ADVANCES IN ATMOSPHERIC SCIENCES, VOL. 23, NO. 2, 2006, 181–189

The Role of the Kuroshio in the Winter North Pacific Ocean-Atmosphere Interaction: Comparison of a Coupled Model and Observations

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(Received 12 January 2005; revised 23 May 2005)

ABSTRACT

A comparative study between the output of the Flexible Global Climate Model Version 1.0 (FGCM-1.0) and the observations is performed. At 500 hPa, the geopotential height of FGCM is similar to the observations, but in the North Pacific the model gives lower values, and the differences are most significant over the northern boundary of the Pacific. In a net heat flux comparison, the spatial patterns of the two are similar in winter, but more heat loss appears to the east of Japan in FGCM than in COADS. On the interannual timescale, strong (weak) Kuroshio transports to the east of Taiwan lead the increasing (decreasing) net heat flux, which is centered over the Kuroshio Extension region, by 1–2 months, with low (high) pressure anomaly responses appearing at 500 hPa over the North Pacific (north of 25°N) in winter. The northward heat transport of the Kuroshio is one of the important heat sources to support the warming of the atmosphere by the ocean and the formation of the low pressure anomaly at 500 hPa over the North Pacific in winter.

Key words: coupled GCM, Kuroshio, net heat flux, atmospheric circulation anomaly, North Pacific

doi: 10.1007/s00376-006-0181-4

1. Introduction

There exists a largely-linear, stationary response to the SST anomaly in the tropical atmosphere, but in the extratropical atmosphere, the response is much more complicated because of the strong atmospheric internal variation and the strong feedback of the ocean-to-atmosphere forcing. In the Atmospheric Model Inter-comparison Project (AMIP), various models produced different results about the response of the atmosphere to SST anomalies in the middle latitudes (Kushnir et al., 2002). Some results are in a form of linear baroclinic response with a surface low pressure downstream of a warm SST anomaly, while others are an equivalent barotropic high response downstream of a warm SST anomaly (Kushnir et al., 2002). In general, the atmospheric response to the extratropical ocean is modest rather than strong, especially at monthly-to-interannual timescales. Therefore, determining the response of the atmosphere to mid-latitude SST variation remains a major challenge. Recently, it has been pointed out that the heat flux forces a low pressure downstream, resulting from a coupled AGCM-slab ocean model, in which an anomalous surface heat flux is prescribed to force the atmosphere (Yulaeva et al., 2001; Sutton and Mathieu, 2002). Liu and Wu (2004) suggested that the SST forcing favors a warm-ridge response, while the heat flux forcing tends to be associated with a warm-low response, because when the ocean loses heat at the sea surface, the SST will decrease. They suggested that the correct atmospheric response is generated in the fully coupled model that produces the correct combination of SST and heat flux naturally.

The SST anomaly in the Kuroshio region is an important factor that influences the atmospheric circulation and precipitation in China in summer (Li and Long, 1992), because the meridian heat transport is the main heat source to maintain the large net

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heat flux from the Kuroshio region to the atmosphere. There is a positive feedback process in the ocean and atmospheric interaction in winter based on the results of a simple ocean-atmosphere coupled model (Liu et al., 1993), and the maximum heat loss area is the Kuroshio Extension (KE) in the North Pacific (Liu et al., 2004c). Furthermore, in the heat balance of the mixed layer at a specific area (30°–34°N, 140°–170°E), namely the center of the heat loss in KE, only the geostrophic advection term is positive (to support the temperature increase) and the other terms are negative.

From previous research, it can be seen that the SST anomaly is not an ideal indicator of the ocean forcing to the atmosphere, whereas the net heat flux anomaly, on the other hand, can represent the interaction between the ocean and the atmosphere because, physically, the SST forces the atmosphere through the surface heat flux and is not independent of the heat flux. The atmospheric response to oceanic change depends not only on the SST, but also on the air-sea heat exchange. The net heat flux can either reflect the extent of the ocean's heating of the atmosphere or describe the effect of the atmosphere on the ocean. However, the problem is that the net heat flux partly depends on the atmospheric variation. It is fine to look at the response of the atmosphere to either SST or heat flux, but one must be aware that the response may not be the true response (Liu and Wu, 2004).

