ERA-Interim/Land: A global land surface reanalysis dataset

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Abstract

ERA-Interim/Land is a global land-surface reanalysis dataset covering the period 1979–2010. It describes the evolution of soil moisture, soil temperature and snowpack. ERA-Interim/Land is the result of a single 32-year simulation with the latest ECMWF land surface model driven by meteorological forcing from the ERA-Interim atmospheric reanalysis and precipitation adjustments based on GPCP v2.1 (Global Precipitation Climatology Project) with a horizontal resolution of about 80km and 3-hourly frequency. ERA-Interim/Land includes a number of parameterization improvements in the land surface scheme with respect to the original ERA-Interim dataset, which makes it more suitable for climate studies involving land water resources. The quality of ERA-Interim/Land is assessed by comparing with ground-based and remote sensing observations. In particular, estimates of soil moisture, snow depth, surface albedo, turbulent latent and sensible fluxes, and river discharges are verified against a large number of site measurements. ERA-Interim/Land provides a global integrated and coherent estimate of soil moisture and snow water equivalent, which can also be used for the initialization of numerical weather prediction and climate models.

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. 2006, 2009, 2011). The land-surface state estimates used in those studies were 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 (e.g. Oki and Kanae 2006). A state-of-the-art land-surface reanalysis 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 conditions to weather and seasonal forecast models.

In recent years several improved global atmospheric reanalyses of the satellite 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) and NASA's Modern Era Retrospective-analysis for Research and Applications (MERRA, Rienecker et al. 2011). Simmons et al. (2010) have demonstrated the quality 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 daily to annual over the conterminous US. They proposed a scale-selective rescaling method to address remaining biases based on the Global Precipitation Climatology Project monthly precipitation data (GPCP, Huffman et al. 2009). This bias correction method addresses issues related to systematic model errors and non-conservation typical of data assimilation systems (Berrisford et al. 2011). Szczypta et al. (2011) have evaluated the incoming solar radiation provided by the ERA-Interim reanalysis with ground-based measurements over France. 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 only 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. Albergel et al. (2013) have already shown the value of an ERA-Interim/Land variant (with no precipitation readjustment) together with other model-based and remote-sensing datasets for the detection of soil moisture climate trends in the past 30 years.

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) used in ERA-Interim, which was based on the 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. 2013a), and a revised bare-soil evaporation (Balsamo et al. 2011, Albergel et al. 2012a). The majority of improvements in ERA-Interim/Land in the Northern hemisphere can be attributed to land parameterization revisions, while the precipitation correction is important in the Tropics and the Southern hemisphere.

The purpose of this paper is to document ERA-Interim/Land and its added value from ECMWF's perspective. This will be done by providing some limited verification and diagnostics comparing ERA-Interim/Land and ERA-Interim with the purpose of explaining what is the origin of the differences. A very basic question is: how can offline assimilation have added value because in its current form it does not include data assimilation of soil moisture and snow? Alternatively one could ask: would it have been beneficial to have no soil moisture and snow assimilation in ERA-Interim? The answer is non-trivial, but it is known that in a coupled system, data assimilation for soil moisture is a necessity; otherwise precipitation can "run away" through a positive precipitation/evaporation feedback at the continental scale (Viterbo and Betts 1999, Beljaars et al. 1996). The soil moisture increments keep precipitation under control and tend to be beneficial for fluxes, but not always for soil moisture (Drusch and Viterbo 2007). An offline land simulation produced after the coupled reanalysis has the advantage that there is no positive feedback because precipitation is prescribed and the surface water budget is closed as there are no soil moisture increments. The problems with snow reanalysis are mainly related to observations; snow gauges can have large biases, and the simple analysis scheme used in ERA-Interim occasionally results in negative impact of observations.

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. The 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 systems make use of the ERA-Interim/Land scheme. A summary and recommendations for the usage of the ERA-Interim/Land product are reported in the conclusions.

2 Dataset and methods

The experimental set-up makes use of offline (or stand-alone) land simulations, which represents a convenient framework for isolating benefits and deficiencies of different land surface parameterizations (Polcher et al. 1998). In addition, given the complexity of the coupling with the atmosphere, offline simulations are much more cost-effective (faster) to run than a coupled atmosphere / 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 United States Geophysical Survey - Global Land Cover Classification (USGS-GLCC) and the United Nations - Food and Agriculture Organization (UN-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).

2.1 Validation and supporting datasets

The quality of ERA-Interim/Land relies on: (i) the accuracy of the ERA-Interim forcing, (ii) bias correction of precipitation with the GPCP v2.1 data, and (iii) the realism of the land surface model. Its accuracy can be documented by verification with independent data e.g. surface fluxes, runoff, and soil temperature / moisture. In the following, the datasets entering the ERA-Interim/Land generation and its verification are briefly presented.

2.1.1 ERA-Interim meteorological reanalysis

ERA-Interim (Dee et al. 2011) is produced at T255 spectral resolution (about 80 km) and covers the period from January 1979 to present, with product updates approximately 1 month delay from real-time. The ERA-Interim atmospheric reanalysis is built upon a consistent assimilation of an extensive set of observations (typically tens of millions daily) distributed worldwide (from satellite remote sensing, in-situ, radio-sounding, profilers, etc.). The analysis step combines the observations with a prior estimate of the atmospheric state produced with a global forecast model in a statistically optimal manner. In ERA-Interim two analyses per day are performed at 00 and 12 UTC, which serve as initial conditions for the subsequent forecasts. As a result of the data assimilation, the short-range forecasts (first-guess fields) stay close to the real atmosphere and the 12-hourly adjustments due to observations remain small. This justifies the use of a concatenation of short-range forecasts for forcing the offline land-surface reanalysis. The forecasts have the advantage of being available every 3 hours and they also provide estimates of precipitation and radiation. Experience with ERA-Interim has shown that the estimates of wind, temperature and moisture (at the lowest model level), which are well-constrained by observations, are generally of high quality in the 0 to 12 hour forecast range and show only very small jumps from one 12-hour cycle to the next (see Simmons et al. 2010 for a comparison of reanalysis temperature estimates with observations). Estimates of precipitation and radiation, however, although indirectly constrained by temperature and humidity observations, are generated by the forecast model and are therefore subject to a small but systematic spin-up during the first few hours of the forecasts (Kållberg 2011).

Therefore the 9-21 hour forecast range is used for the fluxes co-located in time with the other fields as illustrated in Figure 1.

2.1.2 GPCP v2.1 precipitation

The monthly GPCP dataset merges satellite and rain gauge data from a number of satellite sources including the Global Precipitation Index, the Outgoing long-wave radiation 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. Adler et al. (2003) detail the datasets and methods used to merge these data.

Compared to earlier releases, version 2.1 of 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 the result of 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).

The motivation for re-scaling ERA-Interim precipitation estimates using GPCP data is to combine the best aspects of both data sets. ERA-Interim precipitation shows excellent synoptic variability but can be biased. Bias adjustments based on GPCP add the constraint of observations on a monthly time scale e.g. through the calibration of GPCP with SYNOP gauges. Balsamo et al. (2010a) evaluate ERA-Interim precipitation before and after rescaling with independent high-resolution data over the USA. They conclude that in the extra-tropics, ERA-Interim is already close to GPCP in terms of performance, but that the monthly bias correction with GPCP gives a improvement. Much less is known about the tropics and areas with snow. Errors in ERA-Interim precipitation are much larger in the tropics than in the extra-tropics and benefit from bias correction with GPCP is expected to be substantial. Runoff verification results shown below provide indirect evidence for this conclusion. For snowfall, Brun et al. (2013) conclude, on the basis of snow accumulation verification, that the quality of ERA-Interim is excellent and exceeds those based on gauge observations, which tend to suffer from substantial under-catch. The impact of GPCP bias correction on snowfall is fairly small.

2.1.3 FLUXNET land energy fluxes

FLUXNET is a global surface energy, water, and CO_2 FLUX observation NETwork and consists of a collection of regional networks (Baldocchi et al. 2001, http://fluxnet.ornl.gov). Additionally, observational data for the year 2006 from the Boreal Ecosystem Research and Monitoring Sites (BERMS, Betts et al. 2006), and the Coordinated Energy and water cycle Observations Project (CEOP) were used in this study.

The FLUXNET observations 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 original observational archive (excluding gap filled values) with a high quality flag only (see Table 1).

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 a woody savannah region (Brasilia).

2.1.4 ISMN soil moisture observing network

In-situ soil moisture observations are extremely useful for the evaluation of modelled soil moisture. In recent years, huge efforts were made to collect observations representing contrasting biomes and climate conditions. Some of them are now freely available such as data from The International Soil Moisture Network (ISMN, Dorigo et al. 2011, 2013, http://ismn.geo.tuwien.ac.at/). 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 nearly 1000 stations (with data from 2007 up to present) 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. Data from 6 networks are considered for 2010: NRCS-SCAN (Natural Resources Conservation Service - Soil Climate Analysis Network) and SNOTEL (short for SNOwpack TELemetry) over the United States, with 177 and 348 stations, respectively; SMOSMANIA (Soil Moisture Observing System-Meteorological Automatic Network Integrated Application) with 12 stations in France; REMEDHUS (REd de MEDición de la HUmedad del Suelo) in Spain with 20 stations, the Australian hydrological observing network labelled OZNET with 38 stations; and AMMA (African Monsoon Multidisciplinary Analyses) in western Africa with 3 stations. Data at 5 cm and the year 2010 is used for the comparison because it is the depth and the year for which most of the stations have observations (Table 2 includes references for different networks).

