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A revised land hydrology in the ECMWF model: a step towards daily water flux prediction in a fully-closed water cycle

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Abstract:

The ECMWF land surface hydrology has been revised in the last 3 years in its soil and snow hydrological components, leading to improvements in weather and seasonal predictions. It has been shown that efforts devoted to the improvement of land surface processes can lead to a more accurate representation of the global water cycle on monthly timescales. In this paper, we analyse the impact of land hydrology revisions at daily timescales on both atmospheric near-surface quantities and river discharges by coupling the ECMWF land surface model (HTESSEL) to a river routing scheme total runoff integration pathways (TRIP2). This application defines a hydro-meteorological verification for land surface models and it shows the usefulness of river discharge observations for quantitative evaluation of the global water cycle at daily timescales. The relative contributions of the soil and snow hydrology revisions on atmospheric state, in particular for temperature, and the predicted river discharge are evaluated showing a significant incremental performance with the land surface updates.

KEY WORDS ECMWF land hydrology; global river discharge; water cycle study

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INTRODUCTION

Predictions of the global hydrological cycle involve accurate atmospheric analyses and forecasts and a realistic representation of land surface processes for correctly timing water recirculation (Oki and Kanae, 2006). Physical parameterizations of the ECMWF Integrated Forecast System (IFS) (IFS, 2006), involved in the predictions of soil moisture and snow, are periodically revised to address known shortcomings of the land surface scheme (e.g. Balsamo *et al.*, 2009). An improved representation of land water reservoirs is proven to be essential in global weather prediction (Drusch and Viterbo, 2007) due to both, partitioning of incoming solar radiation (e.g. via snow reflection/insulation and soil moisture/ice control on turbulent fluxes) and timing of fresh water recirculation (e.g. evaporation, sublimation and runoff). The snow and soil moisture states have recently received much more attention for their impact on monthly to seasonal prediction skills (Koster *et al.*, 2004, 2009; Douville, 2009).

At ECMWF, the hydrology in the Tiled ECMWF Scheme for Surface Exchanges over Land (HTESSEL) land surface scheme including a soil texture map and revised hydrological properties (Balsamo *et al.*, 2009) is verified together with an improved snow scheme (Dutra *et al.*, 2010, named hereafter SNOWHTESSEL). In this scheme, snow albedo has been revised, and a new snow density formulation with a diagnostic liquid water reservoir has been introduced. The revision of the land surface hydrology for both soil and snow have been extensively validated using the atmospheric forcing provided by the Global Soil Wetness Project II (GSWP2, Dirmeyer *et al.*, 1999, 2002) covering a 10-year period (1986–1995).

Routing runoff generated by the land surface model through a river network allows a closure of the global water cycle and extends model forecasts verification, particularly the land surface components, on daily time scales for large spatial areas by the use of routinely observed river discharges. There are objective difficulties in predicting river discharges at daily timescales. Pappenberger *et al.* (2009) noted that only a subset of the world river basins can be considered for verification of weather forecasts due to large mass balance errors related to precipitation errors, coarse resolution river network and over-simplified treatment of soil water storage.

In this study, river outflows produced by coupling the total runoff integration pathways (TRIP2) (Oki and Sud, 1998; Ngo-Duc *et al.*, 2007) river routing model to the land models are verified against major world rivers on a daily base in the evaluation period. This comparison

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to river discharge data shows the relative merits of soil and snow hydrological revisions and the impact on the daily timescales previously not considered. In the following sections, we present the modelling framework and results on the impact of the revision of the soil and snow hydrology components on the atmosphere and river discharge at daily timescales.

THE MODELLING FRAMEWORK

The Tiled ECMWF Scheme for Surface Exchanges over Land (TESSEL) illustrated in van den Hurk *et al.* (2000) is the backbone of the current operational land surface scheme at ECMWF. It includes up to six land surface tiles (bare ground, low and high vegetation, intercepted water and shaded and exposed snow). The soil freezing is parameterized according to Viterbo *et al.* (1999), while the soil water and energy transfers are following Viterbo and Beljaars (1995). Two recent revisions concerning the snow and the soil hydrology are detailed below and are the object of the hydro-meterological verification method illustrated in Figure 1.

Soil hydrology

A revised soil HTESSEL has been investigated by van den Hurk and Viterbo (2003) for the Baltic basin. These model developments were a response to known weaknesses of the TESSEL hydrology: specifically, the choice of a single global soil texture that does not characterize different soil moisture regimes and a Hortonian runoff scheme that hardly produces any surface runoff. A revised formulation of the soil hydrological conductivity and diffusivity, spatially variable according to a global soil texture map, and surface runoff based on the variable infiltration capacity approach were proposed remedies. Balsamo *et al.* (2009) verified the impact of HTESSEL from field site to global-atmospheric-coupled experiments in data assimilation cycles, showing an improvement in monthly runoff. The impact of HTESSEL is a reduction in baseflow compared to TESSEL, which had virtually zero surface runoff in unfrozen conditions.

