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Key Points:

- Long term trends in atmospheric circulation are emerging across different regions and seasons with some attributed to human activities
- Many circulation signals have been linked to dynamical mechanisms involving thermodynamic changes, although discrepancies remain
- Emerging signals in combination with new tools promise considerable progress in understanding the dynamical response in the coming decade

Supporting Information:

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

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Emerging Climate Change Signals in Atmospheric Circulation

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Abstract The circulation response to climate change shapes regional climate and extremes. Over the last decade an increasing number of atmospheric circulation signals have been documented, with some attributed to human activities. The circulation signals represent an exciting opportunity for improving our understanding of dynamical mechanisms, testing our theories and reducing uncertainties. The signals have also presented puzzles that represent an opportunity for better understanding the circulation response to climate change, its contribution to climate extremes, interactions with moisture, and connection to thermodynamic discrepancies. The next decade 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 been documented in many regions. Some of the signals are expected and have been attributed to human activities whereas others are not. The next decade represents an exciting time to better understand the dynamical mechanisms underlying these signals and their relationship to thermodynamic 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. 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). Thermodynamically driven changes in regional hot extremes, heavy precipitation and drought have also been confidently attributed to human activities in some regions (IPCC, 2021, Figure SPM.3). This progress on thermodynamic signals has been achieved through multiple lines of evidence: 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 and pressure. These changes can subsequently influence moisture, clouds and radiation. Many generations of climate models have predicted robust circulation responses to climate change by the end of the century, including an upward shift and acceleration of the subtropical jet streams, weakening and 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 more uncertain as compared to thermodynamic ones, especially at the regional scale, due to large internal variability and the lack of sufficiently strong constraints on atmospheric dynamics (Shepherd, 2014). Furthermore, competing influences on dynamics in a changing climate, for example, 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 (Perlwitz, 2012; 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).

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Over the last decade an increasing number of atmospheric circulation signals, here defined as statistically significant linear trends over the satellite era or longer, have been documented in the literature. These signals are part of a growing number of regional climate change signals, some of which exhibit discrepancies with climate model predictions (Shaw et al., 2024). Here we focus specifically on atmospheric circulation signals that have been documented in the literature since recent assessments (IPCC, 2021; Shepherd, 2014). We specifically highlight signals that have emerged and been attributed to human activities; discuss progress on understanding dynamical mechanisms underlying the signals; and describe remaining puzzles, including the role of internal variability versus the forced response versus observational uncertainty, model-observation discrepancies and the impact of mean state biases. We discuss the importance of linking statistical analysis and understanding of dynamic and thermodynamic signals. In particular, some thermodynamic signals exhibit discrepancies with model predictions, for example, the "pattern effect" of SST trends, and are potentially linked to the atmospheric circulation, for example, 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. Circulation Signals

The number of atmospheric circulation signals reported in the literature across different regions, hemispheres, and seasons has grown significantly in recent years (Table 1). Some are zonal-mean signals (8 out of 20) but many are regional (12 out of 20). For example, increased sea-level pressure near South-West Western Australia is associated with recent drying trends in this region (Figures 1a, 1c and 1e; Hope et al., 2006). Furthermore, many Southern Hemisphere signals are zonally symmetric, leading to similar impacts across longitudinal regions (Kang, Shaw, Kang, et al., 2024).

In some cases the signals have been detected and attributed to human activities (see below and Table 1). In other cases 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 in some cases there is a discrepancy between observations and models. In still other cases, expected regional signals, like reduced precipitation in the Central and Western Mediterranean associated with higher sea-level pressure, will take more time to emerge (Figures 1b, 1d and 1f) (Seager et al., 2024).

One of the earliest examples of an atmospheric circulation signal being formally attributed to human activities involved ozone depletion (Gillett et al., 2013). The circulation signals include an increase in the strength of the winds in the southern hemisphere stratosphere, an associated delay of the spring-time breakdown of the stratospheric polar vortex, and a poleward shift of the eddy-driven tropospheric jet stream (Figure 2) and southern Hadley cell edge in austral summer (Lee & Feldstein, 2013; Thompson et al., 2011; WMO, 2018). Since the 2000s, ozone recovery, which opposes the influence of greenhouse gas increases on the circulation, has been associated with reduced SH circulation trends (Banerjee et al., 2020; Zambri et al., 2021), though these are sensitive to end points (Figure 2).

