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# Évaluation des interactions neige-sol-végétation pour différents sites forestiers avec le modèle SURFEX/ISBA-MEB

Théo Welfringer

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**Evaluation of the snow-ground-vegetation interactions  
for various forested sites with the SURFEX/ISBA-MEB model.**

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# Abstract and Résumé

## **Evaluation of the snow-ground-vegetation interactions for various forested sites with the SURFEX/ISBA-MEB model.**

The ISBA-MEB (Intéraction Sol-Biosphère-Atmosphère - Multi Energy Balance) option provides a new significant algorithm for the surface simulation in forested areas. The main improvement is the consideration of an explicit vegetation layer which includes new schemes for the interception and unloading of precipitations.

In this paper, twelve years local runs with ISBA-MEB are compared with the operational version ISBA. The studied sites are located in the Canadian Boreal forest and are part of the Boreal Ecosystem Research Study (BERMS).

A better representation of the snow fraction on the surface in MEB improves the simulation of the snowpack and the ground temperature. It mostly impacts the melting period of the snowpack, by representing more accurately the energy exchanges of the air and the ground with the snowpack. The new vegetation layer provides improvements in the modeled energy fluxes. Sensitivity tests established a new value for the coefficient of longwave transmission through the canopy.

A 30 years global simulation and a local study on another site highlighted the fact that some behaviors of the MEB option are still to be understood before being coupled with an atmospheric model.

## **Evaluation des interactions neige-sol-végétation pour différents sites forestiers avec le modèle SURFEX/ISBA-MEB.**

L'option ISBA-MEB (Intéraction Sol-Biosphère-Atmosphère - Multi Energy Balance) contient une amélioration importante du modèle de surface ISBA pour les simulations dans les domaines forestiers. La principale modification concerne l'ajout d'une couche explicite pour représenter la végétation, qui intègre des nouveaux schémas d'interception et de déchargement des précipitations.

Dans ce papier, douze années de simulations sont effectuées avec ISBA et ISBA-MEB afin de comparer les résultats de chaque modèle. Les sites étudiés sont situés dans la forêt boréale canadienne et font partie du programme Boreal Ecosystem Research Study (BERMS).

MEB permet une meilleure représentation de la fraction de neige sur la surface et ainsi de mieux modéliser le pack de neige et la température du sol. C'est notamment la période de fonte du pack de neige qui est améliorée avec MEB, en représentant d'une façon plus réaliste les échanges d'énergie entre l'air, le sol et le pack de neige. La nouvelle couche de végétation améliore aussi la modélisation des flux d'énergies. Des tests de sensibilité permettent d'établir une nouvelle valeur pour le coefficient de transfert des grandes longueurs d'onde à travers la canopée.

Une simulation globale de 30 années ainsi qu'une étude locale sur un autre site ont permis de montrer qu'il reste encore certains fonctionnements à comprendre dans l'option MEB avant de pouvoir coupler le modèle avec un modèle atmosphérique.



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# Nomenclature

$\alpha_g$	ground albedo	-
$\alpha_n$	snow albedo	-
$\alpha_v$	vegetation albedo	-
$\epsilon_g$	ground emissivity	-
$\epsilon_n$	snow emissivity	0.99 -
$\epsilon_v$	vegetation emissivity	-
$\lambda_{g,i}$	thermal conductivity for the $i$ th ground layer	$\text{W m}^{-1}\text{K}^{-1}$
$\Phi_v$	phase changes term of the intercepted precipitations	$\text{kg m}^{-2}\text{s}^{-1}$
$\Phi_{g,1}$	phase changes term of the water contained in the first layer of ground	$\text{kg m}^{-2}\text{s}^{-1}$
$\Phi_{n,1}$	phase changes term of the water contained in the first layer of snow	$\text{kg m}^{-2}\text{s}^{-1}$
$\rho_a$	air density at the lowest atmospheric level	$\text{kg m}^3$
$\rho_w$	water density	$\text{kg m}^3$
$\rho_{n,v}$	intercepted snow density	$\text{kg m}^3$
$\sigma$	Stefan Boltzman constant	$5,67 \cdot 10^{-2} \text{ W m}^{-2} \text{ K}^{-4}$
$\sigma_{LW}$	vegetation absorption	-
$\tau_{LW}$	LW radiation transfer coefficient	-
$C_l$	effective heat capacity of the litter	$\text{J m}^{-2}\text{K}^{-1}$
$C_{n,1}$	effective heat capacity of the first layer of the snowpack	$\text{J m}^{-2}\text{K}^{-1}$
$c_p$	thermal capacity of air	$\text{J m}^{-2}\text{K}^{-1}$
$C_s$	effective heat capacity of the composite layer	$\text{J m}^{-2}\text{K}^{-1}$
$C_v$	effective heat capacity of the vegetation	$\text{J m}^{-2}\text{K}^{-1}$
$D_{rv}$	drip of water through the vegetation	$\text{kg m}^{-2}\text{s}^{-1}$
$E$	total evapotranspiration flux	$\text{kg m}^{-2}$
$E_g$	evaporation flux from the ground to the canopy air	$\text{kg m}^{-2}$
$E_n$	sublimation flux from the snow to the canopy air	$\text{kg m}^{-2}$
$E_v$	evaporation flux from the vegetation to the canopy air	$\text{kg m}^{-2}$

$E_{gf}$	sublimation of the frozen water contained in the first layer of ground	$\text{kg m}^{-2}$
$E_g$	evaporation flux of the water content of the first ground layer	$\text{kg m}^{-2}$
$E_{rn}$	sublimation of intercepted snow by the canopy	$\text{kg m}^{-2}$
$E_r$	evaporation flux of intercepted water by the canopy	$\text{kg m}^{-2}$
$E_{tr}$	vegetation transpiration	$\text{kg m}^{-2}$
$F_{g,i}$	liquid water flux between the $i$ th and the $i+1$ th ground layer	$\text{kg m}^{-2}\text{s}^{-1}$
$F_{nl,i}$	liquid water flux between the $i$ th and the $i+1$ th snow layer	$\text{kg m}^{-2}\text{s}^{-1}$
$G_{g,1}$	conductive flux between the litter and the ground layer below	$\text{W m}^{-2}$
$G_{n,1}$	conductive flux between the two first layers of snow	$\text{W m}^{-2}$
$G_{n-g}$	conductive flux between the last layer of snow and the first layer of ground (litter or composite layer)	$\text{W m}^{-2}$
$G_s$	conductive flux between the composite layer and the ground layer below	$\text{W m}^{-2}$
$H$	total sensible heat flux to the atmosphere	$\text{W m}^{-2}$
$H_n$	sensitive heat flux from the snowpack to the air of the canopy	$\text{W m}^{-2}$
$H_s$	sensitive heat flux from the composite layer to the air of the canopy	$\text{W m}^{-2}$
$H_v$	sensitive heat flux from the vegetation to the canopy air	$\text{W m}^{-2}$
$H_{g,1}$	sensitive heat flux from the litter to the air of the canopy	$\text{W m}^{-2}$
$I_n$	intercepted snow by the canopy	$\text{kg m}^{-2}$
$L_f$	latent heat of fusion	$0.3337 \cdot 10^6 \text{ J kg}^{-1}$
$L_v$	latent heat of vaporization	$2.5008 \cdot 10^6 \text{ J kg}^{-1}$
$LAI$	Leaf Area Index	$\text{m}^2\text{m}^{-2}$
$LE$	Total latent heat flux	$\text{W m}^{-2}$
$LE_{g,1}$	latent heat flux from the litter to the canopy air	$\text{W m}^{-2}$
$LE_{n,1}$	latent heat flux from the snowpack to the canopy air	$\text{W m}^{-2}$
$LE_s$	latent heat flux from the composite layer to the canopy air	$\text{W m}^{-2}$
$LE_v$	latent heat flux from the vegetation to the canopy air	$\text{W m}^{-2}$
$LW \downarrow$	downward LW radiation	$\text{W m}^{-2}$
$LW \uparrow$	upward LW radiation	$\text{W m}^{-2}$
$LW_n$	net LW radiation	$\text{W m}^{-2}$
$P_{rv}$	liquid precipitations intercepted by the vegetation	$\text{kg m}^{-2}\text{s}^{-1}$
$P_r$	liquid precipitations	$\text{kg m}^{-2}\text{s}^{-1}$
$p_{sng}$	snow fraction on the ground	-

$p_{snv}$	snow fraction on the vegetation	-
$p_{sn}$	snow fraction	-
$P_s$	solid precipitations	$\text{kg m}^{-2}\text{s}^{-1}$
$q_a$	specific humidity for the atmosphere (at the lowest level)	$\text{kg kg}^{-1}$
$q_c$	specific humidity of the canopy air	$\text{kg kg}^{-1}$
$q_{satin}$	specific humidity for snowpack saturation	$\text{kg kg}^{-1}$
$R_0$	surface runoff	$\text{kg m}^{-2}\text{s}^{-1}$
$R_{ac-a}$	aerodynamic resistance between the canopy air and the atmosphere	$\text{s m}^{-1}$
$R_{ag-c}$	aerodynamic resistance between the ground and the air of the canopy	$\text{s m}^{-1}$
$R_{agn}$	aerodynamic resistance between the ground and the canopy air under neutral conditions	$\text{s m}^{-1}$
$R_{an-c}$	aerodynamic resistance between the snow pack under the canopy and the atmosphere	$\text{s m}^{-1}$
$R_{avg-c}$	aerodynamic resistance between vegetation and canopy air	$\text{s m}^{-1}$
$Rn$	global net radiation	$\text{W m}^{-2}$
$Rn_{g,1}$	net radiation for the litter	$\text{W m}^{-2}$
$Rn_{n,1}$	net radiation for the snowpack	$\text{W m}^{-2}$
$Rn_s$	net radiation for the composite layer	$\text{W m}^{-2}$
$Rn_v$	net radiation for the vegetation	$\text{W m}^{-2}$
$SND$	snow depth	$\text{m}$
$SW \downarrow$	downward SW radiation	$\text{W m}^{-2}$
$SW \uparrow$	upward SW radiation	$\text{W m}^{-2}$
$SW_n$	net SW radiation	$\text{W m}^{-2}$
$T_a$	atmospheric temperature at the lowest level	$\text{K}$
$T_c$	air temperature of the canopy	$\text{K}$
$T_f$	melting temperature	273.15 $\text{K}$
$T_l$	litter temperature	$\text{K}$
$T_n$	first snowpack layer (on the top) temperature	$\text{K}$
$T_s$	composite layer temperature	$\text{K}$
$T_v$	vegetation temperature	$\text{K}$
$T_{g,i}$	ground temperature of the $i$ th layer	$\text{K}$
$T_{rad}$	effective surface radiative temperature	$\text{K}$
$U_n$	snow unloading from the vegetation	$\text{kg m}^{-2}\text{s}^{-1}$

$V_a$	wind speed	$\text{m s}^{-1}$
$W_g$	water content in the litter	$\text{kg m}^{-2}$
$W_{gf}$	frozen water content in the litter	$\text{kg m}^{-2}$
$W_n$	snow water equivalent of the snowpack	$\text{kg m}^{-2}$
$W_{rmax}$	maximum intercepted water content by the canopy	$\text{kg m}^{-2}$
$W_r$	intercepted water content by the canopy	$\text{kg m}^{-2}$
$z_{0g}$	surface roughness	$\text{m}$
$z_{0h}$	roughness for latent heat fluxes and sensible heat fluxes	$\text{m}$
$z_{g,i}$	width of the $i$ th ground layer	$\text{m}$

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# Introduction

*French version is available in Appendix C*

In earth environmental sciences, the surface represents the interface between the ground and the atmosphere. The thickness of this interface might varies according to the discipline (i.e. meteorology, climatology, hydrology) and the type of surface (i.e. ocean, land) encountered. For meteorological studies, only the first centimeters will be considered, while for hydrology or geology a much large thickness is taken into account. For meteorology/climatology (research interest of the CNRM), it is the place where exchanges of heat, water and carbon happen with the above atmosphere. The aim of its understanding is to be able to simplify and represent these physical processes in numerical models called surface models. These models will then provide the lower boundary conditions to the equivalent atmospheric models with which they are coupled.

At Météo-France, the SURFEX platform (Surface Externalisée) includes all types of surface models: ocean, lake, town and land. For land surface modeling, which is the point of that study, the Land Surface Models (LSMs) are used. They have been evolving for decades and continue to be improved in terms of accuracy and complexity. The model used at Météo-France is the Intéractions Sol Biosphère Atmosphère (ISBA) model, which first version has been established in 1989 by Noilhan and Planton. Since, this model has received many improvements, notably for the representation of soil, snow and carbon cycle processes.

The last development concerns the representation of the vegetation, which strongly impacts the modeled heat and water exchanges, especially in forested areas where vegetation needs to be accurately described as its vertical dimension implies internal and so complex exchanges. In the default version of ISBA, the vegetation is considered as a mix with the upper ground layer in a single composite layer. The latest development consists in an explicit vegetation layer, through a new option called Multi Energy Balance (MEB) (Boone et al. (2017)). The option has been lately modified by adding a new layer, which stands for the litter laying on the ground (Napoly (2016)), with ISBA-MEB-Litter.

In a mid-term futur, the purpose would be to activate the MEB option in the forecast operational system at Météo-France. For this, it first has to be evaluated for any kind of vegetation and climate, in order to justify its robustness. This work has already been carried out for mid latitude forest, notably over France but no focus was made on snow periods which is one of the weakness of the default model ISBA.

Boreal forests constitute the Northern Hemispheres main type of forest and one fifth of its snow-covered region. Its impact on the atmosphere is non negligible and it is crucial to develop efficient numerical models to produce forecasts at short-term scale: for meteorology, as long as at long-term scale: for climatology.

The purpose of this report is to evaluate the contribution of the MEB option in the specific case of forested sites. The study focuses, beyond a global evaluation, on the behaviour of the model during snow periods. The Earth System Model-Snow Model Intercomparison Project (ASM-SnowMIP) (Krinner et al. (2018)) which has been held in 2017 provides observations data of three well-instrumentalized sites from the Boreal Ecosystem Research Study (Berms) located in Canada. Those data will be the base of the whole study held hereafter.

In the first place, a global presentation of Land Surface Models and more precisely ISBA, ISBA-MEB and ISBA-MEB-L and their main features will be set-up. Afterwards, an overall evaluation

of both ISBA and ISBA-MEB-L will be done, leading to a first comparison between the models. The evaluation will next focus on the ability of the models to represent snow processes. The local evaluation will end with a sensitivity test of the new parameters. Finally, the study will test the MEB-L option on a different site, situated in the Alps. It will open up on a comparison of the two models at a global scale.

# Chapter 1

## The surface physical processes and their numerical modelling

This first section will be a presentation of every processes taking place on earth that result from the solar energy. Then, the history of land surface models and their main developments will be developed. An introduction to the model used in this report, ISBA, and its two options applied to forested areas will close this section.

### 1 Surface processes

Solar energy is the source of every processes that can take place on earth, such as vegetation growth, the atmosphere motion or the water cycle. The solar radiation is almost constant at the upper atmosphere, around  $1380 \text{ W.m}^{-2}$ , and its wavelength is in the nearly visible, called shortwave.

When going through the atmosphere, the solar radiation knows multiple reflections, absorptions and transmissions due to each particles which compose the atmosphere. Depending on the geographical position and the composition of the atmosphere, it is possible to determine the amount of energy which will actually reach the surface. It is relevant to insist on the fact that the term of surface can both relate to the only interface between the atmosphere and the ground but can also represent the part of the ground which goes to the roots.

As seen on Fig. 1.1, 19 % of the total energy is absorbed by the atmosphere, 31 % is reflected outside the atmosphere and only 46 % is actually absorbed by the surface. The absorbed energy induces many processes lead by three exchanges cycle which are the energy, the water and the carbon cycle. Those exchanges are linked, notably through the photosynthesis which controls carbon assimilation, plants transpiration and the energy cycle through latent heat release.

The water and the energy cycle are coupled through the evapotranspiration (i.e. composed of the liquid water evaporation, the solid wather sublimation and the plants transpiration), and the latent heat (which is the energy used in the phase changes of water). The carbon cycle is also coupled with the water budget since the carbon regulation happened with the opening of stomata which allows the transpiration of the plant by releasing the water pumped in the ground in the atmosphere. However, the carbon cycle will not be develop in this report even if it has a big impact in terms of climate study.

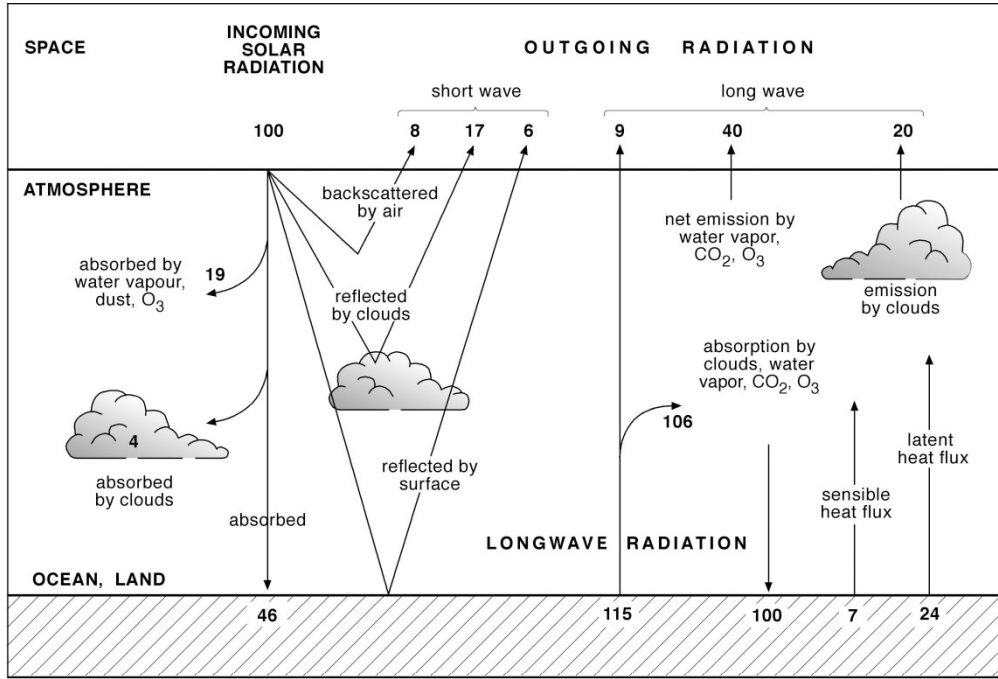


Figure 1.1: The energy cycle on earth. Taken from rosen (1999) and redrawn by Pitman (2003)

## 1.1 Energy budget

This budget is the result of the incoming radiation from the sun and the atmosphere, separating between the energy reflected on the surface and the emission of the surface. It is converted into the latent and sensible heat fluxes, the conductive flux and the storage in the surface layer (see .1.2). The expression of the budget is simply :

$$R_n = H + LE + G + S \quad (1.1)$$

With  $R_n$  the net radiation ( $\text{W.m}^{-2}$ ), composed of the difference between the radiative flux received and the radiative flux reflected and emitted by the surface.  $H$  and  $LE$  are the sensible and latent fluxes ( $\text{W.m}^{-2}$ ),  $G$  the conductive flux ( $\text{W.m}^{-2}$ ) and  $S$  the storage term ( $\text{W.m}^{-2}$ ). The next items will detail each term of Eq. 1.1

### Radiative exchanges

According to Wien's law, the radiation of a black-body is such that  $\lambda_{max} \propto \frac{1}{T}$ , where  $T$  is the temperature of the black-body and  $\lambda_{max}$  its wavelength radiation. Then the sun, with its temperature of approximately 6000 K, will emit in the short wavelength, around  $0.48 \mu\text{m}$ , in the visible range. The earth and the atmosphere, with their temperature of around 300 K, will emit in the infrared range, around  $10 \mu\text{m}$ . Finally, the net budget of the radiative exchanges is a combination of incoming and outgoing longwave and shortwave radiations from the sun, the earth and the atmosphere.

$$R_n = SW_n + LW_n = SW \downarrow - SW \uparrow + LW \downarrow - LW \uparrow \quad (1.2)$$

For each type of wavelength, there is a downward and an upward term.

- For the shortwave domain,

The downward flux ( $SW \downarrow$ ) is the part of the solar radiation that reach the surface. Its value at the top of the atmosphere is around  $1360 \text{ W.m}^{-2}$  but it is attenuated when going through the atmosphere. The highest value appears at the solar noon (around  $900 \text{ W.m}^{-2}$ ) and reaches  $0 \text{ W.m}^{-2}$  at

night.

The upward shortwave (SW $\uparrow$ ) term is the result of the reflection of the downward term on the surface. This term depends on the value of the surface albedo ( $\alpha$ ). The albedo is a characteristic of the surface, depending on its composition (presence or no of vegetation, snow, rocks...), and allows to define the part of the incoming flux which is reflected such as :

$$\alpha = \frac{SW \uparrow}{SW \downarrow} \quad \text{Which allows to deduce that} \quad SW_n = (1 - \alpha)SW \downarrow \quad (1.3)$$

Usual values of albedo for vegetation are 0.2 while it goes from 0.5 to 0.9 for snow.

- For the longwave domain,

The downward flux (LW $\downarrow$ ) is the atmosphere emission, depending on its temperature and its emissivity.

The upward flux (LW $\uparrow$ ) is composed of the emission of the earth and also the reflection of the downward flux on the surface. The reflection is obtained by knowing the emissivity  $\epsilon$  of the surface (LW $\downarrow(1-\epsilon)$ ). The emission of the surface is obtained by using Stefan-Boltzmann, which connects the emission E of a body at a certain temperature T such as  $E = \epsilon\sigma T^4$ , where  $\sigma$  is the Stefan boltzman constant ( $5.67.10^{-8}W.m^{-2}.K^{-4}$ ).

Finally the longwave net budget can be written as :

$$LW_n = \epsilon(LW \downarrow - \sigma T^4) \quad (1.4)$$

### Convective exchanges

The convective exchanges result from the variations in terms of humidity and temperature, and depend on the characteristics of the wind and the atmosphere stability. Two types of convective exchanges exist. One for water exchanges, the latent heat exchange , and one for heat exchanges, the sensible heat exchange . They are described as follows :

$$H = \rho_a C_p \overline{w'\theta'} \quad (1.5)$$

$$LE = \rho_a L_v \overline{w'q'} \quad (1.6)$$

Where H ( $W.m^{-2}$ ) is the sensible heat flux (i.e. heat exchanges), LE ( $W.m^{-2}$ ) the latent heat flux (i.e. water exchanges),  $\rho_a$  the density of air,  $L_v$  the latent heat of vaporization of water ( $J.kg^{-1}$ ) and  $C_p$  the thermal capacity of air at constant pressure ( $J.kg^{-1}.K^{-1}$ ).  $\overline{w'\theta'}$  ( $m.K.s^{-1}$ ) and  $\overline{w'q'}$  ( $m.s^{-1}$ ) are the cinematic flux of heat and humidity respectively. The " ' " describes that it is a fluctuation and the "bar" means that it is a temporal average.

### Conductive exchanges

Conductive exchanges G ( $W.m^{-2}$ ) are the consequence of the thermal transfer which happens in the ground due to different temperatures between two domain in touch. It is the energy that goes through the ground. In this way, it depends a lot on the composition of the ground and especially its amount of water (due to the high thermal capacity of water). Fourier's law gives an expression of G :

$$G = \lambda \nabla T \quad (1.7)$$

Where  $\lambda$  is the thermal conductivity of the ground ( $W.m^{-1}.K^{-1}$ ),  $\nabla$  the gradient operator and T the temperature in Kelvin. The dependance of G on the composition of the ground is because of its conductivity which will vary according to the different components. Generally, the value of G is a lot lower than the other fluxes (radiative or convective) but can not be ignored.

### Storage



Storage is represented by the inner heat variation of the system. For the surface, it takes into account the variation of temperature of the ground, the vegetation and the air. Its expression is:

$$S = C\rho\Delta Z \frac{dT}{dt} \quad (1.8)$$

$C$ ,  $\rho$  and  $\Delta Z$  are the thermal capacity ( $\text{J.kg}^{-1}.\text{K}^{-1}$ ), the density ( $\text{kg.m}^{-3}$ ) and the height (m) of the system respectively.  $T$  is the temperature (K) and  $t$  the time (s). The thermal capacity of the system has a major role in the calculation of the storage for a surface, since it depends a lot on its characteristics. The type of ground and its saturation are the main characteristics which will impact the resistance of the system toward external source of heat.

## 1.2 Water budget

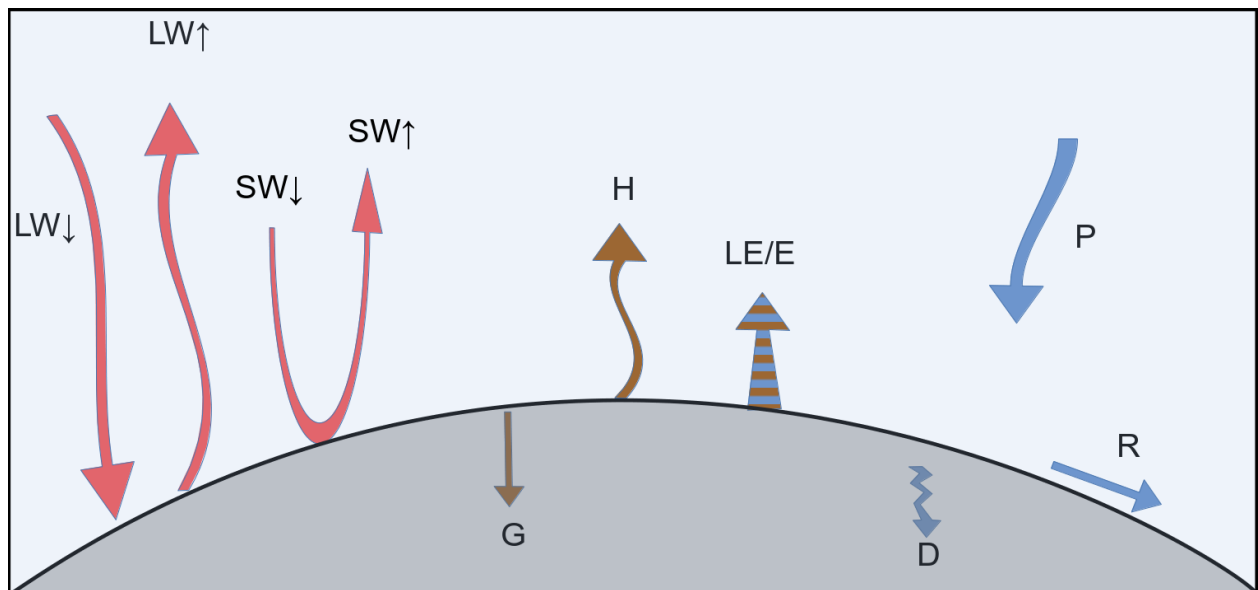
To establish the water budget, it is necessary to define the volume concerned. For the surface, the volume in question is composed of the vegetation (leaves and branches), the ground surface, the underground (with the roots) and the deep underground where can be a potential aquifer.

Considering this volume, the aim of the budget is to know what amount of water will remain in the system through the vegetation or ground interception, and the amount that will leave the system. By adding the inputs and the outputs of the system, the budget is written as :

$$\frac{dW}{dt} = P - E - D - R \quad (1.9)$$

With  $W$  ( $\text{kg.m}^{-2}$ ) the volume of water contained in the volume described above,  $P$  ( $\text{kg.m}^{-2}$ ) the precipitations (liquid and solid),  $E$  ( $\text{kg.m}^{-2}$ ) the evapotranspiration of the system, which is linked to the incoming energy flux and is also present in the energy budget (Eq. 1.1) through  $LE$ , the latent heat flux.  $D$  ( $\text{kg.m}^{-2}$ ) is the drainage of the water in the deep underground, where it leaves the domain, and  $R$  ( $\text{kg.m}^{-2}$ ) is the runoff, the volume of water that is not drained by the ground. The evapotranspiration  $E$  ( $\text{kg.m}^{-2}$ ) of the system is constituted of different processes. There is the evaporation of the intercepted water by the vegetation, the evaporation of the intercepted water by the ground, the transpiration of the vegetation, through the water caught by the roots in the underground, and finally the sublimation of the snow (if there is snow) or the ice on or below the vegetation.

The runoff  $R$  ( $\text{kg.m}^{-2}$ ) can happen in two ways. The first one is when the ground is saturated, then the water cannot infiltrate and must flow on the surface (saturation excess). The second one is when the infiltration capacity of the ground is at its maximum. In this situation, the water cannot infiltrate and then flows on the ground and leaves the domain (infiltration excess).



**Figure 1.2:** Representation of the fluxes which take part in the energy and water budget.

## 2 Surface modelling

### 2.1 Why is it useful to model the surface processes ?

In order to evaluate the different processes explained above, many local measurement tools exist. The problem of those tools is that they are expensive, hard to maintain on the long run and hard to set up on a global scale.

Since the surface is involved in many global processes, an alternative had to be found to allow global scale studies. This alternative is the use of Land Surface Models (LSMs). Thanks to numerical modelling, many parameters of the budgets presented above can be obtained.

There are many types of LSMs, some are more sophisticated, some are used only in precise situations. Three motivations can explain the interest in the use of LSMs :

- The first one is that LSMs can be coupled with atmospheric models in weather forecasting models. They provide the lower limit of the atmospheric model and inform about the energy and mass fluxes outgoing and incoming from the surface domain.

The surface has a key role in various mechanisms, such as the high reflection of the solar radiation during snow period. Its consideration is therefore necessary in weather forecasting models.

- The second motivation concerns the climate studies. While the weather forecast is about the next dozen of days, the climate forecast is the evolution of the weather on at least a hundred years. For those models, LSMs can still be coupled with atmospheric models in order to conduct climate studies.

Dirmeyer (2000) showed that a quality dataset of soil moisture highly improves precipitations simulations. In this way the surface modelling is relevant for climate studies.

Even if the question of the carbon cycle is not detailed in this report, it is relevant to insist on the fact that in climatology the study of carbon has a major role and that the carbon cycle is depending on the surface behavior.

- The last motivation does not concern weather forecast models, but hydrological models. For those models, LSMs provide the upper limit of the domain. It has been shown that the coupling of LSMs with hydrological models provided better results than the classical rainfall-runoff types models, thanks to the better representation of the hydrologic cycle.

At Météo-France, the SAFRAN-ISBA-MODCOU chain (Habets et al.) can give informations about water resources and risks with the hydric composition of soil obtained through ISBA.

