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The Torne-Kalix PILPS 2(e) experiment as a test bed for modifications to the ECMWF land surface scheme

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Abstract

Results from two land surface models participating in the PILPS 2(e) experiment [the default European Centre for Medium-Range Weather Forecasts (ECMWF) scheme and a modified version labeled MECMWF] are examined. Modifications are implemented in the parameterization of snow sublimation, albedo ageing, surface runoff, and soil hydraulical coefficients. Results of a third run, SECMWF, in which the snow changes were incorporated but the runoff and soil changes were not, were also included in the analysis.

Comparison of the model results to observed catchment averaged discharge and the hydrological balance inferred from it showed a pronounced improvement of the annually averaged partitioning of precipitation over evaporation and runoff. The changes were mainly a result of a reduced snow sublimation by an increased aerodynamical resistance.

Comparison to measured discharge from individual calibration basins revealed that the surface runoff parameterization resulted in improved temporal dynamics of discharge from the mountainous Abisko catchment, but it deteriorated results from the low Lansjärve basin. This was not only due to a miscalibration of the surface runoff parameterization, but probably requires an appropriate estimation of deep bottom drainage. Local calibration of soil hydrology appears mandatory for obtaining a better temporal characterization of discharge. For the basin simulations considered, annual averaged runoff is fairly insensitive to the partitioning of runoff over a surface component and a deep drainage term.

Keywords: Torne-Kalix; PILPS 2(e); ECMWF

1. Introduction

A recent experiment in the context of the Project for Intercomparison of Land Surface Parameterization Schemes (PILPS) was devoted to the model performance under Arctic conditions in the Torne-Kalix river basins, in the north of Sweden and Finland (Bowling et al., 2003-this issue). In this PILPS study, labeled PILPS 2(e), approximately 20 modelling groups submitted results of simulated surface fluxes, soil moisture content and temperature, snow properties, and hydrological components of an area covering 58 000 km^2 for a 10-year period (1989–1998) following a 10-year spin-up period (1979–1988).

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Among the participating models were two versions of the recently developed European Centre for Medium-Range Weather Forecasts (ECMWF) land surface scheme. This ECMWF scheme is a tiled version of the well-known scheme by Viterbo and Beljaars (1995). The tiled version has demonstrated to yield a major improvement for the simulation of snow development in boreal forest areas, where the positioning of the snow under the canopy layer inhibited an excessive snow evaporation (Van den Hurk et al., 2000). However, a number of issues related to processes affecting exposed snow and high-frequency runoff events were not addressed during the development of this new ECMWF scheme. Therefore, another version of the ECMWF scheme was constructed, in which assumed difficulties with snow and runoff processes were addressed. This alternative version, labeled MECMWF hereafter, was submitted to the PILPS 2(e) project in order to evaluate the effects of these changes under controlled conditions. In order to disentangle the effects of changing the snow parameterization from the changes to the runoff parameterization, a third model version was developed in which the modifications to the runoff and soil hydraulical parameterization were switched off. This version (SECMWF) was not submitted to the PILPS 2(e) project, but is analysed in this paper. First, a brief description of the incorporated changes is given, followed by an analysis of the effects of these changes on the annual hydrological budget and on the generation of discharge.

2. Modifications to the ECMWF scheme

Compared to the operational ECMWF land surface scheme, four modifications are included in MECMWF: surface runoff generation, soil hydraulic characteristics, sublimation of exposed snow, and ageing of snow albedo. These changes are described in some detail below.

2.1. Surface runoff

In the original ECMWF land surface scheme, surface runoff can only occur when the infiltration rate (throughfall plus snowmelt, where throughfall is the precipitation minus interception) exceeds the maximum infiltration rate, determined by the hydraulic conductivity. This condition is hardly ever met and, with the exception of rainfall or snowmelt over frozen soils, all runoff in the ECMWF model is generated by drainage through the low soil boundary (Van den Hurk et al., 2002). In the MECMWF version, subgrid saturation of the soil is explicitly parameterized as function of soil moisture content and orographic variability, following the approach by Dümenil and Todini (1992). The fraction of the grid box that is saturated and where surface runoff occurs, S, is given by

