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三重大学大学院　生物資源学研究科

修士論文

Abnormal winter weather in Japan during 2012 controlled by large-scale atmospheric and small-scale oceanic phenomena

大気循環と日本海が影響を与えた 2012 年冬の異常気象

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ABSTRACT

Negative Arctic Oscillation (AO) and Western Pacific (WP) pattern indices persisted from October through December 2012. For the first time both the monthly AO and WP were negative for three consecutive months. Although negative AOs and WPs make Siberia, Eastern Asia, and Japan abnormally cold, Japan was warm in October 2012. The temperature of the Sea of Japan was a record-breaking high in October 2012. Heating by these very warm waters overwhelmed the cooling effect of the negative AO and WP in October, even though the Sea of Japan is small. Linear regression analyses showed that Japan tends to be warm in years when the Sea of Japan is warm. Consequently, the temperature over Japan is controlled by interannual variations of small-scale oceanic phenomena as well as by large-scale atmospheric patterns. Previous studies have ignored such small-scale oceanic influences on island temperatures.

Contents

1. Introduction

During the winter of 2012/2013, surface air temperatures (SATs) of the northern midlatitudes were abnormally cool over Europe, the Eurasian continent, and North America. Especially cold winters have continued over Eastern Asia and Japan for the last three years. It is common for variations of large-scale atmospheric circulation to be mainly responsible for year-to-year variations of SATs. It is uncommon for year-to-year variations of the temperatures of islands such as Japan to also be controlled by small-scale variations of temperatures of the surrounding oceans. This paper demonstrates oceanic control over the variations of air temperatures over Japan, the focus being on the anomalous cold winter of 2012/2013 in the Northern Hemisphere.

One of most important components of atmospheric circulation in the winter over the Northern Hemisphere is the Arctic Oscillation (AO) as defined by Thompson and Wallace (1998). The winter AO is strongly coupled with SAT fluctuations over midlatitudes (Thompson and Wallace 2000). The negative phase of the AO has a direct influence on the occurrence of cold surges over Eastern Asia as a result of changes in mid- and high-latitude atmospheric circulation systems, including the Siberian high, upper-level trough, and westerly jet stream (Jeong and Ho 2005; Park et al. 2008; Park et al. 2011).

Another important mode of variability correlated with SAT teleconnections over Eastern Asia is the Western Pacific (WP) pattern identified by Wallace and Gutzler (1981). The negative phase of the WP affects the Eastern Asian monsoon and leads to abnormally cool temperatures over Eastern Asia and Eastern Siberia in the winter (Gong et al. 2001; Zhang et al. 2009).

Temperatures were abnormally cold during the winter of 2012/2013 over Eastern Asia, and the SAT over Japan was especially cold. In Japan, a winter cold wave has social, economic, psychological, and political impacts because of the closure of Japan's nuclear power plants in the post-Fukushima world. Unfortunately, abnormally cold winters create more demand for electricity. Winter weather in Japan and its prediction have come under the world spotlight. In this study, we therefore examined whether the extremely cold weather during the winter of 2012/2013 was accompanied by changes in large-scale atmospheric circulation, specifically negative phases of the AO and WP. We also asked whether small-scale changes in oceanic temperatures also contributed to the cold winter temperatures of 2012/2013 in Japan.

2. Data and Methods

Ogi et al. (2004) identified seasonal variations of the Northern Hemisphere annular mode (SVNAM) by performing an empirical orthogonal function (EOF) analysis. The SVNAM index is available on the web at http://www.bio.mie-u.ac.jp/kankyo/shizen/lab1/AOindex.htm. Because the SVNAM shows the seasonal variations of the Northern Hemisphere annular mode, we used the SVNAM index defined by Ogi et al. (2004), and all references to the AO index in this study mean the SVNAM index. The original AO of Thompson and Wallace (2000) reflects mainly winter atmospheric variability and cannot capture the dominant atmospheric patterns of other seasons (e.g., Ogi et al. 2004; Tachibana et al. 2010).