In the end, LSMs found their utilities in both weather and hydrology study on short and long time scales. For each topic, it represents a limit and allows to determine the response of the surface toward energy and water fluxes and then deduce the impact on the weather or the hydrology.

### 2.2 History of surface simulation

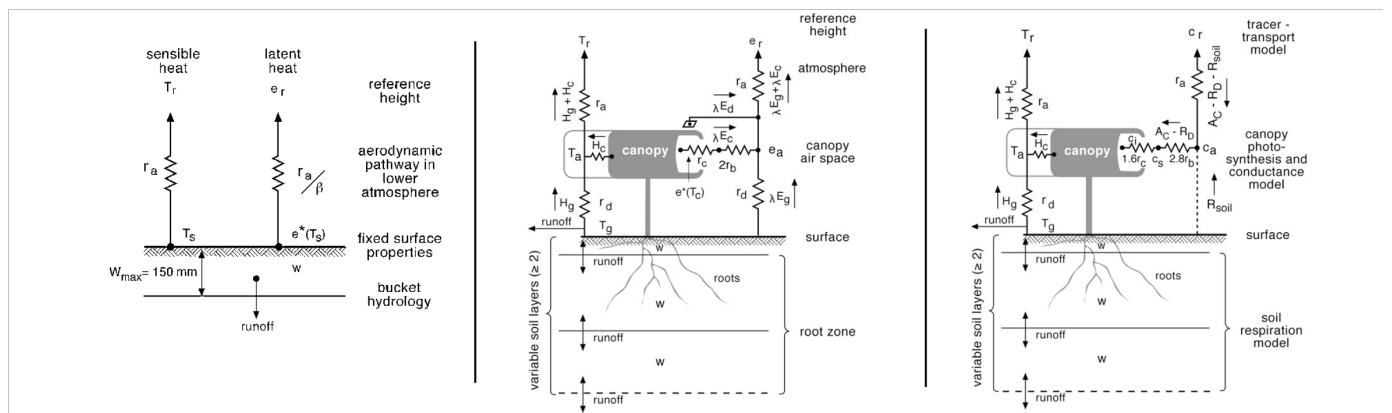
Until the 80s, the only aim of surface models was to provide a low limit for numerical forecast models. Since that day, those models have not stopped evolving (carbon and nitrogen exchanges are now of current interest).

It has been shown that the surface had a big impact on the atmosphere behavior, and it motivated even more the development of surface models. The climatology was also a huge motivation of the advancement of those models. Since the 80s, three periods of models development emerged :

- The first models were aimed to model the interaction between the surface and the atmosphere through a unique equation for the energy budget (Manabe (1969)). The conductive flux was totally ignored and the water budget was described through a single reservoir which received the precipitations and was able to evaporate and overflow when its maximum volume was reached.

They were called *Manabe bucket models* and induced many different models.

- At the beginning of the 80s, it has been realized that vegetation had an important role in the surface processes and that it has to be taken into account. Deardorff (1978) was the first to present a model based on two explicit layers, one for the ground and one for the vegetation. The vegetation's layer was based on the *big-leaf* method, which consists in a representation of the vegetation through a unique leaf that can intercept radiations and then transmit only a fraction of the incoming flux. Over time, processes linked to the vegetation were better represented in the models. The high roughness in forests, water interception and vegetation transpiration regulation were subject to further understanding.
- The last period of improvement concerned the consideration of carbon in LSMs. It appeared during a period of awareness toward the increase of CO<sub>2</sub> in the atmosphere and climate changes. It was linked to the notion of transpiration of vegetation through photosynthesis. Jacobs (1994) was a scheme for the stomatal resistance modeling, involved in the carbon exchanges. It has led to the apparition of A-gs models type.



**Figure 1.3:** Evolution of land surface models. Taken from Pitman (2003).

At the present time, many different types of LSMs exist. There are different types of representation (different schemes for the processes) and complexity. The model ISBA has been first developed by Noilhan and Planton and is relatively simple compared to new models, but it is important to highlight the fact that a higher complexity does not ensure better results. Most of the time a higher complexity leads to more uncertainty on new parameters and ask more computation time.

An inter-comparison of LSMs (PLUMBER, *Protocol for Analysis of Land Surface Models (PALS)* Land Surface Model Benchmarking Evaluation Project, Best et al. (2015)) had the objective to compare 8 models on forced simulation (*offline*, which means that the inputs are observed data and does not come from the coupling with an atmospheric model). The campaign revealed that most of the models led to results of turbulent fluxes that were worse than a simple linear regression on the forced inputs.

In that way, it is really hard to ensure that a more complex representation of some processes will ensure better results. This come from the very complex interactions between each parameters which is not always precisely understood.

### 2.3 The application of land surface models

Since surface models are coupled with atmospheric models, their application scales are relatively close. The use of LSMs is from the regional scale (with around 100 km sided grids) to the global scale, which means at the world scale. But before being used on such scales, every model needs to be evaluate in order to know its different characteristics. The evaluation of models is first made on a local scale on *offline* mode (i.e. on a unique point of the simulation grid with no coupling to avoid retroaction). Those simulations are advantageous in terms of computation time and therefore enable to examine precise aspects of the model.

During the evaluation, a focus can be made on a precise process of a site (type of aquifer, flash flood ...) to examine the response of the model in detail. It is also possible to work on the content of the data set. Indeed, even if the acquisition of data is very sophisticated, some difficulties are hard to overcome and must be taken into account for each simulation. The acquisition of data with remote sensing is also based on algorithms and will therefore bring uncertainties on the obtained data. In that way, each data set contains a certain amount of errors which implies to test the models with a variation of the data set, and then measure its confidence.

Moreover, the data set used at regional or global scales are often not as complete than on the local point used for the evaluation. The data set on higher scale can also provide less precise data due to the fact that each site is not instrumented in the same way. Then, it is relevant to evaluate how would react the model with a dataset that is not complete and then deduce its sensibility towards main parameters.

Once the model is fully evaluated at the local scale, it is run on a regional scale, still on *offline* mode. The aim is to check that it is running well on a higher scale and also to try it on precise zones. After this, the model is evaluated on the global scale.

The last step is to run coupled simulations, to test the potential retroaction of the coupling. It can be made at a global scale (one example is the coupling with ARPEGE (Action de Recherche Petite Echelle Grande Echelle) for climate simulation, S  f  rian et al. (2016)) or with an air-limited model (for exemple with MESO-NH which is an atmospheric model based on mesoscale, used at M  t  o-France).

Meanwhile, there is another way to evaluate the models, which is the intercomparison projects. Those campaigns are based on the comparison of different surface models. The principle is to run blind simulations and then to discover the main issues of the different models. Every participant has to make an *offline* simulation with given inputs without knowing the objectives to reach.

The goal of such campaigns is to bring out the weaknesses of each model, and maybe common weaknesses, which would lead to further studies. One example of intercomparison project is ESM-SnowMIP (Earth Model - Snow Model Intercomparison Project, Krinner et al. (2018)) which goals were to study snow processes on a climate point of view. The project gathered more than 30 different models to lead its study.

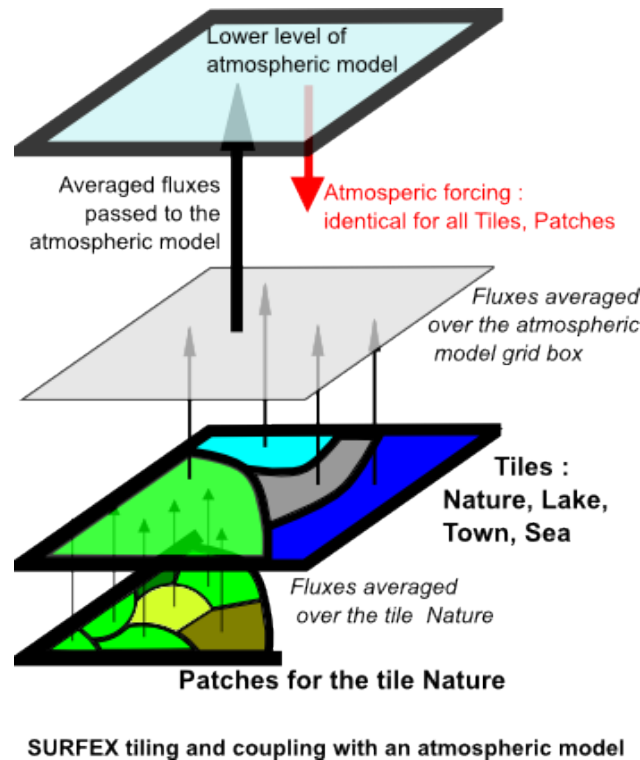
To conclude, surface modelling is used on various scale (local, regional, global) and each of these represents different issues. Once the model is setted up, the evaluation step is primordial to understand its features.

### 3 SURFEX

SURFEX (SURface EXternalis  e) is the platform used at M  t  o-France which gathers every developments towards surface modelling. It is the result of years of developments at the CNRM. SURFEX includes the model covered in this report; ISBA.

SURFEX (Masson et al. (2013)) receives from the atmosphere the forcing that it needs to operate; solar and infrared radiation, rain, snow, humidity, wind, pressure, temperature and returns the data needed by the atmospheric model.

But before returning them, the data are weighted according to the fraction of the different tiles of the domain. There are 4 types of tiles which are : lake, sea, town and nature (Fig. 1.4). The data returned to the atmospheric model are; the momentum, sensible heat and latent heat for the turbulence scheme and radiative characteristics (i.e. albedo, surface temperature) for the radiative scheme.



**Figure 1.4:** Representation of the different types of tiles considered in SURFEX.

The models used for each tiles are briefly described below :

- Sea : The most common models for this tile are based on the Carnock approach; they use a surface temperature to simulate surface fluxes.
- Town : The model used in SURFEX for this tile is called TEB (Town Energy Balance) (Masson (2000)). The method of the model is the "Canyon-Street" scheme. In this scheme, the town is represented as a single street, one roof and two walls facing each other. It is a very efficient way to consider towns and the model knows continuous improvements (such as the consideration of vegetation in towns).
- Lake : For this tile, the model FLake (Mironov et al. (2005)) is used. It gives the surface temperature with a good estimation of energy exchanges in the water and water exchanges between the lake and the atmosphere.
- Nature : The tile Nature is the most complex. The ISBA model considers 19 "tiles" (called *patches*) due to the high variety of cover on the continental area (from the dense forest to the bare ground). For each patch, specific parameters are prescribed.

In this section, the focus will be made on ISBA and the two options that have been developed to study forested areas. The different models features will be presented and the most important equations will be displayed in this order :

- The standard version, that will be called ISBA.
- The new option MEB, (*Multi Balance Energy*) which allows to explicitly describe the canopy.
- The last development that has been made, MEB-L, which considers an explicit layer for the litter laying on the ground.

Note that in each equations, every parameters won't be fully detailed since the aim of this part is to understand the global mechanism of each model. For more details, it is recommended to see Masson et al. (2013), Napoly et al. (2016) and Boone et al. (2017).

### 3.1 ISBA

#### 3.1.1 The basis of ISBA

The first version of ISBA (Noilhan and Planton (1989)) was based on a simplified vegetation scheme. The consideration of the vegetation is done through a single ground-vegetation composite layer (see Fig. 1.5), containing the properties of both the ground and the vegetation. The parameters of the vegetation and the ground are weighted with the fraction  $veg$  of vegetation that occupies the cell where the calculation is done. The model knew some major improvements that will be used in this report and are described below :

- The ground was firstly described with two layers according to the *force restore* method. The current version uses a multi-layer (the default number is 14 but this parameter can be manually chosen) representation based on Richards equation (DIF option, described in Boone et al. (2000), Decharme et al. (2011)).
- The snow scheme was based one the *bucket* method (Manabe (1969), see Section.2.2). The present version uses a multi-layer snow scheme using 12 layers (ISBA-ES, Boone and Etchevers (2001), Decharme et al. (2016)).
- The consideration of the soil's organic matter is possible (Decharme et al. (2016)) with a modification of the thermal and hydrological characteristics of the soil's layers. Two depth intervals are considered; 0 - 30 cm and 30 - 100 cm, and the HWSD (Harmonized World Soil Database) database (Nachtergaele and Batjes (2012)) provides a global map of the concentration in organic matter.

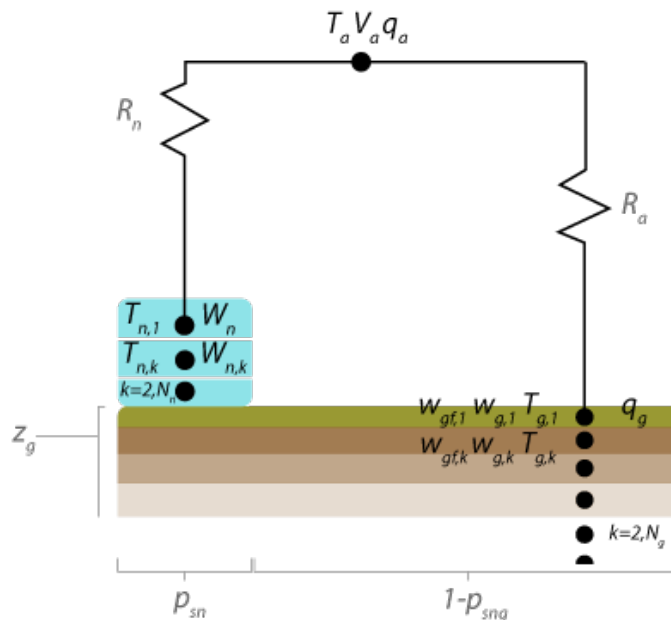


Figure 1.5: Representation of the ISBA model configuration.

#### 3.1.2 ISBA model presentation

##### Energy budget

The variation of temperature on the surface implies the conservation of the energy on the surface. For the ground-vegetation composite (which will be called 'soil') layer and the snow surface, the energy budget is expressed as follow :

$$C_s \frac{dT_s}{dt} = Rn_s - LE_s - H_s - G_s + L_f \Phi_s \quad (1.10)$$

$$C_{n,1} \frac{\partial T_{n,1}}{\partial t} = Rn_n - H_n - LE_n - \tau_{n,1} SWn_n + \xi_{n,1} - G_{n,1} + L_f \Phi_{n,1} \quad (1.11)$$

Where  $T_s$  (K) is the temperature of the composite soil (i.e. the first ground layer) and  $T_{n,1}$  (K) the temperature of the uppermost layer of snow. Note that the subscript indicates the uppermost layer or the base layer (for fluxes) for the soil and snowpack.  $C_s$  and  $C_{n,1}$  ( $J.K^{-1}.m^{-2}$ ) are the effective heat capacities of the composite soil and upper snow layer.

$Rn_s$  and  $Rn_n$  ( $W.m^{-2}$ ) correspond to the net radiative fluxes for the soil and the snowpack, respectively. In the same way,  $LE_s$ ,  $LE_n$ ,  $H_s$  and  $H_n$  ( $W.m^{-2}$ ) are the latent and sensible heat fluxes for these layers.  $G_{s,1}$  and  $G_{n,1}$  ( $W.m^{-2}$ ) are the conductive fluxes between the first layer of soil and the first layer of ground and between the two first layers of snow, respectively.

Part of the incoming shortwave radiation received by the snowpack ( $SWn_n$ ) is transmitted through the uppermost snow layer to underneath layers, and this energy loss is expressed as  $\tau_{n,1} SWn_n$ , where  $\tau$  is a dimensionless transmission coefficient.

$\xi_{n,1}$  represents the effective heating or cooling of a snowpack layer caused by exchanges in enthalpy between the surface and sub-surface model layers when the vertical grid is reset (the snow model grid-layer thicknesses vary in time).

Finally, the phase change terms (freezing less thaw, expressed in  $kg.m^{-2}.s^{-1}$ ) are represented by  $\Phi_s$  and  $\Phi_n$ , and  $L_f$  represents the latent heat of fusion ( $J.kg^{-1}$ ).

### Turbulent fluxes

For the sensible heat flux  $H$ , the expression is basically :

$$H = \rho_a c_p C_H V_a (T_s - T_a) \quad (1.12)$$

Where  $\rho_a$  ( $kg.m^{-3}$ ) is the air density,  $c_p$  ( $J.kg^{-1}.K^{-1}$ ) is the thermal capacity of air,  $V_a$  ( $m.s^{-1}$ ) the wind speed,  $C_H$  a dimensionless coefficient (depending on the atmosphere thermal stability and the surface roughness),  $T_a$  (K) the atmosphere temperature and  $T_s$  the surface (i.e. average between the composite layer and snow) temperature.

The latent heat flux is a bit more complex since the source of latent heat are various. Due to that complexity, the different terms equations will not be detailed here. The different terms that compose the total latent heat flux (LE) are; the evaporation flux from the ground, the sublimation and evaporation fluxes of water (solid and liquid) on the ground, the vegetation transpiration flux (the water is directly pumped from the roots in the ground) and the vegetation evaporation flux of the intercepted liquid precipitations.

The addition of those terms results in the total evapotranspiration flux. Note that the intercepted solid precipitations are not considered in the calculation. This was one motivation which led to the new option MEB, in order to have a better simulation of the snowpack (see Section. 3.2.1).

### Conductive flux

In ISBA, there are four types of equation for the conductive fluxes. The first one is for the conductive flux between the different ground layers, the second one between the snowpack layers and the third and fourth one are for the interface between the composite layer and the first layer of ground and between the last layer of the snowpack and the composite layer. As an example, the equation at

the interface between the composite layer and the first layer of ground is :

$$G_{g,1} = \frac{2(T_s - T_{g,2})}{(\Delta z_{g,1}/\lambda_{g,1}) + (\Delta z_{g,2}/\lambda_{g,2})} \quad (1.13)$$

With  $G_{g,1}$  the conductive flux between the two first layers of ground,  $T_s$  and  $T_{g,2}$  (K) the temperature of the first two layers ( $T_s$ , the temperature of the composite layer, is the surface temperature),  $\Delta z_{g,1}$  and  $\Delta z_{g,2}$  (m) the width of each layer and  $\lambda_{g,1}$  and  $\lambda_{g,2}$  ( $\text{W.m}^{-1}.\text{K}^{-1}$ ) the thermal conductivity of each layer.

The other equations follow the same expression, always involving the temperature, the width and the thermal conductivity of the two layers concerned.

## Radiative Transfer

As shown in Eq. 1.2, the calculation of  $R_n$  includes the calculation of  $SW_n$  and  $LW_n$  and therefore the calculation of the albedo  $\alpha$  and the emissivity  $\epsilon$ . In ISBA, those two parameters need to take into account the fraction of vegetation and ground in the composite layer. Thus, the computation of the effective albedo ( $\alpha_{eff}$ ) is achieved by weighting the contribution of each surface:

$$\alpha_{eff} = p_{sn}\alpha_n + (1 - p_{sn})[veg\alpha_v + (1 - veg)\alpha_g] \quad (1.14)$$

With  $\alpha_n$ ,  $\alpha_v$  and  $\alpha_g$  the snow, vegetation and ground albedos, respectively. The same method is applied to calculate the effective emissivity ( $\epsilon_{eff}$ ) of the surface:

$$\epsilon_{eff} = p_{sn}\epsilon_n + (1 - p_{sn})[veg\epsilon_v + (1 - veg)\epsilon_g] \quad (1.15)$$

with  $\epsilon_n$ ,  $\epsilon_v$  and  $\epsilon_g$  the snow, vegetation and ground emissivity.

## Water budget

In ISBA, the water budget is split into two equations. The first one belongs to the water budget of the canopy (i.e. the variation of water in the reservoir of the canopy) and the other one is for the ground.

The equation for the variation of the canopy water reservoir is :

$$\frac{\delta W_r}{\delta t} = vegP_r - E_r - D_r \quad (1.16)$$

Where  $w_r$  is the amount of water contained in the canopy reservoir ( $\text{kg.m}^{-2}$ ),  $t$  the time (s),  $veg$  the fraction of vegetation,  $P_r$  the precipitations ( $\text{kg.m}^{-2}.\text{s}^{-1}$ ),  $E_r$  the evaporation ( $\text{kg.m}^{-2}.\text{s}^{-1}$ ) of the water trapped into the canopy and  $D_r$  the water drainage, which means the water that exceeds  $W_{rmax}$ , the maximum amount of water that can be contained in the canopy. This maximum is defined as :

$$W_{rmax} = 0.2vegLAI \quad (1.17)$$

Where LAI is the Leaf Area Index, a parameter which represents the surface covered by all the leaves of a tree over one unit of ground area. This value can go to 2 up to 10 for very dense trees. To complete the water budget, it is necessary to establish the water budget of the ground, which receives the precipitations that goes through the canopy and the overage. The equation for the first layer is :

$$\rho_w \Delta z_{g,1} \frac{\delta w_{g,1}}{\delta t} = (1 - veg)P_r + D_r - E_g - R - F_{g,1} - \frac{\Phi_{g,1}}{L_m} \quad (1.18)$$

With  $\rho_w$  the density of water ( $\text{kg.m}^{-3}$ ),  $\Delta z_{g,1}$  the layers' width,  $w_{g,1}$  the amount of water contained in the layer ( $\text{m}^3.\text{m}^{-3}$ );  $E_g$  the water evaporated ( $\text{kg.m}^{-2}.\text{s}^{-1}$ ),  $R$  ( $\text{kg.m}^{-2}.\text{s}^{-1}$ ) the runoff. Note that there are two types of runoff that are described in Decharme and Douville (2006) and in Section. 1.2.  $F_{g,1}$  is the water flux between the first layer and the second layer of ground ( $\text{kg.m}^{-2}.\text{s}^{-1}$ ), obtained



with Darcy's law. Finally  $\frac{\Phi_{g,1}}{L_m}$  is the phase changes term (freezing less melting) ( $\text{kg}\cdot\text{m}^{-2}\cdot\text{s}^{-1}$ ). Note that in ISBA, the aquifer is not considered, neither in ISBA-MEB.

### The snow fraction

The effective fraction of the grid cell covered by snow ( $p_{sn}$ ) is the average between the fraction of snow covering the vegetation and the one covering the ground. It is calculated using the *veg* parameter such as:

$$p_{sn} = vegp_{snv} + (1 - veg)p_{sng} \quad (1.19)$$

with

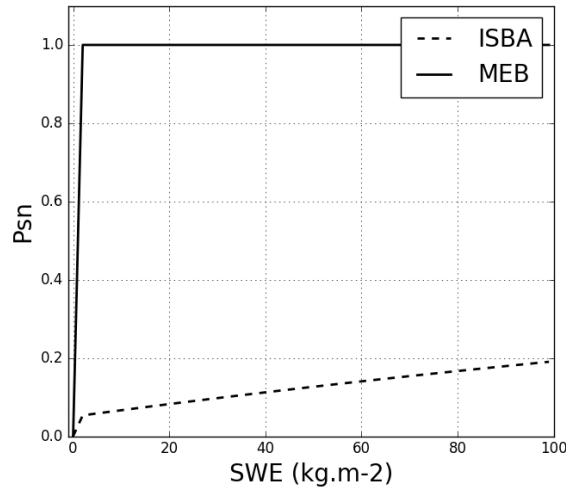
$$p_{snv} = \min(1.0, \frac{D}{D + 2z_0}) \quad (1.20)$$

and

$$p_{sng} = \min(1.0, \frac{SND}{D_g}) \quad (1.21)$$

where the  $p_{snv}$  and  $p_{sng}$  values correspond to snow fraction over the vegetation and the ground respectively, SND is the snow depth (m). The *veg* parameter is set to 0.95 for the studied forests,  $z_0$  (m) corresponds to the surface roughness which is calculated as 0.13 times the vegetation height and  $D_g$  (m) is a snow depth threshold set to 0.01 m.

This notion of snow fraction is significant in this report. Indeed, in the case of forests, since the surface roughness for a forested area is high, the maximum value of snow fraction barely reaches 20% as shown on Fig. 1.6.



**Figure 1.6:** Snow fraction for different values of snow water equivalent (*SWE*) for *ISBA* and *MEB* over a forest of 11 meters height.

### Other processes

Some processes won't be precisely detailed due to their high complexity. A short description is made below and for more details see the articles presented.

- Snow processes are modelled with the Explicit Snow (ES) scheme developed by Boone (2002). It is based on a multi-layer snow model.
- The multi-layer ground model (DIF) (Boone et al. (2000), Decharme et al. (2011)) allows to calculate the temperature and the humidity variation in each layer.

- For the carbon exchanges, a notion of stomatal resistance (Calvet and Soussana (2001)) is used. A notion of radiative transfer inside the canopy has been developed in order to calculate the carbon fluxes. This option, detailed in Carrer et al. (2013b), especially raises the notion of Photosynthetically Active Radiation (PAR), which represents the amount of incoming radiation that will actually serve the photosynthesis.

## 3.2 ISBA-MEB

### 3.2.1 The contributions of an explicit canopy layer.

Over time, measuring methods knew a huge development. The number of measurement sites and the parameters that can be measured increased a lot, covering more and more places in the world. The number of satellites considerably increased too, allowing to get huge data sets for the models. Those improvements made possible to set up more detailed models, with more complex representation of some processes.

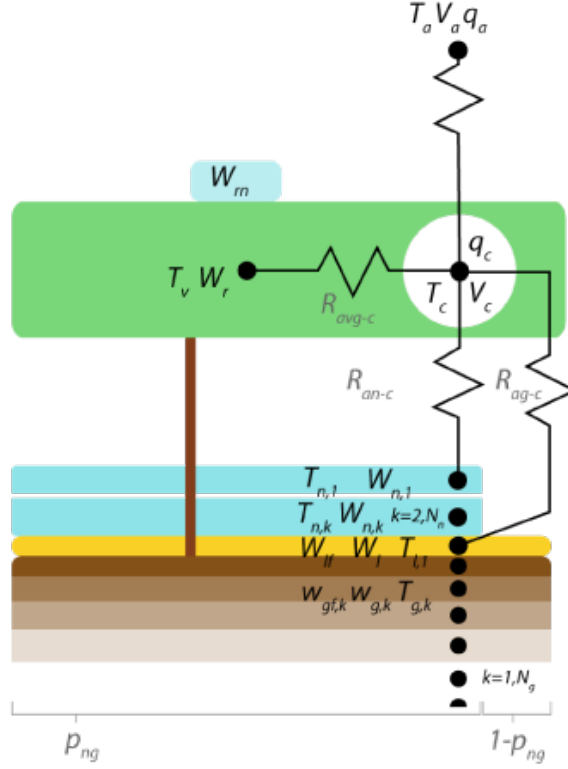
In 2008, a collaboration for the development of an explicit vegetation layer in ISBA started. It assembled the CNRM (Centre National de Recherche Météorologiques) and the SMHI (Swedish Meteorological and hydrologic Institutue) under the international consortium HIRLAM (High Resolution Limited Area Model) and the CESBIO (Centre D'Etude Spatiales de la Biosphere). The main reasons of this development were :

- Since the value of the temperature on the ground and in the canopy are very different (in terms of amplitude and phase), it was relevant to distinguish the temperature of the snow, of the ground and of the vegetation.
- The canopy has a huge impact on the snowpack, since it can intercept and unload significant amount of snow. Also the density of the foliage will affect the snow melt rate because it impacts the amount of radiation that can actually go through the canopy (Rutter et al. (2009)).
- The improvement of the modeling of the carbon cycle. Mainly with an explicit vegetation temperature and a better separation of the evapotranspiration in the different layers. The modeling of the carbon cycle is much better represented with an explicit vegetation with a proper temperature. Also the separation of the canopy from the ground allows to separate the evapotranspiration terms in the different layers in a more realistic way.
- Finally, further developments might need a detailed canopy such as the separation between enlightened leaves and those in the shade or a two levels canopy layer, for the high and low vegetation.

It is in this context that the idea of an explicit layer for the canopy in ISBA emerged. The new option MEB (Multi Energy Balance) took his name from the fact that the consideration of an explicit vegetation layer would give explicit variables for each layer (vegetation, ground and snow), while it was a simple weighting in ISBA.

### 3.2.2 MEB model presentation

The MEB option uses the *big leaf* method which consists in a representation of the canopy with only one leaf. This method has been used and validated in many situation, such as the model SiSPAT (Braud et al. (1995)) or for coupled simulation with the atmosphere (Xue et al. (1991)).



**Figure 1.7:** Representation of the MEB option configuration.

Without snow, the model is a double source model, with only one energy budget for the vegetation and one for the ground. Note that the notion of vegetation can concern the small vegetation (grass) and the high vegetation (forests). Also, there are two snow reservoir. The one that represents the snow on the ground and the one for the intercepted snow. For small vegetation, the ground based snow can exceed the height of the vegetation. Finally, on Fig. 1.7 , the point C represents a fictive zone with explicit characteristics. Those characteristics results from a weighting of the different variable from the ground, the snow and the vegetation and acts as an intermediary before the exchange with the atmopshere.

### Energy budget

The concept remains the same as for ISBA (see Eq.3.1.2). The equation is the same for the snow layer. The difference is that when there was one equation for the composite layer in ISBA, there are two explicit layers in MEB, for the ground and the vegetation. Therefore, the budget is written as :

$$C_v \frac{\partial T_v}{\partial t} = Rn_v - H_v - LE_v + L_f \Phi_v \quad (1.22)$$

$$C_l \frac{\partial T_{g,1}}{\partial t} = (1 - p_{sng})(Rn_{g,1} - H_{g,1} - LE_{g,1}) + p_{sng}(G_{n-g} + \tau_{n,N_n} SWn_n) - G_{g,1} + L_f \Phi_{g,1} \quad (1.23)$$

$$C_{n,1} \frac{\partial T_{n,1}}{\partial t} = Rn_n - H_n - LE_n - \tau_{n,1} SWn_n + \xi_{n,1} - G_{n,1} + L_f \phi_{n,1} \quad (1.24)$$

Where  $T_v$  and  $T_{g,1}$  are the temperature (K) of the vegetation and the first ground layer.  $C_v$  and  $C_l$  correspond to the effective heat capacity ( $J.K^{-1}.m^{-2}$ ) of the vegetation and the ground.  $Rn_v$ ,

$Rn_{g,1}$ ,  $H_v$ ,  $H_{g,1}$ ,  $LE_v$  and  $LE_{g,1}$  ( $W.m^{-2}$ ) are respectively the net radiation, the sensible heat flux and the latent heat flux of the vegetation and the litter.

$G_{n-g,1}$  ( $W.m^{-2}$ ) describes the conductive exchange from the last snow layer and the ground.  $G_{g,1}$  ( $W.m^{-2}$ ) is the conductive flux between the two first ground layers.

