Current Climate Change Reports (2025) 11:2
https://doi.org/10.1007/s40641-024-00199-3

REVIEW

Advancing Our Understanding of Eddy-driven Jet Stream Responses to Climate Change – A Roadmap

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Accepted: 27 September 2024

Abstract

Purpose of Review Extratropical jets and associated storm tracks significantly influence weather and regional climate across various timescales. Understanding jet responses to climate change is essential for reliable regional climate projections. This review serves two main purposes: (1) to provide an accessible overview of extratropical jet dynamics and a comprehensive examination of current challenges and uncertainties in predicting jet responses to greenhouse gas increases and (2) to suggest innovative experiments to advance our understanding of these responses.

Recent Findings While successive generations of climate model ensembles consistently project a mean poleward shift of the midlatitude zonal-mean maximum winds, there remains considerable intermodel spread and large uncertainty across seasonal and regional jet responses. Of particular note is our limited understanding of how these jets respond to the intricate interplay of multiple concurrent drivers, such as the strong warming in polar and tropical regions, and the relative importance of each factor. Furthermore, the difficulty of simulating processes requiring high resolution, such as those linked to sharp sea surface temperature gradients or diabatic effects related to tropical convection and extratropical cyclones, has historically hindered progress.

Summary We advocate for a collaborative effort to enhance our understanding of the jet stream response to climate change. We propose a series of new experiments that take advantage of recent advances in computing power and modelling capabilities to better resolve small-scale processes such as convective circulations, which we consider essential for a good representation of jet dynamics.

Keywords Jet stream · Climate change · Climate projections · Regional climate projections · Projection uncertainty · Sensitivity experiments

Introduction

The jet streams are among the most remarkable atmospheric circulation phenomena. These powerful air currents are a permanent feature of the atmosphere and have a strong influence on climate and weather around the planet. In the zonal average, two (not always distinct) jets may be found in each hemisphere: a *subtropical jet* (hereafter STJ) that approximately marks the transition between the tropical zone and the dry subtropics, and a polar front or *eddy-driven jet* (hereafter EDJ) that separates the cold high-latitude air from

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Published online: 06 November 2024

the warmer subtropical air. The EDJs guide storms towards the west coasts of the continents via relatively narrow paths over the oceans called storm tracks [1, 2], which strongly determine the regional hydroclimate and storminess.

Observational and modelling evidence shows that the position and intensity of the jet streams vary on timescales ranging from days to centuries, accounting for a large fraction of the regional climate variability in the extratropics [3]. In regions located in climatic transition zones such as the Sahel or California, decadal and multidecadal fluctuations in the jet can have dramatic, long-lasting effects (e.g., Wahl et al. [4]), while interannual and intraseasonal variations may lead to anomalous weather regimes and sometimes extreme weather events. For example, in the winter of 2009/2010, a strongly southward-shifted jet over the North Atlantic caused very cold conditions over most of Europe [5], while in the winter of 2011/2012, a poleward-displaced jet resulted in a severe drought over Spain and Portugal [6].

Given the jet´s large impact on regional climate and weather, understanding how it will respond to increased greenhouse gas (GHG) concentrations is a key area of research. Although there is wide agreement on the expected changes in impact-relevant thermodynamic aspects of climate change (e.g., global warming with continental and polar amplification, increase in sea level, ice melt; IPCC, 2023 [7]), the response of many aspects of the atmospheric circulation, including the jets, to climate change, remains poorly understood [8–11]. A single agreed-upon theoretical explanation is lacking [12], although early papers suggested a weak poleward shift (i.e., Kushner et al. [13]), which appeared consistent with the local shift in lower-tropospheric temperature gradients/baroclinicity. Yet this poleward shift is not unambiguously corroborated by observations, and current model projections are also far from being conclusive. For example, while many models project a poleward displacement of the zonal-mean EDJs [14–16], the magnitude of this shift varies significantly between models, and regionally, the models show disparate and often opposite responses [16, 17]. Critically, there exist several competing drivers and associated mechanisms that have the potential to enhance or reduce the intensity of the jet as well as to alter its position (e.g., Shaw [12] and Sect. "Jet phenomenology: A short introduction"). Our quantitative understanding of the relative importance of these drivers is limited, which contributes to the uncertainty and lack of confidence in model projections and observed trends. The simple fact that both the near-surface and the upper-level meridional temperature gradient influence the jet and that these gradients change in the opposite sense as the planet warms (given the observed simultaneous occurrence of polar amplification at the surface and tropical amplification aloft) may lead to misleading results if only one of these metrics is taken into account. The issue is compounded by the limited availability of long records of reliable upper-level observational/reanalysis data, which hinders the clear separation of a forced signal from internal variability in the historical record that could be used to validate projected changes.

Encouragingly, developments in seasonal and decadal forecasting have demonstrated that current models have some skill in predicting certain aspects of the extratropical circulation, such as North Atlantic Oscillation (NAO) fluctuations [18, 19], beyond the deterministic timescales of weather forecasts. The NAO is intimately linked to the strength and position of the North Atlantic jet, and, therefore, these forecasts suggest that a fraction of the EDJ variability is forced by predictable drivers [20, 21], such as sea surface temperatures (SST) and stratospheric circulation anomalies. Identifying these drivers and the specific mechanisms by which they affect the EDJ and determining how they will respond to increasing GHGs is a potential avenue to increase our understanding of the jet response to climate change and reduce the uncertainty in the projections of future jet behaviour.

We believe it is critical to undertake a coordinated effort aimed at improving our understanding of the jet response to increased GHGs. Coordinated experiments, such as the Polar Amplification Model Intercomparison Project (PAMIP) [22], have proved very useful in testing specific individual mechanisms, such as those involved in the circulation response to future sea ice loss [23]. The jet, however, is subject to multiple concurrent influences, and therefore, experiments to test the jet's response to *simultaneous* forcings are urgently needed. Moreover, mounting evidence emphasizes the necessity of accurately representing diabatic processes to capture the jet states faithfully (e.g., Schemm [24]). Thus, such experiments would greatly benefit from recent strides in computational capabilities, which enable high-resolution (~km-scale) coupled climate simulations on a global scale. While these simulations are currently employed to assess climate change impacts (e.g., Wedi et al. [25]; Hohenegger et al. [26]), we argue that they should also serve as a tool for conducting sensitivity studies on the circulation's response to increased GHGs.

This manuscript aims to highlight knowledge gaps, review and reconcile different findings on expected future changes in the midlatitude EDJs and advocate for a coordinated effort to enhance our understanding of their response to global warming. We focus on the EDJ because it is more closely related to surface impacts in the extratropics. However, we fully acknowledge that changes in the subtropical jet are also of significance. Sect. "Jet phenomenology: A short introduction" provides a concise overview of the jet stream's characteristics, intended as a reference for readers from diverse backgrounds. Sect. "Eddy-driven jet response to increased GHG gases" delves into the various mechanisms that potentially contribute to the jet stream's response to anthropogenic forcings, covering changes in mean position, strength and variability. Lastly, Sect. "Key challenges and ways forward" identifies and discusses key knowledge gaps while proposing

potential research avenues, including model experiments, to advance our understanding of the jet stream's response.

