Regional precipitation simulations for the mid-1970s shift and early-2000s hiatus

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Abstract It has been demonstrated that climate models initialized with observations produce better simulations of Pacific sea surface temperature (SST) patterns than uninitialized simulations for the two major climate regime changes of the last 40 years, the mid-1970s climate shift and early-2000s hiatus. A fundamental feature of these hindcasts is the simulation of the SST anomalies associated with the phase of the Interdecadal Pacific Oscillation (IPO). Since regional precipitation patterns over selected land areas in south Asia, Australia, and North America are known to be affected by SST patterns over the Pacific, it is shown that the initialized climate model simulations produce qualitatively better agreement with observations for regional precipitation anomalies in those regions compared to uninitialized climate models. Though the signals are small, the anomalies are consistent with our physical process-based understanding of precipitation responses over certain land areas during different IPO phases.

1. Introduction

The emerging science of decadal climate prediction, though still in its early stages, has shown encouraging signs of being able to predict sea surface temperature (SST) patterns in certain ocean regions beyond the interannual timescale and up to about 10 years in advance [Meehl et al., 2009a, 2014a; Kirtman et al., 2013]. One of the ocean regions that seem to show promise for decadal prediction skill is the North Atlantic for case studies predicting the time evolution of the Atlantic Meridional Overt turning Circulation (AMOC) in the 1990s [Yeager et al., 2012; Robson et al., 2012]. Another is the Pacific, particularly involving case studies for the prediction of the phase of the Interdecadal Pacific Oscillation (IPO; Mochizuki et al., 2010; Ding et al., 2013; Meehl and Teng, 2012, 2014; Meehl et al., 2010, 2014b). The IPO has been shown to affect ocean heat uptake in the early-2000s hiatus [Meehl et al., 2011, 2013; Balmaseda et al., 2013; England et al., 2014; Guemas et al., 2013; Chen and Tung, 2014] with connections to global climate [Kosaka and Xie, 2013; Trenberth et al., 2014]. Correspondingly, regional predictions for the entire CMIP5 hindcast period for initial years 1960 through 2005 show highest skill in the North Atlantic and areas of the tropical Pacific, though overall skill is higher for the Atlantic [Kim et al., 2012; Doblas-Reyes et al., 2013; Kirtman et al., 2013]. However, such measures of overall skill for the entire hindcast period mask a time dependence of decadal prediction skill such that initial years in the late-1980s and early-1990s show a drop of skill in predicting SST patterns in the Pacific and Atlantic during those periods [Meehl et al., 2014b].

Though predicting SST patterns in the oceans is of academic interest due to the science problems involved with being able to simulate coupled processes in the climate system that produce those SST patterns, what is of more relevance for society is to address what can be predicted over land areas where people live. In general, there is less skill in predicting land temperatures than ocean temperatures [Doblas-Reyes et al., 2013], though there are indications from a case study for the 1990s that, for some regions of North America, there could be skill in predicting precipitation associated with SST patterns in the North Atlantic and Pacific [Robson et al., 2013]. Due to spatial noise in precipitation patterns, it has been pointed out that it would be more fruitful to predict area averages of precipitation rather than grid point values [Goddart et al., 2013]. Though most of the focus of analyses of decadal hindcasts has been on surface temperature, it is important to examine other relevant fields such as precipitation to document any indications of skill that may be present in this first generation of multi-model ensemble decadal climate prediction hindcasts.

Here we document area-averaged precipitation simulation skill for some regions previously shown to be influenced by the phase of the IPO in the Pacific due to processes involving atmospheric teleconnections driven by SST and convective heating anomalies by utilizing case studies of the mid-1970s shift and the
early-2000s hiatus. We use as a starting point the results from analyses of surface temperature from single models [Meehl and Teng, 2012] and the CMIP5 multi-model ensemble [Meehl and Teng, 2014; Meehl et al., 2014b] that have documented skill in simulating the phase of the IPO in the Pacific. Those studies showed that the positive phase of the IPO, with positive decadal SST anomalies in the tropical Pacific, characterized the mid-1970s shift, while the early-2000s hiatus had a negative IPO with negative decadal SST anomalies in the tropical Pacific.

2. Models and Data

A hindcast proceeds from imposed initial conditions for a period of 10 years as described in the CMIP5 experiment design [Taylor et al., 2012]. We use 15 CMIP5 models for analysis of the 10 year hindcasts (Table 1). It is the same collection of models that were analyzed in Meehl and Teng [2014] except that one set of CCSM4 decadal prediction experiments has been expanded to cover every start year from 1965 to 2014, and MRI-CGCM3 was not included due to missing data. These hindcasts are compared to the corresponding uninitialized CMIP5 simulations from those same models (including the historical runs during 1960–2005 and RCP4.5 during 2006–2011).

