A mechanism for the response of stationary circulations in the subtropics to global warming

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In collaboration with William R. Boos

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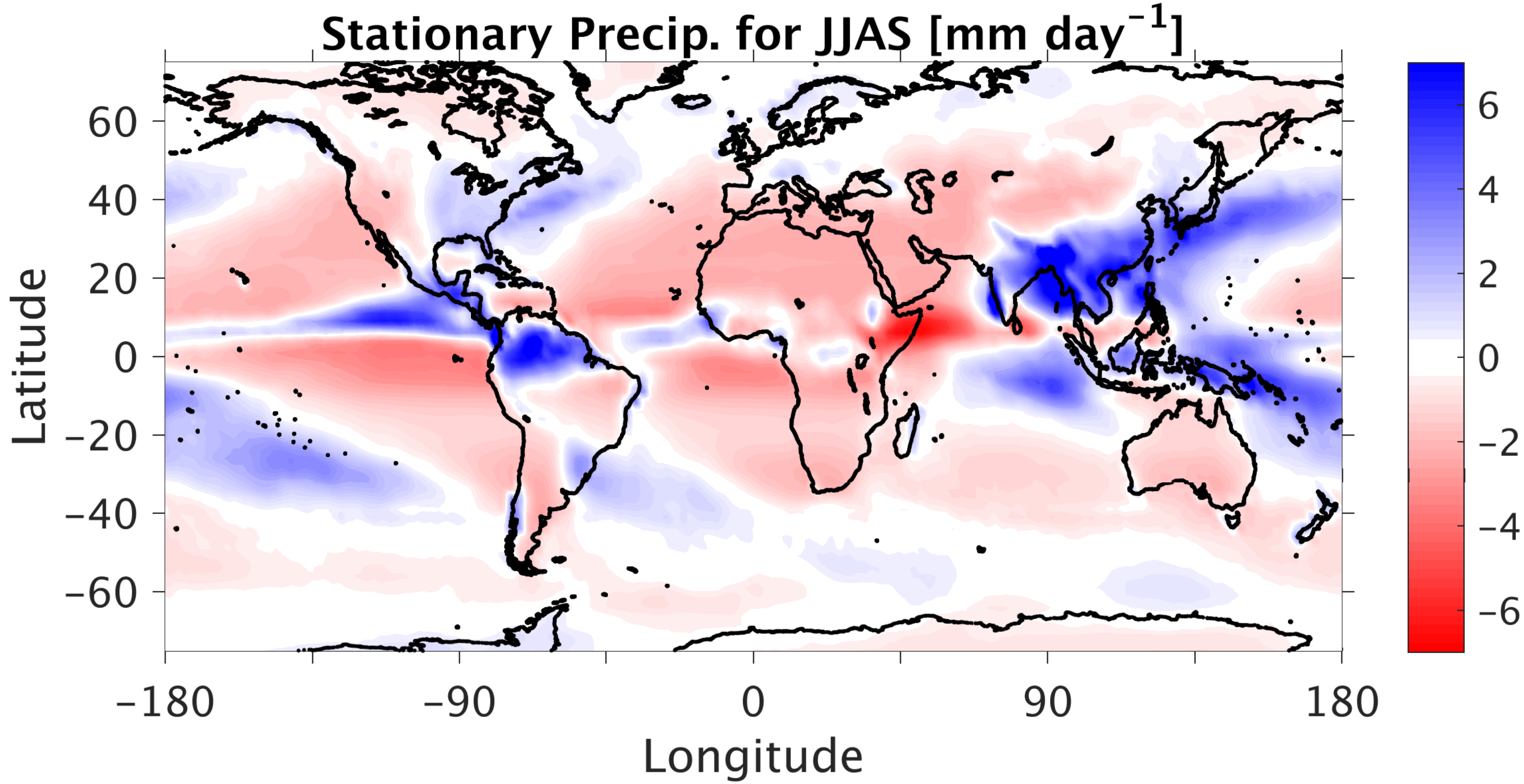
11/04/2016

Rainfall distribution over Asia and Africa shows large zonal asymmetries during boreal summer

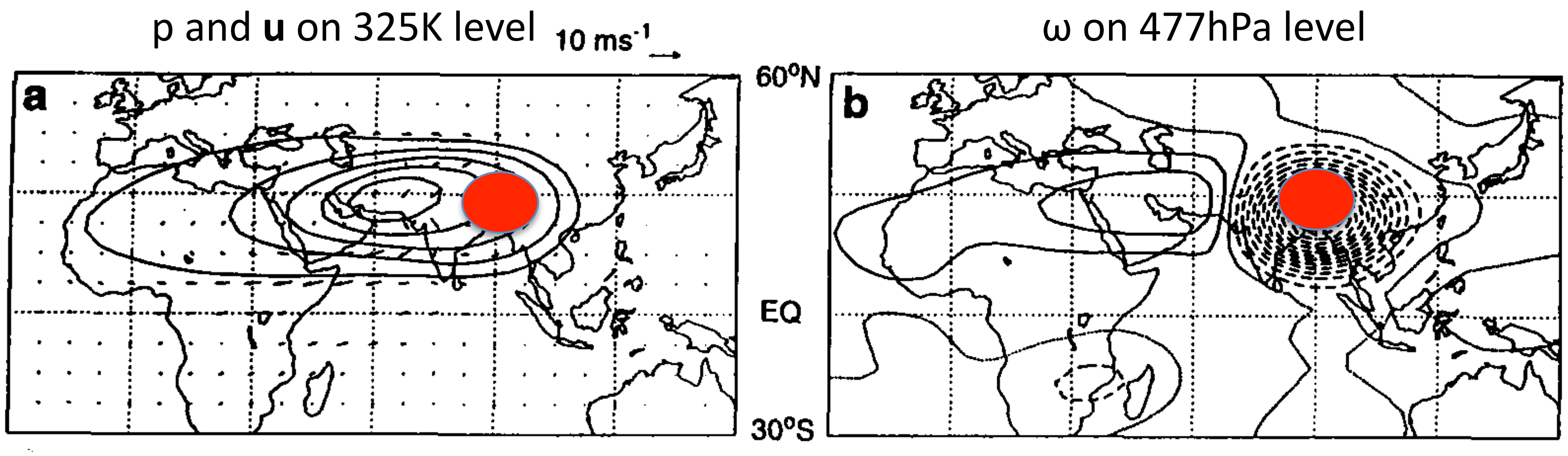


(.)* *defines deviation from zonal-mean*

CMIP5, 2006-2015, ensemble mean of 22 GCMs, RCP8.5

… consistent with dry linear studies

Gill-like circulation in a more comprehensive model



Linear integration about resting basic-state, forced with heating at 90°E, 25°N

Strong heating over South Asia from monsoon rainfall leads to enhanced dryness over Sahara.

(Rodwell and Hoskins, 1996)

Our goals

1. We quantify the sensitivity of the subtropical Rossby gyre to climate change in an idealized moist aquaplanet GCM, over a wide range of climate

2. We devise a mechanism for its climate sensitivity.

3. We diagnose relevance of this mechanism to climate variability in CMIP5 archive simulations.

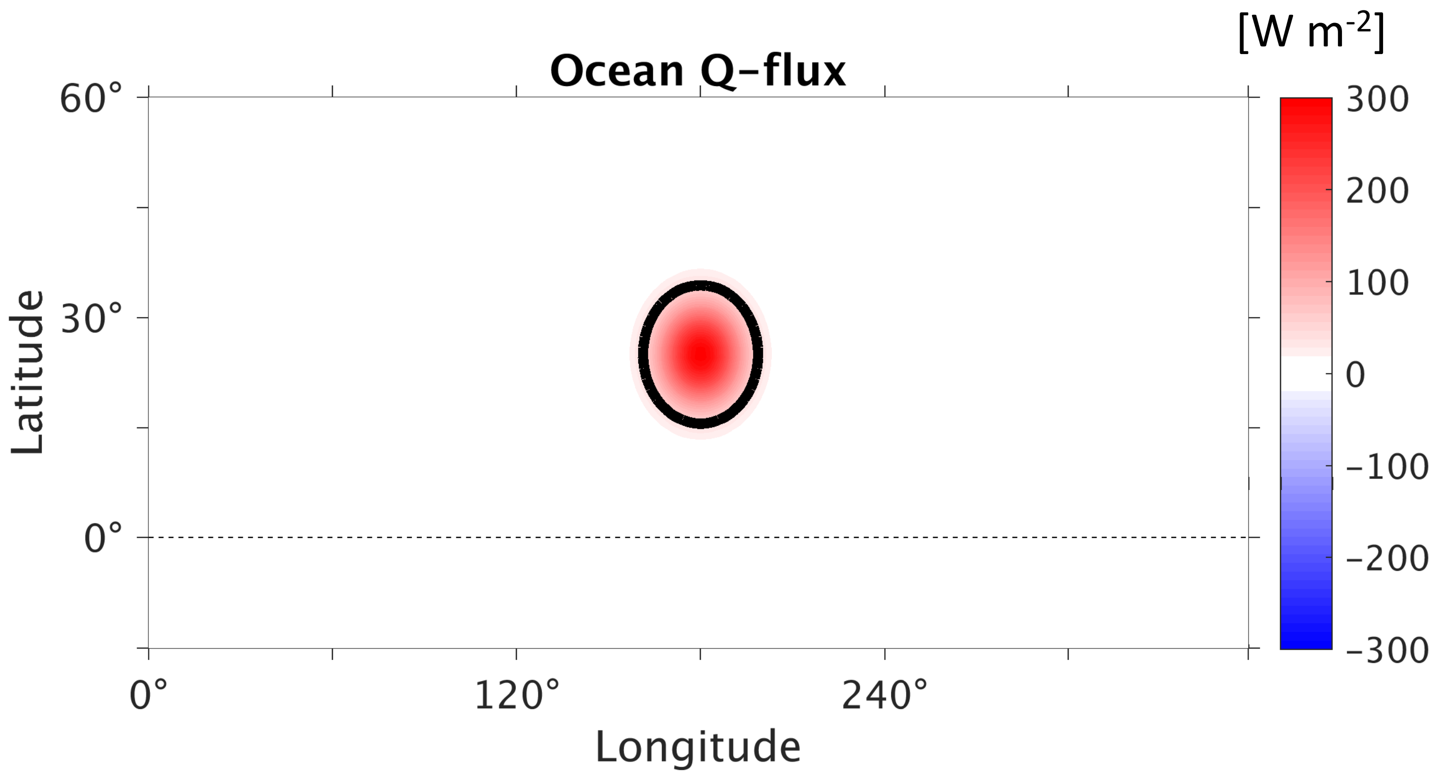
“Gill-like” forcing

Global warming experiment with idealized moist GCM (T85, 30 levels)

