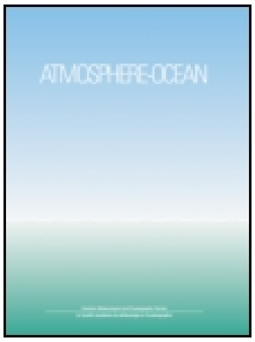

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ABSTRACT *This paper presents the results of a direct comparison of sub-seasonal (60-day) forecast skill using two different land surface initializations in the Canadian Climate Centre for Modelling and Analysis (CCCma) CanCM3 coupled global climate model. The first land surface initialization uses randomized values of soil moisture whereas in the second case the model is initialized with a "best-estimate" of soil moisture derived from offline land surface model simulations. In this experiment the realistic soil moisture initialization improved temperature forecast skill during the boreal summer. Improvement was particularly evident for the wettest and driest quartiles of soil moisture initial conditions. Certain geographic regions, such as North America, showed the greatest improvement in temperature forecast skill. In contrast to temperature forecasts, there was much less skill improvement in precipitation forecasts between the two different soil moisture initializations, although there are geographic regions, such as North America, that do show increased skill.*

RÉSUMÉ *[Traduit par la rédaction] Cet article présente les résultats d'une comparaison directe de l'habileté des prévisions sous-saisonnières (60 jours) faites au moyen de deux initialisations de surface du terrain différentes dans le modèle couplé climatique global CanCM3 du Centre canadien de la modélisation et de l'analyse climatique (CCCma). La première initialisation de la surface du terrain se sert de valeurs d'humidité du sol choisies au hasard alors que dans le second cas, le modèle est initialisé à l'aide des « meilleures valeurs estimatives » d'humidité du sol dérivées de simulations modélisées hors ligne de la surface du terrain. Dans cette expérience, l'initialisation réaliste de l'humidité du sol a amélioré l'habileté des prévisions de température durant l'été boréal. L'amélioration était particulièrement évidente pour les quartiles le plus mouillé et le plus sec des conditions initiales d'humidité du sol. Certaines régions géographiques, comme l'Amérique du Nord, ont montré la plus forte amélioration dans l'habileté des prévisions de températures. Comparativement aux prévisions de température, il y avait beaucoup moins d'amélioration d'habileté dans les prévisions de précipitations entre les deux différentes initialisations d'humidité du sol, bien que certaines régions géographiques, comme l'Amérique du Nord, montrent une habileté accrue.*

KEYWORDS soil moisture; forecast; initialization; prediction

1 Introduction

Soil moisture is an important component of the hydrological cycle, serving as a storage reservoir mediating precipitation with processes such as runoff and evapotranspiration. Because of the role of soil moisture in surface energy fluxes, it is commonly accepted that soil moisture can be an important variable in numerical modelling of weather and climate (e.g., Entekhabi et al., 1996; Dirmeyer et al., 2006). Effects of soil moisture anomalies on the atmosphere have been well documented in both observational (Findell and Eltahir, 1997) and modelling studies (Fennessey and Shukla, 1999; Koster et al., 2004). The effect of land surface attributes such as soil moisture can influence atmospheric models from global (e.g., Koster et al., 2011) to regional scales of 1–100 km (Chen et al., 2001).

Soil moisture is a slowly varying boundary condition to the atmosphere with an element of medium-term (weeks to months) predictability that can potentially be exploited for forecasting (Koster and Suarez, 2001). Therefore, it is generally accepted that initializing numerical models of the atmosphere with a realistic soil moisture state improves model performance and forecast skill (e.g., Koster et al., 2010, 2011).

Unfortunately, direct measurements of root zone soil moisture spanning the geographic domain of most atmospheric models are not available on an operational basis. The root zone is of particular importance because it is the main reservoir available to plants, thereby affecting transpiration. Emerging approaches such as the use of passive microwave estimates (e.g., Owe et al., 2008) and assimilation of soil

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moisture into models (e.g., Reichle, 2008; Dumedah et al., 2011) have been shown to improve the root zone soil moisture estimates. There are significant efforts world-wide to provide this information in near real-time to improve modelling skill (e.g., Entekhabi et al., 2010). However, it is common practice to initialize models with fields derived from sources that reflect soil moisture anomalies. These can be based on compilations of historical field observations or derived from models that are run for a sufficient period of time to develop soil moisture climatology. Examples of these include Sheffield et al. (2006) and Berg et al. (2005) who have developed global-scale soil moisture datasets from which soil moisture climatologies and anomalies can be derived for initialization of coupled land–atmosphere simulations.

