Detected climate change signals in atmospheric circulation: mechanisms, puzzles and opportunities

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Key Points:

- While circulation changes are thought to be more uncertain, many circulation signals have been detected across different regions and seasons
- Detected circulation signals represent an exciting opportunity for understanding the dynamical response to climate change
- Discrepancies have also emerged and in combination with new tools considerable progress is likely in the coming decades

Abstract

The circulation response to climate change shapes regional climate and extremes. We have moved into a new era where circulation signals have been detected across many regions and seasons. The detected circulation signals represent an exciting opportunity for improving our understanding of dynamical mechanisms, testing our theories and reducing uncertainties. They have also presented some puzzles that represent an opportunity for better understanding the circulation response, its contribution to climate extremes, interactions with cloud feedbacks, and connection to thermodynamic discrepancies. The next decade or so is likely to be a golden age for dynamics with many advances possible.

Plain Language Summary

Regional climate change signals in atmospheric circulation (wind and pressure) have emerged from the noise in many regions and seasons. Some of the signals are expected whereas others are not. The next decade represents an exciting time to better understand the dynamical mechanisms underlying the signals and their relationship to thermodynamical signals with the goal of improving regional climate prediction.

1 Introduction

The emergence and attribution of thermodynamic signals in response to anthropogenic climate change is well appreciated. Indeed global-mean warming over land and ocean, amplified warming in the tropical upper troposphere, rising of the tropopause, cooling of the stratosphere, regional land warming, and Arctic amplification of surface warming have all been attributed to human activities (IPCC 2021). Most recently thermodynamically driven changes in regional hot extremes, heavy precipitation and drought have also been confidently attributed to human activities in some regions (IPCC 2021, Fig. SPM.3). This progress on thermodynamic signals has been achieved through a multi-pronged approach: detection of observed signals, attribution to human activities, and understanding of the underlying mechanisms using climate model simulations that exhibit fidelity in the signal and mechanisms.

Atmospheric circulation is well-known to affect regional climate through changes in fluid-dynamic variables, including atmospheric wind, pressure, and associated influences of moisture, clouds and radiation. Many generations of climate models have predicted robust circulation responses to climate change at the end of the century, including an upward shift and acceleration of the subtropical jet stream, weakening of the Hadley circulation, expansion of the Hadley circulation, poleward shifts of the eddy-driven jet streams, strengthening of the storm tracks in the Southern Hemisphere and seasonally varying storm track responses in the Northern Hemisphere. In general, circulation signals are thought to be more uncertain, especially at the regional scale, due to large internal variability and the lack of sufficiently strong constraints on atmospheric dynamics (Shepherd, 2014). Furthermore, opposing thermodynamic responses to climate change, e.g. Arctic versus tropical warming, cloud shortwave versus longwave responses, aerosol cooling versus greenhouse gas warming, etc also can lead to a weak net dynamical response (Shaw et al., 2016). Hence dynamic variables are considered to have a lower signal-to-noise ratio, which has cascading impacts on hydrological cycle signals (Elbaum et al 2022).

Over the last decade we have come into a time where an increasing number of circulation signals have been detected in observational products. Here we define a detected circulation signal as a statistically significant linear trend over the satellite era or longer. The detected circulation signals, which are summarized below, have been noted in regions and seasons where the signal-to-noise ratio is typically high, e.g. the tropics and summertime. Some have already been attributed to human activities, with the best-known anthropogenic circulation signal being the response to ozone depletion during Southern Hemisphere summertime. However others have not and there may be a role for internal variability in some recently documented circulation trends.

This perspective summarizes the detected circulation signals, recent progress on understanding dynamical mechanisms, and puzzles, including the role of internal variability versus the forced response versus observational uncertainty, model-observation discrepancies and impact of mean state biases. We highlight the importance of linking the analysis and understanding of dynamic and thermodynamic signals. In particular, while many thermodynamic signals that have emerged are expected based on predictions, some exhibit discrepancies with observations, e.g. the “pattern effect” of SST trends. These thermodynamic signals are linked to atmospheric circulation, e.g. via thermodynamic gradients and cloud radiative effects. Finally, we highlight how circulation signals, along with existing and emerging tools, represent an exciting opportunity for making progress in the next few decades on understanding the dynamical mechanisms behind the circulation response to climate change.

2 Detected circulation signals

The most robust circulation signal to date induced by human emissions is the circulation response to ozone depletion in the Southern Hemisphere as summarized below. In the past decade several more circulation signals have been detected. Table 1 summarizes detected circulation signals across different regions, hemispheres, and seasons in reanalysis products during the satellite era. Some signals have emerged over localized regions such as the South-West Western Australia and are connected to regional hydro climate signals, whereas in other regions such as the Mediterranean the signal will take more time to emerge (Fig. 1). While many signals have been detected, in only a few cases has a formal attribution to human activities been performed. Thus for the moment many detected signals represent statistically significant linear trends in the time series and the role of internal variability and/or reanalysis biases still needs to be assessed. In many cases the sign of the signal is consistent with model predictions, however there are some cases where there is a discrepancy between the signal in observations and models. Asterisks indicate known discrepancies in observed versus modeled signals.

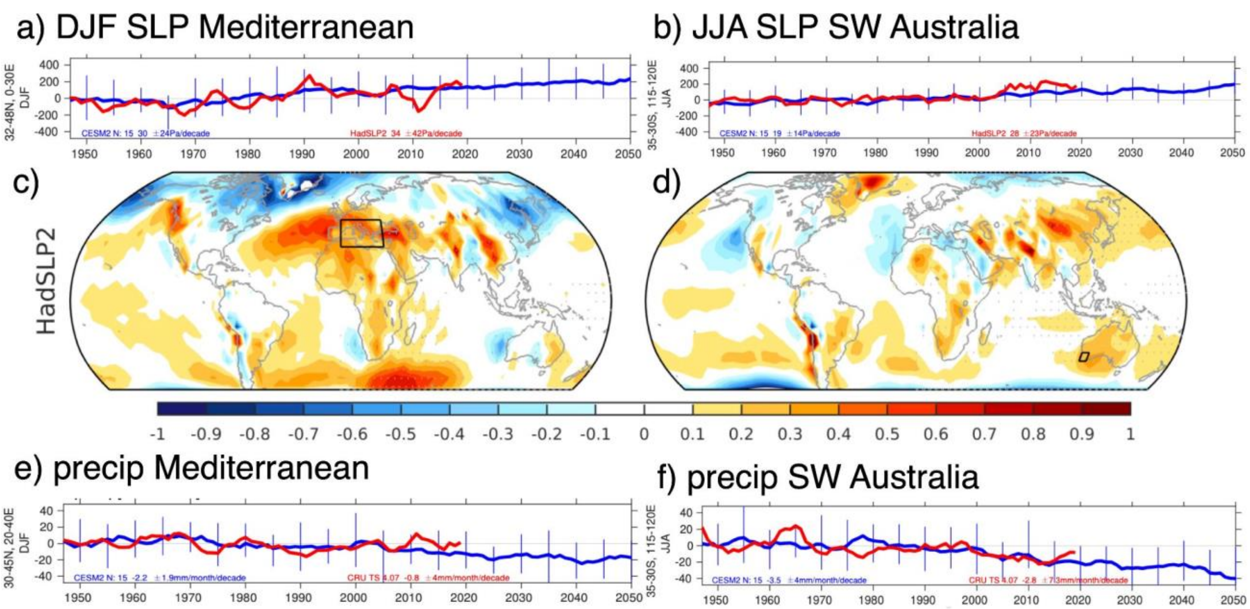

Figure 1: Regional circulation signal. Time series of (a,b) SLP and (e,f) precipitation from 1955 in observations (red line, HadSLPv2 for SLP, and CRU TS v4.07 for precipitation) over the Mediterranean during DJF (left) and South-West Australia during JJA (right). Five-year smoothed mean (blue line) and range (vertical blue line) of the 15-member historical-GHG only simulation in CESM2 of SLP and precipitation. (b,c) Spatial structure of SLP trends from 1950-

2019 in observations with stippling indicating statistically significant linear trends at the 0.05 level.

Box 1: Circulation response to ozone depletion - a strong signal as an opportunity to test our understanding and modeling capabilities of dynamical changes

The chemical depletion of Antarctic ozone loss, and its thermodynamic consequences, was first observed in the mid-1980s and peaked around year 2000, and is linked to the strongest circulation trends we have seen in the observed historical record. It thus offers the opportunity to test our theoretical understanding and modeling capabilities of dynamical changes. The direct consequence of ozone depletion is an increase of the meridional temperature gradient in the lower stratosphere. The circulation trends that result from this, which have been observed and generally well reproduced by climate models, are increases in the stratospheric polar vortex strength and an associated delay of the spring-time breakdown of the stratospheric polar vortex, and a poleward shift of the tropospheric jet stream in austral summer. This poleward shift of the jet goes along with a shift of the southern Hadley cell edge (WMO 2018). Past and projected trends in southeastern South American rainfall have been thought to be potentially linked to circulation changes forced by ozone depletion/recovery, but superposition of multiple driving mechanisms and large model spread hinders clear attribution (Díaz et al., 2021; Mindlin et al., 2021, 2023).

Since around the year 2000, ozone is slowly recovering and a pause in trends in the Southern hemisphere jet stream position and Hadley cell edge was reported a few years ago (Banerjee et al., 2020; Zambri et al., 2021). Model simulations support the attribution of this change in dynamical trends to ozone recovery. However, strong ozone depletion has occurred since 2020 (Kessenich et al., 2023), and the previously detected pause in jet shift trends has “de-emerged” (*see Figure Box 1 below*) though there is some sensitivity to the start year of the trend. Forcing by greenhouse gases generally is expected to cause a delay of the stratospheric polar vortex breakdown and a poleward shift of the tropospheric jet stream, thus counteracting the forcing from ozone recovery (e.g., Arblaster & Meehl, 2006; McLandress et al., 2010; Mindlin et al., 2021; Rao & Garfinkel, 2021; Thompson et al., 2011). Whether the recent “de-emerging” of the pause in trends is related to greenhouse gas forcing, recent influences of volcanic and wildfire aerosols (e.g., Yook et al., 2022), or natural variability is currently unknown.

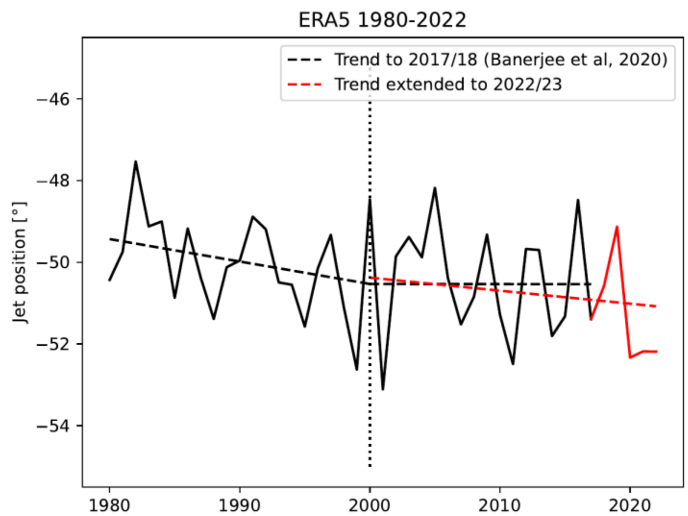

Figure Box 1: Jet stream position response to ozone depletion. Jet position in DJF from ERA5, reproducing Banerjee et al, 2020, for years 1980-2017 (black lines), and extending the timeseries to 2022 (red lines). Trends are fitted by continuous piecewise linear regression (following Banerjee et al), and trend values are -0.5°/dec for the ozone depletion period, 0.0°/dec for 2000-2017 and -0.3°/dec for 2000-2022.

3 Progress in understanding mechanisms

Many dynamical mechanisms have been proposed to explain the robust circulation responses predicted by generations of climate models (Shaw, 2019). Here we summarize recent progress on understanding mechanisms in response to greenhouse gas and aerosol forcing. The response to greenhouse gas forcing is organized into mechanisms related to tropical, extratropical, and Arctic thermodynamic processes (including diabatic processes) and oceanic boundary conditions.

