The climatology and interannual variability of the East Asian summer monsoon simulated by a weakly coupled data assimilation system

LIN Renping, ZHENG Fei and DONG Xiao

International Center for Climate and Environment Sciences, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

ABSTRACT
With the motivation to improve the simulation of the East Asian summer monsoon (EASM) in coupled climate models, oceanic data assimilation (DA) was used in CAS-ESM-C (Chinese Academy of Sciences–Earth System Model–Climate Component) in this study. Observed sea surface temperature was assimilated into CAS-ESM-C. The climatology and interannual variability of the EASM simulated in CAS-ESM-C with DA were compared with a traditional AMIP-type run. Results showed that the climatological spatial pattern and annual cycle of precipitation in the western North Pacific, and the ENSO-related and EASM-related EASM circulation and precipitation, were largely improved. As shown in this study, air–sea coupling is important for EASM simulation. In addition, oceanic DA synchronizes the coupled model with the real world without breaking the air–sea coupling process. These two successful factors make the assimilation experiment a more reasonable experimental design than traditional AMIP-type simulations.

1. Introduction
The East Asian summer monsoon (EASM) is an important sub-system of the Asian–Australian monsoon (Wang 2006). The variability of the EASM can exert great influence on the socioeconomics of East Asia. Thus, understanding the variability of the EASM continually attracts considerable attention from meteorological scientists (Dong et al. 2017).

Climate models are useful tools to investigate and understand the variability of the EASM on multiple time scales. Many previous studies have adopted atmospheric general circulation model (AGCM) experiments, driven by prescribed sea surface temperature (SST) and sea ice. Due to the fact that air–sea coupling in the western North Pacific region is rather important, AGCM-only simulations may be unreasonable to realistically reproduce the behavior of the EASM (Fu, Wang, and Li 2002; Wang et al. 2005; Zou and Zhou 2013; Lin, Zhu, and Zheng 2016). Thus, an oceanic component, e.g. a mixed-layer ocean model or ocean general circulation model, is always coupled with the AGCM through heat and matter exchanges between the interfaces of the two mediums, to simulate the multiple time-scale variability of the EASM more reasonably. Previous studies (Fu, Wang, and Li 2002; Wang et al. 2005; Song and Zhou 2014b) show that taking air–sea coupling into consideration can to some extent improve the simulation of the EASM in climate models. With weakly coupled data assimilation (DA), the performance of climate model simulation lies between AMIP-type and CMIP-type simulations in interannual variability (Zou et al. 2018). However, a weakness of coupled simulation is that the internal variability of the coupled model is independent of that in the real world. Thus, unlike the AMIP-type simulation, the temporal evolution of the climate signals in the coupled model cannot be directly compared with observation.

In this study, by applying oceanic DA in a coupled general circulation model, the internal variability of the climate system was imported into the coupled model. We examined whether the climatology and interannual variability of the EASM simulated in the coupled model with oceanic DA can be more realistic than that simulated in the AMIP-type run.

CONTACT LIN Renping linrenping@mail.iap.ac.cn © 2019 The Author(s). Published by Informa UK Limited, trading as Taylor & Francis Group.
This is an Open Access article distributed under the terms of the Creative Commons Attribution License (http://creativecommons.org/licenses/by/4.0/), which permits unrestricted use, distribution, and reproduction in any medium, provided the original work is properly cited.
2. Data and experimental design

The following observational datasets were used in this study:

1. Monthly mean Global Precipitation Climatology Project data from 1979 to 2014, with a horizontal resolution of 2.5° × 2.5° (Huffman et al. 1997; Adler et al. 2003).
2. Low-level wind from the NCEP–NCAR reanalysis dataset (Kalnay et al. 1996).
3. Monthly mean SSTs from NOAA’s Extended Reconstructed Sea Surface Temperature dataset, version 5, with a horizontal resolution of 2° × 2° (Huang et al. 2017). The monthly SST is used to calculate the observed Niño3.4 index.
4. NOAA’s 1/4° daily Optimum Interpolation Sea Surface Temperature dataset, used in the DA experiment. This daily dataset uses satellite SSTs only from the Advanced Very High Resolution Radiometer (Reynolds et al. 2007).