In recent years several more atmospheric circulation signals have been attributed to human activities (Table 1), including greenhouse gas emissions, but also with ozone depletion or aerosol emissions either in isolation or in combination (e.g., Gillett et al., 2016). In the Northern Hemisphere the combination of anthropogenic greenhouse gas and aerosol emissions have weakened the summertime circulation as measured by the zonal-mean storm tracks (eddy kinetic energy, Chemke & Coumou, 2024), zonal-mean jet stream, and regional surface cyclone activity (mean sea level pressure, Kang, Shaw, & Sun, 2024). Improved estimates of anthropogenic aerosol forcing were important for the improved Northern Hemisphere summertime storm track signals in CMIP5 versus CMIP6 (Chemke & Coumou, 2024). The weakening of the East Asian summertime jet stream has been attributed exclusively to anthropogenic aerosol emissions (Dong et al., 2022).

The weakening of the annual-mean Northern Hemisphere Hadley cell has also been attributed to anthropogenic greenhouse gas and aerosol emissions (Chemke & Yuval, 2023; Lionello et al., 2024). The poleward shift of the Southern Hemisphere Hadley cell edge has been attributed to ozone depletion and anthropogenic greenhouse gas emissions (Grise et al., 2019; Lionello et al., 2024).

Table 1
Emerging Atmospheric Circulation Signals (Statistically Significant Long Term Trends) That Have Been Reported in the Literature

Signal	Region	Season	Reference	Detected	Attributed
Increased wind shear (zonal wind)	North Atlantic	Annual mean	Lee et al. (2019)		
Upper-troposphere jet strengthening (zonal wind)	Zonal-mean	DJF	Woollings et al. (2023), Franzke and Harnik (2023)		
Lower-troposphere jet strengthening (zonal wind, mean sea level pressure)	North Atlantic	DJF	Blackport and Fyfe (2022), Wills et al. (2022)		
Lower-troposphere jet poleward shift (zonal wind)	Zonal-mean	DJF	Lee and Feldstein (2013), Woollings et al. (2023)	x	x
Mid-troposphere jet weakening (zonal wind)	N. Hemisphere Zonal-mean	JJA	Coumou et al. (2015), Kang, Shaw, and Sun (2024)	x	x
Upper-troposphere jet weakening (zonal wind)	Eurasia	JJA	Dong et al. (2022)	x	x
Storm track weakening (eddy kinetic energy)	N. Hemisphere Zonal-mean	JJA	Coumou et al. (2015, Chang et al. (2016), Gertler and O'Gorman (2019), Kang, Yu, et al. (2023), Cox et al. (2024), Chemke and Coumou (2024)	x	x
Extratropical cyclone activity weakening (mean sea level pressure)	North Atlantic, North Pacific	JJA	Kang, Shaw, and Sun (2024)	x	x
Increased blocking (500 hPa geopotential height)	Greenland	JJA	Hanna et al. (2018)		
Storm track strengthening (eddy kinetic energy)	S. Hemisphere Zonal-mean	JJA	Chemke et al. (2022)	x	
Storm track strengthening (eddy kinetic energy)	S. Hemisphere Zonal-mean	Annual mean	Shaw et al. (2022), Cox et al. (2024)		
Hadley cell shift (mass stream function)	S. Hemisphere Zonal-mean	Annual mean	Grise et al. (2019), Lionello et al. (2024)	x	x
Hadley cell intensity (mass stream function)	N. Hemisphere Zonal-mean	Annual mean	Chemke and Yuval (2023), Zaplotnik et al. (2022), Lionello et al. (2024)	x	x
Walker circulation strengthening (mean sea level pressure, surface winds)	Pacific	Annual mean	Chung et al. (2019), Zhao and Allen (2019)	x	
Weakening of upward vertical motion (500 hPa vertical motion)	Global	Annual mean	Shrestha and Soden (2023)	x	x
Increasing sea level pressure	South west Western Australia	JJA	Hope et al. (2006); Knutson and Ploshay (2021); Figure 1c	x	
Increasing stationary wave amplitude (200 hPa geopotential height)	N. Hemisphere (200 hPa geopotential height)	JJA	Teng et al. (2022), Sun et al. (2022)		
Strengthening stationary waves (sea level pressure)	Mediterranean	DJF	Tuel and Eltahir (2020); Figure 1d	x	
Strengthening summer Monsoon	N. Hemisphere	JJA	Eyring et al. (2021)		
	Australian	DJF	Borowiak et al. (2023)		

Note. Following IPCC terminology signals are labeled detected if the likelihood of occurrence by chance due to internal variability is small and attributed if the causal human driver (greenhouse gas, aerosol, ozone forcing, etc.) has been determined.

