NOTES AND CORRESPONDENCE

Role of Air-sea Coupling in the Interannual Variability of the South China Sea Summer Monsoon

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Abstract

A possible role of the air-sea coupling in the South China Sea (SCS) summer monsoon variability is studied using a coupled general circulation model (CGCM) and its atmospheric component (AGCM). The 50-year integration of the CGCM well reproduces the summer monsoon variability over SCS, where the precipitation anomaly is positively correlated with the low-level cyclonic circulation anomaly that accompanies enhanced surface westerlies. Negative sea surface temperature (SST) anomaly is found in SCS during the strong monsoon years, indicating the atmospheric driving SST through wind-induced evaporation. The 50-year AGCM run forced by historical SST obtained from the CGCM reveals the monsoon variability amplified by about 50 percent as compared with the CGCM. The absence of the air-sea coupling keeps SST warm in SCS, which increases the local evaporation and precipitation. The enhanced precipitation over SCS may intensify surface westerly over the remote regions, resulting in an increase in the moisture flux convergence that in turn contributes to the positive precipitation anomaly. This result suggests that the air-sea coupling works to stabilize the monsoon and hence suppress the variability via the large-scale moisture transport and the wind-induced local evaporation.

1. Introduction

The South China Sea (SCS) is located in southeast Asia between Asian and Australian continents, and between Pacific and Indian Oceans. Four monsoon systems pass SCS: East Asian monsoon, Indian monsoon, western North Pacific (WNP) monsoon, and Australian monsoon. Focusing on the boreal summer some previous studies showed that

the monsoon over SCS plays an important role in determining the variability of the climate in the surrounding regions in summer (e.g. Ding 1992; Zhu et al. 2003; Lestari 2010). It has also been shown that SCS and WNP monsoons are weak (strong) in El Niño (La Niña) years (e.g. Jiang and Qian 1999; Wu and Wang 2000; Wang et al. 2009).

The summer monsoon onset first occurs over SCS and thereby it is a key region of the Asian monsoon (e.g. Lau et al. 1999). Before the onset, sea surface temperature (SST) gradually increases in the northern SCS until the end of May or early June (e.g. Ding et al. 2004) and influences the timing of the monsoon onset and the monsoon intensity. After the onset, SCS SST anomalies seem

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to be controlled by in-situ low-level wind anomalies in summer. Ose et al. (1997) showed a negative correlation between SCS SST and SCS wind speed, and argued that a large wind speed may contribute to the SST cooling by enhancing evaporation and ocean mixing. A similar suggestion was made by von Storch (2000), who showed that the atmosphere plays an important role in generating coupled variations of SST and evaporation. The increased cloud cover and surface wind speed over SCS reduce the incoming shortwave radiation and enhance the upward latent heat flux at the ocean surface, thereby decrease the local SST (e.g. Wu 2002; Lau and Nath 2009). On the other hand, Qu (2001) showed that the reduced horizontal temperature gradient over SCS in summer induces vertical entrainment in the ocean subsurface during the southwest monsoon; it works against the surface heating and leads to a decrease of SST earlier than the surface heat flux starts to cool the ocean.

Wu (2002) showed the cloud-radiation and wind-evaporation feedback plays an important role in the seasonal SST variability in SCS/WNP and results in the east-west gradient of SST shifting the heavy precipitation eastward from SCS to WNP in summer. Lau and Nath (2009) showed that the northeastward moisture transport from SCS to East China Sea contributes to reduce precipitation over SCS in summer. They also investigated the roles of the remote and local SST forcings in determining the variability of SCS/WNP summer precipitation after the mature stage of El Niño-Southern Oscillation (ENSO). The precipitation maximum arrives late (early) over SCS in El Niño (La Niña) event. However, the role of the air-sea coupling in controlling the interannual variability in the mature phase of SCS summer monsoon was not yet clearly discussed in the previous studies. We therefore extend to examine this issue without special focus on the different ENSO event. This question is addressed in the present work through experiments using a general circulation model (GCM).