We assimilated observed SST data into the oceanic component of a coupled climate model (Chinese Academy of Sciences–Earth System Model–Climate Component (CAS-ESM-C)) through the Ensemble Optimal Interpolation (EnOI) scheme (Evensen 2003; Oke et al. 2008). This DA approach has been adopted in intermediate coupled models to predict El Niño–Southern Oscillation (ENSO; Zheng et al. 2006; Zheng and Zhu 2008, 2010). In this study, the assimilation interval was seven days. A more detailed description of this assimilation experiment can be found in Dong and Xue (2016) and Lin, Zhu, and Zheng (2016). The coupled model was developed at the Institute of Atmospheric Physics (IAP), CAS (Sun, Zhou, and Zeng 2012), and includes IAP AGCM4 (1.4° × 1.4°; L26) as the atmospheric component (Zhang, Zhang, and Zeng 2013), LICOM 1.0 (1° × 1°; L30) as the oceanic component (Liu et al. 2004), CLM3 as the land component, and CSIM5 as the sea-ice component, all coupled together with Coupler Version 6. Detailed information on these model components is provided in Table 1.

The performance of the model has been investigated in previous studies (Dong et al. 2012, 2014; Dong, Xue, and Zeng 2014; Su, Xue, and Zhang 2014; Su et al. 2015; Dong and Xue 2016). Besides, the AMIP-type simulation for the same period is also performed, to compare with the DA simulation, in which IAP AGCM4 is forced with observed daily SST as the oceanic boundary condition (Taylor, Williamson, and Zwiers 2000). The fully coupled simulation based on CAS-ESM-C (control experiment) is also performed to compare with the DA simulation.

3. Results

3.1. Climatology

Figure 1 shows the climatological spatial pattern of the June–July–August mean precipitation in the East Asian and western North Pacific region. Observationally, there are three precipitation maxima in the low latitudes, located over the Indochina Peninsula, Philippines, and western Pacific, respectively. Besides, another precipitation center is located in the midlatitudes, in the southwestern part of Japan. With respect to the low-level circulation, an anticyclone (western North Pacific subtropical high) is located in the western North Pacific, and southerly flow occurs along the east coast of continental East Asia, which provides the necessary moisture for the summer precipitation in the midlatitudes.

The AMIP-type simulation by IAP AGCM4 is not very realistic compared with observation, especially in the western North Pacific region, in which the summer precipitation is overestimated to some extent (Figure 1(b)). The pattern correlation coefficient (PCC) between the AMIP-simulated precipitation and observation is 0.32. This deviation may result from the fact that, in the AMIP-type simulation, air–sea interaction, which is essential to a realistic simulation in this region, is not considered (Wang et al. 2005). The simulated spatial pattern of summer precipitation is similar to the multi-model ensemble presented by Song and Zhou (2014a). Their results showed that most CMIP AGCMs cannot reasonably reproduce the three observed precipitation maximum centers (Figure 1(a)).

With respect to the DA experiment, the simulated climatological summer precipitation in the region of focus was largely improved compared to the AMIP-type simulation (Figure 1(c)). The three precipitation maximum centers in the low latitudes were reasonably reproduced, especially the one in the western North

