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Article

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Attribution of storm track activity to
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Abstract

North Pacific storm track activity exhibits a widely-known, but counterintuitive, midwinter minimum, given its phasing with the strongest baroclinicity and jet stream. Previous studies mainly built their arguments on climatological-mean jet properties. However, these mean states are compiled from averages over various instantaneous jet states. To disentangle the nature of the mean jet, we classify instantaneous jets into “subtropical” (STJ) and “polar-front” (PFJ) jets and examine their seasonal frequency and associated eddy activity. During midwinter in the North Pacific, STJs dominate while PFJs are infrequent, yielding the climatologically “merged jet”. Typical eddy amplitudes are comparable for STJ- and PFJ-dominant conditions, even though STJs feature a higher baroclinicity. Furthermore, midwinter suppression of eddy amplitude is more pronounced under PFJ conditions. These results indicate that the “midwinter minimum” reflects the seasonal variation and geographic progression of instantaneous jet states, highlighting the importance of utilizing instantaneous jet states to better understand climatological signals.

Keywords: storm track, transient eddies, jet stream, midwinter minimum, midwinter suppression, North Pacific, baroclinicity

047 Introduction

048
049 Given the fundamental role of midlatitude storm tracks in the climate system^{1,2},
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051 featuring cyclones, anticyclones, and extremes, their seasonality and regional char-
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053 acteristics are of great scientific and societal importance. Generally, storm track
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055 activity increases with baroclinicity, consistent with linear baroclinic theory³. How-
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057 ever, while North Atlantic storm track activity peaks midwinter, coincident with the
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059 strongest jet^{4,5}, North Pacific storm track activity exhibits a distinct midwinter mini-
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061 mum (MWM) when the jet is strongest⁴. This counterintuitive phenomenon triggered
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063 numerous studies proposing different mechanisms, including too fast eddy translation
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065 due to excessive jet speed⁴, trapping of upper-level eddies into a jet core away from
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067 the near-surface baroclinic zones⁶, barotropic effects⁷⁻⁹, suppression of anticyclonic
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069 activity¹⁰, properties of the climatological-mean jet^{5,11,12}, and orographic effects¹³.
070
071 Despite these efforts, the mechanisms underlying the MWM still remain elusive. Given
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073 that local eddy energetics indicate that the MWM is caused by multiple mechanisms¹⁴,
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075 we present an attribution analysis onto distinct synoptic jet conditions to further
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077 disentangle the climatological signal.

078
079 In the last decade, efforts have been made to interpret and understand the MWM
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081 by linking the time-mean, Eulerian perspective and the instantaneous, Lagrangian
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083 perspective^{10,15-19}. Separating seasonal and sub-seasonal timescales, a recent study
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085 found that the relationship between eddy activity and jet speed differs on seasonal and
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087 sub-monthly timescales, with seasonal-scale variability dominating in the midwinter
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089 North Pacific jet, whereas sub-monthly variability stands out in the North Atlantic
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091 jet²⁰. These differences arise from the distinct nature of the two types of jets^{21,22}—
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093 the more "subtropical-like" or "merged" Pacific jet^{6,11} and the "eddy-driven" Atlantic
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095 jet²³. The former is more tightly constrained by the edge of the Hadley circulation
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097 and the East Asian trough associated with tropical heating^{21,24}, as well as orographic

forcing^{13,25}, while the latter is more strongly influenced by transient eddy feedback on sub-monthly timescales.

One limitation of most of the considerations above is that they are based on the characteristics of climatological-mean jets. The mean jet, however, is a statistical average of different jet states, with distinct structures and characteristics that vary in time and space. Thus, identifying the connection between instantaneous and climatological jet states will shed new light on our understanding of the MWM.

Using a recently developed objective identification of instantaneous subtropical and polar-front jets (STJs and PFJs, respectively)^{26–28}, it was shown that the "merged" nature of the climatological wintertime North Pacific jet arises from the temporal average of distinct instantaneous STJs and PFJs²⁸. We utilize this methodology to examine the intra-seasonal evolution of these distinct instantaneous jet types in conjunction with storm track activity to provide a new perspective on the MWM in North Pacific storm track activity.