As in the equation of Section. 3.1.2, there are terms of phase changes (freezing less melting, expressed in  $kg.m^{-2}.s^{-1}$ ),  $\Phi_v$  and  $\Phi_{g,1}$ , for the vegetation and the ground respectively.  $L_f$  represents the latent heat of fusion ( $J.kg^{-1}$ ). A part of the incoming shortwave radiation received by the snowpack is transmitted through the uppermost snow layer to underneath layers. This energy loss is expressed as  $\tau_{n,n}SWn_n$ , where  $\tau$  is a dimensionless transmission coefficient and  $SWn_n$  is the net shortwave radiation incoming of snow.

### Turbulent fluxes

The sensible flux is the sum of four different terms. The sensible flux from the vegetation to the canopy, the one from the snow to the canopy, the one from the ground to the canopy and finally the one from the canopy to the atmosphere. They won't be expressed there since only the global sensible flux  $H$  resulting from the sum of each terms will be use. The equation of this term is :

$$H = \rho_a[(1 - p_{na}p_{sng})\frac{T_c - T_a}{R_{ac-a}} + p_{na}p_{sng}\frac{T_n - T_a}{R_{an-a}}] \quad (1.25)$$

With  $\rho_a$  the air density ( $kg.m^3$ ),  $p_{na}$  and  $p_{sng}$  the vertical dimension of the snow fraction (the part of snow that covers the vegetation) and the snow fraction on the ground respectively,  $T_c$  and  $T_a$  ( $J.K.kg^{-1}$ ) are thermodynamic variable and depend on the atmospheric model with which MEB is coupled. Finally  $R_{ac-a}$  and  $R_{an-a}$  are the resistance between the canopy and the atmosphere and between the snow and the atmosphere (Louis (1979), modified by Mascart et al. (1995)). They allow to take into account the fact that the roughness changes when it is about heat exchanges or momentum exchanges.

In the same way, the latent fluxes are separated in 4 main terms. The global evapotranspiration term,  $LE$ , is the sum of the evaporation from the ground, the evapotranspiration of the vegetation, the sublimation of the snow intercepted by the canopy but also the snow under the canopy and finally the flux between the "intermediary" canopy and the atmosphere. The global expression is :

$$LE = \rho_a[(1 - p_{na}p_{sng})\frac{q_c - q_a}{R_{ac-a}} + p_{na}p_{sng}h_{sn}\frac{q_{satin} - q_a}{R_{an-a}}] \quad (1.26)$$

Where  $LE$  is the total evapotranspiration flux to the atmosphere,  $q_a$  ( $kg.kg^{-1}$ ) is the specific humidity of the atmosphere,  $q_c$  is the specific humidity of the canopy air,  $q_{satin}$  is the specific humidity for snowpack saturation, which depends on the temperature and the pressure of the snowpack. The other parameters are already explained above.

### Conductive flux

There are equations for the conductive flux in the snowpack and the ground. There is also one equation for the conductive flux at the interface between the last layer of snow and the first layer of ground. For the interface and other layers of ground and snow, the equations follow the same formulation as in Eq. 1.13, using the parameters of each layer that exchanges.

### Radiative fluxes

With an explicit canopy layer, SW and LW radiation has to go through one more layer. Therefore, the radiative budget becomes more complex since more reflections and transmissions occur. The hypothesis is done that each ray can be reflected only one time, since another reflection would

represent only a few percentage of the main radiation. The effective albedo is modified such as :

$$\bar{\alpha}_{gn} = p_{sng} + (1 - p_{sng})\alpha_g \quad (1.27)$$

With  $\bar{\alpha}_g$  the effective albedo of the ground and  $\alpha_g$  the albedo of the ground. The canopy albedo should be a weighting of the vegetation albedo and the intercepted snow albedo but the impact of snow on the canopy albedo is supposed to be negligible according to the results of Pomeroy and Dion (1996). They indicated that the scattering and multiples reflections of light due to intercepted snow, combined with the high probability for the reflected light to reach the underside of an overlying branch, implies that trees actually behave as light trap. In this way, they concluded that intercepted snow has no significant impact on the canopy shortwave albedo or on the net radiative exchange.

The effective emissivity of the surface is modified such as :

$$\bar{\epsilon}_s = p_{sng}\bar{\epsilon}_{sn} + (1 - p_{sng})\bar{\epsilon}_{sg} \quad (1.28)$$

Where  $\bar{\epsilon}_s$  is the effective emissivity of the surface,  $\bar{\epsilon}_{sn}$  the effective emissivity of the snow (which is a weighting of the emissivity of the vegetation and the emissivity of the snow), and  $\bar{\epsilon}_{sg}$  the effective emissivity of the ground (which is a weighting of the emissivity of the vegetation and the emissivity of the ground).

One process which will be studied later is the radiative transfer through the vegetation for LW. Indeed, the longwave radiations that goes through the canopy have a huge impact on the snowpack in terms of magnitude and delay, and this is a significant point in this report.

The radiative transfer for longwave radiation is a relatively simple model fully described in section 2.4.2. of Boone et al. (2017). It is based on a representation of the canopy as plane and parallel surface. It is mostly driven by the canopy absorption defined as:

$$\sigma_{LW} = 1 - \exp(-\tau_{LW}LAI) \quad (1.29)$$

Where LAI corresponds to the leaf area index ( $\text{m}^2.\text{m}^{-2}$ ) and  $\tau_{LW}$  to a coefficient that will be investigated in the sensitivity tests section (2.2). Its value is set to 0.4 as default, following sensitivity tests presented at the end of the study. The LAI is a very important parameter in this study. It represents the total leaves area per unit of ground. For very dense forests, it can go up to 10.

The radiative transfer for short wave radiation is detailed in Carrer et al. (2013a). It is a more complex multi-layer model that account for different characteristics of the vegetation such as the leaf area index, the clumping index, the thickness of the leaves or the zenithal angle.

## Water budget

In this section, the full water budget is expressed. Even if the equations are a bit complex and detailed, they allow to understand well how does the consideration of an explicit canopy layer impacts the model. Some parameters are common with the water budget in ISBA (see Eq. 3.1.2), but most of them are new. Five water reservoirs are considered and they are described below :

$$\frac{\partial W_r}{\partial t} = P_{rv} + \max(0, -E_{tr}) - E_r - D_{rv} - \Phi_v \quad (1.30)$$

$$\frac{\partial W_{rn}}{\partial t} = I_n - U_n - E_{rn} + \Phi_v \quad (1.31)$$

$$p_{sng} \frac{\partial W_{n,1}}{\partial t} = P_s - I_n + U_n + p_{sng} (P_r - P_{rv} + D_{rv} - F_{nl,1} - E_n + \Phi_{n,1} + \xi_{nl,1}) \quad (1.32)$$

$$\rho_w \Delta z_{g,1} \frac{\partial w_{g,1}}{\partial t} = (P_r - P_{rv} + D_{rv} - E_g) (1 - p_{sng}) + p_{sng} F_{nl,N_n} - R_0 - F_{g,1} - \Phi_{g,1} \quad (1.33)$$

$$\rho_w \Delta z_{g,1} \frac{\partial w_{gf,1}}{\partial t} = \Phi_{g,1} - E_{gf} (1 - p_{sng}) \quad (1.34)$$

Where  $W_r$  and  $W_{rn}$  represent the vegetation canopy water stores: intercepted water, and the intercepted snow and frozen water (all in  $\text{kg}\cdot\text{m}^{-2}$ ), respectively.  $W_{n,1}$  represents the snow liquid water equivalent (SWE) for the uppermost snow layer of the multi-layer scheme. The soil liquid water and solid water (in liquid water equivalent) content are defined as  $w_g$  and  $w_{gf}$ , respectively ( $\text{m}^3 \text{m}^{-3}$ ).

$P_{rv}$ ,  $P_s$  and  $P_r$  ( $\text{kg m}^{-2}\cdot\text{s}^{-1}$ ) are the liquid precipitations intercepted by the vegetation, the solid precipitations intercepted by the vegetation and the total liquid precipitations, respectively. The solid water intercepted by the vegetation is  $I_n$  ( $\text{kg m}^{-2}\cdot\text{s}^{-1}$ ) (Note that all the next parameters have the same unit ( $\text{kg m}^{-2}\cdot\text{s}^{-1}$ ) and therefore it will not be precise for more visibility)

$E_{tr}$  is the transpiration of the vegetation, through the pumping of the water from the roots.  $E_r$  is the evaporation of the intercepted water.  $E_{rn}$  represents the sublimation of the intercepted solid water.  $E_n$  describes the sublimation of the solid water contained in the first layer of snow.  $E_g$  is the evaporation of the liquid water in the first layer of ground (litter). Finally  $E_{gf}$  represents the sublimation of the solid water contained in the first layer of ground. It is obvious that the evaporation fluxes have already been presented in 3.2.2 since the water and energy budget are linked by the evaporation fluxes.

$D_{rv}$  is the drip of liquid water through the vegetation (already seen in Eq. 3.1.2).  $U_n$  represents the unloading of snow from the vegetation.  $R_0$  is the surface runoff.

$\Phi_v$ ,  $\Phi_{n,1}$  and  $\Phi_{g,1}$  are the phase changes terms of the intercepted precipitations, the water contained in the first layer of snow and the water contained in the first layer of ground. It has a positive value when there is more freezing than thawing and reciprocally.

The last parameters concern the liquid water fluxes that flow between the layers.  $F_{nl,1}$ ,  $F_{g,1}$  and  $F_{nl,N_n}$  are the vertical fluxes of water at the base of the first layer of snow, the one at the first layer of ground and the last one is the vertical flux at the base of the last layer of snow, respectively.  $F_{g,1}$  is obtained using Darcy's law and  $F_{nl,1}$  is obtained by using a tipping-bucket scheme.

As a reminder, note that a description of the snow and soil schemes are given in (Boone and Etchevers (2001)) and (Decharme et al. (2011)), respectively.

## New snow processes

MEB also uses the ES scheme. The impact of the MEB option on snow processes compared to the default ISBA are the following:

- Only the snow fraction over the ground is considered so that the snow fraction simply becomes:

$$p_{sn} = p_{sng} = \min(1.0, \frac{D}{D_g}) \quad (1.35)$$

Since the vegetation and the ground are now explicitly separated, there is no point in considering two snow fractions. Note that when snow depth becomes comparable with the height of the vegetation, another parameter, described in Boone et al. (2017), is introduced as snow might even exceed it. However, it is not relevant in that study as it deals with forest vegetation.

- The fluxes from the snowpack are calculated using the specific humidity and temperature of the so called canopy layer (Fig. 1.7) instead of the forcing air layer when using ISBA (Fig. 1.5).
- The sublimation of the snowpack is reduced through a coefficient to take into account the attenuation of the wind speed due to vegetation.
- A snow reservoir over the canopy is considered, including interception and unloading of snow, freezing of liquid water and melting of snow.

## Resistances

Each flux between two distinct layers (i.e. ground-canopy, canopy-atmosphere, with and without snow on the ground or on the canopy) is subject to a resistance in MEB (see Fig. 1.7). Those resistances are various but they are needed to be as realistic as possible in order to represent the different processes. Some of those resistances are :

- The aerodynamic resistance for the vegetation,  $R_{av-c}$ , is a weighting of the situation with and without snow reaching the canopy. It represents the resistance for the flux between the vegetation and the canopy (i.e. the point C on Fig. 1.7).
- The aerodynamic resistance for the ground,  $R_{ag-c}$ , between the ground and the canopy (with or without snow), is based on Choudhury and Monteith (1988). Its expression is complex and will not be detailed but there is one parameter which is involved in this resistance that will be studied in the sensibility section. This parameter,  $\frac{Z_{oh}}{Z_{og}}$ , is the ratio between the turbulent fluxes roughness and the ground roughness.

### 3.3 ISBA-MEB-L

#### 3.3.1 Description of the litter

To present this new option, it is first necessary to present the different characteristics of the litter and why it would be relevant to model it explicitly. In forested areas, the ground is composed of various components and different layers can be defined. The deepest one is the bedrock, then comes the substratum, the subsoil, the surface and finally the litter. From the bedrock to the surface, the amount of organic matter increases. The litter is composed of various types of plants, fruits, woods, corpse of animals... and represents the undecomposed organic matter. The litter is continuously decomposing and alimanted by the fauna and flora of the forest. It covers the ground almost all the time and can weight some kilograms to tons/ha/year.

The litter is therefore the source of multiple processes, mainly due to the transformation of organic matter. But the litter also acts as a significant protecting layer. It retains efficiently the evaporation from the ground. This impact is used in agriculture in order to keep the ground wet. Also the litter is a great insulating material. Since it has a huge porosity (there is mainly air in it), the temperature can hardly go through it. Then in winter the soil is less cold and in summer the soil is less hot.

The consideration of an explicit layer for the litter has been developed and validated in Napoly (2016). The motivation of this project was mainly due to the fact that there were no global model which considered an explicit layer for the litter. However some research were made on a local scale and different methods to model the litter came out and three methods emerged.

The first one consists in using a resistance to the evaporation flux (Sakaguchi and Zeng (2009)). The second, which is the one that is used in ISBA-MEB-L, is to add an explicit layer with precise properties. The advantage of such a method is that both the hydrological and the thermal budgets can be considered. The last one is to use a multi-layer model. It is the most complex method and should be use for high litters (Gonzalez-sosa et al. (1999)).

#### 3.3.2 Model modifications

The litter layer is modeled according to some hypothesis. The main ones are presented below.

- Each precipitation coming from the canopy is intercepted by the litter before reaching the ground. The litter will let pass the water only once it is saturated.
- If a litter layer is considered, the evaporation flux of the ground is supposed null. It is replaced by an evaporation term of the litter. Also there is no capillarity exchanges between the ground and the litter.

- The litter layer is homogeneous and the litter's width is supposed constant.

There is a few new equations in MEB-L. One is for the evolution of the litter's temperature and two are for the amount of solid and liquid water in the litter.

Those equations will not be detailed in this section but the main impact will be described. For the equation of the variation of the litter's temperature, it follows the formulation of Eq. 1.23. The parameters that will change are those that were calculated with the ground thermal characteristics. However, there are no new parameters.

For the liquid water content of the litter, the main differences with Eq. 1.33 are due to the fact that the only water exchange between the litter and the first ground layer is when the litter is saturated. The liquid water content in the first layer of ground is alimented only by the drip of the litter and the thaw.

In conclusion, the consideration of the litter in ISBA-MEB has a major impact on the ground in terms of temperature and water content.

Since now, everytime MEB is called, it means the ISBA-MEB-L option. When ISBA is called, it refers to the default ISBA model. Also, when the first ground layer is called, it relates to the litter for MEB and for the composite layer for ISBA.





## Chapter 2

# Evaluation at a local scale : The Berms sites

This section will present the local evaluation of the new MEB option compared to the default ISBA version. First, a precise presentation of the data sets that are used for each simulation will be made. The study will then focus on the comparison between ISBA and MEB results on the main variables that have been presented above. The local evaluation will end with a sequence of sensibility tests on relevant parameters.

### 1 Available data

The Earth System Model-Snow Model Intercomparison Project phase2 (ESM-SnowMIP2) was based on 10 different reference sites in order to provide a consistent dataset. Three of those sites were taken from the Boreal Ecosystem Research Study (BERMS) which consists in a twelve year (01/01/1999 - 31/12/2010) observational period for three distinct Canadian forest sites. Those sites, presented in Bartlett et al. (2006), constitute the database of all the simulations present in this part.

#### 1.1 The Berms sites

At first, the sites were used for the BOREAS (Boreal Ecosystem-Atmosphere Study) project (1994 - 1996) and then, in 1996, the Berms project began, using the same sites.

The Berms sites consist in three local measurement sites. They are located in the Northern Hemisphere, in the Canadian Boreal forest, in Saskatchewan. Their physical characteristics are described in Tab. 2.1. The three sites, called Old ASpen (OAS), Old Jack Pine (OJP) and Old Black Spruce (OBS), are precisely described below :

- OAS : This site is dominated by 21 m averaged Old ASpen which naturally regenerated after fire in 1919. A large 2 m height understorey composed of hazelnuts is present. The ground is characterized by a peat soil over sandy clay loam and supports a 8-10 cm litter.
- OBS : The Old Black Spruce is the main tree of the site, which peaks at an average of 12 m. But there are also some tamarack ( 10%), a small amount of jack pine and balsam poplar. The understorey is made of shrubs and herbs, mosses and lichens in some dry areas. The soil contains, in humid areas, a hummock-hollow topography, standing on sandy loam and sand, where the water table is raised.
- OJP : The Old Jack Pine site, naturally regenerated after fire in 1915, is approximately 14 m high and is composed of a very sparse understorey (alder, bearberry, cranberry and lichens), laying on a coarse sandy soil.

Only the Old Aspen trees are deciduous. OBS and OJP sites are composed of conifers. This characteristic is significant in this report since for a deciduous tree the radiative transfer is much higher when the trees lost their leaves.

The three sites are instrumented for measuring a lot of meteorological parameters. Depending on the parameter, it can be measured on the surface or above the canopy. The parameters and their measurement methods are detailed in Fig. 2.2. The characteristics for each site used in the different simulations are presented in Appendix A.

Values were obtained through direct measurements on each site or through a database. ECO-CLIMAP is a database used at Météo-France which consists in a 1 km resolution and provides multiple set of land surface parameters. The VEGTYPE is the type of vegetation that is informed in the model (i.e. the patch in Sec. 3). The vegetation and soil albedos are defined for the near infrared (NIR) and for the visible (VIS) wavelengths. HWSD has already been presented in Sec. 3.1.1.

Table 2.1: *Main physical characteristics of the sites.*

Site	OBS	OJP	OAS
Forest type	Black Spruce	Jack Pine	Aspen
Location ( )	53.99N, 105.12W	53.92N, 104.69W	53.63N, 106.2W
Canopy height	11	13	21
LAI (m <sup>2</sup> .m <sup>-2</sup> )	T3.5-3.8	2.5-2.6	winter = 1 & summer = 3.7-5.2
Snow Free Albedo	0.08	0.11	0.14

Table 2.2: *Measured parameters at the Berms sites. The HMP45c contains a Resistance Temperature Detector and Relative Humidity Sensor. The SBP270 sensor is a Barometric Pressure Sensor.*

Site	OBS	OJP	OAS
SW↑ / SW↓	Pyranometers		
LW↑ / LW↓	Pyrgeometers		
Temperature and wind fluctuation	3D sonic anemometers		
Water vapor and CO <sub>2</sub> fluctuation	Infrared gas analyzers		
H / LE / CO <sub>2</sub>	Eddy covariance method		
Air temperature and humidity	HMPC45C probes		
Wind speed	Anemometers		
Surface air pressure	SBP270 sensor		
Precipitations	Weighing rain gauges		
Soil moisture	Time domain reflectometers probes		
Soil temperature	Time domain thermocouples		
Snow Depth	Ultrasonic snow depth sensors		

## 1.2 Simulations

The observations data are obtained for a 12 years period, from the 1st of January 1999 at 00:00 to December the 31st 2010 at 23:30 UTC. Almost all the data were obtained on a half-hourly time step over the full period. Some parameters such as the ground water amount (WG) or the SWE were obtained at a different time step. WG were measured every 4 hours while the SWE was manually measured up to 6 times a year.

The conductive flux observations for the OAS and OBS sites were unavailable. Also, the measurements depth of ground parameters (water, temperature, ice...) were not always the same, but all the results presented below are for measurement depths available on each sites.

The output data were obtained at a half hourly time step too, from the first of October 1997 00:00 to the first of October 2010. Therefore, the last 3 months of 2010 were not available in the model output.

An example of a typical NAMELISTE used for the simulations is available in Appendix A. The NAMELISTE regroups all the information needed by the model to compute.

Before being used, the dataset needed some modifications toward some parameters measurements. The SW flux below the canopy had unavailable data during snow times and for high amplitude (around noon). The latent and heat fluxes had to take into account the energy balance closure.

### Energy closure

The energy balance is based on Eq. 1.2. Therefore the ratio of the closure (see the equation below) should ideally be equal to one. However, Wilson et al. (2002) concluded that the balance closure became acceptable over 80 %. The energy balance closure on these sites has been calculated as:

$$closure = \frac{mean(H + LE)}{mean(Rn - G)} \quad (2.1)$$

The storage is not considered here but it is assumed to be negligible in average compared to net radiation. The ground heat flux was supposed to be equal to 5% of Rn, since it was not available for each site. The energy balance closure was found to be very satisfying as shown in Tab. 2.3.

Table 2.3: *Closure of the energy balance for each of the studied sites.*

Site	OBS	OJP	OAS
Closure (%)	84	91	90

The corrected values of H and LE, in order to obtain a closure of 100 %, were obtained by using the Bowen ratio method. This method is detailed in Appendix A. Those corrected values has been used to establish an interval and reinforce the results (see Fig. 2.2).

### Shortwave flux under the canopy

The observation of SW that passes through the canopy and reaches the ground (SWGND) was derived from the Photosynthetically Active Radiation (PAR). Each day, around midday, measurement errors occurred due to a direct radiation flux on the sensor, leading to absurdly high values. To solve this problem, the data were filtered two times on the basis of a sliding average over three points, excluding values over a certain cap such as:

$$\text{If } abs[SW_g[i] - 0.5(SW_g[i - 1] + SW_g[i + 1])] > 100 W.m^{-2} \text{ Then } SW_g[i] = NaN \quad (2.2)$$

with *NaN* beeing an invalid value.

On the same parameter, it has been realized that during snow periods the values were extremely low. This was due to the lack of a frost and snow cleaning system on the PAR sensor. The decision was made to invalidate each value measured during snow periods.

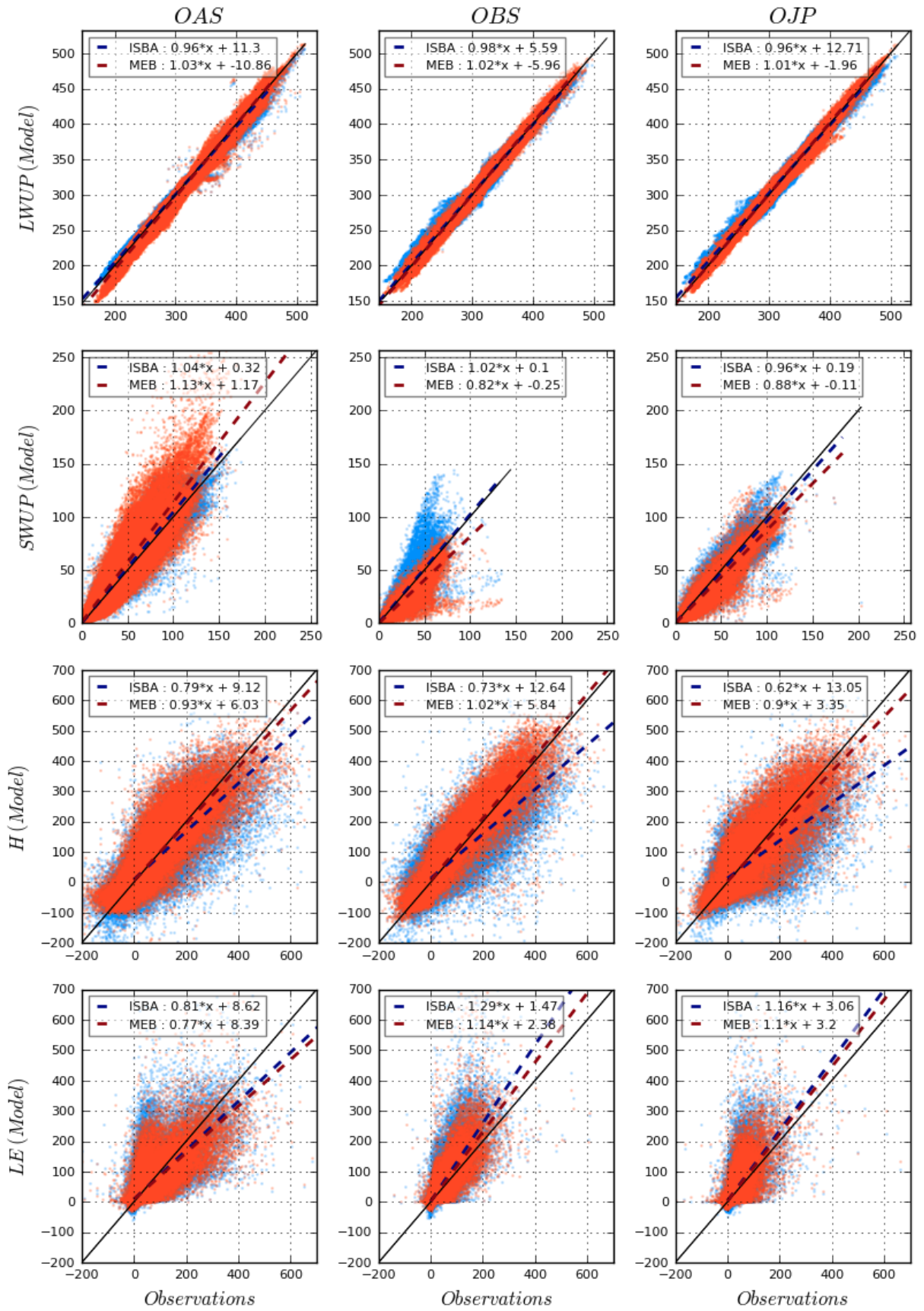
## 2 Results

To evaluate the new option, an evaluation on fluxes, soil variables and the snowpack is carried out. The fluxes and soil variables evaluation will be based on average data. The snowpack evaluation will first present a general aspect and then a focus on precise periods will be made, in order to understand the exact behavior of the models. Finally, a sensitivity analysis is performed to test the new introduced parameters that are the most likely to influence the different processes.

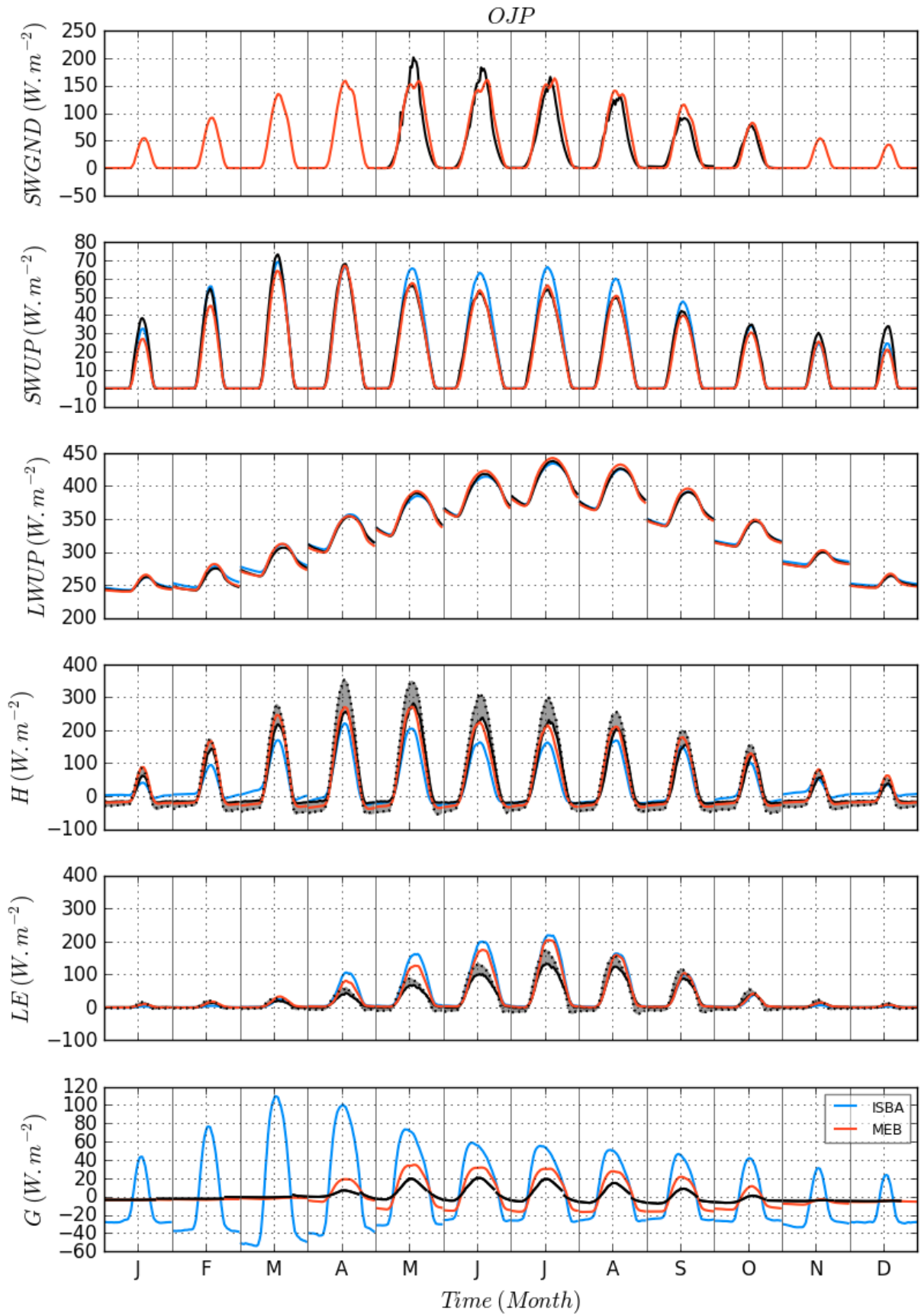
*Each time a figure will be cited, it will be for the OJP site in order to lighten the content of the section. However, all the figures for the other sites will be displayed in the Appendix B. It might be necessary to redirect to these document for some specific results.*

## **2.1 Evaluation**

### **2.1.1 Energy Fluxes**



**Figure 2.1:** Scatter plots performed on the different fluxes and the three sites using only observations with snow on the ground. MEB is in red, ISBA in blue.



**Figure 2.2:** Composite of monthly diurnal cycle at OJP site. MEB is in red, ISBA in blue, measurements are indicated by a solid line and adjusted measurements are represented using a dashed black line.

The simulation of the upward shortwave radiation (SWUP) is relatively close between the two experiments (Fig. 2.1, Fig. 2.2) and leads to rather good results compared to the observations, with averaged RMSE over all sites and years of 7.7 and 7.1  $\text{W.m}^{-2}$  for MEB and ISBA respectively (Tab. 2.4).

Improving the modeling of the reflected solar radiation would mostly consists in improving the quality of the input parameters, which are the albedos (soil / vegetation and visible / near infrared) and LAI.

At the deciduous OAS site, in winter, the LAI is low (about 1.0) and the SWUP is overestimated. We suspect that a stem area index (SAI) should be explicitly considered to lower the effect of snow below the canopy on the effective albedo, especially on such a forest of 22 m height. This would be consistent with results from Napoly et al. (2016).

