Increase of wave height in the North Pacific Ocean

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Abstract

We analyze annual variations and the long-term tendency of wave heights along the coast of Japan, based on observed data for more than 10 years. And we analyze the trend of wave heights over the last 10 years in the North Pacific with hindcast data. As a result of the analysis, the wave height has shown an increase trend at most stations along the Pacific coast of Japan. The average increase rate is 0.6cm/year. The estimated wave height by a wave model also shows an increased trend in the North Pacific Ocean. Since there is a correlation relation between 500hPa height anomaly at specific areas and the wave height anomaly at each station, an increase trend of wave height in the Northern Hemisphere is supposed to be related to the change in an atmospheric planetary wave pattern.

Introduction

In recent years, there has been a growing interest in the climate change represented by the global warming and the influence of the climate change to the world. It is shown by numerical calculations of climate models that if carbon dioxide keeps on being exhausted at the current levels, a surface atmospheric temperature will rise more than 2 ℃ 100 years later. It is imagined that the global warming makes not only the sea level rise but also causes changes of meteorological and ecological system in the oceans.

Ocean waves are important natural conditions for the design of ships and harbors and for the prevention of coastal disasters. It is important for these purposes to understand the current state of a long-term change in ocean waves, which is believed to be related closely to the climate change.

In this paper we analyze the long-term change of ocean waves along the coast of Japan and in the North Pacific Ocean. We use observational data obtained for more

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than 10 years at most stations along the coast of Japan, and 10-year global hindcast data by a wave model. As a result of the analysis, it is shown that the wave height has had the increasing trend over the past 10 to 20 years at most stations along the Pacific coast of Japan and in the North Pacific Ocean.

It is shown that annual variations of ocean wave height at stations are related to the strength of anomaly from the normal monthly mean of 500hPa height of the atmosphere and the strength of Asian monsoon, according to the correlation analysis with a wave height and 500hPa height. It is suggested from these that there is a possibility of the increasing tendency of wave height in the North Pacific to originate in the change of the weather related to an atmospheric circulation in the middle layer.

Data analysis

Figure 1 shows major wave observation stations in Japan. Open circle is the Meteorological Agency's station, and closed circle is the Harbor Bureau's. Japan Meteorological Agency has been executing the wave observation at 11 stations along the coast of Japan for about 22 years from 1976 to present, for the purpose of wave watch and wave forecast for the fishery, the safe navigation and marine leisure in coastal areas. Harbors Bureau in Ministry of Transport has been observing coastal waves at about 44 stations for about 26 years from 1972 to present for the harbor design and the maintenance.

Fig.1 Location of coastal wave observation stations.

Almost all locations of these observation stations are in 1 or 2 kilometers offing from the shore. The depth is about 50m at these stations. Ultrasonic type wave meters are placed at the bottom of the ocean to measure the sea surface level. The observation interval is two hours at the Harbors Bureau's station. It is three hours in the routine observation at Meteorological Agency, but is one hour in the urgent observation like the case of a typhoon. Significant wave height and other parameters are calculated from the record of sea level for 20 minutes. The sampling time is 0.25sec or 0.5sec.

We chose the data from the stations where observations have been continued for a long period without a displacement of the position or an interruption of the observation. Table 1 shows the stations and the period of data chosen for analysis along the Pacific coast. Table 2 is those along the Sea of Japan coast. We use a monthly mean significant wave height, as an index to represent a long-term tendency of ocean waves. Hereafter we use the word the monthly mean wave height to mean the monthly mean significant wave height. A monthly mean wave height is not calculated if the data are not available for more than 80 percents of the time in a month.

Table 1 The period of data analysis (the Pacific coast).

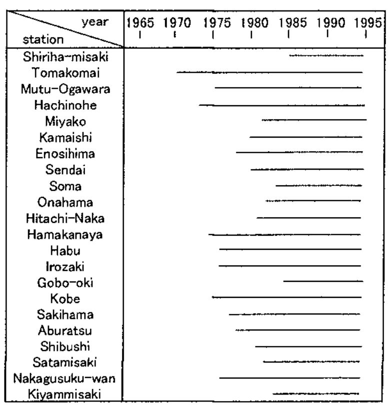


Table 2 The period of data analysis (the Japan Sea coast).

