ERA-Interim/Land: A global land water resources dataset

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Abstract- The ERA-Interim/Land is a global land-surface dataset covering the period 1979–2010 and describing the evolution of the soil (moisture and temperature) and snowpack. ERA-Interim/Land is the result of a single 32yr simulation with the latest ECMWF land surface model driven by meteorological forcing from the ERA-Interim atmospheric re-analysis and precipitation adjustments based on GPCP v2.1 with horizontal resolution of about 80km and 3-hourly frequency. ERA-Interim/Land preserves closure of the water balance and includes a number of parameterisations 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, assessed by comparing with ground-based and remote sensing observations is discussed. 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 sites measurements. ERA-Interim/Land provides a global integrated and coherent water resources estimate that is used also 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. 2011, 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 (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 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) 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 daily to annual over the conterminous US. They proposed a scale-selective rescaling method to address remaining biases based on Global Precipitation Climatology Project monthly precipitation data (GPCP, 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). 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.

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

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 ERA-Interim/Land scheme. A summary and recommendation for the usage of the ERA-Interim/Land product is 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, 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 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 builds upon an error correction methodology applied to the forcing precipitation and on a comprehensive verification applied to the different compartments of the water and energy cycle at the surface. In the following the datasets entering the ERA-Interim/Land generation and its verification are briefly presented. The datasets ERA-Interim and GPCP v2.1 are support to the generation of ERA-Interim/Land while the other datasets are used for the validation of the water cycle components (water storage terms and fluxes).

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 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) distributed worldwide (from satellite remote sensing, in-situ, radio-sounding, profilers, etc.) and by the analysis step that combines observations and Earth system model a-priori information in a statistically optimal manner. In ERA-Interim two analyses per day are performed at 00 and 12 UTC times and serves as initial conditions for the subsequent forecasts. To create a continuous time series of meteorological forcing therefore an opportune combination of analyses and forecasts has been produced as detailed in the Fig. 1. The weather forecast's spin-up effects are typical of fields such as precipitation and radiation fluxes, for which the first hours after the analysis are subject to some initial shock problem. 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 and stored as 3-hourly accumulations. To avoid possible spin-up effects of precipitation and radiation (as documented in Kållberg 2011) on the offline land surface simulations, 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 schematic representation in Fig. 1 shows how the continuous meteorological forcing is generated for a given day. The difference in the choice of forecast range selected for instantaneous and accumulated fluxes is motivated by the spinup effect being a concern mainly for the latter. The forecasts are then concatenated to produce a continuous 3-hourly meteorological forcing data set that can be used to drive land surface simulations. The ERA-Interim 3-hourly precipitation is rescaled to match the GPCP monthly averages, as detailed by Balsamo et al. (2010a).

2.1.2 GPCP v2.1 precipitation

The 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 versions 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).

2.1.3 FLUXNET land energy fluxes

FLUXNET is a global surface energy, water, and CO_2 FLUX observation NETwork and it is a collection of existing regional networks (Baldocchi et al. 2001, http://fluxnet.ornl.gov). Available 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 also 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 original observational archive (excluding gap filled values) with high quality flag only (see Table 1).

2.1.4 ISMN soil moisture observing network

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, 2013, http://ismn.geo.tuwien.ac.at/). 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 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; 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 are used and the year 2010 is retained for the comparison. Table 3 gives a full list of reference for each network as well as the main statistical scores for the comparison.

2.1.5 The GTS-SYNOP observing network

The SYNOP (surface SYNOPtic observation) is an operationally maintained datasets under the 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 measurement on the ground (remote sensing observations have difficulties in representing snow properties). 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 The 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, 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 (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.

2.1.7 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 daily 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 land surface parameterization improvements introduced in the operational ECMWF forecast model since the frozen cycle used in the ERA-Interim reanalysis. The meteorological forcing described in 2.1.3 is used to drive a 11 yr spin-up run (1979 to 1989 included) that serves the purpose of generating plausible initial conditions for the 1st of January (as average of span-up run dates in 1980-1989).

A single continuous 32 yr simulation starting on the 1st of January 1979 is then realised with the latest ECMWF land surface scheme, which includes several updated modelling components. These are briefly described in the following subsections with the highlight of the main components that characterize 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

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 Soil Moisture and Ocean Salinity (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 Albergel et al. (2012a).

3 Results

The quality of ERA-Land builds upon reduced errors in the meteorological forcing and land surface modelling. In the following, selected verification results are included, showing the added value 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 on the period 1979-2010 are shown in Fig. 2 for soil moisture SM and snow water equivalent SWE (both expressed in mm of water or equivalently in kg m^{-2}). The median of the 32-year SWE valid on the 15^{th} of January is particularly adapted to show the typical values for those dates (a single exceptional year with large snow accumulation leaving the median invariant).

The same argument is valid for mid-July SM in which a single exceptional flood will not affect the median. Similarly the 95^{th} percentile of the distribution is shown for comparison in Fig. 3 to illustrate the water resources dynamical range in the past 3 decades associated with snow and unsaturated soil layers and the extent and the magnitude of exceptional events can be appreciated. Figs. 2 and 3 serve the purpose of illustrating the potential of the multi-decadal daily land reanalysis for evaluating typical and extreme value of the global water resources.

The evolution of ERA-Interim/Land along the 32 years 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 the plots of Figs. 3a and 4a for snow water equivalent and Figs. 4b and 5b for the top 1-m soil moisture. The snow changes in Fig. 4a 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. The soil moisture presents large differences in Fig. 5b than can be attributed to the soil hydrology revisions. Fig. 4 is meant to illustrate that ERA-Interim and ERA-Interim/Land are significantly different throughout the 32-year period with respect to land water resources. In these runs observational constraints on the snow and soil water reservoirs such as those applied by data assimilation is totally absent, however the resulting water reservoirs and the fluxes both towards the atmosphere (heat and moisture) and the river discharges, are shown to improve with respect to the original ERA-Interim output. In the following sections a selection of results to prove the added value of ERA-Interim/Land is presented.

3.1 Land fluxes verification

The land surface fluxes resulting from the offline-driven land simulations are validated against two categories of land-controlled fluxes, the land-atmosphere turbulent heat and moisture and the river discharges.

3.1.1 Latent and Sensible heat flux

The fluxes are measured over 34 FLUXNET, CEOP and BERMS flux-towers, as listed in Table 1. Correlation, mean bias and root mean squared differences are improved using the ERA-Interim/Land surface scheme, indicating a higher skill in reproducing the land atmosphere fluxes.

A detailed evaluation of the ERA-Interim (TESSEL) and ERA-Interim/Land (HTESSEL) surface schemes in offline driven simulations for each site confirms a general improved representation of both the latent and sensible heat fluxes (Fig. 6).

An overall quantitative estimate of the improvements is reported in Table 2. Both Latent and Sensible heat fluxes indicate an average improvement of 8%, when adopting the ERA-Interim/Land surface scheme instead of the ERA-Interim surface scheme, evaluated as root-mean-square-error differences.