Results

Seasonality of STJ and PFJ occurrence

The wintertime North Pacific is characterized by higher occurrence of STJs compared to PFJs²⁷ (Figs. 1a–b), yielding the "subtropical-like", "merged" characteristic of the climatological-mean Pacific jet^{6,11}. STJs are frequently observed along the climatological-mean jet core region around Japan, while PFJs tend to appear downstream and are geographically more widely distributed. The occurrence of STJs peaks in midwinter, with STJ dominance (see Methods for definition) occurring about seven times more frequently than PFJ dominance, though diminishing rapidly into spring (Fig. 1c). In April, the probability of PFJs is comparable to that of STJs, even around the climatological-mean jet core region. Thus, the "subtropical-like", "merged" nature

of the climatological-mean jet in the midwinter North Pacific can be understood as the predominance of STJs over PFJs.

The progression of jet-state predominance in the North Pacific clearly contrasts with the steady predominance of PFJs over STJs throughout the cold season in the North Atlantic (Fig. 1d), yielding the “eddy-driven” nature of the climatological-mean North Atlantic jet^{11,23}. The occurrence of STJ dominance in the North Atlantic is nearly zero, except for a value of approximately 10% in November (Fig. 1d).

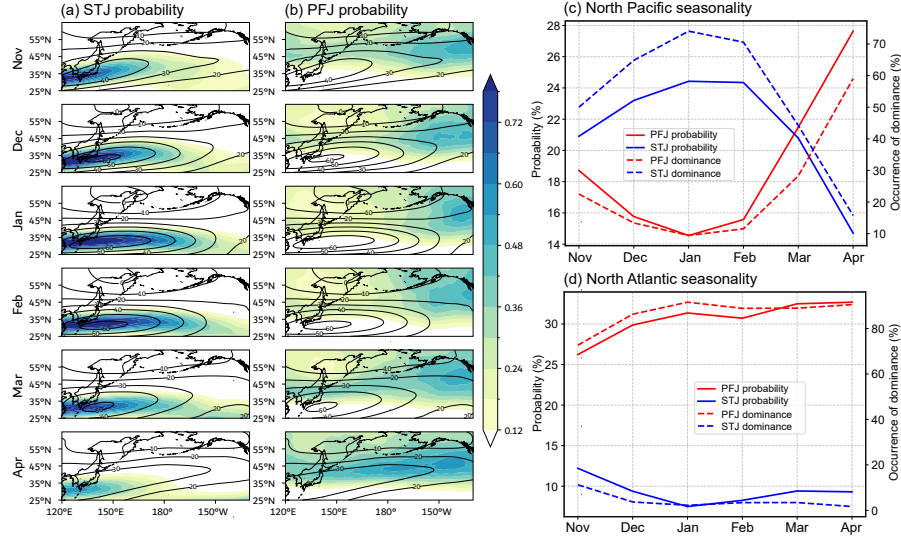


Fig. 1 (a) Climatological-mean STJ probability M_{STJ} (color). Black contours denote climatological-mean zonal wind speed at 300 hPa (m/s). (b) Same as in (a), but for PFJs (M_{PFJ}). (c) Seasonality of climatological-mean $[P_{STJ}]$ and $[P_{PFJ}]$ in $[120-180^{\circ}E, 20-60^{\circ}N]$ (solid lines) and corresponding occurrence of dominance of PFJs and STJs (D_{STJ} and D_{PFJ} ; dashed lines) in the North Pacific domain. (d) Same as in (c), but for the seasonality in the North Atlantic. $[P_{STJ}]$ and $[P_{PFJ}]$ are averages in $[90-30^{\circ}W, 25-65^{\circ}N]$.

Background states associated with STJs and PFJs

To disentangle how these distinct jet states relate to the large-scale background state, we define the background state as a composite of low-pass-filtered upper-level wind and lower-level temperature based on jet dominance (see Methods for details).

