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13 ERA-Interim/Land: A global land-surface reanalysis based on ERA-Interim meteorological forcing

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Abstract

This report describes ERA-Interim/Land, a global land-surface data set covering the period 1979-2010. ERA-Interim/Land is the result of a land-surface model simulation using HTESSEL, with meteorological forcing from ERA-Interim and precipitation adjustments based on GPCP v2.1. ERA-Interim/Land preserves closure of the water balance and is therefore more suitable for climate applications than the land surface parameters included in the original ERA-Interim data set.

We compare with ground-based and remote sensing observations to assess the quality of ERA-Interim/Land, in particular for estimates of soil moisture, snow depth, surface albedo, turbulent latent and sensible fluxes, and river discharges. Impacts of using the new land-surface initial condition in forecasts have been verified in deterministic and probabilistic configurations (up to monthly and seasonal ranges) of the Integrated Forecasting System at ECMWF.

1 Introduction

Multi-model land-surface simulations, such as those performed within the Global Soil Wetness Project (Dirmeyer 2011; Dirmeyer et al. 2002, 2006), combined with seasonal forecasting systems have been crucial in triggering advances in land-related predictability as documented in the Global Land Atmosphere Coupling Experiments (Koster et al. 2010, 2009, 2006). The land-surface state estimates used in those studies was generally obtained with offline model simulations, forced by 3-hourly meteorological fields from atmospheric reanalyses, and combined with simple schemes to address climatic biases. Bias corrections of the precipitation fields are particularly important to maintain consistency of the land hydrology. The resulting land-surface data sets have been of paramount importance for hydrological studies addressing global water resources (Oki and Kanae 2006). A state-of-the-art land-surface dataset covering the most recent decades is highly relevant to foster research into intra-seasonal forecasting in a changing climate, as it can provide consistent land initial condition to weather and climate models.

In recent years several improved global atmospheric reanalyses of the modern era from 1979 onwards have been produced that enable new applications of offline land-surface simulations. These include ECMWF's Interim reanalysis (ERA-Interim, Dee et al. 2011, Richardson et al. 2007) and NASA's Modern Era Retrospective-analysis for Research and Applications (MERRA, Rienecker et al. 2011). Simmons et al. (2010) have demonstrated the reliability of ERA-Interim near-surface fields by comparing with observations-only climatic data records. Balsamo et al. (2010a) evaluated the suitability of ERA-Interim precipitation estimates for land applications at various time-scales from annual to daily over the conterminous US. They proposed a scale-selective rescaling method to address remaining biases based on GPCP monthly precipitation data (Huffman et al. 2009). This method "calibrates" the monthly precipitation amount addressing the issue of non-conservation typical of data assimilation systems, as analysed in Berrisford et al. (2011). Estimates of incoming solar radiation provided by the ERA-Interim reanalysis have been evaluated by Szczypta et al. (2011). They showed a slight positive bias, with a modest impact on land-surface simulations. Decker et al. (2012) confirmed these findings using flux tower observations and showed that the land-surface evaporation of ERA-Interim compared favourably with the observations and with other reanalyses.

Offline land-surface simulations forced by meteorological fields from reanalyses are not only useful for land-model development but can also offer an affordable mean to improve the land-surface component of reanalysis itself. Reichle et al. (2011) have used this approach to generate an improved MERRA-based land-surface product (MERRA-Land, http://gmao.gsfc.nasa.gov/research/merra/merra-land.php). Similarly we have produced ERA-Interim/Land, a new global land-surface data set associated with the ERA-Interim reanalysis, by incorporating recent land model developments at ECMWF combined with precipitation bias corrections based on GPCP v2.1.

To produce ERA-Interim/Land, near-surface meteorological fields from ERA-Interim were used to force the latest version of the HTESSEL land-surface model (Hydrology-Tiled ECMWF Scheme for Surface Exchanges over Land). This scheme is an extension of the TESSEL scheme (van den Hurk et al. 2000) that was used in ERA-Interim, which was based on a 2006 version of ECMWF's operational Integrated Forecasting System (IFS). HTESSEL includes an improved soil hydrology (Balsamo et al. 2009), a new snow scheme (Dutra et al. 2010), a multi-year satellite-based vegetation climatology (Boussetta et al. 2011), and a revised bare-soil evaporation (Balsamo et al. 2011; Albergel et al. 2012a).

The next section describes the various data sets used for production and verification of ERA-Interim/Land. Section 3 describes the offline land-surface model integrations. Section 4 presents the main results on verification of land-surface fluxes, soil moisture, snow, and surface albedo. We also demonstrate that land-surface estimates from ERA-Interim/Land are a preferred choice for initializing ECMWF's seasonal forecasting system (System-4, Molteni et al. 2011), as well as the monthly forecasting system (Vitart et al. 2008), since both these systems make use of HTESSEL. A summary and recommendation for the usage of the ERA-Interim/Land product is reported in the conclusions.

2 Forcing and verification datasets

2.1 ERA-Interim (1979-present)

ERA-Interim (Dee et al. 2011) is produced at T255 spectral resolution and covers the period January 1979 to present, with product updates approximately 1 month delay from real-time. The atmospheric forcing data was gridded on the original reduced Gaussian grid (with a resolution of 0.7° at the Equator) with a 3-hour time interval. ERA-Interim precipitation and radiation fields (incoming long- and short-wave components) are generated by the forecast model in 3-hourly accumulations, and present some initial spin-up (Kållberg 2011). To avoid possible spin-up effects, the 3-hourly surface fluxes correspond to the 09-21h forecast intervals from initial conditions at 00 and 12 UTC. ERA-Interim temperature, surface pressure, humidity and wind fields are instantaneous values representative of the lowest model level corresponding to a height of 10m above the surface and are extracted from the 03-12 forecast-range intervals and from both 00 and 12 UTC runs. The forecasts are then concatenated to produce a continuous 3-hourly meteorological forcing data set that can be used to drive land surface simulations.

2.2 GPCP v2.1 (1979-2010)

The GPCP dataset merges satellite and rain gauge (SG) data from a number of satellite sources including the Global Precipitation Index (GPI), the Outgoing Longwave Radiation (OLR), Precipitation Index (OPI), the Special Sensor Microwave/Imager (SSM/I) emission, the SSM/I scattering, and the TIROS Operational Vertical Sounder (TOVS). In addition, rain gauge data from the combination of the Global Historical Climate Network (GHCN) and the Climate Anomaly Monitoring System (CAMS), as well as the Global Precipitation Climatology Centre (GPCC) dataset which consists of approximately 6700 quality controlled stations around the globe interpolated into monthly area averages, are used over land. More details on the datasets and the method used to merge these data are provided by Adler et al. (2003).

The Version 2.1 of the GPCP used in this study takes advantage of the improved GPCC gauge analysis and the usage of the OPI estimates for the new SSM/I era. Thus, the main differences between the two versions are introduced by the use of the new GPCC full data reanalysis (Version 4) for 1997-2007, the new GPCC monitoring Product (version 2) thereafter and the recalibration of the OPI data to a longer 20-year record of the new SSM/I-era GPCP data. Further details on the new version can be found in Huffman et al. (2009).

2.3 Turbulent energy fluxes datasets

Available observational data for the year 2006 from the Boreal Ecosystem Research and Monitoring Sites (BERMS, Betts et al. 2006), the FLUXNET project (Baldocchi et al. 2001) and the Coordinated Energy and water cycle Observations Project (CEOP) were used in this study.

As part of the CEOP program, reference site observations from the Amazonian region also belonging to the LBA experiments (the Large Scale Biosphere-Atmosphere Experiment in Amazonia) are available for scientific use. In this study, observations are taken from flux towers located within an evergreen broadleaf forest (Manaus) and a woody savannah region (Brasilia).

The FLUXNET observations used in this study are part of the LaThuile dataset which provides flux tower measurements of latent heat flux (LE), sensible heat flux (H) and net ecosystem exchange (NEE) at high temporal resolution (30 min to 60 min). For verification purposes, hourly observations from the year 2004 were selected from the non-gapped filled archive with high quality flag only. (see Table 3).