$$S = 1 - \left(1 - \frac{W}{W_{\mathrm{sat}}}\right)^{b} \quad (1)$$

where W is the moisture content in the top portion of the soil and W_{sat} is a (soil type-dependent) maximal soil water content. The coefficient b is a grid box-dependent parameter, expressed as a function of the orographic variance σ_0 according to

$$b = 0.01 \leq \frac{\sigma_0 - \sigma_{\min}}{\sigma_0 + \sigma_{\max}} \leq 0.5 \quad (2)$$

in which $\sigma_{\min}$ and $\sigma_{\max}$ are orographic scaling parameters. Integrating Eqs. (1) and (2) over the grid box area results in a surface runoff rate R_{S} given by

$$R_{\mathrm{S}} = T - (W_{\mathrm{sat}} - W) + W_{\mathrm{sat}}\left[\left(1 - \frac{W}{W_{\mathrm{sat}}}\right)^{1/(b+1)} - \left(\frac{T}{(b+1)W_{\mathrm{sat}}}\right)\right]^{b+1} \quad (3)$$

with T the sum of throughfall and snowmelt.

For the water transport through the bottom of the soil volume, we kept the free drainage boundary condition as applied in the original ECMWF formulation. However, a modification of the soil hydraulical coefficients (see Section 2.2) was introduced together with the new surface runoff parameterization, and has an effect on the bottom drainage rate.

Calibration of this parameterization requires adequate choices for the deep soil drainage, $\sigma_{\min}$ and $\sigma_{\max}$, and the definition of the depth over which W is

Table 1
Soil type specific Van Genuchten coefficients

Parameter	Symbol	Units	Texture class				
			Coarse	Medium	Medium-fine	Fine	Very fine
Saturation soil moisture content	W_{sat}	m^3/m^3	0.403	0.439	0.430	0.520	0.614
Residual soil moisture content	w_r	m^3/m^3	0.025	0.010	0.010	0.010	0.010
Fit parameter	α	m^{-1}	3.83	3.14	0.83	3.67	2.65
Fit parameter	λ	–	1.250	− 2.342	− 0.588	− 1.977	2.500
Fit parameter	n	–	1.38	1.18	1.25	1.10	1.10
Saturated hydraulic conductivity	K_{sat}	10^{-6} m/s	6.94	1.16	0.26	2.87	1.74

calculated. The values of σ_{min} and σ_{max} are principally dependent on the spatial scale of operation (Dümenil and Todini, 1992). However, extensive site-specific calibration will be difficult to accomplish when the scheme is operated on a routine and global basis. Therefore, we have chosen to avoid this calibration and adopt constant values of 100 and 1000 m, respectively, as suggested by Dümenil and Todini (1992) when applied at the coarser resolution T106. W and W_{sat} are calculated using the (maximum) soil moisture content in the top 0.5 m of the soil, following Liang et al. (1996).

2.2. Soil hydraulic coefficients

In the original ECMWF scheme, all global land area is represented by a single soil type (an "average" loam soil), and soil hydraulic coefficients are parameterized using the expressions of Clapp and Hornberger (1978). Sensitivity analyses were carried out over Europe by IJpelaar (2000), in which this ECMWF approach was replaced by specifying a geographical distribution of five broad soil texture classes, and where the Clapp and Hornberger relations were replaced by the parameterization of Van Genuchten (1980), which is generally better capable of fitting observed retention curves at high water contents owing to one additional fit parameter. Following Van Genuchten (1980), the soil moisture content w as function of pressure head h is given as

$$w(h) = w_r + \frac{w_{sat} - w_r}{(1+\alpha h)^{1-1/n}} \tag{4}$$

whereas the hydraulic conductivity K is given by

$$K(h) = K_{sat}\frac{[(1+\alpha h^n)^{1-1/n} - \alpha h^{n-1}]^2}{(1+\alpha h^n)^{(1-1/n)(\lambda+2)}} \tag{5}$$

with K_{sat} the saturated hydraulic conductivity and w_r, α, n, and λ the soil type specific fitting parameters, listed in Table 1. For most soil types except coarse sand and medium-fine soils under dry conditions, the hydraulic conductivity is reduced compared to the original formulation in the ECMWF scheme (IJpelaar, 2000).

