
--------------------------------------------------------------------------------
   25.7     .7   -2.50   .132    .00      -80.59/59.80        0   19940902
   25.0     .7   -2.50   .128    .00      -89.45/54.56        0   19940902
   24.3     .8   -2.24   .122    .00      -97.31/48.93        0   19940902
   23.5     .8   -1.89   .116    .00      -96.47/47.47        0   19940902
   22.7     .9   -1.65   .107    .00      -95.98/46.98        0   19940902
   21.8    1.7   -1.50   .129    .00      -87.91/48.72        0   19940902
   20.1    1.6   -1.37   .136    .00      -81.74/56.96        0   19940902
   18.5    1.5   -1.28   .142    .00      -73.61/57.01        0   19940902
   17.0    1.5   -1.21   .148    .00      -66.04/59.54        0   19940902
   15.5    1.4   -1.14   .153    .00      -58.31/60.34        0   19940902
   14.1    4.1    -.96   .158    .00      -52.43/61.72        0   19940902
   10.0     .8    -.72   .154    .00      -73.55/30.40        0   19940901
    9.2    5.1    -.42   .175    .00       83.34/ 3.42        2   19940901
    4.0    1.0     .00   .260    .01       99.00/ 5.40        2   19940831
    3.0    3.0     .00   .242    .01       99.00/10.18        2   19940831
```

7.4 The program inipro

This program writes the initial snow profile in the first record of the file PRO.
You must create a ASCII file which contains the following elements :

- Date of the profile (YYYY MM DD HH)
- Number of layers (between 0 and MNMAXST)
- For each layer : thickness, temperature, density, liquid water content, grain1, grain2, historical variable, date of the snowfall (YYYYMMDDHH)

The information by layer must be written with respect of the following fortran format :
FMT=(9X,F5.1,2X,F6.2,3X,F4.3,2X,F5.2,6X,F6.2,'/',F5.2,8X,I1,3X,I8.8)

An example of ASCII file is given below (lines beginning by # are not read) :

```
###############################################################################
#         PROFIL INITIAL POUR CROCUS/ INITIAL PROFILE FOR CROCUS
###############################################################################
# DATE : |AAAA MM DD HH|
1994 09 09 12
# NOMBRE DE COUCHES / LAYERS NUMBER (MAX 50) |NN|
05
###############################################################################
# CARACTERISTIQUES  DE CHAQUE         |CHARACTERISTICS OF EACH
# COUCHE EN COMMENCANT PAR            | BEGINNING BY THE TOP OF THE
# LA COUCHE DU HAUT                   | SNOW COVER
##########################################################################
#           DZ      T     RO   TEL/LWC     G1      G2      HIST    DATE
#           cm    deg C  g/cm3  g/cm3
#        XXX.X  XXX.XX   .XXX  XX.XX      XXX.XX XX.XX        X   YYYYMMDD
##########################################################################
            .6   -3.07   .118    .00      -84.99/43.51        0   19940909
            .7     .00   .121    .01       99.00/ 3.00        2   19940909
            .7     .00   .121    .01      -18.08/99.00        0   19940909
           5.8     .00   .189    .01       99.00/ 3.04        2   19940908
           1.6     .00   .222    .01       99.00/ 3.85        2   19940908
```

Other examples are given in the files **pro_ex1** and **pro_ex2** of the directory **outils/exemples.** The easiest way is to modify these files to initialise CROCUS.

To initialise a profile without snow on the ground the 1st of January 1996, it necessary to prepare the following file :

```
1996 01 01 00
00
```

inipro asks the name of the ASCII file and the file **PRO**. Informations on the PRO file is also necessary : maximum number of layers (MNMAXST variable) and units (SI or not).
Then the profile is written in the first record of the file **PRO**

8. Running CROCUS

This section describes the different necessary steps before any snow cover simulation.

8.1 Compilation

The first step is the compilation of the code. Use the procedure compilv24. This procedure executes a makefile for HP make. If you use GNU make, modify MAKE variable at the beginning of this file. At the same manner, you must check and eventually modify compilation variables (F90 and FFLAGS variables).

Type **`compilv24 crocus`**
Executable with the name crocus is created under the directory RUN/.

NB: it is not necessary to compile CROCUS after a modification of the namelists file PARAM.

8.2 Build the meteorological data file (MET)

The file must contain the 9 variables described in the § 5.1 (one record per hour). The order of the variables must be strictly respected. You can verify this file with the program visumet.

8.3 Write the initial profile (PRO)

It is possible to use an article of an existing PRO file or to create a new profile with the intermediate of an ASCII file.
In case of using the intermediate of an ASCII file, the initial snow profile must be written in an ASCII file **pro_init**. The easiest method to complete this file is to copy and modify the files **pro_ex1** or **pro_ex2** (directory outils/exemples).
If the ground is not covered by snow at the beginning of the simulation, one can copy the file **pro_ex2** and modify the date. In the other cases, **pro_ex1** must be used. The comments included in the file and the § 7.3 will help you to build the file.
One of the main problem you will encounter is the coding of the historical and grain description variables (MSHIST, SGRAN1 and SGRAN2). It is necessary to read attentively the APPENDIX A to initialise correctly theses 3 variables.

The writing of the initial snow profile in the binary file PRO will be done with the program inipro (§ 7.3). The correct writing can be easily verified with visupro.

Attention : You must choice in inipro, if you prefer or not to use SI units in the different PRO files. It is necessary to have accordance between this choice and the value of the logical variable LVPROSI (namelist NVSIMU) when you will execute the CROCUS model.

8.4 Characteristics of the simulation : Namelists file PARAM

First, copy the Namelists file PARAM_93CDP in the directory outils/exemples/Col_de_Porte/ with the name PARAM and modify it. In general case, you have only to modify the namelist NVSIMU (characteristics of the simulation**)** and eventually NVGEO (geographical characteristics).
After a simulation, it is recommended to verify that the characteristics of the simulation are correct. For that, you must consult the file named TRACROCUS, the main characteristics are written at the beginning of this file.

8.4.1 Temporal characteristics of the simulation :

You must control and modify the namelist NVSIMU in the PARAM file.
Definition of the different variables of this namelist can be found in the source code (file yomsimu.f90).

Description of the variables :

MNHSI : Number of hours in the simulation.

Example : To run a simulation which begin 10/11/1993 at 00UTC and finish 10/11/1993 at 12UTC put 12

MNPASI : Number of time-steps in one hour. Usually 4 (time step 15mn).

MDATSI : array containing the date of the beginning of the simulation : year, month, day, hour (remember that all CROCUS dates are UTC time).

MNFREQPRO : Hours saved in the output file PRO. Array with 24 values (between 0 and 23). Values are 0 or 1. Example : MNFREQPRO(0)=1 means profiles at 00UTC are saved. Moreover, the first and the last profile of the simulation are always saved.

MNARTM : Number of the first record to read in the file MET.

MNARTP : Number of the record of the initial snow profile in the file PRO input.

MNARTQ : Number of the current record in QUOT. The next record to write will be MNARTQ+1 (usually MNARTQ=0)

MNARTS : Number of the current record in the file tsurf_xxx. The next record to write will be MNARTS+1 (usually MNARTS=0)

MHQ : Reference Hour for daily outputs : QUOT and FLUX file if LVFLUH=.F.

LVPROSI : If LVPROSI =T, profiles in the file PRO are saved in S.I. units. Attention : The init file PRO must respect LVPROSI

LVNEWFMT: Formats of the file QUOT, FLUX and TSURF are slightly modified following this logical key (see § 5.3 to 5.5)

LVDISK : Following of layers without thickness (see document evol_crocusv22_24.doc in french only or contact JM Willemet for more informations)

LVQUOT : Logical key for the writing of daily outputs (QUOT file)

LVFLUX : Logical key for the writing of fluxes (FLUX file)

LVFLUH : Logical key for the writing of hourly fluxes (LVFLUH=.T.) or daily fluxes (LVFLUH=.F.)

LVSCM : Logical key for the chain SAFRAN-CROCUS-MEPRA at the CEN. (Let LVSCM=.FALSE.)

LVMNEP : Logical key for thick snow cover (> 15m)

LVAGMO : Logical key for aggregation of layers with mean parameters (instead of the parameters from one of the layers

LVRI : Logical key for the calculation of turbulent fluxes with a Richardson number (Lejeune and Martin 1995)

LISBA : Let LISBA=F. If you want to use LISBA=T (In this case, Crocus is used inside of the SVAT ISBA), contact JM Willemet (this package is not sufficient). See also APPRENDIX E

LCOUCHSAT : LCOUCHSAT=F is recommended. LCOUCHSAT=T gives the possibility to have a saturated layer at the bottom of the snow cover.

LSNOWFALL : accurate repartition of the snowfall. LSNOWFALL=F is recommended. (LSNOWFALL=T may be interesting with non permanent snow cover)

LZONGO : Let LZONGO=F

8.4.2 Geographical characteristics :

There are 2 ways which allow to provide geographical characteristics for the simulation.

First method : modify the namelist NVGEO

Example

```
&NVGEO
 ZLATNAM=45.30,       ; Latitude of the simulation area
 ZLONNAM=5.77,           ; Longitude
 ZEXPONAM=0.,            ; Aspect
 ZALTINAM=1340.,         ; Altitude
 IINCLINAM=0,            ; slope
 IMASQNAM=36*0            ; Masks
&END
```

Description of the variables

ZLATNAM: Latitude of the site in degrees and tenth (between -90. and +90.).
ZLONNAM: Longitude of the site in degrees and tenth (between -180. and +180.).