The solar radiation that passes through the canopy is only modeled with the new MEB option. When data were available, the simulation of the radiation that crosses the canopy is acceptable (Fig. 2.2,a). Unfortunately, the quality of the data was not sufficient enough when LAI was low at the OAS deciduous site (Sec. 1.2). to confirm the assumption of the SAI.

In winter, solar radiation remains low and barely affects the surface energy balance so that this issue is solved for the moment.

Sensible heat flux (H) is well simulated over the three sites with MEB compared to ISBA with an average RMSE of 48.4  $\text{W.m}^{-2}$  (respectively 58.9  $\text{W.m}^{-2}$ ) and average BIAS of 4.1  $\text{W.m}^{-2}$  (respectively -1.0  $\text{W.m}^{-2}$ ). This results are consistent with Napoly et al. (2016) who showed that the large overestimation of the ground heat flux diurnal amplitude from ISBA, confirmed in this study (Fig. 2.2,f), results in a lack of energy in turbulent fluxes and mostly in H. This overestimation is largely decreased with MEB due to the shielding effect of the canopy and the insulating effect of the explicit litter layer. It impacts directly the conductive flux G from the first to the second layer of the ground which has a RMSE of 10.9  $\text{W.m}^{-2}$  with MEB against 47.1  $\text{W.m}^{-2}$  with ISBA. During snow periods, this improvement is even stronger due to the presence of the snowpack and this is investigated in the next section.

Simulations are also improved for the latent heat flux (LE) with an average RMSE of 37.1  $\text{W.m}^{-2}$  for MEB and 47.3  $\text{W.m}^{-2}$  for ISBA and an average BIAS of 6.6  $\text{W.m}^{-2}$  for MEB and 9.9  $\text{W.m}^{-2}$  for ISBA. The main differences appear during spring period where ISBA tends to overestimate the global evapotranspiration through the soil evaporation as a 5% soil fraction is prescribed (Tab. 2.4, Tab. 2.5) whereas MEB limits it with a later melt of the snowpack, as explained in the next section, and the presence of the explicit litter layer.

Table 2.4: *RMSE for the ISBA-MEB and ISBA experiments for fluxes SWUP, LWUP, H, LE and G calculated over half hourly data.*

RMSE ( $\text{W.m}^{-2}$ ) (MEB / ISBA)	OBS	OJP	OAS	Period
SWUP	5.6 / 5.8	5.7 / 6.4	11.8 / 9.0	Full Period
	6.1 / 6.9	6.2 / 6.5	12.5 / 8.1	Snow Period
LWUP	6.1 / 6.7	5.5 / 5.6	7.4 / 5.6	Full Period
	6.7 / 7.0	5.2 / 6.1	7.4 / 5.2	Snow Period
H	47.1 / 57.0	49.4 / 65.9	48.7 / 53.7	Full Period
	43.1 / 53.7	46.2 / 60.1	46.1 / 50.8	Snow Period
LE	35.9 / 48.8	37.5 / 48.4	37.8 / 44.7	Full Period
	25.9 / 34.2	24.5 / 30.1	33.0 / 38.7	Snow Period
G	No data	10.9 / 47.1	No data	Full Period
		5.9 / 50.1		Snow Period

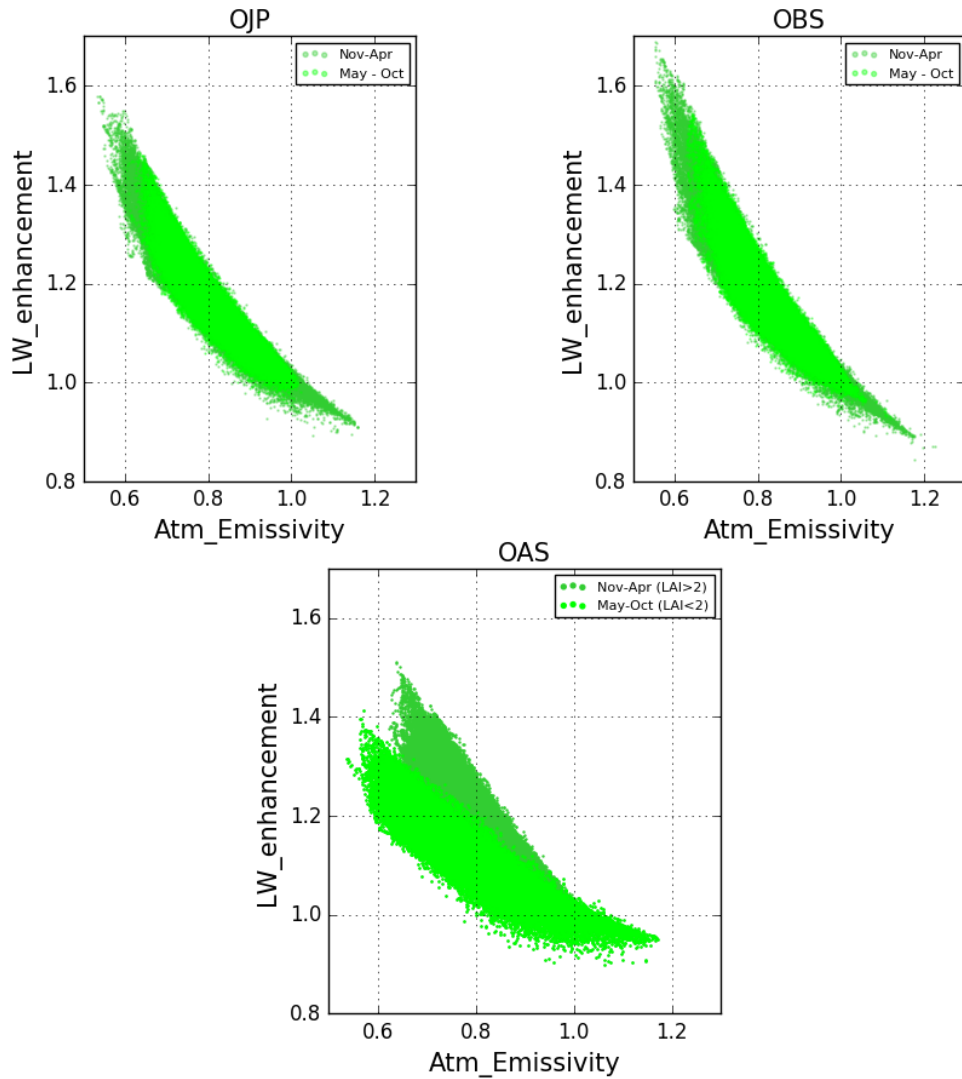


Table 2.5: *BIAS for the ISBA-MEB and ISBA experiments for fluxes SWUP, LWUP, H, LE and G calculated over half hourly data.*

BIAS ( $\text{W}\cdot\text{m}^{-2}$ ) (MEB / ISBA)	OBS	OJP	OAS	Period
SWUP	-2.1 / 0.1	-1.4 / 0.7	2.8 / 1.7	Full Period
	-2.3 / 0.4	-2.0 / 0.6	3.5 / 0.8	Snow Period
LWUP	0.5 / 0.7	0.8 / 1.3	-2.1 / -0.4	Full Period
	0.2 / 1.3	1.0 / 2.6	-2.8 / 0.1	Snow Period
H	7.9 / 0.4	-1.6 / -6.0	6.0 / 2.6	Full Period
	6.8 / 4.6	1.9 / 4.5	5.0 / 5.1	Snow Period
LE	7.8 / 12.4	8.4 / 11.4	3.6 / 5.8	Full Period
	4.0 / 4.6	3.6 / 3.2	2.9 / 3.5	Snow Period
G	No data	0.2 / 1.1	No data	Full Period
		-0.2 / -3.6		Snow Period

Beyond the evaluation of the different fluxes, a similar result as in Todt et al. (2018) has emerged during the study. Todt et al. (2018) worked on the notion of longwave enhancement. It is the process that leads to a higher LW flux under the canopy due to the SW flux intercepted by the canopy. Indeed, this interception causes the canopy to warm up and therefore to emit a higher LW flux. The LW enhancement is represented by the ratio between the LW emitted by the atmosphere and the LW under the canopy. Todt et al. (2018) showed that there were a relation between the LW enhancement and the atmosphere emissivity.

Its study was based on various observations that were not available on the Berms sites, however, by plotting those values, it appears that the exact same shape was found. Fig. 2.3 represents the LW enhancement according to the atmosphere emissivity and allows to confirm that a relation exists between those parameters. Note that the shape are a bit different between OAS and the two other sites. This is due to the fact that OAS trees are deciduous and therefore, the LW enhancement cannot be higher in winter since only the trunks can contribute to the canopy LW emission. For the two other sites, there is a noticeable distinction between the warm period (May - Oct) and the cold period (Nov - Apr). During cold period, the atmosphere becomes very dry and does not allow clouds formation and the emissivity of the atmopshere gets lower.

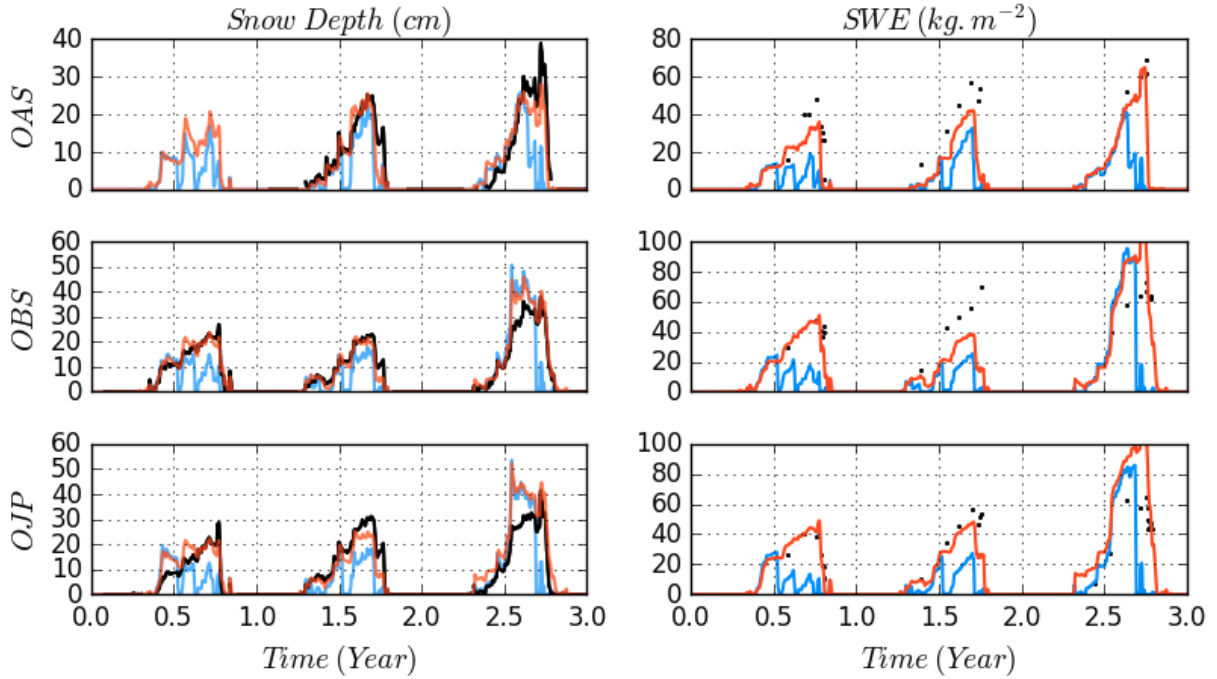


**Figure 2.3:** *LW enhancement according to the atmosphere emissivity on the three sites, over the full period. The snow period (Nov - Apr) is in dark green.*

### 2.1.2 Snow

To evaluate the ability of the model to represent the snowpack below the canopy, Fig. 2.4 shows snow depth (SND) and snow water equivalent (SWE) evolution over three years of the studied period (mid 2001 to mid 2004) (full period is available in Appendix B). The ISBA simulation leads to unsatisfying modeling of the average snowpack with an average RMSE of 9.1 cm and BIAS of -1.6 cm (Tab. 2.7).

The melting of the snowpack happens too early in the spring season. Tab. 2.6 indicates the last day of snow BIAS when comparing simulation to measurements. The last day of snow was considered when, for the first time in the snow season, the two following conditions were satisfied : (i)  $SND \leq 2$  cm and (ii)  $MEAN(SND \text{ over the next } 30 \text{ days}) \leq 2$  cm. This allows to determine quite accurately the melting period of the snowpack without being mistaken by a possible late snow event. Tab. 2.6 shows the average and standard deviation of the BIAS between modeled and observed last day of snow. With the ISBA option, snow melts in average 24 days too early using that score.



**Figure 2.4:** Snow depth (left column) and snow water equivalent (right column) for the three sites from 07/02/2001 to 07/02/2004. MEB is in red, ISBA in blue and observations in black.

Table 2.6: Average and standard deviation of the BIAS between model and observations of the last day of snow expressed in number of days. The OAS site has only six years of snow observations compared to nine for both the OBS and OJP

	OBS	OJP	OAS
ISBA - MEB	$-1.5 \pm 3.8$	$4.5 \pm 5.5$	$-6.2 \pm 11.4$
ISBA	$-25.0 \pm 12.1$	$-20.7 \pm 7.4$	$-26.7 \pm 4.0$

Using MEB allows to correctly simulate the fluxes showed in the previous section as well as the snowpack with an average RMSE of 5.1 cm and BIAS of 0.5 cm Tab. 2.7. The most important effect appears in springtime where MEB allows to melt the snowpack later with an average BIAS in last snow day of only 1 day too early.

The few values of the SWE allow to confirm the good representation of the timing of snow melt. Also Fig. 2.4 seems to indicate that the density of the snow is correct since underestimation or overestimation of SND and SWE are consistent.

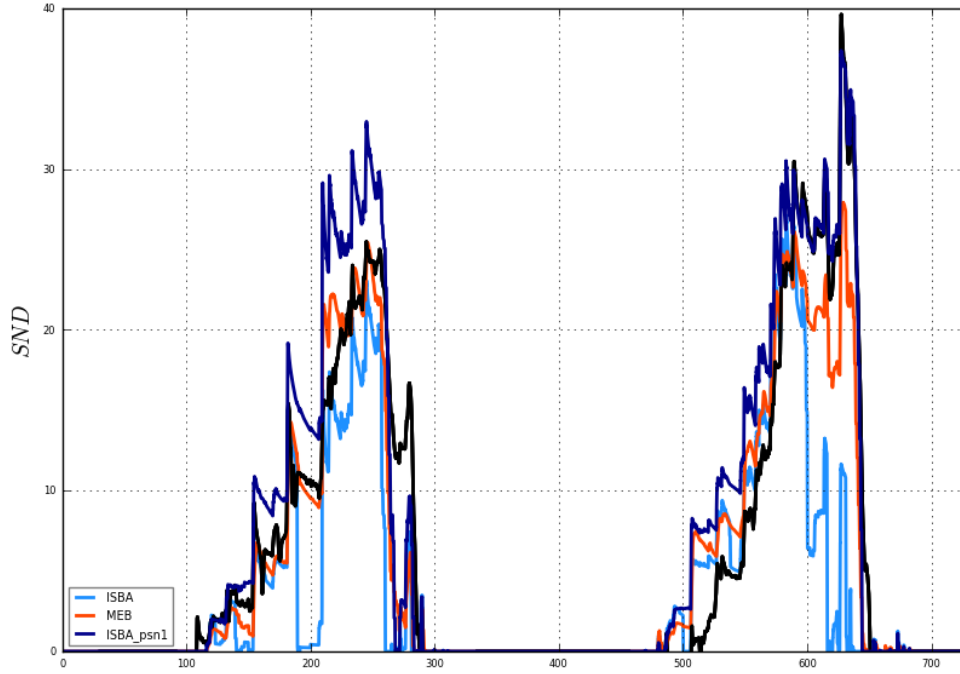
Table 2.7: RMSE and BIAS for the ISBA-MEB and ISBA experiments for snow depth calculated over half hourly data.

(MEB / ISBA)	OBS	OJP	OAS
RMSE (cm)	3.7 / 8.6	4.5 / 8.3	7.2 / 10.4
BIAS (cm)	0.0 / -2.0	1.5 / -0.9	0.1 / -2.0

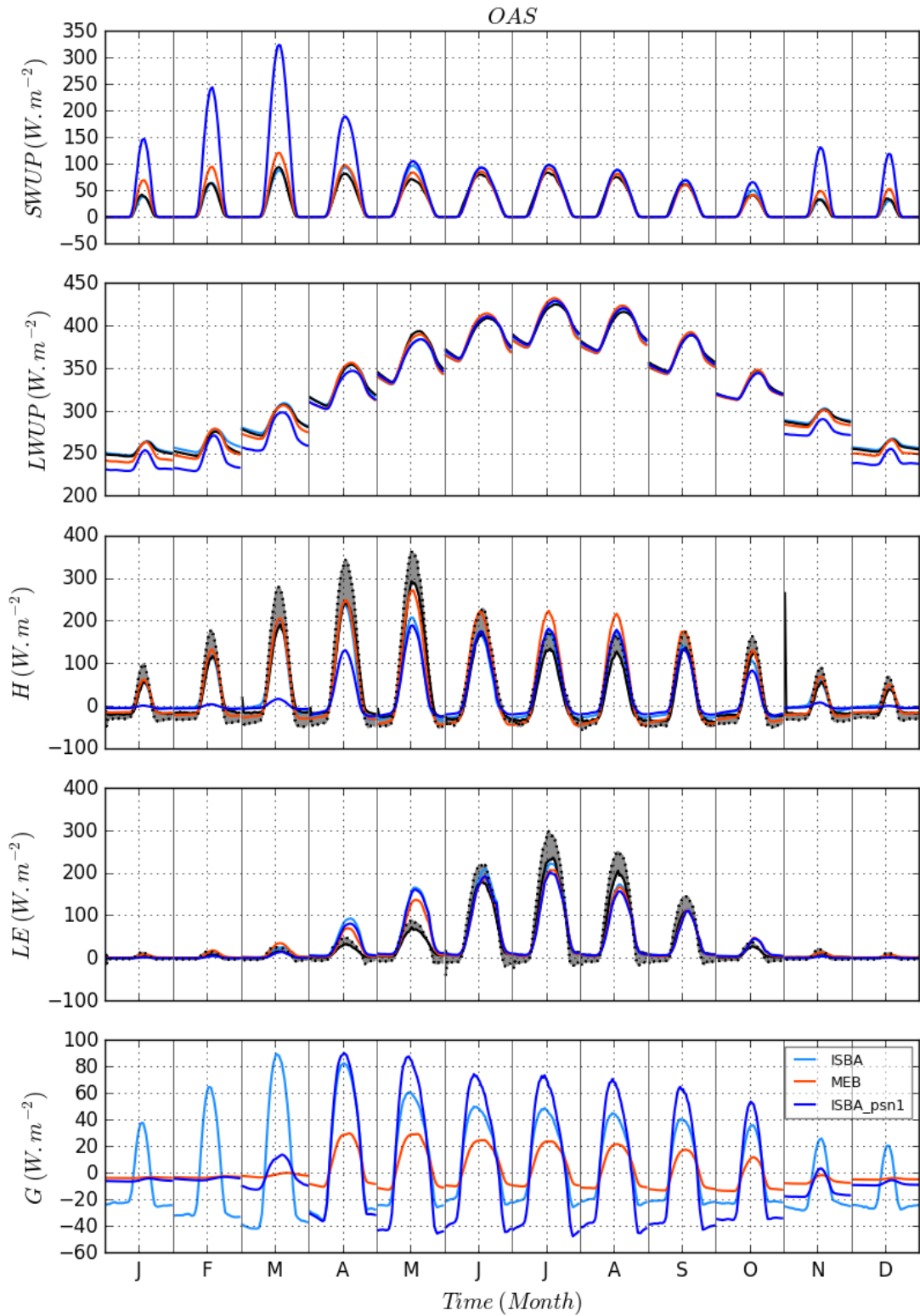
One study based on a simulation of ISBA but with a snow fraction forced at 1 led to a very interesting result. Basically (Fig. 1.6), the snow fraction in ISBA is very low, so the impact of a snow fraction forced at 1 should be significant. Fig. 2.5 represents SND for the 2003 - 2005 period on the OAS site. The snow melt period is a lot more realistic with this feature, with an average last snow day of 5 days earlier, while it was 27 days with default ISBA.

However, Fig. 2.6 shows that the energy budget for this option is totally corrupted, especially SWUP. Indeed, since the snow fraction is forced to 1, the surface in ISBA is seen as a fully

snow-covered surface, thus with a very high albedo, while it should be hidden by the vegetation. Therefore, even if the snowpack knows a huge improvement in its representation, this option is not valuable since it fakes the energy budget. This allow to conclude on the huge role of the snow fraction for the snow melt process which will be detailed below.



**Figure 2.5:** Representation of *SND* during 2003 - 2005 period. Observations are in black, *MEB* in red, *ISBA* in blue and *ISBA* with snow fraction forced at 1 in dark blue.



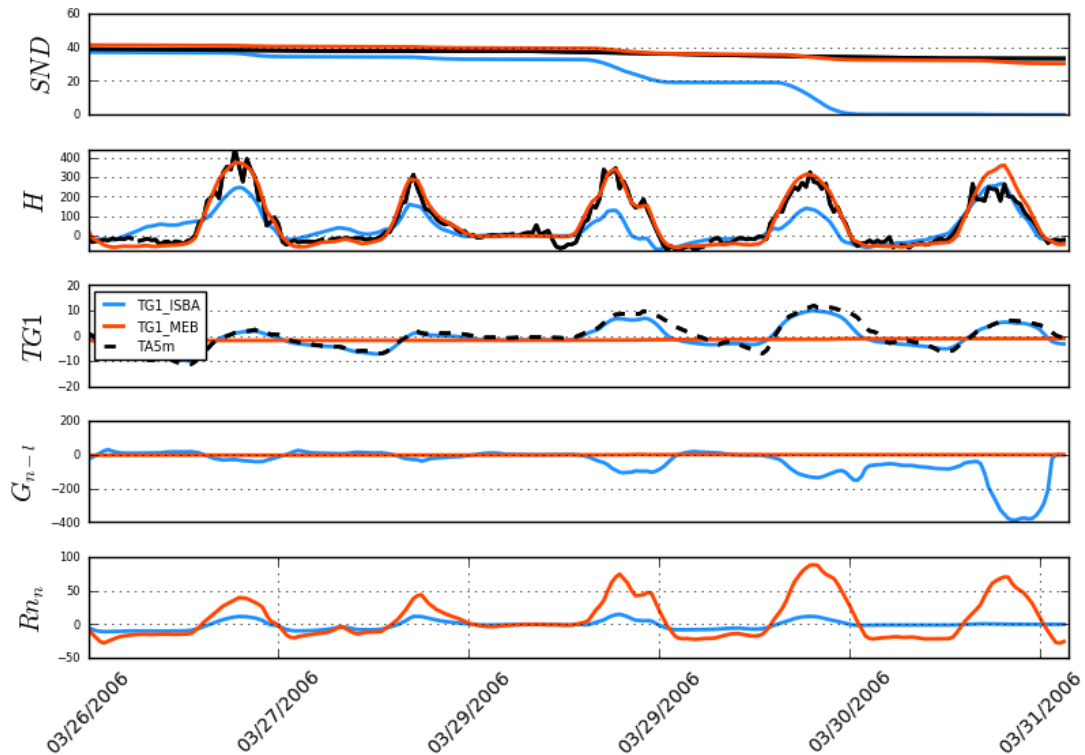
**Figure 2.6:** Composite of monthly diurnal cycle at OAS site. MEB is in red, ISBA in blue, measurements are indicated by a solid line and adjusted measurements are represented using a dashed black line. The dark blue line stands for a simulation with ISBA but with the snow fraction forced at 1.

To better understand the differences of the snowpack modeling, Fig. 2.7 displays different parameters at the OJP site from 03/25/2004 to 03/31/2004 which corresponds to a melting period. It is essential to be aware that the snow melt rate is largely associated to the LW flux received while the SW flux has a very low contribution. In consequence, the albedo of the snow is high for SW (0.7 to more than 0.9 for clean snow) and very low for LW (less than 0.1).

The strong overestimation of the ISBA surface soil temperature fluctuations is obvious (Fig. 2.7,c) and leads to strong conductive heat flux between the soil and the snowpack (Fig. 2.7,d) of hundreds of  $\text{W}\cdot\text{m}^{-2}$ , which is unrealistic compared to net radiation (Fig. 2.7,e). This is explained by the relatively low fraction ( 10%, see Eq. 1.19) occupied by the snowpack for a forest in the composite model ISBA. This fraction allows to model a rather good effective total albedo (Fig. 2.2,c), but thus, 90% of soil is unshielded by snow and is strongly coupled to the atmospheric forcing.

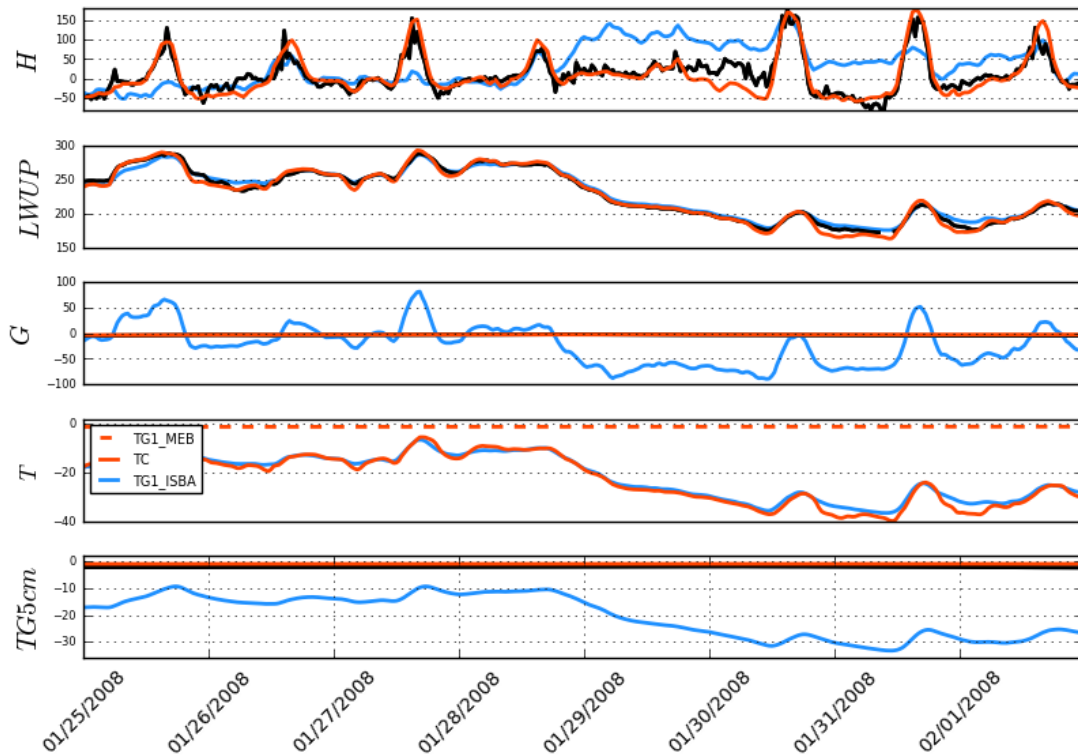
When hotter period comes up in spring, the atmosphere temperature gets closer to 0 C and solar radiation starts to increase. With ISBA, the ground temperature can easily get over 0 C as the heat capacity of that layer is low. Once the ground temperature exceeds 0 C, the conductive flux between the snow and the ground (Fig. 2.7,d) is negative, indicating that the ground is warming up the snowpack from below. The early melt of the snowpack in ISBA is thus due to that energy received from the ground, which is largely overestimated (Fig. 2.7,c) since the ground is almost fully protected by snow and do not reach such temperatures.

In MEB, the insulation of the soil from the snowpack is total as the horizontal characteristics of the layers is more realistic. The flux coming from the ground is very close to 0  $\text{W}\cdot\text{m}^{-2}$  (Fig. 2.7,d) which prevents it from overheating. Thus, the melt of the snowpack only comes from the upper layer. The net radiation (Fig. 2.7,e) received by the first layer of the snowpack is higher in MEB than in ISBA due to the LW enhancement effect, and allows to melt the snowpack at a speed comparable to the measurements (Fig. 2.7,a). This response from MEB allow to get a better representation of the snowmelt period.



**Figure 2.7:** Multiple variables at the OJP site from 03/25/2004 to 03/31/2004 which corresponds to a melting period of the snowpack. MEB is in red, ISBA in blue and observations in black. The third panel represents the ground temperature at 1 cm for ISBA and MEB in blue and red respectively. The black dotted line is the atmosphere temperature at 5 meters.

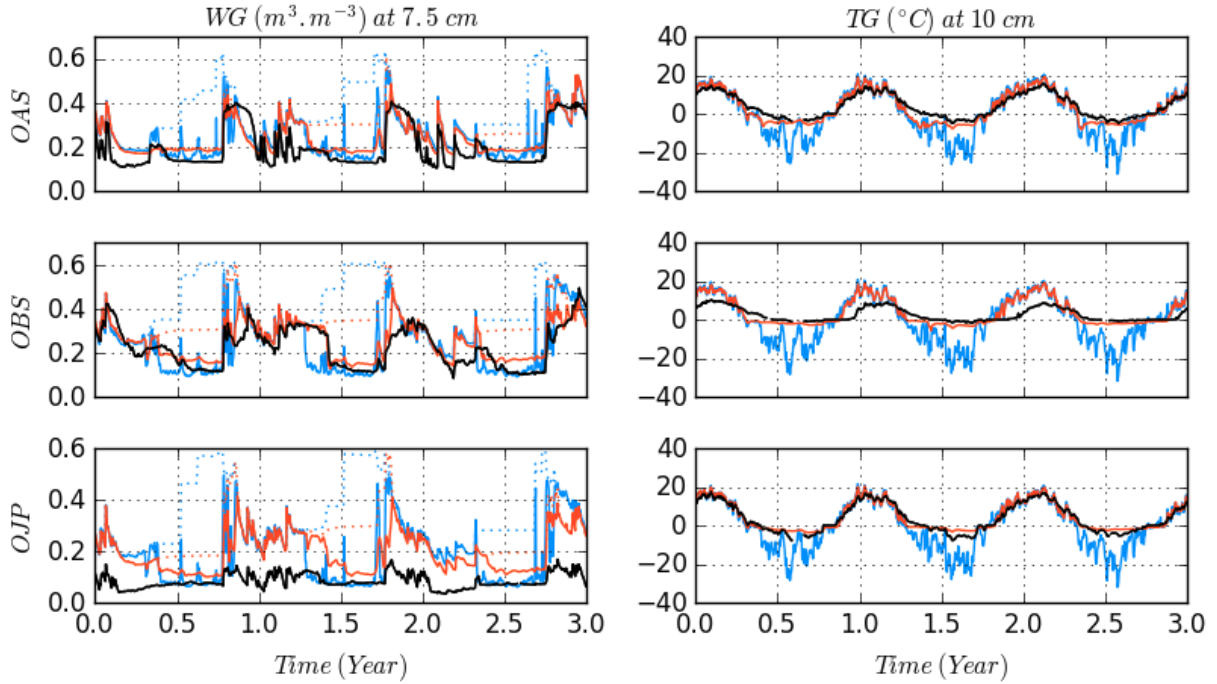
Fig. 2.8 shows a period before the melt of the snowpack occurs. The energy budget of ISBA (H and G) appears unbalanced when compared to observations. Indeed, because the snowpack does not cover the full grid, the available energy is used to warm up or cool down the surface soil temperature which provokes strong amplitude of G instead of being released to the atmosphere through H. With MEB, two prognostic temperatures (Fig. ??,b) are used,  $T_{G1}$  for the soil temperatures exchanges, which barely varies in time and  $T_C$  for the exchanges with the atmosphere which is related to an explicit heat capacity of the vegetation (lower than the composite heat capacity of ISBA). These two temperatures, totally uncorrelated thanks to the snowpack which occupies the full surface of the ground, lead to correct modeling of energy fluxes.



