Assessing the Importance of Prominent Warm SST Anomalies over the Midlatitude North Pacific in Forcing Large-Scale Atmospheric Anomalies during 2011 Summer and Autumn

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(Manuscript received 11 March 2013, in final form 21 December 2013)

ABSTRACT

Sets of atmospheric general circulation model (AGCM) experiments are conducted to assess the importance of prominent positive anomalies in sea surface temperature (SST) observed over the midlatitude North Pacific in forcing a persistent basin-scale anticyclonic circulation anomaly and its downstream influence in 2011 summer and autumn. The anticyclonic anomaly observed in October is well reproduced as a robust response of an AGCM forced only with the warm SST anomaly associated with the poleward-shifted oceanic frontal zone in the midlatitude Pacific. The equivalent barotropic anticyclonic anomaly over the North Pacific is maintained under strong transient eddy feedback forcing associated with the poleward-deflected storm track. As the downstream influence of the anomaly, abnormal warmth and dryness observed over the northern United States and southern Canada in October are also reproduced to some extent. The corresponding AGCM response over the North Pacific to the tropical SST anomalies is similar but substantially weaker and less robust, suggesting the primary importance of the prominent midlatitude SST anomaly in forcing the large-scale atmospheric anomalies observed in October 2011. In contrast, the model reproduction of the atmospheric anomalies observed in summer was unsuccessful. This appears to arise from the fact that, unlike in October, the midlatitude SST anomalies accompanied reduction of heat and moisture release from the ocean, indicative of the atmospheric thermodynamic forcing on the SST anomalies. Furthermore, the distinct seasonality in the AGCM responses to the warm SST anomalies may also be contributed to by the seasonality of background westerlies and storm track.

1. Introduction

It is well established that coupled ocean–atmosphere variability in the tropics, including El Niño–Southern Oscillation (ENSO), exerts extensive influence on extratropical climatic conditions via atmospheric teleconnection. In contrast, the influence of extratropical sea surface temperature (SST) anomalies on large-scale extratropical atmospheric circulation has long been believed to be insignificant in the presence of the prevailing dominant remote influence from the tropics (Lau 1997; Alexander et al. 2002) and internal atmospheric variability (Frankignoul 1985; Kushnir et al. 2002). In
Robinson (2000) reported difficulties in atmospheric general circulation model (AGCM) experiments to yield systematic atmospheric responses to prescribed midlatitude SST anomalies. It has been suggested recently (e.g., Taguchi et al. 2012), however, that persistent SST anomalies in the North Pacific subarctic frontal zone (SAFZ) can force basin-scale atmospheric anomalies in winter under positive feedback forcing from anomalous activity of synoptic-scale migratory disturbances along the nearby storm track (cf. Kushnir et al. 2002). As the SAFZ forms the boundary between warm Kuroshio and cool Oyashio waters with climatologically tight SST, meridional displacement of the SAFZ resulting from incoming oceanic Rossby waves yields meridionally confined persistent SST anomalies (Seager et al. 2001; Schneider et al. 2002; Nakamura and Kazmin 2003). Unlike in most of the North Pacific basin, warm (cold) SST anomalies in the SAFZ tend to enhance (reduce) heat release into the atmosphere and thus exert thermodynamic thermal forcing on the overlying atmosphere (Tanimoto et al. 2003; Taguchi et al. 2009, 2012). Frankignoul et al. (2011) have also suggested that warm-season SST anomalies in the SAFZ can force atmospheric anomalies, whose specific mechanisms are, however, still uncovered.

In 2011 summer the United States and Canada underwent a severe heat wave and drought, which lingered into autumn (Crouch et al. 2012; Whitewood and Phillips 2012). Simultaneously over the midlatitude North Pacific, well-defined anticyclonic anomalies persisted over large-scale, prominent warm SST anomalies shifting gradually from the central Pacific in summer to the western Pacific in autumn (Figs. 1a–d). The SST anomalies were strongest since 1982, whose maximum value exceeded $+5^\circ$C in August and $+3^\circ$C in October.

