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Changes in the North Pacific jet stream in recent decades

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Abstract Changes in the path and intensity of jet streams have major impacts on regional weather and climate patterns. We investigated changes in the intensity, meridional position, and altitude of the North Pacific jet in different seasons during the period 1979-2020 using the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis 5th Generation (ERA5) dataset. Our analysis indicates that the intensity and the meridional position of the North Pacific jet exhibit a pronounced seasonal cycle, with the most intense core of the jet in winter and its equatorward shift from 32.75 °N in winter to around 40.75 °N in summer. The jet also has a relatively large latitudinal spread in spring compared to the other seasons. The North Pacific jet has only weakened over the Yellow Sea in summer during the period 1979-2020. Maximum upper-tropospheric wind speeds have intensified over the Sea of Japan in winter in response to the poleward shift of the jet but weakened in spring due to the equatorward shift of the jet. Indeed, the jet has shifted poleward over the far western (125-140 °E) and central (180°-150 °W) North Pacific in winter, but the poleward shift of the jet is smaller over the far western North Pacific where the jet is stronger. This suggests that there might be a link between the speed of the North Pacific jet and the magnitude of its longitudinal poleward shifting variability. The jet has also shifted poleward over the central-eastern North Pacific (135-155 °W) in summer, while changes in the altitude of the North Pacific jet have been insignificant during the period 1979-2020. The identified changes in the characteristics of the North Pacific jet have important implications for the understanding of weather patterns and the frequency of extreme events in the North Pacific and nearby regions.

Keywords: jet stream; North Pacific; weather patterns; extreme events; seasonal cycle

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1 Introduction

Synoptic-scale disturbances, which are expressed as surface storm tracks, tend to develop in the vicinity of jet streams and propagate downstream along the jet axes (Holton, 1992). Hence, jet streams or fast meandering winds have a big impact on weather patterns (Ruti *et al.*, 2006), but the relationship between the activity of synoptic-scale disturbances and the jet stream strength is not straightforward (Nakamura, 1992). There are dynamically two different types of jets in the troposphere: the subtropical jet and the subpolar jet. The subtropical jet is often considered as a thermally driven jet that develops at the poleward boundary of the Hadley cell due to the advection of angular momentum by the Hadley circulation (Held and Hou, 1980). This jet is characterized by a strong vertical wind speed shear, such that it is only an upper-tropospheric feature (Woollings *et al.*, 2010). In contrast, the subpolar jet is driven by eddies and results from the convergence of the eddy momentum flux of baroclinic waves in the troposphere (Held, 1975; Panetta, 1993). This jet generally develops from the upper troposphere to near the surface (Woollings *et al.*, 2010).

Unlike the double jet structure in some places such as above the North Atlantic where both a subtropical jet and an eddy-driven jet are often present, a single or a merged jet exists over the North Pacific during most of the year (Eichelberger and Hartmann, 2007; O'Rourke and Vallis, 2013), although the occasional double jet structure has also been observed over the North Pacific (e.g. Newman and Sardeshmukh, 1998; Christenson *et al.*, 2017). The single jet over the North Pacific exhibits the influence of both eddy-driven and thermally-driven processes. In this region, eddy-driven and subtropical jets are generally merged because the region of strongest baroclinicity is located near the latitude of the jet maximum (Li and Wettstein, 2012). As argued by Lee and Kim (2003), when a preexisting subtropical jet is strong, weak baroclinic eddies remain trapped on the poleward flank of the jet, which is the case over the North Pacific. Hence, the large-scale atmospheric circulation in the North Pacific is largely influenced by the tropical atmosphere, including the El Niño-Southern Oscillation (Ren and Xiang, 2008; Li and Wettstein, 2012). On the other hand, when the preexisting subtropical jet is weak, baroclinic eddies contribute to the development of a relatively strong eddy-driven jet, which is well separated from the subtropical jet (Lee and Kim, 2003). This is mainly the case over the North Atlantic where the thermal forcing of the subtropical jet is relatively weak and the large-scale atmospheric circulation is mostly driven by eddies (Li and Wettstein, 2012). Indeed, it is argued that the dominant mode of climate variability over the North Atlantic (i.e. the North Atlantic Oscillation (NAO)) is driven and maintained by eddies (e.g., Franzke *et al.*, 2004; Woollings *et al.*, 2008; Li and Wettstein, 2012).

