What can moist thermodynamics tell us about circulation shifts in response to uniform warming?

Tiffany A. Shaw¹, Aiko Voigt²

Corresponding author: T. A. Shaw, Department of the Geophysical Sciences, 5734 S. Ellis Ave., Chicago, IL, 60637 USA. (tas1@uchicago.edu)

¹Department of the Geophysical Sciences,
The University of Chicago, Chicago, IL,
USA.

²Lamont-Doherty Earth Observatory,
Columbia University, New York, NY, USA
Aquaplanet simulations exhibit a robust expansion of the Hadley cell and poleward jet shift in response to uniform warming of sea-surface temperature. Here moist thermodynamic and dynamic frameworks are combined to make predictions of circulation responses to warming. We show Clausius-Clapeyron (CC) scaling of specific humidity with warming predicts an expansion of the Hadley circulation according to convective quasi-equilibrium dynamics. A poleward jet shift follows from the control-climate relationship between the Hadley cell edge and jet stream position. CC scaling of specific humidity with warming also predicts decreased diffusivity and a poleward shift of the latitude of maximum latent and dry-static energy transport according to mixing-length theory. Finally, atmospheric cloud-radiative changes shift the latitude of maximum energy transport poleward in most models. Our results show moist thermodynamics can predict meridional shifts of the circulation when combined with dynamical frameworks, however additional feedbacks are important for the simulated response.
1. Introduction

Confidence in the projected thermodynamic and dynamic response of the climate system to anthropogenic climate change requires a physical understanding of the underlying mechanisms. It is well understood that the thermodynamic response to increased CO$_2$ involves warming, increased near-surface specific humidity over the ocean following the Clausius-Clapeyron (CC) relation, warming of the tropical-upper troposphere and a raising of the tropopause [e.g. Held, 1993; Allen and Ingram, 2002; Held and Soden, 2006; Vallis et al., 2015]. Held and Soden [2006] used CC scaling to predict the “wet-get-wetter, dry-get-drier” response to warming. The dynamic response to increased CO$_2$, e.g. the response of the Hadley cell and jet stream, is less well understood [Shepherd, 2014; Vallis et al., 2015]. However, the majority of coupled-climate models, atmosphere only models and aquaplanet models participating in the Coupled Model Intercomparison Project Phase 5 (CMIP5) project a robust (in terms of model agreement) poleward expansion of the circulation, including a poleward shift of the edge of the Hadley cell and zonal-mean jet stream position, in response to anthropogenic climate change [Held, 1993; Vallis et al., 2015; Medeiros et al., 2015]. While models may not agree on the magnitude of the response, the meridional direction is robust and motivates the search for a physical explanation.

Given our understanding of the moist thermodynamic response to global warming, we ask the question: What can moist thermodynamics tell us about the circulation response to uniform warming? Previous authors have linked moist thermodynamics, in particular warming of the tropical upper troposphere and increased tropopause height, to Hadley...
circulation expansion a posteriori [Held, 2000; Lu et al., 2007; Vallis et al., 2015]. Building on those results here we put forward physical arguments linking moist thermodynamic changes to dynamic responses using different theoretical frameworks. We focus on two different moist thermodynamic responses to warming. The first is the increase of near-surface specific humidity with warming following CC scaling. We investigate the implication of this increase for near-surface moist entropy and moist-static energy changes, which are linked to dynamical responses following convective quasi-equilibrium dynamics [Emanuel et al., 1994; Emanuel, 1995] and mixing-length theory [Held, 2000; Kushner and Held, 1998]. In both cases we show increased specific humidity following CC scaling can be used to predict meridional shifts of the circulation in response to uniform warming.

The second response to warming we consider is changes in atmospheric cloud-radiative effects (ACREs). ACRE changes can result from both thermodynamic as well as dynamic changes [Stevens and Bony, 2013; Voigt and Shaw, 2015]. An important cloud response to warming is the rise of tropical high clouds that is expected from the fixed-anvil temperature hypothesis [Hartmann and Larson, 2002; Kuang and Hartmann, 2007; Zelinka and Hartmann, 2010]. Here we consider ACRE changes as a thermodynamic response in the sense that they change the energy balance of the atmosphere and demand a change in the meridional energy transport [Hwang et al., 2011]. The ACRE-induced energy transport can impact the latitude of maximum energy transport. The latitude of maximum energy transport occurs in the extratropics where storm tracks dominate the energy transport.