2. Model, data, and analysis

We use observational data of HadISST, CPC Merged Analysis of Precipitation (CMAP) and Japanese Reanalysis (JRA) for 29 years (January 1979–December 2007) (Rainer et al. 2003; Xie et al. 2007; Onogi et al. 2007). These are all monthly basis and used to identify the observed feature of SCS monsoon variability.

We use the GCM called the Model for Interdisciplinary Research on Climate (MIROC), which has been jointly developed at the Center for Climate System Research, the University of Tokyo, the National Institute of Environmental Studies, and Japan Agency for Marine-Earth Science and Technology (Hasumi and Emori 2004). The MIROC used in this study is the version 5i, which is an interim model of the latest MIROC (Watanabe et al. 2010a, b). The horizontal resolution is T42 and vertically 40-levels are adopted. After the conventional spin-up procedure, MIROC5i was integrated for 50 years with the pre-industrial radiative forcing. MIROC5i shows more realistic ENSO as shown in Watanabe et al. (2010a, b) and also the Indian summer monsoon precipitation (Kim et al. 2010, in preparation). While the model's performance associated with the western Pacific summer monsoon is not significantly different from the previous version (MIROC3.2). Previous studies have shown that MIROC3.2 well reproduces the onset and withdrawal of the Asian summer monsoon (e.g. Lin et al. 2008; Li and Zhang 2009).

The present work specifically focuses on the interannual variability of the monsoon over SCS (5–25°N, 100–130°E, indicated by a box in Fig. 1a) in summer, June–July–August (JJA). Simple local correlation analysis shows that the coupled GCM (CGCM) reveals a good reproducibility of the atmosphere-ocean relationship over SCS. That is, there is a positive correlation between surface wind speed and surface heat flux (sum of latent and sensible heat) anomalies whereas a negative correlation between SST tendency and surface heat fluxes. This indicates that the model is able to capture the ocean surface cooling due to wind-induced evaporation during the active summer monsoon over SCS.

The active SCS monsoon is associated with heavy precipitation over SCS and the surroundings. As the distribution of the monsoonal precipitation may not be spatially uniform, we attempt to characterize the dominant spatial pattern of the monsoon variability by performing an empirical orthogonal function (EOF) analysis to JJA monthly anomalies of the outgoing longwave radiation (OLR) over 0–30°N, 100–160°E. The leading EOFs in the observation and the model, accounting both for 24% of the total variance, show a spatial pattern similar to each other over SCS (Fig. A1). There is an opposite phase of OLR anomalies between SCS/WNP and the equatorial western Pacific that may be related with ENSO (e.g. Wang et al. 2009).

Fig. 1. (a) Observed precipitation and 850 hPa wind anomalies regressed on the PC time series in JJA. The unit is mm day^{-1} for precipitation and m s^{-1} for winds. (b) as in (a) but for SST anomalies (shading) and surface heat fluxes (contour). The unit is K for SST and mm day^{-1} for surface heat fluxes. (c)–(d) as in (a)–(b) but for the CGCM. (e)–(f) as in (a)–(b) but for AGCM2. Domain of SCS is presented by red boxes in (a)–(c)–(e).

Therefore, we define the associated principal components (PC) as indices for SCS monsoon variability. Linear regression of monthly JJA atmospheric variables and SST on to the PC time series is then calculated to identify the structure of SCS summer monsoon variability. Because there is no reason to expect that the long CGCM run driven by a prescribed radiative forcing reproduces the temporal behavior of the natural variability, we discuss only the spatial structure and the magnitude of SCS monsoon variability in this work.

In order to isolate the role of the air-sea coupling, i.e. the impact of SST on the atmosphere and vice versa, we conduct two atmospheric GCM (AGCM) experiments using climatological and historical SSTs obtained from the CGCM run, referred as AGCM1 and AGCM2, respectively. Both air-sea coupling and remote SST forcing (forcing induced by SST variability in the remote

regions) are absent in the first experiment, whereas in the second one, only the air-sea coupling is absent. The linear regression analysis based on the respective PC time series is also applied to the AGCMs and the results are compared with the CGCM.