The characteristics of the subtropical and eddy-driven jets have been largely discussed in previous studies. For example, Nakamura and Sampe (2002) suggested that, under the excessively strong midwinter Pacific jet, eddies tend to be trapped into the high jet core region meridionally away from the baroclinic zone, hindering the vertical connection between eddies in the upper and lower levels. Yuval and Kaspi (2018) pointed out that eddies tend to be stronger when the jet resembles an eddy-driven jet than when it resembles a subtropical jet. Okajima *et al.* (2021) quantified the extent of the eddy-driven characteristics of the Pacific and Atlantic jets by evaluating the acceleration of westerly winds by transient eddy feedback forcing. They pointed out that the westerly wind is mainly decelerated by anticyclonic eddies in the North Pacific jet core.

Due to non-uniform climate warming in recent decades (e.g., Alizadeh and Lin, 2021; Alizadeh and Babaei, 2022), some evidence suggests that the intensity, the latitude position, and the altitude of the North Pacific jet have changed (e.g. Strong and Davis, 2007, 2008). On the other hand, the analysis of Hallam *et al.* (2022) indicates that the meridional position and the speed of the North Pacific jet have not been affected by global warming during the period 1871–2011. They pointed out that the Pacific Decadal Oscillation (PDO) explains 50% of the winter variance in the meridional position of the North Pacific jet since 1940. Changes in the characteristics of the North Pacific jet in response to global warming or climate variability have important impacts on weather patterns. In particular, meridional shifts in jet streams are associated with meridional shifts in storm tracks (Riviére, 2011), and long-term modulation of the storm-track activity in the North Pacific is associated with that of the North Pacific jet stream (Nakamura *et al.*, 2002; Okajima *et al.*, 2022).

Changes in the meridional position of jet streams may be associated with changes in extreme weather events (e.g. Seager *et al.*, 2010). For example, extreme cold weather events over North America and Eurasia in the winter of 2009-10 were associated with a substantial southward displacement of the North Atlantic jet (Seager *et al.*, 2010). Strong marine heatwaves over the northwestern Pacific Ocean in July-August 2021 were also linked to a substantial northward shift of the North Pacific jet (Kuroda and Setou, 2021). Nevertheless, the extent of changes in the characteristics of the North Pacific jet in recent decades needs to be further examined, particularly in different seasons and based on the application of reanalysis data with a relatively high resolution. Hence, we analyzed the intensity, meridional shifting, and altitude of the upper-tropospheric North Pacific jet during the period 1979-2020. As the seasonal cycle influences the characteristics of the jet, including the meridional position of the maximum wind speed (Eichelberger and Hartmann, 2007), we examined changes in the characteristics of the North Pacific jet in different seasons. To do so, we have used the European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis 5th Generation (ERA5) dataset (Hersbach *et al.*, 2020).

2 Data description and methodology

We used the ERA5 monthly mean dataset (Hersbach *et al.*, 2020) for the period 1979-2020 (also referred to as the study period or climatology hereafter) with the horizontal resolution of $0.25^\circ \times 0.25^\circ$, which is sufficient to resolve regional processes in the atmosphere. We obtained monthly means of wind speed based on daily averages, and the daily averages were calculated using data from 0000 and 1200 UTC. The data that were used include wind speed at 10 pressure levels between 400 and 100 hPa (i.e. 400, 350, 300, 250, 225, 200, 175, 150, 125, and 100 hPa), temperature at pressure levels between 1000 and 100 hPa, and pressure at the surface. We obtained the altitude of the maximum wind speed in each grid point based on the following equation (Andrews, 2010):

$$z_2 - z_1 = - \frac{R_a}{g} \int_{p_1}^{p_2} T \, d(\ln P) \quad (1)$$

where p_1 and p_2 are pressure levels at the surface (z_1) and at height z_2 above the surface, R_a is the specific gas constant for dry air (287.05 J kg^{-1} K^{-1}), g is the gravitational acceleration (9.81 m s^{-2}), T is the mean temperature at the two pressure levels (p_1 and p_2) in Kelvin, and P is pressure.

Based on the obtained data, at each longitude and for latitudes between 20 and 70°N, we analyzed wind speed at different vertical levels from 400 to 100 hPa to detect the upper-tropospheric maximum wind speeds, based on which to identify changes in the intensity, meridional position, and altitude of the North Pacific jet during the period 1979-2020. This implies that changes in the altitude of the maximum wind speed in the upper layers are considered. Our approach is similar to Pena-Ortiz *et al.* (2013), except that they filtered out maximum wind speeds less than 30 m s^{-1} with the assumption that maximum winds weaker than this threshold may not be part of any jet structure.

We conducted our analysis for December-January-February (DJF) as winter, March-April-May (MAM) as spring, June-July-August (JJA) as summer, and September-October-November (SON) as autumn. We applied the t-test to examine the significance of changes in wind at the 95% confidence interval (p-value less than 0.05). Based on the location of the jet stream, the analysis over the North Pacific is conducted over the longitude range from 120 °E to 120 °W.