This paper presents the results of a direct comparison of sub-seasonal (60-day) forecast skill using two different land surface initializations in a coupled forecast model. The model under consideration is the Canadian Climate Centre for Modelling and Analysis (CCCma) coupled global climate model (CanCM3), based on the third-generation atmospheric general circulation model (AGCM3) described in Scinocca et al. (2008). The land surface processes in the CanCM3 are simulated using the Canadian LAnd Surface Scheme (CLASS; Verseghy, 2000). In one case, the model is initialized with randomized values of soil moisture while in the other case the model is initialized with a "best-estimate" of soil moisture derived from an offline land surface simulation using bias-corrected reanalysis data. The results of this analysis demonstrate the quantity and distribution of skill increase from using a realistic land surface initialization within the CanCM3.

This paper builds on a recent study by Alavi et al. (2011) that examined the seasonal forecast error in the AGCM3 run as part of the Second Canadian Historical Forecasting Project (HFP2). Initialization of soil moisture for the HFP2 in the AGCM3 was assumed to be climatology. The Alavi et al. (2011) study found that errors in sub-seasonal air temperature forecasts could be related to differences between the soil moisture climatology and a realistic estimate of the soil moisture state. In the present study we extend the results from Alavi et al. (2011) to include realistic initialization of the soil moisture state in a fully coupled land-atmosphere-ocean climate model as described below.

A subset of the forecasts considered here contributed to Koster et al. (2010, 2011) in combination with 10 other forecast models as part of the Second Global Land-Atmosphere Coupling Experiment (GLACE-2). However, those studies did not identifiably document the performance of individual models, and the focus of the present analysis is to demonstrate the sensitivity of CanCM3 to soil moisture initialization for a longer historical period than was considered under GLACE-2. Furthermore, none of the participating models, except the CanCM3, considered simultaneous ocean-atmosphere and land-atmosphere coupling, although we have attempted to isolate the land coupling response in this analysis.

2 Methods

a *Generation of the Soil Moisture Dataset*

Global soil moisture at the CCCma T63 grid resolution (approximately 2.8^o latitude by 2.8^o longitude) was calculated using CLASS, version 3.4. Meteorological data to drive CLASS were obtained from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis (Kalnay et al., 1996). The reanalysis data were re-gridded to the T63 grid using a weighted inverse distance squared technique and then bias corrected using the procedure detailed in Alavi et al. (2011).

After bias correction, the 6-hourly reanalysis data were interpolated to the half-hourly time step used by CLASS. Air temperature, humidity, wind velocity, longwave radiation and air pressure were all linearly interpolated. Precipitation was distributed evenly over the 12 half-hour periods. Solar radiation was distributed over the 12 half-hour periods based on the solar elevation angle calculated using the algorithms of Reda and Andreas (2004). Berg et al. (2005) describe, in considerable detail, the advantages of bias-correction of reanalysis precipitation estimates with particular regard to the effect on land surface modelling. The bias-correction procedure essentially matched the quantities of precipitation derived from ground-based observations while the temporal distribution of precipitation is determined from the reanalysis product. When compared to independent high-resolution datasets of precipitation over North America, the bias-correction procedure showed significant improvement in precipitation quantity and timing. Land surface parameters (e.g., soil and vegetation properties) used for the offline CLASS model run were identical to those used in the AGCM3 model (Scinocca et al., 2008) and also detailed in Alavi et al. (2011). A total of 2090 land grid cells that did not consist of ice or solid rock were considered in the land surface calculation. Land surface variables retained included soil temperature, water and ice content at three depths (0–10, 10–35 and 35–410 cm), snow albedo, temperature, depth and density. The plant variables that were saved included the canopy temperature and the mass of frozen and liquid water stored above the ground surface. The CLASS model was run for a period of 29 years from 1979 to 2007. However, to allow CLASS to achieve an equilibrium soil moisture climatology for the data period of interest, the model was initialized using a "spin up" run of the entire 29 years as recommended by Rodell et al. (2005). In effect, the model was run twice, allowing soil moisture to achieve a stable climatology.

An evaluation of the modelled soil moisture initialization data produced from the bias corrected forcing product was performed by Alavi et al. (2011). In the Alavi et al. (2011) study, modelled and observed soil moisture time series from Alberta, Canada, and Illinois, United States, are compared. Statistically significant time series correlations were noted over these locations both at the surface and in the root zone; however, the CLASS estimates showed significant bias. The Alavi et al. (2011) study also performed a global time series assessment of the modelled soil moisture time series and the Advanced Microwave Scanning Radiometer-Earth Observing System (AMSR-E) surface soil moisture estimates (Owe et al., 2008); again statistically significant relationships were observed over very large areas globally. This is not to suggest that we believe that the soil moisture fields are entirely accurate, because studies such as Reichle et al. (2004) and Berg et al. (2005) demonstrate relatively large bias and low correlation (although largely statistically significant) globally when comparing different land surface model-derived soil moisture estimates and observations. It has been suggested that these errors likely impact seasonal to sub-seasonal climate prediction. For example Koster et al. (2011) identify a relationship between land-derived climate predictability (for temperature) and a proxy for the likelihood of soil moisture initialization error based on precipitation gauge density.

