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Key Points:
- The atmosphere is sensitive to midlatitude SST anomalies
- Daily SST changes must be resolved by climate models
- Climate prediction in midlatitudes can be enhanced

Supporting Information:
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Atmospheric response to the North Pacific enabled by daily sea surface temperature variability

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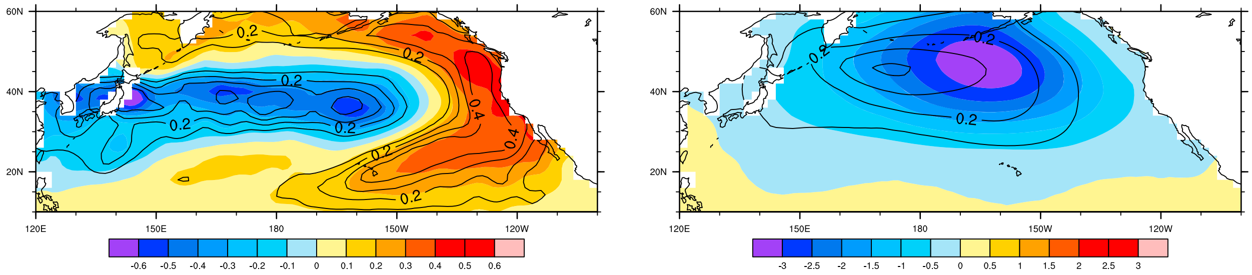
Abstract Ocean-atmosphere interactions play a key role in climate variability on a wide range of timescales from seasonal to decadal and longer. The extratropical oceans are thought to exert noticeable feedbacks on the atmosphere especially on decadal and longer timescales, yet the large-scale atmospheric response to anomalous extratropical sea surface temperature (SST) is still under debate. Here we show, by means of dedicated high-resolution atmospheric model experiments, that sufficient daily variability in the extratropical background SST needs to be resolved to force a statistically significant large-scale atmospheric response to decadal North Pacific SST anomalies associated with the Pacific Decadal Oscillation, which is consistent with observations. The large-scale response is mediated by atmospheric eddies. This implies that daily extratropical SST fluctuations must be simulated by the ocean components and resolved by the atmospheric components of global climate models to enable realistic simulation of decadal North Pacific sector climate variability.

