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A bare ground evaporation revision in the ECMWF land-surface scheme: evaluation of its impact using ground soil moisture and satellite microwave data

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In situ soil moisture data from 122 stations across the United States are used to evaluate the impact of a new bare ground evaporation formulation at ECMWF. In November 2010 the bare ground evaporation used in ECMWF's operational Integrated Forecasting System (IFS) was enhanced by adopting a lower stress threshold than for the vegetation, allowing a higher evaporation. It results in more realistic soil moisture values when compared to in situ data, particularly over dry areas. Use was made of the operational IFS and offline experiments for the evaluation. The latter are based on a fixed version of the IFS and make it possible to assess the impact of a single modification while the operational analysis is based on a continuous effort to improve the analysis and modelling systems, resulting in frequent updates (few times a year). Considering the field sites with a fraction of bare ground greater than 0.2, the root mean square difference (RMSD) of soil moisture is shown to decrease from $0.118 \text{ m}^3 \text{ m}^{-3}$ to $0.087 \text{ m}^3 \text{ m}^{-3}$ when using the new formulation in offline experiments, and from $0.110 \text{ m}^3 \text{ m}^{-3}$ to $0.088 \text{ m}^3 \text{ m}^{-3}$ in operations. It also improves correlations. Additionally the impact of the new formulation on the terrestrial microwave emission at a global scale is investigated. Realistic and dynamically consistent fields of brightness temperature as a function of the land surface conditions are required for the assimilation of the SMOS data. Brightness temperature simulated from surface fields from two offline experiments with the Community Microwave Emission Modelling (CMEM) platform present monthly mean differences up to 7 K. Offline experiment with the new formulation presents drier soil moisture, hence simulated brightness temperature with its surface fields are larger. They are also closer to SMOS remotely sensed brightness temperature.

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1 Introduction

Soil moisture plays a fundamental role in the partitioning of mass and energy fluxes between the hydrosphere, biosphere and atmosphere because it controls both evaporation and transpiration fluxes from bare soil and vegetated areas, respectively. In addition, it is a key variable in hydrological processes (i.e. runoff, evaporation from bare soil and transpiration from the vegetation cover) and has an impact on plant growth and carbon fluxes (Dirmeyer et al., 1999; Entekhabi et al., 1999). Its initialisation is of crucial importance for Numerical Weather Prediction (NWP) models and this topic has been extensively explored in the literature (e.g. Shukla and Mintz, 1982; Dirmeyer, 2002; Douville et al., 2001); soil moisture might play a role in meteorological forecasting (Seneviratne et al., 2010).

The second phase of the multi-institutional numerical modelling experiment GLACE-2 (Global Land–Atmosphere Coupling Experiment) led to several insights about how the realistic initialisation of soil moisture can have a significant impact on the skill of precipitation and air temperature forecasts skill at the sub-seasonal scale (Koster et al., 2011). Notably, while both wet and dry land-surface-model initialisation are likely to generate skill in different areas of the world, dry initialisation provides more skill at the transition between soil-moisture and energy-availability-controlled evaporation. The first phase of GLACE (Koster et al., 2004) focused on the atmospheric response to soil moisture variations. Meteorological variables such as precipitation and air temperature, were found to be particularly affected by soil moisture variations in specific areas: the transition zones between arid and humid areas. Dry-land has recently received more attention both in literature (Wang et al., 2012) and in several initiatives on the Drought Early Warning (DEW) information services world-wide (WMO, Drought monitoring and early warning, 2006). Many studies have focused on the coupled bare soil–canopy processes and the ability of land surface models to simulate bare soil processes has also been of interest (Desborough et al., 1996). Albergel et al. (2012a, b) demonstrated the good quality of the European Centre for Medium-Range Weather Forecasts (ECMWF)

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soil moisture products with respect to global-ground based in situ observations. They found good level of correlations despite the high values of root mean square difference (RMSD) which indicate that ECMWF products tend to overestimate soil moisture, particularly over dry areas. To overcome this problem an improved bare ground evaporation scheme over dry land (Balsamo et al., 2011) was implemented in ECMWF's Integrated Forecasting System (IFS), in November 2010. It is expected that the new scheme will reduce the soil moisture over bare soil by enhancing evaporation, resulting in more realistic soil moisture when compared to in situ data. Because the improved bare ground evaporation was implemented in 2010 along with others modifications affecting soil moisture (e.g. an Extended Kalman Filter for soil moisture analysis, de Rosnay et al., 2011, 2012) it is difficult to isolate the impact of the new evaporation scheme; NWP analyses hardly have their control experiments. For this reason, offline experiments were carried out with and without the new bare ground evaporation to analyse the impact of the specific modification. This study aims at evaluating the impact of this new evaporation scheme on soil moisture.

In the framework of the Soil Moisture and Ocean Salinity (SMOS, Kerr, 2007; Kerr et al., 2010) mission, ECMWF is implementing the direct assimilation of near real time brightness temperature (TB) in the L-band (Sabater et al., 2012). It will only be effective if realistic and dynamically consistent fields of TB are simulated as a function of land-surface conditions. At ECMWF the Community Microwave Emission Modelling platform (CMEM, Holmes et al., 2008; Drusch et al., 2009a; de Rosnay et al., 2009) is used to simulate TB. Surface soil moisture is, amongst other surface fields, coupled with CMEM to produce ECMWF's first-guess TB. The main objective of this study is to evaluate the new evaporation formulation on soil moisture, however as the improved bare ground evaporation is expected to affect surface fields such as soil moisture, it also assesses its impact on simulated TB.

After a description of the ECMWF's analysis and soil moisture products used in this study, the new bare ground evaporation formulation is presented followed by a description of the in situ observations required to evaluate soil moisture analyses. Next

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the CMEM platform is briefly described along with the remotely-sensed SMOS TB data set. Then the impact of the improved bare ground evaporation is assessed using (i) two offline experiments and (ii) ECMWF's operational IFS and in situ soil moisture data for the period 2010–2011 (only 2010 for the offline experiments). Finally, surface soil moisture and soil temperature fields, as well as snow depth and density fields from the two offline experiments, are coupled with the CMEM platform to simulate the TB data set at a global scale; they permit the study of the sensitivity of CMEM to the new bare ground evaporation. Finally the two TB data sets are compared to SMOS TB observations for the year 2010.

