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A global analysis of satellite derived and DGVM surface soil moisture products

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Soil moisture availability is important in regulating photosynthesis and controlling land surface-climate feedbacks at both the local and global scale. Recently, global remote-sensing datasets for soil moisture have become available. In this paper we assess the possibility of using remotely sensed soil moisture (AMSR-E) to evaluate the results of the process-based vegetation model ORCHIDEE during the period 2003–2004. We find that the soil moisture products of AMSR-E and ORCHIDEE correlate well, in particular when considering the root zone soil moisture of ORCHIDEE. However, the root zone soil moisture in ORCHIDEE consistently overestimated the temporal autocorrelation relative to AMSR-E and in situ measurements. This may be due to the different vertical depth of the two products, to the uncertainty in precipitation forcing in ORCHIDEE, and to the fact that the structure of ORCHIDEE consisting of a single-layer deep soil, does not allow simulation of the proper cascade of time scales that characterize soil drying after each rain event. We conclude that assimilating soil moisture in ORCHIDEE using AMSR-E with the current hydrological model may significantly improve the soil moisture dynamics in ORCHIDEE.

1 Introduction

Changes in land carbon uptake and emissions at mid latitudes are strongly related to the frequency and magnitude of droughts (Angert et al., 2005) and are thus ultimately linked to variations and possible future changes in the global hydrological and carbon cycles. Details of when, where, and how strong this coupling is, are largely unknown. Summer droughts under future climate conditions are likely to increase in frequency and intensity over Europe (Seneviratne et al., 2006b), parts of Northern America and the Mediterranean area according to the IPCC, but there is doubt as to whether this is already visible in the observational record (van der Schrier, 2006). Various regions in the world also appear more sensitive to regional and local scale atmospheric feedbacks

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induced by soil moisture that can increase the persistence and likelihood of drought (e.g. Koster et al., 2004; Seneviratne et al., 2006a). D'Andrea et al. (2006) even suggest that wet and dry summers may exhibit bimodal distributions of soil moisture. This implies that changes from relatively wet – and carbon fixation conditions – towards dry and carbon emitting-conditions, may be far more abrupt than previously thought.

Angert et al. (2005) suggest that hydrological processes, such as soil moisture availability, may in fact be more important in the carbon uptake of vegetation than the traditionally studied growth enhancing temperature effects (see also Ciais et al., 2005; Reichstein et al., 2007). Recent land-surface modelling intercomparisons point to the need to focus on an accurate description of the soil moisture in the carbon and climate feedbacks (Reichstein et al., 2007). These are currently not adequately capturing the spatial and temporal response of the biosphere. Our lack of understanding of the coupling of the hydrological and carbon cycle is largely due to the lack of adequate soil moisture observations at relevant scales (e.g. subcontinental).

Unfortunately, soil moisture is notoriously difficult to observe at large scales due to its large spatial and temporal variability. Remote sensing of surface soil moisture has the potential to help fill this gap (Wagner et al., 2007). Microwave remote sensing provides the capability for direct observation of soil moisture in the top soil (upper few centimeters). Microwave measurements have the benefit of being largely unaffected by cloud cover. Accurate soil moisture estimates are however limited to regions that have low to moderate amounts of vegetation cover. In the absence of significant vegetation cover, soil moisture is the dominant effect on the received signal (Njoku and Entekhabi, 1996). During the last few years several global soil moisture datasets have been published (Njoku et al., 2003; Wagner et al., 2003). These products have different characteristics, depending on satellite techniques, the use of active or passive instruments and retrieval approach.

A new global soil moisture dataset has recently been developed by Owe et al. (2008) that uses a microwave radiative transfer model to retrieve soil moisture from the observed brightness temperatures (Land Surface Parameter Model, LPRM). The LPRM

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has been applied to 29 yr of historical microwave data and the retrieved soil moisture has been validated over different parts of the world (De Jeu et al., 2008). This dataset provides an excellent opportunity to test the performance of global land surface models, working at the same temporal and spatial resolution as the microwave observations.

5 Previous work on the spatial variability of soil parameters has shown that the spatial correlation of soil moisture is lost at around 25 km (Skøien et al., 2003; De Lannoy et al., 2006). This makes it in principle possible to test and assess the performance of global land surface models with remotely sensed soil moisture.

10 In this study we use ORCHIDEE, a process-based global vegetation model (Krinner et al., 2005) which is being used for simulation of carbon and water fluxes of point locations, and in European and global applications (Ciais et al., 2005; Piao et al., 2007). The remotely sensed soil moisture data are compared to gridded soil moisture modeled by ORCHIDEE, with the goal to study the possibility of using satellite soil moisture data for soil moisture assimilation with ORCHIDEE. Since satellite soil moisture covers
15 only the first few centimeters of soil, we focus on the relative comparisons and the dynamics of the soil moisture depletion processes after rain events. These processes are strongly affected by climate forcing and by soil hydrological characteristics, and give us valuable information on the performance of both the structure of ORCHIDEE in terms of subsurface soil hydrology, and satellite soil moisture. The soil moisture depletion
20 process time varies between a few days to several months and can be characterized with autocorrelation analysis. The general objective of this study is thus to evaluate the performance of subsurface hydrology of ORCHIDEE in relation to satellite and in situ soil moisture using both comparison and autocorrelation analysis. These are the necessary required first steps before a full assimilation methodology can be implemented.