3.1 **Response to greenhouse gas forcing**

3.1.1 Tropical thermodynamics

A robust thermodynamic response of the tropical atmosphere to greenhouse gas forcing is upper tropospheric warming, which follows from moist adiabatic adjustment (Manabe & Wetherald, 1975, Held 1993). Tropical upper tropospheric warming combined with cooling in the lower stratosphere further increases the meridional temperature gradient near the tropopause. The increased meridional temperature gradient is consistent with increased vertical zonal wind shear in the upper troposphere (Allen & Sherwood, 2008; Lee et al., 2019) and an upward shift and strengthening of the subtropical jet via thermal wind balance. Imposing an increase of CO_2 only in tropical latitudes in idealized aquaplanet model simulations confirms this mechanistic interpretation (Shaw & Tan, 2018). The result was confirmed in slab-ocean atmospheric general circulation models (Shaw 2019).

While tropical thermodynamics is clearly important for the acceleration of the subtropical jet and has been proposed to explain the poleward shift under climate change (Butler et al., 2010; Lorenz & DeWeaver, 2007; Lu et al., 2014), several recent mechanistic studies using idealized models have suggested it does not play a leading order role for the changes in extratropical jet position. These studies imposed CO_2 concentrations only in specific latitude bands (Shaw & Tan 2018), altered the surface boundary flux of moisture (Tan & Shaw, 2020), and modified the convection scheme (Garfinkel et al., 2024). They found that while tropical thermodynamics are important for the response of Hadley cell intensity and position and the subtropical jet strength, the poleward shift of the near-surface storm track and jet in response to CO_2 is not due to tropical diabatic processes (Fig. 2). Rather, these recent studies suggest the midlatitude near-surface response is due to diabatic processes in the subtropics and midlatitudes. Consistently, the poleward shift of the midlatitude near-surface jet and the strengthening of the subtropical jet happen on distinct timescales, suggesting they are driven by different processes (Chemke & Polvani, 2019; Menzel et al., 2019).

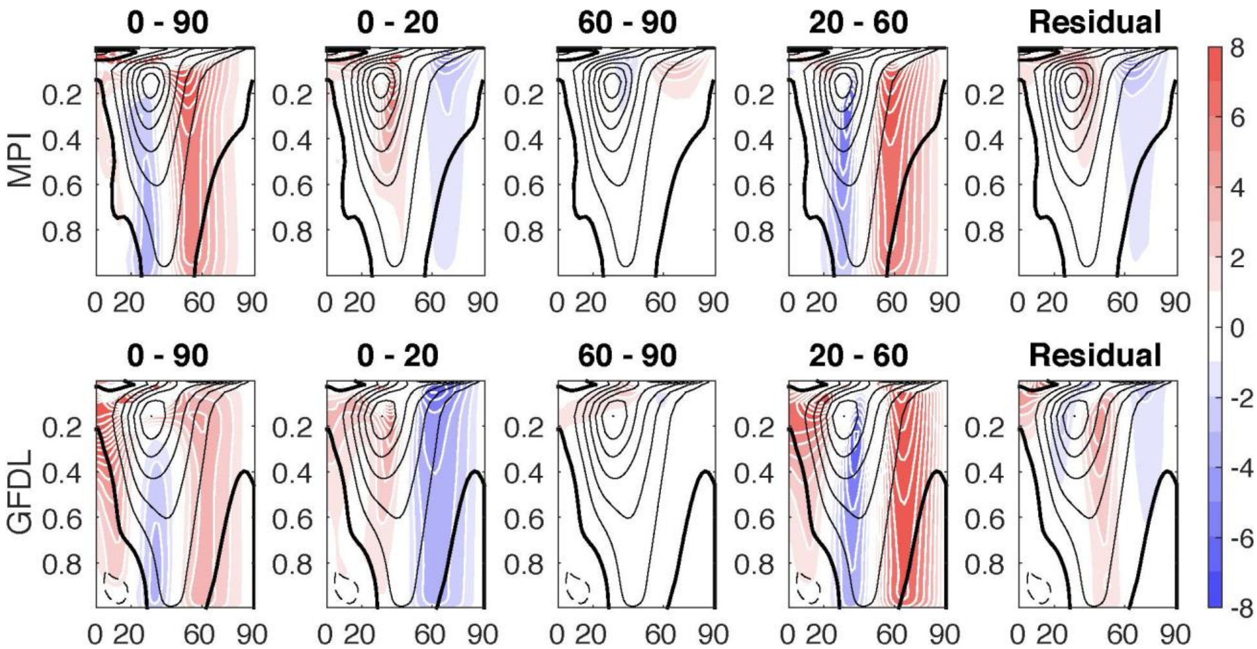

Figure 2: Response of zonal-mean zonal wind to latitudinally dependent quadrupling of CO2 concentration in aquaplanet simulations. Response shown in shading with contour interval of 1 m/s, black contours show climatology with interval 10 m/s with negative contours dashed. Taken from Shaw & Tan (2018).

3.1.2 **Extratropical diabatic processes**

Within the extratropics, several mechanisms involving diabatic processes (moisture, surface fluxes, latent heating and cloud radiative effects) have been shown to be important for the circulation response. A robust thermodynamic consequence of a warmed climate is an increased meridional water vapor gradient because the tropics moisten more than the poles (Shaw & Voigt, 2016). This increased gradient across the extratropics leads to increased moisture and surface flux gradient, increased poleward moisture flux, increased latent heat release and an upward shift of tropopause height and high clouds. These diabatic changes have been linked to increased subtropical static stability, shifts in the Hadley cell edge, jet stream and storm tracks and a poleward deflection of individual storms (Garfinkel et al., 2024; Lachmy, 2022; Shaw & Tan, 2018; Tamarin-Brodsky & Kaspi, 2017; Tan & Shaw, 2020; Voigt et al., 2021). Consistently increasing CO2 only in midlatitudes leads to a poleward shift of the lower-tropospheric jet stream (Fig. 2).

The fundamental role of moist diabatic and cloud radiative processes have been quantified by “locking experiments" whereby cloud radiative (Ceppi & Hartmann, 2016; Voigt &

Shaw, 2015) and surface flux (Tan & Shaw, 2020) responses have been disabled or prescribed in climate model simulations. In addition there have been advances in dynamical frameworks that incorporate and quantify the response of moisture (e.g., PV inversion with latent heat release, moist static energy framework)(Barpanda & Shaw, 2017; Tamarin-Brodsky & Kaspi, 2017; Shaw et al. 2018, Lachmy, 2022; Garfinkel et al 2024; Ghosh et al., 2024). This recent progress demonstrates that moist processes are crucial for understanding the circulation response and that focusing on dry processes (e.g. the temperature or eddy heat flux response) alone is insufficient. However, it is important to note that moist diabatic processes like convection and clouds in climate models are parameterized and their response to climate change remains highly variable across models. This is in part due to cloud-circulation feedbacks that complicate straightforward interpretation of the role of cloud radiative effects.

3.1.3 **Arctic thermodynamics**

The Arctic is warming much faster than the global-mean (Rantanen et al., 2022), which was predicted by climate models (Manabe & Wetherald, 1975) well before it was observed. The dynamical mechanism for how Arctic amplification influences jet stream strength involves a reduction in the meridional temperature gradient and near-surface baroclinicity, which leads to a weakening and equatorward shift of the jet through thermal wind balance and eddy feedbacks (Butler et al., 2010; Cohen et al., 2014).

Though the dynamical mechanisms for the influence of Arctic amplification on mid-latitude jet streams are generally agreed upon, the expected signals are not apparent in observational products during wintertime when the Arctic Amplification signal is largest (Blackport & Screen, 2020). This may be because of competing influences on the jet stream from the tropics or extratropics (Barnes & Screen, 2015). Despite the inability to link observed jet stream trends to Arctic thermodynamic processes during wintertime, new modeling intercomparison efforts have made progress in understanding and constraining the tropospheric jet stream’s response to future sea ice loss (Smith et al., 2022). These studies suggest that climate models simulate too-weak feedbacks between transient eddies and the tropospheric jet stream (Hardiman et al., 2022) and constraining models to account for this bias suggests that the role of Arctic amplification and sea ice loss for the future jet response is likely underestimated by climate models (Screen et al., 2022).

During summertime, when the Arctic Amplification signal is weakest, there is a clear weakening signal in jet strength (Coumou et al., 2015, 2018). Recent modeling results suggest the summertime jet weakening is not driven by Arctic changes and is instead likely related to high latitude warming over land and/or aerosol changes (Dong et al., 2022; Kang et al., 2023). The connection between the summertime increasing stationary wave amplitude in the Northern Hemisphere (Sun et al., 2022; Teng et al., 2022) and Arctic climate change is still actively debated. Recent work suggests the stationary wave signal is connected to a teleconnection from the tropical Pacific (Sun et al. 2022) and that soil moisture deficits can amplify this pattern (Teng et al. 2022).

A related effect is the observed signal of an increase in midlatitude heatwaves in summertime (e.g., Russo & Domeisen, 2023), which have been shown to be underestimated in coupled climate models due to discrepancies in the circulation (Fig. 4, Vautard et al., 2023). The increased summertime heat waves have been suggested to be related to increased "waviness" of the jetstream and the increased occurrence of so-called resonance events (Kornhuber et al., 2017; Mann et al., 2018), often associated with double jets (Rousi et al., 2022). Although it is clear that phase locking of planetary-scale waves can indeed lead to temperature extremes through a change in local atmospheric conditions (Jiménez-Esteve et al., 2022), it is not clear if concurrent heatwaves across multiple longitude areas are indeed linked (Domeisen et al., 2023) or if they simply happen at the same time due to similar processes occurring in several longitudinal areas (White et al., 2022; Wirth et al., 2018), such as the occurrence of Rossby wave packets or blocking, which are the most often identified atmospheric drivers for heatwaves (Fragkoulidis et al., 2018; Pfahl & Wernli, 2012).

3.1.4 Ocean-driven thermodynamics

Predictions from early climate models highlighted hemispherically asymmetric thermodynamic responses due to climate change driven in part by ocean circulation. In particular, cooling (or lack of warming) over the Southern Ocean arises due to the transient response of the ocean circulation (Stouffer et al., 1989), while the Arctic exhibits amplified warming due in part to ice-albedo feedbacks (Manabe & Stouffer, 1980) and ocean energy transport (Chemke et al., 2021). Over the tropical Pacific the Walker Circulation is projected to weaken, however ocean dynamical mechanisms can offset this response (Clement et al., 1996) and the mechanisms are uncertain (Wills et al., 2022). Finally, North Atlantic SSTs exhibit a warming hole with multiple drivers (Keil et al., 2020).

Hemispheric asymmetry is also clear in end of century projections of the atmospheric circulation response: storm tracks strengthen in the Southern Hemisphere across the seasonal cycle but exhibit opposing seasonal changes in the Northern Hemisphere (O'Gorman, 2010; Shaw et al., 2018) and the Hadley cell edge shift is stronger in the Southern Hemisphere (Watt-Meyer et al., 2019). Over the satellite period, hemispherically asymmetric signals have emerged in the storm tracks with the Southern storm track getting stronger and the Northern Hemisphere storm track getting weaker (Shaw et al., 2022). The mechanism underlying this hemispheric asymmetry has been related to energetic asymmetries: increased top-of-atmosphere radiation asymmetry due to Arctic sea ice loss (Hartmann & Ceppi, 2014) and an increased surface flux gradient asymmetry due to equatorward ocean energy transport (Armour et al., 2016). In addition, the oceanic Atlantic Meridional Overturning circulation shapes the projected response of the North Atlantic storm track (Chemke et al., 2022, Woollings et al. 2012).

3.2 Response to aerosol forcing

Most previous work has focused on the circulation response to increased CO_2 concentration, however several recent studies have highlighted the leading order role of tropospheric aerosol forcing for some regional circulation signals. For example, the observed weakening of the Northern Hemisphere summertime jet across Eurasia over 1979-2019 can be almost entirely attributed to anthropogenic aerosol forcing (Dong et al. 2022). Changes in anthropogenic aerosols have also been implicated in the weakening and poleward shift of the subtropical summertime Mediterranean jet from the 1970s to 2010s (Dong & Sutton, 2021), the weakening of the austral winter subtropical jet (Rotstayn et al., 2013), and the poleward expansion of the Northern Hemisphere Hadley cell edge (Allen et al., 2012; Zhao et al., 2020).

