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

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

ABSTRACT

Interdecadal and interannual atmospheric variability in the extratropical Northern Hemisphere is investigated using an atmospheric GCM. The model used for this research is a T42 GCM version of the Japan Meteorological Agency (JMA-GSM89) global model. The 34-yr integration from January 1955 to December 1988 has been performed employing the real observed near-global SST condition. To estimate internal variability of the tropical and extratropical atmospheres, another 34-yr integration was conducted using the seasonally varying, climatological SST without interannual variability.

Using the rotated EOF analysis, the authors made an intercomparison of the Pacific/North American (PNA) wintertime teleconnection patterns prevailing in the observed and simulated extratropical atmospheres in the two experiments. The polarity of PNA derived from the real SST experiment is indicative of definite interdecadal variability, particularly an abrupt change of the midlatitude circulation regime over the North Pacific in the 1976/77 winter. By contrast, this mode, deduced from the climatological SST control run, has intermonthly and short-term interannual variability but no pronounced interdecadal variability.

It is strongly suggested that the anomalous SST forcing exerts strong influence on the PNA mode and modulates its amplitude, and as a consequence, longer-term variability, such as interdecadal variability, has appeared in the time sequence of this mode. It is confirmed from the T42 GCM experiment that the interdecadal variations of the wintertime extratropical atmosphere over the North Pacific are substantially controlled by the anomalous SST forcing in the Tropics, and that, in particular, the tropical forcing is primarily responsible for the abrupt change of the midlatitude circulation regime in the 1976/77 winter.

1. Introduction

The studies of air–sea interaction on interannual timescales have been focused mostly on the El Niño–Southern Oscillation (ENSO) timescale (2–5 years), but investigation of the interdecadal variability of the air–sea interactive system has very recently begun, especially over the Pacific sector. It has been reported that deepened Aleutian lows occurred over the period from 1977 to 1987; this fact is associated with warming of the tropical Pacific SST (Namias et al. 1988; Nitta and Yamada 1989; Trenberth 1990). Furthermore, the interdecadal variability of large-scale SST is observed not only over the North Pacific, but also over the North Atlantic and the Indian Ocean (Polland et al. 1993; Tanimoto et al. 1993; Kushnir 1994; Kawamura 1994; and others). Trenberth and Hurrell (1994) review in detail the decadal-scale variations of the atmosphere–ocean system in the Pacific. New intriguing findings regarding the western Pacific are reviewed by Yamagata and Masumoto (1992).

Interdecadal atmospheric variability in the northern extratropics has been simulated using several atmospheric GCMs with observed near-global SSTs. Kitoh (1991) showed that the leading mode with interdecadal variability appears in the model atmosphere of the Meteorological Research Institute GCM. Graham (1994) demonstrates that the extratropical low-frequency mode simulated with the European Centre for Medium-Range Weather Forecasts–Max-Planck-Institut T21 GCM resembles that observed. Likewise, although their study does not necessarily highlight the interdecadal variations, Lau and Nath (1994) performed 43-yr simulations from 1946 to 1988 with the Geophysical Fluid Dynamics Laboratory (GFDL) R15 GCM employing three kinds of observed, monthly varying SST conditions: near-global ocean, tropical Pacific, and midlatitude North Pacific. Their leading singular value decomposition (SVD) modes for near-global ocean

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SST and tropical Pacific SST experiments are indicative of stronger interdecadal variations. Graham et al. (1994) also presented similar results to Lau and Nath (1994), applying the procedure of canonical correlation analysis similar to SVD. Thus, the interdecadal variations observed in the northern extratropics are, at least partly, simulated using several GCMs. It should be noted, however, that the simulated interannual and interdecadal variability depends strongly on the individuality of the GCM. For example, if a GCM does not have the ability to simulate the internal variability in the midlatitude atmosphere, the conclusions leading to the derived results on the interdecadal variability may be quite different. Therefore, we should further investigate the interannual and interdecadal variability of the model atmosphere using the GCMs with the ability to simulate the current climate accurately.

