Impacts of Ocean Surface on the Northward Propagation of the Boreal Summer Intraseasonal Oscillation in the NCEP Climate Forecast System

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ABSTRACT

Impacts of the ocean surface on the representation of the northward-propagating boreal summer intraseasonal oscillation (NPBSISO) over the Indian monsoon region are analyzed using the National Centers for Environmental Prediction (NCEP) coupled atmosphere–ocean Climate Forecast System (CFS) and its atmospheric component, the NCEP Global Forecast System (GFS). Analyses are based on forecasts of five strong NPBSISO events during June–September 2005–07.

The inclusion of an interactive ocean in the model is found to be necessary to maintain the observed NPBSISO. The atmosphere-only GFS is capable of maintaining the convection that propagates from the equator to 12°N with reasonable amplitude within the first 15 days, after which the anomalies become very weak, suggesting that the atmospheric internal dynamics alone are not sufficient to sustain the anomalies to propagate to higher latitudes. Forecasts of the NPBSISO in the CFS are more realistic, with the amplitude of precipitation and 850-mb zonal wind anomalies comparable to that in observations for the entire 30-day target period, but with slower northward propagation compared to that observed. Further, the phase relationship between precipitation, sea surface temperature (SST), and surface latent heat fluxes associated with the NPBSISO in the CFS is similar to that in the observations, with positive precipitation anomalies following warm SST anomalies, which are further led by positive anomalies of the surface latent heat and solar radiation fluxes into the ocean.

Additional experiments with the atmosphere-only GFS are performed to examine the impacts of uncertainties in SSTs. It is found that intraseasonal SST anomalies 2–3 times as large as that of the observational bulk SST analysis of Reynolds et al. are needed for the GFS to produce realistic northward propagation of the NPBSISO with reasonable amplitude and to capture the observed phase lag between SST and precipitation. The analysis of the forecasts and the experiments suggests that a realistic representation of the observed propagation of the oscillation by the NCEP model requires not only an interactive ocean but also an intraseasonal SST variability stronger than that of the bulk SST analysis.

1. Introduction

The northward-propagating boreal summer intraseasonal oscillation (NPBSISO) over the Asian monsoon region was discovered by Yasunari (1979, 1980) based on satellite-derived cloudiness data and confirmed by Yasunari (1981) and Krishnamurti and Subrahmanyan (1982) using wind observations. The NPBSISO is an essential part of the leading mode of intraseasonal variability during boreal summer, which consists of eastward propagation near the equator from the Indian Ocean to the northwestern Pacific, northward propagation in the Indian Ocean from the equator, and northwestward propagation in the western Pacific (Lau and Chan 1986; Annamalai and Slingo 2001; Hsu and Weng 2001; Kemball-Cook and Wang 2001; Jones et al. 2004; Seo et al. 2007). Within the Indian monsoon region, the NPBSISO is characterized by northward propagation of convection (and associated wind fields) from near the equator with a period of about 40 days. The NPBSISO has strong impacts on the onset, withdrawal, and intraseasonal variability (e.g., active and break phases) of the Indian summer monsoon, and the mei-yu regime over South China (Yasunari 1981; Krishnamurti and Subrahmanyan 1982; Lau and Chan 1986; Annamalai and Slingo 2001; Seo et al. 2007). Tropical storm activity is also strongly modulated by the large-scale circulation associated with the intraseasonal oscillation during the warm season (Liebmann et al.
1994; Maloney and Hartmann 2000a,b). Given the influence of the NPBSISO on various atmospheric phenomena of societal importance, accurate forecasts of the NPBSISO are highly desirable.

Various mechanisms, including atmospheric internal instability, have been proposed to explain the NPBSISO. Wang and Xie (1997) and Lawrence and Webster (2002) showed that the NPBSISO is a manifestation of the Rossby–Kelvin wave packet associated with the equatorially eastward-propagating convection. Jiang et al. (2004) proposed that the presence of mean vertical easterly shear may result in the formation of barotropic vorticity maxima to the north of the convection centers, leading to a northward propagation of the convective systems. The NPBSISO can also result from convection–moisture feedback due to advection of anomalous moisture by the mean meridional wind and advection of mean specific humidity by anomalous wind (Jiang et al. 2004).

Other proposed mechanisms for the NPBSISO involve the interaction between atmosphere and ocean. Many previous observational studies have shown coherent variations in SSTs and atmospheric fields associated at intraseasonal time scales in the northern Indian Ocean. Krishnamurti et al. (1988) demonstrated that both surface winds and sea surface temperatures (SSTs) contribute to variations of surface latent heat flux at intraseasonal time scales. Using observations from moored buoys during the 1998 summer monsoon, Premkumar et al. (2000) and Sengupta and Ravichandran (2001) showed that there was a prominent intraseasonal oscillation in SST in the Bay of Bengal, which could be explained as the direct response to the intraseasonal oscillation of surface net heat flux associated with variations in cloudiness and surface wind speed. Kembhal-Cook and Wang (2001) showed that air–sea interaction is involved in the northward propagation of convective anomalies through the local warming of the ocean surface and destabilization of the atmospheric to the north of the convection. The warming of the ocean surface north of the convection is associated with (a) increased downward solar radiation due to reduced cloudiness, and (b) reduced evaporation due to weaker total wind speed.

