Moist adiabatic scaling explains mean and fast upper-level jet stream wind response to climate change

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Key Points:

- A moist adiabatic scaling is derived for the upper-level jet stream wind response to global warming that depends only on historical surface air temperature.
- The scaling predicts a ~2%/K strengthening of mean and fast jet stream winds and a ~4%/K strengthening of jet stream shear across a hierarchy of complexity.
- The moist adiabatic scaling shows fast-get-faster is explained by a strengthened surface moisture gradient, which impacts the upper-level temperature gradient.

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Abstract

The upper-level jet stream exhibits a robust increase in strength and shear under climate change. Previous work also noted a fast-get-faster response and connected it diagnostically to the Clausius-Clapeyron relation. Here we derive a moist adiabatic scaling that explains the upper-level jet stream wind response. Given the daily surface air temperature distribution and assuming a moist adiabatic atmosphere, the upper-level mean and fast jet stream wind increase by $\sim$2%/K and the jet stream shear increases by $\sim$4%/K across a climate model hierarchy. The scaling shows the increase of the surface moisture gradient following the Clausius-Clapeyron relation dominates the response. The scaling connects the increasing surface moisture gradient to the upper-level temperature gradient thereby reconciling dry and moist perspectives. The results show record-breaking upper-level jet stream wind and increased clear-air turbulence are tied to the Clausius-Clapeyron relation and are therefore robust and well-understood consequences of climate change.

Plain Language Summary

The jet stream, a fast moving current of air above our heads, has been shown to get stronger both in terms of its average speed but also its fastest days in climate model predictions. Here assuming a moist atmosphere whose temperature structure is only influenced by cooling from expansion and heating from condensation of moisture evaporated from the ocean surface we explain why the jet stream strengthens. We show that following this assumption the jet stream gets stronger by 2% per degree of surface warming and the shear of the jet stream (how its strength varies with altitude) gets stronger by 4% per degree of surface warming. Both changes are the result of warmer air on the equatorward side of the jet stream "holding" more moisture under climate change. The results show record-breaking upper-level jet stream wind and increased clear-air turbulence are tied to warmer air "holding" more moisture and are therefore robust and well-understood consequences of climate change.

1 Introduction

The response to anthropogenic climate change is often separated into thermodynamic and dynamic components (Shepherd, 2014). Thermodynamic responses are generally considered robust and well understood in terms of their simulation and theoretical underpinnings. More specifically, theoretical scalings have been used to predict an increase of $\sim$5% per degree of surface air temperature, hereafter $\sim$5%/K, of extreme precipitation (O'Gorman, 2015; O'Gorman & Schneider, 2009), amplification of heat extremes over tropical land relative to ocean (Byrne, 2021) and predict an upper bound for extreme temperatures over midlatitude land (Zhang & Boos, 2023). The thermodynamic scalings all share a common feature: they rely on the increase of saturation specific humidity with temperature following the Clausius-Clapeyron relation.

Dynamical responses are generally considered less robust and less well understood. Although many circulation responses are robust in terms of multimodel agreement, for example the mean acceleration of the upper-level jet stream (Stephenson & Held, 1993; Lorenz & DeWeaver, 2007), the poleward shift of the eddy-driven jet and storm tracks (Manabe & Wetherald, 1975; Vallis & Kidston, 2015), increased vertical jet stream wind shear (Williams & Joshi, 2013), weakening of stationary eddies (Wills et al., 2019) a robust theoretical understanding has been challenging. Many mechanisms have been put forward that involve different thermodynamic starting points (Hoskins & Woollings, 2015; Shaw, 2019), however, competing effects and thermodynamic feedbacks make it challenging to disentangle cause from effect (Shaw et al., 2016). Furthermore, very few dynamical scalings have been established for the climate change response.

To date diagnostic analyses and idealized climate model simulations have been the primary tools used to elucidate the atmospheric circulation response to climate change, however emerging circulation trends are opening up new opportunities (Shaw, Arblaster, et al., 2024). For example, the strengthening of the mean upper-level jet stream wind has been linked to the thermal structure of the atmosphere, including the upward shift of the tropopause, (Lorenz & DeWeaver, 2007) and tropical diabatic heating (Butler et al., 2010). Increased upper-level jet stream wind shear has also been linked to the thermal structure of the atmosphere (Williams & Joshi, 2013; Lee et al., 2019). Several studies have linked the poleward shift response to moist thermodynamics through the Clausius-Clapeyron relation (Shaw & Voigt, 2016), latent heat release (Tamarin-Brodsky & Kaspi, 2017) and parameterized convective heating (Garfinkel et al., 2024). Most recently, the 'fast-get-faster' response of the upper-level jet stream, which represents a strengthening of jet streaks and waviness, was connected diagnostically to the Clausius-Clapeyron relation (Shaw & Miyawaki, 2023; Shaw, Miyawaki, et al., 2024). However, a theoretical scaling explaining the robust $\sim$2%/K increase of mean and fast jet stream winds is lacking. A scaling is important for explaining why the rate of increase is $\sim$2%/K and not higher like for precipitation extremes, and how the near-surface moisture gradient response that follows from the Clausius-Clapeyron relation is connected to latent heat release and temperature gradient responses aloft.