2.1.5 The GTS-SYNOP observing network

The GTS-SYNOP (Global Telecommunications System - surface SYNOPtic observation) is an operationally maintained datasets under coordination of the World Meteorological Organization (WMO), which provides daily ground-based 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 measurements in contrast to remote sensing observations, which have limited information on snow depth. These data are operationally used at ECMWF for the daily global snow analysis as described in Drusch et al. (2004) and de Rosnay et al. (2013a).

2.1.6 Satellite surface albedo

The Moderate Resolution Imaging Spectro-radiometer (MODIS) albedo product MCD43C3 provided data describing both directional hemispheric reflectance (black-sky albedo) and bi-hemispherical 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 on a 0.05° global grid. The accuracy and quality of the product has been studied by several authors (e.g. Roman et al. 2009, Salomon et al. 2006). The MODIS product has served as a reference for model validation (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 ERA-Interim/Land. MODIS albedo was averaged for each month and spatially aggregated to the model grid.

2.1.7 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 discharge to evaluate a coupled land surface / river discharge scheme for river flood prediction.

2.2 Land modelling component

ERA-Interim/Land differs from the land component of ERA-Interim in a number of parameterization improvements introduced in the operational ECMWF forecast model since 2006, when the ERA-Interim reanalysis started. The meteorological forcing described in 2.1.1 is used to drive an 11-year spin-up run (1979 to 1989). The average of the 11 "1st of Januaries" is taken as a plausible initial condition for the 1st of January 1979.

A single continuous 32-year simulation starting on the 1st of January 1979 is then realised with the latest ECMWF land surface scheme. The modelling components that were updated with respect to ERA-Interim are briefly described in the following subsections with emphasis on those changes that have impact on ERA-Interim/Land performance.

2.2.1 Soil hydrology

A revised soil hydrology in TESSEL was proposed 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 operationally introduced in IFS in November 2007. Balsamo et al. (2009) verified the impact of the soil hydrological revisions from field site to global atmospheric coupled experiments and in data assimilation.

2.2.2 Snow hydrology

A fully revised snow scheme was introduced in 2009 to replace the existing scheme based on Douville et al. (1995). The snow density formulation was changed and 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 verification from field site experiments to global offline simulations are 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.

2.2.3 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 was implemented in IFS in November 2010. The detailed description of the LAI monthly climatology and its evaluation is provided in Boussetta et al. (2013a).

2.2.4 Bare soil evaporation

In ERA-Interim, the bare ground evaporation is based on the same stress function as for vegetation. The result is that evaporation is not possible for soil moisture contents below the permanent wilting point. This has been improved by adopting a lower stress threshold for bare soil (Balsamo et al. 2011) which is in agreement with previous experimental findings (e.g. Mahfouf and Noilhan 1991) and results in more realistic soil moisture for dry lands. The new bare soil evaporation in conjunction with the LAI update as reported in Balsamo et al. (2011) has been extensively evaluated by Albergel et al. (2012a) over the USA. The evaluation was based on data from the Soil Climate Analysis Network (SCAN) as well as Soil Moisture and Ocean Salinity (SMOS) satellite data.

3 Results

The quality of ERA-Interim/Land builds upon reduced errors in the meteorological forcing and improved land surface modelling. In the following, selected verification results are illustrating the skill of ERA-Interim/Land in reproducing the main land water reservoirs and fluxes towards the atmosphere and river outlets. The two most active water reservoirs are the root-zone soil moisture (here the top 1m of soil is considered) and the snow accumulated on the ground. These global reservoirs in its median of the distribution calculated over the period 1979-2010 are shown in Figure 2 and Figure 3 for ERA-Interim and ERA-Interim/Land respectively. The median of soil moisture (SM) and snow water equivalent (SWE) are both expressed in mm of water or equivalently in kg/m^2. The medians over the 32-year SM and SWE are based on 11 daily values centered around 15 January and 15 July for 32 years, resulting in 352 samples. The median is of particular interest because it indicates “typical” values and one exceptional year with e.g. extreme snow will leave the median invariant. The same argument is valid for mid-July SM in which a single exceptional flood will not affect the median.

Clear differences can be seen between ERA-Interim and ERA-Interim/Land in both January snow amount and July soil moisture (compare Figure 2 and Figure 3). The differences in snow amount are due to: (i) the GPCP bias correction of precipitation forcing, (ii) improved snow melt, density and albedo in the land surface model, and (iii) the lack of data assimilation of snow depth in ERA-Interim/Land. The GPCP correction results in a slightly reduced snowfall, and the changes in the snow model lead predominantly to differences in the marginal snow areas and seasonal differences. The main difference comes from the data assimilation method used in ERA-Interim. It uses a Cressman (1959) scheme for the assimilation of SYNOP observations, which has documented deficiencies in areas with sparse observations, and strong relaxation to climatology before 2003. After 2003, qualitative information from a snow cover product is used instead of climatology (Drusch et al. 2004). Particularly the use of climatology before 2003 and the poor handling of sparse observations with the Cressman scheme, make ERA-Interim/Land (which relies on forcing and the model only) more suitable for studies of inter-annual variability and extremes. From Figure 2a and Figure 3a, it can be seen that snow mass has more variability in ERA-Interim than in ERA-Interim/Land. This is the result of the Cressman analysis of SYNOP data, particularly in areas with low density observations. To illustrate the dynamical range of the distribution and the capability of reanalysis to reproduce anomalies, the 5th and 95th percentile of the 10 kg/m^2 contour is also plotted in Figure 2a and Figure 3a. As expected there is a large distance between the 5th and 95th percentile indicating a lot of inter-annual variability in the snow line.

The summer soil moisture also shows large differences between ERA-Interim and ERA-Interim/Land. As can be seen from Figure 2b and Figure 3b, soil moisture tends to be lower in ERA-Interim/Land. This is mainly the result of the modified soil hydrology properties which increases the effective size of the soil moisture reservoir, permits a larger amplitude of the seasonal cycle, and allows soil moisture to go lower in summer. Data assimilation in ERA-Interim also tends to reduce the seasonal cycle by adding water in summer (Drusch and Viterbo 2007). ERA-Interim/Land shows more spatial variability than ERA-Interim. This is the result of the spatial variability of soil properties, which ERA-Interim does not have, and the reformulation of the bare soil evaporation.

The evolution of ERA-Interim/Land along a 10-year period of this dataset, and its differences with respect to ERA-Interim are illustrated in Figs. 4 and 5 for both soil moisture and snow water equivalent. The stability and the differences with respect to ERA-Interim can be appreciated in Figure 4a and Figure 5a for snow water equivalent and in Figure 4b and Figure 5b for the top 1-m soil moisture. The snow changes in Figure 5a are mainly consequence of the new snow scheme and highlight both a snow mass increase in high latitudes and a slight reduction in mid-latitudes. There is also a phase shift in the seasonal cycle at mid-latitudes with less snow during accumulation and more snow in the melting season. The soil moisture presents large differences in Figure 5b, which can be attributed to the soil hydrology revisions. Figure 5 is meant to illustrate that ERA-Interim and ERA-Interim/Land are significantly different with respect to land water resources. In these runs, observational constraints on the snow and soil water reservoirs such as those applied by the screen-level data assimilation, are totally absent. However, the resulting water reservoirs of snow and soil moisture, and the river discharges, are shown to improve with respect to the original ERA-Interim data, without deteriorating the turbulent fluxes to the atmosphere. In the following sections a selection of results is presented, to demonstrate the added value of ERA-Interim/Land.

3.1 Land flux verification

In the following sub-sections, fluxes from the offline-driven land simulations are validated against two observation categories: the land to atmosphere turbulent heat and moisture fluxes and the river discharges.

3.1.1 Latent and Sensible heat flux

Fluxes from 34 FLUXNET, CEOP and BERMS flux-towers, as listed in Table 1, are used for verification in 2004. Correlation, mean bias and root mean squared errors are computed based on 10-day averages, so the verification is focusing on the seasonal and sub-seasonal time scales. Figure 6 shows the RMS errors of sensible and latent heat flux for the individual flux towers. The RMS errors of sensible heat flux are of the order of 20 W/m^2, which is typical for point verification. The errors of latent heat flux are larger and vary from station to station. Positive and negative differences are seen in Figure 6, and it is difficult to draw firm conclusions on the relative merit of ERA-Interim/Land compared to ERA-Interim. A major issue with point verification is that the station may not be representative of a large area. The vegetation cover around the station may also be different from the vegetation type as specified in the corresponding model grid box. The latter is probably the case for stations that show a-typical large errors.

An overall quantitative estimate of the errors is reported in Table 3. Latent and sensible heat fluxes have RMS errors of 21.8 (±0.9) and 21.3 (±0.9) W/m^2 with ERA-Interim/Land and 26.0 (±1.1) and 19.6 (±0.8) W/m^2 with ERA-Interim. Correlation is fairly high and typically 0.85. It can be concluded that, given the uncertainty estimates, the latent heat fluxes are better with ERA-Interim/Land, but impact in sensible heat flux is not significant.

Prior to production, preliminary experimentation was performed with intermediate versions towards ERA-Interim/Land: (i) offline with the TESSEL model (which indicates the impact of data assimilation in ERA-Interim), and (ii) offline with HTESSEL but no GPCP corrections (which indicates the effect of the model changes). It turns out that the RMS errors of latent flux are 26.0 W/m^2 with ERA-Interim, 30.4 W/m^2 with version (i), 25.1 W/m^2 with version (ii), and 21.8 W/m^2 with ERA-Interim/Land. All these versions are significantly different on the basis of a typical uncertainty of 1 W/m^2. Deleting the data assimilation increases the error from 26.0 to 30.4 W/m^2, changing the model reduces the error from 30.4 to 25.1, and applying GPCP bias correction reduces the error further from 25.1 to 21.8 W/m^2. It is not surprizing that soil moisture data assimilation with SYNOP observations is beneficial, because this type of indirect data assimilation reduces the atmospheric errors by construction through soil moisture increments. So, in ERA-Interim/Land relative to ERA-Interim, the lack of soil moisture data assimilation and the model improvement compensate each other in the flux tower verification. The GPCP bias correction contributes further to the improvement. Similar signals exist for sensible heat flux (not shown), except that for sensible heat flux the GPCP part is not significant.