An SST–wind–evaporation (SWE) feedback mechanism was proposed by Vecchi and Harrison (2002) and discussed by Schott et al. (2009). This mechanism hypothesized that SSTs to the north (south) of the convection are warmed up (cooled down) as a result of reduced (increased) evaporation due to weakened (enhanced) westerlies, resulting in a tendency for the SSW–convection couplet to move northward. The possibility that the intraseasonal oscillation is a coupled atmosphere–ocean phenomenon is confirmed by Fu et al. (2003), Fu and Wang (2004), Rajendran and Kitoh (2006), and Seo et al. (2007) who showed that the amplitude of the NPBSISO simulated by the coupled models was much stronger and better organized with a more realistic phase relationship between precipitation and the underlying SSTs than that simulated by the (same) atmospheric components without coupling to an ocean.

If the ocean surface plays an active role in the formation of the NPBSISO, that is, if the atmosphere responds to underlying intraseasonal SST anomalies that themselves are driven by the atmospheric anomalies, one would expect that simulations of the NPBSISO with atmosphere-only models will strongly depend on the prescribed intraseasonal SST anomalies. Klingaman et al. (2008a) demonstrated that this is indeed the case in their simulations with the Hadley Centre Atmospheric Model, version 3 (HadAM3) using an observed SST analysis from the U.K. National Centre for Ocean Forecasting that contains greater intraseasonal variability than previous SST products. It was found that the HadAM3 simulated a significantly greater intensity, better organization, and a more reasonable propagation speed of the NPBSISO events across the monsoon domain with daily SSTs than it did with monthly mean SSTs. The simulated intraseasonal variability with 5-day-mean SSTs was slightly weaker than that with daily SSTs, but was much improved compared with the simulation using monthly mean SSTs. The dependence of the simulated NPBSISO on SSTs in Klingaman et al. (2008a) is consistent with the results of Fu and Wang (2004), who found that the simulated NPBSISO with the ECHAM4 atmospheric general circulation model forced with daily SSTs derived from a corresponding coupled atmosphere–ocean model simulation was much stronger than that forced with monthly mean SSTs. Kim et al. (2008) examined the sensitivity of the simulation of the Madden–Julian oscillation (MJO) to SST variability and found that the use of higher temporal SST data produced a better simulation of the MJO in terms of its amplitude and eastward propagation speed.

Another approach to understanding the impact of air–sea coupling is to compare forecasts of the NPBSISO from coupled atmosphere–ocean models and atmosphere-only models. If the NPBSISO were purely a result of internal atmospheric dynamics, forecasts of the NPBSISO with atmosphere-only models would be comparable to those with coupled models. Waliser et al. (2003) analyzed the predictability of the northern summer intraseasonal oscillation over the Asian monsoon region based on the prediction by an uncoupled atmospheric general circulation model forced with climatological SSTs. The model used by Waliser et al. (2003) captured various characteristics of the observed oscillation, including the
period, northwest–southeast orientation, and northward propagation, suggesting that the NPBSISO may indeed result from internal atmospheric dynamics alone. Waliser et al. (2003) showed that the predictability over 4°–24°N, 72.5°–132.5°E is about 25 days for 200-hPa velocity and 15 days for rainfall. Fu et al. (2007) investigated the impacts of atmosphere–ocean coupling on the predictability of monsoon intraseasonal oscillations simulated by a coupled atmosphere–ocean model and found that the air–sea coupling extends the predictability of rainfall over 10°S–30°N, 60°–160°E from 17 days with the uncoupled atmospheric component to about 24 days with the coupled model.

A caveat of predictability studies by Waliser et al. (2003) and Fu et al. (2007) is that they are based on a “perfect model” approach, which takes one of the model-produced ensemble members as the “observation” and treats other members as the prediction. A disadvantage of this perfect model approach is that systematic biases contained in the ensemble could result in errors in the predictability analysis. In this study, we analyze the initialized forecast of the observed NPBSISO by an operational coupled atmosphere–ocean model. The forecast is verified against observations and thus allows an assessment of the model skill. We will focus on the impacts of ocean surface condition on the NPBSISO and address the following two questions: (a) how does the air–sea coupling affect the evolution of the NPBSISO, and (b) how sensitive is the representation of the NPBSISO to the uncertainties in SSTs? The model used is the National Centers for Environmental Prediction (NCEP) coupled Climate Forecast System (CFS). The analysis is based on the forecast of strong events in the summers of 2005–07 for which the operational forecast archive from the CFS is available. Additional experiments are also carried out with the atmospheric component of the CFS to investigate how the modeled NPBSISO depends on the intraseasonal variability of the prescribed SSTs.