We investigate the connection between moist thermodynamic and dynamic responses to uniform warming using prescribed sea surface temperature (SST) aquaplanet models.
Aquaplanet models are an important part of the model hierarchy and provide an idealized setting (comprehensive moist physics with simplified lower boundary condition) for understanding the circulation response to global warming [Blackburn et al., 2013; Medeiros et al., 2015]. CMIP5 aquaplanet model simulations exhibit a robust poleward expansion of the tropics and poleward shift of the eddy-driven jet stream in response to uniform warming [Medeiros et al., 2015] consistent with the response in coupled-climate models with realistic boundary conditions [Vallis et al., 2015].

2. Data

We make use of the aquaControl and aqua4K CMIP5 prescribed SST aquaplanet model experiments [Taylor et al., 2012]. Most models prescribed the aquaControl SST following the QOBS distribution of Neale and Hoskins [2001], however the FGOALS-g2 and MIROC5 models used the CTRL distribution [Medeiros et al., 2015]. Aqua4K mimics global warming by uniformly increasing the aquaControl SST by 4K. We use monthly and zonally-averaged zonal wind (ua), temperature (ta), specific humidity (hus), radiation (rlut, rlutcs, rlus, rldscs, rsut, rsutcs, rsus, rsds, rsdscs) and surface flux (hfls, hfss) data from ten CMIP5 models (CCSM4, CNRM-CM5, FGOALS-g2, FGOALS-s2, HadGEM2-A, IPSL-CM5A-LR, MIROC5, MPI-ESM-LR, MPI-ESM-MR, MRI-CGCM3). The data are interpolated onto a common latitude grid with 0.1° resolution. Since the aquaplanet climate is equatorially symmetric, data from the Northern and Southern hemispheres are averaged together. We quantify inter-model spread as ± 1 standard deviation. Maximum values are obtained by a quadratic fit using the maximum grid point and two adjacent points.
3. Results

We begin by documenting shifts of the Hadley cell edge and eddy-driven jet stream position in response to uniform SST warming by 4K. We define the edge of the Hadley cell as the latitude where the zonal-mean zonal wind transitions from tropical easterlies to extratropical westerlies at 925 hPa, i.e., the latitude of zero zonal wind. The eddy-driven jet stream position is defined as the latitude of maximum zonal-mean zonal wind at 925 hPa. The Hadley cell edge and jet stream position in aquaControl are significantly correlated ($r = 0.96$, $p = 0.00$) and a linear regression accounts for 92% of the model spread (Fig. 1a, solid black line). A similar relationship occurs for aqua4K ($r = 0.95$, $p = 0.00$, $r^2 = 0.90$, Fig. 1a, dashed black line).

All ten CMIP5 aquaplanet models exhibit a poleward shift of the Hadley cell edge (Fig. 1b, y-axis) and jet stream position (Fig. 1c, y-axis) in response to uniform warming. Our results are consistent with alternative metrics of the Hadley cell edge, e.g. the latitude where the mean-meridional streamfunction vertically integrated between 700 and 300 hPa equals zero [see Fig. 5 of Medeiros et al., 2015] and jet stream position, e.g. the latitude where zonal-mean zonal wind averaged between 850 and 700 hPa is maximum [see Fig. 6 of Medeiros et al., 2015].

