The Future of the Rossby Land-Surface Model

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The Rossby Centre Regional Climate model (RCAO) consists of two coupled models the Rossby Centre Regional Climate Atmospheric model (RCA) and the Rossby Centre Ocean model (RCO). RCA started to be developed on the basis of HIRLAM in 1997 but due to different demands in climate modelling with respect to short range forecasts at that time most physics except for the radiation scheme has continuously been replaced with new physics since then. Thus, during some years RCA and HIRLAM ended up to be quite different. However, in the latest couple of years most of the developments of physics in RCA have also been introduced in the SMHI version of HIRLAM. At the moment concepts of the RCA land-surface scheme (LSS) connected to snow and forest processes are on their way into HIRLAM as well (Gollvik 2005, this issue). In this paper we will describe ongoing development of the RCA LSS coupled to interception of snow and to coupling of the LSS with a dynamic vegetation model.

Modelling of Snow Interception

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As much as 60% of a cumulative snow fall may be intercepted by a boreal forest (Hedstrom and Pomeroy, 1998) and under the right conditions, which means weather and dense vegetation, i.e. large “snow-capturing” branch area, it could be retained in the canopy up to several weeks. The sublimation losses of intercepted snow have been observed to be 10-50% of the annual snowfall (Lundberg and Halldin, 2001; Pomeroy et al., 1998). Thus, processes related to interception of snow could be important to consider in numerical simulations over some boreal regions since they will have a large effect on the partition between evaporation and runoff. A parameterization of these processes has been implemented and tested in a version of the RCA LSS by Fredriksson (2002).

Without the snow interception introduced we assume that all snow falls to the ground and nothing is captured in the canopy and still we are not doing that bad in the evaporation/runoff partition. The reason is compensating errors, the rate of evaporation of snow at the forest floor is very sensitive to the aerodynamic resistance in the layer between the floor and the canopy air, r_d (see Figure 1). If this resistance is unrealistically low, which has probably been the case so far, we are still able to evaporate the snow and get a correct division between evaporation and runoff. r_d will of course affect the energy balances in the forest all around the year even if its effect in the winter season, when there is no transpiration from the forest canopy, is most evident.

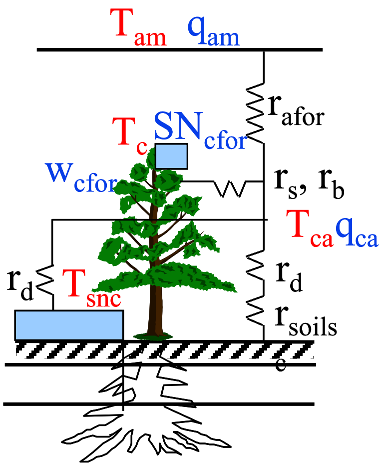


Figure 1. The forest tile of the land-surface scheme showing the added intercepted snow storage, SN_{cfor}, as the blue box in the tree. The coloured variables represent prognostic temperatures, humidities, and water storages. All the r_{xx}'s are diagnostic surface and aerodynamic resistances.

Snow interception model

The change of intercepted snow with time is a result of the balance between the source terms, i.e. interception of snow, freezing of earlier intercepted water, and sublimation of water vapour, and the sink terms, i.e. evaporation of snow and snow unloading:

$$SN_{cfor}^{\tau+1} - SN_{cfor} = \underbrace{SI\Delta t + w_{cfor} - E\Delta t}/\underbrace{\rho_w - UL\Delta t} \qquad (1)$$

SOURCES:	SINKS:
•**Snow interception,** SI (m/s)	•**Evaporation of snow,** E/ρ_w $r_b \approx 10\%$ of r_d Evaporative efficiency Snow-cover fraction
•**Intercepted water friezes,** w_{cfor} (m)	•**Snow unloading,** UL (m/s)
•**Sublimation of water vapor,** E/ρ_w (m/s)	