We used the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset (Kalnay et al. 1996) in this study. We obtained sea surface temperature (SST) data from the daily 1/4° NOAA Optimum Interpolation SST (OISST) V2 (Reynolds et al. 2002). We also used the daily mean 822-station SAT data from the Automated Meteorological Data Acquisition System (AMeDAS) of Japan, compiled by the Japan Meteorological Agency (JMA). The analysis period was 31 years, from 1982 to 2012. All references to indices in this study mean normalized indices by their standard deviations from 1982 to 2012. Some of these datasets evidenced trends of increasing temperature due to global warming; we assumed these trends to be linear functions of time and removed them from the datasets.

3. Large-scale Atmosphere Control

Figure 1 shows the time series of the five-day running means of (a) the AO index (AOI), (b) the WP index (WPI), and (c) the SAT anomaly index averaged over the area of Japan from September to December 2012. During the time intervals shown Fig. 1, the values of the AOI and

WPI were continuously negative. In addition, the time interval from September through December 2012 was the first time that the monthly mean of both the AOI and WPI were negative for three successive months. The unusual two-week continuous negative phases of both the AOI and WPI are shown during P1 (3 October to 16 October) and P2 (1 December to 14 December) in the red boxes in Fig. 1. The anomalously cold SATs during P2 are in agreement with previous studies, because this period coincided with negative phases of the AO (Jeong and Ho 2005; Park et al. 2011) and WP (Gong et al. 2001; Zhang et al. 2009). Despite the fact that the AO and WP were both negative during P1, the SAT anomaly during P1 was normal or high (Fig. 1c). This pattern is contrary to expectations based on previous studies.

Figures 2a and 2b show the estimated geopotential height anomalies at 500 hPa (Z500; contours) and air temperature anomalies at 850 hPa (T850; shaded) for the P1 and P2 periods of 2012 based on multiple linear regression equations with the AOI and WPI as independent variables. Figure 2c and 2d show the observed anomalies of Z500 (contours) and T850 (colors) for the same time intervals.

The general features of the estimated and observed Z500 and T850 anomaly patterns were similar to each other during the two periods. The temperature anomalies were negative over Eurasia, and positive from eastern Siberia to Greenland. However, during P1 of T850 over the central Pacific and Japan, the observed and estimated anomalies were different. The estimated anomalies were negative (Fig. 2a), whereas the observed anomalies were close to zero (Fig. 2c). Thus, large-scale cold atmospheric anomalies associated with the negative phases of both the AO and WP did not strongly influence the temperature of the lower troposphere over Japan during P1.

We herein describe in detail the distribution of temperature over Japan associated with the AO and WP. Figure 3a and 3b show the SAT and SST anomalies in 2012 estimated from multiple regression equations with the AOI and WPI as independent variables. Figure 3c and 3d show the observed SAT and SST anomalies in 2012. Over the Japanese Islands, the observed SATs during P1 were positive almost everywhere (Fig. 3c), in contrast to the expectation based on the regression analysis (Fig. 3a). Only in some narrow areas in southern Japan were weak negative SATs apparent. This result suggests that other factors overwhelmed the cooling influence of the AO and WP. During P2, the estimated SATs (Fig. 3b) were less extreme than the observed SATs (Fig. 3d). This result also suggests that other factors added to the intensity of the cold SATs.

4. Small-scale Ocean Control

As mentioned in Section 3, large-scale, cold atmospheric anomalies associated with both the negative AO and negative WP did not strongly influence the T850 and the SATs over Japan during P1. The SSTs around northern Japan during P1 were several degrees above average (ocean area of Fig. 3c) because of the fact that the anomalously high SSTs persisted from late August to mid-September of 2012. In particular, around northern Japan, the SSTs were the highest of all the years since 1985. We therefore investigated the relationship between the local SSTs around Japan and the SAT over Japan.