The role of tropospheric aerosols has been revealed using standard attribution methods including single forcing experiments from DAMIP simulations (Gillett et al., 2016). The mechanism proposed to explain the circulation response to aerosol forcing over Eurasia is that a reduction in aerosol optical depth over Europe is associated with increased surface radiation across Eurasia, while increased aerosol optical depth over Africa and southeast Asia reduced surface radiation across much of the subtropics. The radiative changes reduced the meridional surface temperature gradient from the tropics to the extratropics, reducing vertical wind shear and weakening the summertime jet over Eurasia. Other studies have proposed additional mechanisms for anthropogenic aerosol influence on the atmospheric circulation that are more closely linked to the indirect influence of aerosols on clouds. For example, sulfate aerosols may brighten clouds which reflect more radiation to space, leading to a change in radiative balance that promotes poleward heat transport by the atmosphere and ocean (Needham & Randall, 2023).

Stratospheric aerosols that naturally originate from, e.g. volcanic eruptions, reflect incoming solar radiation and can temporarily cool surface climate; however, these particles also absorb longwave radiation and warm the stratosphere, driving changes in the circulation. Substantial uncertainties remain about the magnitude of the circulation response and its effects on regional climate (Paik et al., 2023). Stratospheric aerosol changes are not included in future climate projections yet may be an important source of decadal circulation variability. In addition, climate intervention proposals to inject aerosols into the stratosphere in order to cool surface climate may have substantial regional climate impacts due to circulation changes induced by stratospheric aerosol heating (Wunderlin et al., 2024), though the response depends on where the aerosols are injected (Bednarz et al., 2023).

4 Puzzles

4.1 Model-observation discrepancies

The lengthening observational record has provided some "puzzles" where there are apparent discrepancies between observed and modeled signals. There are several well-known thermodynamic discrepancies, including opposite signed SST trends in observations and models in the tropical Pacific (Lee et al., 2022; Seager et al. 2022; Wills et al., 2022) and Southern Ocean (Wills et al., 2022; Kang et al., 2023). There are also cases where models significantly underestimate (Arctic Amplification; Rantanen et al., 2022) and overestimate (larger recent tropical upper tropospheric warming trends; Po-Chedley et al., 2021) trends.

In addition, important circulation discrepancies have been identified. In particular, the Walker circulation trend is toward a strengthening in observations but a weakening in models (Chung et al., 2019). Similar to thermodynamic discrepancies, there are also cases where models capture the signal but it is underestimated as compared to reanalysis trends: increased Southern Hemisphere storminess trends (Chemke et al., 2022; Shaw et al., 2022), Northern Hemisphere summertime circulation trends (Chang et al., 2016), North Atlantic low-level jet trend (Blackport

& Fyfe 2022, Fig. 3). In other cases the models overestimate the trends (strengthening of the upper-tropospheric jet stream; Woollings et al., 2023).

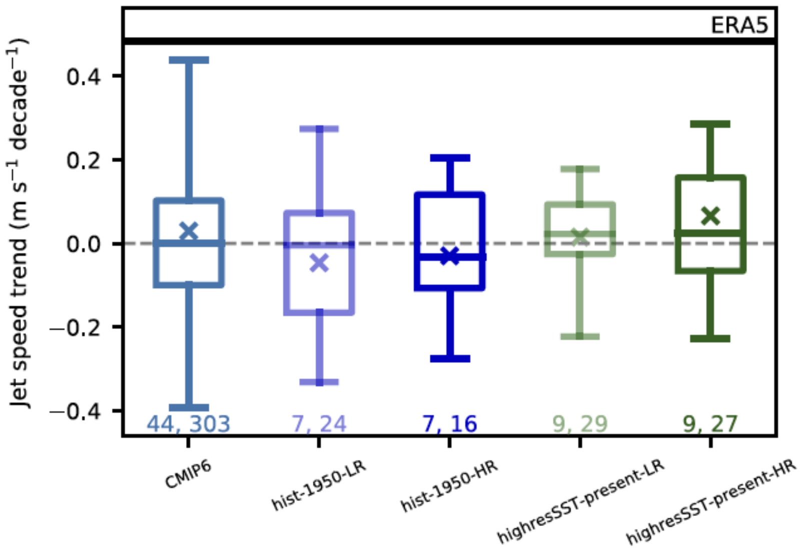

Figure 3: Trends in North Atlantic lower-tropospheric (700 hPa) jet stream strength in reanalysis data and across climate model ensembles. Taken from Blackport & Fyfe (2022).

The relationship between thermodynamic and dynamic discrepancies is an active area of research. Given that many proposed mechanisms for the circulation response to climate change are directly related to warming in the tropical upper troposphere, e.g. acceleration and upward shift of the subtropical jet, it stands to reason that accounting for tropical upper tropospheric warming discrepancies among observations and models is also necessary for circulation features. Furthermore, based on our theoretical understanding of tropical teleconnections (Yang et al., 2021), the tropical SST trend discrepancy should impact the extratropical circulation, as model biases in atmosphere - ocean feedbacks in the tropics can heavily impact teleconnections to the extratropics (Bayr et al., 2019). Recent papers examining heatwave trends over Europe suggest there is a model-observation trend discrepancy that is due in large part to a circulation trend discrepancy, although the details of this circulation trend discrepancy are not well understood and remain to be investigated (Fig. 5; Vautard et al., 2023). The relationship between thermodynamic and dynamic discrepancies needs to be further understood.

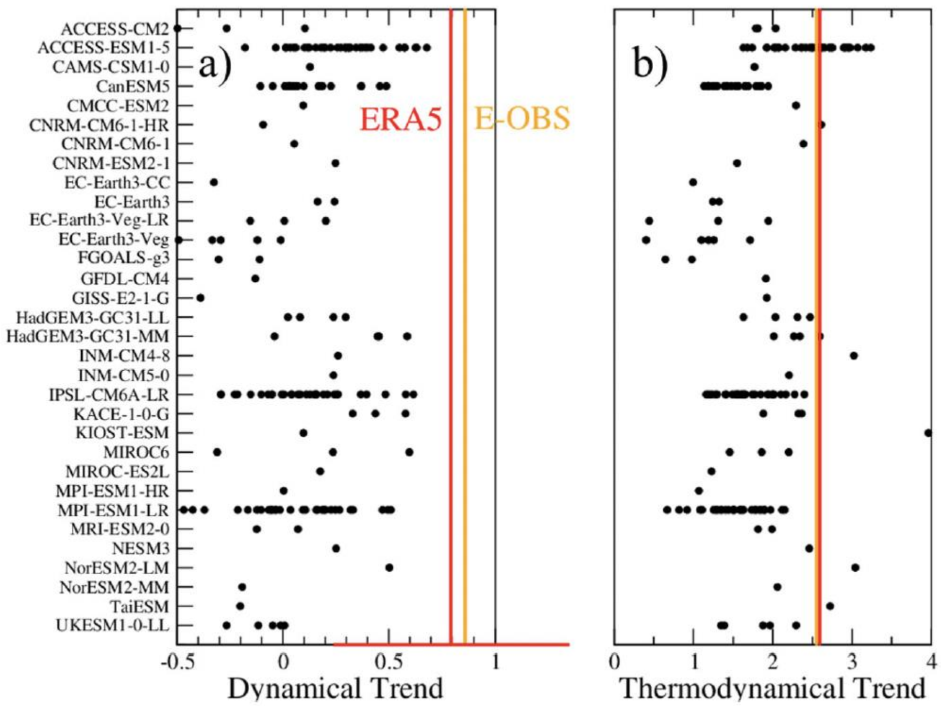

Figure 4: Climate models underestimate trends in heat extremes. Dynamical (a) and thermodynamical (b) contributions to the summer TXx (summer maximum of maximal daily temperature) trends from ERA5 ECMWF Reanalysis (red line), E-OBS observation (orange line), and the 170 CMIP6 model simulations (names in ordinate) that were available (black dots) averaged over Western Europe. Taken from Vautaurd et al. (2023).

4.2 **Disentangling forced response from internal variability**

One of the major challenges in comparing observed and model circulation signals is the confounding factors of internal variability, which can be responsible for multi-decadal trends in observations that can either mask or exacerbate forced trends in the climate system, and observational uncertainty. For example, recent work for the Brewer-Dobson circulation trends shows that observational uncertainty can be large enough to account for the discrepancy in Brewer-Dobson circulation trends in the middle stratosphere (Garny et al, submitted to RoG).

One way to separate the forced response from internal variability is through single forcing experiments such as those in DAMIP. For example, if the signal is present only in response to GHG forcing or aerosol forcing, and observational and model uncertainty is low, then it is likely a forced response. If the signal is in the experiment with natural forcings (or in the preindustrial control experiment), then one cannot rule out the role of internal variability.

Another way to quantify the role of internal variability is using large ensemble simulations in which individual models are run many times with identical external forcing and slightly different initial conditions (Deser et al., 2020; Maher et al., 2021). The two approaches are combined in single-model initial condition large ensembles (SMILEs). With the help of SMILEs, some previously documented "puzzles," in which observed circulation trends were documented to diverge from those of models, have been reconciled after accounting for internal variability, such as the large poleward expansion of the Hadley cell edge documented in the late 2000s (Grise et al., 2019) or cold winters over subpolar Eurasia from 1998 to 2012 (Garfinkel et al 2017; Outten et al 2022). However, given the relatively large magnitude of internal variability at regional scales (particularly in the extratropics) and potential model errors, acknowledging a range of plausible future circulation trends ("storylines") is necessary for impacts planning, as these storylines incorporate both the forced circulation response and different random pathways of internal variability as well as account for model uncertainty (Zappa & Shepherd, 2017; Mindlin et al., 2020; Schmidt & Grise, 2021; Williams et al., 2024).

While large ensembles can help disentangle the signal from the noise, recent work has highlighted a signal-to-noise issue in coupled models suggesting that models may not be properly representing the magnitude of forced signals relative to internal variability. This "signal-to-noise paradox" manifests most clearly when the ensemble-mean signal correlates better with observations of the real world than with individual members of the initialised model forecast ensemble. It implies that the predictability of the real world exceeds the predictability within the model world (Scaife & Smith, 2018; Weisheimer et al., 2024). While the signal-to-noise paradox was initially identified for the winter season in the North Atlantic, similar though weaker findings have been suggested for parts of the Pacific and for predictions of the Southern Annular Mode. New studies have shown evidence that it also occurs for summer precipitation over Northern Europe, the NAO, and the Tibetan Plateau (Dunstone et al., 2018; Yeager et al., 2018; Hu & Zhou, 2021; Dunstone et al. 2023), and in the autumn season East Atlantic pattern (Thornton et al., 2023).

Formally, such a paradox can arise due to excessive noise, a deficit in the signal, or a combination of both. Much recent work has indicated that the predominant issue is overly weak signals. Namely, (i) teleconnections between the tropics and the extratropics due to e.g., ENSO or the MJO are too weak (Garfinkel et al., 2022; Hardiman et al., 2022; Di Capua et al., 2023;

Molteni & Brookshaw, 2023; Roberts et al., 2023; Williams et al., 2023; Lim et al., 2016); (ii) surface impacts from the QBO are too weak (Garfinkel et al., 2018; O'Reilly et al., 2019; Rao et al., 2020); (iii) transient eddy feedback of large-scale climate anomalies in the mid-latitudes (e.g. Lorenz & Hartmann, 2001) is too weak over the North Atlantic (Smith et al., 2022; Hardiman et al., 2022); and (iv) ocean-atmosphere coupling in ocean-eddy rich regions (such as the Gulf Stream) is mis-represented at resolutions commonly used for climate simulations (Osso et al., 2020; Zhang et al., 2021; Yeager et al., 2023). This paradox implies that model projections of changes in circulation patterns in some regions may be underestimated (Scaife & Smith, 2018). Some improvements in these signal-to-noise characteristics have recently been identified in higher-resolution coupled modelling systems (Zhang et al., 2021; Yeager et al., 2023).

4.3 **Role of mean state biases/spread for future change**

In some cases, models exhibit a large spread in their climatologies. The large spread in thermodynamics has been used to constrain thermodynamic signals, e.g. snow-ice albedo feedback (Hall and Qu 2006), through emergent constraints. Emergent constraints are statistical relationships between a model's representation of a particular physical process in the current climate and its future projection in a related field. The assumption is that, if a model accurately represents the physical process in the present-day climate, then the model will also accurately simulate future climate changes related to that process. Emergent constraints are most robust when the relationship persists across multiple generations of models and is supported by a plausible physical mechanism.

