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Land surface anomaly simulations and predictions with a climate model: an El Niño Southern Oscillation case study

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The ability of climate models to reproduce and predict land surface anomalies is an important but little-studied topic. In this study, an atmosphere and ocean assimilation scheme is used to determine whether HadCM3 can reproduce and predict snow water equivalent and soil moisture during the 1997–1998 El Niño Southern Oscillation event. Soil moisture is reproduced more successfully, though both snow and soil moisture show some predictability at 1- and 4-month lead times. This result suggests that land surface anomalies may be reasonably well initialized for climate model predictions and hydrological applications using atmospheric assimilation methods over a period of time.

Keywords: land surface; snow water equivalent; soil moisture; assimilation; El Niño Southern Oscillation

1. Introduction

The land surface is where we live, and is highly variable on multiple scales. The ability of climate models to simulate the temporal and spatial variability of the land surface, particularly important water storage variables such as snow and soil moisture, has been little studied. This is partly because reliable global estimates of soil moisture and snow are difficult to obtain and validate; however, global reanalyses of atmospheric states are readily available and have been well studied.

Here, we investigate whether land surface states within a climate model are realistically reproduced by assimilating atmospheric information, and also whether they are well forecast by such a model on monthly to seasonal time scales. This tests one simple method of initializing land surface conditions for climate predictions, and also allows comparisons with independent land surface data. Better land surface predictions would then aid water resource management, for instance by improving streamflow forecasts.

The Grid for Coupled Ensemble Prediction (GCEP) project (Haines *et al.* 2009) uses cluster computing to run the HadCM3 climate model both with and without oceanic and atmospheric data assimilation over the period 1989–2001. In

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this paper, we choose a case study to demonstrate the reproduction and predictability of soil moisture and snow water equivalent (SWE) anomalies. The winter of 1997–1998 exhibited a large El Niño Southern Oscillation (ENSO) event, an ideal case study as it produces large precipitation and temperature anomalies across the globe, and the consequences can be investigated within the climate model. A comparison of climate model runs, with or without knowledge of the developing ENSO, is presented.

2. Data and climate model experiments

In the GCEP project, oceanic and atmospheric observations are introduced into the HadCM3 climate model using an anomaly assimilation scheme based on that of the DePreSys project at the Met Office (Smith *et al.* 2007). All model runs presented here have identical realistic solar, volcanic and greenhouse gas forcings, representing the end of the twentieth century. The differences are as follows.

— The 'assimilation run' is relaxed to observed atmospheric (ERA40 three-dimensional temperature and winds, and mean sea-level pressure) and oceanic (temperature and salinity) anomalies at every time step (see Haines *et al.* (2009) for details of the scheme). This run then demonstrates the ability of the model to reproduce land surface anomalies given some limited meteorological constraints.

— The 'no assimilation ensemble mean' is the average of an ensemble of five HadCM3 runs with realistic external forcing, and is thus the best estimate of the climate that can be made without the use of direct oceanic or atmospheric conditions. Averaging over this number of ensemble members is normally sufficient to allow the unpredictable weather noise to be removed (Collins & Allen 2002).

— The 'hindcast' here is an ensemble mean of four runs released from a particular point of the assimilation run. In this case, all hindcasts start on 1 November 1997. The model thus has direct information of the climate state at earlier times, but is thereafter allowed to evolve freely. This run demonstrates the potential of this method for forecasting land surface anomalies.

The assimilation and short hindcast runs both reproduce the sea surface temperature anomalies in the Nino3.4 region during the 1997–1998 ENSO event very well (reported in Haines *et al.* 2009). The no assimilation runs will be ENSO neutral and are therefore not expected to reproduce any of the relevant land surface anomalies.

