TECHNICAL MEMORANDUM

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Soil temperature at ECMWF: an assessment using ground-based observations

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Abstract

Soil temperature is an important variable for the representation of many physical processes in Numerical Weather Prediction (NWP). It is the key driver for all surface emissions of energy, carbon dioxide, water and forward operator for all satellite sensors sensitive to land. Yet the forecast quality of this variable in NWP is largely unknown. In this study, in situ soil temperature measurements from nearly 700 stations belonging to four networks across the United States and Europe are used to assess the European Centre for Medium-Range Weather Forecasts (ECMWF) forecasts of soil temperature during 2012. Evaluation of the time series shows a good performance of the short range forecasts (day one) in capturing both soil temperature annual and diurnal cycles with very high level of correlation (0.92 and over), averaged root mean square differences ranging from 2.54°C to 3.89°C and averaged biases ranging from -0.52°C to 0.94°C. The orography dataset used in the forecast system was found to have a strong impact on the outcomes of the evaluation. The difference between elevation of a station and that of the corresponding grid cell in the ECMWF model may lead to large temperature differences linked to linear processes resulting in a constant bias, as well as non-linear processes (e.g. to snow melt in spring). This verification study aims to contribute to a better understanding of the near-surface forecasts performance highlighting land-atmosphere processes that need to be better represented in future model development such as snow pack melting and heat diffusion in the soil.

1 Introduction

Numerical Weather Prediction (NWP) systems produce forecasts of a large variety of geophysical variables, describing the state of the atmosphere as well as ocean-wave and land-surface conditions. In NWP, Land Surface Models (LSMs) are used to provide the lower boundary condition to the atmosphere, influencing the accuracy of the atmospheric forecasts at all ranges (hourly to seasonal scale). They are also a crucial component for representing the hydrological cycle (Mueller and Seneviratne 2012; Entekhabi et al 1999; Koster and Suarez 1992). While some variables directly linked to the intended application of LSM were thoroughly evaluated (e.g. soil water content; Albergel et al., 2012, 2013) very little literature exists on others considered as intermediate, such as soil temperature (Holmes et al., 2012).

Soil temperature is an important variable for the representation of many physical processes in NWP and it is also of paramount importance for satellite retrievals to disentangle atmospheric and land emissions; continental surface radiative emissions in all spectrum frequencies depend on soil temperature, as well as evaporation fluxes, soil water phase change, ecosystem exchange (respiration and gross primary production).

In order to simulate surface emissivity the European Centre for Medium-Range Weather Forecasts (ECMWF) has developed the Community Microwave Emission Modelling platform (CMEM, Holmes et al., 2008; Drusch et al., 2009; de Rosnay et al., 2009). This forward operator enables direct assimilation of near real time brightness temperature (Tb) in the L-band (Muñoz-Sabater et al., 2012) such as those provided by the Soil Moisture and Ocean Salinity (SMOS, Kerr, 2010) mission. However the assimilation can be effective only if realistic and dynamically consistent fields of Tb are simulated as a function of land-surface conditions. The temperature of the first layer of soil is, amongst other surface fields, coupled with CMEM to produce ECMWF's first-guess Tb and therefore an evaluation of its accuracy is important to better characterize the model errors for data assimilation purposes. The soil temperature forecasts from ECMWF are used also in the SMOS level2 (i.e. soil moisture) iterative optimization scheme, as well as in the planned Soil Moisture Active Passive (SMAP) L-band retrieval algorithm (Entekhabi et al., 2010). More generally the soil temperature analyses and forecasts from

ECMWF are used in a large variety of applications; (i) to initialise regional climate models (Cui et al., 2008) and meteorological models (e.g., RAMS, Ødegaard et al., 2005), (ii) to drive production efficiency models (e.g., the TURC model, Lafont et al., 2002), (iii) as an input in the production chain of satellite derived products such as evapotranspiration from the Land-SAF (Land-Satellite Application Facilities, http://landsaf.meteo.pt/) and liquid root zone soil moisture from the H-SAF (Satellite Application Facility on Support to Operational Hydrology and Water Management, http://hsaf.meteoam.it/).

All these applications are influenced to some extent on soil temperature and highlight the importance of this variable as well as the need to assess its accuracy. An important part of evaluating NWP estimates is to determine whether their behaviour matches independent observations. Hence in situ measurements of soil temperature are a highly valuable source of information. In this study, in situ measurements of soil temperature from nearly 700 stations (over more than 800 available) from 4 networks in the United States and one in Europe (SYNOP stations, synoptic reports) are used to evaluate the ability of ECMWF to represent soil temperature annual variability and diurnal cycle amplitude during 2012. The different soil temperature products are described in section 2 (and presented in Table 1) along with the strategy used for the evaluation. Results are described and discussed in sections 3 and 4, respectively. Section 5 provides a summary and conclusions.

Table 1: Presentation of the different soil temperature products used in this study. NWP stand for numerical weather prediction. 891 stations with in situ observations are available.

Soil Temperature data set	**Type**	**Soil layer depth used (cm)**	**Spatial resolution**	**Number of stations**
ECMWF IFS	NWP analysis	0-7	~16 km (T1279)	Global product
NCRS-SCAN (**US**)	In situ observations	~5	Local scale	174 stations
NCRS-SNOTEL (**US**)	In situ observations	~5	Local scale	347 stations
USCRN (**US**)	In situ observations	~5	Local scale	114 stations
Synoptic report (**Ireland, Germany, Czech Republic and Hungary**)	In situ observations	~5	Local scale	256 stations

2 Material and methods

2.1 In situ measurements

Data from 3 networks spanning all over the United States are considered in this study: NRCS-SCAN (Natural Resources Conservation Service - Soil Climate Analysis Network), NRCS-SNOTEL (short for Snow Telemetry) and USCRN (U.S. Climate Reference Network) over the United States (174, 347 and 114 stations). Soil temperatures from synoptic reports from 4 countries in Europe are also used: Ireland, Germany, Czech Republic and Hungary (252 stations). While synoptic reports from some other countries in Europe were available for greater depths, this study focuses on stations which provide observations at 5 cm depth. Figure 1 illustrates the location of the stations.