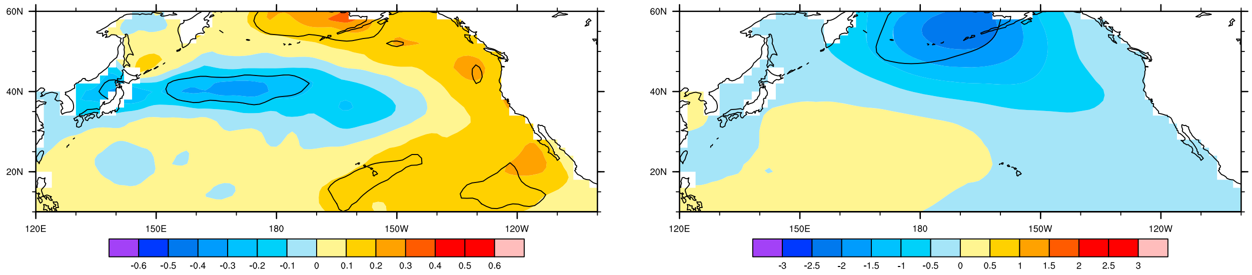
1. Introduction

The North Pacific exhibits sea surface temperature (SST) variability on a variety of timescales. An example is the Pacific Decadal Oscillation (PDO), the leading mode of North Pacific SST variability, which strongly impacts the land surface climate around and ecosystems in the North Pacific [*Mantua et al.*, 1997; *Deser et al.*, 2004]. Atmospheric forcing and a number of oceanic processes such as the reemergence mechanism [*Alexander et al.*, 1999] have been proposed as influences on the North Pacific SST. Independent of their origin, changes in SST alter the lower boundary condition for the atmosphere and have the potential to drive large-scale atmospheric circulation changes [*Czaja and Frankignoul*, 1999, 2002; *Rodwell and Folland*, 2002]. Whereas the atmospheric response to equatorial Pacific SST anomalies is well understood, that to midlatitude SST anomalies is still highly controversial [*Peng and Whitaker*, 1999; *Kushnir et al.*, 2002]. Disentangling the extratropical ocean's impact on the atmosphere using observations is difficult due to the fact that any observable ocean-atmospheric state is the final product of the mutual interaction between the atmosphere and the ocean and that the methods employed are subject to statistical and dynamical constraints. Until now, many observational [*Liu et al.*, 2006; *Frankignoul and Sennéchael*, 2007; *Wen et al.*, 2010; *Liu et al.*, 2012], theoretical [e.g., *Frankignoul*, 1985], forced atmospheric general circulation model (AGCM) [*Palmer and Sun*, 1985; *Latif and Barnett*, 1994; *Kushnir and Held*, 1996; *Peng et al.*, 1997; *Liu and Wu*, 2004], and coupled climate model [*Saravanan*, 1998; *Liu and Wu*, 2004; *Kwon and Deser*, 2007; *Liu et al.*, 2007; *Lee et al.*, 2008; *Zhong and Liu*, 2008] studies presented complex and sometimes controversial results regarding the vertical structure and sign of the atmospheric response to midlatitude SST anomalies. Nevertheless, a shallow (baroclinic) linear response and a deep (barotropic) response driven by atmospheric eddies are commonly suggested [*Kushnir et al.*, 2002].

Although the feedback by baroclinic eddies has been recognized as being important in shaping the atmospheric response to extratropical SST anomalies [*Ting and Peng*, 1995; *Peng and Whitaker*, 1999; *Kushnir et al.*, 2002], the sensitivity to potential factors affecting the generation and evolution of atmospheric eddies has been poorly understood. Recent studies suggest that the presence and variability of sharp SST fronts associated with the Gulf Stream and Kuroshio/Oyashio extensions are important factors influencing the storm track and thus for large-scale air-sea interactions [*Nakamura et al.*, 2004; *Minobe et al.*, 2008; *Taguchi et al.*, 2009; *Kelly et al.*, 2010; *Kwon et al.*, 2010; *Frankignoul et al.*, 2011; *Ogawa et al.*, 2012; *Taguchi et al.*, 2012; *Small et al.*, 2014; *Smirnov et al.*, 2015]. Small-scale ocean surface structures such as ocean mesoscale eddies can impact the atmospheric boundary layer [*Frenger et al.*, 2013], yet whether the influence extends to the large-scale atmospheric circulation outside the boundary layer remains unclear. Here by means of statistical analyses and dedicated numerical experiments, we investigate the impact of daily variability in


(**a**) Lag 0 – SST

(**b**) Lag 0 – SLP


(**c**) Lag 1 – SST

(**d**) Lag 1 – SLP

Figure 1. Regression patterns of (a, c) observed SST (°C) and (b, d) SLP (hPa) anomalies on the ENSO-removed PDO index. Figures 1a and 1b show simultaneous regressions (lag 0). Figures 1c and 1d show regressions when the PDO index leads by 1 year (lag 1 year). Long-term linear trends are removed before computing regression. Color shading indicates the amplitudes (regression coefficients), while contours show the explained variances (contour interval 0.1). According to an *F* test, the 0.1 contour in Figures 1b and 1d is significant at the 99% significance level.

the extratropical background SST on the large-scale atmospheric response to PDO-like extratropical SST anomalies.

This paper is organized as follows: observational evidence of a midlatitude atmospheric response to a North Pacific SST anomaly is presented in section 2. The experimental setup is described in section 3. Section 4 addresses the characteristics of the response. In section 5, the importance of daily SST variability for the response is demonstrated by discussing a number of sensitivity experiments. Summary and discussion are given in section 6.

2. Observational Evidence

The nature of air-sea interactions over the North Pacific is studied first by analyzing observed wintertime (December–February, DJF) SST and sea level pressure (SLP) anomalies using the Extended Reconstruction SST version 2 product [*Smith et al.*, 2008] and the Extended Reconstruction SLP [*Smith and Reynolds*, 2004] data both covering 1909–1997. After linear detrending locally, regression patterns were computed with respect to an "El Niño/Southern Oscillation (ENSO)-removed" PDO index. The index has been obtained from empirical orthogonal function (EOF) analysis of winter mean North Pacific SST anomalies (120°E–80°W, 20°N–60°N) and is defined as the principal component of the leading EOF. ENSO [*Philander*, 1990] effects on the PDO index were strongly damped by previously removing SST variability associated with the leading two EOFs of tropical Pacific SST anomalies (120°E–80°W, 30°S–20°N).