3 Results

3.1 Climatology of the North Pacific jet

Figure 1 shows the climatology of the intensity and location of the North Pacific jet in different seasons based on the ERA5 dataset. The jet is strongest in winter when an eddy-driven jet induced by low-level baroclinicity is combined with a subtropical jet induced by tropical convective outflow (Eichelberger and Hartmann, 2007; Jaffe *et al.*, 2011; Christenson *et al.*, 2017), but followed in decreasing order by spring, autumn, and summer when the low-level baroclinicity weakens (Nakamura, 1992). The seasonal cycle of the jet latitude is also relatively large. In winter, the core of the North Pacific jet is at around 32.75°N, while the jet broadens and extends further to the east in spring (Figure 1a-b). In autumn and summer, the jet shifts considerably poleward compared to winter and spring, such that its core is located at around 41.0 °N and 40.75 °N, respectively. In summer, the North Pacific jet is also extended eastward and its meridional width is much narrower than in the other seasons. Hence, the North Pacific jet is much weaker and shifts greatly poleward during warmer seasons, as previously identified in many studies (e.g. Hallam *et al.*, 2022). The poleward shift of the jet stream in warmer seasons of the year has great impacts on the regional weather and climate of the North Pacific and nearby regions.

We also analyzed the climatology of the altitude of the upper-tropospheric maximum wind speed in the North Pacific in different seasons (Figure 2). In winter, the maximum wind speed across the North Pacific occurs at around 11.3-12 km. In spring, the altitude of the maximum upper-tropospheric wind speed is located at around 12.5 km in the western and far eastern North Pacific, while it is at around 11.2 km just east of the dateline. In summer and autumn, the altitude of the maximum wind speed decreases from the western to the eastern North Pacific, such that it is located at around 12.3 km in the western and around 10.3 (spring) to 11.3 km (summer) in the eastern North Pacific.

3.2 Changes in the characteristics of the North Pacific jet

We analyzed changes in the meridional position of the core of the North Pacific jet in different longitudes and seasons during the period 1979-2020 (Figure 3). In winter, the jet has shifted poleward in most longitudes over the North Pacific, with a value of around 0.2 $^{\circ}$ decade^{-1} from the far western to the dateline, but higher values of around 1.5° decade^{-1} at around 150-170 $^{\circ}$W (Figure 3a), which is the east of the climatological extent of the wintertime jet core (Figure 1a). The poleward shift of the North Pacific jet in winter is only significant in the far western (125-140°E) and central (180°-150°W) North Pacific. In spring, in most longitudes over the North Pacific, the jet has shifted equatorward, with the highest shift of around 2° decade^{-1} between around 160-170 $^{\circ}$W, which is the east of the climatological extent of the springtime jet core (Figure 1b). In contrast, the North Pacific jet is shifted poleward between around 130-140°W, although the shift in most longitudes (except at around 130 $^{\circ}$E) is not statistically significant (Figure 3b). Summer is characterized by a significant poleward shift of the North Pacific jet at around 135-155 $^{\circ}$W (hereafter referred to as the central-eastern North Pacific) (Figure 3c). In autumn, the meridional position of the North Pacific jet has not changed significantly (Figure 3d). Overall, the poleward shift of the jet is significant over the far western and east of the dateline in winter, as well as over the central-eastern North Pacific in summer. The poleward shift of the jet in these seasons, however, is smaller over the far western North Pacific (Figure 3a, d) where the jet is stronger (Figure 1). This suggests that there might be a link between the speed of the North Pacific jet and the magnitude of its longitudinal poleward shifting variability, as outlined by Woollings *et al.* (2018).