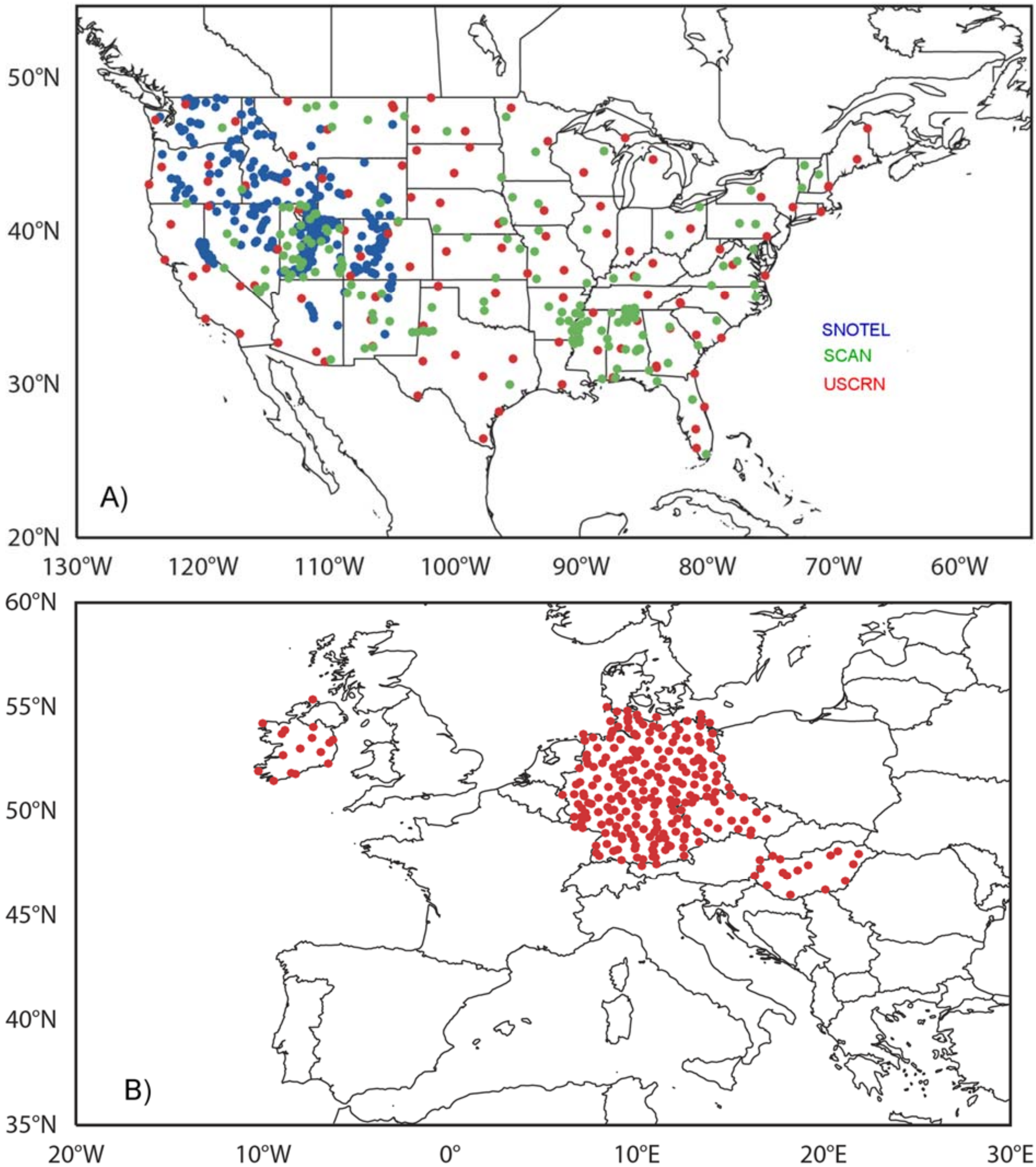

Figure 1: Location of the different in situ soil temperature stations used in this study; A) the stations belong to the NCRS-SCAN (green dots), the NRCS-SNOTEL (blue dots) and USCRN (red dots) networks, B) stations with synoptic measurements. Measurements are available at 5cm depth.

2.1.1 SCAN, SNOTEL and USCRN networks

The SCAN and SNOTEL networks (Schaefer and Paetzold 2000 http://www.wcc.nrcs.usda.gov/) are a comprehensive, nation-wide soil moisture and climate information system designed to provide data to support natural resource assessments and conservation activities. It is administered by the United States Department of Agriculture (USDA) Natural Resources Conservation Service (NRCS) through the National Water and Climate Centre (NWCC), in cooperation with the NRCS National Soil Survey Center. The system focuses on agricultural areas of the U.S. The observing network monitors soil temperature and soil moisture at several depths, soil water level, air temperature, relative humidity, solar radiation, wind, precipitation and barometric pressure amongst others. SCAN and SNOTEL data are used for a variety of purposes ranging from global climate modelling to agricultural studies. The vegetation cover at SCAN sites consists of either natural fallow or short grass. Stations from the SNOTEL network are designed to collect snowpack and related climatic data in the Western U.S. and Alaska. They are located in rather mountainous areas. The U.S. Climate Reference Network from the National Oceanic and Atmospheric Administration's (NOAA's) National Climatic Data Center (USCRN NOAA's NCDC) consists of 114 stations developed and maintained by NOAA in the continental United States with the purpose of detecting the national signal of climate change (Bell et al., 2013). USCRN's main objective is to provide climate-science-quality measurements of air temperature and precipitation. The stations in the network were designed to be extendable to other missions and in 2011, the USCRN team completed at each station in the conterminous United States the installation of triplicate-configuration soil temperature probes at five standards depths. Data from these networks are typically collected by a thermistor; thermometer and measurements are made at 5, 10, 20, 50 and 100 cm.

2.1.2 Synoptic reports

Surface synoptic observations (SYNOP hereafter) report weather observations made by manned and automated weather stations. They are a major source of in situ observations used in NWP. These observations are to a large extend available in near real time on the Global Telecommunication System. In this study soil temperature measurements (5cm depth) from synoptic reports belonging to 4 countries in Europe, Ireland, Germany, Czech Republic and Hungary (252 stations) are used.

2.2 ECMWF's IFS

Analysis and forecast data produced at ECMWF include a large variety of surface parameters, describing atmosphere as well as ocean-wave and land-surface conditions. The atmospheric analysis is produced using a four-dimensional variational (4D-Var) data assimilation scheme (Rabier et al., 2000, Mahfouf et al., 2000a) with an observation time window of 12 hours (Bouttier, 2001). All the available observations (e.g. satellite sensors both from microwave and infrared radiometers, conventional observations from radiosonde and synoptic networks etc.) are combined with prior information provided by the background to estimate the evolving state of the global atmosphere and its underlying surface. At ECMWF this involves the computation of a variational analysis for the upper-air atmospheric fields followed by separate analyses of near-surface parameters, soil moisture, temperature, snow (de Rosnay et al., 2014) and ocean waves. These analyses are then used to initialize a short-range forecast, providing the background estimates needed for the next analysis cycle. A full description of ECMWF's model physics and data assimilation is available at http://www.ecmwf.int/research/ifsdocs/. The versions of the Integrated Forecast System (IFS) used at ECMWF during the time period of this study where 37r2 to 38r1.

2.2.1 Land surface modelling and analysis systems

Many upgrades have recently been implemented in the land surface modelling and analysis systems of the IFS used operationally at ECMWF. The model forecast for the land surface analysis is provided by the Hydrology Tiled ECMWF Scheme for Surface Exchanges over Land (HTESSEL LSM, Balsamo et al. 2009). HTESSEL was implemented in the IFS in November 2007 and verified in various ways including field site comparison, data assimilation and modelling experiments by Balsamo et al. (2009)

and Albergel et al. (2012). The HTESSEL formulation of the soil hydrological conductivity and diffusivity takes into account spatial variability according to a global soil texture map (FAO/UNESCO Digital Soil Map of the World, DSMW, FAO, 2003). The soil heat budget follows a Fourier diffusion law, modified to take into account soil water freezing and melting according to Viterbo et al. (1999). The energy equation is solved with a net ground heat flux as the top boundary condition and a zero flux at the bottom. In HTESSEL, the soil is discretised in four layers (0-7, 7-28, 28-100 and 100-289 cm).

The land-surface analysis includes the screen-level parameters analysis, the snow depth analysis, soil moisture analysis, soil temperature and snow temperature analysis. Three analysis schemes for the surface (and near-surface) variables are used in operations at ECMWF (de Rosnay et al., 2014). They are based on (i) spatial Optimal Interpolation (2D-OI, for snow depth and screen-level analyses), (ii) column Optimal Interpolation (1D-OI, for soil and snow temperature analysis), and an Extended Kalman Filter (EKF for soil moisture analysis, Drusch et al., 2009b; de Rosnay et al., 2013). Analysis of surface parameters is done separately from the main atmospheric analysis. The atmospheric and soil analysis are fused together after each analysis cycle, to produce the background state for the next analysis. Firstly an OI scheme produces estimates of screen-level temperature and relative humidity by analysing synoptic observations over land, using background estimates (short-range forecasts) initialised from the previous analysis (Douville et al., 2001). Analysed fields of screen level temperature and relative humidity are then used as input to the soil moisture and soil temperature analyses. The forecast model predicts a wide variety of physical variables (e.g. including precipitation). Even if not directly observed, the model estimates are constrained by the observations used to the analysis that is the initial state for the forecast. Their accuracy relies on the quality of the forecast model as well as that of the analysis. At the end of each data assimilation cycle an adjustment to the model forecast (e.g. for soil temperature) is produced. It is called the analysis increment and represents the net response of the variational data assimilation to all observations used. The operational IFS analysis is produced four times a day at 00:00, 06:00, 12:00 and 18:00 UTC; from 26 January 2010 it has a spatial resolution of about 16 km (T1279).