2 Material and methods

In situ soil moisture observations are important for evaluating soil moisture products. In this study use was made of soil moisture data from the NCRS-SCAN network (Natural Resources Conservation Service – Soil Climate Analysis Network) in the United States (Schaefer and Paetzold, 2000). They were obtained through the International Soil Moisture Network (ISMN, Dorigo et al., 2011, <http://www.ipf.tuwien.ac.at/insitu/>), a new data hosting centre where globally available ground based soil moisture measurements are collected, harmonized and made available to users. Data at 148 stations in 2010 and 2011 were used to evaluate soil moisture from offline experiments and the operational IFS. The soil moisture data sets used in this study are presented in Table 1.

2.1 ECMWF's land surface analysis

Data produced at ECMWF include a large variety of surface parameters that describe the atmosphere as well as ocean-wave and land-surface conditions (more information at: <http://www.ecmwf.int/products/>). The core atmospheric assimilation system at ECMWF relies on the four-dimensional variational (4D-Var) data assimilation scheme described in Rabier et al. (2000) and Mahfouf and Rabier (2000). It has

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an observation time window of 12 h (Bouttier, 2001). Data provided by satellite sensors (from microwave and infrared radiometers) as well as conventional observations (e.g. radiosonde network) are ingested within the 4D-Var. Use is also made of surface observations such as surface pressure, humidity and wind.

For several decades NWP initialisation has relied on data assimilation approaches which use satellite data to analyse atmospheric variables. Land-surface initialisation is generally independent from the atmospheric system and is based on ground measurements of screen-level variables as a proxy for soil moisture. In recent years, major upgrades have been implemented in the land-surface modelling and analysis systems of the IFS with respect to soil moisture: (i) an improved soil hydrology (Balsamo et al., 2009), (ii) a new snow scheme (Dutra et al., 2010) and (iii) a multi-year satellite-based vegetation climatology (Boussetta et al., 2010) together with enhanced bare ground evaporation (Balsamo et al., 2011). Also a new soil moisture analysis scheme, based on a point-wise Extended Kalman Filter (EKF) for the global land surface, has been developed and this was implemented in the IFS (Drusch et al., 2009b; de Rosnay et al., 2011, 2012) in November 2010.

The model forecast for the land surface analysis is provided by H-TESEL (Van den Hurk and Viterbo, 2003; Balsamo et al., 2009). H-TESEL was implemented in the IFS by Balsamo et al. (2009) and verified in various ways including field site comparison, data assimilation and modelling experiments. Also Albergel et al. (2012b) provide a detailed evaluation of HTESEL soil moisture. Analyses are available at four depths (0–7, 7–28, 28–100 and 100–289 cm). The soil heat budget follows a Fourier diffusion law, modified to take into account soil water freezing/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. The water balance at the surface (i.e. the change in water storage of the soil moisture, interception reservoir and accumulated snowpack) is computed as the difference between the precipitation and (i) the evaporation of soil, vegetation, interception water, (ii) surface and subsurface runoff. First precipitation is collected in the interception reservoir until it saturated. Then, excess

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precipitation is partitioned between surface runoff and infiltration into the soil column. HTESSSEL's formulation of the soil hydrological conductivity and diffusivity is spatially variable according to a global soil texture map (FAO/UNESCO Digital Soil Map of the World, DSMW, FAO, 2003). Surface runoff is based on variable infiltration capacity. At the end of each data assimilation cycles an adjustment to the model forecast (e.g. soil moisture) is produced, it usually referred to analysis increment and represents the net response of the variational data assimilation to all observations used.

Three analysis schemes for the surface (and near-surface) variables are currently used in operations. They are based on: spatial Optimal Interpolation (2D-OI, for snow depth and screen-level analyses), column Optimal Interpolation (1D-OI, for soil and snow temperature analysis), and an EKF (for soil moisture analysis, Drusch et al., 2009b; de Rosnay et al., 2011, 2012). Analysis of surface parameters is decoupled from the main atmospheric analysis. Firstly an OI scheme produces estimates of screen-level temperature and relative humidity by combining synoptic observations over land with background estimates (short-range forecasts) from the most recent analysis (Douville et al., 2000). Analysed fields of screen level temperature and relative humidity are then used to update estimates of soil moisture (and soil temperature) for the layers of the model using the EKF analysis. While producing the forecast, the model estimates a wide variety of physical variables including precipitation. Even if not directly observed, the model estimates are constrained by the observations (in situ measurements of temperature and humidity) used to initialise the forecast and their accuracy relies on the quality of the model physics as well as that of the analysis.

2.1.1 Soil moisture products

In this section a description is given of the major differences between the deterministic operational suite and the offline experiments with respect to soil moisture.

The version of IFS used in operations at ECMWF from January 2010 to December 2011 spans cycles 35r3 to 37r3 (more information at: <http://www.ecmwf.int/research/ifsdocs/>). There are continuous effort to improve the analysis and modelling schemes

bare ground evaporation over dry land has been enhanced by adopting a lower stress threshold than for the vegetation, allowing a higher evaporation (BEVAP_NEW). Its control experiment without the new bare ground evaporation is called BEVAP_OLD.

2.1.2 New bare ground evaporation

5 This section gives a description of the new bare ground formulation. It is in agreement with the experimental findings of Mahfouf and Noilhan (1991) and results in more realistic soil moisture values for dry land (Balsamo et al., 2011). Indeed the evaporation from non-vegetated areas responds to a different physical mechanism compared to densely vegetated areas. Over bare soil the vaporisation of water in the soil pores takes place in
10 a thin layer close to the surface-atmosphere interface as a direct effect of incoming solar radiation providing the latent heat requirements. Atmospheric conditions such as air temperature, humidity, wind velocity and radiation, as well as soil conditions (e.g. water content and roughness length) play a role in modulating the evaporation processes (Hillel, 1980). The relationship between soil moisture and bare soil evaporation is generally parameterized in land-surface models. Mahfouf and Noilhan (1991) compared
15 several of these formulations; in these studies, bare soil evaporation formulations was halted when the soil is completely dry (for soil moisture close to zero). In the previous TESSEL scheme linking of soil moisture and evaporation was assumed to be linear between the permanent wilting point and the field capacity values for soil moisture.
20 With the introduction of a tiling approach, the same stress function was applied to both vegetated and non-vegetated tiles, neglecting the fact that wilting point is a soil moisture threshold that applies uniquely to vegetated areas. The formulation of the bare soil evaporation has been revisited in the latest HTESSEL version to allow a smooth transition between vegetated and non-vegetated areas and to realign the formulation
25 of bare ground evaporation with studies in the literature. Evapotranspiration process (E) is parameterized for each tile i accounting for canopy and soil resistance as:

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$$E_i = \frac{\rho_a}{r_a + r_c} [q_L - q_{\text{sat}}(T_{\text{sk},i})] \quad (1)$$

where ρ_a is the air density, q_L is the humidity at the lowest model level, $q_{\text{sat}}(T_{\text{sk},i})$ is the saturated humidity for the vegetation skin temperature $T_{\text{sk},i}$, r_a is the aerodynamic resistance and r_c is the canopy resistance. Equation (1) is valid for vegetated and non-vegetated tile i in the absence of snow and interception water.

