Impact of Subdaily Air–Sea Interaction on Simulating Intraseasonal Oscillations over the Tropical Asian Monsoon Region

WENTING HU, ANMIN DUAN, AND GUOXIONG WU
State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics, Institute of Atmospheric Physics, Chinese Academy of Sciences, Beijing, China

(Manuscript received 9 June 2014, in final form 24 October 2014)

ABSTRACT

The off-equatorial boreal summer intraseasonal oscillation (ISO) is closely linked to the onset, active, and break phases of the tropical Asian monsoon, but the accurate simulation of the eastward-propagating low-frequency ISO by current models remains a challenge. In this study, an atmospheric general circulation model (AGCM)–ocean mixed layer coupled model with high (10 min) coupling frequency (DC_10m) shows improved skill in simulating the ISO signal in terms of period, intensity, and propagation direction, compared with the coupled runs with low (1 and 12 h) coupling frequency and a stand-alone AGCM driven by the daily sea surface temperature (SST) fields. In particular, only the DC_10m is able to recreate the observed lead–lag phase relationship between SST (SST tendency) and precipitation at intraseasonal time scales, indicating that the ISO signal is closely linked to the subdaily air–sea interaction. During the ISO life cycle, air–sea interaction reduces the SST underlying the convection via wind–evaporation and cloud–radiation feedbacks, as well as wind-induced oceanic mixing, which in turn restrains convection. However, to the east of the convection, the heat-induced atmospheric Gill-type response leads to downward motion and a reduced surface westerly background flow because of the easterly anomalies. The resultant decreased oceanic mixing, together with the increased shortwave flux, tends to warm the SST and subsequently trigger convection. Therefore, the eastward-propagating ISO may result from an asymmetric east–west change in SST induced mainly by multiscale air–sea interactions.

1. Introduction

There are two dominant modes of intraseasonal variability in the tropics: the Madden–Julian oscillation (MJO; Madden and Julian 1971, 1972) during the boreal spring and winter and the boreal summer intraseasonal oscillation (ISO) associated with the tropical Asian monsoon (Yasunari 1979, 1980; Wang and Rui 1990; Kikuchi et al. 2012). Compared with the MJO, the monsoon boreal summer ISO has a more complex structure, with both eastward and northward propagation (Annamalai and Slingo 2001; Lawrence and Webster 2002). The characteristics and mechanisms of the northward-propagating monsoon ISO have been well documented (Webster 1983; Wang and Xie 1997; Jiang et al. 2004), but the accompanying eastward propagation in the off-equatorial area has received less attention (Lawrence and Webster 2002). The correct simulation by models of the ISO associated with the monsoon is a key issue for seasonal forecasting but remains a challenge, and some studies (Lin et al. 2008; Klingaman et al. 2011) have revealed the poor performance of current models in simulating the eastward-propagating ISO off the equator, compared with their much better simulation of the northward propagation of the ISO during boreal summer.

A global air–sea coupled model should give improved magnitude and propagation characteristics for the MJO and the northward-propagating ISO over the Asian summer monsoon region (Waliser et al. 1999; Inness and Slingo 2003; Rajendran and Kitoh 2006; Fu et al. 2007; Woolnough et al. 2007; Wang et al. 2009; Kim et al. 2010; Klingaman et al. 2011). In addition, previous studies indicate that using daily rather than monthly SST data to force the atmospheric general circulation models (AGCMs) may generate subseasonal variability closer to that seen in observational data (Kim et al. 2008; Klingaman et al. 2008). Using an air–sea coupled model
with a near-surface ocean vertical resolution of 1 m and an air–sea coupling frequency of 3 h, Bernie et al. (2005, 2007) were able to simulate 90% (95%) of the diurnal (intraseasonal) SST amplitude in the western Pacific. However, neglecting the subdaily change in surface forcing can reduce the intraseasonal SST response to the MJO by 20%. Note that most state-of-the-art global air–sea coupled models adopt a coupling frequency of 24 h (Lin et al. 2008), which might partly explain the relatively poor simulation of the eastward-propagating ISO during the boreal summer.