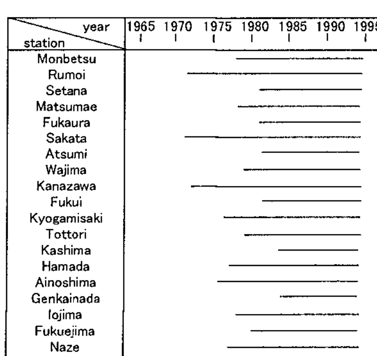


Figure 2 shows a seasonal change of the monthly mean wave height and the 12 months running mean at the coast of Japan Sea (the top figure) and the coast of Pacific Ocean (the bottom figure). As can be seen, the monthly mean wave height at the coast of Japan Sea exhibits seasonal variations, low in summer and high in winter. High waves are caused by a strong wind in the northwest of the Asian monsoon in the Sea of Japan in winter.

On the other hand, the monthly mean wave height at the Pacific coast generally fluctuates over a period of about six months. The wave height is larger in both spring and autumn and is lower in both winter and summer at the Pacific coast. For this weather factor, it is thought that although monsoonal wind blows in the northwest in winter, waves don't greatly develop at the Pacific coast, because the Fetch is short in this direction. Waves develop in spring and autumn at the Pacific coast, because depressions occur with the period of a few days in the Sea of Japan or the East China Sea and move from the southwest toward northeast through Japan while developing in these seasons. Moreover, swells and wind waves develop under the influence of typhoons in autumn.

The thick solid line shows the variation with a several years period both at the Sea of Japan and the Pacific coast. When we pay attention to the coast of Japan Sea, we can see the annual variation of wave height has an increasing wave height in 1981, 1984, 1986, and 1988. In these years, the wave height develops in winter (figure 3). Therefore, the annual mean wave height is chiefly controlled by the mean wave height in winter at the coast of Japan Sea.

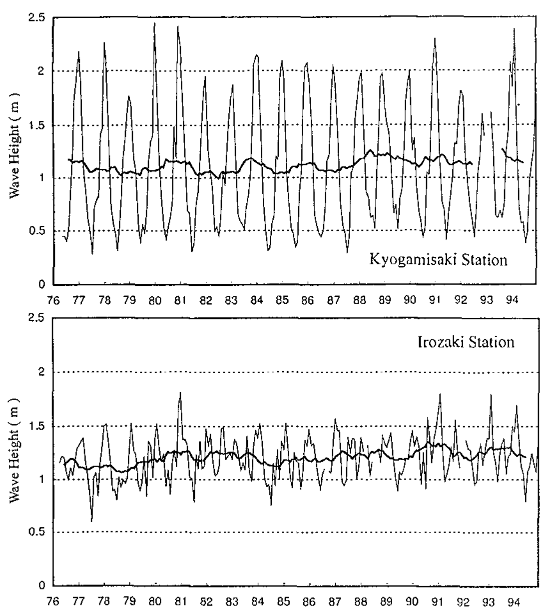


Fig.2 Annual variation of monthly mean wave height (thin line) and 12 months running mean (thick line). (top figure; the Japan Sea coast, bottom figure; the Pacific coast)

On the other hand, it is shown that the seasonal mean wave height at the Sea of Japan coast in winter has a correlation with the seasonal mean temperature at 500hPa height over the Sea of Japan (Figure 3). The solid line with open circles is the seasonal mean temperature in winter at 500hPa height over the Sea of Japan. The dashed line with closed triangles is a seasonal mean wave height in winter at the coast of Japan Sea. These time series show peaks at the same years. For example, in 1981, 84 and 86. It is known that the temperature at 500hPa over the Sea of Japan is related to the intensity of cold air mass on the Asian continent in winter. When the temperature is lower, the intensity of cold air mass is strong and the northwest monsoon wind is strong. It is thought that such a weather condition develops wave heights more than a usual year in the Sea of Japan. After all, it is suggested that the variation of wave heights with a several years period in the Sea of Japan depend on a change in the intensity of Asian monsoon in winter.

