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Key Points:
- Wave height in the midlatitude North Pacific is decreasing for 1996 to 2012
- Wave period in the tropical Pacific is decreasing for 1996 to 2012
- Recent tropical Pacific climate change is the cause of the wave climate change

Supporting Information:
- Readme
- Table S1
- Figure S1

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Changes in the North Pacific wave climate since the mid-1990s

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Abstract Since the mid-1990s, ocean wave reanalysis and in situ wave observations have revealed marked downward trends in wave height, exceeding −0.1 m per decade in the midlatitude North Pacific. The wave period in the tropical Pacific is also on a downward trend, exceeding −0.4 s per decade during this period. These changes in wave climate in the Pacific are attributable to recently strengthened trade winds and La Niña-like conditions in the tropical Pacific. The downward trend in significant wave height in the midlatitude North Pacific is due to strengthening of the negative phase of the Pacific-North American teleconnection. Numerical experimentations with a wave model also showed that the downward trend in the wave period in the eastern equatorial Pacific was induced not only by increased wind waves due to strengthened trade winds but also by weakened propagating swells from the midlatitude North Pacific.

1. Introduction

The increased strength of trade winds in the tropical Pacific since the late 1990s is considered to play a key role in the recent global warming hiatus [*Kosaka and Xie*, 2013; *England et al*., 2014]. The unprecedented ocean-atmosphere state in the tropical Pacific may remotely influence climate in other regions through atmospheric teleconnection (e.g., severe drought in the southwestern United States; see [*McGregor et al*., 2014]). To improve our understanding of climate science, it is important to identify the changes in regional climate attributable to the unprecedented state of the climate in the tropical Pacific. In this paper, I focus on changes in the state of ocean surface waves in the Pacific since the mid-1990s.

Changes in wave climate in the North Pacific have been investigated in terms of interannual variability [*Kako and Kubota*, 2006; *Sasaki and Hibiya*, 2007; *Shimura et al*., 2013], long-term trends [*Graham and Diaz*, 2000; *Wang and Swail*, 2001; *Yamaguchi and Hatada*, 2002; *Sasaki et al*., 2005], and future projections [*Sasaki and Kayahara*, 2008; *Mori et al*., 2010; *Graham et al*., 2012; *Hemer et al*., 2013]. For example, in terms of the long-term trend in significant wave height in the North Pacific, *Graham and Diaz* [2000] found an upward trend in significant wave height in the northern storm track since 1948, reflecting an increase in winter storm activity. With regard to future projections for significant wave height in the North Pacific, *Graham et al*. [2012] projected a future decrease of 10–15% over the lower midlatitude North Pacific in the 21st century under a scenario of medium to high greenhouse gas emission using a wave model forced by near-surface winds from three climate models. More recently, *Hemer et al*. [2013] presented a future projection of the global wave climate using a multi-model ensemble. Thus, the change in wave climate in the North Pacific from the past to future has been investigated extensively. However, decadal change in the North Pacific wave climate has not been fully described. Additionally, changes in mean wave period have been studied less than changes in wave height. Therefore, the aim of this study is to describe the changes in ocean wave height and wave period in the North Pacific since the mid-1990s and their relationship to recent climate change in the tropical Pacific.

The rest of this paper is structured as follows. Section 2 describes the data sets used, and the results and discussions are presented in section 3. Section 4 contains the conclusion.