2.2.2 Soil temperature analysis

The temperature of the uppermost layer of soil is analysed using a point-wise 1-dimensional optimum interpolation (1D OI) technique as described in Mahfouf (1991), Mahfouf et al. (2000b) and Douville et al. (2001). The analysis increments from the screen-level temperature analysis are used to produce increments for the first layer soil temperature and snow temperature (Eq.1).

$$\Delta T = c(T_a - T_b) \qquad \text{(Eq.1)}$$

Ta and Tb are the analysed and model first-guess temperatures, respectively. The coefficient c (Eq.2) providing the analysis increments relies on two empirical functions that account for; (F1, Eq.3) the cosine of the mean solar zenith angle (µM) and (F3, Eq.4) the model orography (to reduce the increments over mountainous areas where observations are considered less reliable).

$$c = (1 - F_1)F_3 \text{ (Eq.2)}$$

$$F_1 = \frac{1}{2}\{1 + \tanh[\lambda(\mu_M - 0.5)]\} \quad \lambda = 7 \qquad \text{(Eq.3)}$$

$$F_3 = \begin{cases} 0 \;\; if\; Z > Z_{max} \\ \left(\frac{Z - Z_{max}}{Z_{min} - Z_{max}}\right)^2 \;\; if\; Z_{min} < Z < Z_{max} \\ 1\; if\; Z < \; Z_{min} \end{cases} \qquad \text{(Eq.4)}$$

Where Z is the model orography, Zmin=500m and Zmax=3000m.

The coefficient c is constructed such that soil temperatures analysis is more effective during night and in winter when the temperature errors are less likely to be related to soil moisture. Figure 2 illustrates soil temperature analysis increments for the first layer of soil (0-7cm) for the first of June 2013 (00:00 and 12:00 UTC).

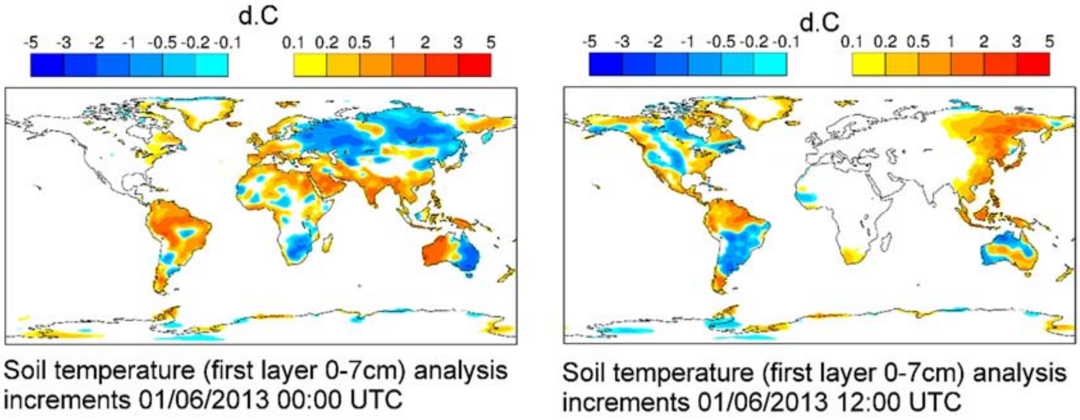

Figure 2: Soil temperature analysis increments for the first layer of soil (0-7cm) represented in ECMWF IFS on 01/06/2013 00:00 UTC (left) and 12:00UTC (right).

2.3 Evaluation strategy

While observations used in this study have an hourly time step, the operational IFS analysis is produced continuously. To investigate the soil temperature diurnal cycle it was decided to evaluate ECMWF forecasts (available hourly) instead of the analysis. Every day of the year 2012, ECMWF forecasts of soil temperature initialized at 00:00 UTC with lead times from 0 to 23 hours (forecast day one) are compared to in situ measurements. The nearest neighbour approach was used to match grid point location of soil temperature from ECMWF with that of in situ measurements. Processing of ECMWF soil temperature also includes a height correction. As illustrated by figure 3 (left) for the stations of the USCRN network, the difference in elevation between the ECMWF grid point and the station is noticeable in several points due to representativeness mismatch between local observations and the gridded model. When this difference is greater than 300 m, a correction was applied to ECMWF IFS (6.5°C/1 km). 300 m is also the difference threshold used in the ECMWF analysis to reject screen level temperature from synoptic reports from the analysis. It represents 8%, 8%, 33% and 4% stations from the USCRN, SCAN, SNOTEL and SYNOP networks, respectively. Figure 3 (right) illustrates this correction for the Darrington station (Washington USA) of the USCRN network; the station is at 124 m ASL and the ECMWF IFS at 787m a.s.l. A correction of about +4K was applied reducing the systematic cold bias of the forecasts.

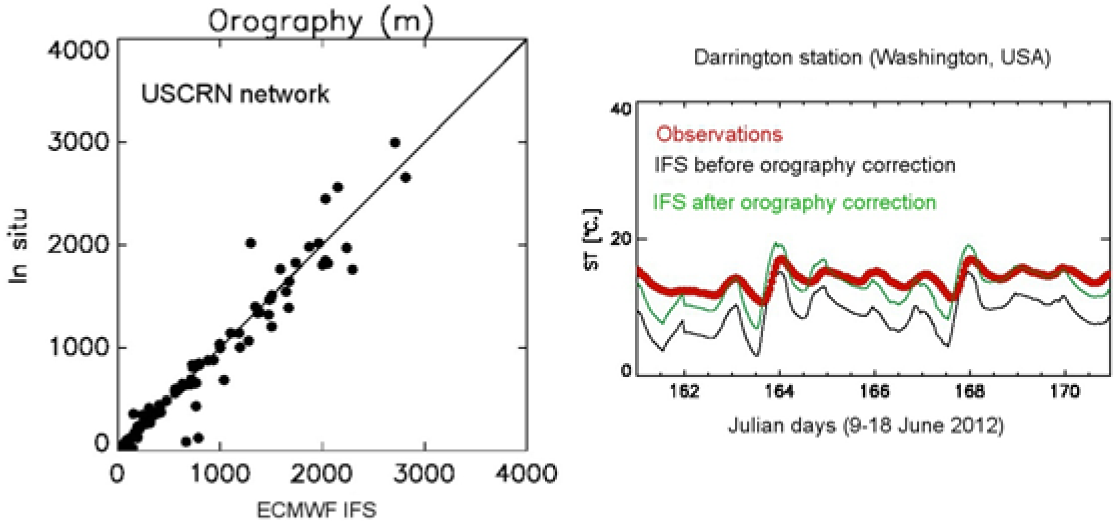

Figure 3: Left; difference in orography between ground measurements and the grid point location of ECMWF IFS for the stations of the USCRN network. Right; impact of the orography correction on surface soil temperature annual cycle (2012) for the Darrington station (Washington DC, USA).

For all stations, correlations (R), bias (in situ minus ECMWF), root mean square difference (RMSD) and p-value are calculated. The latter indicates the significance of the correlation. Using a 95% confidence level in this study (Albergel et al., 2013), only results where the p-value is below 0.05 (i.e. the probability of the correlation being equal to zero is reduced) are retained. Scores are computed for forecast time steps from 00:00 to 23:00, however to reduce the tables size, only scores at 00:00, 06:00, 12:00 and 18:00 are reported in the Tables. While the datasets are originally in Coordinated Universal Time (UTC), they were converted in Local Solar Time (LST), so results at each station of each network can be compared. Finally, ECMWF daily minimum and maximum values of soil temperature are evaluated.