**Figure 2.8:** Multiple variables at the OJP site from 01/25/2008 to 02/01/2008. MEB is in red, ISBA in blue and observations in black. For T, the red curve is TC(MEB), the dotted red curve is TG1cm(MEB) and the blue curve is TG1cm(ISBA)



## Soil Temperature and Water content



**Figure 2.9:** Soil water content and temperature at 7.5 and 10 cm deep respectively for the three sites from 07/02/2001 to 07/02/2004. MEB is in red, ISBA in blue and observations in black. On the WG graphs, the dotted lines represent the liquid and solid water.

The overestimation of the ground heat flux amplitude by ISBA not only impacts energy exchanges with the atmosphere through  $H$  but also the soil temperatures. With the direct contact of about 90% of the composite layer with the atmosphere, soil temperature calculated from ISBA can easily drop below  $-20^{\circ}\text{C}$  in winter (Fig. 2.9) whereas observations show temperatures only slightly negatives. It leads to strong BIAS over each site and depth of  $-2.9\text{ K}$  and RMSE of  $6.8\text{ K}$ . Thanks to the insulation effect of the snowpack, MEB is way more closer to observations with an average BIAS of  $0.1\text{ K}$  and RMSE of  $2.0\text{ K}$ .

Table 2.8: RMSE for the ISBA-MEB and ISBA experiments for soil temperature at 5, 20 and 100 cm calculated over half hourly data.

RMSE (K) (MEB / ISBA)	OBS	OJP	OAS	Period
5 cm	3.3 / 9.2	2.0 / 7.7	2.2 / 8.2	Full Period
	2.1 / 11.0	1.9 / 9.8	2.3 / 9.5	Snow Period
20 cm	3.3 / 8.1	1.5 / 6.3	1.8 / 7.0	Full Period
	2.2 / 10.1	1.7 / 8.3	1.9 / 8.2	Snow Period
100 cm	1.4 / 4.3	1.1 / 5.1	1.0 / 5.0	Full Period
	0.7 / 5.1	0.9 / 4.8	0.9 / 4.9	Snow Period



Table 2.9: *BIAS for the ISBA-MEB and ISBA experiments for soil temperature at 5, 20 and 100 cm calculated over half hourly data.*

BIAS (K)	OBS	OJP	OAS	Period
(MEB / ISBA)				
5 cm	1.1 / -2.4	0.3 / -3.4	-0.5 / -3.8	Full Period
	-0.1 / -6.8	0.7 / -6.2	-0.9 / -5.5	Snow Period
20 cm	1.0 / -2.9	0.2 / -3.8	-0.6 / -4.1	Full Period
	-0.4 / -6.9	0.6 / -6.0	-0.9 / -5.5	Snow Period
100 cm	0.7 / 3.8	-0.2 / -4.6	-0.7 / -4.7	Full Period
	0.1 / -4.5	0.5 / -4.3	-0.7 / -4.6	Snow Period

In ISBA, the strong negative temperatures (Fig. 2.10,b) at all depths reached during early winter lead to an important freezing of the soil (Fig.2.11). In spring, even after snowmelt and due to its inertia, the frozen water remain strong and overestimated in the deep soil layers.

This explains the shape of the temperature profile for ISBA which shows, as a consequence, underestimation of deep soil temperature in summer. Due to the insulating effect of the snowpack in MEB that covers most of the time the entire ground, the water freezing is less intense in depth. Even if there is still a little delay of the temperature at the end of winter (the ground remains cold a bit too long compared to observations), the results match the observations much better.

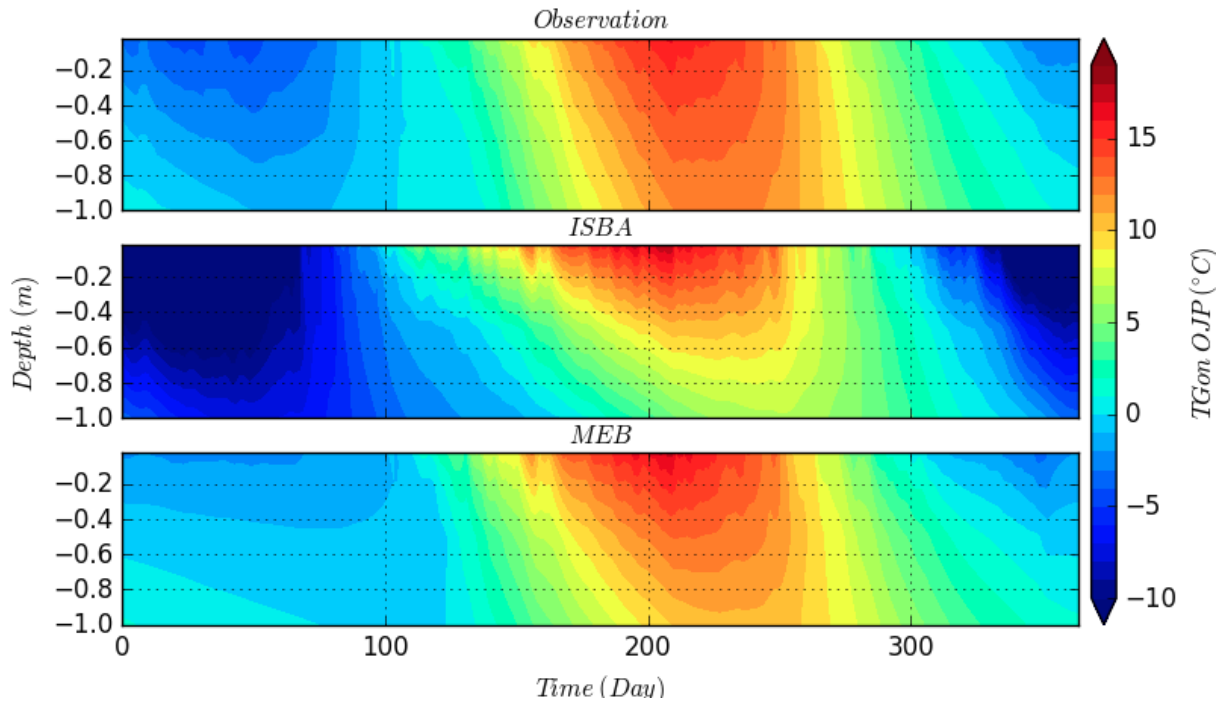
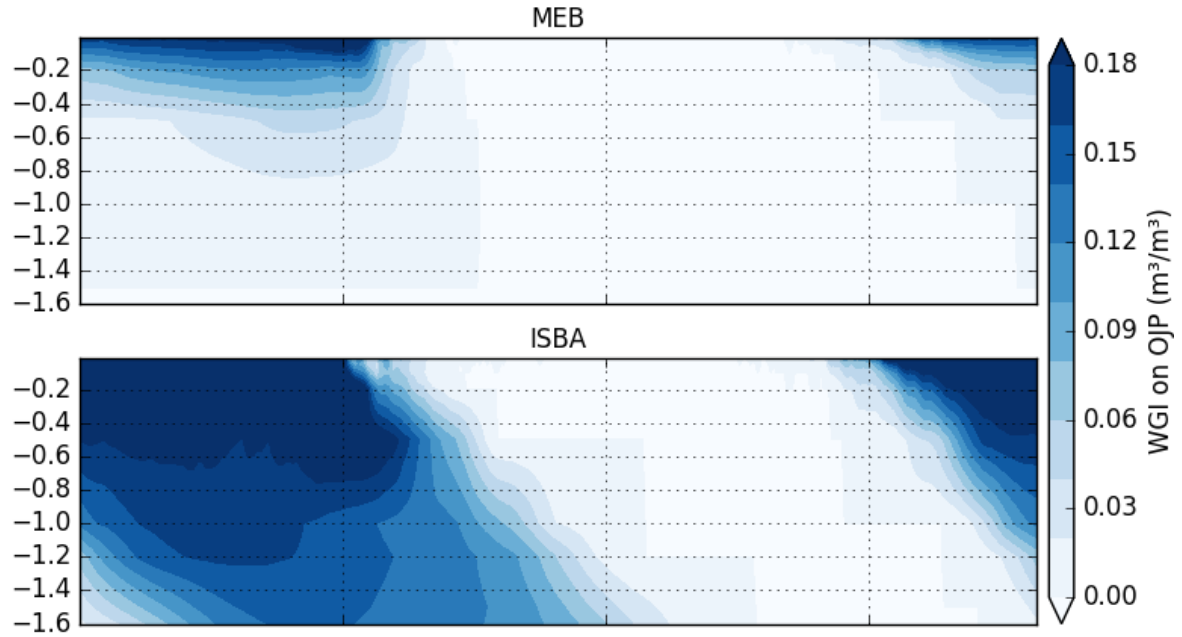


Figure 2.10: *Average annual contours of soil temperature between surface and 100 cm deep at the OJP site.*

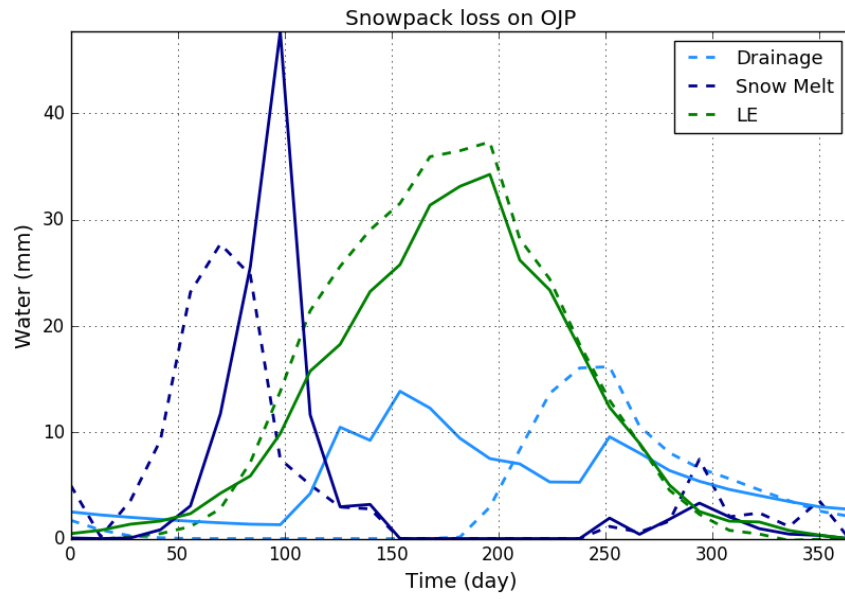


**Figure 2.11:** Average annual iced water content in the ground on the OJP site.

The modeling of the soil water content (Fig. 2.9) correctly fits the observations for both model except for the OJP site. It is likely to be due to the definition of the soil characteristics which are defined through soil textures estimations. As a global use of the model is aimed after this study, no further investigation was lead on that point. A noticeable difference between the two model is that the water content curves are more flat with the MEB option with respect to observations. Indeed, ISBA occasionally melts the entire snowpack as shown on Fig. 2.4, leading to short periods of ice melting and unrealistic peaks of liquid water content.

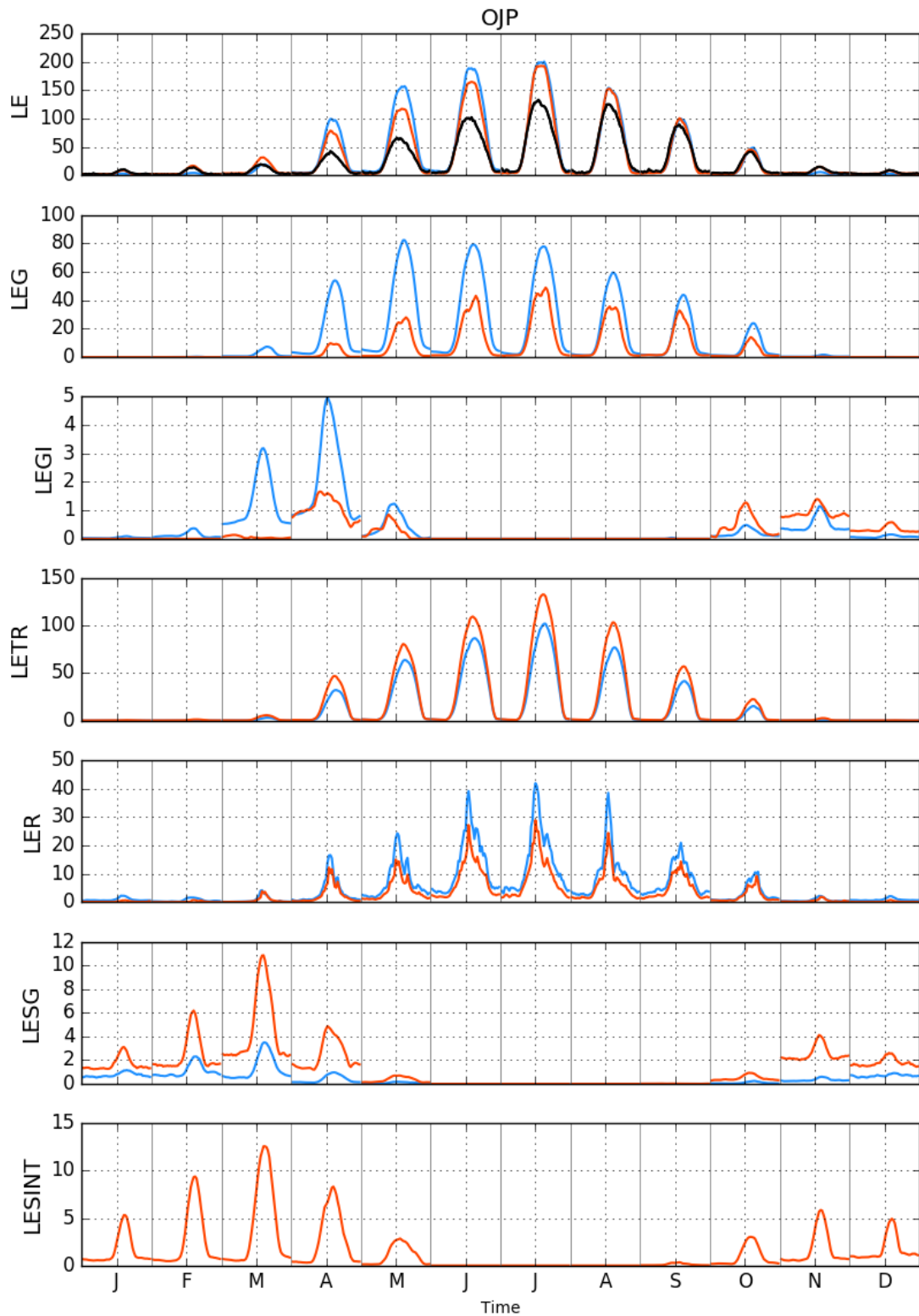
Impacts on drainage and runoff are expected on regional or global studies and might impact the hydrology. These default of the ISBA scheme were pointed out by Decharme et al. (2019) which found a too early springtime peak of river discharge over all Arctic basins. In ISBA and MEB, the runoff option is not activated.

Fig. 2.12 represents the annual average drainage, evapotranspiration and snow melt amount on OJP. The earlier snowmelt in ISBA is noticeable and the evaporation and sublimation are coherent with latter studies. However the drainage is really different for both models. In ISBA, the drainage is positive only after a long period. This is explained by the thaw which happens extremely lately in ISBA (see Fig.2.11) and makes impossible the deep drainage. In MEB, the frozen water contained in the ground does not go as deep as in ISBA. Then, the drainage is always positive, even when the first layers of ground contain frozen water, because deep liquid water can still infiltrate into the deepest layers.



**Figure 2.12:** Representation of the drainage, the evapotranspiration and snow melt on OJP. ISBA is represented with the dotted lines and MEB with the full lines.

### 2.1.3 Evapotranspiration and snow melting

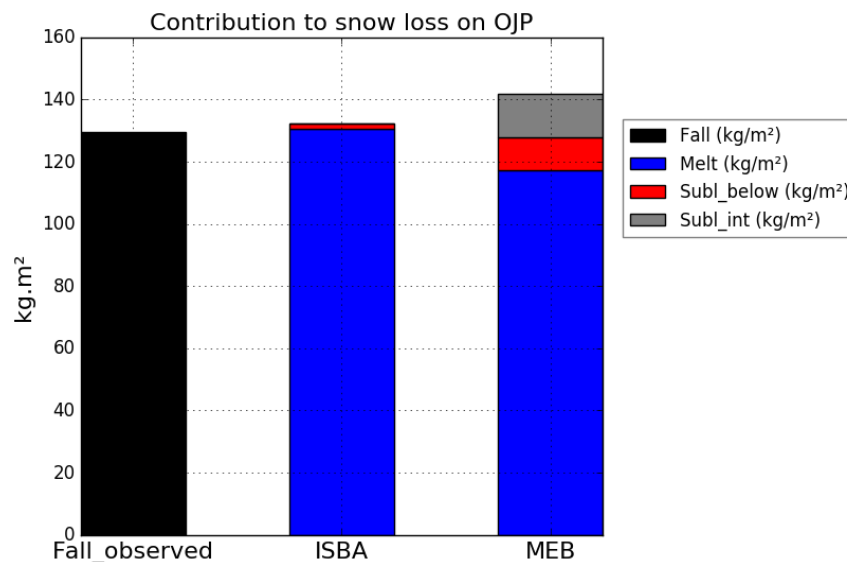


**Figure 2.13:** Composite of monthly diurnal cycle of each terms that compose the global evapotranspiration term on OJP site for ISBA (blue) and MEB (red). LE is the global evapotranspiration flux (i.e. latent heat flux), LEG the ground evaporation, LEGI the sublimation of the ice contained in the ground, LETR the transpiration of the vegetation, LER the evaporation of intercepted water, LESG the evaporation of ground based snow and LESINT the sublimation of intercepted solid water.

Each term that composes the evapotranspiration (LE) are displayed in Fig. 2.13. There are no observations, excepted for LE, but it is possible to compare the contribution of each terms in both model. The vegetation transpiration, the ground evaporation and the intercepted water evaporation are the biggest source of evapotranspiration. While LETR and LER are not that much different in MEB and ISBA, LEG is obviously higher in ISBA.

This is due to the fact that the ground layer has not the same environment in both models. The ground evaporation is based on the humidity difference between the ground and the "air". The higher the difference is, the higher the flux will be. In ISBA, the first ground layer is exchanging directly with the atmosphere (see Fig.??) which has a broadly low humidity compared to the ground. Therefore, it results in an important evaporation flux. In MEB, the first ground layer is exchanging with the intermediate "canopy", which is an intermediate between the canopy and the atmosphere and is described with a higher humidity than the atmosphere. This explains the attenuation of the flux in MEB. This lower ground evaporation flux in MEB leads to a slightly higher water resource in the ground and thus to a higher vegetation transpiration flux.

It is also significant that the sublimation of ground-based snow is always much higher in MEB than in ISBA. The explanation is based on the same reflexion made above for the ground evaporation flux. The snowpack sublimation depends on the temperature difference between the snowpack and the upper layer. The study showed a higher canopy temperature than the atmosphere temperature during winter, which results in a higher sublimation in MEB than in ISBA.



**Figure 2.14:** Contribution in snowpack loss between melting, sublimation above the canopy and sublimation of intercepted snow (only for MEB) in MEB and ISBA on OJP. The solid precipitations (i.e. observations) are represented in black.

This leads to a thinking on the distribution of snow loss. Snow loss is due to snow melt, ground-based snow sublimation and intercepted snow sublimation. Fig. 2.14 displays the average contribution of each terms, compared to the observed snow falls. The sublimation of snow represents 22% (10% from the snowpack itself and 12% from the intercepted snow by the canopy) of total snowfall using MEB whereas it was only 2% with ISBA.

This change has two reasons: (i) the snow fraction parameterization gives low value of snow cover for ISBA and high values for MEB (Fig 1.6), so that the the net radiation attributed to the snowpack is higher with MEB, (ii) with MEB, the interception of the snow by the canopy is explicitly considered and allows more sublimation. Even if no observations can confirm those differences, studies have estimated that in forest, sublimation might represent several 10s of percents of the annual snowfall (Pomeroy et al. (1998)).

Note that on Fig. 2.14, it is noticeable that the total snowpack loss in MEB and ISBA are higher

than the actual snowfalls. This can be explained by the way the model calculate the different terms (melting and sublimation). When liquid precipitations transform into snow in the snowpack and then melt, the model will consider it in the snow melting term, and does not make a difference between the snow coming from snowfalls or the snow coming from solidification of liquid precipitations.

In the end, the consideration of an explicit canopy layer and an explicit litter layer allows a better representation of the evapotranspiration. The litter allows to reduce a lot the evaporation from the ground, which, in general, leads to results closer to the observations. The canopy allows to be more realistic toward the contribution of sublimation in the snowpack loss. Therefore, the sublimation has a bigger role in the snow loss.

## 2.2 Sensitivity tests

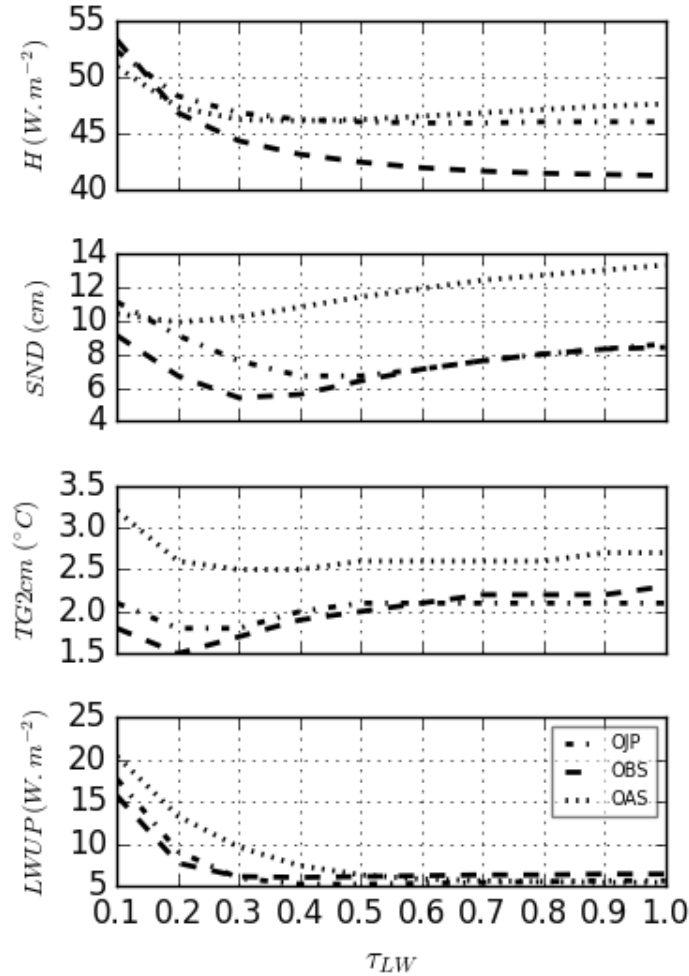
Sensitivity tests were performed on five parameters considered uncertain and potentially sensitive. For each parameter, values were tested for each site around the default value defined in Boone et al. (2017) and scores were calculated only when snow was observed.

- $\tau_{LW}$ , *The LW radiation transfer coefficient*

To investigate the model sensitivity on the parameter  $\tau_{LW}$ , we focus on its impact on the snowpack and the longwave upward radiation. The original default value was 0.5 and values from 0.1 to 1.0 by step of 0.1 were tested. The  $\tau_{LW}$  parameter is used to calculate the LW radiation transmitted through the canopy (Eq. 1.29) and reacts so that the lower the parameter is, the higher the canopy is likely to transmit LW radiation. The sensitivity to this parameter is relatively high, notably for low values. Fig. 2.15 shows RMSE between model and observations calculated for each values of this parameter, site and the identified 4 more sensitive variables. For each variable, errors decrease with  $\tau_{LW}$  until the value of 0.3-0.4 for which they stabilise (LWUP and H) or start to increase (SND and TG). The value of 0.4 is then chosen to be the new default value.

- *The Litter Thickness*

The litter thickness is supposed to be a key parameter of MEB (Napoly et al., 2016). Indeed it affects both thermic and hydrology in the model. Its value is very specific to each site and its accurate measurement is hard to set up at a large scale. Moreover, in MEB the litter thickness is supposed constant. All those facts make it relevant to test this parameters sensitivity. The default value applied to each site is 3 cm. According to the usual values of the parameter, its variation scale for the test is 1 cm to 10 cm. Despite this, tests showed no significant sensitivity on this parameters (< 10% variation of RMSE on the tested values compared to the default value) on most variables. Only the soil temperatures were found to be significantly impacted, with optimized scores of 1-2 K obtained with values above 6 cm, instead of 3-4 K with 1 cm.



**Figure 2.15:** RMSE calculated for different values of  $\tau_{LW}$  for each site during the snow period and for the sensible heat flux (a), snow depth (b), soil temperature at 2 cm (c) and LWUP (d).

- *The Ratio of roughness length*

The ratio of roughness length  $Z_{0h}/Z_{0g}$  which determined the roughness used in heat exchanges calculation according to the roughness for momentum exchange is tested. The lower this ratio is the higher is the roughness for heat exchanges is and so are the turbulent fluxes. In ISBA the default value of this parameter is 10 while it is  $\text{Ln}(1)$  in MEB (Napoly et al. (2016)) following Yang and Friedl (2003). The uncertainty above this parameter motivates the sensitivity test with values from 1 to 10. The sensitivity to this parameter during snow period is very little on the three studied sites with a maximum of  $3 \text{ W.m}^{-2}$  variation on the RMSE compared to the default value on H and LWUP.

- *The Snow interception coefficients*

The snow interception process added in MEB implies notably two uncertain parameters which are (i) the maximum capacity of the canopy snow reservoir and (ii) the melt rate of snow intercepted by vegetation. We decide to test here the sensitivity of these parameters by dividing and multiplying per 2 and 4 their default value. The results showed a very low sensitivity to those parameters on each sites.

## Chapter 3

# The case of the Col de Porte station and opening to a global study

This final chapter will focus on two works that were made in parallel with the evaluation work. It will first focus on a project set up at the Col de Porte station in Grenoble, based on snow simulation in forested area with the ISBA-MEB model, but using another snow scheme, CROCUS. It appeared that the simulation with CROCUS encountered some issues and the goal was to check the results obtained with the ES (explicit snow) snow option of ISBA.

A primary global study has also been simulated. It will be presented there, with a link to the Col de Porte results.

### 1 The Col de Porte Station



**Figure 3.1:** *View of the measurement tools at the Col de Porte station, during April 2019.*  
*Photo : Theo W.*

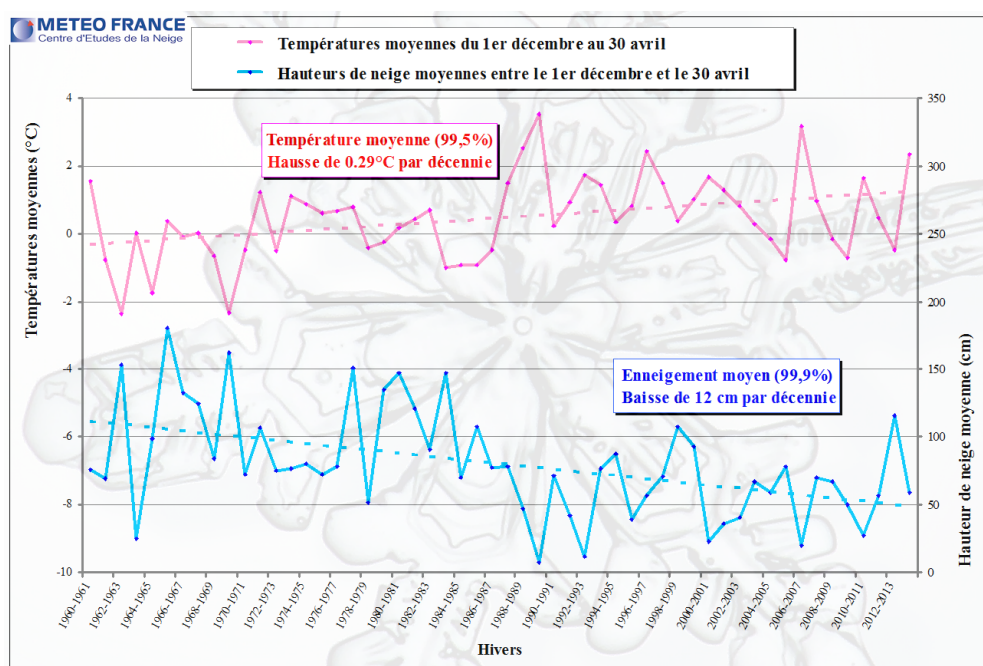


## 1.1 The station

The station is situated, since 1961, at the Col de Porte in the Northern Alps, next to Grenoble city. The CEN (Centre d'Etude de la Neige) is in charge of this site.

The station's objective is to collect meteorological and nivological measurements. The parameters measured are; the air temperature and humidity, the SW and LW radiation, the snow height, the SWE and the snow density, the wind speed, the precipitations and finally the temperatures and the snow compaction. The instrumentation of the station is very advanced and provides observations of many parameters on a very long period (almost 70 years), which makes this site an exceptional site. Some observations data, which are displayed inside the building, such as the average snow depth, combined with the long period of available data, even allow a climate change study (in 60 years it is obvious that the average snow depth has decreased...). Fig. 3.2 highlights the increasing temperature trend, coupled with the decreasing of the average snow depth.