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2 Data

2.1 Satellite derived soil moisture

Satellite observations from the Advanced Microwave Scanning Radiometer (AMSR-E) on board the AQUA satellite are used for soil moisture retrieval. The AQUA satellite was launched in May 2002. The instrument measures the microwave radiation emitted by the Earth's surface in vertical and horizontal polarization, expressed in terms of brightness temperature. AMSR-E provides global passive microwave observations at 6 different frequencies, including 6.9 GHz (C-band), 10.7 GHz (X-band) and the 36.5 GHz (Ka-band). The spatial resolution of the footprint measurements is 56 km at C-band, 38 km at X-band and 12 km at Ka-band. AMSR-E scans the Earth's surface in an ascending (01:30 p.m.) and descending (01:30 a.m.) mode. Level 2A globally swatted brightness temperatures (Ascroft and Wentz, 2003) are obtained from the National Snow and Ice Data Center (NSIDC) and used in the Land Parameter Retrieval Model (Owe et al., 2008) to retrieve surface soil moisture. The LPRM is based on the inversion of the $\omega - \tau$ radiative transfer model (Mo et al., 1982).

The retrieval methodology uses a nonlinear iterative procedure in a forward modeling approach to partition the surface emission into its primary source components, i.e. the soil surface and the vegetation canopy, and optimizes on the canopy optical depth and the soil dielectric constant. Once convergence between the calculated and observed brightness temperature is achieved, the model uses a global data base of soil physical properties (Rodell et al., 2004) together with a soil dielectric model (Wang and Schmugge, 1980) to solve for the surface soil moisture. No field observations of soil moisture, canopy biophysical properties, or other observations are used for calibration purposes, making the model largely physically-based with no regional dependence and applicable at any microwave frequency suitable for soil moisture monitoring (i.e. L-, C-, X-, or Ku-band).

For this study we used the descending C-band frequency retrievals because this data set has been shown to be the most reliable soil moisture data set (Owe et al.,

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2008). The default C-band derived Soil Moisture is replaced with the X-band if the grid cell is diagnosed with radio frequency interference (RFI) according to the method of Li et al. (2004). In addition, a low pass filter (i.e. a 5 day moving average) is applied on the dataset to minimize the random noise on the signal. The noise is mainly caused by the accuracy of the instrument itself and partly due to the low revisit time of the satellite (~16 days). The noise had to be reduced before the spatial analysis because it has a strong impact on the temporal autocorrelation.

The soil moisture retrievals are produced from Level 2A AMSR-E swaths with a sampling density of about 0.1 degree and a spatial resolution of 74 by 43 km. Daily Earth coverage is nearly 100% above and below 45 north and south latitudes, while mid latitudes experience about 80% coverage (Ascroft and Wentz, 2003). The swath soil moisture data is globally averaged and gridded in order to create daily maps at a 0.25 degree grid scale. These satellite derived soil moisture products are representative of soil moisture of approximately the first centimeter. The uncertainty of soil moisture retrieval is a function of the vegetation density and sensor characteristics and was previously estimated to be $0.04 \text{ m}^3 \text{ m}^{-3}$ for sites with sparse vegetation to 0.1 for regions with moderate to dense vegetation cover (De Jeu et al., 2008). This is a relative small number, since the range of soil moisture between a dry and wet state is about 10 times higher ($\sim 0.4 \text{ m}^3 \text{ m}^{-3}$) than the uncertainty. The global soil moisture products retrieved using the LPRM method are well validated with in situ observations, land surface models and other global satellite derived soil moisture products over a variety of vegetation covers. (e.g., Draper et al., 2009; Wagner et al., 2007; De Jeu et al., 2008; Rüdiger et al., 2009).

2.2 ORCHIDEE soil moisture

ORCHIDEE is a process-oriented model of the terrestrial water-carbon-energy cycles. It consists of three sub-models (Krinner et al., 2005). The Soil Vegetation Atmosphere Transfer (SVAT) scheme SECHIBA (Ducoudré et al., 1993; de Rosnay and Polcher, 1998), which calculates water fluxes in the soil-plant-atmosphere continuum

decreasing exponential function with depth. A residual fraction of 20% of the maximum potential root uptake is still possible when the bottom layer is almost empty. The variable HUMREL (in this study indicated as ROOT_SM) is defined as the soil moisture that is available in the root zone, adjusted for the plant functional types present in each grid.

