Detailed description of the research program

A Scientific background

The atmospheric jet stream is a fast stream of air concentrated at subtropical or middle latitudes approximately ten kilometers above the ground. It is tightly coupled to surface weather systems through mutual interactions, and its variability time scales range from days to years and even decades. Elucidating the dynamical processes that control the jet variability is crucial for understanding climate variability in the subtropics and midlatitudes.

The response of the jet to climate change induced by the anthropogenic increase in greenhouse gas concentration is complex, and the attempts to explain it have not been conclusive (Shaw, 2019). The most prominent response detected in climate models and observations is a poleward shift of the jet (Woollings et al., 2023), which is explained by zonally symmetric dynamical mechanisms, i.e., longitudinally independent mechanisms. However, the jet structure is zonally asymmetric and can be viewed as a combination of jets at large longitudinal sectors covering large oceanic basins and continents. The jet variability and response to climate change are often explained by applying zonally-symmetric arguments while referring to jets at certain longitudinal sectors (Eichelberger and Hartmann, 2007; Barnes and Polvani, 2013). ***We propose to investigate the extent to which zonally symmetric or asymmetric processes influence jet dynamics across large longitudinal sectors***.

The jet is driven by two mechanisms. The first mechanism is the conservation of absolute angular momentum: Planetary angular momentum is highest at the equator and decreases toward the poles. Air rises at the tropics and moves poleward in the upper branch of the Hadley circulation cell, advecting absolute angular momentum and increasing the relative angular momentum, proportional to the zonal wind (Held and Hou, 1980). This mechanism creates a strong jet at the subtropical edge of the Hadley cell in the upper troposphere, called a subtropical or thermally-driven jet (Lee and Kim, 2003). The second mechanism involves momentum transport by extratropical eddies, also called storms or weather systems. Due to potential vorticity conservation, extratropical eddies transfer zonal momentum into the latitude from which they propagate meridionally. As a result, they create a jet at midlatitudes, called a midlatitude, polar-front, or eddy-driven jet (Lee and Kim, 2003). The conceptual distinction between subtropical and eddy-driven jets is useful but can be misleading since the jet is generally affected by both mechanisms (Lachmy and Harnik, 2014, 2016).

Based on the mechanisms described above, observed jets are classified according to their structure. A jet at the Hadley cell edge in the upper troposphere is classified as subtropical, whereas a jet inside the midlatitude Ferrel cell, with surface westerlies below, is classified as eddy-driven. Thus, the latitudes of maximum vertical shear of the zonal wind and maximum surface westerlies are used as metrics for the subtropical and eddy-driven jet latitudes, respectively (Waugh et al., 2018), which applies also to zonally-asymmetric jets (Liu et al., 2021). Following these diagnostics, a strong subtropical jet is identified during the Southern Hemisphere (SH) winter in the Indo-Pacific sector, with weak westerlies below (Figure 1a,c). During the same season, a midlatitude eddy-driven jet with strong surface westerlies exists in the Atlantic sector (Figure 1a,c). The SH summer jet is more zonally-symmetric (Figure 1b,d) and is classified as eddy-driven (Kim and Lee, 2004). However, observations indicate the jet driving mechanisms in each sector and season are a mixture of processes (Williams et al., 2007; Li and Wettstein, 2012; Gillett et al., 2021; Spensberger et al., 2023).

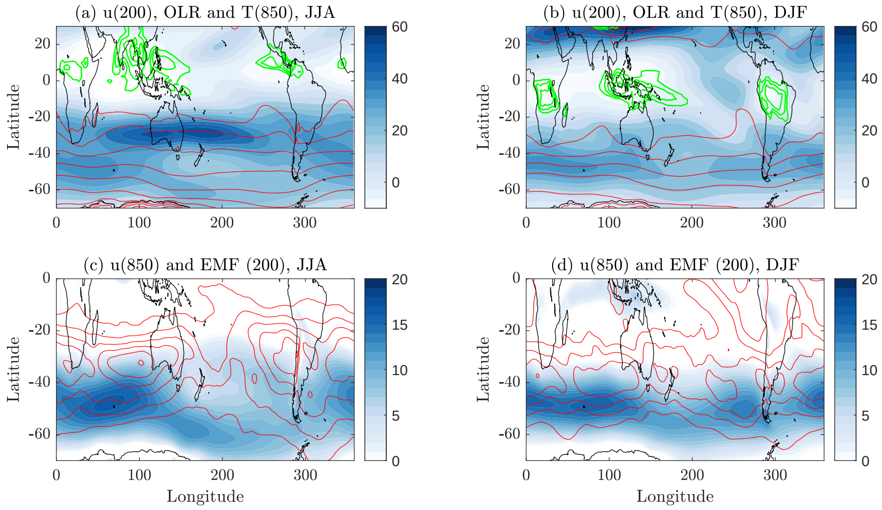

Figure 1: Zonal wind climatology (blue shading, in m s^{-1}), in the upper (200 hPa) (a,b) and lower (850 hPa) (c,d) troposphere, during SH winter (June-August, JJA) (a,c) and summer (December-February, DJF) (b,d). The red contours in (a,b) represent the temperature at 850 hPa, with a contour interval of 5 K and the hottest contour level of 285 K. The red contours in (c,d) represent the poleward eddy momentum flux, where eddies are defined as deviations from the monthly mean, with a contour interval of 20 m^2 s^{-2}, starting from zero. The green contours in (a,b) show the outgoing longwave radiation (OLR), with a contour interval of 10 W m^2, from 180 to 220 W m^2. These contour levels represent the lowest values of OLR, which indicate strong convection.

