

manuscript submitted to *Journal of Geophysical Research: Atmospheres*

Understanding the processes that control the interannual variability of the Northern Hemisphere wintertime polar front and subtropical jet streams

Xinhuiyu Liu¹, Kevin M. Grise¹, Daniel F. Schmidt¹, Robert E. Davis¹

¹ Department of Environmental Sciences, University of Virginia, Charlottesville, VA, USA

Corresponding author: Xinhuiyu Liu (xl7pd@virginia.edu)

Key Points:

- The interannual movement and intensification of the Northern Hemisphere wintertime polar front jet reflect variations in surface baroclinicity.
- Variations in tropical convection over the Pacific Ocean are linked to variations of the Northern Hemisphere wintertime subtropical jet.
- Tropical convection in CMIP6 models is often displaced westward when compared to observations, reflecting a climatological bias.

Abstract

The interannual movement and intensification of the subtropical jet (STJ) and polar front jet (PFJ) streams have important implications for global and regional climate. Previous studies have related the position and strength of the STJ to tropical thermodynamic processes, whereas the position and strength of the PFJ are more associated with mid-latitude eddies. These conclusions have largely resulted from studies using idealized models. In this study, ERA-Interim reanalysis and CMIP6 global climate models are used to examine the mechanisms responsible for controlling the interannual variability of the STJ and PFJ at different longitudes in the Northern Hemisphere (NH) during winter. Consistent with idealized modeling studies, a close relationship is found between tropical outgoing longwave radiation (OLR) and the STJ, and between mid-latitude surface temperature gradients and the PFJ. The movement and intensification of the NH PFJ reflect variations in surface baroclinicity. Variations in tropical convection over the Pacific Ocean are linked to variations in the strength and position of the NH STJ at almost all longitudes, with different phases of the El Niño-Southern Oscillation (ENSO) associated with the poleward shift and strengthening of the STJ in different regions. CMIP6 models generally capture these relationships, but the models' tropical convection is often displaced westward when compared to observations, reflecting a climatological bias in OLR in the western tropical Pacific Ocean in many models. The displaced tropical convection in models excites different paths of Rossby wave propagation, resulting in different ENSO teleconnections on the STJ over North America and Europe.

1. Introduction

Jet streams are relatively narrow bands of strong west-to-east winds in the upper troposphere. In the zonal mean climatology, there are two jet streams, the subtropical jet (STJ) and polar front jet (PFJ), located in both the Northern Hemisphere (NH) and Southern Hemisphere (SH). The STJ is commonly viewed as being driven by the angular momentum conservation in the poleward flowing upper tropospheric branch of the tropical Hadley circulation (Held & Hou, 1980; Schneider, 1977), and thus it is located near the poleward edge of Hadley Cell in each hemisphere. The PFJ is driven by the convergence of momentum by transient midlatitude eddies (Held, 1975; Panetta, 1993) and is consequently located at mid-latitudes where baroclinic instability is strongest.

This simple picture of the two jet streams, however, does not apply at all longitudes and in all seasons. For example, in the NH wintertime climatology, there are clearly two distinct jets in Eurasia, the Eastern Pacific Ocean, and the North Atlantic Ocean, while the STJ and PFJ are merged into a single jet stream in East Asia, the Western Pacific Ocean, and the Eastern United States (Christenson, Martin, & Handlos, 2017; Eichelberger & Hartmann, 2007; Koch, Wernli, & Davies, 2006; Li & Wettstein, 2012). The strength of the two jets also varies by region, with both the STJ and PFJ usually strongest over the Pacific Ocean during winter (Archer & Caldeira, 2008; Koch et al., 2006). The NH jet streams are weaker and further poleward during summer months (Archer and Caldeira 2008; Koch et al. 2006; Woollings et al. 2014). In the Southern Hemisphere (SH), a single jet stream is observed during summer, whereas somewhat more distinct subtropical and polar front jets are observed during winter (Bals-Elsholz et al., 2001; Kim & Lee, 2004)

The positions and strengths of the jets are not constant in time and vary from month to month and from year to year. Understanding variability in the position and strength of the jet streams is important, as it directly influences impactful surface weather events, such as extratropical cyclone tracks (Dickson and Namias 1976; Athanasiadis et al. 2010), blocking anticyclone frequency (Kaas and Branstator 1993; Barnes and Hartmann 2010; Woollings et al. 2018), heatwaves and cold air outbreaks (Mahlstein, Martius, Chevalier, & Ginsbourger, 2012; Petoukhov, Rahmstorf, Petri, & Schellnhuber, 2013), and atmospheric rivers and their associated heavy precipitation events (Ryoo et al., 2013; Zhang & Villarini, 2018). Previous studies have documented relationships between variability in the jet streams and known teleconnection patterns, including but not limited to the El Niño-Southern Oscillation (ENSO), the Northern Annular Mode (NAM)/North Atlantic Oscillation (NAO), the Pacific-North American teleconnection pattern (PNA), and the Southern Annular Mode (SAM). Variability in the PFJ is closely tied to the NAM/NAO, PNA, and SAM (Gallego, Ribera, Garcia-Herrera, Hernandez, & Gimeno, 2005; Strong & Davis, 2008; Woollings et al., 2014), whereas variability in the STJ is expected to correlate with ENSO (Gallego et al., 2005; Lu, Chen, & Frierson, 2008; Seager et al., 2003). Jet streams, of course, also vary with synoptic weather systems on daily timescales (Handlos & Martin, 2016; Winters & Martin, 2016), but in this study, we focus on month-to-month and interannual variability of the two jet streams.

Whether the STJ and PFJ are merged together or in two distinct branches may also have important implications for global and regional climate. One example is the relative minimum in North Pacific storm track activity that occurs during mid-winter (January and February), even though the baroclinicity is the strongest during these months (Nakamura, 1992). A similar feature occurs in the North Atlantic storm track during years with a strong STJ (Afargan &

Kaspi, 2017). Several recent studies have attributed the existence of a mid-winter storm track minimum to the merging of the STJ and PFJ (Yuval et al. 2018; Novak et al. 2020). Previous studies have used idealized models to explain the merging and splitting of the two jets. Lee and Kim (2003) found that, when the STJ is relatively weak, the most favorable region for baroclinic wave growth often lies in midlatitudes, establishing an eddy-driven PFJ that is well separated from the STJ. In contrast, when the STJ is relatively strong, baroclinic wave growth occurs close enough to the STJ so that a single merged jet evolves. Son and Lee (2005) further found that a single merged jet forms preferentially when tropical heating is strong, while a double-jet state forms when tropical heating is weak enough to allow midlatitude eddies to grow more poleward and form a separate eddy-driven jet. Yuval and Kaspi (2018) concluded that baroclinic eddies are stronger when there is a strong distinct PFJ and are weaker when there is a merged jet.

These idealized model results provide insight into the processes that control the variability of the polar front and subtropical jets, but they are not entirely consistent with the jet characteristics found in observations or comprehensive global climate models. Based on the results of Lee and Kim (2003), one might expect that the positions and strengths of the STJ and PFJ are negatively correlated. That is, when the STJ is weak and equatorward, there should be a strong and poleward PFJ. However, several recent studies have found that interannual variability in the position and strength of the jets is only weakly correlated in the zonal mean (Davis & Birner, 2016, 2017; Menzel et al., 2019; Solomon et al., 2016; Waugh et al., 2018). To our knowledge, the relationship between the interannual variability in the position and strength of the jets has not been examined in detail at individual longitudes.

The purpose of this study is to better understand the interannual variability in the position and strength of the STJ and PFJ at individual longitudes. To do this, we define the position and

105 strength of polar front and subtropical jets using both reanalysis data and global climate models.
106 For this study, we focus our analysis on the wintertime (December–February) jets in the NH
107 because longitudinal asymmetries are much greater in the NH and the jets are strongest in the
108 winter season when the pole-to-equator temperature gradient is largest. We find that variations
109 in (1) tropical convective heating and (2) horizontal surface temperature gradients at midlatitudes
110 are closely linked to interannual variations in the position and intensity of the jet streams.
111 Tropical convective heating plays a more important role in modulating the STJ, consistent with
112 the idealized modeling studies discussed above (Lee & Kim, 2003; Son & Lee, 2005),
113 observations associated with the El Niño–Southern Oscillation (Gallego et al., 2005; Lu et al.,
114 2008), and case studies of synoptic-scale weather events (Handlos & Martin, 2016; Winters &
115 Martin, 2016). Horizontal surface temperature gradients are critical in modulating the PFJ, as
116 variations in baroclinicity are closely linked to the location and strength of the PFJ (Brayshaw et
117 al. 2008; Sampe et al. 2010; Hall et al. 2015).

118 The paper is organized as follows. Section 2 describes the data and methods used in this
119 study. Section 3 examines the interannual variability in STJ and PFJ position and strength in
120 observations, and their linkage to tropical convective heating and midlatitude horizontal surface
121 temperature gradients. Section 4 explores the causes of model biases in these relationships.
122 Section 5 concludes with a discussion and summary of the results.

123

2. Data and Methods

2.1 Data

To examine observed variability in the jets, we use monthly-mean wintertime (December–February) zonal wind and surface temperature data from the European Centre for Medium-Range Weather Forecasts (ECMWF) Interim reanalysis data set (ERA-Interim; Dee et al., 2011). The data are provided at a spatial resolution of 0.75 degrees latitude \times 0.75 degrees longitude. We also make use of monthly-mean outgoing longwave radiation (OLR) data from the National Oceanic and Atmospheric Administration (NOAA) interpolated OLR dataset (Liebmann & Smith, 1996), which has a spatial resolution of 2.5 degrees latitude \times 2.5 degrees longitude. Our observational analysis is based on the 40-year period from January 1979 to December 2018.

To compare the observed jet variability with that in global climate models, we examine output from the historical runs of 23 global climate models that participated in phase 6 of the Coupled Model Intercomparison Project (CMIP6; Eyring et al., 2016), which are listed in Table S1 in the supplementary material. The historical runs of the models are designed to simulate the past climate over the period 1850–2014 by prescribing observed changes in radiative forcings (greenhouse gases, stratospheric and tropospheric ozone, tropospheric aerosols, volcanic eruptions, changes in solar output, etc.). We examine one ensemble member per model. The spatial resolution of the model output is highly variable and ranges from about 0.7 degrees to about 2.8 degrees (Table S1), so before analysis, all variables are interpolated to a common spatial resolution of 2.5 degrees latitude \times 2.5 degrees longitude. All of the model analyses are based on the 36-year period from 1979 to 2014, as the models' historical runs end in 2014. The

observational analysis based on the 40-year period from 1979 to 2018 is very similar to that based on the 36-year period from 1979 to 2014 and thus can be directly compared to the model analyses in this study.

2.2 Methods

To define the position and strength of the PFJ and STJ, we exploit the fact that the STJ is defined by a baroclinic vertical structure (strong westerlies aloft and near-zero surface winds), whereas the PFJ is defined by an equivalent barotropic vertical structure (westerly wind maximum throughout the depth of the vertical column). Even though the wind speeds associated with both jets are maximized in the upper troposphere, it is challenging to uniquely identify the position and strength of each jet using the upper tropospheric wind field alone. Thus, following previous studies, we define the position and strength of the PFJ using the lower tropospheric wind field (e.g., Ceppi & Hartmann, 2013; Barnes & Polvani 2013). Specifically, in this study, we define the position of the PFJ as the latitude of the maximum of the lower tropospheric (850 hPa) zonal wind averaged over a given longitude band between 20°N and 65°N. The location of maximum winds is determined by fitting a quadratic to the peak and finding the latitude of maximum wind speed at an interval of 0.01° (Barnes & Polvani, 2013). The strength of the PFJ is then determined using the value of the 850 hPa zonal wind at the identified PFJ latitude.