3.1.2 River discharge

River discharge is used here to provide an integrated quantity of the continental water cycle for verifying improvements in the representation of land hydrology. For each discharge station, ERA-Interim and ERA-Interim/Land runoff are averaged over the corresponding catchment area and correlated with the observed monthly values covering the entire reanalysis period. Then a PDF of the correlation coefficients is created by clustering over large areas. Figure 7 shows the cumulative distribution function of the correlations from ERA-Interim/Land (blue line) and ERA-Interim (red line). A general improvement is seen in ERA-Interim/Land as the correlations are higher at all levels in nearly all cases (the blue line is nearly always to the right of the red line indicating a higher frequency of high correlation).

The improvements in runoff are large for two reasons: (i) the revised hydrology, i.e. soil infiltration, soil properties and runoff formulation, and (ii) the GPCP bias correction in the Tropics and the Southern hemisphere. Both effects can be seen in Figure 7. The improvements over Asia, North America and Europe are mainly the result of the model changes, whereas the impact over Africa, South & Central America and Australia are much larger as the result of the additional effect of GPCP bias correction.

Although there is still some way to go in effectively representing river discharge in large-scale land surface schemes, coupling such schemes to state-of-the-art river hydrology models can bring further improvement (Pappenberger et al. 2012). In the current evaluation it is particularly encouraging that the average improvement of river discharge correlations of ERA-Interim/Land over ERA-Interim occurs on all continents, which encompass different rivers and different water balance regimes.

3.2 Land water reservoir verification

The water reservoir verification aims at assessing the daily performance of ERA-Interim/Land in soil water content and the snow water equivalent, which are responding to the diurnal, synoptic and seasonal variations of fluxes. The deeper and slowly evolving soil moisture layers, such as the water table, are not considered in the present verification since they are not yet properly represented in the ECMWF model.

3.2.1 Soil moisture

The changes in 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 over the ERA-Interim period. However the spatial variability has greatly increased with the introduction of the revised soil hydrology (Balsamo et al. 2009). 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. (2012b) to validate soil moisture from both ECMWF operational analysis and ERA-Interim.

Considering the field sites of the NRCS-SCAN network (covering the US) with a fraction of bare ground greater than 0.2 (according to the model), the root mean square error (RMSE) of soil moisture decreases from 0.118 m^3/m^3 with ERA-Interim to 0.087 m^3/m^3 with ERA-Interim/Land, mainly due to the new formulation of bare soil evaporation. In the TESSEL formulation of ERA-Interim, 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 at bare soil locations, e.g. at the Utah and Washington sites from May to September 2009 shown in Figure 8. The new soil hydrology and bare ground evaporation allows the model to go below the wilting point which is in much better agreement with the observations than in ERA-Interim.

The improved capability of ERA-Interim/Land to simulate soil moisture in bare soil areas is also clear from Figure 9. It illustrates the gain in skill in reproducing the observed soil moisture in dry land as a function of vegetation cover. With the RMSE being positive definite and calculated against in-situ soil moisture observations, the RMSE differences between ERA-Interim and ERA-Interim/Land indicate improvements realized by the latter. The RMSE difference is calculated for locations with varying vegetation fraction and the improvement is shown to be larger on points with sizeable bare soil. This is a demonstration that the enhanced match to the observed soil moisture is indeed the result of the bare soil evaporation revision as detailed in Albergel et al. (2012a).

The correlation of ERA-Interim/Land soil moisture with the various observed soil moisture networks varies depending on the network (Figure 10 and Table 2). In general the correlations are similar to those with ERA-Interim and not significantly improved. However, the variability is increased as can be seen in the Taylor diagram of Figure 11. The distance to the point marked “In situ” has been reduced with ERA-Interim/Land, because the standard deviation of observations is better reproduced.

The site verification of soil moisture presented in this section, has also been applied to an offline experiment where the only difference is that ERA-Interim forcing is not corrected with GPCP. It turns out that the results are indistinguishable. It can be concluded that GPCP bias correction has no impact on soil moisture in the extra-tropics, in spite of the small beneficial impact on precipitation as was seen by Balsamo et al. (2010a) over the USA.

Interestingly, Albergel et al. (2013) verified an ERA-Interim/Land variant (with no precipitation readjustment) and MERRA-Land for the full 1988 to 2010 with all available in situ soil moisture observations. They find average correlations for superficial soil moisture (95% confidence interval) of 0.66 (±0.038) for ERA-Interim/Land, and 0.69 (±0.038) for MERRA-Land. Root zone soil moisture correlations of 0.68 (±0.035) are found for ERA-Interim/Land and 0.73 (±0.032) for MERRA-Land. It is impossible to speculate on the origin of the differences between these two reanalyses, because they are different on many aspects.

3.2.2 Snow

Dutra et al. (2010) attributed the largest improvement in the new snow scheme to the snow density representation. This could be confirmed with station data from the former USSR. At a large number of sites, snow density was measured in the snow season at typical Northern latitudes from October to June from 1979 to 1993 (Brun et al. 2013). In ERA-Interim, as well as ERA-Interim/Land, snow density is not constrained by data assimilation due to a lack of observations that are exchanged routinely 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. Figure 12 clearly shows that the seasonal evolution of snow density of ERA-Interim/Land is much more realistic than in ERA-Interim, mainly because the density formulation in ERA-Interim relaxes too quickly to the 300 kg/m^3 value. This is obviously also important for data assimilation of any snow depth observations, because snow depth has to be converted to snow mass making an assumption about snow density.

Verification of snow mass is difficult, because at best snow depth is measured without information on density. Here routine SYNOP observations are used although the network is fairly sparse. Figure 13 shows the seasonal cycle of the RMS error of snow depth from ERA-Interim and ERA-Interim/Land over Europe (more than 600 observations daily). It is remarkable that ERA-Interim/Land has smaller RMS errors than ERA-Interim, because the latter assimilates the same SYNOP observations and ERA-Interim/Land does not. The explanation is that the background field in ERA-Interim is so much worse than in ERA-Interim/Land that the analysis increments do not fully compensate for the poor background field. It is also remarkable that a good quality land snow mass analysis can be obtained without any constraint from direct snow mass observations. A good quality snowfall is obviously key to such a success.

Finally, the MODIS land surface albedo is used to verify ERA-Interim/Land, particularly in the snow representation in forest areas (Figure 14) in Northern Canada and Siberia, where conventional SYNOP observations are generally less informative. Figure 14c points to a substantially reduced albedo bias in ERA-Interim/Land attributed to the snow scheme revision described in Dutra et al. (2010) and in particular the snow-vegetation albedo retuning. The main improvement comes from the albedo optimization for vegetated areas. Particularly forests tend to keep a low albedo with snow accumulating under the canopy rather than on it, but in ERA-Interim, most forests remained too dark, not accounting for the openness of many forests. As albedo is an important component of the surface energy balance, it significantly affects the atmospheric heating and the timing of snow melt in spring.

4 Discussion

Dedicated land surface reanalyses, such as ERA-Interim/Land described and evaluated here, are becoming established added-value products within the reanalysis efforts worldwide (Dee et al. 2014). They allow computationally efficient testing of new land surface developments, including improvements to the process representation and parameterization of the hydrological and biogeochemical cycles that contribute to a fast-track land surface model developments as identified by van den Hurk et al. (2012). Future research into improved representation of the land surface is high priority, and work already underway in this area includes land carbon exchanges (Boussetta et al. 2013b), vegetation inter-annual variability, and hydrological applications such as global water-bodies reanalysis (e.g. Balsamo et al. 2012) and global flood risk assessment (e.g. Pappenberger et al. 2012). More sophisticated rescaling methods (e.g. Weedon et al. 2011, 2014) are envisaged to bias correct the meteorological forcing and to permit a high resolution downscaling of land reanalysis. In addition, consideration of land surface parameterization uncertainty could be used to further improve predictive skill (e.g. Cloke et al. 2011).

Important developments with advanced land data assimilation methods such as the Extended or Ensemble Kalman Filters (Reichle et al. 2014, de Rosnay et al. 2013b, Drusch et al. 2009) can be combined with offline surface simulations. The experimental equivalence of offline and atmospheric coupled land data assimilation (Balsamo et al. 2007, Mahfouf et al. 2008) offers also in this case a two orders of magnitude computational saving. This is expected to provide a fast land surface reanalysis as envisaged within the EU-funded ERA-CLIM2 project. Moreover it can open up new possibilities of more advanced data assimilation schemes (e.g. Fowler and van Leeuwen 2012), especially designed for non-linear systems.

5 Conclusions

This paper documents the configuration and the performance of the ERA-Interim/Land reanalysis in reconstructing the land surface state over the past 3 decades. ERA-Interim/Land is produced with an improved land surface scheme in offline simulations forced by ERA-Interim meteorological forcing. It has been demonstrated that the ERA-Interim/Land dedicated land surface reanalysis has added value over the standard land component of the ERA-Interim reanalysis product. The ERA-Interim/Land runs are an integral part of the ERA-Interim on-going research efforts and respond to the wish to re-actualize the land surface initial conditions of ERA-Interim, following several model parameterization improvements. The newly produced land-surface estimates benefit from the latest land surface hydrology schemes used operationally at ECMWF for the medium-range, monthly, and seasonal forecasts. The ERA-Interim/Land added value components encompass soil, snow and vegetation description upgrades, as well as a bias correction of the ERA-Interim monthly-accumulated precipitation based on GPCP v.2.1. In the Northern hemisphere, the precipitation correction is shown to be effective in reducing the bias over US, it is rather neutral over Eurasia, while over tropical land clear benefits are seen in the river discharge.

