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# MECHANISM FOR THE SUSTAINING ATMOSPHERIC RESPONSE TO WARM WINTERTIME SEA SURFACE TEMPERATURE ANOMALY IN THE KUROSHIO EXTENSION

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**Abstract:** Sensitivity experiments with atmospheric general circulation model CAM3 have been performed to investigate the atmospheric response to warm wintertime sea surface temperature anomalies in the Kuroshio Extension (KE). Mechanism for the sustaining abnormal atmospheric response to sea surface temperature anomaly (SSTA) is revealed. It is found that the warm wintertime SSTA in KE leads to soil moisture changes across the Asia continent. The abnormal soil moisture may possibly be one of the reasons for the sustaining of abnormal atmospheric response intrigued by SSTA. Oscillations of perturbations intrigued by warm wintertime SSTA in KE, which have similar frequencies with that of intrinsic atmospheric oscillations, are superposed on the atmospheric oscillations and propagate with primary periodic oscillation of the atmosphere. These SSTA-intrigued oscillations are coupled with natural atmospheric oscillation and finally become parts of it. This is probably another reason for the sustaining of abnormal atmospheric response to SSTA in KE.

**Key words:** Kuroshio Extension; sea surface temperature anomaly; atmospheric response; low-frequency oscillation; mechanism; soil moisture
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## 1 INTRODUCTION

The impacts of sea surface temperature anomalies (SSTA) on general circulation and climate have long been studied. Previous results indicate that there exits a largely-linear, stationary atmospheric response to the SST anomaly in the tropics (Matsuno[1]; Gill[2]; Neelin and Held[3]; Neelin et al.[4]). In the extratropics, however, the atmospheric response to SSTA is much more complicated due to the strong internal atmospheric variations and feedbacks of the ocean to atmospheric forcing. A number of observational and theoretical studies on mid-latitude SST variations and their impacts on short-term climate anomalies have been conducted (Palmer and Sun[5]; Lau and Nath[6, 7]; Kushnir[8]; Mantua et al.[9]; Shiling and Jeffrey[10]; Kushnir et al.[11]; Liu and Wu[12]; David and Claude[13]; Minobe et al.[14]; Fang and Yang[15]). These studies have revealed that the mid-latitude SSTAs have significant influences on the atmospheric circulation. Generally, the atmospheric response to the extratropic SSTA, which remains a major challenge in the earth system study, is modest and quick especially at monthly to inter-annual timescales.

Recent studies based on observational analysis and numerical model simulations have revealed strong atmospheric response to mid-latitude SSTA forcing. It is several months lagged behind signal of SSTA and affects large areas at hemispheric scale (David and Claude[13]; Minobe et al.[14]; Czaya and Frankigoul[16]; Frankigoul and Sennechael[17]; Wang et al.[18]). Lau and Nath[6] and Wallace et al.[19] found that the mid- and high-latitude SSTA could intrigue low-frequency atmospheric oscillations and specific teleconnection patterns in the mid- and high-latitude. Yamagata and Havahsi[20] and Lu[21] achieved similar results through theoretical study and numerical simulation respectively. Wang et al.[22] revealed that the atmospheric low-frequency oscillation could be caused by SSTA in the Kuroshio Extension and

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apparently SSTA in mid- and high-latitude affects the global general circulation and climate change by modulating low-frequency atmospheric oscillations. Li[23] suggested that low-frequency atmospheric oscillation intrigued by the mid-latitude SSTA farther propagated after the enhanced process in the tropics. This indicated that the tropics played an important role on the maintenance and propagation of atmospheric response. All above studies have demonstrated that low-frequency atmospheric oscillations have close relations with the propagation and persistence of abnormal atmospheric response to mid-latitude SSTA.

The Kuroshio Extension (KE) refers to the direct continuation of the Kuroshio that flows into the open basin of the North Pacific from the coast of Japan at (35ºN, 140ºE). It covers the area of large meso-scale and synoptic-scale variations with most active air-sea interaction in the Pacific outside the tropics (Nakamura et al.[24]; Nakamura and Kazmin[25]; Schneider and Cornuelle[26]; Qiu et al.[27]; Kwon and Deser[28]). Various observational studies indicate that in the KE the geostrophic ocean circulation changes in response to basin-scale wind stress curl fluctuations induce the SST variations (Qiu[29, 30]), which in turn alter the local air-sea energy exchange, especially the surface turbulent energy fluxes exchange in winter (Tanimoto et al.[31]; Kelly[32]). The nature of the atmospheric response to the SSTA in the KE becomes a hotspot in current scientific studies. Atmospheric response to SSTA in the KE is not local and can sustain long after the SSTA disappears (Wang et al.[18, 22]). The question why and how the atmospheric response to SSTA persists after SSTA no longer exists has not been addressed yet. In this study we explore the mechanisms for the sustaining atmospheric response to warm wintertime SSTA in the KE based on results of atmospheric general circulation model (Community Atmosphere Model 3, or CAM3). Two numerical experiments, i.e. the control run and the sensitivity run with warm wintertime SSTA, are performed in this work. The difference between results of the two experiments is considered as atmospheric response to wintertime SSTA in the KE. The mechanisms of the sustaining Northern Hemisphere (NH) atmospheric response to the SSTA are explored.

