The Low-Frequency Relationship of the Tropical–North Pacific Sea Surface Temperature Teleconnections

SANG-WOOK YEH
Korea Ocean Research and Development Institute, Ansan, South Korea

BEN P. KIRTMAN
Rosenstiel School of Marine and Atmospheric Science, University of Miami, Miami, Florida

(Manuscript received 23 August 2006, in final form 13 November 2007)

ABSTRACT

The low-frequency relationship between interannual tropical and North Pacific sea surface temperature anomalies (SSTAs) in observations and a coupled general circulation model (CGCM) is investigated. The authors use the interactive ensemble CGCM, which advances a new approach for artificially increasing the signal-to-noise ratio, making it easier to detect physical and dynamical links with much reduced interference by atmospheric noise. The results presented here suggest that decadal variations in the relationship between the dominant modes of tropical and North Pacific interannual SSTA variability result from changes of spatial manifestation of North Pacific SSTA, both in the observation and in the model.

The authors conjecture that the details of tropical Pacific SST forcing ultimately determine the tropical–North Pacific SST teleconnections, and this conjecture is examined in a much longer time series from a CGCM simulation. There are two patterns of North Pacific interannual SSTA variability in the model. The first pattern is locally forced by noise in the surface air–sea fluxes associated due to internal atmospheric dynamics. The second pattern is remotely forced by tropical SSTA. As the relationship of tropical–North Pacific SST teleconnections varies in the model, the spatial manifestation of the North Pacific SSTA changes from the atmospheric noise-forced pattern to the remotely forced pattern and vice versa. In the model, the amplitude of the tropical Pacific SSTA variance varies on decadal time scales and this largely determines the dominant structure of North Pacific SSTA variability. Furthermore, the change in location of the maximum tropical SST forcing is associated with the changes in the spatial manifestation of North Pacific interannual SSTA variability.

1. Introduction

Understanding tropical–extratropical teleconnections is important in terms of extended-range prediction of weather and climate. Although the midlatitude atmospheric circulation anomalies associated with tropical sea surface temperature (SST) forcing have been studied extensively (Hoskins and Karoly 1981; Horel and Wallace 1981; Hoerling et al. 1997; Hoerling and Kumar 2002; Straus and Shukla 2002; DeWeaver and Nigam 2002; Kumar et al. 2005), the issue of how extratropical Pacific SST anomalies (SSTAs) are related to tropical Pacific SSTAs still remains an outstanding problem (Zhang et al. 1997; Alexander et al. 2002; Newman et al. 2003; Deser et al. 2004; Schneider and Cornuelle 2005).

The connection between SSTAs in the tropical Pacific and those in the North Pacific was first documented by Weare et al. (1976). Since then many studies have suggested that there is a link between SSTAs in the equatorial Pacific and those in the North Pacific based on observational and modeling studies (Pan and Oort 1983; Alexander 1992; Deser and Blackmon 1995; Lau and Nath 1996; Lau 1997; Chao et al. 2000; Alexander et al. 2002; Deser et al. 2004). Generally, the spatial manifestation of SSTA in the North Pacific associated with warm (cool) tropical Pacific SSTA is characterized by cool (warm) temperatures in the western and central North Pacific with an elliptical shape and is accompanied by anomalies of the opposite sign to the east, north, and south. However, these spatial patterns

Corresponding author address: Dr. Sang-Wook Yeh, Korea Ocean Research and Development Institute, P.O. Box 29, Ansan, 425-600, South Korea.
E-mail: swyeh@kordi.re.kr

DOI: 10.1175/2007JCLI11648.1

© 2008 American Meteorological Society
of remote SSTAs in the North Pacific are not the same for each tropical Pacific warm or cold event. For example, Figs. 1a,b show the SSTA composite for two strong El Niño cases (i.e., 1982/83 and 1997/98) in the North Pacific during winter (November–March). The overall structure of the anomalous mean SSTA for the 1997/98 yr during winter (Fig. 1b) is characterized by zonally extended negative anomalies in the western and central North Pacific, which is largely consistent with general spatial manifestation of the North Pacific SSTA associated with warm tropical Pacific. On the other hand, the negative anomalies for the 1982/83 yr during winter (Fig. 1a) show a northeast-to-southwest orientation rather than a zonally extended structure. The processes responsible for detailed structural changes in the remote SSTAs in the North Pacific, which might be associated with tropical Pacific SSTA variability, are not yet clear.