3 Results

3.1 Soil temperature annual and diurnal variability, daily amplitude

The statistical scores for the comparison between ground measurements and ECMWF IFS soil temperature are presented in Table 2 for 699 stations. Averaged over all time steps, correlations (R) from all stations for each network range from 0.92 to 0.96. Averaged RMSD are between 2.54°C and 3.89°C, and Biases between -0.52°C and 0.94°C. Smallest RMSD values are found at 00:00 and 06:00 LST (below 3°C for the stations over the USA and below 2°C for those in Europe), while daytime values are generally higher (particularly from 12:00 to 15:00 LST). Over Europe positive bias values (in situ minus forecasts) indicate that the forecasts slightly underestimate soil temperature at all-time range. Biases are however higher at daytime than at night-time. Considering the United States, averaged biases from 00:00 to 06:00 LST are positive while values at 12:00 LST (to 18:00 LST to a lesser extent) are negative. Evaluation of the daily minimum and maximum values gives similar results (see Table 2).

Table 2: Statistical scores for the comparison between ECMWF operational forecast of soil temperature (initialized at 00:00 UTC with lead times from 0 to 23 hours) and ground measurements for 2012 (times are Local Standard Time, LST). Only stations that have significant correlation values (p-value<0.05) are considered leading to a total of 699 stations. Correlations are dimensionless, RMSD and Bias are in Celsius degrees. Values in parenthesis correspond to the same evaluation considering stations that have an elevation difference with ECMWF grid point (operational Integrated Forecast System) smaller than 50m.

	Scores	All	00:00	06:00	12:00	18:00	D. min	D. max
USCRN (US) 108(71) stations	R	0.96(0.96)	0.97(0.97)	0.97(0.97)	0.97(0.97)	0.97(0.97)	0.97	0.96
	RMSD	3.14(2.81)	2.56(2.16)	2.55(2.19)	3.79(3.68)	3.15(2.74)	2.55	3.88
	Bias	-0.08(-0.55)	1.12(0.61)	1.32(0.87)	-2.23(-2.61)	-0.20(-0.70)	1.22	-1.51
SCAN (US) 140(80) stations	R	0.95(0.96)	0.96(0.97)	0.96(0.97)	0.96(0.97)	0.96(0.96)	0.96	0.95
	RMSD	3.32(2.87)	2.48(2.20)	2.50(2.24)	4.15(3.55)	3.43(2.95)	2.46	4.42
	Bias	-0.52(-0.40)	0.57(0.49)	0.93(0.85)	-2.31(-1.93)	-1.00(-0.84)	0.84	-1.92
SNOTEL (US) 273(46) stations	R	0.92(0.93)	0.95(0.95)	0.94(0.94)	0.95(0.96)	0.95(0.96)	0.94	0.94
	RMSD	3.89(3.43)	2.91(2.57)	2.79(2.49)	4.89(4.36)	4.30(3.67)	2.75	5.21
	Bias	-0.41(-0.15)	0.80(0.92)	1.09(1.02)	-2.03(-1.63)	-1.38(-0.82)	1.05	-1.93
SYNOP (Europe) 178(121) stations	R	0.96(0.96)	0.97(0.97)	0.97(0.98)	0.97(0.97)	0.97(0.97)	0.96	0.97
	RMSD	2.54(2.54)	1.80(1.73)	1.52(1.45)	3.27(3.35)	2.88(2.88)	1.78	3.94
	Bias	0.94(0.93)	0.30(0.25)	0.27(0.19)	1.48(1.57)	1.47(1.48)	0.30	2.22

The highest RMSD values are found for the SNOTEL network and the smallest for the SYNOP network. These results were expected. Stations from the SNOTEL network are designed to collect snowpack and related climate data; they are located at rather high altitude where more extreme conditions prevail. Figure 4 illustrates the soil temperature annual cycle for two stations belonging to the SNOTEL network.

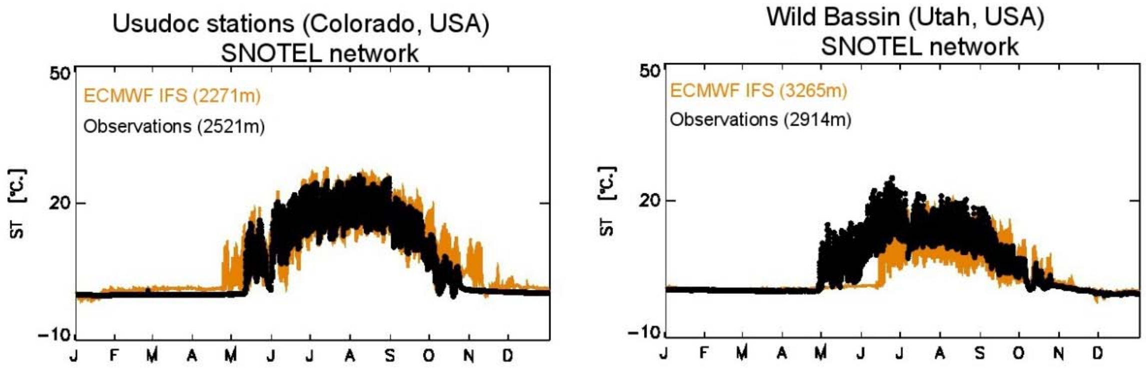

Figure 3: Annual cycle for 2012 of surface soil temperature observations (black) and IFS estimates (orange) for two sites of the US SNOTEL network in Colorado (left) and Utah (right).

In Fig.4 (left) the local station elevation is 2521m while that of the corresponding ECMWF IFS grid point is lower (2271m). As a result, in reality the ground is still frozen until early May with observations close to 0°C while in the forecasts temperatures are already above 0°C in April. Fig.4 (right) presents a different scenario obtained for another location: the station elevation is 2914m and that of ECMWF IFS is 3265m. For a few weeks (May to mid-June) soil temperature forecasts are close to 0°C while observed daily maximum values are above 15°C. These conditions lead to high values of bias and RMSD, highlighting the difficulty of soil temperature evaluation in mountainous areas due to representativeness issues; difference in orography between local measurements and ECMWF IFS grid points does not imply that the latter is not correct.

The better agreement obtained between local measurements and forecasts for the SYNOP network (smaller RMSD) is partly due to the fact that the SYNOP network also reports 2-metre temperature values that are used in the soil temperature analysis.

Table 3 presents the annual mean of soil temperature daily amplitude and figure 5 illustrates (i) the annual mean of soil temperature diurnal cycle and (ii) the RMSD diurnal cycle for the four networks used in this study. All the year 2012 is represented as well as January to March (JFM) and July to September (JAS). Correlations values are 0.92, 0.90, 0.97 and 0.99 for USCRN, SNOTEL, SCAN and SYNOP networks, respectively. On average, soil temperature observed over the US presents smaller amplitude than that of ECMWF IFS (by a difference of 3°C) while over Europe it is the opposite, with observations having a 1.5°C higher amplitude than that of ECMWF IFS. As already mentioned the IFS forecasts model tend to overestimate soil temperature over the US and underestimate it over Europe, particularity during daytime. Looking at the RMSD diurnal cycle, similar error structures are observed considering JFM and JAS with higher RMSD at daytime (particularly from 12:00 to 15:00 LST). As expected, during daytime JAS has higher temperatures than JFM, which results in higher RMSD (more subject to error in the forcing). Smallest errors are obtained between 06:00 and 08:00 for to the period considered.

Table 3: Observed and forecast soil temperature annual daily mean amplitude for the 4 networks considered in this study.