The North Pacific background state features faster westerlies under STJ dominance compared to PFJ dominance, particularly in midwinter (Fig. 2), while the overall configurations of the westerlies and low-level baroclinic zones bear some similarity. In addition, the negative signal in the STJ–PFJ difference north of the climatological jet core regions suggests that the mean Pacific jet also tends to be narrower under STJ dominance compared to PFJ dominance (Fig. 2c). In midwinter, the core of the background westerlies associated with both jet types is located equatorward of the low-level baroclinic zone, with the latter oriented along the oceanic frontal zone^{6,29}. Similar results are obtained with jet masking, except for the wind speeds being more comparable in April (Fig. S1).

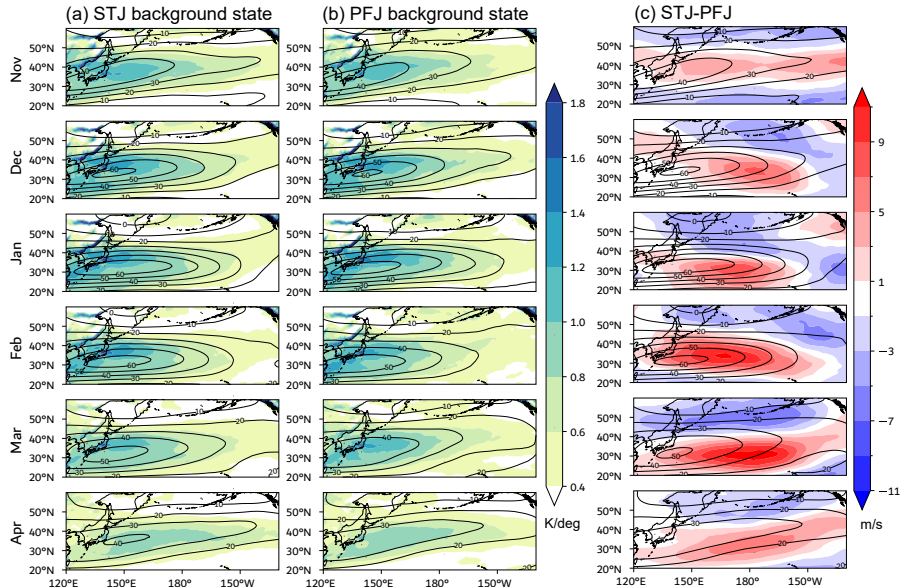


Fig. 2 (a) Composites background 300-hPa zonal wind speed ($\overline{U_{300}^{*STJ}}$) (black contours; m/s) and 850-hPa meridional temperature gradient ($\frac{dT_{850}^{*STJ}}{dy}$) (color, K/100 km) for STJ-dominant conditions. (b) Same as in (a), but for PFJs ($\overline{U_{300}^{*PFJ}}$ and $\frac{dT_{850}^{*PFJ}}{dy}$). (c) Difference in composites background 300-hPa zonal wind speed ($\overline{U_{300}^{*STJ}} - \overline{U_{300}^{*PFJ}}$) (colors, m/s). Black contours denote climatological-mean 300-hPa zonal wind speed (m/s).

Thus, the STJ-associated background state during North Pacific winter exhibits a faster and narrower westerly jet compared to that associated with PFJs, with the STJ-associated background state shaping the climatological-mean subtropical-like, faster Pacific jet in midwinter due to the STJ predominance. Given the relatively lower variability of North Pacific jet states on timescales of 5-10 days compared to the North Atlantic (Fig. S2), the midwinter predominance of STJ occurrence is consistent with weaker sub-monthly variability of the North Pacific westerlies compared to the North Atlantic²⁰.

Eddy activity associated with STJs and PFJs

When transient eddy activity is composited onto the distinct jet-dominance states (see Methods), amplitudes in the wintertime North Pacific are roughly comparable, with a similar distribution under STJ and PFJ dominance (Fig. 3a-d), although the STJ-associated background state exhibits significantly stronger westerlies than the PFJ-associated background state (Fig. 2). Around the storm track core region, low-level eddy amplitude under STJ dominance is even weaker than that under PFJ dominance throughout the winter (Fig. 3e). Thus, even though more frequent STJs in the midwinter North Pacific result in an excessively strong, “subtropical-like” climatological-mean jet, these conditions do not contribute to a midwinter increase in eddy activity, yielding the midwinter “suppression” of North Pacific eddy activity. Hence, the midwinter North Pacific eddy activity is mostly associated with STJ-dominant conditions, in contrast to the overwhelming contribution of PFJs to the North Atlantic eddy activity (Fig. S3).