In the following subsections we provide examples of how moist thermodynamic changes can be used to infer circulation shifts in response to uniform warming. We focus on two thermodynamic changes in response to uniform warming: 1) increased specific humidity following CC scaling and 2) ACRE changes.
3.1. Circulation changes predicted from CC scaling

Following Held and Soden [2006] we assume changes in near-surface specific humidity $q$ exhibit CC scaling in response to warming, i.e.,

$$\delta q \approx \alpha \delta T q$$

(1)

where $\alpha = L/RT^2 \approx 0.07 K^{-1}$, $L$ is the latent heat of vaporization, $R$ is the dry gas constant, $T$ is temperature, and $\delta T = 4 K$. The change in specific humidity affects two important thermodynamic variables: near-surface or sub-cloud (925 hPa) moist entropy, $s_b = c_p \ln \theta_e \approx c_p \ln(\theta + Lq/c_p)$, and moist-static energy, $m_s = c_p T + Lq + \Phi$, where $c_p$ is the specific heat at constant pressure, $\theta_e$ and $\theta$ are the near-surface equivalent potential temperature and potential temperature, respectively, and $\Phi$ is geopotential.

Following CC scaling, the near-surface moist entropy and moist-static energy responses to uniform warming are

$$\delta s_b \approx c_p \theta_e \delta \theta_e \approx \frac{\delta T (c_p + \alpha Lq)}{\theta_e}$$

(2)

$$\delta m_s \approx c_p \delta T + L \delta q \approx \delta T (c_p + \alpha Lq).$$

(3)

These responses are largest in the tropics implying an increased meridional gradient, i.e.,

$$\frac{1}{a} \frac{\partial \delta s_b}{\partial \phi} \approx \alpha \delta T L \frac{1}{a} \frac{\partial q}{\partial \phi} \left( \frac{\theta_e}{\theta_e^2} \right) \approx \alpha \delta T L \frac{q}{a} \frac{\partial T}{\partial \phi}$$

(4)

$$\frac{1}{a} \frac{\partial \delta m_s}{\partial \phi} \approx \alpha \delta T L \frac{1}{a} \frac{\partial q}{\partial \phi} \approx \alpha^2 \delta T L \frac{q}{a} \frac{\partial T}{\partial \phi}$$

(5)

where $a$ is the radius of the Earth and we have assumed constant relative humidity with latitude in the last step, which is a reasonable approximation for aquaControl (Supplementary Fig. 1a). We neglect $-Lq \partial \theta_e / \partial \phi / \theta_e^2$ in (4) because specific humidity dominates the equivalent potential temperature gradient in low latitudes (Supplementary Fig. 1b).
These thermodynamic responses to uniform warming can be connected to dynamical responses via two frameworks: 1) quasi-equilibrium dynamics and 2) mixing-length theory.

In both cases we make predictions of circulation shifts in response to uniform warming and compare them to the simulated response (aqua4K-aquaControl).

Quasi-equilibrium connects thermally-direct circulations to the region of supercritical near-surface moist entropy and constrains the vertical structure of the atmosphere to be moist adiabatic [Emanuel et al., 1994]. The moist adiabatic assumption is reasonable for Earth’s tropics and subtropics [Korty and Schneider, 2007] and quasi-equilibrium is a reasonable approximation over the tropical oceans [Brown and Bretherton, 2007] and in Monsoon regions [Boos and Emanuel, 2009; Nie et al., 2010].

According to quasi-equilibrium dynamics, the balanced component of the surface zonal wind $u_s$ is related to the degree of supercriticality of the near-surface moist entropy $s_b$, i.e.,

$$u_s = \frac{(T_s - T_t)}{fa} \frac{\partial}{\partial \phi} (s_b - s_{crit})$$

(6)

where $s_{crit}$ is the critical value of moist entropy, $T_s$ and $T_t$ are the temperatures at the surface and tropopause, respectively, and $f$ is the Coriolis parameter [see equation (18) in Emanuel, 1995]. The tropopause is defined following the World Meteorological Organization’s definition. The critical value of moist entropy is connected to the onset of a thermally direct circulation. Here we estimate the critical value following equation (11) in Emanuel [1995], i.e.,

$$s_{crit} = c_p \ln(\theta_{e,crit}) = c_p \ln \left\{ \theta_{em} \exp \left( -\frac{\Omega^2 a^2}{2c_p (T_s - T_t)} \frac{(\cos^2 \phi_m - \cos^2 \phi)^2}{\cos^2 \phi} \right) \right\}$$

(7)
where $\theta_{em}$ is the maximum equivalent potential temperature located at latitude $\phi_m$ and $
abla$ is the rotation rate. According to quasi-equilibrium dynamics the multi-model mean edge of the Hadley cell is located where $s_b - s_{crit}$ is minimum, i.e., at 22.5°, as compared to its actual location of 24.6° in aquaControl.