Several recent studies have suggested that the physical origin of the correlation between SST changes in the tropical Pacific and the North Pacific is an important issue for understanding the variability of the coupled system. For instance, Lee et al. (2002) argued that the intensity of the atmospheric response to El Niño–Southern Oscillation (ENSO) depends on both tropical and North Pacific SSTA. In the presence of negative SSTA in the North Pacific and positive SSTA in the equatorial eastern Pacific, the atmospheric response is much stronger than the case with positive SSTA in the North Pacific. Lau et al. (2004) identified two interannual SST modes in the North Pacific that play a role in regulating the boreal summer climate over Eurasia and North America. Both of these modes have a different relationship with El Niño. Vimont (2005) explored the role of the SST patterns associated with ENSO in setting the pattern of decadal variability in the North Pacific. All of these results suggest that further studies are needed to understand how North Pacific SSTAs are related to tropical SSTA. In this paper, we investigate the tropical–North Pacific SST teleconnections on low-frequency time scales in observations and in an ocean–atmosphere coupled general circulation model (CGCM).
The current study is motivated by the preliminary results in Yeh and Kirtman (2004b, hereafter YK04b). YK04b examined the effects of stochastic forcing on the relationship between the North Pacific Oscillation and ENSO using CGCM simulations. YK04b argued that when the amplitude of the stochastic forcing at the air–sea interface is reduced, stronger ENSO variability is consistent with a stronger ENSO and North Pacific Oscillation correlation. Furthermore, YK04b showed that the dominant spatial pattern of the North Pacific Oscillation changes with the variations of ENSO amplitude—again, in the presence of reduced stochastic forcing. The important difference between the present study and YK04b is that here we fully diagnose the physical mechanisms for the changes in the North Pacific SST teleconnections with specific attention to the details of the spatial structure of the tropical forcing. YK04b did not diagnose the physical mechanisms or examine the details of the tropical SST forcing.

The study is organized as follows: The description of the model and data is outlined in section 2. The tropical–North Pacific SST teleconnections based on the observational analysis are described in section 3. We included the results from the coupled model in section 4. Concluding remarks are provided in section 5.

2. Model and data

We used the interactive ensemble CGCM model developed at the Center for Ocean–Land–Atmosphere Studies (COLA; Kirtman and Shukla 2002). The atmospheric component of the interactive ensemble CGCM is the COLA atmospheric general circulation model (AGCM) with triangular truncation at wavenumber 42 and with 18 unevenly spaced vertical levels (Kinter et al. 1997). The ocean model is adapted from the Geophysical Fluid Dynamics Laboratory (GFDL) Modular Ocean Model version 3 (MOM3; Rosati and Miyakoda 1988; Pacanowski et al. 1993). The interactive ensemble CGCM has six realizations of the COLA AGCM coupled to a single realization of the ocean general circulation model (OGCM; Kirtman and Shukla 2002). As the interactive ensemble evolves, each AGCM realization experiences the same SST predicted by the OGCM. The OGCM, on the other hand, experiences surface fluxes that are the ensemble average of the six AGCM realizations at the air–sea interface. The AGCM is identical for each ensemble member and the six AGCM realizations only differ in their initial conditions. Because the atmosphere is sensitively dependent on initial conditions, the six realizations evolve differently. The component models are anomaly coupled in terms of heat, momentum, and freshwater (Kirtman et al. 2002) to avoid the serious climate drift encountered with the conventional coupling with flux corrections. The model climatology generally agrees with the observations though some systematic biases are still present (Kirtman et al. 2002). The interactive ensemble CGCM produces reasonable realistic and irregular ENSO variability (Kirtman and Shukla 2002). Power spectral analysis (not shown) of the Niño-3.4 SST index, which is the averaged SSTA over the region (5°N–5°S, 170°E–240°E), yields a broad peak between 2 and 4 yr with more power near biennial time scales.

The interactive ensemble CGCM is designed to increase the signal-to-noise ratio, making it easier to detect physical and dynamical links with much reduced interference by atmospheric noise (Wu and Kirtman 2003; Kirtman et al. 2005). However, the internal ocean dynamics are not removed in the interactive ensemble CGCM. The interactive ensemble CGCM is specifically designed to significantly reduce the variability due to internal atmospheric dynamics in the air–sea fluxes. We used the interactive ensemble CGCM in order to explicitly focus on the tropical–North Pacific SST teleconnections with much reduced interference by atmospheric noise (Yeh and Kirtman 2004a). This signal isolation procedure has the advantage of clearly identifying the structure and mechanisms associated with the tropical–extratropical SST teleconnections. We are not arguing that atmospheric noise is unimportant to North Pacific SST variability. Indeed, much of the North Pacific SST variability is noise driven (Hasselmann 1976; Barsugli and Battisti 1998). We are arguing that the atmospheric noise makes it difficult to detect the teleconnections from the tropics and that the interactive ensemble approach helps isolate the signal that is not noise driven.

The analysis of the interactive ensemble CGCM simulation is based on data for a 500-yr period. Some model results presented herein are compared with the standard CGCM (i.e., one single AGCM is coupled to a single OGCM) for the simulation period of 400 yr. We also used monthly mean observed SST data for the period of 1901–2005, which were recently released by the National Climatic Data Center, the so-called Extended Reconstruction SST version 2 (ERSST.v2; Smith and Reynolds 2004). This dataset has values at ocean points on a 2° latitude–longitude grid.

3. Observational analysis

We first examine the tropical–North Pacific SST teleconnections for the observed period from 1901 to 2005 based on empirical orthogonal function (EOF) analysis. It is already known that the two systems, the tropical Pacific Ocean and North Pacific, are linked to each other on decadal time scales (Graham 1994; Kawamura
The focus of this paper is to examine how the relationship between interannual North Pacific and interannual tropical Pacific SSTA varies on decadal time scales. In other words, we are attempting to understand the low-frequency modulation in relationships between interannual modes of the North Pacific and tropical Pacific SSTA. Thus, we first process the SST data by high-pass filtering to retain only interannual periods (period < 10 yr) using the fast Fourier transform method. The filtering reduces the possibility that results are due to purely decadal teleconnections that are not directly associated with the interannual variations. Even with this filtering there are low-frequency variations in the interannual teleconnections. The challenge is to determine whether these variations are robust.

