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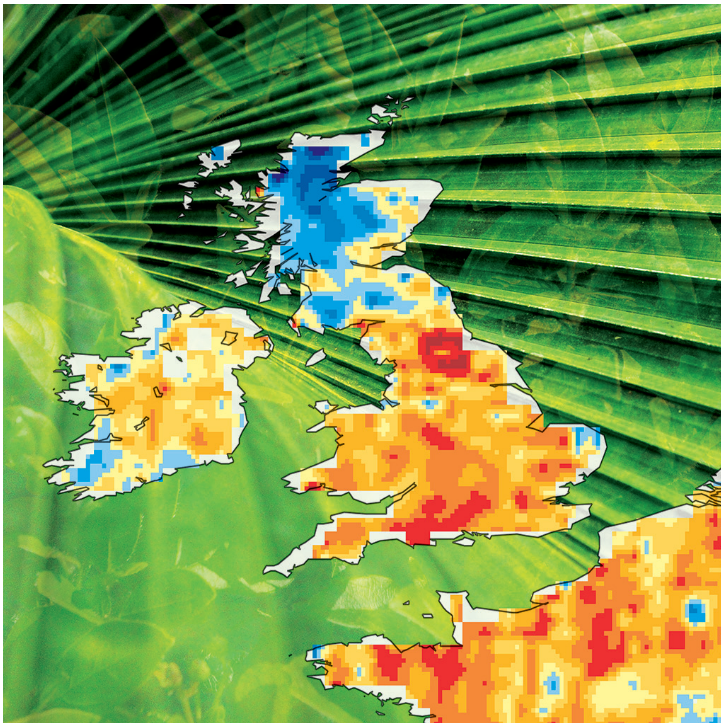
Evolution of land-surface processes in the IFS



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Evolution of land-surface processes in the IFS

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Major upgrades have been implemented over the last few years in the soil hydrology, snow and vegetation components of the ECMWF land-surface parametrization. Compared to the scheme used in ERA-Interim and ERA-40 reanalyses, the current model has an improved match to soil moisture and snow field-site observations with a beneficial impact on the forecasts of surface energy and water fluxes and near-surface temperature and humidity. This is verified by conventional synoptic observations and by dedicated flux-tower sites for forecasts ranging from daily to seasonal. The gain in hydrological consistency is also of crucial importance for data assimilation of land-surface satellite observations in water sensitive channels. The scheme described here, currently used for daily medium-range forecasts, will be adopted by the new Seasonal Forecasting System and included in future reanalyses.

A brief description of the main hydrological components of the land-surface model with selected validation results will now be presented followed by an outlook for future research activities.

Development of the land-surface model

In recent years the land-surface modelling at ECMWF has been extensively revised. An improved soil hydrology (*Balsamo et al.*, 2009), a new snow scheme (*Dutra et al.*, 2010) and a multi-year satellite-based vegetation climatology (*Boussetta et al.*, 2011) have been included in the operational Integrated Forecasting System (IFS). These have had a positive impact on both the global hydrological water cycle and near-surface temperatures compared to the TESSEL (Tiled ECMWF Scheme for Surface Exchanges over Land) scheme which was used in the ECMWF's ERA-40 and ERA-Interim reanalyses.

In particular the soil hydrology affected the quality of seasonal predictions during extreme events associated with soil moisture-precipitation feedback as in the European summer heat-wave in 2003 (*Weisheimer et al.*, 2011). The new snow scheme improved the thermal energy exchange at the surface with a substantial reduction of near-surface temperature errors in snow-dominated areas (i.e. northern territories of Eurasia and Canada).

More recently, the introduction of a monthly climatology for vegetation Leaf Area Index (LAI) to replace the fixed maximum LAI has shown a reduction of near-surface temperature errors in the tropical and mid-latitude areas, particularly evident in spring and summer. At the same time the bare ground evaporation has been enhanced over deserts by adopting a lower stress threshold than for vegetation. This is in agreement with experimental findings (e.g. *Mahfouf & Noilhan*, 1991) and results in a more realistic soil moisture for dry-lands.

The participation in international projects such as GLACE2 (Global Land-Atmosphere Coupling Experiment-2) and AMMA (African Monsoon Multidisciplinary Analysis), in which the ECMWF model was coupled with a realistic set of soil moisture fields, have improved the understanding of the mechanisms and areas of strong coupling between the land surface and the atmosphere.