The snow interception, *SI*, and the snow unloading, *UL*, parts of the model are based on Hedstrom and Pomeroy (1998). The results of their model have been verified against measured data and a sensitivity analysis shows that temperature is relatively unimportant to the modelled interception efficiency, while other variables, such as snowfall, snow load, leaf area and time since snowfall are quite important. The snow interception is parameterized as

$$SI\Delta t = (SN_{cfor,\max} - SN_{cfor})(1 - \exp(-kP_{SN})) \qquad (2)$$

where $SN_{cfor,max}$ = f(LAI, $1/\rho_{sn}(T_c)$) ~ 20 mm
k = (snow-leaf contact area) / $SN_{cfor,max}$
P_{SN} = snowfall

$SN_{cfor,max}$, which is the maximum allowed amount of intercepted snow, is a function of leaf-area index, *LAI* and the density of intercepted snow, ρ_{sn}. A typical value of $SN_{cfor,max}$ is 20 mm of snow-water equivalent which is 20 times larger than the corresponding value for intercepted water. The factor k is a function of the snow-leaf contact area which depends on the canopy structure and the direction of falling snowflakes. For a dense boreal forest the snow-leaf contact area is close to one.

The unloading of snow is parameterized as

$$UL\Delta t = (SN^{*}_{cfor} \exp(-U\Delta t) \qquad (3)$$

where $SN^{*}_{cfor,max}$ = new preliminary value
U = a constant unloading rate coefficient
(SN_{cfor} goes to zero for T_c>0°C)

We have simplified the problem by assuming that intercepted water and snow can only exists separately in time. Thus, any water present on the canopy when reaching freezing temperature is transformed to snow and any snow present on the canopy when reaching melting temperature is immediately unloaded as snow.

The snow evaporation, E/ρ_w, part of the model is parameterized as

$$E = \beta_s \rho_a \frac{q_{sat}(T_c) - q_{ca}}{r_b} \qquad (4)$$

where ρ_a = air density
q = specific humidity
r_b = aerodynamic resistance
β_s = evaporative efficiency
(modified from Nakai et al. 1999)

As for intercepted water we assume potential evaporation but restricted by an evaporation efficiency factor. Nakai et al. (1999) present an empirical expression of β_s which we apply in a modified form so β_s is forced to zero when there is no intercepted snow on the canopy. The shape of the final expression of β_s is

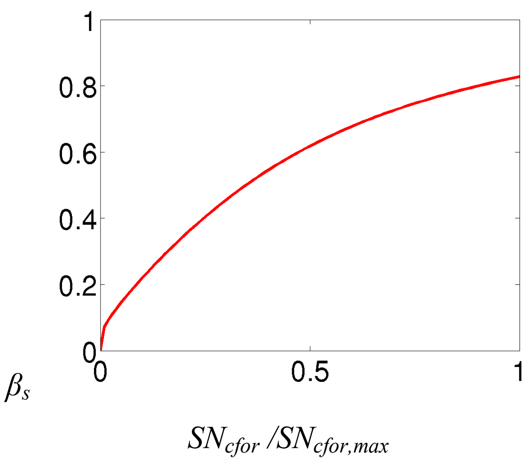
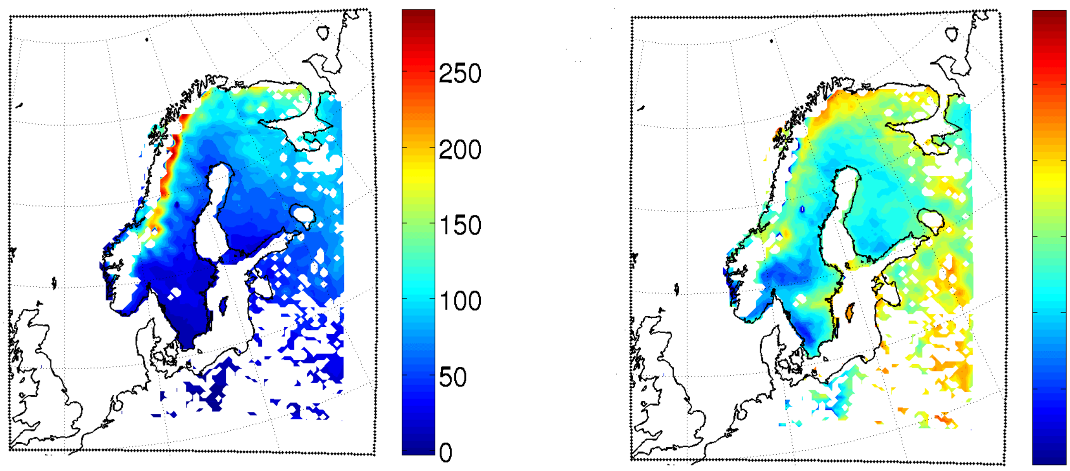