The present study examines the potential of those prominent warm SST anomalies observed in the North Pacific to force the overlying atmospheric anomalies and their remote influence on the abnormal weather conditions in the United States and southern Canada. For this purpose, a pair of ensemble AGCM experiments has been conducted, paying attention to the seasonal evolution of

![Fig. 1. SST anomalies (°C; color) observed in (a) July, (b) August, (c) September, and (d) October 2011 that are prescribed as the model boundary condition for MID. Climatological SST is superimposed with contour lines (every 2°C). (e) As in (d), but for TROP where contour lines for the climatological SST are omitted.](image-url)
the background westerlies and migratory eddy activity. In addition, the importance of the midlatitude SST anomalies in forcing the atmospheric anomalies is assessed relative to the remote influence from La Niña–like cool SST anomalies in the tropical Pacific (Fig. 1e), whose importance for warm-season precipitation anomalies over North America has been pointed out by recent studies (Ruiz-Barradas and Nigam 2010; Wang et al. 2010).

2. Data and numerical experiments

a. Observational data

Monthly-mean SST data used in this study are derived from the National Oceanic and Atmospheric Administration (NOAA) Optimum Interpolation Sea Surface Temperature (OISST) dataset, in which SST data from satellite observations and in situ observations have been blended since November 1981 (Reynolds and Smith 1994). Assigned on a $0.25^\circ \times 0.25^\circ$ grid, the data can resolve the fine structure of SST anomalies in SAFZ. The final OISST product was mostly used in this study, but the preliminary product substituted for the period in which the final product was not available at the time of the model experiments. The strongest positive SST anomaly in October over the North Pacific in the final product is found to be slightly stronger (by less than 10%) than in the preliminary

![Fig. 2. Hovmöller diagram of monthly anomalies of the net upward fluxes of radiation and sensible and latent heat from the sea surface averaged over 37°–47°N (W m⁻²; colored as indicated and contoured for ±80, ±65, ±50, ±35, ±20, and ±5 W m⁻²) based on the JRA-25 data for 2011. Red contours indicate the monthly-mean SST anomalies for +1 and +3°C (hatched).](image)

![Fig. 3. (a) Map of monthly Z250 anomalies (contoured every 20 m; dashed for negative values) in October 2011 and associated wave activity flux (arrows), formulated by Takaya and Nakamura (2001), with scaling at the bottom, based on the JRA-25 data. (b) Monthly SLP anomaly (contoured every 1 hPa; dashed for negative anomalies) in October 2011 based on the JRA-25 data. Red hatches indicate SST anomalies warmer than the climatology by more than +1°C. (c),(d) As in (a),(b), but for the ensemble response of MID. Color shading indicates the response significant locally at the 95% confidence level based on the t statistic.](image)
The model used in the present study is the AGCM for the Earth Simulator (AFES; Ohfuchi et al. 2004, 2007; Kuwano-Yoshida et al. 2010) with horizontal resolution of T119 spectral truncation (equivalently 125-km grid intervals) and 56 vertical levels up to the 0.1-hPa level. With this horizontal resolution, both pronounced SST gradient and meridionally confined SST anomalies in SAFZ, if prescribed as the model boundary condition, can be resolved reasonably well. Convective parameterization adopted in AFES is based on Emanuel (1991) and Emanuel and Zivković-Rothman (1999).

In total, three sets of ensemble experiments have been conducted with AFES. In the control experiment (CTRL), AFES was forced with the climatological-mean monthly SST and sea ice cover. Reproducibility of the observed climatological-mean atmospheric state over the North Pacific in CTRL has been confirmed. In addition, a pair of sensitivity experiments has been conducted. One is the “midlatitude hindcast experiment” (MID), for which the SST field for AFES was constructed in such a way that warm anomalies stronger than +0.5°C observed during the 2011 warm season were added to the climatological-mean field only within the midlatitude North Pacific (25°–50°N, 140°E–129°W) to represent the observed SST field in that region. The other is “tropical hindcast experiment” (TROP), for which the observed SST was assigned only
in the entire tropics between 25°S and 25°N and the climatological-mean SST was assigned anywhere else. Figure 1 shows the SST anomalies in July, August, September, and October 2011 prescribed for MID and in October 2011 for TROP.

Each of the three experiments comprises 10 members, whose initial conditions were taken from the JRA-25 data for individual days from 27 May to 5 June 2011. All the members were integrated to the end of October, with daily SST fields interpolated linearly from the monthly fields. Deviations of the ensemble-mean atmospheric fields simulated in MID and TROP from that in CTRL are regarded as the modeled atmospheric responses to the midlatitude and tropical SST anomalies, respectively, and their robustness was assessed locally by the $t$ statistic.