ZEXPONAM: orientation of the site in degrees and tenth (between 0. and 359.99). South= 180, North=0.
ZALTINAM: Altitude of the site in meters.
IINCLINAM: Slope of the site in degrees (flat terrain = 0).For a slope of 30 degrees with the horizontal line, write 30.
IMASQNAM: array containing the masks for the solar radiation. These masks are given with a 10° step (36 rose) the first value corresponds to 10 degree in the North. If the input values are measured code 36 * 0. The masks are used when input data are measured on a flat terrain and the simulation is realised in uneven terrain.

Second method : A file named GEO is created and put in the current directory :
This file contains one value by line

Example for the Col de Porte site :

```
45.30
5.77
0.
1340.
0   _
0    |
0    |  36 values
...  | for the masks
0   _|
```

So, the file GEO contains the same information than the namelist NVGEO. If the Crocus model find a file GEO, the namelist NVGEO will not be used, if this file does not exist, namelist NVGEO will give the geographical characteristics.

8.4.3 Other variables

The other variables are numerical or physical constants for CROCUS (for a first use, you should not need to modify them). You can multiply the precipitation amounts by the coefficient VRR3 (zone NVMET). Usually VRR3=1.

8.5 Example of simulation : the Col de Porte

The Col de Porte is located near Grenoble, at an elevation of 1340m, in the French Alps. The following files are in the directory exemples/Col_de_Porte :

MET_93CDP : Binary file (built with a HP workstation) containing 4369 records (4369 hours of meteorological data). The dates of the first and last records are the 10th November 1993 00UTC and 11th May 1994 00UTC.

MET_93CDP_visumet : The same thing that the file MET_93CDP but in ASCII (result of the visumet tools).

pro_init93 : ASCII file containing the initial snow profile : 10th November 1993 at 00 UTC, no snow.

PRI_93CDP : Binary file containing only one record (the initial snow profile without snow on the ground) at the beginning of the simulation. This file has been written by using inipro and the file pro_init93.

PARAM_93CDP: Namelist file containing the characteristics of the simulation. The values correspond to a 4368 hours simulation. The beginning of the simulation is the 10th of November 1993 at 00UTC (MDATSI) It is also the date of the first record of the file MET_93CDP. The first record to be read in MET_93CDP is the record number 1 (MNARTM). Daily values are written at 00 UTC (MHQ=0). The file TSURF will be created (LVSTS=.TRUE.). QUOT and FLUX will also be created.
The geographical characteristics are in the zone NVGEO.
The precipitation amount are not multiplied (VRR3=1. in the zone NVMET).

To run CROCUS on the Col de Porte data set you must compile the model (`compilv24 crocus`), compile the different tools (ascii2met and inipro) and launch the script "script_crocus_`cdp`".

Results can be visualised under the Col_de_Porte directory. File QUOT output may be compared to the file QUOT_CHECK in the same directory.

After each simulation, consult TRACROCUS and ERRCROCUS, it allows to verify the correct execution of the model, it is particularly important when problems are encountered.

8.6 Main program for CROCUS : cro_lanc.f90

This program allows to define the name of the input and output files of the simulation. This file is under progs/crocus/lanceur directory.
The names of the files defined in the main program are in the 2 tables below.

INPUT FILES

Name of the file	Variable name	What is the file ?
PARAM	CLPAR	Namelists file
GEO	CLGEO	Geographical characteristics (eventually)
MET	CLMET	Meteorological data
PRI	CLPRI	Initial snow profile
DISK	CLDINI	layers to follow if LVDISK=T

OUTPUT FILES

Name of the file	Variable name	What is the file ?
TRACROCUS	CLTRA	General informations on the simulation
ERRCROCUS	CLERR	Details when an error occurs
PRO	CLPRO	snow profile
QUOT	CLQUOT	Daily output
TSURF	CLTSURF	Hourly surface temperature output
FLUX	CLFLUX	Fluxes output (daily or hourly)
ZONGO	CLZONGO	Particular output if LZONGO=T (do not use)
DISKHT	CLDISK	output file if LVDISK=T

Directories of the files are also defined in theses variable names. Current directory is defined for all the files.
You can modify theses directories and names if necessary.
You can define the same file for the input and output PRO file (CLPRO must be defined equal to CLPRI).

Attention : If you modify cro_lanc.f90 file, you must compile again the source code (see §8.1)

APPENDIX A : CROCUS REPRESENTATION OF THE GRAIN

To describe snow evolution using metamorphism laws, it has been necessary to introduce a formalism to describe snow as a function of continuous parameters.
These parameters are dendricity, sphericity and grain size. To maintain the knowledge on the history of the layer, a 4th variable has been added.
Dendricity evolves between 1 and 0 (always decreasing), sphericity between 0 and 1 (may increase or decrease), grain size, when it is calculated, is diameter of the grain (positive value, always increasing).

In CROCUS the variables used to describe the grains present in a snow layer are MSHIST, SGRAN1 and SGRAN2. MSHIST is the historical variable, SGRAN1 and SGRAN2 are used to describe the 3 others parameters.

A.1 MSHIST variable :

This variable is qualified of historical variable. It gives information on past evolution of the layer.

The six possibilities for MSHIST are :

1 : Faceted grain
2 : This grain is in contact with liquid water for the first time but it was never faceted in the past
3 : This grain is in contact with liquid water for the first time and it was a faceted grain in the past.
4 : Same as 2 but this grain underwent several melting freezing cycle
5 : Same as 3 but this grain underwent several melting freezing cycle
0 : Other cases (dendritic snow, rounded grain, ...)

general evolution of this variable during a simulation :

↗ 1 → 3 → 5
0
↘ 2 → 4

When you build the initial profile of the simulation, if you have any doubt, set this parameter to "0".

A.2 SGRAN1 and SAGRAN2 variables (to describe dendricity, sphericity and size)

2 cases are differenced. The layer is said dendritic or not dendritic. A layer is dendritic when original crystal are still remaining. So dendricity decreases during the simulation. In this case, only dendricity and sphericity are calculated (grain size is not calculated). In the other case, the layer is said non dendritic (in fact dendricity is equal to 0), and sphericity and grain size are calculated. It explains why 2 variables are sufficient to calculate the 3 grain parameters.

DENDRITIC CASE :
SGRAN1 = -99* dendricity (with dendricity > 0)
SGRAN2= 99 * sphericity (sphericity between 0 and 1)

NON DENDRITIC CASE :
SGRAN1= 99 * sphericity (sphericity between 0 and 1)
SGRAN2= grain size (diameter in meters)

A.3 Accordance between the crocus variables (SGRAN1, SGRAN2 and MSHIST) and observed snow grains coded with the international classification

The two tables below present several examples for the coding of the three variables SGRAN1, SGRAN2, MSHIST in relation with observed snow grains.

Dendritic case

Gain type (diameter in mm if necessary)	MSHIST Historical	SGRAN1 Dendricity	SGRAN2 Sphéricity
+ +	0	-99.0	50.0
+ /	0	-75.0	50.0
/ /	0	-50.0	50.0
/ □	0	-25.0	25.0
/ •	0	-25.0	75.0
□□ (d < 0.4)	0	-5.0	0.0
• • (d < 0.3)	0	-5.0	99.0

Fig A.1 : Relation between simulated and observed grains in the dendritic case

Non dendritic case

Grain type diameter in mm	MSHIST Historical	SGRAN1 Sphéricity	SGRAN2 (d/1000)
□□ d = 0.4	1	0.0	0.4 E-3
• • d = 0.3	0	99.0	0.3 E-3
/\ /\ d = 1.2	1	0.0	1.2 E-3
o o d = 1.2	2	99.0	1.2 E-3

Fig A.2 : Relation between simulated and observed grains in the non dendritic case

The symbols are those of the international classification (Colbeck et al., 1990).

+ : Neige fraîche	Fresh snow	(Symb. 1)
/ : Particules reconnaissables	Fragmented particles	(Symb. 2)
• : Grains fins	Rounded grains	(Symb. 3)
□ : Grains à faces planes	faceted cystals	(Symb. 4)
/\ : Givre de profondeur (gobelets)	Depth Hoar	(Symb. 5)
o : Grains ronds	Wet grains	(Symb. 6)

The 2 figures below explain the way the grain types are described in CROCUS.