Figure 2. β_s as function of $SN_{cfor}/SN_{cfor,max}$. See Fredriksson (2002) for numerical expression.

Result and discussion

The parameterization of intercepted snow has been implemented in a test version of the land-surface scheme RCA3 (Samuelsson and Gollvik, 2001). Simulations were performed for the period September 1996 – June 1997 on a model domain as seen in Figure 3 with 0.2° resolution. ERA15 data has been used on lateral boundaries and for surface water temperature.

Figure 3a shows the accumulated amount of evaporation of intercepted snow during a snow season (September-May). In most of Scandinavia the amounts are less than 50 mm but in the northern parts and close to the mountain region the values can be as high as 250 mm or more. In figure 3b the accumulated evaporation has been divided by the accumulated amount of snowfall during the same period. Thus, the figure shows the percentage of the snowfall that evaporates from intercepted snow. Values between 20 and 30 percents dominate the domain but close to the mountain, in the northern part, and in the eastern part the values reach up to 50%.



a) b)

Figure 3. RCA simulation using new land-surface scheme including parameterization of snow interception. The results show accumulated values for the period September 1996 – May 1997. (a) Accumulated evaporation of intercepted snow (mm). (b) Ratio of accumulated evaporation of intercepted snow and accumulated snowfall (% .

The most common reason for high ratios of evaporation at some locations is probably that the climate is cold enough so the intercepted snow stays on the trees and is therefore exposed to high evaporation rates for long periods of time. This explanation holds for the mountain region, in the north, and for the continental climate regions in the east. If the winter climate is less cold the snow is frequently unloaded as the canopy temperature reaches melting. This is probably the case for the main part of Scandinavia. Some parts of the domain, which cannot be characterized with cold winter climate, still shows high evaporation ratios at the same time as the total amount of evaporation is small according to Figure 3a. Such regions are the islands in, and the coast around, the Baltic Sea. Here the amount of snow at each snowfall event is probably quite small. Therefore, the maximum amount of snow that is allowed to intercept is seldom reached and a considerable part of the intercepted snow has time to evaporate before melting is reached.

The interception efficiency is sensitive to the density of the canopy, as expressed by the snow-leaf contact area in Equation 2. In the present version of RCA the characteristics of the forest are the same all over the domain. Thus, the forest in cold climate regions is not less dense compared to the forest in the south, which is mostly the case in reality. Consequently the amount of intercepted snow, and its evaporation, is probably overestimated in the cold regions in the simulations. This is supported from comparisons with observed evaporation in Sodankylä in northern Finland (not shown). Due to the large sensitivity on intercepted snow of forest characteristics we will postpone the implementation of snow interception processes in the operational land-surface scheme until the more detailed data base on vegetation represented by ECOCLIMAP is introduced.

Coupling of the RCA LSS and a dynamic vegetation model

Ben Smith and Patrick Samuelsson

The reasons why we wish to couple RCA to a dynamic vegetation model are several:

- Constant vegetation during a climate simulation (in the order of 100 years) may be a bad approximation! At the moment the LSS includes a LAI dependence on soil temperature following the suggestion by Hesselbjerg Christensen et al. (2001), which accounts for some adjustment of the vegetation to climate conditions. However, the model vegetation is far from being allowed to adjust to changing climate conditions compared to what can be expected in the reality.
- Biosphere-climate feedbacks on climate time scale – does vegetation matter? Climate is not only affecting the vegetation but there could also be a feedback that causes climate to change due to changing vegetation. A climate model coupled to a dynamic vegetation model allows us to investigate the importance of such a feedback.
- Better(?) regional scenarios of future change in ecosystem properties and services. A coupled system will increase our possibility for more realistic estimates of the following properties and services:
    - potential vegetation, ”natural” species distributions
    - forest and crop productivity
    - C stocks and fluxes
    - N cycling
    - water storage and runoff

In a research cooperation between the Rossby Centre, SMHI, and the department of Physical Geography and Ecosystem Analysis at Lund University, Sweden, RCA is presently being coupled to the dynamic vegetation model LPJ-GUESS (Sitch et al., 2003; Smith et al., 2001). LPJ-GUESS is built on development of vegetation models since the mid 80's. LPJ-GUESS includes processes on a time scales from daily to annual as shown in Figure 4.

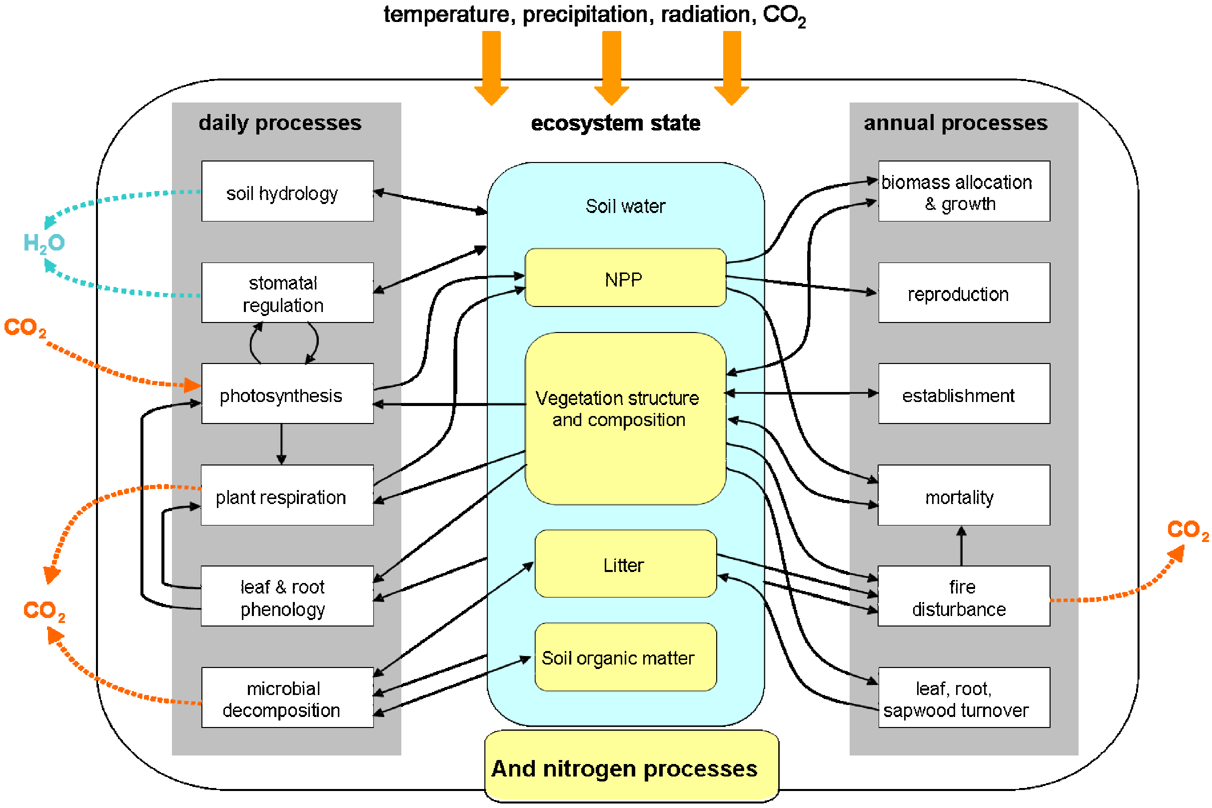


Figure 4. Processes included in the LPJ-GUESS vegetation model.