Several emergent constraints have been proposed for circulation signals (Simpson et al., 2021): for example, the eddy-driven jet position in the Southern Hemisphere (Kidston & Gerber, 2010), and the regional stationary wave response during Northern Hemisphere wintertime over the Pacific (Simpson et al., 2016). In each case a physical mechanism was proposed to explain the emergent constraint: fluctuation dissipation theorem for jet position, and stationary wave dynamics. Unfortunately, these two emergent constraints are not robust across CMIP versions (Wu et al., 2019; Curtis et al., 2020; Karpechko et al. submitted). Furthermore, the Southern Hemisphere jet position constraint, which only occurs in wintertime (Simpson & Polvani,2016), appears to be an artifact of the zonal mean (Breul et al., 2023). It is puzzling that robust emergent constraints on the circulation have proven difficult to find and to date are few and far between. It may therefore prove insightful to study why the climate system's response to increased CO2 level is often very different from that expected by internal climate fluctuations following the fluctuation dissipation theorem.

Mean state biases can have important implications for the forced response. For example, even if a model accurately simulates the observed circulation response to climate change (e.g., a poleward shift of the jet stream), if the circulation feature does not have the correct location or magnitude in the present-day climate, then the model's projected future climate change may be misplaced/incorrect (Maraun et al., 2017; Grise, 2022). It is challenging to systematically address this issue globally and requires detailed understanding of the circulation features relevant for a particular region. For example, for reducing model uncertainty in future projections of regional hydroclimate, assessing models' representation of present-day precipitation in a particular region may not be sufficient, as the model may get the correct present-day precipitation for the wrong reason if the relevant circulation features in the region are improperly represented.

5 Opportunities for progress

Understanding the circulation signals that are beginning to emerge and unraveling the puzzles they present make it clear that there are exciting opportunities for making progress in understanding the dynamical response to climate change. At the same time, new tools are available and these should be leveraged along with existing tools. Here we highlight some opportunities for future research.

5.1 Investigate signals across the seasonal cycle

Almost all of the dynamical signals in Table 1 are for the winter and summer seasons. Investigating signals in other seasons such as autumn and spring as well as seasonal transitions is important. During these seasons some signals may be stronger (Watt-Meyer et al., 2019) because there potentially exist fewer competing thermodynamic signals.

It is also unclear how climate change affects the seasonal cycle of dynamical features beyond the Monsoons, which exhibit a well-documented delay in response to climate change (e.g., Seth et al., 2013) and the stratospheric polar vortex, which is expected to form earlier and decay later in the future (Ayarzaguena et al., 2020). Quantifying and understanding the seasonality of dynamical changes has important implications for impacts such as severe weather, ecosystems, forest fires, agriculture, etc.

5.2 **Move beyond the longitudinal and time mean**

Almost all of the dynamical signals in Table 1 reflect the zonal- or time-mean. Circulation extremes have received very little attention beyond blocking yet recent work suggests the signal of climate change may be larger in the tails of the circulation distribution consistent with multiplicative behavior of the Clausius-Clapeyron relation (Shaw & Miyawaki, 2024). This implies that the ``thermodynamic" (depends on global-mean temperature that leads to a moisture increase) and ``dynamic" (independent of global-mean temperature) terminology is misleading (Neelin et al. 2022). Indeed dynamical responses occur as a result of the need to satisfy thermodynamical balances and perhaps ``moisture” (changes in global mean temperature, Clausius-Clapeyron relation, geostrophic) and ``convergence” (changes in vertical motion, ageostrophic) terminology would be more appropriate. It is also important to understand how circulation trends affect trends in other variables such as heat waves (Vautard et al., 2023), which have been reported to exhibit discrepancies between observations and climate models.

Along similar lines, there is much work to be done to understand how the dynamical response to climate change varies longitudinally across different regions. For example, insights have been gained into recent trends by defining the Hadley Cell for different regional sectors (Nguyen et al., 2018; Staten et al., 2019; Hoskins et al., 2020; Gillett et al., 2021). The well-known model-observation discrepancy in tropical SST trends represents an opportunity for understanding how tropical climate change affects regional circulation trends and this should be investigated further. Furthermore, the impact of regional and time evolving anthropogenic forcings such as aerosols on regional circulation trends are also not well understood. Ultimately we need to better understand changes in teleconnections, e.g. differences between ocean basins, circulation over land vs ocean. Many theoretical frameworks focus on the zonal mean, which is of course an important starting point. Exciting new regional frameworks have emerged, e.g. local finite amplitude wave activity (Huang & Nakamura, 2016), and should be leveraged and expanded to better understand the regional signals. The use of models in which dynamics and composition change/chemistry are interactively simulated allows for a better representation of these forced longitudinal changes (e.g. Morgenstern, 2021; Revell et al., 2022).

5.3 **Use signals to test mechanisms and model fidelity**

Now that we have entered into a time where circulation signals have emerged we can begin to unravel the dynamical mechanisms underlying the circulation trends and compare them to theoretical expectations and model predictions. Thus, we can move beyond just detecting the signal and move toward understanding it. Applying the numerous theoretical frameworks that have been proposed to explain dynamical responses to climate change (Shaw, 2019) offers great potential for progress. Of course, it should be expected that such analyses will reveal puzzles and showcase examples where models lack fidelity.

Large ensembles can also be leveraged to investigate whether internal variability involves dynamical mechanisms that are distinct from the forced response to anthropogenic climate change.

5.4 Leverage the power of existing and emerging tools

Recent progress in understanding the dynamical responses to anthropogenic climate change discussed above has been achieved through a combination of theoretical advances, conducting experiments across the climate model hierarchy (across processes, resolution, timescale etc.) and performing observational data analysis. This approach should be leveraged further to understand model-observation discrepancies in dynamical signals. It is important to balance the scales between computing and thinking (Emanuel, 2020), i.e. to carefully design analysis or numerical experiments so they serve to confirm/deny hypotheses or expectations. More specifically, idealized models (Schemm & Röthlisberger, 2024), mechanism denial experiments targeted toward understanding circulation signals and nudging are all powerful tools for understanding mechanisms and unraveling the relationship between circulation signals and other trends, or to understand the role of mean-state biases in the atmospheric circulation (e.g. Friesen et al., 2022). Imposing local CO2 forcing or locking mechanisms and using single forcing simulations can be useful to unravel the role of different forcings in different regions. Finally, the impacts of known thermodynamic biases, e.g. SST trend biases, can be understood and quantified through targeted model experiments, e.g. using pacemaker simulations with coupled models (Kang et al. 2024).

Several new tools have emerged in the last decade that can be leveraged for making progress on dynamical understanding. Seasonal to subseasonal forecasting has emerged as a more widespread tool, with large ensembles of S2S forecasts that could be leveraged for understanding dynamical mechanisms and model-observation discrepancies. By pooling different ensemble members and different initializations for a given target forecast, and by assuming that atmospheric initial conditions are lost after the first month, tens of thousands of potential realizations of climate can be created (e.g. Kelder et al., 2020; Kolstad et al., 2022).

This method has been used to better estimate return periods of extreme events (e.g. van den Brink et al., 2004; Thompson et al., 2019), but could also be exploited to improve mechanistic understanding of data-limited dynamical processes such as teleconnections. S2S ensemble forecasts can additionally be used to diagnose common model biases that also exist on climate timescales (L'Heureux et al., 2022; Beverley et al., 2023; Randall & Emanuel, 2024).

AI/ML methods have exploded in the last few years. It will be very fruitful to leverage this new tool. Physics-informed and explainable AI have the potential to advance our understanding of the circulation signals. In particular, these methods have potential in terms of being able to "learn" the source of discrepancies between models and observations, and structural uncertainties across different models.

Finally, high resolution models going down to km scale resolution are on the horizon. These models present an exciting opportunity for understanding as they break away from the large-scale hydrostatically balanced dynamics with parameterized diabatic processes. There is much to be learned about how large- and meso-scales dynamics interact. A better understanding will require theoretical investigations that move beyond the small Rossby number limit (geostrophy). High resolution simulations will likely lead to surprises (or food for thought) as we resolve (and not parameterize) diabatic heating and treat it as fully coupled to the flow. This may include new mechanisms or new versions of older mechanisms. However, high resolution simulations will most likely not provide final/definitive answers to outstanding (dynamics/circulation) questions. For the latter, carefully designed mechanistic model experiments across the model hierarchy are still crucial, which should be informed by results from new high-resolution (or large ensemble) model experiments. High resolution models also have the potential to reveal where model-observation discrepancies are the result of not properly representing mesoscale dynamics in both the atmosphere and ocean. However, even high-resolution models inevitably involve a length-scale truncation and thus cannot be considered to fully resolve the dynamical spectrum of the circulation phenomenon at hand.

We have moved into a new era of climate change research where the signal has emerged, some attribution is becoming possible and puzzles and discrepancies are accumulating. As a community we have the opportunity to embrace these signals and the puzzles they present, including cases where there is a lack of consensus, and use it as an opportunity to further advance our understanding of the climate system and improve predictions of regional climate change.

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Open Research

No data was generated.

References

Allen, R. J., & Sherwood, S. C. (2008). Warming maximum in the tropical upper troposphere deduced from thermal winds. *Nature Geoscience*, *1*, 399.

Allen, R. J., Sherwood, S. C., Norris, J. R., & Zender, C. S. (2012). Recent Northern Hemisphere tropical expansion primarily driven by black carbon and tropospheric ozone. *Nature*, *485*(7398), 350–354. https://doi.org/10.1038/nature11097

Arblaster, J. M., & Meehl, G. A. (2006). Contributions of External Forcings to Southern Annular Mode Trends. *Journal of Climate*, *19*(12), 2896–2905. https://doi.org/10.1175/JCLI3774.1

Armour, K. C., Marshall, J., Scott, J. R., Donohoe, A., & Newsom, E. R. (2016). Southern Ocean warming delayed by circumpolar upwelling and equatorward transport. *Nature Geoscience*, *9*(7), 549–554. https://doi.org/10.1038/ngeo2731

Ayarzagüena, B., Charlton-Perez, A. J., Butler, A. H., Hitchcock, P., Simpson, I. R., Polvani, L. M., et al. (2020). Uncertainty in the response of sudden stratospheric warmings and stratosphere-troposphere coupling to quadrupled CO2 concentrations in CMIP6 models. *Journal of Geophysical Research: Atmospheres*, 125, e2019JD032345. https://doi.org/10.1029/2019JD032345

Banerjee, A., Fyfe, J. C., Polvani, L. M., Waugh, D., & Chang, K.-L. (2020). A pause in Southern Hemisphere circulation trends due to the Montreal Protocol. *Nature*, *579*(7800), 544–548. https://doi.org/10.1038/s41586-020-2120-4

Barnes, E. A., & Screen, J. A. (2015). The impact of Arctic warming on the midlatitude jet-stream: Can it? Has it? Will it? *Wiley Interdisciplinary Reviews: Climate Change*, *6*(3), 277–286. https://doi.org/10.1002/wcc.337

Barpanda, P., & Shaw, T. (2017). Using the moist static energy budget to understand storm track shifts across a range of timescales. *Journal of the Atmospheric Sciences*, *74*, 2427–2446. https://doi.org/10.1175/JAS-D-17-0022.1

Bayr, T., Domeisen, D.I.V. & Wengel, C. (2019). The effect of the equatorial Pacific cold SST bias on simulated ENSO teleconnections to the North Pacific and California. *Climate Dynamics*, *53*, 3771–3789. https://doi.org/10.1007/s00382-019-04746-9

Bednarz, E. M., Butler, A. H., Visioni, D., Zhang, Y., Kravitz, B., & MacMartin, D. G. (2023). Injection strategy – a driver of atmospheric circulation and ozone response to stratospheric aerosol geoengineering. *Atmospheric Chemistry and Physics*, *23*(21), 13665–13684. https://doi.org/10.5194/acp-23-13665-2023

Beverley, J. D., Newman, M., & Hoell, A. (2023). Rapid development of systematic ENSO-related seasonal forecast errors. *Geophysical Research Letters*, 50, e2022GL102249. https://doi.org/10.1029/2022GL102249

Blackport, R., & Fyfe, J.C. (2022). Climate models fail to capture strengthening wintertime North Atlantic jet and impacts on Europe. *Science Advances*, *8*, eabn3112. https://doi.org/10.1126/sciadv.abn3112

Blackport, R., & Screen, J. A. (2020). Weakened evidence for mid-latitude impacts of Arctic warming. *Nature Climate Change*, *10*(12), 1065–1066. https://doi.org/10.1038/s41558-020-00954-y

Breul, P., Ceppi, P., & Shepherd, T. G. (2023). Revisiting the wintertime emergent constraint of the southern hemispheric midlatitude jet response to global warming. *Weather and Climate Dynamics*, *4*, 39–47.

https://doi.org/10.5194/wcd-4-39-2023, 2023.