The SSTs over much of the Sea of Japan were significantly correlated with the SAT anomalies during P1 and P2 (ocean areas of Fig. 4a and 4b), the indication being that the SST around Japan is high (low) when the SAT is high (low). It should be again noted that the correlation of the SST around Japan with the AOI or WPI at the same time during P1 and P2 was not significant on an interannual time scale (Fig. 3a and 3b), the implication being that neither the AO nor WP determine the SST.

Here we describe in detail the distribution of temperature over Japan and its association with the area-averaged value of the SST in the Sea of Japan. The averaging area is 36.0–43.5°N, 130.0–140.0°E, the area of ocean in the orange box in Fig. 4a and 4b. The Sea of Japan is located climatologically upstream of Japan during the winter monsoon season. The island area maps in Fig. 4a and 4b show the SAT anomalies in 2012 estimated from a regression equation, with the SST index as the independent variable. During P1 the estimated SAT was positive everywhere, whereas the estimated SAT was negative during P2 because the SST anomaly in the Sea of Japan changed from positive to negative in 2012. The island area maps in Fig. 4c and 4d show the residual SAT anomalies in 2012; the observed SAT in 2012 minus the SAT estimated from the AO and WP shown in Fig. 3a and 3b. The residual SAT isolates the SAT pattern that is not accounted for by the AO or WP. The residual SAT patterns were everywhere similar to the SAT patterns estimated from the SST (island areas of Fig. 4a and 4b), the suggestion being that the SSTs control the SATs. The observed SST distribution in 2012, shown in Fig. 3c and 3d, is again plotted (ocean areas of Fig. 4c and 4d) in order to easily compare the distribution of the residual SAT with the distribution of the observed SST surrounding Japan. The reddish areas over the Japanese islands tend to be surrounded by reddish oceans. This pattern also suggests that SSTs control the SATs. This relationship is discussed in the next section.

5. Discussion and Conclusions

Both the negative AO and WP continued from October through December 2012. Because a negative AO and WP make Japan cold (see Fig. 2a, 2b, 3a and 3b), Japan was expected to be cold in 2012. Nevertheless, Japan was warmer than expectations in October (see Fig. 3c). Furthermore, in December, it was very much colder than expectations (see Fig. 3d). Therefore, the negative AO and WP cannot by themselves account for the temperatures over Japan in 2012.

There was a significant positive correlation between the SST in the Sea of Japan and SAT on an interannual scale (see Fig. 4a and 4b). Therefore, a warm (cold) SST tends to make the SAT high (low). In fact, the SST anomaly in October 2012 was high, whereas in December it was low. As noted in the previous section, the AO and WP were not significantly correlated with the SST (see ocean areas of Fig. 3a and 3b), the indication being that the SST variation was independent of the AO and WP. The SAT pattern that was not accounted for by the negative AO and WP closely resembled the SAT expected on the basis of the SST (see island areas of Fig. 4). This resemblance supports the assumption that the SST influenced the SAT. Also, the Sea of Japan is effectively upstream of Japan during the winter monsoon season, the implication being that cold Siberian air masses that pass over the Sea of Japan are heated by the sea.

We should also consider the possibility of another "unknown" large-scale atmospheric circulation that might influence both the SAT and SST. We investigated the possible existence of an "unknown" large-scale atmospheric circulation. We compared large-scale atmospheric anomaly patterns estimated from linear regressions, using the SAT anomaly index or SST index as independent variables, with the observed large-scale anomaly patterns in 2012. The anomaly patterns estimated with the regressions did not resemble the observed anomaly patterns in 2012 (figures not shown). Accordingly, an "unknown" large-scale atmospheric circulation did not exist from October to December 2012. Hence, the SST appears to influence the SAT.

The time series of the vertical distribution of air temperature over the Sea of Japan (Fig. 1d) signifies that cold air descended from upper levels to lower levels during P1 and P2. This cold air, however, did not descend to the surface of the earth in October. Anomalous upward sensible and latent heat fluxes released heat from the ocean to the atmosphere during these periods (Fig. 1e). These upward heat fluxes resulted from the negative AO and WP, which tended to cool Japan, but the record-breaking warm SST blocked the upper-level cold air. The SST anomaly gradually changed from warm in October to cold in December (Fig. 1f). This change may have resulted from the continuously negative AO and WP and continuous upward heat fluxes. This analysis suggests that a negative AO and WP can potentially cool Japan, but their effect is moderated by the ocean.

