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Key Points:
- We find a significant poleward trend in the winter North Pacific Jet position that is robust to reanalysis and metric uncertainty
- The choice of jet metric creates more uncertainty than the choice of reanalysis in estimating the winter North Pacific Jet trend
- We find an end-of-century poleward shift during autumn under very high emissions that is robust to metric and model uncertainty

Supporting Information:
Supporting Information may be found in the online version of this article.

Correspondence to:
T. Keel,
thomas.keel.18@ucl.ac.uk

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Author Contributions:
Conceptualization: Tom Keel, Chris Brierley, Tamsin Edwards, Thomas H. A. Frame
Formal analysis: Tom Keel, Chris Brierley, Thomas H. A. Frame
Methodology: Tom Keel
Software: Tom Keel
Supervision: Chris Brierley, Tamsin Edwards
Visualization: Tom Keel
Writing – original draft: Tom Keel, Chris Brierley
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Exploring Uncertainty of Trends in the North Pacific Jet Position

Tom Keel[1,2], Chris Brierley[1], Tamsin Edwards[2], and Thomas H. A. Frame[3]

[1]Department of Geography, University College London, London, UK, [2]Department of Geography, King's College London, London, UK, [3]Department of Meteorology, University of Reading, Reading, UK

Abstract It has been difficult to establish trends in the observed jet streams, despite modeling studies suggesting they will move polewards in a warming world. While this is partly due to biases between the models and observations, we propose that another uncertainty is rooted in the choice of statistic used to determine the 'jet latitude' — one measure used to quantify the jet position. We use seven different jet latitude statistics, four climate reanalysis products, and CMIP6 simulations to assess the relative importance of different uncertainties associated with lower-tropospheric North Pacific Jet (NPJ) trends. Our results show a statistically significant poleward trend in the observed winter NPJ across all reanalyzes and using all jet latitude statistics. The magnitude of this trend is most sensitive to the choice of statistic. Furthermore, we find that the NPJ shifts poleward in Autumn under high emission scenarios, which is robust to the choice of jet statistic.

Plain Language Summary Jet streams are ribbons of fast-flowing air that flow from west to east in both hemispheres high up in the atmosphere. Their speed and position affect how moisture and heat are transported across the planet, making them an important control on surface weather patterns. In a warming world, the atmosphere does not warm uniformly, creating an imbalance in the processes determining where jet streams form. While climate models have generally suggested that these processes will shift the jet streams toward the poles, this has been difficult to establish in observations. Here, we argue that a major part of the uncertainty of determining this poleward trend comes from precisely which statistic is used to define a jet's location. Our analysis measures the differences in the North Pacific Jet position trend using different jet statistics and data sets. We show that the choice of statistic used to define the jet stream produces more uncertainty than the choice of data set. We find a statistically significant poleward trend in the wintertime North Pacific Jet position in the observational record and a significant end-of-century autumn poleward shift projected under very high emission scenarios.

1. Introduction

Jet streams are instantaneous features of the Earth's general atmospheric circulation that manifest as fast-flowing ribbons of air (Vallis, 2019). The impact of increased anthropogenic greenhouse gas concentrations on the climatological position of the jet streams has received much attention recently, but it has been difficult to establish trends in their position that are robust to both modeling and observational analysis (Archer & Caldeira, 2008; Pena-Ortiz et al., 2013; Stendel et al., 2021). Modeling studies generally predict a poleward shift of the jet's position in response to an amplified upper-level tropical warming, which is expected to strengthen the upper-level poleward temperature gradient in the 21st century (Barnes & Polvani, 2013; Lorenz & DeWeaver, 2007; Lu et al., 2007; Rivière, 2011). On the other hand, modeling has also shown the sensitivity of jet position to a competing effect, lower-level Arctic Amplification, which weakens the poleward shift of the Northern Hemisphere jets in winter (Curtis et al., 2020; Peings et al., 2019; Screen et al., 2022). The upper-level tropical amplification is thought to play a larger role than the lower-level Arctic amplification, with weakening of the stratospheric polar vortex also contributing, especially over the North Pacific (Manzini et al., 2014; Oudar et al., 2020; Zappa & Shepherd, 2017).

From observational research, there has generally been little consensus about the past movement of the jet position. Recently, trends have begun emerging that share similarities to trends in modeling studies: that is, a (weak) poleward shift of the jet position in the Northern Hemisphere over the last few decades (e.g., Martin, 2021; Woollings et al., 2023). However, these findings are subject to significant uncertainties and are not fully consistent with modeling research (Cohen et al., 2020; Oudar et al., 2020). As noted in these studies, there are differences between the trends produced when using different methods of jet identification (Martin, 2021) and time periods (Woollings et al., 2023). Woollings et al. (2023) also noted the climate models are less well-equipped to capture the seasonal to sub-seasonal interactions and decadal variability of the determinants of the jet position.