The surface zonal wind response to uniform warming can be decomposed as

$$
\delta u_s = \frac{\delta(T_s - T_t)}{fa} \frac{\partial}{\partial \phi} (s_b - s_{crit}) + \frac{(T_s - T_t)}{fa} \frac{\partial}{\partial \phi} \delta s_b - \frac{(T_s - T_t)}{fa} \frac{\partial}{\partial \phi} \delta s_{crit}
$$

[see (6)]. We focus on the predicted zonal-wind response due to changes in moist entropy following CC scaling [see (4)], which dominate in the tropics and subtropics (Supplementary Fig. 1c), i.e.,

$$
\delta u_s \approx \frac{(T_s - T_t)}{fa} \frac{\partial}{\partial \phi} \delta s_b \approx \frac{(T_s - T_t)}{fa} \alpha \delta T \frac{L}{\theta_e} \frac{\partial q}{\partial \phi} \approx \frac{(T_s - T_t)}{fa} \alpha^2 \delta T \frac{L}{\theta_e} \frac{\partial T}{\partial \phi} < 0.
$$

This predicted decrease in zonal wind enhances tropical easterlies and shifts the Hadley cell edge poleward.

The predicted shift of the Hadley cell edge in response to uniform warming following CC scaling, quasi-equilibrium dynamics and using only information from aquaControl, is poleward when the predicted zonal-wind response is added to the aquaControl zonal wind (3.2°±0.6°, Fig. 1b). The predicted poleward shift overestimates the simulated (aqua4K-aquaControl) zonal wind response and Hadley cell edge shift (1.6°±0.3°, Fig. 1b). The predicted response is not correlated with the simulated response across the models.

Given the predicted Hadley cell edge for the warmed climate, we predict the jet stream position for the warmed climate using the linear relationship between Hadley cell edge and jet position in aquaControl (Fig. 1a, top left). Consistent with the linear relationship, a poleward shift of the edge of the Hadley cell following CC scaling leads to a poleward...
shift of jet stream position $(3.8^\circ \pm 0.7^\circ$, Fig. 1c). Once again the predicted poleward shift generally overestimates the aqua4K-aquaControl response $(2.8^\circ \pm 0.7^\circ$, Fig. 1c) and the predicted response is not correlated with the simulated response across the models.

Changes in specific humidity following CC scaling also affect the near-surface moist-static energy gradient, which is connected to the kinematic diffusivity $D$ and vertically-integrated meridional transport of moist-static energy $\langle vm \rangle$ via mixing-length theory, i.e., $\langle vm \rangle \approx -(D/a) \partial m_s/\partial \phi$ where $\langle \cdot \rangle$ represents a vertical integral between the surface and 10 hPa weighted by the acceleration due to gravity. The diffusivity in aquaControl, i.e., $D \equiv -(1/a)\langle vm \rangle/(\partial m_s/\partial \phi)$, involves midlatitude $(38.7^\circ)$ and high-latitude $(65.5^\circ)$ maxima (Fig. 2a, vertical black lines). The diffusivity maxima are related to latent and dry-static energy transport, respectively (Supplementary Fig. 2a).