The land-surface components

TESSEL as documented by van den *Hurk et al.* (2000) and *Viterbo & Beljaars* (1995) 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) which can co-exist under the same atmospheric grid-box. Recent revisions of the soil and snow hydrology as well as vegetation characteristics are illustrated in Figure 1.

Soil hydrology

A revised soil hydrology in TESSEL was investigated by van den *Hurk & 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, which does not characterize different soil moisture regimes, and an infiltration-excess runoff scheme which produces hardly any surface runoff. Therefore, 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 introduced in IFS Cy32r3 in November 2007. *Balsamo et al.* (2009) verified the impact of HTESSEL from field site to global atmospheric coupled experiments and in data assimilation.

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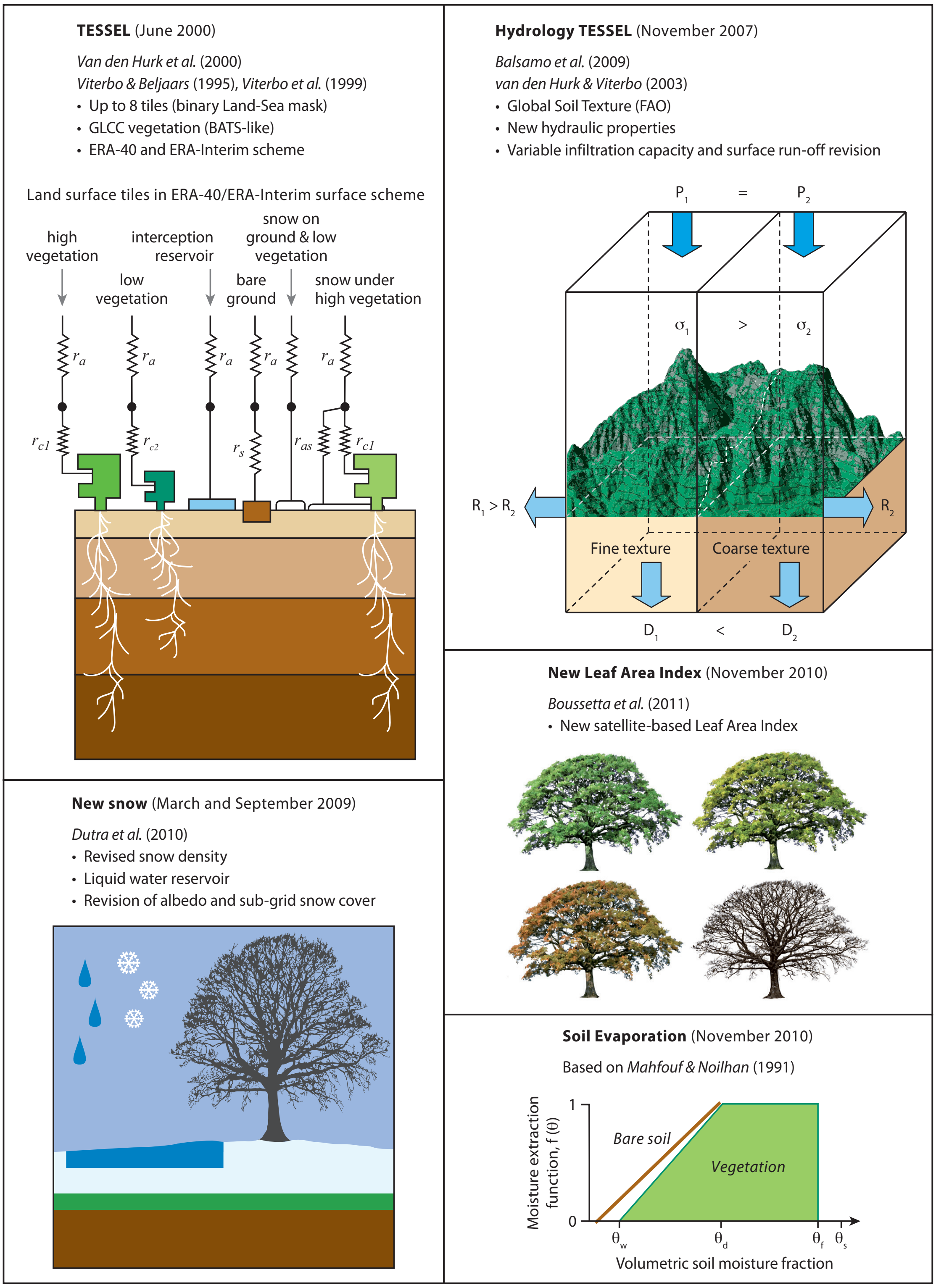

Figure 1 Recent revisions to the land-surface model with the timeline for activation in the operational IFS.