The ORCHIDEE model was forced by the CRU-NCEP dataset (<http://dods.extra.cea.fr/data/p529viov/cruncep/readme.htm>). This dataset is based on CRU2.0 monthly climate anomalies at a $0.5^\circ \times 0.5^\circ$ covering the period 1901 to 2002 (Mitchell and Jones, 2005) and the NCEP reanalysis covering the period 1948 to 2009 (Kanamitsu et al., 2002). The two datasets are combined using the 6 hourly variability of NCEP and the monthly fields of CRU to obtain a pseudo $0.5^\circ \times 0.5^\circ$ 6 hourly dataset covering the period 1901 to 2009.

For the spinup, ORCHIDEE was run using the 1910–1930 climate in loop until equilibrium of water and carbon pools in soil and vegetation. Then simulation is launched using climate from 1901 to 2008 taking into account increasing CO_2 . ROOT_SM and other relevant model output variables have been archived for the period from 2000 to 2008 at a daily time step for comparison with satellite observations.

2.3 FLUXNET soil moisture

FLUXNET is a global network of micrometeorological flux measurement sites that estimate the exchange of carbon dioxide, water vapor, and energy between the biosphere and atmosphere. At present over 300 sites are operating on a long-term and continuous basis. Vegetation under study includes temperate conifer, broadleaf evergreen and deciduous forests, tropical and boreal forests, crops, grasslands, chaparral, wetlands, and tundra. Sites exist on five continents and their latitudinal distribution ranges from 70° N to 30° S . Data and site information are available online at the FLUXNET Website, <http://www.fluxdata.org> (Baldocchi et al., 2001).

From this database we selected 15 sites that have both a reliable two year record of top soil moisture within the time frame of AMSR-E (June 2002–end 2008) and are

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located in a region with low vegetation density (optical depth <0.8 , see De Jeu et al., 2008). This vegetation selection was added to provide reliable AMSR-E soil moisture observations for these sites. These sites have a variety of vegetation types and climates. Table 1 lists the selected FLUXNET sites, their coordinates and the vegetation type at the site.

3 Comparison studies

3.1 Setup

3.1.1 Comparison of soil moisture values

For both AMSR-E and ORCHIDEE, quarter degree soil moisture values have been calculated for the years 2003 and 2004. We have calculated several state variables in ORCHIDEE, i.e. SHALLOW_SM, DEEP_SM, TOT_SM (SHALLOW_SM + DEEP_SM) and ROOT_SM, and compared these to the AMSR-E values.

The routine for AMSR-E has an output in volumetric soil moisture (in $\text{m}^3 \text{m}^{-3}$), while for ORCHIDEE the output is in mm available water. To calculate the correspondence between AMRS-E and ORCHIDEE soil moisture, we first calculated the correlation coefficient (r) between the output of AMSR-E and the different state variables of ORCHIDEE for 2003 and 2004. The correlation can be skewed due to errors or scale differences in precipitation forcing in ORCHIDEE. This version of ORCHIDEE used CRU-NCEP data, which are monthly CRU data adjusted to daily values, while AMSR-E is a direct measure of surface soil moisture and therefore expected to be very sensitive to actual precipitation. To identify the accuracy of the CRU-NCEP forcing, we correlated the CRU-NCEP daily rainfall data to the AMSR-E soil moisture data. Next, we analyzed the inter-annual variability between two consecutive years, by analyzing daily values of the soil moisture normalized change defined by:

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$$\text{Inter-annual variability} = \frac{(2004 - 2003)}{0.5 \cdot (2003 + 2004)} \quad (1)$$

The years 2003 and 2004 were different climatic years (e.g. heatwave in Europe in 2003, Ciais et al., 2005). As expected, the relationship between ORCHIDEE and AMSR-E varies at a global scale. To learn more about the inter-annual differences, we used the FLUXNET data for in situ comparisons between AMSR-E and ORCHIDEE.

3.1.2 Autocorrelation

Modeled, satellite and in situ observed soil moisture products do not necessarily have to agree since they are a result of processes at a different spatial scale. For example, a small local rainstorm could have a significant impact on an in situ observation, but only a limited impact at 0.25 degree scale. However, despite the differences in scale, in situ, modeled and satellite products should have a similar response to rainfall if the rainfall was equally distributed. An autocorrelation analysis captures the general temporal dynamics of soil moisture and is thus a powerful tool to analyze different soil moisture products, because it describes the direct soil moisture response to hydrological processes, being less sensitive to scaling issues.

For continuous variables we characterize persistence in terms of temporal autocorrelation (lagged correlation), which is the correlation of a variable with its own future and past values (Wilks, 1995). Therefore, a dry-down and rewetting pattern should show similar autocorrelation values if their dynamics are similar, even though the climate forcing might not be timed simultaneously. In this study, the Pearson product-moment correlation coefficient was used to calculate the lagged correlation, where the lag- k autocorrelation coefficient can be written as (Wilks, 1995):

$$r_k = \frac{\sum_{i=1}^{n-k} (x_i x_{i+k}) - (n-k) \bar{x}^2}{\sum_{i=1}^n x_i^2 - n \bar{x}^2} \quad (2)$$

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two products is very closely related. In the northern latitudes, the coefficient is close to -1 , which is caused by the fact that frozen soil in ORCHIDEE contains little water, while the water content is retrieved close to saturation in AMSR-E. In very dry areas, we find almost no correlation, since ORCHIDEE simulates no difference in soil moisture during drought, while there is largely noise in the AMSR-E field (De Jeu et al., 2008).