3.1.2 River discharge

River discharge is used here to provide an integrated evaluation of the continental water cycle for verifying improvements in the representation of land hydrology. The ERA-Interim/Land discharges are compared to those obtained from ERA-Interim by consideration of their correlation to observed GRDC monthly river discharges clustered by continent. Fig. 7 shows the cumulative distribution function of the correlations between simulated and observed monthly river discharges ERA-Interim/Land (blue dashed line). A general improvement over ERA-Interim (red solid line) is evident since the correlations are higher at all levels in nearly all cases (blue line is nearly always above the red line and area under the blue curve is greater). The improvements on river discharge correlation coefficients (ERA-Interim/Land to GRDC river discharge observations) are averaged on all the continental rivers indicated in each panel of Fig. 6.

Although there is still some way to go in effectively representing river discharge in large-scale land surface schemes, modelling cascades can enable bridging the ERA-Interim/Land with river hydrology (Pappenberger et al, 2012). In the current evaluation what is particularly encouraging is the average improvement of river discharge correlations of ERA-Interim/Land over ERA-Interim occurs on all continents that therefore encompass different rivers and water balance regimes.

3.2 Land water resources verification

The water reservoirs verification aims at assessing the daily performance of ERA-Interim/Land in reproducing the top metre of soil water content and the snow water equivalent, which are responding to the diurnal, synoptic and seasonal fluxes variations. 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 model.

3.2.1 Soil moisture

The changes in the land surface parameterization have largely preserved the mean annual soil moisture, which ranges around 0.23-0.24 m^3m^{-3} as global land average on 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. Offline land surface simulations were also used by Albergel et al. (2012a) to evaluate the new bare ground evaporation formulation mentioned in section 3.2. 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 difference (RMSD) of soil moisture is shown to decrease from 0.118 m^3m^{-3} to 0.087 m^3m^{-3} when using the new formulation in offline experiments (and from 0.110 m^3m^{-3} to 0.088 m^3m^{-3} in operations). It also improves correlations. Fig. 8 illustrates the effect of the model changes 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 used in 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 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. The better correlations and reduced RMSD are explained by a more realistic decrease in soil moisture after a precipitation event due to its higher water holding capacity and are attributed to soil hydrology revisions (Balsamo et al. 2009, Balsamo et al. 2011, Albergel et al. 2012a).

The ability of ERA-Interim/Land and ERA-Interim to reproduce soil moisture is also presented by Fig. 9. This illustrates also the gain in skill in reproducing the observed soil moisture in dry land as a function of vegetation cover. With the RMSD being positive definite and calculated against in-situ soil moisture observation, the differences between RMSD between ERA-Interim/Land and ERA-Interim are measuring improvements realized by ERA-Interim/Land. The RMSD difference is calculated for several vegetation fractions 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 results 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 selected (Fig. 10). This variation is similar in manner to that seen with ERA-Interim but the correlation is not significantly improved. However, in Fig. 11 a Taylor diagram is used to illustrate a more detailed statistical comparison of ERA-Interim/Land (in red), ERA-Interim (in blue), and in situ observations for 2010. In Fig. 11 the distance to the point marked “In situ” has been reduced with the ERA-Interim/Land, which indicates more realistic soil moisture variability (better reproduction of the standard deviation of observations).

3.2.2 Snow

The verification of snowfields considers two different observational datasets to evaluate the snow evolution in ERA-Interim and ERA-Interim/Land: (i) the SYNOP daily snow depth and (ii) datasets from the former Union of Soviet Socialist Republics (USSR). The 1979-1993 former USSR dataset was used in Brun et al. (2013) to evaluate simulated snow properties, such as density, which is 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 measured for the typical Northern latitudes snow season (October to June) average for 1979-1993 period (Balsamo et al. 2012). In ERA-Interim, as well as ERA-Interim-Land, 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. This means that ERA-Interim/GPCP-rescaled is not always beneficial and outperforming ERA-Interim precipitation forecasts at each single location (this is not an easy achievable target).

In this case, ERA-Interim original snowfall, without bias correction, lead to higher skill in simulating snow accumulations in this particular verification area and to accurate snow accumulations as confirmed by Brun et al. (2013). Given the difficulty in applying precipitation corrections only partially at this stage it is only possible to document this exception and limitation of the bias correction method and/or the used precipitation datasets.

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

(i) 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, and

(ii) 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).

The ability of two offline simulations driven by ERA-Interim to represent snow cover was assessed for ERA-Interim surface scheme (control) and ERA-Interim-Land (experiment) offline experiments. Fig. 12 (left) shows the Snow Detection Rate (SDR) function of the snow cover for both ERA-Interim/Land and ERA-Interim configurations and Fig. 12 (right) presents the cumulative distribution function of the SDR for two periods, 2005/06 and 2009/10. SDR is much better with ERA-Interim/Land than with ERA-Interim scheme for both periods. For instance, considering the 2005/06 period, while 50% of the SDR is above the value 0.49 for ERA-Interim scheme, 50% of the SDR is above 0.70 for ERA-Interim/Land. Fraction of Correct Accuracy (FCA) are 80 and 86 in 2005/06, 76 and 83 in 2009/10 for ERA-Interim and ERA-Interim/Land surface schemes respectively (Fig. 12). This index is a robust indicator and is more resilient to model biases compared to SDR, which in case snow abundance may favour a biased snow scheme. The MODIS land surface albedo is used to verify the ERA-Interim/Land, particularly in the snow representation in forest areas (Fig. 13) in Northern Canada and Siberia, where conventional SYNOP observations are generally less informative. Fig. 12c points to a substantially reduced albedo bias in the ERA-Interim/Land attributed to the snow scheme revision described in Dutra et al. (2010) and in particular at the snow-vegetation albedo retuning.

4 Discussion

Dedicated land surface reanalyses, such as the ERA-Interim/Land described and evaluated here, are becoming established added-value products within the reanalysis efforts worldwide (Dee et al. 2013). They allow computationally effective testing of new land surface developments, including improvements to the process representation and parameterisation 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 used in applications such as 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 parameterisation 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-CLIM project, moreover it can open up new possibilities of considering more advanced data assimilation schemes (e.g. Fowler and van Leeuwen, 2012), especially designed for non-linear systems.

The skill 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 is evaluated in Albergel et al. (2013). This study, using the methodology described in this paper, represents an attempt to gain insights on soil water reservoirs and its evolution in response to natural and anthropogenic forcing.

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. The ERA-Interim/Land is produced from the ERA-Interim meteorological forcing offline land-surface model simulations. In this paper it has been demonstrated that the ERA-Interim/Land dedicated land surface reanalysis is of added value over the standard land component for 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 need 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 weather, 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 and rather neutral over Eurasia, while in the tropical land benefits are visible 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. Improved match to observations largely attributed to the land surface revisions in the latest ECMWF land surface scheme, is found in the latent and sensible heat fluxes and in soil moisture and snow.

The 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.

While river discharges 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 in the soil 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 real added value and not the result of compensation.

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 (Balsamo et al., 2012). Interannual variability of vegetation state (Leaf-Area-Index) is currently studied at ECMWF in the framework of the EU-FP7 project IMAGINES (http://fp7-imagines.eu) and it is not yet implemented in ERA-Interim/Land.

The ERA-Interim/Land dataset has been used operationally at ECMWF since 2010 for the initialization of the past reforecasts needed for the monthly forecasting (Vitart et al. 2008) and the seasonal prediction systems (Molteni et al., 2011).