3. Progress in Understanding Mechanisms

Many dynamical mechanisms have been proposed to explain atmospheric circulation responses to anthropogenic forcing that have been robustly predicted by generations of climate models (Hoskins & Woollings, 2015; Shaw, 2019; Thompson et al., 2011; Vallis et al., 2015; Wills et al., 2019). Here we highlight progress on understanding mechanisms underlying the response to ozone depletion, greenhouse gas and aerosol forcing as they relate to the circulation signals listed in Table 1.

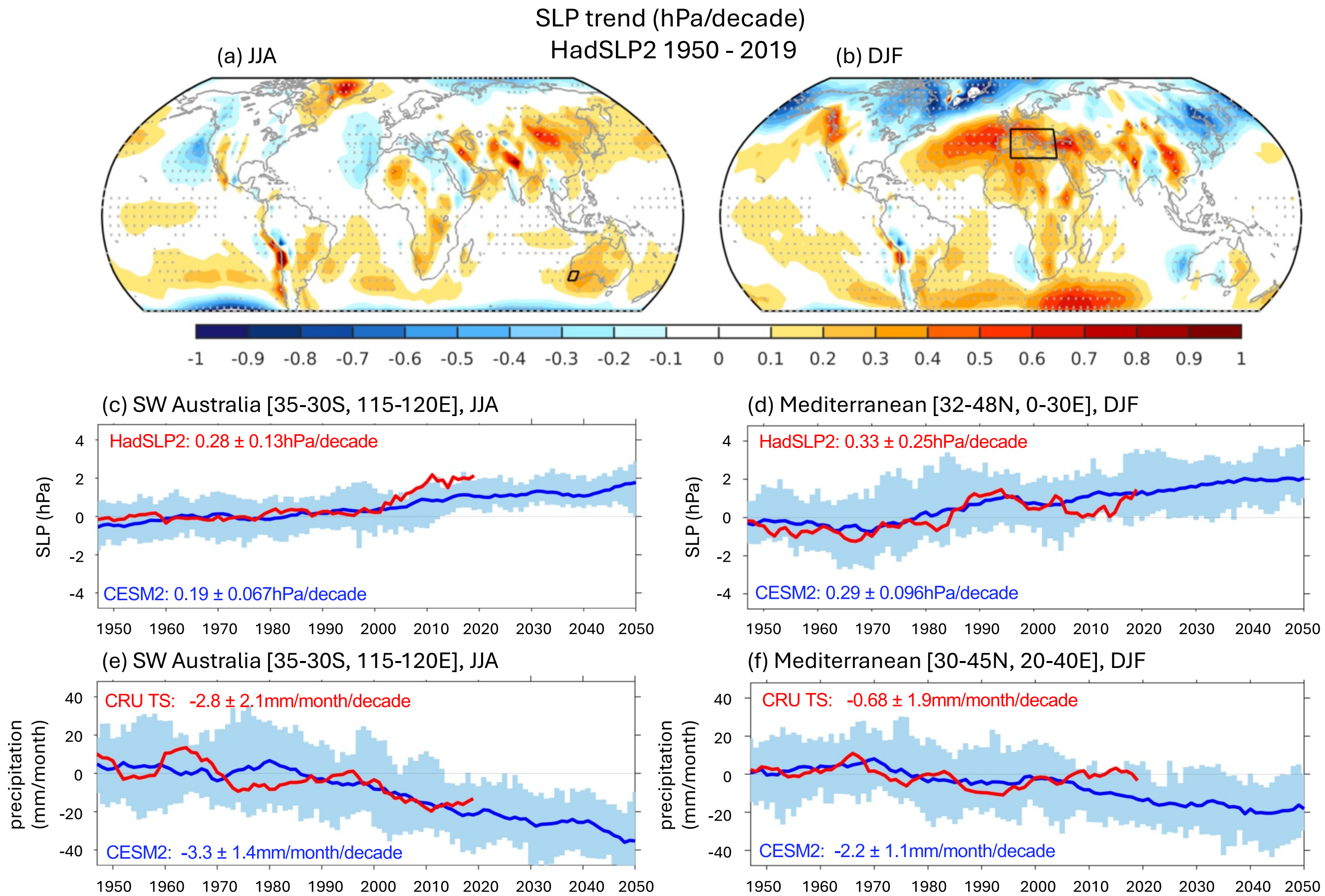

Figure 1. Regional circulation signals for JJA (left) and DJF (right). (a, b) Spatial structure of SLP trends from 1950 to 2019 in observations with stippling indicating statistically significant linear trends at the 0.05 level. Time series of (c) SLP [Pa] and (e) precipitation [mm/mon] anomalies in observations (red line, HadSLPv2 for SLP, and CRU TS v4.07 for precipitation) over South-West Australia (black box in a) during JJA. (d, f) DJF SLP and precipitation over Mediterranean regions (black box in b) defined in Tuel and Eltahir (2020). Mean (blue line) and range (blue shading) of the 15-member historical-GHG only simulation in CESM2 of SLP and precipitation (Simpson et al., 2023). All time series have been smoothed with a 10-year running mean.