The new land surface reanalysis has been verified against several datasets for the main water reservoirs (snow and soil moisture), together with the energy and water fluxes that have direct impact on the atmosphere. The verification makes use of both in-situ observations and remote sensing products. A modest improvement has been seen in the latent heat fluxes, which turns out to be the result of a combination of deterioration due to the lack of soil moisture data assimilation, a substantial improvement due to model changes, and a small improvement due to GPCP precipitation bias correction. It is encouraging to see that the modelled runoff has been improved when compared to observed river discharge from the GRDC river network showing an enhanced correlation to the observations. The improvement compared to ERA-Interim is the combined effect of the GPCP precipitation correction and the land surface model improvements.

Variability of soil moisture is improved due to the hydrology improvements and the introduction of a soil texture map. Also bare soil areas indicate a distinct improvement related to the handling of the low soil moisture regime. Both snow depth and snow albedo are shown to have a better seasonal cycle, mainly due to the new model formulations. The model improvement appears to overwhelm the lack of data assimilation.

While river discharge verification is not enough for a global water balance assessment, the results from the verification of evaporation fluxes (the other main outgoing land water flux) and of the two main water reservoirs (soil moisture and snow-pack), permit to qualify the ERA-Interim/Land enhanced accuracy as genuine. When water fluxes and water storages terms show consistent indication of improvements there are in fact good grounds to believe that the parameterization changes are physically meaningful and not the result of compensating errors.

Finally, it is worth noting that offline land reanalysis plays an important role in the model development cycle of the operational system at ECMWF. The forecasting system uses back-integrations covering the last 30 years with ERA-Interim as initial condition to obtain a model climate as reference for anomalies. As soon as the land surface model is changed substantially, it turns out to be important to have a consistent initial condition, and the latter is obtained by offline reanalysis. It has been demonstrated that this procedure has a positive effect on the back-integrations particularly for the longer lead times (Balsamo et al. 2012, Vitart et al. 2008, Molteni et al. 2011).

Ongoing work focuses on inter-annual variability of vegetation state (Leaf-Area-Index), efforts to extend the current ERA-Interim/Land dataset beyond 2010, and future ECMWF reanalyses (Dee et al. 2014).

6 Dataset access

The ERA-Interim/Land dataset is freely available and can be downloaded from:

http://apps.ecmwf.int/datasets/

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Tables

Table 1: List of flux tower sites used for the verification. The listed 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	Lon	Veg Type	N	Site	Lat	Lon	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

Table 2: Comparison of surface soil moisture with in situ observations for ERA-Interim/Land (italic, bold) and ERA-Interim (normal font) in 2010: Mean correlation (R), Bias (observation minus ERA), Root Mean Square Error (RMSE), and Normalized Standard Deviation ($NSDV=SDV_{model}/SDV_{obs}$). Scores are given for significant correlations with p-values <0.05. For each R estimate a 95% Confidence Interval (CI) was calculated using a Fisher Z-transform.

Network (N stations with significant R)	R (95%CI)	Bias (m^3/m^3)	RMSE (m^3/m^3)	NSDV= ($\sigma_{model}/\sigma_{obs}$)
AMMA, W. Africa (3)	***0.63(±0.06)***	***-0.060***	***0.082***	***2.67***
Pellarin et al., 2009	0.61(±0.07)	-0.153	0.154	0.69
OZNET, Australia (36)	***0.79(±0.05)***	***-0.112***	***0.131***	***1.01***
Smith et al., 2012	0.78(±0.05)	-0.078	0.106	0.55
SMOSMANIA, France (12)	***0.83(±0.04)***	***-0.080***	***0.108***	***0.83***
Albergel et al., 2008	0.82(±0.05)	-0.037	0.099	0.41
REMEDHUS, Spain (17)	***0.76(±0.04)***	***-0.152***	***0.175***	***1.57***
Ceballos et al., 2005	0.79(±0.04)	-0.110	0.135	0.84
SCAN, USA (119)	***0.64(±0.07)***	***-0.078***	***0.130***	***0.95***
Schaefer and Paetzold, 2010	0.62(±0.07)	-0.063	0.110	0.54
SNOTEL, USA (193)	***0.62(±0.10)***	***-0.045***	***0.115***	***0.78***
Schaefer and Paetzold, 2000	0.69(±0.08)	-0.088	0.123	0.44

Table 3: Summary of mean latent heat flux (LE) and sensible heat flux (H) statistics averaged over the 34 sites (units: W/m^2). The Confidence Interval (CI) of RMSE is based on the Chi-squared distribution. Mean correlation R of model fluxes to observations include a 95% CI calculated using a Fisher Z-transform.

Model	LE RMSE	LE Bias	LE R	H RMSE	H Bias	H R
ERA-Interim/Land	21.8 (±0.9)	14.4	0.85 (±0.02)	21.3 (±0.9)	-2.6	0.83 (±0.02)
ERA-Interim	26.0 (±1.0)	18.2	0.83 (±0.02)	19.6 (±0.8)	-3.8	0.85 (±0.02)

Figures

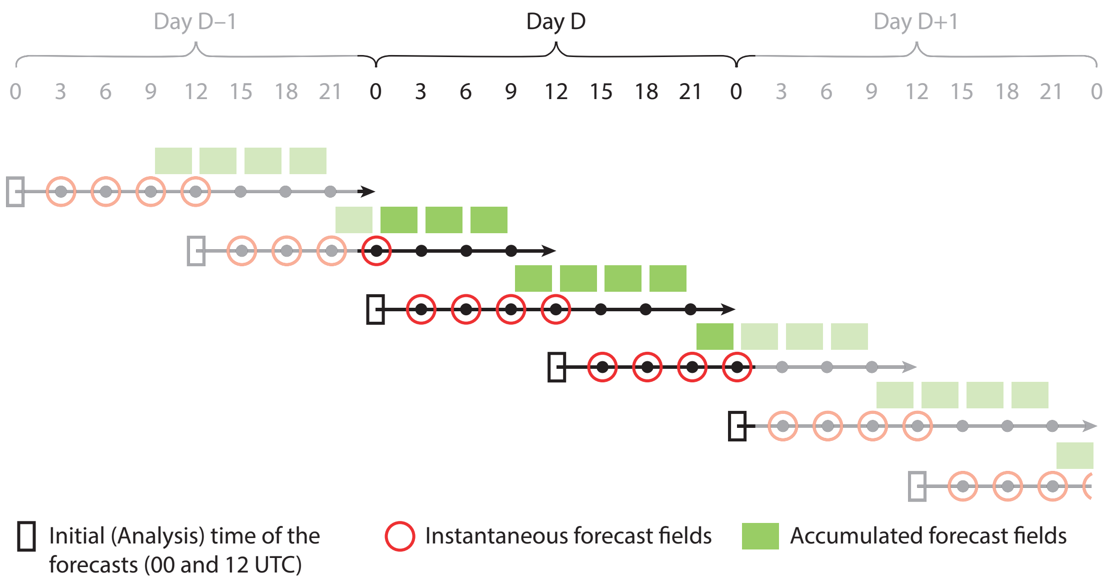

Figure 1: Schematic representation of the ERA-Interim meteorological forecasts concatenation for the creation of the 3-hourly forcing time-series used in ERA-Interim/Land for a given day. Orange circles indicate instantaneous variables valid at their timestamp: 10m temperature, humidity, wind speed, and surface pressure. Green boxes indicate fluxes valid on the accumulation period: surface incoming short-wave and long-wave radiation, rainfall, and snowfall.

