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Key Points:

- A midwinter minimum of eddy activity is found in the North Atlantic storm track
- The minimum occurs despite the stronger wintertime jet and enhanced baroclinicity
- The minimum is more pronounced in winters of stronger and more equatorward Atlantic jet

Supporting Information:

- Supporting Information S1

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A Midwinter Minimum in North Atlantic Storm Track Intensity in Years of a Strong Jet

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Abstract This study investigates the occurrence of a midwinter suppression in synoptic eddy activity within the North Atlantic storm track. It is found that eddy kinetic energy over the Atlantic is reduced during winter relative to fall and spring, despite the stronger wintertime jet and enhanced baroclinicity. This behavior is similar to the well-known Pacific midwinter minimum, yet the reduction over the Atlantic is smaller and persists for a shorter period. To examine the conditions favorable for this phenomenon, we present an analysis of years with stronger jet intensity versus years of weaker jets over the Atlantic and Pacific basins. When the wintertime jet is stronger, the midwinter suppression of eddy activity is more pronounced, and the jet is more equatorward. Since the climatological Atlantic jet is weaker relative to the Pacific jet, the conditions for a midwinter suppression in the Atlantic are generally less favorable, yet a midwinter suppression often occurs in years of a strong jet.

1. Introduction

In the Northern Hemisphere, synoptic-scale eddy activity is mostly concentrated in two regions, known as the Pacific and Atlantic storm tracks. Linear theories of baroclinic instability suggest that the baroclinic growth of eddies is associated with regions of strong vertical shear of the westerly winds (e.g., Charney, 1947; Eady, 1949). These linear theories have provided significant insights on the influence of the zonal mean flow on generation of baroclinic eddies. However, eddy activity observed over the northern Pacific during the winter season contradicts linear theory predictions and suggests that the relationship between the mean flow and the eddies within the storm tracks may be more complex. As shown by Nakamura (1992), baroclinic wave activity over the northern Pacific is reduced in midwinter, relative to late fall and early spring, despite the enhanced baroclinicity and stronger westerlies. This reduction is referred to as the Pacific midwinter minimum (Figure 1a). Recent studies have suggested that such a midwinter suppression of eddy activity may occur in other regions as well. A midwinter minimum has been observed in the upstream region over East Asia (Penny et al., 2010; Ren et al., 2010), and a weak signal of late winter suppression has been identified in the North Atlantic (Ren et al., 2014).

The relation between the observed strengthening of the Pacific jet during midwinter and the associated decrease in eddy activity has been discussed in several studies. Nakamura (1992) has shown that on the seasonal, as well as on the interannual time scales, a positive correlation between the intensity of the storm track and the strength of the jet exists as long as the speed of the jet is below $\sim$45 m s^{-1}. Above this threshold, the correlation becomes negative and storm track intensity is decreased as the jet strengthens (see also Christoph et al., 1997).

It has been suggested that increased advection by the strong westerlies may suppress eddy growth, by causing the eddies to move fast out of the baroclinic region before they reach large amplitudes (Chang, 2001; Nakamura, 1992). Moreover, the strong westerlies also lead to a less efficient energy conversion from the mean flow to the eddies (Chang, 2001; Nakamura et al., 2002). Nakamura and Sampe (2002) showed that winters of pronounced midwinter minimum are associated with stronger jets, suggesting that the intensified jet suppresses baroclinic growth by trapping the upper level disturbances within the subtropical jet, meridionally away from the surface baroclinic zone. Other studies have focused on variations in the jet structure and their relation to storm track activity. Harnik and Chang (2004) examined the effects of variations in the jet width on the growth of baroclinic waves and showed that weakening of the storm tracks during periods of strong jets can be related to the narrowing of the jet during that time. However, while this effect may be important for interannual variability, they showed that the seasonal changes in the width of the jet are relatively small

