Decadal prediction skill of BCC-CSM1.1 climate model in East Asia

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ABSTRACT: The forecast skill of BCC-CSM1.1 model in summer East Asian climate was evaluated with the decadal prediction experiments launched annually during 1961–2005. Results of the decadal prediction were compared with those of the historical simulation to estimate contribution of the initialization. Improved prediction skill is found for summer surface air temperature (SAT) in central eastern China measured by both root mean square error (RMSE) and anomaly correlation coefficient (ACC) for the forecast years 2–5. The decadal hindcast of precipitation in central eastern China shows increased skill in RMSE but not ACC. Such improvement in East Asia is related to enhanced prediction skill of the western Pacific (WP) sea surface temperature (SST) originated from the oceanic initialization. In the decadal hindcast, the lower tropospheric atmospheric circulation associated with warm WP exhibits an anticyclone over the South China Sea, which resembles the observation. The southwesterly increases over southeast China associated with warm WP, favouring higher SAT in central eastern China. This reveals that the decadal predictions could more realistically reproduce the relationship between summer East Asian atmospheric circulation and WP SST. The 4-year average forecast within a decade shows that the initialization increases the ACC skill up to forecast years 4–7 for summer SAT in central eastern China.

KEY WORDS: decadal prediction; East Asia; initialization; hindcast; BCC-CSM

Received 21 November 2016; Revised 24 May 2017; Accepted 7 June 2017

1. Introduction

The need to predict near-term (2–30 years) climate has been recognized and given considerable attention by scientists and policymakers for a few decades. Pioneered studies about decadal prediction indicated that realistic ocean initial conditions in a climate model could improve the forecast of globally averaged surface air temperature (SAT) in central eastern China measured by both root mean square error (RMSE) and anomaly correlation coefficient (ACC) for the forecast years 2–5. The decadal hindcast of precipitation in central eastern China shows increased skill in RMSE but not ACC. Such improvement in East Asia is related to enhanced prediction skill of the western Pacific (WP) sea surface temperature (SST) originated from the oceanic initialization. In the decadal hindcast, the lower tropospheric atmospheric circulation associated with warm WP exhibits an anticyclone over the South China Sea, which resembles the observation. The southwesterly increases over southeast China associated with warm WP, favouring higher SAT in central eastern China. This reveals that the decadal predictions could more realistically reproduce the relationship between summer East Asian atmospheric circulation and WP SST. The 4-year average forecast within a decade shows that the initialization increases the ACC skill up to forecast years 4–7 for summer SAT in central eastern China.

While most of the previous studies provide annual mean result over the globe when analysing the decadal climate prediction, little hindcast skill was found in East Asia. However, East Asian climate exhibited distinct seasonal discrepancy whether on climatology or the decadal variability (Yu and Zhou, 2007). The main forcing for the decadal change of East Asian summer climate is the observed warming in the tropical Pacific and Indian Ocean (Zhou et al., 2008; Li et al., 2010). Since the initialization

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of the observed SST has been taken consideration into the decadal prediction experiment, it is necessary to investigate whether the prediction skill can be improved in summer climate over East Asia. This is the main purpose of this study. Possible reasons will also be revealed through analysing predictions of East Asian atmospheric circulation and SST.

The remainder of the paper is organized as follows. The model, experimental design and methodology are introduced in Section 2. Section 3 compares the historical and decadal prediction experiments in forecasting surface climate, atmospheric circulation in East Asia, and the SST in the ocean. Major findings are concluded in Section 4.

2. Model, experimental design and methodology

2.1. Model

The climate model used in this study is Beijing Climate Center Climate system model version 1.1 (BCC-CSM1.1), which includes four model components. The atmospheric model is BCC_AGCM2.1 with spectral discretization at T42 resolution and 26 levels in the vertical (Wu et al., 2008, 2010). The ocean model is the Modular Ocean Model version 4 (MOM4) with the tripolar grid 1°×0.33° and 40 vertical levels (Griffies et al., 2005). The land component is BCC-AVIM1.0 (Ji et al., 2008) and the sea ice component is Sea Ice Simulator. More detailed description about BCC-CSM1.1 is presented in Wu et al. (2013).

2.2. Experimental design

The decadal prediction and historical experiments of BCC-CSM1.1 were used in this study, which were carried out within the CMIP5 framework (Xin et al., 2013). The historical simulation was performed from 1850 to 2005 with the evolved radiative forcing includes greenhouse gases, the solar irradiation, volcanic activity, ozone and aerosols. Three realizations were carried out with different initial states taken from the pre-industrial control simulation. The ensemble mean of the three members are used in the analysis.