Here we build on previous diagnostic work connecting the circulation responses under climate change to moist thermodynamics. We derive a moist adiabatic scaling for the upper-level jet stream wind response and thereby fill a gap in theoretical scalings for the circulation responses under climate change. Overall, the approach is complementary to scalings that leveraged moist thermodynamics to explain the response of extreme precipitation (O'Gorman & Schneider, 2009), heat waves (Byrne, 2021; Zhang & Boos, 2023) and tropical cyclone intensity (Emanuel, 1988a).

2 Data & Methods

The moist adiabatic scaling derived below depends on surface air temperature and assumes a moist adiabatic atmosphere. In order to quantify the scaling we use daily surface air temperature data from simulations across the climate model hierarchy made available as part of the Coupled Model Intercomparison Project phase 6 (Eyring et al., 2016, Supplementary Table S1). In particular, we make use of the aquaplanet configuration, hereafter AQUA, with sea surface temperature prescribed following the QOBS distribution (Neale & Hoskins, 2001). The atmosphere-land model configuration, hereafter AMIP, with sea surface temperature prescribed from observations (Gates, 1992). Finally, we make use of fully coupled models of the historical period (1980 to 2000), hereafter HIST.

The moist adiabatic scaling is applied to the mean and fast upper-level jet stream wind response to global warming. For the response of the mean jet stream wind, the surface air temperature averaged over all days is combined with a moist adiabat vertical temperature structure (Miyawaki et al., 2020, eq. 8). For the response of the fast jet stream wind, the surface air temperature corresponding to days when the upper-level jet stream wind exceeds the 99th percentile at each latitude following previous work (Shaw & Miyawaki, 2023) is combined with a moist adiabat vertical temperature structure. The scaling response is derived by applying a uniform global warming. For AQUA and AMIP the warming is 4 K and for HIST the warming is the difference of global-mean surface air temperature between the end of 21st century (2080 to 2100 following the SSP5-8.5 scenario) and the historical period (1980 to 2000).

3 Results

Previous work showed thermal wind balance dominates the upper-level (200 hPa) jet stream wind response under climate change on the daily timescale at each longitude-latitude grid point (Shaw & Miyawaki, 2023; Shaw, Miyawaki, et al., 2024). Thermal wind relates the vertical shear of the jet stream wind to the density contrast

$$\frac{\partial u}{\partial p} = \frac{1}{fa}\frac{\partial \alpha}{\partial \phi} \qquad (1)$$

$$u_T \approx \int_{p_s}^{200\text{hPa}} \frac{1}{fa}\frac{\partial \alpha}{\partial \phi} dp \tag{2}$$

where u is the zonal component of the jet stream wind, p is pressure, f is the Coriolis parameter, a is the radius of Earth, $\alpha = 1/\rho$ is the specific volume where ρ is density, p_s is surface pressure and ϕ is latitude. We neglect the surface wind in (2), which is small consistent with previous work (Lee et al., 2019; Shaw & Miyawaki, 2023).

To derive the moist adiabatic scaling we relate specific volume (density) to saturation (moist) entropy s^* and pressure, i.e. $\alpha = \alpha(s^*, p)$. Saturation entropy is the sum of dry entropy ($s_d = c_p \ln\theta$ where θ is potential temperature) and saturation specific humidity (q^*), i.e. $s^* = s_d + L_v q^*/T$ where L_v is the latent heat of vaporization (Emanuel, 1995). Saturation entropy is conserved in the presence of water vapor phase changes.

For a moist atmosphere thermal wind becomes

$$\begin{aligned} u_T &\approx \int_{p_s}^{200\text{hPa}} \frac{1}{fa}\frac{\partial \alpha}{\partial s^*}\frac{\partial s^*}{\partial \phi} dp \\ &\approx \int_{p_s}^{200\text{hPa}} \frac{1}{fa}\left(\frac{\partial T}{\partial p}\right)_{s^*}\frac{\partial s^*}{\partial \phi} dp \end{aligned} \tag{3}$$

following the chain rule and applying the Maxwell relation $\partial\alpha/\partial s^* = (\partial T/\partial p)_{s^*}$ where $(\partial T/\partial p)_{s^*}$ is the moist adiabatic lapse rate (Emanuel, 1995). Note that at this point no moist adiabatic assumption has been made. The moist adiabatic lapse rate in (3) is simply a weighting function. One is free to relate density to any thermodynamic variables via the equation of state. In what follows we connect the moist thermodynamic perspective with $\alpha = \alpha(s^*, p)$ to the dry thermodynamic perspective $\alpha = \alpha(T, p)$.

3.1 Derivation of moist adiabatic scaling

A moist adiabatic scaling is derived by assuming that the atmosphere is moist adiabatic. Under this assumption the saturation entropy is constant with pressure and hence the moist thermal wind relation simplifies to

$$\begin{aligned} u_T &\approx \frac{1}{fa}\frac{\partial s_s^*}{\partial \phi}\int_{p_s}^{200\text{hPa}} \left(\frac{\partial T}{\partial p}\right)_{s^*} dp \\ &\approx \frac{1}{fa}\frac{\partial s_s^*}{\partial \phi}\left(T|_{s^*,200\text{hPa}} - T|_{s^*,p_s}\right) \end{aligned} \tag{4}$$

where s_s^* is the near-surface saturation moist entropy, which is chosen as a representative value following previous work (Emanuel, 1995; Prive & Plumb, 2007; Shaw & Voigt, 2015), and $T|_{s^*,200\text{hPa}}$ and $T|_{s^*,p_s}$ are the moist adiabatic temperature evaluated at 200 hPa and the surface pressure, respectively.