The site is also subject to research study and developments toward snow physic, such as the development of the snow scheme CROCUS (detailed in Vionnet et al. (2012)).



**Figure 3.2:** Average temperature and snow evolution at Col de Porte between 1960 and 2014. Météo-France, CEN.

## 1.2 The SNOUF project

The project aimed the study of snow in forested areas, firstly between 2016 and 2017. To do so, a forested zone at the Col de Porte station was fully instrumented, becoming the SNOUF station. This zone is next to the plain measurement station and is described by high trees (25 to 40 meters) with various density (there is a big hole in the canopy at one place). A meteo station, 18 manual snow depth and SWE measurement points were set up at different locations and a LaserScan was used to measure continuously the snow depth. Other tools were installed for temperature and precipitation measurements.

The 2016 - 2017 measurement period allows to obtain significant results. it appeared that the snow depth was extremely variable on the site. Between two measurement points, it was possible to get a difference of more than 20 cm. It triggered a reflection on the impact of the snow interception by the canopy on the actual snow depth. That is why, in 2018, the SNOUFi project began (Vincent (2018)), setting up new measurement tools to focus on the snow under the canopy after each snow events.



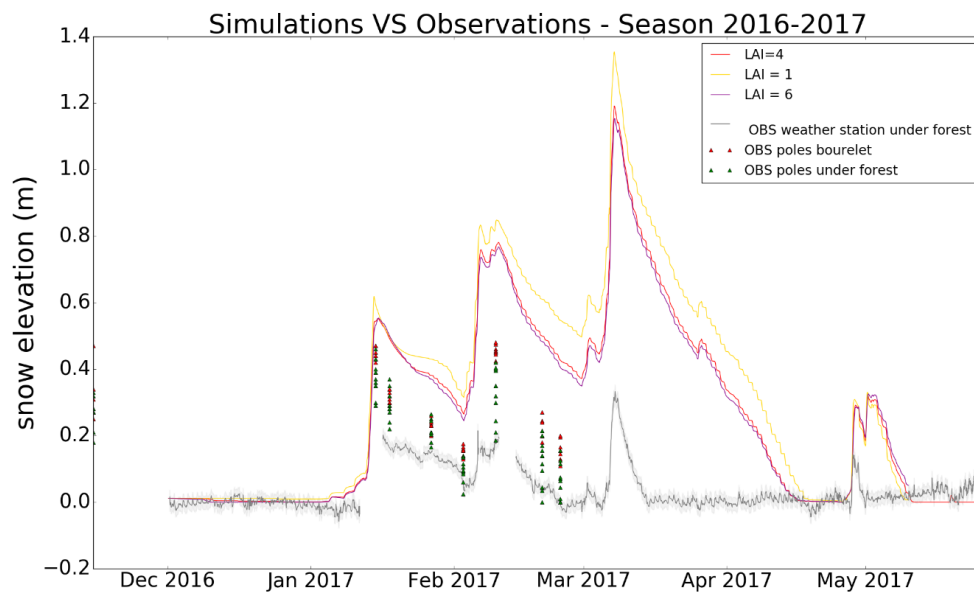
**Figure 3.3:** A view of the different manual measurement points. On the right, the meteo station can be seen.

Photo : Theo W.

## 2 The snow simulation issue

### 2.1 MEB-CROCUS results

CROCUS is, as ES, a snow scheme. The main difference is that CROCUS is based on a multi-layer scheme and the focus is made on the snow structure. The scheme, used at the CEN, has the vocation to be applied for avalanche simulation, where the snow structure is significant. The SNOUFi project contained the snow simulation with MEB-CROCUS, and it appeared that the results were not the one expected (Fig. 3.4). Indeed, while the snow depth observed under the canopy was a lot lower than on the plain, the MEB-CROCUS results were closer to the plain observations.



**Figure 3.4:** Representation of the snow depth at the Col de Porte with MEB-CROCUS. Different values of LAI are tested. Taken from Vincent (2018).

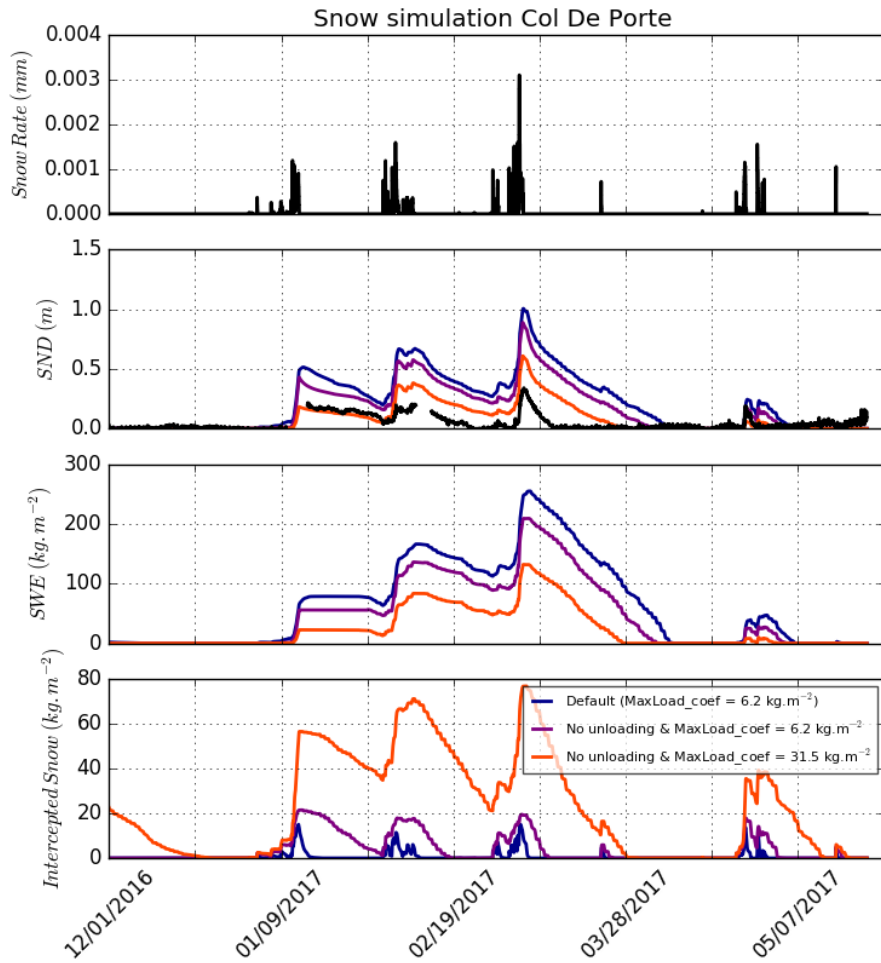
This observation led to different hypothesis. (1) There was a possibility that a process was not

taken into account in the model and thus, the results were wrong. (2) An informatic issue, in the coupling between MEB and CROCUS, could have happen, and then led to uninterpretable results. Matthieu LAFAYSSE came at the CNRM to present its results in 2019 and those from Vincent (2018). The first tests were made on the LAI and the maximum capacity of the vegetation for snow interception. It appears that those parameters had a very low impact on the results. Tests were also made on the air temperature. Indeed, the vegetation temperature used for the simulations at the Col de Porte is the temperature of the air, measured in the plain. Therefore, higher temperature were provided, but no major impact on the snow depth were noticed. The last test concerned the snow melt rate coefficient of the intercepted snow. It appeared that multiplying this parameter by 100, which was initially of  $0.48 \text{ kg.m}^{-2}.\text{day}^{-1}.\text{K}^{-1}$ , allowed to fit a lot more the snow depth observations. However, this value of snow melt rate might be unrealistic. It was therefore relevant to test the MEB-ES model to see what results could be obtained.

## 2.2 MEB-ES results

A simulation was made with the MEB-ES model. As obtained with the CROCUS model, It appears that the same result, which was that too much snow were obtained in the forested area, has been observed.

Knowing the tests that were already made in Vincent (2018), it was decided, in a first place, to test the impact of the maximum intercepted snow (max load) coefficient coupled with the unloading option disabled. Disabling the unloading option means that the intercepted snow will only be able to melt or to sublimate.



**Figure 3.5:** Representation of the SND, the SWE and the intercepted snow in MEB for different values of Max Load and with the unloading option disabled. The first panel represents the snow fall observations. The black line on the second panel is for the observation at the Col de Porte under the forested site.

Fig. 3.5 displays the tests made for two values of the max load coefficient. It seems that for a higher value of this coefficient, the results begin to fit the observations. However, it is hard to confirm that this modification is relevant since no observations for the intercepted snow have been done. Therefore, it is not possible to know if a value of  $60 \text{ kg.m}^{-2}$  of intercepted snow is realistic or not, and thus to conclude on the relevance of the test.

### 2.3 Suggestions and opening

The results observed at the Col de Porte revealed a limit of MEB in a certain case. The main reason might be the snow interception scheme, which could not represent in the exact way what happens on the site.

The interception scheme, described in Hedstrom and Pomeroy (1998), is used in almost every land surface models that explicitly represent the vegetation. However, this scheme has been set up based only on boreal forests, and has never been evaluated for other types of site. In the case of the Col de Porte, the forested area knows a very different weather than in boreal forests (with higher temperatures). Therefore the interception scheme might not be appropriate on this site.

Many investigations are possible. Mainly about the interception scheme, but more observations toward the snow interception process would be significant for further studies.

Since different results were obtained for two types of site (Berms and the Col de Porte), it is relevant



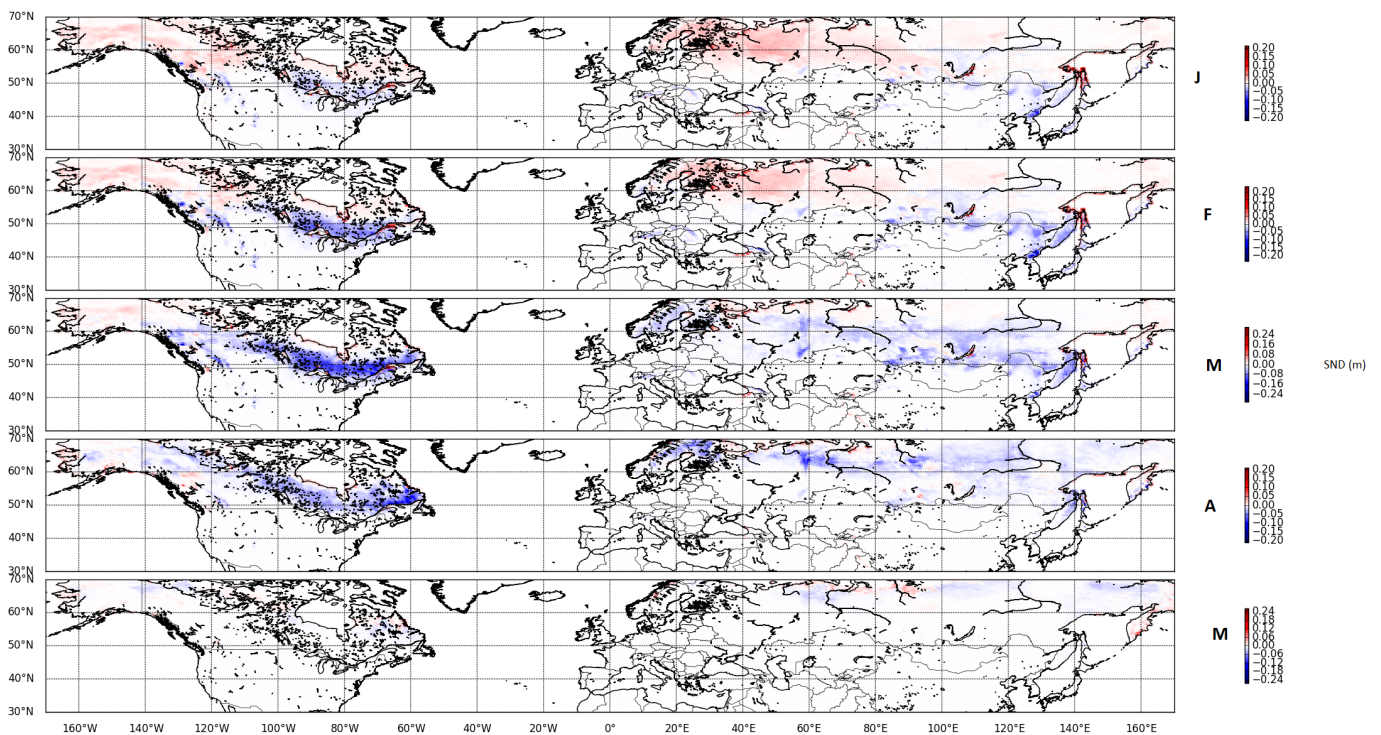
to look at the global scale.

### 3 Global aspect

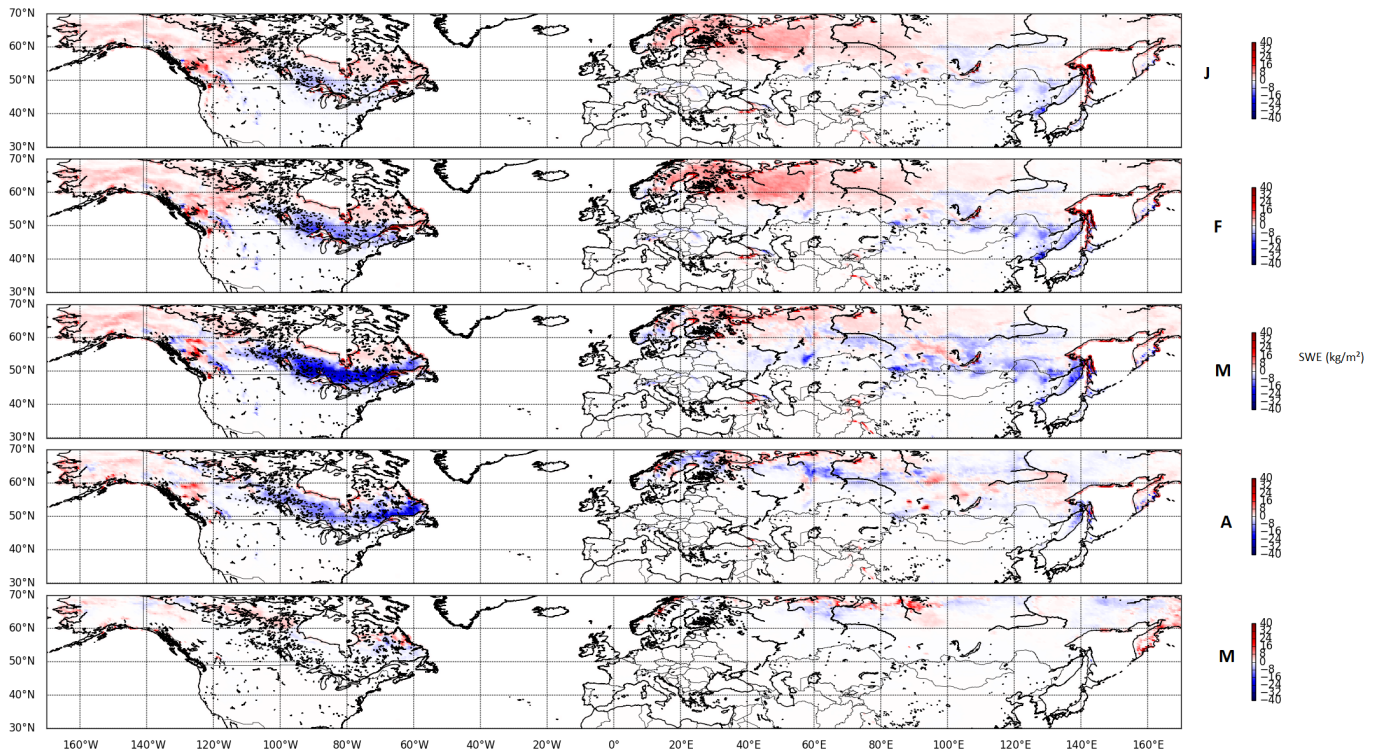
The aim of the global study is to confirm the results obtained at a local scale. The simulation provided 30 years of result, from 1980 to 2010. A first analysis was focused on the snow with monthly average values. No observations are available, however the global simulation allows to compare ISBA and MEB for different areas.

#### 3.1 First results

The difference of monthly average snow depth and snow water equivalent over 30 years between MEB and ISBA are displayed in Fig. 3.6 and Fig. 3.7. According to the local study, it is expected that the snowpack in MEB melts later than in ISBA.



**Figure 3.6:** Representation of the difference between MEB and ISBA with the monthly average snow depth with the global simulation, from January to May. A higher value in MEB is therefore represented in red.



**Figure 3.7:** Representation of the difference between MEB and ISBA with the monthly average snow water equivalent with the global simulation, from January to May. A higher value in MEB is therefore represented in red.

It appears that the snow depth is mostly higher in ISBA during the snow melt period, which is not in accordance with the results observed on Berms. Also, in one area in the east of North America, ISBA models a lot more snow than in MEB.

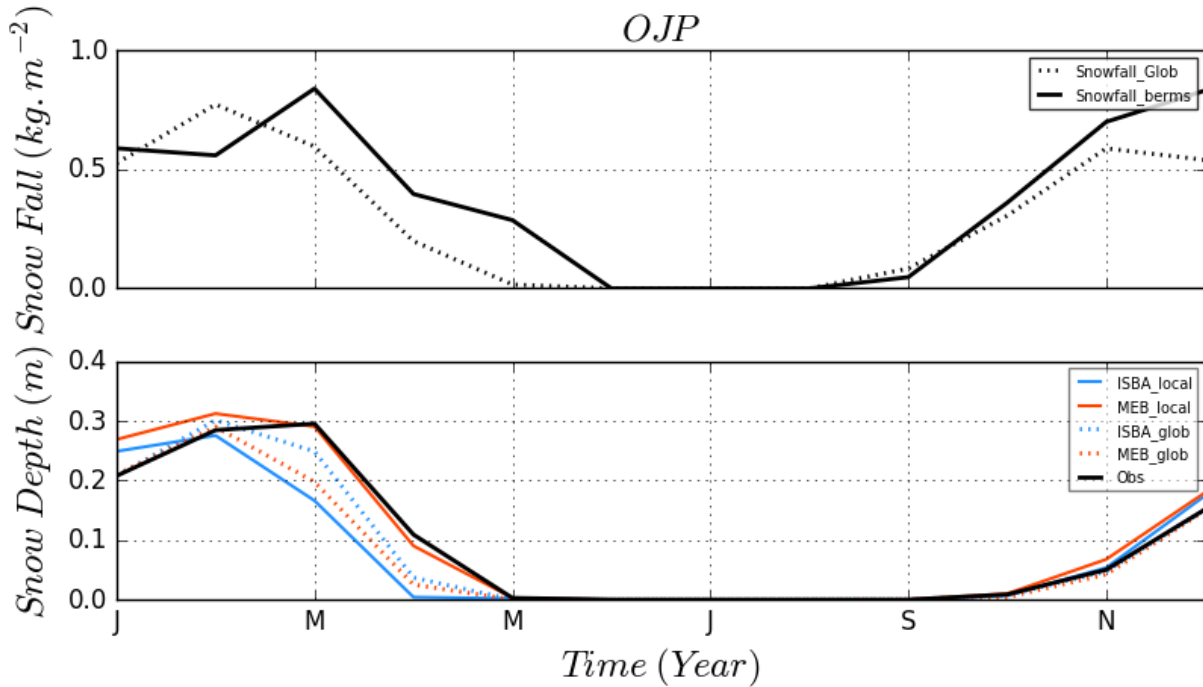
This study encourages to watch the results for the snow water equivalent. Indeed, a higher snow depth does not necessarily translate that there is more snow, since the snow can have a higher density. For the snow water equivalent, it appears that in some areas, MEB gives more satisfying results. In northern Europe and east of Canada, the SWE is higher in MEB during the snow melt period, which translates that the snow remains longer in MEB. However, the same zone in eastern Canada remains, where ISBA models much more snow than in MEB.

Those observations lead to different issues. In any case, it appears that the snow density is higher when using MEB. Two hypothesis are possible; (1) The snow which melts from the canopy might refreeze in the snowpack and therefore increase its density. (2) It is known that the density of the snow falling from the canopy is computed with the canopy temperature and not the air temperature. The canopy air is a little higher and so is the density. While the first possibility is physical, the second one is not really.

Another issue is that different results are obtained on eastern Canada. In this area, there is much more snow with ISBA. It has not been possible to examine precisely the issue due to the lack of time but this zone must have different characteristics that impact the results. It might be a specific value of LAI, which represents a limit of MEB, or due to a specific type of vegetation cover. The lack of time prevented to do a more precise study of the global results. A lot of different factors can impact the results and a deeper investigation of them is needed to understand the behavior of ISBA and MEB in the different area.

One last work has been done during the study of the global results. Its purpose was to examine the results given by the global results for the closest pixel to the Berms sites. Fig. 3.8 reveals that the results between the global and the local simulation are actually different. This observation

leads to a lot of questioning toward the differences between the two simulations and about what can impact that much the results. The source of the difference is double : It can come from the forcing that are not the same. However a comparison of the local and global forcing revealed that there were no huge difference between them. The second source of difference might be the information informed in the NAMELISTE, which gathers a lot of specific parameters that can impact the results.



**Figure 3.8:** Representation of the monthly average snow depth at the OJP site for MEB and ISBA for both local and global simulations. The local simulation is represented by full lines while the global is represented by dotted lines. On the first panel, the forcing in both simulations is represented.

### 3.2 View on further studies

The global study revealed that there are still investigations to do in order to understand the behavior of the MEB option.

About the comparison between the local and global results, two simulations could help to see where the difference comes from. The first one is to compute the local simulation but with the global forcing, and the second one is to compute the local simulation with the global NAMELISTE.

The global results which displayed various differences between ISBA and MEB in different areas can also be investigated. To do so, it would be interesting to check if the snow water equivalent has a specific behavior with precise values of LAI, vegetation height and vegetation type. Such an investigation could reveal that MEB knows some limits in a certain range of values of one parameters.

# Conclusion

*French version is available in Appendix C*

This study evaluates the impact on snow conditions of the multi energy balance (MEB) option, recently implemented in the interactions between soilbiosphereatmosphere (ISBA) land surface model. The default representation of the vegetation in ISBA consists in a composite layer for which physical parameters are averaged considering a fraction of surface that vegetation actually occupies. The new option improves the representation of the forests through the addition of two explicit layers: one for the canopy itself, the other for the litter laying on the ground forest.

To carry out the evaluation, twelve years of observations at the three Berms (Boreal Ecosystem Research Study) sites were available. Besides from the forcing measurements necessary to run the model, turbulent and radiative fluxes, soil temperatures and water contents and snow measurements were used.

During non snow periods, comparable results from previous study (Napoly et al., 2016) were confirmed. Due to shading effect of the canopy layer and the low thermal diffusivity of the litter layer, the ground heat flux is strongly reduced as long as soil temperature amplitudes in better agreement with the measurements (RMSE of  $47.1 \text{ W.m}^{-2}$  with ISBA and  $10.9 \text{ W.m}^{-2}$  with MEB on the whole period). This new available energy (net radiation being barely impacted) is sent to the turbulent fluxes and mostly to the sensible heat flux (RMSE of  $58.9 \text{ W.m}^{-2}$  with ISBA and  $48.4 \text{ W.m}^{-2}$  with MEB) as latent heat flux is limited by available water in the soil. In spring, the latent heat flux is also improved with a limited contribution of the ground evaporation due to the litter layer. Available measurements of short wave radiation below the canopy also shows the ability of MEB to correctly model the transfer radiative through the canopy. Unfortunately, long wave radiation below the canopy was not measured to complete this analysis.

During snow periods, the improved realism of the MEB option allows to uncouple the ground from the atmosphere. Indeed, the snowpack laying on the ground is fully covered and insulated. As a results subsurface soil temperature is constant and close to  $0^\circ\text{C}$  with regard to observations. Improvements of soil temperature are consistent at different depths. With the default composite version of ISBA, this uncoupling cannot be done as an effective snow fraction is calculated in the range of 10 to 20 %. Consequently, a large fraction of the surface is directly connected with the atmosphere and ground heat flux becomes strong when the atmosphere temperature decreases. This leads to a strong unrealistic cooling of the soil with an average bias for the all sites, depths and years of  $-5^\circ\text{C}$  compared to  $-0.1^\circ\text{C}$  with MEB. Comparably to the litter effect, this better representation of the ground heat flux provides energy to turbulent fluxes (and again mostly the sensible heat flux) which were underestimated. The average RMSE on sensible heat flux calculated on snow periods only drops from  $54.9$  to  $45 \text{ W.m}^{-2}$ .

The impact on the snowpack modeling is significant. In general, the snow depth is improved with MEB. The RMSE with is  $5.1 \text{ cm}$  on average while with only ISBA it is  $9.1 \text{ cm}$ . This is due to a general better agreement during the season but mostly to melting period. Indeed, the snow melts, in average, 24 days too early with ISBA, while only one day with MEB. This default in ISBA is due to the coupling of the ground with the atmosphere. When the air temperature increases over zero degrees, the composite layer temperature follows, warm up the snowpack from below and melts it. In MEB, the snowpack occupies the whole fraction of ground so that it can only melt from its surface due to a positive energy balance. As a consequence, sublimation represents only 2 % of the total snowpack loss in ISBA, while it represents a 22 % when using MEB. About half of this



quantity corresponds to snow intercepted by the canopy, the other half is directly sublimated from the snowpack.

Two hydrologic and antagonist impacts are to be expected with the MEB option. First, the soil freezes less deep and especially less long. With ISBA, the deep soil can be freeze more than half of the year, while it never is with MEB. This effect flatten the deep drainage evolution during spring while it is concentrated on mid summer with ISBA. Second, as the snowmelt happen about three weeks later with MEB, the surface runoff peak will be similarly delay. These effects will be study on global runs coupled with hydrological model.

Sensitivity test were performed in order to evaluate the new parameters from the MEB option. These parameters were chosen as their physical meaning (and so their values) were quite uncertain. Only one parameter among the 5 tested was found to be significantly sensitive, the LW radiation transfer coefficient, showing a good robustness of the model. The default value of 0.5 has therefore been changed to 0.4.

After this evaluation, the study focused on another local site, the Col de Porte, close to Grenoble, and then on the global scale. This showed up that the snow interception scheme in MEB might have limitations in certain situations. Indeed this parmeterisation was validated on very cold climate which is not the case of this last site. At Col De Porte, it seems that the forest could intercept and sublimate much more snow that for the Berms sites so that the snowpack is thinner that what is modeled with MEB.

Finally, we performed a global scale experiment with a forcing data set from a reanalysis. Results are still under progress but a first inconsistency appeared, at the location of the Berms site the experiment using the MEB option have a snowpack that melted faster than the reference experiment. However, the lack of time restrained a deeper study. Further work is planned, such as a thesis at the CEN in Grenoble, which would focus on those aspects. Therefore, the work made during this internship will be the support for future work.

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# Appendix

## A Additional content

### Energy closer method

The method is based on the Bowen ratio and allows to say that :

$$H_{adj} = H + residu * \frac{H}{H + LE} \quad (1)$$

$$LE_{adj} = LE + residu * \frac{LE}{H + LE} \quad (2)$$

With :

$$residu = R_n - G - S - H - LE \quad (3)$$

Where  $H_{adj}$  and  $LE_{adj}$  ( $W.m^{-2}$ ) are the corrected fluxes.