The conditions leading to the zonally-asymmetric jet structure vary between the two hemispheres. In the Northern Hemisphere (NH), continents and ocean currents play a major role in shaping the longitudinal structure of the jet (Nakamura et al., 2004), in addition to tropical convection (Li and Wettstein, 2012; Hoskins and Yang, 2021). The SH jet flows mostly above the ocean, and its asymmetric structure arises from tropical convection that drives a localized Hadley circulation (Inatsu and Hoskins, 2004; Hoskins et al., 2020; Patterson et al., 2020). The SH winter subtropical jet is also influenced by eddy momentum flux and Rossby wave propagation (Williams et al., 2007; Gillett et al., 2021; Hoskins et al., 2020; Hoskins and Yang, 2023). The zonal-asymmetry of the SH winter eddy-driven jet is due to the subtropical jet zonally-asymmetric structure (Nakamura and Shimpo, 2004), Antarctic orography (Patterson et al., 2020) and Rossby wave propagation from the tropics (Ding et al., 2012). ***We will analyze observational data in order to quantify the relative roles of different processes in the climatological zonally-asymmetric jet structure***.

Identifying processes that control the jet structure and variability is particularly challenging due to internal feedback mechanisms within the atmospheric circulation. The interaction between the jet and midlatitude eddies is responsible for much of the jet variability on daily to monthly time scales (Lorenz and Hartmann, 2001, 2003). Other processes affecting the jet variability at a wide range of time scales include sea surface temperature (SST) variability, large-scale tropical convection, and coupled oceanic-atmospheric oscillations such as El-Niño Southern Oscillation (ENSO) (Liu et al., 2021). ***Our goal is to identify jet variability drivers at***

time scales ranging from monthly to interannual and quantify their relative roles in altering jet properties.

A common approach for detecting relations between observed climatic variables is to use lagged correlations. If a significant correlation is found between one variable and another following it temporally, this supports the hypothesis that the first variable drives the lagging variable. However, it is well known that a significant correlation between two time series does not imply that one is causing the other. In recent years, sophisticated statistical methods have been introduced to climate science, enabling more rigorous detection of causal relations between variables (Kretschmer et al., 2016; Runge et al., 2019; Barnes et al., 2019; Kretschmer et al., 2021). For a given set of variables, causal discovery algorithms identify spurious correlations due to autocorrelation or common driver effects among the variables (Runge et al., 2014, 2019). ***We will apply causal discovery methods to observational data, allowing us to estimate quantitatively the role of different variables in causing jet variations***.

The simulated jet response to climate change is affected by the historical circulation produced in each model. Biases in the representation of longitudinal jet structure could lead to biases in the projected jet response. For example, the poleward shift of the eddy-driven jet has a large inter-model spread and is correlated with the historical jet latitude during SH winter (Curtis et al., 2020; Simpson et al., 2021), while this correlation is limited to the Pacific sector (Breul et al., 2023). Recent studies emphasize the role of tropical SST biases in driving zonally-asymmetric jet biases in climate models (Oudar et al., 2020; Waugh et al., 2020; Liu et al., 2021; Liu and Grise, 2023). ***We propose combining climate model data analysis with causal discovery methods to identify and quantify biases in the representation of jet driving processes across large longitudinal sectors***.

A direct way to examine jet driving processes is to perform controlled experiments using idealized numerical global circulation models. We will use an idealized moist aqua-planet model and set it up with localized tropical heating. The localized heating drives a localized Hadley cell and subtropical jet, similar to the observed jet (see Figure 4 below). Our preliminary results indicate that zonal momentum flux and stationary Rossby waves, which are negligible in a zonally-symmetric configuration, play a major role in jet maintenance in the presence of a tropical asymmetric heat source (see Figure 5 below). ***We aim to isolate the effect of asymmetric tropical heating on jet properties and on longitudinal transitions between jets of subtropical or eddy-driven characteristics***.

The proposed research is expected to fill a gap between the theoretical understanding of jet driving mechanisms, which is currently based on zonally-symmetric models, and the observed zonally-asymmetric jet. The combination of observational and climate model data analysis with idealized model experiments and novel causal discovery methods will enable us to obtain a robust conceptual understanding of the jet dynamics across large longitudinal sectors. This will provide the climate dynamics community with a framework for interpreting the observed jet variability and projections of the longitudinally-dependent jet response to climate change.

B Research objectives & expected significance

B.1 Research objectives

The overall goal of the proposed study is to advance the understanding of jet dynamics across large longitudinal sectors, where the jet properties are relatively uniform. Our proposal will address the following questions:

1. To what extent can the climatology, variability, and climate change response of the jet across large longitudinal sectors be explained by theoretical arguments that apply to statistically zonally-symmetric circulations?

2. What are the relative roles of jet variability drivers over large longitudinal sectors in the NH and SH during different seasons? The drivers include angular momentum advection from the tropics, extratropical eddy activity generated due to an SST front, and Rossby wave propagation from the tropics.

3. What are the climate model biases associated with historical jet dynamics over large longitudinal sectors, and what is their effect on projections of the jet response to climate change?

4. How does the jet respond to localized tropical heating in terms of its longitudinally-dependent properties?

To address the above questions, we propose three research objectives:

1. **Assessing the relative roles of jet variability drivers in observations (section C.3.1).** Causal discovery will be used to quantify the roles of jet variability drivers across large longitudinal sectors in the NH and SH during the four seasons. We will analyze the momentum budget to reveal the processes by which the drivers influence the jet at each longitudinal sector. This analysis will determine whether zonally-symmetric or asymmetric processes are dominant in maintaining the jet structure.

2. **Identifying sources of jet biases and inter-model variability in climate models (section C.3.2).** We will analyze the connection between jet properties and their driving variables in the inter-model spread, focusing on large longitudinal sectors. We will apply causal discovery to compare the strength of causal links between jet properties and their drivers in models with those in observations. This comparison will be used to constrain the jet response to climate change across large longitudinal sectors and to identify sources for jet biases in models.

3. **Elucidating the effect of a localized tropical heat source on the jet using an idealized model (section C.3.3).** We will perform an experiment using an aqua-planet model to examine how variations in a tropical heat source affect the jet properties in the subtropics and midlatitudes. This controlled experiment will allow us to isolate the effects of angular momentum advection and stationary Rossby wave generation on the jet structure.