We present an analysis of the anomalies in two important land surface variables, SWE and soil moisture, with the analysis restricted to the North American and Eurasian continents. Spatial distributions in the climate model are compared with the ERA40 reanalysis, for both SWE and soil moisture, where land properties are partially set from available observations so as to provide surface boundary conditions for the atmospheric analysis. In the absence of anything better, and bearing in mind the lack of observed soil moisture in constraining the reanalysis, we take these ERA40 land surface anomalies as the best estimates of the true values and validate the HadCM3 land surface anomalies against them. Note that ERA40 has a higher resolution (1.125° latitude and longitude) than HadCM3 (2.5° latitude by 3.75° longitude). For SWE anomalies, we do have independent passive microwave data from the Special Sensor Microwave/Imager (SSM/I; Armstrong *et al.* 2005), which has been producing data since 1987. The retrieval used is a simple linear fit to two frequency channels (Chang *et al.* 1987) and has been validated in many conditions (Armstrong & Brodzik 2002; Koenig & Forster 2004; Foster *et al.* 2005). The data are provided on a 25 km equal area grid. Independent global soil moisture measurements will not be available until the SMOS mission (due to launch 2009).

The assimilation period is December 1989 to November 2001, and fields are output as monthly means. All land surface anomalies are calculated with respect to a monthly climatology based on this 12-year period. For the model runs, the climatology comes from the no assimilation run. For ERA40 and SSM/I, anomalies are with respect to their own climatology states. An exception is the SWE anomalies for ERA40, which are calculated with respect to a 1984–2001 climatology, but omitting 5 years owing to an error in the snow analysis during the period 1989–1994 (Uppala *et al.* 2005).

3. Results and discussion

Anomalies of soil moisture and snow are both driven by patterns of temperature and precipitation. Positive ENSO events bring wetter weather to the USA (Ropelewski & Halpert 1986) and parts of Europe (Fraedrich 1994). In this section, monthly anomalies of soil moisture and SWE are presented for North America and Eurasia. Figure 1 shows these anomaly maps for November 1997 and February 1998, through the peak of the ENSO event. Note that the hindcast results for both November 1997 and February 1998 are initialized on 1 November 1997, and therefore the results represent 1- and 4-month forecasts, respectively.

The soil moisture in November 1997 (figure 1*a*) in the assimilation run shows spatial agreement with ERA40 (although the anomaly amplitudes are larger) over much of northern and western Eurasia, especially Europe and China. There are also broadly similar patterns over North America, with western Canada and the southeastern USA showing good agreement. In February 1998 (figure 1*b*), the assimilation soil moisture is again in reasonable agreement with ERA40 over Europe (although the positive anomalies are shifted further north), southern Asia and the USA. In both February and November, the model has difficulty in India and northeastern Canada. The no assimilation ensemble mean has much smaller soil moisture anomalies in both months, indicating gridbox-to-gridbox variability that is averaged out between ensemble members, and the patterns do not appear well correlated with those from ERA40 or the assimilation run.

Moving on to the hindcast predictions, in November 1997 (1-month lead time), the soil moisture anomalies are still very similar to the assimilation run. Agreement with ERA40 is still seen in northwest and southeast North America, and across Europe and central and northern Siberia. There is also still agreement in southeastern China. In February 1998 (with a 4-month lead time), the hindcast still shows remarkably good agreement with the assimilation run (and ERA40) in these parts of Eurasia. Southeastern North America is also well