We define the position of the STJ as the latitude of the maximum value found in the difference field between the upper tropospheric (250 hPa) zonal wind and the lower tropospheric (850 hPa) zonal wind averaged over a given longitude band between 10°N and 40°N. The lower tropospheric zonal wind is subtracted to isolate the vertically integrated thermal wind shear (Davis & Birner, 2016), as the STJ is defined by strong westerlies aloft and near-zero surface

winds. In the zonal mean, this method yields a comparable position to the NH subtropical jet identified using tropopause height gradients (Maher et al., 2020). The strength of the STJ is then determined using the value of the upper tropospheric (250 hPa) zonal wind at the identified STJ latitude.

The above definitions of the jet streams have been used in a number of recent studies for zonal-mean diagnostics (Adam et al. 2018; Waugh et al. 2018). However, here we intend to apply these definitions both in the zonal mean and at specific longitudes. To do this, we define regional jet indices, in which north-south zonal wind profiles are averaged over specific longitude bands prior to finding the jet positions and strengths. The six regions are defined as: Europe (0°-50°E), Asia (50°E-130°E), the Western Pacific Ocean (130°E-160°W), the Eastern Pacific Ocean (160°W-130°W), North America (130°W-80°W), and the Atlantic Ocean (80°W-0°). We also calculate the four jet indices (PFJ position, PFJ strength, STJ position, STJ strength) at each individual longitude (i.e., using the north-south zonal wind profile at each longitude) (see Fig. 1).

3. Observed variability in the subtropical and polar front jet streams

We begin by reviewing the observed climatology of the NH wintertime jet positions and strengths. Figure 1 shows the NH wintertime (December–February) climatological positions (Fig. 1a) and strengths (Fig. 1b and Fig. 1c) of the polar front and subtropical jets along with their standard deviations at each longitude. In the NH wintertime climatology, there are clearly two distinct jets in Eurasia, the Eastern Pacific Ocean, and the North Atlantic Ocean, while the STJ and PFJ are merged into a single jet stream in East Asia, the Western Pacific Ocean, and the Eastern United States (Fig. 1a), as also documented in previous studies (Christenson et al., 2017;

193 Eichelberger & Hartmann, 2007; Koch et al., 2006; Li & Wettstein, 2012). The PFJ position has
194 a similar standard deviation at most longitudes (6.73 degrees latitude on average), with the
195 largest standard deviations occurring over western Eurasia. In contrast, the standard deviation of
196 the STJ position varies more substantially by longitude, with very small standard deviations
197 (2.09 degrees latitude) over Eurasia and the western Pacific Ocean and standard deviations
198 comparable to that of the PFJ position at most other longitudes.

199 The strength of the two jets also varies by region. The strength of the PFJ (as measured
200 by the 850-hPa zonal wind maximum) is largest (10–15 m/s zonal wind at 850 hPa) and displays
201 the most variance over the storm track regions of the North Pacific and North Atlantic Oceans
202 (Fig. 1b). The strength of the STJ (as measured by the 250-hPa zonal wind maximum) is largest
203 (> 40 m/s zonal wind at 250 hPa) over Eurasia and the western Pacific Ocean, with the largest
204 wind speeds (~70 m/s) observed where the STJ and PFJ are merged over the western Pacific
205 Ocean (Fig. 1c). A secondary peak in STJ strength is also observed in eastern North America
206 where the two jets are merged. The standard deviation of the STJ strength varies little with
207 longitude.

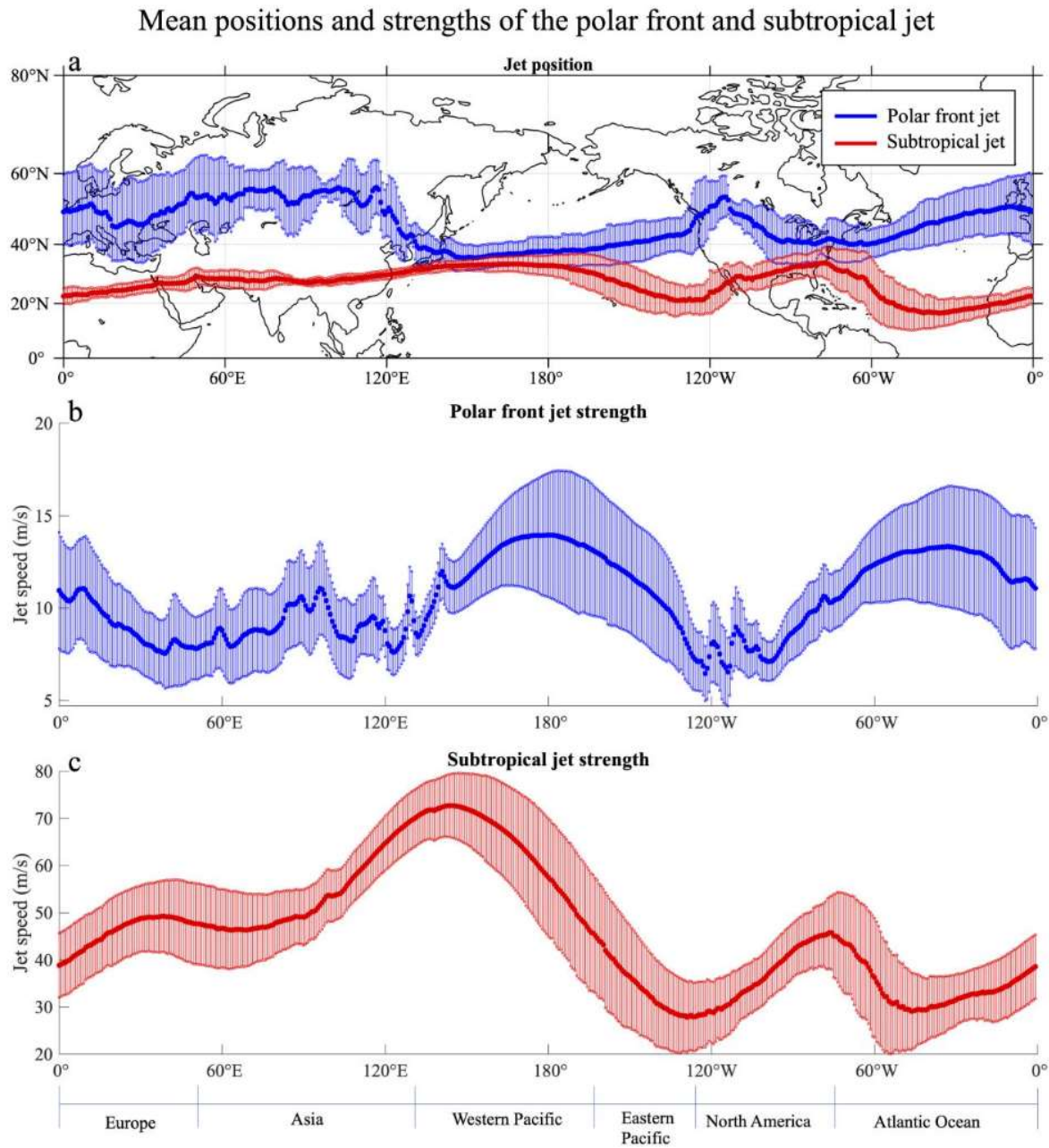


Figure 1. Mean positions (a) and strengths (b and c) of NH wintertime (December–February)

polar front and subtropical jet with ± 1 standard deviation (shading) shown at all longitudes using jet indices derived from the ERA-Interim reanalysis dataset from 1979–2018. Note that the jet speeds in panels b and c are plotted on different scales. The polar front jet is defined at 850 hPa whereas the subtropical jet is at 250 hPa.

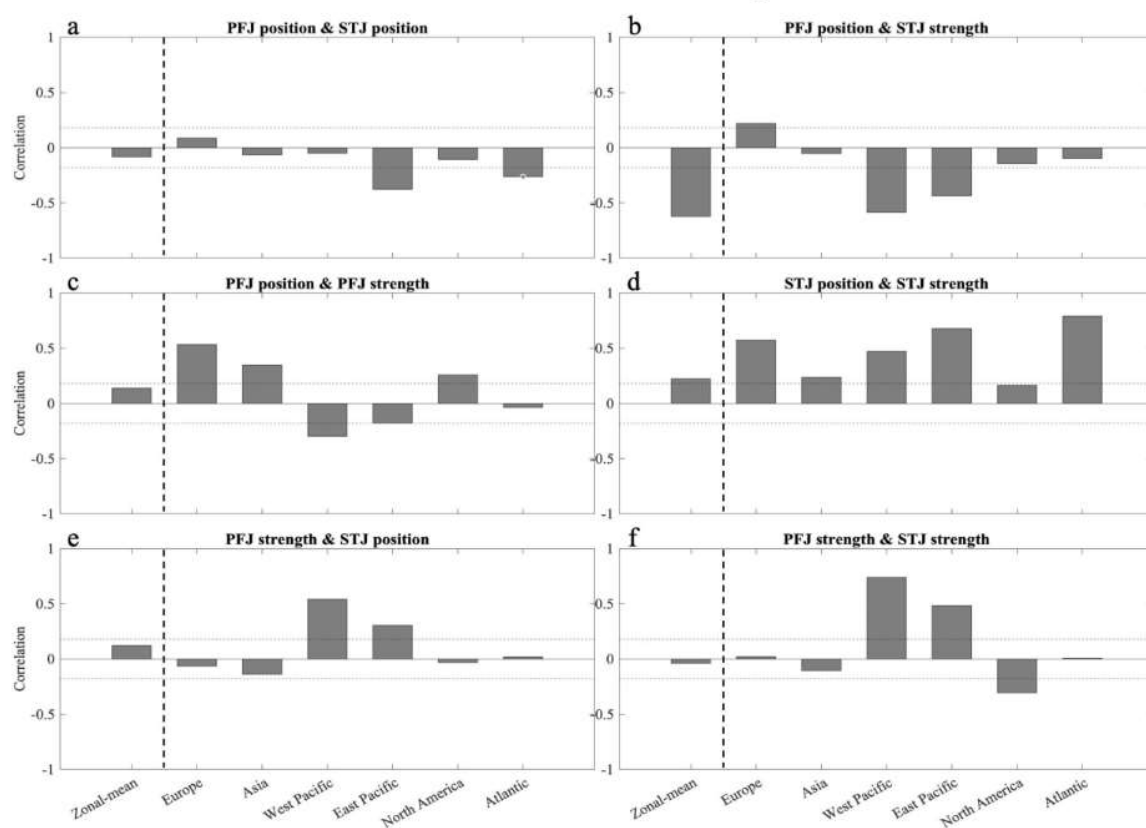
We next examine whether variability in the jet strengths and positions are correlated with one another, as could be anticipated from the results of Lee and Kim (2003). Figure 2 shows the correlations among the monthly time series of the positions and strengths of the STJ and PFJ. The correlations are shown for the zonal-mean (leftmost bar in each panel) and the 6 different regions defined in Section 2.2. The horizontal dashed lines in each panel indicate the minimum value for statistically significant correlations at the 95% confidence level.

With respect to the overall correlations between position and strength from the zonal-mean wind field, few statistically significant correlations are found, consistent with the results of Menzel et al. (2019). A significant negative correlation is found between the PFJ position and STJ strength (Fig. 2b), as a more poleward distinct PFJ is associated with a weaker STJ (as could be anticipated from the results of Lee and Kim 2003). A weakly significant positive correlation is also found between the strength and position of the STJ (Fig. 2d), in contrast to the weak negative correlation found in climate models by Menzel et al. (2019). This difference could be due to the fact that Menzel et al. (2019) defined STJ strength using the difference field between the upper tropospheric (250 hPa) zonal wind and the lower tropospheric (850 hPa) zonal wind, whereas in this study, we use only the upper tropospheric (250 hPa) zonal wind to define the STJ strength. If we define the STJ strength as in Menzel et al. (2019), we also find a weak negative correlation (-0.0718) between STJ position and strength.