Ongoing research effort includes the extension of this dataset beyond 2010 using a different dataset for precipitation based on the latest GPCC collections (Weedon, et al. 2014) and application of the described methodology to future ECMWF reanalyses (Dee et al. 2013).

6 Dataset access

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

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

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Tables

Table 1: 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	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/WS A
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: Summary of mean latent heat (LE) and sensible heat (H) statistics averaged over the 34 sites (units of W/m^2). Mean correlations R of model fluxes to observations include a 95% Confidence Interval (CI) calculated using a Fisher Z-transform.

Model	LE rmse	LE bias	LE mean R	H rmse	H bias	H mean R
ERA-Interim Land (HTESSEL)	25.14	16.01	0.84 (±0.10)	20.14	-4.87	0.84 (±0.10)
ERA-Interim (TESSEL) scheme	30.42	21.58	0.81 (±0.12)	24.64	-8.90	0.78 (±0.13)

Table 3: Comparison of surface soil moisture with in situ observations for ERA-Interim/Land [Italic, bold] and ERA-Interim in 2010. Mean correlations (R), bias (in situ measurements minus products) root mean square differences (RMSD), normalized standard deviation (SDV) and the centred RMSD model and in situ patterns, normalized by the in situ standard deviation are given for each network. 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)	Mean R (95%CI)	Mean Bias (m3m-3)	Mean RMSD (m3m-3)	Mean SDV (σmodel/σobs.)	Mean E
AMMA, W. Africa (3)	***0.63(±0.06)***	***-0.060***	***0.082***	***2.67***	***2.20***
Pellarin et al., 2009	0.61(±0.07)	-0.153	0.154	0.69	0.85
OZNET, Australia (36)	***0.79(±0.05)***	***-0.112***	***0.131***	***1.01***	***0.90***
Smith et al., 2012	0.78(±0.05)	-0.078	0.106	0.55	0.97
SMOSMANIA, France	***0.83(±0.04)***	***-0.080***	***0.108***	***0.83***	***0.95***
(12) Albergel et al., 2008	0.82(±0.05)	-0.037	0.099	0.41	1.20
REMEDHUS, Spain (17)	***0.76(±0.04)***	***-0.152***	***0.175***	***1.57***	***1.40***
Ceballos et al., 2005	0.79(±0.04)	-0.110	0.135	0.84	1.25
SCAN, USA (119)	***0.64(±0.07)***	***-0.078***	***0.130***	***0.95***	***1.48***
Schaefer and Paetzold, 2010	0.62(±0.07)	-0.063	0.110	0.54	1.28
SNOTEL, USA (193)	***0.62(±0.10)***	***-0.045***	***0.115***	***0.78***	***1.27***
Schaefer and Paetzold, 2010	0.69(±0.08)	-0.088	0.123	0.44	1.03

Figures

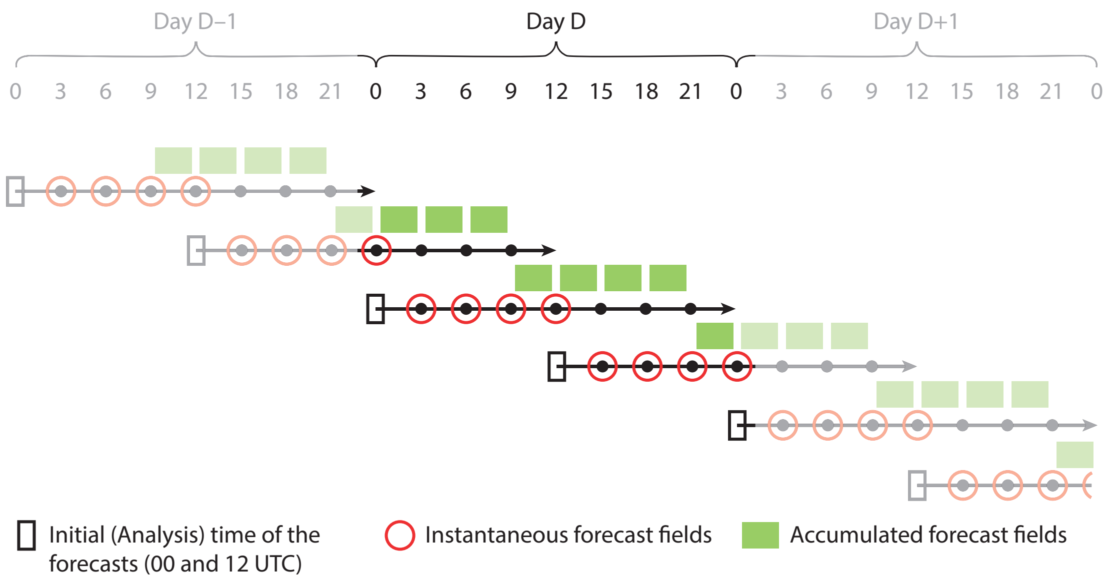

Fig. 1: Schematic representation of the ERA-Interim meteorological forecasts concatenation for the creation of the 3-hourly forcing time-series used in ERA-Interim/Land for a given day. Orange circle indicate instantaneous variables valid at their timestamp: 10m temperature, humidity, wind speed, and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