The North Pacific Jet (NPJ) plays a key role in modulating East Asian and North American weather, especially the lower-tropospheric part through its connection with storm tracks (Bosart et al., 2017; Shaw et al., 2016). It is both eddy- and thermally driven (unlike the North Atlantic, which is primarily eddy-driven) and exhibits a relatively large seasonal cycle, approaching closest to the equator in winter (Lee & Kim, 2003; Li & Wettstein, 2012; Nakamura, 1992; Yuval et al., 2018). Understanding how its mean position changes is vital for understanding the trajectory of the mid-latitude climate in the 21st century, regardless of whether direct causation to larger climatic changes can be drawn.

We propose that a major limitation of most research into jet stream trends is a reliance on a single statistic to determine jet latitude position. Each statistic has assumptions about the appropriate region, vertical level and temporal resolution with which to capture the structure and/or climatology of a given jet stream within a given time window (Keel et al., 2024).

In this research, we examine climatological-scale trends of the lower tropospheric NPJ and assess the relative importance of the associated uncertainties in estimating its position. To do this, we define and assess three types of uncertainty: (a) *metric uncertainty* arising from uncertainty about the choice of jet statistic, (b) *reanalysis/model uncertainty* arising from the choice of reanalysis or model, and (c) *internal variability* arising from spread amongst the realizations of the same climate model.

2. Data and Methods

2.1. Data

We use daily zonal wind speed data (in ms^{-1}) between 1 January 1980 and 28 February 2023 from four climate reanalysis data sets: ERA5 (Hersbach et al., 2020), JRA-55 (Kobayashi et al., 2015), MERRA-2 (Gelaro et al., 2017) and NCEP DOE II (Kanamitsu et al., 2002). A standardised North Pacific region (120°W–240°W, 20°N–70°N) is adopted at two pressure levels: 850 and 700 hPa. All data are processed at its native resolution.

Daily u-component wind (in ms^{-1}) were also retrieved from 28 models from 16 modeling groups of the Coupled Model Intercomparison Project Phase 6 (CMIP6; Eyring et al., 2016) for the *historical*, *SSP1-2.6*, *SSP2-4.5*, *SSP3-7.0*, *SSP5-8.5* experiments. Where available, multiple realizations of each simulation were obtained. A full list of models and realizations used in this study is provided in Table S1 in Supporting Information S1.

Three climate indices are computed from zonal mean conditions in ERA5 (after e.g. Oudar et al., 2020): average upper-level temperature (400-150 hPa, 20°S-20°N) to track tropical amplification; average lower-level temperature (1,000-700 hPa, 60°N–90°N) for Arctic amplification; and stratosphere zonal wind strength (250-30 hPa, 70°N–90°N) to follow the Polar vortex strength.

These indices are presented as anomalies relative to 1980–2022. Only consecutive December-January-February are considered when computing winter seasons.

2.2. Analysis Techniques

We use seven different jet statistics to extract a jet latitude from zonal wind speed (Table 1). These statistics have been chosen based on their popularity and similarity of scope (to extract a single value of jet latitude in lower tropospheric winds), and each are available in Python's jsmetrics package (Keel et al., 2024). These methods were primarily developed for low-level (500–925 hPa) zonal winds, making them more appropriate for assessing the eddy-driven components.

We compute each statistic on the standardised North Pacific region (regardless of the original metric definition). Each metric also estimates jet speed, but this analysis focuses only on jet position. Zappa et al. (2018), here Z18, initially developed for monthly resolution data, is calculated at a daily resolution in this research using jsmetrics (Keel et al., 2024). B18 was developed for seasonal and annual means, so it is not included in the comparison of monthly jet latitude.