Snow hydrology

A fully revised snow scheme has been introduced in 2009 to improve the existing scheme based on *Douville et al.* (1995). The snow density formulation was changed and a liquid water storage in the snow-pack was introduced, which also allows the interception of rainfall. On the radiative side, the snow albedo and the snow cover fraction have been revised and the forest albedo in presence of snow has been retuned based on MODIS satellite estimates. A detailed description of the new snow scheme and a verification from field site experiments to global offline simulations is presented in *Dutra et al.* (2010). The results showed an improved evolution of the simulated snow-pack with positive effects on the timing of runoff and terrestrial water storage variation and a better match of the albedo to satellite products.

Vegetation seasonality

The Leaf Area Index (LAI), which expresses the phenological phase of vegetation (growing, mature, senescent, dormant), was kept constant and assigned by a look-up table depending on the vegetation type, thus vegetation appeared to be fully developed throughout the year. To allow for seasonality, a LAI monthly climatology based on a MODIS satellite product has been implemented in IFS Cy36r4 in November 2010. The detailed description of the LAI monthly climatology and its evaluation is provided in *Boussetta et al.* (2011).

Site validation and global offline simulations

The HTESSEL scheme has been compared to TESSEL for the soil moisture evolution on two contrasting field sites (SEBEX Sahel and BERMS Canada, Figure 2), while the HTESSEL+SNOW has been evaluated on forest and open sites (SNOWMIP2 Fraser, US, Figure 3). These results show that the soil moisture simulated by the new model had an improved match to observed values while preserving the soil moisture-evaporation link. Also the snow accumulated on the ground is largely improved by HTESSEL+SNOW scheme, with the snow density playing an important role, both on forest and open-field sites.

The revised land-surface hydrology for both soil and snow has been extensively validated using global offline simulations based on the atmospheric forcing provided by the Global Soil Wetness Project II (GSWP2) covering a 10-year period (1986–1995). A summary of the runoff improvements obtained in the upgrades from TESSEL to HTESSEL and HTESSEL+SNOW for large river catchments in the northern hemisphere is reported in Table 1.

The runoff error, calculated against observed river-discharges from the Global Runoff Data Centre (GRDC) of the current scheme (including snow and soil revisions), is estimated as 23% of the observed runoff in dominant snow-free basins (over Europe) and 26% in snow-dominated basins. Those results are likely to be affected by the coarse spatial resolution of the simulations (with GSWP2 at a resolution of 1°×1° degrees), but overall they already indicate a substantial increase in predictive skill for monthly river discharges (~33% relative improvement on root-mean-squared-error for the ensemble of river catchments in Table 1).

Parametrization scheme	Runoff RMSE (mm/day)	Observed area-weighted average runoff from GRDC (mm/day)
Area-weighted average of snow-free basins (~1,632,601 km²): Northeast-Europe and Central-Europe		
TESSEL	0.28	0.76
HTESSEL	0.17	
Area-weighted average of snow basins (~12,334,161 km²): Yukon, Podka., Lena, Tom, Ob, Yenisei, Mackenzie, Volga, Irtish and Neva		
HTESSEL	0.75	1.96
HTESSEL+SNOW	0.51	

Table 1 Runoff root-mean-square error (RMSE) for GSWP2 from global offline simulations (1986–1995) verified with GRDC observations on snow-free basins for TESSEL, HTESSEL, and snow-dominated basins for HTESSEL, HTESSEL+SNOW.

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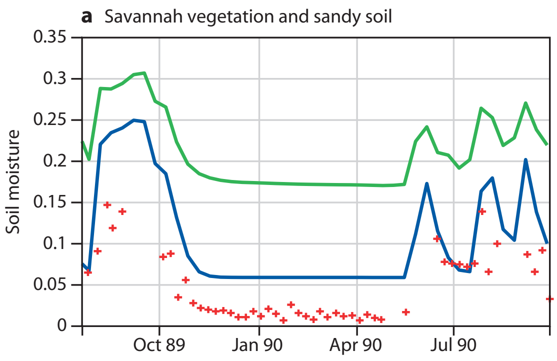

Figure 2 Evolution of soil moisture in TESSEL and HTESSEL in terms of volumetric content (m^3/m^3) compared to observations for two contrasting sites used for field experiments: (a) savannah vegetation and sandy soil (SEBEX, Sahel) and (b) boreal forest (BERMS, Canada).