Following mixing-length theory, changes in moist-static energy transport can be decomposed as

$$\delta \langle vm \rangle \approx -\frac{\delta D}{a} \frac{\partial m_s}{\partial \phi} - \frac{D}{a} \frac{\delta m_s}{\partial \phi}. \quad (10)$$

In contrast to previous studies that examined heat transport changes assuming fixed diffusivity, i.e., $\delta D \approx 0$, and hence circulation [e.g. Frierson et al., 2007; Kang et al., 2009], here we are interested in diffusivity changes as a proxy for the circulation response to uniform warming. Assuming $\delta \langle vm \rangle \approx 0$, i.e., compensation occurs between dry-static and latent energy transport [see Supplementary Fig. 2b, Frierson et al., 2007; Manabe et al., 1965, 1975; Held and Soden, 2006; Hwang et al., 2011], and following CC scaling [see (5)] we obtain

$$\delta D \approx -\frac{\partial \delta m_s/\partial \phi}{\partial m_s/\partial \phi} D \approx -\alpha \delta TL \frac{\partial q/\partial \phi}{\partial m_s/\partial \phi} D \approx -\alpha^2 \delta TLq \frac{\partial T/\partial \phi}{\partial m_s/\partial \phi} D < 0. \quad (11)$$
Thus, CC scaling predicts diffusivity will decrease in response to uniform warming.

The predicted latent and dry-static energy transport responses to uniform warming following CC scaling and mixing-length theory are:

\[ \delta \langle L v q \rangle \approx - \frac{L}{a} (\delta D + \alpha \delta T D) \frac{\partial q}{\partial \phi} \approx - \frac{L}{a} (\delta D + \alpha \delta T D) \alpha q \frac{\partial T}{\partial \phi}, \]

\[ \delta \langle v s \rangle \approx - \frac{\delta D}{a} \frac{\partial s}{\partial \phi} \approx - \frac{c_p}{a} \frac{\delta D}{a} \frac{\partial T}{\partial \phi}, \]

which satisfy \( \delta \langle v m \rangle \approx 0 \) assuming (11). We note that a diffusive latent energy transport prediction is not accurate for the deep tropics, however we are interested in changes in the latitude of maximum transport, which occur in midlatitudes where the diffusive approximation is valid. We label the terms in (12)-(13) proportional to \( \delta D \) as dynamic transport responses and those proportional to \( \delta T \) as thermodynamic transport responses.

Note there is no predicted thermodynamic dry-static energy transport response to uniform warming (there is no temperature gradient change). We cannot make predictions assuming compensation and fixed diffusivity in response to uniform warming because \( \delta \langle v m \rangle = \delta D = 0 \rightarrow \partial \delta m_s / \partial \phi = 0 \) [see (10)].

The predicted diffusivity decrease in response to uniform warming following CC scaling is largest in high latitudes (Fig. 2a, red line). However, the largest fractional decrease occurs in the subtropics and high latitudes (Fig. 2b, red line). The predicted subtropical decrease leads to a poleward shift of the latitude of maximum midlatitude diffusivity (0.4°±0.2°, Fig. 2c). However, the predicted shift underestimates the aqua4K-aquaControl response (3.5°±0.8°, Fig. 2d) and the two responses are not significantly correlated. The underestimate occurs because the aqua4K-aquaControl diffusivity increases in midlatitudes (Fig. 2a,b, black lines) enhancing the poleward shift. The predicted diffu-
sivity decrease in high latitudes leads to an equatorward shift of maximum high-latitude diffusivity (-0.4°±0.3°, Fig. 2c). This prediction is not accurate: the simulated high-latitude diffusivity shifts poleward in most models (1.8°±1.7°, Fig. 2d). The discrepancy occurs because the aqua4K-aquaControl diffusivity does not change in high-latitudes (Fig. 2a,b, black line) instead the largest decrease occurs further south, which leads to the poleward shift. We discuss the discrepancy between the predicted and simulated high-latitude diffusivity response below.