[Frierson et al., 2006; O’Gorman and Schneider, 2008]

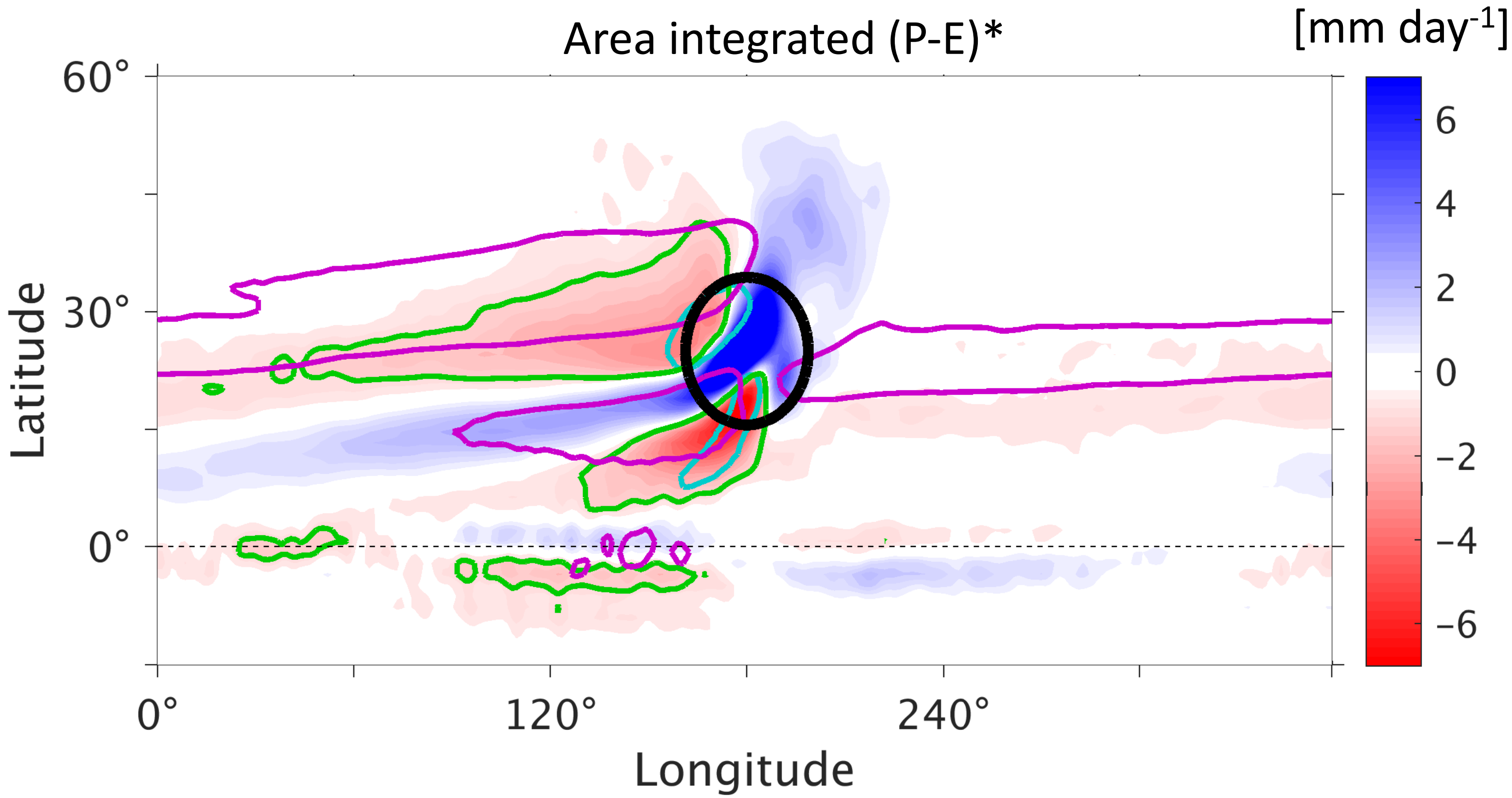
Surface conditions: Slab ocean, uniform thermal inertia and albedo

Forcing: Uniform insolation



(Levine and Boos, 2016; J. Clim.)

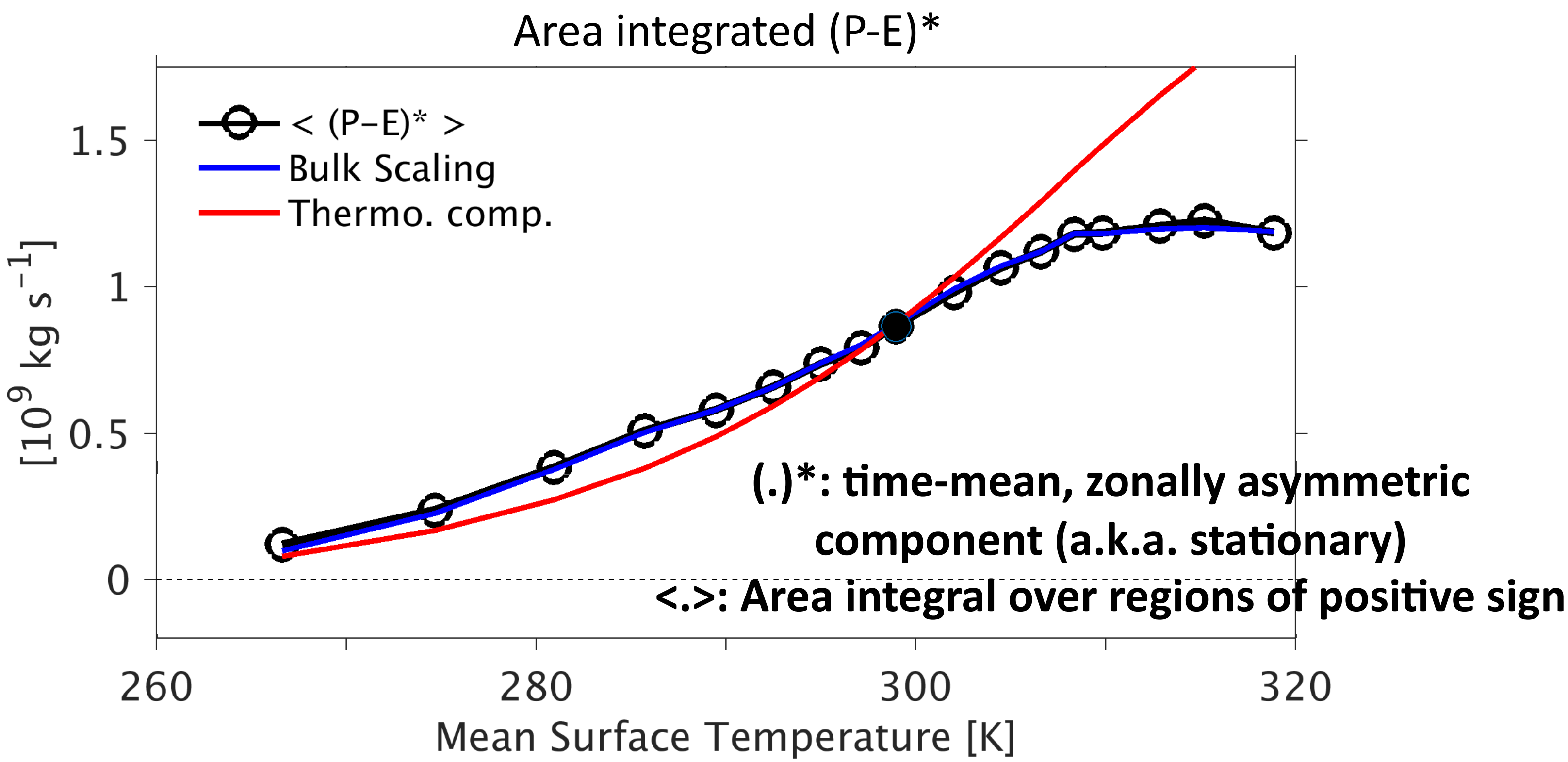
Wet zones near heating zone, enhanced dryness to the west.



Contours: **P-E ≤ -1.5 mm day^{-1} in cold (Ts=291K, cyan), reference (Ts=302K, green) and warm (Ts=311K, magenta) climates**

(Levine and Boos, 2016; J. Clim.)