Jet phenomenology: A short introduction

According to theory, rotating planets with differential meridional heating support the existence of two different types of jets: a "thermally-driven" jet that results purely from conservation of angular momentum (in the absence of eddies, Held and Hou [27]) and an "eddy-driven" solely due to momentum flux convergence by transient eddies (neglecting advection of angular momentum, Panetta [28]). On Earth, which is a fast rotating planet, the two types of jets coexist, although they are not always clearly separated. The STJ is located at the poleward edge of the Hadley Cell (HC): it primarily results from angular momentum conservation in the upper branch of the HC and is, therefore, baroclinic. The EDJ is located further poleward, is equivalent barotropic, extending throughout the depth of the troposphere, and results from transient momentum flux convergence by Rossby waves [29–31]. The two driving processes interact and the jets can mutually influence each other. Moreover, in many instances, the jets merge into a single structure (e.g., Lee and Kim [32]).

In the absence of zonal asymmetries, the planet's jet streams would form continuous, uniform belts around the Earth. However, zonal asymmetries such as the distribution of land and ocean, the presence of mountain ranges, tropical convection and east–west midlatitude SST gradients contribute to the formation of distinct regional jet streams. In the Northern Hemisphere (NH) winter, at upper levels, the jets exhibit very different characteristics across longitudinal sectors: in the Asian/North Pacific region, the STJ and the EDJ merge into a very strong jet that stretches from eastern Asia to the central Pacific along approximately 35°N, while in the North Atlantic sector two distinct weaker jets are present with the subtropical branch located at about 25°N and the eddy-driven branch further north, the latter with a pronounced southwest-to-northeast tilt. The Pacific jet also displays reduced variability compared to the North Atlantic jet (e.g., Held and Wang [33]). In summer, a weaker EDJ is present north of 40°N at most longitudes, although this appears to be an artefact of the temporal averaging as the actual jet resembles a succession of short, varying, "jetlets" [34].

The Southern Hemisphere (hereafter, SH) is characterized by a primarily eddy-driven jet commonly known as the Southern Hemisphere jet. During the summer months, a single EDJ can be found at about 45°S at most longitudes, albeit with varying strength. In the winter season, the jet exhibits more pronounced zonal asymmetries [35], including a strong STJ in the South Pacific that is often well separated from the EDJ. These asymmetries have been linked to the influence of tropical SSTs [36] and Antarctic orography [37].

The EDJ is accompanied by planetary and synoptic scale Rossby waves (RWs), successions of cyclonic and anticyclonic anomalies that give the jet its meandering character. The interplay between the jet and the RWs contributes to local weather variations; when RWs become stationary, they can lock in place persistent weather anomalies, leading to extreme weather events (e.g., Screen and Simmonds [38]). Rossby wave breaking sometimes results in a long-lasting deflection of the jet and storm tracks in a phenomenon known as an atmospheric block (e.g., Barriopedro et al. [39]). These blocks typically consist of a meridionally oriented dipolar anomaly of geopotential height in the upper troposphere, often accompanied by a surface anticyclone, and are more common in the eastern basins of the North Pacific and Atlantic Oceans. Like RWs, atmospheric blocks may become quasi-stationary and persist beyond the typical decay time of an anticyclonic anomaly, sometimes for several weeks. They are frequently linked to severe cold spells in winter and drought and heatwaves in summer [40–42] and can also lead to flooding [42].

Eddy-driven jet response to increased GHG gases

Time-mean jet response to anthropogenic forcing

Observed and simulated historical trends

Recent research by Woollings et al. [43] suggests that zonally averaged zonal wind trends are emerging from internal variability in both the Northern and Southern hemispheres. The authors examined zonal indices designed to capture global scale zonal wind changes in four reanalyses and found robust and statistically significant trends consistent with an overall poleward shift of the jets. Additionally, the study also suggests that this shift is driven by upper tropospheric tropical warming. However, the authors found that the jet response to upper tropospheric tropical warming in CMIP6 historical simulations is often weaker than observed.

Studies of the changes in the *individual* Atlantic and Pacific jets remain less conclusive and depend on the season, period, and the vertical level of analysis. For instance, Robson et al. [44] analysed low-level zonal winds from the ERA-Interim reanalysis spanning 1979–2016 and found that there has been a significant equatorward displacement and weakening of the North Atlantic (hereafter, NATL) EDJ during summer, while, in winter, they found the trends to be small in comparison with the interannual variability. In contrast, Blackport and Fyfe [45] found a significant low-level winter strengthening of the NATL EDJ in ERA5 and NCEP/NCAR reanalysis from 1951 to 2020. Additionally, Hallam et al. [46] also found a winter NATL jet strengthening during

1871–2011 in the Twentieth Century Reanalysis (hereafter, 20CR) dataset. Furthermore, Blackport and Fyfe [45], as in Woollings et al. [43], highlight that the observed changes of the jet are large compared to the simulated historical trends in CMIP6 climate models.

As for trends at upper levels, Lee et al. [47] analyzed four reanalysis products and found that the annual mean upper tropospheric zonal wind speed in the NATL has not changed since the start of the observational satellite era in 1979, but the vertical shear has increased by 15 per cent. The authors attribute this increase in vertical shear to an intensified upper tropospheric meridional temperature gradient. In contrast, Simmons [48] found a weakening of the winter NATL zonal wind at 200 hPa over the Arctic but a strengthening in the mid-latitude band between 50°N and 60°N.

For the North Pacific (NPAC) jet, results are also inconclusive. For instance, Hallam et al. [46] analysed 20CR reanalysis upper-level data spanning from 1871 to 2011 and concluded that there was no significant change in the latitude or speed of the NPAC jet over this period. Zhao et al. [49], however, found a small but significant poleward shift of the NPAC upper-level jet in the winter season by analysing ERA5 data from 1979 to 2019.

In the Southern Hemisphere (hereafter, SH), several observational and modelling studies have shown that the upper-level and low-level winds have shifted in summer about 2° poleward since the mid-1970s [50–55]. This shift has been mostly attributed to ozone depletion and the associated cooling at high latitudes [56–61]. As expected from the ongoing ozone recovery, the poleward jet shift ceased after 2000. Encouragingly, coupled climate models, such as CMIP5 and CMIP6, have reproduced this observed shift, as well as the slow-down after 2000 [62], indicating the models' ability to capture the jet response to external forcing in the SH. Considerable regional variation, however, is seen within the observed poleward shift, likely due to internal variability [63].

Some modelling studies suggest that aerosols have also played a role in the historical jet trends (e.g., Dong et al. [64]). Simulations solely forced with historical anthropogenic aerosols during the twentieth century suggest that the effect of aerosols was to displace the jet equatorward in the NH and weaken it in the SH [65–67]. If this effect is important in nature, it would offset and obscure any poleward shift and strengthening of the EDJ due to greenhouse forcing.