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Table 1
Jet Latitude Statistics Used in This Study

Code	Study	hPa	Temporal	Method
W10	Woollings et al. (2010)[a]	700–925	Daily	Lanczos low-pass filter over max wind speed
BP13	Barnes and Polvani (2013)	700–850	Daily	Low-pass filter then quadratic interpolation
GP14	Grise and Polvani (2014)	850	Daily	Quadratic interpolation of max wind speed
BS17	Barnes and Simpson (2017)	700	10 day	Maximum wind speed
B18	Bracegirdle et al. (2018)	850	Annual	Cubic-spline interpolation of max wind speed
Z18	Zappa et al. (2018)[b]	850	Monthly	Centroid of wind speed profile
K20	Kerr et al. (2020)[c]	500	Daily	Smoothed max wind speed by longitude

Note. The original methodology provides all pressure levels and temporal specifications. All statistics are included in the *jsmetrics* Python package (Keel et al., 2024). For an explanation of the methodological steps involved in the computation, see Table S2 in Supporting Information S1. [a]Without Fourier filtering from the original methodology after Woollings et al. (2014); [b]Adapted from Ceppi et al. (2018); [c]Adapted from Barnes and Fiore (2013).

We use a Mann-Kendall test to analyze jet position trends. This test looks for monotonically increasing or decreasing trends, and the null hypothesis is that no monotonic trend exists. We use a Mann-Whitney U test for differences to determine shifts in the jet position between 1985-2015 and 2070–2100. The null hypothesis is that no difference in distribution exists between the two time periods. Finally, we use a Gaussian Kernel Density Estimation to generate the probability density function of jet latitude trends and shifts.

3. Results

3.1. Observational Trends in the North Pacific Jet Position

A linear poleward trend in the latitude of the low-level NPJ is shown in the record of each jet statistic, varying between 0.18 and 0.25°N per decade (Figure 1). However, this poleward trend is only a statistically significant monotonic increase using GP14, Z18, and K20. Estimates of the jet latitude vary between the methods, with the jet latitude from K20 being relatively more poleward than the other statistics. Estimates from B18 indicate that the annual mean jet position has become increasingly narrow, and this has also been suggested in modeling research (e.g., Peings et al., 2018, who look at the narrowing of the winter North Atlantic Jet).

Between 1980 and 2022, there are increasing trends in the Arctic and Tropical Amplification indices, and they show a non-significant correlation with the jet statistics (the two uppermost panels of Figure 1). Although, when this is broken down by season, there is some negative correlation shown between AA and jet latitude in MAM and SON and a positive correlation with PV in JJA (Figure S1-S4 in Supporting Information S1; Table S3 in Supporting Information S1).

Next, the NPJ position trend is separated into four seasons and with four climate reanalyzes (Figure 2). By introducing additional reanalyzes here, we can quantitatively compare the relative importance of *metric* and *reanalysis uncertainty* in estimating the jet latitude trend between 1980 and 2022. For every season except DJF, there is some uncertainty in the sign of the observational trend (i.e., at least one statistic-observation combination shows an equatorward trend) with JJA expressing the largest spread (−0.07°N–0.74°N per decade; Figure 2c). Yet in DJF, when the climatological average jet is furthest south and is most closely linked to the edge of the Hadley Cell (e.g., Park & An, 2014), the trend of the NPJ latitude is shown to have been moving poleward between 0.28 and 0.75°N/dec (Figure 2a). The poleward DJF trend is statistically significant when examined using every combination of reanalysis and jet latitude statistics.

In each season, the jet latitude statistic used (i.e., the *metric uncertainty*) has a larger influence than which reanalysis is used (i.e., the *reanalysis uncertainty*) for the estimation of the jet latitude trend. We quantify reanalysis uncertainty for each metric individually by calculating the spread of estimates using that metric that is, the black dashed line in Figure 2a indicates reanalysis uncertainty of 0.11°N/dec when using Kerr et al. (2020). Similarly, we calculate metric uncertainty for each reanalysis by calculating the spread of estimates using that reanalysis product, that is, the red solid line in Figure 2a indicates metric uncertainty of 0.26°N/dec when using NCEP/DOE II (for all values see Table S4 in Supporting Information S1).