A brief description of the model, forecasts, and observations is given in section 2. Analysis of the impacts of air–sea coupling is presented in section 3. Section 4 examines the impacts of prescribed SSTs on the representation of the NPBSISO. A summary is provided in section 5.

2. Models and data

a. The models

The model used in this study is the current NCEP operational coupled CFS. The atmospheric component of the CFS is the 2003 version of the NCEP atmospheric Global Forecast System (GFS) with a spectral truncation of 62 waves (T62) in the horizontal (equivalent to a nearly 200-km grid) and a finite differencing in the vertical with 64 sigma layers. The oceanic component of the CFS is the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model version 3 (MOM3; Pacanowski and Griffies 1998), with a zonal resolution of 1° and a meridional resolution of 1/3° between 10°S and 10°N, gradually increasing through the tropics until becoming fixed at 1° poleward of 30°S and 30°N. The vertical resolution of the oceanic component is 10 m from the surface to the 240-m depth, gradually increasing to about 511 m in the bottom layer. The atmospheric and oceanic components are coupled without any flux adjustment. The two components exchange daily averaged quantities once a day. More details of the CFS can be found in Wang et al. (2005) and Saha et al. (2006). Initial conditions for the CFS are taken from the NCEP/Department of Energy (DOE) Global Reanalysis 2 (GR2; Kanamitsu et al. 2002) for the atmosphere and from an NCEP Global Ocean Data Assimilation System (GODAS) for the ocean.

b. Forecasts

The forecasts and additional experiments analyzed in this study are summarized in Table 1. Forecasts of the NPBSISO with CFS and GFS for June–September 2005–07 are diagnosed to investigate the impacts of ocean surface on the forecasts of the NPBSISO. For both the CFS and GFS two forecast runs are produced every day for the years of 2005–07. The atmospheric initial condition for one forecast is taken as the GR2 0000 UTC analysis, and that for the other run is from the same GR2 initial state, but with a small perturbation to all atmospheric prognostic variables. The perturbation for each variable is taken as 10% of the difference between its values at the forecast initial time and its values 24 h ago. In our analysis, an ensemble average of four forecast members is used for each initial day. The four-member ensemble consists of two forecast runs from the initial day and two members from the previous day. The forecast target length is 30 days.

SSTs in the CFS are predicted by the oceanic component of the model. The two daily runs start from

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identical ocean initial conditions from the GODAS. For the atmosphere-only GFS, SSTs are taken as the observed climatology (1982–2004 average) plus anomalies that decay from the observed initial value with an e-folding time scale computed based on the weekly optimal interpolation (OI) analysis of Reynolds et al. (2002), which ranges from about 30 days in the Indian Ocean to 180 days in the east-central Pacific.

c. **Experiments with the atmosphere-only model**

In addition to the above-described CFS and GFS forecast runs from the observed initial conditions, four additional experiments of 30-day integrations are performed with the atmosphere-only GFS to examine atmospheric sensitivity to various specifications of SSTs (Table 1). All experiments are from the same atmospheric initial conditions as the CFS and GFS forecasts. The first experiment (GFSAnnCyc) is made with the specification of the mean annual SST cycle of 2005–07 and does not include intraseasonal anomalies.

The other three experiments are similar to the Atmospheric Model Intercomparison Project (AMIP)-type integrations using prescribed SST anomalies. In the second experiment (GFSAMIP), SSTs are taken as the observed climatology plus daily anomalies from the analysis of Reynolds et al. (2002) for the entire 30-day forecast target period. The third and fourth experiments (GFSAMIP2 and GFSAMIP3, respectively) are the same as GFSAMIP, except that the SST anomalies are doubled and tripled. These two experiments are performed in light of the results of Woolnough et al. (2007), where the authors compared two coupled models: one used a mixed layer ocean with high vertical resolution (1.4 m for the top layer) and a diurnal cycle in the coupling; and the other used a full dynamical ocean component with coarser vertical resolution (10 m for the top layer) and no diurnal cycle in the coupling. The authors concluded that the high-resolution model produced daily SST anomalies that were 2–3 times as large as the coarse-resolution model. Further, compared to the coupled model with the full dynamical ocean model, the coupled model with the mixed layer ocean produced more realistic daily mean SST variations and improvements in forecast skill of the Madden–Julian oscillation (Woolnough et al. 2007).