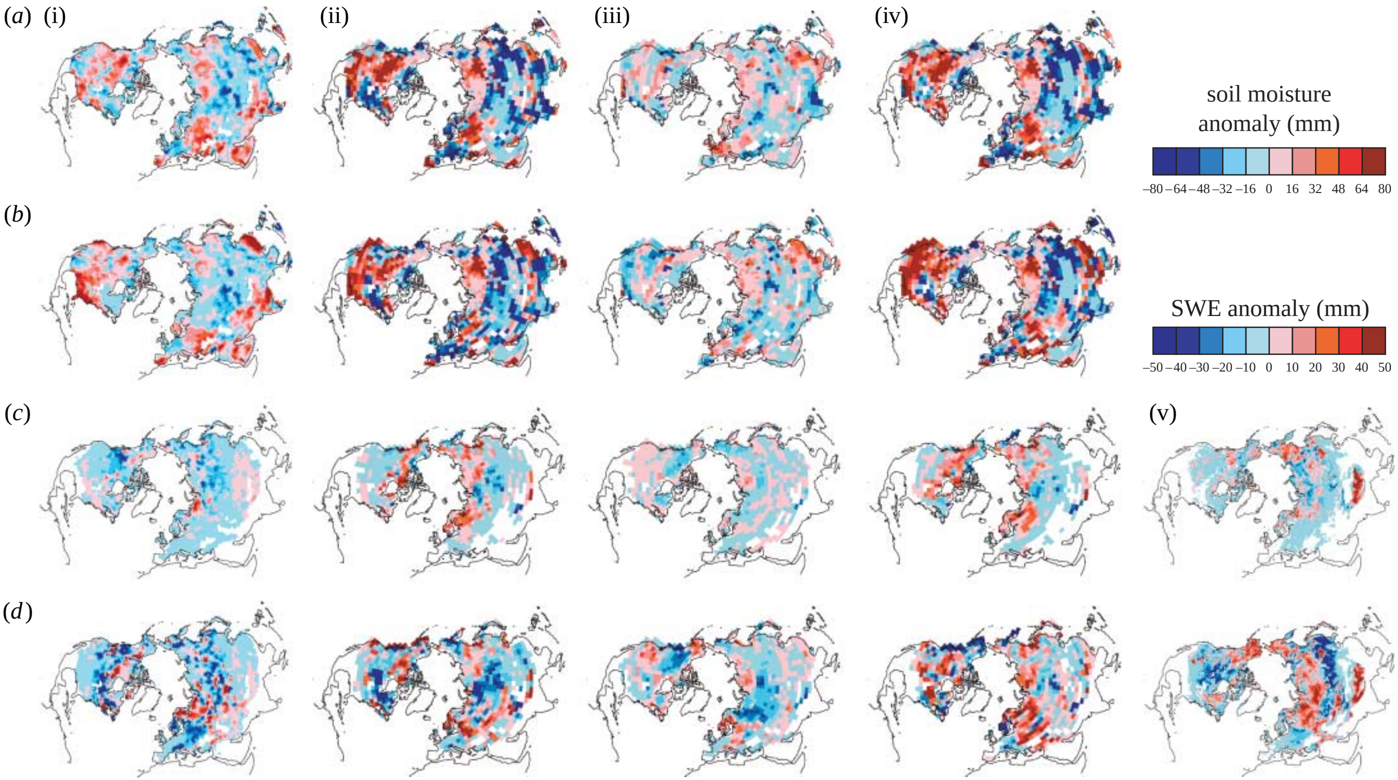

Figure 1. Modelled and observed fields of (*a*,*b*) soil moisture (mm) and (*c*,*d*) SWE (mm) from (*a*,*c*) November 1997 and (*b*,*d*) February 1998. (i) ERA40, (ii) assimilation run, (iii) no assimilation ensemble mean, (iv) mean of the hindcast ensemble launched on 1 November 1997, (v) SSM/I (for SWE only). Note that the soil moisture and SWE anomalies are plotted on different scales.

Table 1. Quantitative comparisons with ERA40: root-mean-square error (r.m.s.e.) and spatial correlation.

run	field	date	r.m.s.e. (mm)	spatial correlation
assimilation run	soil moisture	Nov 1997	58	0.62
		Feb 1998	59	0.64
	snow water equivalent	Nov 1997	15	0.44
		Feb 1998	36	0.07
no assimilation ensemble mean	soil moisture	Nov 1997	25	0.01
		Feb 1998	27	0.02
	snow water equivalent	Nov 1997	11	0.13
		Feb 1998	26	0.22
hindcast	soil moisture	Nov 1997	58	0.65
		Feb 1998	61	0.63
	snow water equivalent	Nov 1997	16	0.24
		Feb 1998	36	−0.01

reproduced, although the positive anomalies extend too far west. While the case study focuses on an ENSO event centred in the Pacific, European soil moisture, which can be strongly influenced by Atlantic weather patterns, still shows some level of skill.

Table 1 shows the root-mean-square error (r.m.s.e.) between the three model runs and ERA40. Despite the spatial distribution of anomalies in the assimilation and hindcast runs being visibly more similar to ERA40 than the no assimilation run, the r.m.s.e. is much larger. This is because the r.m.s.e. is a pointwise comparison of gridboxes; the anomalies in the assimilation run and ERA40, while having a similar spatial pattern, are not exactly coincident, and so large gridbox-to-gridbox errors occur. As the no assimilation field is an ensemble mean of a noisy field, the anomalies are much smaller and smoother, so the r.m.s.e. is generally lower.