However, the weak correlations among the positions and strengths of the jets in the zonal mean mask significant correlations among the positions and strengths of the jets that occur on the regional level, which highlights the need to examine the variability of the jets and the underlying mechanisms at individual longitudes. As in the zonal mean (Davis & Birner 2017; Waugh et al. 2018; Menzel et al. 2019), there are few significant correlations between the positions of the PFJ

237 and STJ, except in the Eastern Pacific and Atlantic sectors where a small negative relationship is
 238 observed (Fig. 2a). Consistent with the results of Lee and Kim (2003), the PFJ position is
 239 negatively correlated with the STJ strength in the zonal mean, and this negative correlation arises
 240 predominantly from the Pacific Ocean regions (Fig. 2b). However, in other regions, the
 241 correlations are small. The strength and position of the PFJ are positively correlated over
 242 continents and negatively correlated over oceans (Fig. 2c), whereas the strength and position of
 243 the STJ are positively correlated in all regions (Fig. 2d). Significant positive correlations also
 244 exist between the PFJ strength and STJ position/strength over the Pacific Ocean, particularly in
 245 the Western Pacific where there is a merged jet (Fig. 2e and Fig. 2f).

Cross-correlations between four jet indices



246

247 **Figure 2.** Correlations between monthly time series of the positions and strengths of the
 248 subtropical and polar front jets during NH winter, based on ERA-Interim reanalysis (1979–

2018). The jets are defined in the zonal mean and for the six different regions defined in Section 2.2. The seasonal cycle is removed prior to the analysis. The horizontal dashed lines in each panel indicate the minimum value for significant correlations at the 95% confidence level according to a two-tailed Student's t-test.

To interpret the correlations shown in Fig. 2, we now examine the physical processes associated with variability in the positions and strengths of the jets. To do this, we regress monthly anomalies of OLR and surface temperature onto each of our four jet indices (PFJ position, PFJ strength, STJ position, STJ strength). Before the regression analysis, we remove the seasonal cycle of each timeseries and normalize the jet indices by subtracting the climatological mean and then dividing by the standard deviation. Results for the PFJ and STJ are shown in the following two subsections. We note that regressions on the distance between the two jets (i.e., the difference in the PFJ and STJ latitudes) are generally dominated by the processes that govern the PFJ position, which has a greater standard deviation at most longitudes (Fig. 1a). Only over the eastern Pacific Ocean and Atlantic Ocean do processes that govern both the PFJ and STJ position play comparable roles in affecting the separation distance between the jets.

3.1 Polar front jet

Regression of surface temperature onto polar jet position (observed)

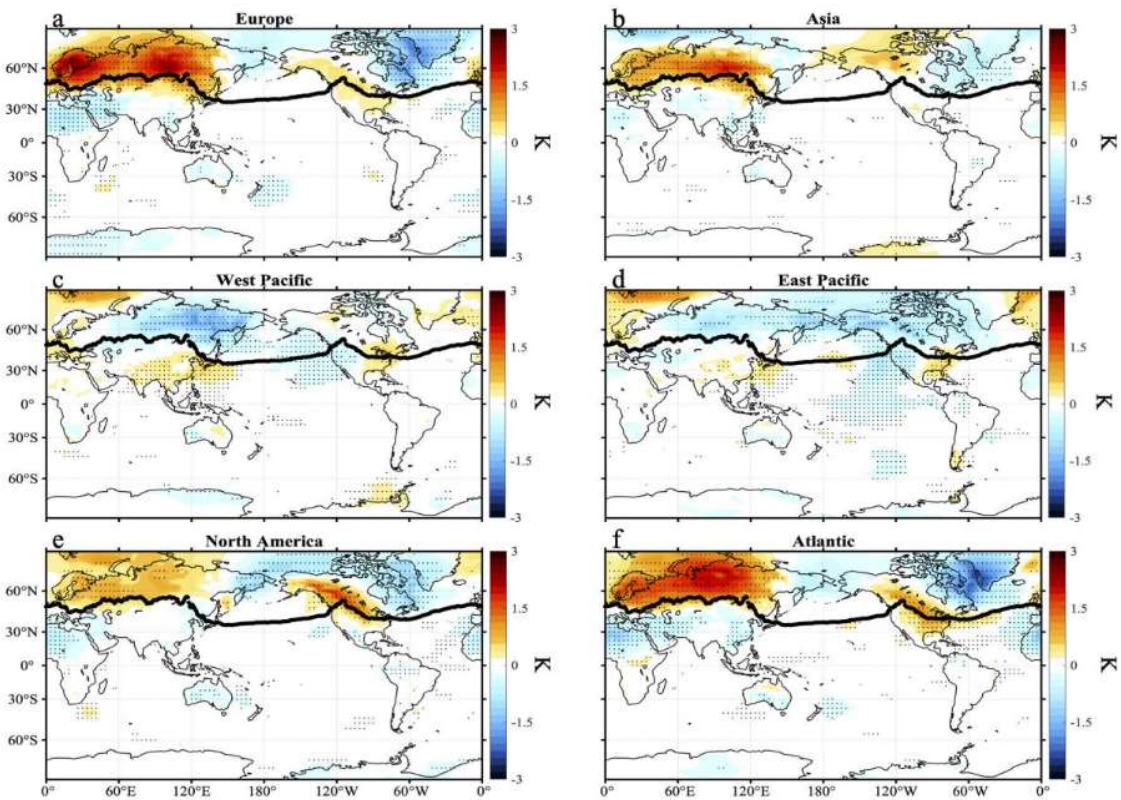


Figure 3. Regression of wintertime monthly surface temperature anomalies onto six different regions' PFJ position in observations. Patterns correspond to surface temperature anomalies associated with a 1 standard deviation poleward shift of the polar front jet in each region. Thick black lines on each panel are climatological PFJ positions in observations as shown in Fig. 1a. Stippling indicates that regression patterns are statistically significant at the 95% level according to a two-tailed Student's t-test. The model version of this figure is shown in Fig. S1 in the supplementary material.

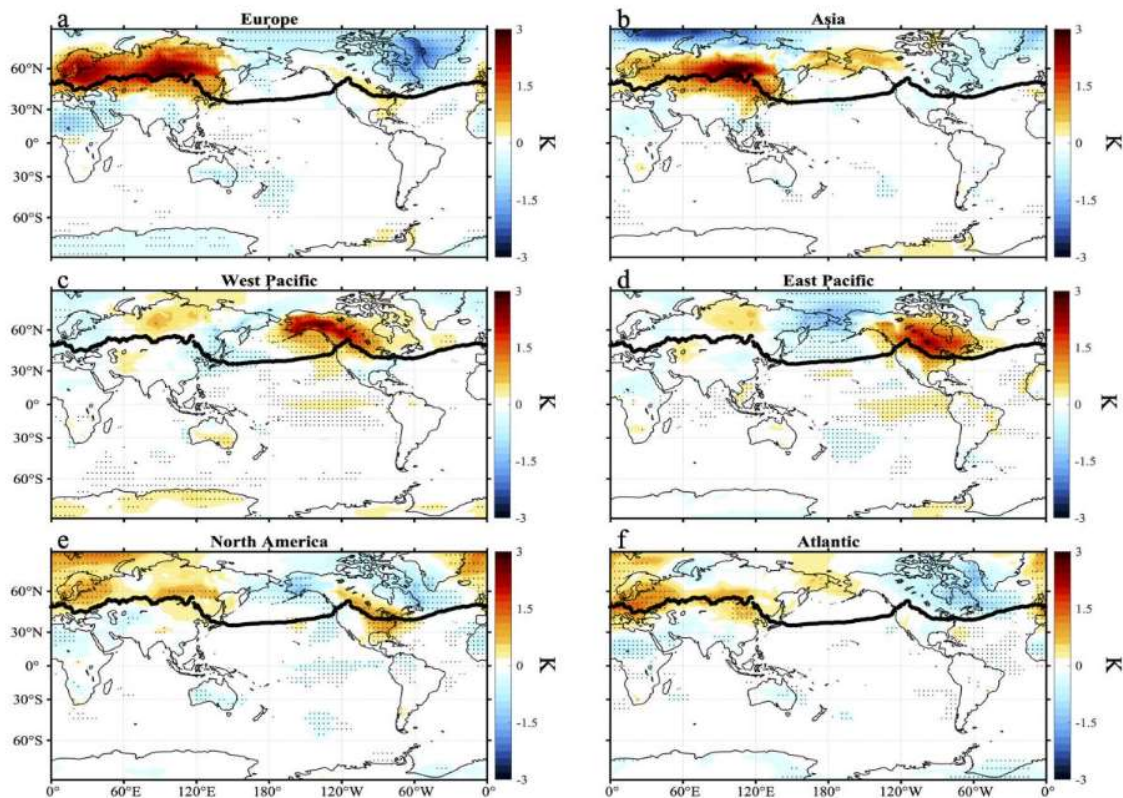
Figure 3 shows the regressions of observed wintertime surface temperature anomalies

278 onto the position of the PFJ in six regional sectors (as defined in section 2.2). The surface
279 temperature anomalies shown in each panel correspond to a one standard deviation poleward
280 shift of the PFJ in each of the six regional sectors. Based on idealized aqua-planet simulations,
281 we expect the location of the polar front jet to be controlled closely by shifts in local
282 baroclinicity (Brayshaw, Hoskins, & Blackburn, 2008). This is indeed the case in Fig. 3 in the
283 Asia, West Pacific, and North America sectors. In Asia, the climatological PFJ position is around
284 53°N (Fig. 1), so an anomalously warm Eurasian continent is correlated with a shift in the
285 maximum baroclinicity further poleward, which is consistent with a poleward Asian PFJ shift
286 (Fig. 3b). Likewise, in North America, the climatological PFJ position is oriented from
287 northwest-to-southeast to the east of the Rocky Mountains (Fig. 1a), so anomalous warming over
288 the interior of the North American continent is linked with a shift of the maximum baroclinicity
289 and North American PFJ further poleward (Fig. 3e). Alternatively, because the West Pacific PFJ
290 is located at around 40°N to the south of eastern Russia (Fig. 1a), anomalous cooling over the
291 continent to the north shifts the maximum baroclinicity and West Pacific PFJ further poleward
292 (Fig. 3c).

293 In other regions, the jet position appears to be closely linked to well-known global
294 teleconnection patterns and less clearly to fluctuations in surface baroclinicity at the same
295 longitude. For example, the surface temperature anomalies associated with poleward shifts in
296 the PFJ in the Atlantic and European sectors closely resemble those associated with the positive
297 phase of the North Atlantic Oscillation (NAO), which is characterized by above-normal
298 temperatures over northern Europe and below-normal temperatures over Greenland and Eastern
299 Canada (Hurrell, 1995). A positive NAO signature is also weakly seen for the North American
300 PFJ, suggesting that poleward shifts in the North American PFJ are affected by both the NAO

301 and changes in local surface baroclinicity over the continent. In the eastern Pacific sector, the
 302 surface temperature anomalies associated with a poleward shift in the PFJ closely resemble those
 303 associated with the Pacific-North America pattern (PNA; Wallace & Gutzler, 1981; Yu & Lin,
 304 2019).

Regression of surface temperature onto polar jet strength (observed)



305
 306 **Figure 4.** As in Fig. 3, but for the PFJ strength. The model version of this figure is shown in Fig.
 307 S2 in the supplementary material.