B.2 Expected significance

Current theoretical models primarily apply to zonally-symmetric conditions, whereas the actual jet is zonally-asymmetric. It has not yet been assessed if jet dynamics over large longitudinal sectors are similar to those of a zonally-symmetric jet. Previous studies used linear regression and lagged correlation methods to correlate jet variability with climatic variables. These methods add insight into the processes leading to jet variability but do not establish causal relationships. The proposed research will use novel methods that enable a rigorous analysis of causal relationships between variables. By combining statistical analyses of observational and climate model data with controlled numerical experiments, we will isolate the processes leading to the observed jet structure and variability. Our proposal will lead to a better understanding of the jet response to external forces related to interannual variability and anthropogenic climate change. This will improve the interpretation of climate model projections, reducing the uncertainty in future jet dynamics.

C Detailed description of the proposed work

C.1 Working hypothesis

We hypothesize that due to the zonally-asymmetric driving of the jet, its variability and response to climate change cannot be adequately explained by zonally-symmetric theory. We further hypothesize that angular momentum transport driven by localized tropical convection is a major determinant of the longitudinal structure of the jet, its variability, and its response to climate change, particularly in the SH. Due to the zonally-asymmetric jet structure caused by tropical convection, the momentum budget is affected by processes relevant only to a zonally-asymmetric jet: zonal advection, zonal pressure gradients, and Rossby wave propagation. The longitudinally-dependent interaction between the jet and extratropical eddies brings the jet to its equilibrated state. We hypothesize that all these processes play a role in determining the jet variability and response to climate change.

C.2 Research design and methods

The first two objectives described in section B.1 focus on statistical analysis of observational and climate model data. The third objective includes a controlled experiment using an idealized model. In the following paragraphs, we describe the statistical methods that will be used, the observational and climate model data that will be analyzed, and the idealized model experiment.

C.2.1 Causal discovery method

Dynamical atmospheric processes can be described in a mathematically compact way by defining indices that best capture a specific phenomenon. Such indices include the Niño-3.4 SST index, which measures the state of the atmosphere and ocean with respect to El-Niño Southern Oscillation (ENSO), the North Atlantic Oscillation (NAO), the Northern Annular mode (NAM) and the Southern Annular mode (SAM) indices. Other indices are defined for targeting longitudinally-dependent jet variability phenomena (Gillett et al., 2021; Liu et al., 2021). Lagged correlations between indices provide insightful information but can be inflated by autocorrelation effects or results from a common driver. Therefore, they are strongly limited in interpretability and might not reflect the actual physical processes.

Recent studies have used causal detection methods, called causal discovery algorithms, to identify and quantify causal connections between time series of climatic indices (Kretschmer et al., 2016; Runge et al., 2019; Saggioro and Shepherd, 2019). The algorithm we will use is called PCMCI (Kretschmer et al., 2016; Runge et al., 2019), a variation of the PC algorithm (Spirtes et al., 2001). Before applying the algorithm, the user needs to define the relevant time series that are physically related based on expert knowledge. The PCMCI algorithm then finds the causal relationships among them. The algorithm includes two steps:

1. Conditional independence test. The connections between the different time series are tested to identify indirect connections. The time series' that remain associated with a specific variable, after controlling for the effect of other time series, form the set of parent processes for that variable (Kretschmer et al., 2016). This test uses partial correlations in case linear relationships between the variables are assumed.

2. Quantifying the strength of the relationships. The strengths of the relationships are quantified using multiple linear regression, taking into account the parent processes identified in step 1.

The outcome of this analysis is a graphical causal model of the connections between the variables analyzed. Each node in this causal network describes a variable. The arrows connecting them describe the causal relationships between the variables, with the coefficients calculated in step 2 assigned to each respective arrow.

C.2.2 Observational data

Data on atmospheric variables such as zonal and meridional wind speeds and temperature will be from ERA5 reanalysis (Hersbach et al., 2020). Data on outgoing longwave radiation (OLR), indicating the strength of tropical convection, will be from the National Oceanic and Atmospheric Administration (NOAA) interpolated OLR data set (Liebmann and Smith, 1996). SST data will be from the HadISST data set (Rayner et al., 2003). The proposed observational data analysis is described in section C.3.1.

C.2.3 Comprehensive climate model data

We will use data from the Coupled Model Intercomparison Project Phase 6 (CMIP6). We will use the historical experiment to compare the representation of physical processes in climate models with observations. This experiment mimics the climate conditions during the time period for which a wide coverage of observational data exists. The SSP5-8.5 scenario simulations will be analyzed to compare with the results from the historical simulations to constraint future projections using emergent constraints (Simpson et al., 2021). To investigate how jet driving mechanisms are affected by anthropogenic climate change, we will compare data from the pre-industrial (piControl) experiment with data from the abrupt $4\times CO_2$ experiment. These two experiments include at least a 50-year period when the flow is in a statistically steady state, allowing an examination of the atmospheric circulation maintenance under steady climate conditions. The proposed climate model data analysis is described in section C.3.2.

C.2.4 Idealized model experiment

We will use the Model of an idealized Moist Atmosphere (MiMA, Jucker and Gerber, 2017), which is embedded in the ISCA modeling framework (Vallis et al., 2018). This idealized model includes a representation of water vapor and parameterizations for convection and condensation, as elaborated in Frierson et al. (2006). The model uses a full radiation scheme, including the water vapor radiative effect. It is considered as an intermediate complexity model (Maher et al., 2019), because its default configuration is an aqua-planet with no continents, clouds or ice, and excludes chemical processes. While more idealized than comprehensive climate models, moist processes make the model more complex and realistic than dry idealized models, such as the Held-Suarez model (Held and Suarez, 1994). The model is designed to incorporate modifications of the forcing and boundary conditions and reproduces a realistic structure of climatological stationary waves (Garfinkel et al., 2020). We will run the model with solstice conditions to produce both subtropical and eddy-driven jets. We will also add localized tropical diabatic heating to create a zonally-asymmetric circulation, capturing the observed jet characteristics (see section C.3.3 for more details).