Also presented in table 1 are spatial correlations (right-hand column). Here, it can be seen that, for soil moisture, the correlations of the assimilation run with ERA40 are always better than the no assimilation ensemble mean. The hindcast also shows correlations with ERA40 equally as good as the assimilation run.

We proceed to make the same comparisons for the SWE anomalies in figure 1*c*,*d*. The SWE anomalies for November 1997 in the assimilation run share some features with the ERA40 anomalies: positive anomalies west of the Urals, across the Himalayas and Tibetan Plateau, and parts of northern Canada. Negative anomalies are well reproduced over the USA and central Siberia, but less so in eastern Siberia. In February 1998, the areas of agreement between ERA40 and the assimilation run are different from November. The SWE anomalies show most agreement over North America, particularly at higher latitudes. There is more agreement over Siberia than in November, but less over eastern Europe, although the Alps show consistent negative anomalies. Both datasets show positive anomalies over the Himalayas, though these are too large in the assimilation run.

As with soil moisture above, the no assimilation ensemble mean has much smaller SWE anomalies across the hemisphere, indicating that, by averaging over the ensemble members, the patterns have been smoothed. Although the remaining anomalies are larger in February 1998 than in November 1997, as would be expected with a deeper snowpack at this point in the season, there is no particular agreement with ERA40.

The hindcast prediction of SWE in November 1997 shares some features with the assimilation run (and ERA40), such as the large anomalies over the Himalayas, the large positive anomalies west of the Urals and widespread positive anomalies in Siberia (the latter not seen in ERA40). However, over North America, there is a band of positive anomalies that are not seen in either the assimilation run or ERA40. In February 1998, the hindcast SWE (with 4-month lead time now) shows some similarities to the assimilation run and, to an extent, ERA40, in western Russia along the Pacific coast of North America, but similarities decrease towards the Atlantic coast.

We have the independent SWE anomaly estimates from the SSM/I dataset for comparison, shown figure 1(v). The ERA40 anomalies are of a similar size to those of SSM/I in both months, and exhibit some spatial correlation. In November 1997, the observations show a small positive anomaly west of the Urals, and positive anomalies across the Tibetan Plateau, in agreement with ERA40 and the assimilation run. While the spatial scales of anomalies across North America and Siberia are similar to ERA40, the locations of those anomalies are different. In February 1998, however, there is a rather better agreement in central Asia, particularly around the Black and Caspian seas, in Europe and Scandinavia. Siberia and North America show considerable differences, however.

The r.m.s.e. and spatial correlation for the SWE fields are also shown in table 1. Once again, the r.m.s.e. in both November and February is lowest for the no assimilation ensemble mean. Turning to the spatial correlations, in November 1997, the best correlation (0.44) is seen for the assimilation run. The hindcast also shows more correlation with ERA40 than does the no assimilation ensemble mean. However, in February 1998, although similarities between the assimilation run and ERA40 are shown in figure 1, the correlations between all model runs and ERA40 are low.

4. Conclusions

In general, the assimilation run reproduces ERA40 soil moisture anomalies better than snow anomalies, with North America, western Europe and Siberia showing the most agreement across the majority of cases studied here. Where independent SSM/I observations exist for SWE, some agreement is seen with ERA40 and the assimilation run. A pointwise measure of skill, such as r.m.s.e., does not reflect the spatial agreement between the fields as the anomalies are unlikely to be exactly coincident. A spatial correlation ranks the assimilation run as better than the no assimilation ensemble mean in all but one case (February 1998, where all correlations are low).

Data assimilation in the ocean and atmosphere has been shown to improve the reproduction of soil moisture and snow water mass anomalies, and to show some predictability for midwinter conditions with a 4-month lead time, at least in this particular ENSO case. This result means that land surface anomalies may be reasonably well initialized for climate model predictions using atmospheric assimilation methods over a period of time. Work is ongoing within GCEP to extend this study to longer time periods, and to investigate other important climate variables such as sea ice, which may help to further constrain initial conditions for short-term climate predictions and forecasts for hydrological applications.

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