b *Forecast Experiment*

The forecast experiment described in this paper is a modified version of that used as part of the GLACE-2 project (Koster et al., 2010, 2011). In the GLACE-2 project, a total of 10 different sub-seasonal to seasonal forecast models were examined with specific regard to the effect of realistic land surface initialization. Each participating model was run for 60 days with 10 start dates on the first and the fifteenth of each month from 1 April to 15 August of each year considered. Each forecast consisted of 10 ensemble members, distinguished by slightly different atmospheric initial conditions (derived from reanalysis). The method used to produce such ensembles of initial conditions differed among the various models (for a general discussion see Koster et al. (2011)). For CanCM3 they were produced through a set of model runs, one per ensemble member, that assimilated the same atmospheric data but were begun from different initial conditions as described in Merryfield et al. (2011). The GLACE-2 project considered the period 1986 to 1995. However, for this analysis we include additional forecasts starting from the first of each month from 1986 to 2004 (1 April to 1 August). Because forecasts starting on the 15th day were not carried out from 1996 to 2004, only the first of the month start dates will be considered in this analysis. Of note, CanCM3 was the only fully coupled model (ocean, atmosphere, land surface) included in the GLACE-2 project. Therefore, the sea surface temperature was also initialized to a realistic value and evolves over the course of the forecast. CanCM3 is one of two models (the other being CanCM4) that form the new multiseasonal forecast system developed for operational use in Canada.

The experimental component of the GLACE-2 project and the results presented in this paper compare two different versions of the aforementioned model runs. In the first set, each ensemble member used the realistic soil moisture estimated for that particular start date. In the second set, each ensemble member used a different soil moisture state chosen from the same start day and month but selected from different non-adjoining years. Initial conditions for the other climate system components including the atmosphere and ocean were identical in the two sets of runs. The resulting soil moisture initialization errors for individual ensemble members are typically larger than if soil moisture had been initialized with model climatological values. However, because the specified randomized values are largely uncorrelated, their ensemble means will approximate the climatological means. The ensemble mean forecast should thus behave similarly to that of an ensemble using climatological soil moisture initialization.

Because soil moisture initialization fields were calculated independently of the forecast model using the offline forcing dataset previously described, it is expected that there will be differences between the two climatologies. To ensure that the initialization fields were consistent with the forecast model climatology, they were scaled prior to use in the experiment. This procedure, described in Koster et al. (2010), amounts to matching the standard normal deviates of forecast model climatology and the offline generated fields. After the scaling, the fields were clipped if necessary to remain within physical bounds determined by the soil porosity.

c *Forecast Skill Assessment*

Forecast anomalies of the 60-day model runs were averaged over four periods of 15 days each while observational anomalies of temperature and precipitation used for this analysis were obtained from the bias-corrected NCEP/NCAR reanalysis (regridded to the CCCma T63 grid) and calculated over the same time period as the forecast sets (Alavi et al., 2011). In the case of the forecasts, anomalies were calculated by subtracting from the forecast fields the forecast climatology, obtained by averaging over all years in the forecast set for a given start date and lead time. For each forecast set, the correlation coefficient between the observed and modelled forecast sets is calculated as representing the fraction of explained model variance and, thus, is a measure of forecast skill (Koster et al., 2010) The primary skill assessment tool used in this analysis is the difference in the anomaly-squared correlation coefficient for the two initialization scenarios. To remain consistent with the methodology of Koster et al. (2010), any correlations that were negative are assumed to be sampling noise and set to zero. This difference in *r*-squared (r^2_{diff}) values for the realistic and non-realistic initializations is the measure of the potential predictability used to assess the role of land initialization in forecast skill.

Calculation of statistical significance follows Koster et al. (2011) who use a Monte Carlo approach where the time series of forecast skill differences (assessed as r^2_{diff}) between the initialized and non-initialized model runs (for a given variable, lead time and location) are compared with multiple reshufflings of these same time series. In this case the statistical significance of a forecast can be determined using multiple reshufflings of the time series at a given location, variable and lead-time to produce a skill level. We can then assess the null hypothesis that there is no soil moisture initialization related skill at a predetermined confidence level (95% in this study).

3 Results and discussion

In the following sections we describe the results for forecast skill change resulting from soil moisture initialization for both temperature and precipitation in CanCM3.

a *Forecast Temperature Comparison Results*

The anomaly correlation for the 0–15 day temperature forecasts, averaged over the entire globe, was always higher for the realistically initialized case. However, because the aim of this research is to examine the effect of soil moisture on sub-seasonal forecasting, the 0–15 day temperature forecast results will not be discussed here. In Fig. 1, a global map of r^2_{diff} for the entire forecast period (all forecasts that fall within June, July or August) is presented without selecting drier or wetter cases. Over the regions illustrated in red, r^2_{diff} is positive indicating that the realistically initialized forecasts performed better than the non-realistic soil moisture initializations.