Snow hydrology

The snow scheme in HTESSEL followed Douville *et al.* (1995) and showed some shortcomings in the SnowMip2 inter-comparison (Rutter *et al.*, 2009). A fully revised snow scheme (hereafter referred to as SNOWHTESSEL) has been introduced in two implementation phases: firstly a revised snow density and diagnostic liquid water storage and in a second step the revision of snow/forest albedo, snow cover fraction and the rainfall interception in the snow pack. The snow density revision follows from Anderson (1976) and Boone and Etchevers (2001). The formulation of a liquid water reservoir in the snowpack is parameterized as a diagnostic quantity. A similar approach was adopted by Viterbo *et al.* (1999), who applied a heat capacity inflation to represent soil freezing. The snow albedo revision was implemented

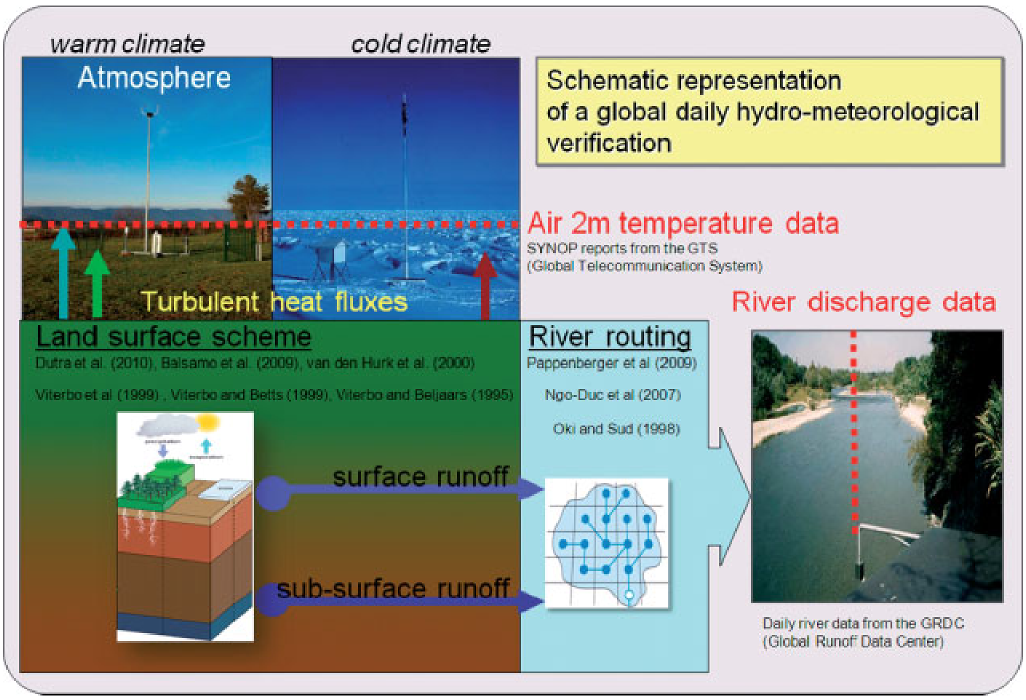

Figure 1. Schematic representation of the global hydro-meteorological verification of the land surface schemes. Key processes for the land-atmosphere/rivers interaction are evaluated against routine data (in red): water and energy exchanges (arrows) at the interface of land–atmosphere (soil evaporation, vegetation transpiration, snow sublimation and melting) are verified by 2-m temperature data, which are sensitive to turbulent heat fluxes; Water exchange at the interface of land–river (surface and sub-surface runoff) are evaluated by river discharge data. These fluxes are largely connected to soil moisture in summer (active on partitioning latent and sensible heat flux and on surface/sub-surface runoff via soil infiltration) and to snow in winter (active on partitioning solar and thermal radiation fluxes via changes in the albedo and thermal capacity respectively and surface/sub-surface runoff via soil insulation)

in the second phase following the results of Pedersen and Winther (2005) and Molders *et al.* (2008). Forest albedo in the presence of snow has been retuned to values adapted from Moody *et al.* (2007). Viterbo and Betts (1999) showed that a retuning of forest albedo had a beneficial impact on lower troposphere temperature bias. Snow cover fraction was changed to be a function of snow density also, in addition to the dependence on snow mass as in the original scheme. Dutra *et al.* (2010) verified the new snow module using data from site to global offline simulations. Results obtained showed an improved behaviour of the simulated snow pack with positive effects on the timing of runoff and terrestrial water discharges and a better match of albedo to satellite products.

Offline land surface driver

The land surface scheme versions (TESSEL, HTESSEL, SNOWHTESSEL) have been driven offline with trihourly prescribed GSWP2 atmospheric forcing (1986–1995). This experimental setup is computationally affordable and it allows simulations over an extended period of time concentrating on merits and errors of the land surface exposed to a fixed atmospheric forcing. A spin-up period of 2·5 years is considered, as indicated by the GSWP2 protocol, to allow all the considered schemes to reach an equilibrium. The daily output for surface and baseflow runoff is used as input to the river discharge scheme.