Subdaily change is one of the most important features in monsoon regions. The diurnal cycle of precipitation and cloud directly influences radiative heating and surface fluxes and then further affects the subseasonal variability (Sui et al. 1997). Sperber and Yasunari (2006) proposed that the subdaily change has an impact on physical processes at the subseasonal time scale. Woolnough et al. (2007) conducted MJO predictability experiments by coupling the K-profile parameterization (KPP) ocean boundary layer model with the monthly forecasting system of the European Centre for Medium-Range Weather Forecasts (ECMWF). Their results indicated that simulations with 1-m ocean vertical resolution and 3-h coupling, rather than 10-m resolution and 24-h coupling, offer improved forecast skill and are better than the 3D Hamburg ocean primitive equation ocean GCM with 10-m resolution and 24-h coupling. Klingaman et al. (2011) used an atmosphere–ocean coupled model [coupled Hadley Centre–KPP model (HadKPP)] and performed four 30-member ensemble experiments that varied in ocean vertical resolution between 1 and 10 m and in coupling frequency between 3 and 24 h to determine the effects of subdaily air–sea coupling on the representation of the Asian summer monsoon ISO. Only the 1-m, 3-h configuration generated organized northward-propagating convection, but it still had difficulty in reproducing the eastward propagation of the boreal summer ISO.

The purpose of this study is to estimate the impact of subdaily air–sea interaction on simulating the eastward-propagating ISO over the tropical Asian monsoon region and to elucidate the physical processes that are responsible for the eastward-propagating ISO. Relevant data, the model, and the experiment design are described in section 2. The characteristics of the eastward-propagating ISO associated with the Asian monsoon, as identified in the observations and seen in the results from three experiments, are analyzed in section 3. The mechanism by which the subdaily air–sea interaction influences the eastward-propagating ISO is investigated in section 4, and the summary and discussion are presented in section 5.

2. Data, model, and experiment design
   a. Data and model description

The daily ECMWF Interim Re-Analysis (ERA-Interim) dataset (Dee et al. 2011) for the period 1980–2006 is used to determine the spatial and temporal characteristics of the ISO over the Asian monsoon region. This dataset (available from http://apps.ecmwf. int/datasets/data/interim_full_daily) gives a reasonable representation of the ISO (Wang et al. 2012). We also use National Oceanic and Atmospheric Administration (NOAA) interpolated outgoing longwave radiation (OLR; Liebmann and Smith 1996), from 1980 to 2006 with 2.5° × 2.5° spatial resolution, which can be considered as a reasonable substitute for precipitation in the tropics. Fifteen years (1990–2004) of Global Precipitation Climatology Project (GPCP) version 2 (Huffman et al. 1997) pentad data and the NOAA optimum interpolation SST (OISST) version 2 (V2) (Reynolds et al. 2002) daily data are combined to analyze the interaction between air and sea. To better reflect the relationship between precipitation and SST in the observations, the time interval and horizontal resolution of the OISST dataset are interpolated to a temporal span of one pentad and a spatial resolution of 2.5° longitude × 2.5° latitude.

The AGCM used in this study is Spectral Atmospheric Model of the IAP LASG, version 2.2.3 (SAMIL2.2.3), which is a global spectral model developed at the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Fluid Dynamics (LASG), Beijing, China. The horizontal resolution of SAMIL2.2.3 is rhomboidally truncated at a zonal wavenumber (R42) roughly equal to a grid of 2.8125° longitude × 1.67° latitude. In the vertical direction, 26 layers are deployed within a hybrid coordinate system. The dynamical framework uses a standard atmosphere reduction scheme (Zeng 1963) and involves semi-implicit integration in time. The integration time step in SAMIL2.2.3 is 10 min. The radiation scheme is based on Edwards and Slingo (1996). Land surface processes are represented using the Simplified SiB model (SSiB; Xue et al. 1991; Liu and Wu 1997). Convection and condensation processes are parameterized using the Zhang–McFarlane scheme (Zhang 2002; Zhang and Mu 2005). The planetary boundary layer (PBL) element of the model involves a higher-order closure scheme that computes the turbulent transfer of momentum, heat, moisture, and cloud water (Brinkop and Roeckner 1995). The cloud scheme is a diagnostic method based on vertical motion and relative humidity. A parameterization of gravity wave drag is also applied, which depends on wind speed, density, and the static stability of the low-level flow (Palmer et al. 1986).
The ocean mixed layer model (OMLM) used in this work is a second-order turbulence closure model developed by Noh and Kim (1999). The surface boundary conditions for turbulent kinetic energy (TKE), the parameterization of stratification effects on turbulence, and the formulation of convective processes are all improved in this model compared with those in Mellor and Yamada (1982). The vertical resolution is 5 m throughout, with 50 vertical levels. The model can successfully simulate the evolution of profiles of both the dissipation rate and temperature, and reproduces various important features of the oceanic boundary layer. This OMLM has been coupled to an oceanic GCM (Noh et al. 2002), an AGCM (Duan et al. 2008), and a coupled GCM (Yim et al. 2008) to study many aspects of climate variability and has generated reasonable simulation results.