The upper panel of Fig. 1 illustrates the 15- to 30-day forecast and shows the broad swaths of the land surfaces where the realistic soil moisture initialization improves forecast skill. Grid cells denoted by dots illustrate locations where there is a statistically significant difference in r^2_{diff} between the realistic and non-realistic initialization cases. For each panel in Fig. 1, the mean r^2_{diff} is calculated using

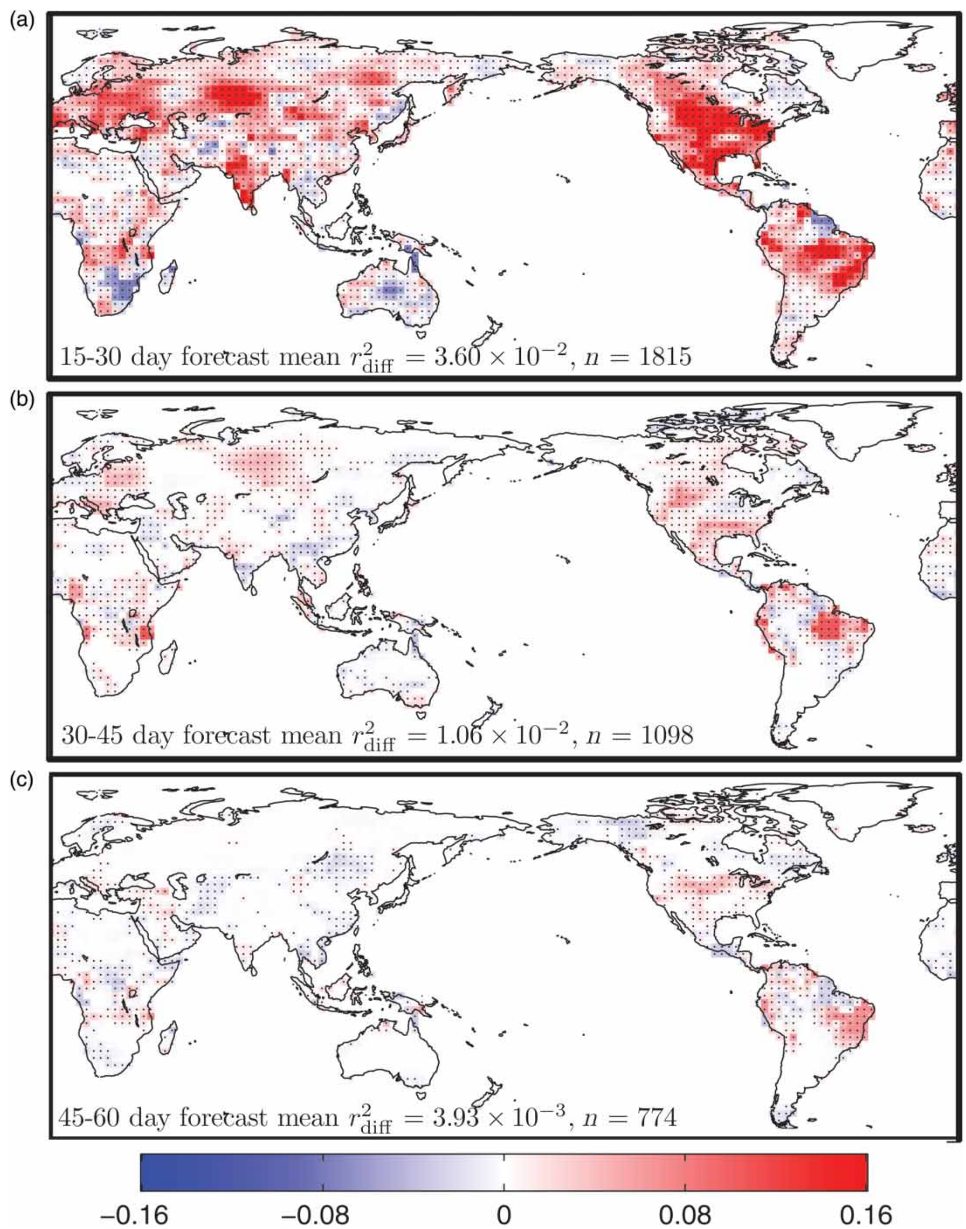

Fig. 1 Spatial pattern of r^2_{diff} for temperature forecasts for all June, July and August forecasts at a) 15- to 30-day, b) 30- to 45-day and c) 45- to 60-day lead times. Grid cells denoted by black dots are significant at the 95% confidence level. The number of grid cells with significant points is given by n.