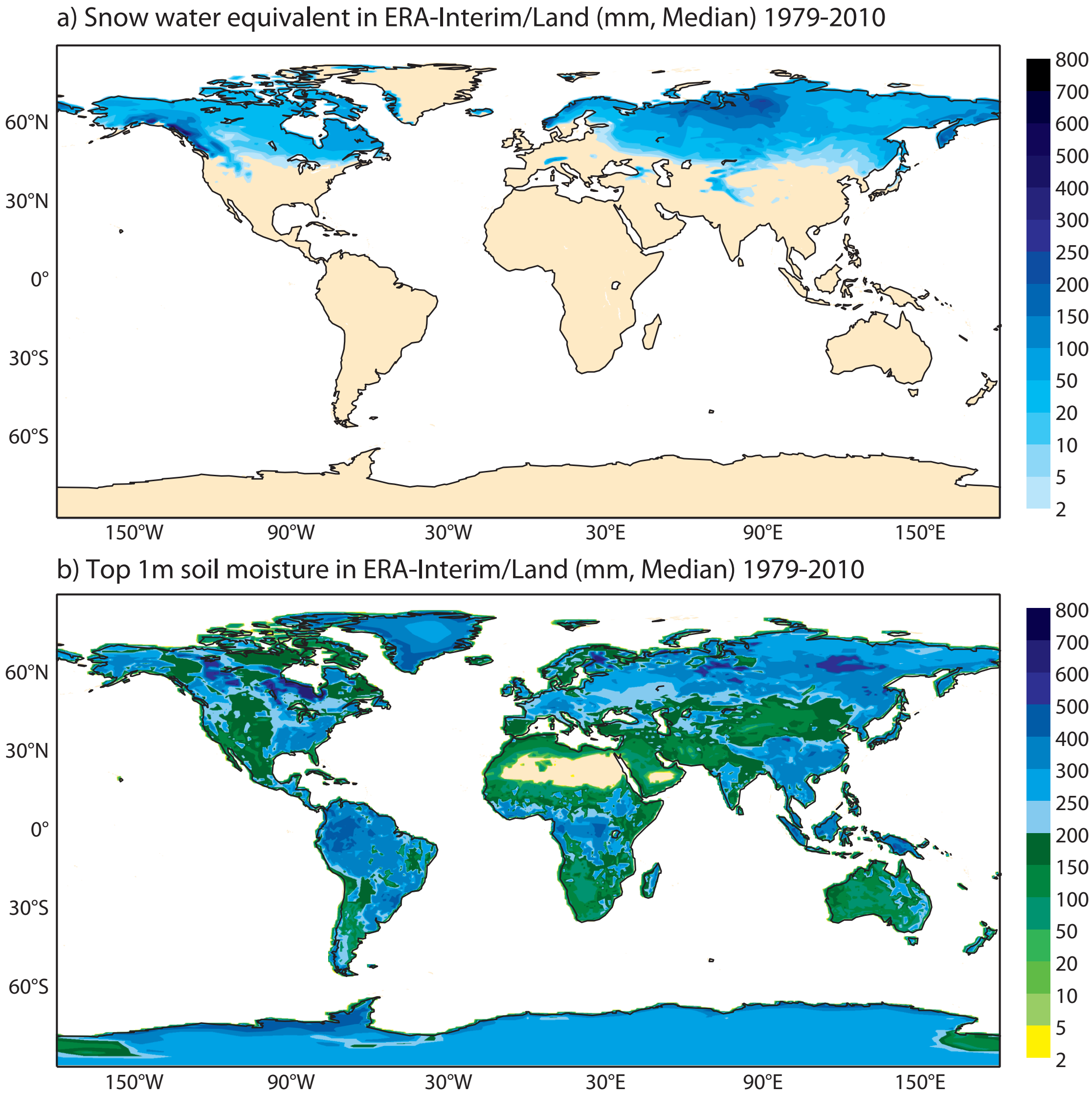

Fig. 2: Median of the land water reservoirs in the 1979-2010 period: (a) Snow Water Equivalent (mm or kg/m2) and (b) Top 1m Soil Moisture (mm or kg/m2), for 2 different dates: (a) 15 January (b) 15 July

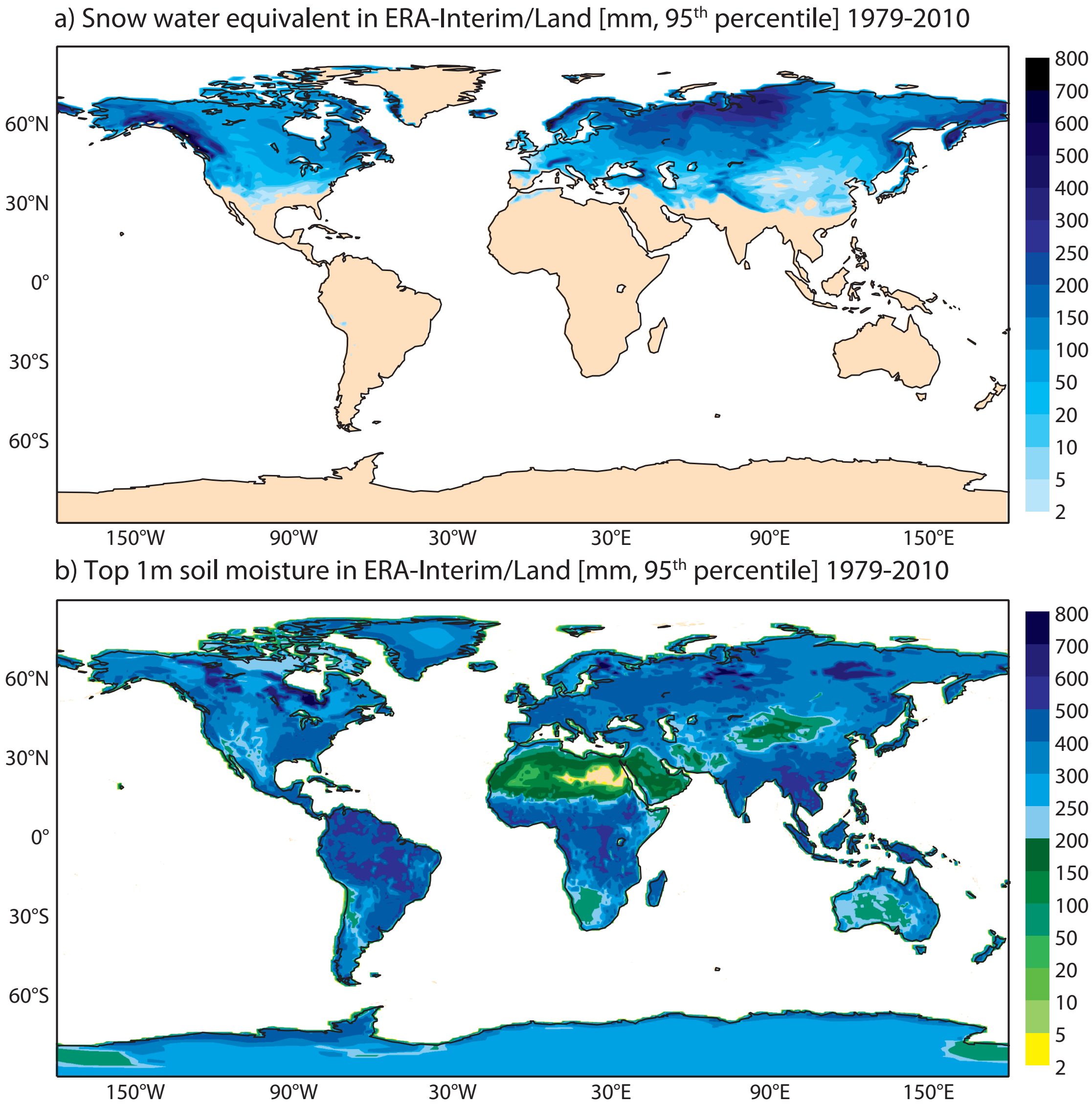

Fig. 3: Same as Fig. 2, but for the 95th percentile of the distribution.