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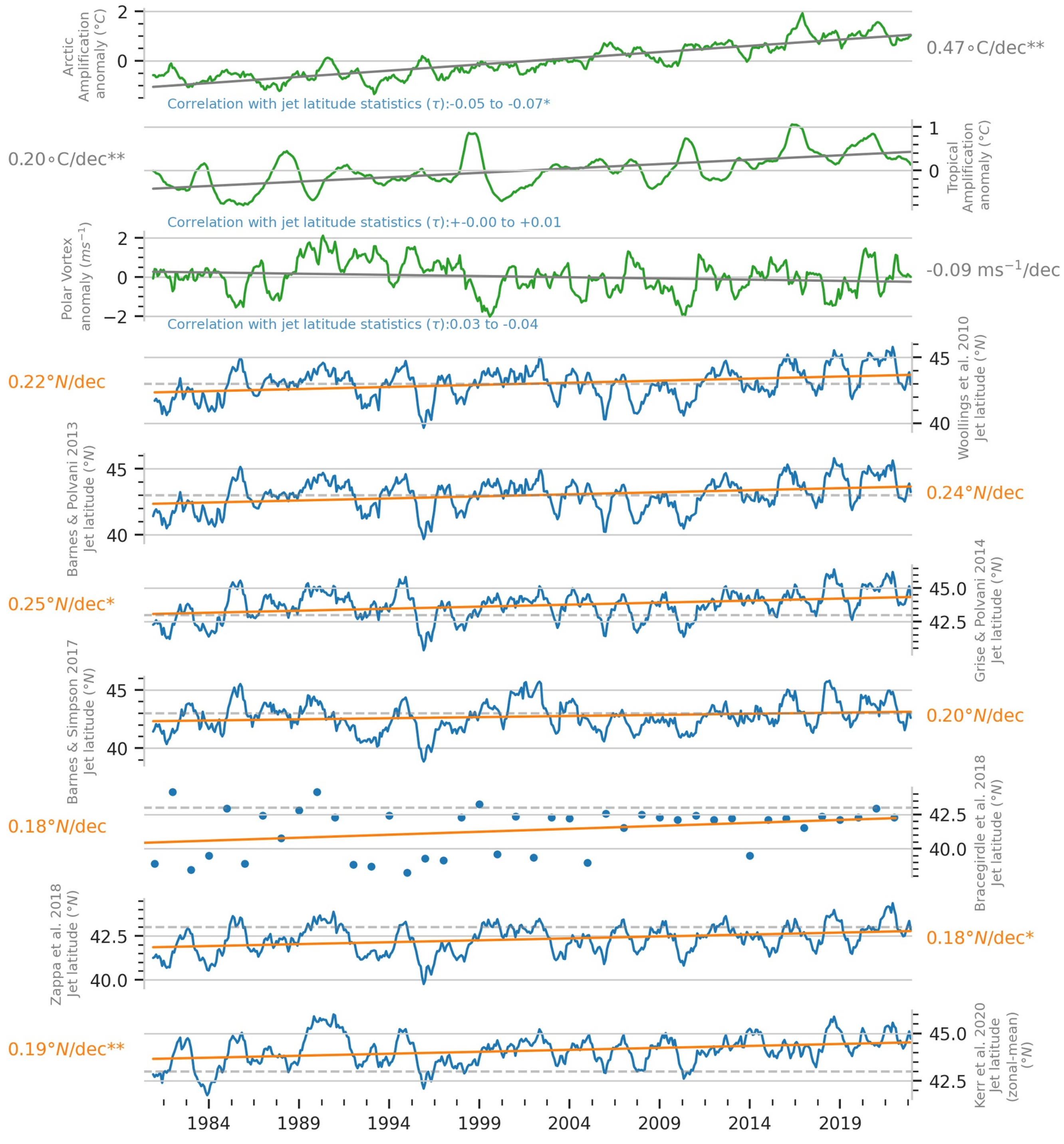

Figure 1. Annually smoothed monthly mean trends of four climate indices and seven jet latitude statistics (B18 is one value per year) over a standardised North Pacific region calculated using ERA5 (Hersbach et al., 2020). A linear regression is drawn through each variable, and the slope is presented by year. Mann-Kendall tests are run for each variable, and their p-values are expressed next to the slope (*$p < 0.05$, **$p < 0.01$). Kendall's Tau correlation coefficients are provided to show the range of correlation between each of the three climate indices and the jet statistics, except B18 (*$p < 0.05$, **$p < 0.01$). The mean latitude of W10 is 43°N, which is additionally represented as a gray dashed line on each other jet statistic.

For DJF, the uncertainty in the choice of statistic lies outside, and is more than, the spread of uncertainty from choice of reanalysis in DJF (i.e., by at least 0.05°N per decade; Table S4 in Supporting Information S1). In all the other seasons, the average reanalysis uncertainty is lower than metric uncertainty. The widest spread of both