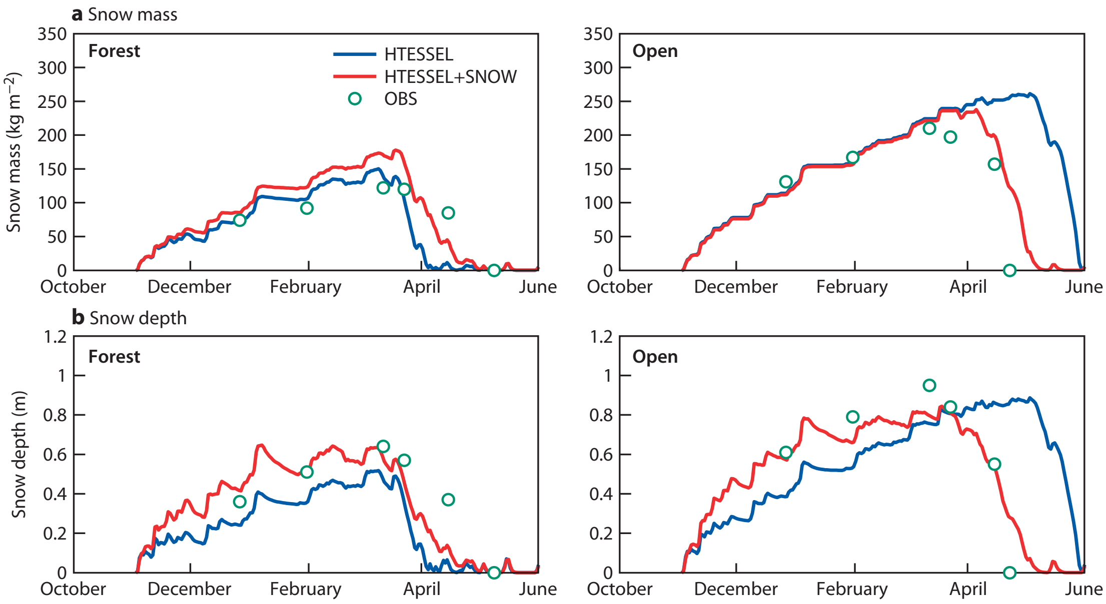

Figure 3 (a) Model-simulated snow mass (in terms of snow water equivalent) and (b) snow depth with HTESSEL and HTESSEL+SNOW during the 2003–04 winter season compared to observations from Fraser forest (left panels) and open (right panels) sites in Colorado that are part of the SnowMIP2 (Snow Model Intercomparison Project).

Forecasts sensitivity experiments

Sets of 10-day forecasts covering one full year have been performed at T399 (~ 50 km horizontal resolution) with the operational IFS (Cy36r1) and TESSEL, HTESSEL, HTESSEL+SNOW and HTESSEL+SNOW+LAI configurations. Forecasts are run 10 days apart to cover the period between the 1 January to 31 December 2008 (37 forecasts per experiment). The effect of the model on near-surface temperature is evaluated for short-term (36-hour) forecasts.

The 2-metre temperature 'sensitivity', defined as the mean difference of HTESSEL+SNOW compared to the TESSEL configuration, is shown in Figure 4 for both the winter and summer seasons. The corresponding improvements on 2-metre temperature forecasts 'impact' are shown in Figure 5. The 'impact' is defined as the mean absolute error difference calculated with respect to the operational 2-metre temperature analysis.

HTESSEL particularly improves the temperate climates where evapotranspiration processes are most active. The temperature sensitivity shows positive and negative patterns which are associated to the spatially varying soil texture and the revised soil hydrology.

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The changes introduced in HTESSEL+SNOW are very effective at high latitude and therefore the two revisions have complementary impact (as already demonstrated for the runoff). In fact, the sensitivity at northern latitudes consists of a cooling (Figure 4) 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 has a beneficial impact on near-surface temperature forecasts over snow-dominated regions (Figure 5). 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. HTESSEL and HTESSEL+SNOW, when coupled to a river routing model (*Pappenberger et al.*, 2009), bring an improved correlation to daily river discharge time-series (*Balsamo et al.*, 2010).