C.3 Work plan and preliminary results

C.3.1 Jet variability drivers in observations

Jet variability at monthly and longer time scales arises from a combination of internal jet-eddies interactions and other climatic variables that can be viewed as external to the jet-eddies system. Many studies point to the role of tropical SST variability in driving jet variability in both hemispheres (Ding et al., 2012; Li and Wettstein, 2012; Baker et al., 2019; Yang et al., 2020; Gillett et al., 2021; Liu et al., 2021). Zonally-asymmetric tropical convection, induced by zonally-asymmetric SSTs, affects the jet via two main processes: localized angular momentum advection by the upper tropospheric divergent flow (Hoskins and Yang, 2023) and generation of quasi-stationary Rossby waves that propagate from the tropics (Jin and Hoskins, 1995; Inatsu and Hoskins, 2004). While zonal asymmetries arising from topography and land-sea contrast are dominant in the NH, these factors play a secondary role in SH jet asymmetry (Patterson et al., 2020). We will analyze observational data to assess the roles of tropical convection and other processes in driving jet variability across wide longitudinal sectors.

Preliminary results: We performed a preliminary observational analysis of the SH winter jet to demonstrate the importance of zonally-asymmetric tropical convection in driving jet variability and the usefulness of causal discovery. We focused on the Pacific sector, where the jet characteristics are typical of a subtropical jet (Figure 1), and examined variables regressed on the jet speed (**Figure 2**). We included variables related to tropical convection (measured by OLR), eddy-driven jet strength (measured by the lower tropospheric wind), and the extratropical temperature gradient (measured by the high latitude lower tropospheric temperature).

We calculated the correlation coefficients between the time series of the variables in Figure 2 and the winter Pacific jet speed (**Table 1**). The winter Pacific jet speed is defined as the zonal wind at 200 hPa, averaged over the box in Figure 2a, during the winter months. The four variables $\overline{u}_{200}$, $\overline{u}_{850}$, OLR and $\overline{T}_{850}$ represent the upper tropospheric zonal wind, lower tropospheric zonal wind, OLR and the lower tropospheric temperature, respectively, averaged over the respective boxes in Fig. 2. We used time series for the years 1979-2013, with the winter months denoted by JJA (June, July, and August) and the time series leading by one and two months denoted by MJJ (May, June, and July) and AMJ (April, May, and June), respectively.

Variables significantly correlated with $\overline{u}_{200}$(JJA) at leading months (MMJ and AMJ) are potential drivers of winter subtropical Pacific jet variability on monthly time scales. In this example, four relevant variables

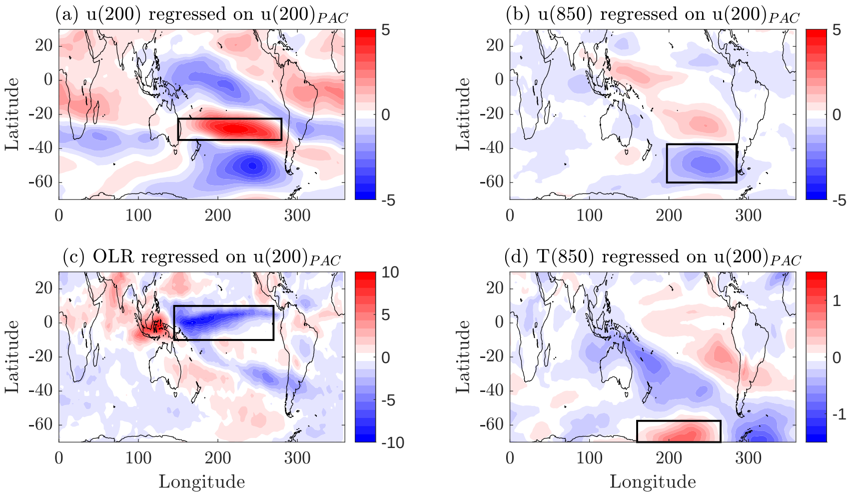

Figure 2: Variables regressed on the SH winter Pacific jet speed: (a) Upper tropospheric (200 hPa) zonal wind, in m s^{-1}; (b) Lower tropospheric (850 hPa) zonal wind, in m s^{-1}; (c) OLR, in W m^{-2} (negative anomalies indicate stronger convection); (d) Lower tropospheric (850 hPa) temperature in K. The rectangle boxes mark the averaging region for the causal discovery analysis (see text).

were found: $\overline{u}_{200}$(MJJ), $\overline{u}_{200}$(AMJ), $\overline{u}_{850}$(MJJ) and OLR(MJJ). The first two correlations are due to the jet speed autocorrelation time scale, leaving $\overline{u}_{850}$(MJJ) and OLR(MJJ) as potential drivers. The high latitude lower tropospheric temperature anomaly ($\overline{T}_{850}$) is not a potential driver on monthly time scales, though it is correlated with the jet strength during JJA (Table 1).

	$\overline{u}_{200}$	$\overline{u}_{850}$	OLR	$\overline{T}_{850}$
JJA		**-0.67**	**-0.38**	**0.28**
MJJ	**0.49**	**-0.32**	**-0.36**	0.02
AMJ	**0.36**	-0.23	-0.19	0

Table 1: Correlations with the Pacific winter jet speed time series (see text for the definition of each time series). Correlations marked in bold letters are significant at the 99% level.

The significant correlation does not necessarily imply a causal relation. Thus, we next applied the first step in the causal discovery method described in section C.2.1. We examined if the correlation of OLR(MJJ) with $\overline{u}_{200}$(JJA) is an indirect effect, with $\overline{u}_{200}$(MJJ) acting as a mediator. To test this, we calculated the partial correlation between OLR(MJJ) and $\overline{u}_{200}$(JJA) conditioned on $\overline{u}_{200}$(MJJ). The result was a significant partial correlation of -0.27 (**Table 2**), consistent with the hypothesis that OLR is a direct driver of the jet speed anomaly on a time scale of one month. In contrast, we showed in a similar test that $\overline{u}_{850}$(MJJ) is not a direct driver of the jet speed anomaly on a monthly time scale (Table 2). These preliminary results imply that tropical convection is a driver of SH winter Pacific jet variability on monthly time scales, though the full causal discovery algorithm needs to be applied to confirm this hypothesis.