The regions where ORCHIDEE and AMSR-E are closely related (r close to 1), are similar to another study by Wagner et al. (2003), in which the European Remote Sensing Satellites (ERS) soil moisture products were compared with soil moisture output by the global dynamic vegetation model LPJ. Correlating the precipitation forcing (CRU-NCEP) to the AMSR-E soil moisture results in low r -values, comprised between 0 and 1 (Fig. 2). Precipitation forcing fields are highly uncertain, and land surface models are most sensitive to this forcing to calculate soil moisture (Guo and Dirmeyer, 2006). New methods are being developed to improve precipitation forcing along with soil moisture fields, e.g. using satellite-based rainfall accumulation estimates to improve surface soil moisture retrievals (Schumann et al., 2009), sometimes including the use of hydrological models (Crow et al., 2009; Parajka et al., 2009).

Even though the geographic patterns of correlation between AMSR-E and ORCHIDEE for 2003 and 2004 look very similar, Fig. 3 shows that they are not. In this figure, the average difference between ORCHIDEE and AMSR-E soil moisture for 2003 minus 2004 is shown (Eq. 1). Figure 3c shows the binned combination map of AMSR-E and ORCHIDEE, Table 2 gives an index for these different combinations, and the associated area covered. The regions where both AMSR-E and ORCHIDEE agree are the yellow and the green regions, which sums to a total of 53.2% globally. The northern latitudes, western Europe, north-America, mid-Africa and the middle region of south America are dominated by blue, indicating that AMSR-E observations indicate a dryer 2004 compared to 2003, while ORCHIDEE simulates oppositely a wetter 2004. Figure 3c does not give an indication of the size of difference, solely shows discrepancy between modeled and observed soil moisture change from 2003 to 2004. It is interesting to see is that in areas where climate was different between the two years, e.g.

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western Europe, AMSR-E and ORCHIDEE do not agree for the sign of soil moisture change between 2003 and 2004. Small differences can be due to the uncertainty of AMSR-E and ROOT_SM. We will look into this difference in further detail later in the paper, using autocorrelation methods.

3.2.2 Evaluation with in situ data

The correlation coefficients between the soil moisture observations at the FLUXNET locations and AMSR-E and ROOT_SM are shown in Table 3. AMRS-E values are compared with available FLUXNET data between June 2002 until the end of 2007, while ROOT_SM is only available for years 2003 and 2004 in ORCHIDEE. At some locations the r coefficients could not be calculated for ROOT_SM, because FLUXNET data were not available in these locations for 2003 and 2004.

The variability in correlation between in situ and modeled/satellite soil moisture is large, ranging from $r = 0.1$ in a grassland in Matra Hungary, to $r = 0.9$ in the savanna of Las Majadas del Tietar, Spain. No significant relation can be found between the value of the correlation coefficient and vegetation cover and it seems that the correlation coefficient rank is mainly determined by the existence of local processes like land cover heterogeneity and subgrid precipitation events affecting each site. The correlation coefficients for ORCHIDEE are generally higher than for AMSR-E, however, this does not necessarily imply a better performance of soil moisture estimation by ORCHIDEE. Cosh et al. (2006) suggest that at least 16 soil moisture stations are needed to obtain a reliable spatially averaged soil moisture value at a 0.25 degree scale. Here, just a single observation is analyzed in comparison with 0.25° averaged satellite observations. So care should be taken by the interpretation of these results. However, a temporal autocorrelation signature is likely to be spatially more stable and thus a more a powerful tool for data analysis when a dense soil moisture network is not present.

The soil-moisture autocorrelation was calculated as a function of varied lag k , for the in situ FLUXNET measurements, the satellite AMSR-E retrievals, and the ORCHIDEE

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ROOT_SM simulated variable at each FLUXNET site (Tables 1 and 3) during the period 2003–2004. Two years of data were needed to generate a stable autocorrelation signature. In Fig. 4, we show the autocorrelation plots of these different variables for sites in Spain, Hungary, Ireland and South Africa. On the y-axis r_k is shown, which is a measure of autocorrelation (Eq. 2). An autocorrelation of 1 shows a perfect autocorrelation (autocorrelation of data with itself), and an autocorrelation of 0 shows that there is no autocorrelation between the original and the shifted original dataset. On the x-axis the lag-time in days is shown for the corresponding autocorrelation values. We choose as a cutoff for the existence of autocorrelation the value of $1/e$ (~ 0.37) for autocorrelation (r_k), which is represented by the black dashed horizontal line. The associated lag-time will be referred to as characteristic lag-time. For example, at the Spanish site, AMSR-E (red) and the in-situ data (blue) have an autocorrelation value of $1/e$ at a characteristic lag-time of 15 days, which means that the “soil memory” is 15 days, while ROOT_SM has an autocorrelation value of $1/e$ at a characteristic lag-time of a little over 30 days.