Butler, A. H., Thompson, D. W. J., & Heikes, R. (2010). The Steady-State Atmospheric Circulation Response to Climate Change–like Thermal Forcings in a Simple General Circulation Model. *Journal of Climate*, *23*(13), 3474–3496. https://doi.org/10.1175/2010JCLI3228.1

Ceppi, P., & Hartmann, D. L. (2016). Clouds and the Atmospheric Circulation Response to Warming. *Journal of Climate*, *29*(2), 783–799. https://doi.org/10.1175/JCLI-D-15-0394.1

Chang, E. K. M., Ma, C.-G., Zheng, C. & Yau, A.M.W. (2016). Observed and projected decrease in Northern Hemisphere extratropical cyclone activity in summer and its impacts on maximum temperature. *Geophysical Research Letters*, *43*, 2200–2208. https://doi.org/10.1002/2016GL068172

Chemke, R., & Polvani, L. M. (2019). Opposite tropical circulation trends in climate models and in reanalyses. *Nature Geoscience*, *12*(7), 528–532. https://doi.org/10.1038/s41561-019-0383-x

Chemke, R., & Yuval, J. (2023). Human-induced weakening of the Northern Hemisphere tropical circulation. *Nature 617*, 529–532. https://doi.org/10.1038/s41586-023-05903-1

Chemke, R., Polvani, L. M., Kay, J. E., & Orbe, C. (2021). Quantifying the role of ocean coupling in Arctic amplification and sea-ice loss over the 21st century. *Npj Climate and Atmospheric Science*, *4*(1), 1–9. https://doi.org/10.1038/s41612-021-00204-8

Chemke, R., Ming, Y. & Yuval, J. (2022). The intensification of winter mid-latitude storm tracks in the Southern Hemisphere. *Nature Climate Change, 12*, 553–557. https://doi.org/10.1038/s41558-022-01368-8

Chemke, R., Zanna, L., Orbe, C., Sentman, L. T., & Polvani, L. M. (2022). The Future Intensification of the North Atlantic Winter Storm Track: The Key Role of Dynamic Ocean Coupling. *Journal of Climate, 35*(8), 2407–2421. https://doi.org/10.1175/JCLI-D-21-0407.1

Chung, E.-S., Timmermann, A., Soden, B. J., Ha, K.-J., Shi, L., & John, V. O. (2019). Reconciling opposing Walker circulation trends in observations and model projections. *Nature Climate Change*, *9*(5), 405–412. https://doi.org/10.1038/s41558-019-0446-4

Clement, A. C., Seager, R., Cane, M. A., & Zebiak, S. E. (1996). An Ocean Dynamical Thermostat. *Journal of Climate*, *9*(9), 2190–2196. https://doi.org/10.1175/1520-0442(1996)009<2190:AODT>2.0.CO;2

Cohen, J., Screen, J. A., Furtado, J. C., Barlow, M., Whittleston, D., Coumou, D., Francis, J., Dethloff, K., Entekhabi, D., Overland, J., & Jones, J. (2014). Recent Arctic amplification and extreme mid-latitude weather. *Nature Geoscience*, *7*, 627.

Coumou, D., Di Capua, G., Vavrus, S., Wang, L., & Wang, S. (2018). The influence of Arctic amplification on mid-latitude summer circulation. *Nature Communications*, *9*(1), 2959. https://doi.org/10.1038/s41467-018-05256-8

Coumou, D., Lehmann, J., & Beckmann, J. (2015). The weakening summer circulation in the Northern Hemisphere mid-latitudes. *Science*, *348*(6232), 324–327. https://doi.org/10.1126/science.1261768

Cox, T., Donohoe, A., Armour, K. C., Frierson, D. M. W. and G. H. Roe. (2024). Trends in Atmospheric Heat Transport Since 1980. J. Climate, doi: 10.1175/JCLI-D-23-0385.1.

Curtis, P. E., Ceppi, P., & Zappa, G. (2020). Role of the mean state for the Southern Hemispheric jet stream response to CO2 forcing in CMIP6 models. *Environmental Research Letters*, *15*, 064011. https://doi.org/10.1088/1748-9326/ab8331

Deser, C., Lehner, F., Rodgers, K.B., Ault, T., Delworth, T.L., DiNezio, P.N., et al. (2020). Insights from Earth system model initial-condition large ensembles and future prospects. *Nature Climate Change*, *10*, 277–286. https://doi.org/10.1038/s41558-020-0731-2

Díaz, L. B., Saurral, R. I., & Vera, C. S. (2021). Assessment of South America summer rainfall climatology and trends in a set of global climate models large ensembles. *International Journal of Climatology*, *41*(S1), E59–E77. https://doi.org/10.1002/joc.6643

Di Capua, G., Coumou, D., van den Hurk, B., Weisheimer, A., Turner, A. G., & Donner, R. V. (2023). Validation of boreal summer tropical–extratropical causal links in seasonal forecasts. *Weather and Climate Dynamics*, *4*, 701–723. https://doi.org/10.5194/wcd-4-701-2023

Domeisen, D. I. V., Eltahir, E. A. B., Fischer, E. M., Knutti, R., Perkins-Kirkpatrick, S. E., Schär, C., Seneviratne, S. I., Weisheimer, A., & Wernli, H. (2023). Prediction and projection of heatwaves. *Nature Reviews Earth & Environment*, *4*(1), 36–50. https://doi.org/10.1038/s43017-022-00371-z

Dong, B., & Sutton, R. T. (2021). Recent Trends in Summer Atmospheric Circulation in the North Atlantic/European Region: Is There a Role for Anthropogenic Aerosols? *Journal of Climate*, *34*(16), 6777–6795. https://doi.org/10.1175/JCLI-D-20-0665.1

Dong, B., Sutton, R. T., Shaffrey, L., & Harvey, B. (2022). Recent decadal weakening of the summer Eurasian westerly jet attributable to anthropogenic aerosol emissions. *Nature Communications*, *13*(1), 1148.

https://doi.org/10.1038/s41467-022-28816-5

Dunstone, N., Smith, D., Scaife, A., Hermanson, L., Fereday, D., O'Reilly, C., et al. (2018). Skilful seasonal predictions of summer European rainfall. *Geophysical Research Letters*, 45, 3246–3254. https://doi.org/10.1002/2017GL076337

Dunstone, N., Smith, D.M., Hardiman, S.C., Hermanson, L., Ineson, S., Kay, G., et al. (2023). Skilful predictions of the Summer North Atlantic Oscillation. *Communications Earth & Environment*, *4*, 409. https://doi.org/10.1038/s43247-023-01063-2

Elbaum, E., Garfinkel, C. I., Adam, O., Morin, E., Rostkier-Edelstein, D., & Dayan, U. (2022). Uncertainty in projected changes in precipitation minus evaporation: Dominant role of dynamic circulation changes and weak role for thermodynamic changes. *Geophysical Research Letters*, 49, e2022GL097725. https://doi.org/10.1029/2022GL097725

Emanuel, K. (2020). The Relevance of Theory for Contemporary Research in Atmospheres, Oceans, and Climate. *AGU Advances*, 1, e2019AV000129. https://doi.org/10.1029/2019AV000129

Eyring, V., et al., 2021: Human Influence on the Climate System. In Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 423–552, doi:10.1017/9781009157896.005.

Fragkoulidis, G., Wirth, V., Bossmann, P., & Fink, A. H. (2018). Linking Northern Hemisphere temperature extremes to Rossby wave packets. *Quarterly Journal of the Royal Meteorological Society*, *144*(711), 553–566. https://doi.org/10.1002/qj.3228

Franzke, C. L. E., & Harnik, N. (2023). Long-Term Trends of the Atmospheric Circulation and Moist Static Energy Budget in the JRA-55 Reanalysis. *Journal of Climate*, *36*(9), 2959-2984. https://doi.org/10.1175/JCLI-D-21-0724.1

Freisen, P. F., Arblaster, J. M., Jakob, C., & Rodríguez, J. M. (2022). Investigating tropical versus extratropical influences on the Southern Hemisphere tropical edge in the Unified Model. *Journal of Geophysical Research: Atmospheres*, 127, e2021JD036106. https://doi.org/10.1029/2021JD036106

Garfinkel, C. I., Son, S. W., Song, K., Aquila, V. and Oman, L. D. (2017) Stratospheric variability contributed to and sustained the recent hiatus in Eurasian winter warming. Geophysical research letters 44, no. 1: 374-

382.

Garfinkel, C. I., Schwartz, C., Domeisen, D. I. V., Son, S.-W., Butler, A. H., & White, I. P. (2018). Extratropical atmospheric predictability from the quasi-biennial oscillation in subseasonal forecast models. *Journal of Geophysical Research: Atmospheres*, 123, 7855–7866. https://doi.org/10.1029/2018JD028724

Garfinkel, C. I., Chen, W., Li, Y., Schwartz, C., Yadav, P., & Domeisen, D. (2022). The Winter North Pacific Teleconnection in Response to ENSO and the MJO in Operational Subseasonal Forecasting Models Is Too Weak. *Journal of Climate*, *35*(24), 8013-8030. https://doi.org/10.1175/JCLI-D-22-0179.1

Garfinkel, C. I., Keller, B., Lachmy, O., White, I., Gerber, E. P., Jucker, M., & Adam, O. (2024). Impact of parameterized convection on the storm track and near-surface jet response to global warming: Implications for mechanisms of the future poleward shift. *Journal of Climate*, *37*, 2541–2564. https://doi.org/10.1175/JCLI-D-23-0105.1

Garny, H. , F. Ploeger , M. Abalos, H. Bönisch, A. Castillos, T. von Clarmann, M. Diallo , A. En-gels , J. C. Laube , M. Linz, J. Neu , A. Podglajen , E. Ray, L. Rivoire, L. N. Saunders , G. Stiller, F. Voet, K. A. Walker: Age of stratospheric air: Progress on processes, observations and long-term trends, *submitted to Reviews of Geophysics.*

Gertler, C.G., & O'Gorman, P.A. (2019). Changing available energy for extratropical cyclones and associated convection in Northern Hemisphere summer. *Proceedings of the National Academy of Sciences*, *116*, 4105-4110. https://doi.org/10.1073/pnas.1812312116

Ghosh, S., Lachmy, O., & Kaspi, Y. (2024). The role of diabatic heating in the midlatitude atmospheric circulation response to climate change. *Journal of Climate*, *1*(aop). https://doi.org/10.1175/JCLI-D-23-0345.1

Gillett, N. P., Shiogama, H., Funke, B., Hegerl, G., Knutti, R., Matthes, K., Santer, B. D., Stone, D., & Tebaldi, C. (2016). The Detection and Attribution Model Intercomparison Project (DAMIP v1.0) contribution to CMIP6. *Geoscientific Model Development*, *9*(10), 3685–3697. https://doi.org/10.5194/gmd-9-3685-2016

Gillett, Z. E., H. H. Hendon, J. M. Arblaster, and E.-P. Lim. (2021). Tropical and extratropical influences on the variability of the Southern Hemisphere wintertime subtropical jet. *Journal of Climate*, **34**, 4009–4022, https://doi.org/10.1175/JCLI-D-20-0460.1.