Evaluation of the monthly LAI climatology (HTESSEL+ SNOW+LAI) is shown to affect particularly the tropical areas where the seasonality is rather marked due to the monsoon precipitation. The sensitivity indicates generally a warming as shown in Figure 6a for spring as a consequence of lower LAI and reduced evaporation (which provides more energy to the sensible heat flux). At the same time the impact is a reduction of the systematic 2-metre temperature errors, particularly in tropical regions as shown in Figure 6b.

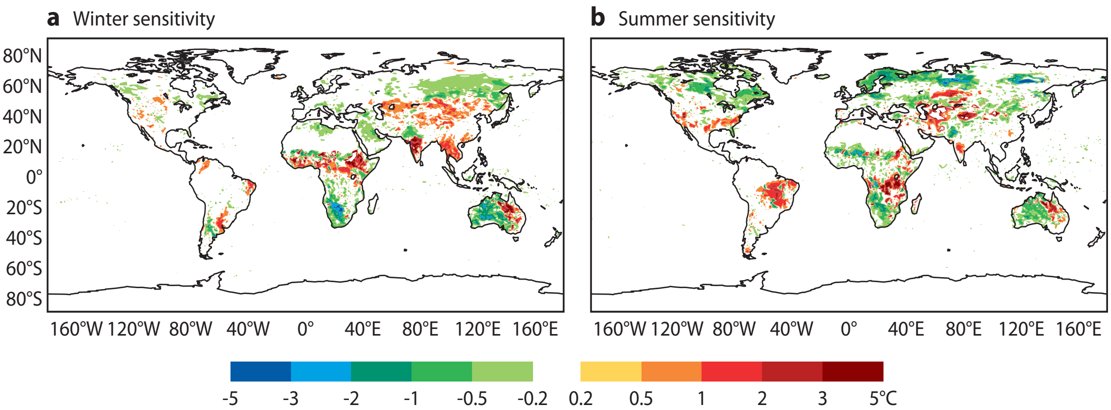

Figure 4 Sensitivity (mean difference) of 36-hour (12 UTC) forecasts of 2-metre temperature for the northern hemisphere (a) winter (December–February) and (b) summer (June–August) for HTESSEL+SNOW compared to TESSEL. Negative values indicate cooling.

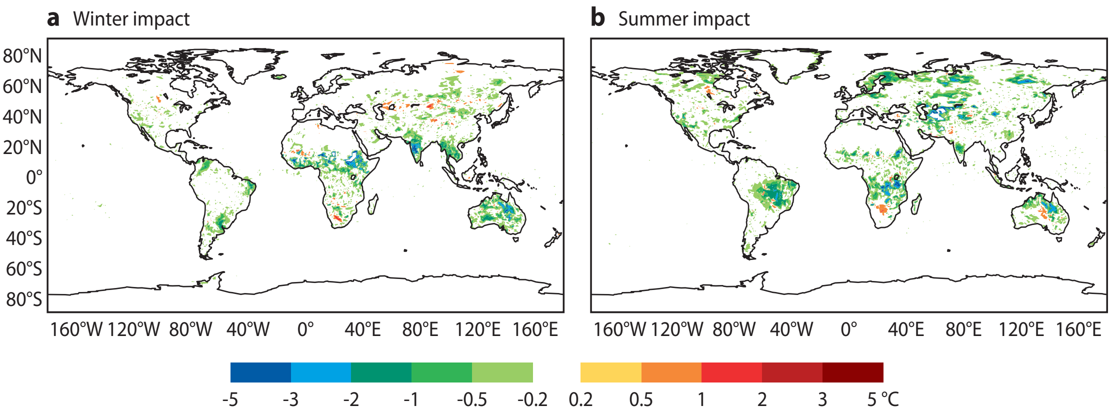

Figure 5 Impact (difference of mean absolute errors) of 36-hour forecasts of 2-metre temperature for the northern hemisphere (a) winter (December–February) and (b) summer (June–August) for HTESSEL+SNOW compared to TESSEL, verified against the ECMWF operational 2-metre temperature analysis.