It should be pointed out that the latitudinal profile of the climatological-mean SST for a given longitude tends to be smoother than the corresponding profiles observed in individual years. Owing to the variability in its axial latitude, this tendency should be particularly evident around an oceanic front across which the SST gradient is pronounced. One may thus wonder whether CTRL may underestimate the possible influence of the frontal SST gradient across the SAFZ on the atmosphere, and therefore the possible atmospheric response defined as the difference between MID and CTRL may be overestimated. This issue is addressed in the final section.

3. Results

a. Net surface heat flux anomalies in the observation and the model

Figure 2 shows a time–longitude section of meridionally averaged anomalies (37°–47°N) in the net surface heat flux based on JRA-25. Downward net surface heat flux anomalies were observed around the SST anomalies over the eastern portion of the basin in July and over its western portion in September, indicating atmospheric thermal forcing on the warm SST anomalies, which contributed to their formation. In MID, however, anomalous net surface heat flux simulated over the warm SST anomalies is upward throughout the summer and autumn (not shown). This discrepancy of the heat flux anomalies arises from the fact that the ocean is supposed to have infinite heat capacity in AGCM experiments, while, in reality, oceanic heat capacity is finite and particularly small in summer. In the situation where the observed and simulated anomalous surface heat fluxes are inconsistent, it is therefore inappropriate to interpret the observed atmospheric anomalies as responses to the North Pacific SST anomalies. For this reason, we mainly focus on the
observed and simulated atmospheric anomalies in October in the following.

b. Structure of a realistic midlatitude atmospheric response in October

Figure 3 shows the monthly-mean anomalies of SLP and 250-hPa height (Z250) in October 2011 over the North Pacific in the observations (JRA-25) and the corresponding response in the MID experiment. Over the midlatitude North Pacific a well-defined basinscale anticyclonic anomaly was observed in both the lower and upper troposphere (Figs. 3a,b). The normalized amplitude of the anticyclonic anomaly was approximately 0.7 in Z250 and approximately 0.9 in SLP. Although somewhat overestimated in the upper troposphere, the anomaly is well reproduced in MID (Figs. 3c, d), including its slight westward phase tilt with height, as a robust response to the underlying warm SST anomaly (Fig. 1d). This anticyclonic anomaly is such a robust model response that it is simulated in any of the 10 ensemble members. As another robust response, MID also reproduces a cyclonic anomaly observed to the northwest of the anticyclonic anomaly. In a manner consistent with the JRA-25 data, MID simulates anomalous upward turbulent heat fluxes over the warm SST anomaly within the SAFZ (not shown), indicative of their thermodynamic forcing onto the overlying atmosphere (Tanimoto et al. 2003; Taguchi et al. 2009, 2012). In fact, a wave activity flux (Takaya and Nakamura 2001), which is parallel to the local group velocity of stationary Rossby waves, diverges out of the well-defined anticyclonic anomaly over the midlatitude North Pacific, both in the observations and the AGCM (Figs. 3a and 3c, respectively).

In the following, the maintenance mechanisms for the anticyclonic anomaly in October are discussed from a viewpoint of vorticity balance. The anomaly is observed and simulated around the climatological-mean westerlies and “storm track” along which activity of migratory synoptic-scale eddies is particularly strong and thus marked as a band of RMS maxima of subweekly Z250 fluctuations. As indicated with colors in Figs. 4a and 4c, the RMS of subweekly Z250 fluctuations is enhanced substantially along and slightly to the north of the climatological-mean storm track both in the observations and in MID (Figs. 4a, c). The poleward shift of the storm track is consistent with the corresponding shift of the upper-level westerlies and enhanced surface baroclinicity on
the northern flank of the warm SST anomaly. Along this northward-shifted storm track, poleward eddy vorticity flux is also augmented, inducing an anomalous anticyclonic tendency over the upper-level anticyclonic anomaly through anomalous divergence of eddy vorticity flux (shadings in Figs. 4b and 4d). In the presence of this positive feedback forcing with the anomalous storm track activity, the background westerlies act to advect the anomalous anticyclonic vorticity and thereby induce anomalous anticyclonic tendency to the east. These upper-level tendencies are balanced with the effect of anomalous horizontal convergence, reinforcing anomalous descent in the midtroposphere. The associated anomalous low-level divergence acts to maintain the near-surface anticyclonic anomaly against frictional effects. An anomalous poleward eddy heat flux along the northward-shifted storm track acts to render the monthly anticyclonic anomaly more barotropic by acting to relax the temperature gradient, thereby reinforcing the near-surface anticyclonic anomaly (not shown). Overall, the aforementioned transient eddy feedback is of particular importance in maintaining the warm, equivalent barotropic structure of the observed atmospheric anomaly in October 2011 as a robust response to the warm SST anomalies, which is consistent with Kushnir et al. (2002) and Taguchi et al. (2012). As evident in Figs. 3a and 3c, a wave activity flux for stationary Rossby waves is strongly divergent from the upper-tropospheric anticyclonic anomaly observed and simulated, respectively, above the warm SST anomaly. This is also an indication of the former anomaly as a local response to the latter anomaly.