We can consequently interpret the observed SATs in 2012 as follows. The negative AO and WP tended to cool Japan during both P1 and P2, particularly in southern Japan in October, whereas the SST strongly heated (cooled) all of Japan in October (December), despite the small size of the Sea of Japan. The resultant observed SAT reflected the net effect of the cooling influences of the negative AO and WP and the heating (cooling) influence of the SST as shown over the island areas in Fig. 4a and 4b. Because the heating influence of the record-breaking warm SST overwhelmed the cooling influence of the negative AO and WP, it was warm in October. The anomalously cold December was influenced by both the negative AO and WP, and the cold surrounding ocean.

Our conclusion may be relevant to other islands, to peninsulas surrounded by the ocean, and even to coastal continental areas. There are many islands on the earth like Japan, and some of them have large populations. The relationship between an island climate and the surrounding ocean temperature should be considered further. This study also suggests that an island climate cannot be correctly predicted by a numerical experiment, such as a simulation of global warming, if the surrounding small-scale ocean temperature distribution cannot be correctly predicted as well.

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The Grid Analysis and Display System (GrADS) and Generic Mapping Tools (GMT) were used to draw the figures.

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and P2, respectively, were estimated from a regression equation, with the SST index in 2012 as the independent variable. The SST index was an areal average in the part of the Sea of Japan within the orange box, between 36.0–43.5°N and 130.0–140.0°E. For the ocean areas of panels (a) and (b), the SST anomalies during time intervals P1 and P2, respectively, were estimated from a regression equation with the SAT index as the independent variable. The SAT index was the mean SAT of all the stations in Japan. The contour interval is 0.2°C (solid lines: positive, dotted lines: negative), and significance levels of 90%, 95% and 99% based on t-tests are shaded, respectively, light green, normal green, dark green. For the island areas of panels (c) and (d), the residual SAT (the observed SAT minus the SAT estimated from the AO and WP shown in Fig. 3a and 3b, respectively) corresponds to the component of temperature that is not accounted by the AO or WP. For the ocean areas of panel (c) and (d), observed SST anomalies. The units are °C.