A nudging method is used in the decadal experiment to relax the oceanic temperature to the monthly full-field observed data from the Simple Ocean Data Assimilation (Carton and Giese, 2008). The initial states of atmosphere, land and sea ice model are from the consecutive restored run with the oceanic nudging applied during 1958–2005. In addition to the standard forecast starting every 5 years over the period of 1960–2005 prescribed by CMIP5 (Taylor et al., 2012), additive decadal prediction experiments initialized in the rest years from 1960 to 2005 were also carried out. Each forecast run has at least 10 years’ prediction and three realizations with different initiated time. The ensemble mean of the three members were used in the analysis. External forcings of these decadal climate predictions are the same as the historical simulation until 2005 and as the RCP4.5 projection beyond 2005.

2.3. Methodology

Initialization with the observed oceanic full-field data in the decadal prediction leads to systematic errors in the forecasts, because the climate model drifts towards its preferred climatology (García-Serrano and Doblas-Reyes, 2012). The decadal prediction of BCC-CSM1.1 also had model drift, which increases over the forecast time (Han et al., 2017). To avoid the influence of the model drift on the prediction skill, we remove the climatology of each forecast year and compare the anomalies between the forecast and the observation. The method used is a standard approach to compute anomalies for decadal predictions based on World Climate Research Program recommendations, which is often used in the assessment of decadal predictions (García-Serrano and Doblas-Reyes, 2012; Goddard et al., 2012; Kim et al., 2012; Gaetani and Mohino, 2013). The procedure is shown in Equation (1):

\[
Y_{jt}' = Y_{jt} - \frac{1}{N} \sum_{j=1}^{N} Y_{jt}
\]

where \(Y_{jt}\) represents the forecast value and \(Y_{jt}'\) represents the forecast anomalies, with \(j = 1, 2, \ldots, N\) identifies the initial years (1961, 1962, …, 2005) and \(t = 1, 2, \ldots, 10\) denotes the forecast range. The average of the \(t\) forecast year over the \(N\) initial-time predictions is first calculated. Then the anomaly of the \(j\) initiated year prediction at forecast year \(t\) (\(Y_{jt}'\)) is computed by subtracting the average from the original forecast value (\(Y_{jt}\)).

This study focus on the 4-year average forecast periods of the decadal prediction. That is, the forecast anomalies of 1–4, 2–5, 3–6, 4–7, 5–8 and 6–9 years are averaged. For a given 4-year average forecast period, for example 2–5 year, the hindcasts for the years 1962–1965 of the prediction started at 1961 are calculated and denoted as 1962. And so on, the average for the years 2002–2005 of the prediction started at 2001 is shown as 2002. The prediction years after 2005 are beyond the observational external forcing period, which are not considered in the analysis. So the numbers of the 4-year forecast time series are different with each other. For the forecast years 2–5, there will be 41 years’ forecast anomalies for the predictions started from 1961 to 2001. For the forecast years 6–9, there will be 37 years’ anomalies for the prediction started from 1961 to 1997. A 4-year running mean is applied to the observed and history simulated anomalies to compare with the decadal prediction as in earlier studies (García-Serrano and Doblas-Reyes, 2012).

The observation used to validate the prediction skill includes the Global Historical Climatology Network–Climate Anomaly Monitoring System global land SAT (Fan and van den Dool, 2008), the Climatic Research Unit Time-Series Version 3.23 (CRU-TS3.23) precipitation data (Jones, 2015), and the atmospheric circulation data from the NCEP/NCAR reanalysis (Kalnay et al., 1996). All these data set are monthly means and interpolated on the model’s T42 Gaussian grid. The observed SST data are from the Hadley Centre Sea Ice and
Sea SST data set (HadISST) (Rayner et al., 2003). The SST data from the model are interpolated to the 1°×1° rectangular grid as that of HadISST. This study focuses on the analysis in summer (June–August). The predictive skill is evaluated by computing the root-mean-square error (RMSE) and the anomaly correlation coefficient (ACC) related to observed seasonal anomalies. The statistical significance of the ACC is verified with a two-tailed Student’s t-test. The effective sample size of the test is calculated by removing the autocorrelation both time series of the hindcast and the observation (Bretherton et al., 1999).

3. Results

In the following study, the non-initialized historical simulation (NoInit henceforth) and initialized decadal prediction (Init henceforth) are compared to study the impact of the initialization on prediction skill. Both NoInit and Init are intended to capture the forced response to changing atmospheric composition, but only the Init prediction carries the initial state of the internal variability modes.