Integrated changes in P-E with climate change

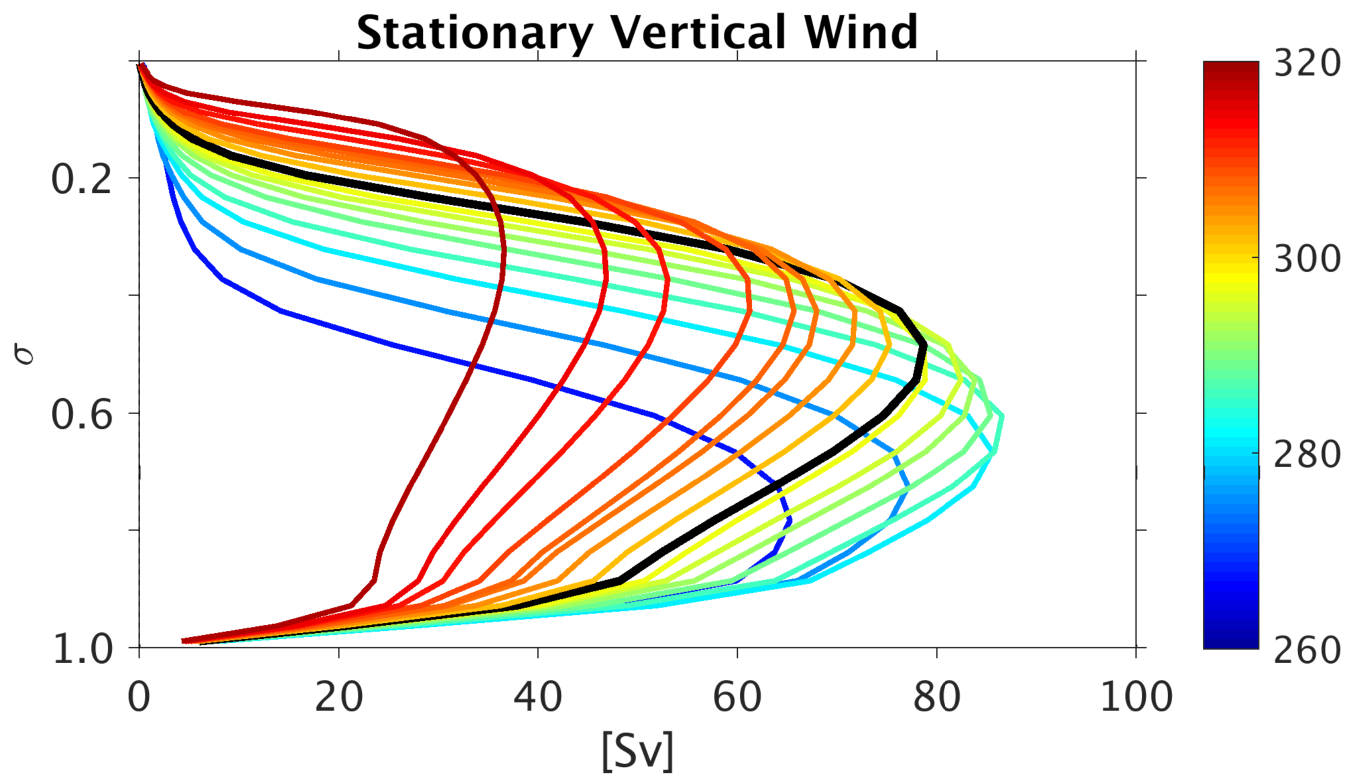


P-E averaged over areas where < P-E>0

P-E increases faster than CC in cold climates but slower in warm climates, implying strong modulation by dynamics

(Levine and Boos, 2016; J. Clim.)

Vertical velocity profile

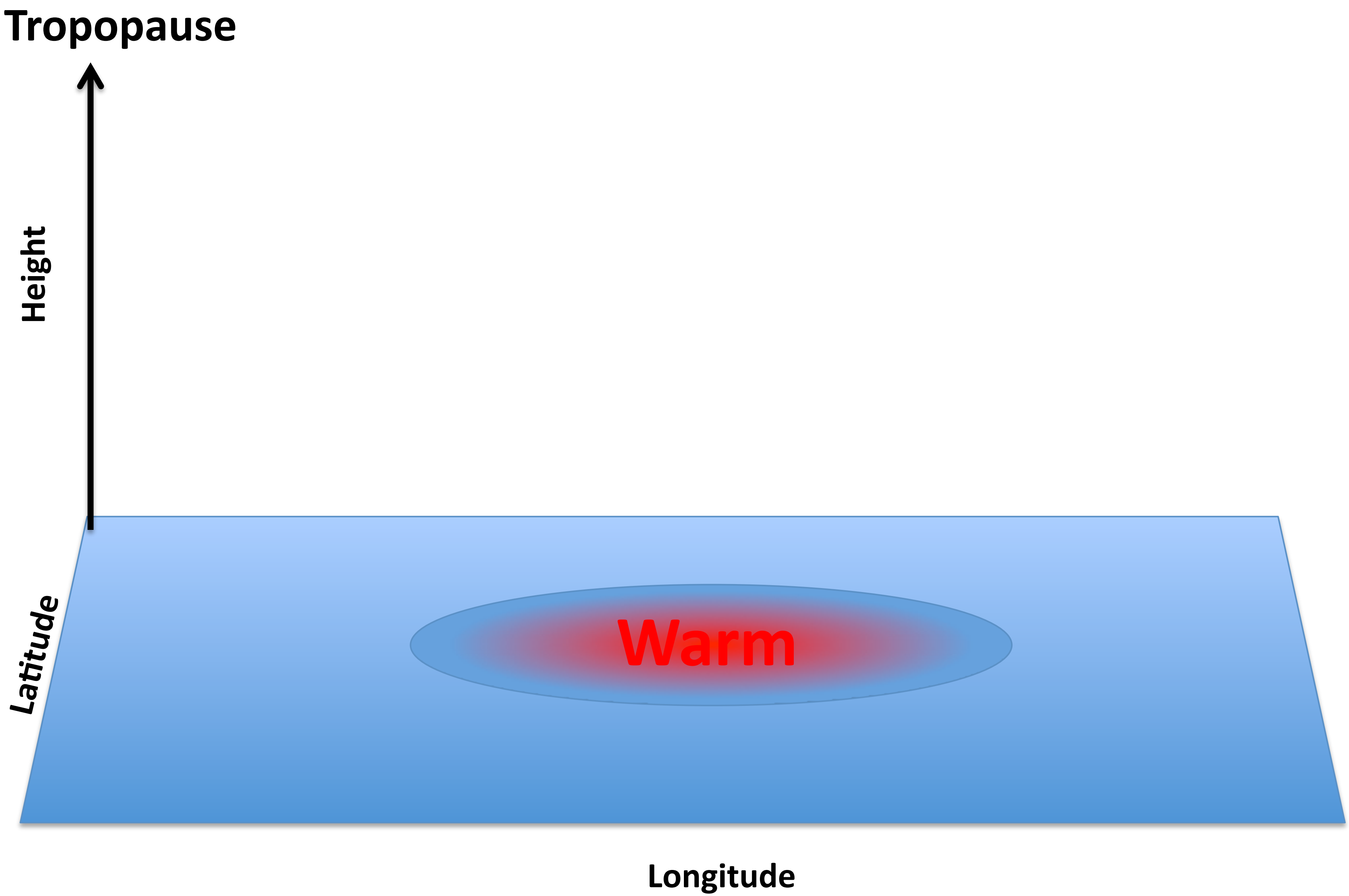


Vertical wind averaged over ascent regions

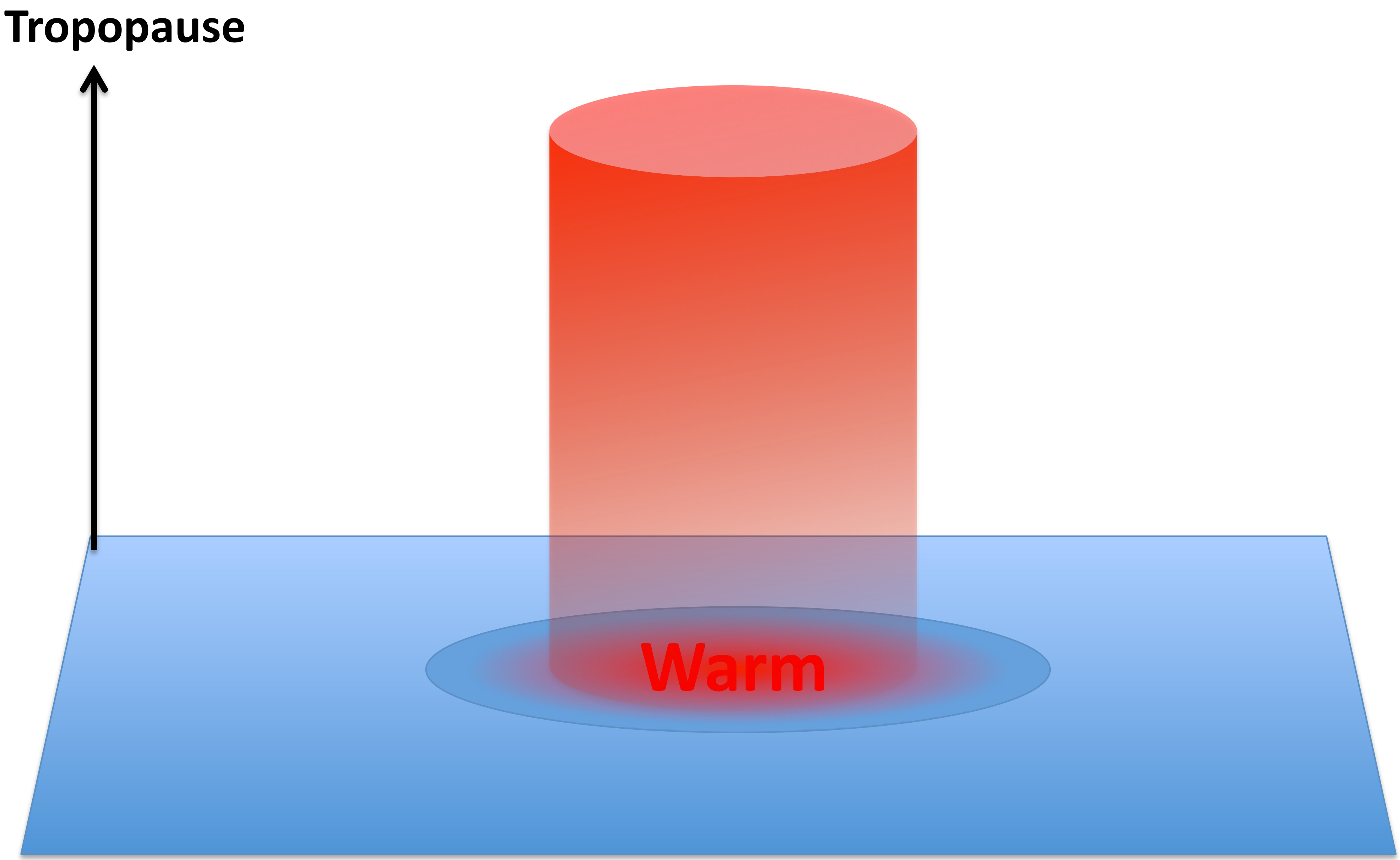
Circulation has a 1st baroclinic structure