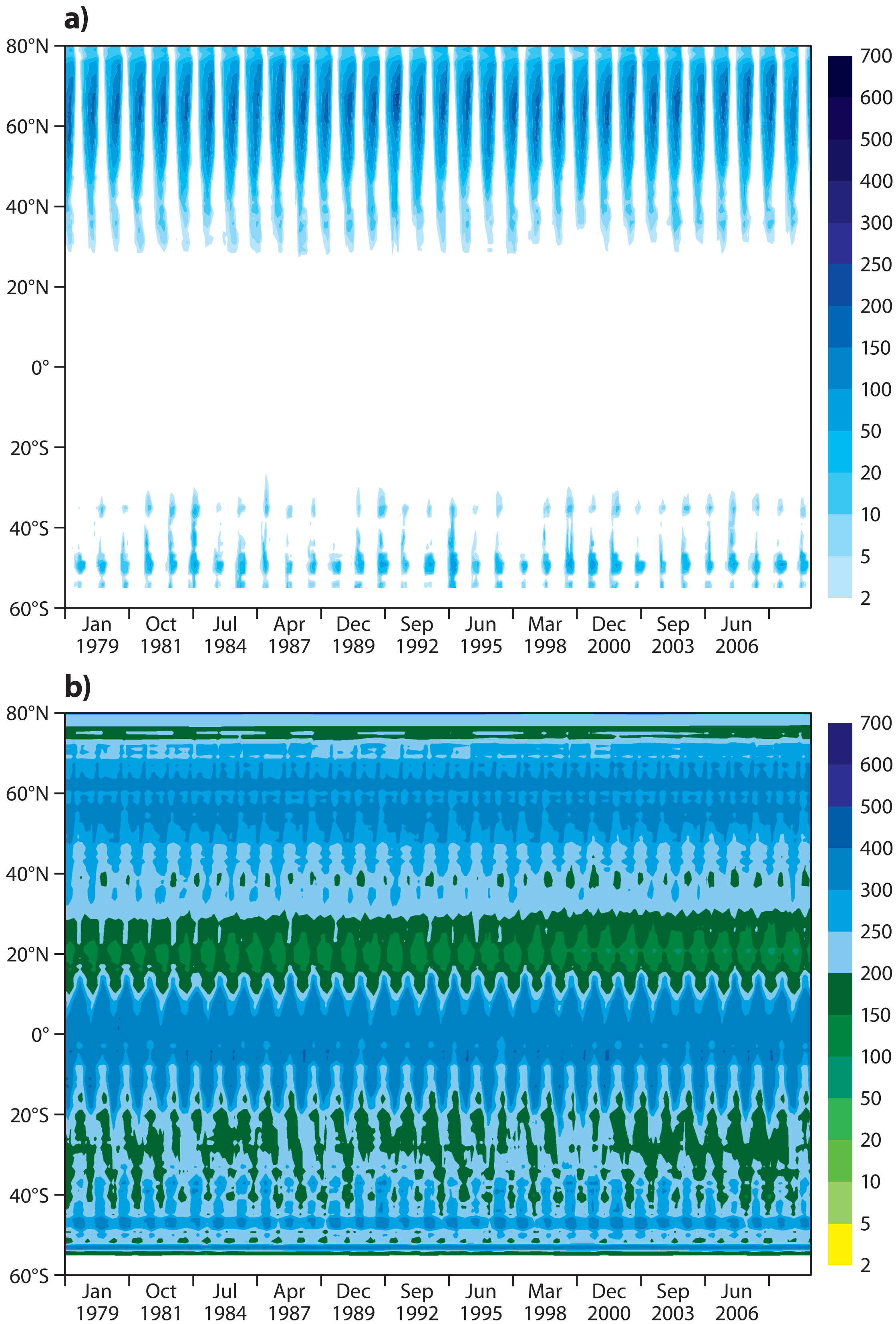

Fig. 4: Hovmöllers of the land water reservoirs for the 1979-2010 period: (s) Snow Water Equivalent (SWE, mm or kg/m^2) and (b) Top 1m Soil Moisture (TCSM, mm or kg/m^2).

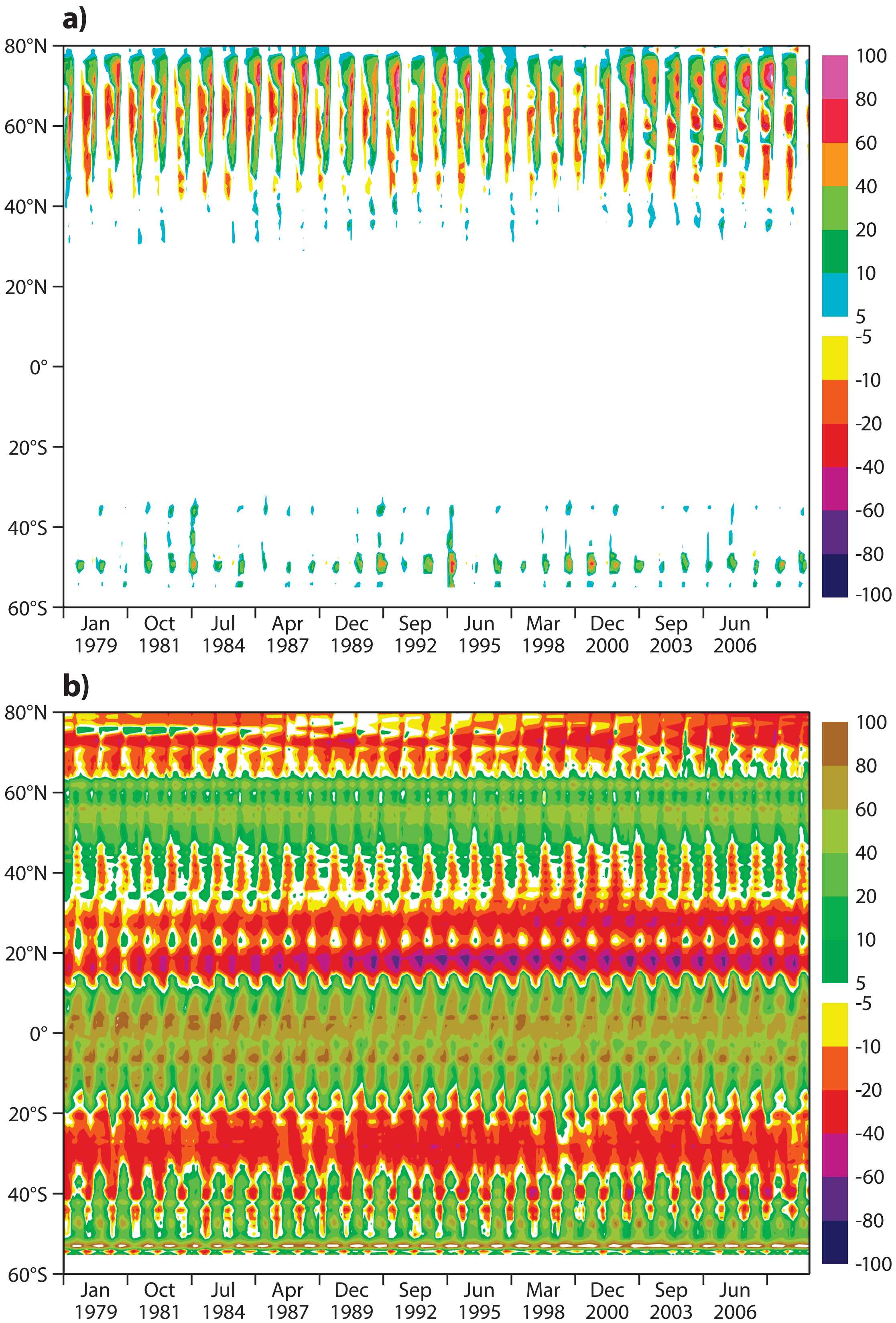

Fig. 5: Same as Figure 4, but for the Differences ERA-Interim/Land minus ERA-Interim