2.4 Soil moisture observing networks

In-situ soil moisture observations are valuable to evaluate modelled soil moisture. In the recent years huge efforts were made to collect observations representing contrasting biomes and climate conditions. Some of them are now freely available on the Internet such as data from The International Soil Moisture Network (ISMN, Dorigo et al. 2011, http://www.ipf.tuwien.ac.at/insitu/). The ISMN is a new data hosting centre where globally available ground-based soil moisture measurements are collected, harmonized and made available to users. This includes a collection of more than 500 stations (with data from 2007 to March 2012) gathered and quality controlled at ECMWF. Albergel et al. (2012a, b, c) have used these data to validate various soil moisture estimates produced at ECMWF, including from ERA-Interim as well as from offline land simulations.

2.5 The GTS-SYNOP network

The SYNOP datasets provide daily observations of the main weather parameters and selected land surface quantities such as snow depth, at a large number of sites worldwide. The snow data are acquired at a minimum frequency of once a day and represent the only quantitative snow-depth measurement on the ground (remote sensing observations have difficulties in representing snow properties).

2.6 Surface albedo

The Moderate Resolution Imaging Spectroradiometer (MODIS) albedo product MCD43C3 provided data describing both directional hemispheric reflectance (black-sky albedo) and bihemispherical reflectance (white-sky albedo) in seven different bands and aggregated bands. Data from the *Terra* and *Aqua* platforms are merged in the generation of the product that is produced every 8 days, with 16 days acquisition, and available on a 0.05° global grid. The accuracy and quality of the product has been studied by several authors in different locations (e.g Roman et al. 2009; Salomon et al. 2006). The MODIS product has served as a reference for model validations (e.g. Dutra et al. 2010, 2012; Wang and Zeng 2010; Zhou et al. 2003). In this study, we compare the white-sky broadband shortwave albedo (2000-2010) with ERA-Interim and offline simulations. MODIS albedo was averaged for each month and spatially aggregated to the simulation grid.

2.7 The GRDC river discharge dataset

The Global Runoff Data Centre (GRDC) operates under the auspice of the World Meteorological Organization and provides data for verification of atmospheric and hydrologic models. The GRDC database is updated continuously, and contains daily and monthly discharge data information for over 3000 hydrologic stations in river basins located in 143 countries. Over the GSWP-2 period the runoff data of 1352 discharge gauging stations was available and used for verification of the soil hydrology (Balsamo et al. 2009). Pappenberger et al. (2009) and Balsamo et al. (2010b) used the GRDC daily discharge to evaluate a coupled land surface – river discharge scheme for river flood prediction.

3 The offline land surface simulations

This study focuses on the validation of HTESSEL land-surface model integrations covering the period 1979-2010, using meteorological forcing from ERA-Interim and GPCP. The offline (or stand-alone) mode is a convenient framework for isolating the benefits and the deficiencies of different land surface parameterizations (Polcher et al. 1998). In addition, in terms of computational cost, given the complexity of the coupling with the atmosphere, offline simulations are much more cost-effective (faster) to run than a full atmospheric-land assimilation system.

In this study, offline runs are performed both at the global and point scales. All the 3-hourly meteorological forcing parameters were linearly interpolated in time to the land surface model integration time -step of 30 minutes.

The land-use information has been derived from the GLCC and FAO data set at the same resolution as the forcing data. A comprehensive description of the land surface model and the ancillary datasets is given in the IFS documentation (2012, Part IV, chapters 8 and 11, http://www.ecmwf.int/research/ifsdocs/CY37r2/index.html).

Table 1 lists the land surface experiments considered in the comparison in order to show the added value of the ERA-Interim/Land and its components.

Table 1: List of land surface experiments considered in the land surface verification

Land surface experiments	**Period of availability**
ERA-Interim	1979-present
HTESSEL offline (GPCP-ERA-I forcing): ERA-Interim/Land	1979-2010
HTESSEL offline (ERA-I-forcing)	1979-2010
TESSEL offline (ERA-I forcing)	1979-2010

3.1 The ERA-Interim and GPCP-merged precipitation

ERA Interim precipitation is evaluated against the European Land Data Assimilation System (ELDAS) dataset (accounting for about 22000 rain-gauges; see Rubel and Brugger 2009) and to the PRISM dataset (Daly et al. 1994, 2001, Lin and Mitchell 2005, Lopez and Bauer 2007).

The summary of annual statistics in comparison with both datasets is reported in Table 2. The mean annual ERA-Interim precipitation in 2000 is compared to ELDAS in Figure 1. Figure 2 compares ERA-Interim to PRISM for 2000-2008. It is clear that ERA-Interim reproduces the patterns very well, but also some biases become evident, e.g. over the South East of the USA. In these well-observed areas, the precipitation forcing benefits from a GPCP-based bias correction.

Table 2: Precipitation bias, RMSE (mm/day) and correlation averaged over 2000-2008 with respect to PRISM data for the USA, and similarly over the year 2000 for Europe with respect to ELDAS data.

Domain	Index	**ERA-Interim (mm/day)**	**ERA-Interim rescaled (mm/day)**	**GPCP V2.1 (mm/day)**	**GPCP V2.0 (mm/day)**
Conterminous US domain (vs. PRISM data)	**BIAS**	-0.063	0.286	0.214	-0.52
	RMSE	0.793	0.778	0.805	1.130
	Correlation	0.884	0.888	0.875	0.725
Europe domain (vs. ELDAS data)	**BIAS**	-0.013	0.101	0.081	-0.068
	RMSE	0.852	0.687	0.675	0.889
	Correlation	0.853	0.902	0.899	0.816

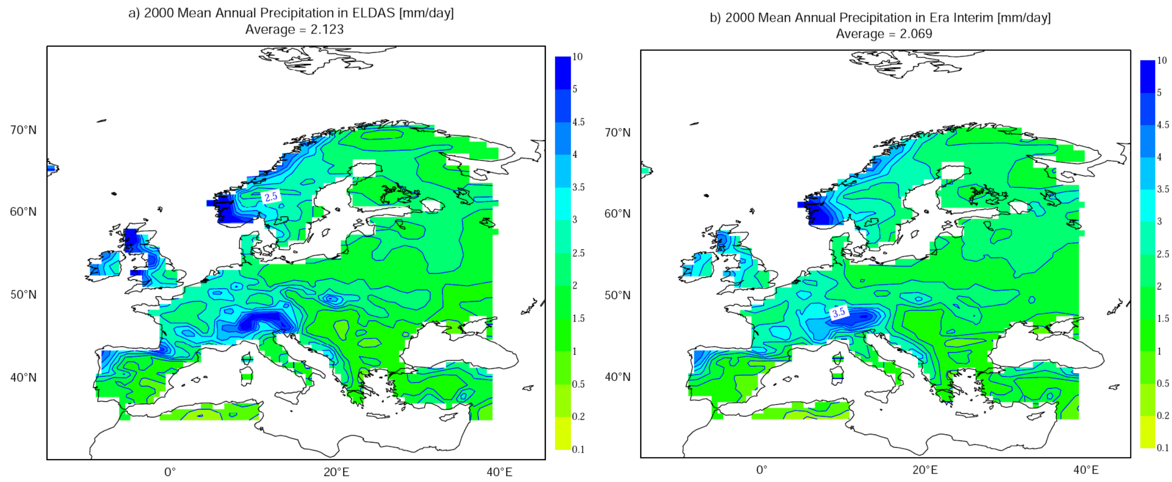

Figure 1: Mean-precipitation over the year 2000 from the ELDAS network (about 22000 rain gauges, left panel) and ERA-Interim (right panel).