(Levine and Boos, 2016; J. Clim.)

Conceptual model of circulation

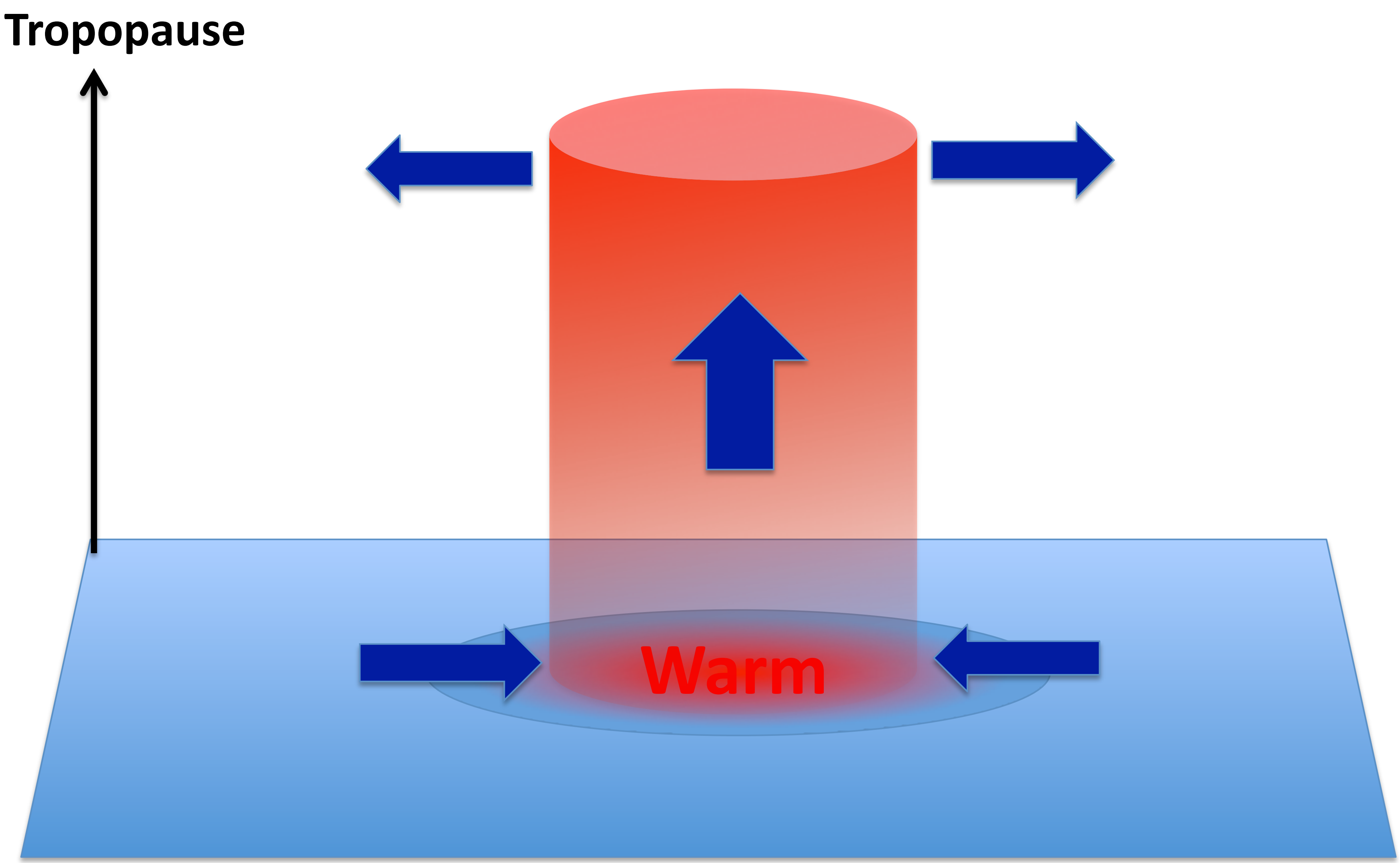


Conceptual model of circulation



Convection communicates near-surface perturbation to air column

Conceptual model of circulation



1st baroclinic circulation is set up in air column

1^{st} baroclinic mode theory

Dynamics can be linearized:

$$\delta(\mathbf{u}) \simeq \partial_{T_r}(\mathbf{u})(\delta T_r)$$

***wind mode:* sensitivity of wind to low-level temperature anomaly**

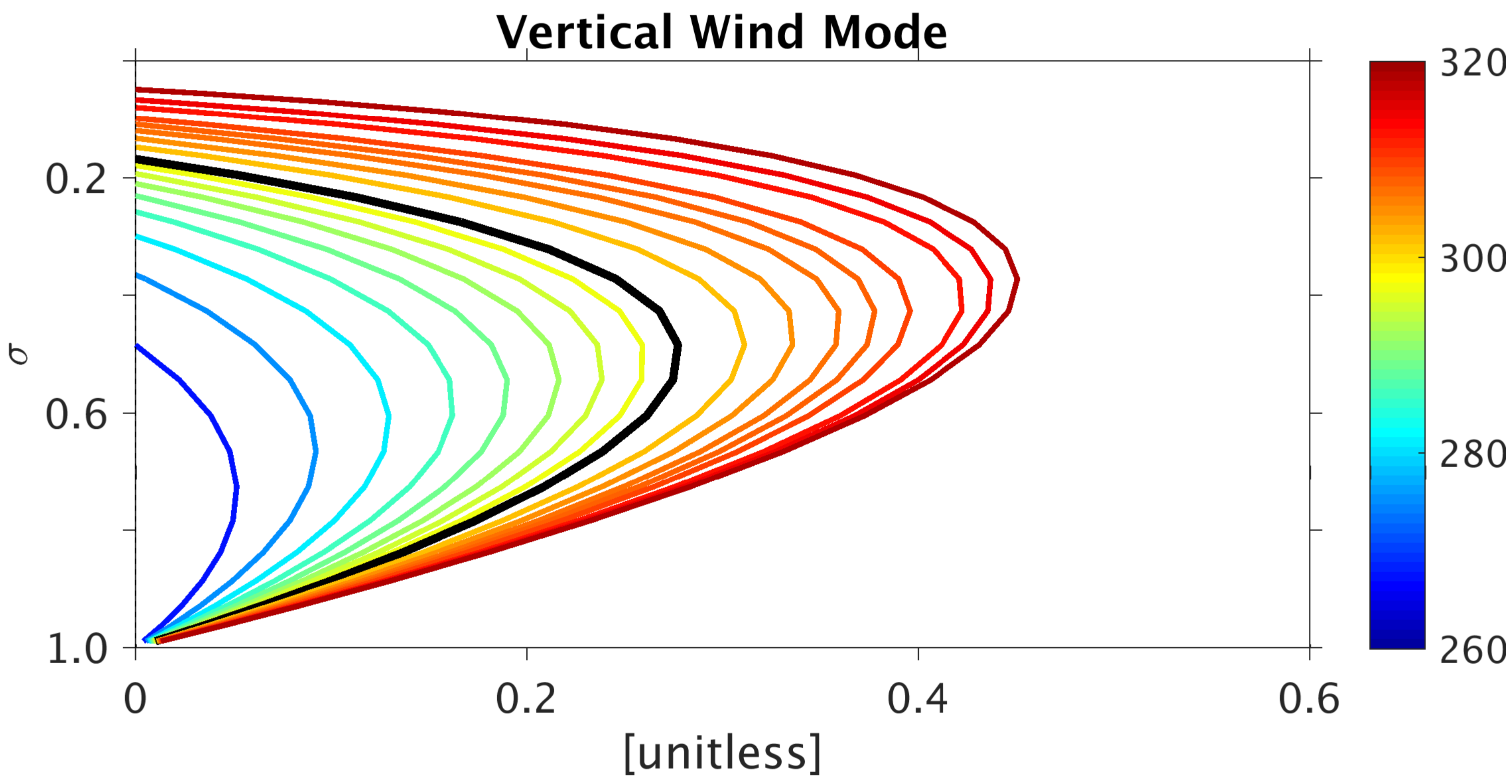
(e.g., Neelin and Zeng, 2000)

Wind mode depends only on tropical-mean lapse-rate and tropopause level

Wind mode varies with climate change!