3.1. SST and precipitation

In order to examine prediction skills of SAT and precipitation anomalies with the initialization, the ratio of RMSE of Init and NoInit for the average of 2–5 and 6–9 years’ forecast time are calculated and shown in Figure 1. The decreasing region (less than 1.0 in Figure 1) implies where the Init RMSE is lower and more skillful than the NoInit hindcast. Improvement for the initialized decadal hindcast is apparent over Europe and central eastern China at forecast years 2–5 (Figure 1(a)). The Init RMSEs of these regions are reduced by 20–30% relative to the NoInit. Init RMSE of precipitation also decreases over Europe and most area in China (Figure 1(b)). The patterns of the RMSE ratio for both SAT and precipitation are similar between the forecast periods of 2–5 and 6–9 (Figures 1(c) and (d)). But the area regarding to the decreased RMSE of SAT in the Init for the 6–9 year’s forecast is less than that for the 2–5 year’s forecast over Europe and East Asia, indicating the weaker influence of the initialization over forecast time.

The improved prediction skill of SAT in Europe for the decadal hindcast of BCC-CSM1.1 is consistent with previous studies, which is related to the positive Atlantic multi-decadal variability skill (Keenlyside et al., 2008; Doblas-Reyes et al., 2013). The decrease of the Init RMSE in East China can also be found in some other models (figure 3 in Kim et al., 2012). This phenomenon has less been studied. The ACC skill and source of the predictability in East China will be further explored in the following analysis focusing on forecast years 2–5.

Figure 2 shows the ACC skill of the climate model in the decadal prediction of SAT and precipitation over East Asia. Both Init and NoInit show skillful prediction of SAT in western and northeastern China (Figures 2(a) and (c)). After de-trending, the ACC in western China is still significant for Init and NoInit, indicating the
combined impacts from external forcings and initialization (Figures 2(b) and (d)). The insignificant ACC for both Init and NoInit SAT over northeastern China after de-detrending indicates main contribution of the warming trend from the external forcing there. The ACC of Init SAT is significantly positive in central eastern China (Figure 2(b)), while the NoInit produce negative ACC. This implies the internal signal from the initialization plays dominant role in predicting the SAT in central eastern China. The forecasts of precipitation by Init and NoInit show little skill in China except for some region in western China (Figure 2(f)).
The SST is one of the primary variables affected by the initialization. Figure 4 shows that less RMSE mainly appears in western and subtropical Pacific Ocean, indicating improved skill of the Init hindcast. Little improvement appears in the Indian Ocean.

The Init and NoInit both have high ACC skill in western Pacific and Indian Oceans (Figures 5(a) and (b)). After removing the linear trend, the NoInit shows poor ACC skill in the western Pacific Oceans (Figure 5(d)), indicating the dominant role of the external forcing in the NoInit. The ACC of de-trended Init SST is still significant at the 10% level in the tropical western Pacific Ocean, although it is weakened after de-trending (Figure 5(c)). So the initialization plays an important role in the hindcast of the SST in tropical western Pacific Ocean.

The de-trended SST anomalies averaged over the western Pacific Ocean (125°–150°E, 0°–15°N) with high ACC skill (rectangle in Figure 5(c)) is defined as the WP SST index. The hindcast of the WP SST indices are shown in Figure 6. Both time series of Init and NoInit show obvious decadal variations in the past 40 years. The Init hindcast shows closer relationship with the observation. The ACC is 0.40 and 0.15 for the Init and NoInit hindcasts, respectively. This indicates that the initialization is important for the model to capture the internal variability of the WP SST.

It is known that the western Pacific Ocean influences the interannual and interdecadal variability of East Asian summer monsoon (Huang and Sun, 1992; Hu, 1997). To quantify the relationship between WP SST and the atmospheric circulation in the hindcast, the regression of the zonal and meridional winds at 850 hPa upon the standardized WP SST index are calculated. The circulation data are de-trended before the calculation. As can be seen in Figure 7, the Init hindcast reproduces an anticyclone over the South China Sea as the observation. The southwesterly to the west of the anticyclone dominates over southeast China. This is the region where the East Asian summer monsoon prevails and carries warm and wet air to central eastern China. So the SAT is higher in central eastern China associated with the warmer WP. However, the anticyclone in the NoInit hindcast centred at Philippine. The corresponding wind anomalies have little influence upon East Asian summer monsoon. Moreover, there is an anomalous cyclone over North China in

**3.2. SST and atmospheric circulation**

The main difference between the Init and NoInit hindcasts is whether the oceanic temperature is initialized.
We further investigate the 2- to 5-year forecast of the wind anomalies in eastern China. The de-trended zonal and meridional wind anomalies at 850 hPa are averaged over region (110°–120°E, 25°–35°N) to define the wind anomalous time series (Figure 8). Comparisons show that the ACC skill has improved significantly for meridional wind in East China with the initialization (Figure 8(b)). The correlation coefficients are 0.32 for the Init hindcast and −0.17 for the NoInit hindcast. Some improvement is also found in the ACC of East China meridional wind with the initialization (Figure 8(a)).