In the version of LPJ-GUESS coupled to RCA the vegetation is represented by five different plant-functional types (PFTs): boreal/temperate needle leaved evergreen, temperate shade-tolerant broadleaved, summer green, boreal/temperate shade-intolerant, broadleaved summer green, temperate broadleaved evergreen and grass. The individual types are characterized by a number of different parameters like e.g. minimum temperature for survival, minimum degree day level for reproduction, maximum establishing rate and so on.

The GUESS vegetation modelling strategy when coupled to RCA is that each RCA grid square contains a number of independent patches. In each patch (0.1 ha) the PFTs compete for resources. The reason for having a number of patches in each grid square is that there is a certain degree of randomness included in the GUESS modelling.

To simulate the development of natural vegetation successfully some disturbance must be introduced. The disturbance can represent e.g. fires, human and/or fauna influence. If no disturbance is introduced the model vegetation will develop to include only shade tolerant species in the end since the shade intolerant species are eliminated through competition.

Figure 5 shows how GUESS models changes in net primary production (NPP) due to climate change when forced off-line by output from a RCAO simulation. When changes in precipitation and temperature are considered alone we can see an increase of NPP in northern Sweden but a decrease in southern Sweden. Also including the effect of increasing CO2 concentration in the atmosphere as in the right most panel shows an increase of NPP over all of Sweden. These results indicate that excluding the effect of CO2 when modelling the photosynthesis/evapotranspiration process, as is presently the case in the RCA LSS, can have a significant effect on the final water balance.

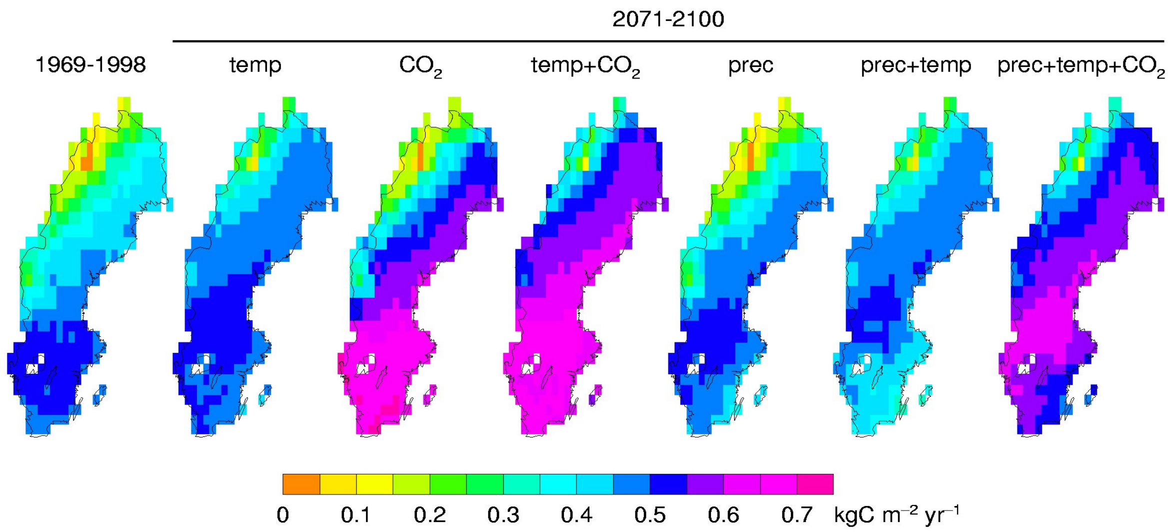


Figure 5. Simulations of net primary production (kgC m-2 yr-1) for Sweden according to GUESS when forced off-line with data from RCAO. The left most panel shows the present day conditions (1969-1998). The following panels show the scenarios for 2071-2100 including the effects of changes in (from left to right) only temperature, only CO2, temperature and CO2, only precipitation, precipitation and temperature and the last including all effects.

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