| Model component | Model ID | Horizontal resolution (Lon × Lat) | Vertical levels | Originating group(s), country | References |
|-----------------|---------|----------------------------------|----------------|-------------------------------|------------|
| Atmosphere      | IAP AGCM4 | 1.4° × 1.4°                      | 26             | IAP, CAS, China               | Zhang, Zhang, and Zeng (2013) |
| Ocean           | LICOM 1.0 | 1° × 1°                          | 30             | IAP, CAS, China               | Liu et al. (2004)              |
| Land            | CLM3    | 1.4° × 1°                        | 10             | NCAR, USA                     | Oleson et al. (2004); Dickinson et al. (2006) |
| Ice             | CSIM5   | 1° × 1°                          | 1              | NCAR, USA                     | Briegleb et al. (2004)         |
Paciﬁc. This may be because, compared to the AMIP-type simulation, in our DA experiment, the atmospheric feedback can be portrayed through air–sea coupling, rather than simply driving the atmospheric component using prescribed SST and sea ice as in the AMIP-type run. The improved SST–precipitation relationship in the western North Paciﬁc region may be the reason why summer precipitation was largely enhanced (Dong and Xue 2016; Lin, Zhu, and Zheng 2016). The DA experiment showed similar results as the fully coupled simulation in reproducing the climatology (Figure 1(d)). The PCCs were 0.41 and 0.43 for SST_Assim and the control experiment, respectively.

Figure 2 further shows the annual cycle of precipitation in the western North Paciﬁc region. Clearly, compared with the AMIP-type run, the DA experiment largely improved the evolution of precipitation during the year in this region. Observationally, the evolution of precipitation exhibits a sinusoidal curve, in which a maximum (minimum) occurs in August (March). However, in the AMIP-type simulation, due to the inaccurate SST–precipitation relationship in this region, there is no peak in summer and the maximum precipitation occurs in November. Instead, in the DA experiment, the sinusoidal curve was reasonably reproduced, with a slightly delayed maximum in September, rather than August in the observation. The control

**Figure 1.** Spatial pattern of climatological summer precipitation in (a) observation, (b) the AMIP-type run, (c) the DA experiment, and (d) the control (fully coupled simulation) run. The centered PCCs between the simulated and observed precipitation are shown.

**Figure 2.** Annual cycle of area-averaged precipitation (10°–20°N, 120°–150°E) in the observation (black), AMIP-type run (blue), DA experiment (red), and fully coupled run (green). The unit is mm day$^{-1}$. 

R. LIN ET AL.
3.2. Interannual variability

Although the atmosphere–ocean coupled model can overcome the difficulty that the AMIP-type simulation cannot reasonably describe the atmospheric feedback in the East Asian monsoon region, the output of the coupled model cannot be compared to observation directly, because the internal variability of the coupled model is independent of the real world. Through assimilating the observed SST into the coupled model, we imported the observed internal variability of the real world into the model (e.g. ENSO). Thus, as with the AMIP-type simulation, we can directly regress the meteorological variables of the East Asian monsoon system onto the observed Niño3.4 index (5°S–5°N, 120°–170°W), to investigate whether the impacts of ENSO on the EASM can be improved in the DA simulation, compared to the AMIP-type simulation.

In the developing summer of an El Niño year, observationally there exists a cyclonic anomaly in the low-level circulation in the western North Pacific region (Figure 3). Meanwhile, positive (negative) precipitation anomalies are mainly situated to the east of the Philippine Sea (along a zonal band across 30°N). However, in the AMIP-type simulation, the positive precipitation anomaly center shifts northwestward to the region along the east coast of China, associated with the bias in the low-level cyclonic anomaly. Compared to the wrongly portrayed patterns of low-level circulation and precipitation in the AMIP-type run, in the DA experiment, the locations of both the positive and negative precipitation centers were more consistent with observation. The low-level cyclonic anomaly was located slightly southeastward compared with observation, with a weaker magnitude.

With respect to the decaying summer of an El Niño event, observationally the precipitation field shows a south–north dipole pattern, associated with the anticyclonic anomaly in the western North Pacific region. The dipole precipitation pattern is not evident in the

Figure 3. Regressions of summer precipitation and 850-hPa wind field anomaly on observed Niño3.4 index. The upper (lower) panels are the developing (decaying) summer of an El Niño event.
AMIP-type run and the anticyclonic anomaly is much weaker than observed. This bias was reduced in the DA experiment to some extent. There was a notable dipole pattern of precipitation, with positive (negative) anomalies in the north (south). The location of the anticyclonic anomaly was much more consistent with observation than the AMIP-type simulation.