Figures 2a,b show the leading SST EOFs in the North Pacific (20°–60°N, 120°E–120°W, hereafter the NP mode) and tropical Pacific (20°N–20°S, 120°E–90°W, hereafter the TP mode) for the period of 1901–2005.

1 The spatial structure of the second EOF of the North Pacific is characterized by a strong meridional SST gradient around 40°N with a change in the sign of the SSTA in the meridional direction (not shown). The correlation between the PC time series of the second EOF SST mode in the North Pacific and those of the TP mode for the entire period of 1901–2005 is lower than that between the NP and TP mode.
The spatial pattern of the NP mode (Fig. 2a) has an elliptical center of action located in the western and central North Pacific accompanied by anomalies of the opposite sign to the eastern Pacific coast, and to the north and south. This EOF accounts for 20.8% of the filtered variance. The TP mode shown in Fig. 2b is the leading EOF of tropical Pacific SSTA and accounts for 56.9% of the filtered variance.

To show changes in the connection of TP–NP mode, the 9-yr sliding correlation coefficient of the time series of the principal components (PCs) of the TP and NP modes is presented in Fig. 2c. Note that the correlation value with 95% confidence level is 0.33 based on a t test (Livezey and Chen 1983). The mean sliding correlation value for the entire period is 0.36, which is marginally significant. The length of data in the observations and the sliding window used in this study is different from that in YK04b. While the length of the observed data and the sliding window in YK04b are 51 and 20 yr, respectively, those used in this study are 105 and 9 yr. Both a longer data and a 9-yr window length enable us to focus on how the relationship between the North Pacific and the tropical Pacific SSTA varies on decadal time scales.

The decadal variations are readily apparent in the relationship between the TP and NP mode of variability. There are periods where these two modes are well correlated and periods where these two modes are unrelated. Simply put, this result indicates the existence of the low-frequency modulation in relationships between the dominant modes of the North Pacific and tropical Pacific interannual SSTA variability. Figure 2c suggests that during high TP–NP periods, the TP and NP modes are in phase. However, during low TP–NP periods we do not know whether the correlation is low because the two modes are in quadrature or because the structure of variability has changed. For example, the variability in the North Pacific could be dominated by some other structure. The possibility of the two modes being in quadrature during low correlation periods is tested by doing a lagged correlation between the PCs of the TP and NP modes. The lead–lag correlation is similar to that during low TP–NP periods (not shown). As we show below, the correlation is reduced because the structure of the North Pacific SSTA during periods of low correlation is different from that of the NP mode.

To determine some potential physical links between the TP and NP modes, we computed composites based on the state of the tropical Pacific and the correlation shown in Fig. 2c. Figures 3a,b show the SSTA composite for the tropical warm (cold) events during the high TP–NP period, whereas Figs. 3c,d show the SSTA composite for the tropical warm (cold) events during the low TP–NP period. Figures 3e,f show the differences between composites for each period during warm events (Fig. 3a minus Fig. 3c) and cold events (Fig. 3b minus Fig. 3d). Large differences are found in the North Pacific along 40°N (Figs. 3e,f).

Along 40°N during the high TP–NP period (Figs. 3a,b), the North Pacific SSTA is of the opposite sign to the SSTA in the central and eastern tropical Pacific. During the low TP–NP period (Figs. 3c,d), this out-of-phase relationship with the SSTA in the North Pacific is shifted to the central North Pacific. This suggests that the dominant spatial structure of interannual North Pacific SSTA changes on decadal time scales. The reason why the sliding correlation is low is that the pattern of North Pacific SSTA associated with tropical forcing (Figs. 3c,d) is different from that of the overall NP mode as detected from the EOF analysis. Conversely, the pattern of North Pacific SSTA during the high TP–NP period (Figs. 3a,b) is similar to that of the NP mode. On the other hand, the maximum center of anomalous tropical SSTAs in Figs. 3c,d are shifted to the east compared to Figs. 3a,b. We compared the zonal structure of the composite warm and cold events along the equator during the high and low TP–NP periods. The maximum center of composite warm/cold event along the equator during the low TP–NP period (Figs. 3a,b) is similar to that of the NP mode. The maximum center of composite warm/cold event along the equator during the low TP–NP period (Figs. 4a,b) is shifted eastward to that of warm/cold event during the high TP–NP period (thin lines in Figs. 4a,b). Previous studies suggested large sensitivity of the North Pacific pattern to the location of the tropical SST forcing (Alexander et al. 2002; Barsugli and Sardeshmukh 2002). Such changes could enhance the magnitude of the extratropical atmospheric response to ENSO and hence the decadal modulation of SSTAs in the North Pacific (Vimont 2005). For example, Pacific–North American (PNA)-like atmospheric anomalies are sensitive to near–date line tropical SST (Barsugli and Sardeshmukh 2002) and stronger anomalous North Pacific SST is associated with tropical SSTAs centered near the date line (Newman 2007). However, it is unclear whether changes in the amplitude of the tropical Pacific SSTA variability during the high and low TP–NP period are significant in observations (Figs. 3e,f).