The purpose of this study is 1) to investigate interdecadal and interannual variability of the simulated leading wintertime recurrent modes appearing in the northern extratropics, and 2) to discuss the wintertime response of the model atmosphere to SST anomalies, using a T42 GCM. The plan of this paper is as follows. We first document the experimental design in section 2, with a brief description of the data and the analysis procedure. Section 3 offers the spatiotemporal variability of low-frequency recurrent modes prevailing in the northern extratropics. In section 4 we examine the tropical and extratropical responses of the model atmosphere to the prescribed SST anomalies. A concluding summary of the results is found in section 5.

2. Experimental design and analysis procedure

An atmospheric GCM is integrated for 34 yr from January 1955 to December 1988. The model used for the present study is a low-resolution (T42/L21) GCM version of the Japan Meteorological Agency (JMA-GSM89) global model. The horizontal resolution is equivalent to approximately 2.8° latitude by 2.8° longitude. The parameterization of deep convection in the model employs a modified Kuo scheme. In radiation processes, longwave cooling and solar heating with interactive cloud are taken into account. The land surface process uses a simple biosphere model. The surface exchanges employ Louri’s scheme for surface fluxes and a level-2 closure model for vertical diffusion. A detailed explanation of the model is given by JMA/NPD (1993). The 34-yr integration has been conducted using the real observed near-global SST for 30°S to 55°N. Also used are the monthly mean SST data compiled by the U.K. Meteorological Office (Parker and Folland 1988). We give climatological SST data for higher-latitude regions south of 30°S and north of 55°N. A seasonal climatology is prescribed for the sea ice distributions. To estimate internal variability of the model atmosphere, another 34-yr integration was performed employing the seasonally varying, climatological SST without interannual variability.
The CAS/JSC working group in numerical experimentation has made an intercomparison of the climates simulated by 14 atmospheric general circulation models (Boer et al. 1991). Evident systematic errors seen in the atmosphere simulated by our experiment show common features. That is, the simulated temperatures of the atmosphere are colder than those observed on average and especially in the polar lower stratosphere and tropical lower troposphere. Another notable feature is the presence of too strong westerlies in the extratropical regions and excessive easterlies in the upper tropical troposphere. A brief comparison between simulated and observed climates is reported by Sugi et al. (1995). They conclude that the T42 GCM version of the JMA global model is capable of accurately reproducing basic aspects of the current climate.

To extract major low-frequency modes in the northern extratropical atmosphere, we employ rotated EOF analysis for the 500-hPa geopotential height anomalies. According to Horel (1981) and Barnston and Livezey (1987), in fact, the rotated EOF (hereafter R-EOF) analysis is a better diagnostic tool for deducing dominant modes such as teleconnection patterns classified by Wallace and Gutzler (1981). To compare the simulated atmosphere with that observed in the northern extratropics, we used monthly mean 500-hPa geopotential heights compiled at the Japan Meteorological Agency. The geopotential heights of the Northern Hemisphere are given at a spatial resolution of 10° × 10° regular rectangular mesh, extending from 20° to 80°N; the data are available only from 60°E to 130°W at 20°N latitude. Also used are the sea level pressure data of the National Meteorological Center for the period 1955–88.

3. Low-frequency recurrent modes appearing in the northern extratropics

a. Interdecadal-scale sea level pressure anomalies

First of all, the difference in simulated wintertime (December–February) sea level pressure for the period 1977–86 versus the period 1967–76 are compared to that observed, as shown in Fig. 1. In the observed sea level pressure field, highly significant negative anomalies are indicated over the Aleutian low region with an extreme value of −5 hPa, whereas weak positive anomalies are seen over northwestern Canada and the polar region east of Greenland. This feature is already demonstrated by Venrick et al. (1987) and Nitta and Yamada (1989). It is noted in the simulated field, on the other hand, that similar significant negative anomalies are indicated over the North Pacific region. The magnitude of simulated anomaly is −4 hPa there, which is comparable to that observed. Although we can see weak positive anomalies over northern Eurasia and the North Atlantic region, they do not have the 5% level of statistical significance. It should be noted, further-more, that the climatological SST experiment does not produce low sea level pressure anomalies over the Aleutian low region during the decade 1977–86 (not shown).