The analysis in this subsection shows that the Init hindcast improves the ACC skill of horizontal winds at 850 hPa in eastern China, which is related to the enhanced hindcast skill of WP SST. It is inferred that the improved predictive skill in East China climate may be attributed to the correction of the modelled climate response to the oceanic forcing induced by the initialization.

3.3. Hindcast skill in different lead-time periods

The hindcast skill along the forecast time for the 4-year averages (1–4, 2–5, 3–6, 4–7, 5–8 and 6–9 year) for WP SST, central eastern China SAT and central eastern China precipitation are calculated and shown in Figure 9. The Init RMSE skill of WP SST is higher than the NoInit for all the forecast periods (Figure 9(a)). The RMSE skills for East China SAT and precipitation also improve obviously for all forecast ranges (Figures 9(c) and (e)). This indicates that the benefits of the initialization on reducing the modelled error for SAT and precipitation in central eastern China.

The Init ACC of the de-trended WP SST improves relative to the NoInit and exhibits slight decrease over the forecast time (Figure 9(b)). The ACC is significant for forecast years of 1–4 and 2–5 at the 10% level. The ACC skills of WP SST are low beyond forecast years of 3–6. The ACC of central eastern China SAT is significant for the forecast years of 3–6 and 4–7 at the 10% level (Figure 9(d)). The prediction skill of the 1–4 and 2–5 year for central eastern China SAT is lower than the forecast years of 3–6 and 4–7. The improved ACC skill at long lead times may be related to the fact that removal of the mean hindcast drift at each lead year is not adequate to correct the predicted results (Goddard et al., 2012; Geatani and Mohino, 2013). The initialization shocks at the beginning of the forecast years and the non-linear interaction between drift and evolution of the variables being predicted could also induce uncertainty of the forecast skill (Goddard et al., 2012).
There is no improvement for the Init ACC in central eastern China precipitation for any forecast range (Figure 9(f)), implying the difficulty of decadal prediction in precipitation. Currently, even the prediction skill of BCC_CSM model in seasonal precipitation over East Asia needs further improvement, because of the model bias and the complicated dynamic processes influencing East Asian precipitation (Liu et al., 2005).

4. Conclusions

The performances of BCC-CSM1.1 model in predicting summer climate in East Asia were evaluated with the decadal experiments initialized at each year during 1960–2005. The decadal (Init) and historical (NoInit) experiments were compared to assess the role of the initialization. Improved predictive skill for the decadal hindcast is detected for central East China SAT in both RMSE and ACC at forecast years 2–5. The improvement on central eastern China precipitation is evident in the RMSE but not in the ACC skill.

The origin of the predictability in central East China is further investigated by analysing the forecast of SST. The ACC and RMSE skill of the WP SST both increase distinctly for the decadal hindcasts, implying crucial contribution of the initialization. The regression of the low-tropospheric winds upon the WP SST exhibits an anticyclone over the South China Sea in accordance with the observation. The southwesterly airflow to the east of the anticyclone dominates over southeast China, which favour for higher SAT in central eastern China. However, the anticyclone predicted by the historical experiment resides in Philippine, which has little influence on the atmospheric circulation in China. So the improved predictive skill of SAT in central eastern China from the initialization is related to the realistic response of lower tropospheric atmospheric circulation over East Asia forced by the western Pacific Ocean. The hindcast performance of 4-year average within a decade shows that there is improvement up to forecast years 4–7 for central eastern China SAT. The RMSE skill of WP SST, SAT and precipitation in central eastern China improves up to forecast years 6–9 in the Init, indicating the robust influence of the initialization.
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Figure 9. RMSE (left) and ACC (right) of Init (line with circle) and NoInit (line with star) hindcasts for WP SST (a,b), central East China SAT (c,d) and central East China precipitation (e,f) relative to the observational for 4-year averages. The ACC is calculated after de-trending. The black lines correspond to the 10% levels of statistical significance for the Init ACC. [Colour figure can be viewed at wileyonlinelibrary.com].

Acknowledgements

This work was jointly supported by the National Key Research and Development Program of China under grant nos. 2016YFA0602103 and 2016YFE0102404, Laboratory for Climate Studies (LCS) Open Funds for Young Scholars (2016), and China Meteorological Administration under grants no.GYHY201306020.

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