In winter, the net heat flux in the KE area is negative (oceanic heat loss) (Liu et al., 2004c). At the same time, effects of the southward Ekman transport and the mixing in the upper mixed layer are negative, for the former is the effect of cold advection and the latter is the reduction of the temperature in the mixed layer, and only the geostrophic advection effect is positive, which supports the heat balance in the KE area. Thus the northward heat transport of the Kuroshio is the only heat source to maintain the net heat flux from the ocean to atmosphere and the high SST in the KE area during winter. But we do not know whether the heat balance will be different or the same on interannual timescales. How important a role does the Kuroshio heat transport anomaly play in the interaction between ocean and atmosphere in winter in the interannual variability of atmospheric circulation? What is the response of the atmosphere to the net heat flux anomaly?

This paper is organized as follows. Section 2 gives a brief description of the observation data and the coupled model. In section 3, the similarities and differences between the climatic average results of observation and the coupled model output are given. In section 4, some statistics analysis, based on the observation data and coupled model output data, and a comparison between the two sets of data are made. Finally, summaries and discussions are given in section 5.

2. Data from observation and coupled model

The observational atmospheric variables are the monthly means of the geopotential height at 500 hPa (hereafter $Z500$) on a $2.5° \times 2.5°$ grid in the Northern Hemisphere from the NCEP–NCAR reanalysis during 1958–1999. The monthly mean net heat flux is from the COADS (Comprehensive Ocean and Atmosphere Dataset) data on a $1.0° \times 1.0°$ grid in the North Pacific.

The sea level data come from the University of Hawaii (UHSLC). Daily data are available from tide station Keelung (25°N, 121°45′E) during 1980–1999 as well as from Ishigaki (24°N, 124°E) during 1969–2000. Based on sea level data, Jia and Liu (2004) obtained the Transport of Kurishio to the East of Taiwan (TKET) and studied the period of its annual variation. In this paper, we use the data to calculate the monthly means of the transport of Kurishio to the east of Taiwan during 1980–1997.

The coupled ocean-atmosphere general circulation model (CGCM) used in this study is the Flexible General Circulation Model for climate systems, version 1.0 (FGCM-1.0) developed by the State Key Laboratory of Numerical Modeling for Atmospheric Sciences and Geophysical Dynamics (LASG) (Yu et al., 2002; Yu et al., 2004). The FGCM-1.0 is formulated based on the NCAR CCSM-2 (Kiehl and Gent, 2004) by replacing the original ocean component model, Parallel Ocean Program (POP) model (Smith et al., 2002), with the LASG/IAP Climate Ocean Model (LICOM) with an eddy-permitting resolution ($0.5° \times 0.5°$) (Liu et al., 2004a, b) in virtue of the CCSM's flux coupler. The coupled GCM FGCM-1.0 can reproduce a reasonable mean climatology and climate variability, such as ENSO, etc. (Yu et al., 2004; Yu and Liu, 2004; Li et al., 2004) although it suffers from some serious biases as a coupled GCM without any flux correction. In this paper, the geopotential height at 500 hPa, the net heat flux and the upper current data from FGCM during model years 242–298 are used. Furthermere, seasons always refer to those of the Northern Hemisphere—for example, the winter of 1999 refers to the three months of December 1998 and January and February 1999.

3. Comparison between the observed and modeled climate averages

Figure 1 shows the climatological background field of the geopotential height at 500 hPa in winter from the FGCM data and the NCEP–NCAR reanalysis data during 1958–1999 as well as the differences between the two sets of data. The pattern of the background circulation from FGCM is very similar to that from the observations (NCEP–NCAR), but a different maximum of 120 m appears on the north boundary of the Pacific (65°N, 180°) at 500 hPa, indicating that the result of the geopotential height in FGCM is lower than that nearby the north boundary of the Pacific but higher around the subtropical North Pacific. In the comparison of the climatological net heat flux, the two spatial patterns of net heat flux in winter are similar, but more heat loss appears to the east of Japan in FGCM compared to COADS (Fig. 2).

Figure 3 is the climatological current field to the east of Taiwan from the FGCM- LICOM1.0. From the figure, in the 24°N section, it can be seen that the West Boundary Current is strong above 500 m, between 122°E and 125°E (Fig. 3a). The maximum meridian current speed is 0.45 m s^{-1} at the surface (Fig. 3b). In this paper, we use the West Boundary Current above 500 m to calculate the transport of Kuroshio to the East of Taiwan (TKET).