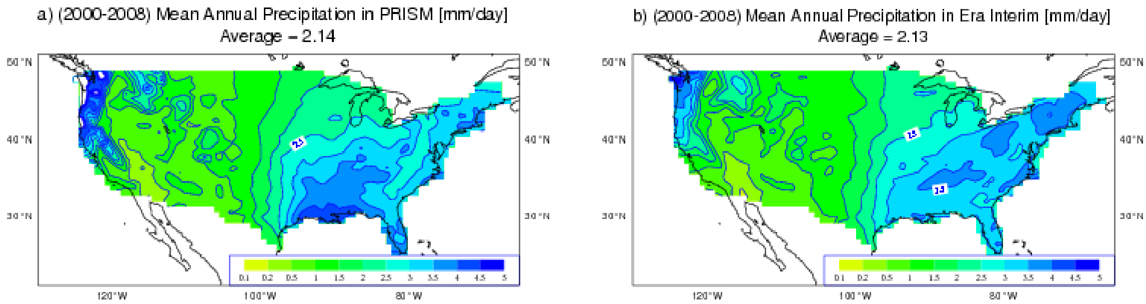

Figure 2 Mean-precipitation over the years 2000-2008 from the PRISM network (about 8000 rain gauges, left panel) and ERA-Interim (right panel).

Balsamo et al. (2010a) used a scale-selective rescaling procedure to improve the ERA-Interim precipitation fields. The procedure corrects the 3-hourly precipitation in order to match the monthly accumulation provided by the Global Precipitation Climatology Project (GPCP) v2.1 product (Huffman et al., 2009) at grid-point scale. The method uses information from GPCP v2.1 at the scale for which the dataset was provided (for a spatial resolution of 2.5 degrees) and rescales the ERA-Interim precipitation at full resolution (about 0.7 degrees). The advantage of this procedure is that small-scale features of ERA-Interim (for instance related to orographic precipitation enhancement) can be preserved while the monthly totals are rescaled to match GPCP.

The RMS errors are reduced and the correlation improved mainly via the reduction of regional monthly biases (Table 2). Large corrections also occur in tropical regions where the GPCP-based rescaling is effective in modifying the ERA-Interim precipitation.

An independent verification of the precipitation is not feasible in all geographical areas, particularly over the Tropics, due to the lack of observations. However river discharges from GRDC can provide an overall evaluation of the water cycle and are considered in the verification of the land surface simulations.

3.2 Land model upgrades from the ERA-Interim version

In recent years the land surface model at ECMWF has been extensively revised with positive impact on both the global hydrological water cycle and near-surface atmospheric variables. In particular the introduction of a new soil hydrology (Balsamo et al. 2009) has improved the quality of seasonal predictions during extreme events associated with soil moisture-precipitation feedback as in the European summer heatwave in 2003 (Weisheimer 2010). A new snow scheme (Dutra et al. 2010) has improved the thermal energy exchange at the surface with a substantial reduction of near-surface temperature errors in snow-dominated areas (e.g. northern territories of Eurasia and Canada). Boussetta et al. (2011) have replaced the fixed maximum Leaf Area Index (LAI) by a monthly climatology for vegetation LAI, leading to 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 (Albergel et al. 2012a; Balsamo et al. 2011) has been enhanced over deserts by adopting a lower stress threshold than for vegetation. A brief description of the major land surface modelling changes introduced in the operational model is reported hereafter.

3.2.1 Soil hydrology

A revised soil hydrology in TESSEL was investigated by van den Hurk and Viterbo (2003) for the Baltic basin. These model developments were in 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 a Hortonian 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.

3.2.2 Snow

A fully revised snow scheme has been introduced in 2009 to replace 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.

3.2.3 Vegetation seasonality

The Leaf Area Index (LAI), which expresses the phenological phase of vegetation (growing, mature, senescent, dormant), was kept constant in ERA-Interim 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).

3.2.4 *Bare soil evaporation*

The bare soil evaporation included in the HTESSEL model in conjunction with the LAI update as reported in Balsamo et al. (2011) has been extensively evaluated by Albergel et al. (2012a) over the US. The evaluation was based on data from the Soil Climate Analysis Network (SCAN) as well as SMOS satellite data. The bare ground evaporation has been enhanced over deserts by adopting a lower stress threshold than for vegetation. This is in agreement with previous experimental findings (e.g. Mahfouf and Noilhan 1991) and results in a more realistic soil moisture for dry lands, as was largely confirmed by Abergel et al. (2012a).

4 Results

The ERA-Interim and ERA-Interim-GPCP-rescaled precipitation are used in offline land surface model runs as listed in Table 1. The evaluation of land surface fluxes, soil moisture, and snow is reported hereafter. Apart from the GPCP-based bias correction on the monthly precipitation, no other land surface observations were used to constrain the model errors in these land surface runs. The relative improvement introduced by the HTESSEL model version used here and the TESSEL model used in ERA-Interim reanalysis is highlighted in dedicated runs. For the main prognostic variables the comparison with ERA-Interim is produced.

4.1.1 *Land surface fluxes verification*

The land surface fluxes resulting from the offline-driven land simulations indicate an average improvement of 8%, when adopting the HTESSEL scheme instead of the TESSEL scheme, evaluated as root-mean-square-error reduction on both the latent and sensible heat fluxes measured over 34 FLUXNET, CEOP and BERMS flux-towers as listed in Table 3.

The evaluation of the TESSEL and HTESSEL offline driven simulations is performed for each site showing a generally improved representation of both the latent and sensible heat fluxes (Figure 3).

An overall quantitative estimate of the improvements is reported in Table 4. The latent and sensible heat fluxes have a reduced RMSE and increased correlation, compared to 34 flux towers estimates.

Table 3: List of sites used for the verification of the simulated fluxes, where the biome types are: deciduous broadleaf forest (DBF), evergreen broadleaf forest (EBF), deciduous needle-leaf forest (DNF), evergreen needle-leaf forest (ENF), mixed forest (MF), woody savannahs (WSA), grasslands (GRA), crops (CRO), wetlands (WET)

N	Site	Lat [°N]	Lon [°E]	Veg. type	N	Site	Lat [°N]	Lon [°E]	Veg. type
1	sk-oa	53.63	-106.20	DBF	**18**	it-ro2	42.39	11.92	DBF
2	sk-obs	53.99	-105.12	ENF/WET	**19**	nl-ca1	51.97	4.93	GRA
3	brasilia	-15.93	-47.92	WSA/GRA/SH	**20**	nl-haa	52.00	4.81	GRA
4	at-neu	47.12	11.32	GRA	**21**	nl-hor	52.03	5.07	GRA
5	ca-mer	45.41	-75.52	WET	**22**	nl-loo	52.17	5.74	ENF
6	ca-qfo	49.69	-74.34	ENF	**23**	ru-fyo	56.46	32.92	ENF
7	ca-sf1	54.49	-105.82	ENF	**24**	ru-ha1	54.73	90.00	GRA
8	ca-sf2	54.25	-105.88	ENF	**25**	ru-ha3	54.70	89.08	GRA
9	ch-oe1	47.29	7.73	GRA	**26**	se-sk2	60.13	17.84	ENF
10	fi-hyy	61.85	24.29	ENF	**27**	us-arm	36.61	-97.49	CRO
11	fr-hes	48.67	7.06	DBF	**28**	us-bar	44.06	-71.29	DBF
12	fr-lbr	44.72	-0.77	ENF	**29**	us-ha1	42.54	-72.17	DBF
13	il-yat	31.34	35.05	ENF	**30**	us-mms	39.32	-86.41	DBF
14	it-amp	41.90	13.61	GRA	**31**	us-syv	46.24	-89.35	MF
15	it-cpz	41.71	12.38	EBF	**32**	us-ton	38.43	-120.97	MF/WSA
16	it-mbo	46.02	11.05	GRA	**33**	us-var	38.41	-120.95	GRA
17	it-ro1	42.41	11.93	DBF	**34**	us-wtr	45.81	-90.08	DBF