The resulting SST anomaly pattern (positive phase shown by Figure 1a) is very similar to the PDO pattern, i.e., the leading EOF, with a band of cold SST anomalies along the Kuroshio/Oyashio Extension that is surrounded by warm SST anomalies. When the regression analysis is repeated with a time lag of 1 year, the cold SST anomaly reappears with reduced size and strength (Figure 1c). The SLP anomaly pattern associated with the PDO index at lag 0 depicts anomalously low pressure over the Aleutian Low region downstream and slightly to the north of the cold SST anomaly (Figure 1b), which also persists into the next winter but with weaker amplitude (Figure 1d). These features are statistically significant at the 99% level. Our results also suggest multiyear persistence of the SST and SLP anomalies (Figures S1 and S2 in the supporting information). The persistence of SST can be explained by the thermal inertia of the ocean mixed layer and by the reemergence mechanism [*Alexander et al.*, 1999; *Czaja and Frankignoul*, 1999, 2002], in which the temperature perturbations are stored in the deep oceanic mixed layer and brought up to the surface repeatedly for several winters by wind mixing. Bearing in mind the exclusion of most ENSO forcing and the short atmospheric adjustment time [*Ferreira and Frankignoul*, 2005], the long persistence of the linkage between SLP and SST presumably stems from the persistence of SST [*Kushnir et al.*, 2002]. This view is in general accordance with *Frankignoul et al.* [1998], *Frankignoul and Sennéchael* [2007], and the temporal "oceanic bridge" proposed by *Rodwell and Folland* [2002] except that in our results the oceanic bridge acts for multiple years rather than months. Our findings agree well with the recent observational and modeling studies of, e.g., *Liu et al.* [2007], *Wen et al.* [2010], and *Liu et al.* [2012].

3. Experimental Design

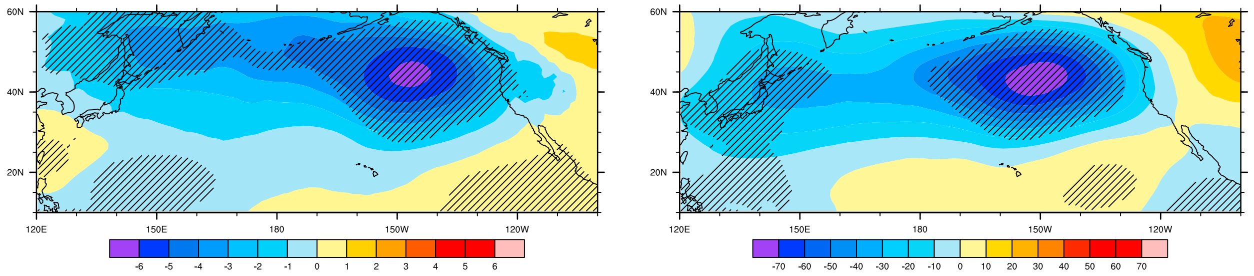
In order to investigate the dynamics of the atmospheric response to North Pacific SST variability, the European Centre/Hamburg version 5 atmospheric general circulation model [*Roeckner et al.*, 2003] was integrated on a T213 (about 0.56°) grid with 31 levels up to 10 hPa. The daily observational data set NOAA-OI-SST [*Reynolds et al.*, 2007] covering 1981–2010 is used to derive the SST anomaly patterns in the North Pacific used to force the model. To do so, the multiyear time series of SST averaged over each respective calendar month are regressed against the ENSO-removed wintertime PDO index using the same data set, producing 12 anomaly patterns. We then position the 12 patterns at the middle of each month and linearly interpolate the time series to create a daily time series. Figure S3 shows the winter mean pattern of the daily varying SST anomaly. This daily SST anomaly time series was superimposed, with both positive and negative polarity, onto the observed high-resolution daily SST and used to drive the model. The model was integrated for each of the 10 winters during 1981–1990, where each experiment starts from a different 1 November initial condition taken 1 year apart from a continuous run forced by daily observed SST during 1981–1990. The background SST variability is substantial and associated with both small-scale perturbations which affect the structure of oceanic fronts and significant interannual variability. Thus, our configuration using observed daily SST considerably differs in comparison to previous studies where SST anomalies have been added to the monthly SST climatology [e.g., *Ting and Peng*, 1995]. We name the ensemble of the 10 winter runs "DAGL" (meaning *da*ily *gl*obally) and depict the atmospheric response in terms of the 10 year mean winter differences between cases with positive and negative SST forcing polarity. Vertical sections show zonal means across the North Pacific (120°E–100°W). Statistical significance of the 10 year mean differences is assessed by a one-sample t test using 9 degrees of freedom. Storm track is defined as the standard deviation of band-pass (2–8 days) filtered geopotential heights.