Figure 2 exhibits the time sequences of observed and simulated sea level pressures over the Aleutian low region. We can see a common feature of the decreasing trend over the period 1955–88 and, in particular, an abrupt change in the 1976/77 winter in both observed and simulated fields. Hence, the abnormal decreasing of sea level pressure over the North Pacific region after the 1976–77 winter, which has been pointed out by observation (Venrick et al. 1987; Nitta and Yamada 1989; Trenberth 1990), is fairly well simulated by the real SST experiment. This implies that the GCM used for the present study has the ability to discuss the interdecadal variations of the wintertime extratropical atmosphere over the North Pacific.

b. Wintertime leading modes

The amplitude of the observed atmospheric interdecadal variation is remarkably large over the North Pacific, evidently in association with the dominance of the well-known Pacific/North American (PNA) teleconnection pattern (e.g., Namias et al. 1988; Nitta and Yamada 1989; Trenberth and Hurrell 1994). Hence, by applying an R-EOF analysis to the wintertime (December–February) monthly 500-hPa geopotential height anomalies, we made an intercomparison of the PNA teleconnection patterns appearing in the observed and simulated extratropical tropospheric atmospheres in the real and climatological SST runs (Fig. 3). We employ a cross-correlation matrix in computing eigenvalue solutions and retain up to 10 EOFs of the geopotential height anomalies, which are associated with about 70% of the total variance in each anomaly data. The set of 10 EOFs are linear transformed using the varimax-orthogonal rotation in order to derive 10 R-EOFs. The PNA patterns deduced from observation and the real SST run are identified with R-EOF1, accounting for 11.2% and 11.4% of the total variance, respectively, but in the climatological SST run R-EOF3 explains the PNA mode with about 9.2% of the total variance. The three PNA patterns have almost the same spatial structure in the loading pattern, but significant loadings over the central North Pacific in the real SST experiment are located somewhat eastward compared to that in the climatological SST control run. The striking similarity between the loading patterns derived from the two experiments affords evidence that the PNA teleconnection pattern is essentially identified with a particular mode of internal variability in the wintertime northern extratropics.

The interdecadal and interannual variability of these model-derived loading patterns, on the other hand, is quite different with one another. Figure 4 shows the time coefficients of the PNA modes simulated by the
climatological and real SST runs. The PNA mode derived from the climatological SST run has intermonthly and short-term interannual variability but no evident interdecadal variability. In contrast, definite interdecadal variability of the PNA mode is found in the real SST experiment. As shown in lower panel of Fig. 4, in fact, observed PNA mode is characterized by an interdecadal time-scale trend (e.g., Namias et al. 1988; Wallace et al. 1993; Kawamura 1994) and the predominance of this mode is in accordance with the deepened Aleutian low from the late 1970s to the late 1980s (e.g., Venrick et al. 1987; Kashiwabara 1987; Nitta and Yamada 1989; Trenberth 1990). The long-term trend is not necessarily prominent in the PNA mode derived from the real SST experiment. It should be emphasized here, however, that the PNA modes extracted by observation and the real SST run have a common feature of pronounced interdecadal variability. The PNA mode obtained by the climatological SST control run may be an eigenmode of the internal variability in the northern extratropical atmosphere and its variability extends only short-term interannual timescales at the most, as depicted in the upper panel. These facts strongly suggest, therefore, that anomalous SST forcing exerts strong influence on the polarity of the PNA mode and modulates its amplitude, and as a consequence, longer-term variability such as interdecadal variability has occurred in the time sequence of this mode.

On the other hand, other major recurrent modes, such as the Northern Atlantic oscillation, the Eurasian, and the western Pacific patterns, appearing in the model atmosphere are also detected (figure not shown) and coincide quite well with those observed, which have been well documented by Wallace and Gutzler (1981), Barnston and Livezey (1987), and others. However, we can see no pronounced interdecadal variability in the model-generated recurrent modes.