As in Meehl and Teng [2014], bias adjustment was applied to the model predictions in order to remove systematic errors. Two different bias adjustment methods have been recommended by CLIVAR [2011] and Smith et al. [2012]. Here we applied the method recommended for models using full field initialization to all 15 models:

\[
\tilde{Y}_{jt} = Y_{jt} - \frac{1}{N-1} \sum_{k=1}^{N} (Y_{kt} - O_{kt})
\]

where \(Y_{jt}\) and \(\tilde{Y}_{jt}\) are the raw and bias-adjusted values for hindcast or prediction \(j\) at lead year \(t\). \(O_{kt}\) represents the observed values corresponding to \(Y_{kt}\), and \(N\) is the number of hindcasts (start years) that can be used to assess the model bias. Note that the bias is calculated in a “cross-validated” manner where the hindcast/forecast to be corrected does not contribute to the model bias \((N - 1)\) instead of \(N\) hindcasts are used). Though this method may not be optimum for some models it is chosen here because it is more feasible for multi-model analysis.

The precipitation observations are taken from the monthly Global Precipitation Climatology Centre (GPCC) data set with a spatial resolution of 2 degrees [Rudolf et al., 2010]. We calculated December–January–
February–March (DJFM) and June–July–August–September (JJAS) seasonal means from each model and interpolated to the same spatial resolution of GPCC data. We focus on 5 year averages from year 3–7 predictions. As in Meehl and Teng [2012, 2014], we compare runs starting from 1976 (except for CCSM4 that started from year 1975) with the uninitialized during the same period. We compute each model’s ensemble mean first, followed by the multi-model ensemble average. As in Meehl and Teng [2014], for the mid-1970s shift the precipitation anomalies are computed for the 1978–1982 prediction period (5 year average of the prediction for years 3–7 from the initial year 1976) minus the 1946–75 reference period; for the 2000s hiatus, the precipitation anomalies for years 2007–2011 (prediction for years 3–7 from the initial year 2005). Observed SST data are HadISST from 1850 to 2012 [Rayner et al., 2003]. Before calculating the CCSM4 precipitation empirical orthogonal function (EOF), to remove model systematic error first the year 3–7 predictions were computed for the seasonal averages for each start year, then the average year 3–7 prediction was removed from all 50 start years. In all figures, the stippling indicates the 90% confidence level from Student's t test.

3. Results

Earlier studies have shown that regional precipitation anomalies in parts of North America, western Pacific, and southern Asia are affected by the phase of the IPO due to processes associated with the tropical Pacific SST and consequent convective heating anomalies that drive atmospheric teleconnections and regional precipitation anomalies [Meehl and Hu, 2006; Dai, 2012]. This is illustrated in Figure 1 where the IPO index (defined as the principal component (PC) time series of the second EOF of low-pass filtered SSTs, see Meehl et al., 2009b) is regressed against observed gridded land precipitation. For DJFM (Figure 1a), the sense of the sign of the anomalies is for positive IPO with above-normal decadal SSTs in the tropical Pacific (Figure 1e), and shows
increased precipitation over the southwest US and parts of south Asia, with decreased precipitation over Indonesia and eastern Australia. For JJAS (Figure 1c) there are mostly decreases of precipitation over the Indian monsoon region and Indonesia, with increases over northwest North America. As noted above, these precipitation anomalies over those land regions are driven by processes involving large-scale teleconnections through the atmosphere associated with the tropical Pacific SST anomalies that produce precipitation and convective heating anomalies that influence large-scale atmospheric circulation [e.g., Meehl and Hu, 2006].

The leading EOF pattern of seasonal precipitation from year 3–7 hindcasts in one CMIP5 model (CCSM4, see also Meehl and Teng, 2012) shows similar regional features as the observed IPO precipitation anomalies (Figures 1b and 1d). The anomalies are computed relative to the model year 3–7 predictions for every start year from 1965 to 2014. Without any forecast calibration based on observations, the spatial patterns show a number of similarities to the observed pattern associated with the IPO in the left-hand panels of Figure 1. There are positive precipitation anomalies in the central tropical Pacific in both seasons with a strong western cell of the Walker Circulation that produces anomalous subsidence over the Australian monsoon region in DJFM and Indian monsoon region in JJAS with reduced precipitation in most of those areas [Meehl et al., 2003; Meehl and Hu, 2006]. Meanwhile, the associated convective heating anomalies in the tropical Pacific drive an anomalous atmospheric Rossby wave response that includes a trough over parts of southwestern (DJFM) and northwestern (JJAS) North America and enhanced precipitation over those regions in Figures 1b and 1d [Meehl and Teng, 2007]. These regional precipitation anomalies simulated in the CCSM4 hindcasts correspond to the observed anomalies for those seasons and regions and are consistent with our process-based understanding of the large-scale teleconnections associated with IPO phases (Figure 1a and 1c).