c. Model response for summer months

Unlike for October 2011, MID fails to reproduce the prominent near-surface anticyclonic anomaly observed in July over the prominent warm SST anomaly in the eastern North Pacific (Figs. 5b,d). Rather, the model yields a robust cyclonic response in the lower troposphere (Fig. 5d). In the upper troposphere, the model simulates an anticyclonic anomaly to the northwest of the warm SST anomaly as a robust response and, although less robustly, another anticyclonic response to the northeast (Fig. 5c). In reality, however, a prominent anticyclonic anomaly was observed in the upper troposphere only above the northern portion of the SST anomaly.
anomaly, and a cyclonic anomaly was observed to the south (Fig. 5a). The observed anomalies were thus warm and equivalent barotropic to the north and cold and baroclinic to the south, whereas the simulated response represents a warm anomaly over the SST anomaly. MID also fails to reproduce the anticyclonic anomaly observed in September over the SST anomaly. These discrepancies are attributable to the abovementioned discrepancies of surface heat flux anomalies between the reanalysis and our simulation (Fig. 2).

A diagnosis based on a wave activity flux reveals strong Rossby wave propagation into the midlatitude North Pacific from its upstream position in July (Fig. 5a), whereas no such wave activity injection is diagnosed with the model response (Fig. 5c). The wave activity injection into the anticyclonic anomaly over the SST anomaly is consistent with the observed downward heat flux anomaly as atmospheric forcing onto the SST anomaly. In the monthly anomaly field for July, a circumglobal wave train pattern was observed over the extratropical Northern Hemisphere (not shown). These wave activity injections observed must be a manifestation of atmospheric internal variability or a response to SST anomalies in a maritime domain other than the midlatitude North Pacific.

In August, anomalies of the net surface heat flux were upward over the decaying warm SST anomaly in the eastern North Pacific (Fig. 2), indicative of thermodynamic forcing onto the overlying atmosphere. Because Rossby wave activity injection into these anomalies was not observed, an upper-tropospheric anticyclonic anomaly (Fig. 6a) and a lower-tropospheric cyclonic anomaly just above the SST anomaly (Fig. 6b) might be a response to its thermal forcing. In fact, MID simulates an upper-level anticyclonic response to the northeast of the warm SST anomaly (Fig. 6c) and a shallow cyclonic response just above the SST anomaly (Fig. 6d). Although weak, the cyclonic anomaly observed in August over the warm SST anomaly seems to be consistent with the model response. However, the vertical structure of the simulated response, if any, differs substantially from that of the observed anomalies and the anomalies away from the SST anomaly are likely to be distorted strongly by remotely forced or internally generated Rossby waves (Fig. 6c).
A comparison between Figs. 5 and 6 reveals a certain consistency in the model response between July and August, which is characterized by a shallow cyclonic circulation over the warm SST anomaly and an anticyclonic circulation in equivalent barotropic structure to the northeast. The local shallow cyclonic response for the summer months is in sharp contrast to the deep anticyclonic response for October. Compared with the October situation, the background westerlies over the North Pacific are weaker in summer, especially near the surface, and so is the storm track activity (Figs. 7 and 8), which may not be favorable for yielding a deep, equivalent barotropic response to SST anomalies.

d. Downstream influence toward North America

In October 2011, upper-tropospheric anticyclonic anomalies were observed over southeastern Canada and the northern United States and over the U.S. West Coast as well (Fig. 9a), giving rise to abnormal dryness and warmth locally (Figs. 10a,b; Crouch et al. 2012; Whitewood and Phillips 2012). Although failing to reproduce the one observed over the West Coast, MID can simulate the anticyclonic anomaly over the northern United States and southern Canada (Fig. 9b). This perhaps corresponds to its observational counterpart to its northeast but the simulated anomaly is displaced southwestward.