Projected jet changes

For the twenty-first century, a broad range of numerical experiments, including three generations of CMIP coupled climate models, project an overall poleward shift of the zonally-averaged upper and low-level zonal winds in response to rising concentrations of GHGs. However, these shifts vary significantly depending on the region and season (e.g., Yin [51] for CMIP3; Barnes and Polvani [50]; Grise & Polvani [68]; Simpson et al. [69]; Vallis et al. [14] for CMIP5; and Harvey et al. [15] and Oudar et al. [16] for CMIP6).

The diversity of model regional and seasonal responses within the CMIP6 ensemble is illustrated in Fig. 1, which displays latitudinal jet shifts (Fig. 1A) and zonal velocity changes (Fig. 1B) at low levels across three basins and seasons for 31 models. The changes are computed by subtracting the "past" (1980–2014) jet climatology obtained from the historical simulations from the "future" (2065–2099) jet climatology from the Shared Socioeconomic Pathway SSP5-8.5 scenario simulations, and the results are not sensitive to the details of the methodology (see Methods).

During spring (MAM), summer (JJA), and autumn (SON), most models project a poleward shift of the NATL jet, consistent with previous studies with CMIP5 (e.g., Simpson et al. [69]) and CMIP6 (e.g., Harvey et al. [15]) data. However, there are significant differences between the models. For instance, during SON, when the shift is most pronounced, the multimodel mean shift is around 2° (a rather small change given we are considering the most extreme forcing scenario), but while in some models the shift is twice as large, others show almost no discernible change. During winter (DJF), the NATL jet intensifies (Fig. 1B), but the multimodel mean shift is close to zero. These results align with previous findings indicating that in winter, rather than shifting, the NATL jet narrows, intensifies, and extends farther eastward towards Europe [15, 16, 69].

In the NPAC, the multimodel mean indicates a robust poleward shift of the jet during DJF, JJA, and SON, while the shift is close to zero in MAM. Regarding changes in wind speed, there is virtually no agreement between models in either winter or summer, with a 50/50 split in the sign of the response and a zero mean signal. During the transitional seasons, most models concur on deceleration.

In the SH, most CMIP6 models project a poleward shift of the jet in DJF, MAM, and JJA. This is consistent with previous CMIP5 studies (e.g., Barnes and Polvani [50]; Simpson et al. [69]). However, unlike those studies, we found that the multimodel mean shift is zero during SON, with an even split in the sign between individual models. This result aligns with Curtis et al. [70], who found a weaker shift in austral winter (May–October) in CMIP6 compared to CMIP5. All models agree on a jet acceleration across all seasons, consistent with previous research (e.g., Barnes and Polvani [50]; Simpson et al. [69]).

The year-round intensification of the SH jet is by far the strongest and most robust projected change in the CMIP6 simulations (with no model exhibiting a weakening in any season), albeit with a substantial spread, partially related to different treatment of the ozone field across models [71–73]. This consistency sharply contrasts with the changes in the

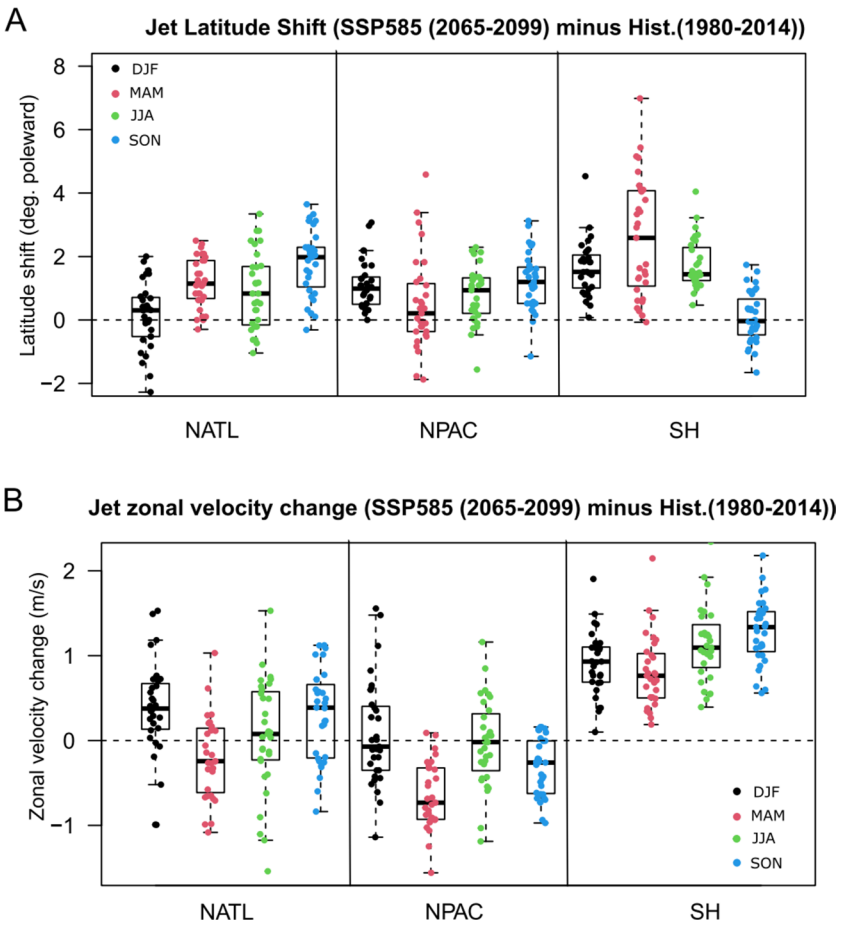

Fig. 1 (A) Seasonal-mean latitudinal jet shift (degrees poleward) and (B) zonal velocity change between the historical and SSP585 CMIP6 experiments for three sectors. The bars denote the 25th and 75th percentile range of the multimodel spread of a total of 31 models. The calculation of the jet latitudinal and velocity changes are described in *Methods*

NH, which vary with season and basin, and with a range of uncertainty that spans positive and negative values.

The large variation in model projections stems from differences in the representation of physical processes and spatial resolution within each model (i.e., structural uncertainty), as well as internal variability (aleatoric uncertainty). In Fig. 1, we used only the first ensemble member of each model, so, in order to assess the impact of internal variability alone, we repeated the calculation of the jet shift and speed response to climate change using a large ensemble comprising 39 members (r1i1p1 to r39i1p1) of the ACCESS-ESM1.5 model, which differ solely in their initial conditions (Fig. 2). Figure 2A shows that the spread in the jet shift response due to internal variability is roughly half the intermodel spread shown in Fig. 1. The spread associated with internal variability in the wind speed is about half of the intermodel spread, except in SON in the NPAC and MAM in the SH, when it is about 75%. This result suggests that a significant portion of the intermodel uncertainty in CMIP6 can be attributed to irreducible internal variability.