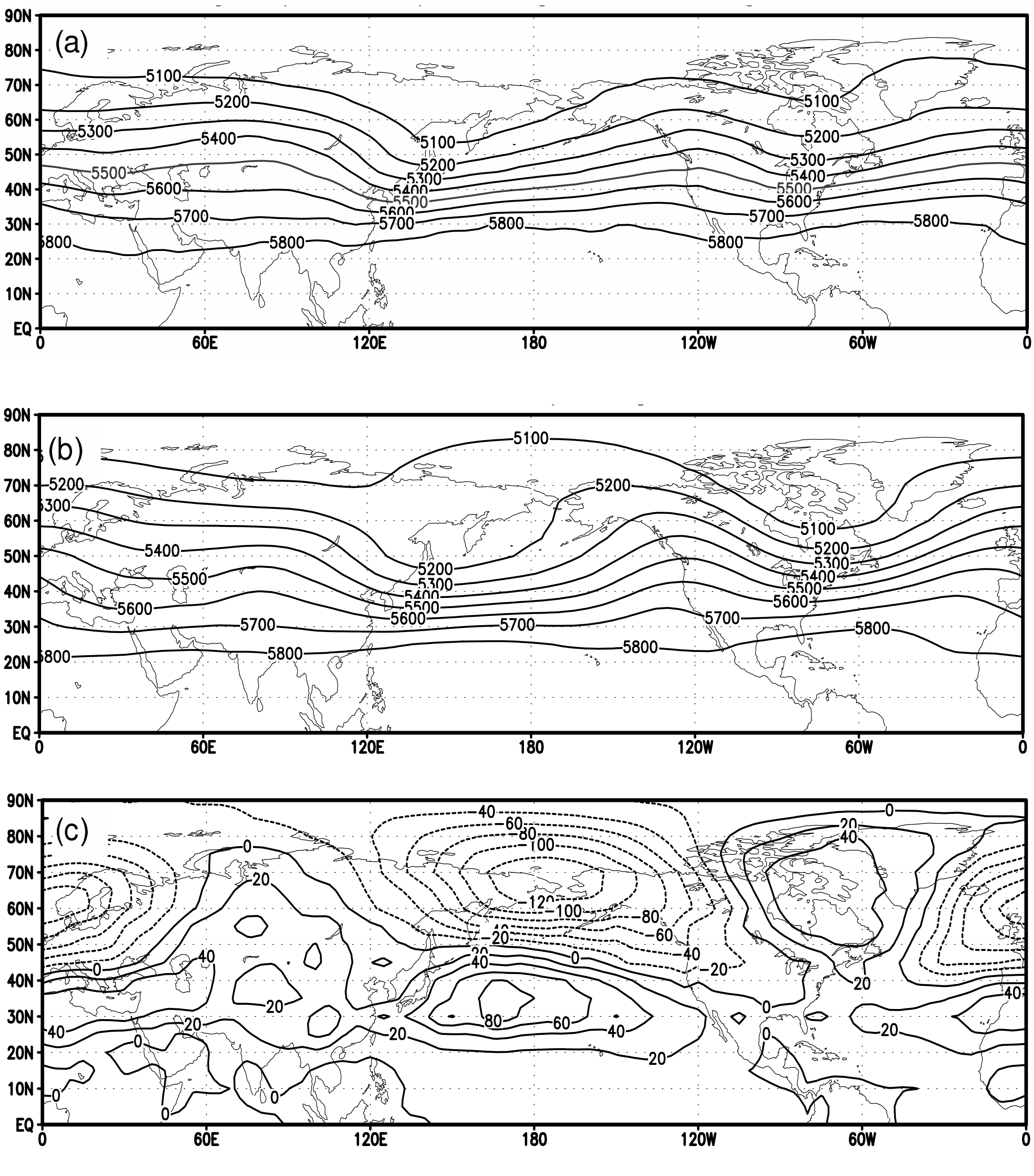

Fig. 1. Climatological background field of geopotential height (unit: m) at 500 hPa from (a) FGCM output, and (b) NCEP data, and (c) the difference between them in winter.