Figure 4 shows changes in the intensity of the upper-tropospheric maximum wind speed in different seasons during the study period. In winter, maximum wind speeds in lower (approximately 20-33 $^{\circ}$N) and higher (approximately 35-50 $^{\circ}$N) latitudes of the North Pacific have weakened and intensified, respectively (Figure 4a). In terms of statistically significant changes, however, the maximum upper-tropospheric wind speeds have significantly increased over east of North China, North and South Korea, the Sea of Japan, and western Japan. Considering the location of the jet stream (Figure 1a), Figure 3a suggests that an increase in the maximum wind speed over these regions is due to a poleward shift of the jet in winter during the study period. The upper-tropospheric maximum wind speeds have also significantly increased in high latitudes (45-50 $^{\circ}$N) over and east of the dateline (145-170 $^{\circ}$W). In contrast, in lower latitudes of the North Pacific (20-30 $^{\circ}$N), near and east of the dateline (180 $^{\circ}$-165 $^{\circ}$W), the upper-tropospheric maximum wind speeds have significantly decreased. This result is consistent with a poleward shift of the jet at these longitudes. While not investigated here, this could be caused by a reduced poleward transport of angular momentum in the Hadley circulation in association with a poleward shift of the intertropical convergence zone (ITCZ) (Hilgenbrink and Hartmann, 2018). In spring, the upper-tropospheric maximum wind speeds have significantly decreased over the Sea of Japan (Figure 4b), which based on the location of the jet stream (Figure 1b), is due to an equatorward shift of the jet in this region (Figure 3b). In summer when the North Pacific jet is remarkably weaker (Figure 1), changes in the upper-tropospheric maximum wind speeds are not statistically significant over most regions of the North Pacific (Figure 4c). In autumn, the jet has weakened significantly from the South Yellow Sea across the North subtropical Pacific to near the central Pacific at 170 °W (over the latitude range from 31 to 35 °N) (Figure 4d). As the meridional shift of the jet over these regions has not been significant during the study period (Figure 3d), the weakening of the upper-tropospheric wind speeds over these regions in autumn is not related to the meridional shift of the jet.

Our analysis indicates that the intensity of the North Pacific jet has decreased mostly across the North Pacific in all seasons, with the highest decrease between around 180° to 150 °W in winter and spring, while in summer, the highest decrease is in the western North Pacific (Figure 5). This is in contrast to the results of Strong and Davis (2007) who analyzed the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis data and found that the subtropical jet over the western and central North Pacific had intensified during the period 1958-2007. In autumn, a relatively similar decrease in the intensity of the North Pacific jet is visible from the western North Pacific to around 160 °W, while the jet is less weakened further eastward of the North Pacific. In summer, the jet stream has also weakened over the far western and near the dateline of the North Pacific. Nevertheless, the weakening of the jet stream over none of the abovementioned regions in different seasons is statistically significant, except over the Yellow Sea in summer. In contrast, the jet stream is slightly intensified at around 130 °E in winter and spring, and in the central-eastern North Pacific in summer, but none of these changes is statistically significant.

In winter, the North Pacific jet has risen mostly across the North Pacific in response to the rising of the tropopause under global warming in recent decades (Meng *et al.*, 2021), except over the eastern North Pacific where the altitude of the jet has declined (Figure 6a). However, the rising of the jet stream in winter is statistically significant only in some limited regions over the North Pacific (around 130-135 °E and 160-170 °E) (Figure 6a). In spring, depending on the longitude, both decreases and increases in the altitude of the North Pacific jet have occurred, but only a decrease and an increase of its altitude are statistically significant over the Yellow Sea and at around 165 °E, respectively (Figure 6b). In summer, the jet stream in most regions of the North Pacific has risen during the study period, except over the Yellow Sea and central-eastern North Pacific, although in most regions, the changes are statistically insignificant (Figure 6c). In autumn, both increases and decreases in the altitude of the North Pacific jet in different longitudes are detected, but the changes are small and mostly insignificant (Figure 6d). Overall, changes in the altitude of the North Pacific jet in recent decades are mostly statistically insignificant. We have also analyzed changes in the zonal jet stream flow over the North Pacific (not shown), which show quite similar patterns to those provided in Figures 3 to 5.

4 Conclusions

We investigated the climatology and changes in the intensity, meridional position, and altitude of the North Pacific jet in different seasons during the period 1979-2020 using the ERA5 data. A pronounced seasonal cycle is identified for both the strength and meridional position of the North Pacific jet, with the highest (47.5 m s^{-1}) and lowest (26.8 m s^{-1}) intensity in winter and summer, respectively. The poleward shift of the North Pacific jet from colder to warmer seasons is also notable, such that the jet stream core lying on average 8.0° further north in summer than in winter. The jet stream also has a relatively large latitudinal spread in spring and extends further to the east in spring and particularly summer compared to the other seasons. Hence, the seasonal cycle of the intensity and meridional position of the North Pacific jet is relatively large.

The North Pacific jet has weakened in all seasons during the period 1979-2020, but the weakening of the jet is mostly insignificant, except over the Yellow Sea in summer. Statistically significant weaker jets are more likely to be wavy in the north-south path, which generally favors persistent weather patterns and more frequent blocking events (e.g., Francis and Vavrus, 2015; Alizadeh and Ghafarian, 2023; Ahmadi and Alizadeh, 2023). Hence, wavy jets have important implications for the occurrence of more weather extremes including heavy precipitation and heatwaves, as well as more air pollution episodes (Woollings *et al.*, 2018), which remain to be investigated in future studies.