## 2 DATA, MODEL, AND EXPERIMENT DESIGN

### 2.1 *Data*

The monthly mean 1º × 1º SST data of Global Ice and Sea Surface Temperature (GISST) from 1948 to 2007 and the monthly reanalysis data of the National Centre for Environmental Prediction/National Centre for Atmospheric Research Reanalysis Project (NCEP/NCAR NNRP) from 1948 to 2007 are used to verify our model simulations. NNRP data has a horizontal resolution of 2.5º × 2.5º and GISST is a global 1º × 1º dataset.

### 2.2 *Model description*

The global atmospheric general circulation model GCM CAM3.0 is used in this study. CAM3.0 is developed in the National Center for Atmospheric Research (NCAR). It is a global spectral model with the triangular spectral truncation. In this study, CAM3.0 is run at T85 spectral resolution, which is equivalent to a grid spacing of 1.4°. Semi-implicit scheme is used for integration and the time step is 10-minute. Radiation, cloud, convection, land surface, boundary layer, and other physical processes are all included in this model (Collins et al.[33]).

### 2.3 *Experiment design*

Two experiments are conducted in this study to explore the mechanism for sustaining atmospheric response to warm wintertime SSTA in the KE. The CAM3.0 is first run for 76 months (from September of year 0000 to December year 0006) using monthly mean climatology of SST. By the end of the 76th month, the model reaches quasi-stationary condition. From then on, two simulations with extra 12-month integration are performed. In the control run (CTRL), monthly mean SST is used for the extra 12-month integration. In the sensitivity run (TEST), SST is increased by 1K from January to March over the area of 31º–37ºN and 140º–180ºE, which is roughly corresponding to the area of the KE (Qiu[29]). Differences between results of CTRL and TEST are used to represent the atmospheric response to warm wintertime SSTA in the KE. Mechanism for sustaining atmospheric response to SSTA is explored based on the results of the modeling simulations.

## 3 MECHANISM FOR THE SUSTAINING ATMOSPHERIC RESPONSE TO WARM WINTERTIME SSTA

### 3.1 *Soil moisture and temperature changes and impacts*

It is well known that abnormal boundary conditions, most notably sea surface temperature anomalies, can lead to large changes in surface-atmosphere fluxes of sensible and latent heat and momentum. These changes in fluxes between surface and atmosphere subsequently influence large-scale atmospheric circulation and moisture transport and thus contribute to global climate variability.

To explore the mechanism for the sustaining atmospheric response to warm wintertime SSTA in the KE long after the SSTA disappears, we first analyze the monthly mean soil moisture anomalies in the northern hemisphere (Fig.1).