We hypothesize that the structural changes in the North Pacific SSTA are associated with the tropical

---

2 High TP–NP periods are based on periods when the sliding correlation coefficients exceed the mean sliding correlation value (0.36). Similarly, low TP–NP periods are based on periods when the sliding correlation coefficients are less than the mean sliding correlation value.
SST variability. This hypothesis is from the notion that the tropics play a key role in the North Pacific SSTA variability (Deser et al. 2004). We conjecture that the tropical–North Pacific SST teleconnections are influenced by the details of tropical Pacific SST forcing, resulting in changes in the dominant spatial structure of the interannual North Pacific SSTA. The change in location of the tropical Pacific SST forcing might be a key factor that is important for the change in the tropical–North Pacific SST teleconnections. Despite the lack of observational evidence, the amplitude of the tropical Pacific SST variability may also be a factor influencing the relationship between tropical–North Pacific SST teleconnections. We can examine this conjecture in a much larger time series from a coupled model simulation, and the model results will be shown in the next section.

4. Model results

a. The NP and the TP modes

The tropical–North Pacific SST teleconnections are examined based on a long (500 yr) simulation from the
interactive ensemble CGCM. There are two purposes in the model analysis. First, we are able to examine a time series that is long enough to achieve statistical significance. Second, we can then examine whether the model results support the conjecture based on the observations in the above section. Furthermore, the motivation for using the interactive ensemble CGCM is to examine how the tropical and North Pacific SSTAs are related in the presence of much reduced noise. We remind the reader that we are using a coupling strategy that artificially enhances the signal-to-noise ratio.

Figures 5a,b are the same as in Figs. 2a,b except we have used the SSTA simulated by the interactive ensemble CGCM for the period of 500 yr. As with the observations, the model SST data are also high-pass filtered to retain only interannual periods (period < 10 yr). The geographical pattern of the model’s NP mode is different from the observations. The NP mode (Fig. 1a) is dominated by a zonally extended structure in the western and central North Pacific, whereas the simulated NP mode is oriented to the northeast–southwest in the central and southern North Pacific. It is not surprising that the model NP mode is different from the observations. This difference is likely due to the interactive ensemble coupling approach. Since the interactive ensemble CGCM has reduced noise at the air–sea interface, the overall pattern (i.e., EOF1) corresponds to the remotely forced pattern, whereas the observed NP mode might be dominated by the noise-forced pattern. The above relative roles of the noise-forced versus remotely forced North Pacific SSTA pattern can be examined by comparing results from the standard CGCM (i.e., one AGCM coupled to one OGCM) and the interactive ensemble CGCM. The noise amplitude increases in the standard CGCM compared to the interactive ensemble CGCM by design (YK04b). Furthermore, Yeh and Kirtman (2004c) analyzed the tropical decadal variability between the two CGCMs. We provide the NP mode based on the results for the simulation period of 400 yr in the standard CGCM (Fig. 6). The spatial pattern of the simulated NP mode in the standard CGCM resembles that in the observations rather than that in the interactive ensemble CGCM (i.e., a zonally extended pattern from the coast of Asia into the central North Pacific) suggesting that, in fact, the noise-forced pattern dominates in nature.

The structure of the TP mode in the interactive ensemble CGCM (Fig. 5b), which accounts for 42% of the filtered variance, has some differences compared to the observations. For instance, the SST variability is weak in the eastern tropical Pacific, is too narrowly confined to the equator, and extends too far to the west. This meridional scale problem in coupled GCMs has been noted in many other coupled simulations (Kirtman and Zebiak 1997) and is consistent with the fast ENSO in the model. This difference might be due to some of the biases in the model-simulated ENSO, for instance, zonal wind stress or thermocline structure. In spite of these differences, the variability of the TP mode represents the ENSO simulated in the interactive CGCM. Power spectral analysis of Niño-3.4 SST index in the interactive ensemble CGCM is similar to that of the PC time series of the TP mode. In addition, both the NP mode and TP mode have significant spectral density at interannual time scales with the same preferred periodicity (not shown). This result argues that the NP
mode (Fig. 5a) is a well-defined tropical-related SSTA mode in the interactive ensemble CGCM.

b. Changes in the NP mode

Figures 7a–e show the 9-yr sliding correlation coefficient of the PC time series of the TP and NP modes for the period of 500 yr. The correlation remains positive for the entire period as in the observations. Note that a value of 0.41 is the 95% confidence level, and that there are more than 150 yr where the correlation exceeds the 95% confidence level. The temporal relationship between the TP and NP modes varies on decadal time scales and those also have periods in which the correlation is above mean correlation coefficient value (0.39) (model years 40–70, 129–148, 215–225, 275–284, 310–320, 340–350, 455–465, and 479–488, i.e., high TP–NP period) and periods when the correlation is below mean correlation coefficient (model years 95–105, 115–124, 190–200, 225–234, 260–270, 291–300, 325–334, 350–359, 385–394, 415–430, and 440–450, i.e., low TP–NP period).