The predicted dynamic latent-energy transport decreases in response to uniform warming (Fig. 3a, solid red line) and shifts the latitude of maximum latent energy transport poleward in most models (0.2°±0.2°, Fig. 3c), which agrees with the aqua4K-aquaControl response (0.8°±0.5°, Fig. 3c). However, this is partly offset by increased thermodynamic transport (Fig. 3a, dashed red line). The predicted dynamic dry-static energy transport decreases in response to uniform warming (Fig. 3b, solid red line) and shifts the latitude of maximum dry-static energy transport poleward (0.6°±0.2°, Fig. 3d). However, the aqua4K-aquaControl dynamic dry-static energy transport response increases in midlatitudes (Fig. 3b, black solid line) and shifts the latitude of maximum transport equatorward (-2.2°±0.7°, Fig. 3d). The aqua4K-aquaControl thermodynamic dry-static energy transport response (Fig. 3b, dashed black line), which is not considered in the prediction [see (13)], leads to a poleward shift of the latitude of maximum dry-static energy transport.

The discrepancy between predicted and simulated diffusivity (Fig. 2a,b red versus black lines) and energy transport (Fig. 3a,b, red versus black lines) responses suggests a missing component of the mixing-length theory prediction. The difference between the simulated
and predicted diffusivity response (Supplementary Fig. 3a, black line) is due to changes in moist-static energy transport (assumed to be zero in the prediction) and deviations of the moist-static energy gradient response from CC scaling in response to uniform warming. The simulated increase of moist-static energy transport in response to warming leads to increased diffusivity, particularly in high latitudes (Supplementary Fig. 3a, red line). Deviations of the moist-static energy gradient response from CC scaling leads to increased mid-latitude diffusivity (Supplementary Fig. 3a, blue line), which dominates the discrepancy between the simulated and predicted dynamic latent and dry static energy transport responses (Supplementary Fig. 3b, solid lines). The discrepancy between the simulated and predicted thermodynamic latent and dry static energy transport responses is dominated by deviations of the moist-static energy gradient response from CC scaling. The change in dry static energy gradient (dominated by temperature) and the change in latent energy gradient both produce meridional dipoles of energy transport (Supplementary Fig. 3b, dashed lines). Meridional dipoles of latent energy transport occur in response to internal eddy-zonal flow feedbacks [Boer et al., 2001; Lorenz and Hartmann, 2001, 2003; Thompson and Woodworth, 2014], thus these feedbacks might be a missing component of the predictions.

3.2. Circulation changes inferred from ACRE response

The second response to warming we consider is ACRE changes. ACRE is defined as the difference of CRE at the top of the atmosphere and surface, including both longwave and shortwave components, i.e., \( ACRE = (F_{\text{toa}} - F_{\text{toa} \text{clr}}) - (F_{\text{sfc}} - F_{\text{sfc} \text{clr}}) \) where \( F \) is the total radiative flux, \( F_{\text{clr}} \) is the clear-sky radiative flux, \( sfc \) refers to the surface, and \( toa \)
refers to the top of the atmosphere. The radiative fluxes are defined as positive in the downward direction. Here we assess how ACRE changes in response to uniform warming affect moist-static energy transport, in particular its impact on the latitude of maximum transport. In contrast to the previous subsection where we made predictions following CC scaling solely based on information from aquaControl, the predictions made here use information from both aquaControl and aqua4K, i.e., the ACRE response to uniform warming is taken as given.

The ACRE response to uniform warming generally increases in the tropics and robustly decreases in high latitudes (Fig. 4a). (We removed the global average but that does not affect our conclusions.) Longwave radiation dominates the ACRE response (Supplementary Fig. 4a). We note that ACRE changes are an indirect measure of the cloud-radiative response. We confirmed the ACRE changes for the MPI-ESM-LR and IPSL-CM5A-LR models agree with the cloud-radiative response diagnosed from forward partial radiative perturbation calculations following Weatherald and Manabe [1988] (see Supplementary Fig. 4b).

The ACRE changes can be converted into a meridional moist-static energy transport response following Hwang and Frierson [2011], i.e.,

$$\delta F_{ACRE} = \left[ \int_{\phi - \pi/2}^{\phi + \pi/2} a^2 \cos \phi \delta ACRE \, d\lambda d\phi + \int_{\phi}^{-\pi/2} a^2 \cos \phi \delta ACRE \, d\lambda d\phi \right] / 2. \quad (14)$$

The ACRE changes increase poleward energy transport in both hemispheres (Fig. 4b).