The response to global warming is

$$\Delta u_T \approx \frac{1}{fa}\left[\Delta\left(\frac{\partial s_s^*}{\partial \phi}\right)\left(T|_{s^*,200\text{hPa}} - T|_{s^*,p_s}\right) + \frac{\partial s_s^*}{\partial \phi}\Delta\left(T|_{s^*,200\text{hPa}} - T|_{s^*,p_s}\right)\right] \tag{5}$$

where Δ is the difference between the warm climate and the climatology. The fractional climate change response is

$$\frac{\Delta u_T}{u_T} \approx \frac{\Delta\partial s_s^*/\partial\phi}{\partial s_s^*/\partial\phi} + \frac{\Delta(T|_{s^*,200\mathrm{hPa}} - T|_{s^*,p_s})}{(T|_{s^*,200\mathrm{hPa}} - T|_{s^*,p_s})}. \tag{6}$$

The saturation entropy gradient response can be further decomposed into moist and dry contributions, e.g.

$$\frac{\Delta u_T}{u_T} \approx \underbrace{\frac{\Delta\partial(L_v q_s^*/T)/\partial\phi}{\partial s_s^*/\partial\phi}}_{moist-get-moister} + \underbrace{\frac{\Delta\partial s_{d,s}/\partial\phi}{\partial s_s^*/\partial\phi}}_{dry\ entropy} + \underbrace{\frac{\Delta(T|_{s^*,200\mathrm{hPa}} - T|_{s^*,p_s})}{(T|_{s^*,200\mathrm{hPa}} - T|_{s^*,p_s})}}_{moist\ adiabatic\ adj.}. \tag{7}$$

Note the moist adiabatic scaling depends only on the surface air temperature. The surface air temperature determines the vertical temperature structure through the moist adiabat assumption. Furthermore, the scaling in (7) only emerges from moist thermodynamics. If one assumes dry thermodynamics, i.e. $\alpha = \alpha(p, T)$, the thermal wind relation does not simplify, i.e.

$$\frac{\partial u}{\partial p} = \frac{R}{fpa}\left(\frac{\partial T}{\partial\phi}\right)_{s^*} \tag{8}$$

$$u_T \approx \frac{R}{fpa}\int_{p_s}^{200\mathrm{hPa}}\left(\frac{\partial T}{\partial\phi}\right)_{s^*} dp \tag{9}$$

where R is the dry gas constant.

The moist adiabatic scaling provides insights into the physical mechanisms controlling the jet stream response under climate change. The first term on the right-hand side of (7) is identified as the moist-get-moister response (Shaw & Voigt, 2016). It encodes the steep increase of the surface meridional saturation specific humidity gradient under global warming following the Clausius-Clapeyron relation:

$$\Delta\frac{\partial s_s^*}{\partial\phi} \approx \frac{L_v}{T}\Delta\frac{\partial q_s^*}{\partial\phi} \tag{10}$$

(Shaw & Miyawaki, 2023, see their Fig. 3a). The air on the equatorward side of the jet is warm and moist whereas the air on the poleward side is cold and dry (Henrik et al., 2024). Global warming increases saturation specific humidity more on the equatorward side of the jet increasing the saturation specific humidity gradient.

The second term on the right-hand side of (7) is the surface meridional dry entropy gradient which is negligible for global warming (no change in temperature gradient). However, since the saturation entropy gradient is constant with pressure, aloft where saturation specific humidity is small the dry entropy gradient will be large

$$\Delta\frac{\partial s_s^*}{\partial\phi} \approx \Delta\frac{\partial s_{200\mathrm{hPa}}^*}{\partial\phi} \approx \Delta\frac{\partial s_{d,200\mathrm{hPa}}}{\partial\phi}. \tag{11}$$

The response of the dry entropy gradient aloft encodes the meridional gradient of latent heat release aloft (Shaw & Miyawaki, 2023, see their Fig. 3c). This connection between surface saturation specific humidity and upper-level dry entropy (10) and (11) is an important link between the moist and dry interpretations of the jet stream wind response as discussed below.

Finally, the third term on the right-hand side of (7) represents moist adiabatic adjustment, which leads to warming aloft (Shaw & Miyawaki, 2023, see their Fig. 3b), and is therefore a negative feedback that weakens the jet stream wind. Thus, the increase of the upper-level jet stream comes from the meridional gradient of near-surface saturation entropy and hence depends on the Clausius-Clapeyron relation following (10).

The moist adiabatic scaling also provides insight into the response of upper-level jet stream wind shear. Following the moist adiabatic scaling, the fractional response of upper-level jet stream wind shear is

$$\left.\frac{\Delta\partial u/\partial p}{\partial u/\partial p}\right|_{200\mathrm{hPa}} \approx \left.\frac{\Delta\partial s^*/\partial\phi}{\partial s^*/\partial\phi}\right|_{200\mathrm{hPa}} + \left.\frac{\Delta(\partial T/\partial p)_{s^*}}{(\partial T/\partial p)_{s^*}}\right|_{200\mathrm{hPa}} \tag{12}$$

$$\approx \underbrace{\left.\frac{\Delta\partial(L_v q^*/T)\partial\phi}{\partial s^*/\partial\phi}\right|_{200\mathrm{hPa}}}_{moist-get-moister} + \underbrace{\left.\frac{\Delta\partial s_d\partial\phi}{\partial s^*/\partial\phi}\right|_{200\mathrm{hPa}}}_{dry\ entropy} + \underbrace{\left.\frac{\Delta(\partial T/\partial p)_{s^*}}{(\partial T/\partial p)_{s^*}}\right|_{200\mathrm{hPa}}}_{moist\ adiab.\ adj.} \tag{13}$$

where the first and second terms on the right-hand side of (13) reflect the moist-get-moister and dry entropy contributions for jet stream strength (7). The third term on the right-hand side of (13) reflects the upward shift of the tropopause. Following the arguments above, the shear should increase due to the increase of surface saturation entropy gradient following (11).