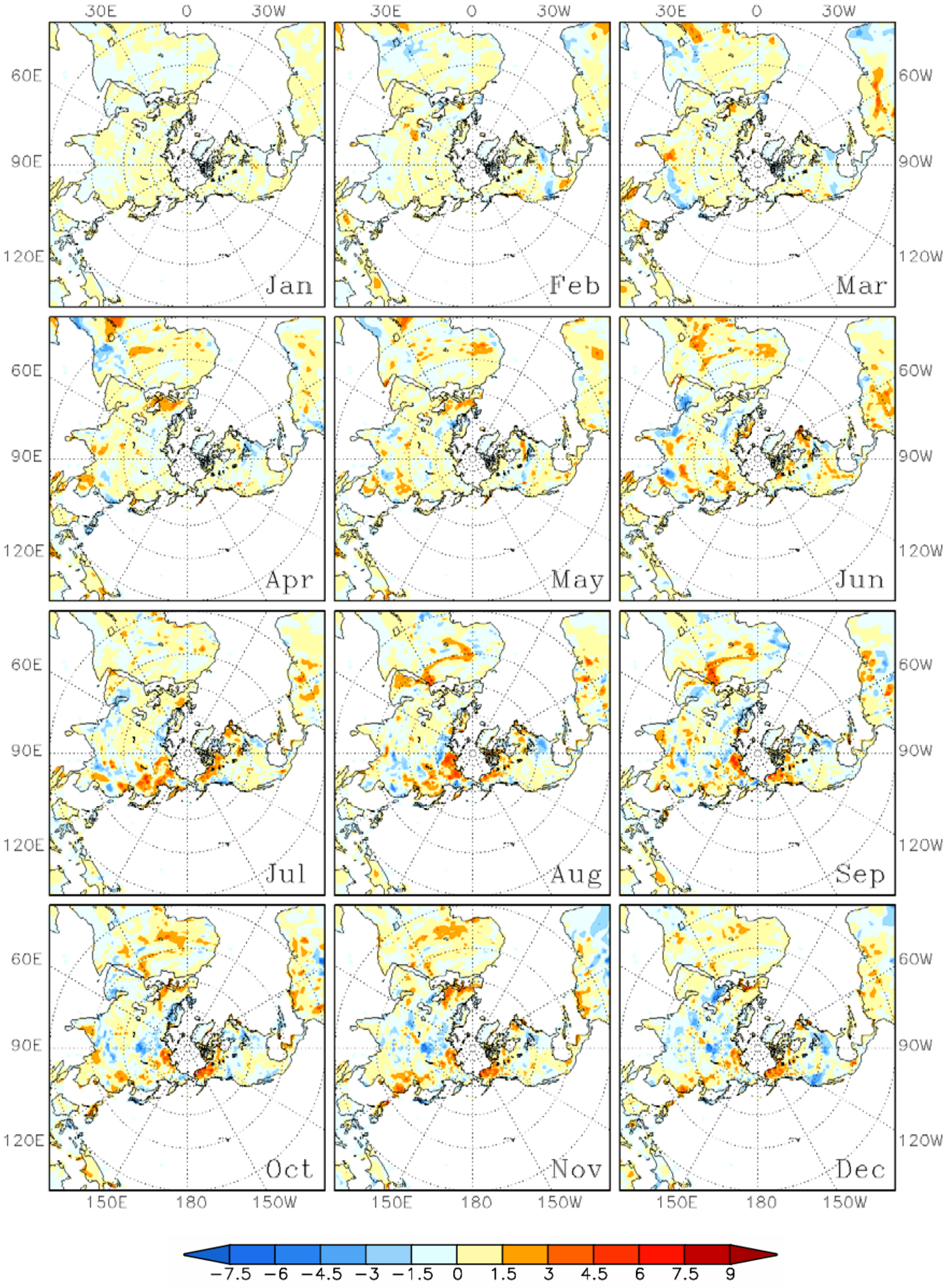

**Figure 1.** Distribution of monthly soil moisture anomaly (unit: kg/m$^2$) for the soil layer from surface to the depth of 2.86 m.

Accompanying the warm SSTA in the KE, distinct soil moisture anomalies appear and gradually intensify over large areas of northern hemisphere. Although the warm SSTA disappears since April, soil moisture anomalies still persist throughout summer and autumn. In general, large soil moisture anomalies appear in two latitudinal zones of 30º–35ºN and 50º–55ºN with the largest anomaly of 9 kg/m$^2$

occurring in East Asia. Soil temperature anomalies (Fig.2) exhibit similar patterns to that of soil moisture, with distinct anomalies sustaining long after SSTA disappears.