It is shown in the time sequence of the PNA mode derived from the real SST run that a definite abrupt change has occurred in the 1976–77 winter with one particular polarity. In addition, the PNA mode indicates one peculiar polarity at several periods on the decadal scale. Negative amplitudes indeed tend to be predominant during the periods from the 1963/64 to 1969/70 winters and from the 1976/77 to 1982/83 winters, whereas conspicuous positive amplitudes are seen during the period from 1970–71 to 1975–76. Here, to examine how an anomalous circulation regime in the simulated PNA mode affects the temperature and geopotential height fields of wintertime extratropical atmosphere, the characteristic periods I and II are defined as the 1971–76 and 1977–83 periods, respectively, based upon the polarity of PNA, where 1983 refers to the 1982/83 winter.

Figure 5 shows the difference in mean 500-hPa geopotential heights for period II for December through February versus period I. The most noteworthy change in model-derived 500-hPa height anomalies is the change over the central North Pacific region around 30°–60°N latitude; significant anomalies in the sur-
rounding regions (e.g., low-latitude region near the Hawaiian Islands, central North America, and southeastern United States) also reveal systematic features. We can apparently see the reversed anomaly patterns over northern Eurasia and the Black Sea. In addition, the increase in the 500-hPa height has occurred throughout the Tropics from period I to period II. The composite anomaly map for the period 1971–76 versus period 1964–70 shows a reversed tendency in the anomaly field (figure not presented).

Figure 6 is the same as in Fig. 5 but for the difference in model-simulated wintertime surface air temperature. Positive temperature anomalies in the northern extratropical atmosphere are indicated over northern Eurasia, Canada, and the northwestern United States, whereas negative anomalies are seen over northeastern Europe and the Bering Sea. Hence it is expected that the change of hemispheric wintertime circulation regime, which is accompanied by a predominance of PNA, contributes substantially to the overall features of interdecadal variations of wintertime surface air temperature in the northern extratropical atmosphere. This partly corroborates the results of Gutzler et al. (1988) and Trenberth (1990).

Figure 7 reveals the difference in wintertime seasonal mean model rainfall for period II versus period I. The anomaly pattern in the Tropics is closely associated with that in surface temperature (Fig. 6). If we highlight the abrupt abnormal change of circulation regime in the 1976/77 winter, we can find an increase in tendency in model rainfall over the central equatorial Pacific and the eastern part of tropical Indian Ocean, and a decrease over the maritime continent. It is most likely, furthermore, that the increase along the west coast of North America is brought by northward intrusion of advected warmer and moister air along there, with deepened Aleutian lows. This understanding is also supported by some observational studies (e.g., Cayan and Peterson 1989; Trenberth 1990). In a similar fashion, the simulated 200-hPa zonal wind difference is shown in Fig. 8. From period I to period II, there were indications of easterly anomalies over the central equatorial Pacific, westerly anomalies over the midlatitude North Pacific around 30°N, and further easterly anomalies over Alaska. We can thus see that marked anomalies are distributed from the Tropics toward the northern extratropics over the Pacific region, and in addition, similar tendency is observed in the South Pacific. The above feature implies that the extratropical response of the model atmosphere to tropical Pacific SST anomalies occurs on interdecadal timescale, with meridional displacement of the subtropical jet over the North Pacific. These points will be elaborated on further in the next section. Significant but weaker anomalies with the same sign are indicated over the subtropical region of eastern Indian Ocean around 15° latitude in both hemispheres, and this may be in-...
4. Response of model atmosphere to SST anomalies

4.1 Tropical region

Figure 9 shows the distribution of the ratio of 200-hPa geopotential height standard deviations in the real SST run to the corresponding values in the climatological SST control run in northern winter. The 200-hPa geopotential height standard deviation is used to infer the magnitude of upper-tropospheric response to SST forcing in the Tropics (e.g., Lau 1985). It can be seen in northern winter that the variability in the Tropics in the real SST run is considerably larger than that in the climatological SST run, with maxima over the central equatorial Pacific around 160°E–150°W, and that the ratios are largely in excess of 300%. Moreover, the region where the ratios of rainfall standard deviations are be-
Fig. 5. Differences in the simulated wintertime 500-hPa geopotential height for the period 1977–83 versus period 1971–76, where 1976 refers to the period from December 1975 through February 1976. Contour interval is 10 m and shading indicates negative values. The regions where values differ from zero at the 5% level of statistical significance using a t test are denoted by dots.