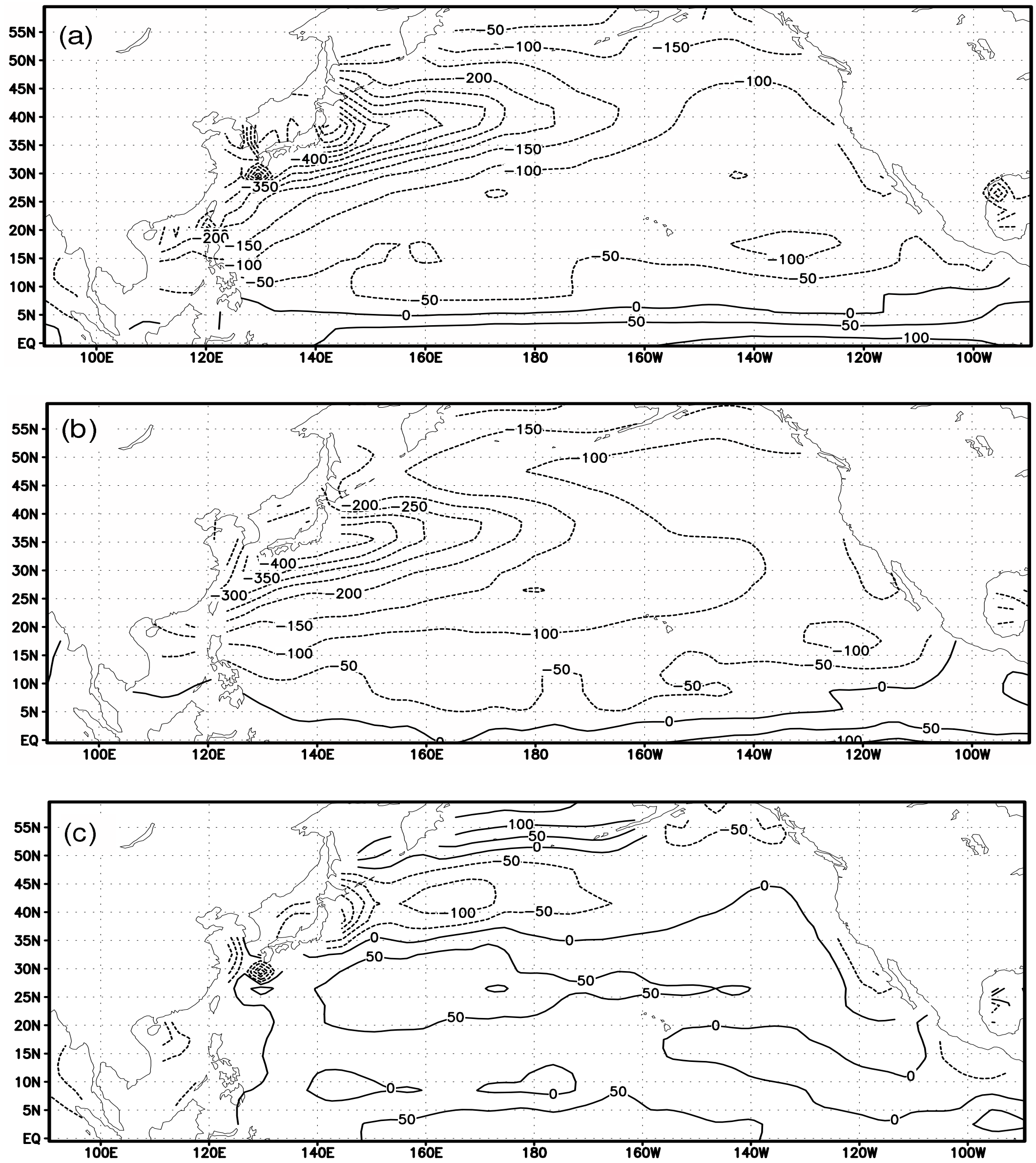

Fig. 2. The climatological net heat flux (W m^{-2}) in the North Pacific from (a) FGCM output, (b) COADS data, and (c) the difference between them in winter.

4. Statistical analysis of role of Kuroshio in the Ocean-Atmosphere interaction in the North Pacific

Using the observational datasets and coupled model simulations, it was shown that a surface heat flux pattern associated with the Gulf Stream variation plays an important role in forcing the winter North Atlantic oscillation (Wu and Rodwell, 2004). But what is the role of the Kuroshio in the annual variation of the ocean-atmosphere interaction in the North Pacific?

The singular value decomposition (SVD) between the geopotential height anomaly at 500 hPa and the net heat flux anomaly in the North Pacific is used in this paper. In order to make the number of spatial grids correspond to the size of the time sample during the SVD analysis, the sampling is made at $5° \times 5°$ grid in the Northern Hemisphere (0°–90°N, 0°–360°E) for Z500 and at a $2° \times 2°$ grid in the Northwest Pacific (10.5°–45.5°N, 120.5°–180.5°E) for the net heat flux.