This lack of agreement has important implications since the jet response has been identified as a key source of uncertainty in regional climate impacts (e.g., Karpechko [8]; Fereday et al. [74]). Overall, we believe that caution is warranted when interpreting these projections for the following reasons:

1. There is a significant spread in projected jet changes, not only in terms of the magnitude but even the sign (Fig. 1).
2. Recent evidence from Woollings et al. [43] and Blackport and Fyfe [45] suggest that models underestimate the jet stream response to anthropogenic forcing during the historical period, raising the possibility that the future jet response is also underestimated.
3. Biases in the mean jet position persist in all model generations (e.g., Harvey et al. [15]), and their impact on the jet response remains uncertain. For instance, a model's future SH jet shift has been shown to be related to its jet position in present-day climate across several generations of CMIP models [14, 50, 70, 75, 76]. Whether this relationship arises from dynamics or mainly reflects geometric effects is not fully understood [76–78]. Still, the biases in the jet latitude could reflect misrepresentations of certain dynamical processes, thus also compromising the simulated projected changes.
4. Crucially, there is no consensus on the relative importance of the physical mechanisms driving the jet's forced response, nor is there a complete understanding of the

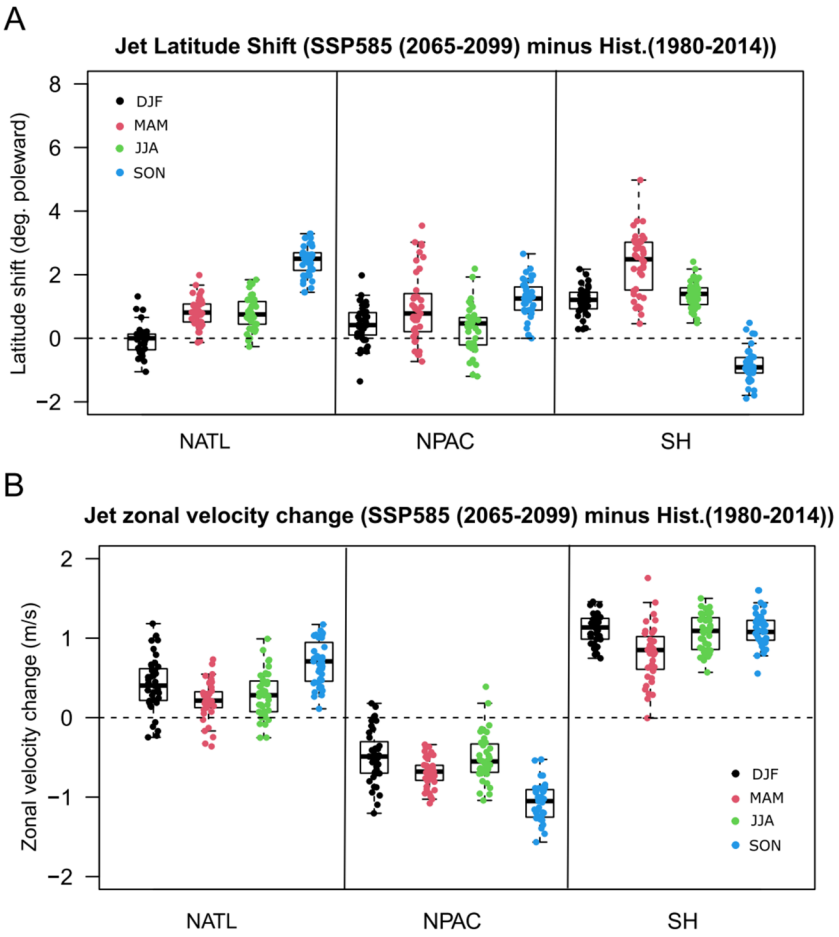

Fig. 2 (A) Seasonal-mean latitudinal jet shift (degrees poleward) and (B) zonal velocity change between the historical and SSP585 for the ACCESS-ESM1 large ensemble (39 members) experiments for three sectors. The bars denote the 25th and 75th percentile range of the multimodel spread. The calculation of the jet latitudinal and velocity changes are described in *Methods*

mechanisms themselves [12, 14]. Both limitations make it difficult to develop constraints to reduce the uncertainties in the jet projections.

Mechanisms mediating the mean jet response to increasing GHG concentrations

The EDJ is driven by the convergence of eddy momentum fluxes and the poleward transport of heat by eddies. Eddies originate in the baroclinically unstable source regions of the midlatitudes, and propagate away from the jet as Rossby waves when they reach a critical size [30, 79]. According to linear theory, many of these Rossby waves break in critical layers located equatorward of the jet, often referred to as sink regions. These critical layers are zones where the background zonal flow speed matches the Rossby wave phase speed and beyond which the waves can no longer propagate. The wave-breaking decelerates the zonal flow locally, so that a wave propagating out of the jet and breaking in a critical layer is associated with a flux of westerly momentum from the vicinity of the critical layer into the jet core. On the poleward side of the jet, there is typically a turning latitude where Rossby wave reflection dominates over breaking. However, wave breaking can also occur on the poleward side for large-amplitude Rossby waves and weak background westerlies [80, 81].

As for the changes expected in the jet as a result of increased GHGs, historically, there has been a strong focus on investigating the competing influences of tropical and polar warming, in what is referred to as a "tug-of-war" on the jets ([82] and Fig. 3). All else being equal, warming on the poleward flank of the jet reduces the meridional temperature gradient, which, according to thermal wind balance, weakens the jet. Conversely, warming on the tropical flank enhances the meridional temperature gradient and strengthens the jet. With climate change, we expect both polar and tropical warming, but with the former maximizing near the surface and the latter maximizing aloft in the upper troposphere (e.g., Hansen et al. [83]). Which effect will dominate the jet changes remains uncertain (e.g., Stendel et al. [84]).

Moreover, while the perturbed jet must remain in thermal wind balance, this constraint alone is not enough to predict future changes in the jet. The adjustment of the jet to external forcing arises through a complex sequence of dynamic alterations in the properties of eddies and their source and sink regions, as well as in their associated fluxes. This leads to

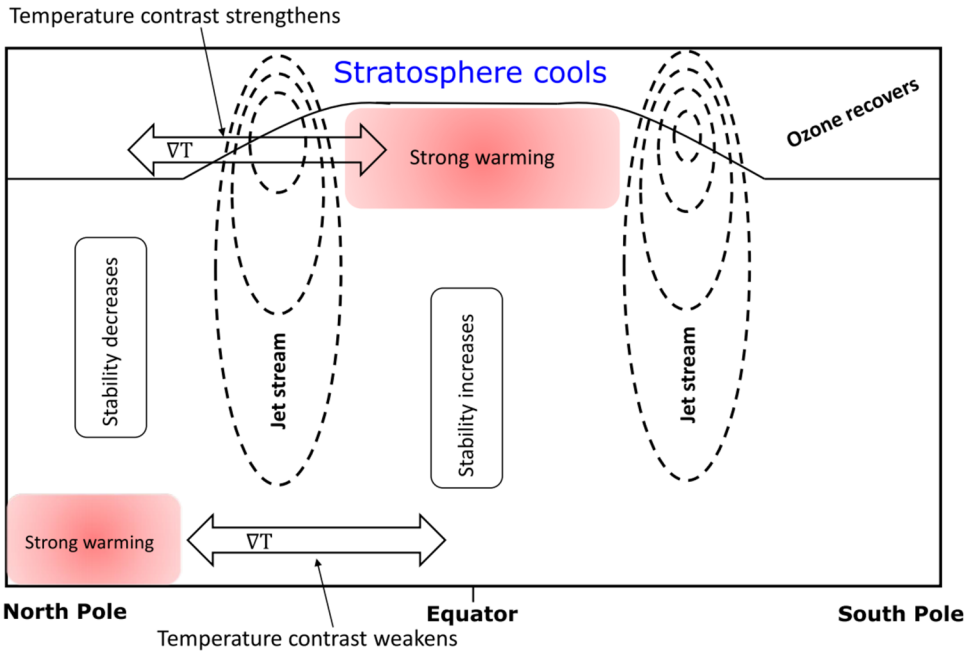

Fig. 3 Warming patterns impact the jet stream in different ways. In the Arctic, strong low-level warming reduces both the horizontal temperature gradient between the equator and the pole and the vertical stability on the poleward side of the jet, leading to a weakened jet. In contrast, upper-level tropical warming strengthens the upper-level equator-to-pole temperature gradient and increases vertical stability on the equatorward side, intensifying and shifting the jet poleward. Both Arctic and tropical warming are projected with climate change, but the dominant influence on the jet's future behaviour remains uncertain