River routing

A river routing scheme has been coupled to HTESSEL following Pappenberger *et al.* (2009). The scheme is derived from the TRIP2, first introduced by Oki and Sud (1998) and updated to account for variable river velocity, presented in Ngo-Duc *et al.* (2007). This scheme is capable of representing the delays in the travel time between the runoff generated on each model grid box and the river (mouth or transect). A single calibration is performed for the HTESSEL scheme as described in Pappenberger *et al.* (2009). As the coupling is one-way, the three different GSWP2 model simulations have been coupled to TRIP2.

Verification datasets

The verification of the three land surface model versions considered uses a number of observed variables and it is separated in two levels: atmospheric impact and river discharge impact. The first level concentrates on near surface air temperature, which responds to changes in soil moisture via the Bowen ratio, and in snow thermodynamic properties via insulation and (to a lesser extent) sublimation. The 2-m temperature observations are gathered by the Global Telecommunication System (GTS) from SYNOPs reports, and merged into operational 2-m analyses used as reference. A next verification level concerns surface and sub-surface runoff, collected by the river routing scheme and transported to the river where the modelled discharge is compared with river hydrometric observations (see Figure 1). Daily river discharges are provided by the Global Runoff Data Centre (GRDC). River stations with daily data for at least 5 years between 1986 and 1995 have been considered (466 stations). Among them, a sub-set of 211 stations for which the accuracy of the water budget closure is ensured within ±30% is selected according to Pappenberger *et al.* (2009). This sub-set, labelled *selected* in the following, is considered reliable for a quantitative evaluation of river discharges.

RESULTS

Results presented here are based on a set of weather forecasts to show the atmospheric impact (spanning 1 year) and offline land surface integrations (10 years) to characterize river discharge. Three sets of experiments based on model configurations for the land surface schemes are listed in Table I. The main land surface physics modifications from TESSEL (van den Hurk and Viterbo, 2003) have been isolated to show the impact of the revisions of soil (HTESSEL, Balsamo *et al.*, 2009) and snow (SNOWHTESSEL, Dutra *et al.*, 2010).

Atmospheric impact

Sets of 10-day forecasts covering one full year are performed at T399 (about 50 km horizontal resolution) with the 2009 operational IFS and TESSEL, HTESSEL and SNOWHTESSEL configurations (see IFS Documentation, 2006). Forecasts are run 10 days apart to cover the period between 1 January to 31 December 2008 (37 forecasts per experiment). The effect of the model on near surface temperature is evaluated for a set of day + 1 forecasts (36-h range) valid at 12 UTC. This choice is motivated by the focus of the present study on daily timescales. The 2-m temperature sensitivity of SHOWHTESSEL compared to the TESSEL configuration is shown in Figure 2 for both the winter (DJF) and summer (JJA) seasons. Improvements on 2-m temperature forecasts are shown in Figure 3. The metric shows the mean absolute error difference calculated with respect to the operational 2-m temperature analysis.

In particular, HTESSEL is shown to improve the temperate and tropical climates where evapotranspiration processes are most active. The temperature sensitivity shows positive and negative patterns that are associated with the spatially varying soil texture and the revised soil hydrology.

Table I. Land surface model configurations and references

Exp.	Land surface scheme
1	TESSEL (Viterbo and Betts, 1999; Viterbo *et al.*, 1999; van den Hurk *et al.*, 2000)
2	HTESSEL (van den Hurk and Viterbo, 2003; Balsamo *et al.*, 2009)
3	SNOWHTESSEL (Dutra *et al.*, 2010)