The maximum upper-tropospheric wind speed has significantly intensified in winter but weakened in spring over the Sea of Japan during the study period in response to poleward and equatorward shifts of the North Pacific jet, respectively. Indeed, the poleward shift of the jet has been significant over the far western and central North Pacific in winter, as well as over the central-eastern North Pacific in summer. The poleward shift of the jet, however, is much smaller over the far western North Pacific where the jet is stronger. Hence, there is an inverse relationship between the jet speed and the degree of its poleward shift in the North Pacific, similar to the results of Woollings *et al.* (2018). The altitude of the North Pacific jet has not changed significantly.

The obtained results in this study are only based on the analysis of the ERA5 data, and the robustness should be tested in future studies using other reanalysis data and model simulations. In addition, it is unclear whether the discussed changes in the characteristics of the North Pacific jet are a response to global warming, multidecadal variations, or a combination of both. The dynamic behind the poleward shift of the North Pacific jet in recent decades, particularly in winter, is also left as a subject for future research. Further research is also required to understand the dynamic reason behind a smaller poleward shift of the jet over the far western North Pacific where the jet is stronger.

Author Declarations

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Competing interests

The authors declare no competing interests.

Ethics approval/declarations

Not applicable.

Consent to participate

Not applicable.

Consent for publication

The authors consent to the publication of the manuscript, should the article be accepted by the Editor-in-chief upon completion of the refereeing process.

Data availability

We obtained the ERA5 data from the ECMWF data server on pressure levels at `https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-pressure-levels?tab=form` and on single levels at `https://cds.climate.copernicus.eu/cdsapp#!/dataset/reanalysis-era5-single-levels?tab=form`.

Authors' contributions

Omid Alizadeh: Conceptualization; methodology; investigation; formal analysis; visualization; writing the original draft; review and editing
Morteza Babaei: Methodology; investigation; visualization

Code availability

The open-source NCAR Command Language (NCL) codes were used in this study and they are available upon request from the corresponding author (omid.alizadeh@ut.ac.ir).

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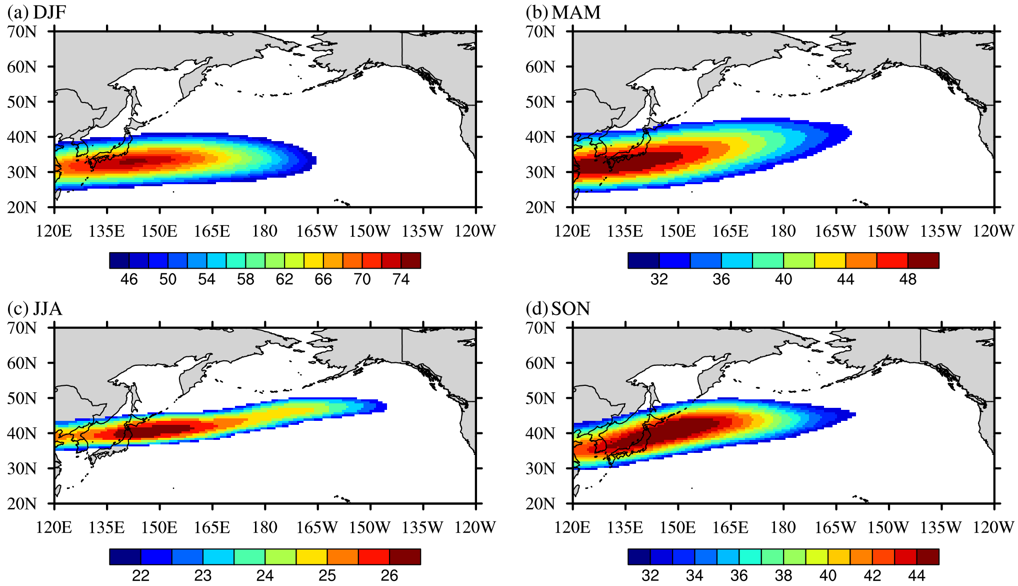

Fig. 1. The climatology (1979-2020) of the maximum wind speed (m s^{-1}) in the upper troposphere (400 to 100 hPa) over the North Pacific in different seasons. Wind speeds smaller than certain values (as can be inferred from the label bars) are masked to better highlight the location and intensity of the jet stream. Note the different label bars in the panels.