308
 309 Figure 4 shows analogous results to Fig. 3, but for the PFJ strength. The regression
 310 patterns of surface temperature anomalies onto polar jet strength (Fig. 4) are similar to that of
 311 polar jet position (Fig. 3) for Europe, Asia, and North America, but very different in the Pacific.
 312 This suggests that similar processes control the PFJ position and intensity over the continents,

but not necessarily over the oceans (see also Fig. 2c). As for the PFJ strength in the Pacific sector, the surface temperature anomalies associated with PFJ intensification closely resemble those associated with the warm phase of the El Niño-Southern Oscillation (ENSO; Halpert & Ropelewski, 1992; Ropelewski & Halpert, 1989). Intensification of the western and eastern Pacific PFJ is associated with enhanced convection (anomalously low OLR) in the eastern tropical Pacific Ocean and suppressed convection (anomalously high OLR) in the western tropical Pacific Ocean (Fig. S3). Alternatively, intensification of the North American PFJ is associated with the cool (La Niña) phase of ENSO (Fig. S3). Intensification of the PFJ in other regions is not associated with significant variations in tropical convection (Fig. S3), and variability in tropical convection also has little to no correlation with variability in PFJ position in any region (not shown).

3.2 Subtropical jet

Figures 5 and 6 show the regressions of observed wintertime OLR anomalies onto the position and strength of the STJ in six regional sectors (as defined in section 2.2). The OLR anomalies shown in each panel correspond to a one standard deviation poleward shift (Fig. 5) or strengthening (Fig. 6) of the STJ in each of the six regional sectors. We also examined regressions of wintertime surface temperature anomalies onto the position and strength of the STJ, but found few significant relationships (not shown).

Previous studies have concluded that tropical convection plays a critical role in forcing the position and strength of the STJ locally, particularly over the Pacific sector where El Niño is known to strongly modify the subtropical jet (Gallego et al., 2005; Lu et al., 2008; Seager et al., 2003). Over the western Pacific, enhanced convection is associated with a strengthening and

poleward shift of the STJ (Figs. 5c and 6c), consistent with the idealized model results of Lee and Kim (2003) and Son and Lee (2005) and the correlation between western Pacific STJ latitude and speed in Fig. 2d. Over the eastern Pacific, there is a robust relationship between enhanced convection (an El Niño-like pattern) and a strengthened STJ, but there is only a weak relationship between local convection and the STJ position (Figs. 5d and 6d). Additionally, there is a robust relationship between a strengthened STJ over Asia and enhanced convection over the same longitude band (i.e., over the northern Indian Ocean).

At most other longitudes, the variability in the STJ latitude and strength is more affected by teleconnections from remote tropical convection anomalies over the Pacific basin than by tropical convection anomalies at the same longitude. Figure 5 shows that a poleward shift of the STJ over Europe, Asia, and North America is associated with enhanced convection over western tropical Pacific Ocean (i.e., a La Niña-like pattern). This La Niña-like pattern is strongest for North America, indicating a large influence of ENSO on the position of the North American STJ, which is consistent with the well-known teleconnections of ENSO over North America (Cook & Schaefer, 2008; Eichler & Higgins, 2006; Ropelewski & Halpert, 1989; Smith, Green, Leonardi, & O'Brien, 1998). As for the STJ strength, Figure 6 shows that enhanced convection in the eastern tropical Pacific Ocean (i.e., an El Niño-like pattern) is associated with a strengthened STJ over North America. Because enhanced convection in the western tropical Pacific Ocean is associated with a strengthened PFJ over North America (Fig. S3), there is a negative correlation between PFJ and STJ strength over North America (Fig. 2f). Enhanced convection in the western tropical Pacific Ocean is also associated with a strengthened STJ in Europe (see also positive correlations between STJ position and strength in Europe in Fig. 2d).

To summarize these relationships, the left column of Figure 7 shows the regression

coefficients of observed tropical (5°N - 5°S) OLR anomalies onto indices of the STJ position and strength calculated at every longitude (as shown for the climatology in Fig. 1). In other words, for each longitude on the y-axis in Fig. 7, the horizontal line at that y-value shows the zonal cross section of tropical OLR anomalies associated with STJ variability at that longitude. Figure 7 reveals that the STJ variability at nearly all longitudes is associated with a dipole of OLR anomalies over the tropical Pacific Basin. This figure shows the dominance of ENSO (rather than local tropical convection) in governing STJ variability globally.

Consistent with Fig. 5, Fig. 7a reveals that a La Niña-like pattern of anomalous tropical convection is associated with a poleward shift of the subtropical jet from the eastern Atlantic Ocean to the east coast of Asia, and over North America. Consistent with Fig. 6, Fig. 7c reveals that enhanced tropical convection from the western Indian Ocean to the eastern Pacific Ocean strengthens the STJ at that longitude. A La Niña-like pattern of anomalous tropical convection also strengthens the STJ over the eastern Atlantic Ocean and Europe, but an El Niño-like pattern of anomalous tropical convection strengthens the STJ over North America. In other words, La Niña strengthens the subtropical jet from the western Pacific Ocean to the eastern Atlantic Ocean, and El Niño strengthens the subtropical jet from the central Pacific Ocean to the western Atlantic Ocean (Seager et al., 2003).

Regression of OLR onto subtropical jet position (observed)

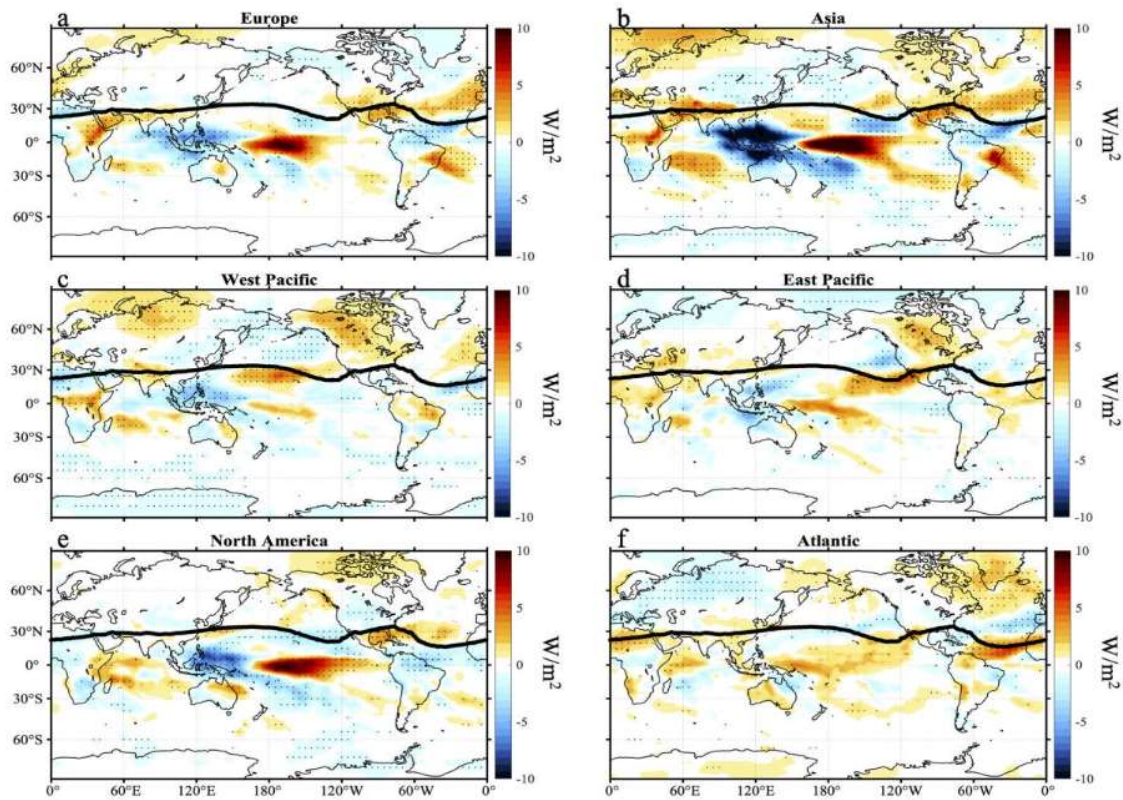


Figure 5. Regression of wintertime monthly OLR anomalies onto six different regions' subtropical jet position in observations. Patterns correspond to OLR anomalies associated with a 1 standard deviation of poleward shift of the subtropical jet in each region. Thick black lines on each panel are climatological STJ positions in observations as shown in Fig. 1a. Stippling indicates that regression patterns are statistically significant at the 95% level according to a two-tailed Student's t-test. The model version of this figure is shown in Fig. S4 in the supplementary material.

Regression of OLR onto subtropical jet strength (observed)

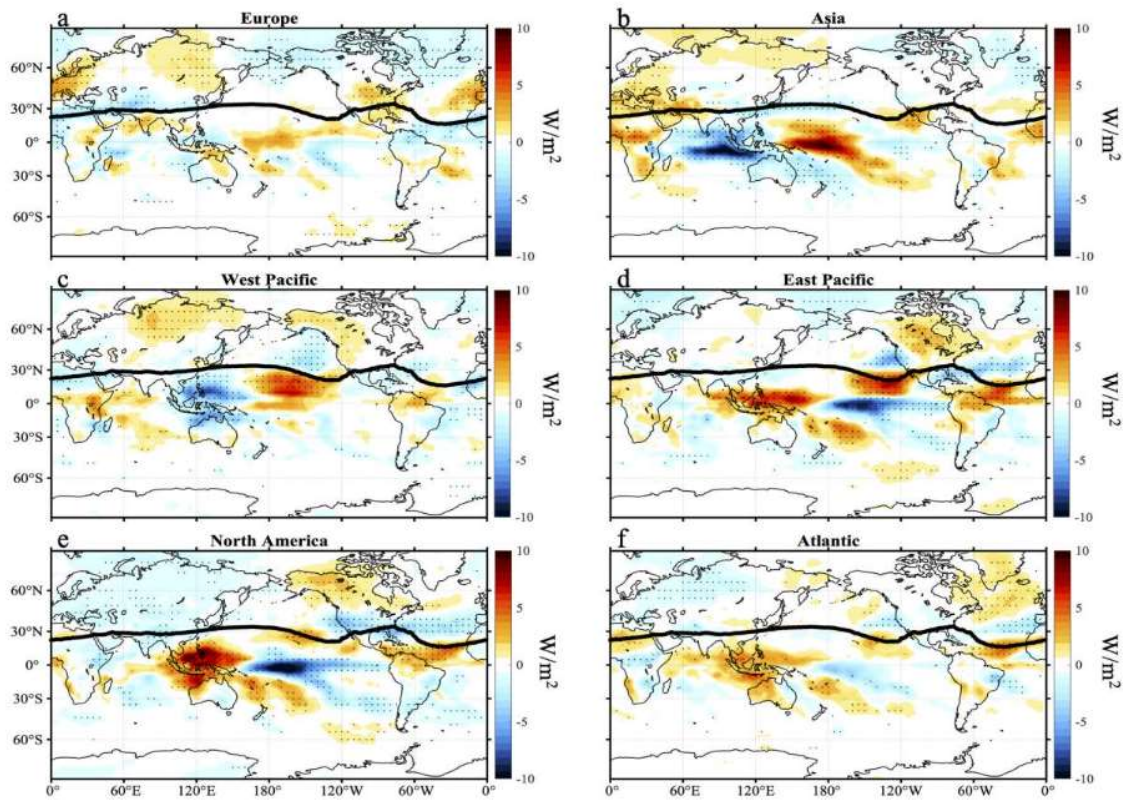


Figure 6. As in Fig. 5, but for STJ strength. The model version of this figure is shown in Fig. S5 in the supplementary material.