In this study, the OMLM is coupled to the SAMIL2.2.3 model in the great warm pool (GWP; i.e., the area with annual-mean SST above 28°C across the Indian and western Pacific Oceans: 15.76°S–20.737°N, 59.0625°E–168.75°W in the model). This coupled model (SAMIL–OMLM) is simple but includes the main physical processes of air–sea interaction in the warm pool. For the coupled integration, the AGCM provides surface heat fluxes (i.e., sensible heat flux, latent heat flux, net shortwave radiation flux, and net longwave radiation flux) and meridional and zonal wind stresses to the OMLM at each integration step (10 min) in the GWP area; the OMLM then feeds back an updated SST to the AGCM. Clearly, the subdaily physical processes and the effect of the diurnal cycle of SST are included in this coupled model. Assuming that the effect of oceanic salinity variation on SST is insignificant in this coarse-resolution modeling, we prescribe the salinity as a constant in the OMLM.

Because of the absence of oceanic dynamics, a nudging term is added to the OMLM to restore the long-term integrated SST toward the climatological SST in the first layer. This is incorporated into the thermodynamic equation as

\[
\frac{\partial T}{\partial t} = \frac{Q^*}{\rho C_p \Delta z_1} + \frac{(T_s^* - T_s)}{\tau},
\]

where \(Q^*\) is the net heat flux generated by the atmospheric model, \(\rho\) is the density of seawater, \(C_p\) is the specific heat of water at constant pressure, \(\Delta z_1\) is the thickness of the first layer of the OMLM, \(\tau\) is the restoring time scale, \(T_s^*\) is the temperature of the first model layer, and \(T_s\) is the observed SST. To minimize the impact of nudging and highlight the influence of air–sea interaction, \(\tau\) is set to 20 days in the coupled run of this study, based on multiple sensitivity tests, rather than 5 days as in Duan et al. (2008).

b. Experiment design

Three coupled runs of SAMIL–OMLM and one sensitivity experiment are used to investigate the effects of local subdaily air–sea interaction on the ISO simulations. A more detailed description of the experimental design is given in Table 1.

The three coupled runs consist of ensemble experiments that are generated as follows. First, the Atmospheric Model Intercomparison Project phase 2 (AMIP-II) 20-yr-averaged monthly SST and sea ice data are prescribed and interpolated linearly to each integration step in the AGCM. This AMIP run is then integrated for 30 yr. The first 3 yr is taken as the spinup period and the results ignored. The outputs from the first day of each of the remaining 27 yr are used as initial inputs to conduct 1-yr coupled integrations, and these 27 1-yr integrations compose a 27-member ensemble experiment. The three coupled experiments differ in the exchange frequency between the AGCM and OMLM. In the control run (DC_10m), the AGCM exchanges sea surface information with the OMLM every 10 min, keeping pace with the model integration step. This implies that every

### Table 1. Experiment Design

<table>
<thead>
<tr>
<th>Experiments</th>
<th>Air–sea coupled area</th>
<th>Coupling frequency</th>
<th>SST Goal</th>
<th>Goal</th>
</tr>
</thead>
<tbody>
<tr>
<td>DC_10m</td>
<td>GWP</td>
<td>10 min</td>
<td>Generated by the air–sea coupled processes within the GWP and AMIP-II climatology outside the GWP</td>
<td>Examine the general performance on the ISO simulations of SAMIL–OMLM, which includes SST diurnal cycle</td>
</tr>
<tr>
<td>DC_1h</td>
<td>GWP</td>
<td>1 h</td>
<td>Daily SST provided by DC_10m</td>
<td>Show the differences of ISO simulation with varied coupling frequency</td>
</tr>
<tr>
<td>DC_12h</td>
<td>GWP</td>
<td>12 h</td>
<td>Daily SST provided by DC_10m</td>
<td>Show the simulation of AGCM derived by daily SST of DC_10m, and estimate the effects of subdaily air–sea interaction compared with DC_10m</td>
</tr>
<tr>
<td>AGCM_D</td>
<td>None</td>
<td>None</td>
<td>None</td>
<td>Daily SST provided by DC_10m</td>
</tr>
</tbody>
</table>


slight change of surface heat flux and wind stress in the AGCM can be reflected in the OMLM. Meanwhile, the resulting change in SST will feed back to the AGCM and lead to an adjustment in the atmosphere. In the other two coupled runs (DC_1h and DC_12h), the coupling frequencies are 1 and 12 h, which means that the information exchange happens every 6 and 72 integration steps of the AGCM, respectively. To investigate the subdaily air–sea interaction, we have conducted a sensitivity experiment (AGCM_D) using the daily SST output of DC_10m to force the AGCM. The daily data from all the experiments and 5 yr of 1-hourly data from DC_10m are retrieved for the following analysis.