changes in the jet's position as well as its speed (e.g., Hoskins and Woollings [85]; Baker et al. [86]). For example, the latent heat release that warms the tropical upper troposphere may also affect the location of the background temperature gradient [87], the effective diffusivity of the atmosphere [88], or the dominant eddy length scales [89] such that the jet is pushed poleward. In addition, greenhouse warming is associated with other effects such as stratospheric cooling, lifting of the tropopause and expansion of the Hadley Cell, which can also influence the jet. We refer the reader to Shaw [12] for a comprehensive overview of proposed mechanisms for jet changes.

During the last decade, new research has refined our understanding of the role played by changes in the distribution of latent and radiative heating in altering the jet. For instance, on synoptic- to basin-scales, latent heating in extratropical weather systems due to the condensation of water vapour has been shown to strengthen the upper-level jets [90–93] by enhancing the cross-jet potential vorticity gradients. On a global scale, besides warming of the upper tropical troposphere, latent heating also plays an important role in the EDJ and storm track dynamics by contributing to balancing the adiabatic cooling in the ascending branch of the Ferrell cell [1, 94]. Further, modelling evidence suggests that enhanced midlatitude diabatic heating in response to climate change induces a meridional circulation, and the Coriolis deflection of the meridional flow decelerates the windshear on the poleward flank of the jet [95].

Radiation and its representation in models is also crucial for the present-day jet streams and their response to climate change [96–101]. In addition to well-known effects such as greenhouse-induced radiative cooling of the stratosphere, clouds play an important role because their strong variations in space and time make them effective in creating temperature contrasts. Modelling clouds and their interactions with radiation remains one of the key challenges in climate research. Cloud-radiative interactions shape the jet streams on both the long time scales of climate and the short time scales of weather. On climate time scales, a number of modelling studies in which cloud-radiative interactions were carefully manipulated found that changes in the radiative heating of clouds contribute to the poleward shift of the jet streams under global warming [99, 102, 103] and also to regionally distinct changes such as the downstream strengthening of the North Atlantic jet stream during winter [104, 105]. On weather time scales, cloud-radiative interactions were found to modulate the intensity of extratropical cyclones that travel along the extratropical jet stream [106–109]. Throughout these studies, upper-tropospheric ice clouds in the tropics and extratropics and low-level mixed-phase clouds in the extratropics have emerged as key drivers of the cloud-radiative impact on the midlatitude circulation.

Changes in the variability of jet streams in response to anthropogenic forcing

Changes in jet variability are an integral part of the overall jet response to increased GHG and can greatly impact regional weather and climate. We believe discussions of the climate projections of the jet stream should not only cover changes in the mean state but also changes in the jet variability. However, how the jet variability will be altered in response to increasing GHG is a topic of ongoing debate with no clear consensus (e.g., Hoskins and Woollings [85]). The problem is further complicated because variability

changes are closely linked to changes in the mean state and because findings are highly sensitive to how variability is defined.

The variability of the jet stream can be broadly divided into three main types: meridional shifting, which involves local zonal wind shifts poleward and equatorward; pulsing, which involves local zonal wind accelerations without a change in latitudinal position (e.g., Lee and Feldstein [110]; Lorenz and Hartmann [111]; Thompson et al. [112]) and meandering, wave-like jet excursions or undulations along its course. The type of variability that prevails differs across ocean basins and depends on the local jet characteristics. For instance, both shifting and pulsing are observed in the NATL extratropics, while pulsing dominates the exit region of the Asia–Pacific jet [113, 114].

Shifting and pulsing

The latitudinal shifts of the jet stream are closely linked to the occurrence of Rossby-wave breaking on both sides of the jet. Locally, wave breaking causes a deceleration of the eastward flow, resulting in a poleward shift of the jet when wave breaking occurs on the equatorward side and an equatorward shift of the jet when wave breaking occurs on the poleward side [3, 115–118].

Jet shifting and pulsing are often conflated in statistical analysis, such as teleconnection or principal component analysis [119], but they are physically distinct structures of variability, exhibiting different sensitivities, feedbacks, timescales and impacts (e.g., Baker et al. [86]). The preferred behaviour can vary regionally, with strong jets often inhibiting meridional shifts, and also on decadal time scales [3]. Such decadal variability presents a clear challenge to the detection and attribution of regional anthropogenic changes.

Several studies have shown that the dominant mode of variability depends on the mean position of the jet so that when the EDJ moves meridionally, whether closer to the poles or the equator, its primary mode of variability changes from a meridional shift to pulsing [81, 120, 121]. This change can be qualitatively understood from linear RW theory. If the mean jet is located in midlatitudes, far from both the poles and the STJ, when a random eddy fluctuation changes the jet position, the jet "self-modifies" the position of the critical lines so that momentum fluxes can be redistributed to sustain the jet in its new position. In this case, shifting tends to dominate. However, if the mean jet is close to the poles, an anomalous jet position cannot be easily maintained because the smaller potential vorticity (hereafter, PV) gradients at high latitudes facilitate the creation of a turning latitude (where the wave is reflected), which impedes the poleward displacement of the critical line and the redistribution of momentum. In this situation, the jet variability will be primarily controlled by equatorward wave propagation (and poleward momentum flux), changing the dominant mode from shifting to pulsation. A similar situation arises when the EDJ is close to a strong STJ: the equatorward critical line is set by the relatively stationary STJ, preventing the redistribution of momentum and favouring pulsations over displacements [113, 121].

According to this reasoning, if the jet moves poleward in response to increased GHG, the jet would transition from shifting to a more pulsing mode of variability, and as a consequence, the persistence of anomalous meridional shifts would decrease [75, 81, 120, 121]. This change has been shown to occur in some CMIP5 simulations, in which the jet latitude variability decreases while the jet speed variability increases as the jet moves poleward [50]. However, the magnitude of these changes and mechanisms remains unclear [122] and are dependent on the mean jet response, which, as we have discussed, is uncertain.

