Effects of the coupling process on shortwave radiative feedback during ENSO in FGOALS-g

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ABSTRACT
Satisfactory simulation of negative shortwave (SW) radiative feedback during ENSO in the equatorial Pacific remains a challenging issue for climate models. Previous studies have focused on specific physical processes in the atmospheric and/or oceanic model, but the coupling process in coupled models has not received much attention. To investigate the coupling effect on SW feedback, two versions of an AGCM and their corresponding coupled models are analyzed. Results indicate that the effects of the coupling process in the two versions lead to weakening and enhancement of the negative feedback in the earlier and new versions, respectively, mainly due to their different changes in cloud fraction feedback and dynamical feedback. Further examination of the nonlinearity of the feedback reveals that the opposite coupling effects in the two versions originate from their different responses to El Niño and to La Niña.

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1. Introduction
ENSO, the strongest interannual signal in global climate variability, is characterized by large-scale SST anomalies in the eastern equatorial Pacific Ocean, and affects the atmospheric circulation on a global scale (Magnusson, Alonso-Balmaseda, and Molteni 2013; Bellenger et al. 2014). As a complex climate phenomenon, ENSO is amplified by positive Bjerknes feedback and damped by negative heat flux feedback, and the role of atmospheric feedback has increasingly been emphasized (Guilyardi et al. 2004; Lloyd et al. 2009; Lloyd, Guilyardi, and Weller 2011, 2012; Chen, Yu, and Sun 2013). In particular, the simulation of shortwave (SW) radiative feedback (the dominant component of heat flux feedback) has become a key indicator for ENSO simulation. However, the simulation of SW feedback remains a challenging task in most coupled and uncoupled models, with problems such as underestimated negative feedback in the equatorial Pacific (Bellenger et al. 2014; Kim et al. 2014), and even incorrect positive feedback in the Niño3 region (5°S–5°N, 150°–90°W) in the models participating in CMIP5.

The biases in SW feedback have been investigated in many studies, and are mainly attributed to the physical processes in specific model components. For example, in the atmospheric component, the convective parameterization scheme (Neale, Richter, and Jochum 2008; Guilyardi et al. 2009), nonconvective condensation processes (Li, Wang, and Zhang 2009), and the coupling of cloud radiative effects to atmospheric circulation (Rädel et al. 2016), may play an important role in SW feedback. The climatological mean state of some variables in the oceanic model, such as an excessive equatorial SST cold tongue, may also have an effect (Sun, Yu, and Zhang 2009). However, the effect of the coupling process on SW feedback in coupled models has not received sufficient attention. To investigate this effect, simulations of two
versions of the Grid-point Atmospheric Model of the LASG, IAP (GAMIL1 and GAMIL2) and the corresponding coupled models, FGOALS-g1 and FGOALS-g2, are analyzed in the present study.

The paper is organized as follows: Section 2 gives a brief description of the four models, the observational data and the method used for decomposing the SW feedback. In Section 3, the simulations of SW feedback are compared in the four models, and in particular the coupling effects on SW feedback are investigated in the two versions of FGOALS-g. Finally, a summary and discussion are given in Section 4.

2. Models, data, and decomposition method

2.1. Models and observational data

In this study, we select AMIP runs (AMIP years 1979–2008) of the two versions of GAMIL (GAMIL1 and GAMIL2) (Li and Wang 2010; Li et al. 2012, Li, Wang, et al. 2013), and CMIP runs (the first ensemble member of their historical runs (years 1951–2005) (Taylor, Stouffer, and Meehl 2012)) of their corresponding coupled models (FGOALS-g1 and FGOALS-g2) (Yan et al. 2009, 2010; Yu and Sun 2009; Yu et al. 2011; Li, Lin, et al. 2013). GAMIL1 and GAMIL2 are the atmospheric components of FGOALS-g1 and FGOALS-g2, which have participated in the CMIP3 and CMIP5, respectively. All these models have been developed by the LASG, IAP, Chinese Academy of Sciences. After a series of improvements, GAMIL2 still shares the same dynamical core and grids as GAMIL1, but the physical processes have been improved considerably in GAMIL2, including the adoption of many upgraded cloud-related processes and retuning some parameters in convection, cloud macro/microphysical and boundary layer schemes. In particular, the convective rainfall is reduced and stratiform rainfall is enhanced in the new deep convective parameterizations; for nonconvective cloud processes, the one-moment cloud microphysical scheme (Rasch and Kristjánsson 1998) is replaced by the two-moment scheme (Morrison and Gettelman 2008). In addition, the new oceanic component in FGOALS-g2 has increased the grid resolution, introduced the two-step shape-preserving advection scheme advection scheme (Xiao 2006), and improved some physical processes (Liu et al. 2012), as compared with that in FGOAL1-g1, the detail of which can be found in Li, Lin, et al. (2013), and Li, Wang, and Zhang 2014.