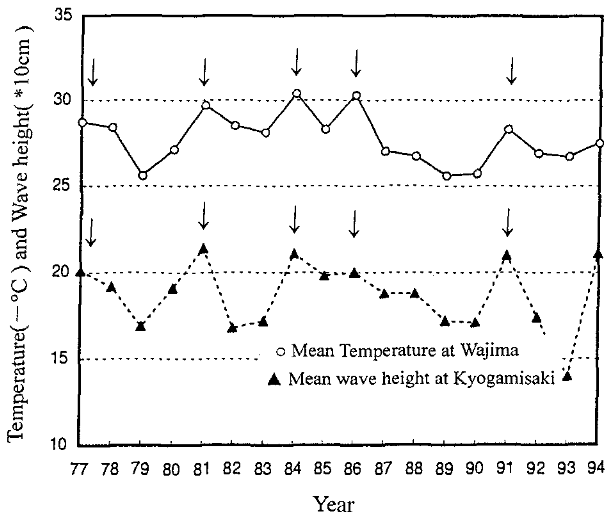


Fig.3 Time series of mean wave height in winter at Kyogamisaki and mean temperature in winter at 500hpa height over the Japan Sea.

We determined the long-term tendency of the monthly mean wave height by a least square method at observation stations, where data has existed for more than 10 years from a year before 1985 to 1994 (Table 1, 2). Figure 4 gives the examples of the time series of the monthly mean wave height and the linear trend at the Pacific coast (the top figure) and the Japan Sea coast (the bottom figure). The wave heights show the increasing trend at these stations.

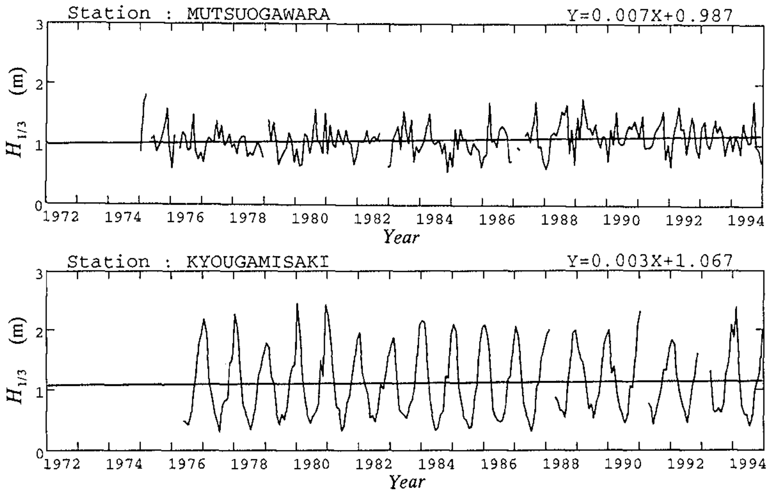


Fig.4 Time series of monthly mean wave height and the liner trend. (top figure; the Pacific coast, bottom figure; the Japan Sea coast)

The trend of wave heights was gotten in a nationwide coast. Figure 5 shows the rate of change of wave heights per year at each station along the coast of Japan. According to this result, the long-term tendency of wave height at the coast of the Sea of Japan differs from one station to another (the bottom figure). The tendency is not uniform along the coast of the Sea of Japan. On the other hand, the monthly mean wave height at the Pacific Ocean coast shows the increasing tendency in most observation stations. The average rate of the increasing tendency is about 0.6cm/year along the coast of the Pacific Ocean (the top figure).