3. The boreal summer ISO: Observations and simulations

Figure 1 shows the boreal summer–mean precipitation and 850-hPa wind fields averaged over 27 yr (1980–2006) and the associated difference maps. In the observations (Fig. 1a), the low-level circulation systems are dominated by vigorous southwesterlies and the monsoon trough over the tropical Asian monsoon region, along with the subtropical high to the east. The maximum precipitation appears over the Bay of Bengal (BOB). In general, all three experiments are able to reproduce the basic circulation systems and precipitation pattern (not shown). The difference map between DC_10m and the observations (Fig. 1b) shows that the southwesterlies are systematically overestimated over 10°–20°N but underestimated to the south of 10°N. The subtropical high over the western Pacific is somewhat eastward of its actual position, and below-normal precipitation occurs over most of the tropical Asian monsoon region, especially over India, the northeast BOB and the northwest South China Sea (SCS). The differences DC_10m minus DC_1h (Fig. 1c) and DC_10m minus AGCM_D (Fig. 1d) both indicate negative precipitation anomalies over the Indian Subcontinent, Indochinese Peninsula, and western Pacific, with easterly anomalies south of 20°N and an anticyclonic circulation anomaly over the western North Pacific. This implies that subdaily processes are likely to have a limited effect on the climate-mean model bias in this model. The model biases may be related to the cumulus convective parameterization scheme used in the AGCM and shortcomings in other physical processes (Song and Zhang 2009; Mukhopadhyay et al. 2010; Hu et al. 2011). Nevertheless, the generally acceptable performance of the model in simulating the boreal summer–mean circulation and precipitation pattern over the tropical Asian monsoon regions provides sufficient confidence.
for us to carry out the following analysis concerning ISO evolution.

Wavenumber–frequency spectral methodology (Hayashi 1982) is often utilized to investigate the spatial and temporal scales of tropical convection. Figure 2 shows the observed and simulated May–October-averaged wavenumber–frequency spectra of the 27-yr 850-hPa zonal wind anomalies between 10° and 20°N. A parallel analysis has been conducted using the OLR anomalies from the observations and four experiments. The spectra obtained display similar characteristics to those of the 850-hPa zonal wind.

In ERA-Interim (Fig. 2a), the predominant period of 40–80 days occurs mainly in zonal wave 1, and the eastward variance (maximum up to 0.1 m² s⁻² per frequency interval per wavenumber interval) is a factor of 10 larger than the westward counterpart. The coupled-mode ensemble run with 10-min coupling frequency (Fig. 2b) captures the eastward-propagating signal and the dominant 40–80-day period reasonably well. If we reduce the coupling frequency from 10 min to 1 and 12 h (Figs. 2c,d), two eastward variance maxima occur at periods of <40 and approximately 80 days. The results from DC_1h and DC_12h show a similar bimodal pattern of variance, indicating that the simulation of DC_10m is more realistic than these two coupled runs. In the AGCM run driven by daily SST (AGCM_D; Fig. 2d), although the spectral power of the eastward component is larger than that of the westward component, the energy is located mainly at lower frequencies and with a period greater than 80 days. The comparisons of lag–longitude cross correlations for the four experiments also show that only DC_10m could simulate the off-equatorial eastward propagation, especially from the BOB to the SCS (not shown).
Variance fields of the May–October 40–80-day filtered 850-hPa zonal wind are shown in Fig. 3. The variance in ERA-Interim (Fig. 3a) covers the 10°–20°N band of the Asian summer monsoon region and is centered on the SCS. The DC_10m and AGCM_D generally overestimate the 40–80-day variance, especially over the BOB. The DC_10m simulates more a realistic variance center over the SCS than do the other three experiments. The variances in DC_1h and DC_12h (Figs. 3d and 3e) appear weaker over the monsoon region than in the observations. Thus, the subdaily air–sea interaction has a profound and positive impact on the simulated eastward-propagating ISO in both intensity and period, but it remains unclear why the boreal summer ISO is characterized by a 40–80-day predominant period.

The evolution of the off-equatorial eastward-propagating ISO associated with the Asian monsoon can be seen in the observations. Figure 4 shows the evolution of the 40–80-day filtered 850-hPa zonal winds (vectors), OLR (shading), and SST (contours) anomalies using the phase composite technique. This technique has been widely used to analyze the ISO life cycle (e.g., Chan et al. 2002; Mao and Chan 2005). Based on the BOB domain-averaged (10°–20°N, 80°–100°E) OLR anomaly, a strong ISO cycle is defined as one including both a wet and a dry period, with the peak amplitude of each period greater than a threshold of one standard deviation of the referenced time series. Consequently, 36 strong ISO cycles are selected from the 27 boreal summers (1980–2006). Each cycle is divided into eight phases. Phase 3 represents the maximum value denoting the dry period, while phase 7 corresponds to the wet period.