For comparison, the following reference datasets are used in this study: SW flux, cloud cover, and liquid water path (LWP) datasets from the ISCCP (Rossow and Schiffer 1999) for the period July 1983 to December 2008; and vertical velocity from NCEP Reanalysis-2 (Kanamitsu et al. 2002); SST from HadISST (Rayner et al. 2003). All these reference datasets are bilinearly interpolated onto a uniform 1.875° × 1.875° grid.

2.2. Decomposition method

Following the previous study of Li, Wang, and Zhang (2015), the feedback of an atmospheric variable $F$ during ENSO is defined by the linear regression coefficient $\alpha$:

$$\alpha = \alpha(SST),$$

where the angle brackets indicate averaging over the Niño3 region ($5^\circ S–5^\circ N, 150–90^\circ W$), and FA (SSTA) is the anomaly of $F$ (SST) after removing the annual cycle. To calculate the nonlinearity of a variable with respect to the El Niño and La Niña conditions, the feedback at each grid point is first computed separately for SST > 0 and SST < 0 before averaging over the Niño3 region (Lloyd, Guilyardi, and Weller 2012).

Based on the highly idealized decomposition method of SW feedback developed by Lloyd, Guilyardi, and Weller (2012), Li, Wang, and Zhang (2014) developed a more accurate method that can be written as

$$\frac{\delta SWCF}{\delta SST} = \frac{\delta SWCF}{\delta CLD} \frac{\delta CLD}{\delta SST} + \frac{\delta SWCF}{\delta LWP} \frac{\delta LWP}{\delta SST} .$$

(2)

This allows the SW feedback to be decomposed into cloud fraction feedback, $\frac{\delta CLD}{\delta SST}$, and LWP feedback, $\frac{\delta LWP}{\delta SST}$.

Furthermore, $\frac{\delta SWCF}{\delta SST}$ contains the atmospheric dynamics feedback, $\frac{\delta SWCF}{\delta SST}$.

3. Results

3.1. SW feedback behavior

First, we compare the SW feedback of the four simulations against the observations, as shown in Figure 1. In ISCCP, the negative SW feedback mainly occurs in the equatorial Pacific, east of 150°E, with a maximum near the dateline where convection is enhanced, resulting in an increased convective cloud amount and decreased SW flux reaching the surface during El Niño warming. On average, the negative feedback in the Niño4 region ($5^\circ S–5^\circ N, 160^\circ E–150^\circ W$), $−13.6 \ W \ m^{-2} K^{-1}$, is much larger than in the Niño3 region ($5^\circ S–5^\circ N, 150–90^\circ W$), $−6.4 \ W \ m^{-2} K^{-1}$. Compared with the observations, both the two earlier versions (GAMIL1 and FGOALS-g1) exhibit much weaker negative feedback in the above two regions, with the value in the Niño3 region even turning positive. The simulations in the two new versions (GAMIL2 and FGOALS-g2) are more reasonable, although the negative feedback is a little too strong. Moreover, the effect of the coupling process on the negative strength, which indicates that the SW feedback in an AGCM may be weakened or enhanced in coupled models because of its interactions with other components, is found to be...
opposite in the earlier and new versions: weakening in the earlier versions (coupling GAMIL1 to FGOALS-g1) and enhancement in the new versions (coupling GAMIL2 to FGOALS-g2).

The seasonal variations of the SW feedback in the observations and the four simulations in the Niño3 region are then investigated (Figure 2). The two earlier versions exhibit weaker negative SW feedback throughout the whole year, and the new versions exhibit a stronger negative value than the observations, except in spring. For the coupling process, the weakening of the feedback after coupling in the earlier versions mainly occurs in spring and may have little influence on ENSO, while the strengthening of the coupling dominates in late summer, autumn, and winter in the new versions, which may play an important role in the evolution of ENSO.

