Seasonal and regional jet stream changes and drivers

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Abstract | The eddy-driven jet streams, which are regions of strong westerly wind in the mid-latitudes of both hemispheres, exert a leading influence on regional climate. In this Review, we outline the seasonally and regionally varying drivers, characteristics and changes in the jet streams. State-of-the-art models commonly predict a future poleward shift of the zonal- and annual-mean jet streams, typically ranging between 0° and 2° latitude by the end of the century under a high-emissions scenario, but with large model-to-model uncertainty. Furthermore, regional and seasonal projections can deviate substantially from the annual- and zonal-mean picture and the drivers of these projected changes are not fully understood. Jet trends have emerged in the reanalysis record since 1979, of which a poleward shift of the summertime austral jet of ~0.3°/decade is the most clearly attributable to anthropogenic forcing. While other trends have been observed, potentially large internal variability and inconclusive understanding of the drivers of these trends makes a clear anthropogenic attribution not possible at this point. Research is unevenly distributed across regions and seasons, with winter receiving the most attention, particularly in the North Atlantic. To support physical understanding and impact assessments, future research should provide a more complete picture of the seasonally and regionally varying jet stream drivers, and their changes, especially in spring and autumn.

Editor's summary
Eddy-driven jet streams have a strong influence on regional climate. This Review explores the seasonality and regional characteristics of mid-latitude eddy-driven jets, as well as the drivers influencing jet climatology and projected jet stream changes under continued anthropogenic climate change.

[H1] Introduction

Strong eastward winds, known as eddy-driven jets, extend from the Earth's surface to the tropopause in the midlatitudes of both hemispheres. These jets differ from the subtropical jets, which are not driven primarily by eddies and are localised in the upper troposphere[1]. Eddy-driven jets steer high- and low-pressure systems and transfer heat and moisture, governing regional weather by influencing cloudiness, precipitation, temperature, and winds. The connection goes both ways as these jets owe their existence to and are influenced by weather systems. As a result, the dynamics of these jets are complex. The North Atlantic, North Pacific and Southern hemisphere jets are most often considered, with numerous centres of population and agriculture situated in areas affected by these jets. Owing to the strong connections between eddy-driven jets and extreme weather events such as heatwaves, floods and droughts, understanding their current state and future change is crucial to assessing climate change impacts, particularly on human health and food production[2,3].

Model projections strongly suggest that jets will change with warming under increasing greenhouse gas concentrations[4–9]. In particular, a poleward shift of all jets and a strengthening of the Southern Hemispheric jet is predicted in the zonal and annual mean winds by most models[6]. However, there are substantial regional and seasonal variations in both the present-day jet climatology and in their future response[8,10], in addition to persistent uncertainties in model projections and incomplete theoretical understanding. Much of this regional and seasonal variation is due to large-scale environmental drivers, such as changes in sea-surface temperature (SST) or stratospheric vortex strength, which act as boundary conditions for the jets[11–13]. Note that there is not always a clear unidirectional interaction between drivers and jet stream[14]. We distinguish these drivers from physical mechanisms, for example changes in wave generation or propagation, which describe how the drivers influence the jet[15].

Understanding regional characteristics is crucial for local climate adaptation. For example, the winter North Pacific jet stream is projected to shift poleward in the zonal mean, whereas the opposite is predicted in the East Pacific, which influences the hydroclimate of the western United States[16,17] A clear picture of the regional variability and seasonality of future changes in the jets is crucial, as they can impact extreme events[18–20], such as the 2018 European heatwave[19], the California drought of 2011–2017[21] and the 2019–2020 Australian bushfires[22]. Yet a comprehensive review of the large-scale jet stream drivers and their influence on projected jet stream changes is lacking. A synthesis of the seasonal and spatial characteristics of the jet, their proposed drivers, and their projected changes will facilitate process understanding of future midlatitude circulation changes and assessment of their regional impacts.

In this Review, we assess the drivers of the seasonal and regional characteristics of the midlatitude eddy-driven jets and their projected future change, focusing on ocean basins where eddy-driven jets are most prominent. First, we explore the drivers influencing present-day jet climatology, in particular jet position, strength, and variability. Next, we discuss projections of future jet stream changes. Throughout, we highlight the seasonal and regional dependencies and discuss numerical climate model biases and their ability to accurately capture the relevant drivers. We then consider observed regional and seasonal jet trends and assess their consistency with projections and physical understanding. Finally, we put forward our recommendations for future research priorities, including optimising the detectability of jet stream responses, better identification and quantification of jet stream drivers, and developing a hierarchy of model resolution.

[H1] Present-day jet streams

Prior to assessing changes in the jet streams, it is helpful to consider their characteristics in the present climate. The controls and climatology of the jet from a zonal-mean perspective, as well as the drivers and seasonal characteristics of the North Atlantic, North Pacific and Southern Hemisphere jets are now discussed.

[H2] *The zonal-mean perspective*

A commonly-chosen altitude level to isolate the eddy-driven component of the jet from the subtropical jet, which exists higher up, is at 700 hPa in the lower half of the troposphere, approximately 3000 meters above sea level. At 700 hPa, the zonal-mean zonal wind climatology shows well-defined jet streams in both hemispheres (Fig. 1). The Northern Hemisphere zonal-mean jet displays pronounced seasonality. In winter, the centroid latitude[23] is more equatorward (~42°N; herein the centroid jet latitude is used as a jet latitude measure) and higher mean speed (~11 m/s) than summer (~46°N and 6 m/s). By contrast, the Southern Hemisphere jet stream peaks close to 47°S year-round (~46°S in winter and ~48°S in summer), with small variations in zonal-mean strength between seasons (14 m/s in winter and 16 m/s in summer). These differences are in line with the seasonal strengthening and weakening of meridional temperature gradients in the northern hemisphere exceeding the smaller seasonal variation in SST gradients in the southern hemisphere[24].

Overall, Coupled Model Intercomparison Project Phase 6 (CMIP6)[25] numerical global climate models reproduce the zonal-mean jet climatology and its seasonal variations well. However, model-means mask considerable biases in the individual models (Fig. 1). Inter-model spread is largest in the Southern Hemisphere during June-July-August (JJA), where the jet climatology is particularly zonally asymmetric[26,27]. Despite CMIP6 models performing better on average than previous model generations in their simulation of the zonal-mean jet climatology, they still exhibit a tendency to an equatorward bias in the position of the Southern Hemispheric jet, particularly in JJA[28,29].

Although a predictive, quantitative theory for jet stream location and strength is lacking, there is a qualitative understanding of some key controls of the zonal-mean jet climatology and its seasonal and hemispheric variations. Theory and numerical modelling at various levels of complexity support the importance of both the latitude and strength of baroclinicity, with stronger baroclinicity favouring a stronger, more poleward-located jet[30–34]. Meridional gradients of sea surface temperature (SST) also have profound effects on the zonal-mean jet. Sharp SST gradients tend to anchor the latitude of peak baroclinicity and thus the jet[35,36]. As such, mesoscale ocean eddies can push the jet poleward via altered baroclinicity[37]. In addition, cloud-radiative heating affects baroclinicity, directly through atmospheric heating and indirectly through SST[38]. Sea-ice extent can also impact jets via altering the meridional temperature gradient[39,40].

Variability and change in the zonal-mean temperature structure is closely related to changes in the jet stream. Although the causality is ambiguous given thermal wind balance, there are situations where factors that lead to an altered temperature structure can be considered the cause of jet stream changes, primarily through an influence on the structure, propagation, and momentum transports of transient eddies[41]. For example, the dominant mode of variability in SSTs in the equatorial Pacific (the El Niño-Southern Oscillation, ENSO) is accompanied by hemispherically symmetric changes in the zonal-mean jet streams because of the altered temperature structure and associated influence of altered low latitude winds on transient eddy propagation[42,43].

The stratospheric vortex affects the tropospheric jet by modulating the propagation and dissipation of Rossby waves sustaining the jet. Generally, a stronger vortex favours a more poleward jet stream[44], although the magnitude of this effect is dependent on the tropospheric jet climatology[45]. The seasonality of the vortex, and particularly the timing of its breakdown, has been highlighted as a control on the seasonal cycle of the jet in the Southern Hemisphere[46].