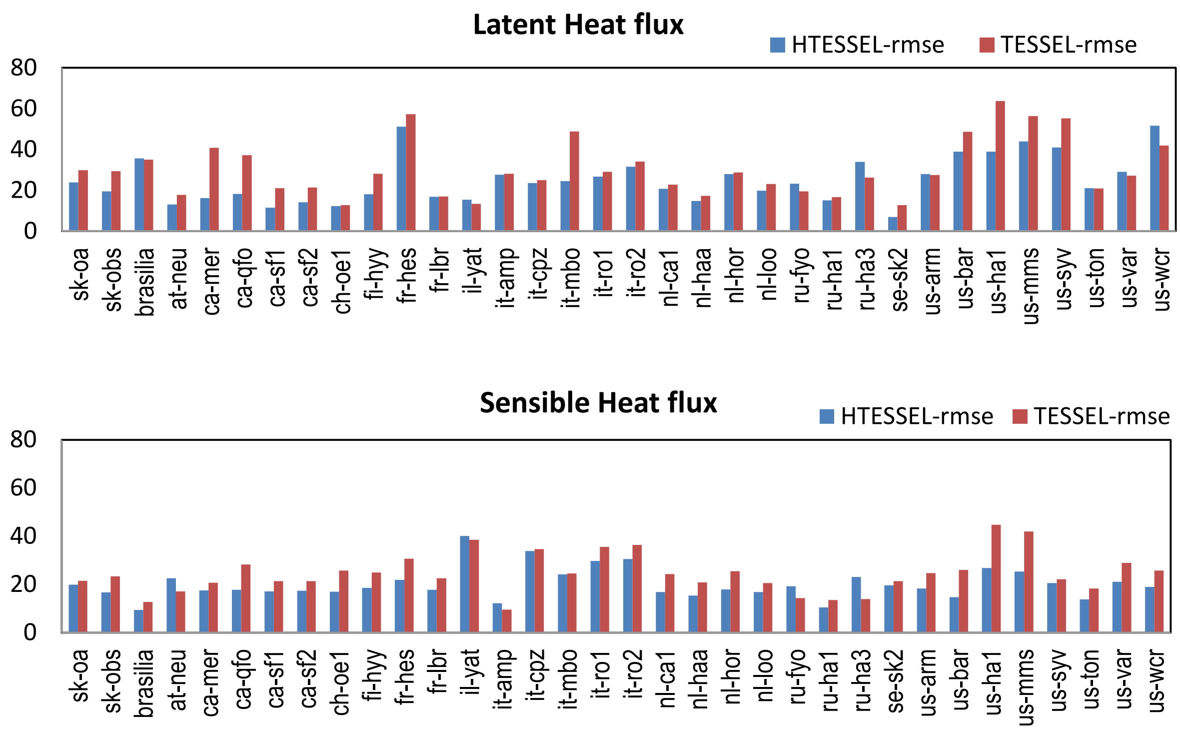

Figure 3: Root-Mean-Square errors of latent and sensible heat fluxes (RMSE, W/m^2) evaluated for 2004 against 34 flux-tower sites for HTESSEL (blue) and TESSEL (red) forced by ERA-Interim meteorological forcing. Observations and model output were available hourly at each site and pre-averaged in 10-days windows prior to calculating the RMSE.

Table 4: Summary of mean latent heat (LE) and sensible heat (H) statistics averaged over the 34 sites (units of W/m^2).

Model	LE rmse	LE bias	LE corr	H rmse	H bias	H corr
HTESSEL	25.14	16.01	0.84	20.14	-4.87	0.84
TESSEL	30.42	21.58	0.81	24.64	-8.90	0.78

4.1.2 Soil moisture verification

The changes in the land surface parameterization have largely preserved the mean annual soil moisture, which ranges around 0.23-0.24 m^{3}m^{-3} as global land average on the ERA-Interim period, however the spatial variability has greatly increased with the introduction of HTESSEL. In order to verify the soil moisture produced by the offline simulations we make use of the International Soil Moisture Network (ISMN) ground-based observing networks. This has been applied by Albergel et al. (2012a) to validate soil moisture from both ECMWF operational analysis and ERA-Interim. Offline land surface simulations were also used by Albergel et al. (2012b) to evaluate the new bare ground evaporation formulation mentioned in section 3.2. Considering the field sites of the NCRS-SCAN network (covering the US) with a fraction of bare ground greater than 0.2 (according to the model), the root mean square difference (RMSD) of soil moisture is shown to decrease from 0.118 m^{3}m^{-3} to 0.087 m^{3}m^{-3} when using the new formulation in offline experiments (and from 0.110 m^{3}m^{-3} to 0.088 m^{3}m^{-3} in operations). It also improves correlations. Figure 4 illustrates the two offline runs (HTESSEL and TESSEL) driven by ERA-Interim forcing as well as the in situ observations for one site located in Utah. ERA-Interim and ERA-Interim/Land soil moisture are shown to illustrate the differences in soil moisture and the contribution of GPCP correction.

In the TESSEL formulation, minimum values of soil moisture are limited by the wilting point of the dominant vegetation type, however ground data indicate much drier conditions, as is clearly observed from May to September 2010. The new soil hydrology and bare ground evaporation allows the model to go below this wilting point so the new analysis is in much better agreement with the observations than in ERA-Interim. A more realistic decrease in soil moisture after a precipitation event due to its higher water holding capacity and this explains the better correlations.

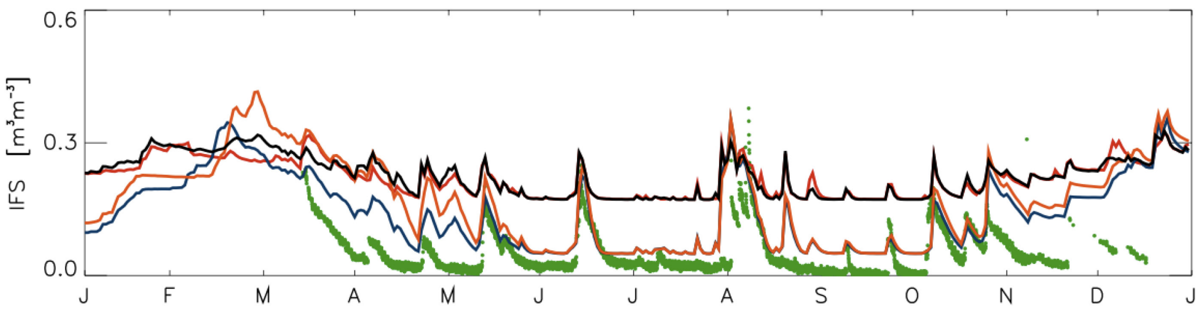

Figure 4: Illustration of volumetric soil moisture time-series for a site in Utah for 2010. The black line is for TESSEL (forced by ERA-Interim), the green line is for HTESSEL (forced by ERA-Interim) and the green dots are the in-situ observations. The original ERA-Interim data is in red and ERA-Interim/Land is in blue.

4.1.3 Snow verification

The verification of snow fields considers two different observations data sets: the SYNOP daily snow depth and the former USSR datasets are used to evaluate the snow evolution in ERA-Interim and in the offline simulations. The 1979-1993 former USSR data set has been already used in Brun et al. (2012) to evaluate simulated snow properties, such as density, that are not routinely measured at SYNOP stations. Dutra et al. (2010) attributed the largest improvement in the new snow scheme to the snow density representation. This is confirmed by the verification results on a large number of sites where snow density was measure, as shown in Figure 5 for the typical Northern latitudes snow season (October to June) average on the 1979-1993 period. In ERA-Interim, the snow density is not at all constrained by data assimilation due to a lack of observations and therefore it relies solely on the capacity of the land surface model to represent the seasonal evolution, from about 100 kg/m^3 at the beginning of the winter season to more than 300 kg/m^3 towards the end of the snow season.

Simulations of snow water equivalent with and without the GPCP V2.1 rescaling have been evaluated against observations, which are available from 1979 to 1993 over the USSR. A significantly lower bias in this case is obtained without the GPCP rescaling (9.7 mm versus 33.8 mm) confirming the general difficulties in measuring snowfall with gauges. In Figure 6 the long-term evolution (1979-1993) of the snow depth simulated by HTESSEL driven by ERA-Interim is illustrated for a station near Perm (58.0N, 56.5E), verified against daily observations. The correlation reaches 0.98 with a reduced bias (less than 1 cm).