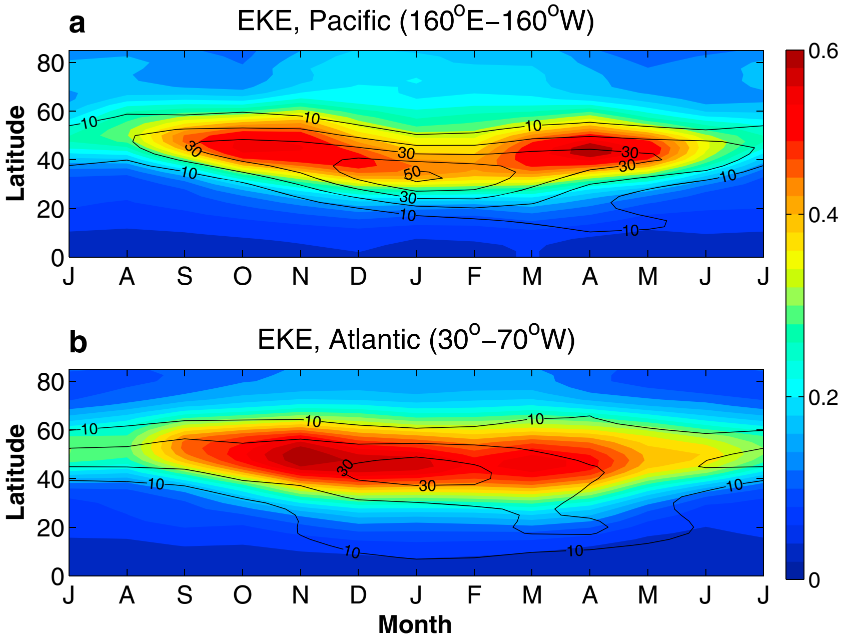

Figure 1. Observed zonally averaged zonal wind (black contours, m s^{-1}) and EKE, vertically integrated from the surface to 100 hPa ($\frac{1}{2g}\int(\overline{u'^2}+\overline{v'^2})dp$, color, MJ m^{-2}), zonally averaged over (a) the Pacific (160°E–160°W) and (b) the Atlantic (30°–70°W) basins. Data are based on NCEP reanalysis, averaged between 1958 and 2014. Similar seasonal patterns are observed for upper level EKE.

and cannot account for the midwinter suppression. Deng and Mak (2005) suggested that a midwinter suppression could be a result of a significant increase in the shearing and stretching deformation of the jet over the North Pacific in midwinter, resulting in a barotropic governor-type mechanism (James, 1987), where reduction in the growth rate of baroclinic waves could be a result of increased barotropic shear within the wintertime jet. Yuval and Kaspi (2016) showed that the reduction in Pacific eddy kinetic energy (EKE) during midwinter might be related to differences in the vertical structure of baroclinicity between midwinter and the shoulder seasons.

In addition, the role of topography in modulating the seasonal cycle of storm track activity has been explored by several studies (Lee et al., 2013; Park et al., 2010; Penny et al., 2010). In particular, a reduction in the seeding of baroclinic waves propagating to the Pacific storm track from midlatitude Asia has been proposed as a mechanism for the midwinter suppression (Penny et al., 2010, 2011, 2013). However, other studies found a lack of a clear relation between interannual variability of the storm track and variability of upstream seeding in the Asian source region (Chang & Guo, 2011, 2012), suggesting a less dominant role of upstream seeding in controlling the midwinter minimum.

In this study, we examine the relation between jet strength and the seasonal cycle of the Pacific and Atlantic storm tracks and demonstrate how a midwinter reduction in storm track intensity can be found over the Atlantic as well. We show that winters with a relatively strong jet are associated with a more pronounced midwinter suppression in both the Pacific and the Atlantic storm tracks. The paper is organized as follows: section 2 describes the data and methodology used for the storm track analysis. Section 3 shows the climatological characteristics of the seasonal cycle of the storm tracks over the Pacific and Atlantic basins. In section 4, we investigate the storm track seasonal cycle during months with stronger jet intensity, followed by discussion and conclusions in section 5.

2. Data and Methodology

We use daily reanalysis data over a 57 year period from 1 January 1958 to 31 December 2014 provided by NCEP/NCAR (National Centers for Environmental Prediction/National Center for Atmospheric Research). The full data set consists of Reanalysis 1 between 1958 and 1980 (Kalnay et al., 1996) and Reanalysis 2 between 1981 and 2014 (Kanamitsu et al., 2002). The data have a horizontal spatial resolution of 2.5° × 2.5°.