### Sites characteristics

Table A0: *Model characteristics prescribed for the three different sites.*

Site	OBS	OJP	OAS	Source
VEGTYPE	5 : BNE	5 : BNE	16 : BBCDS	ECOCLIMAP
Vegetation fraction (ISBA only)	0.95	0.95	0.95	ECOCLIMAP
LAI ( $m^2.m^{-2}$ )	3.65	2.55	1.0-4.9	Measurements
Vegetation albedo (NIR)	0.12	0.18	0.26	Measurements
Vegetation albedo (VIS)	0.04	0.04	0.06	Measurements
Soil albedo (NIR)	0.17	0.17	0.17	ECOCLIMAP
Soil albedo (VIS)	0.07	0.07	0.07	ECOCLIMAP
Root depth (m)	1	1	1	ECOCLIMAP
Ground depth (m)	2	2	2	ECOCLIMAP
Elevation (m)	629	579	600	Measurements
Temperature / Humidity				
Elevation height (m)	25	28	27	-
Wind				
Elevation height (m)	26	29	38	-
Sand (%)	0.58	0.92	0.58	Measurements
Clay (%)	0.1	0.03	0.27	Measurements
Soil Organic Carbon TOP (%) (0 - 30 cm) ( $kg.m^{-2}$ )	18.81	18.75	21.55	HWSD
Soil Organic Carbon SUB (%) (30 - 70 cm) ( $kg.m^{-2}$ )	44.30	44.42	52.18	HWSD

**NAMLISTE example** *More informations are available on the SURFEX support website.*

```

&NAM_FRAC          LECOCLIMAP = T , #Use or not ECOCLIMAP databse
                   XUNIF_NATURE = 1.0 #Fraction of nature tile
                   XUNIF_SEA    = 0.0
                   XUNIF_TOWN   = 0.0
                   XUNIF_WATER  = 0.0

/
&NAM_PGD_GRID      CGRID       = 'LONLATVAL'
/
&NAM_LONLATVAL     XX = AAAA, #X coordinate for the longitude
                   XY = BBBB, #Y coordinate for the latitude
                   XDX = 0.02,
                   XDY = 0.02,
                   NPOINTS = 1

/
&NAM_PGD_SCHEMES   CNATURE = 'ISBA ' , # Nature scheme used
                   CSEA    = 'NONE ' ,
                   CTOWN   = 'NONE ' ,
                   CWATER  = 'NONE '

/
&NAM_COVER         XUNIF_COVERDDDD = 1.0 #Cover fraction of DDDD's ecosystem
/
&NAM_DATA_ISBA     NTIME = 12 ,
                   XUNIF_VEGTYPE 1      = 0 or 1,
                   .
                   . #VEGTYPE concerned among the 19 possibilities
                   .
                   XUNIF_VEGTYPE 19     = 0 or 1,
                   XUNIF_ROOT_DEPTH X   = 1.0,
                   XUNIF_GROUND_DEPTH X = 2.0,
                   XUNIF_H_TREE X= GGGG, #Vegetation height for VEGTYPE X
                   CFNAM_LAI X,1 = 'LAI1_HHHH.txt', #monthly LAI value for VEGTYPE X
                   CFTYP_LAI X,1 = 'ASCLLV',
                   .
                   .
                   .
                   CFNAM_LAI X,12 = 'LAI12_HHHH.txt',
                   CFTYP_LAI X,12 = 'ASCLLV',
                   XUNIF_ZO_O_ZOH X     = 2.3, #Ratio of length roughness for VEGTYPE X
                   XUNIF_ALBNIR_VEG X,1 = IIII,
                   .
                   . #Monthly Albedo Near InfraRed for VEGTYPE X
                   .
                   XUNIF_ALBNIR_VEG X,12 = IIII,
                   XUNIF_ALBVIS_VEG X,1 = JJJJ,
                   .
                   . #Monthly Albedo Near VISible for VEGTYPE X
                   .
                   XUNIF_ALBVIS_VEG X,12 = JJJJ,

/
&NAM_ZS           XUNIF_ZS      = CCCC #Altitude
/
&NAM_ISBA         XUNIF_CLAY    = EEEE , #Fraction of clay in the ground
                   XUNIF_SAND   = FFFF , #Fraction of sand in the ground
                   YSOC_TOP     = 'soc_top', #0 - 30 cm of the ground

```

```

YSOC_SUB      = 'soc_sub', #30 - 70 cm of the ground
YSOCFILETYPE = 'DIRECT'
CPEDO_FUNCTION= 'CH78',
CISBA         = 'DIF' , #Ground scheme
CPHOTO        = 'AST' ,
NPATCH        = 19      , # Nb of patch used in ISBA
NGROUND_LAYER = 14      , # Amount of ground layers
XSOILGRID     = 0.01,0.04,0.1,0.2,0.4,0.6,0.8,1.0,1.5,2.0,3.0,5.0,8.0,12.0 ,
                                     #x limit of each layer
CALBEDO       = 'DRY'   , # Type of bare soil albedo
LMEB          = .FALSE. , #Activate or not MEB
LTR_ML        = .TRUE.  #Activate or not the new radiative transfert calcul

/
&NAM_MEB_ISBA      LMEB_PATCH = .F., .F., .F., .F., .T., .F., .F., .F., .F.,.F., .F., .F.,
                                     .F., .F., .F., .T., .F., .F., .F. ,
LFORC_MEASURE = .TRUE.,
LMEB_LITTER    = .TRUE. #MEB-LITTER option

/
&NAM_PREP_SURF_ATM NYEAR = 1997, #First day of simulation
                    NMONTH = 10,
                    NDAY   = 01,
                    XTIME  = 3600. #Output time step

/
&NAM_PREP_ISBA     XHUG_SURF = 1.0, #Prescribed value of the liquid soil water index SWI for the su
                    XHUG_ROOT = 1.0, #Value of SWI for root zone soil layers
                    XHUG_DEEP = 1.0, #Value of SWI for deep soil layer
                    XTG_SURF  = 280.71, #Surface altitude
                    XTG_ROOT  = 278.71, #Roots' soil layer altitude
                    XTG_DEEP  = 276.71, #Deep ground layer altitude

/
&NAM_PREP_ISBA_SNOW CSNOW = '3-L' , #Snow scheme
                    NSNOW_LAYER = 12 , #Amount of snow layers
                    LSNOW_FRAC_TOT = F

/
&NAM_ISBA_SNOWn    LSNOWDRIFT = T ,
                    LSNOWDRIFT_SUBLIM = F

/
&NAM_SURF_ATM      XRIMAX      = 0.20 ,
                    LNOSOF      = T ,
                    LVERTSHIFT   = F

/
&NAM_SURF_CSTS     XEMISSN     = 0.99 ,
                    XWSNV       = 2.0,
                    XTAU_LW     = 0.3 , #Transmission for LW through the canopy

/
&NAM_ISBAn        CC1DRY      = 'DEF' ,
                    CSCOND      = 'PL98' ,
                    CSOILFRZ    = 'LWT' ,
                    CDIFSFCOND  = 'DEF' ,
                    CSNOWRES    = 'DEF' ,
                    CCPSURF     = 'DRY'

/
&NAM_SGH_ISBAn    LSOC        = T #Activate or not the carbon soil effect

/
&NAM_DIAG_SURF_ATMn LFRAC      = T

/
&NAM_DIAG_SURFn   N2M        = 0 ,