Surface drag, particularly through resolved and parameterised orographic drag, has a profound effect on the position, strength and variability of the jets. Underrepresentation of surface drag can lead, for example, to an equatorward bias in the Southern Hemispheric jet[47]. Orographic drag is even more important in the Northern Hemisphere owing to the presence of planetary-scale mountain ranges that substantially disrupt and slow down the zonal-mean jet[48].

The generation and propagation of stationary waves influences the structure of the jet streams. Stationary waves are generated by diabatic heating, topography, and transient eddy fluxes and their structure and propagation is influenced by the background flow[49]. They affect the local structure of the jet stream, and can also result in net zonal-mean momentum transports that influence the zonal-mean jet stream structure[50].

In numerical climate models, the representation of the jet is also affected by model numerics, particularly horizontal grid resolution. Idealised model results reveal that lower-resolution grids are associated with lower-latitude zonal-mean jets[51], and also simulate overly smooth potential vorticity gradients near the jet[52]. There is tentative evidence for a relationship between horizontal grid resolution and mean-state jet latitude in comprehensive CMIP-class models for the Southern Hemisphere, such that lower-resolution models are more likely to exhibit an equatorward bias in jet position than higher-resolution models [28].

[H2] *North Atlantic*

The wintertime eddy-driven jet tilts from southwest to northeast across the North Atlantic (Fig. 1b). The winter jet has a major role in bringing warm maritime air to moderate European winter climate[53]. Several factors conspire to form this tilt. The stationary Rossby wave downstream of the Rocky mountains, the land-sea temperature contrast[54], the tilted baroclinic zone associated with the North American coastline, the Gulf Stream and the relatively warm subpolar gyre[36], and storm track latent heating[55] are particularly prominent influential factors. Orography also has a key role in slowing down the zonal flow[48]. Although anomalous merging can occur, the tilt in the eddy-driven jet usually facilitates a clear separation from the subtropical jet, which passes over the subtropical North Atlantic and northern Africa[56]. This separation allows strong variability in eddy-driven jet position to develop at the jet exit region over Western Europe[57], with extremes of high and low latitude jets occurring even in the seasonal mean [56,58].

Climate models tend to systematically underestimate the tilt of the jet and storm track, simulating North Atlantic jets that are overly strong and zonal, particularly in winter and spring (Fig. 1). The jet generally extends too far into Europe, where there is an associated underestimate of blocking occurrence[59]. This overly shallow jet tilt is also reflected in a modelled zonal mean jet that is positioned slightly too equatorward and is also too strong compared to observations (Fig. 2). Improvements have been achieved through increasing the horizontal resolution in model simulations, which has reduced SST biases[60] and improved orography[61]. As such, biases have weakened over generations of CMIP models[9], with remaining biases possibly reflecting deficiencies in moist physics[62,63] and/or drag processes[64].

Zonal winds and stationary waves are weaker in summer, owing to reduced baroclinicity (Fig. 1). In addition, the summertime Atlantic jet and storm track are weaker and further poleward compared to winter, with this shift strongest in the western North Atlantic (Fig. 1). Thus, the tilt of the jet is reduced compared to winter. The storm track in spring is weaker than in winter but in a similar position, and the autumn state is similar in position to summer but stronger[65]. There are small biases in CMIP6 model[9] simulations of jets in summer and autumn (Fig. 1d-e), and the modelled seasonal cycle of the movement of the jet is slightly exaggerated in the zonal mean (Fig. 2a-b, Table 1). Overall, model biases are strongly variable in space and time, emphasising the need for a seasonally- and regionally resolved analysis.

As a strongly eddy-driven jet stream[66], the North Atlantic jet exhibits notably high variance that is dominated by jet shifting linked to Rossby wave-breaking and the associated momentum fluxes[67,68]. Variance also arises from changes in jet speed and quasi-stationary waves and blocking patterns[69,70]. Evidence of regime behaviour in the jet shifting exists, but can be sensitive to the methodology used[71]. These synoptic processes are modulated by remote drivers, processes outside the regional jet stream and storm track system, such that up to around 60% of the seasonal mean variability is potentially predictable[72,73].

Indeed, the North Atlantic jet in winter is known to be sensitive to a wide range of physical drivers[74]. Established drivers include tropical SST[13,75], stratospheric variability[44], the Quasi-Biennial Oscillation[74], upstream dynamical influences from the Pacific[76] and potential influence of Greenland orography[77]. Local North Atlantic SSTs also impact the North Atlantic jet [78–80], with numerical global climate models possibly underestimating the wind response to smaller-scale SST anomalies owing to their coarse grids[81,82]. However, the relative importance of these various drivers is not completely clear.

State-of-the-art models capture many aspects of Atlantic jet variability, but biases remain that can affect the response to drivers[83]. In particular, there are specific concerns over features such as European blocking[84], moist diabatic processes[85], decadal variability[86,87] and weak teleconnections[73,88].

[H2] *North Pacific*

The North Pacific jet stream is strongest and at its most equatorward position during boreal winter (Fig. 1b). During this season the strength of the jet stream peaks on the western side of the Pacific basin primarily due to diabatic heating driving stationary wave structures that lead to locally enhanced westerly winds in that region[49], and also owing to the influence of orographic effects from Asian topography, in particular the Mongolian Plateau[89,90]. Downstream, in the East Pacific, the jet stream is deflected poleward toward the

Northwestern U.S. and Western Canada as a result of diabatic heating and orographic influences on the stationary wave structure of the Pacific sector, as well as the influence of transient eddies[91].

Much like the Atlantic jet stream, CMIP6 models struggle to accurately represent the poleward deflection of the jet stream in the East Pacific during winter and spring. Models produce jet streams that are too zonal during those seasons (Fig. 1b-c), which also manifests in a storm track that is too zonal[92] and an overall equatorward bias in the jet stream latitude in most models[29]. This bias is reflected in the winter zonal mean location and, to a minor extent, in the jet strength (Fig. 2a-b, Table 1).

As the seasons progress into spring and summer, the Pacific jet stream weakens and shifts poleward along with the latitudinal gradient in insolation (Fig. 1c-d). Whereas the poleward deflection on the eastern side of the basin becomes less pronounced than during winter, a broader southwest to northeast tilt in the jet stream develops across the entire ocean basin (Fig. 1). During the spring, the relative role of the Tibetan Plateau compared to the Mongolian Plateau in shaping the circulation of the Pacific basin increases[90]. The jet stream then shifts equatorward and strengthens again during autumn (Fig. 1e).

During summer, models simulate a slightly poleward and too weak jet in the zonal mean (Fig. 2a-b, Table 1), in line with a zonally resolved analysis (Fig. 1d). During spring, models show nearly no bias in zonal mean wind speeds. However, the zonally resolved analysis (Fig. 1c) shows that a strong and significant bias exists in the models, albeit only in the East Pacific. The fact that this bias only appears in the zonally resolved analysis demonstrates the shortcomings of considering the zonal mean only. There is very little bias between the model mean and observations in autumn (Fig. 1e; Fig. 2a-b, Table 1).

Variability in the Pacific jet stream arises, among other things, as a result of variations in transient eddy momentum fluxes. Additionally, variability in diabatic heating is important, whose influence is particularly strong when heating occurs in the tropics, altering the angular momentum transport by the thermally direct overturning circulation[66], which in turn forces stationary wave patterns that modify the jet stream structure[49]. Most notable is the influence of the El Niño-Southern Oscillation, which acts to shift the Pacific jet stream equatorward and lengthens it toward the east during DJF (December-January-February) for El Niño events, and vice-versa during La Niña events[93].