2. Data

To investigate changes in the wave climate in the North Pacific, significant wave height, mean wave period, and mean wave direction at 6 h intervals as derived from ERA-Interim [*Dee et al*., 2011], which is the global atmospheric reanalysis produced by the European Center for Medium-range Weather Forecast (ECMWF), are used. The ERA-Interim assimilates ocean wave height data derived from space-borne radar altimeters into the wave model [*Dee et al*., 2011]. The assimilation of satellite wave measurements improves the quality of the ERA-Interim wave reanalysis. However, the lack of the satellite altimeter measurements before the advent of ERS-1 in 1991 introduces a spurious long-term trend in the wave reanalysis data [*Aarnes et al*., 2014]. Therefore, we use the ERA-Interim during the period 1992–2012 in this study. The accuracy of the ERA-Interim wave reanalysis is validated against in situ observed wave data derived from the National Data Buoy Center (NDBC) supporting information Table S1 and Figure S1). The difference in the annual mean of significant wave height between the ERA-Interim and the NDBC buoys is small since the altimeter measurements-derived wave height data are assimilated, while the modeled mean wave period is systematically overestimated.

To examine changes in atmospheric fields associated with changes in the wave climate, near-surface wind vectors at 10 m above the sea surface and 500 hPa geopotential height data are employed.

In situ observed wave data compiled by the NDBC are also utilized, and significant wave height and mean wave period at 3 h intervals for the period of 1992–2012 are employed. The location of the buoys is shown in Figures 2a and 2b. This study investigates the annual mean value of the wave parameters. The annual mean value for observed data is considered “missing data” if the data coverage ratio was less than 80% during the year.

Hereafter, significant wave height, mean wave period, and mean wave direction are referred to as wave height, wave period, and wave direction, respectively.

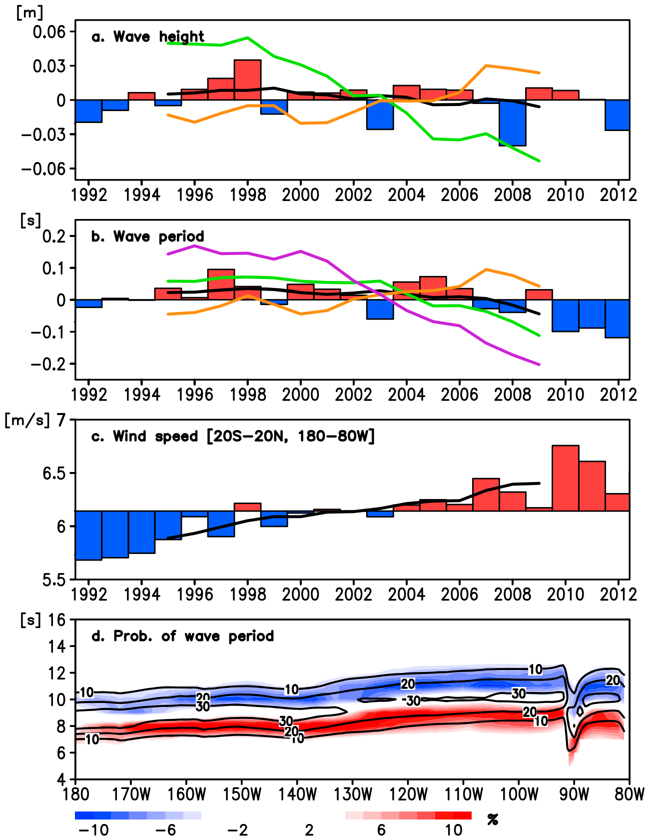

Figure 1. (a) The colored bar indicates the anomaly in the annual mean of significant wave height averaged over the Northern Hemisphere, as derived from ERA-Interim during 1992–2012. The anomaly is the deviation from the climatological annual mean for the period 1992–2012. Black, green, and orange curves indicate the 6 year running mean of the anomaly in the annual mean significant wave height averaged over the Northern Hemisphere, midlatitude North Pacific (30°N–50°N, 150°E–110°W), and western North Atlantic (10°N–40°N, 30°W–80°W), respectively. The units are meters. (b) As in Figure 1a, but for mean wave period. Purple curve indicates the 6 year running mean of the anomaly in the annual average of mean wave period averaged over the central-eastern tropical Pacific (20°S–20°N, 180°W–80°W). The units are seconds. (c) As in Figure 1a, but for the near-surface wind speed averaged over the central-eastern tropical Pacific (20°S–20°N, 180°W–80°W). The units are ms^{-1}. (d) Probability distribution of the mean wave period along the equator for 1996–1999 (%; contour) and the difference in the probability distribution of the mean wave period between the periods 2009–2012 and 1996–1999 (2009–2012 minus 1996–1999; color shade). Red and blue indicate the increased and decreased probability of the mean wave period, respectively.