Figure 6 shows the long-term tendency in each season. In spring from March to May (the top of left side figure), the decreasing tendency is shown at many stations along the Pacific Ocean coast, and the increasing tendency is shown at many stations along the Sea of Japan coast. In summer from June to August, the increasing tendency is shown at most stations along the Sea of Japan coast, but the tendencies are not uniform along the Pacific Ocean coast. In autumn and winter a remarkable wave height increasing is shown at most observation stations along the Pacific Ocean coast. It is found from these that the increase of wave height at the Pacific Ocean coast has occurred in autumn and winter.

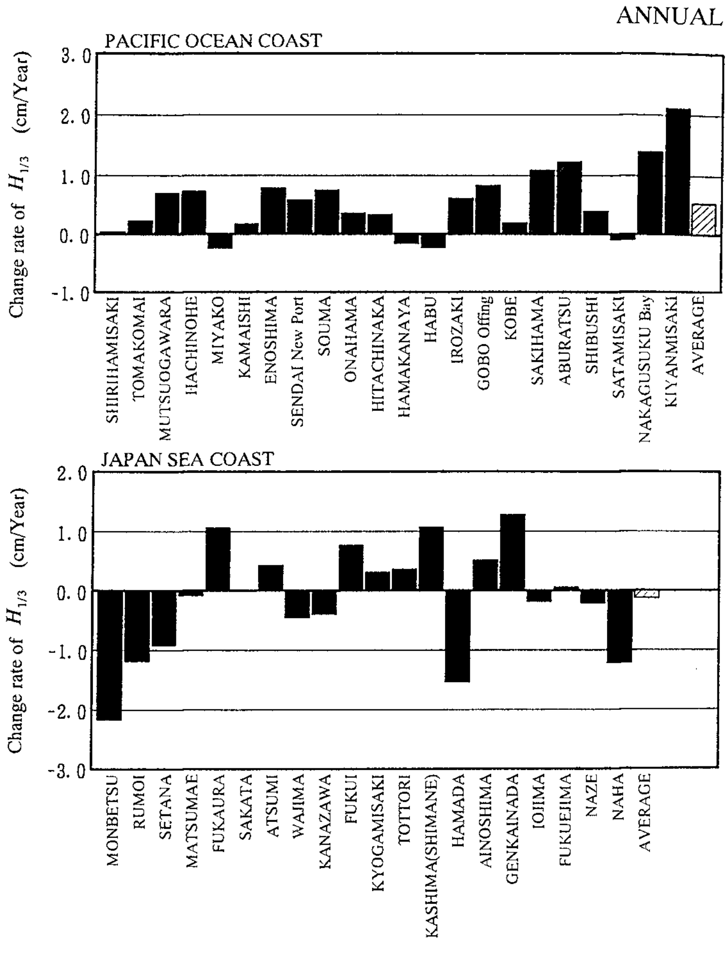


Fig.5 Long-term change rate (cm/year) of the significant wave height. (top figure; the Pacific coast, bottom figure; the Japan Sea coast)