4. Comparison between models and observations

In this section, we compare the observed variability in the position and strength of the jets (as documented in Section 3) with that from CMIP6 models. Model results for the regressions on PFJ position and strength are shown in Figs. S1 and S2, and model results for the regressions on STJ position and strength are shown in Figs. S4 and S5. The model regressions of surface temperature anomalies onto the PFJ position and strength are very similar to those shown for observations (Figs. 3-4), but the model regressions of OLR anomalies onto STJ position and

strength differ significantly from observations (Figs. 5-6). For that reason, in this section, we focus on the comparison of the STJ variability between observations and CMIP6 models.

To summarize the model biases in STJ variability, the right column of Fig. 7 shows the CMIP6 multi-model mean regression coefficients of tropical (5°N - 5°S) OLR anomalies onto indices of the STJ position and strength calculated at every longitude (as shown in the left column for observations). Consistent with observations (Figs. 5-6), it is worth noting that the STJ at each longitude in the multi-model mean is not primarily sensitive to OLR at its own longitude, but rather responds to tropical OLR anomalies in the Pacific. However, for the OLR anomalies associated with a poleward shift in the STJ, tropical convection in the models is displaced westward for Europe, Asia, and the western tropical Pacific when compared to observations (Figs. 7a-b). Additionally, large discrepancies between the observed and model patterns occur in the North America. Over North America in observations, a La Niña-like pattern in anomalous tropical convection is associated with a poleward shift of the STJ position but this pattern is not shown in models. For the OLR anomalies associated with a strengthening of the STJ (Figs. 7c-d), most models capture the observed relationship between La Niña and a strengthened STJ over the western Pacific Ocean, and between El Niño and a strengthened STJ over the eastern Pacific Ocean and North America (see the prominent quadrupole pattern in the left-center of panels c and d). However, most models fail to capture the observed relationship between tropical convection and the STJ strength over the eastern Atlantic Ocean and Eurasia.

We now discuss the possible causes of these model-observation discrepancies shown in Fig. 7. As discussed above, models agree that a La Niña-like pattern in anomalous tropical convection is associated with a poleward shift of the STJ position in the Eurasian and western Pacific sectors, but the dipole of OLR anomalies is shifted to the west in the multi-model-mean

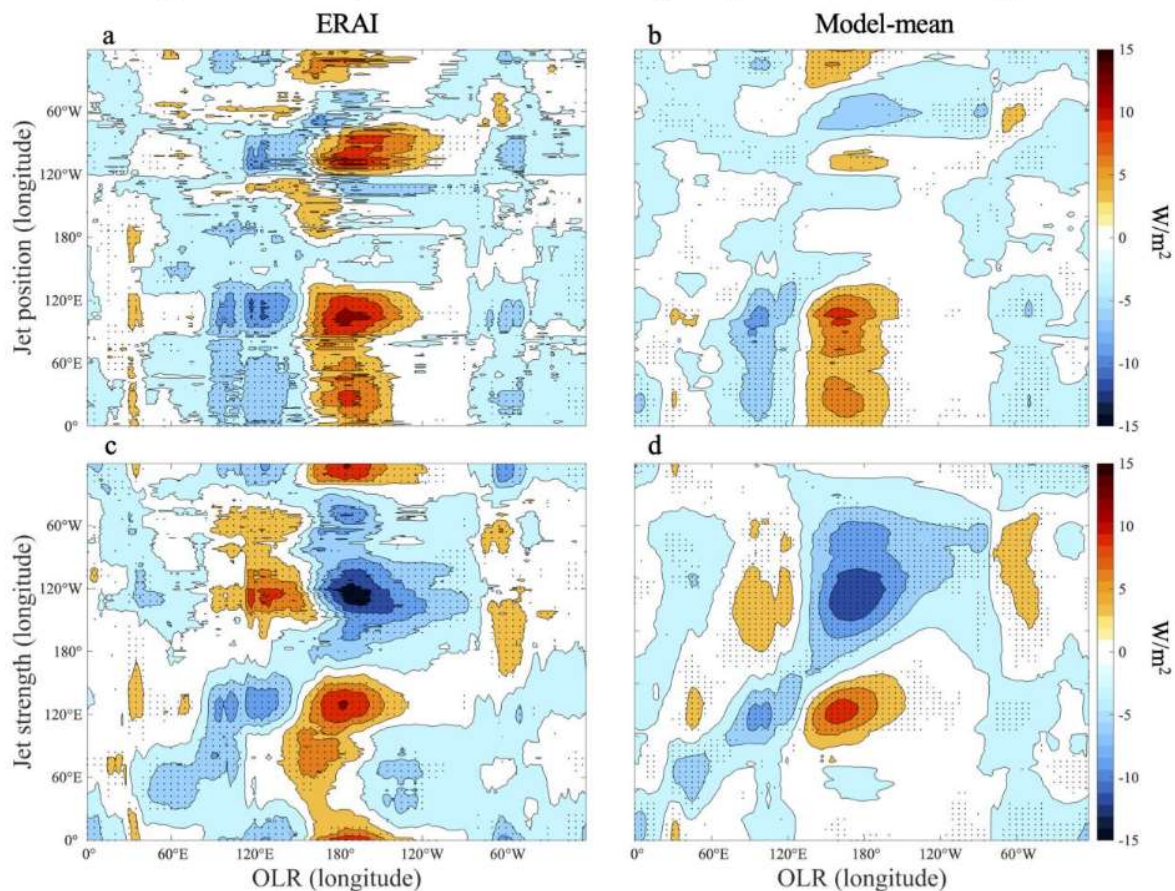
compared to observations (Figs. 7a-b). To illustrate this more clearly, the top row of Fig. 8 shows the regressions of OLR anomalies onto the STJ position in the Asian sector (as shown in Figs. 5 and S4, but zoomed in to show greater detail). In particular, notice that the region of enhanced convection in the multi-model-mean is narrower and confined to longitudes west of the Philippines, and that the region of suppressed convection along the Equator in the multi-model-mean extends much further to the west over New Guinea (Fig. 8b).

One reason for the westward shift of the La Niña-like pattern in models could be that the climatological OLR field in CMIP6 models is different from that in observations, as some previous studies have documented that ENSO diversity is associated with the tropical Pacific background state (Capotondi et al., 2015; Choi, An, Kug, & Yeh, 2011; Chung & Li, 2013). The observed and multi-model-mean OLR climatology in the equatorial Pacific is shown in Fig. 8c and Fig. 8d. The equatorial low OLR region in observations in the western Pacific is wider and extends further eastward than in the multi-model-mean climatology. To illustrate this better, we also plot the cross-section of observed and multi-model-mean climatological OLR at the Equator as a function of longitude in Fig. 8e.

In Fig. 9, we show the correlation between the position of the climatological low OLR region along the Equator in the western Pacific Ocean (as shown in Fig. 8e) and the position of the OLR anomalies associated with a poleward STJ shift over the Asia sector (as shown in Figs. 8a and 8b) across CMIP6 models. The climatological low OLR region is defined as the region where OLR is smaller than 255 W m^{-2} , and we define the position of the low OLR region as the mid-point longitude of the low OLR region in the equatorial western Pacific. The results are not sensitive to the exact choice of threshold value (i.e., values between 250 and 270 W m^{-2} give similar results). The position of the OLR associated with a poleward STJ shift over the Asia

sector, which we refer to as the “La Niña pattern index”, is defined as the transition longitude between 120°E-180°E where the regression coefficient of OLR to Asian STJ position (as shown in Figs. 8a and 8b) averaged over 10° S to 20° N crosses zero. The positive relationship between the midpoint of the climatological low OLR region and La Niña pattern index (Pearson correlation coefficient r is 0.80) indicates that the westward La Niña-like pattern in models’ tropical convection associated with a poleward STJ shift over the Europe-Asia-Pacific sector can be attributed to the biased OLR climatology in the tropical western Pacific Ocean in many models. The western Pacific tropical convection is centered further to the west than observations in nearly all of the models and thus causes a westward shift of the La Niña-like pattern of anomalous tropical convection.

Regression of tropical OLR onto subtropical jet indices at all longitudes



451 **Figure 7.** Regression of the wintertime monthly tropical OLR (5°S - 5°N) anomalies onto
 452 subtropical jet indices at all longitudes. (a) and (b) are regression coefficients for subtropical jet
 453 position; (c) and (d) are regression coefficients for subtropical jet strength. The left column
 454 shows results for observations, and the right column shows results for the CMIP6 multi-model-
 455 mean. Color shading represents the regression coefficient of OLR at the longitude on the x-axis
 456 to the subtropical jet index at the longitude on y axis. For (a) and (c), stippling indicates that
 457 regression patterns are statistically significant at the 95% level according to a two-tailed
 458 Student's t-test. For (b) and (d), stippling indicates that more than 80% of models agree on the
 459 sign of the regression coefficients.

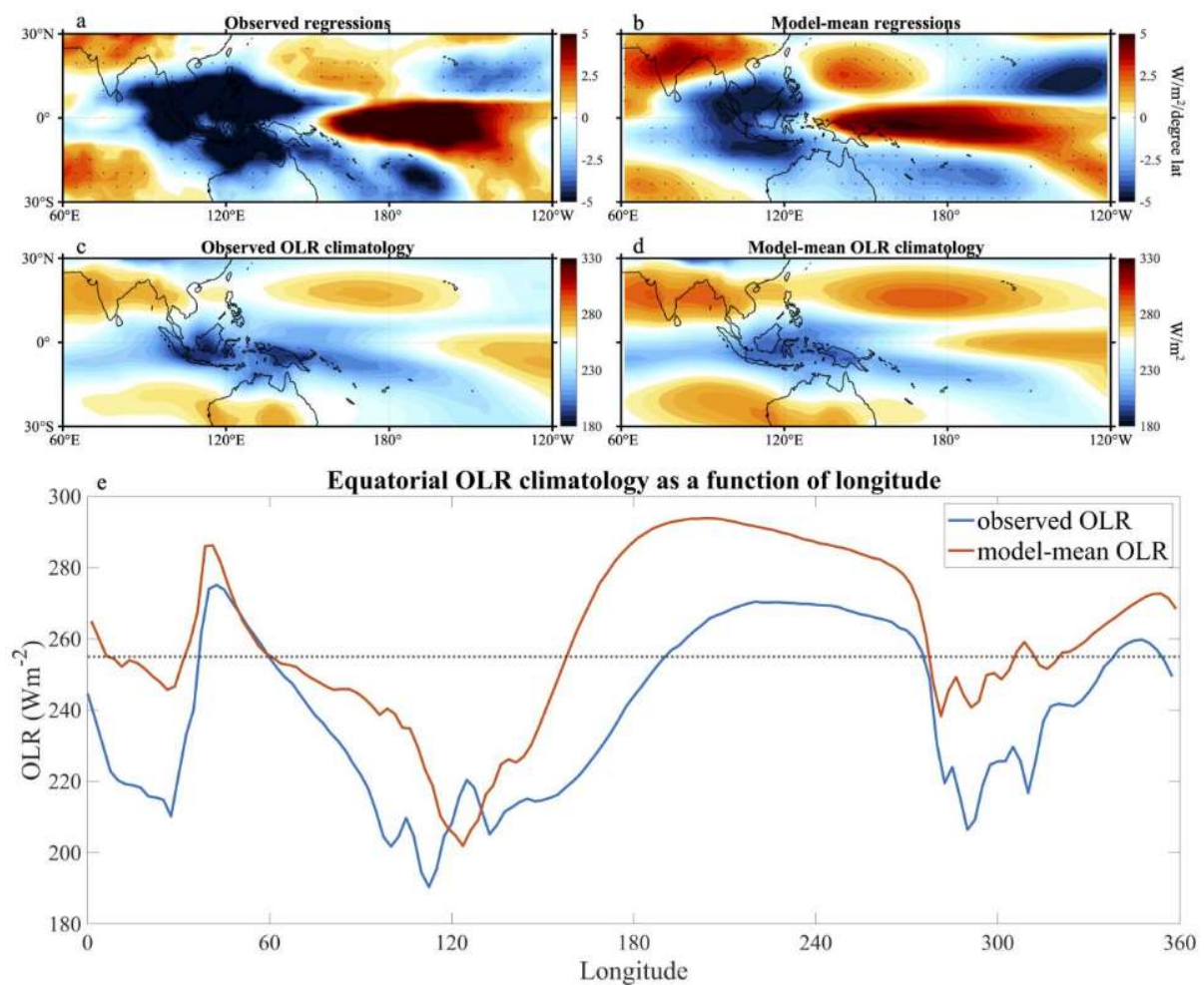


Figure 8. (a) and (b) are regressions of monthly wintertime OLR anomalies to the Asian STJ position for observations and the CMIP6 multi-model mean (reproduced from the second panels of Figure 5 and Figure S4 but zoomed in and with different color scales). (c) and (d) are the wintertime OLR climatology for observations and the CMIP6 multi-model mean. (e) is the observed and multi-model-mean wintertime OLR climatology at the Equator as a function of longitude. The blue line shows the observed OLR, while the red line shows the model-mean OLR. The dashed black line shows the 255 Wm^{-2} OLR value, below which is defined as low OLR.