only those grid cells with significant r^2_{diff} values and is area-weighted to account for the decreasing grid cell area with increasing latitude. For the 15- to 30-day forecasts 1815 of the 2090 (86%) terrestrial land grids had statistically significant improvement in forecasts when a realistic consideration of the land surface wetness was used. Improved forecasts are most notable over North America, the Indian subcontinent, and broad swaths of Europe and central Asia. For the longer range forecasts of 30 to 45 and 45 to 60 days, the r^2_{diff} values decrease in magnitude, and the number of grid cells with significant differences declines. This is because, at longer forecast times, skill for both initialization scenarios decreases and becomes more variable so the average difference in skill between the two cases also decreases. Nevertheless, statistically significant skill improvement is evident across central North America for all forecast periods. In the case of regions with decreased forecast skill, some of them could be attributed to situations where there is very little difference in the realistic and climatological initialization forecast cases. Computing the difference in forecast skill would be expected to produce some areas with negative forecast skill. The presence of areas with significant negative forecast skill suggests a deeper underlying process that is not captured in this analysis. We have also assessed whether the importance of land surface initialization changes under wet or dry initial conditions. Consideration of the role of land

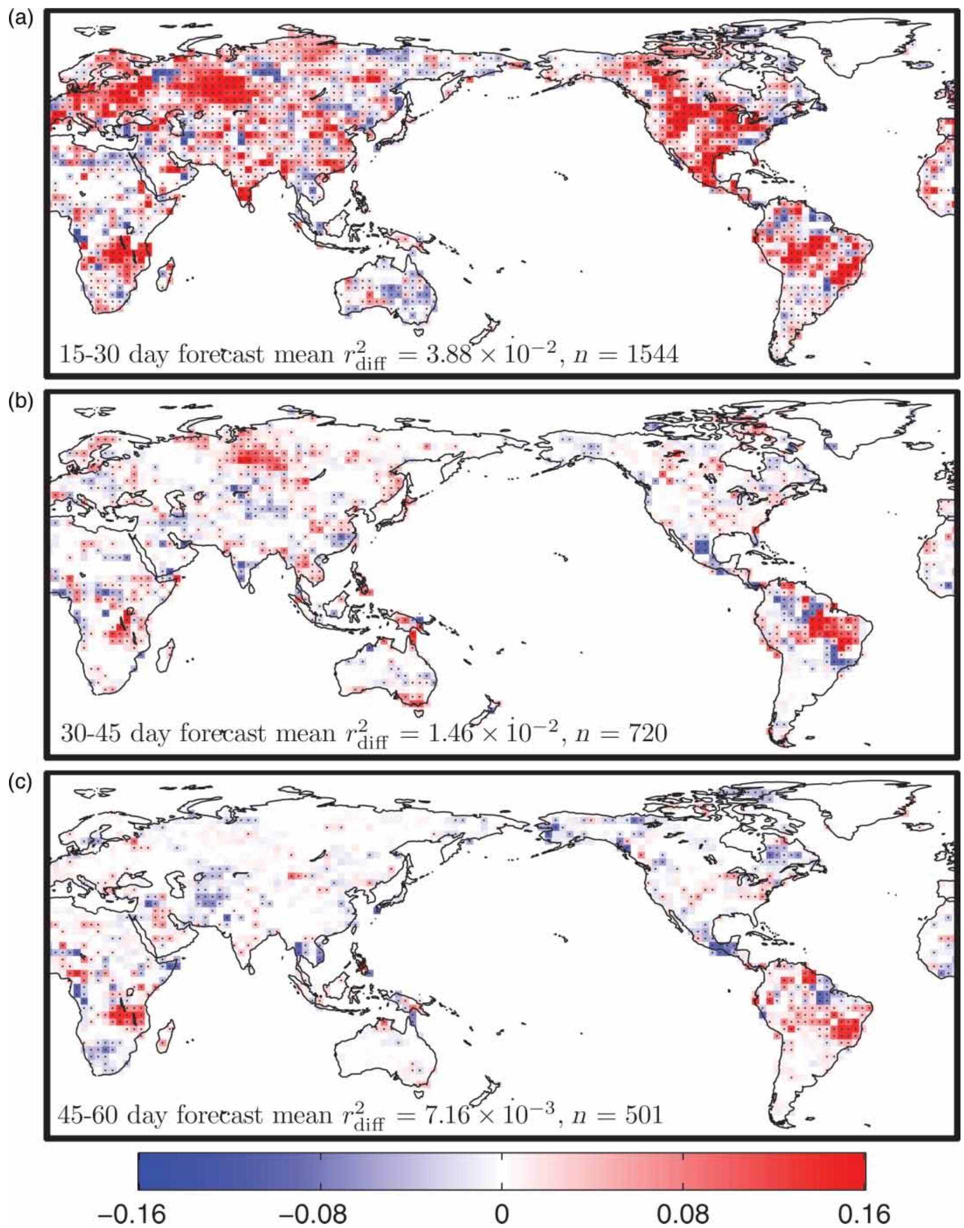

Fig. 2 Spatial pattern of r^2_{diff} for temperature forecasts during the driest quartile of soil moisture starts for June, July and August forecasts at a) 15- to 30-day, b) 30- to 45-day and c) 45- to 60-day lead times. Grid cells denoted by black dots are significant at the 95% confidence level. The number of grid cells with significant points is given by n.