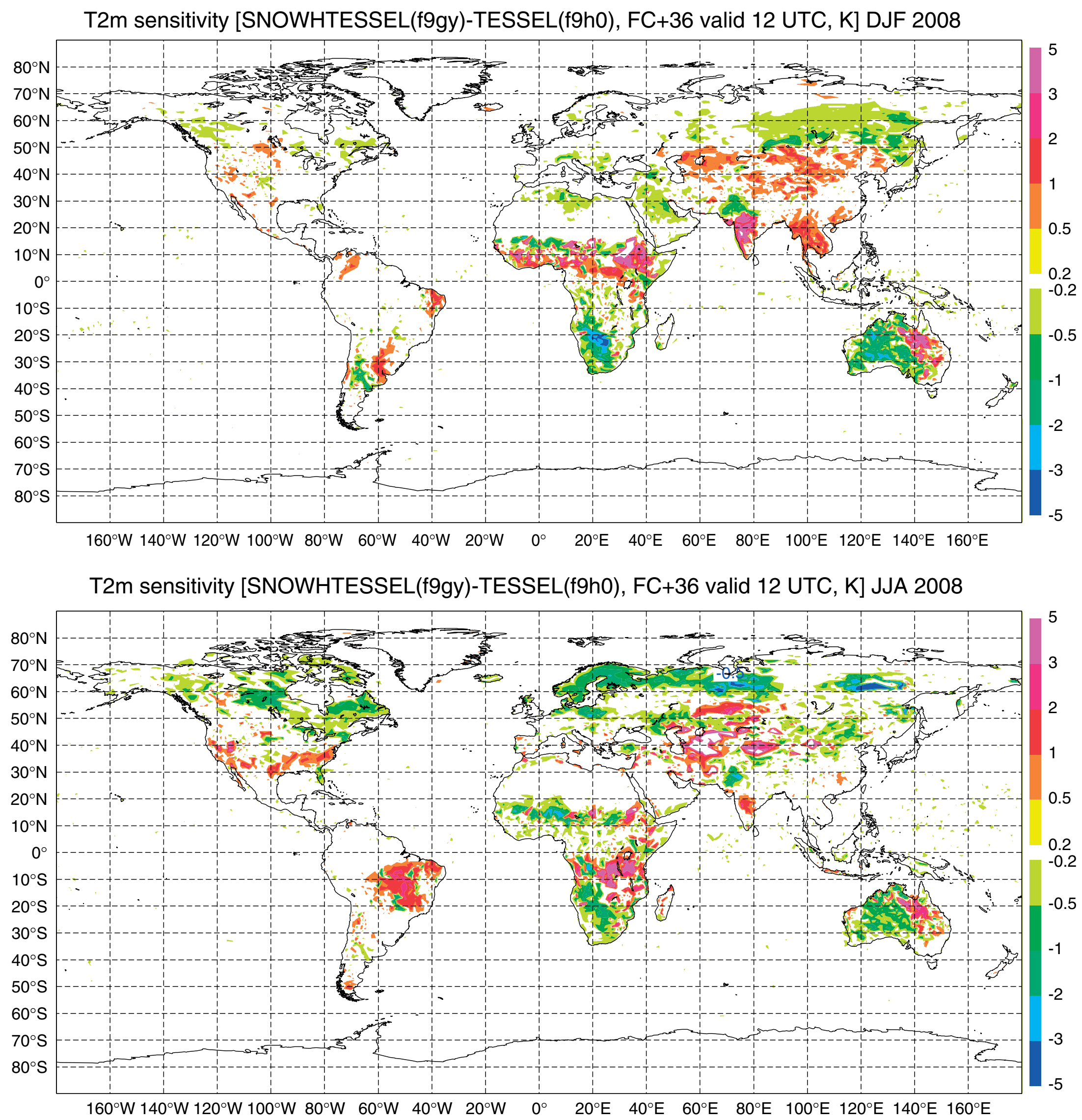

Figure 2. Sensitivity of 36-h T 2-m forecasts (valid at 12 UTC) for SNOWHTESSEL compared to TESSEL, verified against the ECMWF operational T2-m analysis. The upper (lower) panel shows Northern Hemisphere winter (summer) results. Negative values indicate cooling

The changes introduced with the SNOW revision are very effective on temperatures at high latitude and therefore the two revisions have complementary impact (on warm and cold climates as schematized in Figure 1). In fact, the sensitivity at northern latitudes consists of a cooling (Figure 2) associated with the snow pack, providing a greater insulation of the soil underneath, and therefore a weaker coupling of the surface to the atmosphere. This is particularly active in nocturnal radiative cooling where stronger inversions can develop (not shown). The thermal shielding effect of the revised snow has hydrological consequences as the soil remains largely unfrozen and permeable to infiltration also during the cold season.

Runoff and river discharges

Results of the GSWP2 simulations for the surface and sub-surface (or baseflow) runoff components are shown in Figure 4 in terms of monthly means for the three model configurations. The surface runoff in TESSEL has a single peak in winter (when the soil is frozen), while HTESSEL increases the surface runoff in both winter and summer, modifying largely the surface to sub-surface runoff ratio. SNOWHTESSEL reduces the winter surface runoff due to the above-mentioned soil thermal insulation, which enhances the sub-surface runoff as an indication of a larger fraction of snow melting infiltrating into the unfrozen soil. The baseflow is clearly reduced in HTESSEL compared to that in TESSEL. The improved evolution of the snow depth in SNOWHTESSEL appears in a snow melt delay visible in a baseflow enhanced peak in May and with a general shift towards the beginning boreal summer.

Winter and summer mean river discharge differences calculated with the TRIP2 routing scheme are shown as maps in Figures 5 and 6. The HTESSEL river discharge is used as denominator to show the percentage increase (decrease) of the river discharge when using TESSEL or