In phase 1, a positive OLR anomaly center is located over the northern Arabian Sea (ABS) and then moves eastward and reaches its maximum over the BOB in phase 3 (the dry phase), which corresponds to an anticyclonic anomaly in the lower troposphere. In phase 5, the convective center moves northward from the equator to the ABS, intensifies in phase 6, and reaches its
peak in phase 7 (wet phase), accompanied by the 850-hPa cyclonic anomaly. This negative OLR center gradually propagates eastward (phase 8) and ultimately dissipates over the SCS (see phases 1 and 2). Within the summer monsoon region, the maximum SST anomaly (contours) appears in the ABS (phase 4), BOB (phase 6), and SCS (phase 7) before the local emergence of the OLR anomaly minima (shading) and corresponding westerly anomaly (vectors). This indicates that a significant lead–lag relationship exists between the 40–80-day SST and convection: that is, positive anomalies in SST lead to positive anomalies in wind stress and negative anomalies in OLR.

The 10°–15°N-averaged pressure–longitude cross sections of composite 40–80-day filtered airflow and specific humidity from phase 5 to phase 8 are shown in Fig. 5 to further demonstrate (combined with the results in Fig. 4) the 3D characteristics of the ISO. The atmospheric circulation anomaly around the convective center in phases 5 and 6 is a typical Gill-type response (Gill 1980): that is, surface easterly (westerly) anomalies to the east (west) of the heating region together with strong upward motion and a positive specific humidity anomaly over the heating regions and downward motion and a negative specific humidity anomaly to the east (Figs. 5a and 5b). Easterly anomalies in the lower troposphere within a westerly mean state and subsidence-driven clear sky to the east of a convective center imply both evaporation and shortwave fluxes warming up underlying sea surface. By phase 7 (Fig. 5c), the convective center is located in the BOB, with its strong upward motion and abundant moisture, while there is a slight upward movement over the SCS. Then, in phase 8 (Fig. 5d), the upward motion over the SCS begins to increase, and is accompanied by
weakening of the convection in the BOB. This intra-
seasonal air–sea interaction, which reveals the feedback
process between precipitation and underlying SST and
fluxes, has been demonstrated in many previous studies
(e.g., Fu and Wang 2004; Fu et al. 2007; Wu and Kinter
2010). In section 4, we will discuss in detail the differences
in surface fluxes and in water vapor conditions for air–sea
interaction in the experiments.

To clearly demonstrate the phase relationship be-
tween precipitation and SST (or SST tendency) in both
observations and simulations, Fig. 6 shows the lead–lag
correlations between intraseasonal precipitation and
SST (or SST tendency) in three regions (ABS, BOB,
and SCS). The pentad-mean SST tendency is calculated
using centered differencing (Wu and Kinter 2010): that
is, the SST difference between the next and previous
pentads.

In the ABS (10°–15°N, 70°–75°E; Figs. 6a,b), the ob-
servations show that positive (negative) SST leads (lags)
precipitation by about 3–4 pentads, with a correlation

**Fig. 5.** The 10°–15°N-averaged pressure–longitude cross sections of composite 40–80-day filtered airflow (vectors; $u$ in m s$^{-1}$ and vertical velocity in $-200\mu$ Pa s$^{-1}$) and specific humidity (shading; g kg$^{-1}$) for (a)–(d) phases 5–8. Black rectangles denote the Indian Subcontinent and Indochinese Peninsula. Only those values of specific humidity and wind (at least one component) that are statistically significant at the 95% confidence level are shown.
FIG. 6. Lag correlations between area-averaged 40–80-day filtered pentad rainfall with (a),(c),(e) local SST and (b),(d),(f) local SST tendency, using 15 yr of boreal summer model outputs and observational data. The areas are over (a),(b) the Arabian Sea (10°–15°N, 70°–75°E), (c),(d) the Bay of Bengal (10°–15°N, 85°–90°E), and (e),(f) the South China Sea (10°–15°N, 112°–117°E). Purple dashed lines represent 95% significance (Student’s t test).
supports the importance of subdaily air–sea interaction. simulations of intraseasonal air–sea interaction and thus underlying SST. However, the lack of subdaily air–sea in AGCM_D, which ensures the relative accuracy of the DC_10m linearly interpolates into each integration step (20 days) gives an incorrect description of the air–sea back at time scales shorter than the restoring time scale representation of SST diurnal change and related feed- atmosphere every 12 h in DC_12h. This inadequate This is because SST is affected by the transient value in the interaction, DC_12h appears to be worse than AGCM_D. (AGCM_D) also gives unrealistic intraseasonal air–sea (Figs. 6d and 6f). Although the sensitivity experiment (AGCM_D) also gives unrealistic intraseasonal air–sea interaction, DC_12h appears to be worse than AGCM_D. This is because SST is affected by the transient value in the atmosphere every 12 h in DC_12h. This inadequate representation of SST diurnal change and related feedback at time scales shorter than the restoring time scale (20 days) gives an incorrect description of the air–sea interaction. In addition, the daily SST forcing field from DC_10m linearly interpolates into each integration step in AGCM_D, which ensures the relative accuracy of the underlying SST. However, the lack of subdaily air–sea information exchange in AGCM_D still gives unrealistic simulations of intraseasonal air–sea interaction and thus supports the importance of subdaily air–sea interaction.