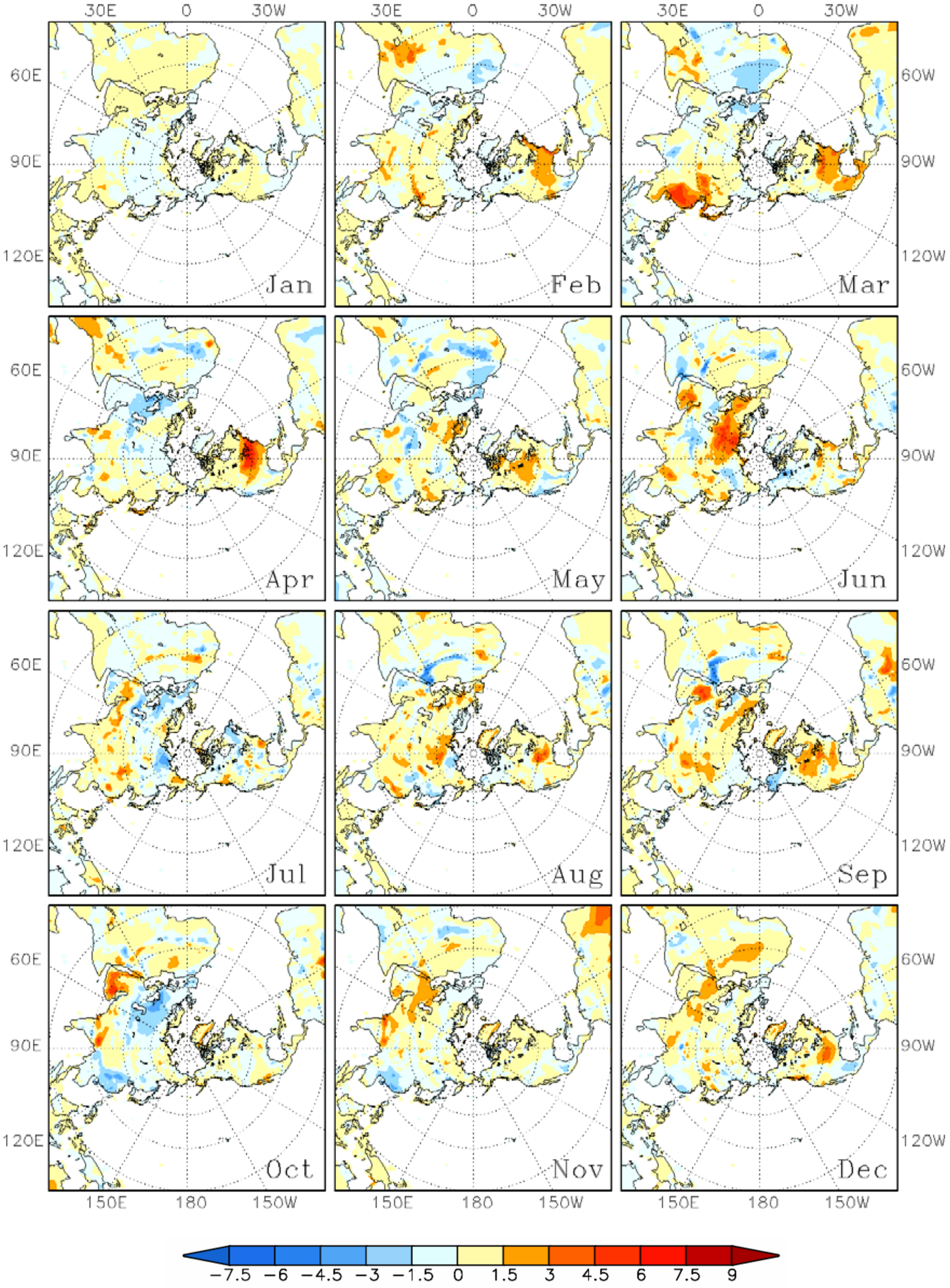

**Figure 2.** Distribution of monthly soil temperature anomaly (unit: °C) for the soil layer from surface to the depth of 2.86 m.

Apparently atmosphere behaves as a linkage between warm SSTA in the KE and abnormal soil moisture and temperature conditions. When SSTA disappears, abnormal signals intrigued by SSTA in the atmosphere and soil moisture/temperature still exist and continue to exert their impact on the entire surface-atmosphere system. Many previous studies have shown that there exists lagged atmospheric response to SSTA (David and Claude[13]; Minobe et al.[14]; Czaya and Frankigoul[16]; Frankigoul and Sennechael[17]; Wang et al.[18, 22]). To further investigate the atmospheric response to warm SSTA in the KE, we analyze the monthly mean geopotential height anomalies at 500 hPa and anomalies of surface temperature, sensible and latent heat fluxes, soil moisture and precipitation. Latitudinal-time cross-section of the anomalies of above variables are shown for 30º−35ºN（Fig.3) and 50º−55ºN (Fig.4).