Potential reasons for the relative inefficiency of STJs in supporting comparable eddy amplitudes to those under PFJ dominance include a greater tropopause height associated with STJs, inhibiting the development of vertically coupled baroclinic eddies⁶, as well as a narrower jet and associated stronger horizontal shear suppressing

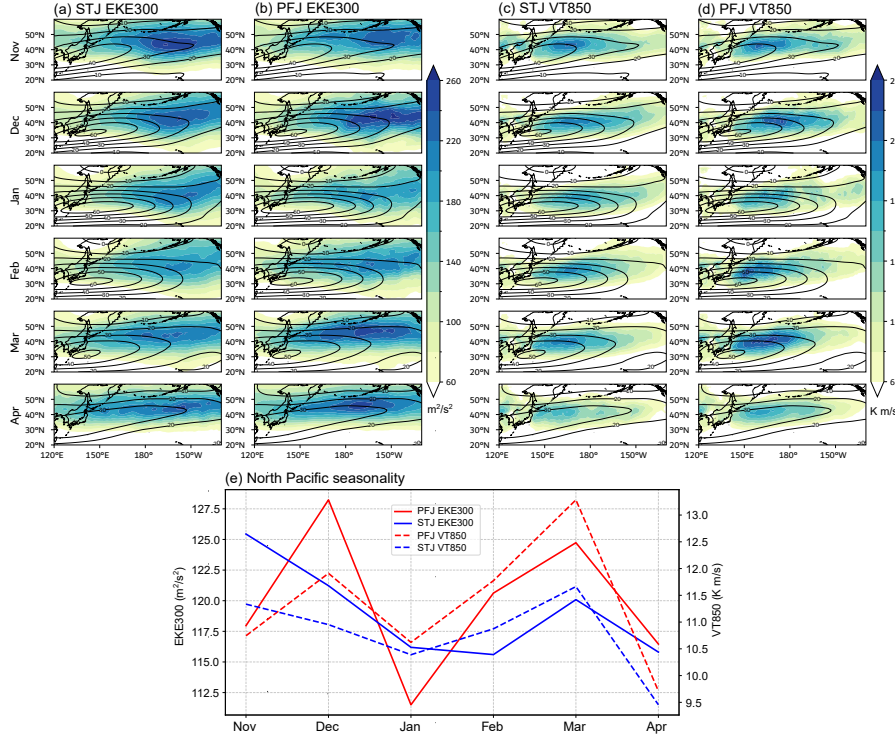


Fig. 3 (a) Climatological-mean typical EKE_{300} (m^2/s^2) under the STJ-dominant conditions ($\overline{EKE_{300}^{STJ}}$). Black contours denote climatological-mean 300-hPa zonal wind speed (m/s). (b) Same as in (a), but for PFJs ($\overline{EKE_{300}^{PFJ}}$). (c-d) Same as in (a-b), respectively, but for $V'T'_{850}$ ($\overline{V'T'_{850}^{STJ}}$ and $\overline{V'T'_{850}^{PFJ}}$). (e) Seasonality of climatological-mean EKE_{300}^* and $V'T'_{850}^*$ in the North Pacific as indicated. Domains for EKE_{300} and $V'T'_{850}$ are $[130^\circ E-130^\circ W, 20-65^\circ N]$ and $[150-180^\circ E, 25-55^\circ N]$, respectively.

eddy activity, referred to as the "barotropic governor" effect^{7,8}. Note that the effects of f and β ³⁰ for STJ- and PFJ-dominant conditions likely have only a secondary role in the growth of eddies, given the similar latitudes of the cores of the STJ- and PFJ-associated background westerlies (Fig. 2).