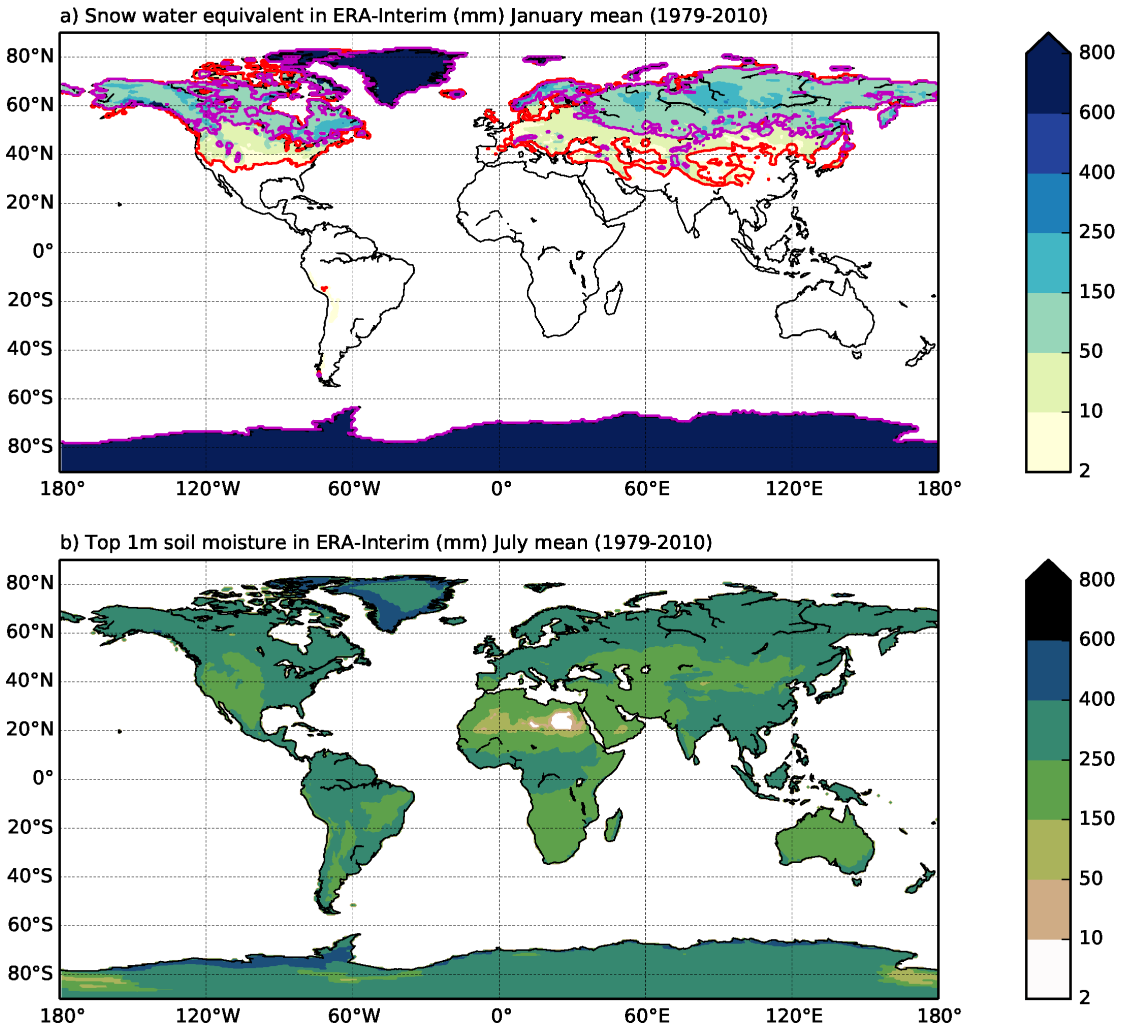

Figure 2: Median of the land water reservoirs in the 1979-2010 period for ERA-Interim: (a) Snow Water Equivalent (kg/m^2) for the 10 to 20 January period, and (b) Top 1m Soil Moisture (kg/m^2) for the 10 to 20 July period. The red and magenta contours in figure (a) indicate the 5 and 95 percentile respectively of 10 kg/m^2 snow water equivalent as an indication of the year to year variability of snow cover.

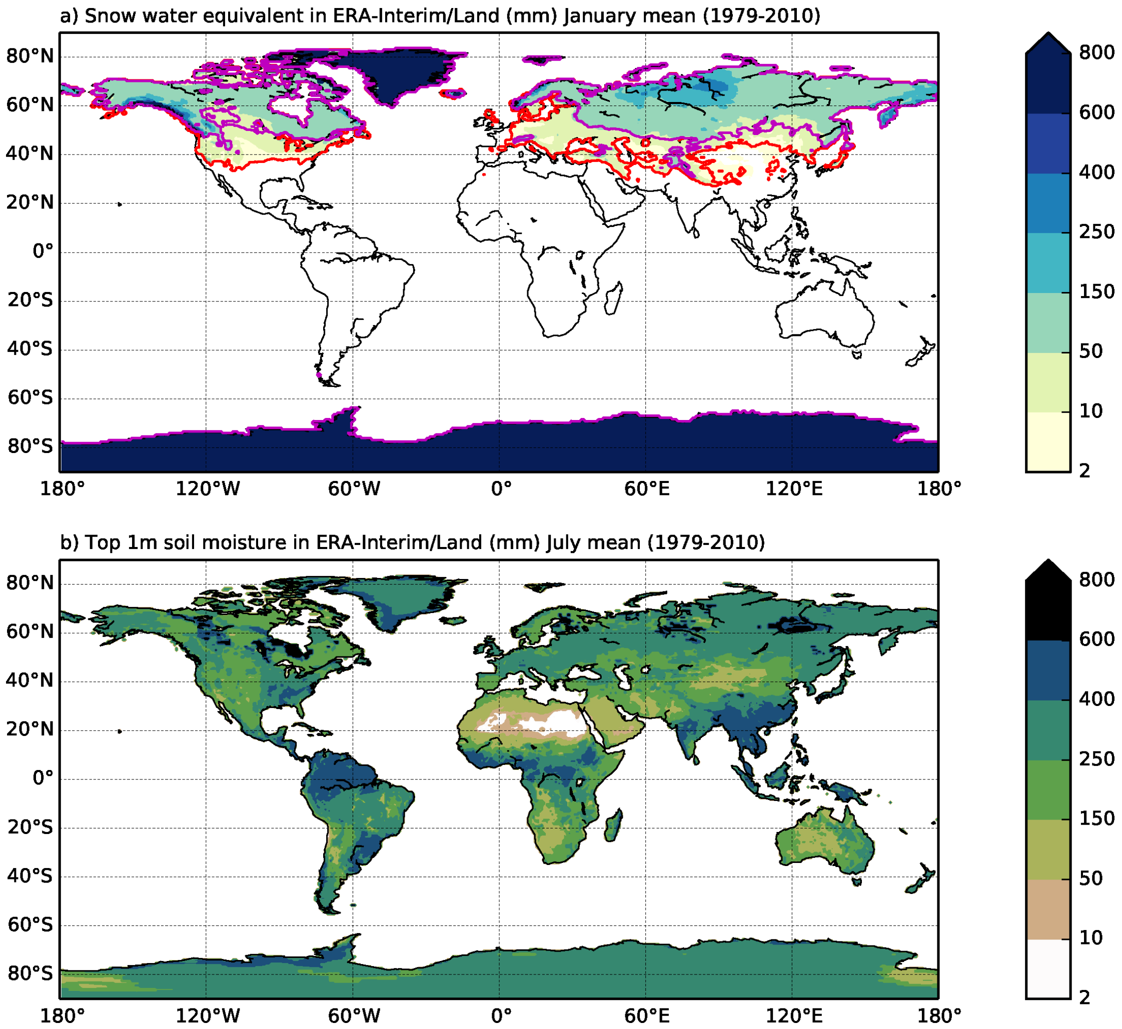

Figure 3: Same as Fig. 2, but for ERA-Interim/Land.

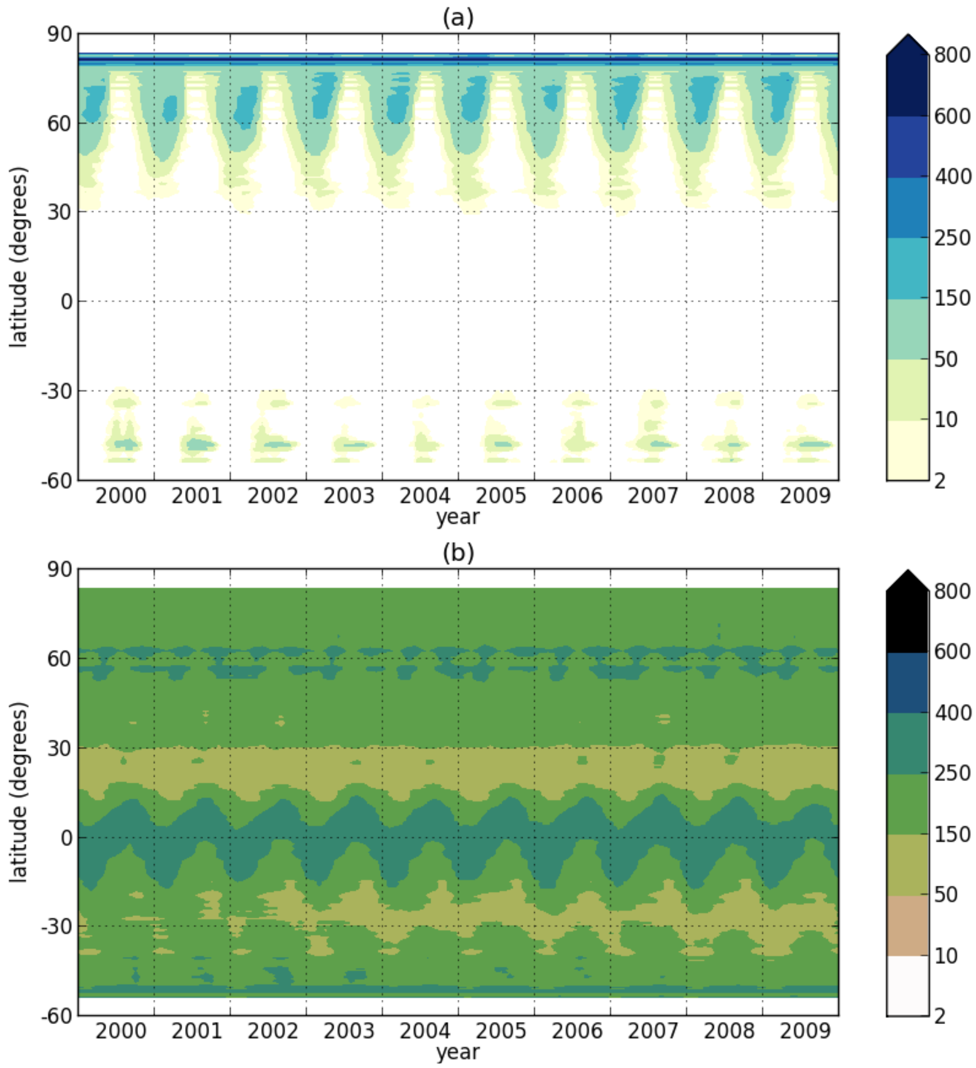

Figure 4: ERA-Interim Hovmöller diagram of the land water reservoirs (zonally averaged over land) for the 2001-2010 period: (a) Snow Water Equivalent (SWE, kg/m^2) and (b) Top 1m Soil Moisture (TCSM, kg/m^2).