From the soil texture information provided by the PILPS team, the soil type in each grid box was assigned a texture class from this table.

2.3. Sublimation of exposed snow

Van den Hurk et al. (2000) demonstrated a strong benefit of reducing snow sublimation in forest grid box fractions in boreal areas. Bowling et al. (2003-this issue) and Nijssen et al. (2003-this issue) concluded that the original ECMWF scheme still generates unrealistically large sublimation rates, in particular, from the exposed portions of the grid box, thereby retaining smaller snow amounts that eventually are removed as discharge of melting snow.

Douville et al. (1995) argued that snow may reduce the aerodynamic roughness of areas with rocks and low vegetation, as it covers the individual obstacles and produces a smooth surface. They incorporated a simple parameterization of this effect by reducing the aerodynamic roughness length z_0 as function of the snow pack depth. Here, we have adopted a similar parameterization that reduces z_0 via a logarithmic curve to 1 mm when the snow deck reaches a depth of 1 m. The ratio of the roughness lengths for momentum and heat remain unchanged.

2.4. Ageing of snow albedo

In the original ECMWF land surface scheme, the surface albedo of snow-covered nonforested surfaces decreases as time since the last fresh snow fall proceeds, to mimic the darkening of snow due to melt, dust and dirt collection, and snow packing. In the ECMWF scheme, the albedo of melting snow decreases exponentially with time, whereas for frozen snow, a linear decrease is followed. Generally, this process is slower at low snow temperatures (e.g. Oerlemans and Knap, 1998), and in the new version of the land surface scheme, this is incorporated by carrying the following equation for the albedo ageing process of nonmelting snow:

$$a(t) = a(t - \Delta t) - \frac{\tau \Delta t}{1 + 0.1 T_{\mathrm{sn}}^4} \tag{6}$$

with $a(t)$ the albedo at time t, Δt the time step, τ an ageing time scale (1/125 day^{-1}), and T_{sn} the snow temperature in °C. For melting snow, the (faster) ageing process was not changed in the new version. The albedo of the snow pack is reset to its default (high) value after snow events exceeding 1 mm/h.

2.5. Summary

These four changes have the effect of:

- reducing the snow sublimation of exposed snow, mainly by an increase of the aerodynamic resistance. This causes an increase of the depth of the snow pack at the end of the winter/early spring season.
- increasing the surface runoff during periods of snowmelt and precipitation. Total runoff changes accordingly from a low-frequency deep drainage to a high-frequency, precipitation-driven, surface runoff generation.

We have used the PILPS 2(e) experiment to evaluate the impact of these changes on the performance of the ECMWF land surface model. In order to distinguish between the snow and soil modifications, a third model version (SECMWF) was evaluated. In this version, the changes to the snow roughness and snow albedo ageing were included, but the treatment of soil hydraulical quantities and surface runoff generation was not modified compared to the ECMWF version. In the following, we will evaluate the impact of the changes on the simulated discharge from small subcatchment, and on hydrological budgets of the whole Torne-Kalix catchment.

3. Comparison of simulated discharge with observations from small subcatchments

As part of the PILPS 2(e) project, discharge data from two small catchments were provided to the participants in order to allow a calibration of the participating models. One basin, Övre Abiskojokk, is located in the mountainous northwestern area in the basement above the tree line and with relatively steep orographic gradients. The orographic shape parameter b used in the MECMWF model version (Eq. (2)) varies between 0.08 and 0.16 for this area. Övre Lansjärve is a basin in the eastern lower region in the basin, where forest vegetation and relatively small orographic differences are present. For all grid boxes in this area, b is set to its minimum value 0.01.

The models are not calibrated specifically using discharge observations from these catchments, but rather a priori estimates of the necessary coefficients have been used.