For vegetated tiles the canopy resistance is formulated according to Jarvis (1976):

$$r_c = \frac{r_{\text{s,min}}}{\text{LAI}} f_1 f_2 f_3 \quad (2)$$

with LAI prescribed from a MODIS satellite-based data set as detailed in Boussetta et al. (2011). In the canopy resistance formulation the $r_{\text{s,min}}$ is the minimum stomatal resistance and f_1 and f_3 are inhibition functions expressing the shortwave radiation deficit and atmospheric humidity deficit, respectively. The soil moisture inhibition function, f_2 , depends on the root-zone soil wetness (w_{root}) normalized between the wilting point (w_{wilt}) and the field capacity (w_{fc}) therefore:

$$f_2 = \frac{w_{\text{root}} - w_{\text{wilt}}}{w_{\text{fc}} - w_{\text{wilt}}} \quad (3)$$

For non-vegetated tiles r_c is uniquely dependent on the soil moisture of the first soil layer, so f_2 is modified to be computed as a function of surface soil moisture $f_2(w_{\text{layer1}})$ and a minimum soil resistance $r_{\text{soil,min}}$:

$$r_c = r_{\text{soil,min}} \cdot f_2(w_{\text{layer1}}) \quad (4)$$

In the new formulation the f'_2 for bare ground is calculated as:

$$f'_2 = \frac{w_{\text{root}} - w_{\text{min}}}{w_{\text{fc}} - w_{\text{min}}} \quad (5)$$

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where w_{\min} is a weighted average of the wilting point and residual soil moisture content (w_{res}). The weights are given by the vegetation cover fraction veg (van den Hurk et al., 2000), so that:

$$w_{\min} = \text{veg} \cdot w_{\text{wilt}} + (1 - \text{veg}) \cdot w_{\text{res}} \quad (6)$$

Formulation of BEVAP_OLD offline experiment used Eq. (3) and the one of BEVAP_NEW Eq. (5).

2.2 In situ soil moisture observations: the NCRS-SCAN network

The SCAN network (<http://www.wcc.nrcs.usda.gov/scan/>) is a comprehensive, nationwide 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 USA. 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 data are used for a variety of purpose ranging from global climate modelling to agricultural studies. Data are collected by a dielectric constant measuring device; typical measurements at 2 inches (about 5 cm) are used. The vegetation cover at those sites consists generally of natural fallow or short grass. In this study, all the stations of the NCRS-SCAN network providing data in 2010 and 2011 are retained (leading to a total of 148 stations). The location of the stations of the NCRS-SCAN network are shown on Fig. 1.

2.3 Statistical comparison between analysis and in situ observations

For all stations, correlations (R , Eq. 7), bias (in situ minus analysis), root mean square difference (RMSD, Eq. 8) and p-value (a measure of the correlation significance) are

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calculated. The latter indicates the significance of the test; the 95 % confidence interval is used in this study (as in Rüdiger et al., 2009; Albergel et al., 2009, 2010); only configurations where the p-value is below 0.05 (i.e. the correlation is not a coincidence) are retained.

$$R = \sqrt{1 - \frac{\sum (SSM_{\text{products}} - SSM_{\text{insitu}})^2}{\sum (SSM_{\text{products}} - \overline{SSM_{\text{insitu}}})^2}} \quad (7)$$

$$\text{RMSD} = \sqrt{\sum (SSM_{\text{products}} - SSM_{\text{insitu}})^2} \quad (8)$$

In situ data contain errors (instrumental and representativeness), so they are not considered as “true” soil moisture. This is emphasised by using the RMS difference terminology instead of RMS error. In situ observations of soil moisture at the NCRS-SCAN stations are associated with soil temperature measurements. The observations of soil moisture were flagged for temperature below 4 °C to avoid frozen conditions. When considering TB, the standard deviation (STD) is also computed.

To avoid seasonal effects, monthly anomaly time-series are calculated. The difference from the mean is produced for a sliding window of five weeks (if there are at least five measurements in this period), and the difference is scaled to the standard deviation. For each surface soil moisture estimate at day (i), a period F is defined, with $F = [i - 17, i + 17]$ (corresponding to a five-week window). If at least five measurements are available in this period, the average soil moisture value and the standard deviation are calculated. The Anomaly (Ano) is then given by:

$$\text{Ano}(i) = \frac{SSM(i) - \overline{SSM(F)}}{\text{stdev}(SSM(F))} \quad (9)$$

The same equation is used to compute in situ anomaly time-series which can be compared with that from ECMWF’s analyses.

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2.4 The terrestrial microwave emission modelling

2.4.1 The Community Microwave Emission Modelling (CMEM) platform

The CMEM platform has been developed by ECMWF as the forward operator for low frequency passive microwave TB (from 1 GHz to 20 GHz) of the surface in the framework of the SMOS mission. CMEM is one of the ESA (European Space Agency) SMOS tools and it is available to the entire community through the ECMWF web pages: http://www.ecmwf.int/research/ESA_projects/SMOS/cmem/cmem_doc.html.

CMEM represents the top of atmosphere TB as a result of the contributions from the following dielectric layers: soil, vegetation and atmosphere. The physics of CMEM is based on the parameterizations used in the L-Band Microwave Emission of the Biosphere (L-MEB, Wigneron et al., 2007) and the Land Surface Microwave Emission Model (LSMEM, Drusch et al., 2001); it includes a modular choice of the physical parameterizations for the various dielectric layers. Multiple parameterizations for the dielectric constant, the effective temperature, the smooth emissivity, soil roughness, vegetation optical depth and the atmospheric opacity lead to 1440 combinations when using CMEM (de Rosnay et al., 2009). The best CMEM configuration according to the finding of de Rosnay et al. (2009) is retained for this study. Sabater et al. (2011) also used this configuration, replacing however the soil roughness parameterization of Choudhury (1979) by the one proposed by Wigneron et al. (2001), because the former showed little sensitivity over larger regions.

