Two typical modes in the variabilities of wintertime North Pacific basin-scale oceanic fronts and associated atmospheric eddy-driven jet

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Abstract

The role of oceanic fronts in the midlatitude air–sea interaction remains unclear. This study defines new indexes to quantify the intensity and location of two basin-scale oceanic frontal zones in the wintertime North Pacific, i.e. the subtropical and subarctic frontal zones (STFZ, SAFZ). With these indexes, two typical modes, which are closely related to two large-scale sea surface temperature (SST) anomaly patterns resembling Pacific Decadal Oscillation (PDO) and North Pacific Gyre Oscillation (NPGO), respectively, are found in the oceanic front variabilities as well as in their associations with the midlatitude atmospheric eddy-driven jet. Corresponding to an PDO-like SST anomaly pattern, an enhanced STFZ occurs with a southward shifted SAFZ, which is associated with enhanced overlying atmospheric front, baroclinicity and transient eddy vorticity forcing, thus with an intensification of the westerly jet; and vice versa. On the other hand, corresponding to an NPGO-like SST pattern, an enhanced SAFZ occurs with a northward shifted STFZ, which is associated with a northward shift of the atmospheric front, baroclinicity, transient eddy vorticity forcing, and westerly jet; and vice versa. These results suggest that the basin-scale oceanic frontal zone is a key region for the midlatitude air–sea interaction in which the atmospheric transient eddy’s dynamical forcing is a key player in such an interaction.

Keywords: Basin scale oceanic front; sea surface temperature; eddy-driven jet; transient eddy forcing; Pacific Decadal Oscillation; North Pacific Gyre Oscillation

1. Introduction

Many previous studies have identified typical modes of the midlatitude North Pacific sea surface temperature (SST) variabilities, such as Pacific Decadal Oscillation (PDO) (Mantua et al., 1997) and North Pacific Gyre Oscillation (NPGO) (DiLorenzo et al., 2008), and their associations with the atmosphere (Miller et al., 1994; Trenberth and Hurrell, 1994). However, how the midlatitude large-scale SST anomaly can affect the atmosphere remains a challenging issue (Peng and Whitaker, 1999; Fang and Yang, 2011; Frankignoul et al., 2011; Liu, 2012). Recent studies have suggested that such an impact might be related to the midlatitude oceanic front (Qiu and Chen, 2005; 2010; Taguchi et al., 2007; Ceballos et al., 2009; Fang and Yang, 2016). There exist two oceanic frontal zones in the wintertime North Pacific, i.e. the subtropical front zone (STFZ) and subarctic frontal zone (SAFZ), respectively (Nakamura et al., 2008; Nakamura and Yamane, 2010). The oceanic front could maintain midlatitude storm track activities by restoring sharp cross-frontal gradient of surface air temperature, via an oceanic baroclinic adjustment mechanism (Nakamura et al., 2008; Taguchi et al., 2009; Brayshaw et al., 2011). Dynamical diagnoses and numerical experiments indicate that the oceanic front and associated atmospheric transient eddy activities could also crucial in the unstable midlatitude air–sea interaction (Fang and Yang, 2016; Wang et al., 2016; Yao et al., 2016).

It is necessary to further characterize the midlatitude oceanic front and its variability with observational analyses. Previous studies have successfully indentified the regional features of SAFZ with the SST gradient maximum and its latitude in the western Pacific (e.g. Taguchi et al., 2012). Considering the large-scale features of SST anomalies in the North Pacific (such as PDO or NPGO) and the zonally-elongated variabilities of the intense meridional SST gradients associated with STFZ and SAFZ in the entire North Pacific, it is of great interest to characterize the feature in the variabilities of the North Pacific oceanic fronts on the zonal-basin scale and their associations with the midlatitude atmosphere.

In this paper, based on two SST datasets with different resolutions, we define four new indexes to quantify the intensity and location of the basin-scale STFZ and SAFZ during winter in North Pacific, respectively. With these indexes, we examine the typical modes of the two oceanic fronts and their associations with overlying atmospheric eddy-driven jet. Section 2 describes
the datasets used. In Section 3, we firstly present a definition of basin-scale front indexes and validate it with two different resolution SST datasets. In terms of these indexes, we then examine the relationship between the oceanic front and large scale SST variabilities, and the associated atmospheric anomalies. The final section is devoted to conclusions.