3.1. Ozone Depletion

Ozone depletion reduces the shortwave absorption of ultraviolet radiation, cooling the lower stratosphere. This cooling induces an increase of the meridional temperature gradient and a strengthening of the stratospheric zonal wind consistent with thermal wind balance. Imposing a cooling of the lower stratosphere in idealized model simulations leads to a poleward shift of the tropospheric eddy-driven jet (Butler et al., 2010; Kushner & Polvani, 2004; Polvani & Kushner, 2002). However, the tropospheric response to stratospheric forcing is sensitive to the state of the troposphere (Chan & Plumb, 2009; Garfinkel et al., 2013). A mechanism proposed to explain the poleward shift of the eddy-driven jet stream in the lower atmosphere links the change in stratospheric winds to a modification of the eastward propagation of tropospheric eddies thereby affecting the momentum flux (Chen & Held, 2007). At this time, there is still not a complete mechanistic understanding that connects the ozone hole to the shift of the jet stream and Hadley cell edge (Kidston et al., 2015; Thompson et al., 2011). This lack of understanding may in part be due to the complex dynamical interactions that are found to be crucial for a downward impact (Kidston et al., 2015).

3.2. Greenhouse Gas Forcing

Greenhouse gas increases lead to tropical upper tropospheric warming consistent with moist adiabatic adjustment (Held, 1993; Manabe & Wetherald, 1975). This response increases the meridional temperature gradient near the tropopause, strengthening the subtropical jet and shear via thermal wind balance (Allen & Sherwood, 2008; Lee

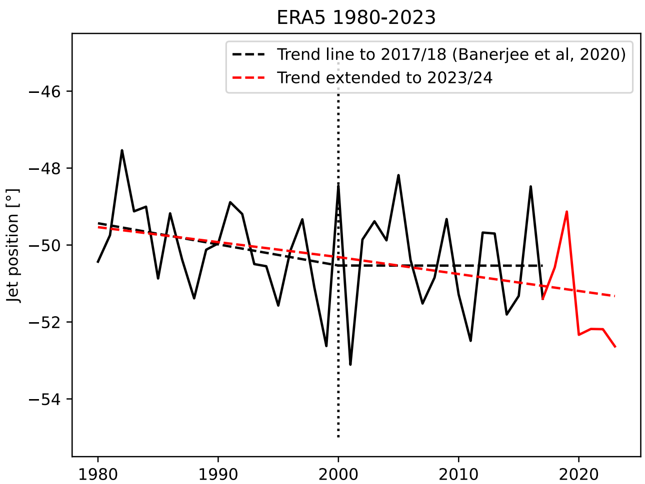

Figure 2. Southern Hemisphere mid-latitude jet stream position response to ozone depletion. Jet position in December, January and February from ERA5, reproducing Banerjee et al. (2020) for years 1980/81–2017/18 (black lines), and extended time series to 2023/24 (red lines). Trends are fitted by continuous piecewise linear regression (following Banerjee et al. (2020)), and trend values are −0.5°/dec for the ozone depletion period (1980/81 to 2000/01), and 0.0°/dec for 2000/01–2017/18. For the extended time series, trend values are −0.4°/dec for both ozone depletion and recovery periods, emphasizing the sensitivity of trend estimates from short records to end points.

et al., 2019). This direct impact of the tropics on the atmospheric circulation is confirmed by a CO_2 increase only in the tropics in model simulations (Shaw, 2019; Shaw & Tan, 2018).

The shift of the jet stream and Hadley cell in response to greenhouse gas increases have been argued to be connected to this tropical warming response (Butler et al., 2010; Lorenz & DeWeaver, 2007; Lu et al., 2007, 2014). However the poleward shift of the midlatitude near-surface jet and Hadley cell edge and the strengthening of the subtropical jet happen on distinct timescales (compare red and blue lines in Figure 3), suggesting the shifts are driven by different mechanisms (Chemke & Polvani, 2019, 2021; Menzel et al., 2019). Consistently the model response to increased CO_2 only in the tropics does not lead to a significant poleward shift (Shaw, 2019; Shaw & Tan, 2018). Recent studies suggest midlatitude processes including local moisture gradient, latent heat release, vertical temperature gradient (static stability), and cloud changes are more important than tropical changes (Chemke & Polvani, 2019, 2021; Garfinkel et al., 2024; Lachmy, 2022; Shaw & Voigt, 2016; Tamarin-Brodsky & Kaspi, 2017; Tan & Shaw, 2020; Voigt et al., 2021; Voigt & Shaw, 2016). The importance of moisture and clouds has been revealed by advancing theory to incorporate moisture (e.g., Lachmy, 2022; Shaw et al., 2018; Tamarin-Brodsky & Kaspi, 2017) and simulations across the model hierarchy (Ceppi & Hartmann, 2016; Garfinkel et al., 2024; Ghosh et al., 2024; Tan & Shaw, 2020; Voigt & Shaw, 2015).