2.4.2 SMOS brightness temperature

SMOS consists in a microwave imaging radiometer with an aperture synthesis collecting top of atmosphere full polarized radiances coming from the scene viewed by its antennas through their power patterns. It is a Y-shaped instrument with several elementary antennas regularly spaced along the arms (69 in total) which provide, at each integrations step, a full image (circa 1000 × 1200 km) at either two polarisations or full

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polarisation, of the Earth's surface (Kerr et al., 2007, 2010). The spatial resolution is about 40 km and the globe is fully imaged at least twice every three days (ascending and descending orbits). Any points at the surface are viewed frequently at different angles and polarisations. The angular information is used to separate the different contributions (soil-vegetation) to the signal (Wigneron et al., 2000). The signal measured at satellite level is a TB for the L-band consisting of four main contributions: (i) the up-welling atmospheric emission, (ii) the Earth's surface emission, attenuated by the atmosphere, (iii) the atmospheric down-welling atmospheric emission reflected at the surface and attenuated along the upward path by the atmosphere, and (iv) the cosmic background emission attenuated by the atmosphere, reflected at the surface and attenuated again along the upward path by the atmosphere. SMOS Near Real Time (NRT) products are processed at the European Space Astronomy Centre (ESAC) and sent to ECMWF via the SMOS Data Processing Ground Segment (DPGS) interface.

3 Results

3.1 Impact of the new bare ground evaporation on soil moisture

3.1.1 Using offline experiments

The statistical scores for the comparison between either BEVAP_OLD or BEVAP_NEW and the stations from the NCRS-SCAN network are presented in Table 2. Very little quality control is applied to measurements from NCRS-SCAN stations. Dharssi et al. (2011) used a simple quality control process to identify stations where sensors might be dysfunctional. Stations are rejected based on the scores obtained when compared to their experiments (in term of correlations, RMSDs and biases). As this study aims to assess the impact of the new bare ground experiment, mostly in term of RMSD, a quality control is applied based only on the correlation level. Stations for which either BEVAP_OLD or BEVAP_NEW have a correlation less than 0.3 are rejected (as in Dharssi

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et al., 2011). Also, stations with a non-significant correlations are rejected (p -value < 0.05). This quality control of the NCRS-SCAN stations, resulting in 122 stations being available (out of 148) for the comparison of the two offline experiments, does not alter the conclusions of this paper. For all stations, the average correlations for volumetric time-series are 0.60 for BEVAP_OLD (control) and 0.62 for BEVAP_NEW (test). Biases (in situ minus analyses) are on average $-0.095 \text{ m}^3 \text{ m}^{-3}$ and $-0.064 \text{ m}^3 \text{ m}^{-3}$, RMSDs are $0.135 \text{ m}^3 \text{ m}^{-3}$ and $0.124 \text{ m}^3 \text{ m}^{-3}$ for BEVAP_OLD and BEVAP_NEW, respectively. Despite a small decrease in RMSD for BEVAP_NEW, both values are high. The new formulation (Eq. 5) is expected to enhance evaporation over bare ground, hence for each station, the fraction of bare ground (according to the model) was used as a filter to evaluate the impact of the new formulation on RMSD. Results are presented in Table 3 and the RMSD difference between BEVAP_OLD and BEVAP_NEW as a function of the fraction of bare ground is displayed on Fig. 2. It identifies a threshold value (0.2) below which the fraction of bare soil is too small for the new formulation to have an impact on RMSD. When scores are computed for stations with a fraction of bare ground greater than or equal to 0.2 (35 stations with significant R values), the correlations, biases and RMSDs are 0.63, $-0.086 \text{ m}^3 \text{ m}^{-3}$, $0.118 \text{ m}^3 \text{ m}^{-3}$ for BEVAP_OLD and 0.65, $0.0007 \text{ m}^3 \text{ m}^{-3}$, $0.087 \text{ m}^3 \text{ m}^{-3}$ for BEVAP_NEW. This decrease in the RMSD for BEVAP_NEW (from $0.118 \text{ m}^3 \text{ m}^{-3}$ to $0.087 \text{ m}^3 \text{ m}^{-3}$), leading to a more realistic soil moisture product regarding the in situ data is attributed only to the new bare ground evaporation formulation. Figure 3 illustrates the two offline runs as well as the in situ observations for one site located in Utah. Minimum values of BEVAP_OLD soil moisture are limited by the dominant wilting point for vegetation types, however ground data indicate much drier conditions, as is clearly observed from May to September 2010. The new bare ground evaporation allows the model to go below this wilting point so the BEVAP_NEW analysis is in much better agreement with the observations than that for BEVAP_OLD. Along with the decrease in RMSD, one may note an increase in the correlation (from 0.63 to 0.65). Also BEVAP_NEW has a more realistic decrease in soil

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moisture after a precipitation event due to its higher water holding capacity and this explains the slightly better correlations.

Considering the short-term variability, the average correlations for the monthly anomaly time series are 0.54 for BEVAP_OLD and 0.55 for BEVAP_NEW. Correlations of volumetric time series are larger than those for the monthly anomaly time-series. The good level of correlation of the volumetric time series is largely explained by seasonal variations, which are suppressed in monthly anomalies.

3.1.2 Using the operational product

The new bare ground evaporation formulation was implemented in operations in November 2010. Its impact on the operational analysis was assessed for the 2010–2011 period. Results are presented in Table 4 and illustrated by Fig. 4. The same threshold of 0.2 for the fraction of bare ground was used. The correlations, bias and RMSD are 0.59, $-0.076 \text{ m}^3 \text{ m}^{-3}$ and $0.110 \text{ m}^3 \text{ m}^{-3}$ for 2010 and 0.69, $-0.010 \text{ m}^3 \text{ m}^{-3}$, $0.088 \text{ m}^3 \text{ m}^{-3}$ for 2011. Figure 4 illustrates the soil moisture time-series for three stations with different fraction of bare ground (~ 0.46 , ~ 0.79 and ~ 0.15 from top to bottom). Compared to 2010, the station with a fraction of bare ground of 0.79 has a lower value of RMSD in 2011 than a station with a fraction of 0.15. As for BEVAP_OLD and BEVAP_NEW, the operational analysis is in much better agreement with the observations for 2011 (with the new bare ground evaporation) than for 2010; this is particularly clear for the period from May to September 2011 (see Fig. 4). If the decrease in RMSD is associated with the new bare ground evaporation, the increase in correlation (from 0.59 to 0.69) is mainly due to the new EKF analysis (also, in situ data are different). As demonstrated in Albergel et al. (2010) and de Rosnay et al. (2011, 2012) the use of the EKF permits to increase the quality of the soil moisture product compare to the former OI method. The higher water holding capacity observed for 2011 also helps in this way (more realistic decrease of soil moisture after a precipitation event). Correlations of anomaly time-series are 0.53 and 0.54 for 2010 and 2011, respectively.

