Interdecadal and Interannual Variability in the Northern Extratropical Circulation Simulated with the JMA Global Model. Part II: Summertime Leading Mode

RYUICHI KAWAMURA AND MASATO SUGI
National Research Institute for Earth Science and Disaster Prevention, Tsukuba, Ibaraki, Japan

NOBUO SATO
Japan Meteorological Agency, Tokyo, Japan

(Manuscript received 27 May 1994, in final form 31 March 1995)

ABSTRACT

Interdecadal and interannual variations of a model atmosphere in the northern extratropics is examined using a T42 GCM forced with observed near-global SSTs from January 1955 to December 1988. The leading mode of summertime 500-hPa height field deduced from the real SST experiment is found to be dominated by interdecadal variability. This mode shows a zonally elongated pattern with prominent loadings in low-latitude regions and accounts for an increase of the zonal, summertime 500-hPa heights in subtropical regions from the 1970s to the 1980s. Simulated springtime leading mode, which is dominated by interdecadal variability, exhibits a mixed pattern with the wintertime PNA mode and the summertime zonally elongated mode, whereas the zonally elongated pattern like the summertime EOF1 cannot be found in northern fall.

From an investigation based on the seasonality of tropical response of the model atmosphere, it is found that the summertime and springtime leading modes with a pronounced zonally symmetric component depend largely upon the tropical SST anomalies of interdecadal variability. The weakness of tropical response in fall contributes largely to the absence of the zonally elongated mode with definite interdecadal variability in this season.

The regional and temporal features of the observed decadal surface air temperature anomalies are well simulated by the real SST experiment. The time sequence of the above summertime EOF1, which accounts for a strong dependence of tropical atmosphere to SST anomalies, is found to coincide well with the summertime mean hemispheric land surface air temperature. It is inferred, therefore, that the tropical SSTs of interdecadal variability contribute a great deal to the decrease and increase in the Northern Hemispheric land surface temperature observed in recent decades.

1. Introduction

In terms of observation, recent long-term trends of global and hemispheric surface air temperatures have been reported by Hansen and Lebedeff (1987), Jones et al. (1982, 1986), Jones (1988), Chapman and Walsh (1993), and others. It is still uncertain, however, why the surface temperatures can fluctuate on an interdecadal timescale. If the interdecadal variability is regarded as one of the natural variations in the global climate system, the understanding of natural interdecadal variations would contribute substantially to the prediction and estimation of CO2 global warming in the near future. This is because we must distinguish the signature of global warming from natural interdecadal variability.

Very recently, Wallace et al. (1993) found that observed leading modes of summertime 500-hPa height and thickness, which is called background field, is strongly correlated with hemispherically integrated thickness and surface temperature. They suggested that the background field should be considered as a thermodynamical response to perturbations in the radiation and/or surface energy balance, rather than dynamical processes that seem to be important for wintertime teleconnection patterns. It is possible that their background field is forced with global-scale SST anomalies. We should thus address the question whether the interdecadal variations seen in the recent hemispheric surface temperature record, associated with the background field, can primarily be reproduced by the large-scale SST forcing. It is a powerful approach for resolving the problem to investigate such variability of the model atmosphere using a GCM forced with observed near-global SSTs.

It has been shown in Part I (Kawamura et al. 1995) that the interdecadal variability of the wintertime extratropical circulation over the North Pacific, which is

© 1995 American Meteorological Society
dominated by the Pacific/North American (PNA) mode, is largely controlled by tropical SST forcing. Although we highlighted the interdecadal-scale feature in North Pacific height fields, we did not discuss in Part I the issue on interdecadal variations of the Northern Hemisphere surface air temperature, which is an indicator of global warming. Graham (1995) already succeeds in demonstrating that global land surface temperature variations from 1970 to 1988 are principally reproduced with the Max-Plank-Institut T21 GCM employing observed global SSTs. He suggested that the recent increase in global tropospheric temperature is caused by an increase in the tropical hydrologic cycle, associated with increasing tropical SSTs. However, since he does not highlight geopotential height fields in the extratropics and discusses only annual mean temperatures in observed and simulated tropospheres, it is still uncertain how tropical and extratropical atmospheres respond seasonally to global SST forcing of interdecadal variability.