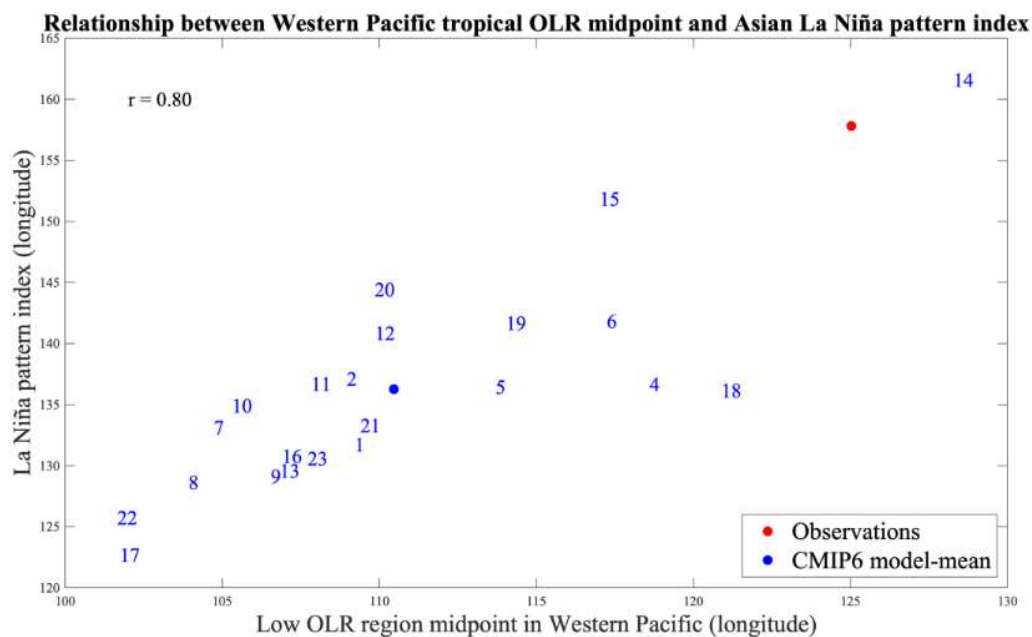


Figure 9. Scatter plot between the midpoint of the wintertime climatological low OLR region over the western Pacific and the La Niña pattern index. The La Niña pattern index is defined as the transition longitude between 120°E - 180°E where the regression coefficient of wintertime monthly OLR anomalies to the Asian STJ position (as shown in Figs. 8a and 8b) averaged over 10°S to 20°N crosses zero. The midpoint of the climatological low OLR region is defined as

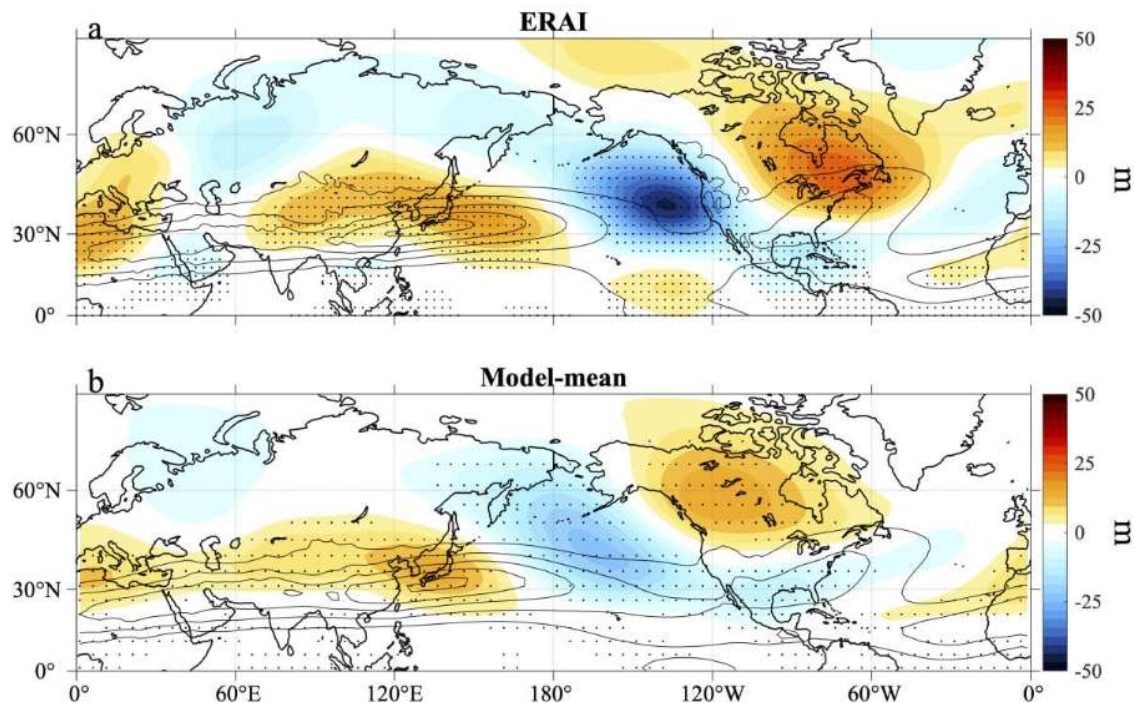
the mid-point longitude of the low OLR region in equatorial Western Pacific (as shown in Fig. 8e). The low OLR region is defined where the OLR is smaller than 255 W m^{-2} . Numbers on the scatterplot correspond to the models listed in Table. S1. The blue dot represents multi-model-mean, while the red dot is for observations.

Another key discrepancy between observations and models shown in Fig. 7 is that models fail to capture the linkage between a La Niña-like pattern of anomalous tropical convection and the poleward shift of the STJ over North America (Fig. 7b). Given the biased OLR climatology in models, it seems plausible that different Rossby wave trains would be excited by tropical convection at different locations associated with El Niño and La Niña patterns in observations and models (Jiménez-Esteve & Domeisen, 2018). To illustrate this, Figure 10 shows the regressions of eddy geopotential height anomalies at 500 hPa onto the Niño 3.4 index (i.e., sea surface temperatures averaged over 5°N - 5°S , 170°W - 120°W) for both observations and the CMIP6 multi-model mean. Here, the term eddy geopotential height anomalies means that both the zonal mean and seasonal cycle has been removed from the geopotential height data. As shown in Fig. 10a, the wave train excited by anomalous tropical convection in observations is further south and east compared to that in multi-model-mean. Consequently, a north-south dipole of eddy geopotential height anomalies is located directly over the STJ in eastern North America in observations, but not in models.

Finally, we noted above that models fail to capture the observed relationship between a La Niña-like pattern of anomalous tropical convection and STJ strength over the eastern Atlantic and European sectors (Fig. 7d). As shown in Fig. 10a, the wave train associated with ENSO in observations propagates poleward to Alaska and Canada and then back equatorward toward the

499 North Atlantic and Western Europe, where it projects onto the STJ in this region. In the multi-
 500 model mean, the wave train associated with ENSO is shifted further westward and thus returns
 501 equatorward over the central Atlantic Ocean (Fig. 10b). However, ENSO's impacts in the North
 502 Atlantic may be highly variable and unstable (note lack of significance in Fig. 10 over North
 503 Atlantic), which means that the observed teleconnections in this sector may be highly sensitive to
 504 the time frame we choose (Greatbatch, Lu, & Peterson, 2004).

Regression of geopotential height anomaly onto Niño 3.4 index



505 **Figure 10.** Regression of wintertime monthly eddy 500 hPa geopotential height anomalies (i.e.,
 506 with both the seasonal cycle and zonal-mean field removed) onto the Niño 3.4 index in
 507 observations (a) and the CMIP6 multi-model mean (b). The Niño 3.4 index is defined as SST
 508 anomalies averaged across 5°N-5°S, 170°W-120°W. Stippling in (a) indicates that regression
 509 patterns are statistically significant at the 95% level according to a two-tailed Student's t-test,
 510 and stippling in (b) indicates that more than 80% of models agree with the sign of regression

coefficients. Black contours indicate the climatology of zonal wind difference fields (250 hPa zonal wind – 850 hPa zonal wind), which are used to define the STJ position. Contours are shown at 20, 30, 40, 50 and 60 m/s.

5. Summary and conclusions

The position and intensity of the polar front and subtropical jet streams in Northern Hemisphere winter exhibit large spatial and temporal variance. Some previous studies (e.g., Lee & Kim, 2003; Son & Lee, 2005) have provided insight into the processes that control the variability of the polar front and subtropical jets, but most of these studies have relied on idealized aqua-planet models with no zonal asymmetries in the jets. Although correlations among variations in the strength and position of the jets could be anticipated from such idealized modeling studies, variability in the position and strength of the zonal-mean STJ and PFJ actually exhibit few significant correlations in observations and comprehensive global climate models (Fig. 2; Solomon et al. 2016; Waugh et al. 2018; Menzel et al. 2019; Davis & Birner 2017). The lack of significant correlations among the position and strength of the jets in the zonal-mean mask significant correlations among those of the jets that occur on the regional level (Fig. 2), which highlights the need to examine the interannual variability of the jets and the underlying mechanisms at individual longitudes.

In this study, we find a close relationship between the observed variability in the position and strength of the STJ and tropical outgoing longwave radiation (OLR), and between the observed variability in position and strength of the PFJ with mid-latitude surface temperature gradients during the NH winter season. Local changes in surface baroclinicity are associated with variability in the position and strength of the NH PFJ, particularly over Asia, western Pacific and

North America (Figs. 2-3). In other regions, global-scale teleconnection patterns (NAO and PNA) play a key role in modulating the position and strength of the PFJ, particularly over the North Atlantic Ocean and Europe. Variations in tropical convection over the Pacific Ocean are linked to variations in the strength and position of the NH STJ at almost all longitudes, with different phases of the El Niño-Southern Oscillation (ENSO) associated with the poleward shift and strengthening of the subtropical jet in different regions (Figs. 4-5).