Grise, K. M. (2022). Atmospheric circulation constraints on 21st century seasonal precipitation storylines for the southwestern United States. *Geophysical Research Letters*, 49, e2022GL099443.

https://doi.org/10.1029/2022GL099443

Grise, K. M., Davis, S.M., Simpson, I.R., Waugh, D.W., Fu, Q., Allen, R.J., et al. (2019). Recent tropical expansion: Natural variability or forced response? *Journal of Climate*, *32*, 1551–1571. https://doi.org/10.1175/JCLI-D-18-0444.1

Hall, A., & Qu, X. (2006). Using the current seasonal cycle to constrain snow albedo feedback in future climate change. *Geophysical Research Letters*, *33*, L03502. https://doi.org/10.1029/2005GL025127.

Hanna, E., Fettweis, X., & Hall, R. J. (2018). Brief communication: Recent changes in summer Greenland blocking captured by none of the CMIP5 models. *The Cryosphere*, *12*, 3287–3292. https://doi.org/10.5194/tc-12-3287-2018

Hardiman, S. C., Dunstone, N. J., Scaife, A. A., Smith, D. M., Comer, R., Nie, Y., & Ren, H.-L. (2022). Missing eddy feedback may explain weak signal-to-noise ratios in climate predictions. *Npj Climate and Atmospheric Science*, *5*(1), 57. https://doi.org/10.1038/s41612-022-00280-4

Hartmann, D. L., & Ceppi, P. (2014). Trends in the CERES Dataset, 2000–13: The Effects of Sea Ice and Jet Shifts and Comparison to Climate Models. *Journal of Climate*, *27*(6), 2444–2456. https://doi.org/10.1175/JCLI-D-13-00411.1

Held, I. M. (1993), Large-Scale dynamics and climate change, Bull. Amer. Met. Soc., 74, doi:10.1175/1520-0477.

Hoskins, B.J., Yang, G.-Y., & Fonseca, R.M. (2020). The detailed dynamics of the June–August Hadley Cell. *Quarterly Journal of the Royal Meteorological Society*, *146*, 557–575. https://doi.org/10.1002/qj.3702

Hu, S., & Zhou, T. (2021). Skillful prediction of summer rainfall in the Tibetan Plateau on multiyear time scales. *Science Advances*, *7*, eabf9395. https://doi.org/10.1126/sciadv.abf9395

Huang, C. S. Y., & Nakamura, N. (2016). Local Finite-Amplitude Wave Activity as a Diagnostic of Anomalous Weather Events. *Journal of the Atmospheric Sciences*, *73*(1), 211-229. https://doi.org/10.1175/JAS-D-15-0194.1

IPCC (2021). *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* [Masson-Delmotte, V., P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud, Y. Chen, L. Goldfarb, M.I. Gomis, M. Huang, K. Leitzell, E. Lonnoy, J.B.R. Matthews, T.K. Maycock, T. Waterfield, O. Yelekçi, R. Yu, and B. Zhou (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, In press, doi:10.1017/9781009157896.

Jiménez-Esteve, B., Kornhuber, K., & Domeisen, D. I. V. (2022). Heat Extremes Driven by Amplification of Phase-Locked Circumglobal Waves Forced by Topography in an Idealized Atmospheric Model. *Geophysical Research Letters*, *49*(21), e2021GL096337. https://doi.org/10.1029/2021GL096337

Kang, J. M., Shaw, T. A., & Sun, L. (2023). Arctic Sea Ice Loss Weakens Northern Hemisphere Summertime Storminess but Not Until the Late 21st Century. *Geophysical Research Letters*, *50*(9), e2022GL102301. https://doi.org/10.1029/2022GL102301

Kang, J. M., Shaw, T. A., Kang, S., Simpson, I. R. & Yu, Y.. (2024). Revisiting the reanalysis-model discrepancy in Southern Hemisphere winter storm track trends. 10.22541/essoar.171224128.81410474/v1

Kang, S.M., Yu, Y., Deser, C., Zhang, X., Kang, I.-S., Lee, S.-S., Rodgers, K.B., & Ceppi, P. (2023). Global impacts of recent Southern Ocean cooling. *Proceedings of the National Academy of Sciences*, *120*, e2300881120. https://doi.org/10.1073/pnas.230088112

Karpechko, A. Yu., Wu, Z., Simpson, I. R., Kretschmer, M., Afargan-Gerstman, H., Butler, A. H., Domeisen, D. I.V., Garny, H., Lawrence, Z, Manzini, E., & Sigmond, M.: Northern Hemisphere Stratosphere-Troposphere Circulation Change in CMIP6 1 Models. Part 2: Mechanisms and Sources of the Spread, submitted to *Journal of Geophysical Research: Atmospheres.*

Keil, P., Mauritsen, T., Jungclaus, J., Hedemann, C., Olonscheck, D., & Ghosh, R. (2020). Multiple drivers of the North Atlantic warming hole. *Nature Climate Change*, *10*(7), 667–671. https://doi.org/10.1038/s41558-020-0819-8

Kelder, T., Müller, M., Slater, L.J., Marjoribanks, T.I., Wilby, R.L., Prudhomme, C., Bohlinger, P., Ferranti, L., & Nipen, T. (2020). Using UNSEEN trends to detect decadal changes in 100-year precipitation extremes. *npj Climate and Atmospheric Science*, *3*, 47. https://doi.org/10.1038/s41612-020-00149-4

Kessenich, H. E., Seppälä, A., & Rodger, C. J. (2023). Potential drivers of the recent large Antarctic ozone holes. *Nature Communications*, *14*(1), Article 1. https://doi.org/10.1038/s41467-023-42637-0

Kidston, J., & Gerber, E.P. (2010). Intermodel variability of the poleward shift of the austral jet stream in the CMIP3 integrations linked to biases in 20th century climatology. *Geophysical Research Letters*, *37*, L09708. https://doi.org/10.1029/2010GL042873.

Kornhuber, K., Petoukhov, V., Karoly, D., Petri, S., Rahmstorf, S., & Coumou, D. (2017). Summertime Planetary Wave Resonance in the Northern and Southern Hemispheres. *Journal of Climate*, *30*(16), 6133–6150. https://doi.org/10.1175/JCLI-D-16-0703.1

Kolstad, E. W., Lee, S. H., Butler, A. H., Domeisen, D. I. V., & Wulff, C. O. (2022). Diverse surface signatures of stratospheric polar vortex anomalies. *Journal of Geophysical Research: Atmospheres*, *127*, e2022JD037422. https://doi.org/10.1029/2022JD037422

Lachmy, O. (2022). The relation between the latitudinal shifts of midlatitude diabatic heating, eddy heat flux and the eddy-driven jet in CMIP6 models. *Journal of Geophysical Research: Atmospheres*, *127*, e2022JD036556. https://doi.org/10.1029/2022JD036556

Lee, S., & Feldstein, S.B. (2013). Detecting Ozone- and Greenhouse Gas–Driven Wind Trends with Observational Data. *Science, 339*,563-567. https://doi.org/10.1126/science.1225154

Lee, S., L'Heureux, M., Wittenberg, A.T., Seager, R., O'Gorman, P.A., & Johnson, N.C. (2022). On the future zonal contrasts of equatorial Pacific climate: Perspectives from Observations, Simulations, and Theories. *npj Climate and Atmospheric Science*, *5*, 82. https://doi.org/10.1038/s41612-022-00301-2

Lee, S. H., Williams, P. D., & Frame, T. H. A. (2019). Increased shear in the North Atlantic upper-level jet stream over the past four decades. *Nature*, *572*(7771), 639–642. https://doi.org/10.1038/s41586-019-1465-z

L'Heureux, M.L., Tippett, M.K., & Wang, W. (2022). Prediction Challenges From Errors in Tropical Pacific Sea Surface Temperature Trends. *Frontiers in Climate*, *4*, 837483. https://doi.org/10.3389/fclim.2022.837483

Lim, E.P., Hendon, H.H., Arblaster, J.M., Delage, F., Nguyen, H., Min, S.K. and Wheeler, M.C. (2016). The impact of the Southern Annular Mode on future changes in Southern Hemisphere rainfall. *Geophysical Research Letters*, 43(13): 7160-7167. https://doi.org/10.1002/2016GL069453

Lorenz, D. J., & DeWeaver, E. T. (2007). Tropopause height and zonal wind response to global warming in the IPCC scenario integrations. *Journal of Geophysical Research: Atmospheres*, *112*(D10). https://doi.org/10.1029/2006JD008087

Lorenz, D. J., & Hartmann, D. L. (2001). Eddy–Zonal Flow Feedback in the Southern Hemisphere. *Journal of the Atmospheric Sciences*, *58*(21), 3312-3327. https://doi.org/10.1175/1520-0469(2001)058<3312:EZFFIT>2.0.CO;2

Lu, J., Leung, L. R., Yang, Q., Chen, G., Collins, W. D., Li, F., Hou, Z. J., & Feng, X. (2014). The robust dynamical contribution to precipitation extremes in idealized warming simulations across model resolutions. *Geophysical Research Letters, 41*, 2971–2978. https://doi.org/10.1002/2014GL059532

Maher, N., Milinski, S., & Ludwig, R. (2021). Large ensemble climate model simulations: introduction, overview, and future prospects for utilising multiple types of large ensemble. *Earth System Dynamics*, *12*, 401–418. https://doi.org/10.5194/esd-12-401-2021

Manabe, S., & Stouffer, R. J. (1980). Sensitivity of a global climate model to an increase of CO2 concentration in the atmosphere. *Journal of Geophysical Research: Oceans*, *85*(C10), 5529–5554. https://doi.org/10.1029/JC085iC10p05529

Manabe, S., & Wetherald, R. T. (1975). The Effects of Doubling the CO2 Concentration on the climate of a General Circulation Model. *Journal of the Atmospheric Sciences*, *32*(1), 3–15. https://doi.org/10.1175/1520-0469(1975)032<0003:TEODTC>2.0.CO;2

Mann, M. E., Rahmstorf, S., Kornhuber, K., Steinman, B. A., Miller, S. K., Petri, S., & Coumou, D. (2018). Projected changes in persistent extreme summer weather events: The role of quasi-resonant amplification. *Science Advances*, *4*(10). https://doi.org/10.1126/sciadv.aat3272

Maraun, D., Shepherd, T. G., Widmann, M., Zappa, G., Walton, D., Gutierrez, J. M., et al. (2017). Towards process-informed bias correction of climate change simulations. *Nature Climate Change*, *7*(11), 764–773. https://doi.org/10.1038/nclimate3418

McLandress, C., Jonsson, A. I., Plummer, D. A., Reader, M. C., Scinocca, J. F., & Shepherd, T. G. (2010). Separating the Dynamical Effects of Climate Change and Ozone Depletion. Part I: Southern Hemisphere Stratosphere. *Journal of Climate*, *23*(18), 5002–5020. https://doi.org/10.1175/2010JCLI3586.1

Menzel, M. E., Waugh, D., & Grise, K. (2019). Disconnect Between Hadley Cell and Subtropical Jet Variability and Response to Increased CO2. *Geophysical Research Letters*, *46*(12), 7045–7053. https://doi.org/10.1029/2019GL083345

Mindlin, J., Shepherd, T.G., Vera, C.S., Osman, M., Zappa, G., Lee, R.W., & Hodges, K.I. (2020). Storyline description of Southern Hemisphere midlatitude circulation and precipitation response to greenhouse gas forcing. *Climate Dynamics, 54*, 4399–4421. https://doi.org/10.1007/s00382-020-05234-1

Mindlin, J., Shepherd, T. G., Vera, C., & Osman, M. (2021). Combined Effects of Global Warming and Ozone

Depletion/Recovery on Southern Hemisphere Atmospheric Circulation and Regional Precipitation. *Geophysical Research Letters*, *48*, e2021GL092568. https://doi.org/10.1029/2021GL092568

Mindlin, J., Vera, C. S., Shepherd, T. G., & Osman, M. (2023). Plausible Drying and Wetting Scenarios for Summer in Southeastern South America. *Journal of Climate*, *36*, 7973–7991. https://doi.org/10.1175/JCLI-D-23-0134.1

Molteni, F., & Brookshaw, A. (2023). Early- and late-winter ENSO teleconnections to the Euro-Atlantic region in state-of-the-art seasonal forecasting systems. *Climate Dynamics, 61*, 2673–2692. https://doi.org/10.1007/s00382-023-06698-7

Morgenstern, O. (2021). The Southern Annular Mode in 6th Coupled Model Intercomparison Project Models. *Journal of Geophysical Research: Atmospheres*, 126, e2020JD034161. https://doi.org/10.1029/2020JD034161