Beyond about 200% coincide well with the maximum region of the 200-hPa geopotential height standard deviations (figure not presented). The above feature is qualitatively consistent with that shown by Lau (1985). In this study, however, the variances of the geopotential heights in upper troposphere are 4–9 times larger over the Tropics compared to those by the climatological SST experiment. It is thus inferred that the tropical response of our model atmosphere to SST anomalies is stronger than that of the GFDL R15 GCM (Lau 1985). However, we cannot easily conclude which GCM has the better ability to simulate the trop-

Fig. 6. As in Fig. 5 but for surface air temperature. Contour interval is 0.5°C and shading indicates negative values.
ical response to SST forcing because of the scarcity of upper-tropospheric observational data.

Figure 10 shows the variability of model-derived 200-hPa geopotential height anomalies in both experiments over the central equatorial Pacific region (10°N–10°S, 170°–140°W), where the tropical model atmosphere responds to the SST forcing most sensi-
tively. During almost all the periods the variability forced by SST anomalies tends to be considerably larger than the internal variability simulated by the climatological SST run. A further indication is that the 200-hPa height fluctuations in this region apparently reflect the ENSO variability and look very sensitive to the SST forcing. The scatter diagram of the SST with
the 200-hPa geopotential height variability obtained by the real SST run in this region is indicated in Fig. 11. In fact, the correlation between them is found to be remarkably strong although it is somewhat poor above 28.5°C of SST.

Figure 12 shows the power spectra of the time sequences of the 200-hPa height anomalies in the central equatorial Pacific for the 34 yr, 1955–88 (Fig. 10), derived from both experiments. This reveals several features of interest. One of the notable features is that
no highly significant spectral powers at periods greater than a year are derived from the climatological SST experiment. The intriguing feature in the real SST run, on the other hand, is enhanced variance in dominant spectral powers at periodicities greater than about 40–50 months. This spectral structure is very similar to that in the tropical Pacific SST, especially on an interannual timescale (not shown), and the dominant spectral peak at periods of 4–5 yr corresponds quite well to the frequency of the ENSO event. It should also be noted that decadal-scale variance is large in the real SST run.

b. Northern extratropical region

Although the leading recurrent modes prevailing in the wintertime northern extratropical troposphere were documented in section 3, we do not fully understand internal variability of extratropical atmosphere itself. Therefore, we will evaluate the internal variability in the model atmosphere, based mainly upon the climatological SST experiment. Figures 13a and 13b exhibit the distribution of the northern winter seasonal mean 500-hPa geopotential height standard deviations in both experiments. The simulated variability in the real SST run (middle panel) is almost equivalent to the observed values (e.g., see Fig. 3 of Kitoh 1991) although smaller model variability in the northern extratropics is reported by Lau and Nath (1990), Kitoh (1991), and others. Differences of the standard deviations between the real and climatological SST runs are also shown in Fig. 13c. We cannot necessarily see positive anomalies throughout the northern extratropics. This feature supports that the internal variability in the extratropics deduced from the climatological SST run is comparable fully with the variability of the observed extratropical atmosphere responding to various external forcings (Manabe and Hahn 1981). Remarkable regional differences are generally found from the North Pacific to Europe, whereas no significant structures are seen over the Eurasian continent. It is inferred that the extratropical response of the model atmosphere to SST anomalies in northern winter tends to be fairly strong in the regions of the Western Hemisphere. Whether the response over the North Atlantic can be explained only by the Atlantic SST anomalies or triggered by extratropical circulation change over the North Pacific, associated with the Pacific SST forcing, remains an open question.

Figure 14 exhibits the power spectra of the monthly 500-hPa geopotential height anomalies in the corresponding region (35°–55°N, 170°E–140°W) for both experiments. The spectral powers in both experiments are indicative of almost the same dominance in high-frequency domain (i.e., intermonthly timescales). However, in the climatological SST run, spectral powers become weak at periods greater than about 40 months, while in the real SST run enhanced variance is found in low-frequency domain. Indeed, this difference between both experiments relies strongly upon the presence of interdecadal variability.

From a composite analysis based on the polarity of the simulated PNA mode, it has been suggested that the extratropical model atmosphere over the North Pacific responds to the tropical Pacific SST forcing. However, to what degree can such a forcing account for the vari-

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Fig. 11. Scatter diagram of 200-hPa height with SST in the central equatorial Pacific region (10°S–10°N, 170°–140°W).