Fig. 1 shows the average annual cycle of the modelled and observed discharge from the mountainous "Abisko" catchment, as well as the flat "Lansjärve" basin. Introducing the smooth snow pack and delayed snow ageing for very cold snow packs (version SECMWF) clearly results in an intensified spring peak related to snowmelt in both areas. For the Abisko catchment, the phasing of the peak is well represented, but the amplitude is slightly overestimated. In contrast, the snowmelt peak extends until well into June in the Lansjärve region, whereas observations show a more intense peak of shorter duration in the 10-year average. This broadening of the snowmelt peak is partially an artifact of the poor temporal resolution

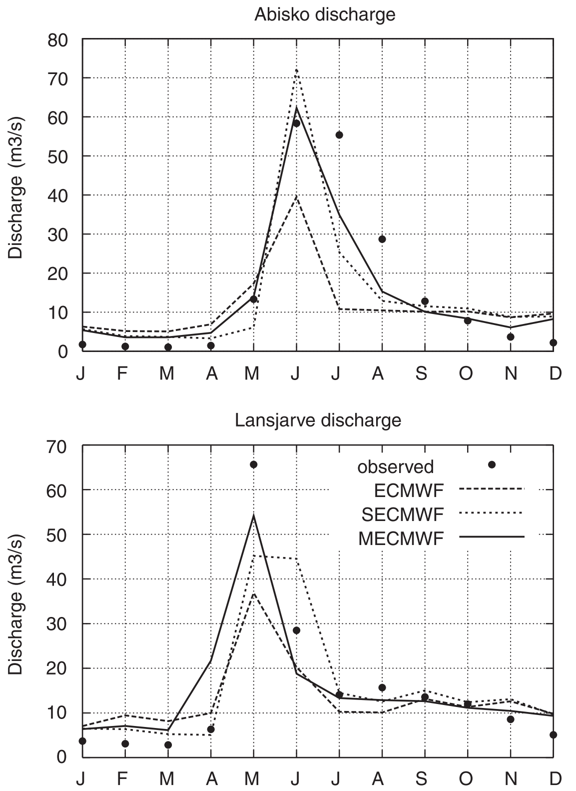

Fig. 1. Simulated and observed discharge from the Abisko basin (top) and the Lansjärve calibration basin (bottom), averaged for 1989–1998.

in Fig. 1, and partially due to an increased amount of melt water that is stored in the soil column before being removed as discharge, compared to the ECMWF simulation.

Introducing in addition the surface runoff and soil hydraulical parameterization (version MECMWF) reduces the peak discharge from the mountainous Abisko catchment slightly to a value in better agreement with observations. The limited impact of these changes can be explained by a strong radiative control of the snowmelt. The longer duration of the snow pack is associated with lower net radiation amounts in this area where no high vegetation is present. On average, snowmelt does not occur until June, and the change of the runoff mechanism cannot alter the phasing of the snowmelt peak. In the milder Lansjärve area, the impact of the surface runoff parameterization is more pronounced. Here, MECMWF shows a clearly intensified average discharge peak associated with snowmelt, since the melting snow is quickly removed as discharge.

Mean root mean square errors (RMSE) have been computed from the daily discharge figures from the two catchments (Fig. 2). For the Abisko catchment, MECMWF has the smallest RMS error, and both the snow processes and the runoff treatment have a separate contribution to this RMS error reduction. For the Lansjärve area, SECMWF performs slightly worse than the default ECMWF version, but the introduction of the surface runoff component and modified soil hydraulic formulations makes the correspondence to observed discharge rates even worse. In spite of an improvement in the seasonal cycle and the intensity of the snowmelt peak in spring, the MECMWF modifications apparently do not result in an improvement in the day-to-day variability in the discharge.