As evident in cross sections for both the observations and MID (Figs. 9a,b), a wave activity flux is upward in the lower and midtroposphere and diverging horizontally aloft around the east flank of the North Pacific positive SST anomaly, reaching into the anticyclonic anomaly over North America. With no apparent influx from upstream, this is a dynamical indication of the forcing of the Rossby wave train over the warm SST anomalies over the North Pacific. Derived from the ensemble-mean anomalies and evaluated with the mean westerlies in CTRL whose speed is somewhat underestimated, the upper-level eastward flux of wave activity for MID is apparently underestimated. The signatures of the downstream influence simulated over North America are thus weaker than observed and displaced from their observational counterpart.

e. Remote influence from the tropics

In October 2011, a negative SST anomaly was observed in the tropical Pacific (Fig. 1e), which was stronger than in July through September. A scatter diagram for October is shown in Fig. 11 between monthly-mean SST anomalies averaged over the midlatitude North Pacific (25°–50°N, 150°E–180°) and monthly values of the Niño-3.4 index, defined as SST anomalies averaged over 5°N–5°S, 170°–120°W. As evident in Fig. 11, the midlatitude positive SST anomaly observed in 2011 was the strongest over the 29 years, while the concomitant cool SST anomaly in the equatorial Pacific was rather modest. The same tendency is obtained even if the Niño-3 index is used in place of the Niño-3.4 index (not shown). Statistically, during a La Niña event, the midlatitude North Pacific in October tends to be warmer than in the climatology (Figs. 11 and 12). In October 2011, the Niño-3.4 index was −0.97, reflecting a La Niña–like
The amplitude of a midlatitude SST anomaly in October regressed linearly on the Niño-3.4 index is about 0.6°C, which is, however, substantially smaller in magnitude than the observed SST anomaly in 2011 (Figs. 11 and 12). A similar regression analysis was performed to identify a pattern of extratropical atmospheric teleconnection from the equatorial Pacific SST. As evident in Fig. 12, anomalies in SLP and Z250 regressed linearly on the Niño-3.4 index are both anticyclonic over the midlatitude North Pacific, as actually observed, but they are substantially weaker than their observational counterpart for 2011. This remote influence of the cool equatorial SST anomaly onto the midlatitudes is assessed through TROP (Fig. 13). As observed in October 2011 (Fig. 3) and consistent with the regression onto the Niño-3.4 index (Fig. 12), TROP simulates an anticyclonic anomaly over the midlatitude North Pacific. The model response in Fig. 13 is, however, substantially weaker than that in the observations. Moreover, the surface and upper-level anticyclonic responses in TROP are weaker and less significant than their counterparts in MID by approximately 30% and 40%, respectively (Figs. 3c,d). Furthermore, compared to MID, the eastward wave activity flux emanating from the North Pacific toward the anticyclonic anomaly over North America is substantially weaker in TROP (Figs. 9b,c). This suggests that the remote influence of the tropical SST anomalies may be of secondary importance in forcing the large-scale atmospheric anomalies over the midlatitude North Pacific and North America observed in October 2011. At the same time, however, TROP also suggests that the observed midlatitude atmospheric anomalies would have been weaker without the remote influence from the tropical Pacific.

4. Summary and discussion

In the present study, three sets of AGCM experiments are conducted to assess the importance of the prominent warm SST anomalies in the 2011 warm season over the midlatitude North Pacific in forcing the persistent local anticyclonic anomaly and its possible downstream influence onto North America. Although not reproduced...
for summer, the anticyclonic anomaly observed in October is well reproduced in the experiment only with the warm SST anomaly in the midlatitude North Pacific. The anticyclonic anomaly with equivalent barotropic structure is found to be maintained through locally enhanced feedback forcing by transient eddies. They migrate along the northward-shifted Pacific storm track in the presence of the warm SST anomaly situated in SAFZ, where meridional SST gradient is climatologically tight. A Rossby wave activity flux diverging eastward out of the anticyclonic anomaly is indicative of the local forcing by the anomalous storm track activity. The flux is also upward over the warm SST anomaly (Figs. 9a,b), indicative of a westward phase tilt of the anticyclonic anomaly and its maintenance through the conversion of available potential energy from the baroclinic westerly jet stream, as observed in the wintertime North Pacific (Taguchi et al. 2012). The collocation of the seasonally intensified westerly jet stream and storm track with the prominent warm SST anomaly appears to be of vital importance for the formation and maintenance of the stationary anticyclonic anomaly over the midlatitude North Pacific in October 2011 (Figs. 7 and 8). The westward shift of the warm SST anomaly from August to September in 2011 also contributed to facilitating the interaction between the SST anomaly and storm track in October, because the SST anomaly in October was located in the vicinity of the climatological core of the storm track.