2. Data

Two SST datasets with different resolutions are used to analyze oceanic front variabilities. One is the Optimum Interpolation SST Version 2 data (OISST) for 1982–2011 with relatively fine spatial resolution of 0.25° and temporal resolution of 1 day, which is developed by the National Oceanic and Atmospheric Administration (NOAA)’s National Climatic Data Center. The other is the Hadley Centre Global Sea Ice and SST (HadISST) monthly mean SST data for 1960–2011, with relatively coarse global spatial resolution of 1.0°. The monthly mean time series of the PDO and NPGO indexes for 1960–2011 are also used to investigate relationship between oceanic front variabilities and large scale SST variability modes. The PDO index is taken from NOAA Climate Prediction Center and the NPGO index is provided by E. Di Lorenzo. Atmospheric anomalies associated with oceanic front variabilities are examined with the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) daily reanalysis dataset for 1960–2011 with a global resolution of 2.5°, as well as with the NCEP Climate Forecast System Reanalysis (CFSR) dataset for 1982–2010 with a global resolution of 0.5°. In this study, all the datasets are averaged over December, January and February (DJF) to represent wintertime mean for 1982–2010 for OISST and CFSR datasets and 1960–2010 for other datasets.

3. Results

3.1. Definition of basin-scale oceanic front indexes

The climatological distributions of wintertime SST and its meridional gradient in North Pacific demonstrate that large SST meridional gradients are located in the midlatitude North Pacific, especially in two separated frontal zones, i.e. the STFZ near 30°N and the SAFZ near 40°N (Figures 1(a) and (b)). Roughly, the two datasets give similar distributions in SST and its

Figure 1. Climatological distributions of wintertime SST (contours, Unit: K) and its meridional gradient (absolute value, shading, Unit: 10^{-5} Km^{-1}) in North Pacific for (a) OISST during 1982–2010 and (b) HadISST during 1960–2010, and the climatological SST meridional gradient (Unit: 10^{-5} Km^{-1}) zonally-averaged over 145°E~145°W as plotted a function of latitude for (c) OISST and (d) HadISSST. The horizontal blue lines signify the empirically-given critical value for front index definition, which is 0.45 for STFZ and 0.8 for SAFZ, respectively. The vertical blue lines indicate the latitudinal range of each frontal zone for front index definition, which is 24°~32°N for STFZ, and 36°~44°N for SAFZ, respectively.
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(a) ITS_STFZ corr(HadISST and OISST)= 0.84
ITS_SAFZ corr(HadISST and OISST)= 0.78
LCT_SAFZ corr(HadISST and OISST)= 0.72
LCT_STFZ corr(HadISST and OISST)= 0.85

(b) (c) (d)

Figure 2. (a) Time series of the intensity index of STFZ (Units: 10^{-5} Km^{-1}) for HadISST during 1960–2010 (blue line) and for OISST during 1982–2010 (red line). (b) The latitudinal location index of STFZ (Units: °N) for HadISST during 1960–2010 (blue line) and for OISST during 1982–2010 (red line). (c), (d) are the same as (a), (b), but for SAFZ. The correlation coefficients between the front indexes for OISST and HadISST during 1982–2010 are annotated in each figure. Coefficient for statistical significance at 95% level is 0.37.

dependent. The gradient in the western SAFZ based on OISST dataset with higher resolution (Figure 1(a)) is larger than that based on HadISST dataset (Figure 1(b)), probably due to the resolution difference. Since we focus on the basin-scale characteristics of the fronts, the SST gradients are zonally-averaged over the whole North Pacific basin, as illustrated in Figures 1(c) and (d). From 20°N to higher latitudes, the SST gradient becomes stronger and reaches its first maximum at 28.5°N, indicating the STFZ. After slightly weakening, the SST gradient increases again and reaches its second maximum (also the strongest) at about 40.5°N, indicating the SAFZ.