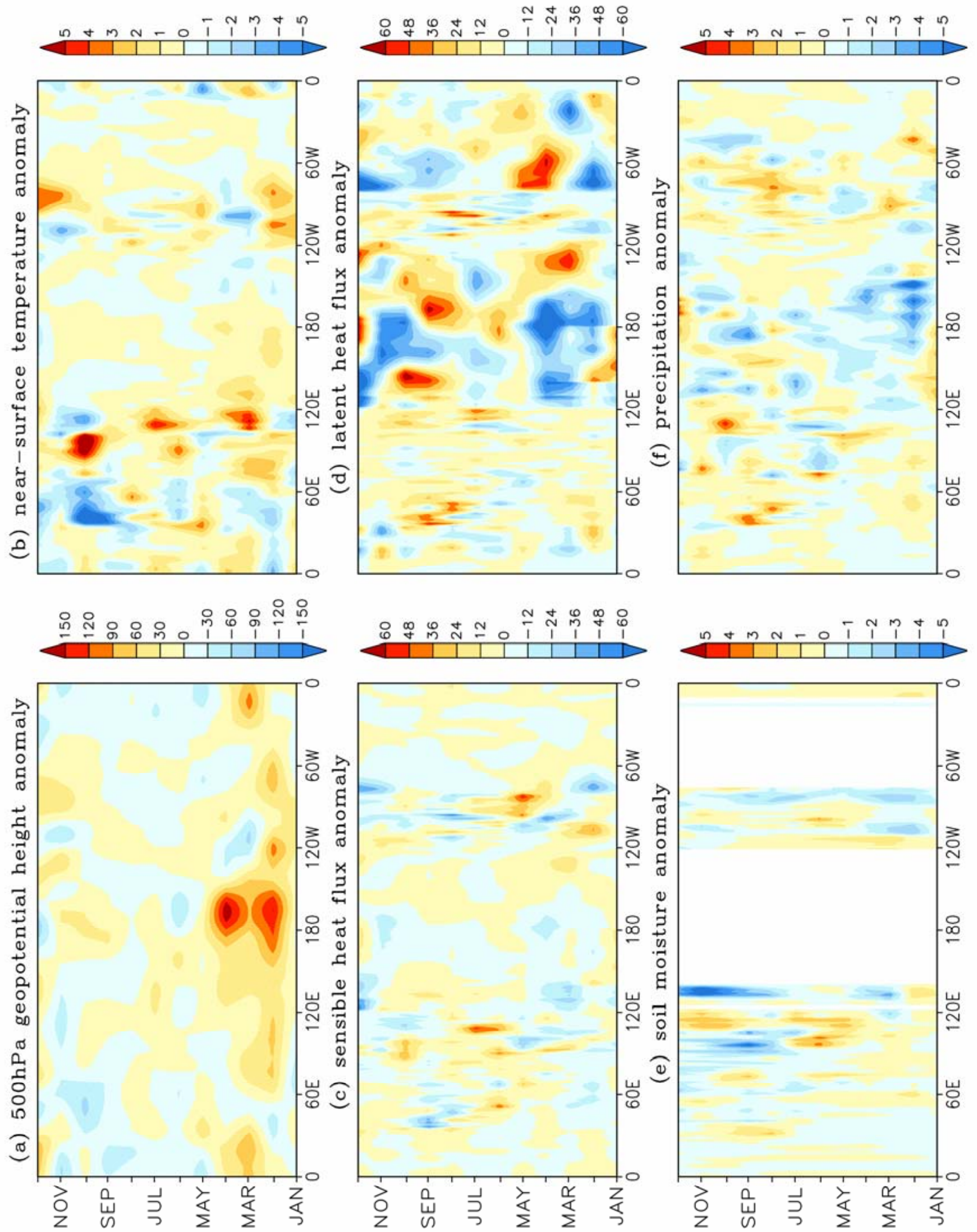

**Figure 3.** Longitude-time cross section of monthly-mean perturbations of (a) geopotential height (unit: m) at 500 hPa; (b) near-surface temperature (unit: ºC); (c) sensible heat flux (unit: W/m$^2$); (d) latent heat flux (unit: W/m$^2$); (e) soil moisture (kg/m$^2$); and (f) precipitation (mm/day). All variables are averaged over 30º-35ºN.