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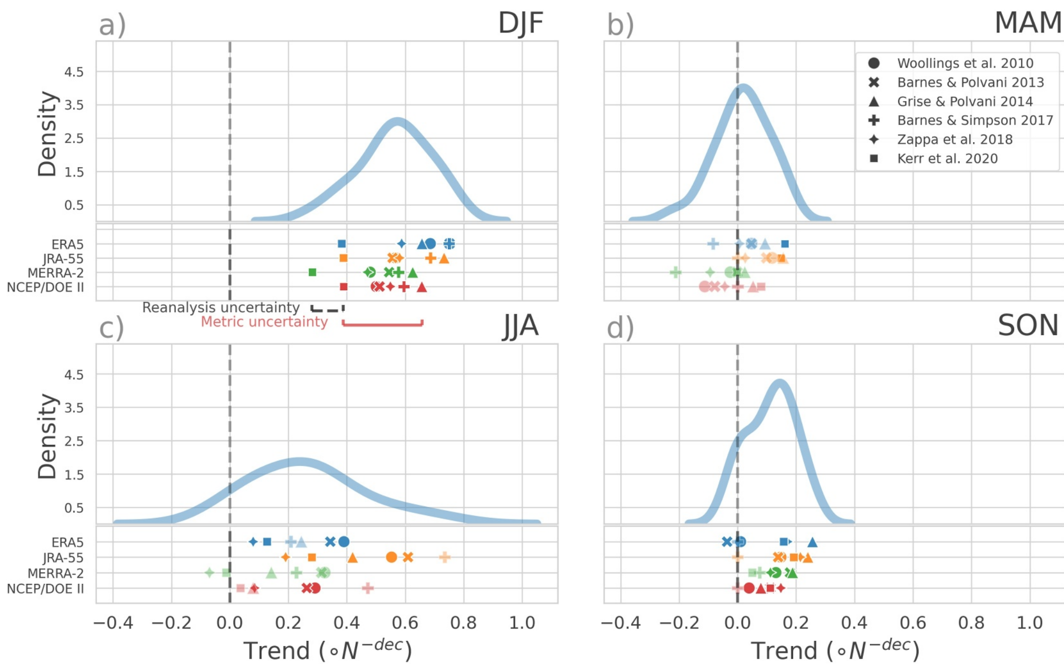

Figure 2. Kernel density estimates of the decadal trend of the North Pacific Jet latitude between 1 March 1980 and 28 February 2023 for each of four seasons (a–d), as estimated by four climate reanalysis products and six jet latitude statistics. Transparency indicates the statistical significance of the monotonic trend, as determined by a Mann-Kendall test. Opaque symbols indicate that the trend is statistically significant ($p < 0.05$).

metric and reanalysis uncertainty about the NPJ trend is in JJA, and this is the only season where the maximum reanalysis uncertainty is higher than the maximum metric uncertainty (occurring across the JRA-55) (Figure 2c; Table S4 in Supporting Information S1). No pattern suggests that some metrics or reanalyzes perform systematically better across the seasons or that an idealized metric-dataset combination exists.

3.2. Projections of the Shift of the North Pacific Jet Position

The end-of-century (2070–2100) annual NPJ position is shown to move further poleward under increased GHG forcing projections in CMIP6 ScenarioMIP, and this shift is irrespective of the metric used (Figure 3). Simulated jet latitudes exhibit an equatorward bias annually when compared to the spread of the four reanalysis sets (e.g., Bracegirdle et al., 2022, and references therein). This equatorward bias is more pronounced in W10, BP13 and GP14, where the historical simulations and observations do not overlap (see purple and gray boxes in Figure 3). The equatorward bias also has seasonal and metric dependence, primarily shown in DJF and SON (Figures S5-S8 in Supporting Information S1). Figure 3 shows consistency in the multi-decadal variability in the reanalysis between all metrics, except BS17, when viewed as a 5 year running mean, unlike the monthly values in Figure 1. A poleward shift that increases under higher GHG emission scenarios is seen each season except JJA (Figures S5-S8 in Supporting Information S1), with the shift in SON the most pronounced across the metrics.

To compare the relative importance of the *internal variability*, *metric* and *model* uncertainty, we examine the shift in the NPJ latitude projected between 30 years in the historical (1985–2014) and SSP5-8.5 (2070–2100) experiments in Figure 4. In this figure, the 28 models are ordered in descending order regarding future mean shift, and the color denotes their similarity to the four reanalyzes. We found no clear relationships between the similarity of any given model to the four reanalyzes and the extent of the jet shift shown (Figure 4a). The majority of the models have an equatorward bias. While the observational trend of the NPJ was found to be poleward in DJF (Figure 2a), across the models, there is no certainty about the sign of a shift in the annual mean jet latitude within the 2.5- to 97.5-percentile interval, hereafter 95 PI (95 PI: −0.42°N–1.93°N) or within in any season at the end-of-century under the stronger GHG forcing scenario. The projected shift was found to be most poleward in SON, versus the other seasons (95 PI: −0.25°N–2.63°N; Figure 4a and Figures S5-S9 in Supporting Information S1).