Four sensitivity experiments with the same SST anomalies as above are conducted for the 10 winters during 1981–1990 to investigate the importance of background SST variability. We first compute the daily SST climatology for the period 1981–1990, which basically eliminates variability superimposing the annual cycle as well as small-scale spatial variability (Figures S4–S6). In the first sensitivity experiment (DANP), the daily climatological SST is used as background SST outside the North Pacific, while the SST is unchanged over the North Pacific. A 10° linear transition zone (10°N–20°N) is applied to the southern boundary of the North Pacific to ensure smooth merging of the two background SSTs. In the second experiment (CLIM), daily climatological SST is used everywhere over the global oceans. In the third experiment (FILT), the same setup is used as that in DANP except that an 11 day running average is applied to the background SST over the North Pacific. For the fourth sensitivity experiment (HFCL), we extract from the winter 1984/1985 the high-frequency component of North Pacific SST by deducting the 11 day running averaged SST from the original data and add it to the daily SST climatology. The winter of 1984/1985 has the largest daily SST standard deviation of all 10 winters. This setup eliminates the interannual variability from the background SST while keeping the high-frequency daily variability and also strongly damps small-scale SST structures (Figures S4–S6).

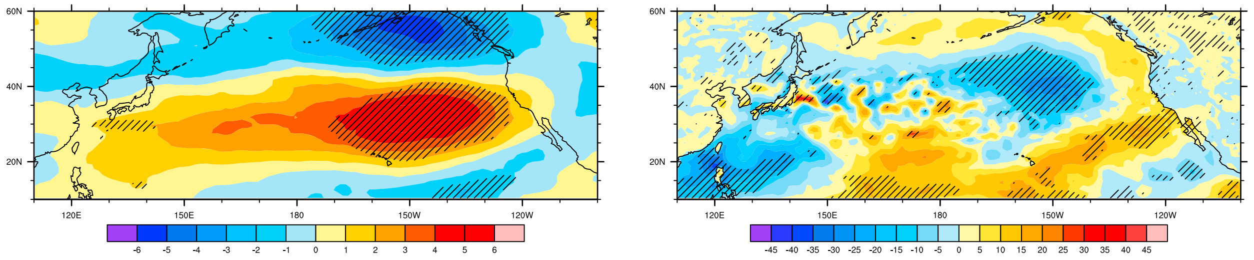
4. Response Characteristics

A statistically significant reduction in SLP is simulated over the North Pacific in DAGL (Figure 2a), which is generally consistent with observations (Figures 1b and 1d) in that large parts of the North Pacific north of 40°N depict lower pressure; regional details, however, differ. The anomalously low pressure at sea level is the surface expression of an equivalent barotropic response centered at around 250 hPa over the latitude belt 35°N–50°N (Figures 2b and 3a). Zonal velocity at 500 hPa depicts a positive anomaly across the North Pacific which is strongest near 150°W and 30°N (Figure 2c), suggesting an eastward extension of the jet stream. Our model results agree with previous observational [e.g., *Wen et al.*, 2010; *Liu et al.*, 2012] and modeling [e.g., *Latif and Barnett*, 1994, 1996; *Liu and Wu*, 2004] studies with regard to the pressure response.