Here we show that there are significant changes in the spatial manifestation of the North Pacific SSTA for each (high/low) TP–NP period. To examine this, we compute the EOFs based on the high or low TP–NP
period separately. Figures 8a,b are the same as in Fig. 5a except for the high TP–NP period and low TP–NP period, respectively. The leading EOF mode for the high TP–NP period captures the distinctive structure of NP mode (Fig. 5a; i.e., the northeast–southwest tilting in the central and southern North Pacific). Moreover, the tilting structure in Fig. 8a is slightly strengthened and its maximum variability is shifted to the south compared to Fig. 5a. The leading EOF for the low TP–NP period (Fig. 8b) is distinctly different from the leading EOF of the high TP–NP period; that is, the tilting structure to the northeast–southwest is changed into the east–west extended pattern with a basin scale in the western and central North Pacific. The anomalies are of the opposite sign centered around 30°N and there is a northward shift of maximum amplitude. Figures 8a,b could be interpreted as the dominant SST variability during the high and low TP–NP periods, respectively. In other words, the southwest–northeast North Pacific SST pattern (Fig. 8a) occurred frequently during the high TP–NP period. In contrast, a zonally extended North Pacific SST pattern (Fig. 8b) occurred frequently during the low TP–NP period. Note that the second EOF SSTA during the low TP–NP period (not shown) is characterized by the northeast–southwest tilting structure in the southern part of North Pacific.

c. Mechanism

To understand the structural changes shown in Fig. 8, we display the root-mean-square (rms) variance of SST for the high TP–NP period (Fig. 9a) and low TP–NP period (Fig. 9b) in the interactive ensemble CGCM. Figure 9c shows the differences in the rms (Fig. 9a minus Fig. 9b). Note that the shading indicates regions above 95% confidence level by an $F$ test. The tropical Pacific forcing is strong during the high TP–NP period in the interactive CGCM. Conversely, the low TP–NP period is marked by relatively weak tropical Pacific forcing. In addition, the zonal structure of the rms variance of SST along the equator (not shown) indicates that the maximum center of SST variance during the high TP–NP period is slightly shifted eastward compared to that during the low TP–NP period. These results show that the structure of the remote SST is affected by the details of the tropical Pacific SST forcing. For instance, when the tropical Pacific SST forcing is strong (weak), the signal from the tropics to the North Pacific is large (small), resulting in the high (low) correlation period for the TP–NP mode in the interactive ensemble CGCM. Simply put, Fig. 8a corresponds to the remotely forced pattern, and Fig. 8b corresponds to the atmospheric noise-forced pattern in the interactive ensemble CGCM. As the TP–NP mode
correlation varies in the interactive ensemble CGCM, the spatial manifestation of the North Pacific SSTA changes from the atmospheric noise-forced pattern (the east–west extended pattern with a basin scale in the western and central North Pacific) to the remotely forced pattern (the northeast–southwest tilting in the central and southern North Pacific) and vice versa.

To clarify whether the teleconnection is strong when the tropical Pacific SSTA is strong, we display the rms variance differences of precipitation (Fig. 10a) and 500-hPa geopotential height anomaly (Fig. 10b) simulated in the interactive ensemble CGCM between the high TP–NP mode and low TP–NP period. The precipitation variance is largely enhanced in the tropical central Pacific when the local SSTA is strong, which occurs during high TP–NP correlation period. On the other hand, the variance of the 500-hPa geopotential height during the high TP–NP period increases compared to the low TP–NP period over the North Pacific except around the west coast of America. The differences between the two periods are characterized by a wavelike pattern to the east of the date line. This result suggests that the atmospheric field (here, 500-hPa geopotential height), which is associated with the details of tropical Pacific SST forcing, tends to show differences in both geographical distribution of anomaly and strength of anomaly between the two periods. We further identify that there are distinct differences in the second EOFs of 500-hPa geopotential (not shown) in terms of spatial structure between the high and low TP–NP periods. In other words, teleconnections from the tropics to the North Pacific are different between the two periods, which may induce different North Pacific SSTA patterns. Figures 9 and 10 raise another important issue as to whether changes in the North Pacific SSTA pattern are caused by changes in atmospheric noise or by changes in teleconnections from the tropics. To address this issue, additional numerical experiments with locally prescribed SST are needed. For example, we could prescribe the SSTAs corresponding to the high or low TP–NP period in the tropical Pacific, leaving the model coupled in the North Pacific. By comparing the simulated SSTA pattern in the North Pacific between the two experiments, we may identify whether the tropical forcing in the low TP–NP period can induce the zonally

Fig. 9. The rms variance of SSTA for the (a) high TP–NP mode and (b) low TP–NP period. The shading indicates above 0.4°C and the CI is 0.2°C. (c) A calculation of (a) – (b). The shading region indicates regions above the 95% confidence level by an $F$ test and the CI is 0.1°C.

Fig. 10. The rms variance differences of (a) precipitation and (b) 500-hPa geopotential height anomaly between the high TP–NP mode and the low TP–NP period. The CI is 0.1 mm day$^{-1}$ in (a) and 5 m in (b). The shading region indicates regions above the 95% confidence level by an $F$ test.
extended North Pacific SSTA pattern. Such experiments are very interesting for the further study of this issue. In this stage, we may only conclude that the North Pacific SSTA pattern depends on both the teleconnections from the tropics and changes in atmospheric noise in the interactive ensemble CGCM.

It is useful to examine whether there are significant changes in the spatial manifestation of the North Pacific SSTA and associated tropical Pacific SST forcing in the standard CGCM. We conduct the same analyses with the standard CGCM as with the interactive ensemble CGCM. We compute the EOFs separately based on the high or low TP–NP period in the standard CGCM (Figs. 11a,b). The high or low TP–NP period is defined in the same way as with the interactive ensemble CGCM. The leading EOF for the high TP–NP period (Fig. 11a) captures the distinctive structure of NP mode simulated in the standard CGCM (Fig. 6; i.e., a zonally extended structure in the western and central North Pacific). On the other hand, the leading EOF for the low TP–NP period (Fig. 11b) has a slightly different pattern from that of the high TP–NP period in that the tilting structure is dominated in the central North Pacific.