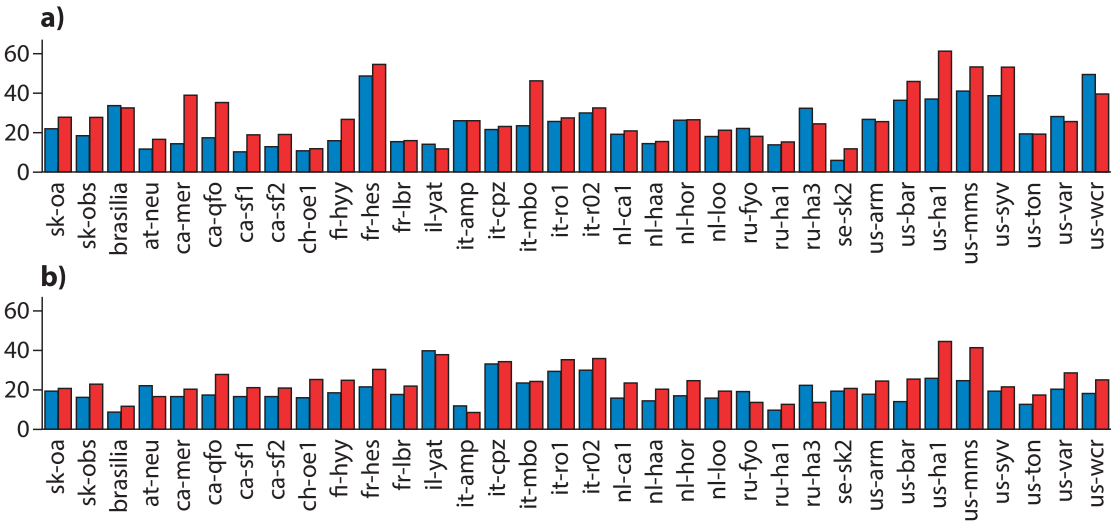

Fig. 6: Root mean square error (W m^{-2})for (a) Latent heat fluxes and (b) Sensible heat fluxes observed at 34 sites (as in Table 1) for ERA-Interim/Land (blue) and ERA-Interim (red) surface schemes.

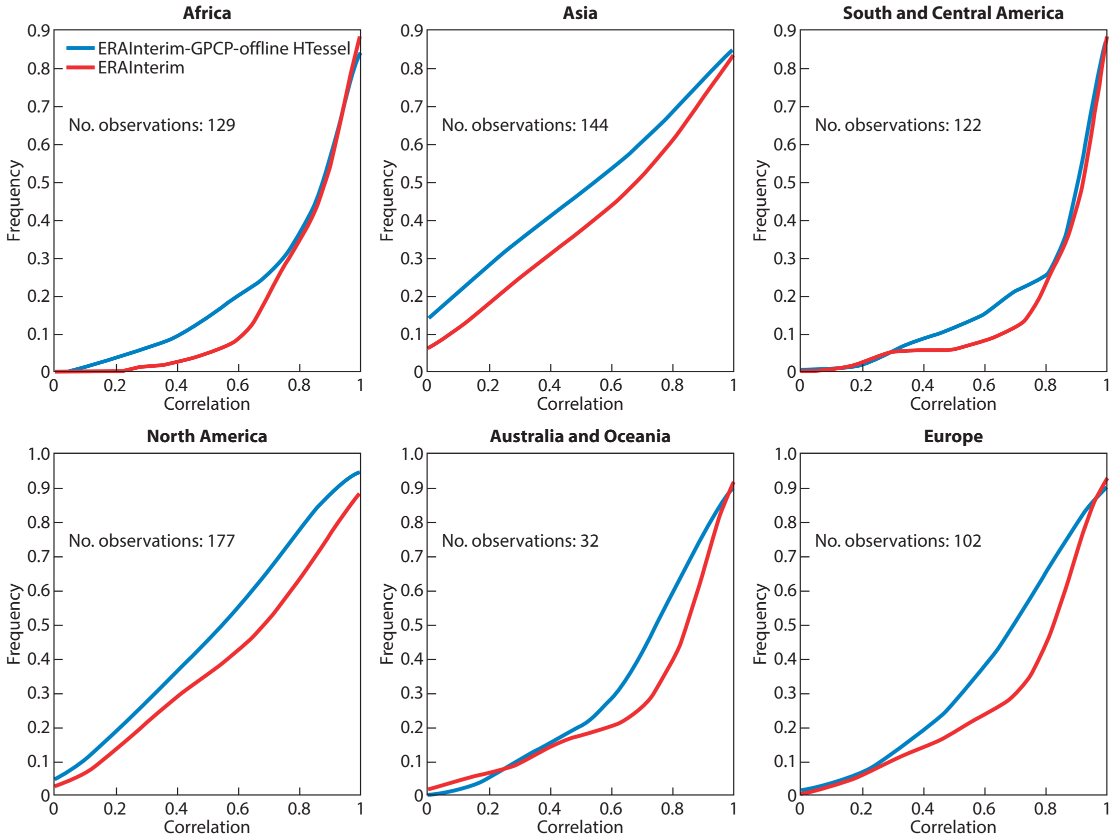

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Fig. 7: Cumulative distribution function of river discharge correlations of ERA-Interim (red) and ERA-Interim/Land (blue dashed line) with GRDC data clustered by continents.

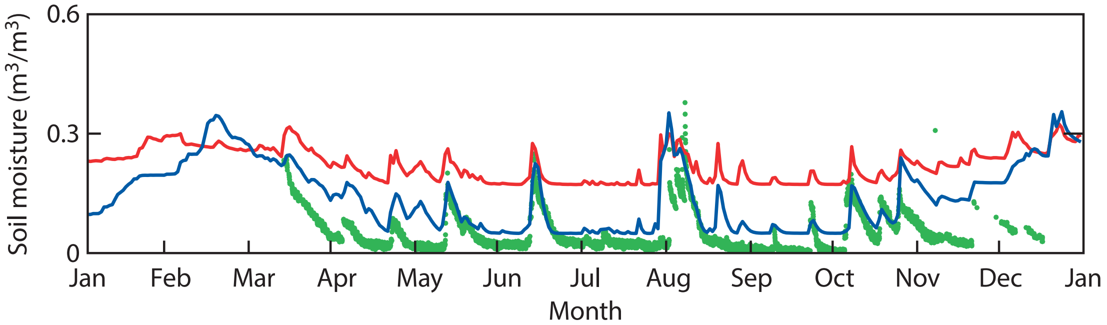

Fig. 8: Evolution of volumetric soil moisture at a site in Utah for the year 2010. In-situ observations in green, ERA-Interim estimates in red, and ERA-Land estimates in blue.