surface initialization under dry soil moisture anomalies has practical significance for the prediction of drought persistence. Figure 2 shows an example of the same analysis shown in Fig. 1; however, here we consider only the forecasts that were initialized from the driest quartile of soil moisture initial conditions. In this figure, there are consistently fewer grid cells with a significant r^2_{diff} as might be expected from the reduced sample size but a higher mean value of r^2_{diff} compared to Fig. 1. In addition to the reduced sample size, the reduction in variability of the initial soil moisture state could lead to a further reduction of the signal-to-noise ratio. The spatial distribution of forecasts for the 15- to 30-day dry-start forecasts shows similar large swaths of increased skill, but there is more variability or patchiness in forecast skill differences over Asia and South America, probably as a result of increased sampling noise. In North America there is a notable lack of skill for the dry-start forecasts in the southwestern United States Great Basin region, although over this region the standard deviation of soil moisture is low because the region is typically dry. For example, in Fig. 4 of Alavi et al. (2011) the climatology of the soil moisture product used here is compared with the individual initialization fields to characterize the mean absolute differences from climatology. Over dry regions, such as the

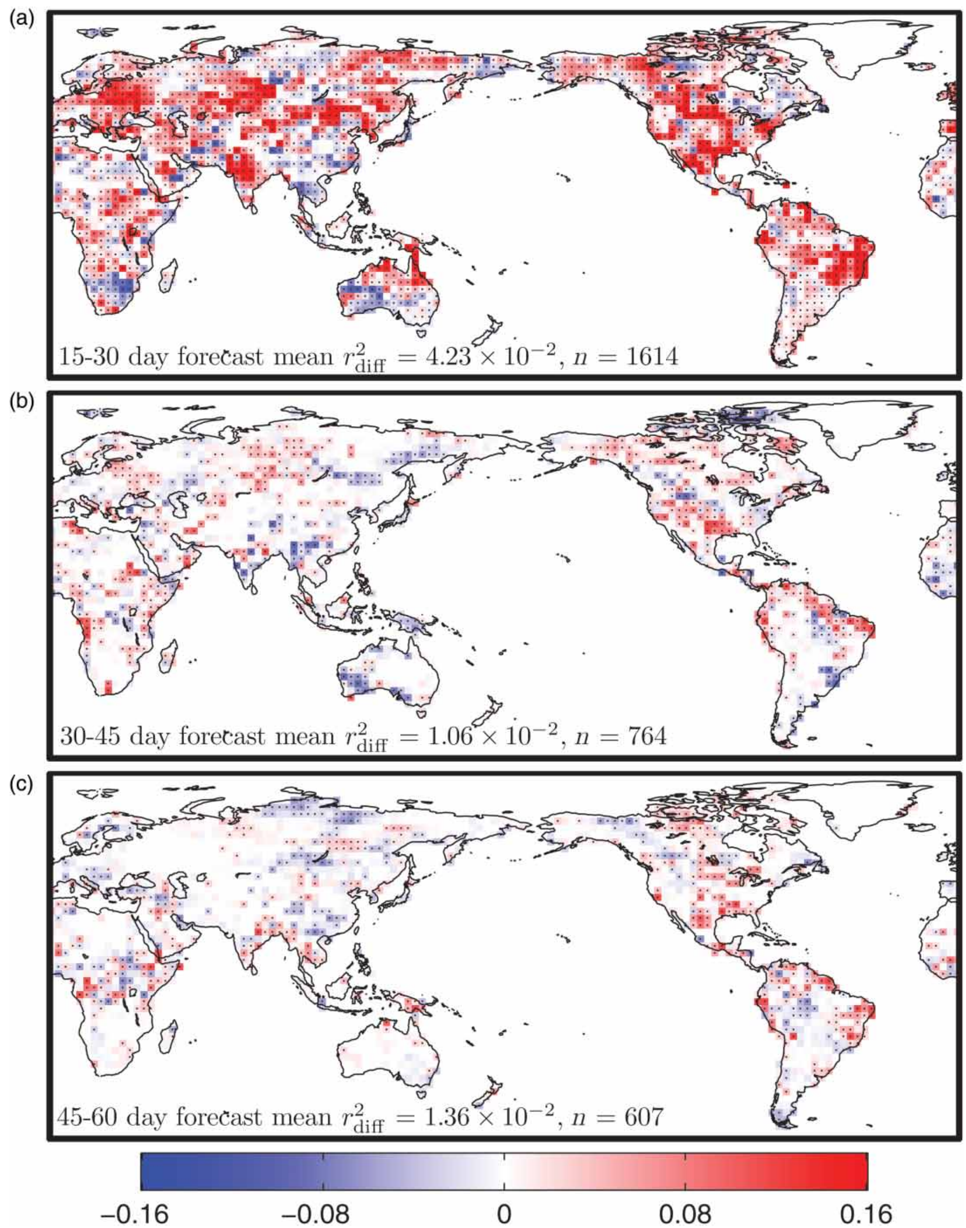

Fig. 3 Spatial pattern of r^2_{diff} for temperature forecasts during the wettest quartile of soil moisture starts for June, July and August forecasts at a) 15- to 30-day, b) 30- to 45-day and c) 45- to 60-day lead times. Grid cells denoted by black dots are significant at the 95% confidence level. The number of grid cells with significant points is given by n.