	$\overline{u}_{200}$	$\overline{u}_{850}$	OLR
MJJ		0.06	**-0.27**
AMJ	0.027		

Table 2: As in Table 1, but showing partial correlation coefficients, conditioned on $\overline{u}_{200}$(MJJ).

Work plan: We propose to analyze the observational data using both traditional analysis of the dynamical variables and the causal discovery method described in section C.2.1. Causal discovery will be used to quantify the relative roles of jet variability drivers at each sector and season. In the first step of the causal discovery, we will calculate a set of time series that optimally capture the different influences on the jet variability. These variables will include OLR to capture tropical convection, midlatitude or high latitude SST gradients, baroclinic eddy sources, and stratospheric polar vortex strength, which affects the eddy-driven jet variability (Kidston et al., 2015). The averaging region of each variable will be chosen based on our observational analysis (as in Figure 2) while performing sensitivity tests to examine the robustness of the results. After identifying the potential drivers in the first step, we will apply the second step of the causal discovery method, which quantifies the strength of each causal connection.

We will perform two analyses using traditional methods before applying causal discovery to identify jet driving processes and to better understand them:

1. The momentum budget: We will calculate the momentum budget terms and their lagged correlations with respect to jet variability events, defined by anomalies in the local jet strength and latitude over specific longitudinal sectors. The momentum budget will be calculated using the zonal momentum equation:

$$\frac{\partial \overline{u}}{\partial t} = -\frac{\overline{v}}{a^2 \cos\phi}\frac{\partial A}{\partial \phi} - \frac{\overline{u}}{a\cos\phi}\frac{\partial \overline{u}}{\partial \lambda} - \overline{\omega}\frac{\partial \overline{u}}{\partial p} - \nabla\left(\overline{\mathbf{v}'u'}\right) - \frac{1}{a\cos\phi}\frac{\partial \Phi}{\partial \lambda} + Res \quad (1)$$

where u, v and ω are the zonal, meridional, and vertical wind components, respectively, $A = a^2\cos^2\phi\Omega + a\cos\phi u$ is the absolute angular momentum, a and Ω are Earth's radius and rotation rate, respectively, Φ is the geopotential, ∇ and $\mathbf{v}$ are the three-dimensional divergence operator, and wind vector, respectively, overbar denotes time averaging and prime denotes deviations from the time average and Res is a residual term. This formulation of the momentum equation will enable us to examine separately the effects of absolute angular momentum advection by the mean meridional wind (first term on the RHS), zonal and vertical momentum advection by the time-averaged flow (second and third terms on the RHS), momentum flux convergence from transient eddies (fourth term on the RHS) and the pressure gradient force (fifth term on the RHS). The terms that disappear when taking the zonal average include the zonal advection term, the zonal component of the eddy momentum flux convergence, and the pressure gradient force. The mean meridional wind ($\overline{v}$) in the angular momentum advection term includes a geostrophic component, which disappears in the zonal mean. Comparing the acceleration terms due to zonally-dependent processes with terms that affect the zonal-mean momentum budget will enable us to assess the importance of zonal asymmetries for jet maintenance and variability.

2. The roles of Rossby waves and angular momentum advection: We will evaluate the influence of tropical convection on jet variability by examining separately the roles of Rossby wave generation and poleward angular momentum advection, which are both driven by tropical convection. We will examine these processes in two steps: First, we will calculate the divergent wind regressed on the jet anomaly, from which we will calculate the local Hadley circulation stream function (Schwendike et al., 2014; Nguyen et al., 2018; Raiter et al., 2024). This will allow us to calculate the meridional angular momentum advection by this circulation. Next, we will calculate the Rossby wave source from the divergent wind in the upper troposphere and use a barotropic model to calculate the stationary Rossby wave it induces (Hoskins and Ambrizzi, 1993). We will examine the extent

of jet variability associated with quasi-stationary Rossby waves excited by a tropical source and variations in angular momentum advection by the local Hadley circulation.

Combining dynamical process analysis using observational data with causal discovery methods will improve our understanding of the mechanisms controlling jet variability over large longitudinal sectors.

C.3.2 Drivers of jet variability and response to climate change in climate models

The zonal-mean jet response to climate change, including a poleward shift of the eddy-driven jet and a strengthening of the subtropical jet, is robust across climate models and forcing scenarios. However, the longitudinally-dependent response is complex and poorly understood (Barnes and Polvani, 2013; Yang et al., 2020; Waugh et al., 2020). The longitudinal dependence of the Hadley cell response affects the jet response. During SH winter, the Hadley circulation weakens over the Indo-Pacific sector and strengthens over the East Pacific (Staten et al., 2019; Raiter et al., 2024). Consistently, the upper-tropospheric subtropical jet slightly weakens over the Indo-Pacific region and Australia and extends further downstream to the East Pacific (Patterson et al., 2021). The exact mechanisms that drive the local jet response have not yet been elucidated.

Recent studies examined the inter-model variability of the response over specific longitudinal sectors (Oudar et al., 2020; Waugh et al., 2020; Liu et al., 2021; Liu and Grise, 2023; Breul et al., 2023). In particular, Breul et al. (2023) found that the inter-model variability of the zonal mean jet latitude during SH winter is a geometric artifact of the Pacific jet variability. They further showed that this geometric artifact explains the linear relationship between climatological jet latitude and jet shift found in Simpson and Polvani (2016), which is used as an emergent constraint for the jet shift (Simpson et al., 2021). This striking example demonstrates that examining the jet response over specific longitudinal domains adds important insight to model biases, which helps reduce the uncertainty in climate change projections of the jet response. We will examine the drivers of jet variability in CMIP6 models and compare them with those we will find in the observational analysis described in section C.3.1.