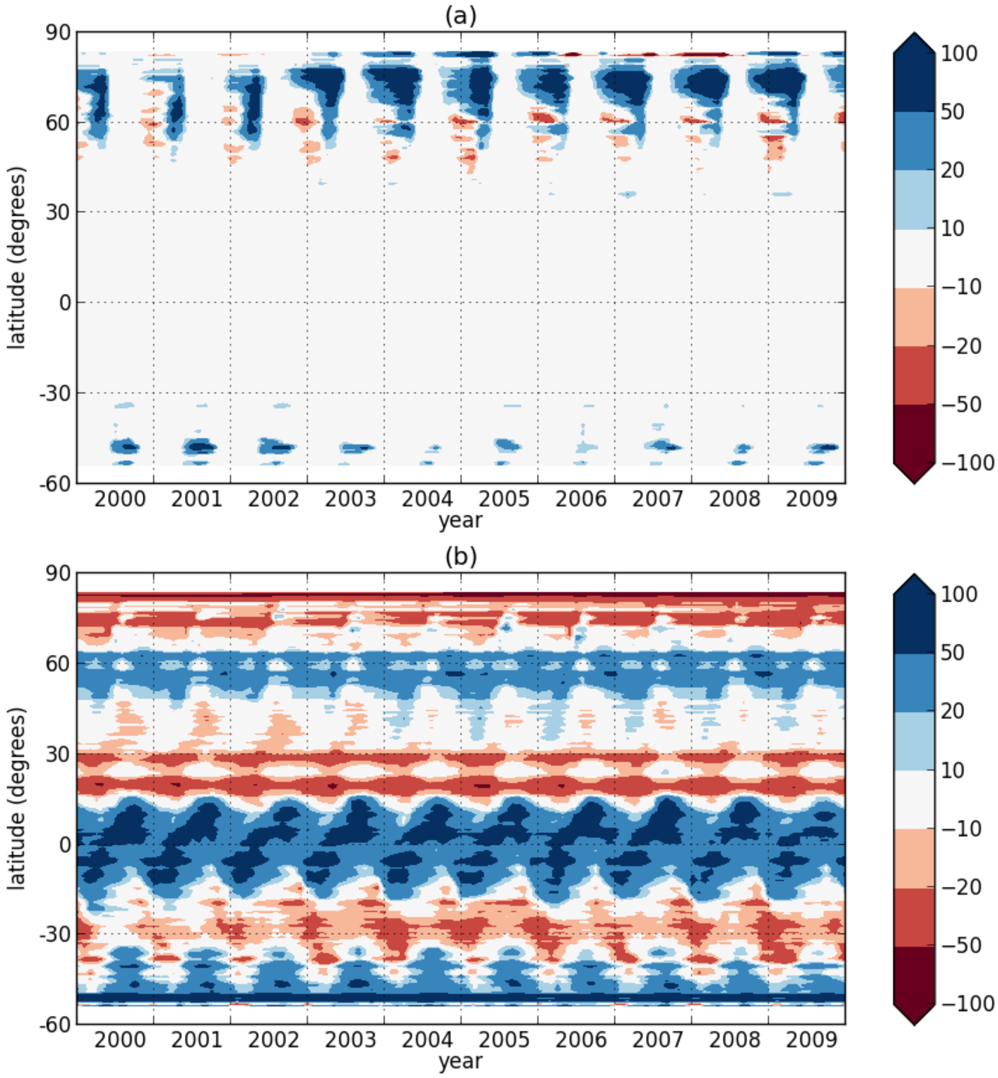

Figure 5: As Figure 4, but for the difference between ERA-Interim/Land and ERA-Interim in (a) Snow Water Equivalent (SWE, kg/m^2) and (b) Top 1m Soil Moisture (TCSM, kg/m^2).

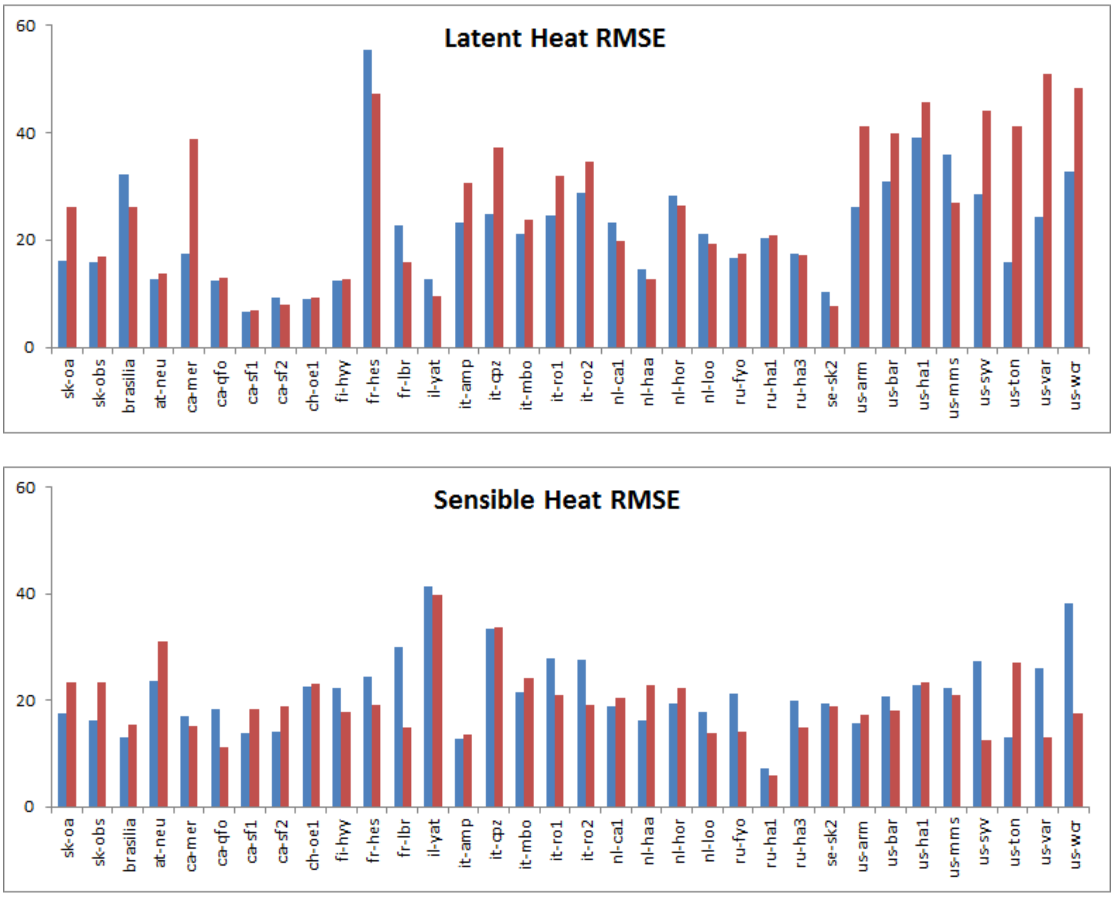

Figure 6: Root mean square error (W/m^2) based on hourly values in 2004 for (a) Latent heat flux and (b) Sensible heat flux with respect to observations at 34 sites (as in **Table 1**) for ERA-Interim/Land (blue) and ERA-Interim (red).

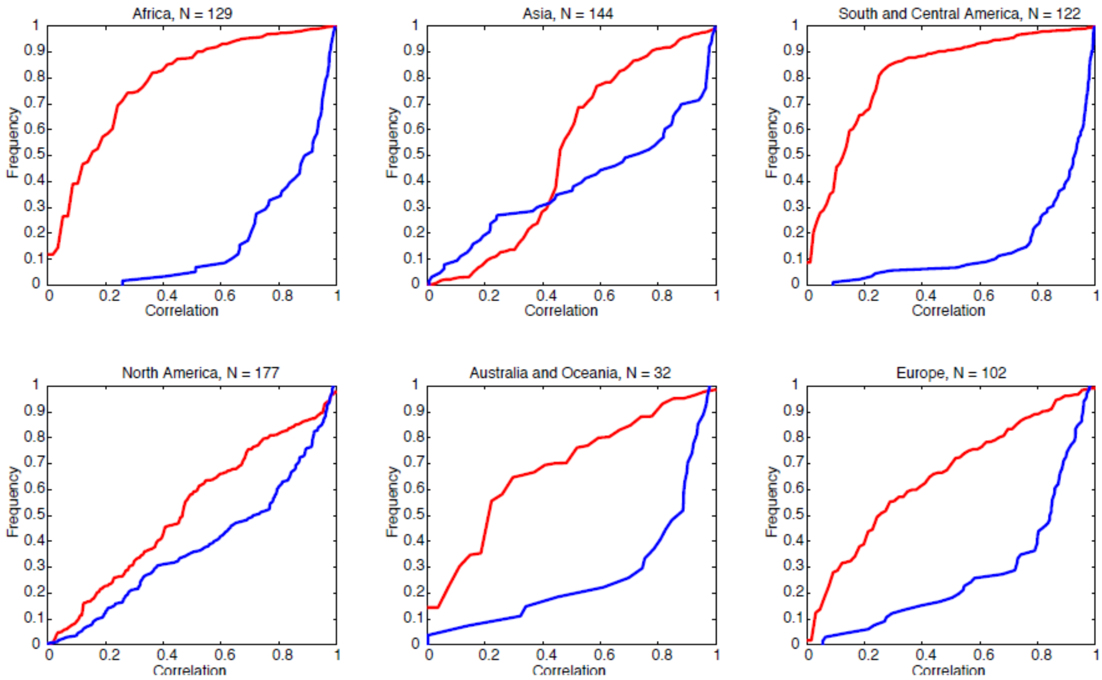

Figure 7: Cumulative distribution function of river discharge correlations of ERA-Interim (red) and ERA-Interim/Land (blue) with GRDC data clustered by continents.