Interestingly, typical eddy amplitudes in both the upper and lower troposphere exhibit a more pronounced reduction during midwinter under PFJ dominance (Fig. 3e) compared to STJ dominance, providing an additional contribution to the midwinter "minimum" of the North Pacific eddy activity. Presumably, this is related to the

equatorward migration of the PFJ-associated background westerlies, leading to a narrower jet in midwinter (Fig. 2). This is likely an additional factor contributing to the midwinter “minimum” of the North Pacific eddy activity.

The more pronounced midwinter reduction in eddy amplitude is also obtained by compositing using a jet masking technique (Fig. 4, see Methods). While low-level eddy amplitudes are roughly comparable between STJs and PFJs, upper-level eddy amplitudes tend to be greater along PFJs compared to STJs (Fig. 4e). This is most likely related to the occurrence of PFJs downstream of the jet core regions (Fig. 1) aligning more with the upper-level eddy amplitudes (Fig. 3a,b).

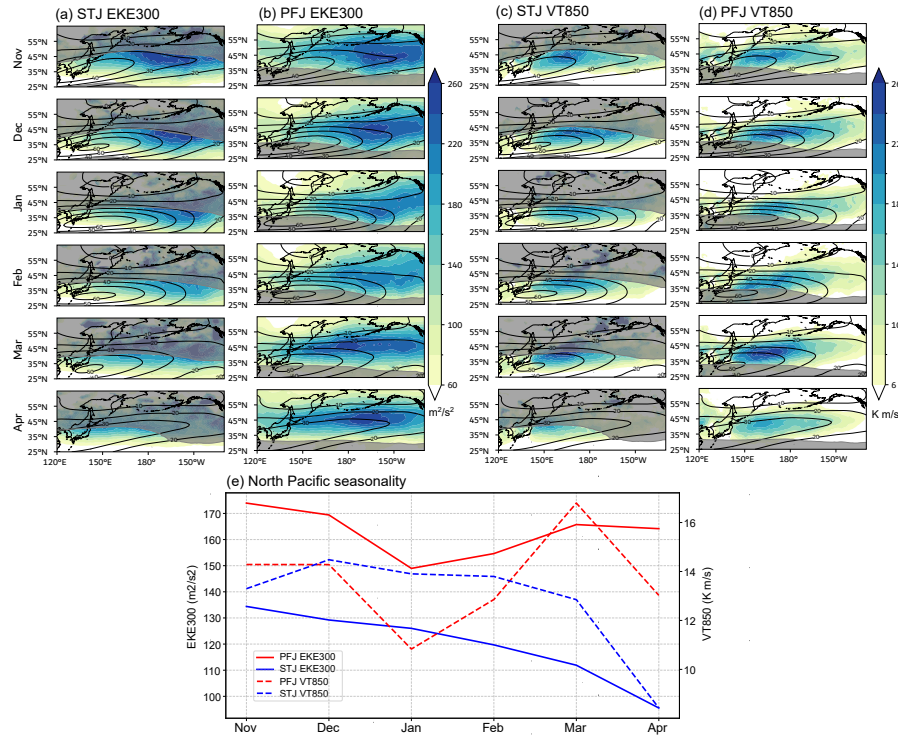


Fig. 4 (a) Climatological-mean EKE_{300} (m^2/s^2) for regions of STJ masking ($\overline{EKE_{300STJ}}^{M*}$). Black contours denote climatological-mean 300-hPa zonal wind speed (m/s). (b) Same as in (a), but for PFJs ($\overline{EKE_{300PFJ}}^{M*}$). (c-d) Same as in (a-b), respectively, but for $V'T'_{850}$ ($\overline{V'T'_{850STJ}}^{M*}$ and $\overline{V'T'_{850PFJ}}^{M*}$). (e) Seasonality of climatological-mean $\overline{EKE_{300}}^{M*}$ and $\overline{V'T'_{850}}^{M*}$ in the North Pacific as indicated. Domains for EKE_{300} and $V'T'_{850}$ are $[130^\circ E-130^\circ W, 20-65^\circ N]$ and $[150-180^\circ E, 25-55^\circ N]$, respectively.