This result indicates that the dominant spatial structure of interannual North Pacific SSTA also changes in the low-frequency relationship of the TP–NP mode in the standard CGCM. However, we did not find significant differences in the details of tropical Pacific SST forcing on the structural changes of interannual North Pacific SSTA in the standard CGCM. We calculated the rms variance of tropical Pacific SSTA for the high TP–NP period and low TP–NP period in the standard CGCM (not shown). Neither changes in strength nor changes in location of the tropical Pacific SSTA are detected, which is different from the observations and the interactive ensemble CGCM. Changes in the NP mode may be due to the variations in noise ultimately projecting onto different eigenmodes associated with North Pacific SSTA variability in the standard CGCM. This is largely consistent with the observational results of Newman (2007), who argued that very large variations in the TP–NP correlation are possible just because of variations in noise projecting on the different eigenmodes. Considering the fact that the noise amplitude in the standard CGCM is much larger than the interactive ensemble CGCM (YK04b), we speculate that local North Pacific internal atmospheric dynamics overwhelm the remote teleconnections between the tropics and the midlatitude in the standard CGCM. Essentially, it appears that there is too much noise forcing in the standard CGCM to adequately detect the remote teleconnections.

The relationship between interannual North Pacific and tropical Pacific SSTA varies on decadal time scales. Similarly, the amplitude of tropical Pacific SSTA varies on decadal time scales. Figures 12a–e show the time series of rms variance of Niño-3.4 SST index with a 9-yr running mean (thick line). Note that the amplitude of the rms time series is indicated on the right of the panel and the thin line is the sliding correlation coefficients as in Fig. 7. With decadal changes of TP–NP mode, the amplitude of tropical Pacific SST varies on decadal time scales with a similar phase relationship. Again, this result supports that the tropical–North Pacific SST teleconnections are related to the variations of the tropical Pacific SSTA amplitude in the interactive ensemble CGCM.

In addition, the rms variance of Niño-3.4 SST index plotted in Fig. 12 indicates not only the changes in amplitude but also the changes in location of the tropical forcing. To show this, we calculated the simulated NP mode and the TP mode for the period of high ENSO amplitude and the low ENSO amplitude. The high ENSO amplitude period is based on periods when the 9-yr running mean time series of the Niño-3.4 rms variance exceeds one standard deviation (0.40°C). Similarly, the low ENSO amplitude period is based on periods when the same time series exceed one standard deviation below normal (0.26°C). Figures 13a,b show the simulated NP mode for the period of high and low ENSO amplitude, respectively. As expected, the spatial pattern of the NP mode for the high (low) ENSO amplitude period (Figs. 13a,b) resembles that for the high

![Fig. 11. The EOF1 for the (a) high TP–NP period and (b) low TP–NP period in the standard CGCM.](image-url)
Furthermore, we show the zonal structure of the simulated TP mode along the equator during the high (thin) and low (thick) ENSO amplitude period (Fig. 13c). The maximum center of the TP mode during the low ENSO amplitude period is shifted westward to that of the TP mode during the high ENSO amplitude period. When the maximum center of tropical SST forcing is shifted to the west, the spatial manifestation of dominant mode of the North Pacific SSTA variability changes from Fig. 13a to Fig. 13b. This result indicates that the change in location of the tropical Pacific SST forcing is important for the structural changes of the NP mode of variability in the interactive ensemble CGCM.

Similar analysis is applied to the high and low TP–NP periods. Figure 14 shows the zonal structure of the TP mode along the equator during the high (thin) and low (thick) TP–NP periods. Figure 14 shows that the maximum center of the TP mode during the low TP–NP period is shifted westward to that of the TP mode during the high TP–NP period in the model. When the maximum center of tropical SST forcing is shifted to the west, the spatial manifestation of dominant mode of the North Pacific SSTA variability changes from the northeast–southwest tilting pattern (Fig. 8a) to the east–west extended pattern (Fig. 8b), which is consistent with the results in Fig. 13. As mentioned in the previous section, the change in the location of the tropical SST forcing could be associated with that in the magnitude of the extratropical atmospheric response to ENSO and hence the decadal modulation of SSTAs in the North Pacific.

5. Discussion

Atmospheric noise is an important element of the climate system and its role in forcing variability needs to be understood (Penland and Sardeshmukh 1995;
Newman et al. 1997; Sura et al. 2005). The interactive ensemble coupling strategy is applied here to quantitatively diagnose how noise in the air–sea fluxes due to internal atmospheric dynamics impacts the low-frequency variability in the Pacific. It is important to recognize that the results presented here are model dependent. However, it is our assertion that this particular model does a reasonable job (or at least comparable to other models) of simulating the phenomenon of interest (i.e., Kirtman et al. 2002; YK04b). Nevertheless, the potential impact of some important model errors is discussed below.