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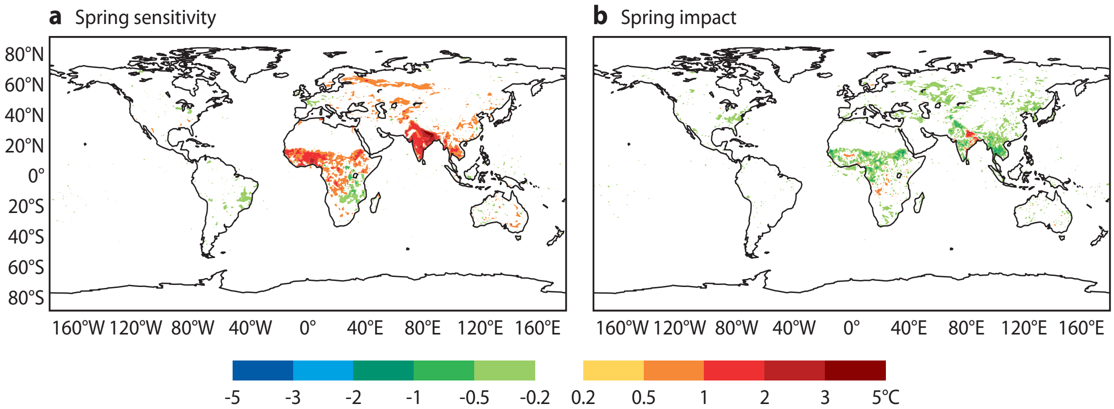

Figure 6 (a) Sensitivity and (b) impact of monthly LAI climatology on 36-hour forecasts of 2-metre termperatures in spring (March–May) as defined in Figures 4 and 5.

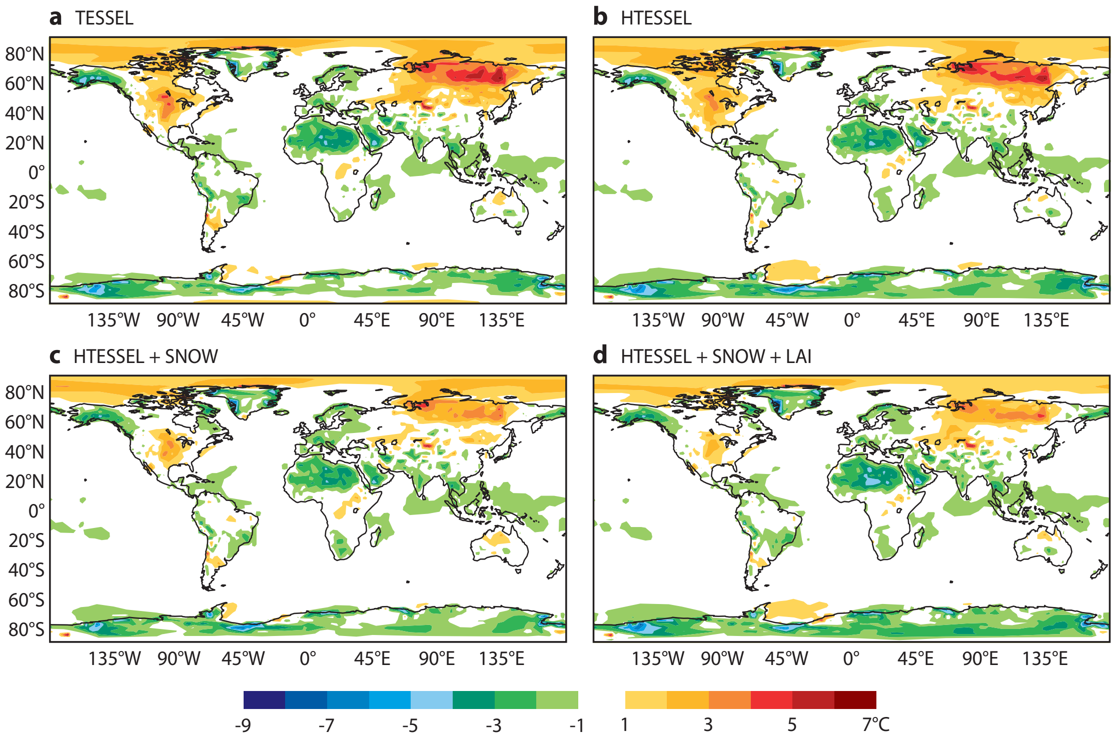

Figure 7 Mean annual 2-metre temperature errors in a long integration compared to ERA-Interim for (a) TESSEL (b) HTESSEL (c) HTESSEL+SNOW and (d) HTESSEL+SNOW+LAI. Negative values indicate error reduction.