	USCRN (US) 108 stations		**SCAN (US) 140 stations**		**SCAN (US) 140 stations**		**SYNOP (Europe) 178 stations**	
Mean Amplitude (ºC)	Obs.	IFS	Obs.	IFS	Obs.	IFS	Obs.	IFS
	6.02	8.87	6.42	9.70	3.34	6.41	6.81	5.23

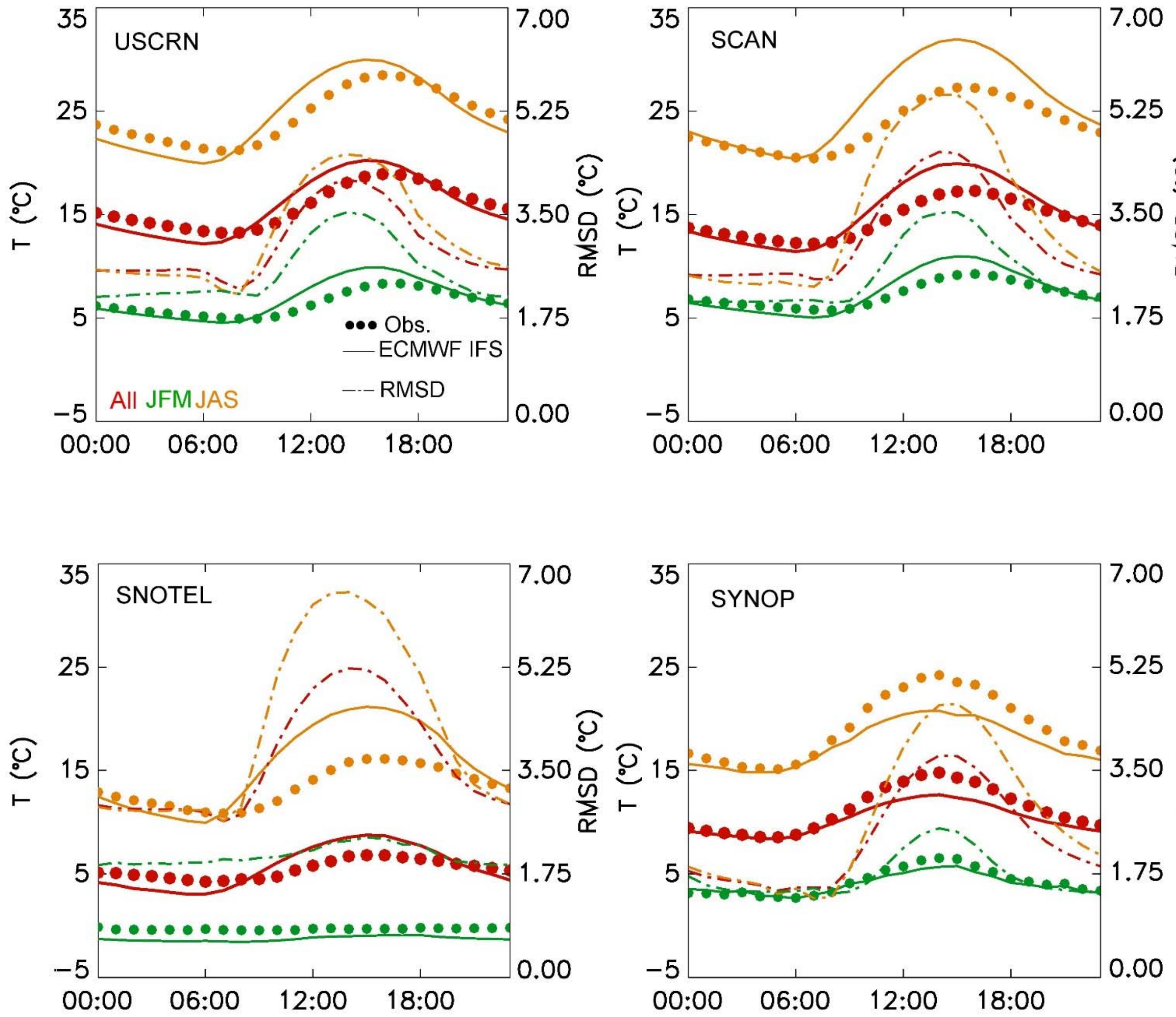

Figure 4: Mean diurnal soil temperature cycle for the 4 networks used in this study (SCAN, USCRN, SNOTEL and SYNOP) for all 2012 (All in red), January to March (JFM in green) and July to September (JAS in orange). Dashed lines represent the mean diurnal RMSD.

3.2 Impact of orography, land cover, soil moisture

Orography plays an important role in the representation of soil temperature. Figure 6 illustrates the diurnal cycle of soil temperature for a period of a nine days in June. Figure 6 top panel shows three stations that have almost a perfect match between observations and forecasts of soil temperature, while Figure 6 bottom panel illustrates stations where the differences between observations and model forecast are considerable. These differences are of different type: a systematic bias (e.g. fig.6d), an error in the amplitude (e.g. fig.6e where the model captures well the minimal values but not the maxima) or a mismatch in both the amplitude and the phase of the diurnal cycle (e.g. fig.5f). One main difference between the three stations from figure 6 top and bottom is the difference in height between the station and the corresponding model point. Differences between the elevation of the stations and that of

ECMWF IFS are 32, 22 and 4.5m for the stations of figure 6a, b and c, respectively. They are 331, 203 and 7m for the stations of figure 6d, e and f, respectively.

The difference in orography is not high for fig.6e but this station is located in an urban area which is not represented well by the land surface model or land cover. This station is part of the SYNOP network which means that the 2-m temperature observed at this location are used to analyse soil temperature. The proximity of the station to Greifswald in northern Germany makes that observations are representative of an urban area that is not represented well in the model. Within ECMWF IFS, each land surface grid-box is divided into tiles, with up to six fractions over land (bare ground, low and high vegetation, intercepted water, shaded and exposed snow). The surface type of the model grid point closest to Greifswald consists of 10% of bare ground, 56% of high vegetation and 34% of low vegetation; this can explain the large bias in fig.6f.

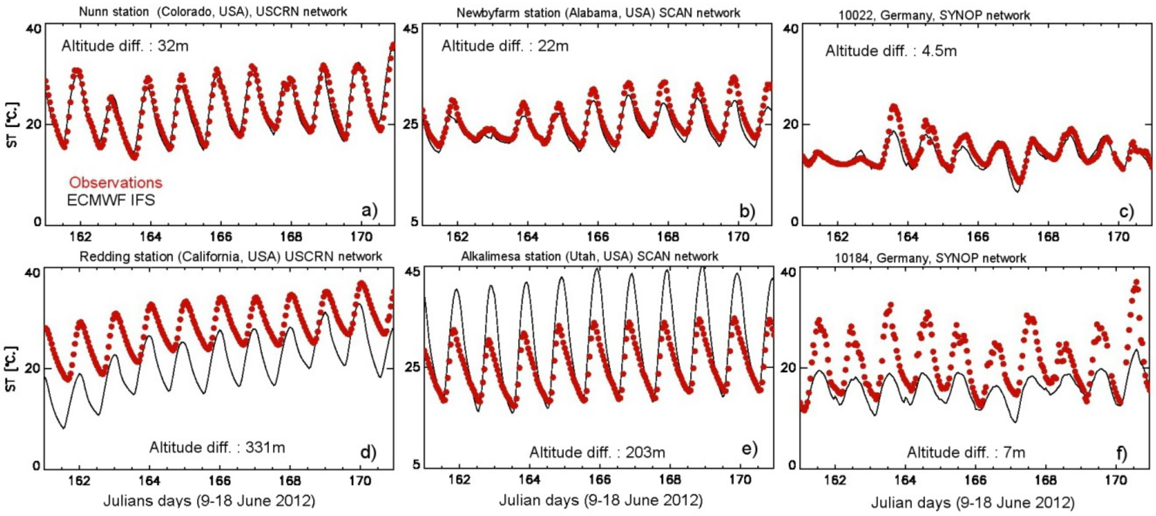

Figure 5: Soil temperature diurnal cycle for 6 stations belonging to the USCRN, SCAN and SYNOP networks (from left to right). Observations are in red, ECMWF IFS in black.

Statistical scores are not particularly better or worse when stratifying them with respect to the fractions of bare ground, low and high vegetation (not shown). Although no relation was found between RMSD values for soil temperature and those for soil moisture (based on observations from the USCRN, SCAN networks), smaller RMSD of soil temperature are found at locations with higher mean soil moisture, as illustrated by figure 7.