AMSR-E and FLUXNET show an excellent agreement in autocorrelation, suggesting that the satellite captures the temporal dynamics of soil moisture on synoptic to seasonal scales well. On the other hand, ORCHIDEE always overestimates the autocorrelation, except for the site Dripsey in Ireland which has a temperate humid climate and relatively high characteristic lag-time values. The overestimation by ORCHIDEE could be due to (1) unrealistic (too smooth) rainfall forcing from CRU-NCEP model (i.e. underestimated precipitation variability because of unresolved rainstorms, (2) structural rigidity in soil moisture dynamics calculation of ORCHIDEE (i.e. not enough runoff or lack of temporally variable root water uptake); in particular the unique deep soil layer imposes a single residence time for water in the soil with respect to plant transpiration removal, whereas in reality, each soil layer has its own residence time, (3) misfit between modeled and observed soil moisture because ORCHIDEE only provides root-zone integrated values, which will show less variability than top-soil values, while AMSR-E and the measurements reflect more shallow soil moisture dynamics, which are characterized by short term variability and thus short characteristic lag-times (Wu

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and Dickinson, 2004; De Lannoy et al., 2006). This is confirmed by Wagner et al. (1999) who found mean correlations between 0.35 to 0.53 and 0.33 to 0.49 when comparing ERS scatterometer data with gravimetric soil moisture measurements in 0–20 cm and 0–100 cm layers respectively.

Figure 5 compares the in situ FLUXNET characteristic lag-time versus the characteristic lag-time of satellite AMSR-E soil moisture and modeled ROOT_SM variables for the sites shown in Tables 1 and 3. The cross-sites correlation coefficient of the characteristic lag-time between in situ and AMSR-E is high ($r = 0.93$ for $n = 15$), and lower for ROOT_SM ($r = 0.37$ for $n = 8$). This demonstrates a high correspondence in the autocorrelation signature between in situ FLUXNET and satellite observations, indicating that both have a similar response to the hydrological processes. The autocorrelation signature of ROOT_SM is significantly different, showing a too slow temporal dynamics in the model, dictated by its “rigid” sub-surface hydrology. This can be expected from a mono-layer bucket, which is also indicative for the ORCHIDEE hydrology since the top layer is often empty. This corresponds to Fig. 4, however, Fig. 5 shows that the model bias is rather constant. Except for the site in Ireland, ORCHIDEE ROOT-SM always overestimates the characteristic lag-time, with a gradient similar to the satellite observations. This may suggest an offset due to the deeper soil depth that ROOT-SM represents relative to AMSR-E.

3.2.3 Global autocorrelation maps

It is assumed that the autocorrelation function r_k becomes insignificant when it takes values lower than $1/e$, defining a characteristic lag-time, also shown in Figs. 4 and 5. In Fig. 6 the characteristic lag-time is plotted on each grid point for 2003–2004, with Fig. 6c identifying the difference in lag-time (in days) between AMSR-E and ROOT-SM. While the lag-time is not very different between ROOT_SM and AMSR-E in western Europe and eastern US, large differences exist in other parts of the globe. In general, the lag-time in ROOT_SM is often longer than in AMSR-E, with differences of up to 40 days. This is in agreement with Fig. 5 and Table 3, again suggesting a discrepancy

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due to the deeper soil depth in ROOT-SM, which produces a too-slow moisture removal after rain compared to AMSR-E. The high correspondence of ROOT-SM in Fig. 5 can be due to an offset to larger values with same trend, which would result in high r^2 , but in large differences between autocorrelation values.

Most of the blue regions in Fig. 3c, indicating that ORCHIDEE simulates a wetter 2004 compared to 2003 while AMSR-E observes a drier 2004 compared to 2003, are related with red areas in Fig. 6c, indicating a much longer autocorrelation for ORCHIDEE than for AMSR-E. This may suggest that in 2004 there were no prolonged dry spells, however, on shorter timescales these areas have dried out in reality quicker than ORCHIDEE simulates. The exception to this is western Europe and northeastern US, which are in blue in Fig. 3c, but Fig. 6c indicates that the difference in characteristic lag-time is between 0 and 10 days over these two regions. This may be due to the use of a prescribed uniform soil of 2 m by ORCHIDEE, while suitable for Europe and northern America, is most likely not suitable for tropical soils. Therefore the dynamic behavior of these regions may not be well captured. Overall, the too sluggish removal of soil moisture after rain in ORCHIDEE, may suggest that this model will underestimate the response of vegetation to dry spells in the future, and hence may underestimate the positive feedback of climate change on the carbon cycle as well. In the recent coupled carbon-climate models intercomparison of Friedlingstein et al. (2006), ORCHIDEE indeed shows a small positive feedback compared to other models. At face value, the too slow characteristic lag-time also reflects some inconsistency between what is modeled (total soil moisture content) and what is observed (top-soil moisture). With that respect, it would help to incorporate in ORCHIDEE a multi-layer soil hydrology, as defined for instance by de Rosnay and Polcher (1998).