CMIP6 models generally capture these observed relationships, but for the STJ variability, the models' tropical convection is often displaced westward when compared to observations (Figs. 7-8). This difference between models and observations can be attributed to the biased OLR climatology over the tropical Western Pacific Ocean in many models, with climatological convection in models displaced westward with respect to observations (Figs. 8-9). The displaced tropical convection in models excites different paths of Rossby wave propagation, making downstream ENSO teleconnections on the STJ over North America, the Atlantic Ocean, and Europe different compared to observations.

Our study examines observed characteristics of the NH wintertime STJ and PFJ at all longitudes and provides insight into the processes governing their interannual variability over the last four decades. Future work could extend this study to the Southern Hemisphere, or investigate the mechanisms governing the jet variability in other seasons in the NH. It may also be worthwhile to examine whether the mechanisms governing the latitudes, strengths, and meridional separation between the jets change in the future as the climate warms. Although climate models show a robust poleward shift of the PFJ in a warming climate (e.g., Barnes & Polvani 2013), the STJ does not show a consistent poleward or equatorward shift, at least in the zonal mean (Davis & Birner 2017; Waugh et al. 2018; Menzel et al. 2019). Recent reanalysis

data also show poleward trends in the PFJ latitude (e.g., Allen and Kovilakam 2017; Grise et al. 2018), but inconsistent trends in the STJ latitude (Maher et al., 2020; Manney & Hegglin, 2018). Not only does this suggest that the mechanisms driving the responses of the STJ and PFJ to climate change could be very different (as discussed by Menzel et al. 2019), but it also implies that the character of the general circulation (i.e., preference for a merged jet at some longitudes and two distinct jets at other longitudes) may change as the climate warms, hence modulating interannual variability of the jets and the associated behavior of synoptic weather events.

Acknowledgments

We acknowledge the World Climate Research Programme, which, through its Working Group on Coupled Modelling, coordinated and promoted CMIP6. We thank the climate modeling groups for producing and making available their model output, the Earth System Grid Federation (ESGF) for archiving the data and providing access, and the multiple funding agencies who support CMIP6 and ESGF. We also thank Carlee Kleppin (University of Virginia) for her initial work on this topic. This material is based in part upon work supported by the National Science Foundation under Grant No. AGS-1752900.

CMIP6 model output is freely available from the Lawrence Livermore National Laboratory (<https://esgf-node.llnl.gov/search/cmip6/>). ERA-Interim reanalysis data are freely available from the European Centre for Medium-Range Weather Forecasts (<https://apps.ecmwf.int/datasets/data/interim-full-moda/>; <https://cds.climate.copernicus.eu/#!/search?text=ERA5&type=dataset>). Monthly outgoing longwave radiation (OLR) datasets are freely available from NOAA Physical Sciences Laboratory (https://psl.noaa.gov/data/gridded/data.interp_OLR.html).

References

- Adam, O., Grise, K. M., Staten, P., Simpson, I. R., Davis, S. M., Davis, N. A., ... Birner, T. (2018). The TropD software package: Standardized methods for calculating Tropical Width Diagnostics. *Geoscientific Model Development Discussions*, 1–35. <https://doi.org/10.5194/gmd-2018-124>
- Afargan, H., & Kaspi, Y. (2017). A Midwinter Minimum in North Atlantic Storm Track Intensity in Years of a Strong Jet. *Geophysical Research Letters*, 44(24), 12,511–12,518. <https://doi.org/10.1002/2017GL075136>
- Allen, R. J., & Kovilakam, M. (2017). The role of natural climate variability in recent tropical expansion. *Journal of Climate*, 30(16), 6329–6350. <https://doi.org/10.1175/JCLI-D-16-0735.1>
- Archer, C. L., & Caldeira, K. (2008). Historical trends in the jet streams. *Geophysical Research Letters*, 35(8), 1–6. <https://doi.org/10.1029/2008GL033614>
- Athanasiadis, P. J., Wallace, J. M., & Wettstein, J. J. (2010). Patterns of wintertime jet stream variability and their relation to the storm tracks. *Journal of the Atmospheric Sciences*, 67(5), 1361–1381. <https://doi.org/10.1175/2009JAS3270.1>
- Bals-Elsholz, T. M., Atallah, E. H., Bosart, L. F., Wasula, T. A., Cempa, M. J., & Lupo, A. R. (2001). The wintertime southern hemisphere split jet: Structure, variability, and evolution. *Journal of Climate*, 14(21), 4191–4215. [https://doi.org/10.1175/1520-0442\(2001\)014<4191:TWSHSJ>2.0.CO;2](https://doi.org/10.1175/1520-0442(2001)014<4191:TWSHSJ>2.0.CO;2)
- Barnes, E. A., & Hartmann, D. L. (2010). Influence of eddy-driven jet latitude on North Atlantic jet persistence and blocking frequency in CMIP3 integrations. *Geophysical Research Letters*, 37(23). <https://doi.org/10.1029/2010GL045700>

- 604 Barnes, E. A., & Polvani, L. (2013). Response of the midlatitude jets, and of their variability, to
 605 increased greenhouse gases in the CMIP5 models. *Journal of Climate*, 26(18), 7117–7135.
 606 <https://doi.org/10.1175/JCLI-D-12-00536.1>
- 607 Brayshaw, D. J., Hoskins, B., & Blackburn, M. (2008). The Storm-Track Response to Idealized
 608 SST Perturbations in an Aquaplanet GCM. *Journal of the Atmospheric Sciences*, 65(9),
 609 2842–2860. <https://doi.org/10.1175/2008JAS2657.1>
- 610 Capotondi, A., Wittenberg, A. T., Newman, M., Di Lorenzo, E., Yu, J. Y., Braconnot, P., ...
 611 Yeh, S. W. (2015). Understanding ENSO diversity. *Bulletin of the American Meteorological*
 612 *Society*, 96(6), 921–938. <https://doi.org/10.1175/BAMS-D-13-00117.1>
- 613 Ceppi, P., & Hartmann, D. L. (2013). On the speed of the eddy-driven jet and the width of the
 614 Hadley cell in the southern hemisphere. *Journal of Climate*, 26(10), 3450–3465.
 615 <https://doi.org/10.1175/JCLI-D-12-00414.1>
- 616 Choi, J., An, S. Il, Kug, J. S., & Yeh, S. W. (2011). The role of mean state on changes in El
 617 Niño's flavor. *Climate Dynamics*, 37(5), 1205–1215. [https://doi.org/10.1007/s00382-010-](https://doi.org/10.1007/s00382-010-0912-1)
 618 [0912-1](https://doi.org/10.1007/s00382-010-0912-1)
- 619 Christenson, C. E., Martin, J. E., & Handlos, Z. J. (2017). A synoptic climatology of Northern
 620 Hemisphere, cold season polar and subtropical jet superposition events. *Journal of Climate*,
 621 30(18), 7231–7246. <https://doi.org/10.1175/JCLI-D-16-0565.1>
- 622 Chung, P. H., & Li, T. (2013). Interdecadal relationship between the mean state and El Niño
 623 types. *Journal of Climate*, 26(2), 361–379. <https://doi.org/10.1175/JCLI-D-12-00106.1>
- 624 Cook, A. R., & Schaefer, J. T. (2008). The relation of El Niño-Southern Oscillation (ENSO) to
 625 winter tornado outbreaks. *Monthly Weather Review*, 136(8), 3121–3137.
 626 <https://doi.org/10.1175/2007MWR2171.1>

- 627 Davis, N., & Birner, T. (2016). Climate model biases in the width of the tropical belt. *Journal of*
 628 *Climate*, 29(5), 1935–1954. <https://doi.org/10.1175/JCLI-D-15-0336.1>
- 629 Davis, N., & Birner, T. (2017). On the discrepancies in tropical belt expansion between
 630 reanalyses and climate models and among tropical belt width metrics. *Journal of Climate*,
 631 30(4), 1211–1231. <https://doi.org/10.1175/JCLI-D-16-0371.1>
- 632 Dee, D. P., Uppala, S. M., Simmons, A. J., Berrisford, P., Poli, P., Kobayashi, S., ... Vitart, F.
 633 (2011). The ERA-Interim reanalysis: Configuration and performance of the data
 634 assimilation system. *Quarterly Journal of the Royal Meteorological Society*, 137(656), 553–
 635 597. <https://doi.org/10.1002/qj.828>
- 636 Dickson, R. R., & Namias, J. (1976). North American Influences on the Circulation and Climate
 637 of the North Atlantic Sector. *Monthly Weather Review*, 104(10), 1255–1265.
 638 [https://doi.org/10.1175/1520-0493\(1976\)104<1255:NAIOTC>2.0.CO;2](https://doi.org/10.1175/1520-0493(1976)104<1255:NAIOTC>2.0.CO;2)
- 639 Eichelberger, S. J., & Hartmann, D. L. (2007). Zonal jet structure and the leading mode of
 640 variability. *Journal of Climate*, 20(20), 5149–5163. <https://doi.org/10.1175/JCLI4279.1>
- 641 Eichler, T., & Higgins, W. (2006). Climatology and ENSO-related variability of North American
 642 extratropical cyclone activity. *Journal of Climate*, 19(10), 2076–2093.
 643 <https://doi.org/10.1175/JCLI3725.1>
- 644 Eyring, V., Bony, S., Meehl, G. A., Senior, C. A., Stevens, B., Stouffer, R. J., & Taylor, K. E.
 645 (2016). Overview of the Coupled Model Intercomparison Project Phase 6 (CMIP6)
 646 experimental design and organization. *Geoscientific Model Development*, 9(5), 1937–1958.
 647 <https://doi.org/10.5194/gmd-9-1937-2016>
- 648 Gallego, D., Ribera, P., Garcia-Herrera, R., Hernandez, E., & Gimeno, L. (2005). A new look for
 649 the Southern Hemisphere jet stream. *Climate Dynamics*, 24(6), 607–621.

- 650 <https://doi.org/10.1007/s00382-005-0006-7>
- 651 Greatbatch, R. J., Lu, J., & Peterson, K. A. (2004). Nonstationary impact of ENSO on Euro-
 652 Atlantic winter climate. *Geophysical Research Letters*, 31(2), 4–7.
 653 <https://doi.org/10.1029/2003GL018542>
- 654 Grise, K. M., Davis, S. M., Staten, P. W., & Adam, O. (2018). Regional and seasonal
 655 characteristics of the recent expansion of the tropics. *Journal of Climate*, 31(17), 6839–
 656 6856. <https://doi.org/10.1175/JCLI-D-18-0060.1>
- 657 Halpert, M. S., & Ropelewski, C. F. (1992). Surface Temperature Patterns Associated with the
 658 Southern Oscillation. *Journal of Climate*, 5(6), 577–593. [https://doi.org/10.1175/1520-0442\(1992\)005<0577:STPAWT>2.0.CO;2](https://doi.org/10.1175/1520-0442(1992)005<0577:STPAWT>2.0.CO;2)
- 660 Handlos, Z. J., & Martin, J. E. (2016). Composite analysis of large-scale environments
 661 conducive to western Pacific polar/subtropical jet superposition. *Journal of Climate*, 29(19),
 662 7145–7165. <https://doi.org/10.1175/JCLI-D-16-0044.1>
- 663 Held, I. M. (1975). Momentum Transport by Quasi-Geostrophic Eddies. *Journal of the*
 664 *Atmospheric Sciences*, 32(7), 1494–1497. [https://doi.org/10.1175/1520-0469\(1975\)032<1494:MTBQGE>2.0.CO;2](https://doi.org/10.1175/1520-0469(1975)032<1494:MTBQGE>2.0.CO;2)
- 665
- 666 Held, I. M., & Hou, A. Y. (1980). Nonlinear Axially Symmetric Circulations in a Nearly Inviscid
 667 Atmosphere. *Journal of the Atmospheric Sciences*, 37(3), 515–533.
 668 [https://doi.org/10.1175/1520-0469\(1980\)037<0515:NASCIA>2.0.CO;2](https://doi.org/10.1175/1520-0469(1980)037<0515:NASCIA>2.0.CO;2)
- 669 Hurrell, J. W. (1995). Decadal Trends in the North Atlantic Oscillation: Regional Temperatures
 670 and Precipitation. *Science*, 269(5224), 676 LP – 679.
 671 <https://doi.org/10.1126/science.269.5224.676>
- 672 Jiménez-Esteve, B., & Domeisen, D. I. V. (2018). The tropospheric pathway of the ENSO-North