Evaluating the true nature of this teleconnection is challenging owing to the short observational record and the large role of sampling of other forms of variability in observed ENSO composites[94]. That said, there are indications that the wintertime teleconnections to the Aleutian low and North Pacific jet stream are too weak in numerical simulations[95,96], due in part to an unrealistically weak Rossby wave source, and the springtime teleconnection to the North Pacific being too strong[97]. Standard resolution numerical climate models (~1° horizontal resolution) are also likely to misrepresent jet stream variability associated with meanderings of the Kuroshio-Oyashio extension SST front[98].

[H2] ***Southern Hemisphere***

Owing to the absence of major landmasses in the Southern Hemispheric midlatitudes, the jet stream is more continuous and zonally symmetric in the annual mean compared to its Northern Hemisphere counterparts (Fig. 1a). Nevertheless, several factors cause the jet to deviate from a purely zonally symmetric behaviour.

During austral summer (DJF), the jet is relatively zonally symmetric (Fig. 1b) and migrates equatorward over the course of the season[46,99]. This equatorward migration has been linked to a seasonal weakening of the stratospheric polar vortex[100–103]. Although the exact mechanism of the coupling is not fully understood, there are indications of a propagating stratospheric signal that is subsequently enhanced by tropospheric dynamics[104]. Jet variability also appears to be more persistent during late spring to early summer[51,105–109], likely resulting from an organising influence from the stratosphere[44,107,110] or, alternatively, at least partially reflecting a regime transition induced by the stratosphere[46,109] rather than true dynamical persistence. Stratospheric influence on the Southern Hemispheric jet stream during springtime can further be linked to hot and dry extremes during the early summer in Australia, enabling long-range predictability given the relatively long timescale of this downward influence[111].

An important influence on Southern Hemispheric jet variability in DJF is the ENSO phenomenon, which usually peaks during this season. Positive ENSO anomalies are correlated with a negative Southern Annular

Mode (SAM), that is an equatorward jet shift, and vice versa[93,112–114]. However, this connection is only found under strong ENSO conditions[115]. ENSO has also been linked to SAM asymmetries, especially in the South Pacific[113]. Part of the ENSO influence on the jet occurs via the stratosphere[14,116,117].

Previous generations of climate models showed a strong equatorward bias of the Southern Hemispheric jet position[7], but the latest generation of models (CMIP6) achieved a significant reduction in this bias despite not fully resolving it[28,29,108]. Remaining bias is mostly found poleward of New Zealand[118] (Fig. 1). The model mean reproduces the zonal-mean jet position and strength very well in DJF (Fig. 2a-b, Table 1). However, the zonal-mean metric obscures regional biases which are significant across models (Fig. 1b). Increasing model resolution is recognised as one cause of the bias reduction[28], as well as an increased midlatitude temperature gradient[119] which might be related to changes in cloud radiative effects[34]. Similar to the reduction in positional bias, the timing of the spring-to-summer increase in variability persistence is closer to reanalysis in CMIP6 relative to previous CMIP generations, although the magnitude of the persistence is still biased high[108,109].

In austral winter (JJA), stronger zonal asymmetries in the jet are observed, with a double jet structure over the Pacific region and a single jet structure over the Indo-Atlantic region[26,120–122] (Fig. 1d). This zonal asymmetry is in strong contrast to the annual mean and the summer season (Fig. 1). Several explanations for the split have been proposed, which are not mutually exclusive. Upper-level Rossby waves from convection in the Indo-Pacific warm pool has an important role in driving zonal asymmetries in the Southern Hemispheric jet stream, these waves are further modulated by local SSTs and orography[26,123,124]. The strengthening of the subtropical jet in this season acts as an additional waveguide in the upper troposphere, diverting momentum flux over the Pacific region[24,125]. Local SST fronts have also been proposed to have an influence[126].

CMIP6 models are capable of simulating the JJA split jet, but on average they place the equatorward branch too far equatorward (Fig. 1d). In the zonal mean, although the equatorward bias in jet latitude has improved from CMIP5 to CMIP6, most models still exhibit a substantial bias[29] (Fig. 2a-b, Table 1), which agrees with the zonally resolved zonal wind analysis (Fig. 1d). However, the zonal-mean statistics of the zonally asymmetric austral winter jet must be interpreted with care, as they represent an average over two related but distinct dynamical features[127].

Spring and autumn seasons (September-October-November, SON, and March-April-May, MAM) are transition seasons, sharing some of the traits of winter and summer (Fig. 1c,e). Polar vortex weakening can affect the jet as early as October[103] whereas the stratospheric ENSO pathway can influence the jet during springtime[14,116,117]. SAM asymmetries linked to ENSO are also found in spring[113]. The austral winter split jet develops in late fall and extends into spring, but is most pronounced during winter[24,121,123,125].

In the zonal mean, CMIP6 models show little bias in MAM jet position or strength (Fig. 2a-b, Table 1). However, this minimal bias results from compensation of significant positive wind bias in the West Pacific and negative bias in the Atlantic (Fig. 1c). In SON, numerical models show a slight equatorward bias in jet latitude, owing to a significant positive bias south-east of Australia (Fig. 1e), and slightly weaker strength (Fig. 2a-b, Table 1).

The jets' climatological characteristics for all regions and seasons are summarised in Table 2 together with proposed drivers, which are additionally summarised in a schematic (Fig. 3a).

[H1] Future projections

This section synthesizes understanding of future projections of the jet stream. The focus remains on the regional and seasonal characteristics of the projections, with particular attention to the drivers of the jet stream responses. The zonal-mean perspective is summarised before the specifics of each region are discussed, focusing on the CMIP6-mean response. The section concludes with a review of uncertainties in jet stream projections. The accompanying figures and discussion are based on the SSP5-8.5 scenario to help identify large signals, although it is potentially an extremely high and unlikely emissions scenario (Supplementary Note 1).

[H2] *The zonal-mean perspective*

From a zonal-mean perspective, the CMIP6 projected jet response under SSP5-8.5 involves a poleward shift in both hemispheres in most seasons (Fig. 4), with a clearer response in the Southern Hemisphere. This response is similar to that found in previous climate model generations[6,128] and in more idealised global warming simulations[31], and is consistent with a shift towards a more positive phase of the annular modes[129]. Considerable inter-model uncertainty exists in the projected response, such that the model spread is often larger than the model-mean response (Fig. 2c-d; Fig. 4). Distinguishing between physical mechanisms (for example changes in wave generation or propagation) and large-scale environmental drivers (for example, changes in SST or stratospheric vortex strength, which could act through any combination of physical mechanisms) can help interpret these jet responses. The physical mechanisms of the jet response to forcing remain a topic of active research[15], and here the focus remains on the role of large-scale drivers.

Of the large-scale drivers, changes to the equator-to-pole temperature gradients, and therefore baroclinicity, are a key contributor to the jet response[30,130,131]. These changes gradients can both be driven by the direct radiative impact of greenhouse gases, and the subsequent SST increase[132–134], with elevated SST resulting in a preferential warming of the tropical upper troposphere, as the tropical atmosphere warms following a moist adiabat[135]. Subsequently, the equator-to-pole temperature gradient increases, raising the tropopause height, and shifting the westerlies poleward[31,136].

Conversely, polar amplification (particularly in the Arctic) has the opposite effect on the lower-level meridional temperature gradient, partly offsetting the effect of tropical upper-tropospheric warming[12,130,136,137]. Furthermore, climate feedbacks – particularly the shortwave feedbacks by cloud and surface albedo changes[131,138] – and changes in ocean circulation[81] have important roles in modulating midlatitude SST gradient and baroclinicity. Greenhouse gas-driven cooling of the stratosphere, in the context of the equator-to-pole slope of the tropopause might also contribute to a poleward shift of the jet stream through an enhanced meridional temperature gradient[128,139], as do local changes in diabatic heating[140]. Anthropogenic aerosols and their interaction with clouds have likely influenced the historical Northern Hemispheric temperature gradient[141]. Future reductions in aerosol emissions are therefore expected to result in an opposite impact on jet projections, although projecting changes in regional emissions offers an additional complication[142].