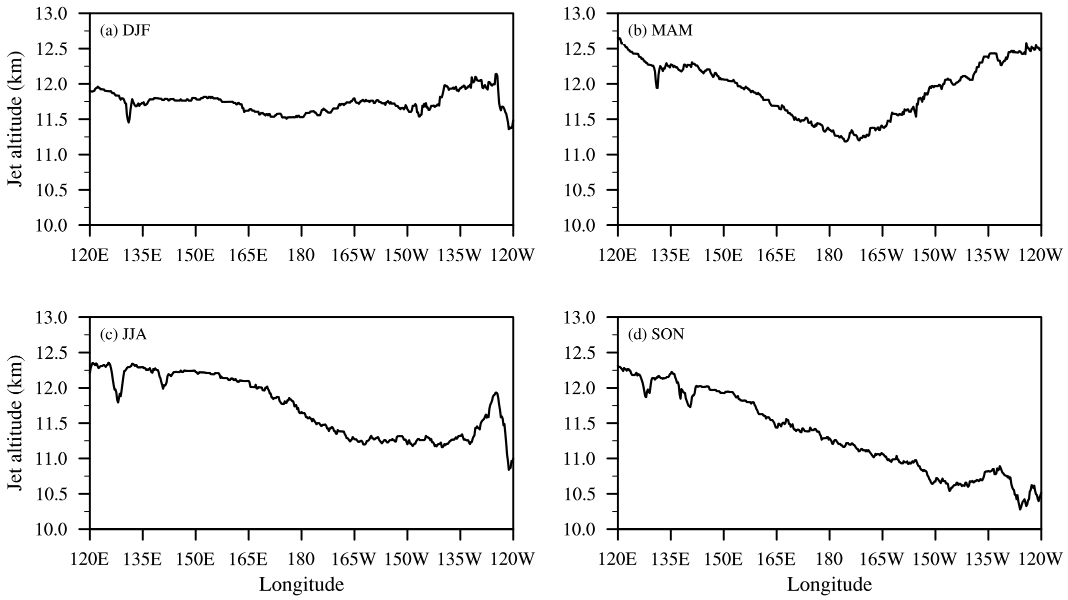

Fig. 2. The climatology (1979-2020) of the altitude (hPa) of the upper-tropospheric maximum wind speed across the North Pacific in different longitudes and seasons. We analyzed wind speeds from 400 to 100 hPa pressure levels at different latitudes (20-70 °N) to obtain altitudes of the maximum upper-tropospheric wind speeds.