We define two new indexes to quantify the intensity and location, respectively, of each basin-scale oceanic frontal zone, using the SST meridional gradient zonally-averaged over 145°E ~ 145°W, as follows. Given an oceanic frontal zone (say, 24° ~ 32°N for STFZ or 36° ~ 44°N for SAFZ, as seen in Figure 1), its intensity for each winter is defined as.

\[
ITS = \frac{1}{N} \sum_{i=1}^{N} G_i \quad (1)
\]

where \(G_i\) is the value of zonally-averaged SST meridional gradient that is no less than an empirically-given critical value (here, 0.45 × 10^{-5} Km^{-1} for STFZ, and 0.8 × 10^{-5} Km^{-1} for SAFZ) at the \(i\)-th latitudinal grid point within the zone, and \(N\) is the number of total grid points that satisfy the criteria above. The intensity index defined reflects an average of the SST meridional gradient within a frontal zone. Furthermore, the location of a front, as a function of latitude, is defined as.

\[
LCT = \frac{\frac{1}{N} \sum_{i=1}^{N} (G_i \times LAT_i)}{\frac{1}{N} \sum_{i=1}^{N} G_i} \quad (2)
\]

where \(LAT_i\) is the latitude at the \(i\)-th grid point within the front zone. Obviously, this definition reflects a weighted-average of \(LAT_i\) with respect to \(G_i\), indicating that the location of a front is mainly determined by larger SST meridional gradients within the frontal zone.

In terms of the definitions above, the time series of zonally-averaged intensity and location of two fronts are computed with two SST datasets, as shown in Figure 2. Overall, the two datasets exhibit consistent variabilities in both the zonally-averaged intensity and location during the common period 1982–2010 for two fronts, except for the intensity of SAFZ which is slightly weaker in HadISST than in OISST, probably due to the resolution difference. Despite the shortcoming,
the indexes based on HadISST data can characterize the North Pacific basin-scale oceanic front long-term variabilities for its longer time spanning. Note that the analyses based on the HadISST and NCEP/NCAR reanalysis datasets for 1960–2010 and the OISST and CFSR datasets for 1982–2010 are respectively made in this study, and consistent results are obtained. In the following subsections, the results based on the HadISST and NCEP/NCAR reanalysis datasets for 1960–2010 are only presented.

3.2. Relationship between the oceanic front and SST variabilities

Correlation coefficients between any two front characteristic indexes are computed to investigate the internal relation of oceanic front variabilities. As shown in Table S1 (Supporting information), there is no significant relationship between the intensity and location variability of either STFZ or SAFZ. Nevertheless, there is a significant negative correlation between the location of SAFZ and the intensity of STFZ, indicating that STFZ gets stronger when SAFZ moves southward; and vice versa. Meanwhile, there is a significant positive correlation between the intensity of SAFZ and the location of STFZ, suggesting that the enhancement of SAFZ is accompanied with the northward movement of STFZ; and vice versa. The two types of correlations between the STFZ and SAFZ variabilities can be further found to be closely associated with different large-scale SST anomaly patterns in North Pacific.

The negative correlation between the intensity of STFZ and the location of SAFZ can be identified by the regressed SST anomalies in Figures 3(a) and (d). The SST anomaly pattern regressed upon the intensity of STFZ (Figure 3(a)) is quite similar to that regressed upon the location of SAFZ (Figure 3(d)), but for the opposite sign. The negative SST anomaly centered around 40°N (the climatological position of SAFZ) tends to induce a southward shift of the strongest SST meridional gradient (i.e. SAFZ); meanwhile, associated with the southward shift of SAFZ, the negative SST anomaly north of 30°N and the positive SST anomaly south of it tend to increase the SST meridional gradient around 30°N (i.e. the intensity of STFZ); and vice versa. This type of SST anomaly pattern exhibits much resemblance to PDO, the leading EOF mode of the SST anomaly north of 20°N in North Pacific. This relationship is further testified by a significant, positive correlation of 0.7 between the STFZ’s intensity and PDO indexes, and a significant, negative correlation of −0.53 between the SAFZ’s location and PDO indexes, as shown in Table S1. This suggests that when PDO is in its positive phase, SAFZ shifts southward, but STFZ gets stronger; and vice versa. Thus, the
intensity of STFZ together with the location of SAFZ is in well correspondence with the interannual and decadal variability of PDO.