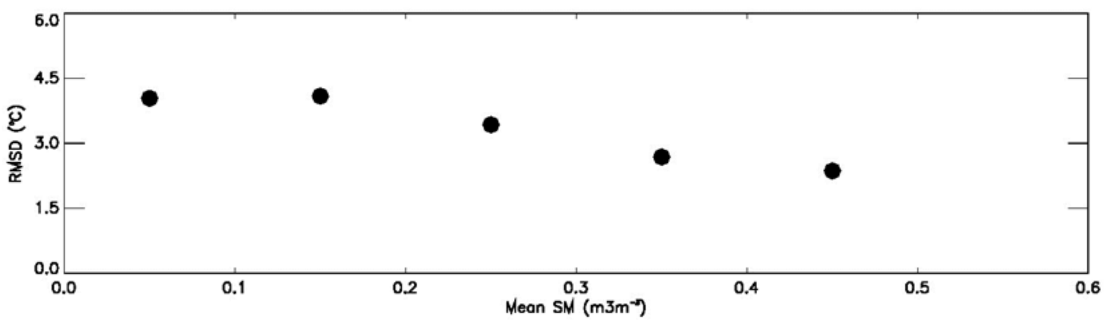

Figure 6: Mean RMSD values for stations from the SCAN network (US) with respect to the mean soil moisture content.

3.3 Sensitivity to snow cover: Wild Basin station

To further highlight the interplay between snow and soil temperature ECMWF LSM was run offline for a single grid point over the Wild Basin station (Colorado, USA, SNOTEL network). As mentioned above, the nearest grid point of this station has an elevation of 3265m while the station is at 2914m. The atmospheric forcing was corrected to match the elevation of the station; a height correction of 6.5°C/km was applied as well as a barometric correction for surface pressure and a correction of specific humidity to conserve relative humidity. Top panel of figure 8 shows daily means of observed and simulated soil temperatures and snow depth for a 3-month period (April to June 2012). A detailed description of the snow scheme and verification from field site experiments to global offline simulations is presented in Dutra et al. (2010). Snow depth is calculated in the model using the snow water equivalent as well as the snow and water densities.

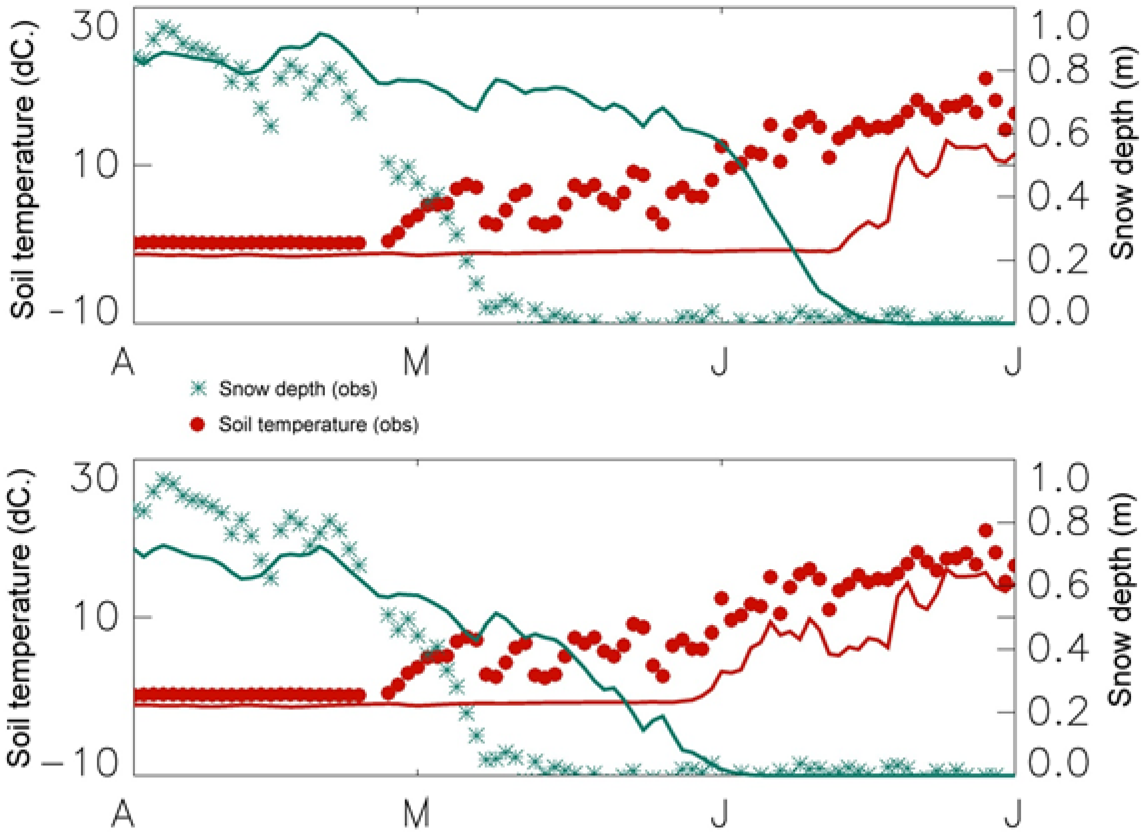

Figure 8: Simulated soil temperature at the Wild Basin station (US SNOTEL network in Colorado) location from April to June using offline H-TESSEL runs with (top) default model orography and (bottom) the corresponding local observation station altitude. Continuous lines are for the model (soil temperature in red and snow depth in blue), red dots for observed temperature and blue stars for observed snow depth.

Observed and modelled soil temperatures and snow depth differ significantly in this case. It is interesting to notice that at the station level, the soil starts warming while there is still a significant amount of snow (about 40cm) while in the model snow depth has to reach 10cm for the soil to start to warm up. Matching ECMWF grid point elevation to that of the station (fig.8, bottom panel) results in an earlier start of soil heating. However the snow amount present in the model is still too high compared to the observations; it takes too long to melt. This case also underlines representativeness issues; the ECMWF spatial grid distance used in this case is 16 km and the station is representative of a single location. While a snow depth of about 40cm is observed at the station when soil temperatures start to rise, in the model it has to wait until the entire grid point is covered by less than 10cm of snow. Forty centimetres of snow at the location of the stations might not be representative of a 16kmx16km surrounding area. Also, in this case study, errors in the precipitation forecast represent an additional source of uncertainty, which is not accounted for. It is also acknowledged that the station was selected for a case where the model deficiencies were very evident.

4 Discussion

The results presented above demonstrate that ECMWF IFS predicts soil temperatures rather well, the smallest errors are present in early morning between 06:00 and 08:00 LST where the soil is most likely to be in near-thermodynamic-equilibrium. The largest errors are present around 12:00 to 15:00 LST. This is the time of strongest coupling between soil and boundary layers due to available incoming radiative fluxes triggering processes that enable water and energy exchanges between the surface and the atmosphere. As forecasts of soil temperature initialized at 00:00 UTC with lead times from 0 to 23 hours (day-1 forecast) have been used in this study, one may expect to obtain worse scores at longer lead times. But day-3 forecast skill (forecast of soil temperature initialized at 00:00 UTC with lead times from 48 to 71 hours) is found to be very similar to that of day-1 (not shown). This suggests that improvements on the amplitude of the diurnal cycle are likely to be maintained at different forecast ranges.

SYNOP stations in Europe have smaller RMSD than stations in the US. As the information contained in meteorological observations of air temperature close to the surface from the SYNOP stations is used to analyse soil temperature, this analysis is more reliable in data-rich areas (i.e. where most synoptic reports are available).

The difference in station height and the ECMWF IFS model orography leads a constant bias and a difference in the length of period with frozen conditions (as illustrated by figures 3, 4 and 8). ECMWF is implementing the use of new climatic fields including a new orography. The difference between the orography used in the model for 2012 and the upcoming one is illustrated by figure 9.