4 Conclusions and summary

It has been shown that the daily soil moisture products of AMSR-E and simulations of ORCHIDEE forced by CRU-NCEP correlate well in time, within know errors of both,

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Table 1. Geographical location and characteristics of the 15 study sites as used in the ground validation study.

No.	Site name	Latitude	Longitude	Vegetation (IGBP Class)	Precip (mm yr ⁻¹)	Reference/ Primary contact
1	Lethbridge, Canada	49.71° N	112.94° W	Grasslands	378	Flanagan and Johnson (2005)
2	Gebesee, Germany	51.10° N	10.91° E	Croplands	492	Anthoni et al. (2004)
3	Las Majadas del Tietar, Spain	39.94° N	5.77° W	Savanna	528	Casal et al. (2009)
4	Vall d'Alinya, Spain	42.15° N	1.45° E	Grassland	1064	Gilmanov et al. (2007)
5	Le Bray, France	44.72° N	0.77° W	Evergreen needleleaf forest	972	Berbigier et al. (2001)
6	Laqueuille, France	45.64° N	2.74° E	Grasslands	1100	Ceschia Eric
7	Bugacpuszta, Hungary	46.69° N	19.60° E	Grasslands	500	Gilmanov et al. (2007)
8	Matra, Hungary	47.85° N	19.73° E	Grasslands	600	Pintér et al. (2008)
9	Dripsey, Ireland	51.99° N	8.75° W	Grasslands	1450	Kiely Gerard, Jaksic et al. (2006)
10	Mitra IV Tojal, Portugal	38.48° N	8.02° W	Grasslands	750	Gilmanov et al. (2007)
11	Pang/Lambourne, UK	51.45° N	1.27° W	Deciduous broadleaf forest	800	Harding Richard
12	Lamont, Oklahoma, USA	35.55° N	98.04° W	Grasslands	740	Fischer Marc
13	Sylvania Wilderness Area, Michigan, USA	46.24° N	89.35° W	Mixed forest	896	Desai et al. (2005)
14	Skukuza- Kruger National Park, South Africa	25.02° S	31.50° E	Savanna	650	Scholes Robert John
15	Flagstaff, Arizona, USA	35.09° N	111.76° W	Evergreen needleleaf forest	540	Kolb Tom, Dore et al. (2010)

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Table 3. Correlation coefficient (r), bias, standard error (Serr) and characteristic lag-times (ch.lag) of measurements, AMRS-E and ORCHIDEE (ROOT_SM).

Site	Name	meas	AMSR-E			ORCHIDEE				
		ch.lag	r	Bias	Serr	ch.lag	r	Bias	Serr	ch.lag
1	Lethbridge, Canada	29.3	0.48	0.09	0.07	12.4	0.42	0.18	0.07	41.6
2	Gebesee, Germany	24.9	0.21	0.17	0.05	25.1	0.8	0.14	0.03	50.4
3	Majadas del T, Spain	43.1	0.9	-0.03	0.04	45.8				
4	Vall d'Alinya, Spain	13.9	0.4	-0.07	0.07	14.2	0.72	0.1	0.06	33.6
5	Le Bray, France	49.7	0.66	-0.15	0.05	52.7				
6	Laqueuille, France	35.5	0.46	0.24	0.06	34.5	0.69	0.19	0.05	39
7	Bugacpuszta, Hung.	8.2	0.69	-0.16	0.04	15				
8	Matra, Hung.	26.5	0.11	0.26	0.06	28.3	0.41	0.24	0.05	57.7
9	Dripsey, Ireland	52.4	0.69	-0.43	0.09	53.2	0.85	0.13	0.07	37.9
10	Mitra IV Tojal, Port.	54.9	0.84	-0.03	0.07	61.2				
11	Pang/Lambourne, UK	54.9	0.75	-0.22	0.06	40.9				
12	Lamont, Oklah, USA	14.2	0.66	0.09	0.05	8.6				
13	Sylvania WA, MI, USA	31	0.22	0.18	0.03	26.4	0.47	0.1	0.03	50.2
14	Skuk-Kruger NP, S.Afr	3.5	0.35	0.04	0.03	8.3	0.2	0.08	0.04	24.4
15	Flagstaff, AR, USA	14.6	0.65	0.13	0.05	9.2				