The capacity of detecting the presence of snow on the ground is examined using the SYNOP network in more recent years considering two snow seasons 2005/06 and 2009/10. Two scores are adopted:

- SDR = Snow Detection Rate (SDR=1 being the best value) measures the fraction of times the snow fields rightly detect the presence of snow divided by the number of times the SYNOP observation detects snow presence (SDR=1 best value), and

- FCA = Fraction of Correct Accuracy (FCA=1 being the best value) measures the fraction of times the snow fields rightly detect the presence or absence of snow in agreement with the SYNOP message (divided by the total amount of stations).

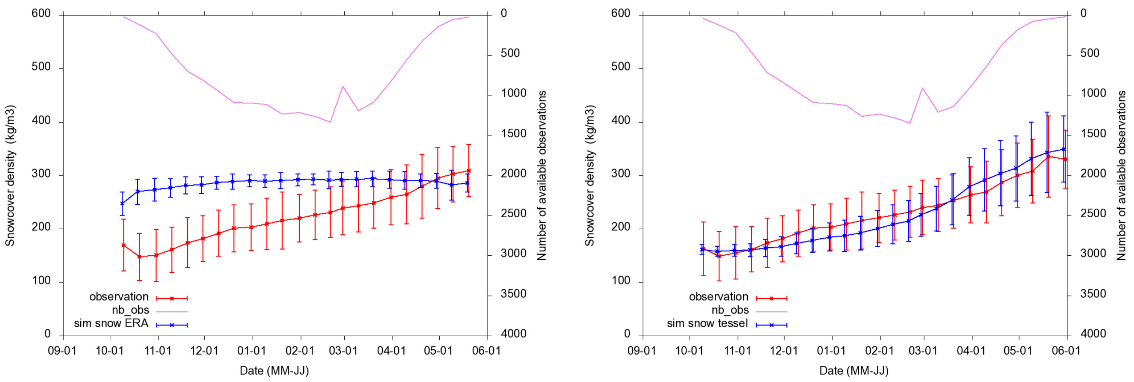

Figure 5: Snow density seasonal evolution as observed (red) and estimated (blue) by the ERA-Interim reanalysis (left) and by the offline HTESSEL simulations (right) driven by ERA-Interim.

The ability of two offline simulations driven by ERA-Interim to represent snow cover was assessed for TESSEL (control) and HTESSEL (experiment) offline experiments driven by ERA-Interim. Figure 7 (left) shows the Snow Detection Rate (SDR) function of the snow cover for both HTESSEL and TESSEL configurations and Figure 7 (right) presents the cumulative distribution function of the SDR for two periods, 2005/06 and 2009/10. SDR is much better with HTESSEL than with TESSEL for both periods. For instance, considering the 2005/06 period, while 50% of the SDR is above the value 0.49 for TESSEL, 50% of the SDR is above 0.70 for HTESSEL. Finally, Fraction of Correct Accuracy (FCA) are 80 and 86 in 2005/06, 76 and 83 in 2009/10 for TESSEL and HTESSEL respectively (Figure 8). This index is a robust indicator and is more resilient to model biases (in case snow abundance the SDR may favour a biased snow scheme).

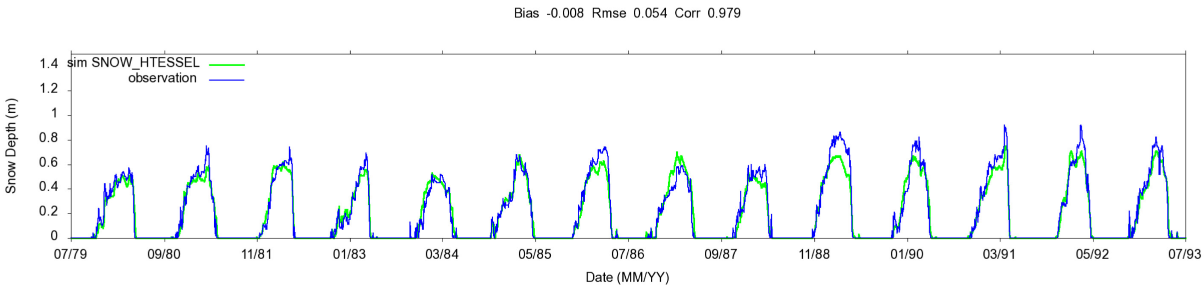

Figure 6: Long term evolution of the HTESSEL snow-depth simulations driven by ERA-Interim compared with in-situ measurements from 1979 to 1993 at Perm (58.0N, 56.5E).

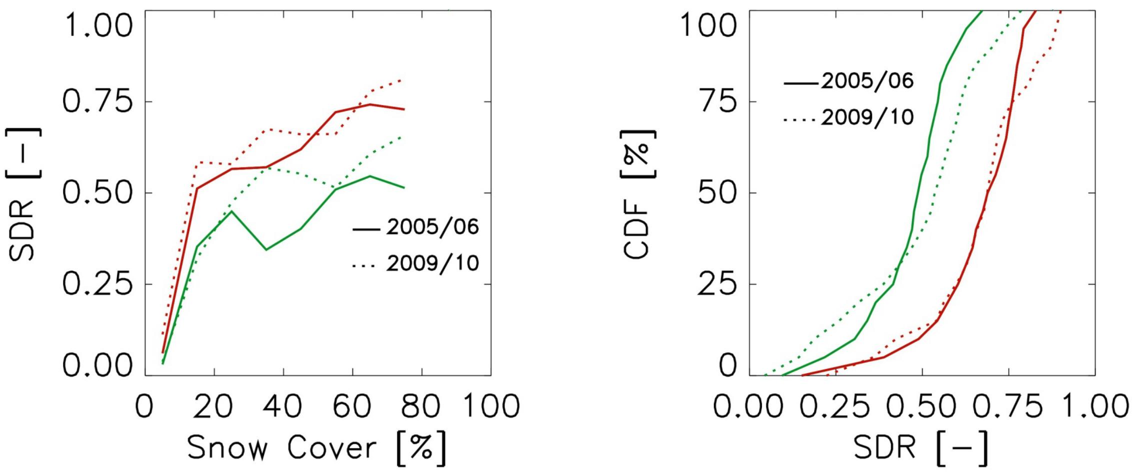

Figure 7: (Left) Snow Detection Rate function of snow cover and (right) cumulative distribution function of the Snow Detection Rate for 2005-2006 and 2009-2010 (1st of July to 30th of June), for HTESSEL (red) and TESSEL (green) offline simulations.

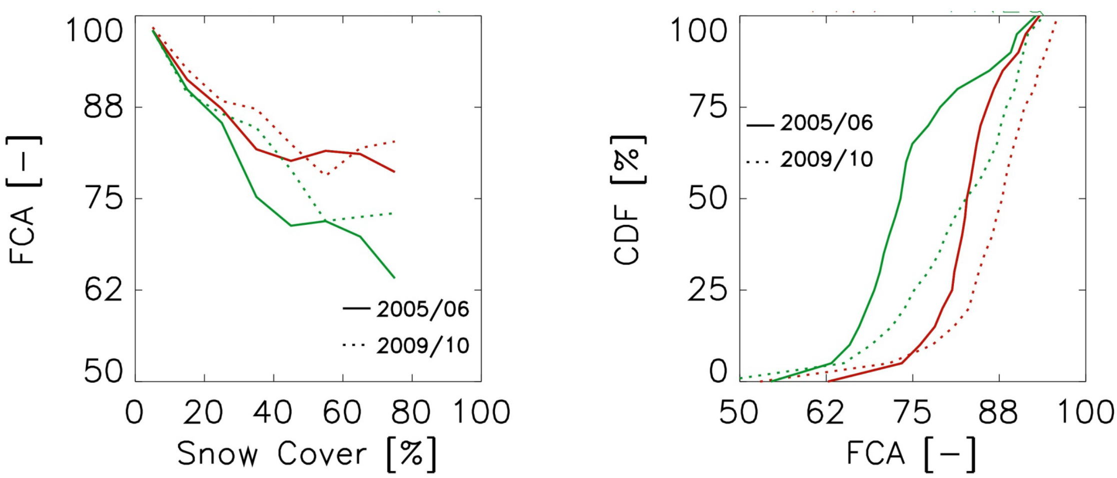

Figure 8: (Left) Fraction of Correct Accuracy function of snow cover and (Right) cumulative distribution function of the Fraction of Correct Accuracy for 2005-2006 and 2009-2010 (1st of July to 30th of June), for HTESSEL (red) and TESSEL (green) offline simulations.