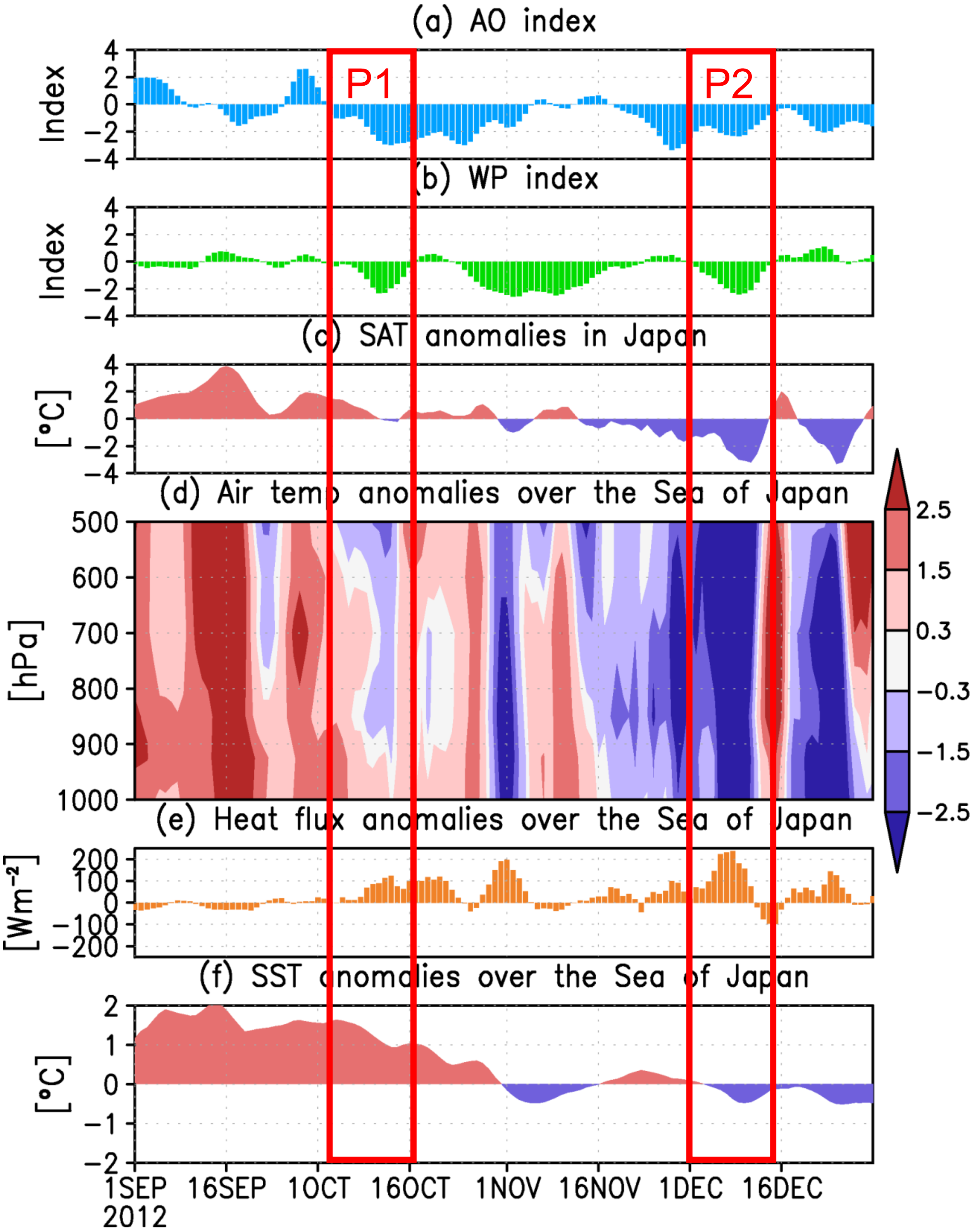

FIG. 1. Five-day running means of (a) AO index as defined by Ogi et al. (2004), (b) WP index, (c) SAT anomalies in Japan from the AMeDAS station data [°C], (d) air temperature anomalies [°C] as a function of time and pressure level, (e) heat flux anomalies index [Wm^{-2}], (f) SST anomalies [°C]. Panels (d), (e), and (f) are areal averages over the Sea of Japan (36.0–43.5°N, 130.0–140.0°E; the area inside the orange box in Fig. 4).