This study focuses on the linear trend in ocean surface wave field and atmospheric field. The linear trend is statistically tested by the Mann-Kendall test [*Kendall*, 1975].

3. Results and Discussions

3.1. Changes in the North Pacific Wave Climate Since the Late 20th Century

I begin by considering recent changes in the average wave height in the Northern Hemisphere. The color bar in Figure 1 shows a time series plot of the annual anomaly of the average wave height in the Northern Hemisphere for the period 1992–2012 relative to the climatological annual mean for the period 1992–2012 from the ERA-Interim. There is no major change in the average wave height in the Northern Hemisphere

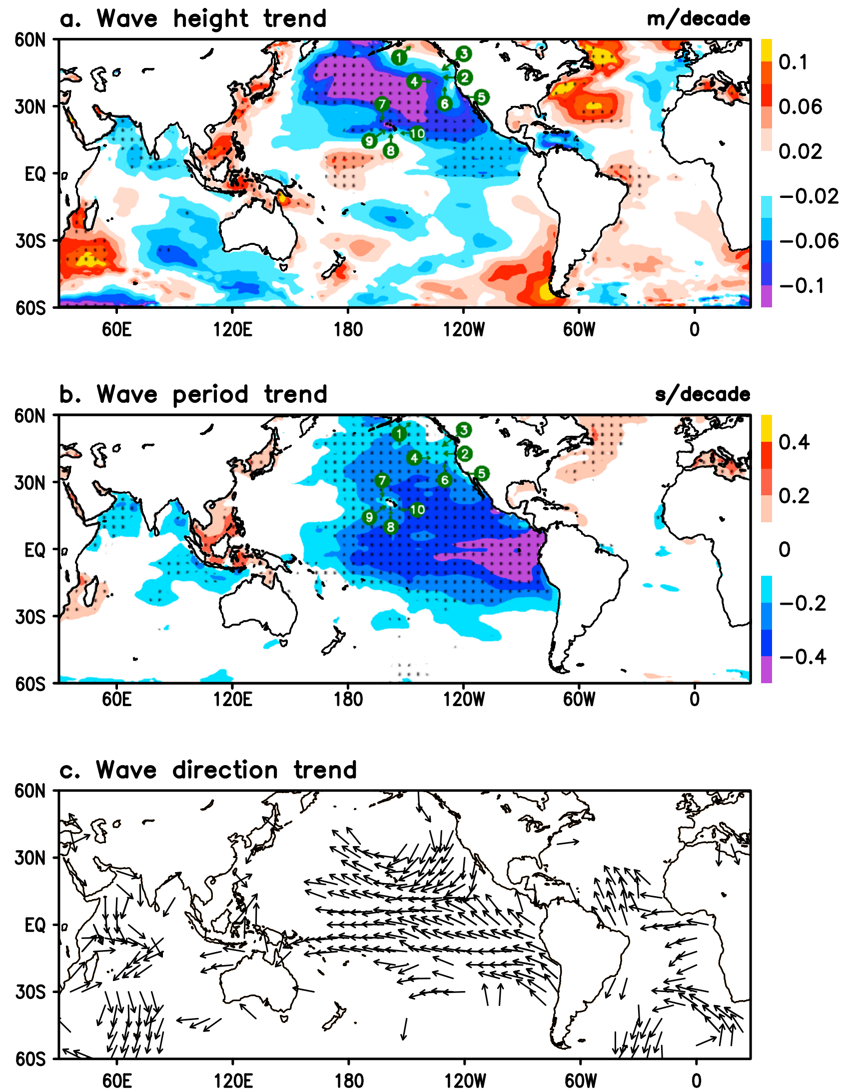

Figure 2. Linear trend in the annual mean of (a) significant wave height, (b) mean wave period, and (c) mean wave direction for the period 1996–2012 from ERA-Interim. Warm and cold colors indicate upward and downward trends, respectively. Stipple shows the grid where the linear trend is statistically significant at the 95% level by a Mann-Kendall test. In Figure 2c, the vector is shown where the linear trend of wave direction for each zonal direction or meridional direction is statistically significant at the 95% level. The green colored circle in Figures 2a and 2b denotes the location of the National Data Buoy Center (NDBC) buoy used in this study (see Table 1).

during the period (see also black line in Figure 1a). Figure 1a also shows a time series plot of the annual anomaly of wave height in the midlatitude North Pacific and the western North Atlantic. Wave height in the western North Atlantic continued to rise after 2000 (orange line in Figure 1a). In contrast, wave height in the midlatitude North Pacific began to decrease in the late-1990s (green line in Figure 1a). Thus, the stagnation of the Northern Hemisphere average wave height after the mid-1990s can be explained by the upward trend of wave height in the western North Atlantic and the downward trend of wave height in the midlatitude North Pacific.

The wave period averaged over the Northern Hemisphere displays temporal variation similar to wave height, except for the dramatic decrease after 2010 (Figure 1b). Since 2000, the wave period in the western North Atlantic has been increasing, whereas that in the midlatitude North Pacific displays the downward trend (Figure 1b). It should be noted that the most notable change in the wave period for the period 1996–2012 is seen in the tropical Pacific (purple line in Figure 1b). The dramatic decrease in the average wave period in the