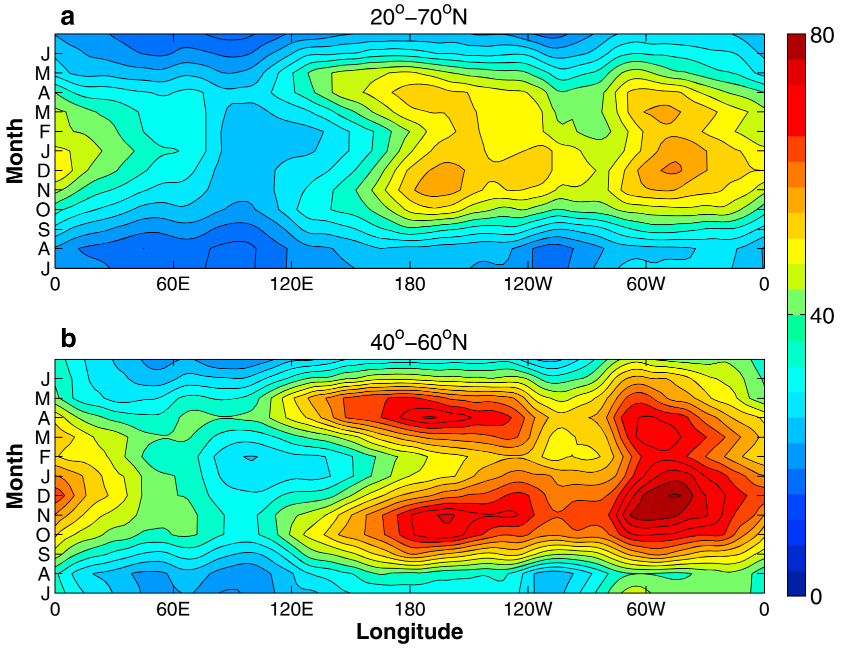

Figure 2. The longitude temporal variation of 250 hPa EKE ($m^2\ s^{-2}$) averaged between latitudes: (a) 20° – 70°N, and (b) 40° – 60°N.

Storm track transient eddies are commonly represented by bandpass time filtering of atmospheric fields (Blackmon et al., 1977). We implement a Butterworth bandpass filter with a 3 – 10 day cutoff period, chosen to match the typical timescale of synoptic cyclones in midlatitudes. This bandpass filter is applied on daily horizontal winds to calculate the storm track EKE. The existence of the Pacific midwinter minimum of eddy activity is not sensitive to the choice of the bandpass cutoff frequencies (Christoph et al., 1997) nor is it sensitive to choosing only the NCEP Reanalysis 2 data set (1981 – 2014). Analysis is performed on eddy quantities and mean flow for both the Pacific (160°E – 160°W) and Atlantic basins (30° – 70°W). All eddy quantities are computed using the same 3 – 10 day bandpass filter.

3. The Atlantic Midwinter Minimum in Climatology

Over the northern Pacific, the jet stream exhibits a pronounced seasonal cycle, with a strong, equatorward jet during winter, and a weaker poleward jet during spring and fall (Figure 1a). As found by Nakamura (1992), the associated EKE over the northern Pacific is weaker in midwinter relative to fall and spring, decreasing by approximately 30% (Figure 1a). The longitudinal distribution of 250 hPa EKE, meridionally averaged between 20° and 70°N (Figure 2a), indicates that in addition to the well-documented Pacific midwinter minimum (160°E – 160°W), it is possible to identify a midwinter decrease in EKE over the Atlantic climatology as well (30° – 70°W).

The main contribution to the midwinter minimum, shown in Figure 2a, comes from midlatitudes (40° – 60°N), where eddy activity is decreased in midwinter over both the Pacific and the Atlantic basins (Figure 2b). While the Pacific seasonal cycle is composed of two distinct peaks, in November and in April, the seasonal cycle of the Atlantic storm track reaches its maximum EKE in November – December, followed by a minimum of nearly 10% during February, and a second maximum around March. Furthermore, a midwinter minimum can be found over Asia in the upstream region of the Pacific storm track (60° – 120°E), in agreement with feature-tracking analysis (Penny et al., 2010).