The relative importance of the local air-sea coupling (air-sea coupling in SCS) against the remote forcing is evaluated by a moisture budget analysis. On the interannual timescale, moisture budget in a column is assumed to be balanced; that is, the atmospheric moisture budget equation can be written as follows:

$$-\nabla \cdot \int_{p_t}^{p_s} q \mathbf{V} dp = P - E, \quad (1)$$

where E is the evaporation, P is the precipitation, q is the specific humidity, $\mathbf{V}$ is the wind vector, and p_s

Fig. A1. The leading EOF analysis to JJA monthly anomalies of the outgoing of long-wave radiation (OLR) over 0–30°N, 100–160°E of (a) the observation and (b) the CGCM. Both are accounting for 24% of the total variance.

and p_t are the surface and top pressures, respectively. We evaluate the budget terms based on the results of the regression of each term in (1) on the respective PC time series, and averaging them over SCS.

3. Results

Regressions of precipitation, 850 hPa winds, and SST on to the respective PC time series are shown in Fig. 1. Despite the discrepancies such as precipitation anomaly over the Indian Ocean and maritime continent, and wind anomaly to the east of the maritime continent, overall feature of the anomalous SCS monsoon activity is captured by MIROC5i CGCM: positive precipitation anomaly around the Philippines and the westerly anomaly associated with the cyclonic circulation anomaly over SCS (Figs. 1a,c). The simulated SST anomalies are not correct in several areas in terms of sign and magnitude, but conspicuous negative SST

anomaly in SCS is well reproduced (shading in Figs. 1b,d). Since the climatological mean westerlies dominates over the southeast Asia in JJA, the wind anomalies (Figs. 1a,c) indicate intensification of surface wind and thereby result in increased surface heat fluxes (contour in Figs. 1b,d). This is consistent with the negative SST anomaly, suggesting the atmospheric driving SST through wind-induced evaporation. This result supports the finding by previous studies (e.g. Ose et al. 1997; Lau and Nath 2009) and the results of the local correlation analysis described in the previous section.

It is difficult to isolate the effect of the atmosphere-ocean interaction from the observations. On the other hand, the model is able to avoid this difficulty by prescribing one media (ocean in the present case). Therefore, the model experiments are helpful to clarify the role of the air-sea coupling in SCS monsoon variability. As mentioned in the previous section, two AGCM experiments with and without SST variability are conducted. In comparison with the CGCM, both AGCM runs show a similar pattern of the leading of EOF, indicating corresponding SCS monsoon variability among all GCMs. The difference between the AGCMs and the CGCM was much larger than the difference between two AGCM runs, so that we concentrate on the AGCM experiment forced by the historical (AGCM2) but not climatological (AGCM1) SST hereinafter.

Figs. 1c,e show that the pattern of the precipitation and wind circulation is unchanged between CGCM and AGCM2, but the magnitude is different. It is shown by taking the difference of the regression anomaly fields between the AGCM2 and the CGCM (former minus latter), that the precipitation and westerly (southwesterly) anomalies in the AGCM2 are enhanced more than 1.5 mm day^{-1} and than 0.1 ms^{-1} , respectively, over the eastern Bay of Bengal and SCS (Fig. 2a). These differences are positively projected on the anomaly patterns associated with the monsoon variability in the CGCM (Fig. 1c), indicating that SCS monsoon variability is amplified in the absence of the air-sea coupling. Quantitatively, the standard deviation of the monsoon indices increases by about 50% in the AGCM2. The enhanced positive surface heat flux anomalies (Fig. 2b) are also found in the AGCM2; this is probably partly due to intensified wind speed over SCS. It should be noted that the difference in SST regression is also positive when surface heat flux enhances (contour in Fig. 2b), which is