The signal of Northern Hemisphere summertime circulation weakening has been linked to a weakening of the near-surface temperature gradient due to Arctic amplification (Coumou et al., 2015), however recent work shows the contribution of Arctic sea ice loss and Arctic amplification to the circulation signal is negligible (Blackport et al., 2019; Blackport & Screen, 2021; J. M. Kang et al., 2023). Instead the weakening signal is related to high latitude warming over land (not ocean or sea ice) induced by greenhouse gas and aerosol forcing (Chemke & Coumou, 2024; Dong et al., 2022; Kang, Shaw, & Sun, 2024).

The strengthening of the Southern Hemisphere wintertime storm tracks, which occurs robustly across all longitudes, has been connected to several mechanisms: An increase in mean available potential energy due to increased latitudinal temperature gradients aloft (O'Gorman, 2010); increased surface flux trends that reflect equatorward ocean energy transport and Southern Ocean cooling (Shaw et al., 2022); and changes in the vertical structure of the jet stream (Chemke et al., 2022).

Mechanisms explaining regional signals are related to stationary wave changes. The strengthening summertime Northern Hemisphere stationary wave signal has been connected to a teleconnection from the tropical Pacific (Sun et al., 2022) and soil moisture deficits (Teng et al., 2022). A related signal is the increase in extratropical heatwaves in summertime (e.g., Domeisen et al., 2023; Russo & Domeisen, 2023), which have been suggested to be related to increased "waviness" of the jet stream 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). However the quantitative mechanism underlying this link has not been established. Instead, anthropogenic aerosol forcing has been argued to be important for regional heat wave signals (Schumacher et al., 2024).

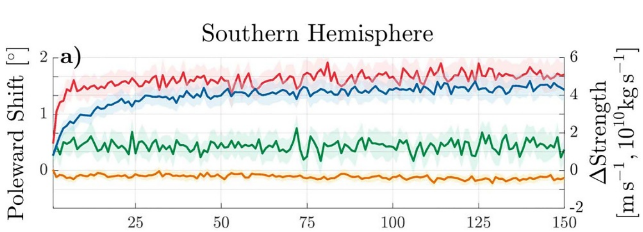

Figure 3. Time series of southern hemispheric response in model years to quadrupling atmospheric CO_2 for (a) the Hadley cell (HC) edge (red) and strength (orange) and the subtropical jet (STJ) location (green) and strength (blue). For each plot, shading represents the 95% confidence interval of model spread. Taken from Menzel et al. (2019).

During wintertime the strengthening high over the Mediterranean has been connected to the large-scale upper-tropospheric circulation and land-sea contrast response, and specifically to a less rapid warming of the Mediterranean sea than of the surrounding land (Tuel & Eltahir, 2020). The large-scale tropospheric circulation response consists of an eastward shift of wintertime stationary waves associated with strengthened eastward subtropical upper-level jet (Simpson et al., 2016; Wills et al., 2019). This eastward shift is associated with uncertainty in regional climate change in for example,

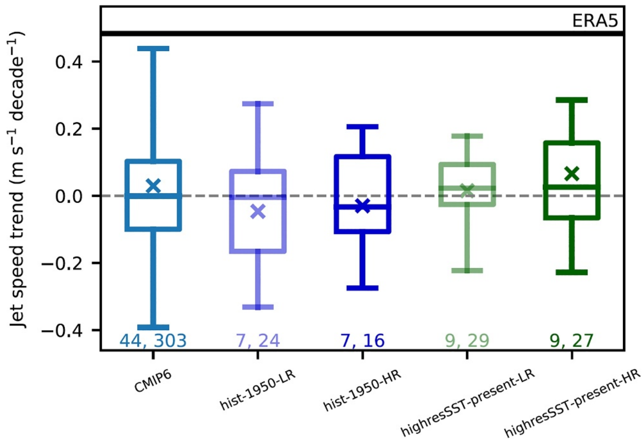

Figure 4. Trends in North Atlantic lower-tropospheric (700 hPa) jet stream strength from 1951 to 2014 in reanalysis data (ERA5) and across coupled (CMIP6) climate model ensemble, and low (LR) and high (HR) resolution HighResMIP climate model ensemble. The box represents upper and lower quartile ranges, and the whiskers represent the minimum and maximum from all ensemble members. The lines in the boxes indicate the median from all ensembles, and the crosses represent the multimodel mean. The two numbers at the bottom indicate the total number of models (left) and total number of ensemble members (right) from each experiment. Taken from Blackport and Fyfe (2022).