4.1 *Observational data analysis*

Using the SVD analysis of the geopotential height anomaly at 500 hPa in the Northern Hemisphere from

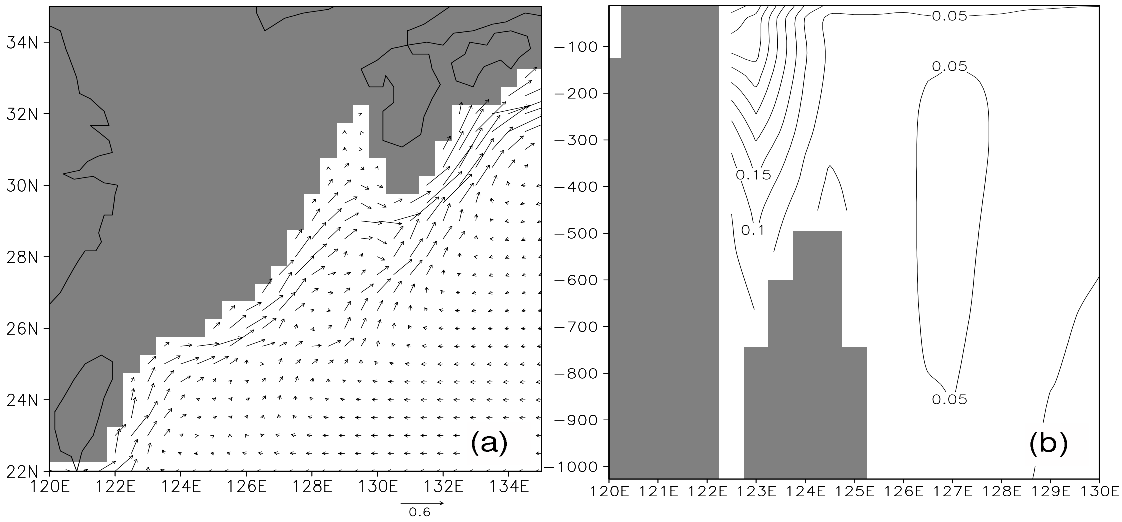

Fig. 3. (a) Current vectors at an ocean depth of 200 m and (b) the speed of the meridian current (contour interval is 0.05 m s^{-1}) along 24°N. The maximum meridian current speed is 0.45 m s^{-1}.

the NCEP–NCAR reanalysis and the net heat flux anomaly on the sea surface of the North Pacific from COADS in the winters of 1958–1999, the spatial distribution and time series of the first SVD mode (66.04%) of $Z500$ and the net heat flux are given in Fig. 4. It is clear that corresponding to the negative (positive) net heat flux anomalies, which means increases (decreases) in the heat-loss from the ocean in the North Pacific or atmospheric warming (cooling) in winter, there are low (high) pressure anomalies in the North Pacific and high (low) pressure anomalies in Asia, Europe, Northwest North America and the tropical Pacific to the south of 20°N at $Z500$. Moreover, it is noticeable that the center of the net heat flux anomaly is located at the Kuroshio and KE area. The correlation coefficient between both time series of the first SVD mode is 0.84, which means that the first SVD mode can represent the main coupling features between the North Pacific and the atmospheric circulations.

The leading and lagged correlation coefficients of three monthly mean TKETs with both time series of the first SVD modes (one is $Z500$ from the NCEP reanalysis data, and the other is the net heat flux in the North Pacific from COADS) during 1980–1992 are shown in Fig. 5. We have found that when the TKET leads both time series by two months, both correlation coefficients reach their maximums (0.65 and 0.75, respectively). This means that the increases (decreases) of TKET in October, November and December correspond to the low (high) pressure anomaly at Z500 and negative (positive) net heat flux anomaly in the North Pacific because the signal of increasing (decreasing) northward heat of TKET arrives in the KE area to influence the heat flux during the 1–2-month period.

According to the observation data, the role of the Kuroshio in the ocean-atmosphere interaction in the North Pacific in winter is such that the northward-transported heat of TKET in fall and winter could support the atmospheric warming by the ocean, and the atmospheric response is a low pressure at Z500 in winter. If this is right, we need to determine whether a similar event will occur with the FGCM.

4.2 *Coupled model result analysis*

Based on the SVD analysis of the $Z500$ anomaly in the Northern Hemisphere from the FGCM data and the net heat flux anomaly on the sea surface of the North Pacific from FGCM during model years 242–298, the spatial distribution and time series of the first SVD modes (59.18%) of $Z500$ and the net heat flux are shown in Fig. 6. There is a similar feature between FGCM and the observations in that the negative heat flux anomaly (the ocean losing heat to warm the atmosphere) should correspond to the low pressure anomaly. The correlation coefficient of both time series of the first SVD mode is 0.76 during model years 242–298. This corresponding relation can be found in the paper of Liu et al. (2004a, b, c, or d): the heat flux forcing tends to be associated with a warm-low response in the Pacific.