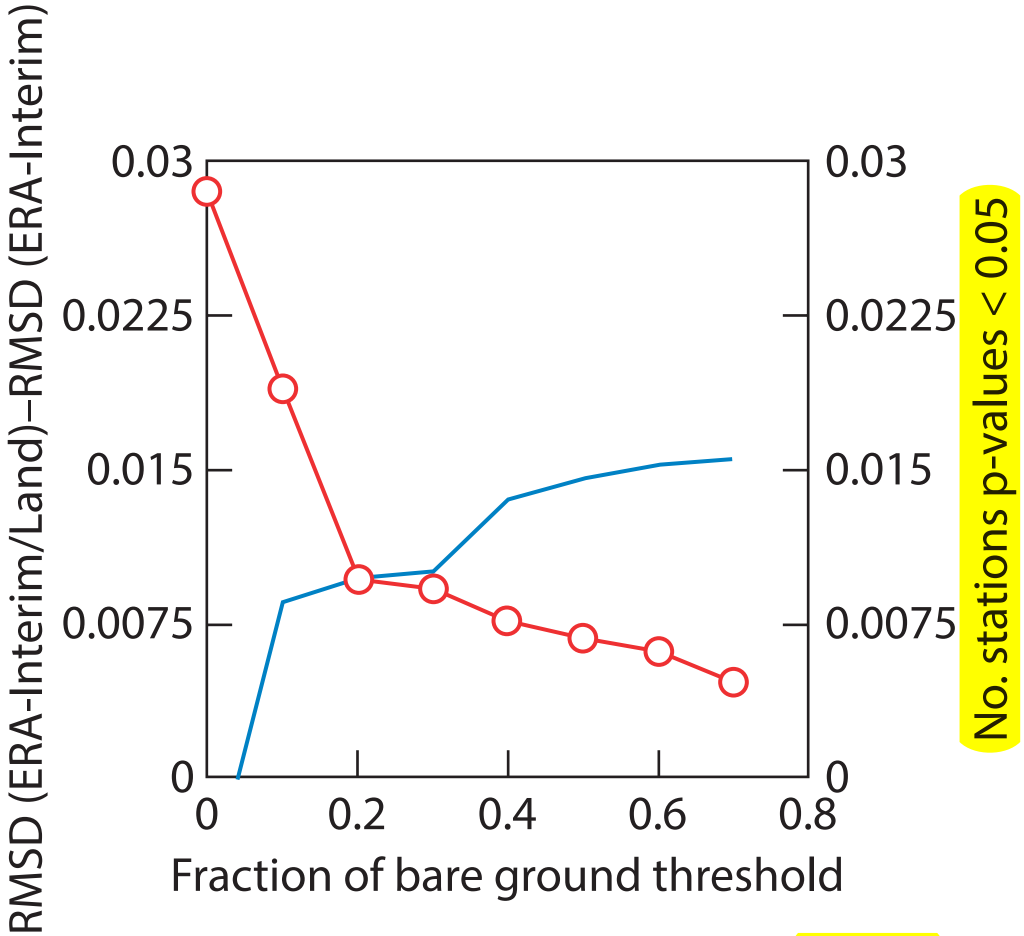

Fig. 9 RMSD difference between ERA-Interim/Land and ERA-Interim (black dots) as a function of the fraction of bare ground (black solid curve, left y-axis), the number of in situ stations with significant correlations is also presented (continues line, right y-axis). The dashed line represents a threshold where the sensitivity to the fraction of bare soil is less pronounced.

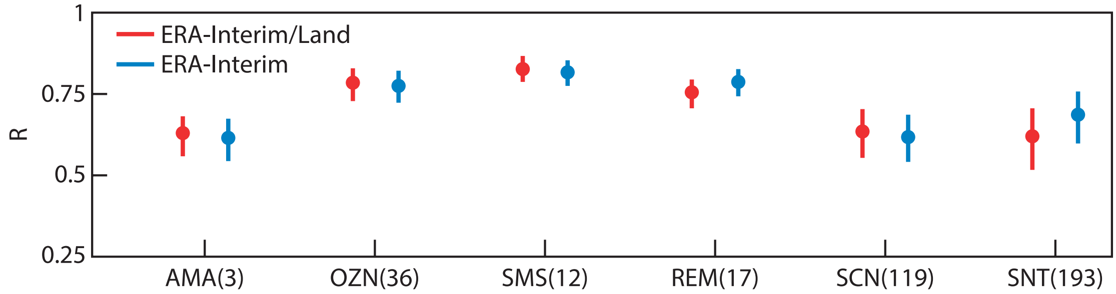

Fig. 10: Correlation with observed ISMN soil moisture networks (as in Table 3) for ERA-Interim/Land (red) and ERA-Interim (orange). Only significant correlations with p-values <0.05 are considered and for each of the observing networks the bars indicate the 95% Confidence Interval calculated using a Fisher-Z-transform.

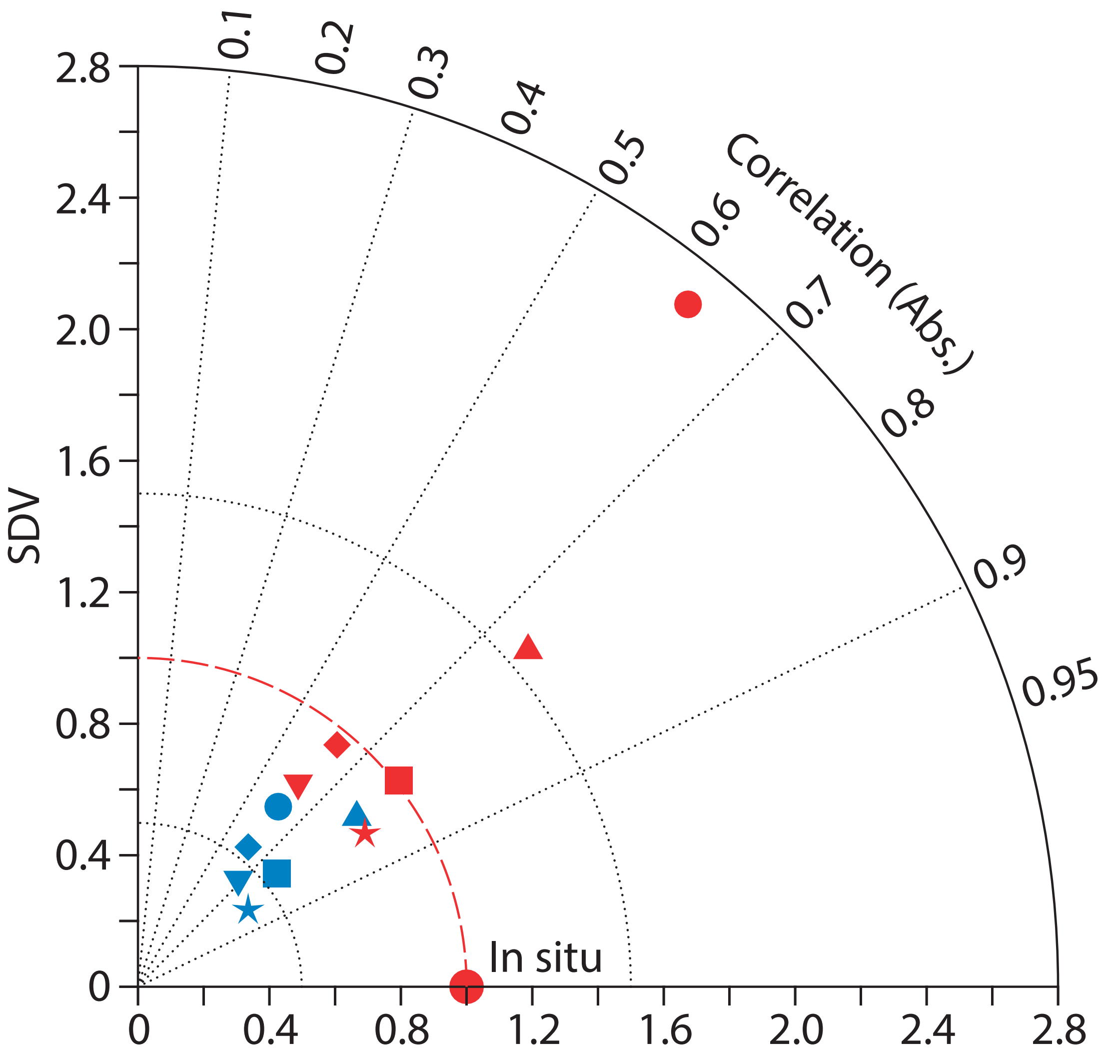

Fig. 11: Taylor diagrams illustrating the statistics from the comparison between ERA-Interim/Land in red and ERA-Interim in blue, compared to situ observations for 2010. Each symbol indicates the correlation value (angle), the normalized SDV (radial distance to the origin point), and the normalized centred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