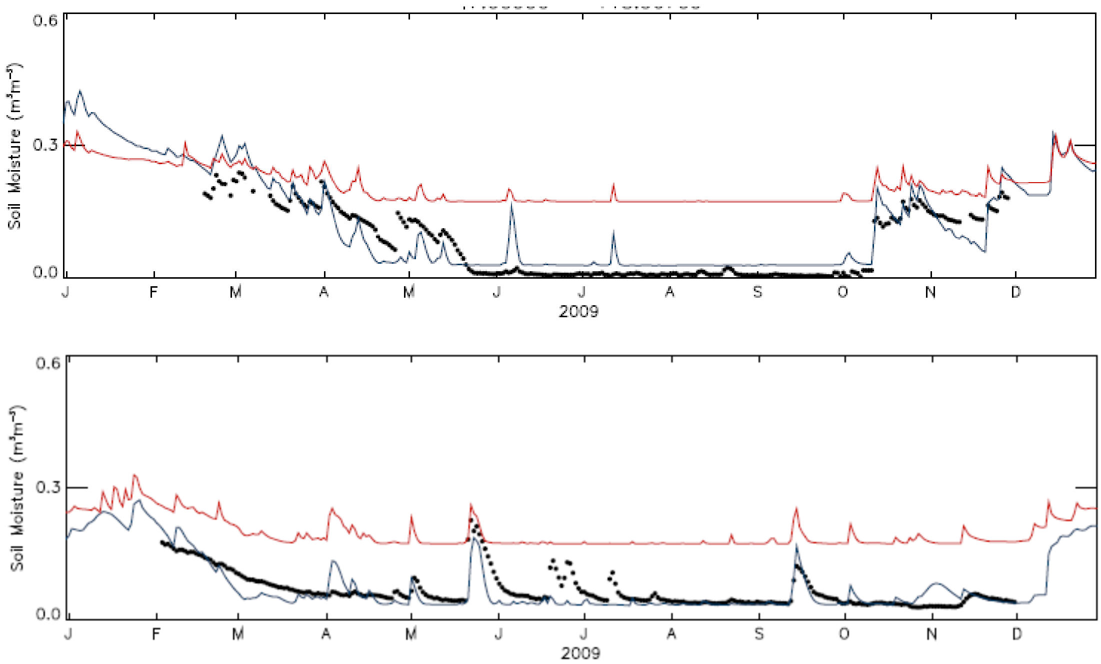

Figure 8: Evolution of volumetric soil moisture at a site in Utah (top panel) and Washington (bottom panel) for the year 2009. In-situ observations are in black, ERA-Interim is in red, and ERA-Interim/Land estimates in blue.

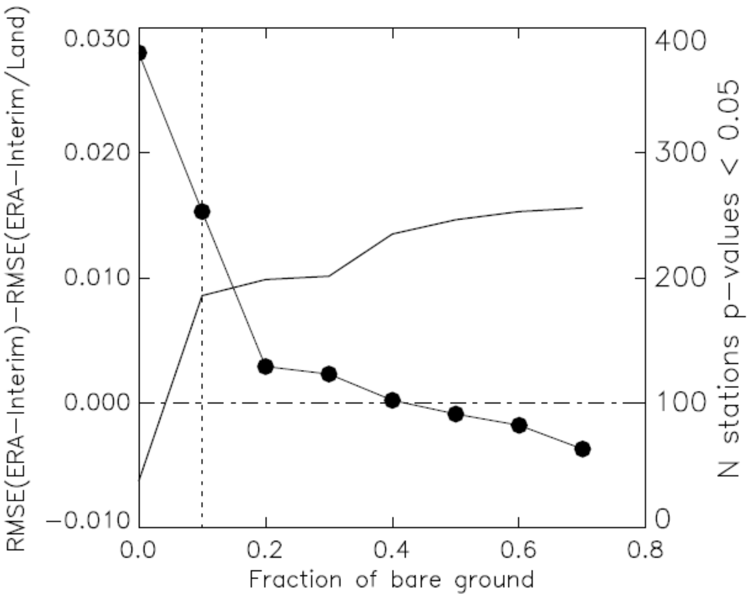

Figure 9: RMSE difference between ERA-Interim and ERA-Interim/Land (solid line, left y-axis) as a function of the fraction of bare ground. The number of in situ stations (line with solid dots, right y-axis) with significant correlations is also presented. Sensitivity to fraction of bare soil is only pronounced above the threshold indicated by the vertical dashed line.

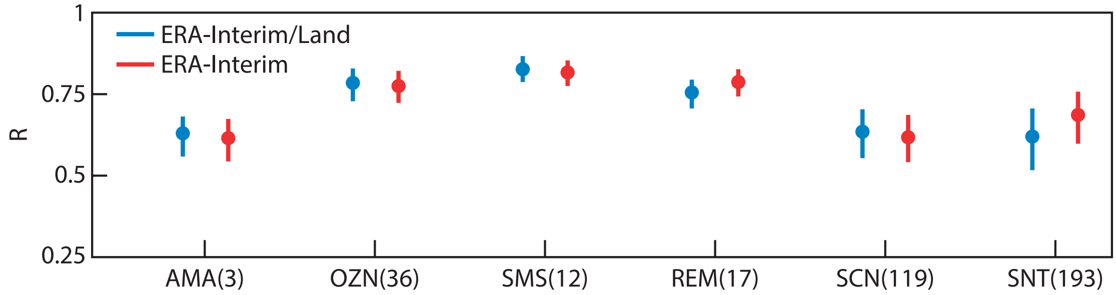

Figure 10: Correlation with observed ISMN soil moisture networks (as in **Table 2**) for ERA-Interim/Land (blue) and ERA-Interim (red). Only significant correlations with p-values <0.05 are considered and for each of the observing networks the bars indicate the 95% confidence interval calculated using a Fisher-Z-transform.

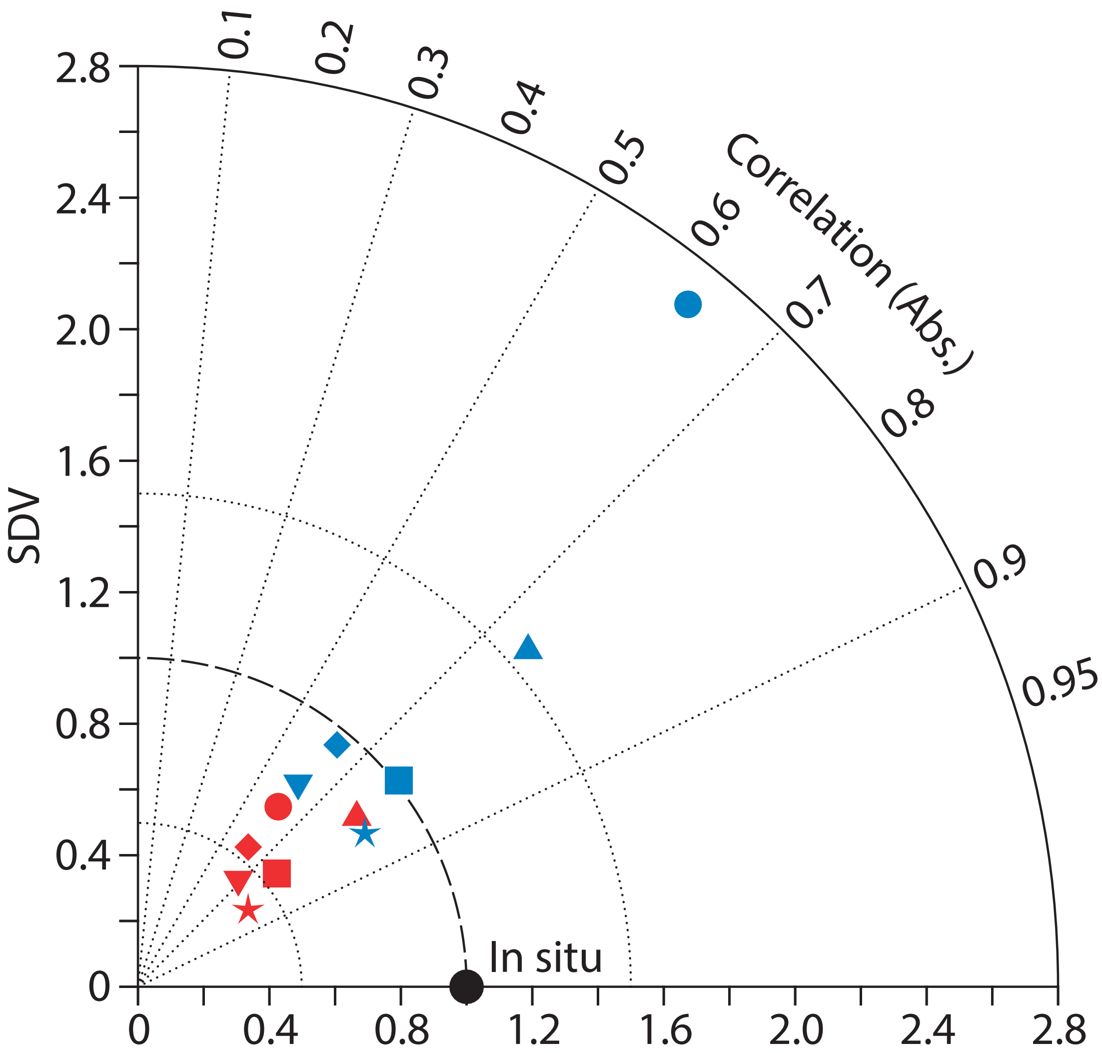

Figure 11: Taylor diagram illustrating the statistics from the comparison between ERA-Interim/Land (blue) and ERA-Interim (red), compared to situ observations for 2010. Each symbol indicates the correlation value (angle), the normalized SDV (radial distance to the origin point), and the normalized centred root mean square error (distance to the point marked "In situ"). Circles are for the stations of the AMMA network (3 stations), square for the OZNET network (36 stations), stars for the SMOSMANIA network (12 stations), triangles for the REMEDHUS network (17 stations), diamonds for the SCAN network (119 stations) and inverted triangle for the SNOTEL network (193 stations). Only stations with significant correlation values are considered.