Another important driver is the strength of the stratospheric polar vortex, with a stronger vortex again favouring a poleward shift and strengthening of the tropospheric jet[143,144]. In the Southern Hemisphere, changes in springtime vortex strength are often associated with changes in the timing of the seasonal vortex breakdown, and contribute to inter-model uncertainty in the summertime tropospheric jet response[145]. Stratospheric ozone depletion can impact the Southern Hemispheric tropospheric jet in summertime via changes in vortex strength, and drove a poleward jet shift between 1970 and 2000[146]. Thus, as the Antarctic ozone hole recovers, the jet response will be an equatorward shift opposing the greenhouse gas-driven poleward shift in future projections[147]. By contrast, the Northern Hemisphere future stratospheric vortex response is highly uncertain, substantially contributing to model spread in the jet response during winter[11,144]. These differences are in part related to the model representation of the stratosphere[148,149].

A substantial fraction of the inter-model spread in future jet responses across CMIP models can be statistically explained by a combination of tropical upper-level warming, polar lower-level warming, and change in stratospheric vortex strength[12,150]. Joint consideration of these drivers allows definition of process-based storylines of future circulation change that span the plausible range of future responses[151].

[H2] *North Atlantic*

In DJF, CMIP6 models predict a tripolar zonal wind response over the jet exit region (Fig. 4b), resembling a squeezing of the jet on its meridional flanks and an eastward extension into Europe[137]. A similar, albeit weaker, pattern is also projected in spring (Fig. 4c). This pattern and a related extension of the storm track has been consistently predicted by several generations of numerical models[152]. Although the zonally resolved response pattern is robust across models, it projects little onto a shift or strengthening of the jet when averaged zonally (Fig. 2c,d, Table 1). The pattern is stronger in CMIP6 than earlier generations, in part due to an increase in climate sensitivity[9]. A similar tripole pattern response to uniform warming in an aquaplanet model with an SST front imposed[153] suggests a potential role for changes in land-sea contrast. In CMIP6 models the tripole pattern is most robust in the seasonal mean, as it is enhanced by combining a poleward jet shift in early winter with a weak equatorward shift in late winter[154], potentially owing to sea ice loss[155]. However, the tripole pattern is only robust in the seasonal mean and, thus, might be an artefact of this combination[154]. Hence, while the eastward extension of the jet seems clear, the squeezing in latitude at any given time might be weaker than seasonal averaging suggests.

The jet is impacted by amplified warming at low levels in the Arctic and at upper levels in the tropics[156,157], changes to land-sea temperature contrasts[158,159] and changes in strength of the stratospheric polar vortex. However, the stratospheric response is inconsistent across models[11,144]. One distinct regional driver is the North Atlantic warming hole, a local minimum in SST warming in the subpolar gyre region which is related to the projected weakening of the Atlantic Meridional Overturning Circulation (AMOC). Associated changes in baroclinicity can affect the local storm track and jet response, albeit with some dependence on the model's basic state[160–162]. In contrast, the remote effect of Pacific SSTs can be an important factor in some models[23,163–165] via a Rossby wave teleconnection that is well validated on seasonal timescales.

Nonlinear interactions between different drivers are non-negligible in North Atlantic winter[166]. Some attempts have been made to apply a storyline approach to disentangle the influence of a multitude of competing factors[167]. There is a notable robustness of the jet and storm track extension into Europe, potentially owing to several different drivers projecting onto this response (such as uniform warming with associated tropical upper-level amplification[153,156] and rise of the tropopause, AMOC weakening[168,169], and clouds[170]). In terms of the intra-seasonal split, the tropical warming and the Atlantic warming hole contribute in early winter, whereas the stratospheric vortex changes dominate in late winter[154].

Projections in summer, and to some extent autumn, show a simpler response pattern corresponding to a poleward shift[9] (Fig. 4d–e) of 1.2°N and 1.5°N in the zonal and model mean, respectively (Fig. 2c, Table 1). In summer Arctic amplification and Rossby wave propagation are both weaker and the stratospheric polar vortex is absent[171], making these less important among other previously mentioned drivers. The North Atlantic warming hole can still affect the local storm track in summer[172], but the agreement across models on the poleward shift suggests that tropical upper-level warming is a major driver in that season (Fig. 2c, Fig. 4d). The larger shift in summer compared to winter can be reproduced in an aquaplanet model with a JJA SST distribution similar to observations[173].

The seasonal forecast skill in the North Atlantic Oscillation is reliant on accurate representation of the underlying jet drivers. However, the strength of the modelled forecast signal is weak relative to the noise[73] and the response to North Atlantic SST might not be captured correctly[79], which raises concerns about the ability of models to capture the North Atlantic jet response to drivers. This discrepancy could have implications for how well models capture the magnitude of the jet response to greenhouse gas forcing, depending on the extent to which the same physical mechanisms are involved in both cases. It is likely that some, but not all, of the mechanisms involved in the jet response to climate change can be tested on the seasonal timescale. The seasonal predictability of the jet is considerably smaller in summer compared to winter[72], suggesting a weaker overall influence of predictable drivers on the jet in summer. There is however considerable variability in seasonal predictability on decadal timescales, which arises in part due to aerosol forcing and decadal ocean variability[174].

[H2] ***North Pacific***

Under anthropogenic greenhouse gas driven warming, some of the most pronounced changes in the Pacific jet stream are predicted to occur during the DJF season (Fig. 4b). In the western portion of the basin, the jet stream strengthens on its poleward flank and weakens on its equatorward flank. Conversely, the jet stream shifts equatorward on the eastern side of the basin. The zonal mean over these differing responses represents a weak poleward shift and no increase in wind speed in the model mean with a large model spread (Fig. 2c-d, Table 1), showcasing the shortcomings of the zonal mean view.

Two factors likely contribute to this circulation pattern in the eastern Pacific. One is the tendency of models to produce an SST pattern in response to global warming that resembles El Niño, which acts to shift the jet stream equatorward in the East Pacific[175,176]. The other is the warming of the tropical upper troposphere and the resulting strengthening of the subtropical upper-tropospheric westerlies, which acts to alter the structure of the stationary waves supported by the Pacific waveguide[17]. The apparent inability of models to reproduce the La Niña-like trends that have occurred over the satellite period[177–179] does raise questions over whether the El Niño-like SST anomalies predicted for the future will actually happen in reality.

During the extended winter period, amplified Arctic warming is a driver that weakens the temperature gradient in the Northern Hemisphere, weakening the jet stream and causing an equatorward shift that can persist into summer[12,180]. However, this effect is projected to be overpowered by tropical upper-tropospheric warming[165], as well as changes to land-sea temperature contrast[159] which are also important in summer[134]. Additionally, the projected weakening of the polar vortex is expected to contribute to a weakening of the jet stream[165].

Comparatively less work has examined the North Pacific jet response in seasons other than winter. Similar to winter, CMIP6 models project a robust poleward shift in autumn across models[181], which is dominated by a weakening on the subtropical side of the jet in the East Pacific (Fig. 4e) and corresponds to a zonal and model mean latitude shift of 1.1°N (Fig. 2c, Table 1). A weaker poleward jet shift is found in MAM but is absent in JJA[181], which instead shows a large spread in zonal mean latitude shift and a more robust decrease in peak jet strength (Fig. 2c-d, Fig. 4c-d, Table 1). More work is needed to understand the possible drivers that could explain the seasonality of this response.

[H2] ***Southern Hemisphere***

For austral summer (DJF), models consistently predict a poleward shift and strengthening of the zonal-mean jet across model generations, from CMIP3[182] (in the annual mean), to CMIP5[6,7,27,118] and CMIP6[28,109,118,183]. The longitudinally resolved response shows a high degree of zonal symmetry of the poleward shift in the model mean with strong model agreement (Fig. 4b). In the zonal mean, the model mean predicts a robust poleward shift of 1.1°S (Fig. 2c, Table 1), with similar projections for the Indo-Atlantic and Pacific regions separately, in line with the high degree of zonal symmetry in projections. The response projects a greater strengthening in the Pacific than in the Atlantic, leading to a robust hemispheric zonal mean strengthening of 1.0 m/s (Fig. 2c-d, Fig. 4b; Table 1).