In FGCM, different from the observations, the pattern of the Z500 first SVD mode clearly shows the zonal low pressure anomaly band (20°N–50°N to west of 150°W and 20°N–40°N to east of 150°W) in the entire Northern Hemisphere. There is an opposite anomaly in the first SVD mode of heat flux in the Kuroshio and KE area of the East China Sea, but in

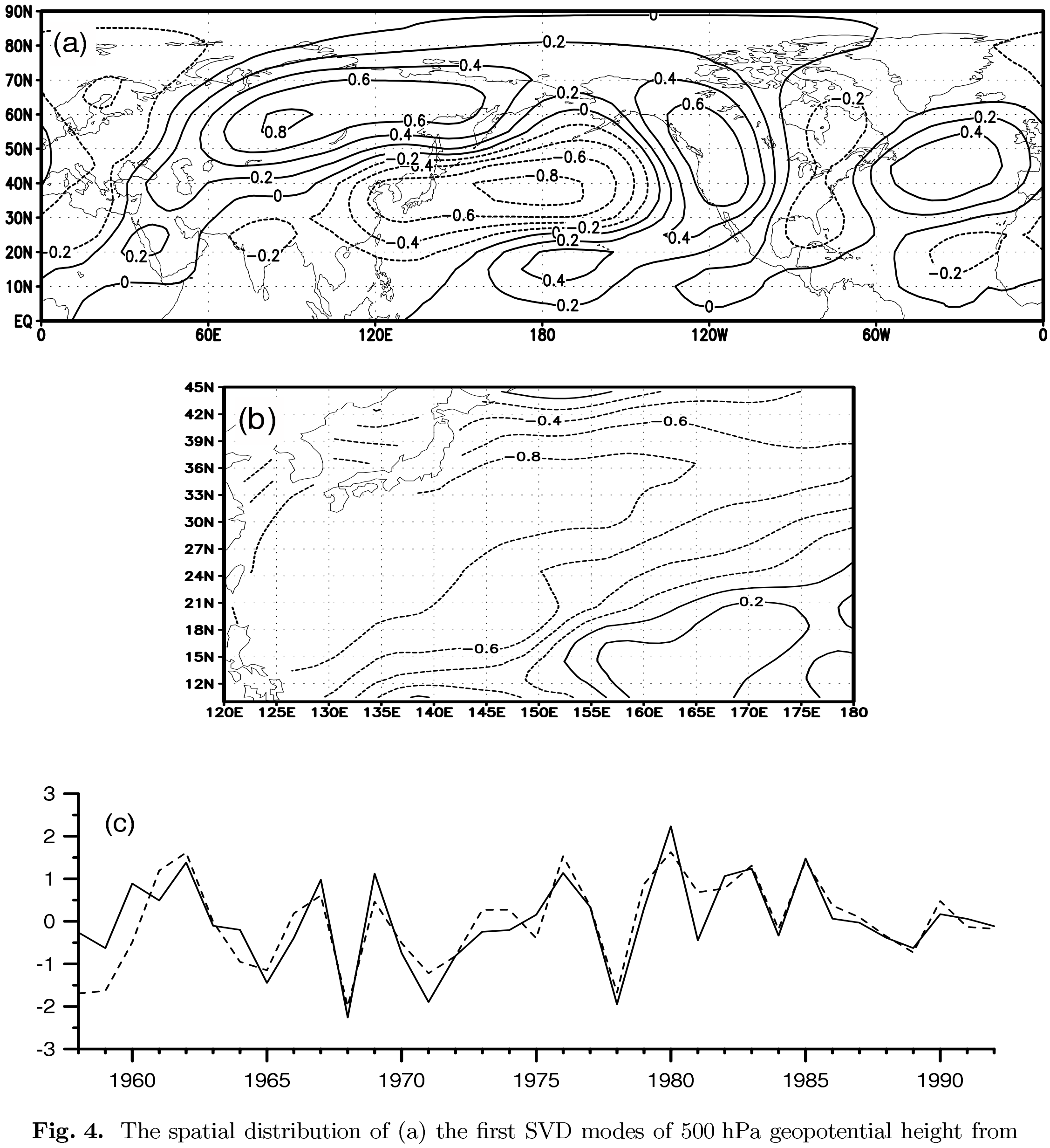

Fig. 4. The spatial distribution of (a) the first SVD modes of 500 hPa geopotential height from NCEP reanalysis data and (b) the first SVD modes of net heat flux in the North Pacific from COADS, and (c) their time series. In (c), the solid line corresponds to 500 hPa geopotential height, and the dashed line corresponds to net heat flux; the correlation coefficient of both time series of the first SVD mode is 0.84.