(a) SLP **(b)** 500 hPa geopotential height



(c) 500 hPa eastward zonal velocity **(d)** Surface downward latent heat flux



(e) 500 hPa storm track **(f)** 500 hPa downward velocity

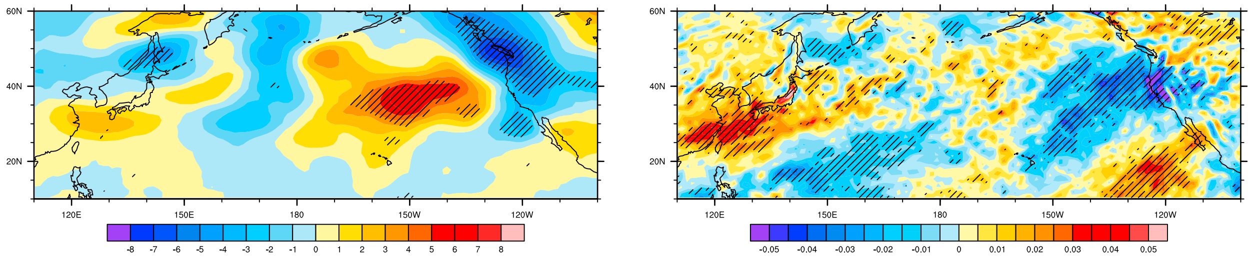


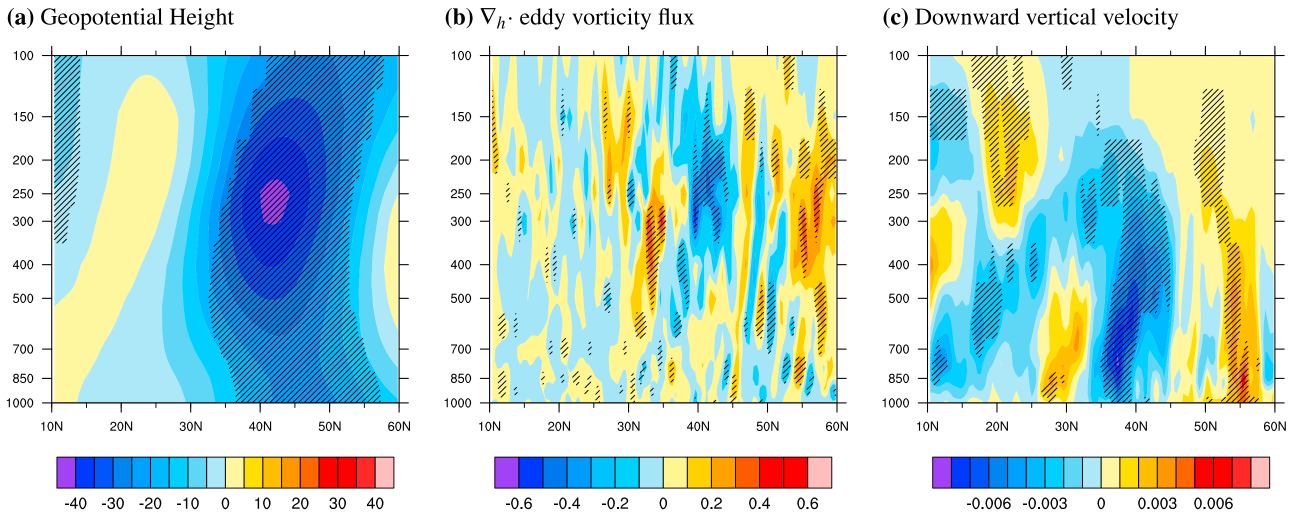
Figure 2. Ten year mean winter (DJF) response of (a) sea level pressure (hPa), (b) 500 hPa geopotential height (m), (c) 500 hPa eastward zonal velocity (m/s), (d) surface latent heat flux (downward positive) (W/m^2), (e) 500 hPa storm track defined as the standard deviation of band-pass (2–8 days) filtered geopotential heights (m), and (f) vertical velocity (downward positive) (Pa/s) simulated by the experiment DAGL. Statistical significance at the 90% level is indicated by hatching.

However, the surface latent heat flux response (Figure 2d) differs from many previous modeling and observational studies [e.g., *Frankignoul and Kestenare*, 2002; *Okajima et al.*, 2014] in that over the western half of the North Pacific, there is no clear damping of the SST anomalies. This discrepancy must be attributed to the inclusion of daily background SST in this study, as discussed below.