```



```

LSURF_BUDGET = T ,
LCOEF = T ,
LRAD_BUDGET = T ,
LSURF_VARS = T ,
LSURF_BUDGETC = T ,
LRESET_BUDGETC = T

/
&NAM_DIAG_ISBAn LPGD = T ,
LSURF_EVAP_BUDGET = T ,
LSURF_MISC_BUDGET = T ,
LSURF_MISC_DIF = T ,
LWATER_BUDGET = T ,
LPATCH_BUDGET = T

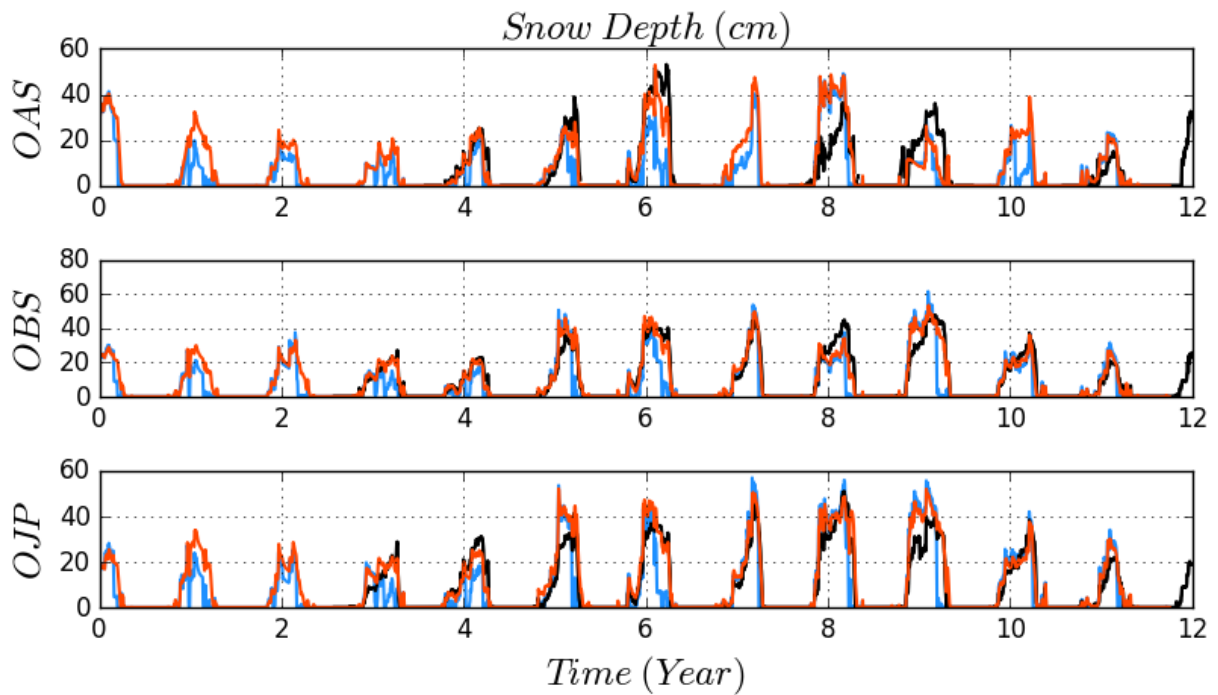
/
&NAM_IO_OFFLINE LPRINT = F ,
CFORCING_FILETYPE = 'NETCDF' ,
CSURF_FILETYPE = 'ASCII' ,
CTIMESERIES_FILETYPE = 'NETCDF' ,
XTSTEP_SURF = 900. , #Model time step
XTSTEP_OUTPUT = 1800. , #Output time step
LLIMIT_QAIR = T ,
LSET_FORC_ZS = F ,
XDELTA_OROG = 2200. ,
LRESTART = T ,
LPRINT = T ,
LOUT_TIMENAME = T ,
LWRITE_COORD = T ,
NB_READ_FORC = 0 ,
LALLOW_ADD_DIM = F

/
&NAM_WRITE_DIAG_SURFh LPROVAR_TO_DIAG = T ,
LSELECT = T ,
CSELECT1 = #OUTPUT VARIABLES

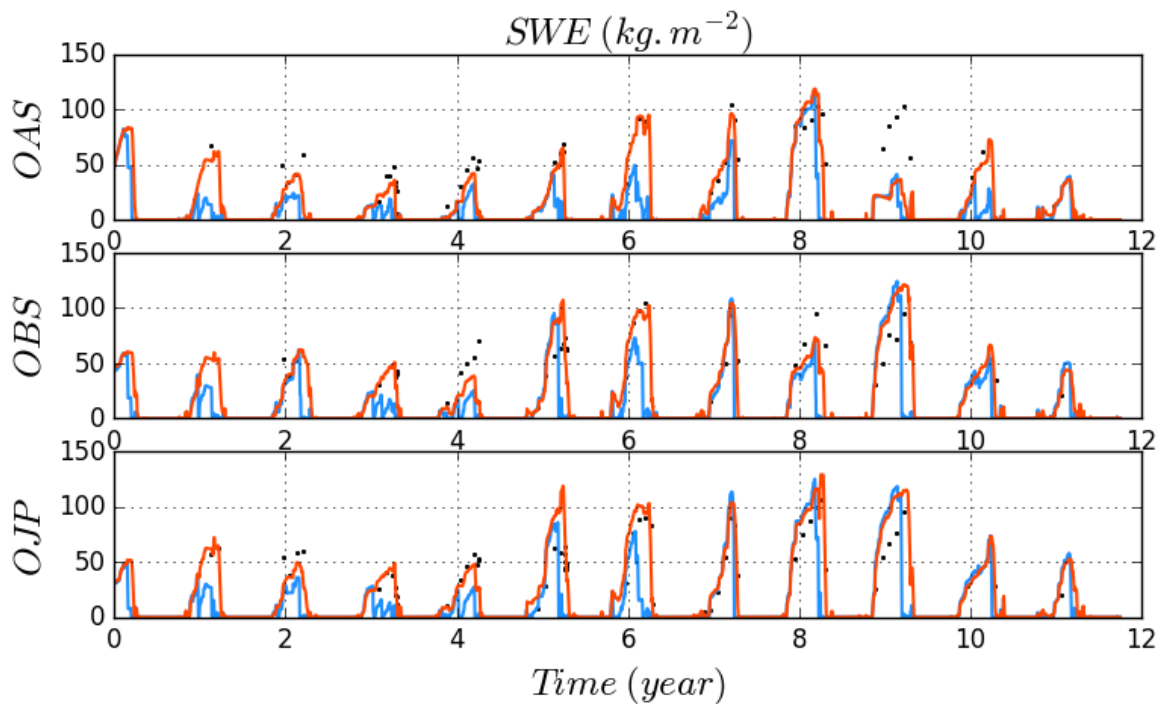
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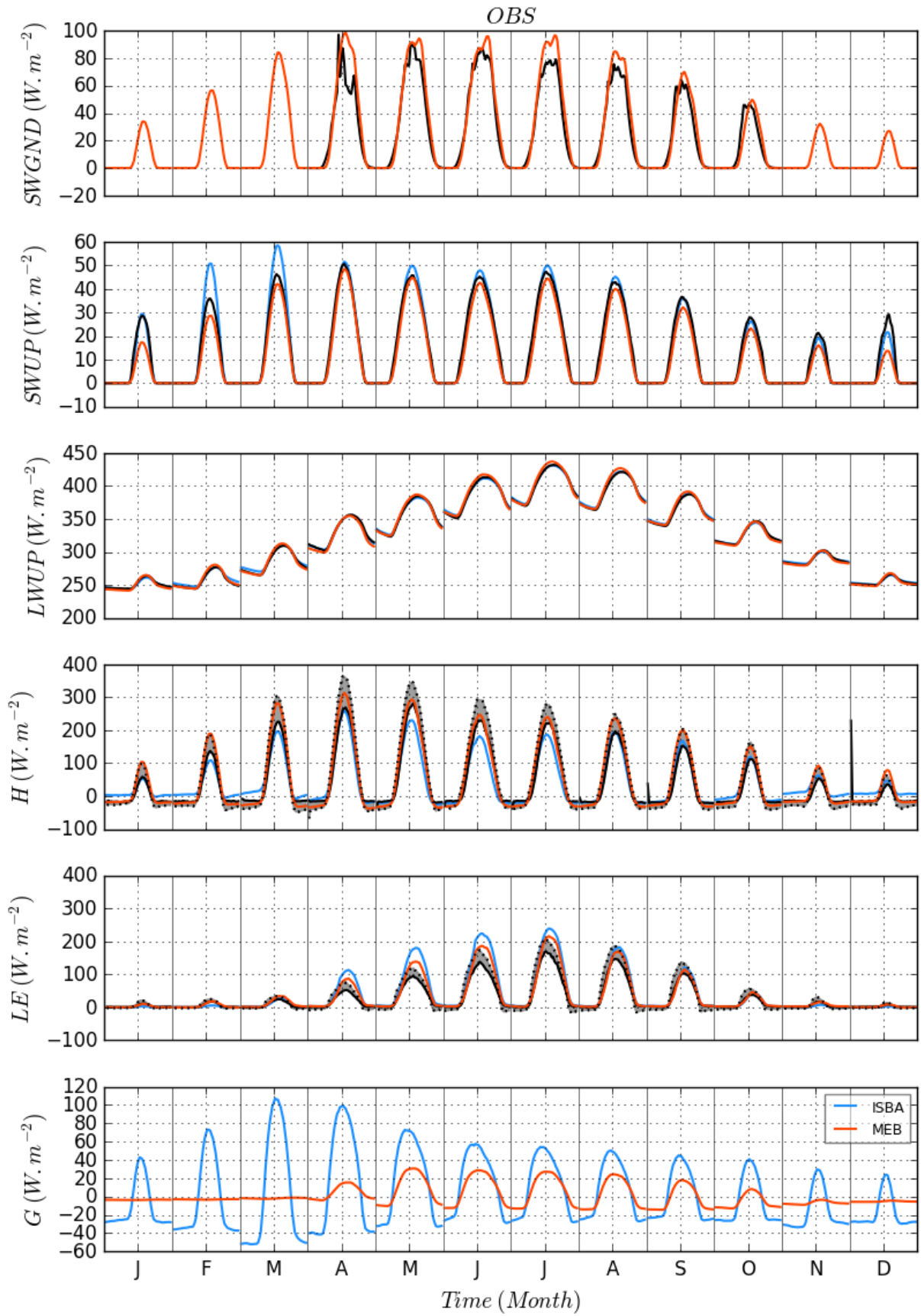
## B Additional figures



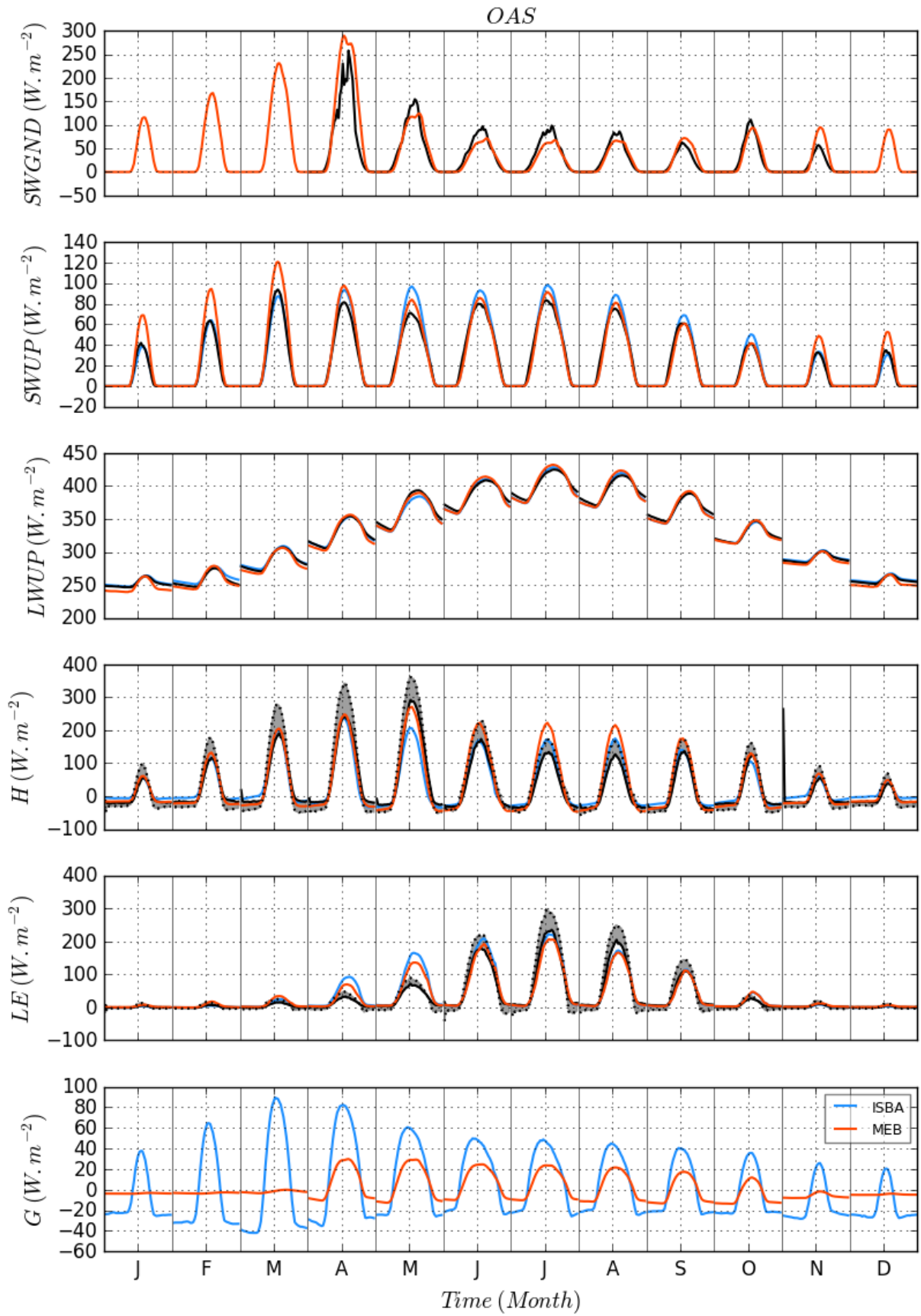
**Figure B1:** Snow depth for the three sites over the full period. MEB is in red, ISBA in blue and observations in black.



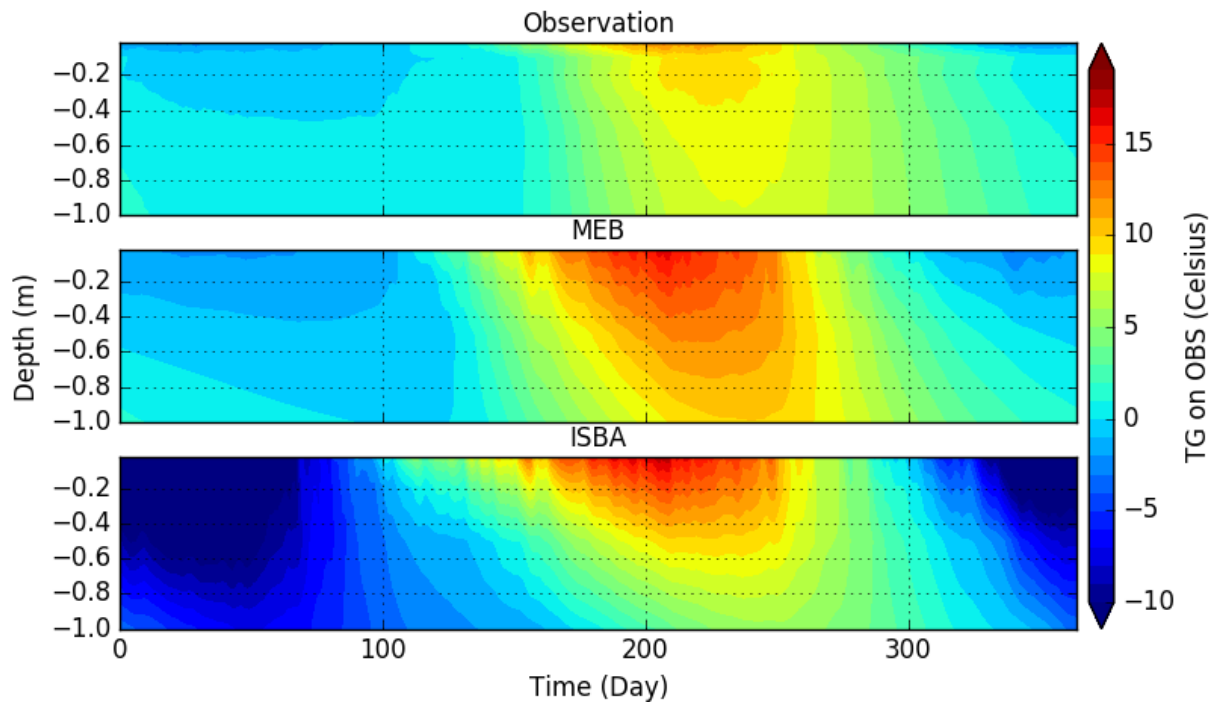
**Figure B2:** Snow water equivalent for the three sites over the full period. MEB is in red, ISBA in blue and observations in black.



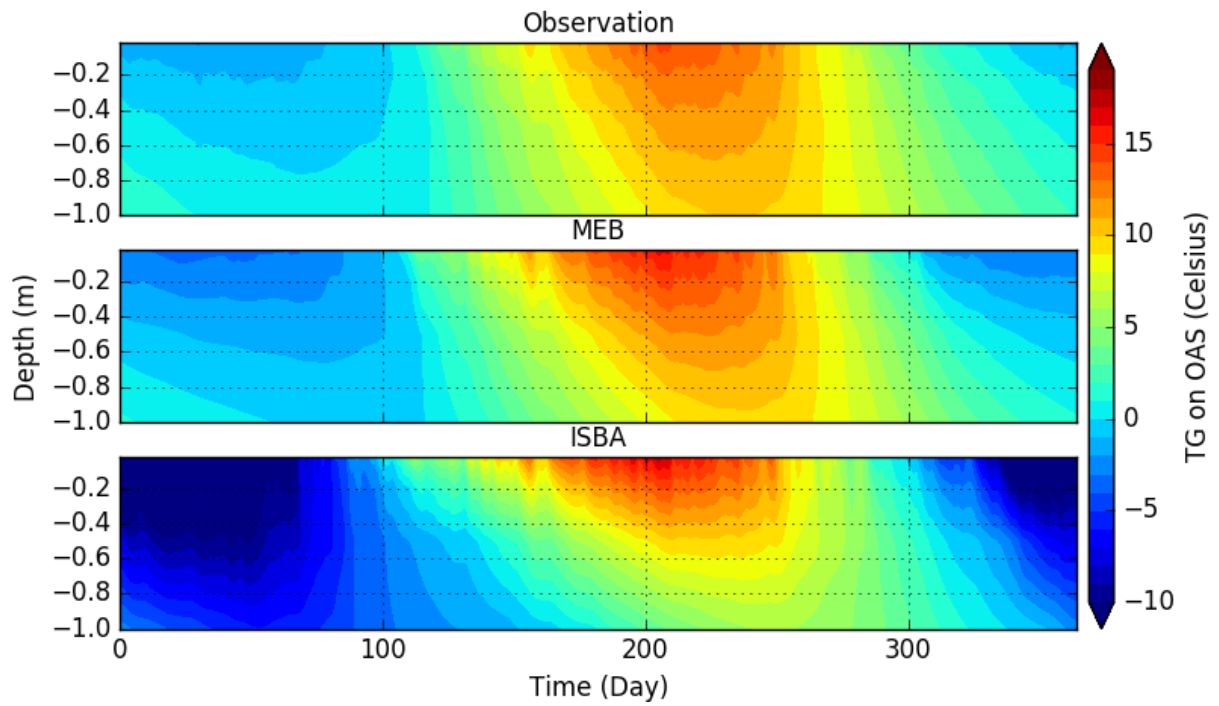
**Figure B3:** Composite of monthly diurnal cycle at OBS site. MEB is in red, ISBA in blue, measurements are indicated by a solid line and adjusted measurements are represented using a dashed black line.



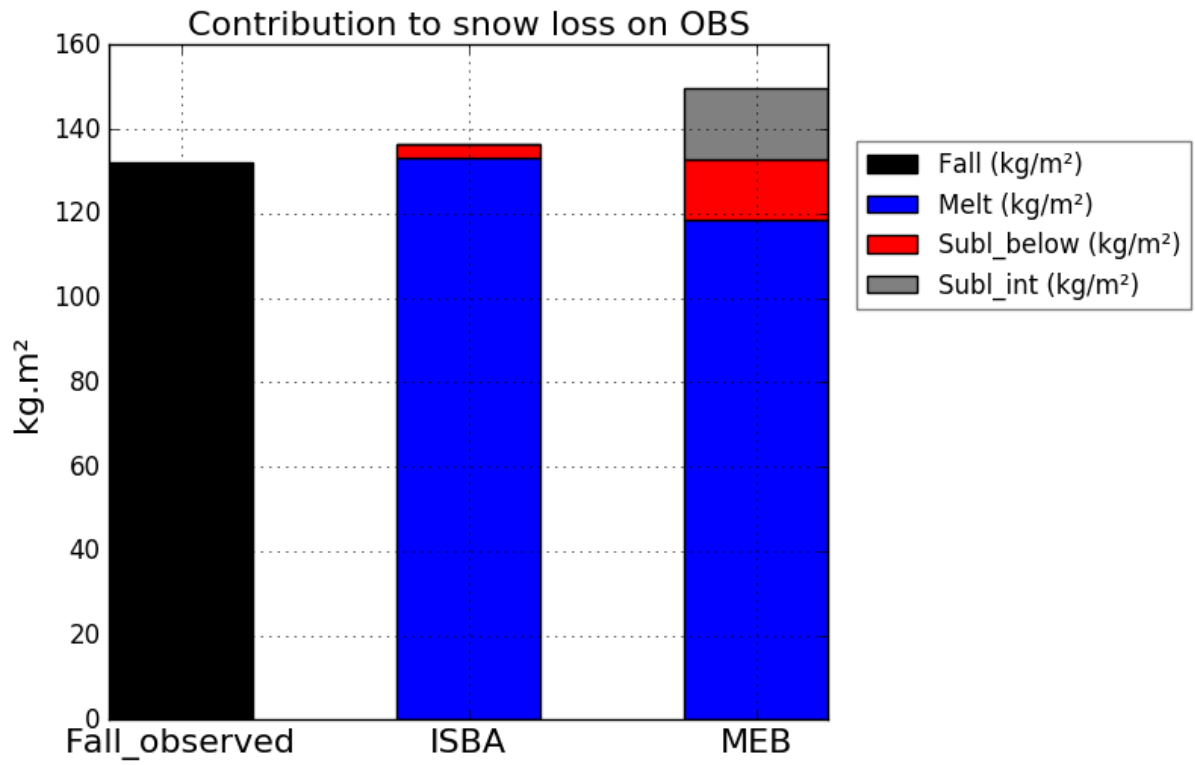
**Figure B4:** Composite of monthly diurnal cycle at OAS site. MEB is in red, ISBA in blue, measurements are indicated by a solid line and adjusted measurements are represented using a dashed black line.



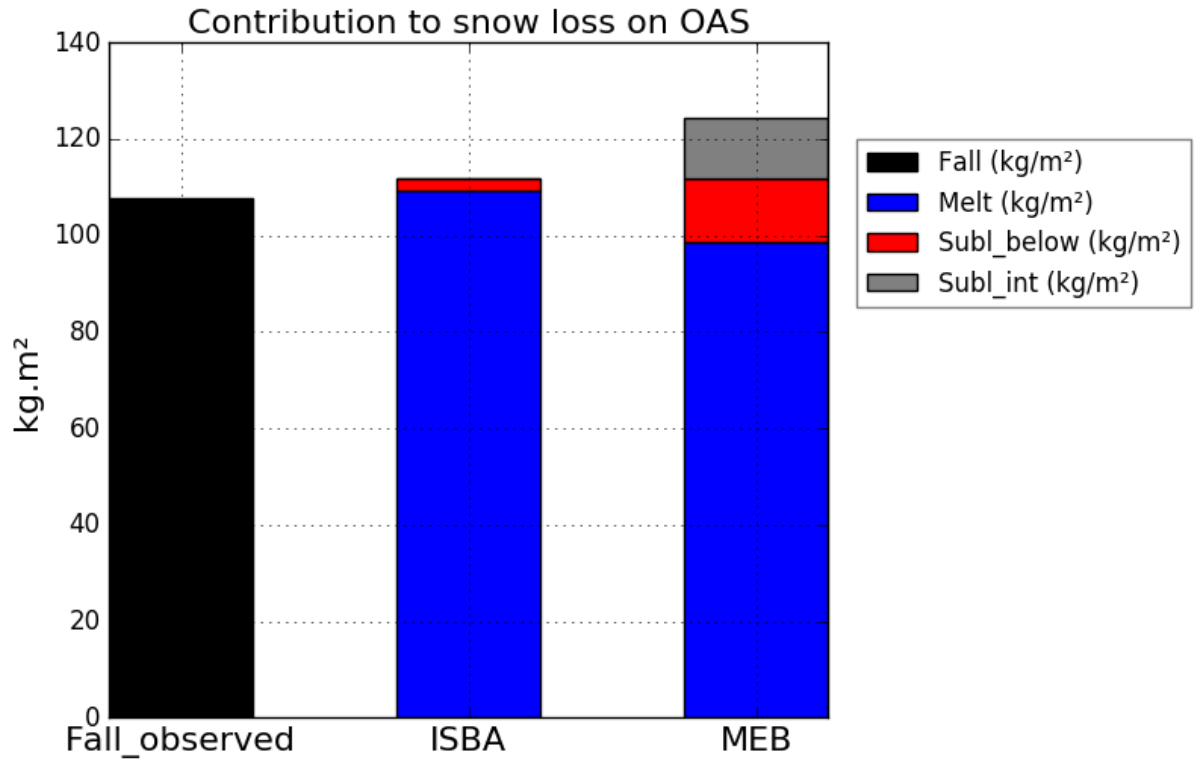
**Figure B5:** Average annual contours of soil temperature between surface and 100 cm deep at the OBS site.



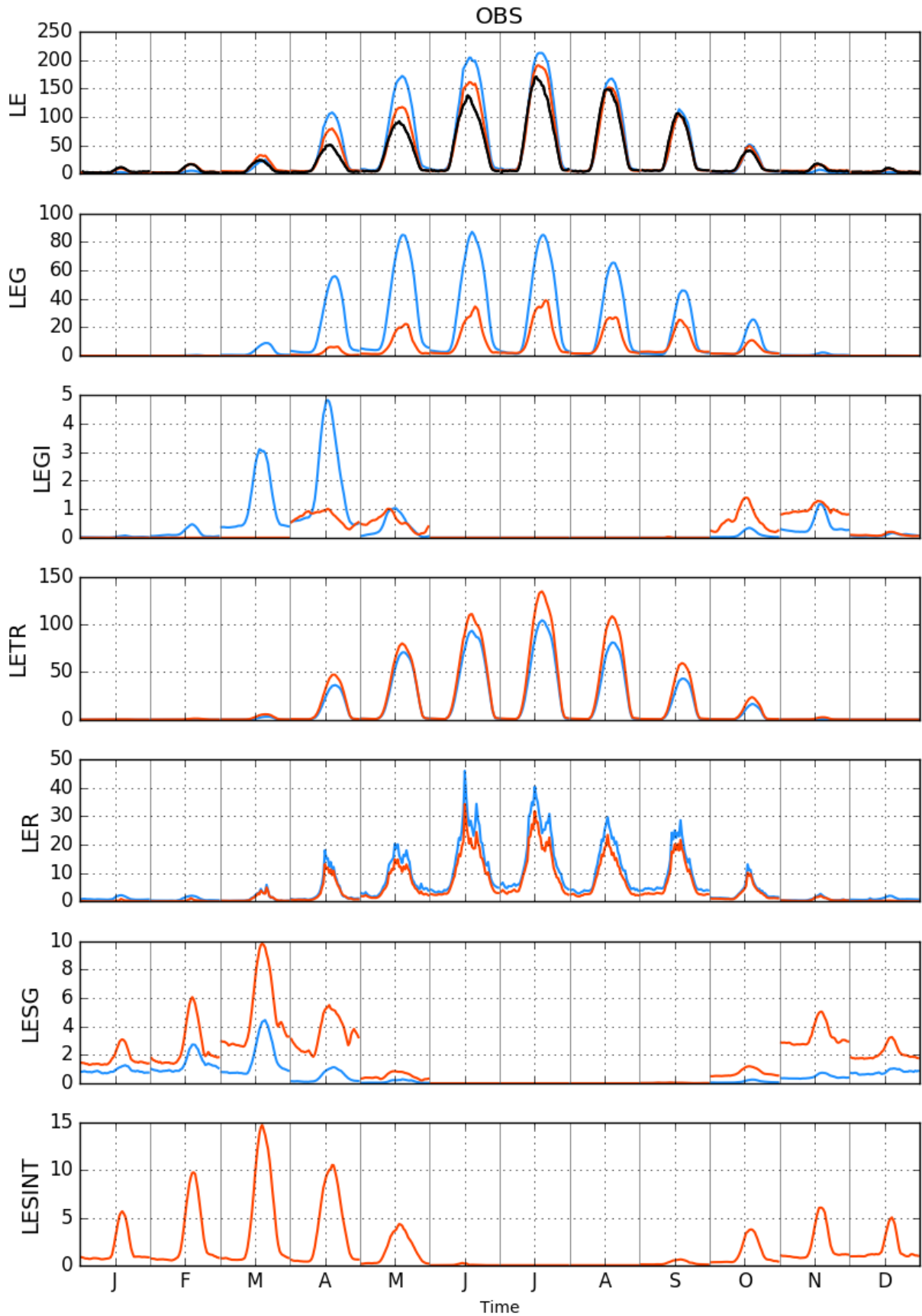
**Figure B6:** Average annual contours of soil temperature between surface and 100 cm deep at the OAS site.



**Figure B7:** Contribution in snowpack loss between melting, sublimation above the canopy and sublimation of intercepted snow (only for MEB) in MEB and ISBA on OBS. The solid precipitations (i.e. observations) are represented in black.

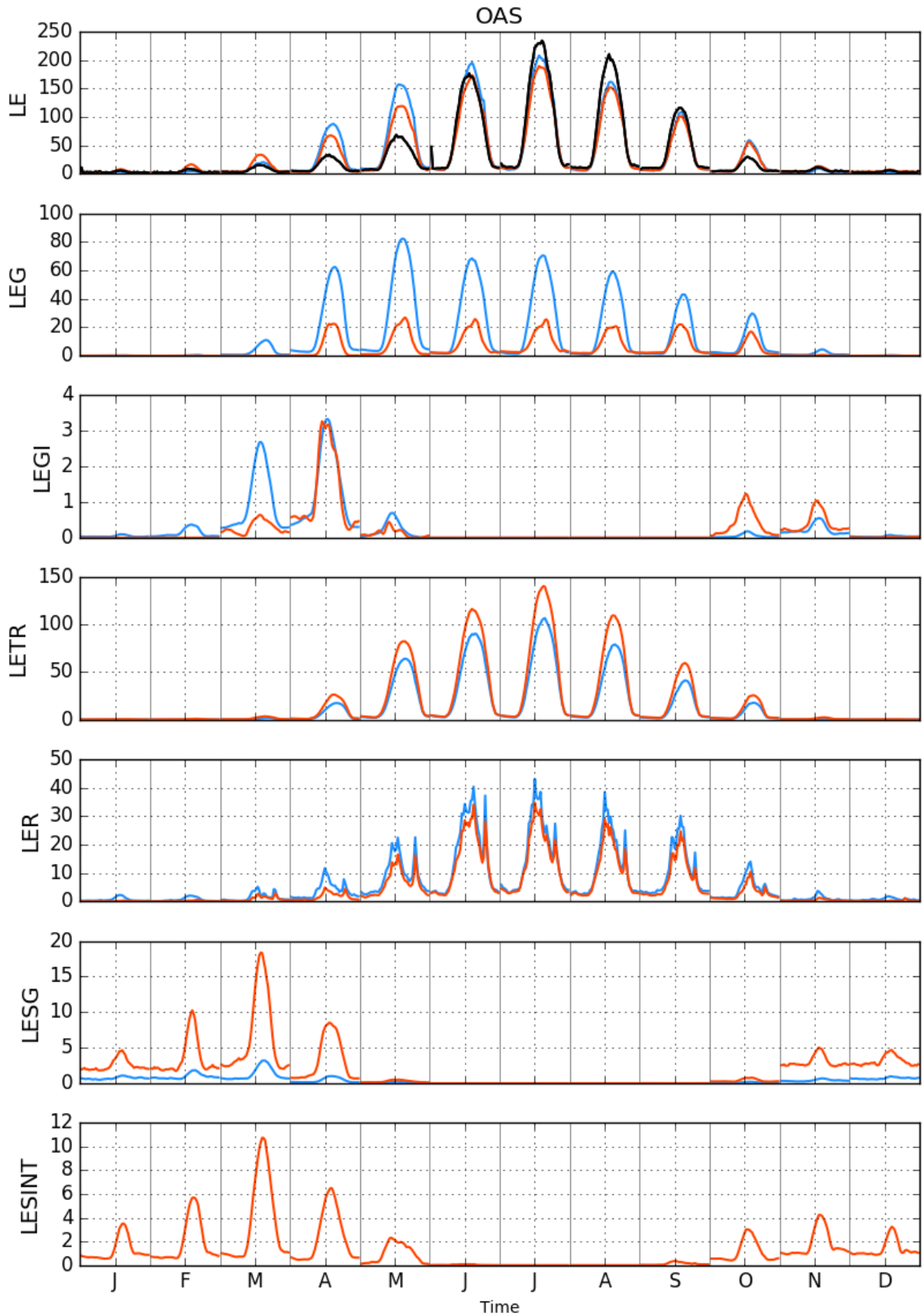


**Figure B8:** Contribution in snowpack loss between melting, sublimation above the canopy and sublimation of intercepted snow (only for MEB) in MEB and ISBA on OAS. The solid precipitations (i.e. observations) are represented in black.

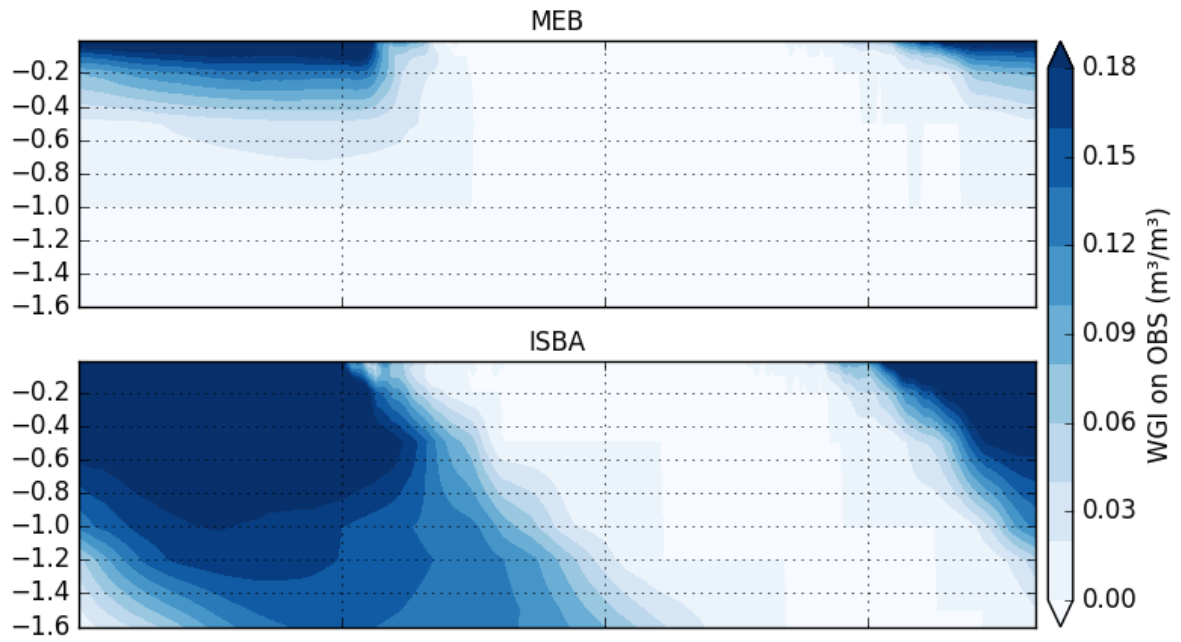


**Figure B9:** Composite of monthly diurnal cycle of each terms that compose the global evapotranspiration term on OBS site for ISBA (blue) and MEB (red). *LE* is the global evapotranspiration flux (i.e. latent heat flux), *LEG* the ground evaporation, *LEGI* the sublimation of the ice contained in the ground, *LETR* the transpiration of the vegetation, *LER* the evaporation of intercepted water, *LESG* the evaporation of ground based snow and *LESINT* the sublimation of intercepted solid water.

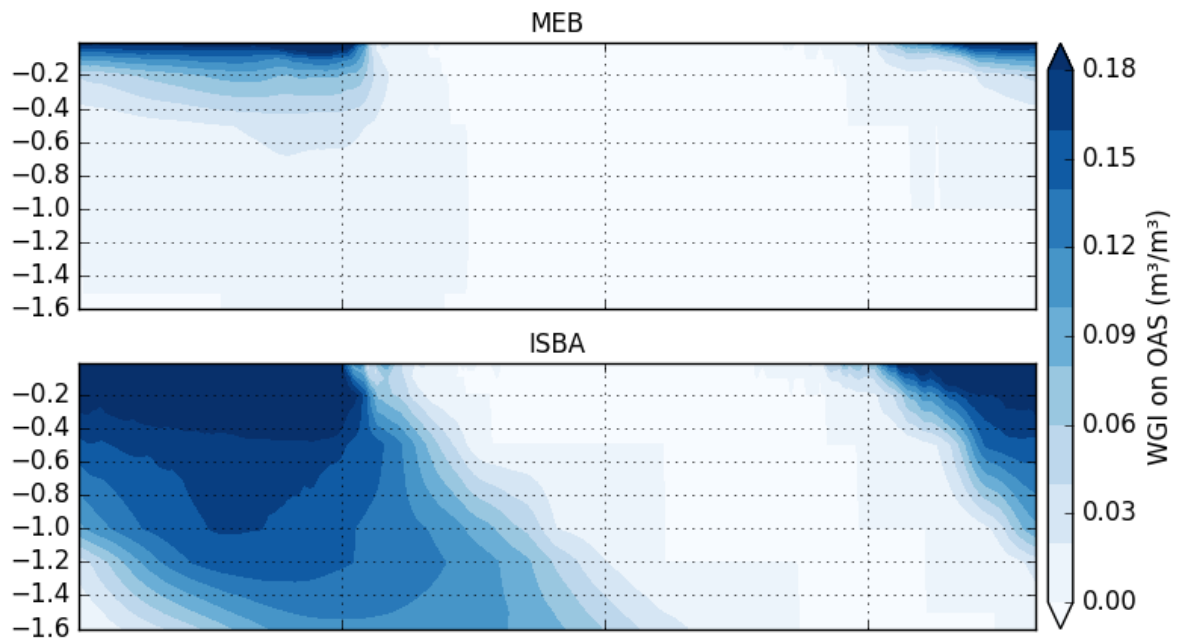




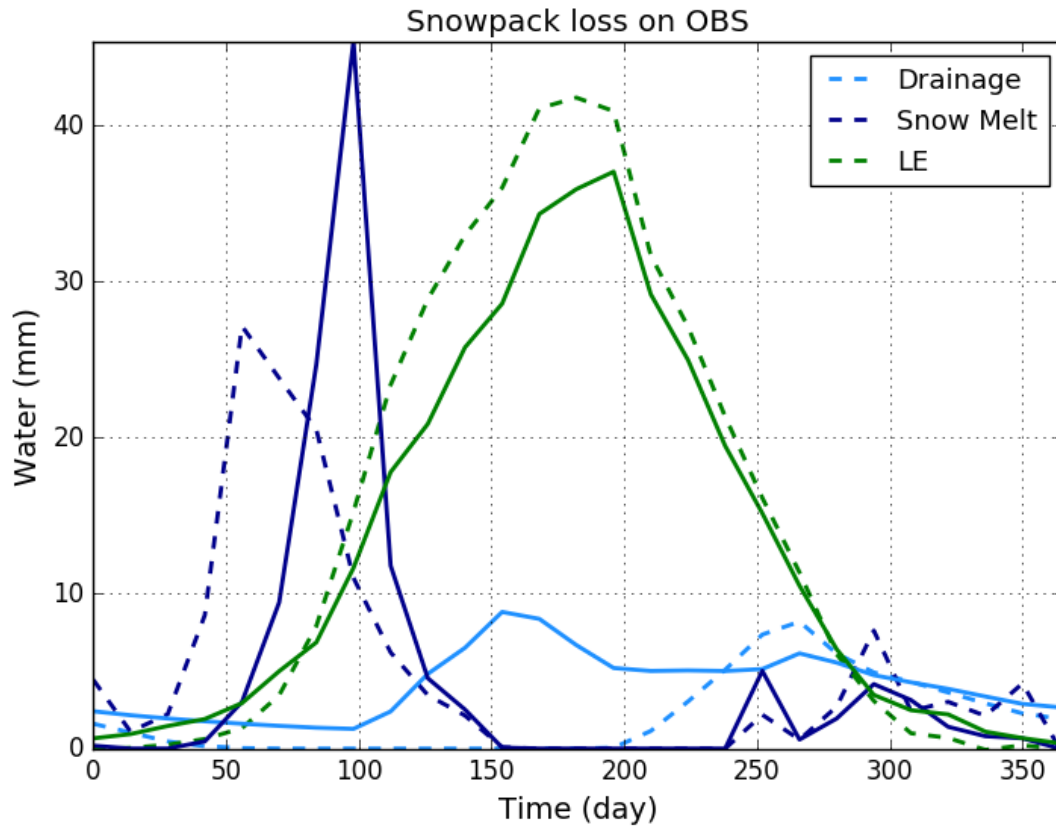
**Figure B10:** Composite of monthly diurnal cycle of each terms that compose the global evapotranspiration term on OAS site for ISBA (blue) and MEB (red). *LE* is the global evapotranspiration flux (i.e. latent heat flux), *LEG* the ground evaporation, *LEGI* the sublimation of the ice contained in the ground, *LETR* the transpiration of the vegetation, *LER* the evaporation of intercepted water, *LESG* the evaporation of ground based snow and *LESINT* the sublimation of intercepted solid water.



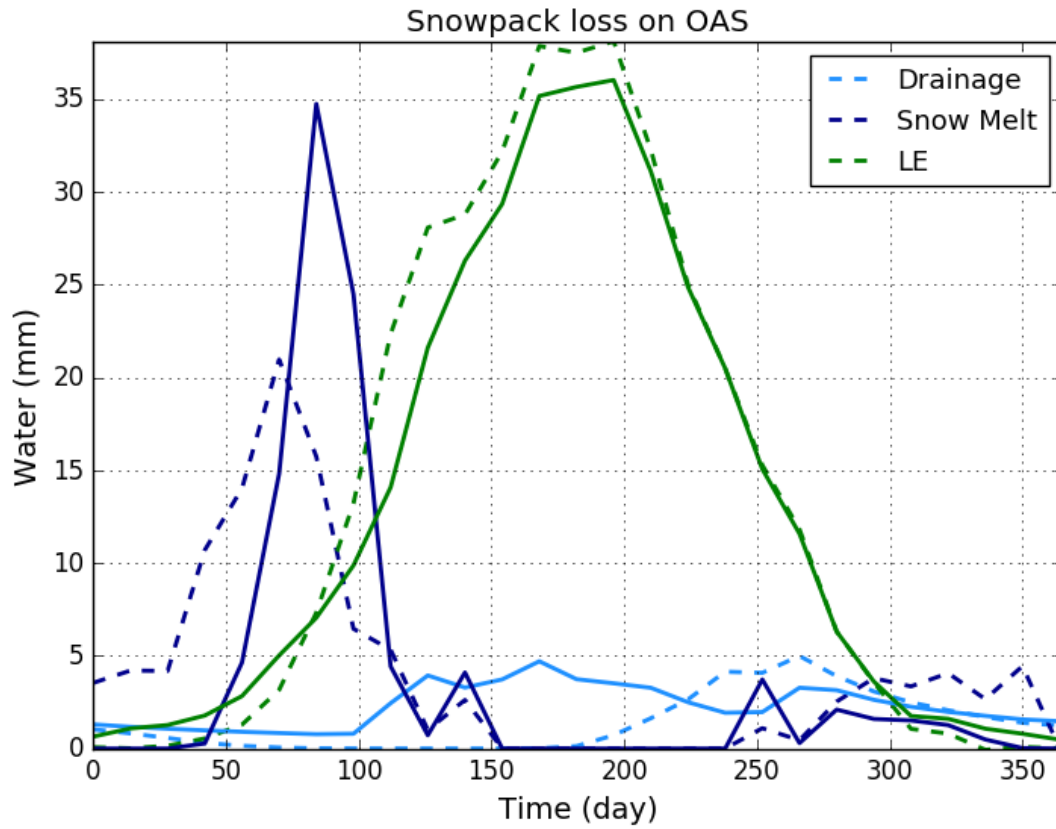
**Figure B11:** Average annual iced water content in the ground on the OBS site.



**Figure B12:** Average annual iced water content in the ground on the OAS site.



**Figure B13:** Representation of the drainage, the latent heat flux and snow melt on OBS. ISBA is represented with the dotted lines and MEB the full lines.



**Figure B14:** Representation of the drainage, the latent heat flux and snow melt on OAS. ISBA is represented with the dotted lines and MEB the full lines.

## C Introduction and Conclusion translation

### French Introduction

Dans l'environnement terrestre, la surface représente l'interface située entre le sol et l'atmosphère. L'épaisseur considérée varie en fonction des disciplines (i.e. météorologie, climatologie, hydrologie) et du type de surface (i.e. océan, continent) considéré. Dans le cas de la météorologie, ce sont uniquement les premiers centimètres qui sont considérés, alors que pour l'hydrologie ou la géologie, une épaisseur bien plus grande doit être prise en compte. En météorologie et climatologie (les centres d'intérêts du CNRM), la surface représente l'endroit où les échanges de chaleur, d'eau et de carbone avec l'atmosphère ont lieu. Afin de comprendre ces processus, il faut être capable de les simplifier et de les représenter de manière numérique, c'est ce qui est appelé les modèles de surface. Ces modèles sont capables de fournir les conditions aux limites basses aux modèles de surface avec lesquels ils sont couplés.

À Météo-France, la plateforme SURFEX (Surface Externalisée) regroupe tous les types de modèles de surface, c'est à dire les modèles pour les océans, les lacs, les villes et les surfaces continentales. Dans le cas des surfaces continentales, qui sont le centre d'intérêt de cette étude, les *Land Surface Models (LSMs)* sont utilisés. Ils ont connu des développements pendant des années et encore aujourd'hui ils gagnent en précision et en complexité. Le LSM utilisé à Météo-France est le modèle Interactions Sol-Biosphère-Atmosphère (ISBA) dont la première version a été développée par Noilhan and Planton en 1989. Depuis ce jour, le modèle a reçu de nombreuses améliorations, notamment dans le cas de la représentation des processus du sol, de la neige et du cycle du carbone. Le développement le plus récent concerne la représentation de la végétation dans le modèle, qui a un impact important sur la modélisation des échanges d'eau et d'énergie. Ces impacts sont encore plus notables dans le cas des zones forestières, où la végétation doit être précisément représentée en raison de sa dimension verticale qui est à l'origine d'échanges très complexes. Dans la version de base d'ISBA, la végétation est associée à un ensemble avec la couche supérieure du sol pour former une seule et unique couche composite. Le dernier développement mis en place permet la représentation de la végétation avec une couche explicite grâce à l'option *Multi Energy Balance (MEB)* (Boone et al. (2017)). Cette option a connu une modification récente, avec l'ajout d'une couche explicite pour la litière qui repose sur le sol (Napoly et al. (2016)), avec ISBA-MEB-Litter. A court terme, l'objectif serait d'activer l'option MEB dans le système opérationnel utilisé pour la prévision à Météo-France. Pour se faire, l'option doit d'abord être évaluée sur plusieurs types de végétations et de climats pour montrer sa robustesse. Ce travail a déjà pu être réalisé pour des zones forestières de latitude moyenne, notamment en France, mais aucun accent précis n'a été mis sur les périodes de neige, qui a été révélé comme une faiblesse de la version de base d'ISBA.

Les forêts boréales représentent la majorité des forêts de l'Hémisphère Nord, ainsi qu'un cinquième de sa zone couverte par la neige. Son impact sur l'atmosphère n'est donc pas négligeable et il devient essentiel de développer des modèles numériques efficaces afin de fournir des prévisions, à courte échelle de temps pour la météorologie et à grande échelle de temps pour la climatologie.

La finalité de ce rapport est d'évaluer la contribution de l'option MEB dans le cas précis des zones forestières. L'étude va se concentrer, en plus d'une évaluation globale de l'option, sur le comportement du modèle pendant les périodes de neige. L'*Earth System Model Intercomparison Project (ASM-SnowMIP)* (Krinner et al. (2018)) qui a eu lieu en 2017 a permis d'avoir accès aux données de trois sites d'observations tirés du projet *Boreal Ecosystem Research Study (Berms)* au Canada. Ces jeux de données vont être la base de l'étude menée ici.

Dans un premier temps, les modèles de surface (LSM) seront présentés de manière générale. Une description plus précise sera donnée sur les caractéristiques des modèles ISBA, ISBA-MEB et ISBA-MEB-L. Dans un second temps, l'évaluation complète des modèles ISBA et ISBA-MEB-L sera effectuée, aboutissant à un premier constat de différences. Un accent sera notamment mis sur la capacité à modéliser les processus liés à la neige avec les deux modèles. L'évaluation locale va conclure sur un test de sensibilité des nouveaux paramètres intégrés dans ISBA-MEB-L. Enfin, l'étude va tester l'option MEB-L sur un autre site, situé dans les Alpes. Cela va permettre une

ouverture sur la comparaison des deux modèles dans le cas d'une simulation à l'échelle globale.

## French Conclusion

Cette étude a évalué l'impact en période de neige de l'option Multi Energy Balance (MEB) qui a récemment été implanté dans le modèle de surface Interactions Sol-Biosphère-Atmosphère (ISBA). La représentation de base de la végétation dans ISBA consiste en une couche composite qui est caractérisée à la fois par une fraction de sol et par une fraction de végétation. La nouvelle option améliore cette représentation dans le cas des forêts grâce à l'implémentation de deux couches explicites : une pour la canopée et l'autre pour la couche de litière qui repose au sol.

Pour mener l'évaluation, 12 années d'observations aux trois sites de Berms (Boreal Ecosystem Research Study) étaient disponibles. En plus des forçages nécessaires au fonctionnement des modèles, les flux turbulents et radiatifs, les températures et contenu en eau du sol et les mesures sur la neige ont été utilisés.

Pendant les périodes sans neige, des résultats comparables à l'étude précédente (Napoly et al. (2016)) ont pu être confirmés. En raison de l'effet d'assombrissement de la couche de végétation et de la faible diffusivité thermique de la couche de litière, le flux de chaleur conductif dans le sol est largement diminué, tout comme l'amplitude de la température du sol, et tout cela en accord avec les observations (RMSE de  $47.1 \text{ W.m}^{-2}$  avec ISBA et  $10.9 \text{ W.m}^{-2}$  avec MEB sur l'ensemble de la période). Cette énergie disponible est alors envoyée dans les flux turbulents et principalement dans le flux de chaleur sensible (RMSE de  $58.9 \text{ W.m}^{-2}$  avec ISBA et de  $48.4 \text{ W.m}^{-2}$  avec MEB), alors que le flux de chaleur latent est limité par la quantité d'eau présente dans le sol. Au printemps, le flux de chaleur sensible est aussi amélioré avec une contribution limitée de l'évaporation du sol grâce à la couche de litière. Les données disponibles sur les courtes longueurs d'onde en dessous de la canopée ont pu montrer la capacité de MEB à correctement modéliser le transfert radiatif à travers la canopée. Malheureusement, la mesure des grandes longueurs d'ondes n'a pas été réalisée sous la canopée pour compléter cette étude.

Pendant les périodes de neige, l'amélioration du réalisme avec l'option MEB permet de séparer le sol de l'atmosphère. En effet, le pack de neige qui est sur le sol va le recouvrir et donc l'isoler totalement. Les températures sous la surface sont alors constantes et proche de  $0^\circ\text{C}$ , ce qui est proche des observations. Avec le modèle ISBA de base, l'absence de cette séparation entre sol et atmosphère est expliquée par la valeur de la fraction de neige effective qui varie entre 10 et 20 %. La conséquence est qu'une grande part du sol est directement connectée aux variations de températures de l'atmosphère. Cela provoque de grandes incohérences au vue du refroidissement du sol, avec un biais moyen sur l'ensemble des sites de  $-5^\circ\text{C}$  contre  $-0.1^\circ\text{C}$  avec MEB. De la même manière qu'avec l'effet de la litière, l'énergie qui n'est pas distribuée dans le sol est distribuée dans les flux turbulents, qui étaient jusqu'alors sous-estimés. Le RMSE moyen sur le flux de chaleur sensible pendant la période de neige passe de  $54.9$  à  $45 \text{ W.m}^{-2}$  avec MEB.

L'impact sur la modélisation du pack de neige est majeur. En général, la hauteur de neige est améliorée avec MEB, avec un RMSE moyen qui était de  $9.1 \text{ cm}$  avec ISBA et qui est de  $5.1 \text{ cm}$  avec MEB. Cela s'explique par une meilleure représentation des processus durant la saison, et surtout durant la période de fonte. En effet, la neige fond, en moyenne, 24 jours trop tôt avec ISBA alors que ce n'est qu'un jour trop tôt avec MEB. Cette erreur dans ISBA s'explique par le couplage entre le sol et l'atmosphère. Quand la température de l'air devient positive, la couche composite suit la même tendance, réchauffant alors le pack de neige par en dessous et le faisant fondre. Dans MEB, la protection prodiguée par le pack de neige fait qu'il ne peut recevoir de l'énergie que par sa surface. En conséquence, la sublimation représente uniquement 2 % de la perte du pack de neige dans ISBA contre 22 % en utilisant MEB. Près de la moitié de ce montant provient de la neige interceptée par la canopée et l'autre moitié provient directement du pack de neige.

Deux impacts hydrologiques sont à prévoir avec l'option MEB. D'une part, le sol gel moins profondément et moins longtemps. Avec ISBA, le sol gel en profondeur et cela peut durer jusqu'à plus de la moitié de l'année, alors que ce n'est pas le cas avec MEB. Cela étale l'évolution du drainage

en profondeur dans MEB alors que dans ISBA le drainage en profondeur à lieu sur une période très courte au milieu de l'été. D'autre part, la fonte des neiges à lieu trois semaines plus tard avec MEB. Le ruissellement de surface devrait donc connaître un retard identique. Ces impacts devront être étudiés sur des simulations globales couplées à des modèles hydrologiques.

Les tests de sensibilité ont été réalisés de manière à évaluer les nouveaux paramètres intégrés avec l'option MEB. Les paramètres ont été sélectionnés car leur sens physique était mal connu. Un seul des 5 paramètres testés s'est avéré être vraiment sensible, le coefficient de transfert pour les grandes longueurs d'onde à travers la canopée, ce qui montre une grande robustesse du modèle. La valeur par défaut de 0.5 du paramètre a donc été modifiée à 0.4.

Après cette évaluation, l'étude s'est focalisée sur un autre site, le Col de Porte, situé près de Grenoble, puis sur l'échelle globale. Cela a permis de mettre en valeur que le schéma d'interception de neige dans MEB pouvait avoir des limitations dans quelques situations. En effet, sa paramétrisation a été validée sur des sites au climat très froids, ce qui n'est pas le cas du site du Col de Porte. Sur ce site, la forêt a l'air d'intercepter et de sublimer une part de la neige bien supérieure que sur les sites de Berms, ce qui expliquerait que le pack de neige modélisé avec MEB est plus faible.

Enfin, une étude globale a été réalisée. Les résultats sont toujours en train d'être étudiés mais de premières incompréhensions sont apparues. Sur les sites de Berms, les résultats globaux ont donné comme résultat que le pack de neige fondait plus rapidement que lors de l'étude locale. Le manque de temps n'a pas permis de continuer l'étude mais des travaux futurs sont prévus, comme une thèse au CEN à Grenoble, qui pourrait se focaliser sur certains de ces aspects. De ce fait, le travail réalisé au cours de ce stage sera le support de travaux futurs.