Bernie et al. (2007) found that resolving the diurnal cycle in an ocean general circulation model (OGCM), which requires a 3-h or better temporal resolution of surface fluxes and a vertical resolution of 1 m (Bernie et al. 2005), increased the intraseasonal SST response to the MJO by around 20%. When the same OGCM is coupled to an atmospheric model, the inclusion of the diurnal cycle resulted in an increase in mean SST in the tropics and an improved representation of the MJO in its spatial coherence and eastward propagation (Bernie et al. 2008). Because the SSTs in the CFS are taken as the daily mean ocean temperature of the top layer, which is 10 m thick, and the observational analysis of SSTs of Reynolds et al. (2002) represents ocean bulk subsurface temperature of the top few meters, the results from Bernie et al. (2007) and Woolnough et al. (2007) suggest that variations of SST may have been underestimated in both the CFS and the observational analysis of bulk ocean temperature.

d. **The analysis**

To diagnose the NPBSISO, we analyzed daily mean precipitation, 850-mb zonal wind (U850), SST, and surface solar radiation and latent heat fluxes in the forecasts and experiments. Observations from GR2 (Kanamitsu et al. 2002), Climate Prediction Center (CPC) MORPHing technique (CMORPH) satellite precipitation (Joyce et al. 2004), and OI SST (Reynolds et al. 2002) are also used for comparison.

Intraseasonal anomalies are defined based on the data for the entire 2005–07 period. For each year, an annual cycle is first computed as the annual mean plus the first four harmonics. Intraseasonal anomalies are then taken as the departure of the total daily mean from the annual cycle. The resulting anomalies only retain variability at time scales shorter than 90 days. For forecasts, both climatology and anomalies are calculated as a function of lead time.

3. **Forecast of the NPBSISO**

Our analysis is based on strong northward-propagating convective events. The choice to analyze strong events helps to isolate the signal, given the shortness of the period (2005–07) with available forecast data, and allows additional targeted experiments requiring only a small amount of computer resources. In this section, we first describe the selection of strong events in the observations for 2005–07. We next analyze the forecasts from the CFS and GFS.

a. **Selection of NPBSISO events**

For the 3-yr analysis period, the observed CMORPH precipitation and U850 anomalies averaged between 65° and 95°E are shown in Fig. 1. The anomalies have been bandpass filtered to retain the components of the 20–90-day periods. Northward-propagating events can be seen in all 3 yr as highlighted with the thick red dashed lines, although during most of the time the anomalies are more disorganized without clear meridional propagation. Generally, northward propagation to the north of
the equator is more evident for the events when westerlies (easterlies) are located to the south (north) of the enhanced convection. Lag correlation between 65° and 95°E average CMORPH precipitation for each latitude, and the 5°S–5°N average (Fig. 2) shows that the oscillation occurs at a period of about 35 days (as measured by the time difference between the two minimum correlation values on the equator on days −18 and 17).

Strong northward-propagating events are selected based on two precipitation indices that are defined as 20–90-day bandpass-filtered precipitation anomalies averaged within two latitude–longitude boxes: 5°S–5°N, 65°–95°E and 10°–20°N, 65°–95°E. The criteria for choosing strong events are as follows: 1) both precipitation indices are greater than one standard deviation, and 2) the lag between the maximum values of the two indices is between 8 and 15 days. The first criterion allows the selection of strong events while the second is used to ensure that the anomalies over the two boxes belong to the same northward-propagating event (Klingaman et al. 2008b). Five strong events are selected based on these criteria for the three summers. The dates of the precipitation maxima of the 5°S–5°N average are taken as the initial time for the forecast analysis. Initial dates of the selected five events are 13 July 2005, 1 September 2005, 18 June 2006, 8 September 2006, and 13 June 2007, with a corresponding lag of 11, 11, 13, 10, and 9 days between maximum values of the two indices.

**Fig. 1.** Time evolution of 20–90-day intraseasonal anomalies of CMORPH precipitation (shaded) and 850-mb zonal wind (contour) averaged between 65° and 95°E for (top) 2005, (middle) 2006, and (bottom) 2007. Precipitation is plotted at −9, −7, −5, −3, −1, 1, 3, 5, 7, and 9 mm day$^{-1}$, and the 850-mb zonal wind is plotted at a 1 m s$^{-1}$ interval with dashed contours for negatives. The northward-propagating events chosen for the analysis are indicated with thick red dashed lines.
b. Forecast of the NPBSISO

Shown in Fig. 3a are composites of observed precipitation and U850 anomalies based on the five selected events averaged between 65° and 95°E. During the first 5 days, enhanced convection is confined to 10°S–10°N. After day 5, the convection moves northward and reaches 20°N on day 16. The wet and dry phases are about 15 days apart. Near the equator, westerlies (easterlies) overlap with maximum enhanced (suppressed) precipitation. North of 5°N, maximum easterlies (westerlies) are located to the south (north) of suppressed convection and to the north (south) of enhanced convection. These distributions of precipitation and U850 are a manifestation of cyclonic (anticyclonic) circulation associated with enhanced (suppressed) convection.