Meandering

The term "jet meandering" is used to refer to large-scale wave-like jet motion or the sinuosity of the jet. Although one could argue that jet meandering and jet shifting are not separate phenomena, meander refers more commonly to hemispheric-scale wavy displacements in the jet. Such meanders are associated with RW propagation and significantly influence regional weather and climate by transporting warm and cold air across latitudes (e.g., Rhines [123]). When these meanders become stationary with respect to the ground, they can lead to persistent weather anomalies. Several extreme events in winter and summer have been linked to high-amplitude RW meanders [38, 124–128].

Several measures of jet meandering have been proposed in the literature. For instance, Cattiaux et al. [129] propose a measure of jet sinuosity as the length of the Z500 isopleth normalised by the length of the latitudinal circle, which provides a measure of the geometric scale of the meanders. Hassanzadeh et al. [130] define jet meandering as the meridional wave amplitude derived from a Fourier decomposition of the Z500 isopleth, which provides an indication of the meander's extent in the meridional direction. Francis and Vavrus [131] employ a measure based on the meridional wind speed relative to the total wind speed, and Huang and Nakamura [132] introduce a local wave activity metric that provides a combined measure of the magnitude of the anomalies and their geometric characteristics.

Changes in jet meandering due to climate change—which would have implications for the temporal characteristics of weather patterns—is a topic of intense research and controversy. Several studies have suggested that the NH EDJ has become "wavier" and associated weather patterns more persistent in recent decades [131, 133, 134]. The central hypothesis is that the increase in waviness is due to a weaker

jet stream resulting from reduced meridional temperature gradients caused by Arctic amplification [131, 133, 134]. However, while this viewpoint has gained traction in non-specialized media, it is not universally accepted within the climate science community (for more specific reviews, refer to Barnes and Screen [135], Hoskins and Woollings [85] and Cross-chapter box 10.1 in IPCC AR6 [7]). It is worth noting that the observed signal of Arctic amplification has emerged from internal variability only over the past three decades, which is likely too short of a period to definitively establish its direct association with changes in midlatitude circulation using reanalysis products [136]. Additionally, observed jet waviness trends are inconsistent across different methodologies and exhibit seasonal and regional dependencies [85, 136–138].

The modelling evidence is also inconclusive, with conflicting results obtained in idealized experiments (e.g., Hassanzadeh et al. [130]; Green et al. [139]). Moreover, research suggests that the specific characteristics of Arctic heating may influence the jet response [140–142]. Additionally, polar warming is not the only driver of jet change, and numerous key processes influencing the jet response are not adequately represented in these highly idealized simulations.

Key challenges and ways forward

In this section, we highlight three key aspects of the jet's response to climate change that require more research. Following that, we present a set of experiments and a methodological framework tailored to improve our understanding of these areas.

Key challenges

CH1Mechanisms: Multiple mechanisms and potential drivers have been proposed to explain the jet response to climate change. These include tropical and Arctic warming, changes in static stability, and alterations in moisture concentrations and cloud properties, among others. The relative importance of these mechanisms remains uncertain, and the specific dynamical mechanisms mediating the jet response are still unclear. This lack of understanding hampers our ability to assess the reliability of model projections.

CH2 Uncertainty in Global and Regional Responses: While climate models suggest that the zonal-mean zonal winds will shift poleward, there is still significant uncertainty regarding the magnitude and the regional and seasonal structure of the changes. Better constraining the regional jet response is crucial for providing accurate regional climate projections that can be used for impact and adaptation studies.

CH3Interactions with Other Climate Factors: In addition to well-mixed GHG, the jet stream is influenced by other processes. Changes in aerosols, ozone, and solar variability, among others (see Table 1 and Hall et al. [143]), can affect the jet. However, the interactions between these factors and the jet stream response to climate change are poorly understood and are a source of uncertainty, particularly at the regional scale.

Proposed experiments

Here, we suggest a series of experiments designed to address the three challenges described in the previous section. While these challenges are interconnected, each experiment focuses on specific aspects (Fig. 4). However, all experiments contribute, to varying degrees, to the overall progress of the entire set of challenges. The detailed design and technical specifications of these experiments are beyond the scope of this manuscript, but all proposed experiments should be feasible with current computing and technical capabilities.

Experiments targeting CH1: Mechanisms

The most crucial challenge in understanding the jet response is to comprehend the mechanisms behind it since, without a better understanding of these processes, we cannot reduce or constrain the sources of projection uncertainty required to make progress in CH2. It is also challenging to confidently attribute and quantify the impact of the other forcings of CH3. Therefore, most experiments are primarily designed to target CH1, even though they indirectly contribute to advancing CH2 and CH3.

Sensitivity experiments to test the jet response to simultaneous forcing mechanisms

There is a rich history of using idealized model experiments to test the jet response to specific forcings (e.g., Polvani and Kushner [144]; Lorenz and DeWeaver [145]; Ring and Plumb [146]; Brayshaw et al. [147]; Butler et al. [87]; Simpson et al. [148]; McGraw and Barnes [149]; Burrows et al. [150]). Although these experiments have provided valuable insights into the mechanisms underlying the jet stream response, they exhibit several limitations as they often relied on atmosphere-only, idealized, low-resolution models. Moreover, by testing individual forcings in isolation, they cannot provide a complete and accurate representation of the real-world climate system feedbacks and interactions.

Table 1 Remote drivers potentially influencing the jet

Driver	Mechanism description	References
Tropical SST variability (e.g., ENSO)	• SST-induced convection and associated upper-level outflow can act as a source of poleward and eastward propagating RWs, which may generate teleconnections in the midlatitude jet regions. These teleconnections might reinforce internal wave-like patterns of variability, modulate the jet, and strongly impact hydroclimate regimes • During El Niño events, the warming of the tropics at all longitudes strengthens the STJ in both hemispheres, consistent with thermal wind balance. This can lead to changes in the meridional potential vorticity gradient and a possible equatorward shift of the EDJ	Hoskins and Karoly [170]; Horel and Wallace [171]; Karoly [172]; Irving and Simmonds [173] Seager et al. [174]; Lu et al. [151]
Extratropical SST variability	• Strong horizontal SST gradient anomalies, such as those found along western boundary currents, as well as basin-wide SST anomolous patterns can induce a deep atmospheric response, shift the jet stream position and modulate its intensity • Low-frequency ocean modes of variability can impact the position and variability of the jets by modulating SST. For instance, the Pacific Decadal Oscillation (PDO) is linked to changes in the strength of the Aleutian low and it is in a tight antiphase with the latitudinal position of the North Pacific jet. Similarly, observational evidence suggests that the Atlantic Multidecadal Variability mode (AMV) can modulate the NAO at multidecadal timescales • The weakening Atlantic Meridional Overturning Circulation (AMOC) in model simulations can lead to regional jet changes in projections	Brayshaw et al. [147]; Minobe et al.[175]; Sheldon and Czaja [176]; O'Reilly and Czaja [177]; Sampe et al. [178]; Wills et al. [179]; Fang and Yang [180]; Gastineau and Frankignoul [181]; Ossó et al. [182, 183] Hallam et al.[46]; Peings and Magnusdottir [184]; Gastineau and Frankignoul [185]; Folland et al. [186]; Sutton and Hodson [187] Woollings et al. [188]; Bellomo et al. [189]
Sea ice and snow patterns	• Snow/ice cover changes can modify the surface energy balance, inducing surface temperature anomalies that may directly impact atmospheric circulation by locally inducing a pair of opposing vorticity anomalies and indirectly via changes in the stratospheric polar vortex (SPV)	Hoskins and Karoly [170]; Cohen and Enthekhabi [190]; Han and Sun [191]; Wegmann et al. [192]; Cohen et al. [193]; Mori et al. [194]; Petoukhov V and Semenov VA [195]
Stratosphere-troposphere coupling	• Observational and modelling evidence indicate that the SPV is dynamically coupled with the troposphere in such a way that an acceleration of the SPV can cause a poleward shift in the storm track and the jet and vice-versa • Observational and modelling studies show that solar variations can influence the surface climate and the NAO via a top-down mechanism involving changes in the strength of the SPV	Karpechko et al. [196]; Kidston et al. [197]; Hall et al. [143]; Gray et al. [198]; Scaife et al. [199]