As for the climatology, the stratospheric polar vortex has an important role in future projections in DJF. Delays in the vortex breakdown induce a poleward shift of the jet alternatively viewed as a delayed equatorward transition[46,145,184]. Increased greenhouse gas concentrations lead to a cooling of the stratosphere and thus a delay in vortex breakdown[185,186], whereas ozone recovery has the opposite effect[186,187]. In high-emission scenarios this tug-of-war is projected to be won by the greenhouse gas increase[183], with models with prescribed (as opposed to interactive) ozone systematically estimating an overall larger response[188], due to less ozone recovery during spring time. Tropical upper-tropospheric warming leads to a zonally asymmetric strengthening of the jet with no signal in the East Pacific and an enhanced strengthening southeast of Australia[150].

In austral winter (JJA), the projected response is more zonally asymmetric than in summer, in line with the underlying asymmetry of the climatology (Fig. 4d). The response reduces the double jet structure at low levels in the Pacific region, making the zonal winds somewhat more zonally symmetric. The zonal-mean response is a poleward shift and strengthening in CMIP5[118] and to a lesser extent in CMIP6[118,183] (Fig. 2 c-d, Table 1), but individual sectors show a more complicated picture likely because of asymmetries in both the climatology and the response[7,127]. In the Pacific, the zonal mean shows a poleward jet shift and strengthening (albeit with high model disagreement), whereas the Atlantic shows comparatively little poleward shift and less strengthening (Fig. 2c-d).

The poleward jet shift in JJA has been attributed to both increasing polar vortex strength and tropical upper-tropospheric warming[31,150,189]. Comparatively, the contribution of polar vortex strengthening is zonally symmetric, whereas tropical upper-tropospheric warming exhibits a more zonally asymmetric signature with strong wind increases poleward of Australia[150]. Part of this asymmetry might be due to changes in stationary Rossby waves triggered by tropical and subtropical SST patterns and circulations[190].

Spring (SON) wind changes are similar to JJA albeit with a more symmetric background climatology, the autumn (MAM) response is similar to DJF but with the response projecting more onto a jet strengthening (Fig. 2c-d; Fig. 4c,e). A robust strengthening is projected in the zonal mean during both seasons, with an additional poleward shift in MAM[183] (Fig. 2c-d; Table 1). Although the impact of ozone depletion is greatest in late austral spring and summer, lower-stratospheric ozone depletion might also drive tropospheric circulation changes in May[191]. However, these changes are expected to reverse with ozone recovery, similar to DJF.

The future jet stream projections for all regions and seasons are summarised in Table 2 together with proposed drivers, which are additionally summarised in a schematic (Fig. 3b).

[H2] ***Uncertainties***

Future projections of the jet stream are highly uncertain owing to internal variability [192]. Despite good model agreement on the sign of forced wind changes in many regions, the magnitude of future changes often remains uncertain[6,28] (Fig. 2c-d, Fig. 4, Table 1). Part of these uncertainties come from uncertainties in the drivers, part relate to how the mean state or internal dynamics of the jet stream respond to those drivers[193]. As the circulation response can be the residual of larger, mutually cancelling responses to individual drivers (for example, the opposing influences on baroclinicity from Arctic warming and tropical upper-tropospheric warming[130,194], or the competing effects of direct CO_2 forcing and SST increase[134]), small changes in the relative strengths of drivers can substantially impact the overall response.

Past efforts to reduce uncertainties have tried to constrain predictions based on observable characteristics of the jets or their drivers, with varying degrees of success. A zonal-mean constraint on the future jet shift in the Southern Hemisphere was found in relation to its climatological position[182], but the seasonality was later questioned[27] with only a constraint in winter remaining. This wintertime constraint was then found to be caused by the confounding effect of zonal averaging over zonal asymmetries in the climatology[127], and the constraint did not hold in individual ocean basins.

Another proposed constraint is for the equatorward jet shift that occurs in both hemispheres due to sea ice loss, which was constrained on the observed eddy feedback. The constrained contribution might even be larger than that due to increasing SST, suggesting a possible equatorward shift[195]. Additionally, to tackle the uncertainty contribution from internal variability, machine learning approaches have been introduced in an attempt to isolate the forced response component in future projections[192]. However, the overall spread in model projections remains relatively unconstrained.

Understanding and characterising uncertainties can help gauge future possibilities. To this end, storylines can be used to connect possible responses with their drivers in a physically consistent way. This storyline approach has been developed in the community to achieve greater physical insight[12]. The technique was applied to the North Atlantic[167] and Southern Hemispheric[150,196] jet streams, using the stratospheric vortex strengthening, polar lower-level warming and tropical upper-level warming as predictors. Another approach to characterizing uncertainty is by apportioning it to its sources[197,198]: scenario uncertainty, the uncertainty in future human emissions; internal variability, the contribution of unforced climate variations; and model uncertainty, differences in responses due to structural differences in the model physics. However, this approach has not yet been applied to midlatitude circulation changes.

[H1] Observed trends

Analysing observed trends in regional jet streams can help assess responses to present-day warming and their alignment with future projections. However, large uncertainties remain in observed trends owing to the relatively short time period over which strong greenhouse gas forcing occurred combined with large internal variability in mid-latitude circulation (compare the difference in observed trends between 1979–2014 and 1979–2023, Supplementary Figure 1) and methodological choices[199,200]. To aid the discussion, wind trends over the period 1979-2014 from reanalysis, CMIP6's historical and atmosphere-only (Atmosphere Model Intercomparison Project, AMIP) simulations and experiments are analysed (Fig. 5, Fig. 2e-f, Table 1, Supplementary Figure 2).

[H2] ***Comparing CMIP6 simulations and reanalysis data***

The presented AMIP simulations are forced with time-varying observed SST, enabling closer comparison with reanalysis by removing model SST biases and controlling for ocean variability. Note however that the atmospheric response to the imposed SST can be mis-represented in the models, and furthermore these experiments cannot distinguish between externally forced and internally generated variations, since the imposed SSTs include both forced and unforced anomalies. That said, the AMIP simulations do capture some observed trends well, particularly in the Southern Hemisphere. For comparison, CMIP6 historical wind trends over the same time period are shown in Supplementary Figure 2. They do not show much trend, with the notable exception of the Southern Hemispheric summer poleward jet shift.

[H2] *Zonal-mean perspective*

A general poleward shift of the jets has been detected in observational datasets[201,202], although often only on the broadest scale as revealed by zonal means. On this scale, the emergence of poleward as opposed to equatorward shifts suggests the effects of tropical upper-level warming might dominate over Arctic low-level warming[136]. However, wind trends can vary widely across basins and are mostly not statistically significant at any given location. For example, despite evidence of a weakening of westerly winds in the Northern Hemisphere summer that is potentially related to Arctic warming[203], significance is limited to a small region in the subtropics, which limits confidence in a sustained weakening trend [136,202]. Beyond the mean-state trends, there is some evidence that the zonal wind distribution is changing such that the fastest jet speeds have accelerated[200,204].

[H2] *North Atlantic*

The North Atlantic jet has notable variability on the multidecadal timescale, which is generally not captured by state-of-the-art numerical climate models[86,205]. As a result, observed trends are sensitive to the time period used. Over the satellite period, wintertime trends are weak when considering the Atlantic in isolation (Fig. 2e-f; Fig. 5b, Table 1), though a signal of increased vertical wind shear associated with changes in the upper-tropospheric temperature gradient has been detected[206]. Over a longer period from 1951, the jet appears to have strengthened substantially[207], not captured by models[207], with multidecadal variability likely being important[208]. An even longer record from 1871 shows signs of a poleward shift[209]. However, regional trends can be quite different as the summertime jet exit is located at a high latitude so can shift equatorward over Europe while still projecting onto a poleward shift in the zonal mean[200].