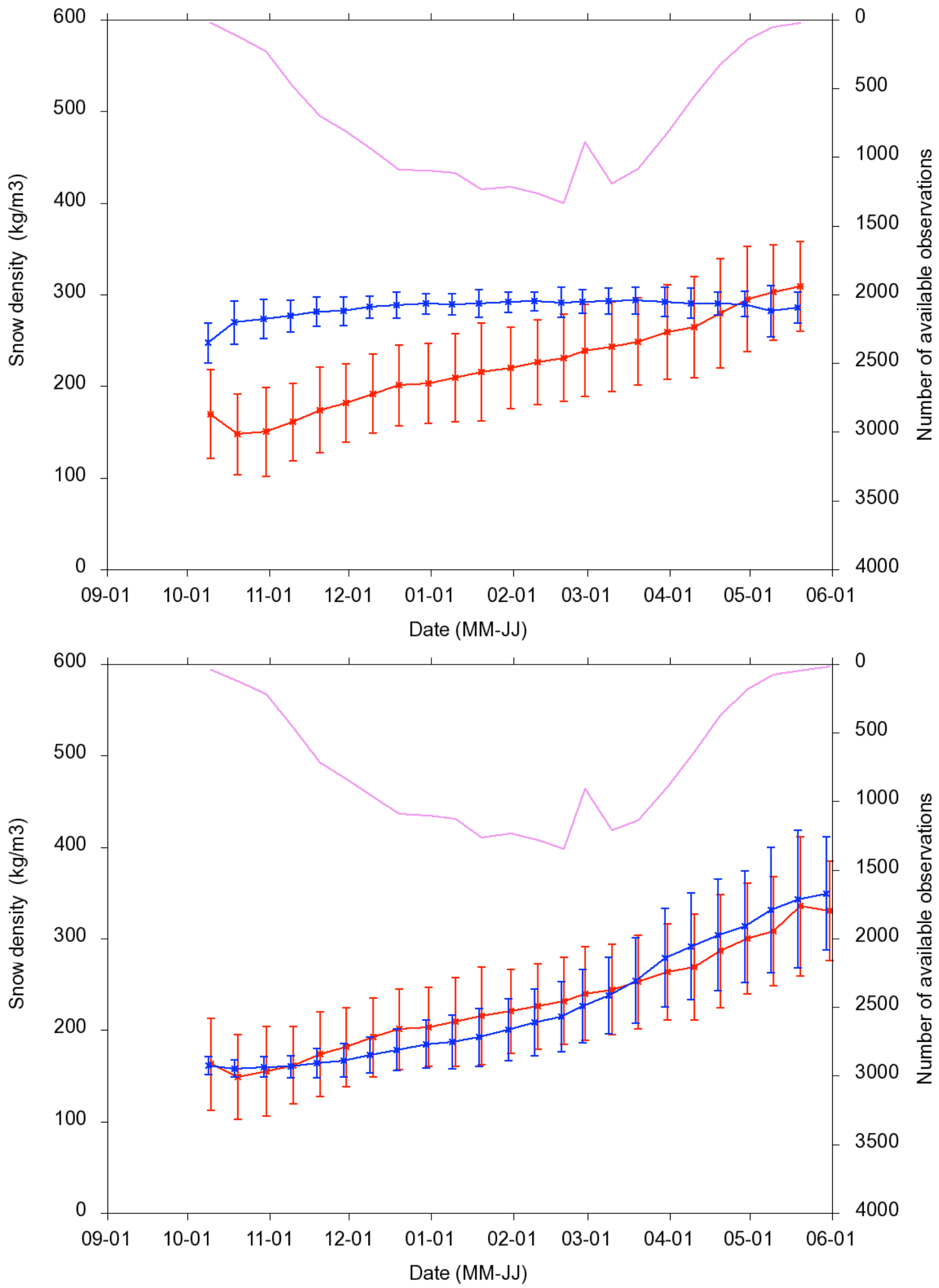

Figure 12: Snow density seasonal evolution as observed (red) and estimated (blue) by ERA-Interim (top panel) and by ERA-Interim/Land (bottom panel). Each point represents the station data from the former USSR, averaged over about 20 points along transects around each station, all stations and all years from 1997 to 1993. The vertical bar indicates ± one standard deviation and the purple line indicates the number of observations with the right hand scale from top to bottom. Observations are only included when both observations and model have snow. The snow season from October to June is considered only.

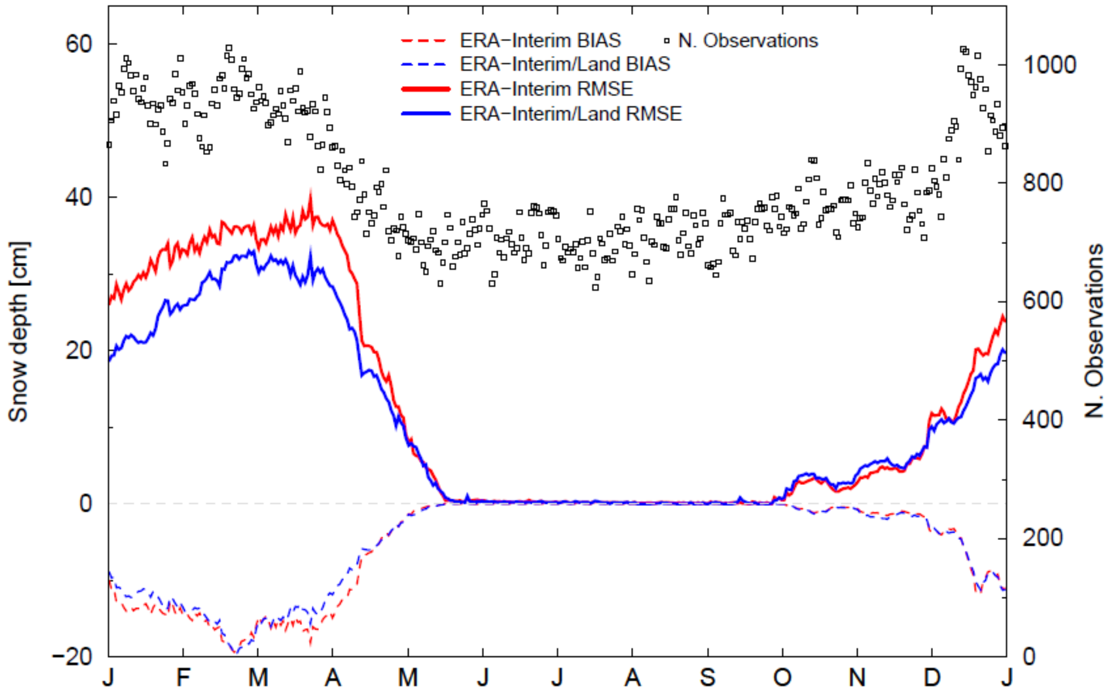

Figure 13: ERA-Interim snow depth RMS error (solid red line) and ERA-Interim/Land snow depth RMS error (solid blue line) with respect to the daily European SYNOP observations at 6UTC. The number of stations with snow is indicated by squares (right y-axis). The thin dashed lines indicate the bias. Model snow depth combines the snow mass and density variables.

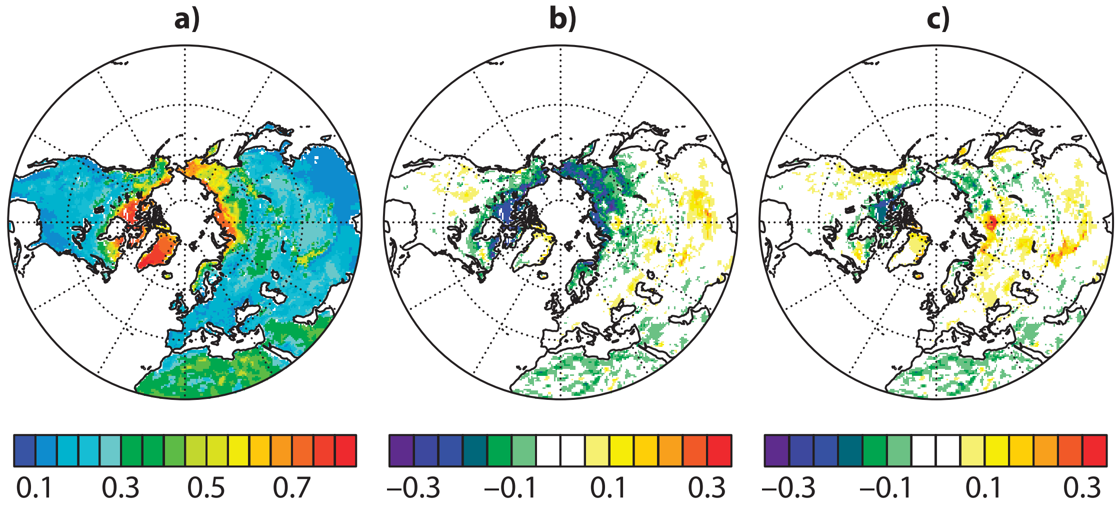

Figure 14: Mean observed Northern hemisphere albedo during spring derived from MODIS (a), difference between ERA-Interim and MODIS (b), and difference between ERA-Interim/Land and MODIS (c).