Vertical wind becomes increasingly sensitive to low-level temperature anomalies as climate warms

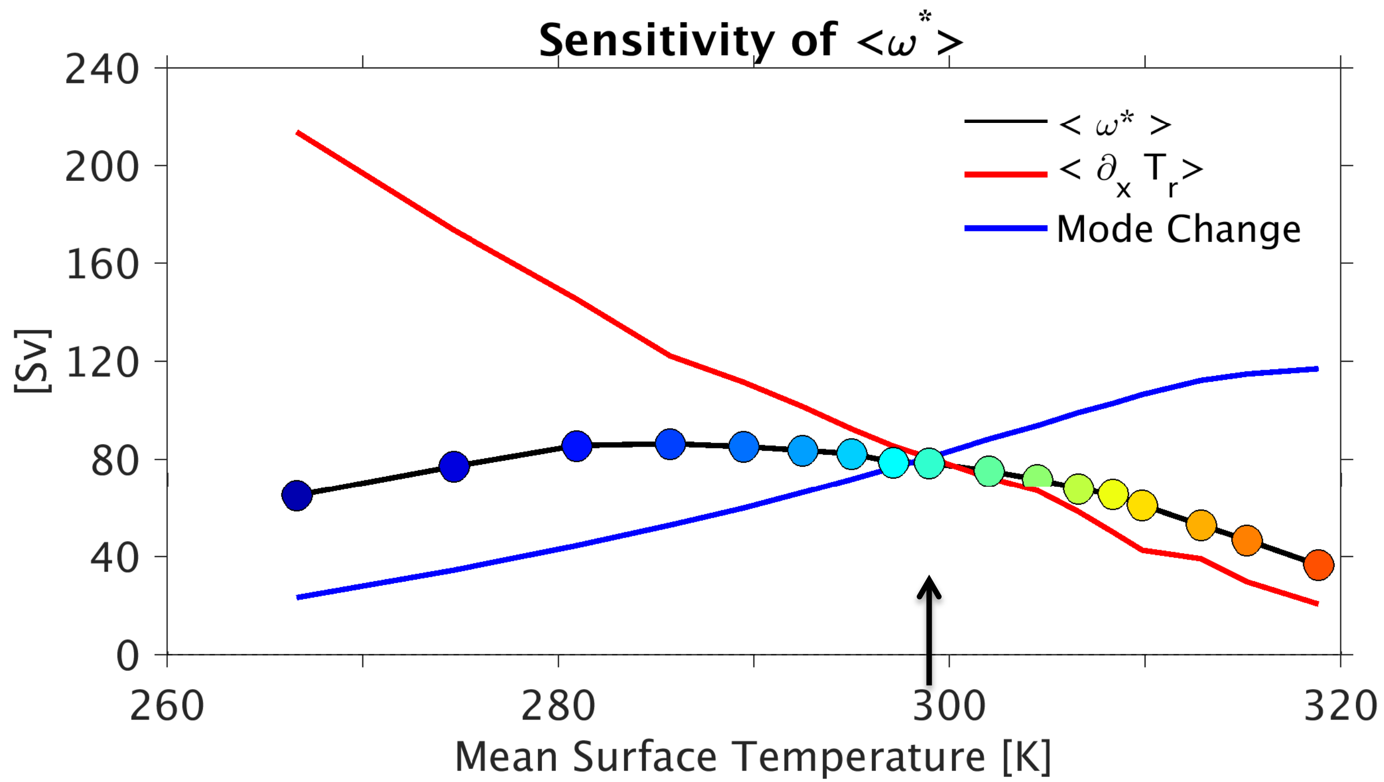
$$\delta\omega \simeq \partial_{T_r}\omega \times \delta T_r$$



Wind mode amplifies as climate warms

(Levine and Boos, 2016; J. Clim.)

Wind mode amplification results in non-monotonic variability of circulation



As climate warms, circulation:

*** strengthens in cold climates from deepening of 1st baroclinic mode.**

*** weakens in warm climates from weakening of low-level temperature anomalies.**

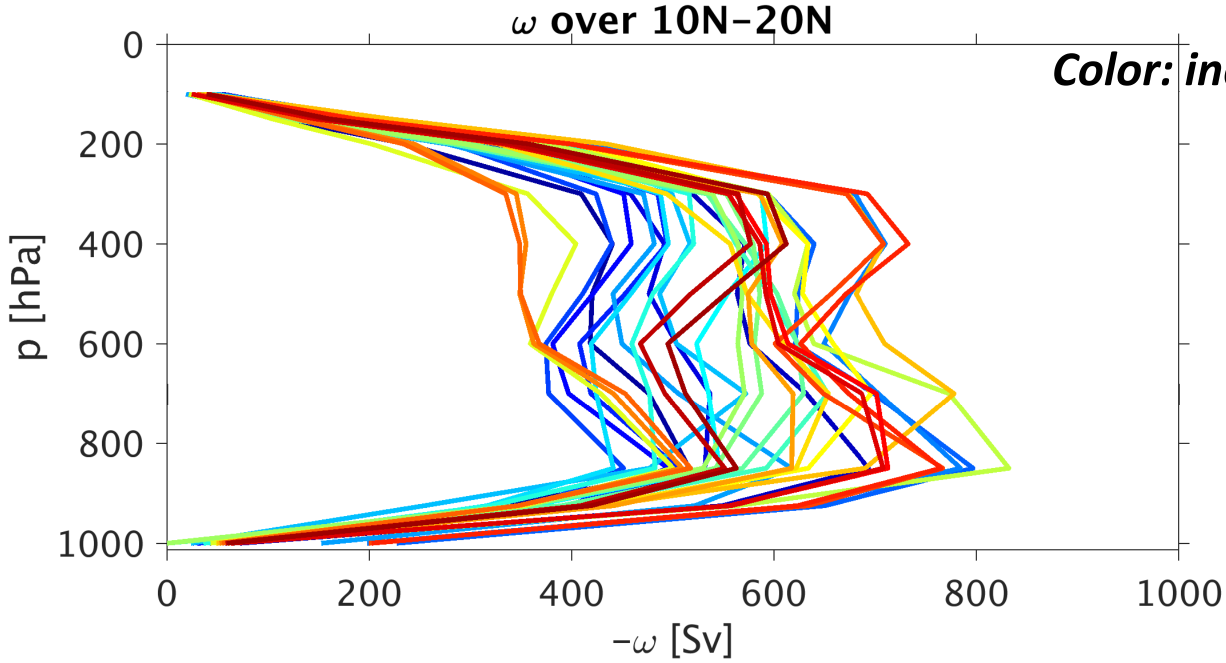
(Levine and Boos, 2016; J. Clim.)

How to test relevance of 1st baroclinic mode mechanism to the "real world"

- ***We compare circulation changes over a thin latitudinal band (10N-20N) in 31 GCMs of the CMIP5 archive between from historical simulations (1984-2004) to RCP8.5 scenarios (2079-2099)***

- ***We quantify contribution from 1st baroclinic mode deepening.***

Step1: diagnose vertical mass flux (1984-2004)

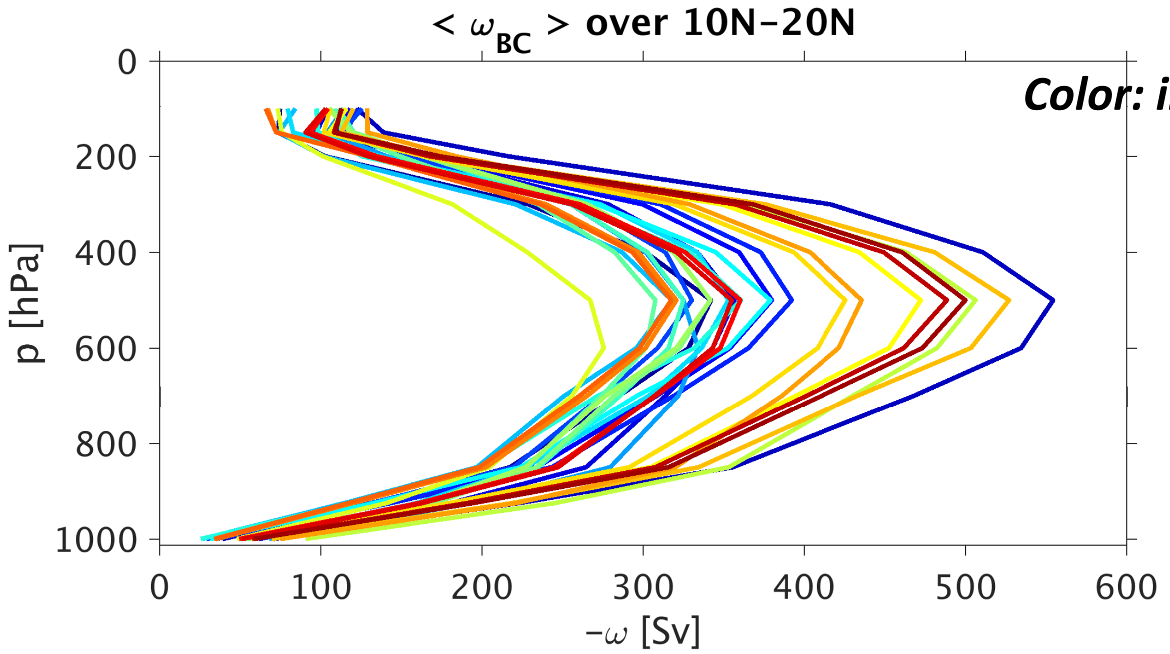


Color: individual GCM

Integrated vertical mass flux over regions of ascent

Large intermodel variability in stationary circulation in present-day climate (1984-2004)