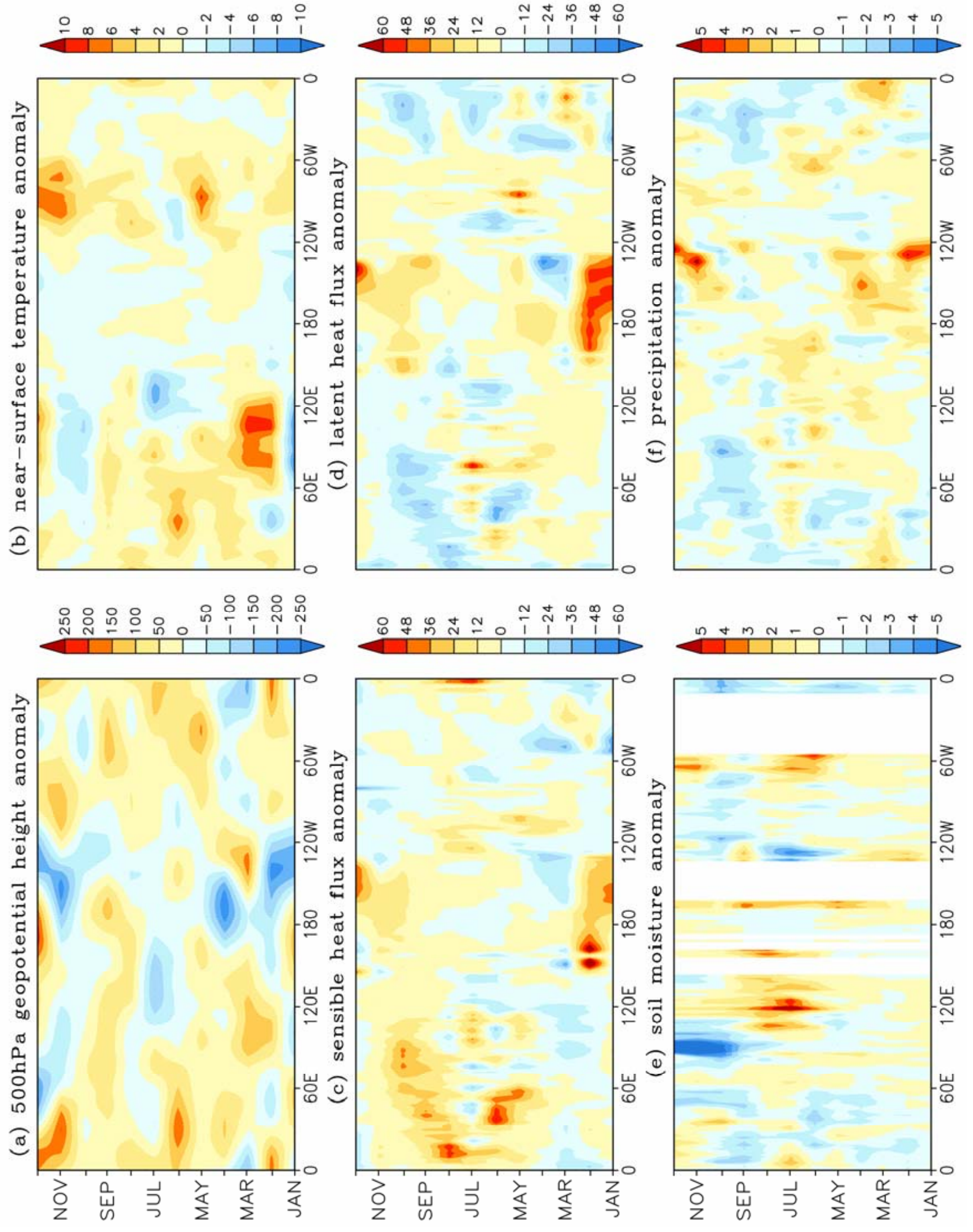

**Figure 4.** Same as Fig.3, but averaged over 50º-55ºN.

Spatial-time variation of abnormal geopotential height at 500 hPa is consistent to that of surface temperature anomalies, i.e. abnormal high (low) geopotential height corresponds to abnormal warm (cold) surface temperature (Fig.3a, b and Fig.4a, b). When warm wintertime SSTA appears in the KE, distinct changes in surface latent and sensible heat fluxes are found over the areas of SSTA. This clearly indicates that the abnormal SST can lead to changes of energy fluxes at local to regional scale between ocean and atmosphere. This result is compatible with studies of Tanimoto et al.[31] and Kelly[32]. Note that abnormal sensible and latent heat fluxes sustain over the land long after the SSTA disappears. Abnormal sensible and latent heat fluxes are significant and in-phase over the ocean in autumn and winter, while in summer they are anti-phase in many areas of the ocean (Fig.3c, d and Fig.4c, d). The sustaining of abnormal sensible and latent heat fluxes and their anti-phase changes in summer are related to abnormal changes in geopotential height, which weakens in summer but intensifies in autumn and winter. Most areas of large abnormal sensible and latent heat fluxes are located where surface temperature is high, e.g. high abnormal fluxes are found over the land from June to August but they are over the ocean from October to December (Fig.3b, c, d and Fig.4b, c, d). This fact indicates that warming surface condition is favorable for the development of abnormal disturbance. Spatial-temporal variations of abnormal soil moisture are consistent to that of sensible and latent heat fluxes especially over areas of large anomalies, indicating that warm wintertime SSTA over the KE can lead to simultaneous soil moisture anomalies. Since soil has a long memory with respect to the environment, the soil moisture anomalies can intrigue new and persistent perturbations in the atmosphere long after SSTA disappears. The atmospheric perturbations intrigued by SSTA affect soil moisture through their impact on precipitation changes, suggesting that precipitation and sensible and latent heat fluxes are important intermediate linkages between soil and atmosphere. In addition, changes in atmospheric temperature, humidity, and wind fields in response to warm SSTA in the KE lead to changes in cloud distribution and variability (Figure not shown), which subsequently affects surface-atmosphere exchanges of long-wave and shortwave radiation fluxes. Such kind of radiation impact, however, is relatively weak compared to that of soil moisture changes. In general, warm wintertime SSTA in the KE leads to simultaneous abnormal changes in soil moisture, which has a long memory and exerts continuous impact through affecting sensible and latent heat fluxes between the soil-atmosphere. Thus the atmospheric response to warm wintertime SSTA becomes sustaining long after the SSTA disappears.