Fig. 2. Differences of the monsoon anomalies defined by the regression on the PC time series between the AGCM2 and the CGCM for (a) precipitation (shading) and 850 hPa winds (vector) and for (b) SST (shading) and surface heat fluxes (contour). The unit is mm day^{-1} for precipitation and heat fluxes, m s^{-1} for winds, and K for SST.

apparently inconsistent with the common understanding that stronger monsoon induces SST cooling through wind-induced evaporation. Indeed, SCS SST anomaly associated with the monsoon variability in the AGCM2 is positive (Fig. 1f) and opposite to that in the observations and the CGCM (cf. Figs. 1b,d). This suggests that in the AGCM2, the direction of the atmosphere-ocean interaction is reversed; that is, the warming of the ocean surface acts to stimulate the strong monsoon via the increasing in surface heat fluxes.

In the linearized form of the bulk formula, the anomalous surface heat flux is a sum of contribution from the anomalies in wind speed, SST, surface air temperature and humidity. In order to demonstrate that these components contribute to the heat flux anomaly in a different manner with and without the air-sea coupling, we make scatter diagrams of the surface heat flux anomalies against wind speed (upper panels) and SST (lower panels) anomalies in summer averaged over SCS (Fig. 3). The SST and wind speed anomalies are normalized for facilitating comparison of the slopes. It is evi-

dent that the heat flux anomalies are positively correlated with the wind speed anomaly in the observations and the GCMs; the correlation coefficients are all above 0.9 and highly significant (Figs. 3a,c). This is indicative of the wind-induced surface heat flux as has been argued so far. We, however, anticipate from Fig. 2b and Figs. 1d,f that the relationship between heat flux and SST in the AGCM2 is different from that in the CGCM (and in the observations). Indeed, the correlation between the two quantities is strongly negative in the observation and the CGCM, but it is positive in the AGCM2 (Figs. 3d–f). In the AGCM2, positive SST anomalies in addition to the stronger westerly work to increase the heat release from the ocean surface and thereby destabilize the atmosphere over SCS; as a result, the AGCM2 run shows stronger monsoon anomalies as compared to those in the CGCM. In other words, the mutual coupling between the atmosphere and the ocean in the CGCM, and probably in nature, acts suppressing the monsoon variability due to negative wind-evaporation-SST feedback. The differences between two GCMs are clearer over SCS than over WNP (cf. Figs. 2a,b) indicating that the effect of the air-sea coupling is stronger influencing the monsoon interannual variability over SCS than over WNP. We suggest that the northeastward shift of SST warming from SCS to WNP is one of the reasons (e.g. Lau and Nath 2009).

Wang et al. (2009) reviewed that SCS summer monsoon variability is influenced by the large-scale atmospheric circulation. The eastward shift of warm SST in SCS to WNP contributes to intensify the westerly over SCS in summer (e.g. Wu and Wang 2007) and may enhance the moisture over there. Since the air-sea coupling is turned off everywhere in the AGCM2, we further investigate the relative role of the local coupling and the remote influence in amplifying SCS monsoon variability (cf. Fig. 2a). The moisture transport is associated with the large scale circulation, but not the local scale feature. Then, we define the local air-sea coupling (remote effect) as the change in evaporation (moisture flux convergence) over SCS.

Table 1 shows the anomalies in the precipitation, evaporation and vertically integrated moisture flux convergence (denoted as $-\nabla \cdot qV$), averaged over SCS for the observations and two GCMs. The result shows positive values of the moisture convergence for all observations and GCMs, indicating that the source of the precipitation anomaly largely

Fig. 3. (a)–(c) Scatter plots of surface heat flux anomalies against the normalized wind speed in the observations, the CGCM, and the AGCM2, respectively. The values are the average over SCS. (d)–(f) as in (a)–(c) but against SST. The correlation coefficients and regression lines are also indicated in each panel.

Table 1. Precipitation (P), evaporation (E), and the column-integrated moisture flux convergence anomalies in JJA regressed on the PC time series. The values are the average over SCS. The unit is mm day^{-1} . The residual of the three budget terms are also indicated.