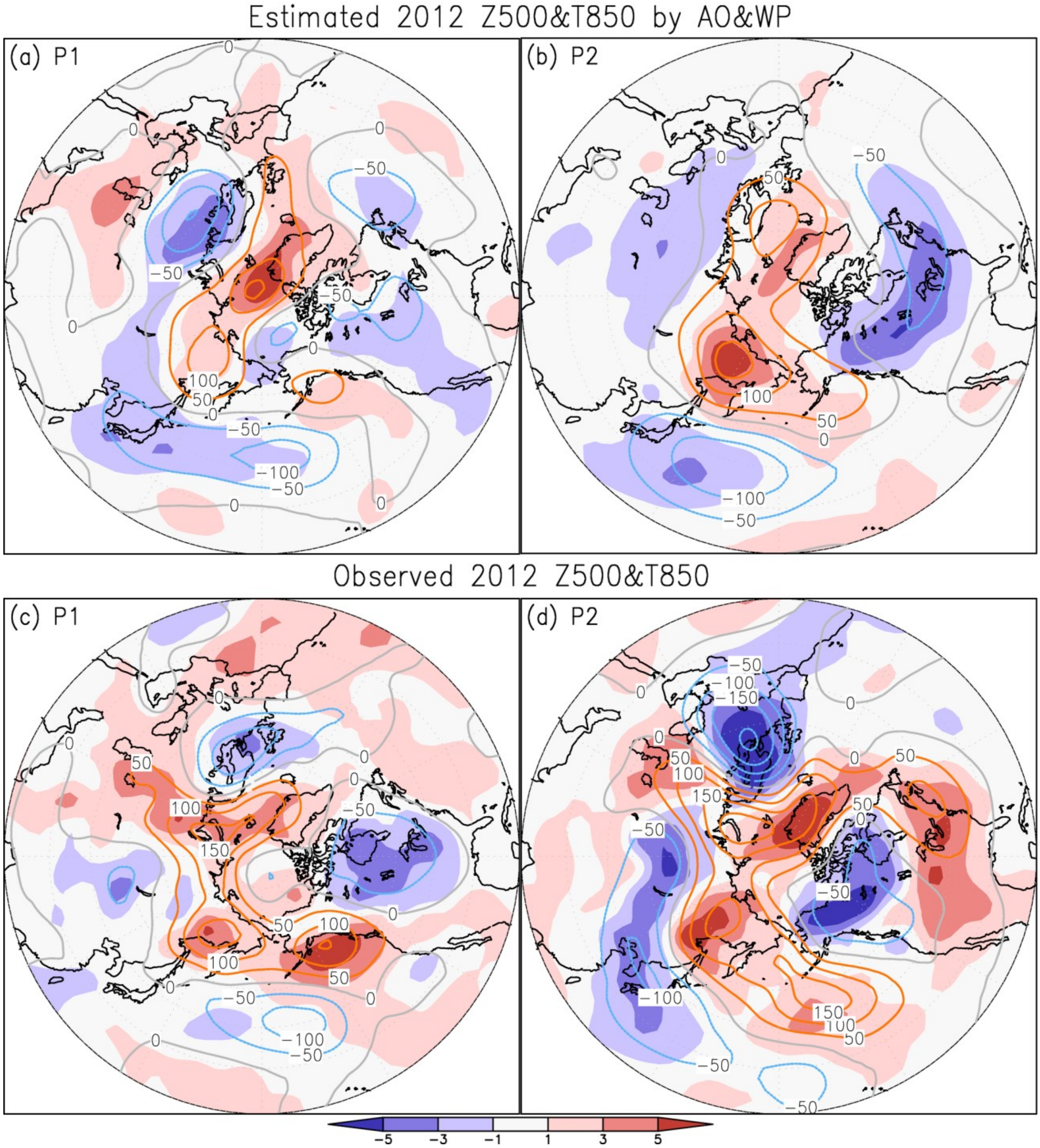

FIG. 2. Anomalies of Z500 (contours) and T850 (shaded) in 2012 estimated from a multiple regression equation with AOI and WPI as independent variables during time intervals (a) P1 and (b) P2. Panels (c) and (d) are the same as panels (a) and (b), respectively, but for observed anomalies. The contour units are meters. The shaded units are °C.