Two types of model response to midlatitude SST anomalies have been noted in the literature, a shallow linear response and a deep response supported by eddy fluxes [*Kushnir et al.*, 2002]. The former has been shown to act at the very initial stage of the response [*Ferreira and Frankignoul*, 2005], while the latter dominantly operates in our high-resolution model. In particular, the mean flow response over the eastern North Pacific is associated with a significant northeast-southwest shift in the storm track (Figure 2e). This change results from the anomalous baroclinic deformation caused by the increased zonal velocity gradient [*Chang et al.*, 2002] and also contributes to the mean flow response. According to the quasi-geostrophic vorticity equation [*Hoskins*, 1983], the eddy vorticity flux convergence in the upper troposphere near 40°N (Figure 3b) is partly balanced by divergence of the mean flow, resulting in ascending motion at low and middle levels (Figures 2f and 3c) and near-surface convergence. Convergence of eddy-induced zonal momentum flux (Figure 3d), on the other hand, directly accelerates the zonal flow aloft (Figure 3e). All these features are statistically significant at the 90% level.

5. Importance of Daily SST Variability

Our experimental setup preserves both spatially small scale and temporally high frequency SST fluctuations and thus resolves local and transient variations in SST. To further investigate the impact of background SST variability on the atmospheric response, we performed a number of sensitivity experiments. In DANP in which



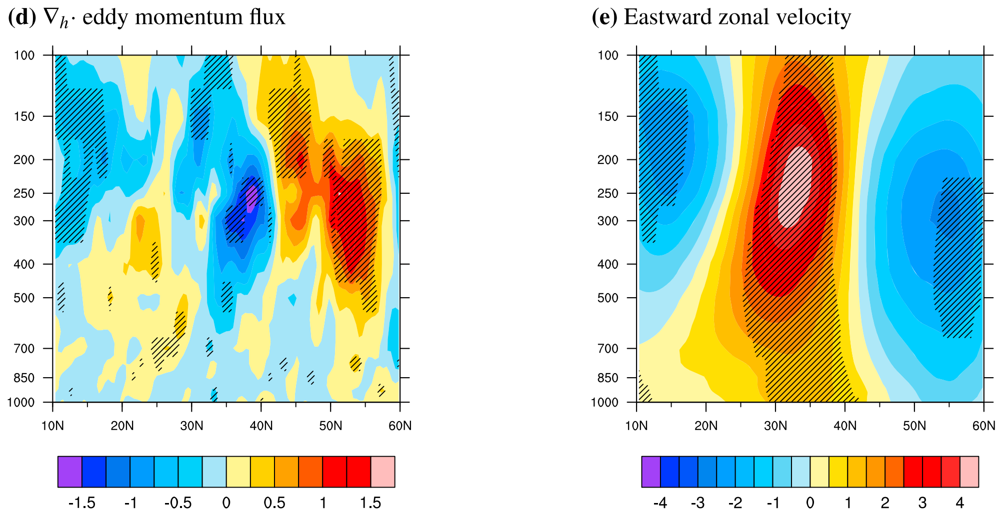


Figure 3. Vertical sections of the 10 year mean winter (DJF) response simulated by the experiment DAGL, zonally averaged over the Pacific sector for (a) geopotential height (m), (b) divergence of eddy vorticity flux (day^{-2}), (c) downward vertical velocity (Pa/s), (d) divergence of eddy momentum flux (m/s/day), and (e) zonal wind velocity (m/s). Statistical significance at the 90% level is indicated by hatching.

daily SST variability is restricted to the North Pacific, the response is similar to that discussed above (Figure 3a) in that there is a reduction in geopotential height of similar amplitude throughout the troposphere over the midlatitude North Pacific (Figure 4a). No statistically significant response is simulated in CLIM in which climatological SST is used everywhere (Figure 4b). These experiments demonstrate that variability in the background SST other than the seasonally varying climatology in the region where the SST anomalies are superimposed is essential to drive a significant large-scale response. The FILT experiment fails to reproduce a statistically significant response (Figure 4c), indicating sufficiently strong daily variability in the background North Pacific SST is crucial in establishing the response in DAGL. The HFCL experiment, which eliminates the effects of interannual variability, yields a very similar response (Figure 4d) to that shown in Figure 3a. Thus, our results suggest that retaining interannual variability in the background SST is of minor importance to the large-scale atmospheric response. Previous studies have used rather strong SST anomalies [*Kushnir et al.*, 2002; *Peng et al.*, 1997; *Peng and Robinson*, 2001; *Liu and Wu*, 2004]. We employed SST anomalies of realistic strength to drive the model. This too may suggest that daily SST variability in the background SST is important for driving a large-scale atmospheric circulation response to midlatitudinal SST anomalies, as it can enhance the atmospheric response to an extent that would otherwise only be achieved by a much stronger SST anomaly.