There are some errors in the precipitation anomalies at the beginning of the forecasts in both the CFS and GFS. For example, the models underestimated the positive anomalies near the equator while the forecast negative anomalies between 10° and 20°N are too strong (Figs. 3b,c). These errors are possibly related to the initial adjustment in the forecasts. To some extent, the CFS (Fig. 3b) and GFS (Fig. 3c) both simulated the observed northward propagation of precipitation and U850. The major deficiency in the GFS is that the amplitude of both precipitation and U850 after day 15 is substantially weaker than that observed. In addition, the propagation during the first 15 days in the GFS is too slow. The enhanced convection reaches 10°N on day 15 in the GFS, compared to 19°N in the observations. Average propagation speed in the GFS forecast is approximately 1.05° latitude day⁻¹, compared to 1.54° latitude day⁻¹ in the observations (Table 2). The CFS predictions have continued propagation of enhanced convection beyond day 15 with consistent wind anomalies. The amplitude of both precipitation and U850 anomalies in the CFS are comparable to the observed for the entire 30-day period. The propagation of the convection in the CFS during the first 15 days is faster than that in the GFS. The overall speed during the entire 30-day forecast period in the CFS is approximately 0.95° latitude day⁻¹, which is slower than that in the observations (Table 2). Figure 4 compares individual events between the observations and the CFS, with the CFS simulating the northward propagation beyond day 15 but with slower speed for all events.

We have calculated the anomaly correlation between the observations and forecasts for precipitation and U850 to assess the models’ overall skill. For both CFS and GFS forecasts, the correlation skill decreases with forecast time very quickly. By day 15, the skill is generally less than 0.3 for U850 and is near zero for precipitation (not shown). This means that the overall average skill of the forecasts for daily anomalies is low, although the models can capture the NPBSISO to some extent beyond day 15.
c. Air–sea coupling

In this subsection, we analyze the relationship between convection, SSTs, and surface heat fluxes. The observational analyses show that the SST anomalies lead the precipitation anomalies by a few days (Fig. 5a). The CFS forecast captured this SST–precipitation phase relationship but with a much longer lag between SST and precipitation anomalies (Fig. 5b). Figure 6 compares the lag correlation between precipitation and SST over the domain of 0°–20°N, 65°–95°E. The maximum correlation is at day 10 in the CFS, and at day 5 in the observations. The lagged phase relationship between SST and precipitation in the observations and CFS is not seen in the GFS forecast, which shows northward propagation in precipitation anomalies while the prescribed SST anomalies decay locally with time (Fig. 5c). The SST–convection relationship in the atmosphere-only GFS model will be further discussed in the next section with additional experiments.

The evolution of SSTs in the observations and the CFS are consistent with downward surface solar radiation and latent heat flux, which lead SST anomalies by several days (Figs. 5d,e,g,h). The solar radiation anomalies are a result of changes in cloudiness as implied by precipitation anomalies (shadings in Figs. 5a,b). The latent heat flux anomalies are associated with wind speed changes north of the equator, where mean background winds are westerlies, resulting in larger total wind speed for westerly anomalies and smaller wind speed for easterly anomalies (Figs. 3a,b). Surface heat flux anomalies in the GFS are similar to that in the CFS during the first 15 days, but are substantially weaker after day 15 (Figs. 5f,i). Possible reasons for these weak flux anomalies after day 15 in the GFS include the lack of air–sea coupling, decaying of SST anomalies, and the lack of anomalous rainfall and convection, which may in turn be attributable to the absence of coupling and the decaying of SST anomalies. These results from the CFS are consistent with previous observational and numerical studies (Krishnamurti et al. 1988; Kemball-Cook and Wang 2001; Vecchi and Harrison 2002; Fu et al. 2003; Seo et al. 2007; Schott et al. 2009) documenting the feedback between the atmosphere and the ocean surface: convection and large-scale circulation associated with the NPBSISO.
Fig. 4. Same as in Fig. 3, but for individual events for the (left) observation and (right) CFS forecast. Starting time is indicated to the left of the left panels.
Fig. 5. Composite anomalies. (top) Precipitation (shaded starting at 1 mm day$^{-1}$, with a 2 mm day$^{-1}$ contour interval) and SST (contours starting at ±0.1 K, with a 0.1-K contour interval, negative values dashed) averaged between 65° and 95°E. (middle) Same as the top row, except that the shading is for downward surface solar radiation (starting at ±10 W m$^{-2}$, with a 10 W m$^{-2}$ contour interval). (bottom) Same as the middle row, except that shading is for downward latent heat flux. (left) Observation, (middle) CFS forecast, and (right) GFS forecast.
generate net positive downward heat flux and result in positive SST anomalies to the north of the convection, leading to the northward movement of the convection (and the associated large-scale circulation).