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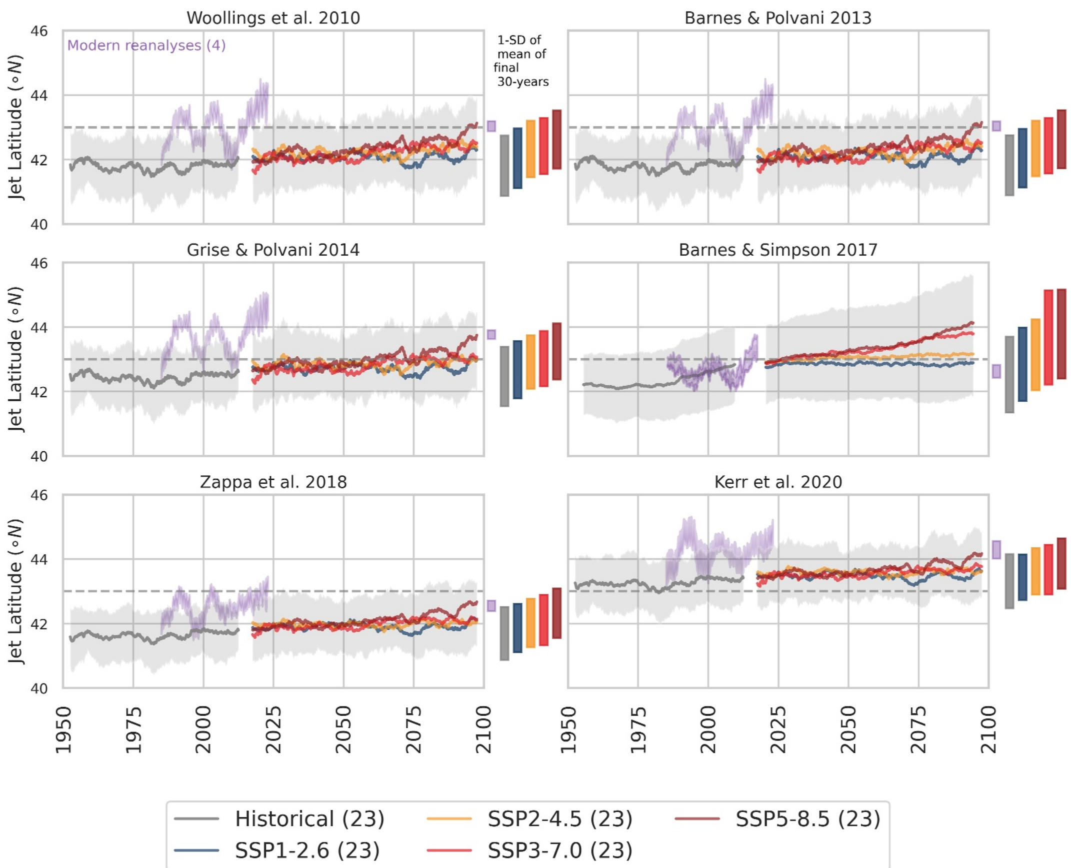

Figure 3. 5 year running mean projections of annual North Pacific Jet latitude with 5 year running standard deviation envelope for all ScenarioMIP experiments (gray envelope). Each CMIP6 experiment contains outputs from the same 23 models. The purple envelope represents the 5 year running mean range from ERA5, JRA-55, MERRA 2 and NCEP/DOE II reanalysis data sets between 1 January 1980 and 31 December 2022. Bars in each subplot relate to the standard deviation range about the mean of the last 30 years of the given model output. For each jet statistic, a gray dashed line is drawn at 43°N as in Figure 1.

The end-of-century DJF jet latitude shift is compared by metric across the models and by model across the statistics in the second and third panels of Figure 4a. The shift is generally associated with greater *model* uncertainty than *metric* uncertainty in DJF and SON (Table S5 in Supporting Information S1; and Figure S9 in Supporting Information S1). The projection of the shift varies between −0.76°N and 2.6°N (95 PI; mean 0.89) across all the jet statistics and between −1.56°N and 3.47°N (mean 0.89) across the CMIP6 models. W10, BP13, GP14 and BS17 express a similar mean (within 0.04° N), and the majority of the models have a well-confined statistical range (mean of 0.74; Table S5 in Supporting Information S1).