the first mode of heat flux from COADS, the anomaly signals are the same between the East China Sea and KE areas. For these differences, one reason is from the difference of the geopotential height at 500 hPa from the FGCM data and the NCEP–NCAR reanalysis data during 1958–1999 (Fig. 1), and another reason could be from the difference of heat flux, where more heat loss appears to the east of Japan (a zonal band of 35°N–50°N) in FGCM than in COADS (Fig. 2). In FGCM, the greater heat loss of the Pacific could mean that the warm-low response of the atmosphere is stronger than in the observations, which is proved in the ocean-atmosphere coupling (Liu and Wu, 2004), thus a zonal band of low pressure anomaly appears in the pattern of the $Z500$ first SVD.

The leading and lagged correlation coefficients of the three monthly mean TKETs with both time series of the first SVD modes (one is $Z500$, the other is the net heat flux in the North Pacific from FGCM) during model years 242–298 are shown in Fig. 6. A similar relation is found when the TKET leads both time seri-

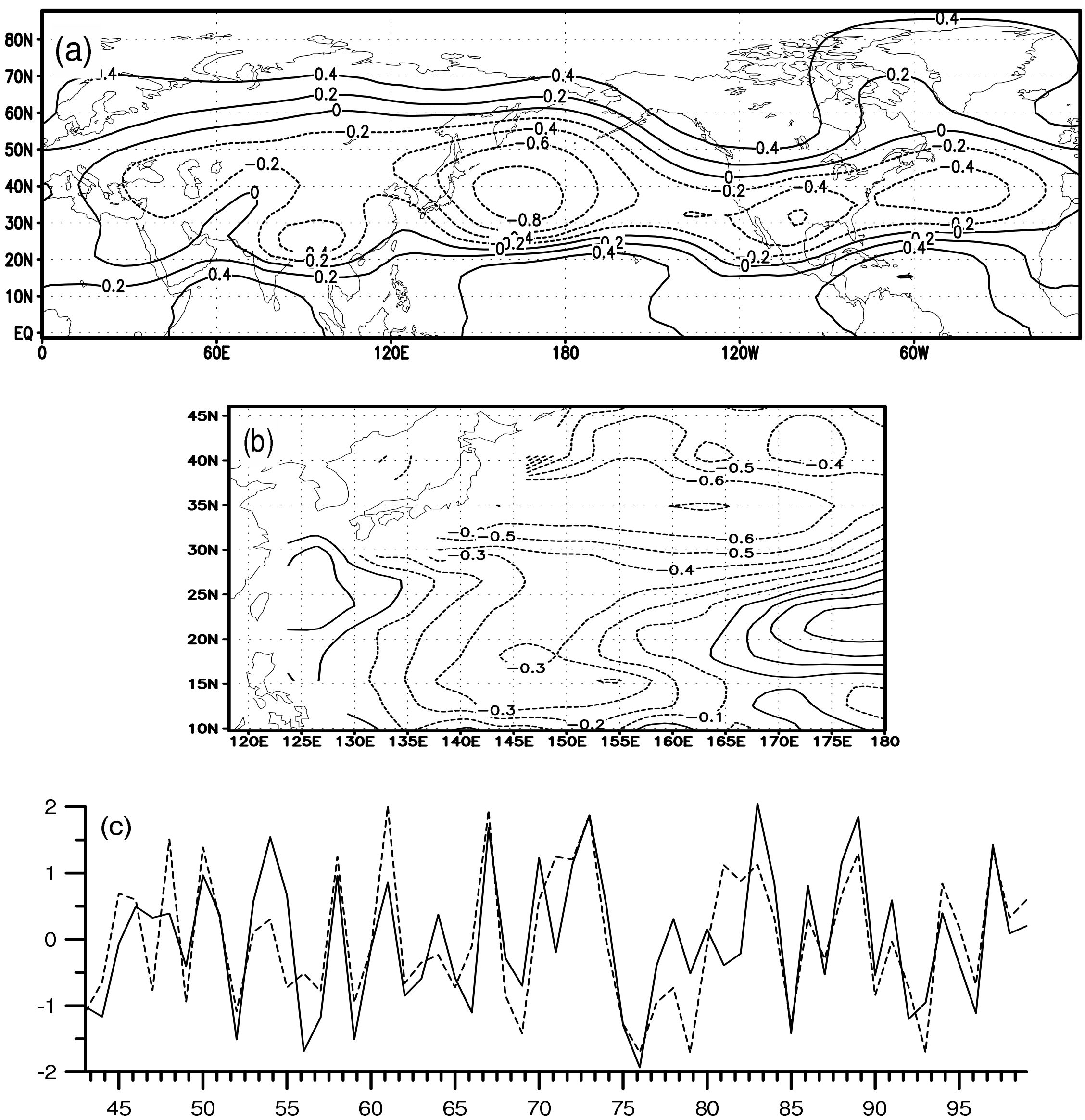

Fig. 5. As Fig. 4 except using FGCM during model years 242–298; the correlation coefficient of both time series of the first SVD mode is 0.76 in (c).

es by one month; both correlation coefficients reach their maximums (0.42 and 0.47, respectively). This means that the increases (decreases) of the TKET in November, December and January correspond to the low (high) pressure anomaly at Z500 and the negative (positive) net heat flux anomaly in the North Pacific in December, January, and February because the signal of increasing (decreasing) northward heat transport of the Kuroshio to the east of Taiwan arrives at the KE area to influence the heat flux in the KE area during the 1–2 month period.

5. Summary and discussion

In this paper, a brief description of the comparative study between the Flexible Global Climate Model (FGCM) and observational data was introduced. A heat loss maximum was found in the region of the Kuroshio Extension based on the climatological average of both the FGCM output and observational data. At 500 hPa, the geopotential height is similar to that of the observations, but it is lower in FGCM than in the observations in the North Pacific, and their differences are most significant in the northern boundary of the Pacific, where the maximum difference is 120 m around 65°N, 180°.