Dendritric snow :

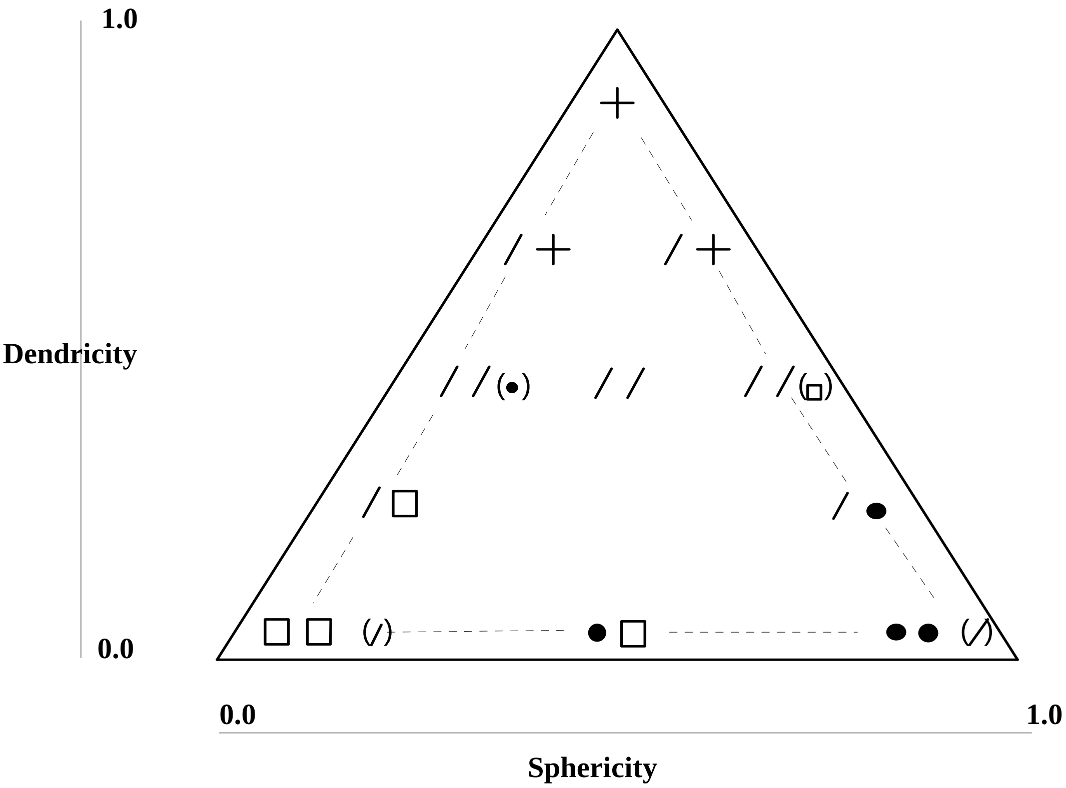


fig A.3 : Grain type of the International Classification as a function of sphericity and dendricity

Non dendritric snow :

Hist. Spher.	0	1		2		3
	□ □	d < 0.5	□ □	∀d	○ □	○ □
		0.5 < d < 1.0	□ ∧			
		d > 1.0	∧ ∧			
0.2	□ ●	d < 0.5	□ ●	∀d	○ □	○ □
		0.5 < d < 1.0	□ ∧			
		d > 1.0	∧ ∧			
0.5	● □	d < 0.5	● □	d < 0.5	● ○	(1)
				0.5 < d < 1.0	○ ○	
				d > 1.0	○ ○	
0.8	● ●	d < 0.5	● ●	d < 0.5	● ○	(1)
				0.5 < d < 1.0	○ ○	
				d > 1.0	○ ○	

fig A.4 : Grain type of the International Classification as a function of sphericity, historical variable and grain (non dendritic snow).
Case (1) : in these situations, grain types depend on the presence (or not) of water during grain growth.
If grain growth occurs in the presence of liquid water, same as MSHIST=2
If grain growth occurs in the presence of high temperature gradient, same as MSHIST=1

APPENDIX B : PRINCIPLE OF THE MODEL

B.1 Heat equation

Inside the snow cover, the energy variations are mainly due to vertical transfers of heat and mass. The base of the model is the heat equation :

$$\frac{\partial \rho C_p T}{\partial t} = \frac{\partial^2 kT}{\partial z^2} + Q$$

ρ : density

$\mathrm{C_p}$: specific heat of ice

k : snow conduction coefficient

Q : local source of heat

B.2 Temporal and spatial discretisation

CROCUS uses the Cranck and Nicholson scheme, implicit and centred. Each flux is calculated at the time $t + \frac{\Delta t}{2}$. If f_i^t is the value of the function f for the layer i and the time t, the temporal and spatial discretisation is done with the following expressions :

$$f_i^{t+\frac{\Delta t}{2}} = \frac{f_i^t + f_i^{t+\Delta t}}{2}$$

$$\frac{\partial f_i^{t+\frac{\Delta t}{2}}}{\partial t} = \frac{f_i^{t+\Delta t} - f_i^t}{\Delta t}$$

$$\frac{\partial^2 f_i^{t+\frac{\Delta t}{2}}}{\partial z^2} = \frac{\left(f_{i-1} - 2 f_i + f_{i+1}\right)^{t+\frac{\Delta t}{2}}}{\Delta z^2}$$

After the linearisation of the term Q (detailed in the following sub sections) with respect to temperature, the new temperature profile $T_i^{T+\Delta t}$ is given by the resolution of the following linear system (N is the total number of layers) :

$$\begin{pmatrix} b_1 & c_1 & & & \\ a_2 & b_2 & c_2 & & \\ & \ddots & \ddots & \ddots & \\ & & a_{N-1} & b_{N-1} & c_{N-1} \\ & & & a_N & b_N \end{pmatrix} \times \begin{pmatrix} T_1^{t+\Delta t} \\ \vdots \\ \vdots \\ \vdots \\ T_N^{t+\Delta t} \end{pmatrix} = \begin{pmatrix} d_1 \\ \vdots \\ \vdots \\ \vdots \\ d_N \end{pmatrix}$$

B.3 Phase changes

The above scheme, which account for temperature only, lead sometime to thermodynamical states impossible in the snow :

$$T^{t+\Delta t} > 273.16K$$

or

$$T^{t+\Delta t} < 273.16K \text{ and } \quad Cw > 0$$

Cw: liquid water content

These anomalies are corrected with heat transfers corresponding to a phase change (**BRUTE**)

B.4 Surface energy balance computation

When the surface temperature Ts is at the melting point at the time t, a preliminary computation of the surface-energy balance is done to determine whether Ts will remain at the melting point at the time t+Δt. In this case, the implicit method is not used because it would lead to a surface temperature Ts greater than the melting point before corrections, strongly affecting the heat exchanges calculated implicitly at $t+\frac{\Delta t}{2}$. The surface temperature is fixed at the melting point and the surface energy balance is exact.

These calculations are done in **RESOLT** : calculation of the surface energy balance and modification of the matrix coefficients.

B.5 snow metamorphism and percolation

The snow metamorphism is calculated once a hour, in **METAMO** : grain evolution and settlement. The percolation is calculated in **EAU**.

APPENDIX C : MAIN PHYSICAL PROCESS

C.1 Specific heat and conduction

The specific heat of ice Cp is a linear function of temperature :

$C_p = A_{c_p} + B_{c_p} T$

$$
\begin{aligned}
Cp &= A_{Cp} + B_{Cp} T \\
&\quad \textit{where} \\
A_{Cp} &= 152.57\, J.kg^{-1}.K^{-1} \\
B_{Cp} &= 7.106\, J.kg^{-1}.K^{-2}
\end{aligned}
$$

The conduction k is an effective snow conduction. Yen (1981) showed that most experimental measurements may be described by the following formula :

$$k = k_i \left(\frac{\rho_n}{\rho_w} \right)^{1.88}$$

k_i : ice conduction coefficient (2.22 $\mathrm{J.s^{-1}.m^{-1}.K^{-1}}$)

ρ_n : snow density

ρ_w : water density

The conductivity given by this formula is too low for low density snow. It has been adapted as follow in the model :

If ρ <= 100 $\mathrm{kg.m^{-3}}$

$$k = 0.1254\, J.s^{-1}.m^{-1}.K^{-1}$$

If 100 < ρ <280 $\mathrm{kg.m^{-3}}$

$$k = 0.1254 + (\rho - 100.) \times 0.00039 J.s^{-1}.m^{-1}.K^{-1}$$

Else : standard formula

The coefficient *k* is called effective as it includes heat fluxes due to vapor diffusion through the snow pack and which may be formally considered as thermal conduction. Therefore, *k* is also limited by the equivalent conductivity for vapor diffusion :

$$L_s D \frac{\partial \rho_v}{\partial T}$$

L_s: latent heat for sublimation

D: vapor diffusion coefficient in snow

ρ_v: vapor density

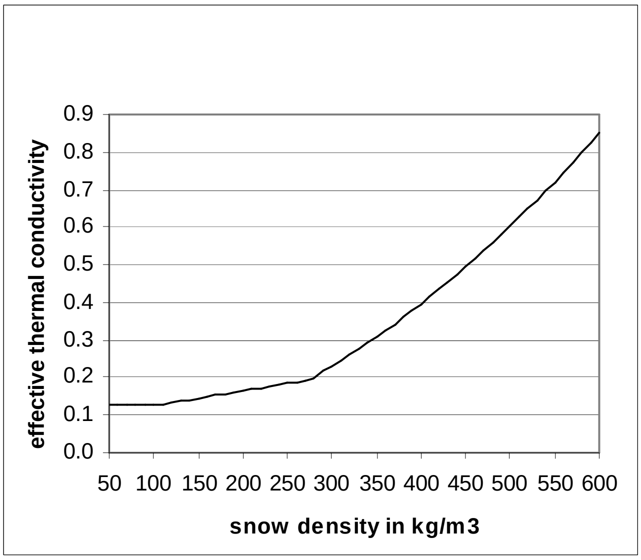


fig C.1 : effective thermal conductivity as function of snow density. Density is expressed in kg/m3 and conductivity in J/(s.m.K)

C.2 Solar radiation

Optical diameter (function ZDIAGR):

The optical diameter of each grain type is calculated by CROCUS in order to further albedo calculations. the optical diameter *Diam :* is given in meter in this section.