Although in Part I we already examined wintertime response of tropical and extratropical atmospheres to SST forcing, seasonal response should further be considered in this part of our study because it is expected from Wallace et al. (1993) that summertime extratropical circulations contribute a great deal to hemispheric-mean surface temperature.

The purpose of this study is 1) to evaluate the ability to simulate the recent warming with interdecadal timescale, 2) to clarify simulated summertime leading modes appearing in the northern extratropics, also considering other seasons, and 3) to discuss the response of the model atmosphere to SST anomalies, associated with hemispheric-mean surface air temperature. Experimental design and data used are the same as those in Part I. An elaborate explanation of the model is given by JMA/NPD (1993). Further used is the land surface air temperature dataset produced by Jones (1988). Section 2 gives spatiotemporal variability of summertime leading modes, with a brief documentation of the other season's analysis. Seasonal response of model atmosphere to SST forcing is discussed in section 3. Section 4 finds a concluding summary of the results obtained in this paper.

2. Interdecadal modes appearing in the Northern Hemisphere

a. Interdecadal-scale surface air temperature anomalies

To discuss interdecadal variability of surface air temperature seen in the model atmosphere, we must assess the interdecadal timescale trend simulated by the GCM used in this study. We will first compare the decadal-scale anomaly patterns of model-simulated annual mean surface air temperature with the observed temperature patterns.

Figure 1 shows the difference in simulated annual mean surface air temperature for the decade 1979–88 versus the decade 1967–76, which is compared to that observed. In the observed surface temperature field, warm anomalies in the northern extratropics are indicated over northern Eurasia, Alaska, and northwestern Canada, while slightly cooler temperatures occurred over northern Europe. Differences between the two decades reach about 0.8°C in northern Eurasia and 1.0°C in Alaska. Simulated regional features coincide well with the observed patterns, although the magnitude of simulated surface temperature anomalies is generally somewhat small compared with that observed. Indeed, the overall patterns of the observed decadal surface air temperature anomalies are well simulated by the real SST experiment. However, there are still local
differences in the anomaly pattern. For instance, one of the remarkable differences is central Eurasia near the Tibetan Plateau, with simulated negative temperature anomalies, but this region is also accompanied by a scarcity of observations.

Northern Eurasia experiences a strong warm winter during the 1979–88 period; this tendency lasts from spring to early summer. In this case, one of the reasons why the model-derived amplitudes are smaller than the observed may be attributed to “zonalization” that the planetary wave is too weak, which is evidently seen in winter. Another reason may be due, at least partly, to the simulated soil moisture variability in the snow-melting process over northern Eurasia from spring to early summer. However, we do not deal with this problem in this paper.

b. Summertime leading modes

In a similar manner as in Part I, we examined low-frequency modes prevailing in the summertime (June–August) northern extratropics. The EOF1 of the summertime 500-hPa height field derived from the real SST run, which accounts for 16.0% of the total variance, exhibits a zonally elongated pattern with prominent loadings in low-latitude regions and positive loadings extend northward up to the midlatitude regions around 40°N latitude (see Fig. 2a). This mode is found to be characterized by the predominance of interdecadal variability, as shown in Fig. 3a. The signature of interdecadal variability is much more evident than that in the model-derived wintertime PNA mode (see Fig. 4b in Part I). Although we also apply the rotated EOF (R-EOF) analysis to summertime 500-hPa geopotential height anomalies, derived R-EOF modes are very similar to the above leading modes in loading pattern and time sequence (not shown). In a sense, this confirms that the modes with a pronounced zonally symmetric component, which are deduced from both experiments, exhibit hardly remarkable local structure in the loading pattern. Conversely, wintertime teleconnection patterns such as the PNA mode have conspicuous regional features. The summertime EOF1 obtained by the real SST run coincides well with that observed, with respect to significant loadings located in low-latitude regions (Fig. 2b) and also the interdecadal feature of time coefficients (Fig. 3b). The observed pattern, which is EOF1 associated with 9.2% of the total variance, is similar to the subtropical zonal mode defined by Barnston and Livezey (1987).
The summertime EOF2 deduced from the real SST run (figure not presented), on the other hand, seems to be the North Atlantic Oscillation--like mode, as documented observationally by Barnston and Livezey (1987), Wallace et al. (1993), and others. It is found, however, that the simulated mode is hardly dominated by any interdecadal variability.