Long integration experiments

Long integration experiments covering one full year with daily specified sea-surface temperatures (hindcasts) are performed at the resolution currently used by the seasonal forecasting system (T159, i.e. ~125 km horizontal resolution). The aim is to assess whether the forecast sensitivities obtained in short-term and medium-range forecasts are also reflected in the climate of the model.

Figure 7 shows the mean annual 2-metre temperature errors with the different land-surface model versions. The 2-metre temperature errors are shown to decrease mostly in areas where the land-surface changes are active and with overall good impact on the model climate.

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Outlook

The land-surface model has been revised in its land-surface hydrological components (soil and snow) and in the description of vegetation seasonality (monthly LAI) with positive impact on the forecasts. Future improvements of the land-surface physics will focus on evaporation from free-water surfaces (lakes and intercepted water on leaves). Finally a vegetation/carbon model will be introduced (within the Geoland2 project) to model the net ecosystem exchange of carbon dioxide at the surface.

Further reading

Balsamo, **G.**, **P. Viterbo**, **A. Beljaars**, **B. van den Hurk**,**M. Hirschi**, **A.K. Betts** & **K. Scipal**, 2009: A revised hydrology for the ECMWF model: Verification from field site to terrestrial water storage and impact in the Integrated Forecast System. *Journal Hydrometeorology,* **10**, 623–643.

Balsamo, **G.**, **F. Pappenberger**, **E. Dutra**, **P. Viterbo** & **B. van den Hurk**, 2010: A revised land hydrology in the ECMWF model: A step towards daily water flux prediction in a fully-closed water cycle. Special issue on large scale hydrology of *Hydrol. Process*., doi:10.1002/hyp.7808.

Boussetta, **S.**, **G. Balsamo**, **A. Beljaars** & **J. Jarlan**, 2011: Impact of a satellite-derived Leaf Area Index monthly climatology in a global Numerical Weather Prediction model. *ECMWF Tech. Memo. No*. *640* (submitted to *Int. Journal of Remote Sensing*)

Douville, **H.**, **J.F. Royer** & **J.-F. Mahfouf**, 1995: A new snow parameterization for the Météo-France Climate Model .1. Validation in stand-alone experiments*. Climate Dyn.,* **12**, 21–35*.*

Dutra, **E.**, **G. Balsamo**, **P. Viterbo**, **P. Miranda**, **A. Beljaars**, **C. Schär** & **K. Elder**, 2010: An improved snow scheme for the ECMWF land surface model: description and offline validation. *J. Hydrometeor.,* **11***,* 899–916 (available as *ECMWF Tech. Memo. No*. *607*).

Mahfouf, **J.-F.** & **J. Noilhan**, 1991: Comparative study of various formulations of evaporation from bare soil using in situ data. *J. Appl. Meteorol*., **30**, 351–362.

Pappenberger, **F.**, **H. Cloke**, **G. Balsamo**, **T. Ngo-Duc** & **T. Oki**, 2009: Global runoff routing with the hydrological component of the ECMWF NWP system, *Int. J. Climatol.*, doi:10.1002/joc.2028

van den Hurk, **B.**, **P. Viterbo**, **A. Beljaars** & **A.K. Betts**, 2000: Offline validation of the ERA-40 surface scheme. *ECMWF Tech. Memo. No. 295*.

van den Hurk, **B.** & **P. Viterbo**, 2003: The Torne-Kalix PILPS 2(e) experiment as a test bed for modifications to the ECMWF land surface scheme. *Global Planet. Change*, **38**, 165–173.

Viterbo, **P.** & **A. Beljaars**, 1995: An improved land surface parameterization scheme in the ECMWF model and its validation. *J. Climate*, **8**, 2716–2748.

Viterbo, **P.**, **A. Beljaars**, **J.F. Mahfouf** & **J. Teixeira**, 1999: The representation of soil moisture freezing and its impact on the stable boundary layer. *Q. J. R. Meteorol. Soc*., **125**, 2401–2426.

Weisheimer, **A.**, **F. Doblas-Reyes**, **T. Jung** & **T. Palmer**, 2011, On the predictability of the extreme summer 2003 over Europe, *Geophys. Res. Lett.*, **38**, L05704, doi:10.1029/2010GL046455.

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