### 3.2 *Atmospheric oscillation*

Analysis in section 3.1 reveals that SSTA and soil moisture anomalies are two external forcings that intrigue abnormal atmospheric response consecutively. The warm wintertime SSTA in the KE starts the atmospheric perturbation in the first place, while the subsequent changes in soil moisture and the long memory of soil intrigue new perturbations and make the anomalies sustainable after the SSTA no longer exists. To further evaluate the forcing mechanism of the sustaining atmospheric response to warm wintertime SSTA in the KE, we conduct power spectrum analysis of average geopotential height anomalies at 500 hPa and 200 hPa over the area of 31º–37ºN, 167º–173ºE, which is located within the KE. Power spectrum analysis of abnormal soil temperature and moisture is also performed over the area of 30º–35ºN, 80º–85ºE, where large soil moisture changes are found. Results are shown in Fig.5.

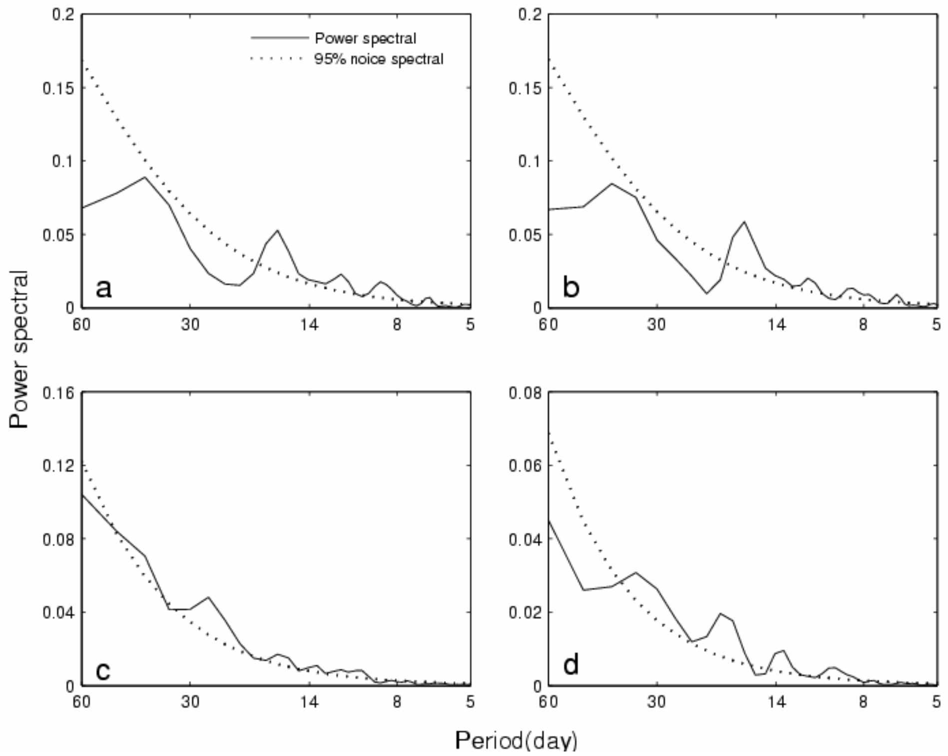

**Figure 5.** Power spectra density distribution of area-averaged geopotential height perturbations in the region (30º-35ºN, 115º-120ºE) at (a) 500 hPa; (b) 200 hPa; (c) soil moisture perturbation; and (d) soil temperature perturbation (at depth of 0.6 m).

All three variables (anomalies of geopotential height, soil temperature and soil moisture) demonstrate three prominent periodic oscillations, i.e. synoptic oscillation with period of 5–8 days, quasi-biweekly oscillation with period of 10–17 days, and weak low frequency oscillation with period in the range of 25–40 days (spectra peaks significant at 95% confidence). This result suggests that oscillations of perturbations in the atmosphere and in the soil are propagating with the same oscillation frequency. Atmospheric and soil perturbations not only remain after SSTA disappears, but also share similar oscillation frequency in their propagation. Signals of atmospheric response to warm SSTA in the KE are transferred between the soil and atmosphere following the three primary oscillation frequencies. Abnormal atmospheric response to SSTA in the KE is thus maintained by continuous forcing of soil anomalies after SSTA diminishes. Wang et al.[22] have found that SSTA in the KE can intrigue low frequency atmospheric oscillation, which is highly correlated with mid-latitude SSTA impact on the atmosphere. Based on power spectrum analysis of average 500 hPa and 200 hPa geopotential height simulated by CTRL over the area of (31º–37ºN, 167º–173ºE), it is found that synoptic oscillation, quasi-biweekly oscillation and low frequency oscillation are part of natural (intrinsic) atmospheric oscillations (Fig.6). Oscillations intrigued by warm wintertime SSTA in the KE, which have similar frequencies with that of natural atmospheric oscillations, are superposed on natural atmospheric oscillation and propagated with primary periodic oscillation of the atmosphere. These SSTA-intrigued oscillations are coupled with natural atmospheric oscillation and finally become parts of it. This is probably another reason for the sustaining atmospheric response to SSTA. Li et al.[34] and He et al.[35] have also found the important impact of SSTA on low frequency atmospheric oscillations.