In Figures 4b and 4c, we examine models with multiple realizations to compare *initial condition uncertainty* in DJF and SON, the two seasons with the strongest poleward shifts. Generally, there is a relatively large spread within realizations of an individual model estimating future mean shift, and this spread is larger for DJF than SON (Table S6 in Supporting Information S1). While not all the individual metric-realisation NPJ shifts are statistically significant across the 10 multi-realizations models, much more significance is shown in SON than in DJF (Table S7 in Supporting Information S1). However, our results may include false positives due to the number of statistical tests computed.

Using one realisation from each of the 28 CMIP6 models available, we find the future mean jet shift projected to be within −0.29°N-1.80°N in DJF and within 0.52°N–2.58°N in SON within 80% of the models. As such, there is a significant agreement about the poleward shift in SON of the NPJ and a general leaning toward poleward shift for DJF (Figures 4b and 4c).

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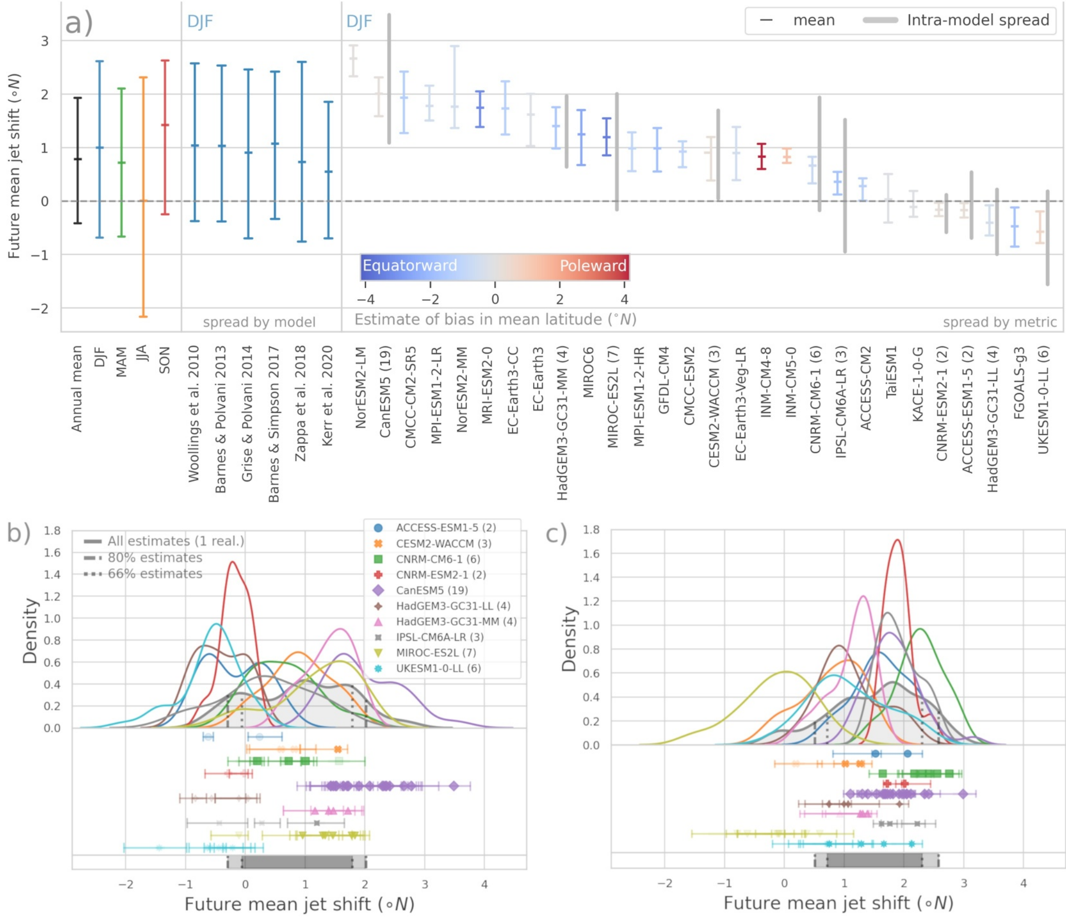