Preliminary results: As a preliminary test, we examined the SH winter jet and tropical convection in two climate models. **Figure 3** shows the pre-industrial zonal wind and OLR and their responses to quadrupling CO_2 for two models: CNRM-ESM-1 and MIROC-ES2L. The zonal wind in CNRM-ESM-1 is similar to the observed wind, whereas in MIROC-ES2L, the subtropical jet is too strong and extends too far zonally, with weak near-surface winds (compare with Figure 1a,c). The OLR profile is more realistic in MIROC-ES2L, whereas it is too narrow and concentrated around the equator in CNRM-ESM-1. The responses of the zonal wind and OLR to quadrupling CO_2 are different between the two models. The differences in the zonal wind response between the models might be attributed to the climatological extratropical circulations (Curtis et al., 2020), or tropical convection (Liu and Grise, 2023). Other factors may be responsible, such as the stratospheric polar vortex (Ceppi and Shepherd, 2019; Williams et al., 2024), cloud radiative effects (Voigt and Shaw, 2016), or coupling with the oceanic circulation (Chemke, 2022).

We repeated the preliminary causal discovery analysis described in section C.3.1 for the two models pre-industrial simulations. The result was a higher correlation of OLR(MJJ) with $\overline{u}_{200}$(JJA) in MIROC-ES2L

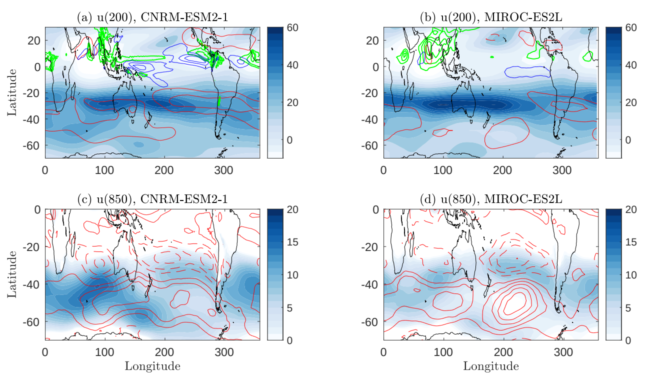

Figure 3: SH winter zonal wind (m s^{-1}) at 200 hPa (a,b) and 850 hPa (c,d) from the pre-industrial simulation of two CMIP6 models: CNRM-ESM-1 (a,c) and MIROC-ES2L (b,d). Solid (dashed) red contours show positive (negative) zonal wind response to quadrupling CO_2, with a contour interval of 5 m s^{-1} in (a,b) and 1 m s^{-1} in (c,d). Green contours in (a,b) show OLR, with a contour interval of 10 W m^2, from 180 to 220 W m^2. Blue contours show its response to quadrupling CO_2, with contour levels -30, -20 and -10 W m^2.

(-0.47) compared to CNRM-ESM-1 (-0.30), after conditioning on $\overline{u}_{200}$(MJJ). In the case of MIROC-ES2L, this correlation is larger than the observed (-0.27, see Table 2). This indicates unrealistically strong driving of the Pacific jet by tropical convection in MIROC-ES2L, which could explain the unrealistically strong jet, though further analysis is required to test this hypothesis.

Work plan: We propose to investigate the sources of the inter-model spread in the jet response over different longitudinal sectors, as well as the sources of internal jet variability in the different models. This effort will include two parts:

1. Analysis of jet driving mechanisms across models: We will examine the inter-model variability of key processes affecting the jet at specific longitudinal sectors and seasons. In particular, we will examine the connection between the inter-model spread of longitudinally-dependent tropical convection and jet latitude and strength over specific longitudinal sectors. While previous studies addressing this question focused on the lower-tropospheric jet representing the eddy-driven jet (Waugh et al., 2020; Oudar et al., 2020), we will examine the upper-tropospheric jet to capture the subtropical and eddy-driven jet variability.

2. Applying causal discovery methods on climate model data: Using causal discovery methods, as described in section C.3.1, we will quantify causal links between the jet and its drivers. By applying these methods to climate model data and comparing them with the results of the observational analysis, we will evaluate model performance in representing jet driving mechanisms. This evaluation will be used to constrain future jet projections across longitudinal sectors. Recent studies explained stratospheric polar vortex model biases and inter-model variability by quantifying causal connections (Kretschmer et al., 2020; Shen et al., 2024), which demonstrates the usefulness of this method for reducing climate change response uncertainty.

For both parts, we will analyze simulations of the historical period to compare the representation of jet-driving mechanisms in models to those in observations. The inter-model spread in the historical simulations will be compared with that in the SSP5-8.5 scenario simulations so that emergent constraints will allow us to determine the likelihood of future jet projections (Simpson et al., 2021; Liu and Grise, 2023). Additionally, we will analyze pre-industrial and abrupt 4×CO_2 simulations to examine the response of the jet driving mechanisms to climate change under statistically steady-state conditions, which will allow for a more rigorous theoretical interpretation.

C.3.3 Jet variability in an idealized model with localized tropical heating

A direct way to examine causal relations in atmospheric circulation is to use a numerical model, where it is possible to control specific processes. The idealized model, MiMA (described in section C.2.4), will be used to examine the jet dynamics in the presence of a zonally-asymmetric tropical heat source. Because the model includes moist processes, it qualitatively captures the sporadic localized nature of tropical convection (Frierson et al., 2006; Frierson, 2007), an essential factor for creating a realistic subtropical jet (Hoskins and Yang, 2023). Localized tropical heating added to a dry model produces a transient subtropical jet, which is not maintained in a steady state (Williams et al., 2007). In fact, a realistic-looking subtropical jet is rarely produced by a dry model, except when forced using observational data (Kim and Lee, 2004; Wu and Reichler, 2018). The preliminary results presented here show that MiMA is able to capture the observed structure of the subtropical jet driven by localized tropical heating.

Preliminary results: We performed a preliminary simulation of NH winter conditions using solar insolation and SST profiles that peak in the SH tropics. A diabatic heat source was added around the latitude of maximum ascent, with a limited longitudinal extent. The localized heat source drives a localized jet resembling the observed subtropical jet, whereas an eddy-driven jet exists at other longitudes (**Figure 4**, compare with Figure 1a,c). This preliminary result demonstrates that the idealized model is suitable for studying the response of the jet to localized tropical heating.