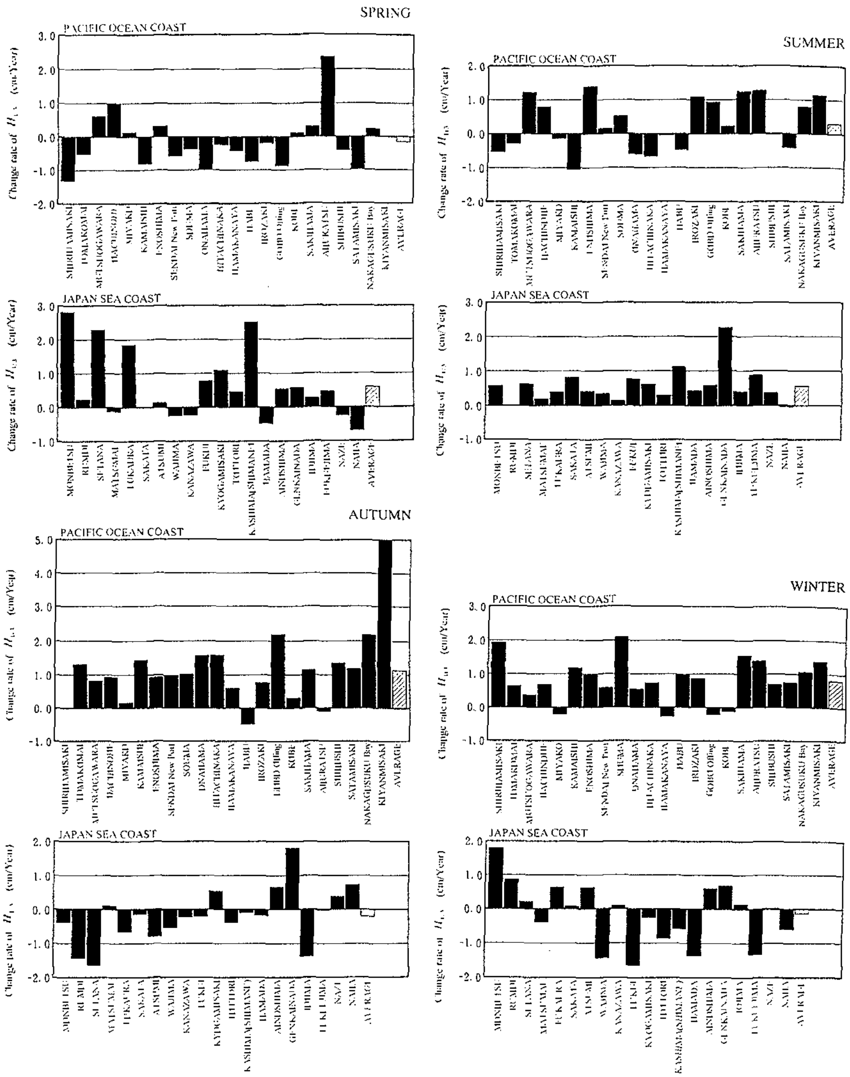


Fig.6 Long-term change rate (cm/year) of SWH in seasons.

Result of wave model

We analyzed the long-term variation of wave heights in the North Pacific Ocean by the wave model, that was developed by Suzuki and Isozaki(1994). This model is classified as the third generation model, which is based on the energy balance equation and considers a non-linear effect among wave components. The source functions of this model consist of the empirical formula of Mitsuyasu-Honda(1982) connected to Hsiao and Shemdin(1983) for the input energy by wind, the empirical formula obtained by dimension analysis for dissipation by whitecapping, and the effective calculation of wave components for nonlinear interaction between waves, respectively. This model uses the hybrid upstream difference scheme for the advection calculation of energy. As for the calculation accuracy of this wave model, the root mean square error of wave height is less than 1m, and the accuracy is very high for practical wave forecasts (Figure 7).