Figure 4. (a) Comparison of the end-of-century North Pacific Jet position shift between SSP5-8.5 (2070–2100) and Historical (1985–2014) experiments by annual mean and season (first panel), by metric (DJF only; second panel) and by CMIP6 model (DJF only; third panel). The height of each error bar represents the 2.5- to 97.5-percentile range, and the middle marker represents the mean. Gray bars represent the 2.5- to 97.5-percentile range of the ensemble spread of all estimations in models with multiple realizations. For these multi-realisation models, the error bar represents the spread of the means. Color represents the difference between each model's mean estimation and the reanalyzes mean for each metric. Kernel density estimation of DJF (b) and SON (c) mean jet position shifts between the end-of-century SSP5-8.5 (2070–2100) and Historical (1985–2014) experiments within multi-realisation CMIP6 models. The error bar of each realisation within the modeling groups represents the range of estimates produced by the six jet statistics, with the markers representing the mean of those values. Transparency of the marker is used to signify the statistical significance of a Mann-Whitney U test. Opaque symbols signify that the trend is statistically significant ($p < 0.05$), and the number of statistically significant realizations per model is provided in Table S7 in Supporting Information S1. Gray bars represent the area between the 10th and 90th percentile (80% of the models) and 17th and 83rd percentile (66% of the models) of one ensemble member from each of the 28 CMIP6 models used in this analysis.

4. Discussion and Conclusions

In this study, we found that the observed wintertime North Pacific Jet (NPJ) has been moving polewards at a rate of 0.28°N–0.75°N per decade between 1980 and 2022, and this trend is robust to any combination of jet statistics and reanalysis. Consistent with recent research in other regions (e.g., Martin, 2021; Woollings et al., 2023), it is likely that the gradual extension of the data record, up to 2022 here, is producing significant trends which are emerging outside of natural variability in winter. These trends also appear clearest in the most recent decades, so the trend may not exist with the last decade removed from the record (e.g., see discussion of similar work done on trends in jet waviness in Blackport & Screen, 2020).

No direct correlation was found between the observed annual mean NPJ position and tropical or Arctic amplification or polar vortex strength over this time frame (Figure 1), and there is no definitive correlation between

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these indices and all jet statistics in any one season either (Figures S1-S4 in Supporting Information S1; Table S3 in Supporting Information S1). This seemingly opposes the results of Manzini et al. (2014), Zappa and Shepherd (2017) and Oudar et al. (2020). However it is likely that the larger sample size of these modeling studies permits detection of mechanisms that have not yet emerged in the observational record (Peings et al., 2018; Woollings et al., 2023). The influence of the tug-of-war between AA-TA and the changes to the stratospheric polar vortex have all been shown to control the climatological jet position in modeling studies (Karpechko et al., 2022; Peings et al., 2019).

Using CMIP6 ScenarioMIP, we found the annual position of the NPJ to continue to extend poleward, consistent with findings of the movement of lower tropospheric jet streams and upper level zonal winds (e.g., Harvey et al., 2020; Oudar et al., 2020; Rivière, 2011). We see no clear pattern between the shift shown in an individual model and its historical equatorward bias compared to reanalyzes (Figure 4). The extent to which this bias in CMIP6 obfuscates the NPJ latitude shift requires further research, but we were able to indicate that there is also a metric uncertainty associated with the extent of this bias in the North Pacific (Figure 3).

A robust poleward shift is seen in the SON end-of-century North Pacific jet position in SSP5-8.5 that is robust to *internal variability* and *metric*, *model* uncertainty. However, there is still some uncertainty about the magnitude of the shift varying between 0.5 and 2.6° N considering the 2.5- to 97.5- percentile range of the models. The inter-model spread has a larger relative uncertainty than the metric choice in estimating this shift. Moreover, as with most analyses, we demonstrate that statistics are still important when studying the North Pacific jet.

In conclusion, we have indicated that using multiple statistics developed for a similar purpose in a standardised manner can be useful for assessing the uncertainty in estimating the climatological jet. The NPJ is coupled to surface conditions through heat and moisture transport and the storm tracks, so plays a key role in the modulation of North American weather downstream (Bosart et al., 2017; Shaw et al., 2016). Understanding how its mean position is changing (regardless of whether direct causation to larger climatic changes can be drawn) is vital for understanding the trajectory of the mid-latitude climate in the 21st century.

Data Availability Statement

The data that support the findings of this study are openly available: CMIP6 (Earth System Grid Federation, 2024); ERA5 hourly (Climate Data Store, 2024); JRA-55 daily (Japan Meterological Agency, 2024); MERRA-2 daily (Global Modeling and Assimilation Office, 2015); NCEP-DOE II daily (NOAA PSL, 2024).

The jsmetrics software is available online (Keel, 2024b), and online documentation for the software is provided in a ReadTheDocs format (Keel, 2024a).

The IPython notebooks to reproduce the figures of this manuscript are available on GitHub (Keel, 2024d). The analysis runner to run jsmetrics in batch on the JASMIN supercomputer is provided on GitHub (Keel, 2024c).

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