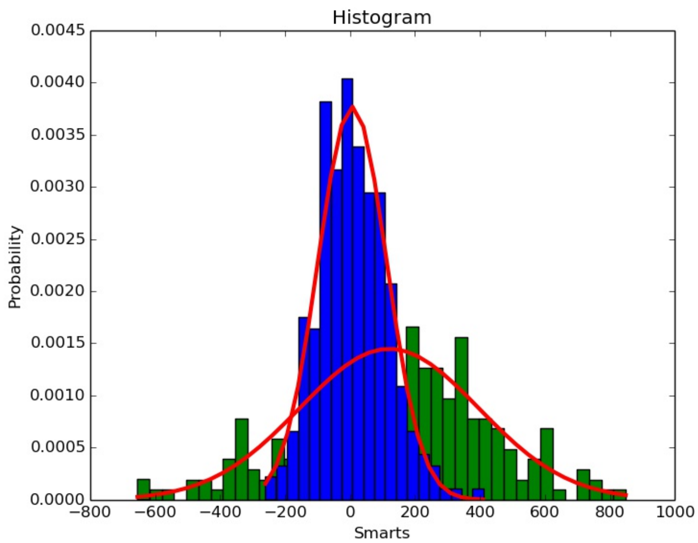

Figure 7: Probability density function of elevation differences for the stations from the SNOTEL network against that of ECMWF IFS nearest grid point; as used in operations in 2012 (green), new orographic fields (blue).

On this figure, the probability density function of elevation differences for the stations from the SNOTEL network and that of ECMWF IFS correspondent nearest grid point (as used in operations in 2012) is represented by the green bars, blue bars are for the new orographic fields. The latter are more centred on 0 with a smaller standard deviation, i.e. in a better agreement. Also one may note that using the new orographic fields removes almost all the outliers (elevation differences greater than 500m). On average, the difference (absolute values) between the elevation of the stations and that of the corresponding points in the IFS is 234m, 104m, 83m and 53m for the SNOTEL, SCAN, USCRN and SYNOP networks, respectively. Using the new orography averaged differences are reduced to 82m, 44m, 29m and 20m for the same group of stations. However, improving the orography will not remove all discrepancies between model and observations as local station/model grid representativeness remains an issue for validation activities (c.f. figures 4, 8). Physical processes such as the melting of snow require a more in depth analysis. It is also acknowledged that the representation of snow in the forecast model is rather crude and a new more advanced scheme is under development. One may also keep in mind that results are complicated by representativeness issues: (i) the fact that single in situ measurements are used to validate areal averages of temperature estimates (~16kmx16km) model grid and that (ii), observations at 5cm depth are compared to the first layer of ECMWF IFS that represents the first 7 cm of soil. Diurnal temperature cycle is determined by the surface energy balance between net radiation, latent and sensible heat flux and the ground heat flux into the soil. Although the incoming solar radiation reaches is maximum at solar noon, the net energy input into the soil remains positive for several hours continuing to warm the soil. There is a time-lag between the daily temperature maximum and its solar noon; the further away a specific layer is from the surface the longer is it. The vertical distance between the measurements depths as well as the thermal properties of the medium determine the length of this time lag making it difficult to compare NWP estimates and in situ observations that are not representative of the same depth. Nevertheless, this study presents an overall assessment of ECMWF IFS's ability to forecast soil temperature using observations from a wide range of climate, vegetation, and soil conditions. For stations from the USCRN network, 2-metre temperature was also investigated. A good agreement was found between observations and ECMWF IFS forecast of 2-metre temperature initialized at 00 UTC with lead times 0 to 23 hours with averaged R, RMSD and Bias of 0.97, 2.56 °C and -0.60 °C, respectively. For this group of stations ECMWF IFS slightly overestimates soil temperature at 00:00, 06:00, 12:00 and slightly underestimate them at 18:00 (LST). As illustrated by figure 10, the amplitude of the annual mean diurnal cycle of 2-metre temperature is higher than that of the soil temperature.

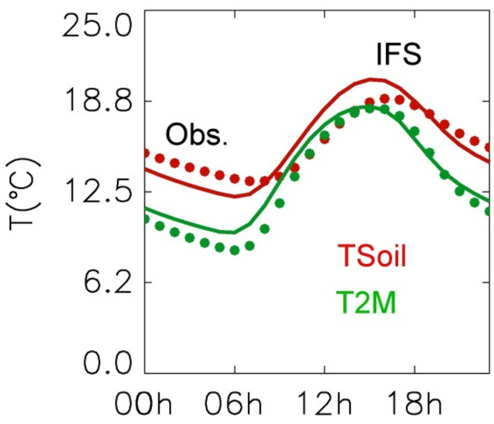

Figure 8: Annual mean diurnal cycle for 2-metre (in green) and soil temperature (in red) for the stations of the USCRN networks spanning all over the United States. ECMWF IFS is represented by solid lines, observations by dots.

A clear link between 2-metre temperature errors and soil temperature errors was found. The correlation between 2-metre biases and soil temperature biases is 0.72 for all data. It is less pronounced for RMSD with a correlation value 0.56. It follows expectations, as both the forecast model and the data assimilation establish strong links between near-surface atmosphere and the uppermost soil layer.

An accurate representation of soil temperature is a prerequisite for SMOS (and later SMAP) brightness temperatures data assimilation at ECMWF using a radiative transfer model such as the CMEM platform. The latter requires the effective temperature of the emitting soil layer, a value related to the physical temperature of all soil layers weighted by the proximity of the surface (and their dielectric properties). To illustrate the sensitivity of CMEM brightness temperatures to soil temperature variations; two experiments were conducted for July 2010: one with a perturbation of +3°C of the temperature of the first layer of soil and one without perturbation acting as a control experiment. It leads to a global mean increase of about 2.61°C and 2.78°C of the simulated brightness temperature at horizontal and vertical polarization, respectively (at an incidence angle of 40°, for 00:00 UTC and 12:00 UTC).

5 Conclusions

In this study, in situ soil temperature measurements from nearly 700 stations belonging to four networks across the United States and Europe are used to assess the ECMWF forecasts of soil temperature during 2012. Results suggest that ECMWF IFS is able to accurately forecast soil temperature. The best performance is obtained at 06:00 LST (smaller root mean square differences). Both annual and diurnal cycles are represented well (with correlations of 0.9 and above). Over the United States a model overestimation was found in the afternoon while an opposite signal was observed over Europe (Ireland, Germany, Hungary and Czech Republic). For Europe, the underestimation is even more pronounced in the afternoon. Scores obtained over Europe are better than those over the United States. ECMWF IFS does not assimilate soil temperature observations, but 2-metre SYNOP temperatures are used to analyse soil temperature. The analysis and forecast are therefore not entirely independent of the verifying observations. This analysis is then more accurate in data-rich areas of Europe. This study also highlights the importance of orography as it has a strong impact on linear and non-linear physical processes linked to soil temperature (e.g. such as the melting of snow). Comparing ECMWF snow cover to that observed at a single location underlines a slower melting of the snow in the IFS, which can partly be explained by the height difference. But this is also due to issues with the rather simple snow model used in the IFS. This has an impact on soil temperature as the latter has to wait until the entire grid cell to be covered by less than 10 cm of snow to start warming up. One may also keep in mind that local station/model grid representativeness remains an issue for validation activities. Future improvements of the land-surface physics will focus on cold processes such as a better representation of snow thermodynamics. Finally, additional work will focus on understanding the different afternoon biases over Europe (positive) and North America (negative) and will link the evaluation with that of 2-meter, and skin temperatures. There is great potential to use the three collocated observations (soil, skin and 2-meter temperatures) to improve the representation land-atmosphere thermal coupling and soil thermal conductivity.

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References

Albergel, C., de Rosnay, P., Balsamo, G., Isaksen, L. & Munoz-Sabater, J.: Soil Moisture Analyses at ECMWF: Evaluation Using Global Ground-Based In Situ Observations. Journal of Hydrometeorology, 13, 1442-1460, 2012.

Albergel, C., Dorigo, W., Reichle, R., Balsamo, G., de Rosnay, P., Muñoz-Sabater, J., Isaksen, L.,Reichle, R., Jeu, R.d., & Wagner, W.: Skill and global trend analysis of soil moisture from reanalyses and microwave remote sensing. Journal of Hydrometeorology, J. Hydrometeor, 14, 1259–1277, 2013. doi: http://dx.doi.org/10.1175/JHM-D-12-0161.1.