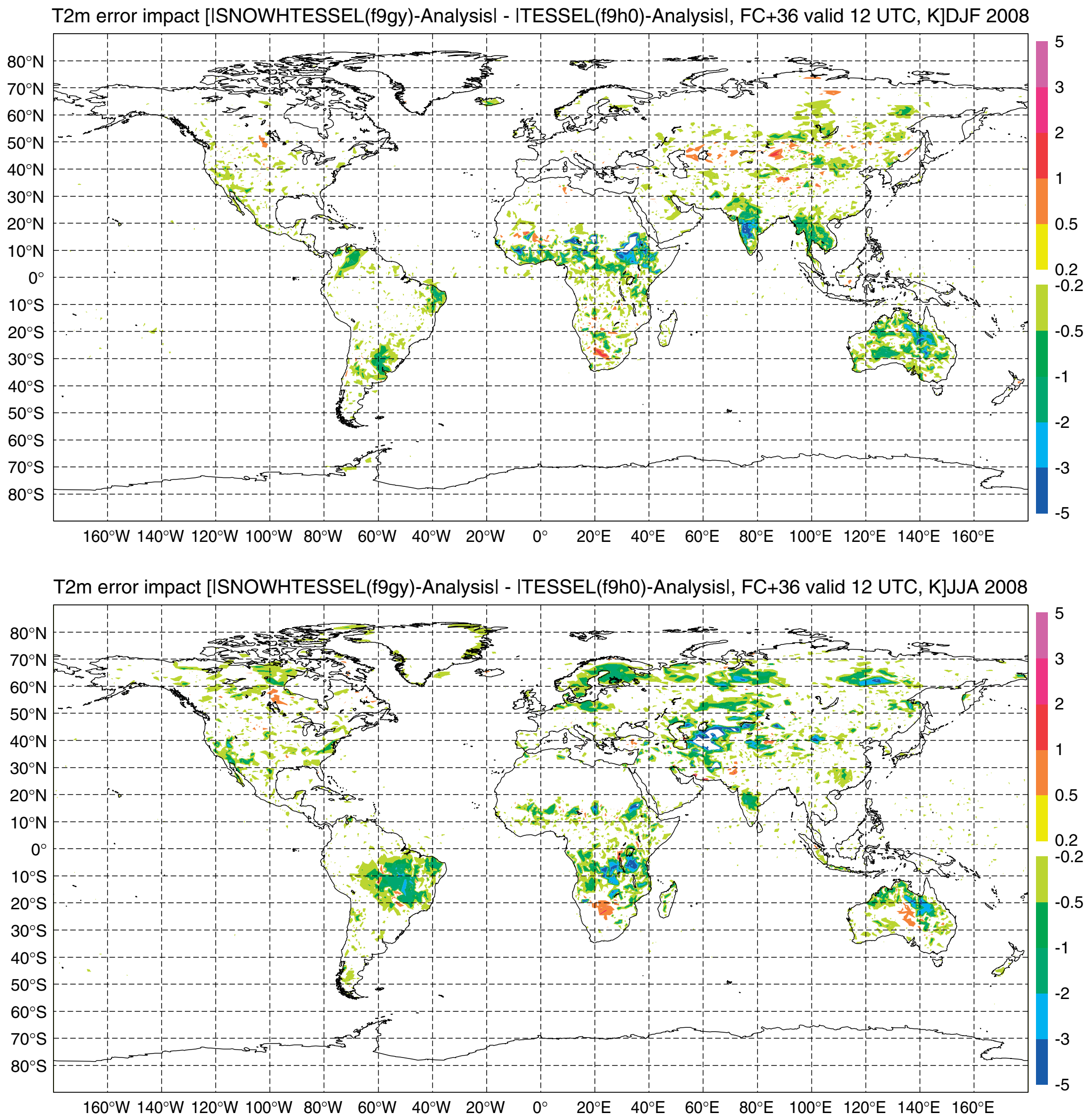

Figure 3. Impact on 36-h T2-m forecasts (valid at 12 UTC) for SNOWHTESSEL compared to TESSEL verified against the ECMWF operational analysis. The upper (lower) panel shows Northern Hemisphere winter (summer) results. Negative values indicate an absolute error reduction (thus a beneficial impact of SNOWHTESSEL)

SNOWHTESSEL schemes for the runoff generation. It is possible to highlight an increased transport of HTESSEL compared to that of TESSEL over a large part of the Northern Hemisphere and tropical areas, essentially due to a more active surface runoff. The river discharge impact of SNOWHTESSEL is most clear in summer (up to 75% reduction in central Eurasia and northern Canada compared to HTESSEL) when the snow pack has melted almost completely. This points to an increased soil permeability throughout the snow season and it is the result of the increased snow thermal insulation effect, which reduces the soil freezing duration (Dutra *et al.*, 2010).

An increased performance skill in daily discharge prediction is shown when comparing with the GRDC daily discharge. Table II resumes the results in terms of number of river basins best correlated to a given model configuration as well as the average correlation on the total number of basins and on the selected basins. SNOWHTESSEL appears to provide the best correlated river discharge simulation. Although the correlation is only 0·33 (average on all *selected* river basins), it has to be stressed that the quality of the

Table II. Average correlation on the best correlated basins and number of river basins in which a given land surface scheme version exhibits the best correlation (on the subset $N_b = 211$ of 'selected' river basins (defined in the text) and on the total of $N = 466$ World rivers, in brackets)

Exp.	Land surface scheme configuration	Average correlation on N_b (N) rivers	Number of best correlated rivers N_b (N)
1	TESSEL	0·09 (0·02)	14 (48)
2	HTESSEL	0·25 (0·15)	81 (175)
3	SNOWHTESSEL	0·33 (0·20)	116 (243)