4. Experiments with specified SSTs

Comparisons between the CFS and the GFS indicate that the air–sea coupling that produces consistent SST anomalies is necessary to capture the northward propagation after day 15. A major deficiency in the CFS is that the propagation is too slow compared to that in the observations. The maximum precipitation reaches 20°N on day 16 in the observations and on day 23 in the CFS (Figs. 3a,b). There are two possible causes for this deficiency. The first is that the internal dynamical and thermodynamical processes of the NPBSISO are not accurately represented in the CFS. The other possibility is due to errors in the CFS-predicted SSTs, which result in an erroneous atmospheric response. The CFS SST errors may result from 1) errors in surface heat fluxes, freshwater fluxes, and wind stress; 2) the thickness of the top oceanic layer, which is too thick and leads to an underestimate of SST intraseasonal variability in response to air–sea interactions; 3) errors in the model physics of the upper ocean; and 4) the lack of a diurnal cycle in the coupling. In this section, we carry out additional atmosphere-only GFS experiments to further examine the impacts of SSTs on the forecast of the NPBSISO. All experiments are from the same atmospheric initial conditions as the CFS and GFS forecast runs, but with the specified observed SSTs.

a. GFSAnnCyc

Figure 7 shows composite precipitation and U850 from two experiments: GFSAnnCyc, in which the mean annual SST cycle of 2005–07 without intraseasonal anomalies is used, and GFSAMIP, in which daily SSTs consisting of the OI mean annual SST cycle of 2005–07 plus intraseasonal anomalies are used (Table 1). These two experiments represent two extremes—one using no information of SST anomalies and the other using the best-available information of the SST anomalies. Anomalies of precipitation and U850 from GFSAnnCyc (Fig. 7a) are mostly confined to the first 15 days, similar to that...
from the GFS forecast (Fig. 3c). Propagation speed of precipitation anomalies in GFSAnnCyc is the same as that in the GFS forecast (1.05° latitude day⁻¹, Table 2). The similarity between the GFS forecast and the GFSAnnCyc indicates that the use of decaying SST anomalies from their initial observed values in the GFS had virtually no significant impacts on the forecast of the NPBSISO.

**b. AMIP-type experiments**

With the OI daily SST anomalies, the GFSAMIP experiment is capable of extending the propagation beyond day 15 with stronger amplitudes in both precipitation and U850 (Fig. 7b), compared to the forecast from the GFS (Fig. 3c). However, the amplitude in GFSAMIP is still weaker than that in the observations and in the CFS forecast (Figs. 3a,b) and propagation speed (1° latitude day⁻¹, Table 2) is slower than that observed (Table 2).

There are a few possible reasons for the slow propagation speed and weak amplitude in the GFSAMIP with observed SSTs. The first is that errors in model physics and in atmospheric initial conditions limit the model’s capability of reproducing the internal atmospheric dynamical processes associated with the NPBSISO, even when realistic surface boundary forcing is included. An analysis of the forecasts from the current NCEP operational Global Forecast System with the latest update of physics packages for the model, and initialized with NCEP’s most recent atmospheric Global Data Assimilation System, does not show any significant improvement in the forecast of the NPBSISO compared to the GFS used in this study, which uses the 2003 version of the atmospheric model and initial conditions from the frozen GR2 analysis developed in 2002 by Kanamitsu et al. (2002, not shown). This may suggest that errors in the GFS model’s representation of the NPBSISO may be caused by errors other than those in the model’s physics and atmospheric initial conditions, although it does not exclude the possibility that both GFS versions contain errors in the physics of the model or initial conditions provided by the reanalyses. The second possible reason is that the response of the atmosphere to realistic SST anomalies is too weak. Another possible reason is that there are errors in the observational SST analysis used in GFSAMIP. As shown in Fig. 8, precipitation and SST anomalies in GFSAMIP are almost out of phase, while precipitation anomalies in the observations lag SST anomalies by a few days (Figs. 5a and 6), suggesting the possibilities that either the response of the GFS to observed SSTs is too weak or the specified observed SST anomalies are too weak.

As described in section 1, the study of Woolnough et al. (2007) suggests that the intraseasonal SST variability in both the CFS, which uses a 10-m top oceanic layer, and the analysis of Reynolds et al. (2002), which represents bulk temperature of the top several meters of the ocean, may be weaker than that in reality. In addition, observed SST estimates that are calibrated to the bulk ocean temperature have large differences between

![Figure 8](image-url)
different products. For example, through spectral analysis, Vecchi and Harrison (2002) found that there was between 2 and 4 times more energy in the weekly smoothed Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) SST retrieval than in a previous version of the Reynolds and Smith (1994) weekly SST analysis. Comparison with in situ moored buoy observations also showed that the SST analysis of Reynolds and Smith (1994) substantially underestimates the SST intraseasonal variability (Premkumar et al. 2000; Sengupta and Ravichandran 2001; Bhat et al. 2004).