This can also be seen from Fig. 3, where scatterplots of daily modelled and observed discharge for both catchments are shown. Fig. 3 compares SECMWF and MECMWF, enabling a focus on the impact of the soil and runoff parameterization alone. For the Abisko catchment, the introduction of the surface runoff and modified soil hydraulical parameterizations results in a reduction of the original preference to generate discharge rates around 10 m^3/s, and the modelled discharge displays a dynamical behaviour in much better correspondence with the observations. For the Lansjärve area, the introduction of the

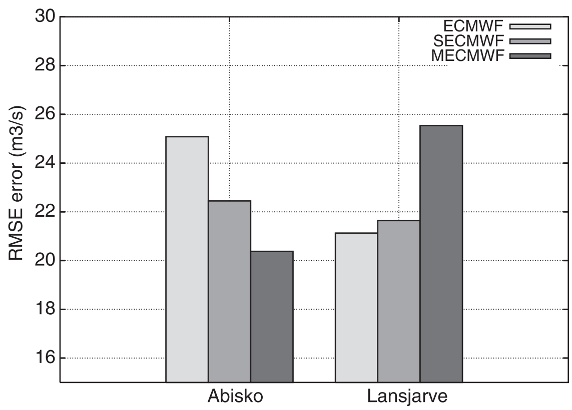

Fig. 2. RMS error of daily discharge in the period 1989–1998 from the two subcatchments of Abisko and Lansjärve for each model version.

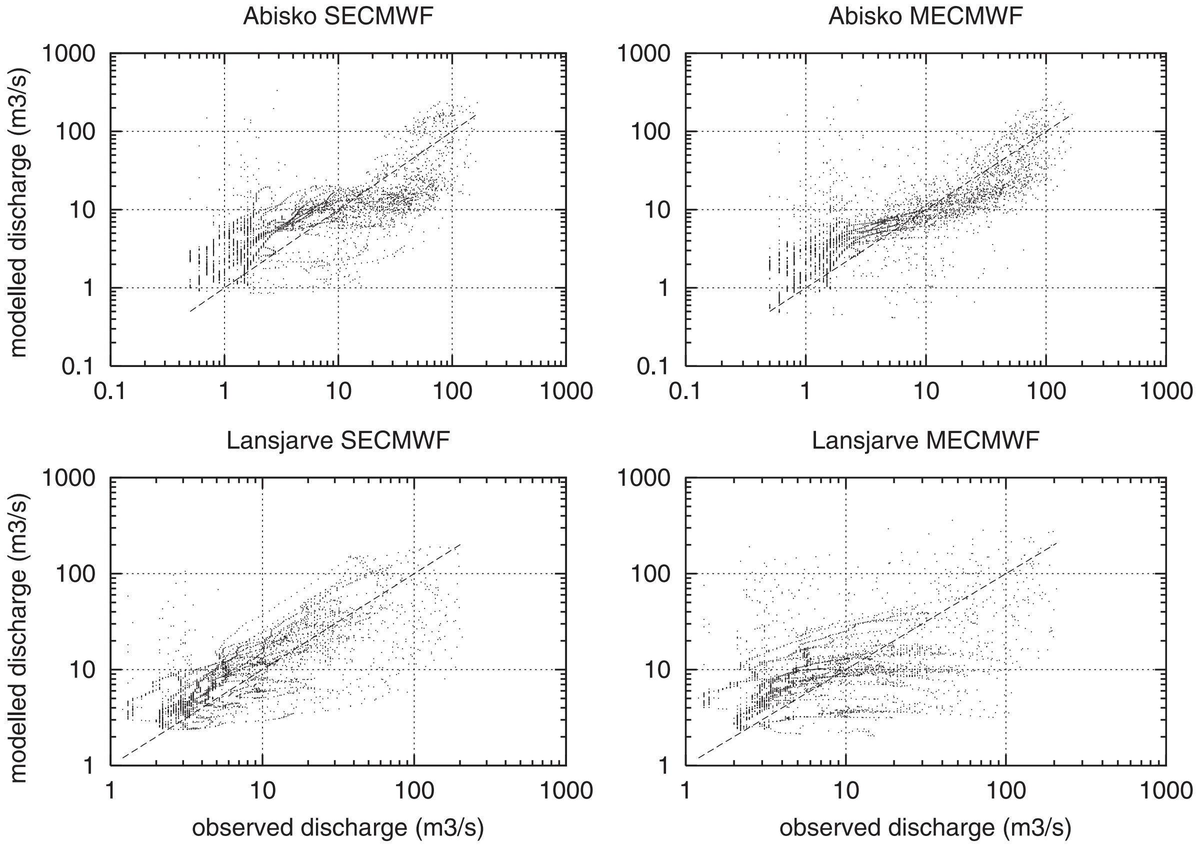

Fig. 3. Scatterplot of daily observed and modelled discharge from the Abisko catchment (top panels) and Lansjärve catchment (bottom), for the model versions SECMWF (left) and MECMWF (right).