3.2. Effect of coupling

To explain the underlying mechanism for the effect of coupling on SW feedback, the SW feedback is decomposed into cloud fraction feedback, LWP feedback, and
cloud fraction feedback containing dynamical (vertical velocity at 500 hPa) feedback, according to Equation (2) (Lloyd, Guilyardi, and Weller 2012; Li, Wang, and Zhang 2014). These three components in the Niño3 region in the AMIP and CMIP runs are shown in Table 1. In the earlier versions, both the weakening of the cloud fraction feedback and the dynamical feedback contribute to the weaker SW feedback, while the LWP feedback operates in the opposite way. In the new versions, both the strengthening of the cloud fraction feedback and the dynamical feedback contribute to the stronger SW feedback, while the LWP feedback weakens. Therefore, the effects of coupling on SW feedback are influenced by the cloud fraction feedback and the dynamical feedback in both FGOALS-g versions.

Moreover, to explore the cause of the different coupling effects on SW feedback in the two FGOALS-g versions, the SW, total cloud fraction, LWP, and dynamic feedbacks in the Niño3 region under El Niño (SSTA > 0) and La Niña (SSTA < 0) conditions in the AMIP and CMIP runs are shown in Table 2. According to observation, the SW feedback tends to be negative for El Niño warming (−8.9 W m⁻² K⁻¹) and positive for La Niña cooling (0.9 W m⁻² K⁻¹). After coupling GAMIL1 to FGOALS-g1, the negative response of SW feedback to El Niño is weakened (from −2.69 to −0.60 W m⁻² K⁻¹), and the positive response to La Niña is strengthened (from 14.92 to 24.03 W m⁻² K⁻¹), both contributing to the weakening of the total negative SW feedback. Whereas, after coupling GAMIL2 to FGOALS-g2, although the negative response of SW feedback to El Niño is weakened (from −10.6 to −10.2 W m⁻² K⁻¹), the incorrect negative response to La Niña is strengthened (from −1.3 to −0.8 W m⁻² K⁻¹), which results in the strengthening of the total negative SW feedback. In other words, by coupling GAMIL1 to FGOALS-g1, both the SW feedback for El Niño and La Niña contribute to the weakening of SW feedback; while by coupling GAMIL2 to FGOALS-g2, the strengthening of SW feedback mainly results from the SW feedback to La Niña.

4. Summary and discussion

The ENSO simulations of the earlier version of the atmospheric model, GAMIL1, and the new version, GAMIL2, and the corresponding coupled models (FGOALS-g1 and FGOALS-g2) are compared to investigate the effect of coupling on SW feedback in the equatorial Pacific. Results indicate that the negative feedback in the earlier versions (GAMIL1 and FGOALS-g1) is much weaker than observed throughout the whole year, while the new versions (GAMIL2 and FGOALS-g2) simulate SW feedback that is much closer to observation, especially in the Niño3 region, albeit the negative feedback is a little stronger. The effect of the coupling process on the negative feedback in the two versions is different, with weakening when coupling GAMIL1 to FGOALS-g1, and enhancement when coupling GAMIL2 to FGOALS-g2. The effects of coupling on the SW feedback are influenced by the cloud fraction feedback and the dynamical feedback in both versions of FGOALS-g; both feedback components weaken in the earlier version and strengthen in the new version. Further examination reveals that the opposite effects of coupling in the two versions are related to the nonlinearity of the SW feedback in El Niño and La Niña: both the responses to El Niño and La Niña contribute to the weakening of SW feedback when coupling GAMIL1 to FGOALS-g1, while the strengthening of SW feedback mainly comes from the response to La Niña when coupling GAMIL2 to FGOALS-g2.
The study also investigates the coupling effect by decomposing the SW feedback into three related atmospheric feedbacks and also considering its nonlinearity. At a deeper and more practical level, the opposite effect of the coupling process on SW feedback in the two versions may be associated with their different physical parameterization schemes in the coupled models; the reduced convective rainfall and stratiform rainfall in the atmospheric component may enhance and weaken the SW feedback through the coupling process. Furthermore, the advection scheme in the oceanic component may also be an important factor. The apparent mechanism will be studied in a follow-up paper. The climatological mean state is another factor determining ENSO behavior (Guilyardi 2006; An and Choi 2013), so the change in mean state (especially wind stress) associated with the coupling process is also worthy of further research.

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