When the ACRE-induced energy transport response is added to moist-static energy transport in aquaControl, there is a poleward shift of the latitude of maximum energy transport in all but one model (0.63° ± 0.40°, Fig. 4c).
The ACRE-induced poleward shift of the latitude of maximum energy transport is consistent with the poleward shift for aqua4K-aquaControl (0.53°±0.31°, Fig. 4c). However, the predicted transport shift is smaller than the predicted jet shift (Fig. 1c) most likely because ACRE changes are small in midlatitudes. Previous work has shown height-dependent midlatitude cloud-radiative changes in response to uniform warming, which do not project onto vertically-integrated ACRE, shift the jet poleward.

4. Conclusion and Discussion

A complete understanding of the response to anthropogenic climate change must involve an understanding of the linkages between thermodynamic and dynamic responses. Here, using physical arguments and aquaplanet simulations, we linked moist thermodynamic and dynamic responses to uniform warming. We focused on CMIP5 aquaplanet simulations because they exhibit robust poleward circulation shifts in responses to uniform warming [Medeiros et al., 2015] and therefore provide an idealized setting for understanding the circulation response in coupled-climate model simulations with realistic boundary conditions. Our results build upon previous work that connected thermodynamic and dynamic responses to global warming a posteriori [e.g. Lu et al., 2007; Vallis et al., 2015] and used dry dynamical core simulations to investigate circulation responses [e.g. Butler et al., 2010; Mbengue and Schneider, 2013; Lu et al., 2014].

We focused on two moist thermodynamic responses to uniform warming and what they tell us about meridional shifts of the circulation. The first is increased specific humidity with warming following CC scaling. According to quasi-equilibrium dynamics, the increased meridional gradient of sub-cloud moist entropy in response to uniform warming
following CC scaling amplifies tropical easterlies and shifts the edge of the Hadley cell, defined here as the latitude of zero near-surface zonal-mean zonal wind, poleward. The control-climate relationship between the Hadley cell edge and jet position predicts the jet will shift poleward following CC scaling. While quasi-equilibrium dynamics is an approximate framework, we have shown it predicts a robust direction for the circulation shift in response to uniform warming (e.g., it predicts a poleward not an equatorward shift) and provides an explanation for the circulation shift (related to increased moist-entropy gradients following CC scaling).

According to mixing-length theory, the increased meridional gradient of moist-static energy in response to uniform warming following CC scaling decreases diffusivity assuming moist-static energy transport changes are small. The diffusivity decrease is largest in the subtropics and high latitudes and shifts the latitude of maximum midlatitude diffusivity (related to moisture transport) poleward and latitude of maximum high latitude diffusivity (related to dry-static energy transport) equatorward. The diffusivity changes can be connected to dynamic energy transport responses that lead to poleward shifts of the latitude of maximum latent and dry-static energy transport in response to uniform warming.

Discrepancies exist between the simulated and mixing-length theory predicted responses, in particular, simulated diffusivity actually increases in midlatitudes and does not change significantly in high latitudes in response to uniform warming. The increased simulated diffusivity is due to increased moist-static energy transport (e.g., due to ACRE changes), which is not accounted for in the prediction, and to deviations of the moist-static...
energy gradient response from CC scaling in response to uniform warming. The differences between the simulated and predicted thermodynamic transport responses involve meridional dipoles that reflect changes in temperature and moisture gradients. Meridional dipoles of energy transport have been shown to occur in response to eddy-zonal flow feedbacks [Boer et al., 2001; Lorenz and Hartmann, 2001, 2003; Thompson and Woodworth, 2014]. These feedbacks, which are not included in the prediction, might be important for determining the full magnitude of the circulation response to warming.

The second moist thermodynamic response to uniform warming examined here is changes in ACRE and its impact on moist-static energy transport. ACRE mostly increases in the tropics and robustly decreases in high latitudes in response to uniform warming. The inferred meridional moist-static energy transport response is poleward in most models and maximizes poleward of the latitude of maximum energy transport in the control climate. Consequently, the latitude of maximum energy transport shifts poleward in all but one CMIP5 aquaplanet model. Our results support previous work that has shown the cloud radiative response to warming induces a poleward jet shift [Voigt and Shaw, 2015; Ceppi and Hartmann, 2016] and contributes to model spread in moist-static energy transport responses [Hwang et al., 2011].