new runoff scheme and soil physical coefficients results mainly in a strong reduction of days with relatively high discharge rates, and a systematic preference to generate 10–20 m^3/s values is introduced. This deterioration of model behaviour is not solely related to the parameterization of the surface runoff. Experiments with deeper or shallower surface buffer reservoirs (W_{sat} in Eq. (1)) did not result in clear improvements of the correlation between observed and modelled daily discharge. The 25.5 m^3/s RMS error for MECMWF (Fig. 2) was not reduced when the buffer depth was doubled to 1 m, and it increased to 31.7 m^3/s when it was reduced to 0.2 m. Also, the deep drainage boundary condition plays an important role in flat areas. Dümenil and Todini (1992) designed a scheme that generates very slow bottom-drainage rates at soils drier than 90% of saturation, and a rapidly increasing drainage rate for wetter soils. Replacement of the Van Genuchten equations for the lowest soil layer by this alternative low boundary condition did also not lead to an improved RMS of the daily discharge from the Lansjärve catchment. Obviously, a proper calibration of the MECMWF scheme on daily discharge volumes requires the involvement of both the surface and deep runoff parameterizations.

4. Annually averaged hydrological budget

The modifications to the runoff have a minor impact on the annually averaged partitioning of precipitation over evaporation and runoff. Since precipitation is a prescribed forcing, and evaporation is basically energy-limited rather than moisture-limited in this area, the runoff formulation can only affect the timing of the runoff and the seasonal cycle of the soil water deficit (see also Bowling et al., 2003-this issue). Increased surface runoff may reduce the equilibrium soil moisture content, thereby increasing the evaporation stress. This increased surface runoff is, however, compensated by a reduced percolation owing to lower soil hydraulic conductivity in the Van Genuchten formulation, and a negative feedback of a lower soil moisture content on surface runoff by increasing the maximum infiltration rate (Eq. (3)).

On the other hand, formulation of the sublimation of snow may result in considerable shifts in the annual water balance, as it affects the partitioning of snowfall over sublimation and melt.

Estimates of total runoff were available for the period 1989–1998 from a long-term simulation of a hydrological model calibrated to the river discharge at a number of locations in the area. Observed evaporation was obtained as a residual term in the water balance, assuming a negligible change of soil moisture storage over the 10-year period.

Fig. 4 clearly demonstrates the considerable impact of the modifications to the snow treatment incorporated in the SECMWF and MECMWF simulations. Averaged over the 10-year period, the total evaporation is reduced by nearly 25% (from ±400 to 300 mm/year). Within the limitations of the method to derive evaporation loss from available data, the change to the snow treatment results in a clearly improved correspondence to the observations.

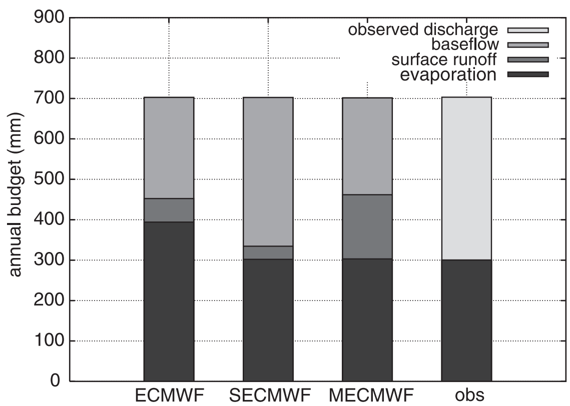

Fig. 4. Ten-year (1989–1998) averaged water budget of the Torne-Kalix river basin. Shown are model values for evaporation, surface runoff and baseflow runoff, and the best estimate of runoff from the catchment. Observed evaporation is inferred from this runoff estimate and the imposed precipitation.