In summer, the North Atlantic jet shifted equatorward on the eastern part of the basin, in a manner not fully captured by the zonal mean (-0.53°N/dec, $p=0.12$; Fig. 2e, Fig. 5d, Table 1), in contrast to historical model simulations[87] (Supplementary Figure 2j). Although internal variability involving North Atlantic SSTs and anthropogenic aerosol forcing[174] likely have a role in this shift, AMIP simulations include both of these components and still do not capture the trend in the model mean (Fig. 5d), suggesting that sub-grid scale processes might explain part of the discrepancy. The SST forcing in both seasons potentially includes a long-term warming hole effect, in addition to the Atlantic Multidecadal Variability phenomenon[200], although the AMIP simulations show little signal in the North Atlantic in any season (Fig. 2e-f; Fig. 5b-e, Table 1). The Mediterranean jet has been found to show an equatorward trend, attributed partly to historical aerosol forcing[210].

[H2] *North Pacific*

There is some evidence of a poleward jet shift in winter[181], especially in the East[200] and Central Pacific[211] and over the Sea of Japan[211]. This shift is consistent with the poleward shift in DJF in the East Pacific and zonal mean (0.31°N/dec, $p=0.05$) and, to some extent, in SON in the West Pacific (Fig. 5 b,e) and zonal mean (0.39°N/dec, $p=0.15$; Fig. 2e). A general weakening of the flow over most parts of the North Pacific basin in all seasons except for JJA was observed[200] (Fig. 2f, Fig. 5b-e). Aerosols have been identified as an important driver in the North Pacific summer over the historical satellite period[212]. However, over a long record from 1871, observed jet trends in the North Pacific have been found to be weak when averaged over the basin[209].

The large variability associated with clear ENSO and PDO impacts[93,209] will hinder the detection of clear trends and might explain differences in findings. However, this variability also indicates that any forced changes in Pacific SST patterns are likely to be important regional drivers. Indeed, the AMIP simulations are indicative of a poleward shift in the annual mean (Fig. 2e, Fig. 5a), which could be partially due to Pacific SST trends as well as greenhouse gas forcing[213].

[H2] *Southern Hemisphere*

The clearest observed trends in the Southern Hemisphere are found in austral summer (DJF), where the zonal-mean jet has shifted poleward (0.29°S/dec, p=0.03) and strengthened (0.29 m/s/dec, p=0.03; Fig. 2e-f; Fig. 5e-f, Table 1). In large part, this trend is due to polar stratospheric ozone depletion since the 1970s, with a further contribution from greenhouse gas-driven global warming[147,214,215]. There is evidence that this poleward trend has paused since the early 2000s, consistent with a stabilisation of the ozone hole[216]. The poleward jet shift in DJF is present in AMIP simulations (Fig. 2e, Fig. 5b and coupled historical simulations[136] (Supplementary Figure 2d), suggesting this trend is predominantly forced. Considering the full vertical profile of observed DJF wind trends also reveals a clear signature of greenhouse gas-driven global warming, with a vertical expansion and strengthening of upper-tropospheric winds[217,136].

A significant strengthening and poleward shift of the zonal-mean jet is also observed in MAM (Fig. 2e-f; Fig. 5h-i; Table 1), as well as in the annual mean (0.13°S/dec, p=0.03; 0.24 m/s/dec, p=0.01; Fig. 2e-f; Fig. 5b-c), but not in other seasons (Fig. 2e-f; Fig. 5; Table 1). By contrast, AMIP simulations indicate a poleward jet shift in all seasons (Fig. 2e-f; Fig. 5). The discrepancy between simulations and observations suggests a role for atmospheric variability that is unrelated to SST, or perhaps a shortcoming of the models. Indeed, models underestimate Southern Hemispheric storminess trends partly due to an incorrect representation of Southern Ocean and tropical East Pacific SST trends, although the observational uncertainties are large[218]. Natural variability makes a substantial contribution to the observed trends in other seasons than DJF, where ozone depletion effects dominate[118].

The observed zonal-mean wind response obscures notable zonal asymmetries across basins. In particular, the Pacific sector trend during 1980–2018 in the annual-mean, as well as during the JJA and SON seasons, differs from the trend in the Atlantic and Indian sectors[219] (Fig. 2e-f, Fig. 5). However, the Pacific sector features a double-jet structure in winter and spring, complicating the interpretation of the wind trends as a simple meridional shift or strengthening[127]. AMIP simulations also feature a zonally asymmetric component to the wind trends, particularly in JJA, where the baseline climatology is most zonally asymmetric (Fig. 5d). The 1979–2014 period featured a pronounced tropical Pacific SST pattern reminiscent of a negative phase of the Interdecadal Pacific Oscillation[178], which is likely to have contributed to the zonal asymmetry of the observed jet stream trends through stationary Rossby wave anomalies[220]. In the future, tropical Pacific SST variability is likely to remain a key control on the austral jet stream, together with the tug-of-war between a recovering Antarctic ozone hole and increasing greenhouse gas forcing[221].

[H1] Summary and future perspectives

Trends in the eddy-driven jet streams are most easily detected at large spatiotemporal scales, such as in zonal and annual means. However, averaging can lead to misleading interpretations of the circulation responses and a regionally and temporally resolved analysis is necessary to fully understand the jet stream, its drivers and its response to anthropogenic climate change. The overall picture is a complex one. Jet dynamics over all ocean basins involve multiple drivers often showing considerable seasonality. Particularly important drivers include the tropical upper-tropospheric warming, changes to the polar stratospheric vortex, and tropical SST warming patterns and the associated changes in Rossby wave generation, particularly in the Pacific. Generally, the jet streams are projected to strengthen and shift poleward, with several notable exceptions mostly in the Northern Hemisphere, such as over the East Pacific (Figs. 2,4, based on 700 hPa winds). A poleward shift in observed trends of the Southern Hemispheric jet stream seems the most robust signal, driven in part by stratospheric ozone depletion[214,215]. Aerosols have likely influenced Northern Hemispheric summer jet trends[141,212]. A poleward shift in winter in the Northeast Pacific is emerging, whose causes are however not understood or simulated.

The authors suggest future research to prioritize optimising detectability of jet stream responses. Careful consideration of the choice of spatio-temporal averaging domain can help maximise the detectability of jet responses. For example, the choice of seasonal averaging of the North Atlantic jet stream is important for the detectability[222] of the future response and its physical interpretation[154]. Performing similar investigations into the optimal choice of spatial and temporal averaging for other jet stream regions is an important area for further work. Employing novel objective jet detection methods, or expanding the use of existing ones[71,223,224], could help circumvent some of the ambiguities related to spatio-temporal averaging[225].

Similarly, quantifying the relative contributions of externally-forced responses versus unforced variability of the jet is necessary to determine when forced responses might be expected to become detectable in the future. Large ensembles, alongside an uncertainty quantification framework[197,198] and novel statistical approaches could be used to isolate the forced response from internal variability in the observational record and address this knowledge gap. However, there is the complication of possible underestimates of both the jets' decadal variability and the jet response to large-scale forcings in models, which underlines the need for joint progress on the various highlighted research areas below.

Further identifying and quantifying the large-scale drivers of jet stream responses in another research priority. Identifying drivers that involve observable aspects of present-day climatology (in terms of mean state or variability) would be particularly powerful, as such drivers lend themselves to observational constraints. A classic example is the proposed relationship between present-day jet latitude and future shift in the Southern Hemisphere, which was originally interpreted in terms of fluctuation-dissipation theory[182]. It has since been shown that the seasonality of the relationship is inconsistent with the theory[27], and that instead the relationship arises as an artefact of zonal averaging over distinct jet features in austral winter[127]. This example points to the importance of carefully considering the temporal and spatial domains for jet averaging. Nevertheless, it seems likely that additional drivers exist whose effects are observable and thus constrainable from climatology.

Novel applications of interpretable machine learning methods might speed up progress towards identifying jet stream drivers and quantifying their impacts, with two methods seeming particularly promising. Causal discovery algorithms can help to disentangle the causal linkages between jet streams and other large-scale phenomena – for example the stratospheric vortex or ENSO – while also providing quantitative information on the magnitude and timescale of the jet response to drivers[14,226]. Controlling factor analysis is another example, where a target variable of interest is modelled as a function of a physically-based set of predictors, and the relationships with each of the predictors are estimated from observable variability to constrain the inter-model spread in future response[227]. Such controlling factor analyses have been successfully applied to the problem of cloud feedback[228] and likely could be used for jet stream responses where a suitable set of controlling factors can be identified. These methods could be used in addition to, or in combination with, the more traditional approach of a model hierarchy.