4.1.4 Surface albedo verification

Surface albedo provides an integrated verification of both snow cover fraction and snow albedo. The mean annual cycle of surface albedo (2000-2010) from MODIS is compared with ERA-Interim and ERA-Interim/Land offline simulations in Figure 9 for all land masses poleward 40°N excluding Greenland. The impact of using the GPCP v2.1 precipitation correction is less beneficial in these regions, consistently to what was found for snow, and the main impact is attributed to the HTESSEL changes. From July to December both ERA-Interim and ERA-Interim/Land overestimate surface albedo. On the other hand, the late winter and spring underestimation of surface albedo in ERA-Interim is significantly improved in ERA-Interim/Land. The mean spring surface albedo maps from MODIS and simulations differences are represented in Figure 10. The strongest underestimation of spring surface albedo in ERA-Interim is mainly localized over snow-covered regions poleward of 60° N, which is reduced in ERA-Interim/Land. These results are consistent with previous offline simulations (Dutra et al. 2010), and atmosphere coupled simulations (Dutra et al. 2012). In the previous studies, offline and coupled atmosphere simulations with the climate model EC-EARTH (Hazeleger et al. 2010), using the old snow scheme and the new snow scheme identified similar biases. This highlights the role of the land surface physics and parameterizations in driving changes in surface albedo, independently of the driving atmospheric conditions, and further confirms the importance and validity of the offline methodology. Interestingly, Dutra et al. (2012,), found an overestimation of surface albedo over the Himalayan range and Rockies, that was associated with an overestimation of snow cover. At the time, this bias was partly associated with an overestimation of winter precipitation in those regions by the coupled model, but it could also be a problem of snow cover and surface albedo. In the results shown here, there is no strong evidence of significant biases over the Himalayan range or Rockies, showing that the model physics and parameterizations perform reasonably well in those regions when driven by unbiased precipitation fields.

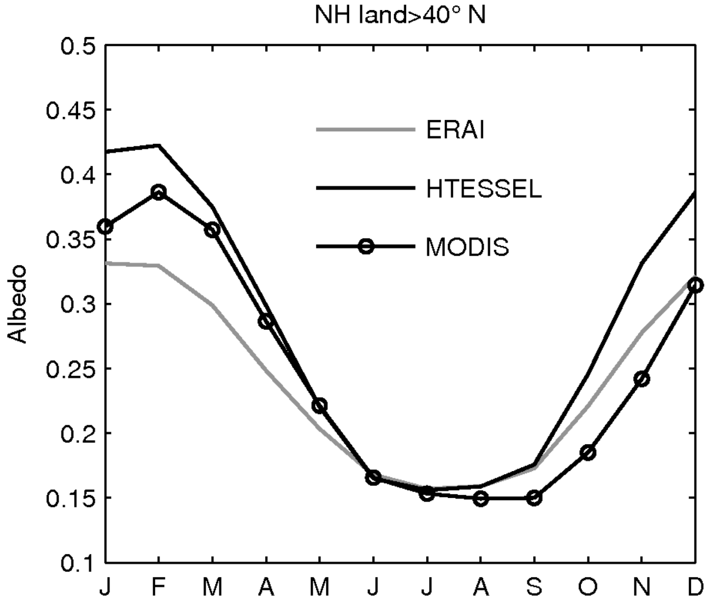

Figure 9: Mean annual cycle of surface albedo (2000-2010) in ERA-Interim (gray) and ERA-Interim/Land (HTESSEL forced by ERA-Interim+GPCP, solid black), and observed from MODIS (open circles) averaged over land masses poleward 40°N excluding Greenland. The spatial averages of the simulations included only grid points where MODIS data was available.

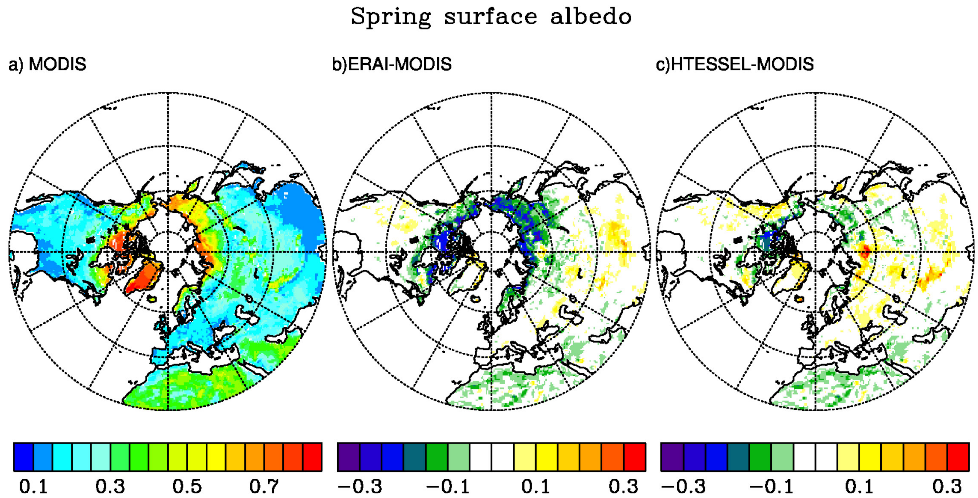

Figure 10: Mean observed albedo during spring derived from (a) MODIS and simulated differences of (b) ERA-Interim and (c) ERA-Interim/Land.

4.1.5 River discharge verification

The river discharges provide an integrated evaluation of the water cycle. The ERA-Interim/Land discharges are compared to the ones obtained from ERA-Interim. In Figure 11 the cumulative distribution function of the correlations between simulated and observed monthly river discharge is plotted for ERA-Interim in red and ERA-Interim/Land in blue. When the blue line lies above the red solid line then the offline runs are in general better. This can be verified for most continents, indicating that the offline runs perform on average better than the ERA-Interim in terms of runoff.

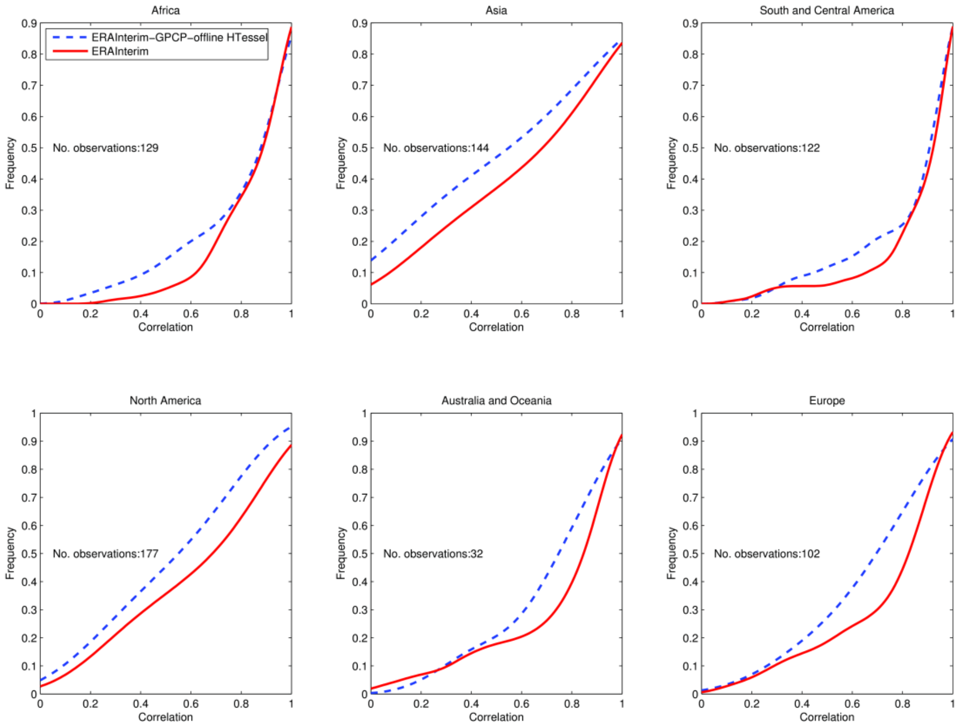

Figure 11: Cumulative distribution function of river discharge correlations of ERA-Interim (red) and ERA-Interim/Land (blue dashed line) with GRDC data by continents.