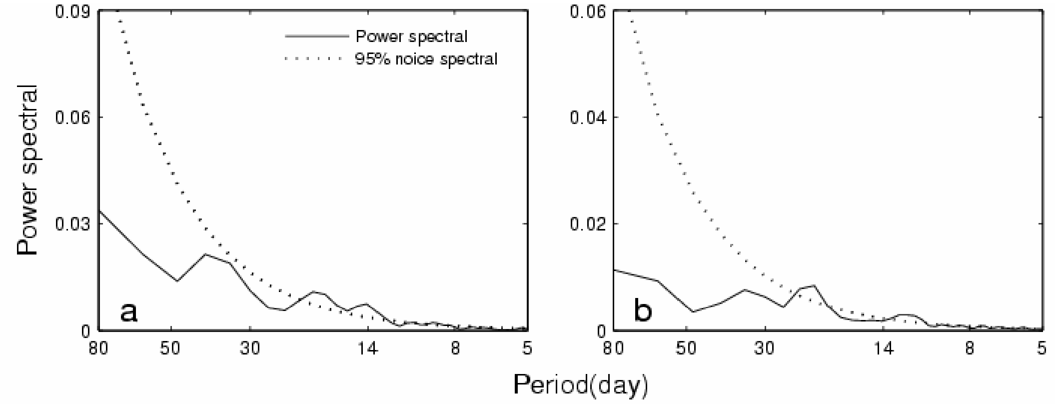

**Figure 6.** Power spectra density distribution of mean geopotential height over the KE region (31º-37ºN, 167º-173ºE) simulated by the control run at (a) 500 hPa and (b) 200 hPa.

## 4 SUMMARY AND DISCUSSION

Mechanism for sustaining atmospheric response to warm wintertime SSTA in the KE is explored based on studies of global atmospheric model CAM3. The results suggest that the atmosphere behaves like a linkage to transfer the anomalies intrigued by warm wintertime SSTA in the KE from atmosphere to soil, i.e. the perturbations coexist in both the atmosphere and soil. The abnormal soil condition interacts with atmosphere, resulting in sustainable atmospheric perturbation that is originally intrigued by SSTA. Apparently the changes in soil condition make significant contribution to maintaining SSTA-intrigued atmospheric perturbation after SSTA no longer exists. The atmospheric perturbation intrigued by warm SSTA in the KE consists of three primary periodic oscillations, i.e. synoptic oscillation, quasi-biweekly oscillation and intra-seasonal oscillation. After the SSTA disappears, these oscillations continue to exist due to feedback of abnormal soil conditions to the atmosphere. Frequencies of these three primary oscillations are close to that of natural atmospheric oscillations, suggesting that SSTA in the KE may affect periodic oscillation of the atmosphere. Oscillation of the abnormal perturbation intrigued by SSTA interacts with natural atmospheric oscillation and finally becomes part of it.

Lu[21] and Yamagata et al.[20] have found the important impact of external forcing on low frequency atmospheric oscillation. The warm wintertime SSTA in the KE can intrigue quasi-biweekly and intra-seasonal oscillations, which become sustainable and propagate in the atmosphere long after the warm SSTA disappears. This phenomenon suggests that the warm SSTA in the KE and the subsequent anomalies in the soil condition are two important external forcings, which can intrigue abnormal perturbations in the atmosphere and exert significant impact on low-frequency atmospheric oscillation by processes of wave-wave interaction. Analysis in section 3.2 indicates that synoptic oscillation still exists after the

SSTA disappears. We believe that this short-period (5–8 days) oscillation is probably attributed to the stationary wave intrigued by anomalies in soil condition. Sensitivity experiments have performed by Kirk-Davidoff and Keith[36] to investigate impact of surface roughness length on atmospheric circulation. Their results implied that abnormal changes in surface roughness length could intrigue quasi-stationary waves, which is closely related to background circulation in the atmosphere. The synoptic oscillation intrigued by SSTA and abnormal soil moisture in this study has similar characteristics to quasi-stationary waves in the atmosphere. We will further address this issue in our future study.

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