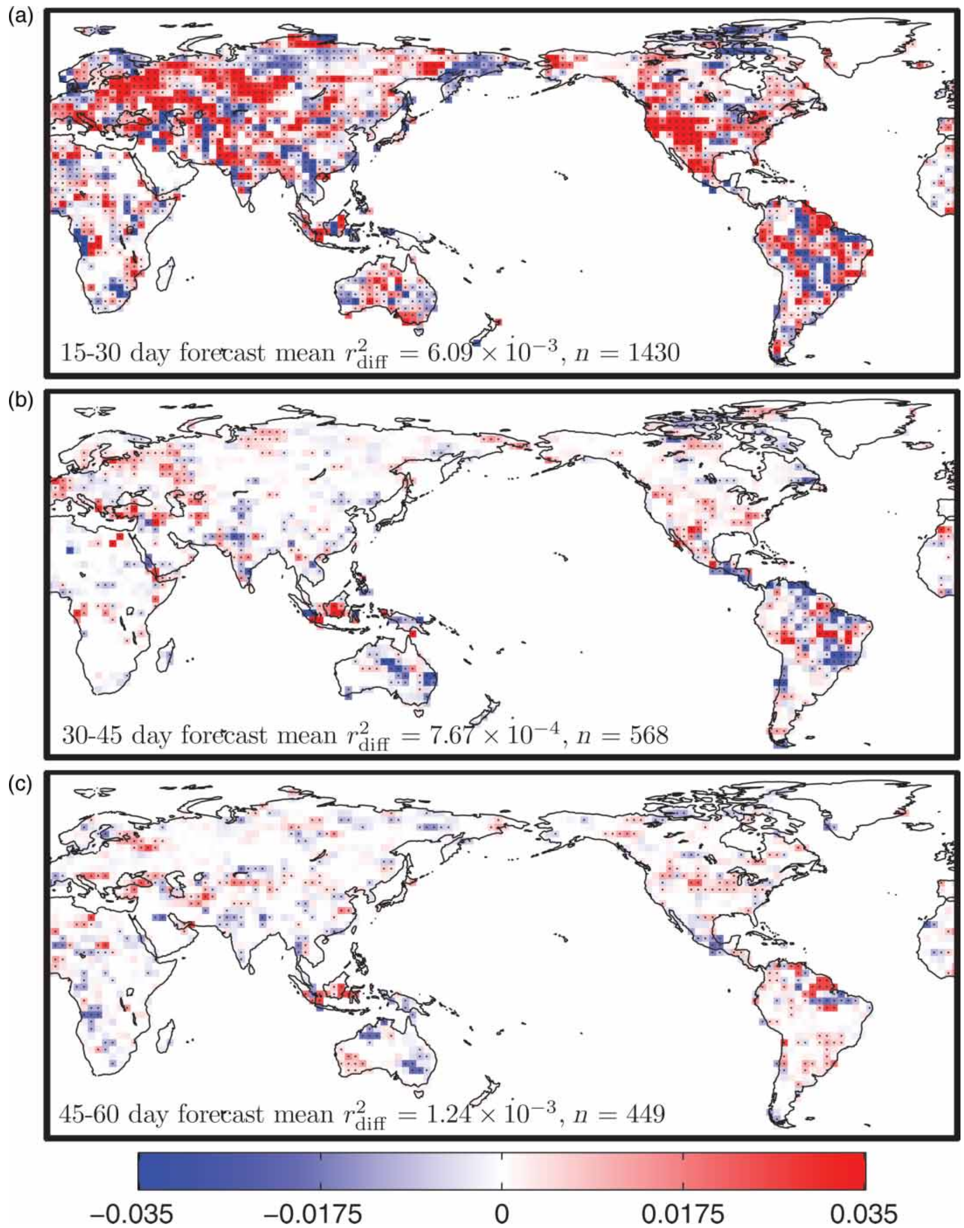

Fig. 4 Spatial pattern of r^2_{diff} for precipitation forecasts for all June, July and August forecast periods at a) 15- to 30-day, b) 30- to 45-day and c) 45- to 60-day lead times. Grid cells denoted by black dots are significant at the 95% confidence level. The number of grid cells with significant points is given by n.

United States Great Basin region, the initialization errors are low because there is low variability as a result of drier conditions.