Discussions and Concluding remarks	369
	370
Utilizing a recently developed scheme detecting instantaneous “subtropical” and	371
“polar-front” jets (STJs and PFJs, respectively) to attribute midlatitude Eulerian	372
eddy statistics to different feature-based jet states, we propose a new interpretation	373
of the relationship between the North Pacific wintertime jet stream and storm track	374
activity.	375
	376
Compositing upper-level wind for STJ and PFJ-dominant states, the “subtropical-	377
like”, “merged” nature of the climatological-mean jet in the midwinter North Pacific	378
can be interpreted as the predominance of STJs over PFJs, while the North Atlantic	379
is dominated by PFJs throughout the entire winter. In midwinter, the STJ-associated	380
background state in the North Pacific features a substantially faster and narrower jet	381
than its PFJ counterpart. However, despite the stronger STJ-associated background	382
westerlies, eddy amplitudes do not vary and remain comparable to PFJ-dominant	383
conditions. While this discrepancy could be interpreted as a midwinter “suppression”	384
of North Pacific eddy activity, it instead points to the “dominant subtropical” or	385
“merged” nature of the climatological-mean Pacific jet, as also pinpointed by previous	386
studies ^{11,12} . Thus, ascribing the climatological-mean jet to the more frequent occur-	387
rence of instantaneous subtropical jets provides a process-based explanation for the	388
midwinter minimum of North Pacific storm track activity, as the subtropical jet is less	389
efficient in supporting eddy instabilities.	390
	391
We identified a slight midwinter reduction in eddy activity for PFJ-dominant	392
states, likely contributing to the midwinter “minimum” in North Pacific eddy activ-	393
ity. This reduction is likely related to narrower midwinter PFJs, featuring stronger	394
horizontal shear that acts to inhibit growth of baroclinic eddies ^{7,8} . STJ-dominant	395
conditions are also characterized by a higher relative frequency of instantaneous	396
cyclonic regions compared to anticyclonic regions when compared to PFJ-dominant	397
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415 conditions³¹ (Fig. S4), possibly contributing to the "anticyclonic suppression" in the
416
417 MWM¹⁰.

418 Thus, overall we demonstrate that the "midwinter minimum" in the North Pacific
419
420 reflects the seasonal variation and geographic progression of instantaneous jet states,
421
422 highlighting the added value of investigating the variability of instantaneous jet states
423
424 for understanding the climatology and seasonality of storm tracks. Our method could
425
426 also provide new insights into the mechanisms underlying biases of climatological-mean
427
428 jets and storm tracks in climate models.

Methods

Atmospheric reanalysis. We analyze 6-hourly and monthly global fields of atmospheric variables obtained from the ECMWF Reanalysis v5 (ERA5³²) for the period 1979–2022, including air temperature (T), as well as zonal and meridional wind velocities (U and V, respectively) in pressure coordinates. We use a 1°x1° horizontal resolution of the ERA5 data with 37 pressure levels.

Transient eddy and background statistics. As a measure of transient eddy activity, we evaluate eddy poleward heat transport at 850 hPa ($V'T'_{850}$) and eddy kinetic energy ($EKE \equiv (U'^2 + V'^2)/2$) at 300 hPa (EKE_{300}), where primes denote 8-day-high-pass-filtered fluctuations with a 121-point Lanczos filter^{14,33}. The background is defined as the 8-day low-pass filtered field.

Instantaneous jet detection. We objectively identify instantaneous jet axes based on a recently developed method^{26,27}, where jet axes are defined as lines separating cyclonic from anticyclonic wind shear in the two-dimensional flow field on the dynamic tropopause, defined as the 2PVU-surface (i.e., the surface where $PV = 2 \times 10^{-6} \text{m}^2 \text{s}^{-1} \text{Kkg}^{-1}$). In addition, we separate STJs and PFJs using a jet core isentropic temperature threshold of 335 K²⁸.

Jet probability and dominance. Jet probability is based on the jet masking

$$M_{\text{STJ/PFJ}}(x, y, t) = \begin{cases} 1 & \text{if distance from } (x, y) \text{ to nearest STJ/PFJ axis} \leq 500 \text{ km,} \\ 0 & \text{else.} \end{cases} \quad (1)$$

If both STJ and PFJ satisfy this condition, the type of the closest jet is kept.