Western North America (Simpson et al., 2016). Finally, the pattern of sea surface temperature warming can modify regional circulation and subtropical precipitation responses to greenhouse gas forcing (Zappa et al., 2020).

3.3. Aerosol Forcing

The mechanism proposed to explain the regional circulation signals in response to aerosol forcing involves the aerosol direct effect (aerosol-radiation interactions). Regions with reductions in aerosol optical depth over the satellite era, for example, Eurasia and Eastern North America, show increases in clear-sky surface shortwave radiation (unmasking effect) whereas regions with increases in aerosol optical depth, for example, South and East Asia, show a decrease in clear-sky surface shortwave radiation. The surface radiation signals weaken the meridional surface temperature gradient from the tropics to the extratropics, which following thermal wind balance weakens the summertime Eurasian jet. The shortwave radiation signals are coupled via the longitudinal circulation to the downstream ocean leading to a weakening of the storm tracks (Kang, Shaw, & Sun, 2024).

Other studies have proposed additional mechanisms 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).

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 (Shaw et al., 2024). 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; J. M. Kang et al., 2023; S. M. Kang et al., 2023).

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). Also, there is a strengthening of the Northern Hemisphere Hadley cell in reanalysis data but a weakening in models, though there is evidence that the reanalysis trends are artificial (Chemke & Polvani, 2019b).

Similar to thermodynamic discrepancies, there are also cases where models capture the signal but it is underestimated as compared to reanalysis trends even after accounting for internal variability: increased Southern Hemisphere storminess trends (Chemke et al., 2022; Shaw et al., 2022) and North Atlantic lower-tropospheric jet strength trend (Blackport & Fyfe, 2022, compare model distributions in colors to black horizontal line representing reanalysis in Figure 4). In other cases the models overestimate the trends (strengthening of the upper-tropospheric jet stream; Woollings et al., 2023).

The relationship between thermodynamic and dynamic discrepancies is an active area of research. Recent papers show SST trend discrepancies impact Southern Hemisphere storminess and midlatitude jet trends (Kang, Shaw, Kang, et al., 2024; Yang et al., 2021), and heatwave trends over Europe are underestimated in models due to a discrepancy in the dynamical contribution (compare black dots representing models to colored lines representing observations in Figure 5), although the details of this circulation trend discrepancy are not well understood and remain to be investigated (Vautard et al., 2023).

An important limitation of atmospheric circulation signals that needs to be taken into account when comparing model and observed signals is that atmospheric circulation signals rely heavily on reanalysis products. Such data sets can exhibit drifts and jumps due to changes in the underlying data sources (SPARC, 2022). In the Southern Hemisphere there is considerable spread in circulation signals across these products (Kang, Shaw, Kang,