As stated previously, it is found that the summertime EOF1 obtained by the real SST run indicates one particular polarity at several periods on decadal to interdecadal scales. Indeed, pronounced negative amplitudes are seen during the period 1971–79, while positive amplitudes are prominent during the period 1980–88. Figure 4 indicates the difference in mean surface air temperatures for the period 1980–88 for June through August versus the period 1971–79. In the northern extratropics, northern Eurasia, with the exception of eastern Siberia, experienced an interdecadal increase in temperature of about 1°C, and a conspicuous increase is indicated to the same degree over Alaska and northwestern Canada, while cooling occurred over Europe, eastern Siberia, and eastern Canada. It can be clearly seen that in the Southern Hemisphere, Australia experienced an increase in temperature of about 1°C. An intriguing feature is that in the northern extratropics this anomaly pattern coincides roughly with the decadal-scale annual mean temperature anomaly pattern shown in Fig. 1.

In a similar fashion, Fig. 5 reveals the differences in summertime mean model-derived sea level pressure and 500-hPa geopotential height. An increase in the 500-hPa height is found over all the low-latitude regions, as expected from the time series of summertime EOF1 deduced from the real SST run. In the northern extratropics, positive anomalies are indicated over central Asia around the Caspian Sea, and a north–south anomaly pattern is predominant over the North Pacific. A further indication is that the 500-hPa height anomaly pattern contains a zonally symmetric component across the equator. Correspondingly, a similar north–south anomaly pattern in the sea level pressure field is found over the North Pacific, and in that sense, the circulation anomaly field there exhibits an almost barotropic structure. In the sea level pressure field negative anomalies are indicated from the northern Indian Ocean to east of the Philippines, and this appears to be originated by the warming Indian Ocean and tropical western Pacific SSTs, as depicted in Fig. 4.

c. Leading modes in spring and fall

To examine seasonal dependence of interdecadal variability in the northern extratropics, we further extracted recurrent modes prevailing during the spring (March–May) and fall (September–November) seasons. As demonstrated in Fig. 6, the EOF2 of springtime 500-hPa height field deduced from the real SST experiment is indicative of a combined pattern with the wintertime PNA mode and the summertime zonally elongated mode (EOF1). The corresponding time series of EOF2 (not shown) is dominated by interdecadal variability and coincides well with those of the summertime EOF1 rather than of the wintertime PNA.

In the northern fall, the zonally elongated pattern like the summertime EOF1 could not be extracted as one of the leading recurrent modes, although the PNA-like mode was derived from the real SST run. Hence, although spring and fall are similar transition seasons, the simulated leading modes in both seasons are con-
for the warmness or coolness of the troposphere in low-latitude regions, in close association with the tropical SST of interdecadal variability. Indeed, Fig. 8 shows that the time component of summertime EOF1 is strikingly in parallel with summertime 200-hPa height variations averaged over the whole tropical region between 10°N and 10°S.

The tropical response (Fig. 9) in spring and fall seasons tends to be weaker than that in winter, and the areas greater than 200% do not extend entirely into the Tropics as the summertime response. Furthermore, if we highlight the tropical Pacific region, the tropical response in fall is weakest in all seasons (Fig. 9b). This fact is intimately in association with the absence of the zonally elongated pattern with pronounced interdecadal variability in northern fall, as documented in section 2c.

b. Northern extratropical surface temperature

As found in the loading pattern of simulated summertime EOF1, the spatial pattern is characterized by an extension of positive loadings up to around 40°N, whereas we cannot find such a zonally elongated mode in the climatological SST run. This fact suggests a possibility that the model atmosphere responds hemispherically to tropical SST anomalous forcing. Thus, we tried to compare 200-hPa height variations in the Tropics, which reflects a response of tropical atmosphere to the SST forcing, with Northern Hemispheric land air surface temperature variations averaged over the Northern Hemisphere north of 20°N.