Table 1. Linear Trend in the Annual Mean Significant Wave Height and Mean Wave Period at National Data Buoy Center (NDBC) Buoys for the Period 1996–2012[a]

No.	Buoy	Linear Trend in Wave Height (m Per Decade)	Linear Trend in Wave Period (s Per Decade)
1	46,001	−0.04	−0.34**
2	46,002	−0.07*	0.004
3	46,005	0.07	−0.33*
4	46,006	0.07	−0.32*
5	46,025	−0.10**	−0.29
6	46,059	−0.42	−0.39
7	51,001	−0.16*	−0.08
8	51,002	−0.11**	−0.11
9	51,003	−0.13**	−0.18**
10	51,004	−0.02**	−0.15

[a] The asterisk and double asterisk indicate that the linear trend is statistically significant at the 90% and 95% level by a Mann-Kendall test, respectively. The location of the buoys is shown by the numbers (No.) in Figure 2.

Northern Hemisphere after 2010 (colored bar in Figure 1b) is presumably due to the decrease in wave period in the tropical Pacific.

Figure 2 shows spatial maps of the linear trend in the annual mean wave height, wave period, and wave direction for the period 1996–2012. As described in the previous paragraph, there are marked downward trends in wave height in the midlatitude North Pacific exceeding −0.1 m per decade, whereas there are upward trends in the wave height exceeding 0.1 m per decade in the western North Atlantic. The downward trend in the wave period in the central-eastern tropical Pacific exceeds −0.4 s per decade (Figure 2b). Wave direction has also changed. Figure 2c, which shows the linear trend in wave direction for the period 1996–2012, reveals a marked increase in westward waves in the tropical Pacific.

Thus, the ERA-Interim wave reanalysis data show that the wave climate in the North Pacific and tropical Pacific changed in the mid-1990s. The changes in wave climate are confirmed by wave data from in situ observation. Table 1 shows the linear trend in wave height and wave period from in situ wave observations. Although there are quantitative differences between the observations and wave reanalysis data in the linear trends of wave height and wave period, the in situ wave observations indicate a downward trend in wave height in the midlatitude North Pacific and a downward trend in wave period in the tropical Pacific since the mid-1990s.