The interannual variability of the Pacific and Atlantic storm tracks between 1981 and 2014 (see supporting information Figure S1) reveals that while over the Pacific the seasonal cycle tends to have a midwinter minimum in most years, as can also be seen in its climatology; over the Atlantic the year-to-year variability is larger, and a midwinter minimum is less prominent. In addition to the interannual variability of the storm track, there are notable changes in the relative intensity of the storm track over the seasonal cycle (Figure 3). Midwinter suppression of EKE occurs in the upper levels of the atmosphere and is most apparent during

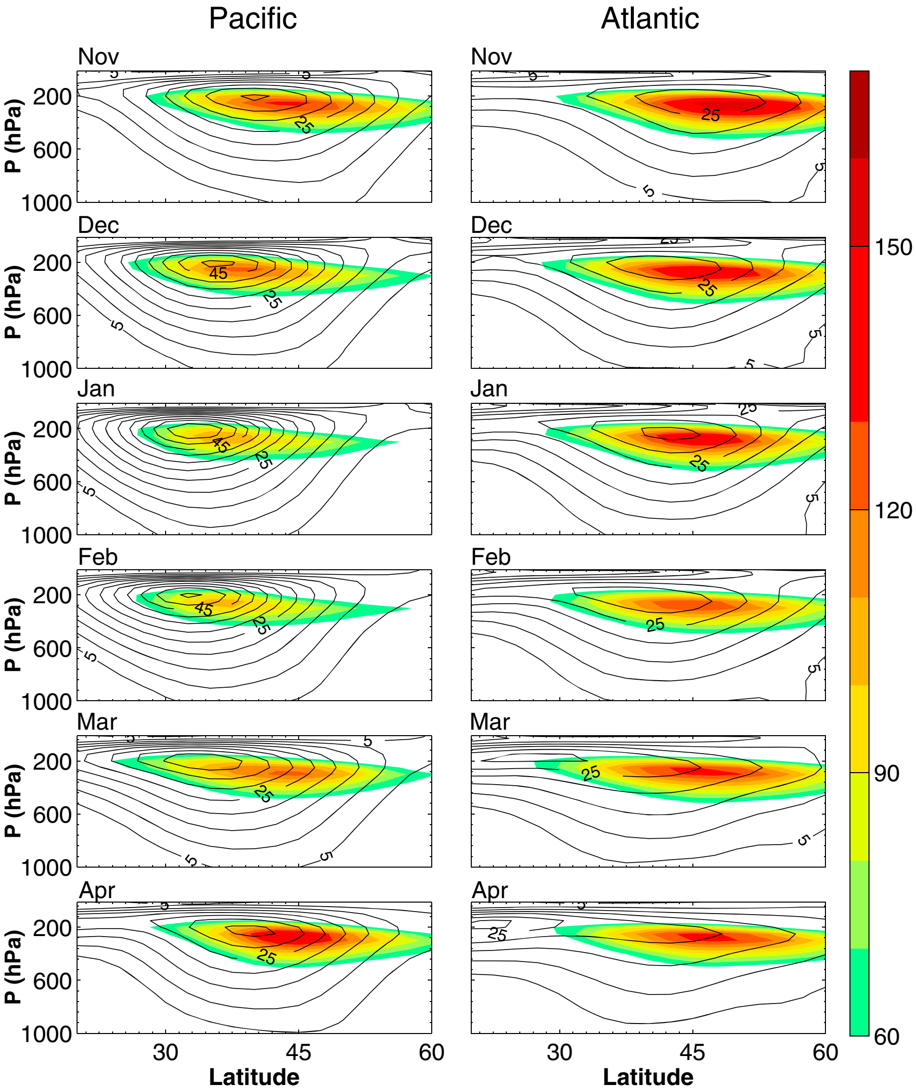

Figure 3. Zonally averaged EKE (color, $m^2\ s^{-2}$, contour interval 10 $m^2\ s^{-2}$) and zonally averaged zonal wind (black contours, $m\ s^{-1}$, contour interval 5 $m\ s^{-1}$) as a function of latitude and pressure averaged over the northern Pacific and northern Atlantic basins during each month between November and April.