3.2 Back-of-the-envelope calculation of moist adiabatic scaling

The moist adiabatic scaling response can be used to perform a back-of-the-envelope calculation of the mean upper-level jet stream wind response to global warming. Note this calculation does not involve running a climate model. The ingredients for the calculation are: climatological mean surface air temperatures on the equatorward (300 K) and poleward (260 K) sides of the jet, the Clausius-Clapeyron relation and the moist adiabatic temperature.

Substituting the climatological mean surface air temperatures on the equatorward and poleward side of the jet into the definition of saturation entropy the corresponding equator-to-pole difference (gradient) is 319.8 J/kg/K. Under global 4 K warming, the equator-to-pole difference increases to 361.7 J/ kg/K due to increased saturation-specific humidity following the Clausius-Clapeyron relation on the equatorward side (Shaw & Miyawaki, 2023, see their Fig. 3a). Thus, the equator-to-pole saturation moist entropy difference (gradient) increases by ∼3.3 %/K.

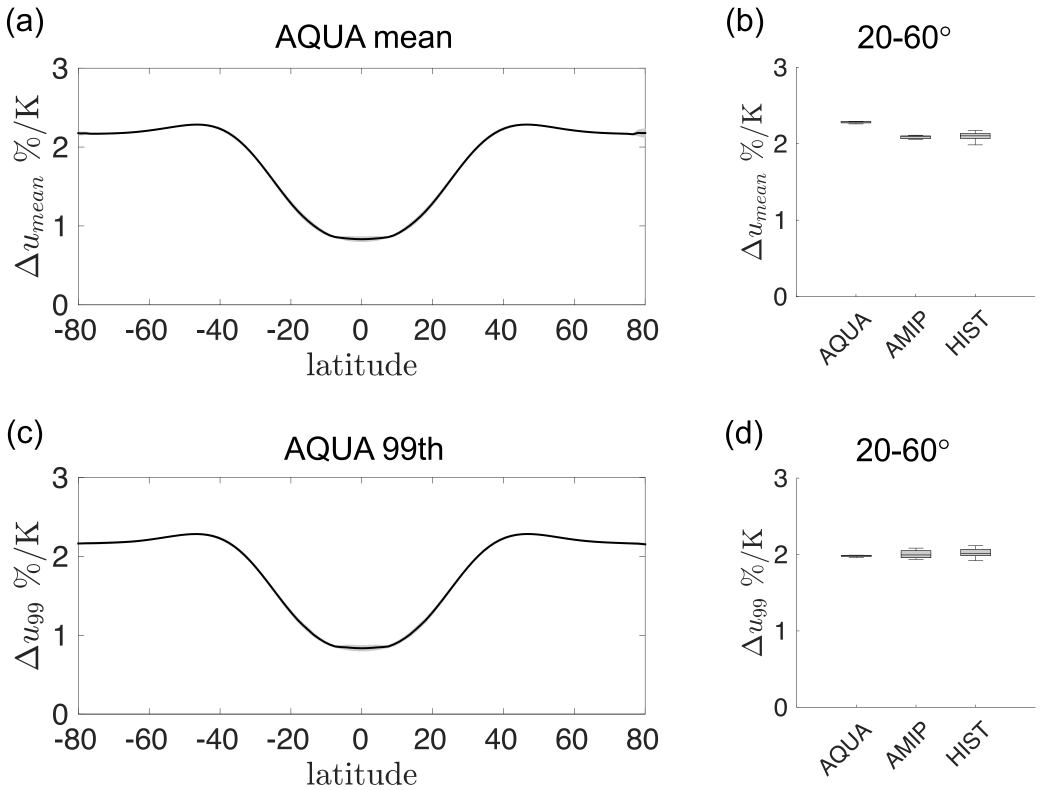

Figure 1. Response of (a) mean upper-level (200 hPa) jet stream wind to global warming following the moist adiabatic scaling and (b) the robustness of the response, averaged from 20 to 60 degrees latitude, across a climate model hierarchy. (c,d) Similar to (a,b) but for fast upper-level jet stream winds.

The surface warming of 4 K on the equatorward side leads to ∼11 K warming aloft (200 hPa) following the moist adiabatic temperature (Shaw & Miyawaki, 2023, see their Fig. 3b). This is relative to a climatological temperature difference between the surface and 200 hPa of ∼ -80 K. On the poleward side, surface warming of 4 K leads to ∼4.1 K warming aloft. This is relative to a climatological temperature difference between the surface and 200 hPa of ∼ -90 K. Thus, the moist adiabatic adjustment contribution is ∼ -2%/K on the equatorward side and and ∼ 0%/K on the poleward side. When weighted-averaged over the extratropics the contribution is ∼ -1.2%/K. Thus, the back-of-the-envelope calculation suggests an increase of the mean upper-level jet stream wind by ∼ 2.1%/K.