Needham, M. R., & Randall, D. A. (2023). Anomalous Northward Energy Transport due to Anthropogenic Aerosols during the Twentieth Century. *Journal of Climate*, *36*(19), 6713–6728. https://doi.org/10.1175/JCLI-D-22-0798.1

Neelin, J.D., Martinez-Villalobos, C., Stechmann, S.N. *et al.* Precipitation Extremes and Water Vapor. *Curr Clim Change Rep* **8**, 17–33 (2022). https://doi.org/10.1007/s40641-021-00177-z

Nguyen, H., Hendon, H. H., Lim, E. P., Boschat, G., Maloney, E., & Timbal, B. (2018). Variability of the extent of the Hadley circulation in the southern hemisphere: a regional perspective. *Climate Dynamics*, *50*(1-2), 129-142. https://doi.org/10.1007/s00382-017-3592-2

O’Gorman, P. A. (2010). Understanding the varied response of the extratropical storm tracks to climate change. *Proceedings of the National Academy of Sciences*, *107*(45), 19176–19180. https://doi.org/10.1073/pnas.1011547107

O'Reilly, C.H, Weisheimer, A., Woollings, T., Gray, L.J., & MacLeod, D. (2019). The importance of stratospheric initial conditions for winter North Atlantic Oscillation predictability and implications for the signal-to-noise paradox. *Quarterly Journal of the Royal Meteorological Society, 145*, 131–146. https://doi.org/10.1002/qj.3413

Ossó, A., Sutton, R., Shaffrey, L., & Dong, B. (2020). Development, Amplification, and Decay of Atlantic/European Summer Weather Patterns Linked to Spring North Atlantic Sea Surface Temperatures. *Journal of Climate*, *33*(14), 5939-5951. https://doi.org/10.1175/JCLI-D-19-0613.1

Outten, S., Li C., King, M. P., Suo, L., Siew, P. Y., Davy, R., Dunn-Sigouin, E. et al. (2022) Reconciling conflicting evidence for the cause of the observed early 21st century Eurasian cooling." Weather and Climate Dynamics Discussions 2022: 1-32.

Paik, S., Min, S.-K., Son, S.-W., Lim, E.-P., McGregor, S., An, S.-I., Kug, J.-S., & Yeh, S.-W. (2023). Impact of volcanic eruptions on extratropical atmospheric circulations: Review, revisit and future directions. *Environmental Research Letters*, *18*(6), 063003. https://doi.org/10.1088/1748-9326/acd5e6

Pfahl, S., & Wernli, H. (2012). Quantifying the relevance of atmospheric blocking for co-located temperature extremes in the Northern Hemisphere on (sub-)daily time scales. *Geophysical Research Letters*, *39*(12). https://doi.org/10.1029/2012GL052261

Po-Chedley, S., Santer, B.D., Fueglistaler, S., Zelinka, M.D., Cameron-Smith, P.J., Painter, J.F., & Fu, Q. (2021). *Proceedings of the National Academy of Sciences*, *118*, e2020962118. https://doi.org/10.1073/pnas.2020962118

Randall, D. A., & Emanuel, K. (2024). The Weather–Climate Schism. *Bulletin of the American Meteorological Society*, *105*(1), E300-E305. https://doi.org/10.1175/BAMS-D-23-0124.1

Rantanen, M., Karpechko, A. Yu., Lipponen, A., Nordling, K., Hyvärinen, O., Ruosteenoja, K., Vihma, T., & Laaksonen, A. (2022). The Arctic has warmed nearly four times faster than the globe since 1979. *Communications Earth & Environment*, *3*(1), 168. https://doi.org/10.1038/s43247-022-00498-3

Rao, J., Garfinkel, C. I., & White, I. P. (2020). Projected strengthening of the extratropical surface impacts of the stratospheric quasi-biennial oscillation. *Geophysical Research Letters*, 47, e2020GL089149. https://doi.org/10.1029/2020GL089149

Rao, J., & Garfinkel, C. I. (2021). Projected changes of stratospheric final warmings in the Northern and Southern Hemispheres by CMIP5/6 models. *Climate Dynamics*. https://doi.org/10.1007/s00382-021-05647-6

Revell, L. E., Robertson, F., Douglas, H., Morgenstern, O., & Frame, D. (2022). Influence of ozone forcing on 21st century Southern Hemisphere surface westerlies in CMIP6 models. *Geophysical Research Letters*, 49, e2022GL098252. https://doi.org/10.1029/2022GL098252

Roberts, C., M. Balmaseda, L. Ferranti and F. Vitart (2023). Euro-Atlantic Weather Regimes and Their Modulation by Tropospheric and Stratospheric Teleconnection Pathways in ECMWF Reforecasts. *Monthly Weather*

Review, 151, 2779-2799, https://doi.org/10.1175/MWR-D-22-0346.1

Rotstayn, L. D., Collier, M. A., Jeffrey, S. J., Kidston, J., Syktus, J. I., & Wong, K. K. (2013). Anthropogenic effects on the subtropical jet in the Southern Hemisphere: Aerosols versus long-lived greenhouse gases. *Environmental Research Letters*, *8*(1), 014030. https://doi.org/10.1088/1748-9326/8/1/014030

Rousi, E., Kornhuber, K., Beobide-Arsuaga, G., Luo, F., & Coumou, D. (2022). Accelerated western European heatwave trends linked to more-persistent double jets over Eurasia. *Nature Communications*, *13*(1), 3851. https://doi.org/10.1038/s41467-022-31432-y

Russo, E., & Domeisen, D. I. V. (2023). Increasing Intensity of Extreme Heatwaves: The Crucial Role of Metrics. *Geophysical Research Letters*, *50*(14), e2023GL103540. https://doi.org/10.1029/2023GL103540

Scaife, A.A., & Smith, D. (2018). A signal-to-noise paradox in climate science. *npj Climate and Atmospheric Science, 1*, 28. https://doi.org/10.1038/s41612-018-0038-4

Schemm, S., & Röthlisberger, M. (2024). Aquaplanet simulations with winter and summer hemispheres: model setup and circulation response to warming. *Weather and Climate Dynamics*, *5*, 43–63. https://doi.org/10.5194/wcd-5-43-2024

Schmidt, D. F., & Grise, K. M. (2021). Drivers of Twenty-First-Century U.S. Winter Precipitation Trends in CMIP6 Models: A Storyline-Based Approach. *Journal of Climate*, *34*(16), 6875-6889. https://doi.org/10.1175/JCLI-D-21-0080.1

Screen, J. A., Eade, R., Smith, D. M., Thomson, S., & Yu, H. (2022). Net Equatorward Shift of the Jet Streams When the Contribution From Sea-Ice Loss Is Constrained by Observed Eddy Feedback. *Geophysical Research Letters*, *49*(23), e2022GL100523. https://doi.org/10.1029/2022GL100523

Seager, R., Henderson, N., & Cane, M. (2022). Persistent Discrepancies between Observed and Modeled Trends in the Tropical Pacific Ocean. *Journal of Climate*, *35*(14), 4571-4584. https://doi.org/10.1175/JCLI-D-21-0648.1

Seth, A., Rauscher, S. A., Biasutti, M., Giannini, A., Camargo, S. J., & Rojas, M. (2013). CMIP5 Projected Changes in the Annual Cycle of Precipitation in Monsoon Regions. *Journal of Climate, 26*(19), 7328-7351. https://doi.org/10.1175/JCLI-D-12-00726.1

Shaw, T. A. (2019). Mechanisms of Future Predicted Changes in the Zonal Mean Mid-Latitude Circulation. *Current Climate Change Reports*, *5*(4), 345–357. https://doi.org/10.1007/s40641-019-00145-8

Shaw, T. A., Baldwin, M., Barnes, E. A., Caballero, R., Garfinkel, C. I., Hwang, Y.-T., Li, C., O'Gorman, P. A., Riviere, G., Simpson, I. R., & Voigt, A. (2016). Storm track processes and the opposing influences of climate change. *Nature Geoscience*, *9*(9), 656–664.

Shaw, T. A., Barpanda, P., & Donohoe, A. (2018). A moist static energy framework for zonal-mean storm track intensity. *Journal of the Atmospheric Sciences*, *75*, 1979–1994. https://doi.org/10.1175/JAS-D-17-0183.1

Shaw, T. A., Miyawaki, O., & Donohoe, A. (2022). Stormier Southern Hemisphere induced by topography and ocean circulation. *Proceedings of the National Academy of Sciences*, *119*(50), e2123512119. https://doi.org/10.1073/pnas.2123512119

Shaw, T.A., & Miyawaki, O. (2024). Fast upper-level jet stream winds get faster under climate change. *Nature Climate Change*, *14*, 61–67. https://doi.org/10.1038/s41558-023-01884-1

Shaw, T. A., & Tan, Z. (2018). Testing Latitudinally Dependent Explanations of the Circulation Response to Increased CO2 Using Aquaplanet Models. *Geophysical Research Letters*, *45*, 9861–9869. https://doi.org/10.1029/2018GL078974

Shaw, T. A., Barpanda, P. and A. Donohoe. (2018). A Moist Static Energy Framework for Zonal-Mean Storm-Track Intensity. *J. Atmos. Sci.*, *75*, 1979–1994. https://doi.org/10.1175/JAS-D-17-0183.1

Shaw, T. A., & Voigt, A. (2016). What can moist thermodynamics tell us about circulation shifts in response to uniform warming? *Geophysical Research Letters*, *43*(9), 4566–4575. https://doi.org/10.1002/2016GL068712

Shepherd, T. G. (2014). Atmospheric circulation as a source of uncertainty in climate change projections. *Nature Geoscience*, *7*(10), 703–708. https://doi.org/10.1038/ngeo2253

Shrestha, S., & Soden, B. J. (2023). Anthropogenic weakening of the atmospheric circulation during the satellite era. *Geophysical Research Letters*, 50, e2023GL104784. https://doi.org/10.1029/2023GL104784

Simpson, I. R., & Polvani, L.M. (2016). Revisiting the relationship between jet position, forced response, and annular mode variability in the southern midlatitudes. *Geophysical Research Letters*, *43*, 2896–2903. https://doi.org/10.1002/2016GL067989.

Simpson, I., Seager, R., Ting, M. & Shaw, T.A. (2016). Causes of change in Northern Hemisphere winter meridional winds and regional hydroclimate. *Nature Climate Change*, *6*, 65–70. https://doi.org/10.1038/nclimate2783

Simpson, I. R., McKinnon, K. A., Davenport, F. V., Tingley, M., Lehner, F., Al Fahad, A., & Chen, D. (2021). Emergent Constraints on the Large-Scale Atmospheric Circulation and Regional Hydroclimate: Do They Still Work in CMIP6 and How Much Can They Actually Constrain the Future?. *Journal of Climate, 34*(15), 6355-6377. https://doi.org/10.1175/JCLI-D-21-0055.1

Smith, D. M., Eade, R., Andrews, M. B., Ayres, H., Clark, A., Chripko, S., Deser, C., Dunstone, N. J., García-Serrano, J., Gastineau, G., Graff, L. S., Hardiman, S. C., He, B., Hermanson, L., Jung, T., Knight, J., Levine, X., Magnusdottir, G., Manzini, E., … Walsh, A. (2022). Robust but weak winter atmospheric circulation response to future Arctic sea ice loss. *Nature Communications*, *13*(1), 727. https://doi.org/10.1038/s41467-022-28283-y

Staten, P. W., Grise, K. M., Davis, S. M., Karnauskas, K., & Davis, N. (2019). Regional widening of tropical overturning: Forced change, natural variability, and recent trends. *Journal of Geophysical Research: Atmospheres*, 124, 6104–6119. https://doi.org/10.1029/2018JD030100

Stouffer, R. J., Manabe, S., & Bryan, K. (1989). Interhemispheric asymmetry in climate response to a gradual increase of atmospheric CO2. *Nature, 342*(6250), 660–662. https://doi.org/10.1038/342660a0

Sun, X., Ding, Q., Wang, S.-Y. S., Topál, D., Li, Q., Castro, C., Teng, H., Luo, R., & Ding, Y. (2022). Enhanced jet stream waviness induced by suppressed tropical Pacific convection during boreal summer. *Nature Communications*, *13*(1), 1288. https://doi.org/10.1038/s41467-022-28911-7