January–February in the Pacific (relative to December and March) (Figure 3). The Atlantic midwinter minimum during February, relative to the January and April, is clear as well. Over both the Pacific and the Atlantic sectors, the jet shifts equatorward during January–February, and the vertical shear is largest then (Figure 3).

The similarity of the storm track seasonal cycle between the Atlantic and the Pacific storm tracks seems to occur despite the differences in the jet characteristics. While the Pacific jet in midwinter is more subtropical, the Atlantic jet is eddy-driven, forced by convergence of eddy momentum flux (e.g., Lee & Kim, 2003) and linked to the dominant modes of variability in the North Atlantic region such as the North Atlantic Oscillation (NAO). In the shoulder seasons, the Pacific jet is more poleward (Figure 1a) and more eddy-driven. The stronger eddies in the shoulder seasons may be associated with the different characters of the jet or its more poleward location (Yuval & Kaspi, 2017). The fact that the Atlantic jet has less of a seasonal variation (Figure 1b), and is generally weaker, may therefore lead to the midwinter minimum being less pronounced (Figures 2 and 3). Lachmy and Harnik (2014) have shown that efficiency of eddy amplification is suppressed at lower latitudes, meaning that a stronger jet and more baroclinicity do not necessarily correlate with more eddies, a result which is consistent with the simulations of Brayshaw et al. (2008) and Sampe et al. (2010). In the Pacific, these conditions of strong jet and enhanced baroclinicity exist over most years, possibly leading to a midwinter