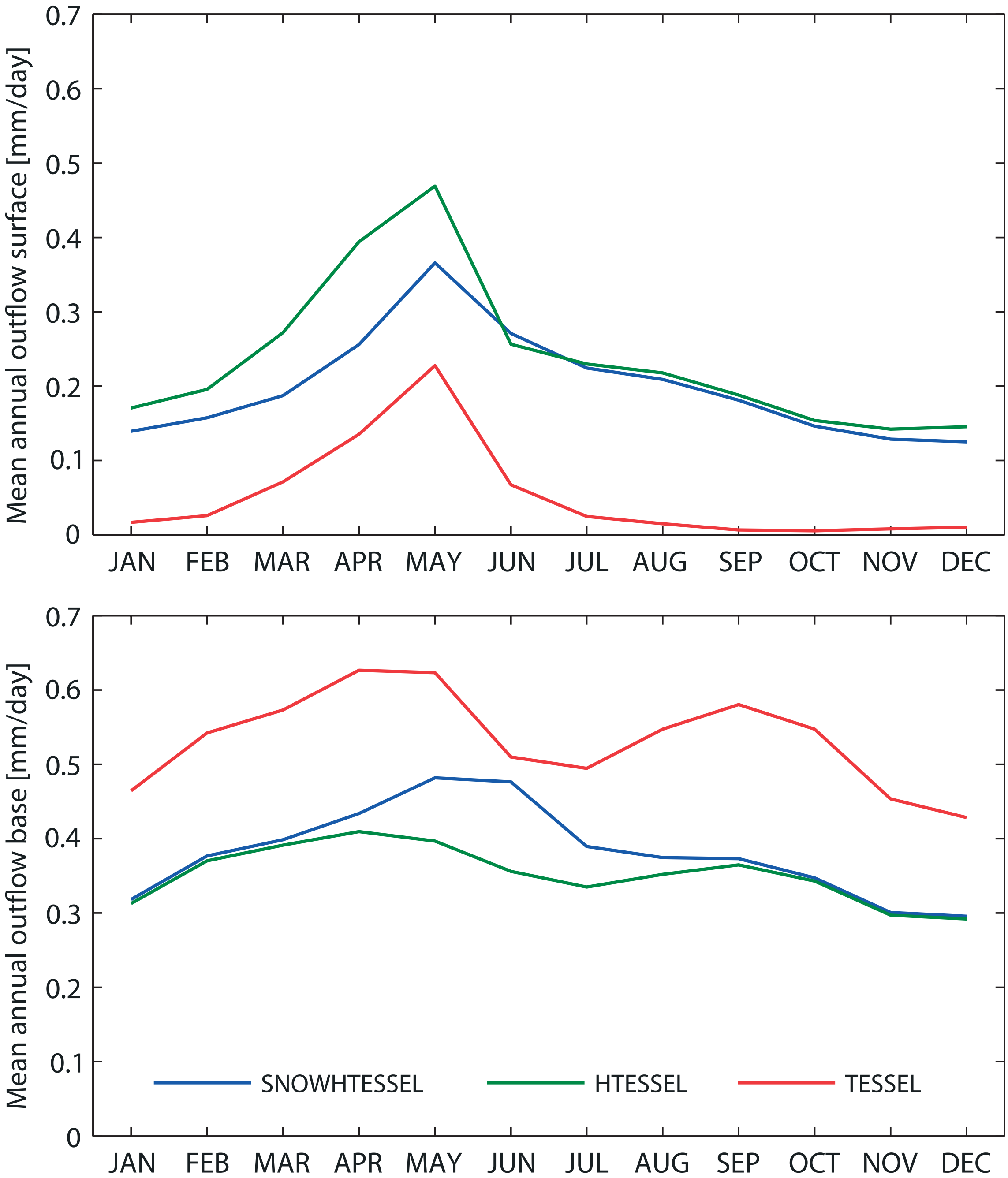

Figure 4. Comparison of monthly mean (1986–1995) surface runoff (upper panel) and sub-surface runoff (lower panel) in SNOWHTESSEL (blue), HTESSEL (green) and TESSEL (red) average over all land points (Antarctica excluded)

precipitation used in the GSWP2 offline simulations is not undisputed, as documented by Decharme and Douville (2006). Moreover the 1° offline resolution constitutes a limitation for small basins. Figure 7 shows the spatial coverage of the river discharge stations, indicating for each point which model configuration appears to be best correlated to the data. HTESSEL and SNOWHTESSEL appear quite evenly distributed over United States while SNOWHTESSEL prevails on most of the Eurasian rivers. In areas where snow is absent or seldom present, the dominance of SNOWHTESSEL is related to the noise (as no plausible improvement is expected in snow-free areas) in the correlation signal. The test of significance was computed by bootstrapping the discharge timeseries and by computing the correlation of the bootstrapped samples. The resulting distributions of correlations have been compared by performing a two-sample Kolmogorov–Smirnov test. The null hypothesis is that the correlations are from the same continuous distribution. The alternative hypothesis is that they are from different continuous distributions with a 5% significance level. A large majority of river basins considered show significant improvements when moving from TESSEL to HTESSEL and SNOWHTESSEL. In Table III, the percentage of times the null hypothesis was rejected indicates that more than 85% of river discharge simulations