Another suggested research priority is to further learn from the signal-to-noise paradox. This term refers to the apparent inability of climate models to accurately simulate the magnitude of the jet response to a given large-scale forcing, a problem identified in the seasonal forecasting of the North Atlantic Oscillation[73,79]. This paradox casts substantial doubt on the ability of climate models to accurately represent the magnitude of jet responses on longer decadal scales. However, despite posing a challenge for seasonal-to-decadal prediction of jet stream changes, the paradox also provides an opportunity for improving both process understanding of driver influences on the jet stream and their representation in models. Leveraging seasonal prediction systems and focusing on case studies of specific seasons with leading contributions to the forecast skill would accelerate progress[229]. These avenues provide an opportunity to probe the mechanistic pathways from a remote driver to the seasonal jet signal, and to quantitatively compare these between models and reanalysis, potentially performing idealised experiments to isolate specific processes.

Future work should also harness the opportunities of high-resolution modelling. A lack of model resolution might contribute to the signal-to-noise paradox, given evidence that coarse-resolution global climate models underrepresent the atmospheric response to ocean forcing[81]. In addition to the development of modelling hierarchies for process understanding[230,231], hierarchies of model resolutions should also be developed to allow systematic assessment of the impacts of resolution of the atmosphere, the ocean, and their coupling. The effectiveness of this hierarchy would be strengthened by applying statistical methods, such as causal discovery algorithms, to understand how the linkages change as a function of model resolution. In particular, high resolution modelling offers the opportunity to understand how sharp SST fronts (particularly near western boundary currents) and ocean mesoscale eddies influence jet stream dynamics and how the winds, in turn, affect ocean conditions[81]. These are a few avenues that can be explored to further constrain projected jet stream change, thereby reducing uncertainty in associated societally relevant climate impacts.

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Author contributions

PB and PC initiated and led the synthesis and writing. IRS created Figs. 1 and 4; PB created all other figures. All authors contributed to the writing and editing of the article and gave feedback on the figures.

Data availability

CMIP6 data used in this study is publicly available from the Earth System Grid Federation (https://aims2.llnl.gov/search/cmip6/). ERA5 data is publicly available from the Copernicus Climate Data Store (https://cds.climate.copernicus.eu/datasets). Code used to analyse the data and produce the figures will be shared upon request.

Competing interests

The authors declare no competing interests.

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Table 1. Jet position and strength measured as zonal-mean centroid latitude and maximum wind speed.

		DJF		MAM		JJA		SON	
		Obs.	MM	Obs.	MM	Obs.	MM	Obs.	MM
Climatology	NA	44.5°N 13.0m/s	43.8°N (3.4) 13.5m/s (2.6)	43.9°N 8.8m/s	43.1°N (3.6) 10.1m/s (2.2)	47.0°N 8.9m/s	47.3°N (3.2) 8.6m/s (2.3)	47.3°N 10.5m/s	46.6°N (3.2) 10.6m/s (2.4)
	NP	38.8°N 14.7m/s	38.1°N (2.0) 15.1m/s (2.7)	40.3°N 11.9m/s	40.0°N (2.0) 11.7m/s (1.6)	43.7°N 7.6m/s	44.7°N (3.7) 7.1m/s (1.7)	44.1°N 11.6m/s	44.3°N (2.2) 11.8m/s (2.1)
	SH	48.4°S 16.4m/s	48.2°S (2.6) 16.4m/s (2.2)	48.6°S 15.8m/s	48.7°S (2.1) 15.9m/s (2.9)	46.4°S 13.6m/s	45.6°S (2.2) 13.1m/s (2.6)	47.7°S 15.5m/s	47.2°S (2.1) 15.2m/s (2.8)
Projected	NA	–	-0.1°N (1.5) 0.4m/s (1.2)	–	0.9°N (1.5) 0.0m/s (0.9)	–	1.2°N (1.1) -0.3m/s (1.0)	–	1.5°N (1.8) 0.4m/s (1.1)
	NP	–	0.6°N (1.1) 0.1m/s (1.8)	–	0.4°N (1.2) 0.0m/s (1.1)	–	-0.3°N (1.6) -0.9m/s (1.2)	–	1.1°N (1.3) -0.4m/s (1.2)
	SH	–	1.1°S (1.0) 1.0m/s (0.7)	–	1.1°S (0.8) 1.3m/s (0.7)	–	0.8°S (0.9) 1.4m/s (0.8)	–	0.5°S (0.8) 1.5m/s (0.9)
Trends	NA	-0.12°N/d (p:0.37) 0.11m/s/d (p:0.94)	0.09°N/d (0.72) -0.13m/s/d (0.6)	-0.34°N/d (p:0.59) 0.18m/s/d (p:0.65)	0.12°N/d (0.75) -0.1m/s/d (0.39)	-0.53°N/d (p:0.12) -0.12m/s/d (p:0.61)	-0.01°N/d (0.55) -0.1m/s/d (0.27)	0.32°N/d (p:0.14) -0.15m/s/d (p:0.38)	0.06°N/d (0.48) -0.11m/s/d (0.45)
	NP	0.31°N/d (p:0.05) -0.19m/s/d (p:0.38)	0.12°N/d (0.41) -0.3m/s/d (0.48)	-0.04°N/d (p:0.67) -0.21m/s/d (p:0.45)	0.34°N/d (0.43) -0.38m/s/d (0.41)	-0.01°N/d (p:0.74) 0.1m/s/d (p:0.61)	0.31°N/d (0.55) -0.08m/s/d (0.37)	0.39°N/d (p:0.15) 0.01m/s/d (p:0.76)	0.23°N/d (0.38) -0.06m/s/d (0.38)
	SH	0.29°S/d (p:0.03) 0.29m/s/d (p:0.03)	0.32°S/d (0.35) 0.16m/s/d (0.24)	0.26°S/d (p:0.05) 0.39m/s/d (p:0.01)	0.18°S/d (0.23) 0.21m/s/d (0.24)	0.01°S/d (p:0.72) 0.05m/s/d (p:0.40)	0.12°S/d (0.29) 0.19m/s/d (0.29)	0.00°S/d (p:0.96) 0.16m/s/d (p:0.38)	0.15°S/d (0.26) 0.14m/s/d (0.28)

Footnote Table 1: Jet position and strength for all seasons and over the three oceanic basins of Southern Hemisphere (SH), Northern Hemispheric Atlantic (NA; 60°W-0°) and Northern Hemispheric Pacific (NP; 120°E-240°E); for ERA5 observations and CMIP6 models. Shown are values for the climatology of 1979-2023 (historical up to 2014 and SSP5-8.5 thereafter for CMIP6), projected change between 2081–2100 (SSP5-8.5) and 1979 to 2023, and historical ERA5 and AMIP trends over 1979-2014 trends (from yearly averaged data using the Theil-Sen estimator[232]). The values correspond to those displayed in Fig. 2. In brackets we show the range of 2 standard-deviations of the multi model ensemble values or the *p*-value of the observed trend calculation, using prewhitening[233] on detrended data, to account for serial dependence, before applying the Mann-Kendall test[234,235]. These values will not cover the true range of uncertainty, since they do not account for observational uncertainty or internal variability. All values are shown for the seasons December-January-February (DJF), March-April-May (MAM), June-July-August (JJA) and September-October-November (SON). Empty cells are denoted with an en-dash (–). The multi-model mean (MM) response is often substantially smaller than the inter-model spread in the response; only in the Southern Hemisphere do we find robust and consistent jet responses across projections as well in the observed trends in DJF and MAM.

Table 2. Summary of characteristics and drivers of jet climatology, projection and trends.