The reason why daily SST variability is so important in the background SST, on which the SST anomaly is superimposed, remains unclear to us. As the atmospheric response itself is maintained by baroclinic eddies, a

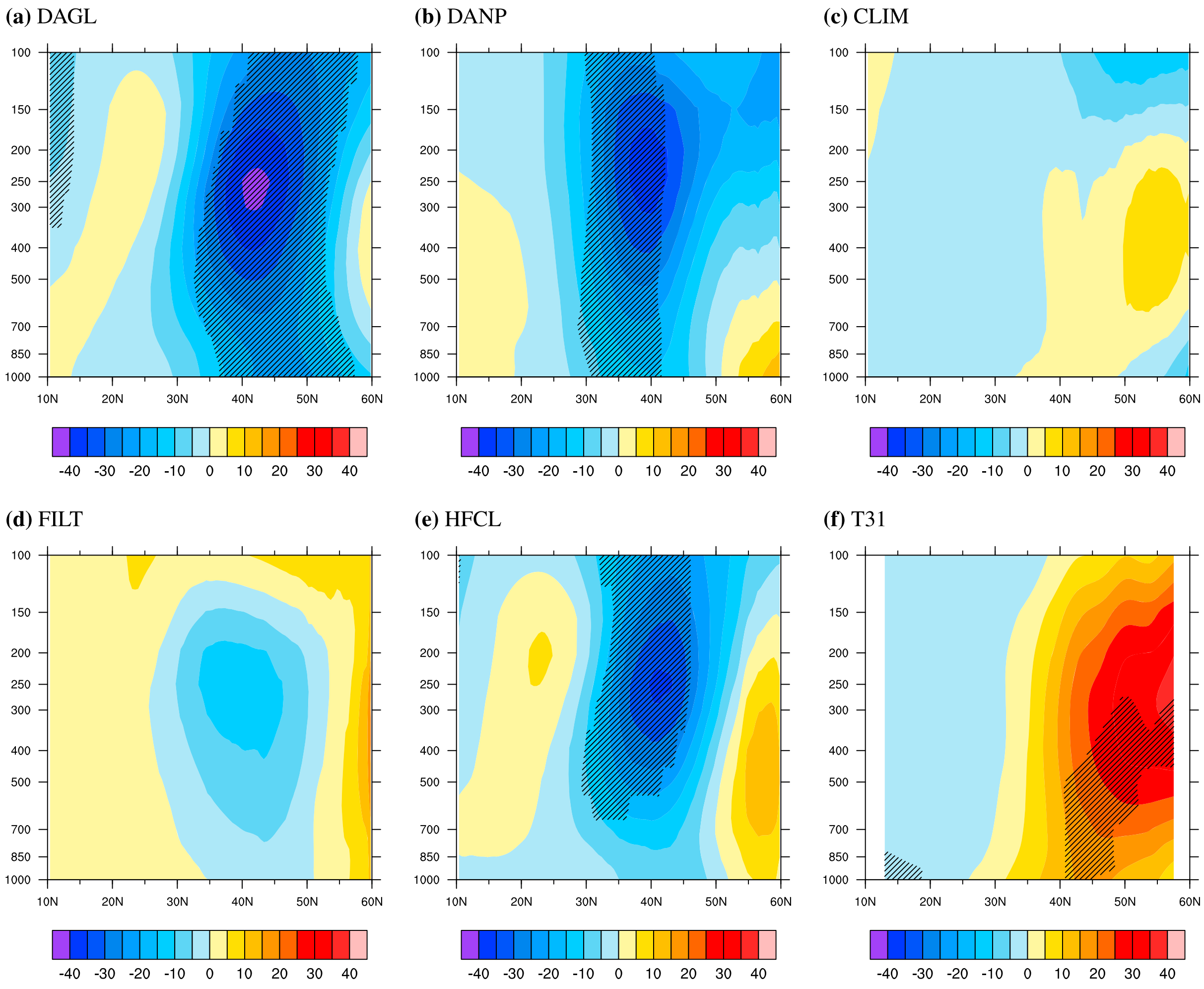


Figure 4. Vertical sections of the 10 year mean winter (DJF) response zonally averaged over the Pacific sector for geopotential height (m) simulated in (a) DAGL, (b) DANP, (c) CLIM, (d) FILT, (e) HFCL, and (f) the T31 experiment. Statistical significance at the 90% level is indicated by hatching.