Step2: diagnose geostrophic vertical mass flux (1984-2004)

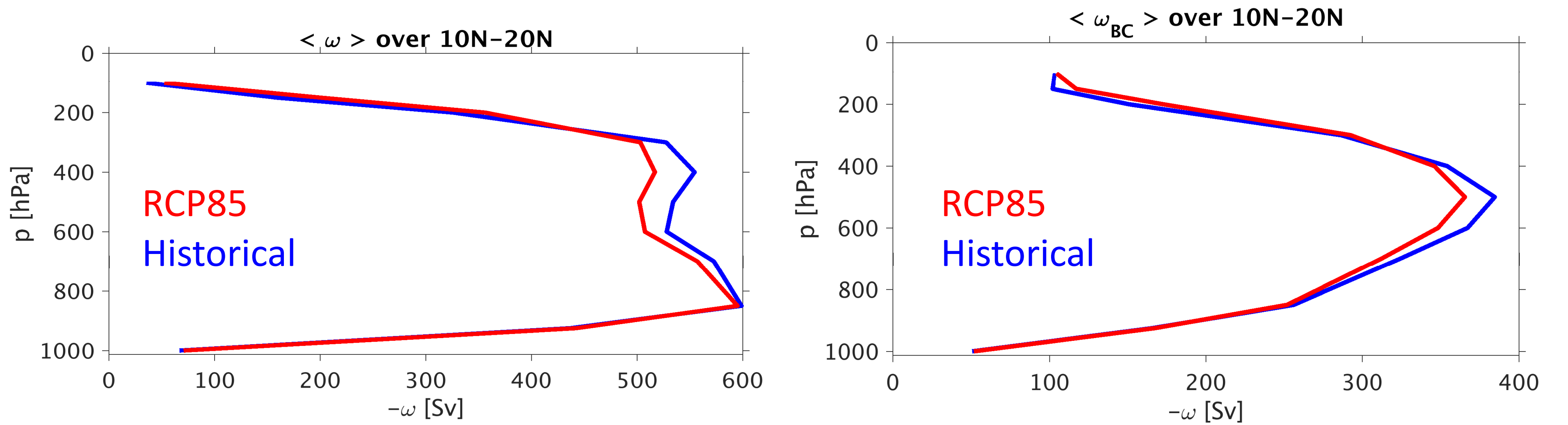


Color: individual GCM

Integrated geostrophic vertical mass flux at each level

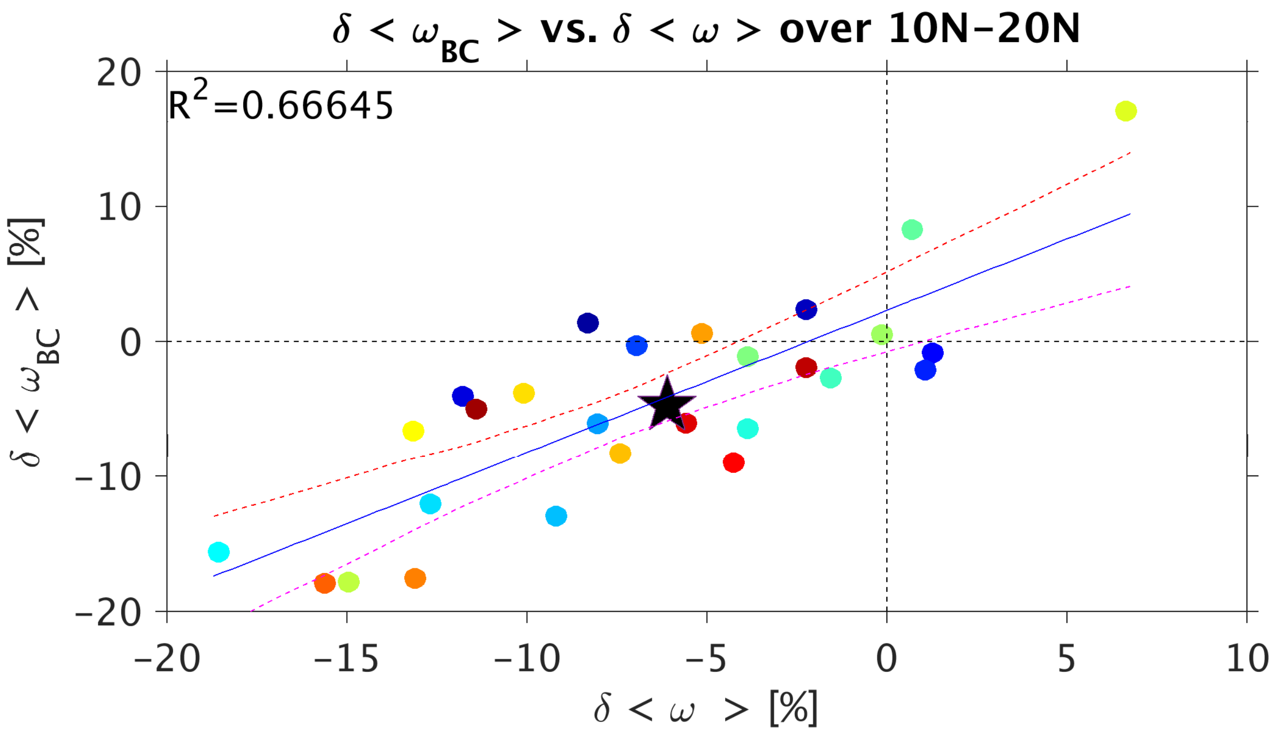
Geostrophic component of the vertical wind is first-baroclinic

Step 3: diagnose changes in vertical winds and and its geostrophic component



In the ensemble-mean, vertical mass flux weakens by about 5% by late 21st century in RCP8.5 scenario.

Change in vertical wind vs. geostrophic vertical wind (at 500 hPa)

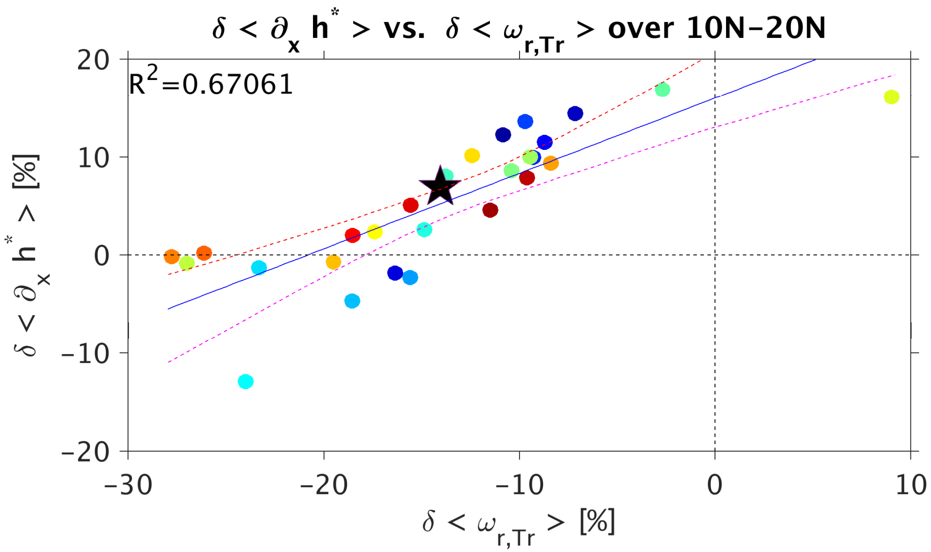


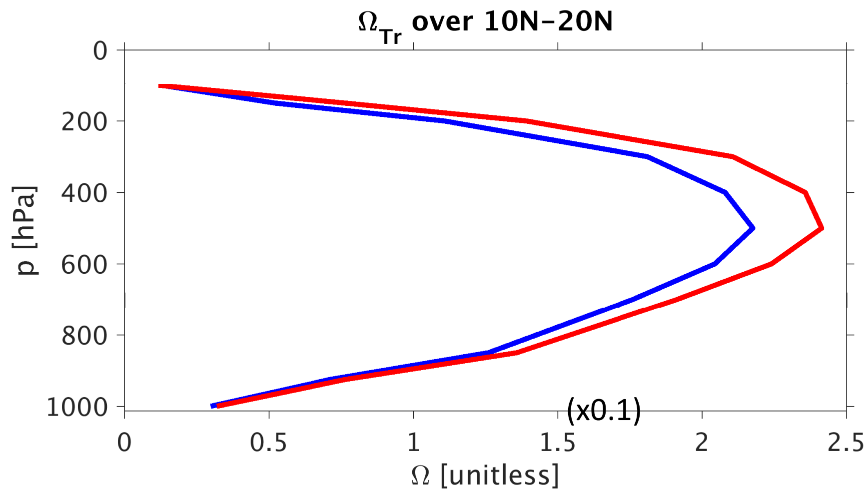
δ(.): RCP8.5 (2079-2099) minus historical (1984-2004)

Color: individual GCM
Star: ensemble-mean

Changes in vertical wind scales with that of its geostrophic component.