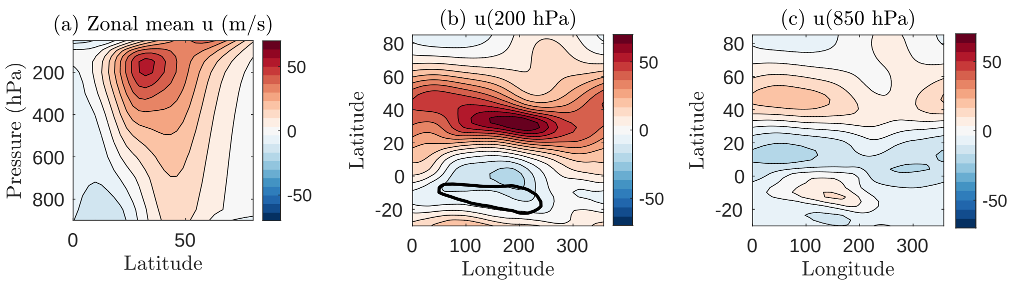

Figure 4: Zonal wind (in m s^{-1}) in the idealized model simulation with additional localized tropical heating, averaged over the statistically steady state period. (a) Zonal mean zonal wind as a function of latitude and pressure. (b) Zonal wind at pressure level 200 hPa, as a function of longitude and latitude. (c) as in (b) but for the pressure level 850 hPa. The thick black contour in (b) marks the 2 K day^{-1} diabatic heating contour at pressure level 300 hPa. The region inside this contour has larger values of diabatic heating.

The zonal momentum budget (equation (1)) for this simulation demonstrates the importance of zonally-asymmetric processes for the jet maintenance (**Figure 5**). The two largest terms are the Coriolis force and the pressure gradient force (panels (b) and (c), note different color-scales), which are close to geostrophically balancing each other. In a zonally-symmetric configuration, the climatological Coriolis force due to geostrophic meridional wind (equal to minus the pressure gradient force by definition) is negligible. In contrast, here, there is a strong geostrophic component associated with a stationary Rossby wave generated by the zonally-asymmetric tropical diabatic heating source. The terms that dominate the observed zonal-mean momentum budget (Dima et al., 2005) - the Coriolis force due to the ageostrophic meridional wind, meridional eddy momentum flux convergence, and the meridional advection by the time-mean flow - have considerable zonal structure, so that their local values are much larger than their zonal-mean (compare Fig. 5d,f,j with Fig. 5a,e, i). Additionally, there are non-negligible zonal eddy momentum flux convergence and zonal advection by the time-mean flow, which would be zero in a climatological zonally-symmetric configuration. These preliminary results indicate that the jet-maintaining processes in the presence of a zonally-asymmetric tropical heat source are different from those in a zonally-symmetric configuration.

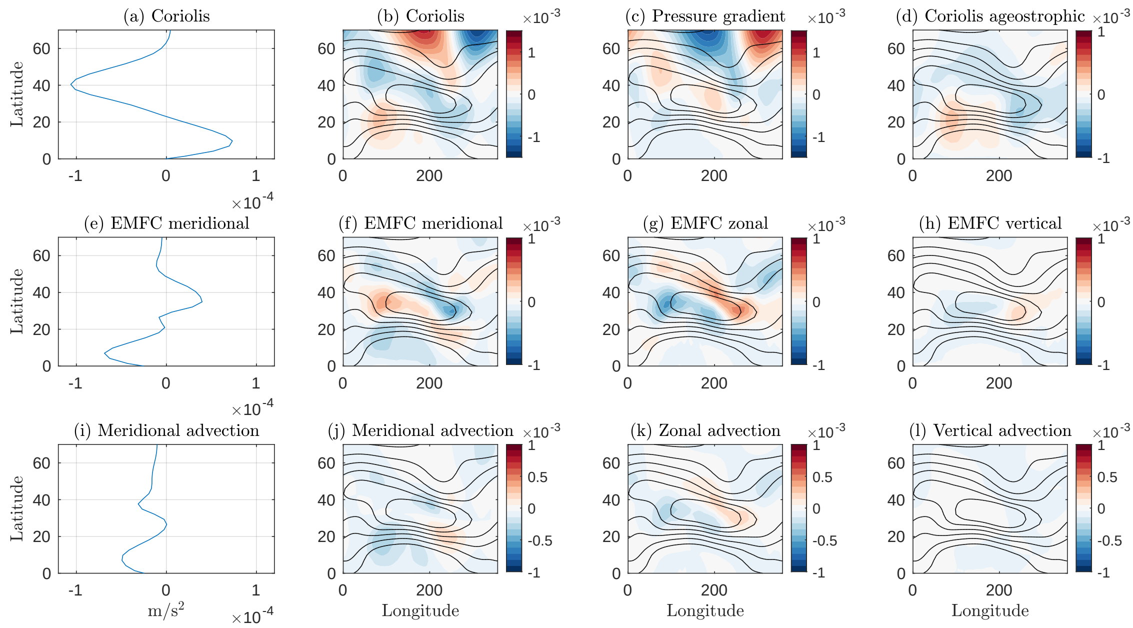

Figure 5: Momentum budget terms for the idealized model simulation at pressure level 200 hPa, averaged over the last 10 years of the 50-year simulation, in m s^{-2}: Coriolis force (b); pressure gradient force (c); Coriolis force due to the ageostrophic meridional wind (d), equal to (b)+(c); meridional (f), zonal (g) and vertical (h) eddy momentum flux convergence, where eddies are defined as deviations from the time-mean; meridional (j), zonal (k) and vertical (l) momentum advection by the time-mean flow. Black contours show the 200 hPa time-averaged zonal wind, with a contour interval of 10 m s^{-1}, starting from 10 m s^{-1}. Panels (a), (e), and (i) show the zonal average of the variables in panels (b), (f) and (j).

Work plan: Using this model, we will perform a series of simulations, modifying the tropical heat source properties across a wide range of values to examine the effect on the jet structure and variability. The controlled properties of the heat source will include its longitudinal, latitudinal, and vertical extent, distance from the equator, and strength. This parameter sweep will produce a wide range of jet profiles, with varying dominance of the subtropical or eddy-driven jets. Additionally, we will perform ensembles of switch-on simulations where localized tropical heating is abruptly changed to examine transitions between steady states.