Balsamo, G., Viterbo, P., Beljaars, A.C.M., van den Hurk, B.J.J.M., Hirschi, M., Betts, A.K. & Scipal K.: A revised hydrology for the ECMWF model: Verification from field site to terrestrial water storage and impact in the ECMWF-IFS, J. Hydrometeor., 10, 623–643, 2009, doi:10.1175/2008JHM1068.1.

Bell, J. E., M. A. Palecki, C. B. Baker, W. G. Collins, J. H. Lawrimore, R. D. Leeper, M. E. Hall, J. Kochendorfer, T. P. Meyers, T. Wilson, and H. J. Diamond.: U.S. Climate Reference Network soil moisture and temperature observations. J. Hydrometeorol., 14, 977-988, 2013.

Bouttier, F.: The development of 12-621 hourly 4D-Var. ECMWF Tech. Memo 622 348, pp21, 2001.

Cui, X., Huang, G. and Chen, W. : Notes of numerical simulation of summer rainfall in China with a Regional Climate Model REMO. Advances in Atmospheric Sciences, vol.25,no.6,999-1008, 2008.

de Rosnay P., Drusch, M. Boone, A. Balsamo, G. Decharme, B. Harris, P. Kerr, Y. Pellarin, T. Polcher, J. and Wigneron, J.-P.: The AMMA Land Surface Model Intercomparison Experiment coupled to the Community Microwave Emission Model: ALMIP-MEM, J. Geophys. Res., Vol 114, doi:10.1029/2008JD010724, 2009.

de Rosnay P., G. Balsamo, C. Albergel J. Muñoz-Sabater and L. Isaksen: Initialisation of land surface variables for Numerical Weather Prediction, Surveys in Geophysics, 2014. doi: 10.1007/s10712-012-9207-x.

de Rosnay P., M. Drusch, D. Vasiljevic, G. Balsamo, C. Albergel and L. Isaksen: A simplified Extended Kalman Filter for the global operational soil moisture analysis at ECMWF, Q. J. R. Meteorol. Soc., 139(674):1199-1213, 2013. Doi: 10.1002/qj.2023.

Douville H., Viterbo P., Mahfouf J.-F. and Beljaars A.C.M.: Evaluation of the optimum interpolation and nudging techniques for soil moisture analysis using FIFE data. Mon. Weather Rev. 128: 1733–1756, 2001.

Drusch, M., Holmes, T., de Rosnay, P. and Balsamo, G.: Comparing ERA-40 based L-band brightness temperatures with Skylab observations: a calibration/validation study using the Community Microwave Emission Model, J. Hydrometeorol., 10, pp.213-226, doi: 10.1175/2008JHM964.1, 2009a.

Drusch, M., Scipal, K,.de Rosnay, P., Balsamo, G., Anderson, E., Bougeault, P. and Viterbo, P.: Towards a Kalman Filter based soil moisure analysis system for the operational ECMWF integrated forecst system, Geophys. Res. Lett., 36, L10401, doi:10.1029/2009GL037716, 2009b.

Dutra, E., G. Balsamo, P. Viterbo, P. Miranda, A. Beljaars, C. Schär and K. Elder: An improved snow scheme for the ECMWF land surface model: description and offline validation, J. Hydrometeor., 11, 899–916, 2010.

Entekhabi D, Asrar G, Betts A, Beven K, Bras R, Duffy C, Dunne T, Koster R, Lettenmaier D, DB ML, Shuttleworth W, van Genuchten M, Wei MY, Wood E.: An agenda for land surface hydrology research and a call for the second international hydrological decade. BullAmMeteorol Soc 10:2043–2058, 1999.

Entekhabi D., E.G. Njoku et al.: The Soil Moisture Active Passive (SMAP) mission, Proceedings of the IEEE, 98(5), 704-716, 2010.

FAO: “Digital soil map of the world (DSMW)”. Technical report, Food and Agriculture Organization of the United Nations, re-issued version, 2003.

Holmes, T., Drusch, M., Wigneron, J.-P. and de Jeu, R.: A global simulation of microwave emission: error structures based on output from ECMWFS Operational Integrated Forecast System. IEEE Transactions on Geosciences and Remote Sensing, 46, pp.846-856, 2008.

Holmes, T. R. H., T. J. Jackson, R. H. Reichle, and J. B. Basara, An assessment of surface soil temperature products from numerical weather prediction models using ground-based measurements, Water Resour. Res., doi:10.1029/2011WR010538, 2012.

Kerr, Y.H., Waldteufel, P., Wigneron, J.-P., Delwart, S., Cabot, F., Boutin, J., Escorihuela, M.-J., Font, J., Reul, N., Gruhier, C., Juglea, S.E., Drinkwater, M.R., Hahne, A., Martín-Neira, M. & Mecklenburg, S.: The SMOS Mission: New Tool for Monitoring Key Elements of the GlobalWater Cycle. Proceedings of the IEEE, 98 (5), 666 - 687, 2010.

Koster RD, Suarez MJ: Modeling the land surface boundary in climate models as a composite of independent vegetation stands. J Geophys Res 97:2697–2715, 1992.

Lafont, S., Kergoat, L., Dedieu, G., Chevillard, A., Karstens, U. and Kolle, O.: Spatial and Temporal variability of land CO2 fluxes estimated with remote sensing and analysis data over western Eurasia. Tellus, 54B, 820-833, ISSN 0280-6509, 2002.

Mahfouf, J.-F.: Analysis of soil moisture from near surface parameters: A feasibility study, J. Appl. Meteorol., 30, 506–526, 1991.

Mahfouf, J.-F. and Rabier, F.: The ECMWF operational implementation of four dimensional variational assimilation. Part II: Experimental results with improved physics. Q. J. R. Meteorol. Soc., 126, 1171-1190, 2000a.

Mahfouf, J.-F., P.Viterbo, H. Douville, A.C.M. Beljaars and S. Saarinen: A revised land-surface analysis scheme in the Integrated Forecasting System. ECMWF newsletter, No 88 – Summer / Autumn 2000, 8-13, 2000b.

Mueller B, Seneviratne S.: Hot days induced by precipitation deficits at the global scale. Proc Nat Acad Sci USA 109(31):12398–12403, 2012. doi:10.1073/pnas.1204330109.

Ødegaard V., D'Allura A., Baklanov A., Diéguez J.J., Fay B., Finardi S., Glaab H., Hoe S.C., Millán M., Mahura A., Neunhäuserer L., Palau J.L., Perez G., Håvard Slørdal L., Stein A and Havskov Sørensen J.: Study of the sensitivity of UAP forecasts to meteorological input Section. Norwegian Meteorological Institute report, ISSN 1503-8025, August 2005, n.13/2005, met.no/Forskning/Publikasjoner/Publikasjoner_2005/filestore/report13.2005.pdf, last access; 22/10/2013.

Muñoz-Sabater, J., Fouilloux. A. and de Rosnay, P.: Technical Implementation of SMOS Data in the ECMWF Integrated Forecasting System, IEEE Geoscience and Remote Sensing Letters, 9(2), 252-256. doi: 10.1109/LGRS.2011.2164777, 2012.

Schaefer, G.L. & Paetzold, R.F. : SNOTEL (SNOwpack TELemetry) and SCAN (Soil Climate Analysis Network) Presented at the Automated Weather Station (AWS) workshop. March 6-10. Lincoln, NE, 2000.

Rabier, F., H. Järvinen, E. Klinker, J.-F. Mahfouf and A. Simmons: The ECMWF operational implementation of four dimensional variational assimilation. Part I: Experimental results with simplified physics. Q. J. R. Meteorol. Soc., 126, 1143-1170, 2000.

Viterbo, P., A. C. M. Beljaars, J.-F. Mahfouf, and J. Teixeira: The representation of soil moisture freezing and its impact on the stable boundary layer. Quart. J. Roy. Meteor. Soc., 125, 2401–2426, 1999.