Dendritic case :	GRAN1 : dendricity	(between -99 and 0)
	GRAN2 : sphericity	(between 0 and 99)

$$Diam = 10^{-4} \times \left(-\frac{GRAN1}{99} \times 1. + \left[1 + \frac{GRAN1}{99} \right] \times \left\{ \frac{GRAN2}{99} \times 3. + \left[1 - \frac{GRAN2}{99} \right] \times 4. \right\} \right)$$

Non dendritic case :	GRAN1 : sphericity	(between 0 and 99)
	GRAN2 : size	in meter

$$Diam = GRAN2 \times \frac{GRAN1}{99} + \max\left(0.0004, \frac{GRAN2}{2.} \right) \times \left[1. - \frac{GRAN1}{99} \right]$$

In the code : see YOMDIAG.F90 for the variable definitions

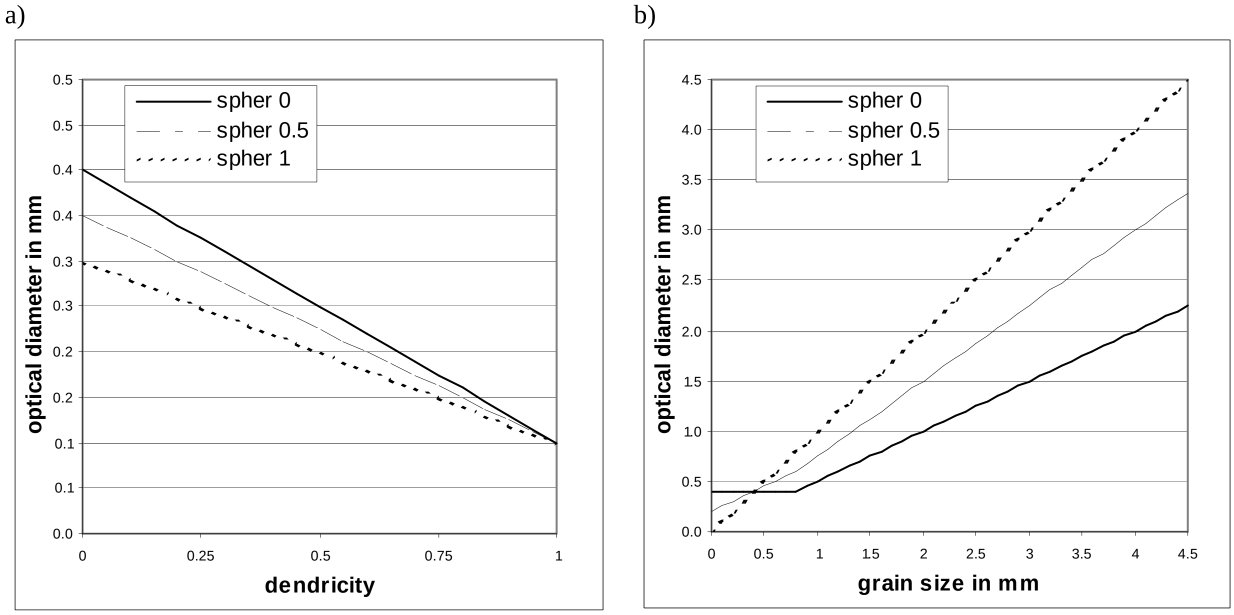

a)
b)

Fig C.2: values of optical diameter for 3 values of sphericity a) as function of dendricity b) as function of grain diameter

Spectral albedo (subroutine **PROPHY**)

Albedo depends strongly on the wavelength. Three spectral bands are considered:
One band in visible radiation :

(1) 0.3-0.8 µm

And two bands in near-infrared radiation :

(2) 0.8-1.5 µm
(3) 1.5-2.8 µm

(1) : 0.3-0.8 µm

In this band, the albedo depends on grain optical diameter (d in meter) and age (in days). The albedo decreases when age increases. The parameterization of this effect is deduced from Col de Porte data. This effect decreases when the mean pressure decreases (at high elevation the aging effect is weaker (Press : mean pressure, $\text{Press}_{\text{Col}}$: mean pressure at Col de Porte).

$$\alpha_1 = \max\left[0.7, \alpha_i - \Delta\alpha_{age}\right]$$

where :

$$\alpha_i = \min\left[0.94,\ 0.96 - 1.58\sqrt{d}\right]$$

and

$$\Delta\alpha_{age} = \min\left[1., \max\left(\frac{\text{Press.}}{\text{Press}_{\text{Col}}}, 0.5\right)\right] \times 0.175\frac{age}{90}$$

(2) : 0.8-1.5 µm

$$\alpha_2 = 0.95 - 15.4\sqrt{d}$$

(3) :1.5-2.8 µm

$$\alpha_3 = 346.3d' - 32.31\sqrt{d'} + 0.88 \text{ where } d' = \min(d, 0.0023)$$

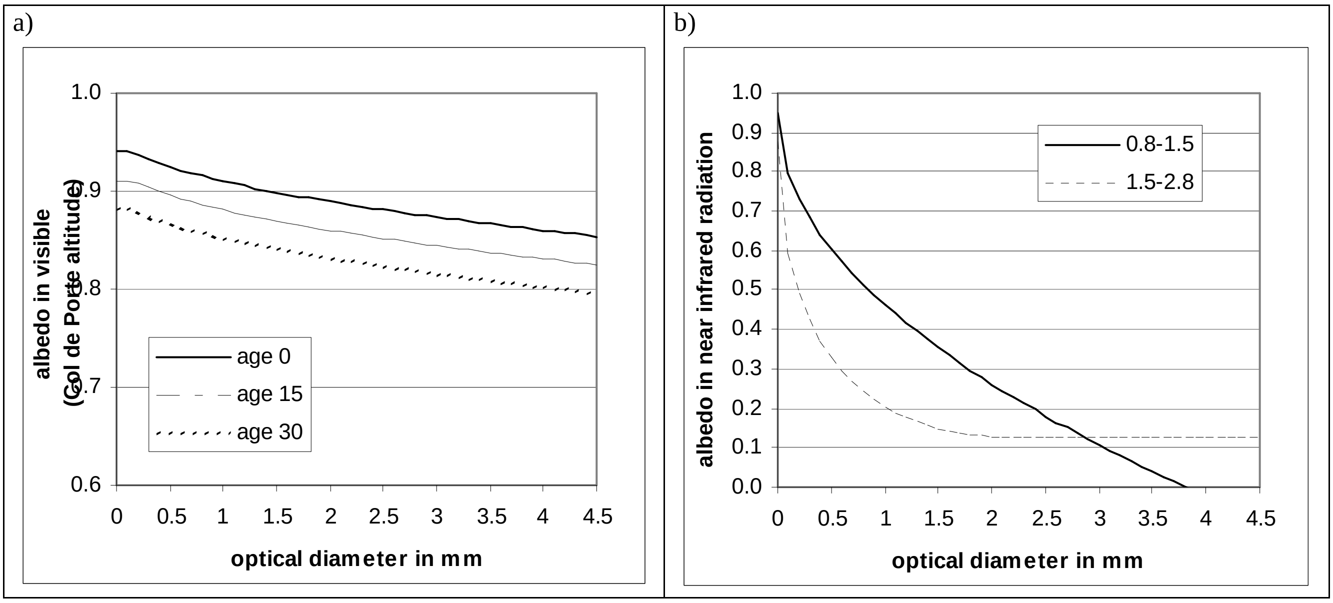


Fig C.3: Albedo as function of optical diameter. a) in the first band (visible), different ages (in days) are presented. b) in the two others bands

If ice is present at the surface (ρ>850 kg.m-3), the albedo is fixed : 0.45 in band 1, 0.30 in band 2, 0.1 in band 3.

In the code :	VALB2	0.96	
	VALB3	1.58	(used for band (1))
	VALB4	0.94	
	VALB5	0.95	
	VALB6	15.4	(used for band (2))
	VDIOP1	2.3 E-3	
	VALB7	346.3	
	VALB8	32.31	(used for band (3))
	VALB9	0.88	
	APRES		mean pressure
	VPRES1	870	(mean pressure at Col de Porte)
	VRPRE1	0.5	(minimum multiplicative factor for aging)
	VRPRE2	1.0	(maximum multiplicative factor for aging)

Spectral absorption (PROPHY)

β is the spectral absorption in m^{-1}. It is also defined on the three bands :

(1) :

$$\beta = \max\left(40.,0.00192\rho\frac{1}{\sqrt{d}}\right)$$

In fact, β is generally equal to 40.