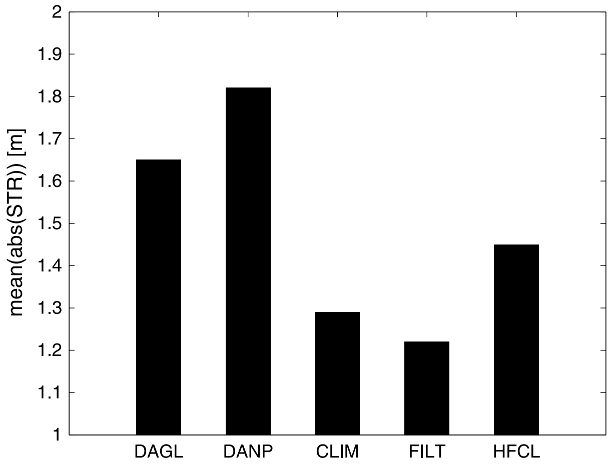


Figure 5. Bar chart showing the mean absolute value of the storm track (m) response at 500 hPa spatially averaged over the eastern North Pacific (180°E–100°W, 10°N–60°N). Storm track is defined as the standard deviation of band-pass (2–8 days) filtered geopotential heights.

plausible pathway is through the modulation of the atmospheric storm track. The storm track response exhibits a common pattern over the eastern North Pacific in all experiments (Figures 2d and S7). However, the response in FILT and CLIM is reduced compared to that in DAGL, DANP, and HFCL (Figure 5). One may assume that sharp local SST gradients are one energy source for midlatitudinal storms and that the probability of occurrence of such gradients is enhanced when the background SST varies on daily timescales. However, the corresponding probabilities are inconclusive (Figure S8b), indicating that other energizing factors should also be considered.

We computed the Eady growth rate (Figures S9a, computed over the region of the cold SST anomaly in the western half of the basin and following *Hoskins and Valdes* [1990]). The Eady growth rate is an indicator of baroclinicity. In the experiments with daily background SST variability (DAGL, DANP, and HFCL), the Eady growth rate response is generally positive, while in the other two experiments (CLIM and FILT), it is basically negative. Moreover, the patterns of surface latent heat flux (Figures 2d and S10) also differ markedly between the experiments with and without daily background SST variability: in CLIM and FILT, the response tends to damp the SST anomaly over the western North Pacific, while in the others the picture is less clear. Due to the atmospheric heat loss in CLIM and FILT, the lower atmosphere is more stably stratified (Figure S9b), which tends to reduce the Eady growth rate (Figure S9a) and thus weakens the storm track downstream (Figure S7). The effect of the vertical wind shear is negligible (Figure S9c). Finally, eddy heat flux convergence in the critical height range of 900–700 hPa is found in DAGL, DANP, and HFCL (Figure S9d), which opposes the thermal damping of the cold SST anomaly, leading to a patchy latent heat flux pattern (Figure S10).

We note that a coarse-resolution (T31, about 3.75°) version of the AGCM with exactly the same setup as DAGL does not reproduce the above results (Figures 4f and S10e). As the coarse-resolution model also resolves daily SST variability, its failure is likely due to its inadequate spatial resolution which inhibits realistic representation of eddy activity.

6. Summary and Discussion

We have shown by high-resolution atmosphere model experiments that the daily component of the background sea surface temperature (SST) variability is important in driving a statistically significant large-scale atmospheric response to PDO-like SST anomalies. The mechanism is most likely through modulation of atmospheric storm activity. Daily SST fluctuations have largely been regarded as noise and were often ignored in previous modeling studies on the atmospheric response to midlatitudinal SST anomalies. Climate variability in the extratropics may be underestimated, if daily SST variability is not realistically simulated by the ocean and not resolved by the atmospheric components of climate models. Moreover, seasonal to decadal prediction [e.g., *Scaife et al*., 2014] may be enhanced when climate models realistically represent the effects of daily SST variability on large-scale air-sea interactions. The exact mechanism why the daily SST variability matters, however, needs further investigation.

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