Variable	P	E	$-\nabla \cdot \int qV$	Residual
OBS	0.81	0.14	0.71	−0.04
CGCM	1.17	0.03	1.21	−0.07
AGCM2	1.70	0.21	1.40	0.09
AGCM2−CGCM	0.54	0.18	0.19	

comes from the moisture transport. Ding et al. (2004) showed that during the active monsoon period, the condensation exceeds evaporation, in which the surplus moisture is supplied from the surrounding region. Our result shows that the moisture is mainly transported from the eastern Indian Ocean. The difference between two GCMs shows that the AGCM2 increases evaporation and moisture convergence almost in same magni-

tude (Table 1) indicating that both parameters work to enhance SCS precipitation in the AGCM2. In comparison with the moisture flux, the effect of the evaporation on the monsoon precipitation is 2.4% and 13% in the CGCM and the AGCM2, respectively (Table 1). In addition, the spatial correlation between the precipitation and the evaporation is 0.08 (0.45) for the CGCM (AGCM2), whereas between the precipitation and the moisture flux convergence is 0.36 (0.38) for the CGCM (AGCM2). These results indicate that the evaporation appears to be more significant in the AGCM2 in determining SCS summer monsoon variability and its effect becomes closer to the effect of the moisture convergence. However, this result cannot yet explicitly state the dominant effect between both parameters, as they may be dependent on each other.

4. Concluding discussion

MIROC5i well reproduces the ocean surface cooling due to wind-induced evaporation during

the active summer monsoon over SCS. Through the AGCM experiments, the role of the air-sea coupling in SCS summer monsoon variability is investigated.

The local air-sea coupling over SCS acts to modulate the activity of SCS summer monsoon as well as the remote forcing. The SST continuously warms over SCS as the feedback from the atmosphere to the ocean does not exist in the AGCM with historical SST (AGCM2). The SST warming contributes to increase evaporation, which results in the monsoon destabilization over SCS. Another impact, the absence of the air-sea coupling enhances heavier precipitation over SCS and induces atmospheric circulation over the remote regions. In this case, the large scale circulation intensifies westerlies that have dual effect to the enhanced moisture flux convergence and local evaporation. Both effects give rise to a positive feedback to the precipitation in addition to the local SST warming and amplify the monsoon variability by about 50 percent over SCS. There is additional heating associated with the enhanced precipitation. The Matsuno-Gill pattern (Matsuno 1966; Gill 1980) showed that response to the heating is automatically westerlies in the west of heating in the off-equator. Thus, the interaction among local evaporation, large-scale moisture transport, and heating over SCS may be coupled with each other. This monotonic relationship among those variabilities is possible because of mean westerlies around SCS in summer.

Our model experiments are able to clarify the impact of the air-sea coupling in the interannual variability of the South China Sea summer monsoon. Present study completes the study by Lau and Nath (2009) who did not clearly discuss the role of the air-sea coupling controlling the interannual variability of SCS summer monsoon. As the ocean dynamics also play a role in SCS SST variability (Qu 2001), further study is needed to clarify its relative importance compared with the air-sea interaction in SST cooling during SCS summer monsoon. Further model improvement is also required, e.g. ensemble runs, in order to have a model that is able to predict the monsoon variability.