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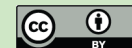
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3.2 Impact of the new bare ground evaporation on terrestrial microwave emission and comparison with SMOS

The differences between the TB simulated using surface fields from BEVAP_NEW and the one from BEVAP_OLD are computed for each month of 2010, for both H (horizontal) and V (vertical) polarizations (referred to as TBH and TBV) for 06:00 UTC and 18:00 UTC. It is useful to study the sensitivity of the simulated TB to the bare soil parameterization as a better representation of soil moisture should lead to more realistic TB, a pre-requisite for SMOS data assimilation. In terms of mean difference, BEVAP_NEW soil moisture is drier than BEVAP_OLD, so simulated TB are larger with the BEVAP_NEW surface fields. For TBH (18:00 UTC) the global monthly mean differences between the two data set range from 4.7 K to 7.01 K, with an annual value of 14.85 K. For TBV (18:00 UTC), global monthly mean biases range from 2.94 K to 4.12 K, with an annual mean difference of 3.7 K. Statistical scores are summarized in Table 5 and Fig. 5 provides a map of the differences between the simulated TB for one month (August 2010 at 06:00 UTC) and one polarization (H). For this month, mean differences are 6.87 K and 3.96 K, with STD of 15.56 K and 9.04 K, for TBH and TBV, respectively. Positives differences are found in relatively dry areas. A look at the North American continent shows that large differences are found in the western part of the United States, where there is a high fraction of bare ground (accordingly to Fig. 1). Figure 6 shows, (i) the global monthly mean sensitivity between the two TB and (ii) the spatial correlations between each TB data sets and the fraction of bare ground. As expected, there is a slight annual cycle due to the larger distribution of the continental areas in the Northern Hemisphere. Spatial correlations between bare ground and TB mean sensitivity are on average 0.66 and 0.65 for TBH (06:00 UTC and 18:00 UTC), and 0.61 and 0.61 for TBV (06:00 UTC and 18:00 UTC).

Both TB data sets are compared to SMOS TB observations at 06:00 UTC, at an incidence angle of 40 degrees (more data available). Radio frequency interference (RFI) disturbs the natural microwave emission observed by SMOS (Zribi et al., 2011).

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At 06:00 UTC SMOS data are mainly over Western Europe and Africa, less affected by RFI than Asia. Results are presented in Table 6, it shows that BEVAP_NEW TB are in better agreement with SMOS than BEVAP_OLD TB, with large differences however. The mean difference (for 2010) between SMOS and BEVAP_NEW TBH is 10.2 K (STD of 21 K) and 14.5 K (STD of 20.8 K) when considering BEVAP_OLD TBH. Values are higher for TBV than for TBH.

4 Discussion

While previous studies (Albergel et al., 2012a, b) have demonstrated the good ability of ECMWF analyses to represent the soil moisture annual cycle as well as its short-term variability, they have also shown an overestimation of soil moisture. The modification of the soil moisture inhibition function (Eq. 5) in the new bare ground evaporation formulation allows a much lower level of soil moisture to be reached over bare soil areas as a consequence of direct bare ground evaporation under strong insolation. Results are more realistic when compared to in situ soil moisture values observed over dry areas; they have a smaller RMSD but also a slightly better correlation. The larger water holding capacity induced by the new bare ground evaporation provides a more realistic decrease in soil moisture after a precipitation event. This explains the slightly better correlations obtained with the new formulation for the offline experiments for both the volumetric and the monthly anomaly time-series. Indeed, the latter reflects the time-integrated impact of antecedent meteorological forcing (e.g. precipitation). ECMWF analyses do not assimilate ground-based observation of precipitation. Over land the information used by the model to generate rain is strongly constrained by in situ measurements of temperature and humidity. The use of precipitation data in the analysis continues to be studied at ECMWF. Lopez (2011) has demonstrated a positive impact on model performance of the direct 4D-Var assimilation of 6-hourly radar and rain-gauge rainfall accumulations. Considering all the stations (122) the differences in RMSDs between the two offline experiments is not very important, $0.135 \text{ m}^3 \text{ m}^{-3}$ and

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0.124 m³ m⁻³ for BEVAP_OLD and BEVAP_NEW, respectively. However, if a threshold of 0.2 for the fraction bare ground is set this difference increases to 0.118 m³ m⁻³ and 0.087 m³ m⁻³. At the spatial resolution of BEVAP_NEW and BEVAP_OLD ECMWF considers that about 46 % of the land is covered by a fraction of bare ground more than or equal to 0.2. Similar RMSDs are obtained with the operational IFS soil moisture product; in 2010, the RMSD is 0.110 m³ m⁻³ and 0.088 m³ m⁻³ in 2011 (new bare ground evaporation implemented in November 2010). The new bare ground parameterization also shows a consistent signal with the L-band microwave emission. Sensitivity in simulated TB to the new bare ground evaporation is found to be close to 15 K and 10 K in H and V polarizations, respectively. As the BEVAP_NEW soil moisture is drier than BEVAP_OLD, the simulated TB are larger with BEVAP_NEW surface fields. The latter are closer to SMOS observations but with large global mean differences and standard deviation (about 10 K and 20 K, respectively). CMEM configuration used in this study is based on de Rosnay et al. (2009) and Sabater et al. (2011) using AMSR-E C-band data and local L-band data, respectively. Results presented in this study are very preliminary and a full calibration of the CMEM platform, underway at ECMWF for SMOS activities, should lead to more realistic simulated TB, in better agreement with SMOS data.