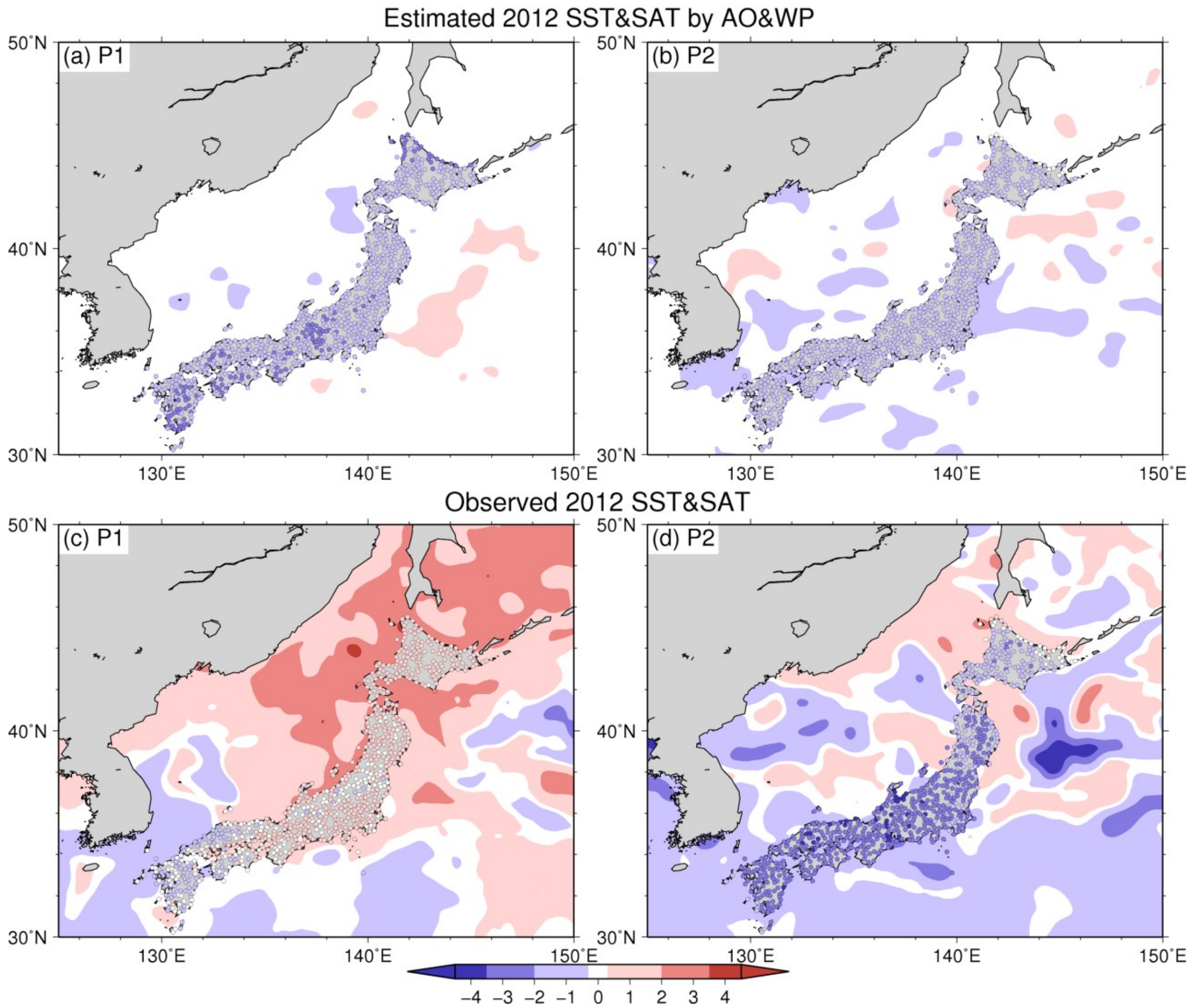

FIG. 3. The same as Fig. 2, but for SAT anomalies over the Japanese Islands and for SST anomalies over the ocean. Circles over the islands indicate the locations of AMeDAS weather stations, and the color of each circle indicates the temperature anomaly at each station. The units are °C.