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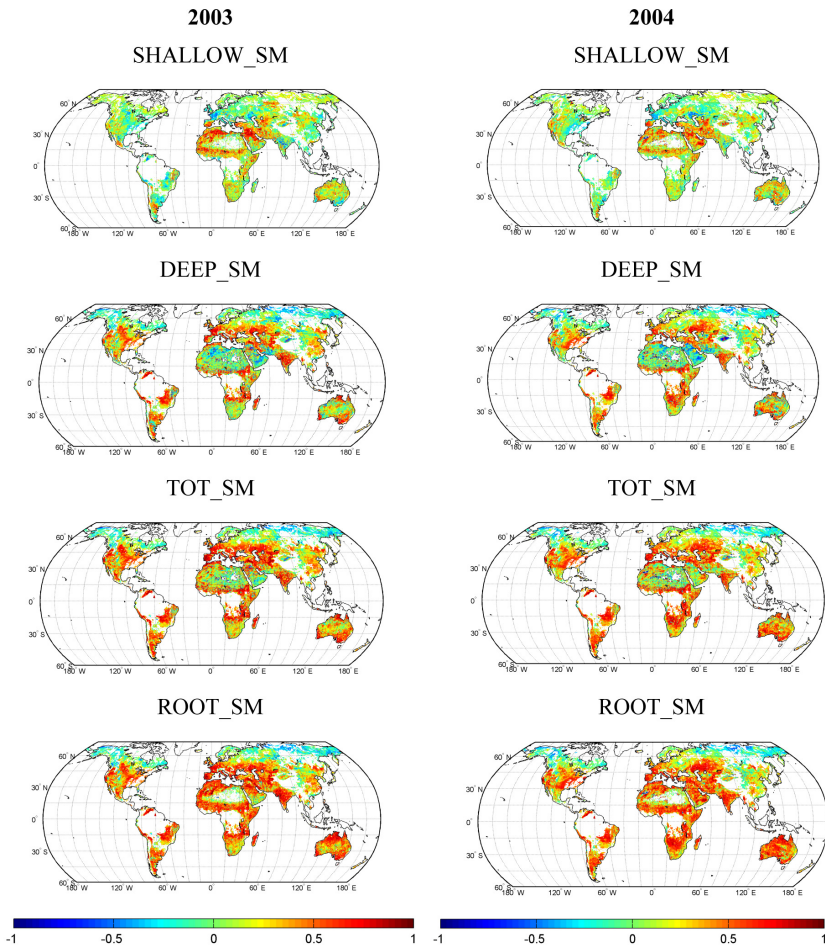



Fig. 1. Global correlation coefficient maps of AMSR-E versus the ORCHIDEE soil moisture parameters SHALLOW_SM, DEEP_SM, TOT_SM and ROOT_SM.

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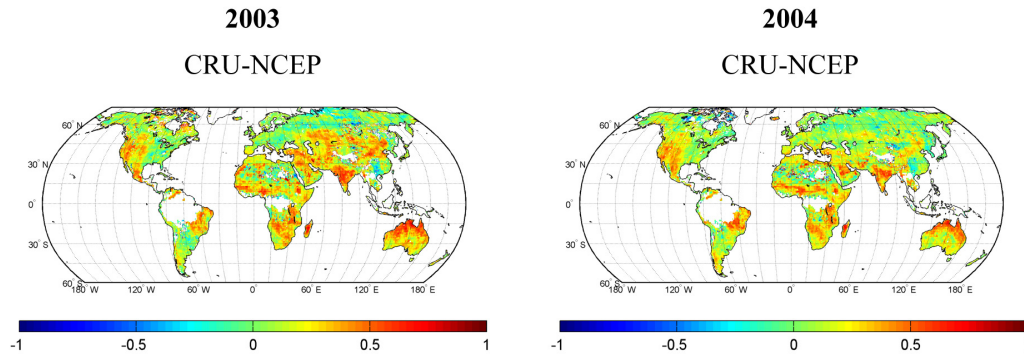


Fig. 2. Global correlation coefficient maps of AMSR-E versus the CRU-NCEP precipitation forcing of ORCHIDEE.

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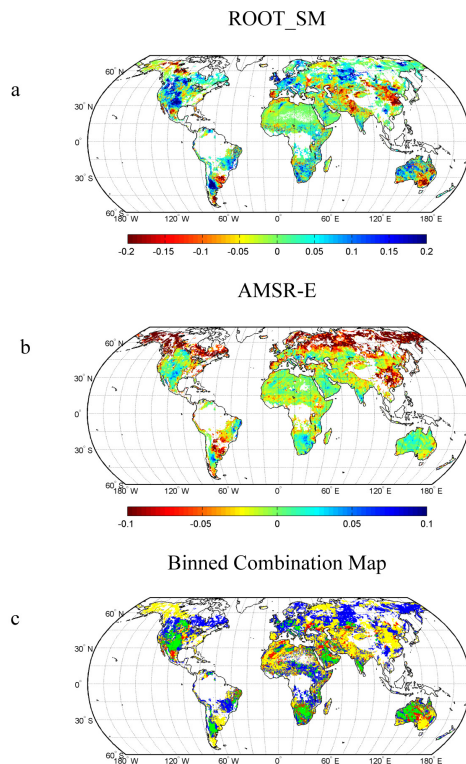


Fig. 3. Difference maps of the average soil moisture values based on Eq. (1). **(a)** represents the difference of the ORCHIDEE parameter ROOT_SM, **(b)** represents the difference of AMSR-E, **(c)** combines the two maps and bins the data in 4 criteria: the green region where both ORCHIDEE and AMSR-E indicates a wet year for 2004 compared to 2003, the yellow region where both ORCHIDEE and AMSR-E indicates a dry year for 2004 compared to 2003, the red region where AMSR-E indicates a wet year for 2004 compared to 2003 while ORCHIDEE indicates a dry year for 2004 compared to 2003, and visa versa for the blue region.