5 Conclusions

This study investigated the new bare ground evaporation formulation implemented in operations at ECMWF in November 2010. Bare ground evaporation over dry lands has been enhanced by adopting a lower stress threshold than for the vegetation, allowing a higher evaporation. Its impact on soil moisture is assessed as well as on the representation of terrestrial microwave emission. The latter is of particular interest for the planned use of SMOS brightness temperature within the new land-surface analyses; it will be effective only if realistic and dynamically consistent fields of brightness temperature are simulated as a function of the land-surface conditions. ECMWF has

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developed offline experiments to assess the impact of model changes. They are produced by a fixed version of the IFS (and used atmospheric forcing from ERA-Interim) while the operational product is based on a continuous effort to improve the analysis and modelling schemes, resulting in frequent updates of the system (few times a year).

5 So offline experiments make it possible to study the impact of a single modification in the land surface modelling. Even if they are at a coarser spatial resolution than the operational product, they have the benefit of being less time-consuming and are very useful between the completion of future reanalyses of ECMWF.

10 In situ soil moisture from 122 stations (over 148 available) of the NCRS-SCAN network from all over the United States are used to evaluate the new bare ground evaporation formulation over two periods, 2010 and 2010–2011. It was first assessed using offline experiments to isolate its impact (2010 only) and then using the IFS operational product (2010–2011). The new scheme results in more realistic soil moisture values, particularly for dry areas; a decrease of about 26 % in RMSD is obtained between the
15 two offline experiments when considering the fraction of bare ground that has a threshold greater than or equal to 0.2 (from $0.118 \text{ m}^3 \text{ m}^{-3}$ to $0.087 \text{ m}^3 \text{ m}^{-3}$). Slightly higher levels of correlations were also obtained. The same conclusion is reached with the IFS operational analysis where a better agreement with in situ data was found in 2011 than in 2010. More realistic soil moisture also lead to better initial fields for simulating
20 brightness temperature with the CMEM platform, a pre-requisite for SMOS data assimilation. This preliminary study demonstrated a better agreement between SMOS data and simulated brightness temperature with surface fields from the new bare ground evaporation. Future improvements of the land-surface physics will focus on evaporation from free water surface such as intercepted water on leaves.

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Table 1. The soil moisture products used in this study. NWP stands for numerical weather prediction and LSM for land-surface model.

Soil moisture data set	Type	Soil layer depth (cm)	Considered period	Spatial resolution	Number of stations	Land use
ECMWF operational analysis	NWP analysis	0–7	Jan 2010 to Dec 2011	Before 26 Jan 2010: ~ 25 km (T799) from 27 Jan 2010: ~ 16 km (T1279)	Global product	Global product
ECMWF BEVAP_OLD (control experiment)	ERA-Interim driven LSM run	0–7	Jan 2010 to Dec 2010	~ 80 km (T255)	Global product	Global product
ECMWF BEVAP_NEW (test)	ERA-Interim driven LSM run	0–7	Jan 2010 to Dec 2010	~ 80 km (T255)	Global product	Global product
NCRS-SCAN (US)	In situ observations	5	Jan 2010 Dec 2011	Local scale	148 stations	Natural fallow or short grass

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Table 2. Statistical scores for the comparison between ECMWF surface soil moisture (offline experiments, BEVAP_OLD and BEVAP_NEW) and in situ data for all the stations from the NCRS-SCAN (USA) network over the 2010 period.

Soil moisture data set	<i>N</i> stations	<i>R</i>	Bias ($\text{m}^3 \text{m}^{-3}$)	RMSD ($\text{m}^3 \text{m}^{-3}$)
ECMWF BEVAP_OLD (control experiment)	122	0.60	−0.095	0.135
ECMWF BEVAP_NEW (test)	122	0.62	−0.064	0.124

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Table 3. RMSDs for the comparison between ECMWF soil moisture (offline experiments, BEVAP_OLD and BEVAP_NEW) and in situ data for all the stations from the NCRS-SCAN network in 2010. Fraction of bare ground is used as a filter to compute RMSDs.

Fraction of bare ground	<i>N</i> stations	BEVAP_OLD (control experiment) RMSD (m ³ m ⁻³)	BEVAP_NEW (test) RMSD (m ³ m ⁻³)
0.0	122	0.135	0.124
0.1	57	0.111	0.089
0.2	35	0.118	0.087
0.3	35	0.118	0.087
0.4	33	0.120	0.087
0.5	28	0.123	0.087
0.6	28	0.123	0.087
0.7	28	0.123	0.087
0.8	24	0.122	0.083

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Table 4. Statistical scores for the comparison between ECMWF operational soil moisture analysis for 2010 and 2011. The new bare ground evaporation formulation was implemented in November 2010. Only stations where the model has a fraction of bare ground greater than or equal to 0.2 were used.

Soil moisture data set	<i>N</i> stations	<i>R</i>	Bias ($\text{m}^3 \text{m}^{-3}$)	RMSD ($\text{m}^3 \text{m}^{-3}$)
ECMWF Operational analysis 2010	35	0.59	−0.076	0.110
ECMWF Operational analysis 2011	35	0.69	−0.010	0.088

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Table 5. Monthly mean statistics of the difference between simulated TB in BEVAP_NEW and BEVAP_OLD. Statistics are given for both horizontal and vertical polarizations, at 06:00 UTC and 18:00 UTC, based on 40° incidence angle simulated TB.

2010	TBH (BEVAP_NEW) – TBH (BEVAP_OLD) 06:00 UTC		TBH (BEVAP_NEW) – TBH (BEVAP_OLD) 18:00 UTC		TBV (BEVAP_NEW) – TBV (BEVAP_OLD) 06:00 UTC		TBV (BEVAP_NEW) – TBV (BEVAP_OLD) 18:00 UTC	
	Mean Bias (K)	SD (K)	Mean Bias (K)	SD (K)	Mean Bias (K)	SD (K)	Mean Bias (K)	SD (K)
Jan	5.01	13.03	4.88	12.75	3.17	8.05	3.06	7.85
Feb	4.93	12.79	4.72	12.49	3.06	7.82	2.94	7.62
Mar	5.57	13.76	5.37	13.56	3.37	8.22	3.27	8.18
Apr	6.19	15.07	6.13	15.05	3.68	9.00	3.70	9.15
May	6.59	15.46	6.66	15.69	3.90	9.19	4.01	9.50
Jun	6.84	15.77	6.97	16.08	3.94	9.12	4.11	9.50
Jul	6.64	15.31	6.77	15.64	3.85	8.86	4.01	9.26
Aug	6.87	15.58	7.01	15.95	3.96	9.04	4.14	9.47
Sep	6.74	15.38	6.86	15.69	3.97	9.11	4.12	9.47
Oct	6.77	15.63	6.80	15.82	4.03	9.40	4.12	9.66
Nov	6.63	15.49	6.50	15.40	4.04	9.52	3.99	9.55
Dec	5.98	14.71	5.75	14.32	3.67	9.09	3.54	8.84

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Table 6. Monthly mean statistics of the difference between SMOS TB observations and simulated TB. Results are given at 06:00 UTC, for both BEVAP_OLD and BEVAP_NEW, at both horizontal and vertical polarizations, based on 40° incidence angle observed and simulated TB.