To further assess the impact of different SST analyses on the amplitude of the SST variability, composite weekly smoothed TMI SST anomalies for the five selected NPBSISO events are shown in Fig. 9. The pattern of the TMI SST anomalies is similar to that of the weekly analysis of Reynolds et al. (2002; see also the contours in Figs. 5a and 8). However, the amplitude of the TMI SST anomalies is much larger than that in the Reynolds et al. (2002) analysis. For example, the amplitude of the negative anomalies extending from the equator on day 1 to 20°N around day 21 in the TMI retrieval (Fig. 9) is about twice as large as that in the analysis of Reynolds et al. (2002; see contours in Figs. 5a and 8). The amplitude of the TMI anomalies is also larger than that of the CFS forecast (contours in Fig. 5b).

To examine the impacts of the uncertainties in SSTs, we have carried out two additional experiments. These two experiments—GFSAMIP2 and GFSAMIP3—are the same as GFSAMIP, but with the amplitude of the intraseasonal SST anomalies doubled and tripled. Comparison between the experiments shows that overall the amplitude of precipitation and U850 anomalies increases when the amplitude of SST anomalies increases (Figs. 7 and 10). The amplitudes of the anomalies from GFSAMIP2 and GFSAMIP3 (Fig. 10) compare better with those observed than those from GFSAnnCyc and GFSAMIP (Fig. 7). The propagation speed of convection in GFSAMIP2 and GFSAMIP3 (1.25° and 1.43° latitude day$^{-1}$) is also closer to the observed value than the CFS and GFS forecasts and other experiments (Table 2). In addition, the correlation values of precipitation between the two additional experiments (GFSAMIP2 and GFSAMIP3) and observations are much higher than the forecasts and other experiments (Table 2). The improved NPBSISO in GFSAMIP2 and GFSAMIP3 compared to GFSAnnCyc and GFSAMIP is consistent with the results of Fu et al. (2003) and Klingaman et al. (2008a), who found that using SSTs with improved high-frequency variance resulted in better simulations of the NPBSISO in its intensity and propagation.

Unlike the almost out-of-phase relationship between precipitation and SSTs in GFSAMIP (Fig. 8), positive (negative) SST anomalies are found to lead wet (dry) precipitation anomalies in GFSAMIP2 and GFSAMIP3 (Fig. 11), similar to those in the observations (Fig. 5a). The lag correlation between precipitation and SST from the AMIP experiments is shown in Fig. 6. The lag of the maximum correlation is 12 days in GFSAMIP, 9 days in GFSAMIP2, and 7 days in GFSAMIP3, compared to the lag of 5 days in the observations and 10 days in the CFS forecast. Because the amplitude of SST anomalies in the GFSAMIP2 and GFSAMIP3 (Fig. 11) is larger than those in the CFS forecast (Fig. 5a), a conclusion based on Fig. 6 is that the phase lag between SST and precipitation decreases with the increase of the amplitude of the SST anomalies. These results suggest that the slow propagation in the CFS and the GFS, and the weak amplitude of forecast anomalies in the GFS, are possibly related to the lack of a realistic representation of the associated intraseasonal SST anomalies.

The lagged relationship between precipitation and SST in the AMIP experiments in our study is different from previous studies of AMIP simulations, which generally showed an almost in-phase relationship between SST and precipitation (Fu et al. 2003; Fu and Wang 2004; Klingaman et al. 2008a). The AMIP experiments in our study suggest that when the model is initialized with an observational atmospheric analysis, the SST–precipitation relationship depends on the amplitude of the prescribed SST anomalies. Our results also suggest that use of an atmosphere-only model initialized from observations with a prescribed surface condition is helpful for understanding the impacts of the ocean surface.

![Figure 9](https://example.com/fig9.png)

**Fig. 9.** Composite SST anomalies averaged between 65° and 95°E from the TMI. Contours start at ±0.1 K, with a 0.1-K contour interval; negative values are dashed.
5. Discussions and summary

In this study, we investigated the impacts of the oceanic surface on the representation of the northward-propagating boreal summer intraseasonal oscillation (NPBSISO) over the Indian monsoon region in the NCEP coupled CFS and the atmosphere-only GFS. The difference between the CFS and the GFS is that SSTs in the CFS are produced by the coupled model itself, while SSTs in the GFS are taken as climatology plus anomalies that decay from the initial values. The analysis is based on forecasts of five strong NPBSISO events during June–September 2005–07. The forecasts are initialized from the dates when the convection is located at the equator. Atmospheric initial conditions for both the CFS and the GFS are from the NCEP/DOE Global
Reanalysis 2 (GR2; Kanamitsu et al. 2002) and oceanic initial conditions for the CFS are from the NCEP Global Ocean Data Assimilation System.