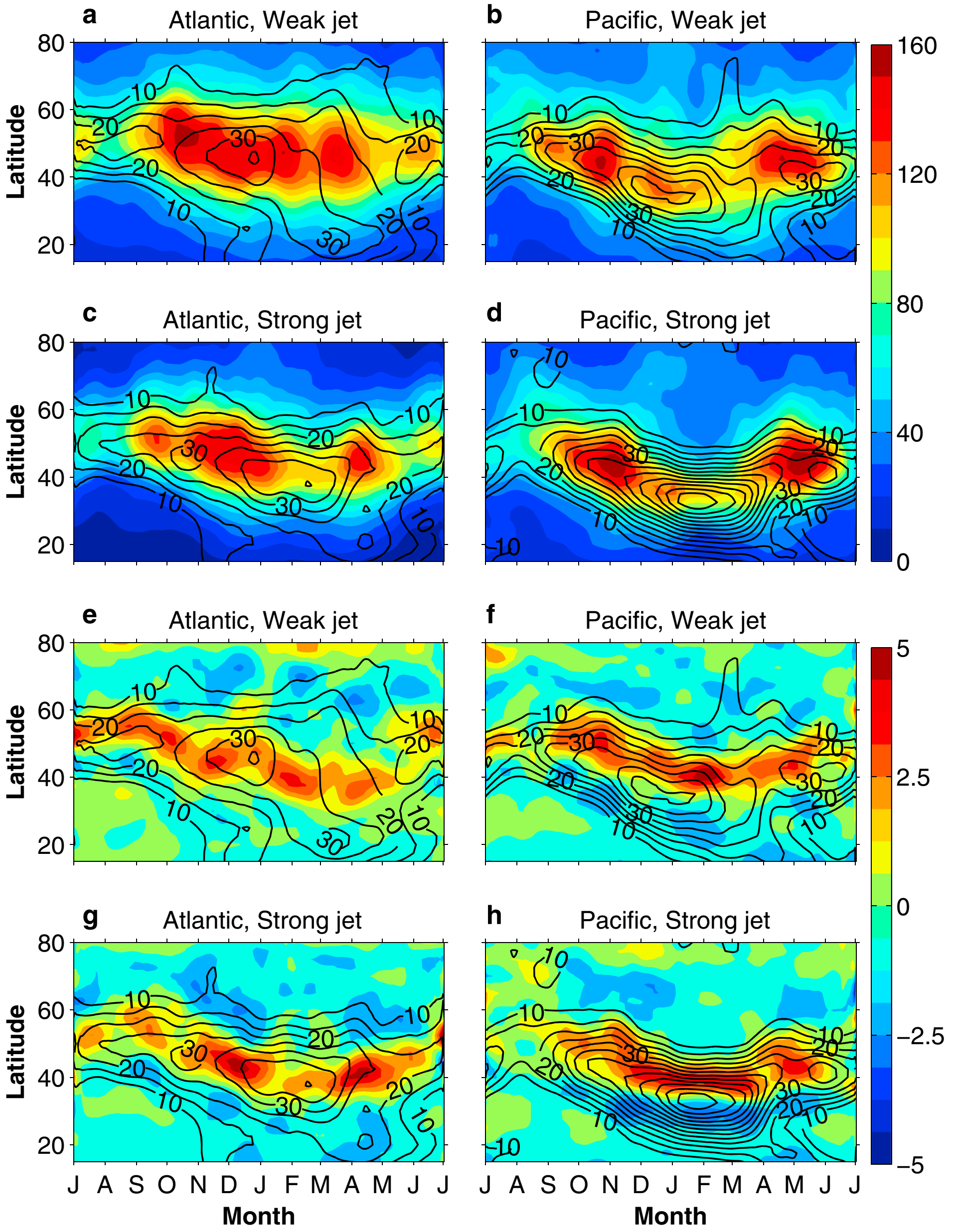

Figure 4. The 250 hPa daily EKE (color, $\mathrm{m^2\ s^{-2}}$) and zonally averaged zonal wind at 250 hPa (black contours, $\mathrm{m\ s^{-1}}$) averaged over years of (a, b) weak jet and (c, d) strong jet, over the Atlantic and Pacific domains. Results in midlatitudes for the months of November–March are statistically significant with 90% confidence level (see supporting information Figure S2). Statistical significance was determined with Student's *t* test. Eddy momentum flux convergence at 250 hPa (color, $10^{-5}\ \mathrm{m\ s^{-2}}$) and 250 hPa zonally averaged zonal wind (black, $\mathrm{m\ s^{-1}}$) in years of (e, f) weak jet and (g, h) strong jet. Results are smoothed using a 31 day running average.

minimum; here we show that in years when the Atlantic jet is stronger (and typically more equatorward) a midwinter minimum occurs over the Atlantic as well.

In the following section, we investigate the existence of a midwinter minimum in the Atlantic storm track and examine how the strength of the Atlantic jet influences the storm track intensity throughout the seasonal cycle by performing an analysis based on years of strongest and weakest wintertime jet over the Atlantic. For comparison, we perform the same type of analysis for the Pacific as well, where the relationship between storm track intensity and jet strength is consistent with previous studies (e.g., Nakamura, 1992; Nakamura & Sampe, 2002; Penny et al., 2013). For the Atlantic such a relation has not been identified before.

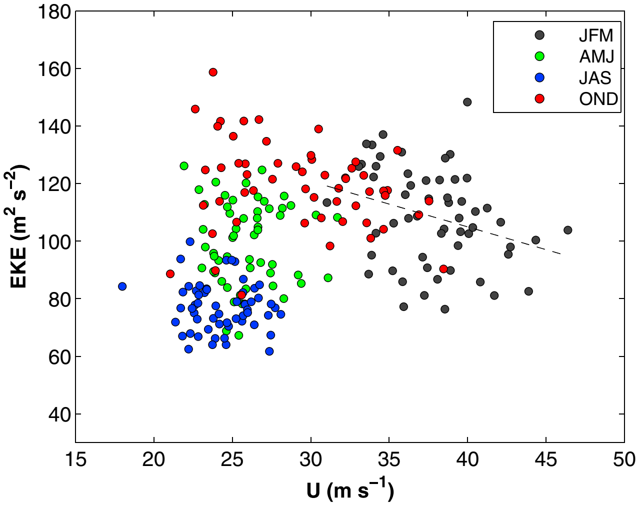

Figure 5. The relation between 250 hPa EKE (m^2 s^{-2}), averaged seasonaly between 40° and 60°N over the Atlantic, and the strength of the jet (m s^{-1}) at the latitude of maximum monthly averaged zonal wind. A linear fit for JFM (dashed) indicates a negative slope of −1.5 m s^{-1}, with corresponding R^2 value of 0.15.