	DJF	MAM	JJA	SON
North Atlantic				
Climatology	Strong Soutwest to northeast tilt (SW-NE) tilt Similar position as MAM	SW-NE tilt, similar to DJF but weaker	SW-NE tilt, poleward compared to DJF and weaker winds	SW-NE tilt, similar to JJA but stronger
Drivers	Rocky Mountains[36], Gulf Stream,American coastline[36], storm track latent heating[55], land-sea contrast[54] and subpolar gyre, tropical SST[13], Stratospheric variability[44], North Atlantic SST[78–80], Greenland topography[77]	-	Similar drivers as DJF but weaker, Aerosols[141]	-
Projected	Tripolar response, possible artefact [154]	-	Poleward shift (PS)	PS
Drivers	Amplified Arctic Warming[156,157] (AAW), Tropical upper-tropospheric warming[153,156] (TUTW), Weakening of AMOC leading to North Atlantic Warming Hole[160–162] (NAWH), Land-sea contrast[158,159], Stratospheric polar vortex strength changes[11,144,158,159],Pacific SSTs cause RW teleconnection[23,163–165]	-	TUTW, NAWH[172], AAW less important, RW teleconnection less important, Aerosols	Similar to JJA
Observed	Increased vertical shear	-	Equatorward shift (ES)	-
North Pacific				
Climatology	Stronger in the West compared to the East SW-NE tilt; especially east side poleward deflection; Strongest and most equatorward	Broader tilt, Poleward shift, Weaker winds	Broader tilt, less poleward deflection in east pacific Most poleward	Equatorward shift Strengthening winds
Drivers	Diabatic heating driving stationary wave[49] , Mongolian Plateau[89,90], Transient Eddies[91], Land-sea contrast[159], ENSO shifts jet equatorward and lengthens to the East[93]	Orography of Tibetan plateau becomes more important[90]	Aerosols[212]	-
Projected	West Pacific PS, East Pacific ES		East Pacific weakening	West Pacific PS
Drivers	ENSO like warming pattern[175,176], Stronger subtropical jet and TUTW[17], AAW[12,180], Polar vortex weakening[165]	AAW[12,180], SST changes, TUTW, Polar vortex weakening	Arctic amplification[12,180] SST changes Aerosols	AAW[12,180], TUTW, Polar vortex weakening
Observed	East Pacific poleward shift	-	-	West Pacific poleward shift
Southern Hemisphere				
Climatology	Equatorward shift throughout season Higher persistence	Double jet starts developing	Zonally asymmetric, double jet over the Indo-Atlantic	Double jet extends into early spring
Drivers	Weakening of stratospheric polar vortex[100–104], ENSO correlates with equatorward jet shift and more asymmetric SAM[93,112–114]	See JJA, Ozone depletion[191]	Tropical SST and orography trigger RW[26,123,124], Stronger subtropical jet[24,125]	Weakening of the stratospheric polar vortex[103]
Projected	Poleward shift and strengthening	Similar to DJF	Asymmetric, Pacific reduced split, Atlantic PS and stronger	Similar to JJA
Drivers	Polar vortex strengthening[145,184], TUTW[150]	-	Polar vortex[31,150,189], TUTW[31,150,189], Tropical SST[190]	-
Observed	Poleward shift	Poleward shift	-	-

Footnote Table 2: The drivers might just cover some aspects of the climatology/projection, are not their sole cause and can also be opposing the resulting behaviour. Furthermore, the seasonality aspect is based on the studies reviewed here; an absence of a driver in a season does not necessarily mean it is not active, only that it was not specifically identified. Abbreviations not defined inside the table itself: December-January-

February (DJF), March-April-May (MAM), June-July-August (JJA), September-October-November (SON).

Figure 1. **Historical 700 hPa zonal reanalysis wind fields with corresponding CMIP6 model bias. a**. Annual mean zonal wind at 700 hPa from ERA5[236] over 1979-2023 (contour levels are drawn at 4 m/s intervals with dashed contours signifying negative values and the zero contour omitted). Model bias, calculated as the difference between CMIP6 model climatology and ERA5, in 700 hPa zonal wind (shading); stippling indicates where at least 39 of 43 models have the same sign in bias. Plots on the right depict zonal mean from ERA5 (black), CMIP6 (red-dashed) and the CMIP6 range (red shading). **b.** As in panel a, but for DJF. **c.** As in panel a, but for MAM. **d.** As in panel a, but for JJA. **e.** As in panel in a, but for SON. While the model-mean, zonal-mean winds reproduce observations well, considerable biases emerge when looking at specific regions and seasons.

Figure 2. Indices of jet latitude and strength in numerical models and observations. a. Climatological CMIP6 model- and ensemble-mean 700 hPa zonal mean centroid latitude[23] from the climatology from 1979 to 2023 (historical up to 2014 and SSP5-8.5 thereafter) in coloured circles and same for ERA5 in black stars; for the Southern Hemisphere zonal mean (SH), Southern Hemisphere Indo-Atlantic (SHA; 60°W-120°E), Southern Hemisphere Pacific (SHP; 120°E-300°E), Northern Hemisphere Atlantic (NHA; 60°W-0°) and Northern Hemisphere Pacific (NHP; 120°E-240°E). **b**. As in panel a, but for the maximum of seasonally-averaged wind speed. **c.** As in panel a, but for the difference between 2081–2100 (SSP5-8.5) and 1979– 2023 **d.** As in panel c, but for the maximum of seasonally-averaged wind speed. **e.** As in panel a, but for the observed trends in ERA5 over the period 1979–2014 (black stars) as well as the AMIP model trends (single realisation) over the same period. **f.** As in panel e, but for the maximum of seasonally-averaged wind speed. The basin average can be a useful simplification but hides strongly contrasting trends in different domains.

Figure 3. Drivers of the jet stream climatology and future response in different regions. a. Climatology. **b** Future response. Not all drivers are included, but the key drivers discussed here and in previous literature are highlighted to provide an overview. Many drivers shape both the climatology and the response of the jet streams, with some active in multiple regions and others confined to a single one.

Figure 4. Projected end-of-century change in zonal wind fields under a high-emissions scenario. a. Annual-mean, CMIP6 ensemble- and model-mean zonal wind climatology at 700 hPa over 1979 to 2023 (contour levels are drawn at 4 m/s intervals with dashed contours signifying negative values and the zero-contour omitted). Shading indicates future projected differences between 2081–2100 (SSP5-8.5) and 1979–2023 (historical up to 2014 and SSP5-8.5 thereafter). Stippling indicates where at least 39 of 43 models agree on the sign in change. Plots on the right depict the CMIP6 zonal-mean (red dashed) and the CMIP6 range (red shading), grey horizontal bars show the climatological jet latitudes. **b.** As in panel a, but for December–January–February (DJF). **c.** As in panel a, but for March-April-May (MAM). **d.** As in panel a, but for June-July-August (JJA). **e.** As in panel in a, but for September-October-November (SON). Future model projections show strong dependence on region and season, which is hidden in the zonal and/or annual mean.

Figure 5. Observed trends in zonal wind fields. a. Annual-mean zonal winds at 700 hPa, left: from the Atmospheric Model Intercomparison Project (AMIP) over 1979–2014 (contour levels are drawn at 4 m/s intervals with dashed contours signifying negative values and the zero contour omitted). Shading signifies trends over the same period, stippling indicates where at least 39 of 43 models agree on the sign of the trend. Trends were computed[237] from yearly averaged data using the Theil-Sen estimator[232]; centre: for ERA5, stippling shows the significance at $p<0.1$, significance was tested by prewhitening[233] the detrended data, to account for serial dependence, before applying the Mann-Kendall test[234,235] and finally controlling for multiple testing[238]; right: zonal mean of the trend maps for AMIP (red lines) and ERA5 (blue lines) as well as AMIP model spread (red shading) and ERA5 climatological jet latitudes (bars). **b** As in a but for December-January-February (DJF). **c** As in a but for March-April-May (MAM). **d** As in a but for June-July-August (JJA). **e** As in a but for September-October-November (SON). Jet stream trends are highly dependent on region and season.