3.3 Scaling for jet stream strength across a climate model hierarchy

The moist adiabatic scaling (7) can also be quantified using daily surface air temperature data from a climate model hierarchy. According to the moist adiabatic scaling, the mean jet stream wind gets faster under global warming (Fig. 1a). Across the extratropics (20-60°) the rate of increase is ∼2%/K (AQUA, Fig. 1b). A similar rate is seen across a climate model hierarchy (Fig. 1b). The ∼2%/K rate is also consistent with the back-of-the-envelope calculation and the response in coupled climate models that do not assume a moist adiabat (Shaw & Miyawaki, 2023).

When the daily surface air temperature distribution is conditioned on climatological days with fast (> 99th percentile) upper-level jet stream winds, the moist adiabatic scaling predicts fast winds get faster (Fig. 1c). Across the extratropics (20-60°) the rate of increase for fast winds is similar to that for the mean wind ∼2%/K (AQUA, Fig. 1d). Once again, the scaling is robust across a climate model hierarchy (Fig. 1d). The scaling is also consistent with the response in coupled climate models that do not assume a moist adiabat (Shaw & Miyawaki, 2023). This shows the ∼2%/K scaling applies to both mean and fast jet stream wind responses.

The moist adiabatic scaling response for mean and fast jet stream winds can be further understood by decomposing it into moist-get-moister, dry entropy and moist-adiabatic adjustment contributions following (7). Moist-adiabatic adjustment leads to mean and fast jet stream winds getting slower (blue line, Fig. 2a,c). The rate of decrease averaged across the extratropics is ∼1.5%/K for both the mean and fast jet stream wind (Fig. 2b,d). The results are robust across a climate model hierarchy (Fig. 2b,d). This scaling is consistent with the back-of-the-envelope calculation and the response diagnosed from coupled climate model simulations that do not assume a moist adiabat (Shaw & Miyawaki, 2023, see their Fig. 4a).

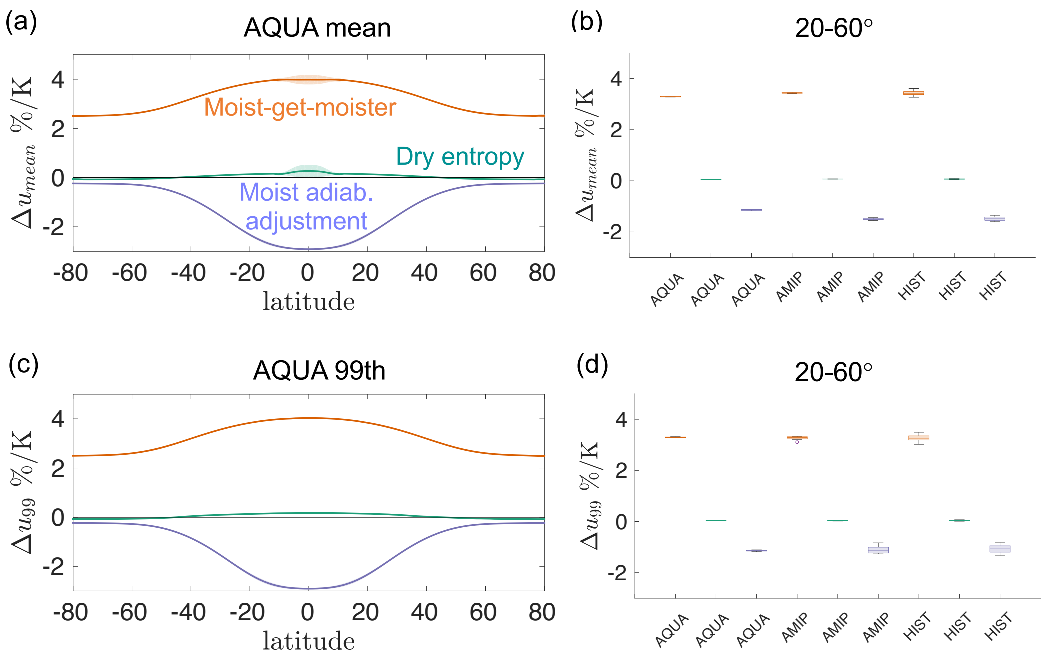

Figure 2. Response of (a) mean upper-level (200 hPa) jet stream wind to global warming following the moist adiabatic scaling decomposed into moist thermal wind contributions (7) and (b) the robustness of the response, averaged from 20 to 60 degrees latitude, across a climate model hierarchy. (c,d) Similar to (a,b) but for fast upper-level jet stream winds.