Deepening of troposphere partially offset weakening of tropospheric temperature gradient (in the ensemble-mean)





(inferred) Zonal temperature gradient weakens by about 15%

Wind mode strengthens by about 10%

Vertical wind mode strengthens circulation with global warming, and acts against weakening of tropospheric zonal temperature gradient

Summary

- Subtropical Rossby gyre can be described by 1st baroclinic mode framework.

- Deepening of the first-baroclinic mode strengthens circulation as climate warms.

- This effect may be significant in comprehensive climate models, offsetting the circulation weakening from the reduction in temperature anomalies.

Thank You!

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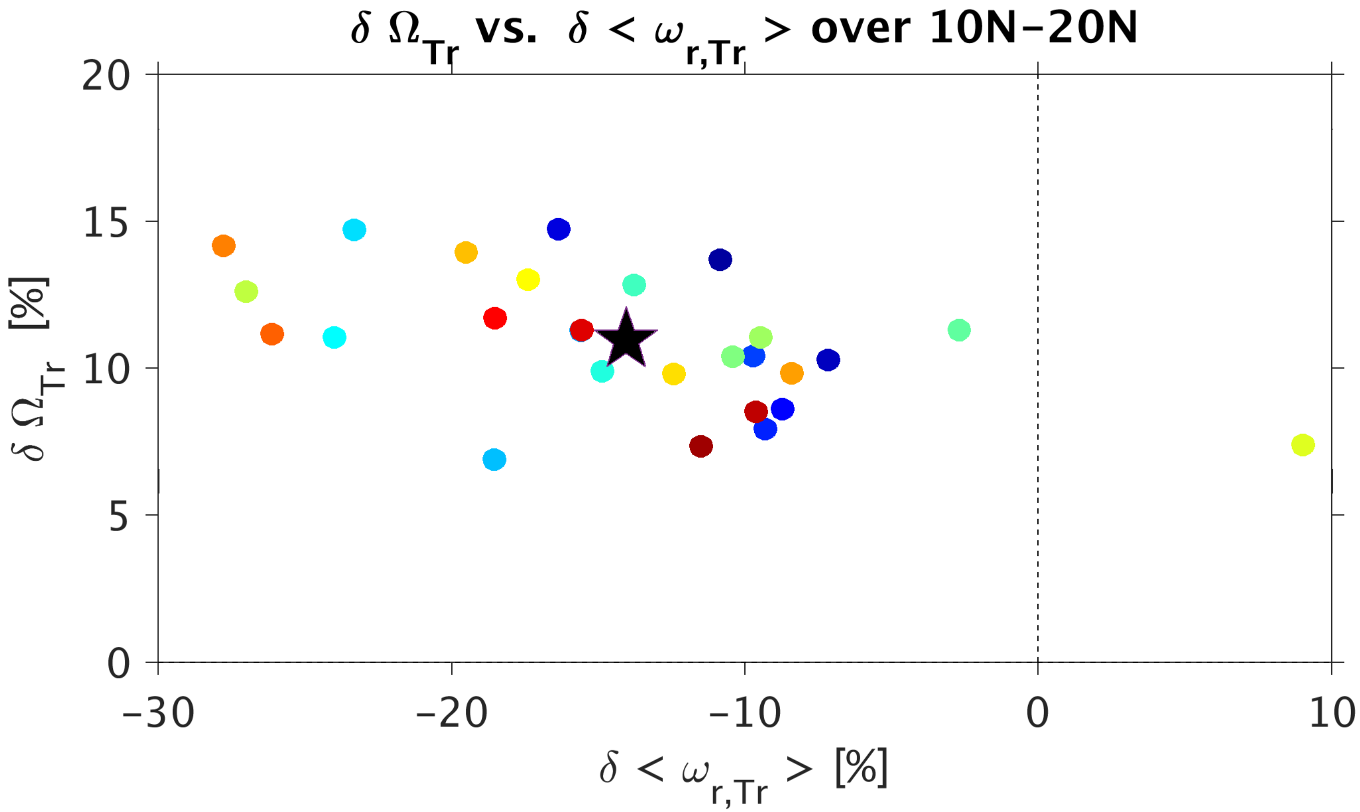
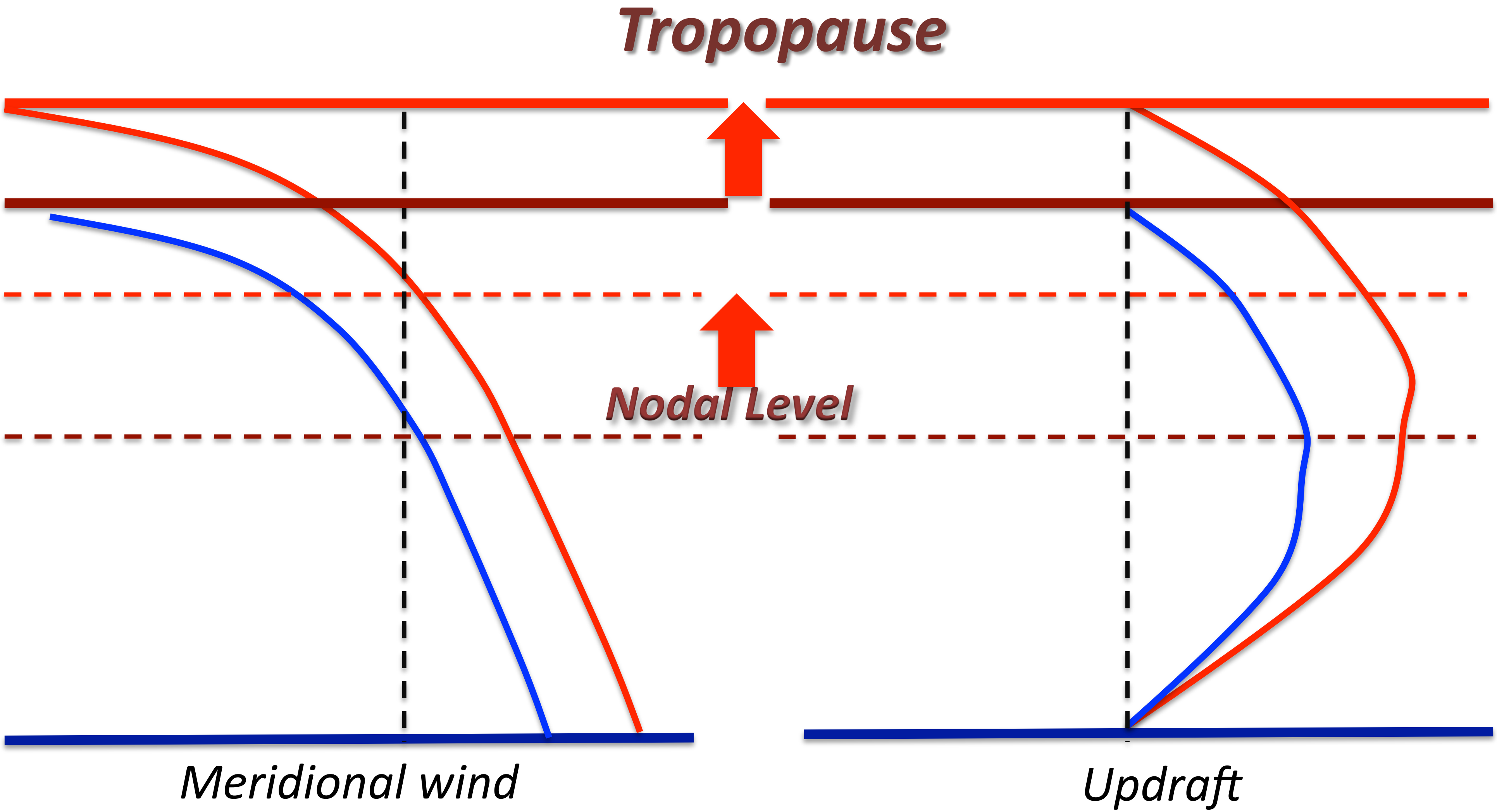
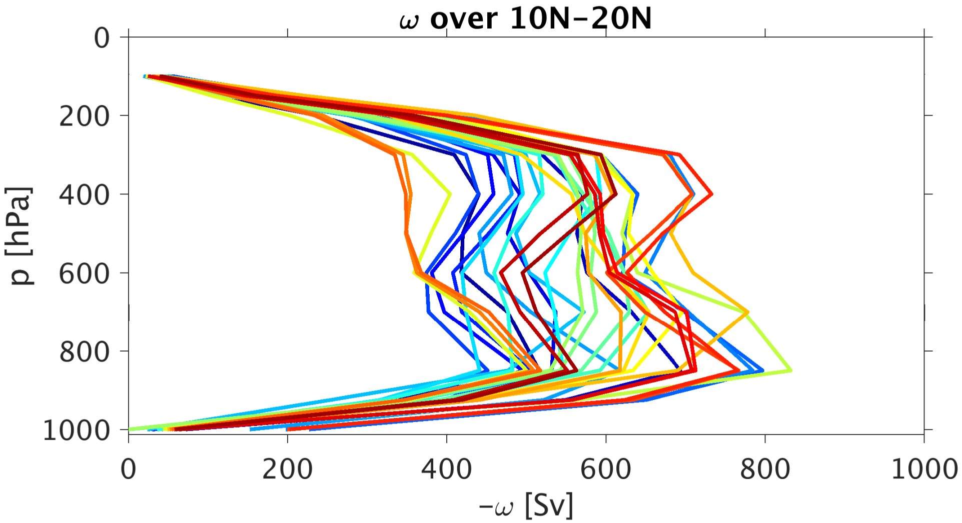
For more details: Levine X. J., and W. R. Boos, 2016: A mechanism for the response of the zonally asymmetric subtropical hydrologic cycle to global warming. *Journal of Climate*, **29**, 7851-7867.