a. Seasonality

We have suggested that the different structure of the NP mode between the observations and the interactive ensemble CGCM is largely due to the change in the noise. However, we do not exclude other possibilities, for instance, an error in seasonality in the interactive ensemble CGCM. To clarify this, we show the leading SST EOFs in the North Pacific during the boreal summer (June–July–August) and the boreal winter (December–February) in the interactive ensemble CGCM (Figs. 15a,b). The simulated EOF1 has a strong seasonality in terms of its spatial structure. The simulated EOF1 during summer (Fig. 15a) is dominated by a zonally extended basin-scale structure centered near 40°N from the western and central North Pacific. On the other hand, the simulated EOF1 during winter (Fig. 15b) is oriented to the northeast and southwest between 30° and 40°N, which is reminiscent of the NP mode (Fig. 5a) in the interactive ensemble CGCM except in the western part of the North Pacific. Simply put, this result suggests that the northeast–southwest-oriented structure of the model’s NP mode, which is different from the observations, is largely attributed to that of the EOF1 during winter. This possibly explains why the model’s NP mode has some marked differences from observations. On the other hand, we can speculate that there is an error in seasonality in the amplitude of atmospheric noise in the interactive ensemble CGCM. An error in the seasonal variations of atmospheric noise amplitude may influence the dominant SSTA pattern in the North Pacific in the interactive ensemble CGCM. Note that the dominant mode of SSTA variability over the North Pacific, as inferred from EOF analysis, exhibits a rather similar spatial structure year-round in observations (Zhang et al. 1998).

However, this result also supports our assertion that the amplitude of the tropical Pacific SSTA variance largely determines the dominant structure of North Pacific SSTA variability in the interactive ensemble CGCM. This is primarily due to the fact that the model ENSO has stronger seasonality than observed with peak amplitude in boreal winter. We are arguing that changes in the spatial pattern of the EOF1 from summer to winter (Figs. 15a,b) are associated with those of the tropical Pacific SST forcing. To support this, we calculated the rms variance of SSTA during summer and winter in the interactive ensemble CGCM (Figs. 16a,b). Not surprisingly, the tropical SST forcing during summer is weaker than that during winter, suggesting that the structure of the remote SSTA is affected by the strength of the tropical Pacific SST forcing (i.e., from the east–west extended pattern with a basin scale in the
western and central North Pacific to the northeast–southwest tilting in the central and southern North Pacific and vice versa). In addition, the location of the tropical forcing is different during summer (Fig. 16a) and winter (Fig. 16b) as we argued earlier. The maximum variance of SSTA during winter (Fig. 16b), which is located between 180° and 160°W along the equator, is located farther to the west compared to that during summer (Fig. 16a). However, it is difficult to directly compare the location of the maximum tropical forcing between winter and summer. This is because the rms variance of SSTA during summer is very weak, with a flat structure in the central and eastern equatorial Pacific.

b. Nonlinearity

Because the atmospheric fluxes are obtained by averaging six ensemble member in the interactive ensemble CGCM, it is possible there are times when the noise reduction is linear and times when it is nonlinear (i.e., regime dependent). In the tropical Pacific, the noise reduction is regime dependent (as discussed in Kirtman et al. 2005; Wu and Kirtman 2006). However, our analysis suggests little evidence for this in the North Pacific. For example, the noise change for 500-hPa geopotential height has no systematic dependence on the high and low TP–NP periods. Furthermore, there are modeling results that indicate that the amplitude of the air–sea flux variability due to internal atmospheric dynamics increases when the system is decoupled at the air–sea interface. This is primarily associated with the damping effects associated with latent heat flux (Wu and Kirtman 2005; Wu et al. 2006). This is relevant since the interactive ensemble approach is “less” coupled than a traditional CGCM. Nevertheless, our analysis of the latent heat flux and wind stress in the North Pacific (YK04b) indicates that the reduction in the amplitude of the noise in the North Pacific is nearly linear in practice.

c. Impact of global noise reduction

A potential problem with the interactive ensemble CGCM is that the atmospheric noise was reduced globally, so that it could not determine how changes in other modes of variability due to the application of the interactive ensemble coupling might influence the results through reduced interactions with the North Pacific. Some of the changes in the North Pacific SST variability may not be associated with the noise reduction in the North Pacific, but may be due to changes in the model ENSO associated with the noise reduction. This issue has been examined further by using the regional interactive ensemble CGCM, in which the number of AGCM realizations coupled to an OGCM is different in the North Pacific and the tropics, respectively (Yeh et al. 2007). It is found that the impact of local noise on the North Pacific SST variability is much larger than that of nonlocal noise from the tropics. However, noise over the tropics due to enhanced internal atmospheric variability causes the modulation of ENSO, which in turn affects the North Pacific SST variability in terms of its frequency.

The ENSO simulation in the interactive ensemble CGCM is largely biennial, which is different from a rich spectrum on 2–7 yr in the observations. We assert that the excessive biennial variability is due to the noise reduction in the western Pacific. By applying the interactive ensemble approach regionally, we can investigate how this biennial tendency influences the results. As we previously mentioned, we examined this issue based on the regional application of the interactive ensemble CGCM. It should be noted that the ENSO simulated in the standard CGCM and the regional interactive ensemble CGCM are quite similar in terms of amplitude and period. It is found that when noise is locally reduced in the North Pacific, the North Pacific SST still has detectable variability on decadal time scales. However, when noise is reduced in both the North Pacific and the tropics, the simulated ENSO is dominated by a biennial time scale, resulting in a biennial variability of central North Pacific SST. This is because the signal from the tropics easily influences the

FIG. 16. The rms variance of SSTA for the (a) summer and (b) winter in the interactive ensemble CGCM.