We will analyze the jet driving mechanisms in the simulations to determine what controls longitudinal transitions in the jet properties. The analysis will include (1) The upper tropospheric zonal momentum budget as a function of longitude and latitude. The terms will be calculated for the steady state and transition periods to identify processes changing the jet properties. (2) Lagged regressions of different variables with respect to events of extreme jet properties to examine mechanisms controlling jet variability. The variables will include the meridional stream function and eddy heat and momentum fluxes to diagnose interactions between the jet, the eddies, and the meridional circulation. (3) Analysis of Rossby wave propagation to determine its role in shaping the zonally-asymmetric jet structure. (4) Causal discovery of jet variability drivers in the model for comparison to the observational data analysis results.

We expect the idealized model experiment will provide an overview of the dynamics leading to a zonally asymmetric jet structure arising from asymmetric tropical heating. In particular, it will reveal processes leading to zonal transitions in the jet characteristics between subtropical and eddy-driven jets. Williams et al. (2007) suggested that the zonal structure of the springtime SH jet arises from localized tropical heating driving a localized subtropical jet. The subtropical jet is baroclinically unstable, leading to eddy growth on its downstream side, which in turn drives an eddy-driven jet further downstream. They used a dry model to test this hypothesis, but the model could only reproduce a realistic jet structure for a limited time. Our preliminary results demonstrate that the moist model we plan to use can maintain this realistic structure in a statistically steady state, and therefore, it is more suitable for examining the processes leading to the zonally asymmetric jet structure.

C.3.4 Work plan summary

Overall, the proposed research will advance our understanding of why and how jet properties change with longitude. The results are expected to bridge the gap between the theoretical concept of the zonally-symmetric thermally-driven (subtropical) versus eddy-driven jet and the observed jet, which transitions between subtropical and eddy-driven jet characteristics as a function of longitude. We expect that the combination of observational data analysis, climate model data analysis, and idealized model simulations will allow us to relate the observed phenomena to the jet response to climate change and to test the basic hypotheses using the idealized model. We expect the climate dynamics community to benefit from the proposed research outcome, as it will enable improved interpretation of jet variability phenomena and jet response to climate change, which are essential for understanding and predicting mid-latitude climate variability and change.

C.4 The researcher's resources for conducting the research

The PI is a faculty member in the Department of Natural Sciences at the Open University of Israel and has published many papers on various aspects of the midlatitude atmospheric circulation and jet stream dynamics. The Open University of Israel owns a high-performance computing (HPC) system with sufficient cores for running the MiMA model at T85 resolution. This resolution captures the dynamics relevant to this proposal. The university employs a full-time technical HPC support team. On this system, 320 cores and 50TB of storage are dedicated exclusively to the PI's group. The Lachmy group has published five papers based on results from running MiMA and observational and climate model data analysis using this HPC system. We request funding to increase the HPC system storage capacity by 50TB (100TB total, to store more reanalysis (observational) data and climate model data output. The storage expansion is essential because most data we have stored so far is zonally averaged as a function of latitude, pressure and time. In contrast, for our proposed research, we must save longitudinally-dependent data as a function of longitude, latitude, and time for several pressure levels.

Our proposed data analysis methods are similar to methods we used previously, except for causal discovery.

For this analysis, we will collaborate with Jun. Prof. Marlene Kretschmer from Leipzig University, who kindly shared her experiences and code in applying causal discovery and causal inference techniques (Kretschmer et al., 2016, 2021), as indicated in the attached letter.

C.5 Expected results and pitfalls

We expect the proposed research to advance the understanding of jet dynamics under zonally asymmetric conditions. The observational data analysis is expected to confirm or negate hypotheses on jet dynamics at specific longitudinal sectors and seasons (e.g., Nakamura et al., 2004; Williams et al., 2007; Hoskins and Yang, 2023). Previous studies examined correlations between jet variability and climatic variables such as eddy momentum flux and OLR. While this type of analysis indicates consistency or inconsistency of data with different hypotheses, it is ambiguous because correlations may not be due to causal relations. We expect that causal discovery analysis will reveal which correlations are due to causal relations, at what time scales, and to what extent. We acknowledge that causal discovery has its limitations. The method assumes that all relevant processes are included in the analysis, which might not be accurate. Therefore, the detected relationships should be considered potentially causal (Barnes et al., 2019). The results could be sensitive to the choice of time scale for the time series. We will perform sensitivity tests to determine the optimal choice of variables and time scales needed to capture the causal relations more reliably. Causal discovery relies on expert knowledge about the physical mechanisms of the system. We will, therefore, include calculations of momentum budget terms and Rossby wave propagation. The combination of these calculations with causal discovery analysis will result in a more knowledgeable picture of the processes controlling the jet variability at large longitudinal sectors.

The climate model data analysis is expected to add insight into the sources of inter-model jet variability. We expect that by revealing the associations between jet properties and their driving processes in models, we will identify specific processes to be captured more realistically to decrease jet biases in models. Our approach will contribute to reducing jet projections uncertainty, for example, by identifying emergent constraints related to jet driving mechanisms (Simpson et al., 2021). In addition to inter-model variability, our analysis may detect sources for biases in the jet representation across all models. While CMIP6 models are improved compared to CMIP5, there are still biases in the jet representation (Bracegirdle et al., 2020). By comparing the jet driving processes in models to those in observations, we expect to shed light on the sources of these biases.

The idealized model simulations are expected to yield new information about the response of the jet to localized tropical heating, which has not yet been studied in a moist model. We expect this numerical experiment to advance our understanding of the processes determining jet properties and their longitudinal transitions. The dynamics of the jet in the real atmosphere are also affected by processes not included in the model, such as ocean variability, cloud radiative effects, and sea ice processes. However, since tropical convection plays a major role in the longitudinal jet structure, we expect the simulations to capture an essential aspect of the dynamics. The comparison between the model simulations and the observational analysis will reveal the extent to which the model captures the actual dynamics.

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