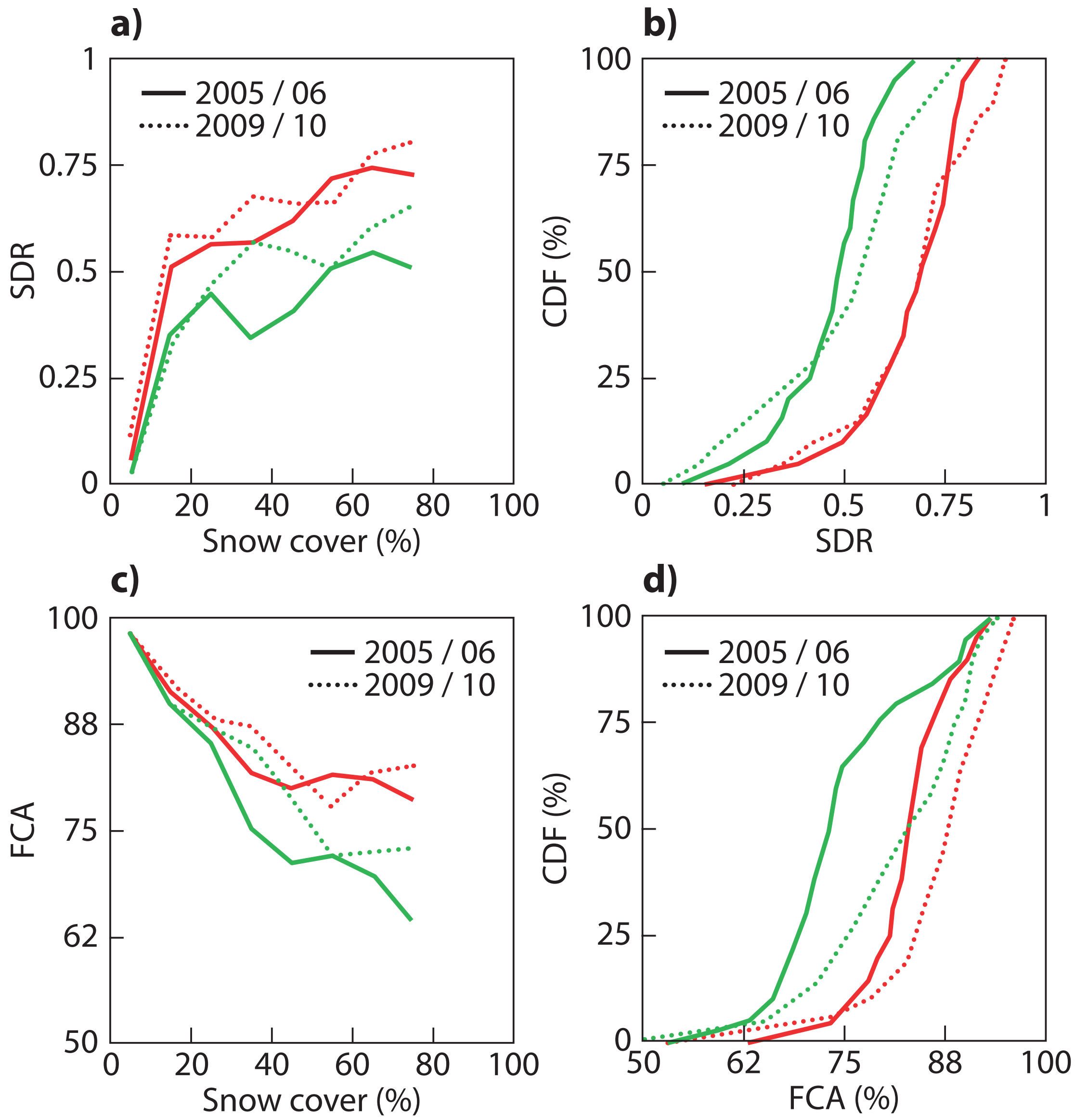

Fig. 12: Snow statistics calculated over Europe for (a) Snow Detection Rate and (b) cumulative distribution function of the Snow Detection Rate for 2005-2006 and 2009-2010 (1st of July to 30th of June), for ERA-Interim/Land (red) and ERA-Interim (green) surface offline simulations. The Fraction of Correct Accuracy function of snow cover (c) and its cumulative distribution function (d) for 2005-2006 and 2009-2010 (1st of July to 30th of June), for ERA-Interim/Land (red) and ERA-Interim (green) surface offline simulations.

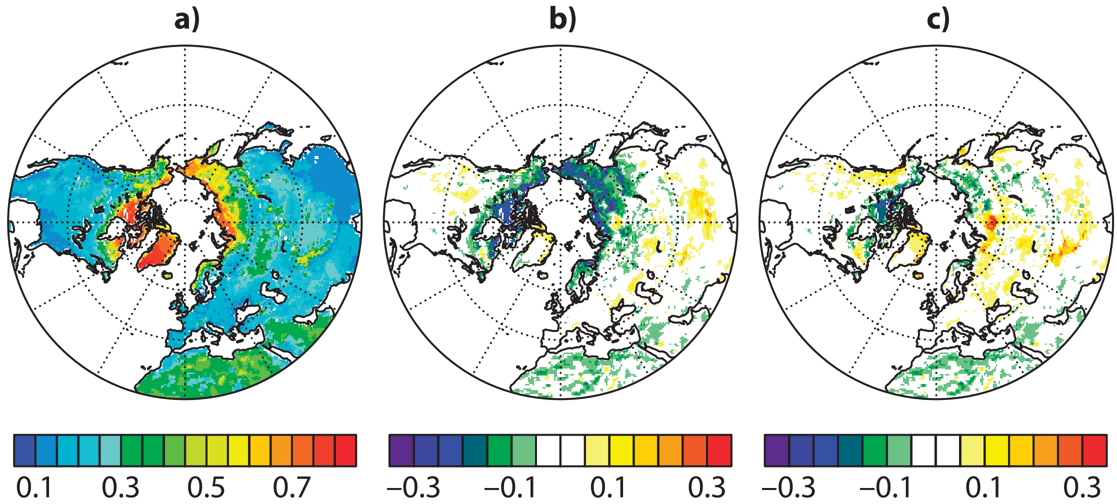

Fig. 13: Mean observed Northern hemisphere albedo during spring derived from (a) MODIS and differences of (b) ERA-Interim and (c) ERA-Interim/Land.