4. Impact of the subdaily air–sea interaction

Two issues will be tackled in this section. First, why does DC_10m perform better in simulating the eastward-propagating ISO? Second, does the subdaily air–sea interaction lead to other changes that may be responsible for the more realistic simulations?

Here we use the BOB as a representative area to describe the possible contribution of subdaily air–sea interaction. The ISO life cycle for the four experiments is determined as in the observations (Fig. 4). There are 31, 27, 25, and 30 strong ISO cases in DC_10m, DC_1h, DC_12h, and AGCM_D, respectively. As outlined previously, a wet phase occurs when the maximum rainfall center is located over the BOB, accompanied by a minimum of the OLR anomaly and negative anomaly in surface shortwave radiation flux. Figure 7 shows composite anomalies of 40–80-day filtered OLR, surface temperature (TS), surface latent heat flux (LH), net surface shortwave radiation flux (SW), and surface specific humidity (SH) averaged over the 10°–15°N latitude band during the wet phase (phase 7).

Over the BOB, AGCM_D has the largest rainfall anomaly during the wet phase, followed in descending order by DC_10m, DC_1h, and DC_12h (Fig. 7a). The precipitation in DC_1h and DC_12h is generally weak because of insufficient moisture (Fig. 7c). Figures 6 and 7 suggest that the prolonged time interval between air–sea information exchanges induces an inaccurate representation of the physical processes in DC_12h. Moreover, the generally cooler SST (Fig. 7b) in DC_1h compared with DC_10m and AGCM_D results in less surface moisture (Fig. 7e) and rainfall (Fig. 7a). Therefore, we focus on the differences between DC_10m and AGCM_D to examine the impact of subdaily air–sea interaction. In DC_10m, the upward surface latent heat flux anomaly over and to the west of the BOB (Fig. 7c) indicates that the ocean provides energy and water vapor to the atmosphere, which will decrease the local SST (Fig. 7b) via the wind–evaporation feedback. To the east of the BOB, the positive SST anomaly accompanied by the negative surface latent heat flux (Fig. 7e) demonstrates that the ocean is gaining energy. The SST in DC_10m over the BOB (SCS) is cooler (warmer) than that in AGCM_D (Fig. 7b). The cooler SST and lower specific humidity (Fig. 7e) over the BOB in DC_10m compared with AGCM_D are conducive to the reduction of in situ convection, while the opposite conditions over the SCS favor the development of new convection in DC_10m. The lack of subdaily air–sea interaction gives a much weaker ISO signal in the AGCM-only case.

Taking account of the asymmetric wind distribution in the lower troposphere over and to the east of the heating region in the observations, we make further efforts to examine the differences in 40–80-day filtered surface latent heat flux and 850-hPa winds between DC_10m and the other three experiments during the wet phase (Fig. 8). The common difference is the anticyclonic anomaly over the western North Pacific, which partly counteracts the eastward retreat of the subtropical high that is a component of the model bias. The weak precipitation, probably induced by insufficient moisture in DC_1h and DC_12h, leads to the near-zero LH anomalies over the whole monsoon region (Fig. 7c). The LH pattern in DC_10m is shown in Figs. 8a,b: positive LH anomalies cover the southern ABS and BOB, while the negative LH anomaly is centered in the SCS, accompanying the easterly anomalies in the 10°–20°N latitude band. It is worth noting that both the easterly anomalies and the northern branch of a cyclonic anomaly in Fig. 8c over the SCS may effectively decrease the
impact of wind–evaporation feedback, inducing the underlying SST warming (Fig. 7b). This suggests that DC_10m might accurately reproduce the asymmetric wind pattern seen in the observations (Fig. 5).