(2) : $$\beta = \max\left(100.,0.01098\rho\frac{1}{\sqrt{d}}\right)$$

(3) : $$\beta = +\infty$$

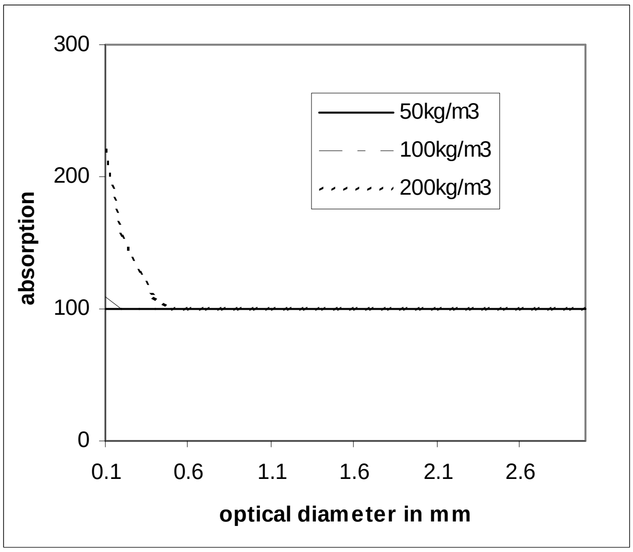


Fig C.4: Absorption in m^{-1} for different values of density in the second band (0.8-1.5 µm)

Energy entering in the snow cover (PROPHY)

The solar energy entering the snow cover is :

$$Q_{sol} = \sum_{i=1}^{3}(1-\alpha_i)Q_{\underset{i}{inc}}$$

$$Q_{\underset{i}{inc}} = \text{incoming solar energy}$$

$Q_{\underset{i}{inc}}$ is determined with the incoming direct and diffuse solar radiation and the cloudiness (**METEO**). At first, the angle for the direct solar radiation is calculated (with Time, latitude, longitude, exposure and slope) and projections to the surface are made. At this stage, the masks are used : if the sun is masked, the direct solar radiation is put to 0. (the diffuse solar radiation remain unchanged). Cloudiness is used to split the solar radiation into the 3 bands. :

$$
\begin{aligned}
Q_{\underset{1}{inc}} &= 0.59 Q_{dir} + Q_{diff}\left(0.95(1-Cl)+0.66Cl\right)\\
Q_{\underset{2}{inc}} &= 0.31 Q_{dir} + Q_{diff}\left(0.05(1-Cl)+0.27Cl\right)\\
Q_{\underset{3}{inc}} &= 0.10 Q_{dir} + Q_{diff}\left(0.00(1-Cl)+0.07Cl\right)\\
Q_{dir} &= \text{Incoming direct solar radiation}\\
Q_{diff} &= \text{Incoming diffuse solar radiation}\\
Cl &= \text{cloudiness (between 0 and 1)}
\end{aligned}
$$

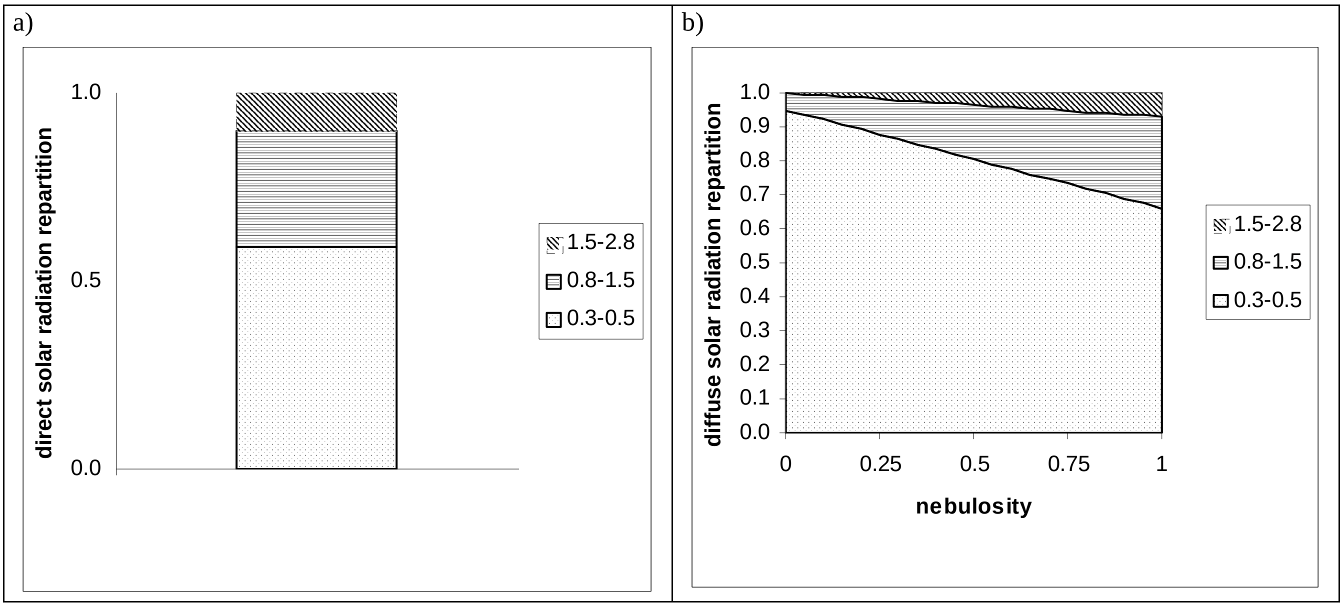


Fig C.5: repartition of solar radiation in the 3 bands , a) direct solar radiation b) diffuse solar radiation as function of nebulosity

Energy absorbed by each layer (RESOLT)

The energy absorbed by the layer *l* is :

$$
Q_{abs} = \sum_{i=1}^{3} (i-\alpha_i) Q_{\underset{i}{inc}} \left(e^{-\left(\sum_{j=1+l}^{N} \beta_i(j)\Delta z(j)\right)} . \left(1 - e^{-\beta_i(l)\Delta z(l)}\right) \right)
$$

where N is the total number of layers.

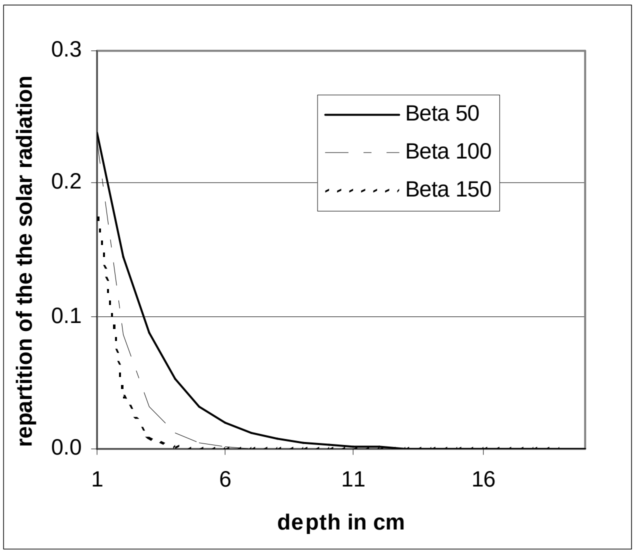


fig C.6: repartition of the incident solar radiation which penetrates in the snow cover with the depth for 3 values of the absorption coefficient. Beta is expressed in m-1 and is supposed constant.

C.3 Surface turbulent fluxes

Turbulent fluxes are estimated with air temperature, air humidity, wind speed, and snow surface temperature (Deardorff, 1968) :

$$Q_{sens} = \rho_a . Cp_a . C.u.(T_a - T_s)$$

$$Q_{lat} = \frac{Ls.\rho_a}{P_a}\frac{M_v}{M_a}C.u.\left[e_i(T_a)H_a - e_i(T_s)\right]$$

ρ_a : air density
Cp_a : specific heat of air
C :Turbulent exchange coefficient which depends of the air stability (same value for the 2 fluxes)
u : wind speed
Ta : air temperature
Ts : snow surface temperature
Ls : Latent heat of sublimation
Pa : air pressure
Mv/Ma : ratio between water vapor and dry air molecular weights
$e_i(T)$: saturation vapour pressure above a flat ice surface at the temperature T
Ha : relative air humidity
Q_{sens}: sensible heat flux
Q_{lat}: latent heat flux

2 methods are proposed for the determination of the exchange coefficient. If the logical LVRI is TRUE, Exchange coefficient will depend on the atmosphere stability and the bulk Richardson number is calculated, else an empirical formulation based on work on the Col de Porte site is used (C = 0.0031 in this case).

Turbulent latent flux may cause evaporation or condensation when liquid water is present at the surface of the snow cover, sublimation or solid condensation when the surface is dry.
Evaporation of liquid water reduces the mass in the uppermost snow layer while leaving the thickness unchanged. Sublimation (solid condensation) on the other hand, reduces (increases) mass by decreasing (increasing) the thickness while leaving the density unchanged.
Grain type is not modified (surface hoar is not generated).

4. Flux between snow and ground

When Crocus is not coupled with a SVAT scheme, a climatological flux is introduced at the snowpack bottom. This flux is positive (Heat from ground toward snow), decreases with altitude, is maximum from August to November (not correct for southern hemisphere). It also depends on the slope.
Moreover, this flux is increased when the temperature at the bottom of the snowpack is negative.

4 Percolation

The liquid water content of the snow is modelled as a serie of reservoirs (one reservoir in each layer). Local changes during a model time step arise due to snow melt, water freezing, evaporation and liquid flow.
Each snow layer has a maximum liquid water holding capacity named irreducible water content which is equal to 5% of the pore volume. This quantity may be expressed by :

$$W_{irr} = 0.05 * (\rho_w * \Delta z * (\rho_{ice} - \rho_{dry}) / \rho_{ice})$$

W_{irr} : irreducible liquid water (in kg/m2) of the layer

ρ_w : liquid water density

ρ_{ice} : ice density

ρ_{dry} : layer dry snow density

Δz : layer thickness

When the liquid water content exceeds this threshold, a water flux is immediately generated toward the layer below.
At the snowpack bottom, water run-off is supposed to penetrate in the ground.