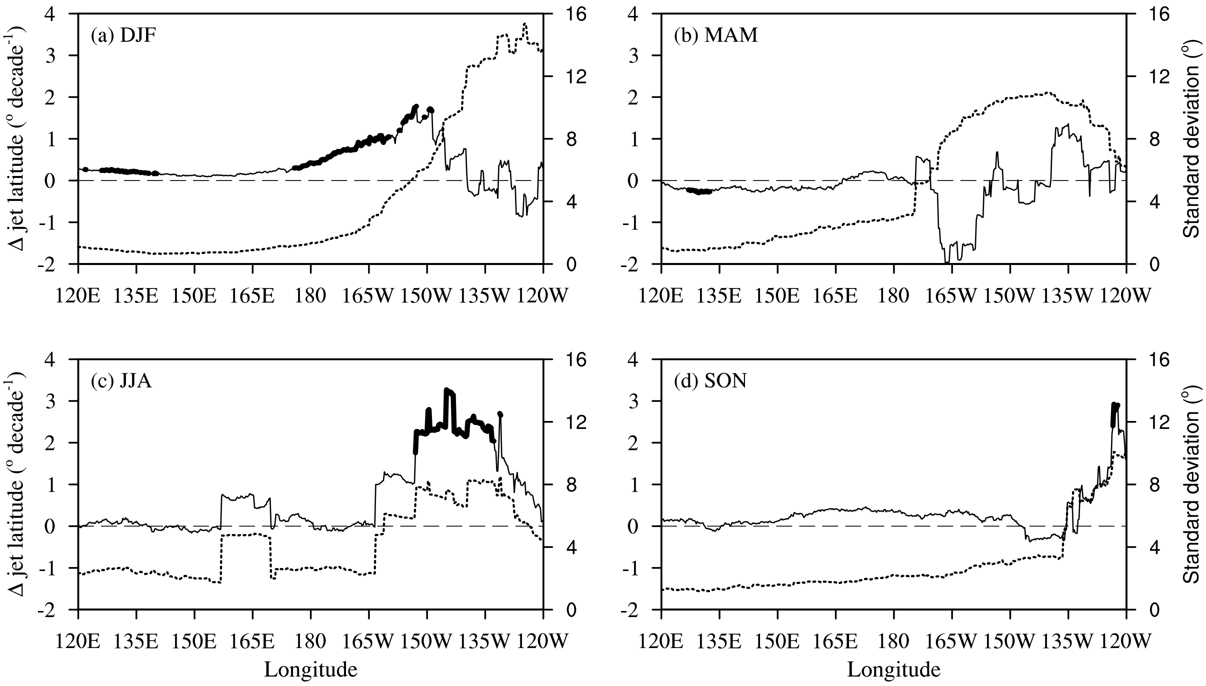

Fig. 3. Changes in the meridional position (solid lines, ° decade^{-1}) of the maximum wind speed and the standard deviation of the meridional position of the maximum wind speed (dotted lines, °) over the North Pacific in different longitudes and seasons during the period 1979-2020. We analyzed wind speeds from 400 to 100 hPa pressure levels at different latitudes (20-70 °N) to obtain the maximum upper-tropospheric wind speeds, based on which to identify the meridional position of the jet and its changes. Statistically significant linear changes at the 95% confidence interval (p-value less than 0.05) are shown by bold lines.

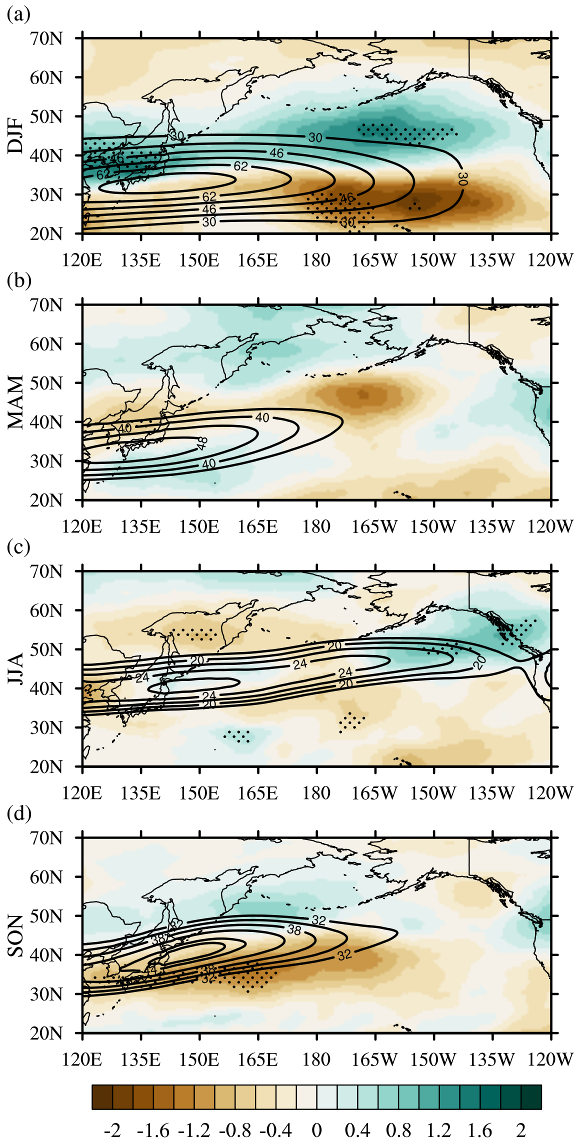

Fig. 4. Changes in the intensity of the upper-tropospheric maximum wind speed (colors, m s^{-1} per decade) over the North Pacific in different seasons during the period 1979-2020 based on the analysis of the maximum wind speed (black contours, m s^{-1}) in the upper troposphere (400 to 100 hPa). Statistically significant linear changes at the 95% confidence interval (p-value less than 0.05) are shown by dots.