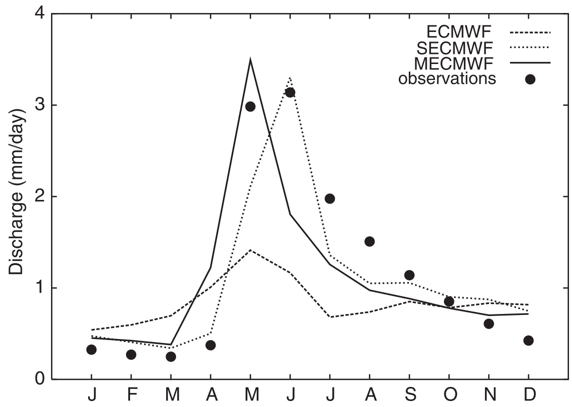

Fig. 5. Monthly averaged discharge from the entire Torne-Kalix river basin.

Since in MECMWF more runoff is generated as surface runoff, also the relative contribution of surface runoff to the total runoff has increased, from 19% in ECMWF to 40% in MECMWF. Fig. 5 shows the effect of the snow and soil changes on the average seasonal cycle of discharge from the river basin. The strong increase in runoff water loss shown in Fig. 4 is clearly seen to be related to a later, sharper, spring melt peak, caused by reduced ablation of snow by sublimation. Similar to the effect shown in Fig. 1, the difference between MECWMF and SECMWF is a delay in the melt peak by approximately 1 month.

5. Discussion

It is clearly demonstrated that the MECMWF model results in a stronger spring melt peak generated by the melting snow from the area, in correspondence to the observed discharge volumes. For both catchments, the ECMWF-predicted spring melt peak is too low, and too little runoff is generated in the period following the peak. This is associated with an excessive snow sublimation in ECMWF, causing an earlier ablation of the snow than in MECMWF. Observations of basin discharge show that the modifications to the snow sublimation in the MECMWF version generated an improvement.

We have not evaluated systematically here which of the snow modifications (aerodynamic exchange or the albedo ageing) has played the dominant role, but it is safe to assume that the reduction of the surface roughness has been the most effective. For experiments with fixed atmospheric boundary conditions, model results are usually relatively sensitive to the formulation of the aerodynamic coupling, which is even stronger for low net radiation areas (see e.g. Beljaars and Viterbo, 1994; Slater et al., 2001). In coupled simulations, the response of the boundary layer may act as a negative feedback to alleviate the strong effect reported in this study.

The changes in the runoff formulation by implementing a variable infiltration capacity method, using a priori estimates of calibration coefficients, were explored by comparing the SECMWF and MECMWF simulations. Although the difference between these two simulations concerned both a modification to the surface runoff and to the soil hydraulical coefficients, experiments not shown here demonstrated that the surface runoff modification played a dominant role in the difference between SECMWF and MECMWF. These changes appear to have a mixed impact on the temporal dynamics of the runoff simulations. For the mountainous Abisko catchment, the temporal dynamics was improved considerably, but for the flat Lansjärve area, worse dynamical behaviour was displayed by a strong reduction of the day-to-day variability of the daily discharge. The implementation of the surface runoff scheme by Dümenil and Todini (1992) involved a combination of a fast surface runoff component and a deep drainage rate that is lower than the parameterization of Van Genuchten (1980) for all soils that are not close to saturation. This bottom drainage plays an important role in the soil hydrology for flat areas as the Lansjärve catchment. Both surface and deep runoff require on site calibration to obtain realistic runoff dynamics. However, for the strongly energy-limited environment of this case study, the change of the runoff dynamics will hardly affect the annual partitioning of the precipitation over evaporation and runoff.

Bowling et al. (2003-this issue) discuss a large range of potential error sources in the precipitation estimate. Comparison between the provided forcing and a number of independent gauge stations revealed RMS errors of up to 15%. We expect that the areally averaged precipitation forcing is more accurate than this, but the accuracy of the evaporation estimate (Fig. 4) is closely related to the error in the precipitation and discharge database.

The PILPS 2(e) experiments (and its predecessors) appear a very useful platform for evaluating and developing land surface parameterization schemes used in large-scale applications.

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