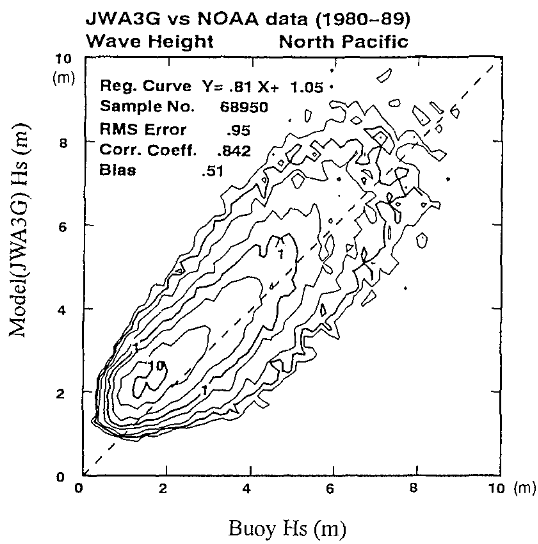


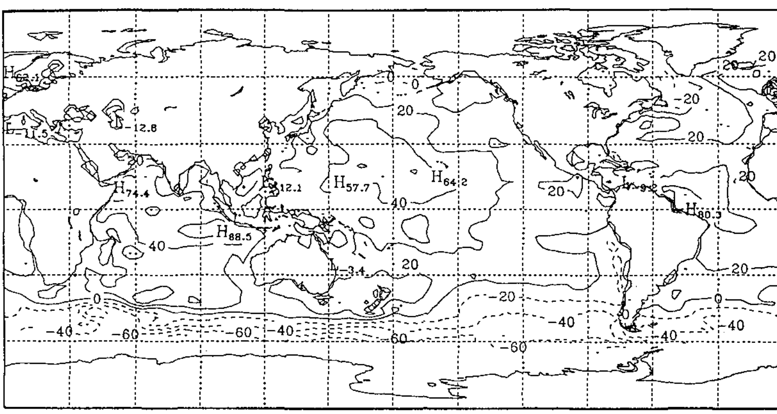
Fig.7 Scatter plot of modeled and measured significant wave height for NOAA buoys in the North Pacific.

The global wave variation in the last ten years has been analyzed by using this model and the wind data of the European Centre for Medium-range Weather Forecasts. An analyzed wind of ECMWF was converted to 10m-wind above a sea surface by using an observed wind at NOAA and JMA buoys and used. The analysis period is 10 years from 1985 to 1994. During this period, the ECMWF model was modified and the accuracy was improved.

Figure 8 shows a global distribution of the trend in wave height for 10 years from 1985 to 1994. The contour interval is 20cm. According to this, one of the largest increasing trends of wave height is shown in the center of the North Pacific Ocean. The maximum value is about 60cm in the last ten years. The increase of wave height is about 20cm at the Pacific coast of Japan over ten years. This magnitude is nearly the same as that of the rate of the increase obtained from the observation data along the coast. It is interesting that both the calculated wave height and the observed one show the increasing tendency with the same magnitude along the Pacific cost of Japan.

The wave height in the middle latitude area of the North Atlantic Ocean shows an increasing tendency, as it does in the North Pacific Ocean. On the other hand, the decreasing tendency of wave height is shown in the high latitude area of the Southern Hemisphere. This reason is not clear yet.

Wave Height Rising (1985–94)



CONTOUR FROM −140 TO 140 BY 20

Fig.8 Increase of wave height during 10 years from 1985 to 1994. Contour lines show the total increase of wave height. Solid lines indicate positive values (increase) and dashed lines indicate negative values (decrease). The increase was obtained by fitting a linear regression curve to the monthly mean wave height.

Discussion

As shown above, the wave height shows the tendency of increase at most of the observation stations along the Pacific coast of Japan. The increasing tendency is shown in all seasons except spring (Figure 6). It is also shown that the increasing tendency is especially dominant in autumn and winter. As the primary weather factor causing the wave height increase, it is thought that the number of typhoon approaching to and hitting Japan has been increasing recently, and that atmospheric depressions develop more frequently in winter around Japan, since Asian Monsoon tends to be weak in recent winters.

According to the numerical simulation by a wave model, the trend of wave height over the recent 10 years shows a tendency of increase in the North Pacific Ocean with a maximum of 6cm/year (Figure 8). A long-term tendency in the mid latitude area of the North Atlantic Ocean is also an increase, with the rate of approximately 2cm/year according to the hindcast data. The order of magnitude of this rate is equal to the result of the analysis of E.Bouws et al (1996) from the wave chart for 27 years from 1961 to 1987, though both these analysis periods are different. It is also interesting that the wave height shows an increasing tendency in both the North Pacific and the North Atlantic Oceans.

As one of the primary factors of a long-term change of ocean waves, there is a possibility that the change of atmospheric circulation in the upper layers is related to this. Figure 9 shows a correlation relation between an anomaly of monthly mean wave height at Sendai and 500hPa height at latitude 45°N longitude 155°E in winter.