3.2. Changes in Atmospheric Fields in the North Pacific Since the Late 20th Century

Changes in wave climate are generally attributable to changes in near-surface wind speed because the surface wind is the driving force for the generation and development of ocean surface waves. The color shading in Figure 3a shows the linear trend in the annual mean near-surface wind speed for the period 1996–2012. As expected, there are significant downward trends in the midlatitude North Pacific. This is generally consistent with the downward trends in near-surface wind speed derived from the altimeter wind measurements (QuickSCAT) during the period 1999–2009 [*Kutsuwada and Kameda*, 2014]. However, strong upward trends in the near-surface easterly winds (trade winds), exceeding 0.5 $\mathrm{ms^{-1}}$ per decade, are seen in the tropical Pacific (Figures 3a and 1c). The persistent strengthening of the trade winds over the tropical Pacific is examined by various observations, reanalysis, and model experiments [*de Boisseson et al.*, 2014].

The strengthening of the trade winds in the tropical Pacific since the mid-1990s is related to the downward trend of wave period in the eastern tropical Pacific. Purple line in Figures 1b and 1c shows a time series plot of the wave period and near-surface wind speed averaged over the eastern tropical Pacific, respectively. The figures show that the trade winds have been increasing in strength since the mid-1990s, whereas the wave period has been decreasing during this period. Presumably, strengthening of the trade winds would induce an increase (decrease) in the frequency of occurrence of wind waves (swells), as indicated by the increase in shorter-period waves and decrease in longer-period waves for the period 2009–2012 compared with 1996–1999 (Figure 1d).

The increased strength of trade winds in the tropical Pacific is identified as the cause of the recent global warming hiatus [*Kosaka and Xie*, 2013; *England et al.*, 2014]. *Balmaseda et al.* [2013] also showed that changes

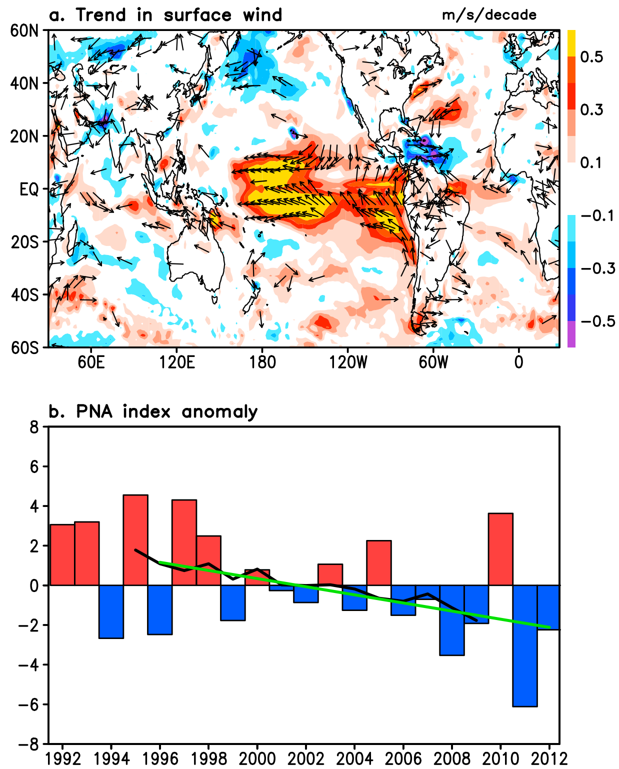

Figure 3. (a) Linear trend in near-surface wind speed (ms^{-1} per decade; color shade) and near-surface wind vector (arrow) for the period 1996–2012. An arrow is shown where the linear trend of the near-surface wind speed is statistically significant at the 95% level by a Mann-Kendall test. (b) Time series plot of the anomalies in the annual PNA index relative to the climatological annual mean for the period 1992–2012. The PNA index is designated by PNA = Z*(15°N–25°N, 180°W–140°W) − Z*(40°N–50°N, 180°W–140°W) + Z*(45°N–60°N, 125°W–105°W) − Z*(25°N–35°N, 90°W–70°W), where Z* denotes the annual mean 500 hPa geopotential height anomaly relative to the climatological annual mean for the period 1992–2012. Black and green show the 6 year running mean and the linear trend for 1996–2012, respectively.