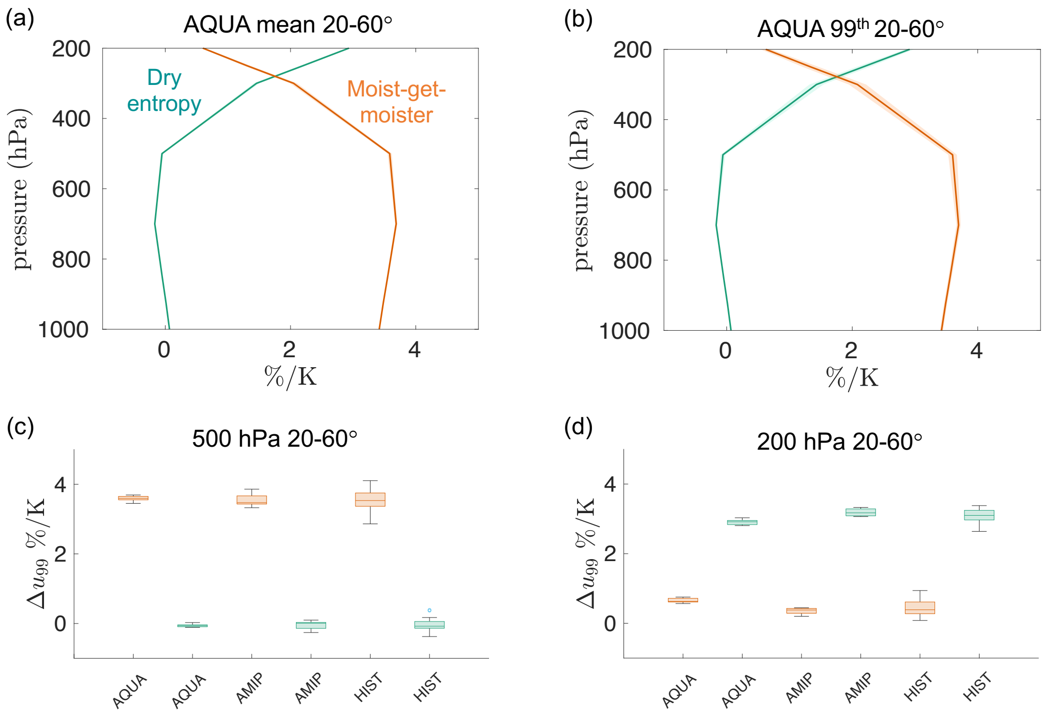

Figure 3. Response of the moist-get-moister and dry entropy contributions (7) to the saturation entropy gradient response for the (a) mean and (b) fast upper-level jet stream wind response versus pressure. The robustness of the response of moist-get-moister and dry entropy contributions at (c) 500 hPa and (d) 200 hPa, averaged from 20 to 60 degrees, across a model hierarchy.

The moist-get-moister response leads to mean and fast upper-level jet stream winds getting faster (orange line, Fig. 2a,c). The rate of increase averaged over the extratropics is ∼3.5%/K for both mean and fast jet stream winds (orange, Fig. 2b,d). The results are also robust across a climate model hierarchy (orange, Fig. 2b,d). The dry entropy contribution is negligible consistent with the imposed global warming (green line, Fig. 2a,c). Overall, the moist adiabatic scaling shows the increase surface moisture gradient (moist-get-moister) explains the strengthening of the mean and fast upper-level jet stream wind under global warming. It also explains the multiplicative ∼2%/K rate of increase and shows it can be predicted solely from the Clausius-Clapeyron relation.

3.4 Connecting upper- and lower-level responses

The saturation moist entropy gradient response is constant with height under the moist adiabatic assumption, however the moist-get-moister and dry entropy contributions vary significantly with height (Fig. 3a,b). From the surface to the mid troposphere (∼500 hPa) the moist-get-moister response dominates the saturation entropy gradient (Fig. 3c) consistent with (10). However, aloft (above 500 hPa) the dry entropy gradient response becomes more important and it dominates at 200 hPa (Fig. 3d) consistent with (11).

The connection between the surface and upper-level responses is consistent with warmer surface air "holding" more moisture via increased evaporation and the Clausius-Clapeyron relation impacting upper-level dry entropy (temperature) through increased latent heat release. The dry entropy gradient increases aloft because it is not conserved in the presence of water vapor phase changes. The vertical structure of the moist adiabatic scaling therefore connects the moist thermodynamic perspective, which explains the strengthened jet stream wind following increased surface moisture gradient (Fig. 2), to the dry thermodynamic perspective, which explains the strengthened jet stream wind following increased upper-level temperature (dry entropy) gradient.

3.5 Scaling for jet stream wind shear across a climate model hierarchy

The moist adiabatic scaling predicts an increase of upper-level jet stream wind shear for mean and fast jet stream winds (Fig. 4a,b). Across the extratropics (20-60°) the rate of increase is ∼4%/K (Fig. 4b,d), twice as large as for jet stream strength (Fig. 1b,d). The physical mechanism underlying the increase of saturation entropy gradient aloft with a small additional contribution from changes in static stability (Fig. 5a,c) consistent with an upward shift of the tropopause. The increased saturation entropy gradient aloft is dom-