A time series of the seasonal EOF PC time series from the year 3–7 hindcasts from CCSM4 in Figure 1f represents the patterns in Figures 1b and 1d for the positive phase of the IPO in the mid-1970s shift, and the negative phase of those precipitation patterns for the negative IPO in the early-2000s hiatus [Meehl and Teng, 2012]. The near-neutral precipitation pattern for the late-1980s and early-1990s in Figure 1f coincides with the time period when there is a drop in predictive skill for the IPO in the models [Meehl et al., 2014b]. Here we test the hypothesis that if the phase of the IPO can be predicted, this will provide skill for area-averaged precipitation simulations over certain land areas noted above that have been shown to be affected by the IPO SST anomalies in the Pacific.

The regional precipitation changes associated with the two climate shifts in the CMIP5 decadal prediction experiments are shown over land areas for the DJFM season for the mid-1970s shift (left part of Figure 2) and early 2000s hiatus (right part of Figure 2). The former was characterized by the positive phase of the IPO so that the associated predictions of precipitation anomalies should have the same sign as those in Figure 1a. Indeed, the observations in Figure 2a show decreases of precipitation over eastern Australia and Indonesia in the Australian monsoon region, with increases over southwestern North America and southern Asia for that time period. The predictions made for the average of years 3–7 compared to the previous 30 years show qualitatively similar characteristics (Figure 2c). The 30 year reference period used here for precipitation is longer than the 15 year reference period in the previous studies by Meehl and Teng [2012, 2014] for temperature in order to provide a better indication of the size of the anomalies compared to a longer reference period. Results for the previous 15 year reference periods are similar to those shown here.

These differences are quantified by taking area averages for the four regions outlined in Figures 2a and 2c and shown in Figure 2e. The initialized predictions for the mid-1970s shift with a positive IPO [Meehl and Teng, 2014] show qualitative agreement with the observations, with decreases of $-0.30 \pm -0.10 \text{mm day}^{-1}$ (i.e., $+/-$ one standard deviation) in the eastern Australian region compared to an observed decrease of $-0.40 \text{mm day}^{-1}$, while the uninitialized model simulations show a slight increase. The observed increase of $+0.50 \text{mm day}^{-1}$ in southwestern North America also has an increase of $+0.10 \pm -0.10 \text{mm day}^{-1}$ in the initialized model simulations, while the uninitialized shows small decreases. For the Australian monsoon Indonesian region, neither the initialized nor uninitialized simulate the decreases seen in the observations. Meanwhile in the southern Asian region, though the area-averaged precipitation decreases in initialized and observed are small and agree in sign, the uninitialized shows a slight increase.

For DJFM in the early-2000s hiatus (right side of Figure 2), there is a negative phase of the IPO that is shown in observations and the initialized models [Meehl and Teng, 2014], so the precipitation anomalies should have the opposite signs to those shown in Figure 1b and the left side of Figure 2. Indeed most observations
show opposite sign anomalies in Figure 2b, with positive precipitation anomalies in the Australian monsoon and eastern Australia, and negative anomalies over southwestern North America. The initialized predictions agree qualitatively with the observations, and, in general, the initialized hindcasts outperform the free-running uninitialized runs (i.e., larger area-averaged precipitation anomalies in closer agreement to the observations). For the Australian monsoon, the observations show an increase of +0.70 mm day$^{-1}$ compared to the initialized models’ predictions of +0.20 +/− 0.10 mm day$^{-1}$ and a near-zero uninitialized value. Similarly, for eastern Australia the observations are +0.60 mm day$^{-1}$ compared to the initialized with +0.20 +/− 0.20 mm day$^{-1}$ and a near-zero uninitialized value. The southern Asian values are all near zero. For southwestern North America, the initialized models show a decrease of −0.10 +/− 0.12 mm day$^{-1}$ compared to the observed decrease of −0.20 mm day$^{-1}$ and a near-zero value for the uninitialized.

For reference, in Figure 2 here and Figure 3 below, the vertical black lines in the observed anomaly bars indicate one standard deviation of the 5 year running means of the observed anomalies. Note that most of the observed anomalies are greater than one standard deviation. Additionally, in terms of magnitude, all of these anomalies amount to roughly 5% to 10% of the area-averaged climatological precipitation values.