As mentioned in the introduction, above-normal surface air temperature (SAT) and/or dry conditions were observed in October 2011 in the U.S. Midwest and to its south and also in southern Canada (Figs. 10a,b) (Crouch et al. 2012; Whitewood and Phillips 2012). The abnormal warmth over these regions is simulated in MID as a significant ensemble response to the warm SST anomaly in the North Pacific (Figs. 10c,d), although the SAT response is underestimated and slightly shifted southwestward to its observational counterpart. These discrepancies are attributable to the underestimated strength and southwestward shift of the upper-level anticyclonic anomaly in MID to its observational counterpart. The underestimation is probably attributable to the underestimated Rossby wave propagation through the westerlies over the eastern North Pacific whose intensity is underestimated in AFES compared to the observations. MID seems to reproduce, although more weakly, the observed dry condition in the U.S. Midwest, but it fails to reproduce a wet condition in Montana and Idaho and a dry condition in southern Arizona, New Mexico, Southern California, and northwestern Mexico. In these
regions, precipitation is climatologically scant and dependent largely on local surface conditions (e.g., evapotranspiration). Although the surface processes are parameterized in the model, the fact that the abnormal warmth and dry condition over the U.S. Midwest are not simulated in summer but first emerge in October in MID suggests that the anticyclonic response over the North America may contribute positively to these surface conditions to some extent. Unlike MID, TROP fails to simulate most of the signals of anomalous warmth and dryness observed in the U.S. Midwest (Figs. 10e,f). These results suggest that the SST anomaly in the midlatitude North Pacific may contribute positively to some of the observed anomalous climatic conditions over North America in October 2011, although they might be caused mostly by other factors, including atmospheric internal variability.

The MID experiment exhibits distinct seasonality in its response. Reproducibility of the monthly atmospheric anomalies over the midlatitude North Pacific is much lower in summer months than in October. Under the midsummer conditions, the model simulates a shallow cyclonic response over the warm SST anomaly and a remote anticyclonic anomaly in equivalent barotropic structure to the northeast. In fact, this local response is similar to the near-surface anomaly observed in August over the warm SST anomaly, where anomalous surface heat flux was upward. Although the cause of the strong seasonality of the model response has not been fully understood, the corresponding seasonality in the climatological-mean westerlies and storm track activity must play an important role, as suggested by Peng et al. (1997) and by Peng and Whitaker (1999) for a wintertime situation. In October, the storm track and westerly axes are located along SAFZ and the storm track activity can be effectively modulated by anomalous surface baroclinicity in the presence of warm SST anomalies. The associated anomalous poleward eddy heat flux and the strong westerlies are favorable for the formation of a deep Rossby wave response (Fig. 7). In summer, by contrast, the storm track and westerlies are both weaker and displaced poleward (Fig. 8), setting conditions unfavorable for the formation of a deep anticyclonic response. Furthermore, the seasonal deepening of the oceanic mixed layer and the resultant increase in its heat capacity established the October situation as being more appropriate for comparison with the AGCM response forced with the prescribed SST anomalies.

In July and September, apparent discrepancies between the model responses and the observed anomalies can be attributed to the difference in causality between the observations and the AGCM experiment where the SST anomalies prescribed as the model boundary condition. This is equivalent to assuming infinite heat capacity of the ocean (Robinson 2000) and supposing enhanced heat release into the atmosphere from warm SST anomalies. In reality, however, the warm SST anomalies accompanied the anomalous downward heat flux into the ocean, corresponding to a buildup stage of the warm SST anomalies under the atmospheric thermal forcing. Therefore, the observed atmospheric anomalies in July and September should not be interpreted as being forced by the SST anomalies. In addition, the midlatitude SST anomalies shifted westward rather abruptly from August to September (Fig. 1), probably in the presence of the shallow seasonal thermocline. This abrupt shift of the SST anomalies might prevent the overlying atmosphere from being in an equilibrated response to them.