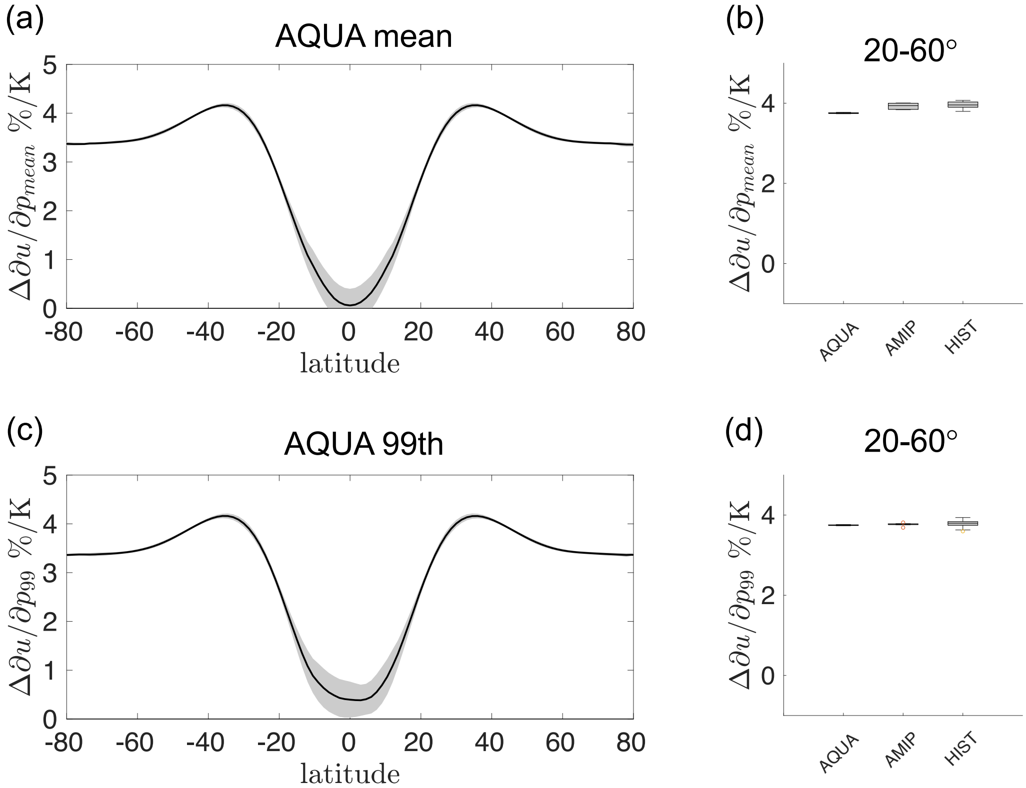

Figure 4. Response of (a) mean upper-level (200 hPa) jet stream wind shear to global warming following the moist adiabatic scaling and (b) the robustness of the response, averaged from 20 to 60 degrees latitude, across a climate model hierarchy. (c,d) Similar to (a,b) but for fast upper-level jet stream wind shear.

inated by the dry entropy component (Fig. 3) and is coupled to the increased surface moisture gradient following (10).

The strengthened jet stream shear aloft can also be interpreted through a dry thermodynamic perspective where jet stream wind shear is related to the upper-level temperature gradient (8). The moist adiabatic scaling leads to a strengthened temperature gradient aloft (200 hPa) consistent with latent heat release aloft maximizing in the tropics and an upward shift of the tropopause (Supplementary Fig. 1). Thus, the moist adiabatic scaling clarifies the connection between moist and dry thermodynamic perspectives. Dry thermal wind starts with the upper-level temperature gradient whereas moist thermal wind traces the origin of the upper-level temperature response to latent heat released from increased surface moisture following the Clausius-Clapeyron relation. It is important to note the connection between temperature and the Clausius-Clapeyron relation was revealed using the moist adiabatic scaling.

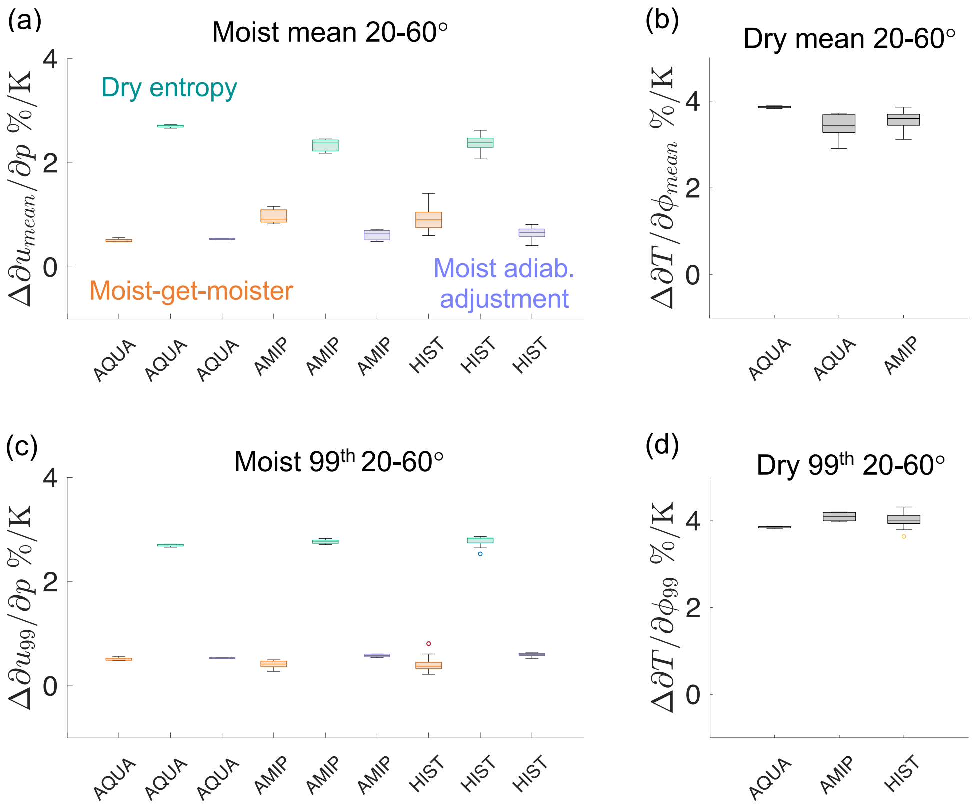

Figure 5. Response of (a,b) mean and (c,d) 99th percentile upper-level (200 hPa) zonal vertical wind shear to global warming decomposed following moist thermodynamics (13) and dry thermodynamics across the climate model hierarchy.