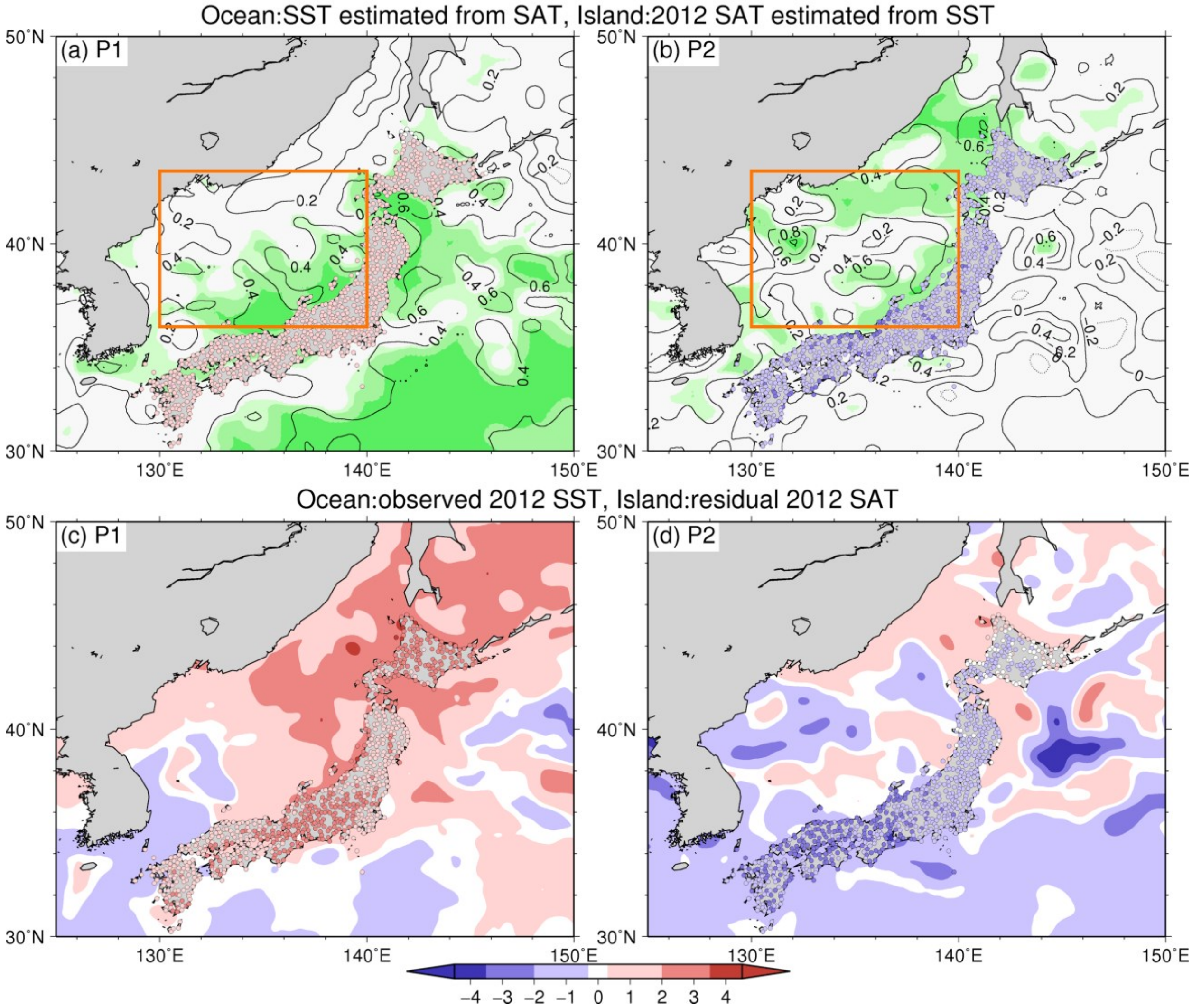

FIG. 4. For the island areas of panels (a) and (b), the SAT anomalies during time intervals P1 and P2, respectively, were estimated from a regression equation, with the SST index in 2012 as the independent variable. The SST index was an areal average in the part of the Sea of Japan within the orange box, between 36.0–43.5°N and 130.0–140.0°E. For the ocean areas of panels (a) and (b), the SST anomalies during time intervals P1 and P2, respectively, were estimated from a regression equation with the SAT index as the independent variable. The SAT index was the mean SAT of all the stations in Japan. The contour interval is 0.2°C (solid lines: positive, dotted lines: negative), and significance levels of 90%, 95% and 99% based on t-tests are shaded, respectively, light green, normal green, dark green. For the island areas of panels (c) and (d), the residual SAT (the observed SAT minus the SAT estimated from the AO and WP shown in Fig. 3a and 3b, respectively) corresponds to the component of temperature that is not accounted by the AO or WP. For the ocean areas of panel (c) and (d), observed SST anomalies. The units are °C.