As mentioned in section 2, the SST field used as the model boundary condition in CTRL was the climatological-mean SST, whose latitudinal profile should be smoother than that actually observed in any single month. In fact, Fig. 14 indicates that meridional SST gradient across the SAFZ for October based on the climatological-mean SST field tends to be weaker than that observed in most of the individual years. If the state of the overlying atmosphere, especially the storm track
activity, is particularly sensitive to the sharpness of frontal SST gradient across the SAFZ, its effect should be underestimated in CTRL. To examine how serious this underestimation can be, an additional set of AGCM experiments has been conducted. The particular set comprises 29 members, in which SST fields observed in individual years from 1982 to 2010 are prescribed globally as the model boundary condition. Numerical settings are the same as in CTRL, but the integration of any member was initiated on 1 June. Therefore, this experiment may be regarded as a single-member Atmospheric Model Intercomparison Project (AMIP)-type control experiment (in the following, CTRL_AMIP) for the 29 years. A comparison between Figs. 3 and 15 clearly indicates that the equivalent-barotropic anticyclonic response over the North Pacific simulated in MID is robust, if defined as departures either from the ensemble-mean state of CTRL or from the climatological-mean October state realized in CTRL_AMIP, with respect to its amplitude and statistical significance. The only minor difference is noticeable in the cyclonic response over the Bering Sea, which loses its significance if defined as a departure from CTRL_AMIP. Although CTRL_AMIP has only a single member, the similarity between Figs. 3 and 15 suggests that the influence of using climatological-mean SST as a boundary condition of CTRL is limited, and results and discussions in the present study are still valid. This is presumably because the SST profile observed in 2011 represents a poleward shift and broadening of the SAFZ and the SST gradient at the SAFZ axis was among the weakest in the 29-yr period (Fig. 14).

The importance of the midlatitude SST anomaly in forcing the atmospheric anomalies in October 2011 has been further verified in comparison with the remote

![Fig. 14. Latitudinal profiles of equatorward SST gradient \( [\text{C}(100 \text{ km})^{-1}] \) in October over the western North Pacific for individual years from 1982 to 2010 (gray lines) and for 2011 (blue line). The corresponding profile based on the climatological-mean SST is superimposed with a red line. For a given profile, SST field based on the OISST data has been interpolated onto the AGCM grid \( (T119) \) before evaluating the gradient locally and then averaging it longitudinally between 150\( ^\circ \)E and 180\( ^\circ \).](#)

![Fig. 15. (a),(b) As in Figs. 3c and 3d, but (c),(d) the model response for MID is defined as the departure from the October mean state realized in CTRL_AMIP rather than from the CTRL experiment.](#)
influence from tropical SST anomalies simulated in TROP. The remote response is found to be substantially weaker and less robust than its counterpart for MID and the observed anomalies over both the North Pacific and North America, suggesting that the tropical influence may be of secondary importance for the formation of the midlatitude atmospheric anomalies. Nevertheless, the atmospheric response in TROP is almost in phase with that in MID. Although the cold SST anomaly in the equatorial Pacific was even weaker in July through September than in October, the warm midlatitude SST anomalies observed in October 2011 might be generated, at least in part, under the remote influence from the tropics via the “atmospheric bridge” (Lau 1997; Alexander et al. 2002). Even if that is really the case, however, the present study has demonstrated that the midlatitude SST anomalies, once generated by October, can locally reinforce the midlatitude atmospheric anomaly that has forced the SST anomalies and its downstream influence onto climatic conditions over midlatitude North America, which has been overlooked in previous studies (Ruiz-Barradas and Nigam 2010; Wang et al. 2010). Although focusing only on a particular October, the present study thus presents another piece of evidence that a midlatitude SST anomaly has the potential to actively force large-scale atmospheric anomalies and associated abnormal weather conditions in the extratropics.

Acknowledgments. The authors express their sincere thanks to the three anonymous reviewers for their sound criticism and constructive comments on the earlier version of the manuscript, which have led to its substantial improvement. The Earth Simulator was utilized in support of JAMSTEC. This study is supported in part by the Japan Society of Promotion of Science (JSPS) through Grants-in-Aid for Scientific Research in Innovative Areas 2205 and 2409 and by the Japanese Ministry of Environment through Environment Research and Development Grants-in-Aid for Scientific Research in Innovative Areas 2205 and 2409 and by the Japanese Ministry of Education, Culture, Sports, Science and Technology (MEXT) through the Program for Leading Graduate Schools.

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