4.1.6 Forecast verification

The impact of the initial conditions (IC) is also evaluated in a 1-year set of re-forecasts (36 FC T255L91, between 1/1/1989-27/12/1989, 10-day spaced) with the new ICs (fg8o) and with ERA-Interim ICs (fg8l) showing a slight improvement in low level (1000 hPa) geopotential height, temperature and relative humidity, more evident for longer lead times (Figure 12).

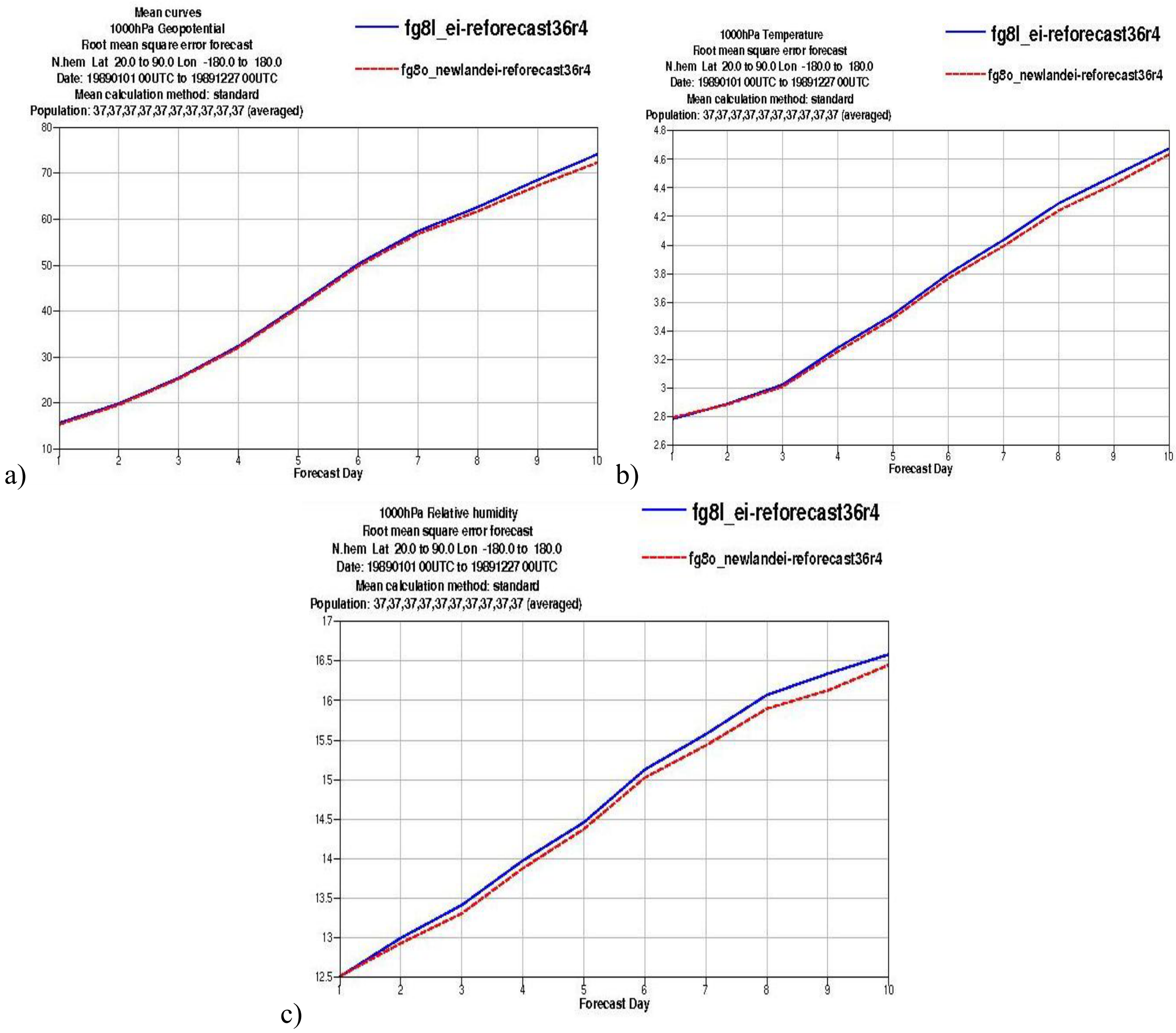

Figure 12: Impact of using the new ERA-Interim/Land initial conditions (red) comparing to ERA-Interim in a set of 10-day forecasts covering 1^{st} of January 1989 to 27^{th} of December 1989 (10-daily spaced). Shown is the RMSE at 1000hPa for a) geopotential height, b) temperature and c) relative humidity

The improvement brought by the usage of the ERA-Interim/Land initial conditions is also assessed in IFS model climate runs for the IFS CY36R4 used in the seasonal forecasting system 4 (Molteni et al. 2010). This is available for comparison on the ECMWF web-site at: http://www.ecmwf.int/products/forecasts/d/inspect/catalog/research/physics_clim/

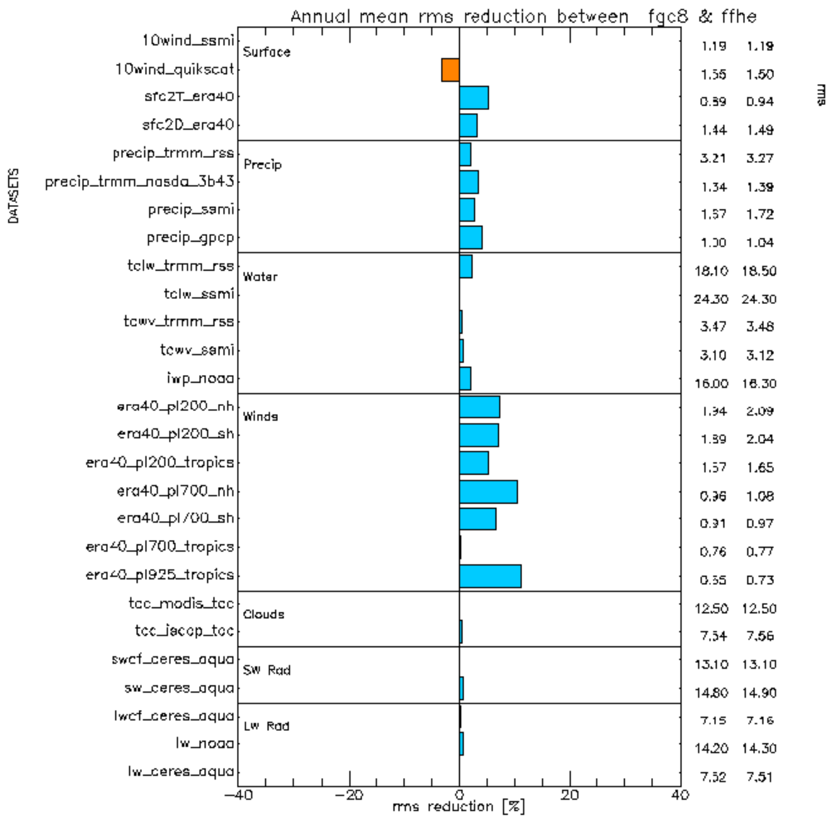

Figure 13: Quantitative evaluation of the IFS model climate (AMIP-run) when initialized with the new land surface conditions as opposed to ERA-Interim (% improvement). The verifying datasets are listed here: http://www.ecmwf.int/products/forecasts/d/inspect/catalog/research/physics_clim/

In Figure 13 the summary of improvements (expressed in % error reduction) indicates neutral to positive effects in all verifying dataset, with the exception of ocean winds.