The moist thermodynamic-dynamic links examined here suggest circulation shifts in response to warming may be fundamentally related to moisture gradients in the current climate and ultimately to temperature gradients assuming fixed relative humidity [e.g. eqns. (9), (11), (12), (13)]. They occur even when the warming perturbation is spatially uniform. The aquaplanet responses to uniform warming are correlated with meridional
temperature gradients in the control climate (Supplementary Fig. 5), highlighting a po-
tential emergent constraint on the circulation response to uniform warming. Additional
research is needed to assess the connection across an ensemble of coupled-climate models
with realistic boundary conditions to determine if a robust constraint emerges.

The circulation shifts predicted from the moist thermodynamic changes and dynamical
frameworks considered here are approximate. While they correctly predict the direction
of multi-model-mean meridional shift of the circulation, they could not account for the
magnitude of the simulated responses. Furthermore, the predicted shifts were not sig-
nificantly correlated with the simulated shifts in most cases suggesting thermodynamic
changes alone are not sufficient to predict model spread. An assessment across a larger
range of models is needed. The results suggest that thermodynamic [Voigt and Shaw,
2015; Ceppi and Hartmann, 2016] and dynamic feedbacks [Lu et al., 2014] are likely im-
portant for determining the simulated circulation responses to warming. Nevertheless
our results show moist thermodynamics can be combined with physical arguments and
dynamical frameworks to make predictions of circulation shifts in response to uniform
warming.

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Figure 1. (a) Latitude of eddy-driven jet stream versus latitude of the Hadley cell edge in aquaControl (circles) and aqua4K (squares). The aquaControl correlation ($r = 0.96$, $p = 0.00$), and linear regression ($r^2 = 0.92$, black line, regression coefficients top left) are statistically significant. Similar results are obtained for aqua4K ($r = 0.95$, $p = 0.00$, $r^2 = 0.89$, dashed line). (b) Simulated shift (aqua4K-aquaControl) of the Hadley cell edge versus the predicted shift in response to uniform warming. The correlation and p-value are in the top-left corner. (c) Same as (b) but for the jet shift predicted using the linear relationship in Fig. 1a.
Figure 2.  (a) Predicted (red) and simulated (aqua4K-aquaControl, black) diffusivity response to uniform warming.  (b) Same as in (a) but for percent change.  The vertical black lines indicate locations of diffusivity maxima in aquaControl.  (c) Simulated shift (aqua4K-aquaControl) of the latitude of maximum midlatitude diffusivity versus the predicted shift in response to uniform warming.  The correlation and p-value are in the top-left corner.  (d) Same as (c) but for the latitude of maximum high-latitude diffusivity.
Figure 3. Predicted (red) and simulated (aqua4K-aquaControl, black) dynamic (solid) and thermodynamic (dashed) (a) latent and (b) dry-static energy transport responses to uniform warming following mixing-length theory. Note there is no predicted change of thermodynamic dry static energy transport in response to uniform warming (no dashed red line in Fig. 3b). The vertical black lines indicate the position of maximum transport in aquaControl. (c) Simulated shift (aqua4K-aquaControl) of the latitude of maximum latent energy transport [see (12)] versus the predicted shift in response to uniform warming. The correlation and p-value are in the top-left corner. (d) Same as (c) but for the shift of the latitude of maximum dry-static energy transport [see (13)].
Figure 4. (a) ACRE response to uniform warming (aqua4K-aquaControl). (b) Moist-static energy transport response due to ACRE changes [see (14)]. The vertical black line indicates the position of maximum moist-static energy transport in aquaControl. (c) Simulated shift (aqua4K-aquaControl) of the latitude of maximum energy transport from the ACRE-induced energy transport response versus the predicted shift. The correlation and p-value are in the top-left corner.