in the trade winds play a crucial role in the recent warming in the deep ocean. Using numerical experimentation with a climate model, *Kosaka and Xie* [2013] showed that the reduction in sea surface temperatures (SST) in the eastern equatorial Pacific after 2000 (i.e., continuous La Niña-like SST anomalies) induced a weakened Aleutian low through the Pacific-North America (PNA; [*Wallace and Gutzler*, 1981]) teleconnection (see Figure 2 in *Kosaka and Xie* [2013]). Therefore, the recent downward trend in wave height in the midlatitude North Pacific is expected to be induced by changes in the PNA teleconnection. Figure 3b shows a time series plot of the annual mean PNA index for the period 1992–2012, which indicates that the negative phase of the PNA occurs more frequently after 2000, and the negative phase of the PNA has been gradually enhanced. Thus, it is presumed that the recent downward trend in wave height in the midlatitude North Pacific resulted from the enhanced negative phase of PNA, which originated from the continuous La Niña-like conditions. The relationship between the decrease in wave height in the midlatitude North Pacific and the negative phase of the PNA is generally consistent with previous studies [*Izaguirre et al.*, 2011; *Shimura et al.*, 2013].

3.3. Model Experiments

Did the weakening of surface wave conditions in the midlatitude North Pacific for the period 1996–2012 create the downward trend in wave period in the tropical Pacific? To examine the impact of the change in wave climate in the midlatitude North Pacific on the wave climate change in the tropical Pacific, two numerical experiments with a third-generation wave model (WaveWATCH III; [*Tolman*, 2002]) are performed. The first experiment is the control (CTL) experiment, in which the wave model is run over the whole globe for the period 1995–2012 using near-surface winds at 6 h intervals derived from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis 1 [*Kalnay et al.*, 1996]. The model is configured with a horizontal resolution of 1° × 1°, and the frequency and direction for the wave spectrum were divided into 32 and 24 bins, respectively. The accuracy of the WaveWATCH III is validated against the NDBC buoys (supporting information Table S1 and Figure S1). The CTL run generally well simulates the downward trends in wave period in the tropical Pacific, and a downward trend in wave height in the midlatitude of the North Pacific for the period 1996–2012 as observed, although the downward trend in wave period in the eastern tropical Pacific is not statistically significant (contour and stipple in Figure 4). Thus, the robust downward trend in wave height in the midlatitude of the North Pacific and wave period in the tropical Pacific for the period 1996–2012 can be confirmed in terms of the ERA-Interim as well as the wave hindcast by the WaveWATCH III forced by the near-surface winds of the NCEP/NCAR reanalysis. The second experiment (Detrend run) is the same as the CTL run, but the linear trend in the near-surface wind speed for the period 1996–2012 is removed from the original near-surface winds in the region poleward of 30°N. Comparing these experiments enables an examination of the impact of the