2010	TB (BEVAP_OLD) 06:00 UTC				TB (BEVAP_NEW) 06:00 UTC			
	TBH		TBV		TBH		TBV	
	Mean Bias (K)	SD (K)	Mean Bias (K)	SD (K)	Mean Bias (K)	SD (K)	Mean Bias (K)	SD (K)
Jan	28.6	28.6	12.8	21.0	22.4	27.6	9.0	20.7
Feb	28.9	28.1	12.7	20.8	22.9	27.1	9.3	20.6
Mar	29.5	29.7	12.7	24.3	23.2	28.8	8.9	21.6
Apr	29.8	29.1	13.7	20.4	23.4	28.6	9.9	20.9
May	31.5	28.0	14.4	20.0	24.4	27.7	10.2	20.7
Jun	32.6	28.9	14.8	21.1	25.5	28.7	10.6	21.7
Jul	31.7	28.2	14.1	20.4	24.8	28.3	9.9	21.0
Aug	33.4	28.8	15.4	20.5	58.8	29.8	11.1	21.4
Sep	34.2	29.1	16.5	20.7	26.6	30.3	12.1	21.8
Oct	33.5	28.7	15.4	20.0	25.65	29.6	10.8	20.9
Nov	32.4	28.2	14.3	19.8	24.4	28.6	9.5	20.4
Dec	30.0	28.2	14.5	20.4	23.8	28.1	10.8	20.4

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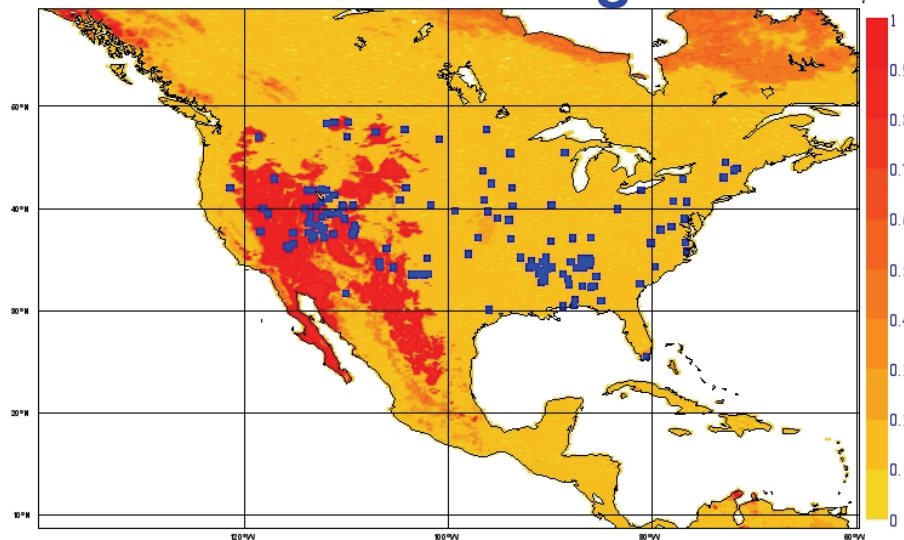
" Fraction of bare ground"

Fig. 1. Location of the different in situ soil moisture stations used in this study (blue squares); the stations belong to the NCRS-SCAN network (United States). Colour scale represents the fraction of bare ground.

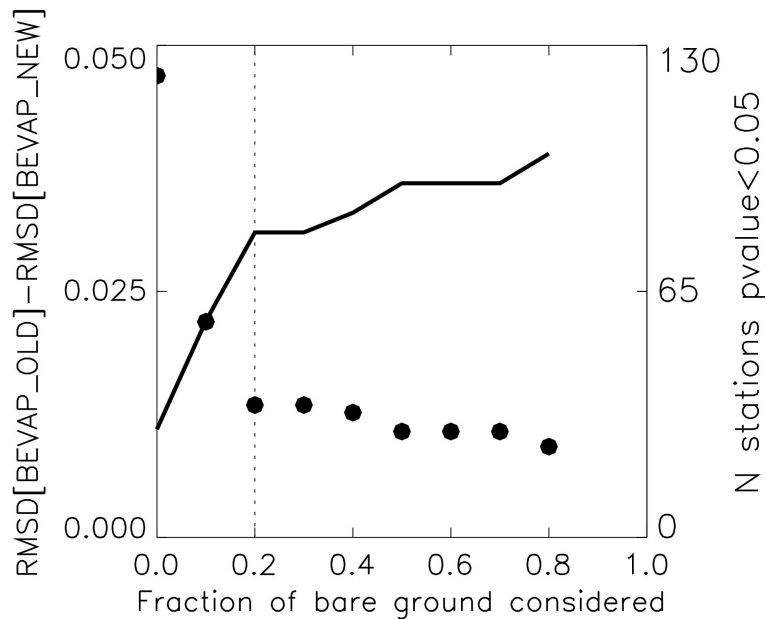


Fig. 2. Soil moisture RMSD between BEVAP_OLD and BEVAP_NEW as a function of the fraction of bare ground (black solid curve, left y-axis), the number of in situ stations used (for which significant correlation is obtained between observations and model time-series) is also presented (black dots, right y-axis). The dashed line represents a bare soil fraction threshold below which the sensitivity of soil moisture to the new evaporation formulation is less pronounced.

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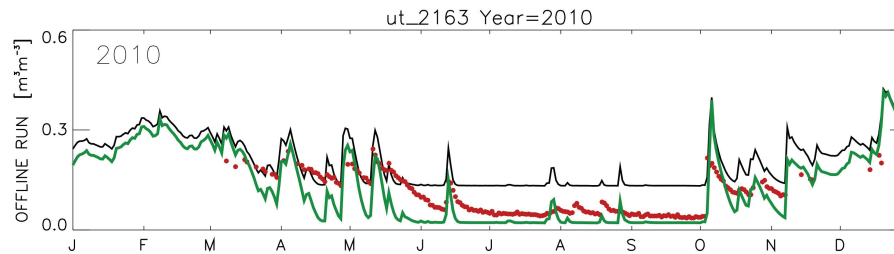


Fig. 3. Illustration of volumetric soil moisture time-series used in this study for one site in Utah for 2010. The black line is for BEVAP_OLD (control experiment without the new bare ground evaporation formulation), green line is for BEVAP_NEW (test with new formulation) and red dots are for in situ observations of soil moisture.