We further investigated the EASM-related circulation and precipitation anomaly in Figure 4, using both observation and the outputs of the three experiments. The meteorological fields were regressed on an EASM index adopted from Song and Zhou (2014a). Observationally, the EASM-related precipitation shows a north–south dipole pattern and an anticyclonic circulation anomaly exists in the low levels, which is similar to the pattern in the decaying year of an El Niño event (Figure 3). Compared to the AMIP-type run, our DA experiment showed better performance in simulating the location and magnitude of the EASM-related precipitation and circulation. The observed positive precipitation anomalies in the southeast of the western North Pacific region were reasonably produced by SST_Assim and the control run, while they were wrongly simulated by AMIP as negative anomalies. The observed positive precipitation center around 10°–20°N was reflected by SST_Assim and the control run, while in the AMIP run it was located slightly north of observation. However, the fully coupled simulation slightly overestimated the positive precipitation anomalies to the south of 8°N. Thus, SST_Assim showed higher PCC values (0.66) than the AMIP and control runs (0.56).

The reason for the above improvement in performance in the DA experiment may be associated with the fact that air–sea coupling processes are considered in the DA experiment. Thus, air–sea coupling processes may be important in the western North Pacific region not only for climatological simulation, but also for the simulation of the interannual variability of the EASM, and thus should be considered in numerical models (Wang, Kang, and Lee 2004; Wang et al. 2005; Zou and Zhou 2013). Our results indicate that oceanic DA in a coupled model may be a more reasonable type of numerical experiment design than traditional AMIP-type simulations.

4. Summary and discussion

In this study, we assimilated observed SST into the ocean component of a fully coupled climate model (CAS-ESM-C) through the EnOI scheme, restoring the internal variability

![Figure 4. Regressions of summer precipitation and 850-hPa wind field anomaly on the EASM index derived from (a) observation, (b) AMIP, (c) SST_Assim, and (d) the control run. The EASM index is defined as the 850-hPa zonal wind difference between the average over (22.5°–32.5°N, 110°–140°E) and that over (5°–15°N, 90°–130°E).](image-url)
of the real world into the coupled model. The performance in simulating the EASM, including the climatology and interannual variability, in our DA experiment and the traditional AMIP-type run were then compared. Results showed that the climatological precipitation pattern and the annual cycle of precipitation in the western North Pacific, the ENSO-related and EASM-related EASM circulation, and precipitation were largely improved in the DA experiment. Our results indicate that oceanic DA in coupled models may be a more reasonable type of numerical experiment design than traditional AMIP-type simulations.

Our results further support that the one-tier method (coupled model prediction scheme) using a coupled climate model is the primary developmental direction in the climate prediction community (Bengtsson et al. 1993; Kanamitsu et al. 2002; Palmer et al. 2004; Saha et al. 2006). Due to the fact that air–sea interaction in the East Asian and western North Pacific region is important in EASM simulation, forcing the AGCM with SST may not be a reasonable enough scheme for climate prediction in East Asia. Thus, through assimilating the previously predicted SST into the coupled model, the one-tier method can be regarded as an improvement to the conventional two-tier prediction scheme (atmospheric model prediction scheme).

In this study, only SST was assimilated into the ocean component of CAS-ESM-C. Although the sea surface height (SSH), subsurface temperature, and salinity were adjusted dynamically, substantial biases still existed. More oceanic observations (e.g. SSH, subsurface temperature, and salinity) will be assimilated into CAS-ESM-C to improve its historical simulation and climate predictions.

Disclosure statement

No potential conflict of interest was reported by the authors.

Funding

This work was supported by the Strategic Priority Research Program of the Chinese Academy of Sciences [grant number XDA19030403], the National Natural Science Foundation of China [grant numbers 41606027 and 41706028], the National Key R&D Program of China [grant number 2017YFA0604201], and the China Postdoctoral Science Foundation [grant number 2015M571095].