The GFS is found to be capable of reproducing the northward propagation of the NPBSISO within the first 15 days with reasonable amplitude, but with a speed slower than that observed. By day 15, the convection only reaches 10°N in the GFS, compared to 19°N in the observations. Beyond day 15, anomalies from the GFS are substantially weaker than that in the observations. Forecasts of the NPBSISO in the CFS are more realistic with the amplitude of precipitation and 850-mb zonal wind (U850) anomalies comparable to those in the observations for the entire 30-day target period. The more realistic representation of the NPBSISO in the CFS is associated with leading SST anomalies that are consistent with anomalies in surface latent heat flux and solar radiation, as in the observations. The differences in forecasts of the NPBSISO between the CFS and the GFS suggest that the inclusion of an interactive ocean improves the northward propagation of the boreal summer intraseasonal oscillation over the Indian monsoon region.

One deficiency in the CFS is that the northward propagation speed of the forecast NPBSISO (0.95° latitude day$^{-1}$) is much slower than that in the observations (1.54° latitude day$^{-1}$). Four atmosphere-only GFS experiments are carried out to examine the impacts of the uncertainties in the SSTs and to explore the possibility that the slow propagation of the NPBSISO in the CFS is related to errors in the SST anomalies. All experiments are from the same atmospheric initial conditions as the CFS and the GFS forecast runs, but with specified SSTs. The SSTs used for the experiments include the SST annual cycle for 2005–07 with no intraseasonal anomalies, with the observed OI anomalies, with doubled OI anomalies, and with tripped OI anomalies. Analysis of these experiments shows that as the amplitude of the SST anomalies increases, the NPBSISO improves in both the amplitude of precipitation and wind anomalies and the propagating speed. When forced without intraseasonal SST anomalies, the GFS is capable of maintaining the convection that propagates from the equator to 12°N with reasonable amplitude within the first 15 days, after which the anomalies become very weak, suggesting that the atmospheric internal dynamics alone are not sufficient to sustain the anomalies to propagate to higher latitudes. When SST anomalies from the observational OI analysis are used, the GFS produces northward-propagating anomalies beyond 15 days but with weaker amplitude and slower propagation than the observations. When amplitude of SST anomalies is doubled and tripped, both the amplitude and the propagation speed of precipitation and wind anomalies compare better to the observed, especially for the experiment with tripped SST anomalies.

One observed feature of the air–sea coupling is the phase lag relationship between precipitation and SST, with SST anomalies leading precipitation anomalies by 5 days. While SST anomalies lead precipitation anomalies in the CFS, the phase lag between SST and precipitation is about 10 days, which is too long compared to that in the observations. Experiments with the atmosphere-only GFS show that the SST–precipitation phase lag decreases with increasing amplitude of the prescribed SST intraseasonal anomalies. The lag between SST and precipitation anomalies is 12 days when the SST anomalies from Reynolds et al. (2002) are used. The lag decreases to 9 and 7 days when the amplitude of the intraseasonal SST anomalies from the analysis of Reynolds et al. (2002) is doubled and tripped. A comparison of composite SST anomalies for the strong NPBSISO events shows that the amplitude of the anomalies of the weekly smoothed Tropical Rainfall Measuring Mission (TRMM) Microwave Imager (TMI) SST retrieval is much larger than that of the analysis of Reynolds et al. (2002) and that in the CFS forecast. These results suggest the possibility of substantial uncertainties in intraseasonal SST anomalies in the observational SST analyses and that errors in the CFS forecast of the NPBSISO may be related to SST anomalies in the model that are too weak. Recent developments with the introduction of the moored buoy array in the Indian Ocean, that is, the Research Moored Array for African–Asian–Australian Monsoon Analysis and Prediction (RAMA; McPhaden et al. 2009), may provide an opportunity to further understand high-frequency SST variability in this region.

Based on the diagnoses of the CFS and GFS forecasts, and the GFS experiments with prescribed SSTs, we speculate that a realistic representation of the observed propagation of the oscillation by the NCEP model requires not only an interactive ocean but also an intraseasonal SST variability that is stronger than that of the OI bulk SST analysis. As indicated by the studies of Woolnough et al. (2007), Bernie et al. (2007), and Bernie et al. (2008), simulating stronger SST variability requires the use of high vertical resolution (about 1 m) for the upper ocean and the inclusion of the diurnal cycle in the coupling. The results presented here also point to consideration of a similar approach toward improving the simulation of the NPBSISO in operational forecast systems.

A shortcoming of this study is that the number of the NPBSISO events is too few for a more comprehensive diagnosis, although the choice to analyze strong events helps isolate the signal. As a longer period of forecast
data becomes available, other aspects of the forecast of the NPBSISO, such as the phase dependency and the relationship between eastward propagation along the equator and northward propagation, can be further diagnosed. In addition, as suggested by one of the anonymous reviewers, a larger sample will be helpful for understanding the impacts of the ocean surface by characterizing the northward propagation in terms of the strength of SST anomalies in the forecasts. It will also be interesting to compare the strength of SST anomalies and the northward propagation of the boreal summer intraseasonal oscillation in the observations.

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