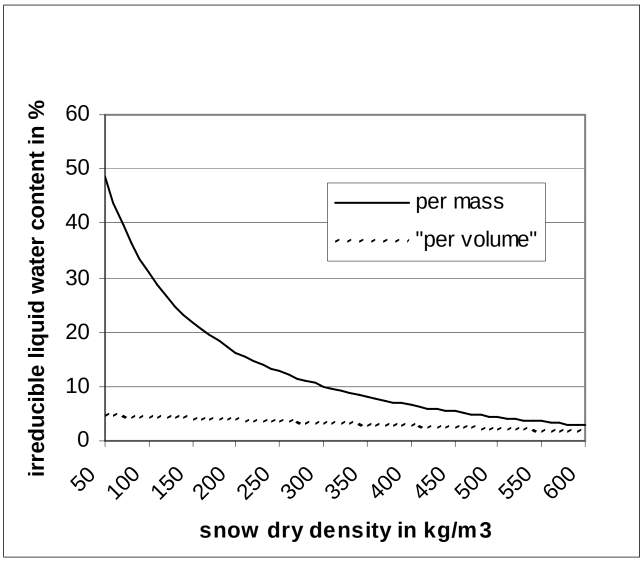


fig C.7 : irreducible water content expressed in % per mass and per volume, as function of the dry density

5 Settling

The snow layers settle by the combined effect of grain metamorphism and the weight of the upper layers. The mechanical effect is simulated, using the equation :

$$\frac{\delta e}{e} = -\frac{\sigma}{\eta}\delta t$$

e : layer thickness
σ: vertical stress (weight of the upper layers) in kg.m-1.s-2
η : viscosity (function of temperature, liquid water content, grain type) in kg.m-1.s-1

In case of dry snow and not angular grain, viscosity is expressed by :

$$\eta = 7.6E6 * e^{0.023*\rho_{dry}+0.1*|T|} * \rho_{dry} / 250$$

T : Temperature in degree C

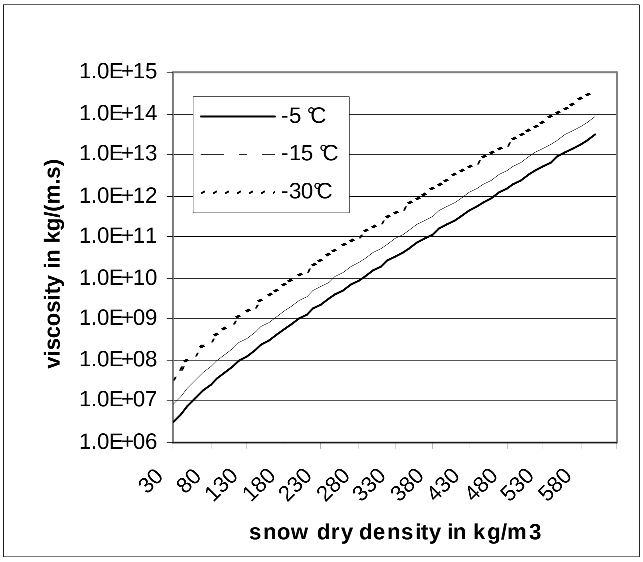


fig C.8 : Viscosity is expressed as function of snow dry density for different temperatures (logarithmic scale), only for dry snow and not completely angular grain.

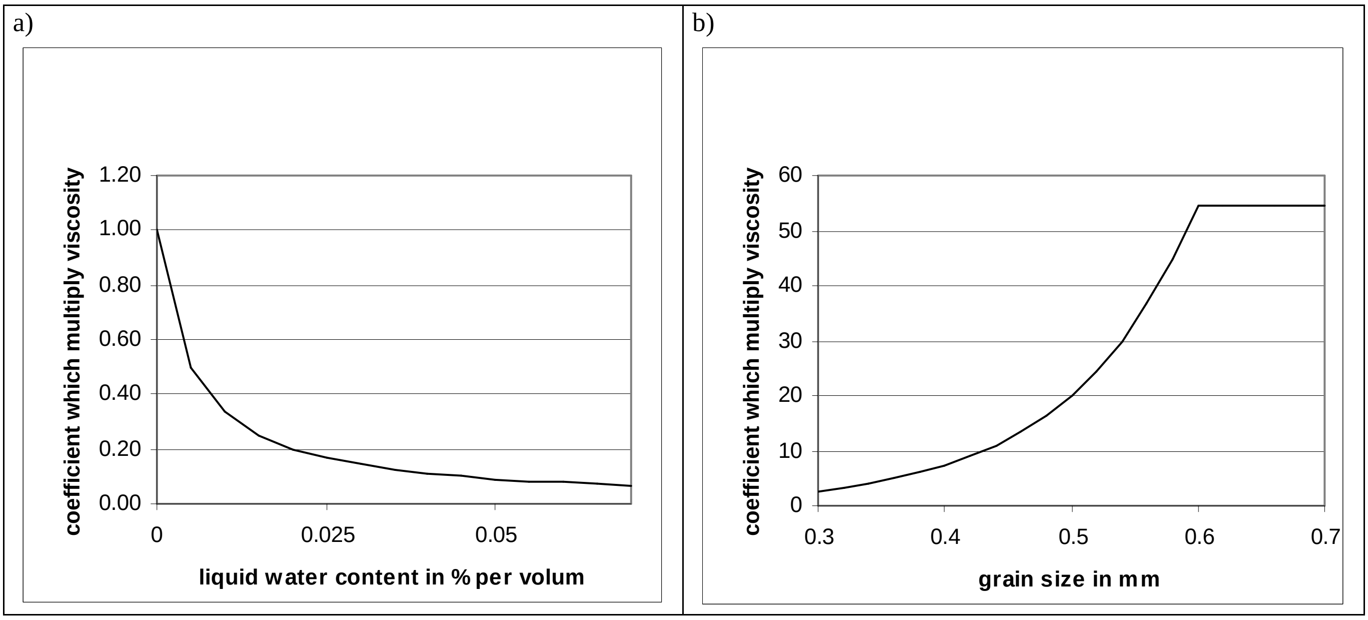


Fig C. 9 : Viscosity is modified in wet snow or with angular grain. a) coefficient which multiply viscosity as function of liquid water content (viscosity is reduced). b) same as a) but with angular grain as function of the size grain (viscosity is increased).

6 New snow layer

A new layer is defined by its temperature, density, liquid water content, and grain type (dendricity and sphericity (see APPENDIX A)). A new snow layer is always associated to snowfall, surface hoar is not treated by Crocus.

Graupel, hail or ice pellets have not a particular treatment in Crocus. Snow metamorphism laws are applied as for dendritic snow.

New snow layer (snowfall) :
Snow is dendritic and grain characteristic only depends of the wind

$$dendricity = MAX(MIN(17.12 * V - 128, -20), -99)/99$$

$$sphericity = MIN(MAX(7.87 * V + 38, 50), 90)/99$$

The new layer temperature is the temperature at the top of the snowpack before the snowfall.

Density of snow falling on the surface is function of air temperature and wind speed :

$$\rho_{NEWSNOW} = Max\ (30, 109 + 6 * T_{air} + 26 * \sqrt{V})$$

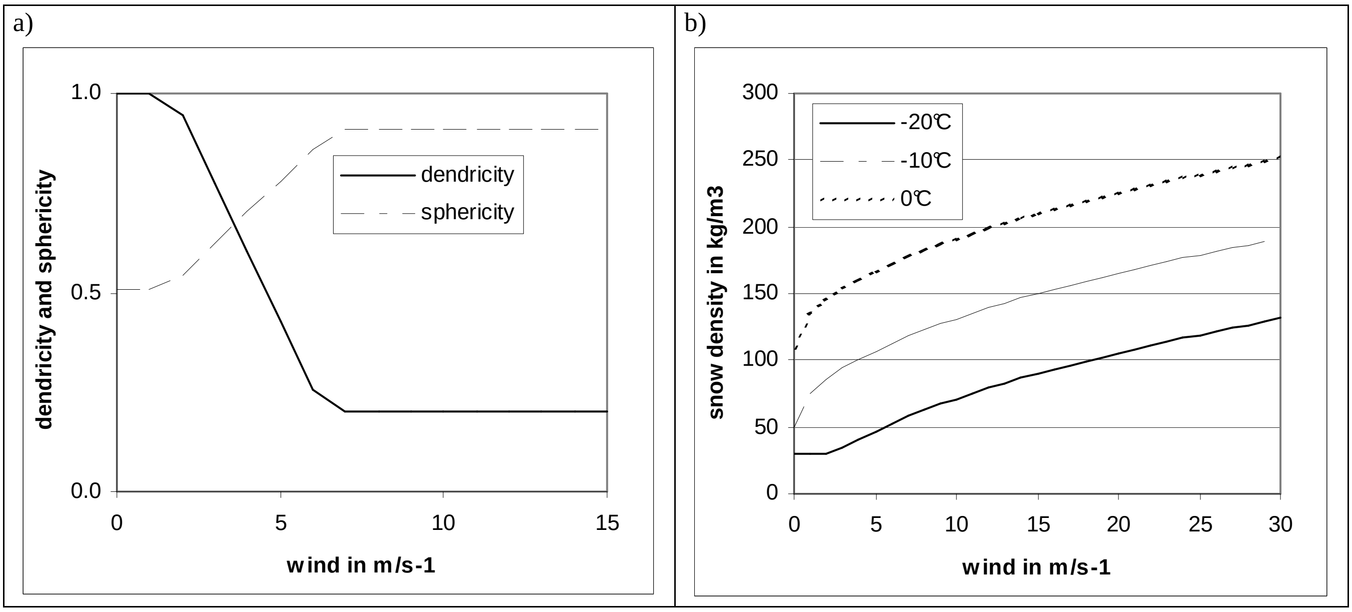


fig C.10 : a) dendricity and sphericity as function of the wind speed. b) Density of a new snow layer as function of the wind speed and for different air temperatures.

7 Snow metamorphism

Snow metamorphism is calculated in **METAMO** according to the following laws.

A snow layer is always initially dendritic, it evolves from dendritic snow towards non dendritic snow. This transformation is realised when dendricity reaches 0.
When dendricity reaches 0, grain size in mm is estimated with the following equation :

$$grain\_size = 0.4 - 0.1 * sphericity$$

So, when this transformation occurs, grain size has a value between 0.4 (angular grain) and 0.3 mm (spherical grain).

Evolution of dendricity, sphériciy and size without liquid water.