In the 30- to 45-day and 45- to 60-day forecasts (Figs 2b and 2c), the areas of increased or decreased skill become very patchy. Two notable regions of increased skill remain in southeastern Brazil and southeastern Africa (particularly Malawi and eastern Zambia). However, as noted by Shukla (1998), the predictability in tropical areas can be dominated by effects ultimately controlled by sea surface temperature.

The case of extreme wet conditions, in which we consider the wettest quartiles of initial conditions, is shown in Fig. 3. In this situation the 15- to 30-day forecasts show a higher mean r^2_{diff} compared to the dry-start forecasts and all forecast start cases shown previously in Figs 1 and 2. Interestingly, the 30- to 45-day forecast mean r^2_{diff} is lower compared with the dry-start forecasts but increases for the 45- to 60-day forecast and again becomes higher compared with the dry-start forecasts, although the number of cells in which r^2_{diff} is significant decreases. Notably in North America, there are regions of increased forecast skill in the 30- to 60-day forecast range.

A detailed discussion of the coupling between soil moisture and temperature, mediated by evapotranspiration, can be found in Seneviratne et al. (2010). Coherent regions of soil moisture anomaly and forecast temperature predictability occur in those geographic areas where evapotranspiration is limited by soil moisture; these concepts are further addressed in Koster et al. (2011).

b *Forecast Precipitation Comparison Results*

Previous work on model initialization has found much less improvement in the forecast precipitation compared with air temperatures (e.g., Kharin et al., 2009; Koster et al., 2010, 2011; van den Hurk et al., 2012). Further discussion of the effects of soil moisture initialization on precipitation predictability was summarized in Seneviratne et al. (2010). In this study, we did not anticipate a large improvement in precipitation skill globally because for many regions precipitation is dominated by the advection of moisture from oceans and, therefore, may not be affected by local soil moisture conditions (van den Hurk et al., 2012). Further reduction in precipitation forecast skill may be related to higher noise levels at the individual grid cell level which limits the identification of large regions exhibiting statistically significant skill improvement (van den Hurk et al., 2012), lower spatial correlation lengths in the precipitation compared with temperature and imperfections in the initial soil moisture conditions (Koster et al., 2011). Overall, this study noted only modest improvement over the entire period of the experiment as shown in Fig. 4 (note change in scale relative to Figs 1–3). In general, this study shows some improvement in precipitation forecast skill using the realistic soil moisture initialization for the 15- to 30-day period, particularly in the western United States, parts of Europe and Russia. However, for the 30- to 45-day and 45- to 60-day forecasts, the overall effect of the realistic initialization on r^2_{diff} is very small. We suggest that it is unlikely that meaningful precipitation skill improvement is observed because of the poor coherence of regions where statistically significant improvements in skill occur.

When looking at the driest or wettest quartiles of forecast starts, the influence of proper initialization is, similar to Fig. 4, very small. Although not shown, the maps of r^2_{diff} for the wettest and driest starts do not show any regions that experience notable benefit from more realistic soil moisture initialization. Table 1 shows the r^2_{diff} for significant land points averaged over the entire globe and the number of points used to compute this average (similar to the r^2_{diff} shown in Figs1–4). Generally, the r^2_{diff} is typically an order of magnitude lower for precipitation forecasts compared with temperature forecasts.

Table 1. Summary of r^2_{diff} and number of significant land points for precipitation forecasts (No.) as shown in Fig. 4 for all forecasts.

	15- to 30-day		30- to 45-day		45- to 60-day	
	r^2_{diff}	No.	r^2_{diff}	No.	r^2_{diff}	No.
All JJA	6.12×10^{-3}	1430	9.46×10^{-4}	568	1.39×10^{-3}	449
Driest quartile	1.15×10^{-3}	1023	3.75×10^{-3}	423	7.83×10^{-3}	327
Wettest quartile	7.56×10^{-3}	1034	1.36×10^{-3}	418	3.01×10^{-4}	355

4 Conclusions

This paper presents the results of a forecasting experiment to determine the role of soil moisture initialization on forecast skill over a 60-day period. The output from the forecast model presented in this study is generally consistent with the results of Koster et al. (2010, 2011), showing a positive improvement in temperature forecast skill, particularly over North America during the summertime. For this experiment and in the case of temperature prediction, realistic soil moisture initialization improved forecast skill with particular improvement for the anomalously wettest and driest quartiles of soil moisture initial conditions. Certain geographic areas were identified as showing particular improvement in skill for such wet and dry forecast starts.

In contrast to the forecast temperature, there was much less skill improvement for the forecast precipitation between the different soil moisture initializations, although there are geographic regions, such as North America, that do show increased skill. Previous work in precipitation forecasting has shown the importance of both energy fluxes and water fluxes on forecast skill. The results of this study provide an initial assessment of the potential for sub-seasonal to seasonal forecast skill improvement through model initialization with realistic soil moisture conditions.

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