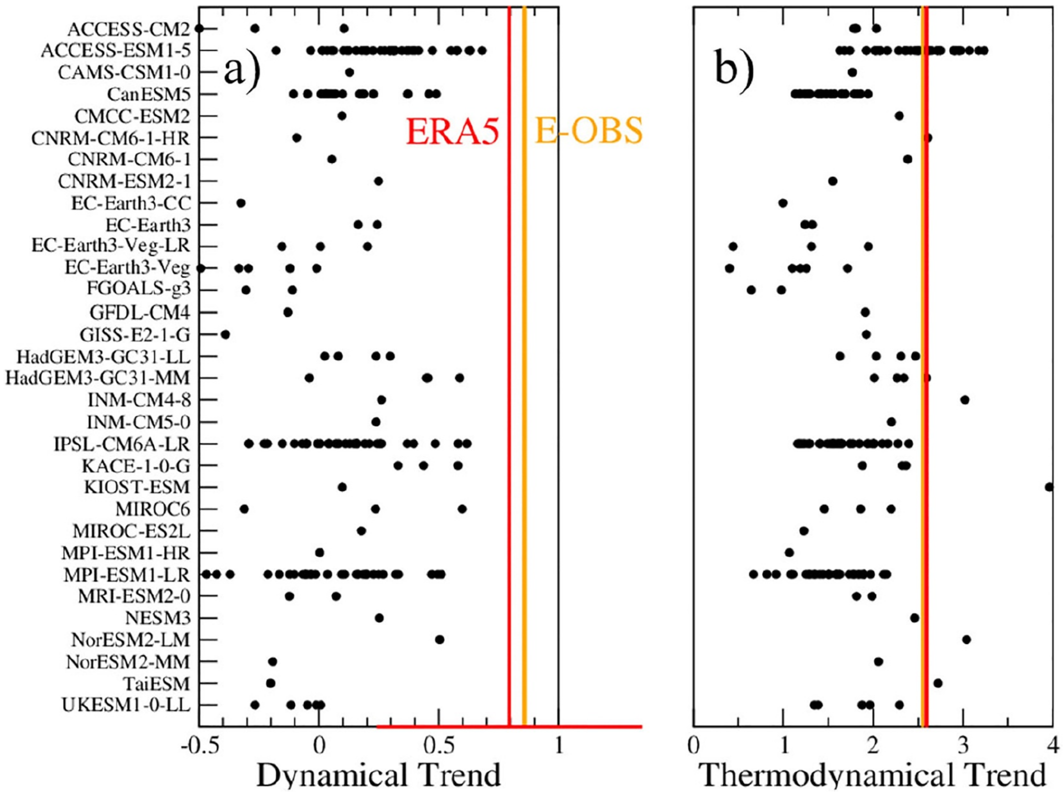

Figure 5. Dynamical (a) and thermodynamical (b) contributions to the summer TXx (summer maximum of maximal daily temperature) trends from ERA5 ECMWF Reanalysis (red line), E-OBS observation (orange line), and the 170 CMIP6 model simulations (names in ordinate) that were available (black dots) averaged over Western Europe. The thermodynamical contributions are simply calculated as residual by subtracting the dynamical trend from the total trend. For reference, the red bar at the bottom of (a) represents the 95% confidence interval of the estimate of the ERA5 TXx dynamical trend, estimated with a Gaussian assumption, that is, the interval is calculated as plus or minus 2* the standard deviation (STD) of the error estimate on the trend coefficient. This confidence range describes the uncertainty related to the internal variability. This shows that this confidence range, calculated with the single realization of the observation, is consistent with the uncertainty range calculated from simulation members (respective standard deviations for observed trend and simulated trends of 0.28 and 0.25). Taken from Vautard et al. (2023).

et al., 2024; Martineau et al., 2024). In the Northern Hemisphere, diabatic heating biases in reanalysis products have been shown to impact Hadley cell signals (Chemke & Polvani, 2019). Surface pressure observations have been used to resolve the discrepancy in Hadley cell signals (Chemke & Yuval, 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 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 with simulated Brewer-Dobson circulation trends in the middle stratosphere (Garny et al., 2024).

One way to separate the forced response from internal variability is using single forcing simulations. For example, if the signal is present in response to greenhouse gas or aerosol forcing only, and observational and model uncertainty is low, then it is likely a forced response. If the signal is present in the experiments without anthropogenic forcing (e.g., 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 with identical external forcing and slightly different initial conditions (Deser et al., 2020; Maher et al., 2021). The two approaches are combined in single-forcing large ensembles, which have been used to reconcile some discrepancies (by accounting for internal variability), such as the 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 during wintertime) and potential model errors, acknowledging a range of plausible future circulation trends ("storylines") is necessary for impacts planning (Mindlin et al., 2020; Schmidt & Grise, 2021; Williams et al., 2024; Zappa & Shepherd, 2017).

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 properly represent 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 initialized model forecast ensemble (Weisheimer et al., 2024).

4.3. Role of Mean State Biases/Spread for Future Change

The spread in model climatologies has been used to constrain thermodynamic climate change signals, for example, the snow-ice albedo feedback (Hall & 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. Emergent constraints are most robust when they are supported by a plausible physical mechanism.

Several emergent constraints have been proposed for circulation signals (Simpson et al., 2021): for example, the Southern Hemisphere eddy-driven jet position (Kidston & Gerber, 2010), and the wintertime stationary wave response over the North Pacific (Simpson et al., 2016). In both cases, a mechanism was proposed to explain the emergent constraint: fluctuation dissipation theorem for jet position, and jet stream strength affecting stationary wavelength. Unfortunately, some dynamical emergent constraints are not robust across CMIP versions (Curtis et al., 2020; Karpechko et al., 2024; Wu et al., 2019). Furthermore, the Southern Hemisphere jet position constraint, which is only robust in wintertime (Simpson & Polvani, 2016), appears to be an artifact of the zonal mean (Breul et al., 2023).