Fig. 12. Power spectra of simulated monthly mean 200-hPa geopotential height anomalies over the central equatorial Pacific for the 34 years, 1955–88.
ability of the extratropical atmosphere? Therefore, we will actually make an intercomparison of simulated geopotential height fluctuations over the tropical and extratropical regions. Figure 15 shows the relationships between wintertime 500-hPa height anomalies over the central North Pacific (35°–55°N, 170°E–140°W) and 200-hPa height anomalies over the equatorial Pacific (10°N–10°S, 170°–140°W) where tropical responses to SST anomalies are remarkably strong. In the climatological SST experiment, the correlation between the two regions is very poor (r = −0.24), and this fact suggests that the variability in the extratropical 500-hPa height field is mostly independent of the internal variability of the tropical atmosphere over the Pacific region. In the real SST run, by contrast, the wintertime fluctuations over the North Pacific are significantly correlated with the 200-hPa height anomalies over the equatorial Pacific, which are indicative of the tropical response to the SST anomalies. That is why the equatorial Pacific SST anomalies contribute substantially to the geopotential height variability over the North Pacific, which is accompanied by anomalous circulations of tropical atmosphere. Comparing the simulated height anomalies in the Tropics with those in the extratropics (Fig. 16), it can be seen that these time series are mostly parallel with each other. Hence, it is concluded that the interdecadal variability of the wintertime extratropical atmosphere over the North Pacific is largely controlled by the anomalous SST forcing in the Tropics and that in particular, the tropical forcing primarily causes an abrupt abnormal change of extratropical circulation regime in the 1976/77 winter.

5. Discussion and concluding remarks

Our experiment using a T42 GCM was successful for the simulation of the abnormal decreasing of sea level pressure over the North Pacific region after the 1976/77 winter. Thus, we can verify a hypothesis that this phenomenon may be a signature of extratropical response to the tropical Pacific SST forcing, which is accompanied by the predominance of PNA (e.g., Nitta and Yamada 1989; Trenberth 1990). It is found, in fact, that the PNA mode deduced from the real SST run is characterized by pronounced interdecadal variability, including the abrupt change in the 1976/77 winter. Furthermore, simulated 500-hPa geopotential height variations over the North Pacific are evidently in accor-

Fig. 13. (a) Simulated standard deviations of the monthly mean 500-hPa geopotential height for December–February for the climatological SST control run. Contour interval is 10 m. (b) As in (a) but for the real SST run. (c) Difference in standard deviations of 500-hPa geopotential height for December–February between the real and climatological SST experiments. Negative values indicate a smaller standard deviation at the real SST experiment. Contour interval is 10 m and shading denotes negative values.
dance with the anomalous circulations of the tropical atmosphere that are indicative of tropical response to SST anomalies. Our model is forced with near-global, not tropical only, SSTs. However, it is hardly inferred that midlatitude SSTs exert strong influence on the tropical response of atmosphere even if they bring anomalous large-scale circulations in the extratropical atmosphere. We cannot find such evidence. Moreover, Lau and Nath (1994) and Graham et al. (1994) pointed out from their GCM experiments that the wintertime remote response of model atmosphere is more sensitive to SST anomalies over the tropical Pacific. The leading SVD mode in the global SST run and the tropical only SST run, demonstrated by Lau and Nath, looks like a combined pattern with the PNA mode and a zonally elongated mode. It is inferred from our experiments that the PNA modes are a fraction of the signature of internal variability in the northern extratropical atmosphere and its variability extends to only short-term interannual timescales at the most. Likewise, we recognize that the PNA mode is modified by the tropical SST forcing and, as a consequence, characterized by the predominance of interdecadal variability. Thus, their SVD mode may account partly for the behavior of the modified PNA mode because they extract dominant atmosphere–ocean coupled patterns applying the SVD analysis to two different fields: model-derived geopotential height and observed SST anomaly fields. Furthermore, their experiments successfully simulate the abrupt abnormal circulation change over North Pacific in the 1976/77 winter. So in that sense, their intriguing results support our study although they did not necessarily explicitly examine the behavior of PNA in the model atmosphere.