4 Conclusions & Discussion

4.1 Conclusions

The atmospheric circulation exhibits many robust responses under climate change and several mechanisms have been proposed to explain them (Shaw, 2019). Previous work focused on unraveling mechanisms through diagnostic analysis and idealized model simulations. Here we follow a scaling approach that assumes a moist adiabatic atmosphere that has been successful for thermodynamic extremes (O'Gorman & Schneider, 2009; Byrne, 2021; Zhang & Boos, 2023) and tropical cyclone potential intensity (Emanuel, 1988a) and applied it to the upper-level jet stream wind response to global warming.

The results show the moist adiabatic scaling, which depends on the surface air temperature distribution and assumes a moist adiabatic atmosphere, predicts an increase of the mean and fast upper-level jet stream wind by $\sim$2%/K across a climate model hierarchy. The $\sim$2%/K scaling is consistent with the projected response from coupled climate models, which do not assume a moist adiabatic atmosphere (Shaw & Miyawaki, 2023). The moist adiabatic scaling shows that the strengthened upper-level jet stream wind and its $\sim$2%/K scaling can be explained by the increased surface moisture gradient following the Clausius-Clapeyron relation. More specifically, air on the equatoward side of the jet "holds" more moisture under climate change steepening the contrast across the jet.

Under the moist adiabatic scaling the saturation entropy gradient increases throughout the vertical column because saturation entropy is constant with pressure. This implies the increased surface moisture gradient is coupled to the increased temperature (dry entropy) gradient aloft. Thus, the moist adiabatic scaling reconciles the moist thermodynamic perspective, which explains the strengthening jet stream wind following an increased surface moisture gradient, with the dry thermodynamic perspective, which explains the strengthening jet stream wind following an increased upper-level temperature (dry entropy) gradient.

The moist adiabatic scaling also predicts a $\sim$4%/K increase of upper-level jet stream wind shear across a climate model hierarchy. The increased wind shear is consistent with the projected response from coupled climate models under climate change, which do not assume a moist adiabat (Williams & Joshi, 2013). Once again the strengthened upper-level jet stream shear is a consequence of the increased surface moisture gradient following the Clausius-Clapeyron relation, which is connected to the increased temperature (dry entropy) gradient aloft.

4.2 Discussion

Connecting climate model responses to theoretical scalings is important for having confidence in climate model predictions. Several thermodynamic responses have been connected to theoretical scalings anchored by the Clausius-Clapeyron relation. To our knowledge the moist adiabatic scaling presented here is the first dynamical scaling connected to the Clausius-Clapeyron relation. The results show record-breaking jet stream wind and increased clear-air turbulence are robust and well-understood consequences of climate change. The results suggest moist thermodynamics influence (geostrophically) balanced dynamical responses. Hence, the "thermodynamic" (depends on global-mean temperature and leads to increased moisture) and "dynamic" (independent of global-mean temperature) (Shepherd, 2014) terminology may be misleading (Neelin et al., 2022).

The moist adiabatic scaling assumes a moist adiabatic atmosphere. There are several lines of evidence for the impact of moisture on extratropical static stability (Emanuel, 1988b; Juckes, 2000; Frierson, 2006; Korty & Schneider, 2007; Emanuel, 2008). However, it is important to note that here we have found the moist adiabatic scaling response under climate change agrees with coupled climate model projections that do not assume a moist adiabatic temperature. The results suggest moisture is important for the response of the upper-level jet stream even though it may not dominate the climatology of the jet stream. The idea is similar to potential intensity of tropical cyclones (Emanuel, 1988a). "Potential" refers to maximizing moist thermodynamics (an upper bound) and potential intensity provides an explanation of the tropical cyclone intensity trends and projected responses to global warming (Kossin & Camargo, 2009; Yu et al., 2010).

The moist adiabatic scaling connects several mechanisms proposed in the literature to explain circulation responses (Shaw, 2019). In particular, 4 of the 8 proposed thermodynamic starting points can be connected: 1) increased latent heat release aloft in the tropics, 2) increased dry static stability and tropopause height outside the tropics, 3) increased specific humidity following the Clausius-Clapeyron relation, and 4) turbulent surface heat flux changes, all follow from the moist adiabatic assumption. Thus, the moist adiabatic scaling represents progress in reducing the number of thermodynamic starting points. Some of the remaining starting points are associated with the response in other regions (the stratosphere) and involve moist thermodynamic responses not included in the scaling (cloud radiative effects).

The results suggest other circulation responses could potentially be explained using a moist adiabatic scaling. They include the poleward shift of the eddy-driven jet and edge of the Hadley cell, the meridional wind response, including the stationary circulation changes (Wills et al., 2019) and synoptic-scale (Prein, 2023) circulation responses. Future work will investigate whether a moist adiabatic scaling can be used to explain these other robust circulation responses.

Open Research Section

This section MUST contain a statement that describes where the data supporting the conclusions can be obtained. Data cannot be listed as "Available from authors" or stored solely in supporting information. Citations to archived data should be included in your reference list. Wiley will publish it as a separate section on the paper's page. Examples and complete information are here: https://www.agu.org/Publish with AGU/Publish/Author Resources/Data for Authors

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