T : temperature (K), $\left|\frac{\delta T}{\delta z}\right|$ **: vertical temperature gradient, t : time (days),**

f, h, g, ϕ **: empirical functions**

Dendritic snow :	**Non dendritic snow**
1. $\left\|\frac{\delta T}{\delta z}\right\| < 5° / m$ $\frac{\delta dendricity}{\delta t} = -\,2.10^8\, e^{\left(\frac{-6000}{T}\right)}$ $\frac{\delta sphericity}{\delta t} = 10^9\, e^{\left(\frac{-6000}{T}\right)}$ (Brun et al, 1992)	**1.** $\left\|\frac{\delta T}{\delta z}\right\| < 5° / m$ $\frac{\delta sphericity}{\delta t} = 10^9\, e^{\left(\frac{-6000}{T}\right)}$ $\frac{\delta size}{\delta t} = 0$ (Brun et al, 1992)
2. $\left\|\frac{\delta T}{\delta z}\right\| > 5° / m$ $\frac{\delta dendricity}{\delta t} = -\,2.10^8\, e^{\left(\frac{-6000}{T}\right)} \left\|\frac{\delta T}{\delta z}\right\|^{0.4}$ $\frac{\delta sphericity}{\delta t} = -\,2.10^8\, e^{\left(\frac{-6000}{T}\right)} \left\|\frac{\delta T}{\delta z}\right\|^{0.4}$ (Brun et al, 1992)	**2.** $5 < \left\|\frac{\delta T}{\delta z}\right\| < 15° / m$ $\frac{\delta sphericity}{\delta t} = -\,2.10^8\, e^{\left(\frac{-6000}{T}\right)} \left\|\frac{\delta T}{\delta z}\right\|^{0.4}$ $\frac{\delta size}{\delta t} = 0$ (Brun et al, 1992)
	3. $\left\|\frac{\delta T}{\delta z}\right\| > 15° / m$ **3.1** *sphéricity>0* $\frac{\delta sphericity}{\delta t} = -\,2.10^8\, e^{\left(\frac{-6000}{T}\right)} \left\|\frac{\delta T}{\delta z}\right\|^{0.4}$ $\frac{\delta size}{\delta t} = 0$ (Brun et al, 1992) **3.2** *sphéricity=0* $\frac{\delta sphericity}{\delta t} = 0$ $\frac{\delta\, size}{\delta\, t} = f\,(T).h(\rho).g\left(\left\|\frac{\delta T}{\delta z}\right\|\right).\phi$ (Marbouty, 1980)

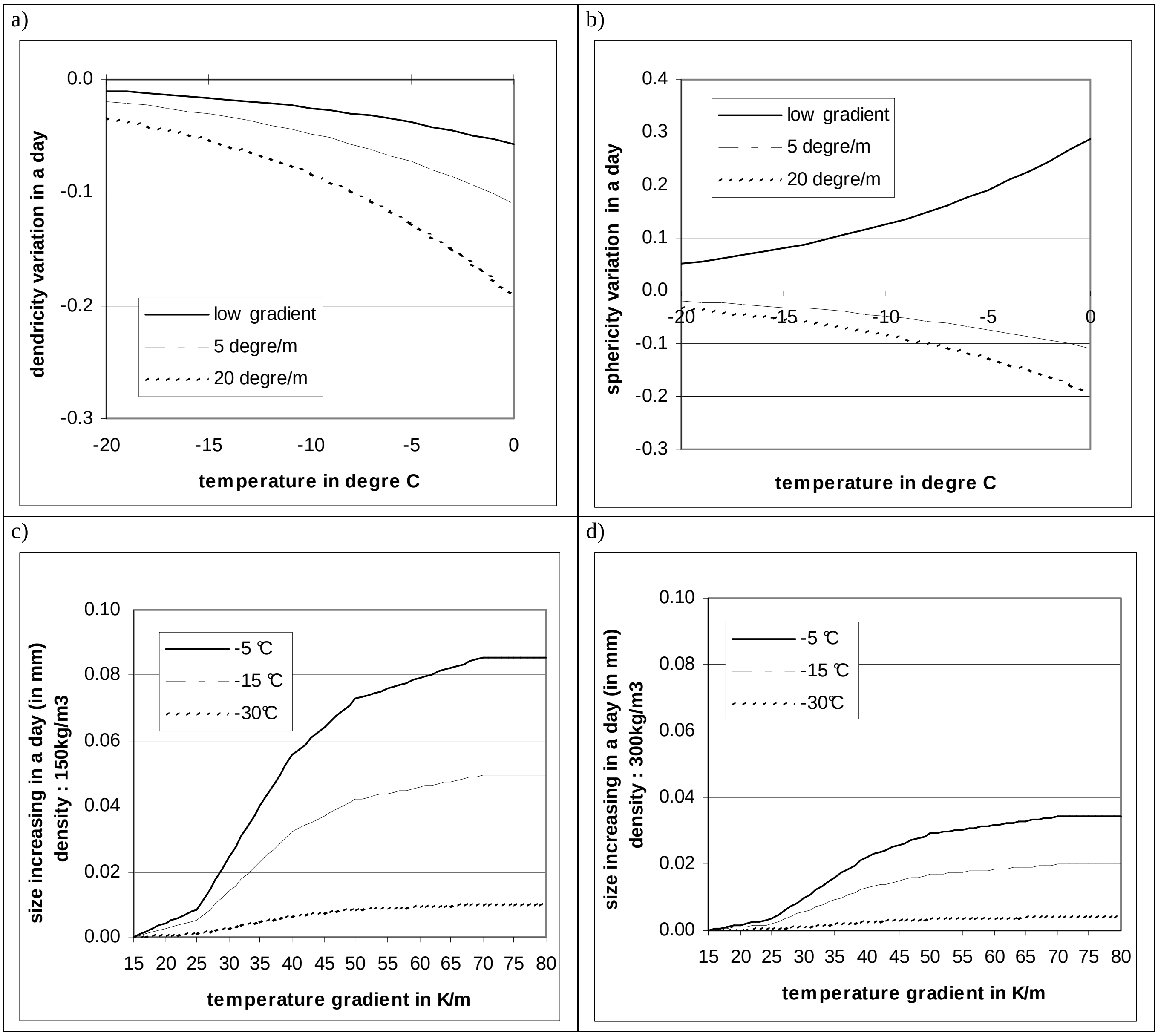


Fig C.11 : Evolution of the variables which describe grains in a layer without liquid water. a)dendricity decreasing in a day as function of the temperature for different temperature gradient. b) as a) for the sphericity (dendritic or non dendritic snow). In contrary of dendricity, sphericity decreases or increases following the temperature gradient. c) size grain increasing (dendricity and sphericity are considered null) as function of temperature gradient for different values of temperature. Layer density is equal to 150kg/m3 . d) same as c) but density is equal to 300kg/m3

Evolution of the dendricity, sphéricity and size in the presence of liquide water.
θ : liquide water content, en % of the mass, t : time (days), v : volume of the snow grain,
v'_0 et v'_1 : empirical constants.

Dendritic snow :	**Non dendritic snow**
$\frac{\delta dendricity}{\delta t} = -\frac{1}{16}\theta^3$ $\frac{\delta sphericity}{\delta t} = \frac{1}{16}\theta^3$ (Brun et al, 1992)	**1.** $0 \le sph\acute{e}ricity < 1$ $\frac{\delta size}{\delta t} = 0$ $\frac{\delta sphericity}{\delta t} = \frac{1}{16}\theta^3$ (Brun et al, 1992) **2.** sphéricity =1 $\frac{\delta sphericity}{\delta t} = 0$ $\frac{\delta v}{\delta t} = v'_0 + v'_1\,\theta^3$ (Brun, 1989)

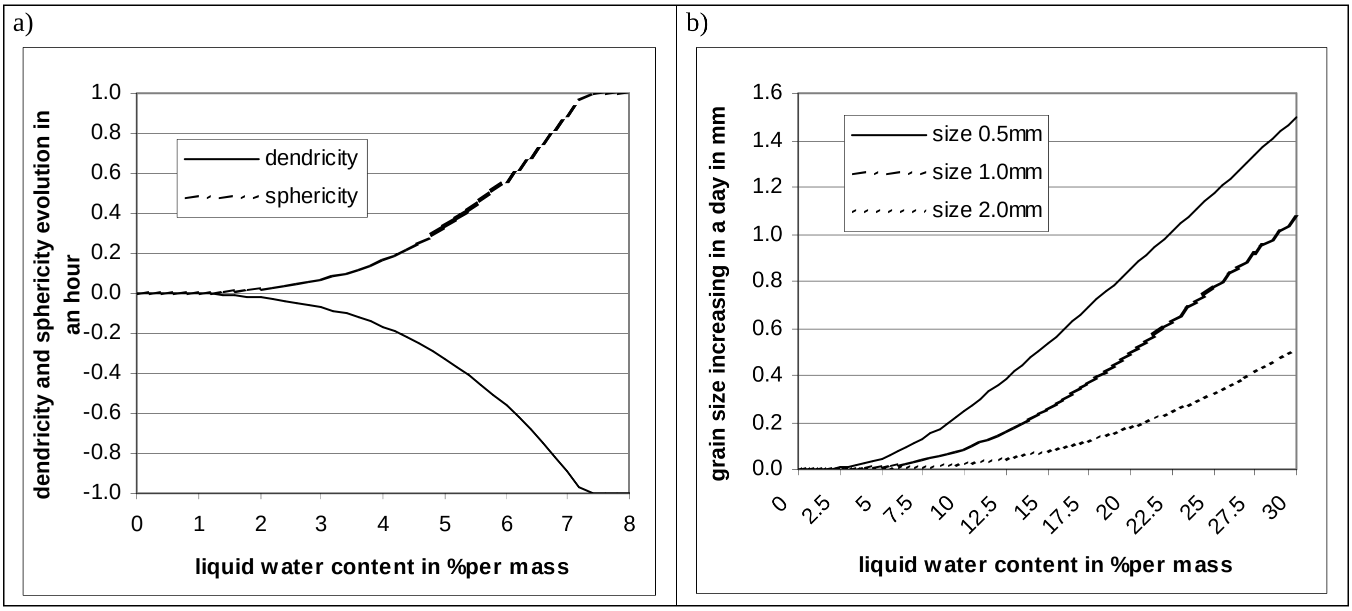


Fig C.12 : Evolution of the variables which describe grains in a layer with liquid water. a) dendricity decreasing and sphericity increasing in an hour as function of liquid water content. b) grain size increasing in a day (dendricity is null and sphericity is equal to 1), different initial grain sizes are considered.