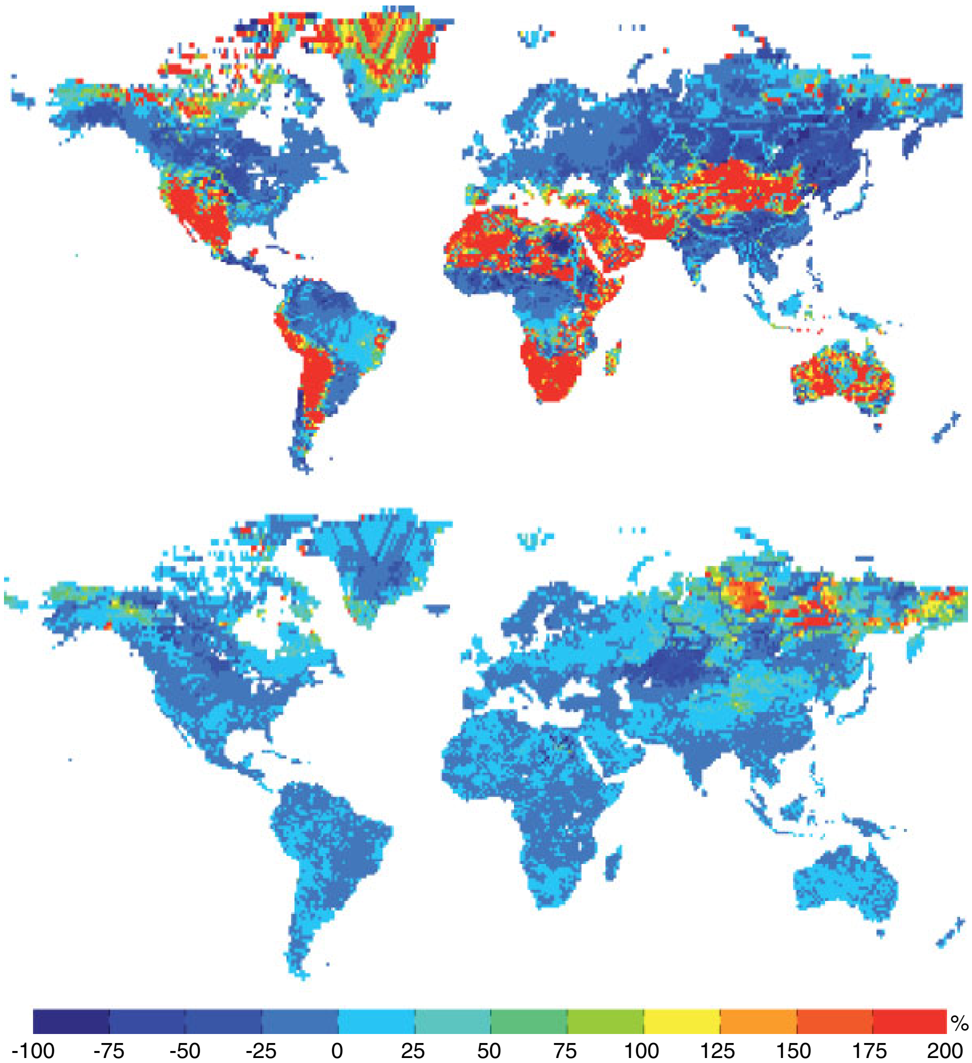

Figure 5. Relative differences (in %) for the river discharges obtained by TESSEL compared to HTESSEL (upper panel) and by SNOWHTESSEL compared to HTESSEL (lower panel) for the Northern Hemisphere winter (mean of December, January, February 1986 to 1995)

Table III. Percentage of hydrographs where correlations are issued from different continuous distributions with a 5% significance level

Exp.	TESSEL	HTESSEL	SNOWHTESSEL
TESSEL	0	97	98
HTESSEL		0	86
SNOWHTESSEL			0

are statistically independent in the three land surface model configurations (and up to 98% when comparing TESSEL to SNOWHTESSEL).

SUMMARY AND DISCUSSION

The revision of the land surface scheme is clearly shown to bring sizeable global scale improvements in the daily weather forecasts (e.g. FC + 36-h), particularly in the near-surface air temperature. The application of the runoff components to a river routing scheme brings in a new dimension for numerical weather prediction (NWP) verification using river discharge measurements for benchmarking land surface hydrology. The results show that, despite clear limitations of the modelling framework for river discharges (particularly the quality of precipitation forcing and the horizontal resolution), incremental performance can be found for documented improvements of the land surface scheme. A horizontal resolution for a daily global river discharge finer that 1·0° will probably have an even larger value for model evaluation.

These results are encouraging and reinforce the motivation to further improve the realism of land surface in NWP models. Current areas of development address the vegetation cycle with the introduction of recent satellite-based vegetation maps and monthly leaf area index (LAI) in order to represent the phenology. In the framework of the GEOLAND2 project, a carbon/vegetation scheme with a LAI data assimilation (Jarlan *et al*., 2008) will be evaluated for pre-operational implementation in order to provide a fully coupled water energy and carbon cycle. In the near future, offline simulations will be