For the JJAS season in Figure 3, the results are similar to those for DJFM, such that for the positive IPO in the mid-1970s shift (left side of Figure 3), there are reductions of regional precipitation for the Australasian regions, and increases over northwestern North America in the observations (Figure 3a) and initialized model simulations (Figure 3c). For the area-averaged precipitation values in Figure 3e, the initialized model predictions perform better for the observed decreases of Indian monsoon (south Asian) precipitation (−0.15 mm day$^{-1}$ for observations, −0.20 +/− 0.09 mm day$^{-1}$ for the initialized, and an increase of
+0.10+/−0.10 mm day$^{-1}$ for the uninitialized) and increases in northwestern North America (observations are +0.10 mm day$^{-1}$, initialized +0.06+/−0.05 mm day$^{-1}$, and negative for uninitialized). JJAS is not the seasonal maximum for the Australian region, though both the Australian monsoon and eastern Australia show observed and initialized decreases, with the uninitialized showing increases.

For the early-2000s hiatus in JJAS (right side of Figure 3), as was the case for DJFM there is an agreement in the sign of the area-averaged precipitation anomalies between the observations and the initialized models, with the latter out-performing the uninitialized in each region except eastern Australia (i.e., closer to the observations). The observed increases in the Indian monsoon and Australian monsoon (+0.27 mm day$^{-1}$ and +1.12 mm day$^{-1}$, respectively) are also increases in the initialized models (+0.14+/−0.11 mm day$^{-1}$ and +0.31+/−0.21 mm day$^{-1}$, respectively). These initialized predictions are larger than the uninitialized predictions, and thus closer to the observations, by at least a factor of two in Figure 3f. Similarly for northwestern North America, the observed decrease of −0.06 mm day$^{-1}$ has an initialized decrease of −0.05+/−0.07 mm day$^{-1}$ while the uninitialized has a small increase. Thus, for both seasons and in the areas identified as having a connection to IPO SST anomalies in the Pacific, the initialized predictions are generally closer to the observations than the uninitialized in both magnitude and sign, though predictions are generally of smaller magnitude with a large spread.

There is the possibility of artificial skill being introduced through the use of a previous observed period as reference since, if the system was in an anomalous state in that reference period, the prediction would tend to bring the system back to climatology which would be an apparent climate shift. This was addressed by Meehl et al. [2014b] in two ways. First, similar results are obtained using the entire period 1960–2011 as reference. Second, by calculating the IPO pattern from observations and correlating that IPO pattern with the hindcasts, the late-90s transition to negative IPO is still evident. Additionally, Figure 1 above shows multidecadal IPO phases simulated in CCSM4 without reference to any observations, indicating some skill in simulating IPO transitions.
4. Summary

Following from the study of Meehl and Teng [2014], who showed that the CMIP5 multi-model initialized hindcasts for the mid-1970s shift simulate a positive phase of the IPO for SSTs in the Pacific, and the early-2000s hiatus a negative IPO phase as observed, here we show simulation skill for area-averaged precipitation for land areas that have previously documented connections to IPO tropical Pacific SST anomalies:

1. There is qualitative agreement between initialized hindcasts and observations for the mid-1970s shift (positive IPO) during DJFM with above normal precipitation in southwestern North America, and below normal precipitation in eastern Australia and southern Asia; there are opposite sign precipitation anomalies in the eastern Australia and southwestern North America areas in the initialized hindcasts and observations for the early-2000s hiatus with negative IPO.

2. The mid-1970s shift with a positive IPO in JJAS shows initialized predictions agreeing with observations with below normal precipitation in the Indian monsoon, Australian monsoon, and eastern Australian areas, with above normal precipitation in northwestern North America; there are opposite sign precipitation anomalies in those areas that are in agreement with the observations in the initialized hindcasts for the early-2000s hiatus with negative IPO.

The amplitude of the predicted precipitation anomalies from the initialized model hindcasts is generally smaller than the observed anomalies, though they are mostly in closer agreement with the observations than the free-running uninitialized simulations and are consistent with process-based understanding of how large-scale atmospheric teleconnections from SST and convective heating anomalies in the Pacific affect land precipitation in certain regions. Though this study does not address the possible role of Atlantic SSTs in affecting the simulated precipitation over land, there are indications that if the IPO SSTs can be predicted in the Pacific, there is some qualitative skill for area-averaged precipitation in regions known to be connected to tropical Pacific SST anomalies associated with the IPO.

References