As shown in upper panel of Fig. 10, we can see that simulated annual and summertime mean land surface air temperatures indicate a significant increase of about 0.2°C from the 1970s to the 1980s, whereas both of the two time series demonstrate a decrease of about 0.25°C from the 1960s to the early 1970s. Another indication is that these time series are well in parallel with each other. These features are supported by observation

---

Fig. 6. Spatial pattern of EOF2 appearing in the 500-hPa height field in northern spring, derived from the real SST experiment. Contour interval is 0.02 in relative units and shading indicates negative values.

SST forcing

a. Tropical response of model atmosphere

As shown in Fig. 7, in northern summer the maximum region of the 200-hPa geopotential height standard deviations is located in almost the same region as the central equatorial Pacific, but response is at most in excess of 250% and somewhat weaker than that in northern winter. Compared with northern winter, furthermore, the tropical response tends to be relatively strong over the Indian Ocean, the Atlantic Ocean, and the African region. In other words, although the wintertime tropical response is strongly localized over the central equatorial Pacific (see Fig. 9 of Part I), the summertime response tends to be comparatively strong throughout the tropical regions, which is expected to bring a significant change of tropical east–west circulation. This finding also supports that the summertime EOF1 (i.e., the subtropical zonally elongated pattern) of interdecadal variability depends mostly on the SST anomalies over the tropical oceans. That is, we can see the summertime EOF1 as a dominant mode accounting

---

Fig. 7. Ratio (%) of standard deviations of simulated 200-hPa geopotential heights in the real SST run to the corresponding values in the climatological SST control run, as computed using the monthly means for June–August. Contour interval is 20% and values greater than 200% are shaded.
(lower panel of this figure). Observed summertime and annual mean temperature anomalies decrease from around 1960 to the early 1970s and then increase up to the 1980s. The difference in temperature between cold and warm periods is approximately 0.2°–0.3°C, which is roughly comparable to that simulated. These coincidences imply that our model is successful in simulating the behavior of interdecadal variations of the hemispheric land surface air temperature as well as Fig. 1. It should be noted, however, that there is a significant difference in temperature between simulation and observation during the late 1960s.

The most notable feature in this figure is that simulated summertime 200-hPa height variations in the Tropics correspond a great deal to the summertime and annual mean Northern Hemispheric land surface air temperatures on the interdecadal scale. It is expected that warming of the upper troposphere over the entire Tropics leads to an increase in poleward heat transport and, as a consequence, affects the tropospheric temperature field in the northern extratropics. It is strongly suggested, therefore, that the interdecadal variability of the hemispheric land surface temperature, at least in summer, is largely controlled by the tropical SSTs of interdecadal variability. In particular, the tropical SST forcing primarily causes the decadal warming of the Northern Hemispheric land surface air temperature from the 1970s to the 1980s. According to observations, it is confirmed that tropospheric temperatures in the Northern Hemisphere are strongly correlated with tropical SSTs with a signal of ENSO (Newell and Weare 1976; Angell 1981, 1990; Angell and Korshover 1981; Pan and Oort 1983). Also in the interdecadal timescale, tropical SSTs seem to influence the Northern Hemispheric tropospheric temperatures in a similar manner.

4. Discussion and concluding remarks

It is found that the time series of summertime EOF1, which is deduced from the real SST experiment, coincide well with the observed annual and summer seasonal mean Northern Hemispheric surface air temperature anomalies. Wallace et al. (1993) found that observed summertime leading mode, which is called background field, is strongly correlated with hemispherically integrated thickness and surface temperature. Our model-derived summertime EOF1 tends to be similar to their background field in many aspects with an exception of the difference in loading pattern. It is inferred that the simulated summertime EOF1 of interdecadal variability is strongly induced from the inter-
decadal-scale SST forcing in the Tropics, as documented in the previous section.