References

Adler, R. F., G. Huffman, A. Chang, R. Ferraro, P. Xie, J. Janowiak, B. Rudolf, et al. 2003. “The Version-2 Global Precipitation Climatology Project (GPCP) Monthly Precipitation Analysis (1979-Present)”. Journal of Hydrometeorology 4: 1147–1167. doi:10.1175/1525-7541(2003)004<1147:TVGPPCP>2.0.CO;2.

Bengtsson, L., U. Schleser, E. Roeckner, M. Latif, T. Barnett, and N. Graham. 1993. “A Two-Tiered Approach to Long-Range Climate Forecasting.” Science 261 (5124): 1026–1029. doi:10.1126/science.261.5124.1026.

Briegleb, B., C. Bitz, E. Hunke, W. Lipscomb, M. Holland, J. Schramm, and R. Moritz. 2004: Scientific Description of the Sea Ice Component in the Community Climate System Model, Version Three, Tech. Rep. NCA/TN-463_STR, 78. Boulder, CO: National Center for Atmospheric Research.

Dickinson, R., K. Oleson, G. Bonan, F. Hoffman, P. Thornton, M. Vertenstein, Z. Yang, and X. Zeng. 2006. “The Community Land Model and Its Climate Statistics as a Component of the Community Climate System Model”. Journal of Climate 19: 2302–2324. doi:10.1175/JCLI3742.1.

Dong, X., T. Su, J. Wang, and R. Lin. 2014. “Decadal Variation of the Aleutian Low- Icelandic Low Seesaw Simulated by a Climate System Model (CAS-ESM-C)”. Atmospheric and Oceanic Science Letters 7 (2): 110–114. doi:10.3878/j.issn.1674-2834.13.0061.

Dong, X., and F. Xue. 2016. “Phase Transition of the Pacific Decadal Oscillation and Decadal Variation of the East Asian Summer Monsoon in the 20th Century.” Adv. Journal of the Atmospheric Sciences 33 (3): 330–338. doi:10.1007/s00376-015-5130-7.

Dong, X., W. Zhang, and Q. Zeng. 2014. “Observational Analysis and Numerical Simulation of the Decadal Variation Inthe Relationship between the Aleutian Low and the Icelandic Low during Boreal Winter.” Climatic and Environmental Research 19(5): 523–535. in Chinese.

Dong, X., F. Xue, H. Zhang, and Q. Zeng. 2012. “Evaluation of Surface Air Temperature Change over China and the Globe during the Twentieth Century in IAP AGCM4.0.” Atmospheric and Oceanic Science Letters 5 (5): 435–438. doi:10.1008/16742834.2012.11447031.

Evensen, G. 2003. “The Ensemble Kalman Filter: Theoretical Formulation and Practical Implementation.” Ocean Dynamics 53: 343–367. doi:10.1007/s10236-003-0036-9.

Fu, X., B. Wang, and T. Li. 2002. “Impacts of Air–Sea Coupling on the Simulation of Mean Asian Summer Monsoon in the ECHAM4 Model.” Monthly Weather Review 130: 2889–2904. doi:10.1175/1520-0493(2002)130<2889:IOASC>2.0.CO;2.

Good, S. A., M. J. Martin, and N. A. Rayner. 2013. “EN4: Quality Controlled Ocean Temperature and Salinity Profiles and Monthly Objective Analyses with Uncertainty Estimates.” Journal of Geophysical Research: Oceans 118: 6704–6716. doi:10.1002/2012JC009067.

Huang, B., W. T. Peter, V. F. Banzon, T. Boyer, G. Chepurin, J. H. Lawrimore, J. M. Menne, T. M. Smith, R. S. Vose, and H. M. Zhang. 2017. “Extended Reconstructed Sea Surface Temperature Version 5 (Ersstv5): Upgrades, Validations, and Intercomparisons.” Journal of Climate 30: 8179–8205. doi:10.1175/JCLI-D-16-0836.1.

Huffman, G. J., R. Adler, P. Arkin, A. Chang, R. Ferraro, A. Gruber, J. Janowiak, A. McNab, B. Rudolf, and U. Schneider. 1997. “The Global Precipitation Climatology Project (GPCP) Combined Precipitation Dataset.” Bulletin of