Water vapor is a fundamental requirement for the development of convection. A buildup of moist static energy (MSE) usually occurs before deep convection, whereas it is discharged during and after ISO convection (Hendon and Liebmann 1990; Maloney and Hartmann 1998; Kiladis et al. 2005; Agudelo et al. 2006; Benedict and Randall 2007; Maloney 2009). MSE is defined as

\[ \text{MSE} = C_p T + gz + Lq, \]

where \( T \) is temperature, \( C_p \) is the specific heat at constant pressure, \( g \) is the gravitational acceleration, \( z \) is height, \( L \) is the latent heat of vaporization at 0°C, and \( q \) is specific humidity.

Figures 9a–c present the vertical differences in the 40–80-day filtered MSE between DC_10m and the other three experiments during the wet phase, averaged over 10°–15°N, with the aim of estimating the possibility of convection developing over the SCS. The MSE simulated by DC_10m is stronger over the whole Asian monsoon region than that simulated by DC_1h and DC_12h (Figs. 9a,b), especially in the lower troposphere. This is consistent with the lack of water vapor in the lower troposphere (not shown). In Fig. 9c the MSE simulated by DC_10m increases the possibility that convection over the ABS and BOB will decay and convection over the SCS will develop, which favors eastward movement of the ISO. Figures 9d–f show the time evolution of the 40–80-day filtered MSE of DC_10m minus that of the other three experiments, averaged over the SCS (10°–15°N, 110°–120°E), obtained using the phase composite method. During the wet phase (phase 7, when the OLR over the BOB
reaches a minimum), the difference in MSE between DC_10m and AGCM_D (Fig. 9f) shows that a more abundant buildup of MSE occurs over the SCS before the development of convection, while it dissipates after the convective center moves to the SCS.

Figures 7–9 show that the heat-induced atmospheric response tends to generate descending motion and easterly anomalies to the east of the convective center, which will decelerate the westerly basic flow and decrease oceanic mixing. In addition, descending motion facilitates a positive anomaly in shortwave radiation flux, although the magnitude is much lower than that of the latent heat flux. The combined effect of these air–sea feedbacks will increase SST to the east of convection, and provide favorable conditions for triggering convection. Therefore, the eastward-propagating ISO may be, to a considerable degree, influenced by the east–west asymmetric SST change induced by subdaily air–sea interaction. When the intraseasonal signal propagates to the SCS, the climate-mean surface easterly over the Philippine Sea will be intensified by the heat-induced easterly anomaly, which will further enhance evaporation and oceanic mixing and also offset the SST warming effect caused by the descending motion. This may explain why the ISO signal is unable to propagate any farther east.

The above analysis has highlighted the impact of subdaily air–sea interaction within an intraseasonal...
context. Next, we attempt to determine its impacts over subdaily time scales. The root-mean-square (RMS) of TKE represents the extent of seawater stirring, which is calculated in OMLM every time step. We selected a strong 40–80-day ISO case (18 May–15 July 1981) to analyze the variation of the RMS TKE and SST using the hourly output from DC_10m. Figure 10a shows the time series of the RMS TKE and the domain-averaged SST anomaly over the BOB (10°–15°N, 85°–90°E), which indicates that the variability of the ocean mixed layer exists on multiple scales ranging from intraseasonal to diurnal. During the dry phase, RMS TKE is relatively small and induces a shallow ocean mixed layer due to the strong solar radiation, weak winds, and reduced evaporation. As a result, the sea surface warms quickly. However, during the wet phase, strong surface winds and reduced solar radiation at the surface enhance the TKE substantially in the upper layer of the ocean and deepen the mixed layer, which further reduces the SST. Previous studies have pointed out that active–break monsoon cycles can induce SST variation of around 1°C in the Indian Ocean (Bhat et al. 2001; Webster et al. 2002; Joseph and Sabin 2008). The air–sea coupled model used here shows comparable results.

The difference in the number of active convection events between DC_10m and AGCM_D at each grid point is shown in Fig. 10b. The criterion for active convection is an OLR anomaly less than −1 standard deviation. Over the whole monsoon region, DC_10m produces more active convection cases (approximately 20% more than AGCM_D), which implies more opportunities to generate a well-organized convection system. Adequate convection caused by diurnal variation is also a necessary precursor to the deep convection.