Kitoh (1991) reports, on the other hand, that the leading mode in the northern extratropics simulated by the Meteorological Research Institute GCM has a decadal variability and is closely connected with tropical SST, although his mode cannot be identified with the PNA mode. He has already pointed out the importance of the tropical SST anomalies to the interdecadal variations in the northern extratropical circulation, which is consistent with our results. He also insists that the SSTs over the tropical western Pacific northeast of New Guinea exert significant influence on his decadal mode. However, this feature is not necessarily evident in our results. Moreover, Lau and Nath (1994) showed that the extratropical response of model atmosphere for a run is considerably different from the other three runs. Therefore, such extratropical responses of the model atmosphere must await a more comprehensive investigation.

In this study, we could simulate the PNA mode of pronounced interdecadal variability in close association with the central equatorial Pacific SST. However, there still remain significant differences on the interdecadal scale between the observed and simulated modes. One of the most different features is that although the decadal-scale abnormal decreasing of sea level pressure over the North Pacific region is seen observationally from the 1976/77 winter to the 1986/87 winter, the simulated decreasing persists only until the 1982/83 winter. The other is that simulated North Pacific sea level pressure tends to be below normal in the late 1960s in spite of the observation of above normal. We cannot deny that deficiencies of the GCM might create the discrimination between simulation and observation. However, it is also possible that even if tropical SST forcing is quite the same, the extratropical response of model atmosphere to SST anomalies is different due to the internal variability of the extratropical atmosphere itself. This might be one of the reasons for the discrimination. Using the same GCM, an ensemble experiment is now in progress to clarify this issue. On the other hand, one may argue a possibility that a positive feedback in the atmosphere–ocean system in the North Pacific leads to high persistence of anomalous circulation regime there. In fact, Miller (1992), using a simplified coupled model, suggests that extratropical SST anomalies contribute to the persistence of the anomalous circulation. So in that sense, an ocean–atmosphere coupled GCM could play an important role in examining the mechanism of internal interdecadal variability in the climate system.

The conclusions obtained in the present study are summarized as follows.

The abnormal decreasing of surface pressure over the North Pacific region after the 1976/77 winter, which has been pointed out by observation, is fairly well simulated by the real SST experiment. It is confirmed that the JMA T42 GCM used in this study has the ability to simulate basic aspects of the recent de-
Fig. 15. Scatter diagrams of the wintertime 500-hPa height anomalies over the North Pacific region (35°–55°N, 170°E–140°W) with the 200-hPa height anomalies over the central equatorial Pacific (10°N–10°S, 170°–140°W), which are derived from (a) the climatological SST control run and (b) the real SST run, respectively.

cadal-scale wintertime circulations in the northern extratropical atmosphere accurately.

From an intercomparison of the PNA teleconnection patterns appearing in the observed and simulated atmospheres in the real and climatological SST runs, we find that these three patterns have mostly the same spatial structure, but their interannual and interdecadal variability is different with one another. The PNA mode deduced from the climatological SST control experiment has intermonthly and short-term interannual

Fig. 16. Time series of the wintertime 500-hPa height anomalies (dashed line) over the North Pacific and 200-hPa height anomalies (solid line) over the central equatorial Pacific. Note that the sign for the 200-hPa height anomaly is inverse.
variability but no pronounced interdecadal variability. By contrast, definite interdecadal variability of the PNA mode is found in the real SST run. These strongly suggest that anomalous SST forcing exerts strong influence on the polarity of the PNA mode and modulates its amplitudes, and as a result, longer-term variability, such as interdecadal variability, has appeared in the time sequence of this mode. The interdecadal variability of the wintertime extratropical atmosphere over the North Pacific, which is accompanied by the predominance of PNA, is largely controlled by the anomalous SST forcing in the Tropics and in particular, the tropical forcing primarily causes the decadal-scale change of extratropical circulation regime beginning in the 1976/77 winter.

Acknowledgments. We wish to specially thank Dr. Kanzaburo Gambo and Dr. Kevin E. Trenberth for their helpful comments. The authors deeply appreciate the anonymous reviewers for their 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.

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