Tamarin-Brodsky, T., & Kaspi, Y. (2017). Enhanced poleward propagation of storms under climate change. *Nature Geoscience*, *10*(12), 908–913. https://doi.org/10.1038/s41561-017-0001-8

Tan, Z., & Shaw, T. A. (2020). Quantifying the Impact of Wind and Surface Humidity-Induced Surface Heat Exchange on the Circulation Shift in Response to Increased CO2. *Geophysical Research Letters*, *47*(18), e2020GL088053. https://doi.org/10.1029/2020GL088053

Teng, H., Leung, R., Branstator, G., Lu, J., & Ding, Q. (2022). Warming Pattern over the Northern Hemisphere Midlatitudes in Boreal Summer 1979–2020. *Journal of Climate*, *35*(11), 3479–3494. https://doi.org/10.1175/JCLI-D-21-0437.1

Thompson, D. W. J., Solomon, S., Kushner, P. J., England, M. H., Grise, K. M., & Karoly, D. J. (2011). Signatures of the Antarctic ozone hole in Southern Hemisphere surface climate change. *Nature Geoscience*, *4*(11), 741–749. https://doi.org/10.1038/ngeo1296

Thompson, V., Dunstone, N.J., Scaife, A.A., Smith, D.M., Hardiman, S.C., Ren, H.-L., Lu, B., & Belcher, S. E. (2019). Risk and dynamics of unprecedented hot months in South East China. *Climate Dynamics*, *52*, 2585–2596. https://doi.org/10.1007/s00382-018-4281-5

Thornton, H. E., Smith, D. M., Scaife, A. A., & Dunstone, N. J. (2023). Seasonal predictability of the East Atlantic Pattern in late autumn and early winter. *Geophysical Research Letters*, 50, e2022GL100712. https://doi.org/10.1029/2022GL100712

Tuel, A., & Eltahir, E. A. B. (2020). Why Is the Mediterranean a Climate Change Hot Spot?. *Journal of Climate*, *33*(14), 5829-5843. https://doi.org/10.1175/JCLI-D-19-0910.1

van den Brink, H. W., Können, G. P., & Opsteegh, J. D. (2004). Statistics of Extreme Synoptic-Scale Wind Speeds in Ensemble Simulations of Current and Future Climate. *Journal of Climate*, *17*(23), 4564-4574. https://doi.org/10.1175/JCLI-3227.1

Vautard, R., Cattiaux, J., Happé, T., Singh, J., Bonnet, R., Cassou, C., Coumou, D., D'Andrea, F., Faranda, D., Fischer, E., Ribes, A., Sippel, S., & Yiou, P. (2023). Heat extremes in Western Europe increasing faster than simulated due to atmospheric circulation trends. *Nature Communications*, *14*(1), Article 1. https://doi.org/10.1038/s41467-023-42143-3

Voigt, A., Albern, N., Ceppi, P., Grise, K., Li, Y., & Medeiros, B. (2021). Clouds, radiation, and atmospheric circulation in the present-day climate and under climate change. *WIREs Climate Change*, *12*, e694. https://doi.org/10.1002/wcc.694

Voigt, A., & Shaw, T. A. (2015). Circulation response to warming shaped by radiative changes of clouds and water vapour. *Nature Geoscience*, *8*(2), 102–106. https://doi.org/10.1038/ngeo2345

Watt-Meyer, O., Frierson, D. M. W., & Fu, Q. (2019). Hemispheric Asymmetry of Tropical Expansion Under CO2 Forcing. *Geophysical Research Letters*, *46*, 9231–9240. https://doi.org/10.1029/2019GL083695

Weisheimer, A., Baker, L. H., Bröcker, J., Garfinkel, C. I., Hardiman, S. C., Hodson, D. L., Palmer, T. N., Robson, J. I., Scaife, A. A., Screen, J. A., Shepherd, T. G., Smith, D. M., & Sutton, R. T. (2024). The Signal-to-Noise Paradox in Climate Forecasts: Revisiting our Understanding and Identifying Future Priorities. *Bulletin of the American Meteorological Society* (published online ahead of print 2024). https://doi.org/10.1175/BAMS-D-24-0019.1

White, R. H., Kornhuber, K., Martius, O., & Wirth, V. (2022). From Atmospheric Waves to Heatwaves: A Waveguide Perspective for Understanding and Predicting Concurrent, Persistent, and Extreme Extratropical Weather. *Bulletin of the American Meteorological Society*, *103*(3), E923–E935. https://doi.org/10.1175/BAMS-D-21-0170.1

Williams, N. C., Scaife, A. A., & Screen, J. A. (2023). Underpredicted ENSO teleconnections in seasonal forecasts. *Geophysical Research Letters*, 50, e2022GL101689. https://doi.org/10.1029/2022GL101689

Williams, R. S., Marshall, G. J., Levine, X., Graff, L. S., Handorf, D., Johnston, N. M., Karpechko, A. Y., Orr, A., Van de Berg, W. J., Wijngaard, R. R., & Mooney, P. A. (2024). Future Antarctic Climate: Storylines of Midlatitude Jet Strengthening and Shift Emergent from CMIP6. *Journal of Climate*, *37*(7), 2157-2178. https://doi.org/10.1175/JCLI-D-23-0122.1

Wills, R. C. J., Dong, Y., Proistosecu, C., Armour, K. C., & Battisti, D. S. (2022). Systematic Climate Model Biases in the Large-Scale Patterns of Recent Sea-Surface Temperature and Sea-Level Pressure Change. *Geophysical Research Letters*, *49*(17), e2022GL100011. https://doi.org/10.1029/2022GL100011

Wirth, V., Riemer, M., Chang, E. K. M., & Martius, O. (2018). Rossby Wave Packets on the Midlatitude Waveguide—A Review. *Monthly Weather Review*, *146*(7), 1965–2001. https://doi.org/10.1175/MWR-D-16-0483.1

WMO (World Meteorological Organization), Scientific Assessment of Ozone Depletion: 2018, Global Ozone Research and Monitoring Project–Report No. 58, 588 pp., Geneva, Switzerland, 2018.

Woollings, T., Gregory, J., Pinto, J. *et al.* (2012). Response of the North Atlantic storm track to climate change shaped by ocean–atmosphere coupling. *Nature Geosci* **5**, 313–317. https://doi.org/10.1038/ngeo1438

Woollings, T., Drouard, M., O'Reilly, C.H., Sexton, D.M.H., & McSweeney, C. (2023). Trends in the atmospheric jet streams are emerging in observations and could be linked to tropical warming. *Communications Earth & Environment, 4*, 125. https://doi.org/10.1038/s43247-023-00792-8

Wu, Y., Simpson, I. R., & Seager, R. (2019). Intermodel spread in the Northern Hemisphere stratospheric polar vortex response to climate change in the CMIP5 models. *Geophysical Research Letters*, 46, 13290–13298. https://doi.org/10.1029/2019GL085545

Wunderlin, E., Chiodo, G., Sukhodolov, T., Vattioni, S., Visioni, D., & Tilmes, S. (2024). Side Effects of Sulfur-Based Geoengineering Due To Absorptivity of Sulfate Aerosols. *Geophysical Research Letters*, *51*(4), e2023GL107285. https://doi.org/10.1029/2023GL107285

Yang D., Arblaster J. M., Meehl G. A. and England M. H. (2021). The role of coupled feedbacks in the decadal variability of the Southern hemisphere Eddy-driven jet, *J. Geophys. Res*. 126 e2021JD035023. https://doi.org/10.1029/2021JD035023

Yeager, S. G., Danabasoglu, G., Rosenbloom, N. A., Strand, W., Bates, S. C., Meehl, G. A., Karspeck, A. R., Lindsay, K., Long, M. C., Teng, H., & Lovenduski, N. S. (2018). Predicting Near-Term Changes in the Earth System: A Large Ensemble of Initialized Decadal Prediction Simulations Using the Community Earth System Model. *Bulletin of the American Meteorological Society*, *99*(9), 1867-1886. https://doi.org/10.1175/BAMS-D-17-0098.1

Yeager, S.G., Chang, P., Danabasoglu, G., Rosenbloom, N., Zhang, Q., Castruccio, F.S., Gopal, A., Rencurrel, M.C., & Simpson, I.R. (2023). Reduced Southern Ocean warming enhances global skill and signal-to-noise in an eddy-resolving decadal prediction system. *npj Climate and Atmospheric Science, 6*, 107. https://doi.org/10.1038/s41612-023-00434-y

Yook, S., Thompson, D. W. J., & Solomon, S. (2022). Climate Impacts and Potential Drivers of the Unprecedented Antarctic Ozone Holes of 2020 and 2021. *Geophysical Research Letters*, *49*(10), e2022GL098064. https://doi.org/10.1029/2022GL098064

Zambri, B., Solomon, S., Thompson, D. W. J., & Fu, Q. (2021). Emergence of Southern Hemisphere stratospheric circulation changes in response to ozone recovery. *Nature Geoscience*. https://doi.org/10.1038/s41561-021-00803-3

Zaplotnik, Ž., Pikovnik, M., & Boljka, L. (2022). Recent Hadley Circulation Strengthening: A Trend or Multidecadal Variability?. *Journal of Climate, 35*(13), 4157-4176. https://doi.org/10.1175/JCLI-D-21-0204.1

Zappa, G., & Shepherd, T. G. (2017). Storylines of Atmospheric Circulation Change for European Regional Climate Impact Assessment. *Journal of Climate*, *30*(16), 6561-6577. https://doi.org/10.1175/JCLI-D-16-0807.1

Zhang, W., Kirtman, B., Siqueira, L., Clement, A., & Xia, J. (2021). Understanding the signal-to-noise paradox in decadal climate predictability from CMIP5 and an eddying global coupled model. *Climate Dynamics*, *56*, 2895–2913. https://doi.org/10.1007/s00382-020-05621-8

Zhao, X., & Allen, R.J. (2019). Strengthening of the Walker Circulation in recent decades and the role of natural sea surface temperature variability. *Environmental Research Communications*, *1*, 021003.

https://doi.org/10.1088/2515-7620/ab0dab.

Zhao, X., Allen, R. J., Wood, T., & Maycock, A. C. (2020). Tropical Belt Width Proportionately More Sensitive to Aerosols Than Greenhouse Gases. *Geophysical Research Letters*, *47*(7), e2019GL086425. https://doi.org/10.1029/2019GL086425

Table 1. Detected circulation signals

Signal	Region	Season	Reference
Increased wind shear	North Atlantic	Annual	Lee et al. (2019)
Upper-troposphere jet strengthening	Zonal-mean	DJF	Woollings et al. (2023), Franzke & Harnik (2023)
Mid-troposphere jet weakening	Zonal-mean	JJA	Coumou et al. (2015)
Upper-troposphere jet weakening	Eurasia	JJA	Dong et al. (2022)
Lower-troposphere jet strengthening*	North Atlantic	DJF	Blackport & Fyfe (2022)
Lower-troposphere jet position	Zonal-mean	DJF	Lee & Feldstein (2013), Woollings et al. (2023)
Storm track strengthening*	S. Hemisphere Zonal-mean	JJA	Chemke et al. (2022)
		Annual mean	Shaw et al. (2022), Cox et al. (2024)
Storm track weakening	N. Hemisphere Zonal-mean	JJA	Coumou et al. (2015, Chang et al. (2016), Gertler & O'Gorman (2019), Kang et al. (2023), Cox et al. (2024)
Increased blocking*	N. Hemisphere	JJA	Hanna et al. (2018)
Hadley cell expansion	Both Hemispheres	Annual mean	Grise et al. (2019)

Hadley cell intensity	Both Hemispheres	Annual mean	Zaplotnik et al. (2022), Chemke & Yuval (2023)
Walker circulation strengthening*	Both Hemispheres	Annual mean	Chung et al. (2019), Zhao and Allen (2019)
Weakening of upward vertical motion in the tropics	Both Hemispheres	Annual mean	Shrestha & Soden (2023)
Increasing stationary wave amplitude	Mediterranean	DJF	Tuel & Eltahir (2020)
	N. Hemisphere	JJA	Teng et al. (2022), Sun et al. (2022)
Strengthening summer Monsoon	N. Hemisphere	JJA	Eyring et al. (2021)