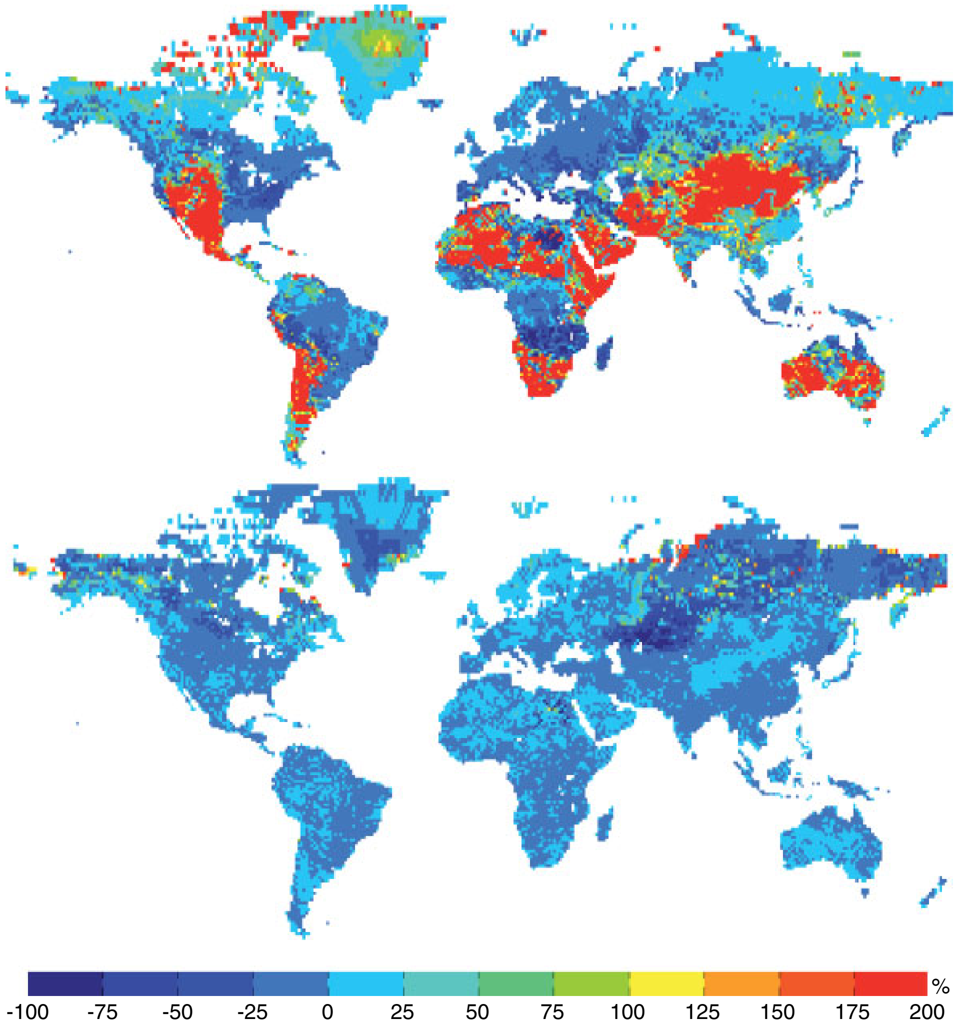

Figure 6. Same as Figure 2 but for Northern Hemisphere summer (mean of June, July, August 1986–1995)

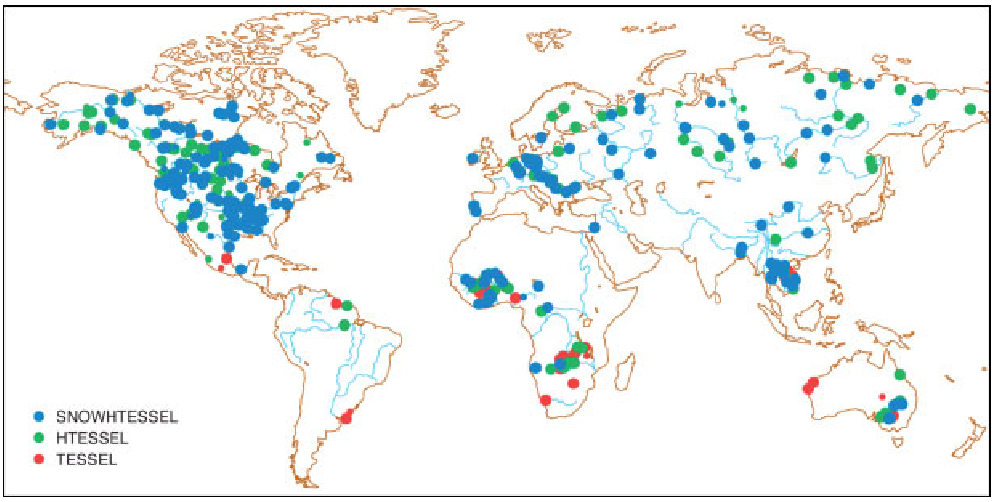

Figure 7. Indication of best correlated modelled and observed river discharges. Models include SNOWHTESSEL (blue), HTESSEL (green), and TESSEL (red). Large circles indicate the best performing scheme is significantly better than the others at a 5% significance level, while small circle indicate non-significant improvements. All river discharges plotted have positive correlation significantly different from zero

continued with a state-of-the-art reanalysis (e.g. ERA-Interim) used as the basis for the forcing, combined with observation-based precipitation datasets (e.g. global precipitation climatology project (GPCP) 1DD).

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