APPENDIX D : SPLITTING AND AGGREGATION OF LAYERS

Splitting or aggregation are realised in MODPRO routine. It can also be realised in NEIGE routine if snowfalls occurs on a cover which contains MNMAXST layers.

The main objectives of aggregation is both : to maintain the layers number under MNMAXST (usually 50 layers) and to avoid layers with too little thickness.

Threshold on thickness (see fig D.1), grain type (20 on a scale between 0 and 200) and age (2 days) difference between 2 consecutive layers are successively considered. If values for a layer is below (respectively above) these thresholds, aggregation (respectively splitting) occurs.

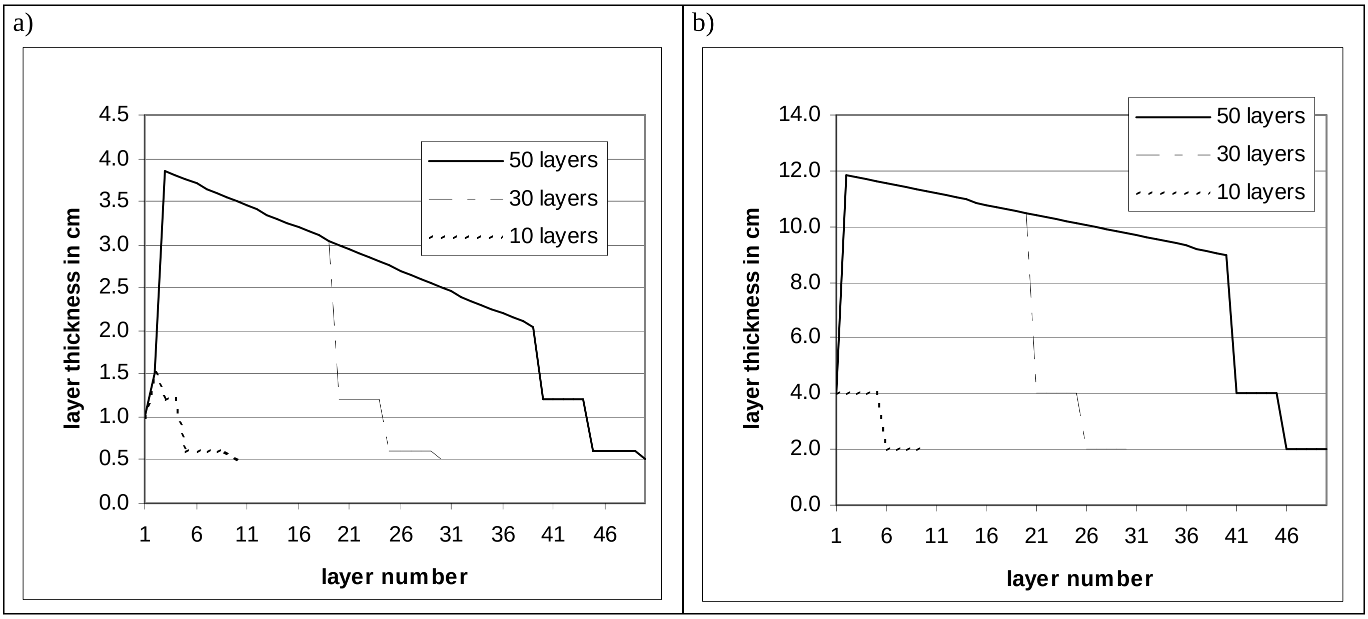


fig D.1 : Threshold on the layer thickness for different total number of layers a) for aggregation. b) for splitting

When maximum number layers is reached and new snowfall must be integrated, aggregation is forced. The 10 layers, near the surface, are not aggregated. For the others, a weight is calculated. This weight is dependent of the thickness of the snow cover, thickness of the layers, grain type and age difference between the 2 layers (see fig D.2). Moreover, weight function decreases with the layer number (layers near the bottom will be aggregated preferentially).

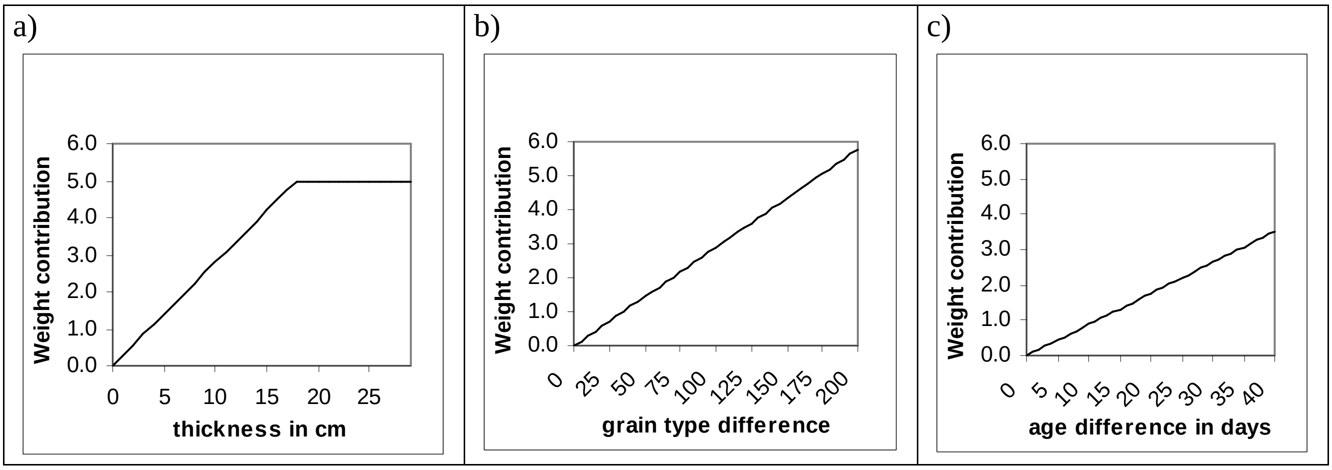


Fig D.2 : Contribution to the weight function of thickness, grain type and age difference between 2 layers. These weights are calculated for the layer 10 (9 layers are under this one). a) the 2 layers are considered with the same thickness. Thickness indicated is the thickness of one layer. b) grain type difference is evaluated by a value between 0 and 200. For example, 0 correspond to the same grains in the 2 layers, and 200, grains are very different (for example, dendritic and non dendritic snow) c) Layers are dated, here the number of days between the 2 snowfall are considered

In case of aggregation, characteristics of the resulting layer is defined by :
- Sum of the thickness and liquid water content
- mass conservation for the dry density calculation
- heat conservation for the temperature
- grain type is dependent of the grain type of the 2 initial layers (one layer is considered dominant)

APPENDIX E : USE OF CROCUS WITH ISBA

Flux between ground and snow is modelled very simply in the crocus model. Sometimes, bad quality of the crocus simulation may be caused by this ground flux. It may be, for example, the case, with non permanent snow cover. Ground simulation allows the calculation of a more realistic ground flux.

So, the 2.4 version of the model Crocus may be used inside a SVAT (Soil Vegetation Atmosphere Transfer) model. This model is ISBA, developed by METEO-FRANCE. See Bouilloud and Martin, 2006 for description of the coupling.

Information on ISBA may be found at the following address :
http://www.cnrm.meteo.fr/isbadoc/index.html

If you are interested by this possibility, you must contact JM Willemet because the initial soft package of Crocus does not include ISBA code source.

References

Bouilloud L, Martin E (2006) : "A Coupled Model to Simulate Snow Behavior on Roads", J of Applied Meteorology, Vol 45, n°3,p 500-516

Brun E., Martin E., Simon V., Gendre C., Coléou C. (1989) : "An energy and mass model of snow cover suitable for operational avalanche forecasting", J. of Glaciol., Vol 35, N°121, p333-342.

Brun E., David P., Sudul M., Brunot G. (1992) : "A numerical model to simulate snowcover stratigraphy for operational avalanche forecasting", J. of Glaciol., Vol 38, N°128, p 13-22.

Colbeck. S., Akitaya E., Armstong R., Gubler H., Lafeuille J., Lied K., McClung D., Morris E. (1990) : "The International Classisication for Seasonal Snow on the Ground", ICSI, IGS.

Coléou C, XU K, Lesaffre B, Brzoska JB (1999) : "Capillary rise in snow", Hydrological Process, Vol 13, p1721-1732

Dang H, Genthon C, Martin E. (1996) : "Modélisation du manteau neigeux polaire", La Houille Blanche, n°5/96, p62-65.

Deardorff J. (1968) : "Dependence of air-sea transfer coefficients on bulk stability", Journal of Geophysical Research, Vol 73, p 2549-2577.

Lejeune Y., Martin E. (1995) : "Application du modèle CROCUS aux données de la saison 93/94 du Col de Porte et de la campagne LEADEX92". Note du Centre d'études de la Neige n°6, 55p

Marbouty, D. (1980) : "An experimental study of temperature-gradient metamorphism", J of Glaciology, Vol 26(94), 303-312