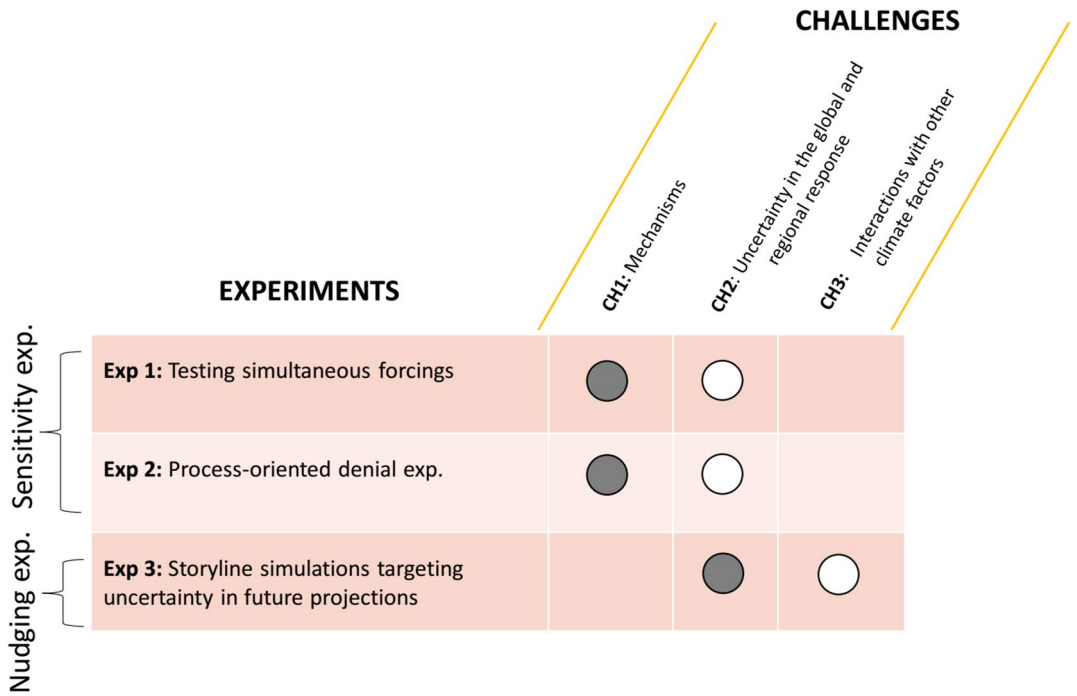

Fig. 4 Proposed experiments contributing to solving the three challenges. A filled grey circle indicates the primary experiment target challenge. White circles indicate challenges likely to also benefit from the experiment

In reality, the jet is influenced by multiple simultaneous and sometimes opposing forcings, and its overall response is determined by complex feedback processes.

Building from these pioneering works, we propose a significant advancement by employing high-resolution global models that can simulate sharp SST gradients and allow for independent switching on and off topography, moisture and a coupled slab ocean representation. Initially, experiments would be run with topography, moisture, and the slab ocean turned on, and the model could be subjected to multiple simultaneous forcings with adjustable strengths. Moreover, different heating patterns could be tested since the evidence suggests that the jet response may be sensitive to the particular heating pattern, especially over the tropics (e.g., Lu et al. [151]). For instance, one experiment could involve investigating the jet stream response to different spatial patterns of upper tropospheric tropical warming, along with a low-level Arctic warming anomaly, with various combinations of forcing strengths.

Conducting these experiments at a high spatial resolution is essential to better resolve small-scale processes such as convective circulations and test the circulation sensitivity to the representation of regional scale processes. The use of high resolution might also potentially reduce model biases. A recent study by Schemm [24], for instance, has shown that using a 5 km resolution substantially reduces the biases in the NATL storm track, which are common in coarser model resolutions.

We emphasize that sufficient computational resources must be available to run multiple experiments with varying initial conditions. This requirement is crucial given that internal variability, as illustrated in Fig. 2 and shown in various studies (e.g., Giorgi and Xi [152]; O'Reilly et al. [153]), contributes significantly to uncertainties in projections of future extratropical climate.

Process-oriented denial experiments

In a subsequent phase, we aim to refine our understanding by choosing experiments from the first set that manifest a robust jet response and identify the underlying processes and modelling assumptions upon which the model's response relies. To achieve this, our experimental approach would involve systematically disabling topographical effects, moisture dynamics, cloud processes, and the influence of the slab ocean, enabling us to probe their individual impacts on the system's response. Furthermore, the model's sensitivity to resolution and parameterisation schemes could also be tested. Process-oriented denial experiments have already proven useful, for example, in studying the role of the Arctic and Antarctic stratospheric vortex disturbances for surface predictability [154].

Experiments targeting CH2 and CH3: Uncertainty in global and regional responses and interactions with other climate factors

Typically, the uncertainty in the future climate response to changes in GHG and aerosols is explored by analysing multimodel ensembles of climate projections. However, the typical multimodel ensemble approach is problematic: the ensemble mean may mask the circulation response to specific forcings since different models show different and sometimes opposite circulation responses (e.g., Shaw et al. [155]), and this washout effect can lead to an underestimation of the mean response. An alternative storyline-based approach has recently been proposed to overcome the problems of interpreting multimodel ensembles [156, 157]. In the storyline approach, the climate responses can be conditioned to the occurrence of plausible changes in drivers (e.g., Arctic and tropical warming, stratospheric cooling, SSTs and sea-ice anomalies, among others) and to different levels of GHG forcing [11].

Storyline simulations targeting uncertainty in future projections in the drivers (also contributing to CH3)

Storylines of regional atmospheric circulation changes have been mainly developed via regression analyses across the spread in the projections from CMIP models [11, 158]. However, this approach cannot directly verify the causality of the relationship between the selected drivers and the regional atmospheric circulation, hence limiting confidence in the results. Nonetheless, various studies have demonstrated the value of different forms of nudging experiments or atmosphere-only runs to link the spread in CMIP projections to individual drivers. In free-running mode, detecting a model's response to a perturbation typically requires many samples. By contrast, in a nudging experiment, certain climate system components are constrained to stay close to a predefined reference state while the rest of the system evolves freely. This approach enables the study of the model response to a perturbation with a high signal-to-noise ratio but with a substantially smaller amount of data. The nudging technique has been applied to analyse the jet response to, e.g., NH winter stratospheric vortex responses [159, 160], radiative feedback and cloud changes [97, 102] and sea ice [161]. Building on these approaches, we suggest that there is a need for a protocol of experiments covering the uncertainty in the key drivers influencing the jet (Table 1) based on atmospheric and/or SST nudging. The approach should lead to a reasonable number of "storyline experiments", each describing a different plausible future surface and stratospheric climate that are expected to span most of the spread in the inter-model jet response. These *storylines experiments* would aim to shed light on the worst-case scenarios of regional climate impacts and their key driving remote climate agents.