4. The Relation Between Jet Intensity and the Storm Track Minimum

Over the Pacific, winters of reduced eddy activity (and most pronounced minimum) are associated with a strong jet, which is nearly 10 m s^{-1} stronger relative to winters of increased eddy activity (Nakamura & Sampe, 2002). In order to examine the effect of this intensified jet on the seasonal cycle of the storm track, we compare between 7 years of the strongest jet and 7 years of the weakest jet (hereafter referred to as "strong jet" and "weak jet" winters, respectively) in the North Atlantic and North Pacific domains. The criterion used for this analysis determines the strength of the jet according to the maximum intensity of the zonally averaged 250 hPa zonal wind, averaged over the domain between January and March. The results are not sensitive to this height nor to the exact months or number of years chosen. For both sectors, the differences between years of strong and weak jet are statistically significant in midwinter, with over 90% confidence level (supporting information Figure S2).

Figures 4a–4d show the seasonal cycle of EKE at 250 hPa for these two types of winters. To indicate the position of the jet, as well as its intensity, the 250 hPa zonally averaged zonal winds are displayed. As expected, in years of strong jet over the Pacific (1970, 1978, 1981, 1983, 1984, 1995, and 2003), the midwinter suppression of EKE is more prominent relative to years of weak jet (1969, 1972, 1982, 1989, 1990, 2006, and 2009). Specifically, the minimum is more pronounced during January–February, when the jet is strongest. We note that EKE in midwinter is weaker relative to spring and fall also in years of weak Pacific jet, suggesting that the characteristics of the Pacific jet are favorable for a midwinter suppression even in those years of relatively weak jet (Figure 4d).

A similar analysis of the Atlantic domain (Figures 4a and 4c) reveals that in years of strong jet (1960, 1964, 1974, 1977, 1989, 2010, and 2014) EKE decreases in midwinter by nearly 30% relative to spring and fall, similar to the observed midwinter minimum in the Pacific. Such seasonal variations in EKE are not observed during years of weak jet over the Atlantic (1968, 1973, 1983, 1995, 1998, 2000, and 2012), in which the eddies reach their maximum intensity in winter. In years of strong jet, the jet is significantly more equatorward than years of weak jet (Figures 4a and 4c). These differences in the jet and the storm track, between years of strong and weak jets, are statistically significant during midwinter, with over 90% confidence level (supporting information Figure S2).

To identify the position of the eddy-driven component of the jet, in which eddy momentum fluxes contribute to eastward flow, we examine the seasonal evolution of eddy momentum flux convergence over the Pacific and Atlantic basins (Figures 4e–4h). Over both domains eddies converge momentum in midlatitudes. However, over the Pacific, eddy momentum flux convergence occurs poleward of the jet during midwinter (around latitude 40°N), while over the Atlantic the maximum zonal wind coincides with regions of eddy momentum flux convergence throughout the year, except for periods when there is not a clear separation between subtropical and the eddy-driven jets (i.e., during March–April). In years of strong jet, the eddy momentum flux convergence is stronger in the shoulder seasons (October–December, March–May) (Figure 4g), leading to enhanced EKE in those seasons, while in midwinter (January–February), when the jet is more equatorward, there are less eddies. Over the Pacific, though, eddy momentum flux convergence is maximal in midwinter, particularly in years of strong Pacific jet (Figure 4h). Recently, Robert et al. (2017) have shown that the effect of strong shear by the mean flow may lead to a decrease of eddy energy through strong barotropic decay. This effect may explain the decrease in EKE during periods of strong jet (Figure 4h).

On the interannual timescale, the strength of Atlantic storm track eddies and zonal wind speed is positively correlated for weaker wind speeds and negatively correlated for stronger winds (Figure 5). Storm track intensity tends to increase with jet strength for upper level wind below 30 m s^{-1} but decreases when the wind speed is higher than this threshold. This correlation resembles the complex relationship that was found for the Pacific (Christoph et al., 1997; Nakamura, 1992). However, for the Pacific the threshold is estimated around 45 m s^{-1}, and since zonal wind speeds over 45 m s^{-1} are rare over the Atlantic, it remained unclear if the negative correlation is a unique feature of the Pacific or if the same kind of complex relationship can be found in both basins (Christoph et al., 1997). Interestingly, we find that over the Atlantic the negative correlation mostly occurs during January to March, when the wind speed is more intense relative to the other seasons.