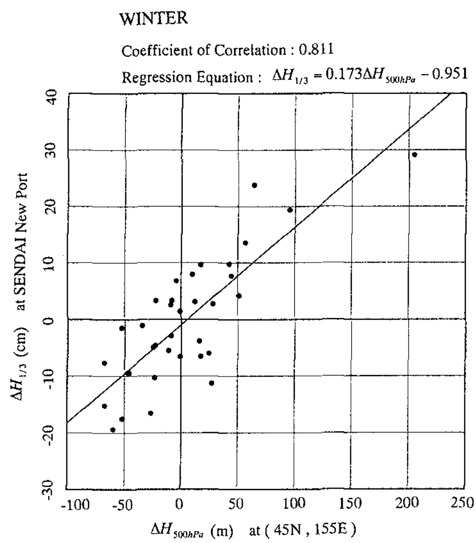
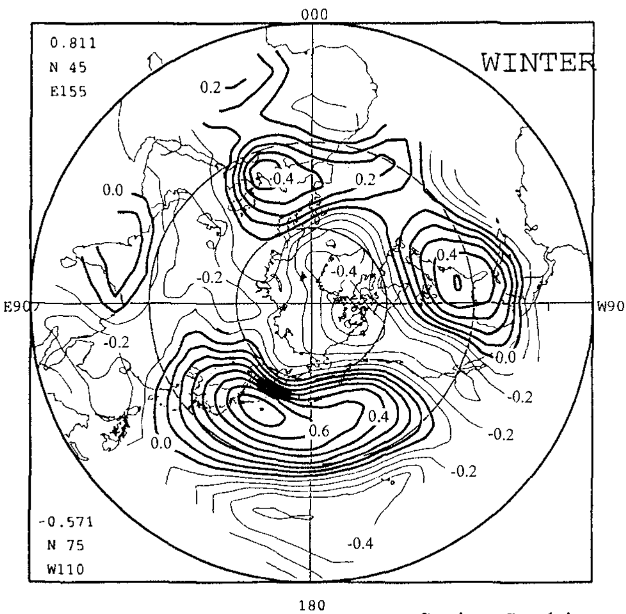


Fig.9 Scatter plot of anomaly of monthly mean wave height at Sendai and anomaly of monthly mean 500hPa height at 45° N, 155° E.

Figure 10 shows the distribution of correlation coefficient between an anomaly of monthly mean wave height from a climatic value at Sendai and an anomaly of monthly mean 500hPa height in the Northern Hemisphere. It is shown that there are three places with evident correlation relation between anomaly of ocean wave height and 500hPa height in this figure. The correlation relation between the anomaly of 500hPa height and wave height is shown to exist also at other wave observation stations. This means that when atmospheric circulation fields in the upper layer change compared with ordinary states, a weather system at the ground surface tied to these circulation changes too, and as a result, wave statistics values change. Therefore, wave height showing the increase tendency in the North Pacific Ocean suggests the possibility that the weather system at the ground surface is changing.



Station: Sendai

Fig.10 Correlation coefficients between anomaly of monthly mean wave height at Sendai and anomaly of monthly mean 500hPa height in the northern Hemisphere in winter. Thick contour lines indicate plus correlation and thin lines indicate minus correlation.

Conclusion

A long-term tendency of monthly mean wave height has shown the tendency of increase at most observation stations along the Pacific coast of Japan. The increasing tendency of wave height based on the observation data does not contradict with the numerical calculation result. Therefore, there is a possibility that wave height has increased over the recent ten years in the North Pacific Ocean.

The following is thought as this factor. It has been shown that the anomaly of monthly mean wave height at each wave observation station has a high correlation with the anomaly of 500hPa height in a specific area. This suggests that the change in the planctary wave pattern in the upper layer of atmosphere generate the changes of wave climate. For instance, in the winter when the planetary wave moves to the north and locates in a higher latitude area than a usual year, it tends to cause a warm winter in Japan. At that time the monthly mean wave height tends to be larger than usual along the Pacific coast of Japan, since synoptic-scale weather disturbances are frequently generated in such a warm winter.

The long-term change in weather systems related to a planetary wave is thought to be one of the factors controlling the wave height increase tendency in the North Pacific. However, the evidence or the mechanism of the change in the weather disturbance has not been clarified yet. It is indeed necessary to investigate the change in the weather disturbance activity.

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