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References

- Ding, Y., C. Li, and Y. Liu, 2004: Overview of the South China Sea Monsoon Experiment. *Adv. Atmos. Sci.*, **21**, 343–360.
- Ding, Y. H., 1992: Summer monsoon rainfalls in China. *J. Meteor. Soc. Japan*, **70**, 373–396.
- Gill, A. E., 1980: Some simple solutions for heat-induced tropical circulation. *Q. J. R. Meteor. Soc.*, **106**, 447–462.
- Hasumi, H., and S. Emori, 2004: K-1 coupled model (MIROC) description. *K-1 Tech. Report*, pp. 34, Center for Climate System Research, Univ. of Tokyo. Available at: <http://www.ccsr.u-tokyo.ac.jp/kyosei/hasumi/MIROC/tech-repo.pdf>.
- Jiang, J., and Y. Qian, 1999: The study on the interannual variation and the mechanisms of the South China Sea monsoon. *Adv. Atmos. Sci.*, **16**, 544–558.
- Lau, N. C., and M. J. Nath, 2009: A model investigation of the role of air–sea interaction in the climatological evolution and ENSO-related variability of the summer monsoon over the South China Sea and Western North Pacific. *J. Climate*, **22**, 4771–4792.
- Lau, K., and Coauthors, 1999: A report of the field operations and early results of the South China Sea Monsoon Experiment (SCSMEX). *Bull. Amer. Meteor. Soc.*, **81**, 1261–1270.
- Lestari, R. K., 2010: *Mechanisms of seasonal march of Precipitation over Maritime Continent Regions: Observational and Model Studies*. VDM Publishing House, Germany.
- Li, J., and L. Zhang, 2009: Wind onset and withdrawal of Asian summer monsoon and their simulated performance in AMIP models. *Clim. Dyn.*, **32**, 935–968.
- Lin, J. L., and Coauthors, 2008: Subseasonal variability associated with Asian summer monsoon simulated by 14 IPCC AR4 coupled GCMs. *J. Climate*, **21**, 4541–4567.
- Matsuno, T., 1966: Quasi-geostrophic motions in the equatorial area. *J. Meteor. Soc. Japan*, **44**, 25–42.
- Onogi, K., and Coauthors, 2007: The JRA-25 reanalysis. *J. Meteor. Soc. Japan*, **85**, 369–432.
- Ose, T., Y. Song, and A. Kitoh, 1997: Sea surface temperature in the South China Sea—an index for the Asian monsoon and ENSO system. *J. Meteor. Soc. Japan*, **75**, 1091–1107.
- Qu, T., 2001: Role of ocean dynamics in determining the mean seasonal cycle of the South China Sea surface temperature. *J. Geophys. Res.*, **106**, 6943–6955.
- Rayner, N. A., and Coauthors, 2003: Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *J. Geophys. Res.*, **108**, doi:10.1029/2002JD002670.

- von Storch, J. S., 2000: Signatures of air–sea interactions in a coupled atmosphere–ocean GCM. *J. Climate*, **13**, 3361–3379.
- Wang, B., F. Huang, Z. Wu, J. Yang, X. Fu, and K. Kikuchi, 2009: Multi-scale climate variability of the South China Sea monsoon: A review. *Dyn. Atmos. Oceans*, **47**, 15–37.
- Watanabe, M., and Coauthors, 2010a: Improved climate simulation by MIROC5: Mean states, variability, and climate sensitivity. *J. Climate*, in press.
- Watanabe, M., M. Chikira, Y. Imada, and M. Kimoto, 2010b: Convective control of ENSO simulated in MIROC. *J. Climate*, submitted.
- Wu, R., 2002: Processes for the northeastward advance of the summer monsoon over the Western North Pacific. *J. Meteor. Soc. Japan*, **80**, 67–83.
- Wu, R., and B. Wang, 2000: Interannual variability of summer monsoon onset over the Western North Pacific and underlying processes. *J. Climate*, **13**, 2483–2501.
- Wu, R., and B. Wang, 2007: Multi-stage onset of the summer monsoon over the Western North Pacific. *Clim. Dyn.*, **17**, 277–289.
- Xie, P., P. A. Arkin, and J. E. Janowiak, 2007: CMAP: The CPC merged analysis of precipitation, in measuring precipitation from space. Levizzani, V., P. Bauer, F. T. Turk (eds.), *Advances in Global Change Research Ser.*, Vol. **28**, Springer.
- Zhu, C. W., T. Nakazawa, and J. P. Li, 2003: The 30–60 day intraseasonal oscillation over the Western North Pacific Ocean and its impacts on summer flooding in China during 1998. *Geophys. Res. Lett.*, **30**, doi:10.1029/2003GL017817.