- 673 Atlantic teleconnection. *Journal of Climate*, 31(11), 4563–4584.
 674 <https://doi.org/10.1175/JCLI-D-17-0716.1>
- 675 Kaas, E., & Branstator, G. (1993). The Relationship between a Zonal Index and Blocking
 676 Activity. *Journal of Atmospheric Sciences*, 50(18), 3061–3077.
 677 [https://doi.org/10.1175/1520-0469\(1993\)050<3061:TRBAZI>2.0.CO;2](https://doi.org/10.1175/1520-0469(1993)050<3061:TRBAZI>2.0.CO;2)
- 678 Kim, H. K., & Lee, S. (2004). The wave-zonal mean flow interaction in the Southern
 679 Hemisphere. *Journal of the Atmospheric Sciences*, 61(9), 1055–1067.
 680 [https://doi.org/10.1175/1520-0469\(2004\)061<1055:TWMFII>2.0.CO;2](https://doi.org/10.1175/1520-0469(2004)061<1055:TWMFII>2.0.CO;2)
- 681 Koch, P., Wernli, H., & Davies, H. C. (2006). An event-based jet-stream climatology and
 682 typology. *International Journal of Climatology*, 26(3), 283–301.
 683 <https://doi.org/10.1002/joc.1255>
- 684 Lee, S., & Kim, H. K. (2003). The dynamical relationship between subtropical and eddy-driven
 685 jets. *Journal of the Atmospheric Sciences*, 60(12), 1490–1503. [https://doi.org/10.1175/1520-0469\(2003\)060<1490:TDRBSA>2.0.CO;2](https://doi.org/10.1175/1520-0469(2003)060<1490:TDRBSA>2.0.CO;2)
- 687 Li, C., & Wettstein, J. J. (2012). Thermally driven and eddy-driven jet variability in reanalysis.
 688 *Journal of Climate*, 25(5), 1587–1596. <https://doi.org/10.1175/JCLI-D-11-00145.1>
- 689 Liebmann, B., & Smith, C. A. (1996). Description of a Complete (Interpolated) Outgoing
 690 Longwave Radiation Dataset. *Bulletin of the American Meteorological Society*, 77, 1275–
 691 1277.
- 692 Lu, J., Chen, G., & Frierson, D. M. W. (2008). Response of the zonal mean atmospheric
 693 circulation to El Niño versus global warming. *Journal of Climate*, 21(22), 5835–5851.
 694 <https://doi.org/10.1175/2008JCLI2200.1>
- 695 Maher, P., Kelleher, M. E., Sansom, P. G., & Methven, J. (2020). Is the subtropical jet shifting

- 696 poleward? *Climate Dynamics*, 54(3–4), 1741–1759. [https://doi.org/10.1007/s00382-019-](https://doi.org/10.1007/s00382-019-05084-6)
 697 05084-6
- 698 Mahlstein, I., Martius, O., Chevalier, C., & Ginsbourger, D. (2012). Changes in the odds of
 699 extreme events in the Atlantic basin depending on the position of the extratropical jet.
 700 *Geophysical Research Letters*, 39(22), 1–6. <https://doi.org/10.1029/2012GL053993>
- 701 Manney, G. L., & Hegglin, M. I. (2018). Seasonal and regional variations of long-term changes
 702 in upper-tropospheric jets from reanalyses. *Journal of Climate*, 31(1), 423–448.
 703 <https://doi.org/10.1175/JCLI-D-17-0303.1>
- 704 Menzel, M. E., Waugh, D., & Grise, K. (2019). Disconnect Between Hadley Cell and
 705 Subtropical Jet Variability and Response to Increased CO₂. *Geophysical Research Letters*,
 706 46(12), 7045–7053. <https://doi.org/10.1029/2019GL083345>
- 707 Nakamura, H. (1992). Midwinter Suppression of Baroclinic Wave Activity in the Pacific.
 708 *Journal of Atmospheric Sciences*, 49(17), 1629–1642. [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0469(1992)049<1629:MSOBWA>2.0.CO;2)
 709 0469(1992)049<1629:MSOBWA>2.0.CO;2
- 710 Panetta, R. L. (1993). Zonal Jets in Wide Baroclinically Unstable Regions: Persistence and Scale
 711 Selection. *Journal of the Atmospheric Sciences*, 50(14), 2073–2106.
 712 [https://doi.org/10.1175/1520-0469\(1993\)050<2073:ZJIWBU>2.0.CO;2](https://doi.org/10.1175/1520-0469(1993)050<2073:ZJIWBU>2.0.CO;2)
- 713 Petoukhov, V., Rahmstorf, S., Petri, S., & Schellnhuber, H. J. (2013). Quasiresonant
 714 amplification of planetary waves and recent Northern Hemisphere weather extremes.
 715 *Proceedings of the National Academy of Sciences of the United States of America*, 110(14),
 716 5336–5341. <https://doi.org/10.1073/pnas.1222000110>
- 717 Ropelewski, C. F., & Halpert, M. S. (1989). Precipitation Patterns Associated with the High
 718 Index Phase of the Southern Oscillation. *Journal of Climate*, 2(3), 268–284.

- 719 [https://doi.org/10.1175/1520-0442\(1989\)002<0268:PPAWTH>2.0.CO;2](https://doi.org/10.1175/1520-0442(1989)002<0268:PPAWTH>2.0.CO;2)
- 720 Ryoo, J. M., Kaspi, Y., Waugh, D. W., Kiladis, G. N., Waliser, D. E., Fetzer, E. J., & Kim, J.
- 721 (2013). Impact of rossby wave breaking on U.S. west coast winter precipitation during
- 722 ENSO events. *Journal of Climate*, 26(17), 6360–6382. [https://doi.org/10.1175/JCLI-D-12-](https://doi.org/10.1175/JCLI-D-12-00297.1)
- 723 00297.1
- 724 Sampe, T., Nakamura, H., Goto, A., & Ohfuchi, W. (2010). Significance of a midlatitude SST
- 725 frontal zone in the formation of a storm track and an eddy-driven westerly jet. *Journal of*
- 726 *Climate*, 23(7), 1793–1814. <https://doi.org/10.1175/2009JCLI3163.1>
- 727 Schneider, E. K. (1977). Axially Symmetric Steady-State Models of the Basic State for
- 728 Instability and Climate Studies. Part II. Nonlinear Calculations. *Journal of the Atmospheric*
- 729 *Sciences*, 34(2), 280–296. [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0469(1977)034<0280:ASSSMO>2.0.CO;2)
- 730 0469(1977)034<0280:ASSSMO>2.0.CO;2
- 731 Seager, R., Murtugudde, R., Naik, N., Clement, A., Gordon, N., & Miller, J. (2003). Air-sea
- 732 interaction and the seasonal cycle of the subtropical anticyclones. *Journal of Climate*,
- 733 16(12), 1948–1966. [https://doi.org/10.1175/1520-0442\(2003\)016<1948:AIATSC>2.0.CO;2](https://doi.org/10.1175/1520-0442(2003)016<1948:AIATSC>2.0.CO;2)
- 734 Smith, S. R., Green, P. M., Leonardi, A. P., & O'Brien, J. J. (1998). Role of Multiple-Level
- 735 Tropospheric Circulations in Forcing ENSO Winter Precipitation Anomalies. *Monthly*
- 736 *Weather Review*, 126(12), 3102–3116. [https://doi.org/10.1175/1520-](https://doi.org/10.1175/1520-0493(1998)126<3102:ROMLTC>2.0.CO;2)
- 737 0493(1998)126<3102:ROMLTC>2.0.CO;2
- 738 Solomon, A., Polvani, L. M., Waugh, D. W., & Davis, S. M. (2016). Contrasting upper and
- 739 lower atmospheric metrics of tropical expansion in the Southern Hemisphere. *Geophysical*
- 740 *Research Letters*, 43(19), 10,496–10,503. <https://doi.org/10.1002/2016GL070917>
- 741 Son, S. W., & Lee, S. (2005). The response of westerly jets to thermal driving in a primitive

- 742 equation model. *Journal of the Atmospheric Sciences*, 62(10), 3741–3757.
- 743 <https://doi.org/10.1175/JAS3571.1>
- 744 Strong, C., & Davis, R. E. (2008). Variability in the position and strength of winter jet stream
- 745 cores related to northern hemisphere teleconnections. *Journal of Climate*, 21(3), 584–592.
- 746 <https://doi.org/10.1175/2007JCLI1723.1>
- 747 Wallace, J. M., & Gutzler, D. S. (1981). Teleconnections in the Geopotential Height Field during
- 748 the Northern Hemisphere Winter. *Monthly Weather Review*, 109(4), 784–812.
- 749 [https://doi.org/10.1175/1520-0493\(1981\)109<0784:TITGHF>2.0.CO;2](https://doi.org/10.1175/1520-0493(1981)109<0784:TITGHF>2.0.CO;2)
- 750 Waugh, D. W., Grise, K. M., Seviour, W. J. M., Davis, S. M., Davis, N., Adam, O., ... Ming, A.
- 751 (2018). Revisiting the relationship among metrics of tropical expansion. *Journal of Climate*,
- 752 31(18), 7565–7581. <https://doi.org/10.1175/JCLI-D-18-0108.1>
- 753 Winters, A. C., & Martin, J. E. (2016). Synoptic and mesoscale processes supporting vertical
- 754 superposition of the polar and subtropical jets in two contrasting cases. *Quarterly Journal of*
- 755 *the Royal Meteorological Society*, 142(695), 1133–1149. <https://doi.org/10.1002/qj.2718>
- 756 Woollings, T., Barriopedro, D., Methven, J., Son, S. W., Martius, O., Harvey, B., ... Seneviratne,
- 757 S. (2018). Blocking and its Response to Climate Change. *Current Climate Change Reports*,
- 758 4(3), 287–300. <https://doi.org/10.1007/s40641-018-0108-z>
- 759 Woollings, T., Czuchnicki, C., & Franzke, C. (2014). Twentieth century North Atlantic jet
- 760 variability. *Quarterly Journal of the Royal Meteorological Society*, 140(680), 783–791.
- 761 <https://doi.org/10.1002/qj.2197>
- 762 Yu, B., & Lin, H. (2019). Modification of the wintertime Pacific–North American pattern related
- 763 North American climate anomalies by the Asian–Bering–North American teleconnection.
- 764 *Climate Dynamics*, 53(1–2), 313–328. <https://doi.org/10.1007/s00382-018-4586-4>

manuscript submitted to *Journal of Geophysical Research: Atmospheres*

- 765 Yuval, J., & Kaspi, Y. (2018). Eddy sensitivity to jet characteristics. *Journal of the Atmospheric*
766 *Sciences*, 75(5), 1371–1383. <https://doi.org/10.1175/JAS-D-17-0139.1>
- 767 Zhang, W., & Villarini, G. (2018). Uncovering the role of the East Asian jet stream and
768 heterogeneities in atmospheric rivers affecting the western United States. *Proceedings of the*
769 *National Academy of Sciences of the United States of America*, 115(5), 891–896.
770 <https://doi.org/10.1073/pnas.1717883115>
771