From statistical analysis, based on the observational data and coupled model output data, it can be seen that on the annual timescale, the main coupled

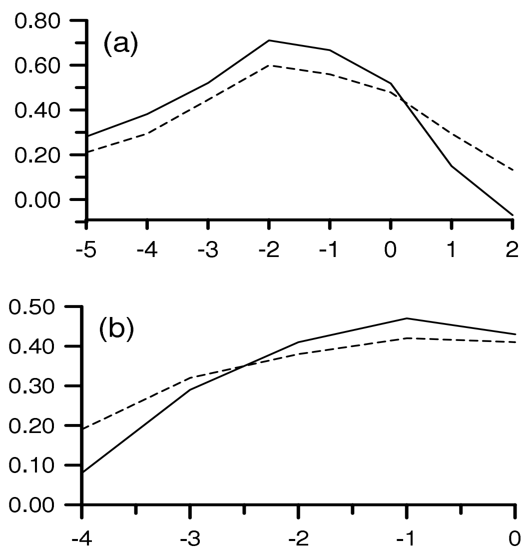

Fig. 6. Leading and lagged correlation coefficients of the three-monthly mean transport of Kuroshio to the east of Taiwan with the time series of the first SVD mode of 500 hPa geopotential height from (a) NCEP reanalysis data (sold line) and with the time series of the first SVD mode of the net heat flux in the North Pacific from COADS (dashed line) during 1980–1992, and (b) using FGCM data during model years 242–298.

mode of heat flux with atmospheric circulation at 500 hPa in the North Pacific is related to the Kuroshio transports to the east of Taiwan. The strong (weak) Kuroshio transports to the east of Taiwan lead the increasing (decreasing) net heat flux, centered at the Kuroshio Extension region, by 1–2 months, with low (high) pressure anomaly responses appearing at 500 hPa over the North Pacific (north of 25°N) in winter. The northward heat transport of the Kuroshio is one of the important heat sources to support the warming of the atmosphere by the ocean and the formation of the low pressure anomaly in the North Pacific in winter. There is some agreement between the observational and FGCM results regarding the role of the Kuroshio in the ocean-atmosphere interaction in the North Pacific. This study is consistent with the work on coupled models (Liu and Wu, 2004) in that the heat flux forcing tends to be associated with a warm-low response.

Now we still do not know why there is a corresponding low pressure anomaly when the atmosphere is warmed by the ocean anomaly in the North Pacific in winter, nor what the physical process of the response is. In the future, we will perform numerical experiments and detailed analyses with FGCM to prove the effectual process of the heat flux on the atmosphere.

Acknowledgments. The authors would like to thank Prof. Zhengyu Liu, Mr. Wei Liu and Mr. Wu Shu for giving good suggestions and comments. This work was jointly supported by an open project of LASG, the Natural Science Foundation of China (Grant Nos. 40333030 and 40231004), and the National Key Programme (G2000078502).

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