Jet dominance is defined by comparing the area averages $[M_{\text{STJ/PFJ}}]$ of the STJ and PFJ masking within the domains [120–180°E, 20–60°N] and [90–30°W, 25–65°N] for

507 the North Pacific and Atlantic, respectively, such that

$$508$$

$$509$$

$$510 \quad D_{\text{STJ/PFJ}}(t) = \begin{cases} 1 & \text{if } [M_{\text{STJ/PFJ}}(x, y, t)] \geq 12.5\% \text{ and} \\ 511 & [M_{\text{STJ/PFJ}}(x, y, t)] - [M_{\text{PFJ/STJ}}(x, y, t)] \geq 4\%, \\ 512 & 0 \quad \text{else.} \end{cases} \quad (2)$$

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516 Note that our key conclusions are insensitive to the choice of the distance threshold
 517 for jet masking (e.g., Figs. S5 and S6 with a threshold of 200 km).
 518

519 **Eddy statistics, typical eddy amplitude, and background states asso-**
 520 **ciated with jet types.** Instantaneous fields include both eddy and background
 521 components. To circumvent the difficulty of separating these two components, we
 522 mainly evaluate eddy statistics and background states associated with STJs and PFJs
 523 according to their dominance.
 524

525 Climatological-mean eddy and background state statistics based on jet dominance
 526 $\bar{X}$ are computed by accumulating instantaneous eddy or background fields $X(x, y, t)$
 527 (e.g., $V'T'_{850}$ or low-pass filtered wind) as:
 528

$$529 \quad \bar{X}_{\text{STJ/PFJ}}(x, y) = \frac{\sum_{t_0}^{t_N} X(x, y, t) D_{\text{STJ/PFJ}}(t)}{N}, \quad (3)$$

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535 where the overbar denote temporal averaging over all time steps N . Furthermore,
 536 we evaluate typical eddy amplitude $\bar{X}^*$ by dividing these climatological-mean jet-
 537 associated statistics by the corresponding occurrence of jet dominance
 538

$$539 \quad \bar{X}_{\text{STJ/PFJ}}^*(x, y) = \frac{\sum_{t_0}^{t_N} X(x, y, t) D_{\text{STJ/PFJ}}(t)}{\sum_{t_0}^{t_N} D_{\text{STJ/PFJ}}(t)}, \quad (4)$$

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Similarly, we used the jet masking to calculate climatological-mean eddy and background state statistics $\bar{X}^M$

$$\bar{X}_{\text{STJ/PFJ}}^M(x, y) = \frac{\sum_{t_0}^{t_N} X(x, y, t) M_{\text{STJ/PFJ}}(x, y, t)}{N} \quad (5)$$

and typical amplitudes $\bar{X}^{M*}$

$$\bar{X}_{\text{STJ/PFJ}}^{M*}(x, y) = \frac{\sum_{t_0}^{t_N} X(x, y, t) M_{\text{STJ/PFJ}}(x, y, t)}{\sum_{t_0}^{t_N} M_{\text{STJ/PFJ}}(x, y, t)}. \quad (6)$$

Even though the statistics based on jet masking include both eddy and background components, they nevertheless provide valuable insights into eddy activity and the composition of the background state along STJs and PFJs.

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Supplementary information. Figures S1–S6 are shown in the separate Supplementary Information.

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791 **Competing interests**

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794 All authors declare no financial or non-financial competing interests.

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797 **Data availability**

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799 The ERA5 data on pressure levels used in this study are publicly available from
800 the Copernicus Climate Change Service (C3S) Climate Data Store (CDS) at
801 <https://doi.org/10.24381/cds.bd0915c6>.
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806 **Code availability**

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808 The jet axis detection algorithm is available as part of Dynlib, a library of meteoro-
809 logical analysis tools (<https://doi.org/10.5281/zenodo.10471187>). Other code used for
810 the analyses in this study is available from the corresponding author upon reasonable
811 request.
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