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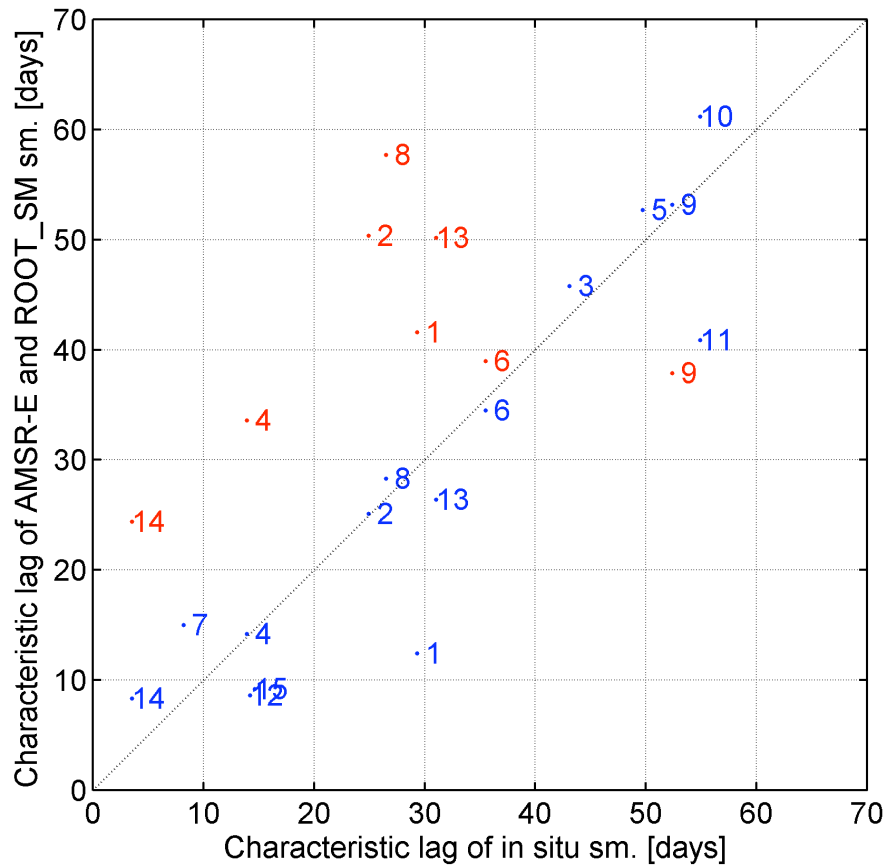


Fig. 5. Autocorrelations length of in situ soil moisture characteristic lag-time against characteristic lag-time of AMSR-E (blue) and ROOT_SM (red).

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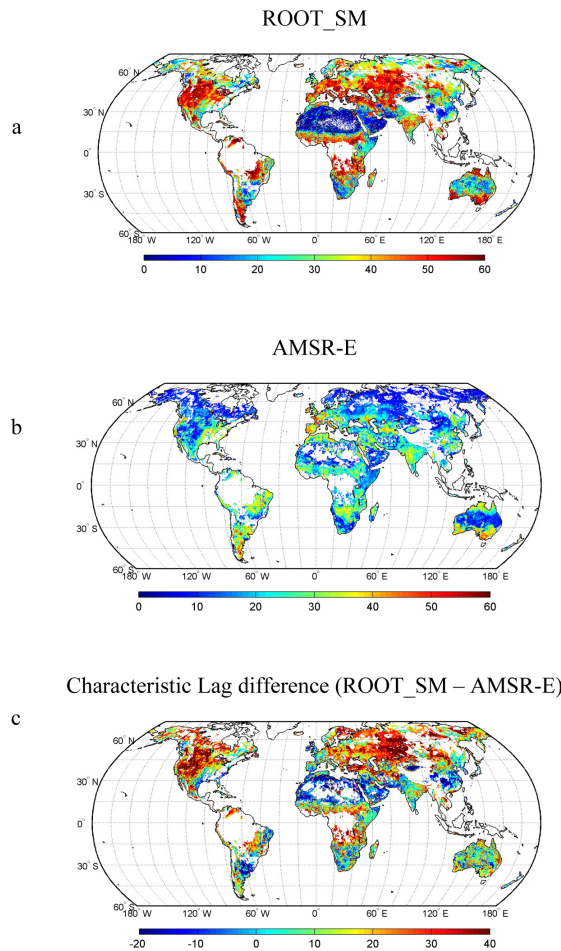


Fig. 6. Global characteristic lag-time for 2003 till 2004. The difference in characteristic lag is calculated as AMSR-E – ROOT.SM.

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