5. Summary and discussion

An atmosphere–ocean mixed layer coupled model was used to simulate the eastward-propagating ISO associated with the tropical Asian monsoon during boreal summer. Three control runs with coupling frequencies of 10 min, 1 h, and 12 h and one sensitivity test (Table 1)
were conducted to examine the impact of subdaily air–sea interaction on the simulations. The coupled run with high frequency (DC_10m) simulated the observed ISO signal over the tropical Asian monsoon regions well in terms of period, intensity, and propagation direction. The results of the other two coupled runs (DC_1h and DC_12h) show a bimodal pattern of variance with periods of approximately 40 and 80 days. Moreover, compared with DC_10m, the prolonged time interval between air–sea information exchanges in these two coupled runs induces cooler SST and less moisture in the lower troposphere, leading to less rainfall. Thus, subdaily air–sea interaction may considerably affect the simulation of the eastward-propagating ISO associated with the Asian monsoon.

In the AGCM run driven by the daily SST generated by the coupled run (i.e., AGCM_D), the energy spectrum of the eastward component was mainly focused at lower frequencies, with a period greater than 80 days. Further analysis indicates that the air–sea interactions, particularly the subdaily air–sea interaction, play an important role in generating the eastward-propagating ISO signal and the lead–lag phase relationship between SST (SST tendency) and precipitation.

Because of the effect of subdaily air–sea interaction in DC_10m, negative feedback associated with cloud radiation and wind evaporation and the deepening of the ocean mixed layer act to reduce SST beneath the convective precipitation and restrain convection afterward. However, to the east of the convection, the heat-induced Gill-type response leads to descending motion and a reduced surface westerly in the background due to the easterly anomalies. Subsequently, decreased evaporation and oceanic mixing, together with the increased shortwave flux, result in rapidly increasing SST. This in turn increases specific humidity and moist static energy and triggers the organized convection. Therefore, the eastward-propagating ISO may be modulated largely by the east–west asymmetric SST change induced by air–sea interaction.

The realistic simulation by DC_10m may be related to the synchronous integration in the AGCM and ocean
mixed layer model, which allows seamless exchange of information. However, two issues still need to be addressed further. First, why does the experiment with hourly air–sea coupling not give a good simulation of intraseasonal variability, since 1-h time resolution should be able to capture the diurnal cycle (subdaily variability) in SST? Klingaman et al. (2011), using a 3-h coupling interval, were able to capture the SST diurnal cycle and daily coupling was able to reproduce 80% of the observed intraseasonal SST variation. Second, why is the phase relationship between SST and precipitation over the BOB (SCS) absent in DC_12h (AGCM_D)? The results may be somewhat model specific, dependent on different dynamical cores and physical schemes, in addition to the effects of instantaneous coupling in DC_1h and DC_12h.

The ISO has often been considered an atmospheric mode that may be enhanced by air–sea coupled processes (Fu and Wang 2004; Fu et al. 2007; Kim and Kang 2008), but the mechanism of subdaily air–sea interaction remains unclear. This study has shown that a model with a high coupling frequency reproduces the eastward-propagating ISO associated with the Asian summer monsoon, and confirms that the east–west asymmetric SST change induced by a more accurate representation of air–sea interaction leads to the eastward movement of convection. However, the related processes in the upper ocean and the lower atmosphere require further research. We need to find a way to quantitatively demonstrate the physical mechanisms that connect the subdaily coupling to the amplification of the ISO, including the influence of heat content buildup via the diurnal warm layer, the difference in the moistening and drying cycle within the lower troposphere on diurnal time scales, and other relevant processes.

The regional ocean mixed layer model used in this study is a one-dimensional (1D) ocean boundary layer model rather than a 3D dynamical ocean model, and the effects of ocean salinity and currents are neglected here. However, Vinayachandran et al. (2012) employed an Indian Ocean model forced by QuikSCAT winds and climatological river discharge to suggest that salinity effects are crucial in determining the amplitudes of intraseasonal SST variations in the BOB. It is therefore essential to use a high-resolution model with salinity processes or a three-dimensional dynamical ocean model to further examine the impact of subdaily air–sea interaction. We also conducted an air–sea coupled run in which the ocean vertical resolution of OMLM was changed from 5 to 1 m. Our results indicate that the ISO simulation is less sensitive to ocean vertical resolution. The impact of horizontal resolution on the simulation of the ISO is the subject of our ongoing research. Jiang et al. (2004) proposed a physical mechanism related to the northward-propagating ISO, and the atmospheric dynamics of the eastward-propagating ISO will be discussed in a separate paper.

Acknowledgments. We thank Prof. Xiouhua Fu and two anonymous reviewers for their helpful comments. This work is jointly supported by a CAS project (XDA11010402), a National Key Basic Research Program of China grant (2014CB953902), and National Natural Science Foundation of China grants (91337216 and 41305065).

REFERENCES