The fact that the initial condition has long-lived effects is not surprising, given that root-zone soil moisture has shown long memory in HTESSEL (Weisheimer et al. 2010). The soil memory feature is common to other land surface models participating in the GLACE2 initiatives as analysed by Seneviratne and Koster (2012).

4.1.7 Impact on monthly forecasts

Monthly ensemble forecasts (32-day ahead) are produced at ECMWF twice a week. These forecasts are calibrated using a series of re-forecasts that consist of a series of 5-member 32-day ensemble integrations starting the same day and same month as the real-time forecasts but over the past 18 years. It is important for the re-forecasts to be as consistent as possible to the real-time forecasts in order to avoid spurious anomalies The use of ERA-Interim/Land based on the HTESSEL scheme in the EPS re-forecasts in Cycle 38r1 eliminate some of the spurious anomalies linked to these inconsistencies (Figure 14).

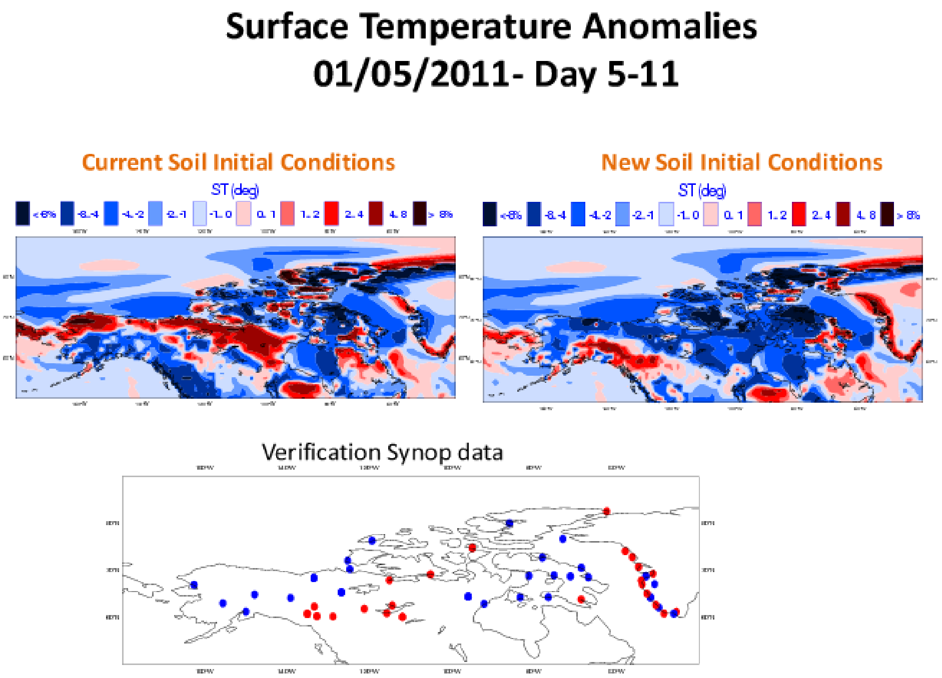

Figure 14: The top left panel shows the day 5-11 forecast of surface temperature anomalies starting on 1st May 2011 and calibrated by the re-forecasts using the ERA Interim soil analysis as initial condition. The top right panel shows the same forecast but this time it has been calibrated using the re-forecasts with the new soil re-analysis. The real-time forecasts use the operational soil analysis. The bottom panel shows surface temperature anomalies computed from synop data for the same period as the forecasts displayed above. The blue (red) colour indicates negative (positive) anomalies.

5 Summary and perspectives

This study documents the configuration and the performance of a land surface reanalysis produced from the ERA-Interim meteorological forcing and based on offline land-surface model simulations. These runs are an integral part of the ERA-Interim on-going research efforts and respond to the need to re-actualize the land surface initial conditions of ERA-Interim. The newly produced land-surface estimates benefit from the latest land surface model improvements used operationally at ECMWF for weather, monthly, and seasonal forecasts. They encompass several land model upgrades, as well as a bias correction of the ERA-Interim monthly accumulated precipitation based on GPCP v.2.1. The precipitation correction is shown to be effective in reducing the bias over US and rather neutral over Europe.

The new land surface reanalysis, named “ERA-Interim/Land” has been verified against several datasets for the main water reservoirs, snow and soil moisture, that have direct atmospheric impact, together with the energy and water fluxes. The verification makes use of both in-situ observations and remote sensing products. Improved match to observations largely attributed to the land surface revisions in the HTESSEL scheme, is found in the latent and sensible heat fluxes and in soil moisture and snow.

The overall water balance is verified with the observed river discharge from the GRDC river network showing an enhanced correlation to the observations with respect to ERA-Interim as combined effect of the GPCP precipitation correction and the land surface improvements. The MODIS land surface albedo is used to show improvements in the snow and forest representation.

Finally, the impact of adopting ERA-Interim/Land as initial condition in retrospective forecasts has also been verified with a generally positive effect of the new land initial condition, more evident in longer lead times of the forecasts.

Future perspectives of the offline simulations include combining this methodology with advanced land data assimilation methods such as the Extended Kalman Filter (de Rosnay et al. 2012). This is expected to provide a fast land surface reanalysis as envisaged within the EU-funded ERA-CLIM project. More sophisticated rescaling methods (e.g. Weedon et al. 2011) are envisaged to bias correct the meteorological forcing.

From a model development point of view, in the near future the inclusion of land carbon exchanges (Boussetta et al. 2012) will be envisaged and applications of the offline run will be explored for a global water bodies reanalysis (e.g. Balsamo et al. 2012) and for global flood risk assessment (e.g. Pappenberger et al. 2012).

The ERA-Interim/Land dataset is used operationally at ECMWF for the initialization of the past reforecasts needed for the monthly forecasting and seasonal prediction systems.

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We would like to thank several colleagues at ECMWF for their valuable comments. GPCP data were kindly provided by the Laboratory for Atmospheres, NASA Goddard Space Flight Center (http://precip.gsfc.nasa.gov/). Manuel Fuentes made the data available on the ERA-Interim server.

FLUXNET community is greatly acknowledged for providing the LaThuile Open-Access synthesis dataset available via the web-site (http://www.fluxdata.org). We would also thank The Fluxnet-Canada Research Network for making available the BERMS data (http://berms.ccrp.ec.gc.ca/Overview/e-overview-about.htm), as well as the PIs and researcher involved in the CEOP project for provision and archiving the data used in this study (http://www.ceop.net/).

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Appendix

The ERA-Interim/Land dataset covers 1979-2010 for the HTESSEL simulations forced with GPCP-corrected precipitation. This cannot be extended into real-time due to the GPCP (v2.1) data being discontinued. The data from the new ERA-Interim/Land is available from the ERA-Interim archive through MARS (CLASS=ei, EXPVER=2). The field provided in the new ERA-Interim/Land are listed in Table 5.

Table 5: Surface fields in the New ERA-Interim/Land dataset archived in MARS with relative names and GRIB code.

Code	Name	short	Unit	Table	MARS
32	Snow albedo	ASN	(0 - 1)	128	Yes
33	Snow density	RSN	kg m^{-3}	128	Yes
39	Volumetric soil water layer 1	SWVL1	m^3 m^{-3}	128	Yes
40	Volumetric soil water layer 2	SWVL2	m^3 m^{-3}	128	Yes
41	Volumetric soil water layer 3	SWVL3	m^3 m^{-3}	128	Yes
42	Volumetric soil water layer 4	SWVL4	m^3 m^{-3}	128	Yes
139	Soil temperature level 1	STL1	K	128	Yes
141	Snow depth	SD	m	128	Yes
170	Soil temperature level 2	STL2	K	128	Yes
183	Soil temperature level 3	STL3	K	128	Yes
236	Soil temperature level 4	STL4	K	128	Yes
238	Temperature of snow layer	TSN	K	128	Yes

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