On the other hand, the positive correlation between the location of STFZ and the intensity of SAFZ can be identified by the regressed SST anomalies in Figures 3(b) and (c). The SST anomaly pattern regressed upon the location of STFZ shown (Figure 3(c)) is rather similar to that regressed upon the intensity of SAFZ (Figure 3(b)). The positive SST anomaly around 30°N tends to induce a poleward movement of the large meridional SST gradient in STFZ; meanwhile, the positive SST anomaly south of 40°N together with the negative SST anomaly north of 40°N tends to strengthen SAFZ; and vice versa. This type of SST anomaly pattern reflects NPGO, the second leading EOF mode of the sea surface height anomaly or the SST anomaly in North Pacific (Di Lorenzo et al., 2008). As shown in Table S1, the coefficients between the SAFZ’s intensity (or STFZ’s location) and NPGO indexes are significantly positive, suggesting that the positive phase of NPGO is accompanied with the intensification of SAFZ and northward movement of STFZ; and vice versa.

3.3. Associated atmospheric anomalies

Owing to the significant cross correlation between the intensity of one front and the location of another, as found above, the atmospheric anomalies are regressed only upon the intensity and the location of STFZ, respectively. Figure 4 shows the latitude-latitude distributions of the regressed atmospheric anomalies zonally-averaged over 145°E~145°W for the meridional air temperature gradient, baroclinicity represented by the maximum Eady growth rate (Hoskins and Valdes, 1990), zonal wind speed, and tendency of zonal wind speed forced by the diabatic heating and transient eddy forcing. As the meridional gradient is taken of the quasi-geostrophic potential vorticity (QGPV) equation used in Lau and Holopainen (1984) and Fang and Yang (2016), then the tendency of seasonal mean zonal wind speed (mm) induced by the diabatic heating (F1), the transient eddy thermal forcing (F2) and the transient eddy vorticity forcing (F3) can be written as,

\[ \bar{Q}_d = \text{the diabatic heating, } Q_{\text{eddy}} \text{is the transient eddy thermal forcing, } Q_{\text{eddy}} = -\nabla \cdot (\bar{V}T') \text{, and } F_{\text{eddy}} \text{ is the transient eddy vorticity forcing, } F_{\text{eddy}} = -\nabla h' \left( \frac{\nabla\cdot\bar{V}'}{\bar{\rho}'} \right). \]

For comparison, the climatological distributions for those atmospheric variables are also shown with contours in Figure 4. Climatologically, the meridional air temperature gradient (Figures 4(a) and (b)) and baroclinicity (Figures 4(c) and (d)) are the strongest in the lower- and mid-troposphere at midlatitudes, while the westerly jet prevails with center at about 200 hPa over 30°~40°N with equivalent barotropic structure (Figures 4(e) and (f)). Compared with the diabatic heating (Figures 4(g) and (h)) and the transient eddy thermal forcing (Figures 4(i) and (j)), only the transient eddy vorticity forcing (Figures 4(k) and (l)) is substantially positive slightly north of the jet center, acting to reinforce the midlatitude jet. Note that the wintertime jet over the midlatitude North Pacific is basically a merging of the eddy-driven jet and the subtropical jet.

We find that the atmospheric anomalies regressed upon the intensity of STFZ are thoroughly in phase with their corresponding climatologies over 30°~40°N, indicating their variabilities only in intensity, as shown with shading in the left panels of Figure 4. When the intensity of STFZ is stronger than usual, which occurs with a southward shifted SAFZ, both the meridional air temperature gradient (atmospheric front) and the baroclinicity below 300 hPa are considerably increased (Figures 4(a) and (c)), which favors more transient baroclinic eddy activities in the vicinity of 35°N. As a result, the transient eddy vorticity forcing induced zonal wind tendency gets stronger with equivalent barotropic structure over 30°~40°N (Figure 4(k)), which tends to enforce a positive anomaly of zonal wind speed appearing at the center of jet and thus intensify the westerly jet (Figure 4(e)). However, the diabatic heating (Figure 4(g)) and the transient eddy thermal forcing (Figure 4(i)) tend to decrease the upper level jet and increase lower level westerly, with a baroclinic structure.