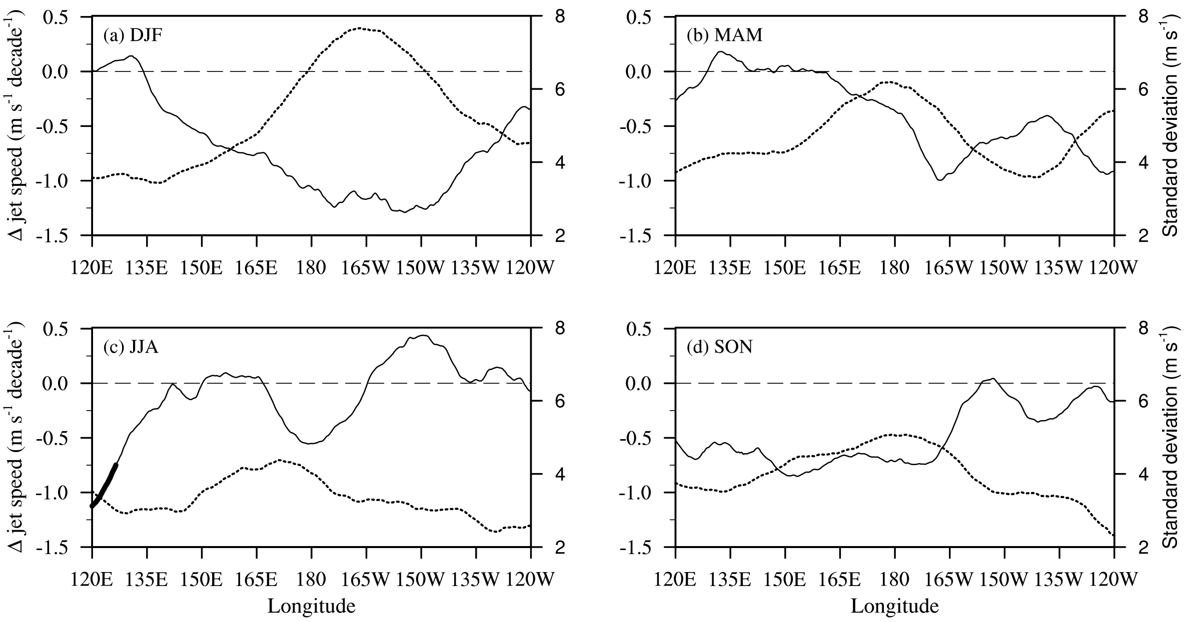

Fig. 5. Similar to Figure 3, but for changes in the intensity of the upper-tropospheric maximum wind speed (solid lines, m s^{-1} $decade^{-1}$) and the standard deviation of the intensity of the maximum wind speed (dotted lines, m s^{-1}) over the North Pacific.

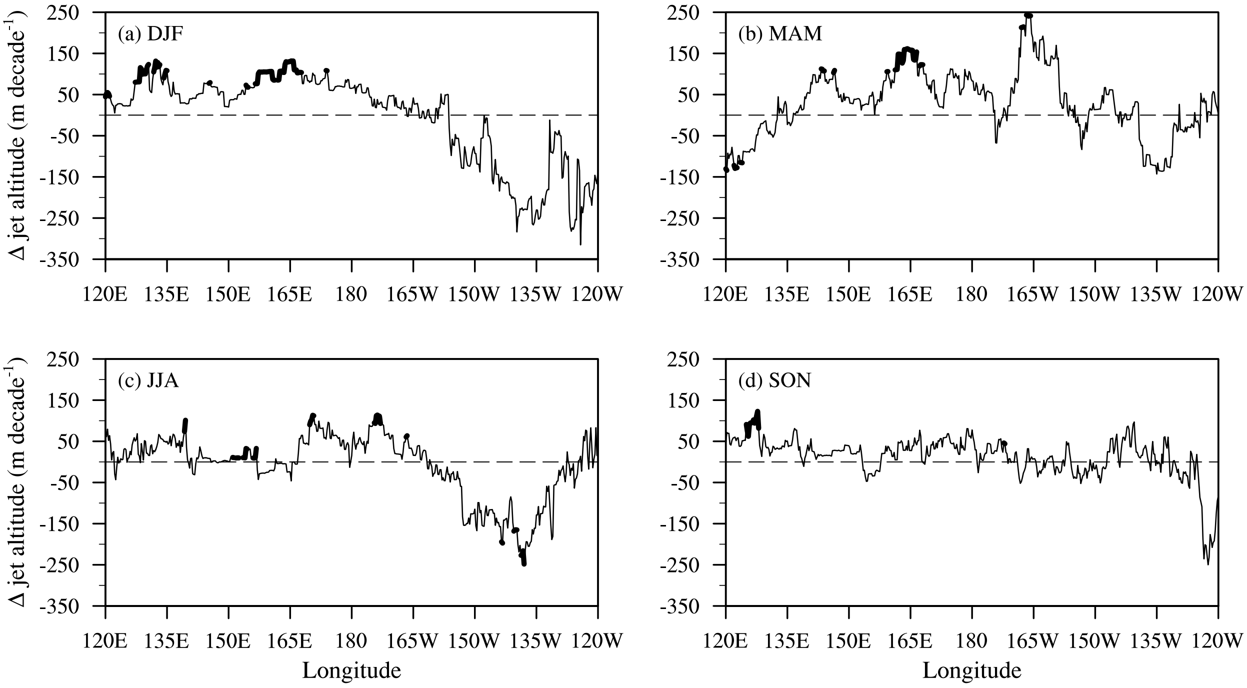

Fig. 6. Changes in the altitude of the upper-tropospheric maximum wind speed (m decade^{-1}) over the North Pacific in different longitudes and seasons during the period 1979-2020. Statistically significant linear changes at the 95% confidence interval (p-value less than 0.05) are shown by bold lines.