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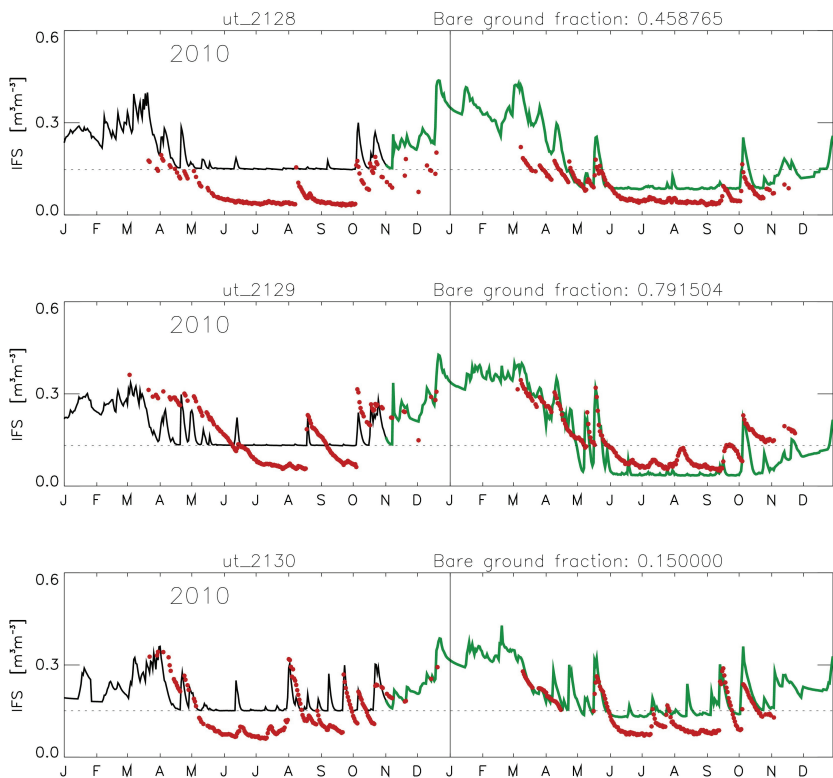


Fig. 4. Time-series of the operational volumetric soil moisture analysis for three sites in Utah for the 2010–2011 period. The black solid line becomes green when the new bare ground evaporation formulation is implemented in November 2010. Red dots are for in situ observations of surface soil moisture. Fraction of bare ground (according to the model) for each site is indicated. The dashed line represents the model minimum soil moisture limit before the implementation of the new bare ground evaporation (permanent wilting point).

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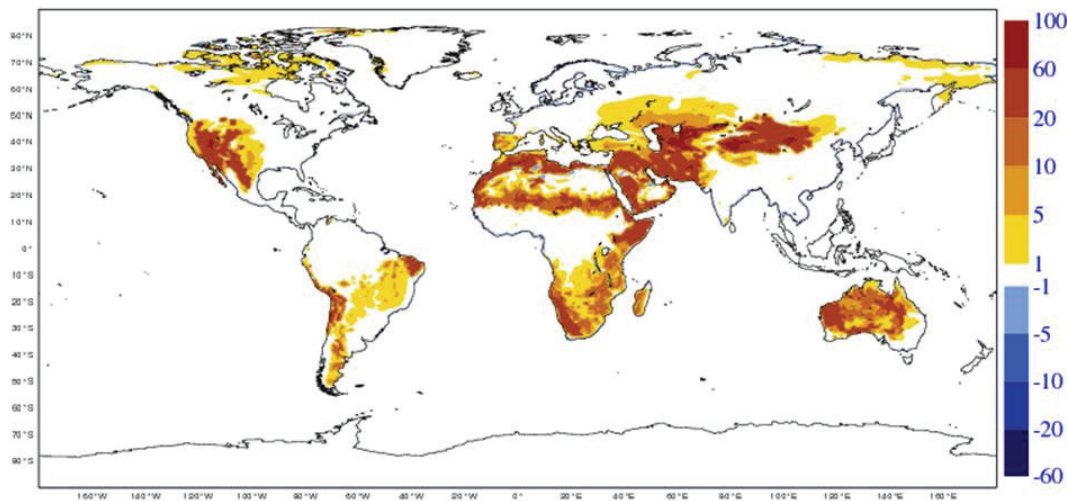
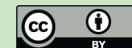


Fig. 5. Map of differences between TB (in K) simulated using model fields from BEVAP_NEW and BEVAP_OLD for August 2010 (06:00 UTC).

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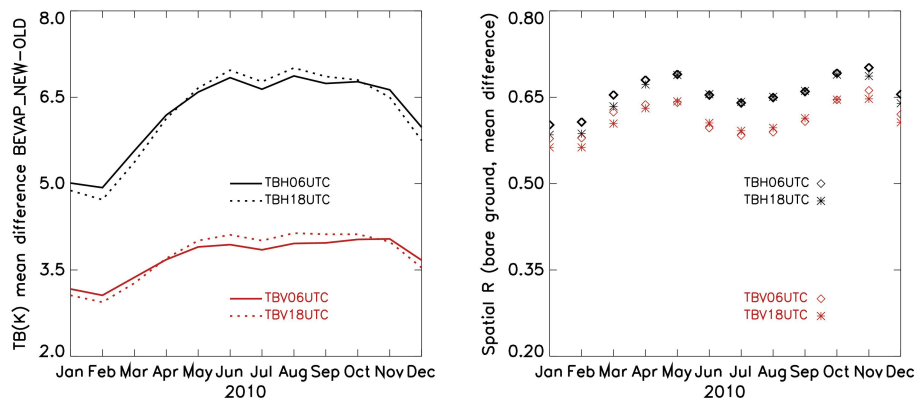


Fig. 6. Left panel: brightness temperature global monthly mean sensitivity to the new bare soil parameterization for 2010 (solid and dashed lines). Right panel: spatial correlation between the fraction of bare ground and the brightness temperature global monthly difference (stars and diamonds). Both horizontal and vertical polarizations are represented for 06:00 UTC and 18:00 UTC.

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