Mean state model 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 eddy-driven 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 signal may be biased in terms of location and/or magnitude (Grise, 2022; Maraun et al., 2017). Systematically addressing this issue globally is challenging and requires a detailed understanding of the circulation features for all relevant regions.

5. Opportunities for Progress

Understanding the emerging circulation signals and unraveling the puzzles they present provide exciting opportunities for making progress in understanding the dynamical response to climate change. Some opportunities for future research are listed below.

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 projected to form earlier and decay later in the future (Ayarzaguena et al., 2020; Rao & Garfinkel, 2021). Quantifying and understanding the seasonality of dynamical changes has important implications for impacts such as severe weather, ecosystems, forest fires, and agriculture.

5.2. Move Beyond the Longitudinal and Time Mean

Almost all of the dynamical signals in Table 1 reflect the time-mean. Circulation extremes have received only limited attention beyond blocking. Yet, recent work suggests the signal of climate change may be larger in the tails of the circulation distribution (Shaw & Miyawaki, 2024). It is also important to understand how circulation trends affect trends in other variables such as heat waves (Vautard et al., 2023).

Along similar lines, for a wide range of extremes and processes, there is much work to be done to understand how the dynamical response to climate change varies across different regions. New dynamical frameworks have emerged (Huang & Nakamura, 2016) that can be applied to trends. For example, insights have been gained into recent trends by defining the Hadley Cell for different regional sectors (Gillett et al., 2021; Hoskins et al., 2020; Nguyen et al., 2018; Staten et al., 2019). The well-known model-observation discrepancy in tropical SST trends (Seager et al., 2022; Wills et al., 2022) represents an opportunity for understanding how tropical climate change affects regional circulation trends and this should be investigated further. Ultimately, teleconnections bridging different regions will change due to mean state changes under climate change and more work is needed to understand how.

5.3. Use Signals to Test Mechanisms and Model Fidelity

Now that circulation signals are emerging, the dynamical mechanisms underlying the circulation trends can be compared to theoretical expectations and model predictions. Applying the numerous theoretical frameworks that have been proposed to explain dynamical responses to climate change (Hoskins & Woollings, 2015; Shaw, 2019; Vallis et al., 2015; Wills et al., 2019) offers great potential for progress. Large ensemble, single forcing simulations (Smith et al., 2022) can also be leveraged to attribute observed circulation changes, to investigate whether internal variability involves dynamical mechanisms that are distinct from the forced response to anthropogenic climate change, to clarify the relative importance of different anthropogenic forcings, to showcase examples where models lack fidelity, to isolate and potentially correct signal-to-noise biases (Section 4.2), and to directly examine how climate forcings affect the tails of the distribution (e.g., Section 5.2).

5.4. Leverage the Power of Existing and Emerging Tools

Existing tools such as idealized models (Jiménez-Esteve & Domeisen, 2022; Jiménez-Esteve et al., 2022; Schemm & Röthlisberger, 2024), model hierarchies (Maher et al., 2019), mechanism denial experiments targeted toward understanding circulation signals and nudging (Hitchcock et al., 2022) are all powerful 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., Grise, 2022). The impacts of known thermodynamic biases, for example, SST trend biases, can be understood and quantified through targeted model experiments, for example, using pacemaker simulations with coupled models (Kang, Shaw, Kang, et al., 2024).

Several new tools have emerged in the last decade that can be leveraged for making progress. Subseasonal to seasonal (S2S) forecasting models has emerged as a more widespread tool, with large ensembles of S2S forecasts that can 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 within 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 could 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; Garfinkel et al., 2022; Lawrence et al., 2022; Beverley et al., 2023; Randall & Emanuel, 2024).

The use of AI/ML methods has exploded in the last few years. Physics-informed and explainable AI has the potential to advance our understanding of circulation signals (Connolly et al., 2023). In particular, these methods may be able to "learn" the source of discrepancies between models and observations, and structural uncertainties across different models.

Finally, high resolution global models going down to kilometer scale resolution present an exciting opportunity for understanding how large- and small-scale dynamics interact. In order to answer outstanding questions, 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 small-scale dynamics in both the atmosphere and ocean (Yeager et al., 2023).

A new era of climate change research is upon us, one where atmospheric circulation signals are emerging, attribution is becoming possible and puzzles and discrepancies are accumulating. There is an opportunity to embrace these signals and the puzzles they present, including cases where there is a lack of consensus, and use the signals as an opportunity to further advance our understanding of the climate system and improve predictions of regional climate change.

Conflict of Interest

The authors declare no conflicts of interest relevant to this study.

Data Availability Statement

No data was generated.

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