Recent decadal-scale wintertime temperature fluctuations in Alaska, northwestern Canada, and central northern Eurasia contribute substantially to hemispheric mean surface air temperature (e.g., Trenberth 1990; Folland et al. 1990). It was confirmed in Part I, in fact, that the change of circulation regime linked with the dominance of PNA substantially influences wintertime temperature anomalies in these regions. On the other hand, Wallace et al. (1993) insisted that the PNA contributes largely to the increase in the hemispheric annual mean surface air temperature from the late 1970s to the 1980s but that the decrease from around 1960 to the early 1970s depends on summertime mean temperature. From our model results, it is seen that the hemispheric annual mean temperature time series are more highly correlated with the summertime mean temperatures (0.81) than with the wintertime mean temperatures (0.65). It is most likely that differences in such seasonal mean temperature contributions are due, at least partly, to the predominance of leading modes such as simulated wintertime PNA and summertime zonally elongated modes (EOF1).

It is further found that the tropical and extratropical responses of the model atmosphere to SST anomalies depend largely upon season and geography. In the wintertime northern extratropics, as shown in Part I, localized response confined to the central equatorial Pacific exerts a strong influence upon the polarity of the simulated PNA mode, whereas summertime tropical response is found to extend not only over the equatorial Pacific but also over other tropical regions. In northern summer the tropical Indian and western Pacific Oceans actually experience warming from the 1970s to the 1980s. By what is the seasonal and regional dependence of tropical SST anomalies of interdecadal variability caused? One may regard the signature of the interdecadal variability of SST as a result of modulation of ENSO. One may argue that the interdecadal mode is independent of the ENSO mode. It is not easy to answer the above question, and further studies on the interdecadal atmospheric variability must be done through reexamination of the model deficiencies. It can be emphasized in this paper, however, that the regional and seasonal dependence of tropical response of the model atmosphere to SST anomalies affects the features of the interdecadal variability appearing in the northern extratropical atmosphere.

The conclusions obtained in this paper are summarized below.
The leading mode of summertime 500-hPa height field derived from the real SST experiment is a zonally elongated pattern with prominent loadings in low-latitude regions. This mode is characterized by pronounced interdecadal variability. The summertime tropical response tends to be comparatively strong throughout the Tropics, although the wintertime response is strongly localized over the central equatorial Pacific. This mode of interdecadal variability depends largely upon SST anomalies in the Tropics.

The springtime leading mode exhibits a mixed pattern with the wintertime PNA mode and the summertime zonally elongated mode (EOF1). The corresponding time series is dominated by interdecadal variability and coincides well with those of the summertime EOF1 rather than of the wintertime PNA. In northern fall, the zonally elongated pattern such as the summertime EOF1 is not seen as one of the leading recurrent modes. The weakness of the tropical response in fall brings the absence of the zonally elongated pattern with definite interdecadal variability.

The simulated summertime mean hemispheric land surface temperature is found to coincide well with the time sequence of summertime EOF1 and 200-hPa height variations averaged over the entire tropical region. It is inferred that the interdecadal variability of the Northern Hemispheric land surface air temperature, at least in summer, is controlled by the tropical SSTs of interdecadal variability. The decadal changes of the hemispheric land surface temperature seen in recent decades, in particular, are primarily caused by the tropical forcing.

Acknowledgments. We wish to specially thank Dr. Kanzaburo Gambo and Dr. Kevin E. Trenberth for their helpful comments. The authors deeply appreciate anonymous reviewers’ relevant comments, which led to an improved presentation of the manuscript. This research was supported by the Science and Technology Agency through the project study of disaster predictions in global hydrological processes. Computations were performed with the CRAY Y-MP2E/264 supercomputer of the National Research Institute for Earth Science and Disaster Prevention.

REFERENCES