On the other hand, the atmospheric anomalies regressed upon the location of STFZ are characterized by a meridional dipole pattern with zero contour around 35°N, indicating their variabilities only in location, as shown with shading in the right panels of Figure 4. When STFZ goes northward, which occurs with an enhanced SAFZ, both the meridional air temperature gradient and the atmospheric baroclinicity below 300 hPa exhibit positive anomalies over 40°~50°N and negative anomalies over 20°~30°N (Figures 4(b) and (d)). In comparison with their climatologies, such an anomaly pattern implies a northward shift of the atmospheric front and baroclinic zone. Consequently, the transient eddy vorticity forcing is strikingly enhanced along 40°~50°N (Figure 4(l)), especially in the upper troposphere, giving rise to a northward movement of the westerly jet, as shown in Figure 4(f). In this case,
Figure 4. Altitude-latitude distributions of the climatologies (contours) and the atmospheric anomalies (shading) zonally-averaged over 145°E − 145°W regressed upon the intensity index of STFZ (left panels) and upon the location index of STFZ (right panels) for (a, b) the air temperature meridional gradient (Units: $10^{-5}$ Km$^{-1}$), (c, d) the baroclinicity or maximum Eady growth rate (Units: $10^{-5}$ ms$^{-2}$), (e, f) the zonal wind speed (Units: ms$^{-1}$), (g, h) the tendency of zonal wind speed forced by diabatic heating (F1, Units: $10^{-5}$ ms$^{-2}$), (i, j) the tendency of zonal wind speed forced by transient eddy thermal forcing (F2, Units: $10^{-5}$ ms$^{-2}$), and (k, l) the tendency of zonal wind speed forced by transient eddy vorticity forcing (F3, Units: $10^{-5}$ ms$^{-2}$). The front indexes are based on the HadISST data for winter of 1960–2010. Areas with statistical significance no less than 95% level are dotted.

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the diabatic heating (Figure 4(h)) and the transient eddy thermal forcing (Figure 4(j)) are also characterized by a meridional dipole pattern, but with a baroclinic structure.

### 4. Summary

This study characterizes the variabilities of two zonally-basin-scale oceanic frontal zones (i.e. STFZ and SAFZ) in the wintertime North Pacific as well as their associations with the midlatitude atmosphere, especially with the eddy-driven jet. New characteristic indexes are defined with zonally-averaged SST meridional gradient over 145°E–145°W to quantify the intensity and the location of each basin-scale frontal zone, respectively, and further validated with the fine resolution OISST data for 1982–2010 and the coarse resolution HadISST data for 1960–2010. These indexes measured by two different resolution SST datasets are almost the same over the overlapping period (1982–2010), except for the intensity of SAFZ which is slightly weak when measured by the coarse resolution data.

Cross-correlation analyses exhibit that the variabilities of two basin-scale oceanic fronts in the wintertime North Pacific are not independent of each other. There is a significant negative (positive) cross correlation between the intensity of STFZ (SAFZ) and the location of SAFZ (STFZ), indicating that STFZ (SAFZ) gets stronger when SAFZ (STFZ) moves southward (northward), and vice versa. The two types of cross correlations between STFZ and SAFZ are closely associated with two different modes of large scale SST variabilities in the wintertime North Pacific, i.e. the PDO and NPGO, respectively.

Regression analyses demonstrate that the two types of the basin-scale oceanic front variabilities identified above are also characterized by two types of the overlying atmospheric anomalies, as summarized in Figure 5. When there is a PFO-like positive SST anomaly in North Pacific (Figure 5(a)), STFZ gets stronger while SAFZ goes southward, which is associated with significantly enhanced lower- and mid-level atmospheric front, baroclinicity, and transient eddy vorticity forcing with equivalent barotropic structure, thus with an intensification of the westerly jet; and vice versa. On the other hand, when there is an NPGO-like positive SST anomaly in North Pacific (Figure 5(b)), SAFZ gets stronger while STFZ goes northward, which is associated with a northward shift of the atmospheric front, the baroclinic zone, the transient eddy vorticity forcing strikingly in the upper troposphere, and the westerly jet; and vice versa.

These results suggest that the basin-scale oceanic frontal zone is a key region for the large-scale air–sea interaction in the midlatitudes, in which the dynamical forcing of the transient eddy activity that is determined by the oceanic front-induced low-level atmospheric meridional temperature gradient and baroclinicity is a key player in such an interaction. Note that, although this study is based on observational analyses, the major findings presented here agree well with those results from higher resolution numerical experiments (Wang et al., 2016; Yao et al., 2016), and support the hypothesis for the unstable mid-latitude air–sea interaction proposed by Fang and Yang (2016).
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Supporting information
The following supporting information is available:

Table S1. Correlation coefficients between two oceanic front indexes, and between the front indexes and the PDO and NPGO indexes

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