5. Discussion and Conclusions

In this study, we show that a midwinter minimum in EKE occurs over the Atlantic ocean, similar to the well-known Pacific midwinter minimum. The Atlantic midwinter minimum is more mild on average compared to the Pacific, with a midwinter decrease in EKE of only 10% relative to fall or spring (the Pacific EKE decrease is nearly 30%). However, the Atlantic midwinter minimum is more pronounced in years of a stronger jet.

The climatological characteristics of the Pacific and Atlantic jets may account for the frequency and strength of the midwinter suppression in these sectors. While the average intensity of the Atlantic jet in winter is around 35 m s^{-1}, the Pacific jet is stronger, reaching 60 m s^{-1}, and therefore may represent more favorable conditions for a midwinter suppression. We find that when the jet is stronger over the Atlantic, then a midwinter minimum is observed over the Atlantic as well. These results are consistent with the Pacific midwinter minimum, which is also more pronounced in years of stronger jet (Nakamura, 1992; Nakamura & Sampe, 2002; Penny et al., 2013). In addition, despite the Atlantic jet being mostly eddy-driven throughout the year, in years when it is stronger it is more equatorward in midwinter (Figure 4c), which can lead to less eddy activity (Lachmy & Harnik, 2014; Sampe et al., 2010; Yuval & Kaspi, 2017) relative to the shoulder seasons.

Over the North Atlantic, the dominant mode of atmospheric variability is the North Atlantic Oscillation (NAO), which is associated with a latitudinal displacement of the jet, where positive and negative phases correspond to poleward and equatorward shifts of the jet, respectively (e.g., Hurrell, 1995; Lee & Feldstein, 1996; Orlanski, 2003; Riviere & Orlanski, 2007, Thorncroft et al., 1993; Woollings et al., 2010). We find that winters associated with a negative phase of the NAO are related to reduced EKE over the Atlantic (not shown), suggesting that a midwinter minimum is more likely to occur in the Atlantic during years of negative NAO. In our analysis, most years of strong jet are associated with negative NAO in winter (five out of seven), and years of weak jet are associated with positive NAO (six out of seven).

While previous studies have shown that the midwinter minimum is a robust feature of the atmospheric circulation over the North Pacific storm track, they found no or weak evidence for the existence of a midwinter suppression over the Atlantic (e.g., Christoph et al., 1997; Nakamura, 1992; Penny et al., 2010; Ren et al., 2014). Others note briefly that when the Atlantic jet is strong, the Atlantic storm track is weak (Penny et al., 2013). To further evaluate the Atlantic midwinter minimum, we examine the sensitivity of our results to the data set, period of averaging and measure of eddy activity, and compare to the original study of Nakamura (1992). For consistency, we use National Centers for Environmental Prediction (NCEP, formerly the National Meteorological Center) data sets. All fields were averaged over the same period as in Nakamura (1992) (1965–1984) and are zonally averaged over the same domain boundaries as in Nakamura (1992). Averaging over an earlier period produces qualitatively similar results to the more recent data set used in our study (NCEP Reanalysis 2, averaged between 1981 and 2014), with a shallow midwinter minimum in EKE over the Atlantic domain. This analysis suggests that the choice of data and period of averaging do not seem to explain the differences between previous studies. Therefore, the lack of a midwinter minimum in Atlantic climatology in Nakamura (1992) may be a result of how the eddy fields are defined. When a 2–6 day bandpass filter is used to represent eddy fields, the midwinter suppression over the Atlantic is less pronounced in EKE climatology, yet appears clearly in geopotential height variance (Penny et al., 2010) and appears in EKE when choosing the years of the strongest jet.

In summary, a midwinter minimum of EKE occurs over the Atlantic when the wintertime jet strengthens, possibly related to the Atlantic jet being more equatorward in these winters with characteristics more similar to the Pacific jet. The occurrence of the midwinter minimum in winters with a strong Atlantic jet is consistent with a midwinter minimum being more prominent in the Pacific, where the jet is naturally stronger.

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