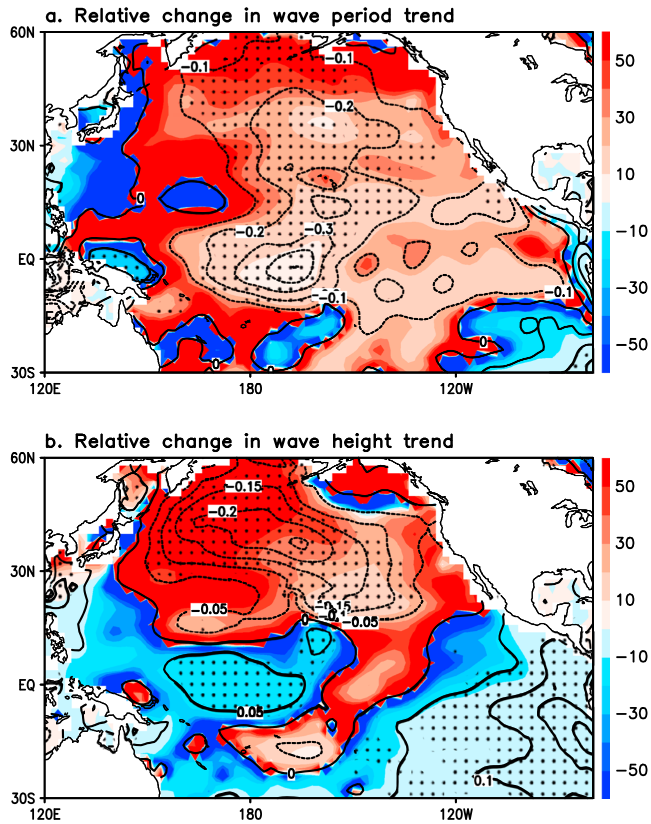

Figure 4. (a) Linear trend in the annual mean of the mean wave period for 1996–2012 in the CTL run (sec. per decade; contour) and the relative change in the linear trend in the mean wave period induced by the downward trend in near-surface wind speed in the region poleward of 30°N for 1996–2012 (%; color shade). The stipple indicates the grid where the linear trend in the annual mean of the mean wave period in the CTL run is statistically significant at the 95% level. (b) As in Figure 4a, but for significant wave height. The units for the linear trend in the annual mean of significant wave height are meters per decade. The linear trends in wave height in the midlatitude North Pacific and the wave period in the tropical Pacific were negative in the Detrend run (not shown).

recent weakening of surface wave conditions in the midlatitude North Pacific on the change in wave climate in the tropical Pacific.

Color shade in Figure 4a shows the relative change in the linear trend of the annual mean wave period due to the downward trend of near-surface wind speed in the region poleward of 30°N for the period 1996–2012. The downward trend of the wave period in the central equatorial Pacific and eastern equatorial Pacific is enhanced less than 10% and more than 20%, respectively, suggesting that the weakening of surface waves in the midlatitude North Pacific during 1996–2012 contributes to enhance the downward trend in the wave period in the eastern equatorial Pacific. Thus, the numerical experimentations show that the downward trend in the wave period in the eastern equatorial Pacific is induced not only by increased wind waves due to strengthened trade winds but also by weakened propagating swells from the midlatitude North Pacific. The weakening of surface waves in the midlatitudes of the North Pacific also contributes to enhance the downward trend in wave period and wave height around the Hawaiian Islands (Figure 4).

4. Conclusion

This study has considered changes in the wave climate in the midlatitude North Pacific and tropical Pacific during 1996–2012. Significant wave height in the midlatitude North Pacific and mean wave period in the tropical Pacific have been decreasing since the mid-1990s. These changes in wave climate are attributable to the continuous La Niña-like conditions in the tropical Pacific since the mid-1990s. The downward trend in wave height in the midlatitude North Pacific is related to the enhanced negative phase of the PNA, which may be caused by the recent continuous La Niña-like conditions. The downward trend in wave period in the central-eastern tropical Pacific is due to the increased wind waves and decreased swells. Numerical experimentations with a wave model have shown that the downward trend in wave period in the eastern equatorial Pacific is induced not only by the enhanced trade winds associated with the La Niña-like conditions but also by the weakened swells propagating from the midlatitude North Pacific. The downward trends in wave height and wave period around the Hawaiian Islands during 1996–2012 are partially due to the weakened surface waves in the midlatitude North Pacific.

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