Advanced diagnostics by means of improved model output

Jet detection

Jet streams exhibit a complex structure and vary rapidly, making it necessary to employ temporal or spatial averaging of the wind field when analyzing long-term changes. Numerous methods have been proposed to detect and analyze the jet stream. One commonly employed approach involves identifying local maxima of zonal mean zonal wind in height-latitude space or at specific heights (e.g., Blackmon et al. [162]; Rikus [163]; Woollings et al. [164]). These methods typically employ criteria based on latitude and velocity thresholds or different vertical levels to distinguish between the subtropical and extratropical jet streams. These methodologies are very valuable for examining the average zonal and vertical variations in the flow. However, they do not capture the longitudinal structure of the jet stream. Other researchers have proposed 3D detection schemes that identify wind maxima in latitude, longitude, and height space and use different methods to "reconstruct" the jet stream (e.g., Limbach et al. [165]; PenaOrtiz et al. [166]; Spensberger et al. [167]; Barriopedro et al. [168]). Each methodology has advantages and disadvantages, and it is essential to employ various methods to address different research questions. However, certain results, such as changes in waviness or the timing of jet response emergence, may inevitably depend on the chosen methodology.

To advance our mechanistic understanding of the jet stream response, new numerical experiments must provide adequate diagnostic tools. These diagnostics could be made available through a dedicated jet stream software package, along the lines of the *TropD* software of Adam et al. [169] for tropical circulations. This would help to increase the reproducibility and comparability of results. Table 2 presents a suggested list of model outputs likely to be required.

Finally, the simulation output must have at least daily temporal resolution. Daily data is crucial to investigate, for instance, changes in the persistence of specific jet states and their variability. Additionally, the simulation output should include an adequate number of vertical levels, particularly near the tropopause, to effectively detect changes in the vertical position of the jet stream.

Table 2 Suggested model output to be provided by the new jet experiments. 3D and 4D refer to three and four dimensions, respectively

Wind	Temperature	Radiation and heat	Water vapour	Others
U-component of wind (4D)	Air-temperature (4D)	Short and long wave radiation heating rates (4D)	Relative humidity (4D)	Potential vorticity (4D)
V-component of wind (4D)	Sea-surface temperature (3D)	Cloud-radiative heating rates	Specific humidity (4D)	Sea-ice cover (3D)
Eastward and northward turbulent surface stress (3D)	Soil-temperature (3D)	Latent heating rate (4D) Surface sensible and latent heating rates (3D)	Total precipitation (3D)	Soil moisture (3D) Land albedo (2D)

Conclusions

Changes in the eddy-driven jet stream as a response to climate change have the potential to strongly alter the hydroclimate of many extratropical regions. However, as highlighted in this manuscript, the response of the jet to increased GHGs is uncertain, which poses a substantial challenge to providing reliable regional climate change projections. This uncertainty propagates to climate change impact studies and could render their outcomes of limited utility if the atmospheric circulation response is inadequately constrained.

Thermodynamic aspects of the climate response, such as a ubiquitous warming with polar and tropical amplification, differential rates of ocean and continental warming, or the increase in the atmospheric water vapour holding capacity, are well constrained in model projections and, crucially, grounded in well-understood physics. In contrast, the jet stream response depends on several competing drivers, and although substantial progress has been made in recent decades, there is yet no complete agreed-upon theory describing the mechanisms governing the jet's response to climate change. The absence of a theoretical framework complicates the identification of sources of uncertainty in current climate change projections, leading to a lack of confidence in regional-scale jet stream responses.

To address these challenges, we advocate for a coordinated, collaborative effort aimed at enhancing our understanding of the jet stream response to climate change. We propose a series of new experiments that take advantage of recent advances in computing power and modelling capabilities to better resolve small-scale processes such as convective circulations, which are essential for a good representation of jet dynamics. Additionally, these experiments should be accompanied by standardized outputs and agreed-upon detection algorithms to ensure the comparability of results across studies.

In conclusion, we believe it is crucial to bridge the gap in our understanding of the jet stream's response to climate change in order to lay the foundations for more robust and reliable regional climate change projections and informed climate change mitigation and adaptation strategies.

Methods

Jet latitude and speed diagnoses

The assessment of the latitudinal position of the eddy-driven jet uses an algorithm reminiscent of the one described in Blakport and Fayfe [45]. The algorithm follows these key steps:

(1) Firstly, the monthly mean zonal wind is averaged across three pressure levels: 925 hPa, 850 hPa, and 700 hPa from historical and SSP585 CMIP6 experiments [200]. Identifying the EDJ from low-level winds avoids confusing wind maxima associated with the STJ and the EDJ [164].
(2) Next, at each longitude, the algorithm identifies the maximum westerly wind speed, which is considered the "jet-core" speed. To prevent erroneous detections associated with small-scale wind extremes related to topography and coastlines, wind maxima above 75°N or 75°S are disregarded [164]. The latitude at which this maximum wind speed occurs becomes the latitude of the jet core event.
(3) Then we calculate a jet latitudinal index for each basin by zonally averaging the latitudinal maxima of jet speeds over specific longitudinal ranges, which are (60W to 0E for the North Atlantic, 180W to 180W in the Southern Hemisphere, and 150E to 240E for the North Pacific). It is worth noting that the algorithm's performance remains robust, even when the specific latitudinal range is subject to minor adjustments.

In addition to the method outlined above, alternative approaches to detect the jet core were explored, including prominence detection and the use of a parabolic fit, as detailed in Blakport and Fayfe [45], all yielding congruent results.

Acknowledgements We would like to thank Isla Simpson from NCAR, Francisco J. Doblas Reyes from the BSC, Laurent Terray from CERFACS, and Rein Haarsma from KNMI for providing valuable suggestions for the manuscript. We would also like to thank the University of Graz for providing funding for the open-access publication.

Author Contribution A.O. Conceptualized, wrote the main manuscript text and prepared the Figs. 1–4. I.B., A.K., C.L., D.M., O.R., A.V., T.W., and G.Z. conceptualized, edited and reviewed the manuscript. L.S., Edited and reviewed the manuscript.

Funding Open access funding provided by University of Graz.

Data Availability CMIP6 data used in Fig. 1, 2 is described in Eyring et al. [200] and was downloaded from the Copernicus Climate Change Service (C3S) (2023).https://cds.climate.copernicus.eu/ The code used in this study is available via personal request to the corresponding author.

Declarations

Competing Interests The authors declare no competing interests.

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