Unauthenticated | Downloaded 04/10/22 08:01 PM UTC
SSTA variability in the central North Pacific region because the locally reduced noise has a reduced impact on the variability.

Previous studies argued that much larger ensembles are necessary to determine ENSO signals in the extratropics (Latif et al. 1998; Sardeshmukh et al. 2000; Hoerling and Kumar 2002; Alexander et al. 2002; Quan et al. 2004). The interactive ensemble CGCM used in this study has six realizations of the AGCM coupled to a single realization of the OGCM. The choice of six ensemble member is primarily ad hoc; however, Kirtman and Shukla (2002) provided some justification in terms of reducing the noise in the wind stress over the tropical Pacific. We have checked that 6 and 12 ensemble member largely give the same results. For example, YK04b showed that the amplitude of the tropical Pacific SSTA variance determines the dominant structure of North Pacific SSTA variability in the 12 interactive ensemble CGCM. In spite of different methodology used in YK04b, our results based on the interactive ensemble CGCM have some similarities compared to that using doubling the ensemble size (i.e., 12 AGCM realizations).

6. Concluding remarks

Based on an EOF analysis of observed SSTA in the North Pacific and tropical Pacific, our results suggest that there are low-frequency variations in the relationship between the TP and NP modes. The results show that the North Pacific SSTA is dominated by a zonally extended structure from the western to central North Pacific. During periods when the relationship is weak, the western North Pacific SSTA along 40°N is not out of phase with the eastern tropical SSTA.

We speculated that the details of tropical Pacific forcing ultimately determines the tropical–North Pacific SST teleconnections. This speculation seems to support the premise that the tropics can act as a source for North Pacific SST variations. While the tropics could influence the North Pacific SST variability, the reverse is also possible [i.e., that extratropical variability may modulate the tropics either through the atmosphere (Pierce et al. 2000; Vimont et al. 2001, 2003), the ocean (Kleeman et al. 1999; McPhaden and Zhang 2002), or a combined tropical–extratropical oceanic coupling (e.g., Gu and Philander 1997)]. Moreover, recently several studies argued that atmospheric noise and midlatitude ocean dynamics along with the role of tropical forcing explains the dominant mode of SSTA variability in the North Pacific (Schneider and Cornuelle 2005; Newman et al. 2003). Newman (2007) showed that very larger variations between the North Pacific and the tropical Pacific SSTAs are possible just because of variations in noise projecting on the different eigenmodes.

We examined the tropical–North Pacific SST teleconnections based on a much longer time series (500 yr) from the interactive ensemble CGCM. The observed temporal variations of the TP–NP teleconnections are reproduced in the model simulation. The model results show that the relationship between the TP and NP modes varies on decadal time scales, suggesting the existence of a non-noise physical link. As in the observations, the model shows evidence that there are significant changes of spatial structure in the North Pacific SSTA associated with periods of high and low correlation between the TP–NP modes. There are two patterns of North Pacific interannual SSTA variability in the interactive ensemble CGCM. The first pattern is locally forced by atmospheric noise due to internal dynamics. The second pattern is remotely forced by tropical SSTA via an atmospheric bridge. The model results show that the atmospheric noise-forced pattern corresponds to a zonally extended structure in the western and central North Pacific, whereas the remotely forced pattern corresponds to the northeast-to-southwest orientation in the central and southern North Pacific.

The model results shed light on the tropical–North Pacific SST teleconnections in observations. We argue that the observed NP mode, which has a zonally extended structure in the western and central North Pacific, is primarily driven by local atmospheric noise in observations. However, during periods of low correlation this pattern is relatively weak. The structure of North Pacific SST variability has changed to the mixed pattern of positive and negative SSTAs in the western and central North Pacific. The model results show that the tropical–North Pacific SST teleconnections are strongly connected to the amplitude of the variability in the central and eastern tropical Pacific and/or the change in location of the tropical Pacific SST forcing. Furthermore, the atmospheric response in the North Pacific, which is associated with the details of tropical Pacific SST forcing, tends to show differences in both geographical distribution of the anomaly and the strength of anomaly.

The intensity of tropical Pacific SSTA variance varies along with the location of the maximum tropical forcing on decadal time scales, thus leading to decadal variations in the tropical–North Pacific SST teleconnections in terms of the spatial structure of North Pacific SSTA. In this paper, we did not explore details of the changes in location of the tropical forcing because this would require additional numerical experiments. Sensitivity experiments of atmospheric and oceanic response in the North Pacific to change in location of the tropical
SST forcing are needed. For example, Barsugli and Sardeshmukh (2002) have conducted numerical experiments in order to investigate the sensitivity of the atmospheric response to SSTAs throughout the tropical Indian and Pacific Ocean. They concluded that the extratropical response including the PNA region is most sensitive to SSTAs in the Niño-4 region of the central tropical Pacific rather than the SSTAs in the Niño-3 region, indicating the importance of the location of the tropical SST forcing.

Acknowledgments. The authors are grateful to three anonymous reviewers for their constructive comments, which greatly improved the manuscript. S.-W. Yeh is supported by the Korea Meteorological Administration Research and Development Program under Grant CATER 2006-4202. BPK acknowledges support from the National Ocean and Atmosphere Administration under Grant NA05OAR431135.

REFERENCES