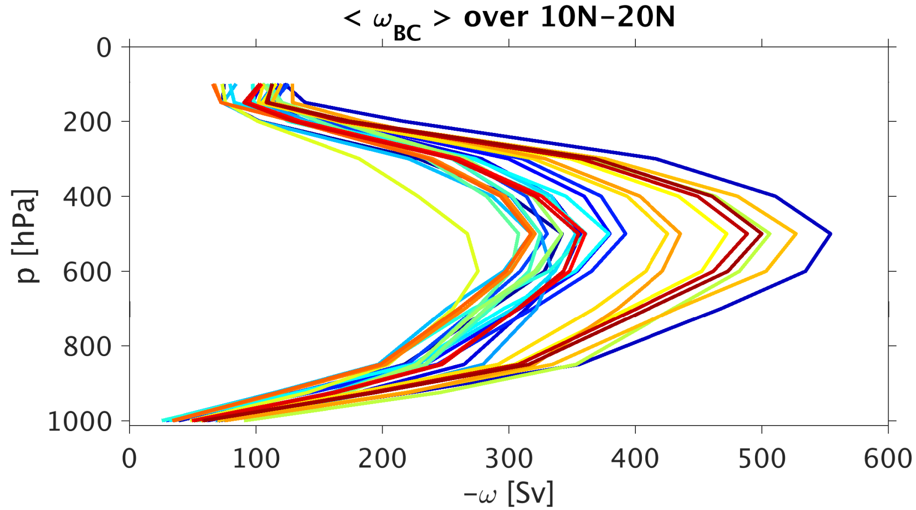


δ Ω_Tr vs. δ < ω_r,Tr > over 10N-20N
20
15
10
5
0
δ Ω_Tr [%]
-30
-20
-10
0
10
δ < ω_r,Tr > [%]

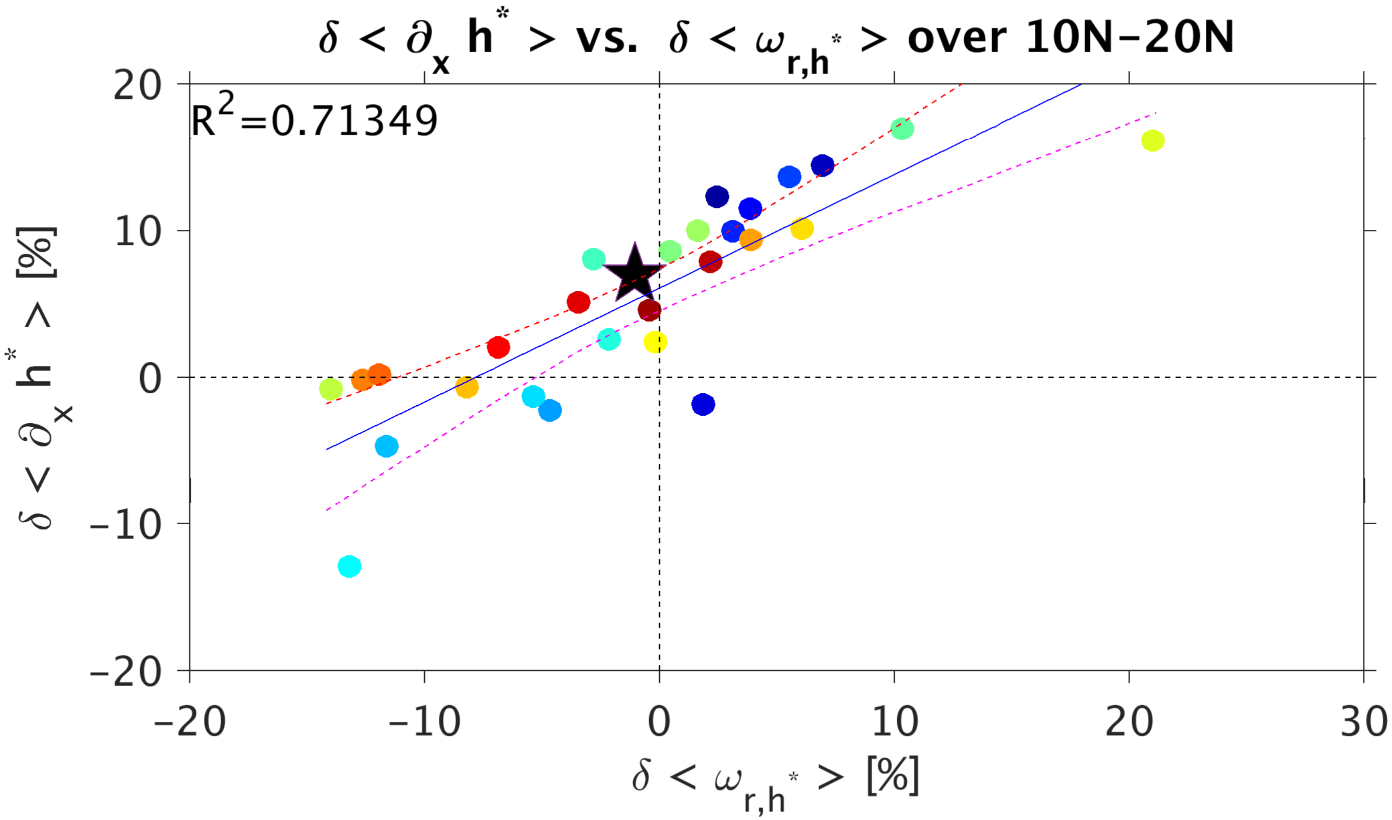

Tropopause
Nodal Level
Meridional wind
Updraft

We diagnose vertical wind and its component associated with baroclinic flow

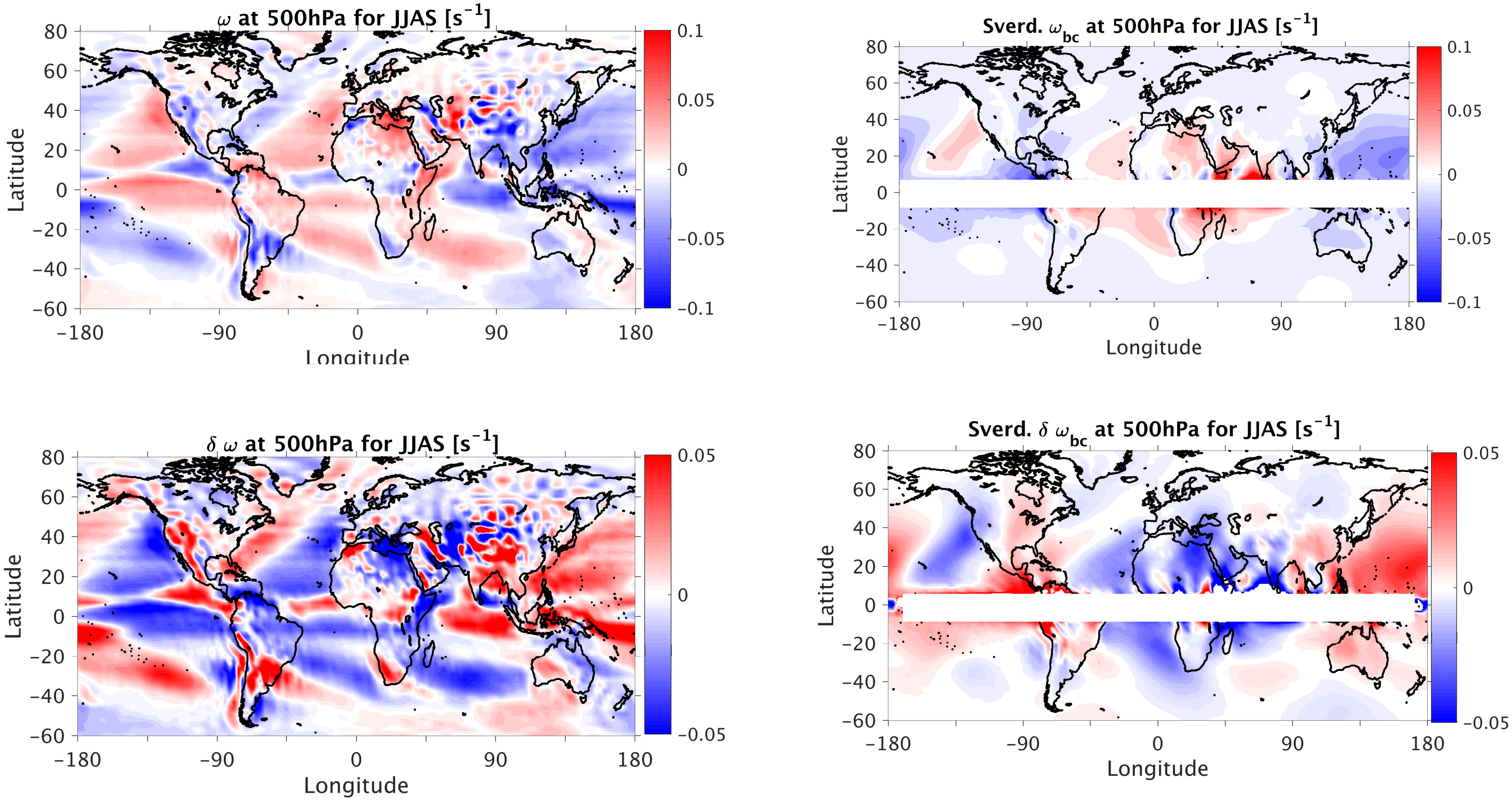




We diagnose stationary vertical wind and its baroclinic component.



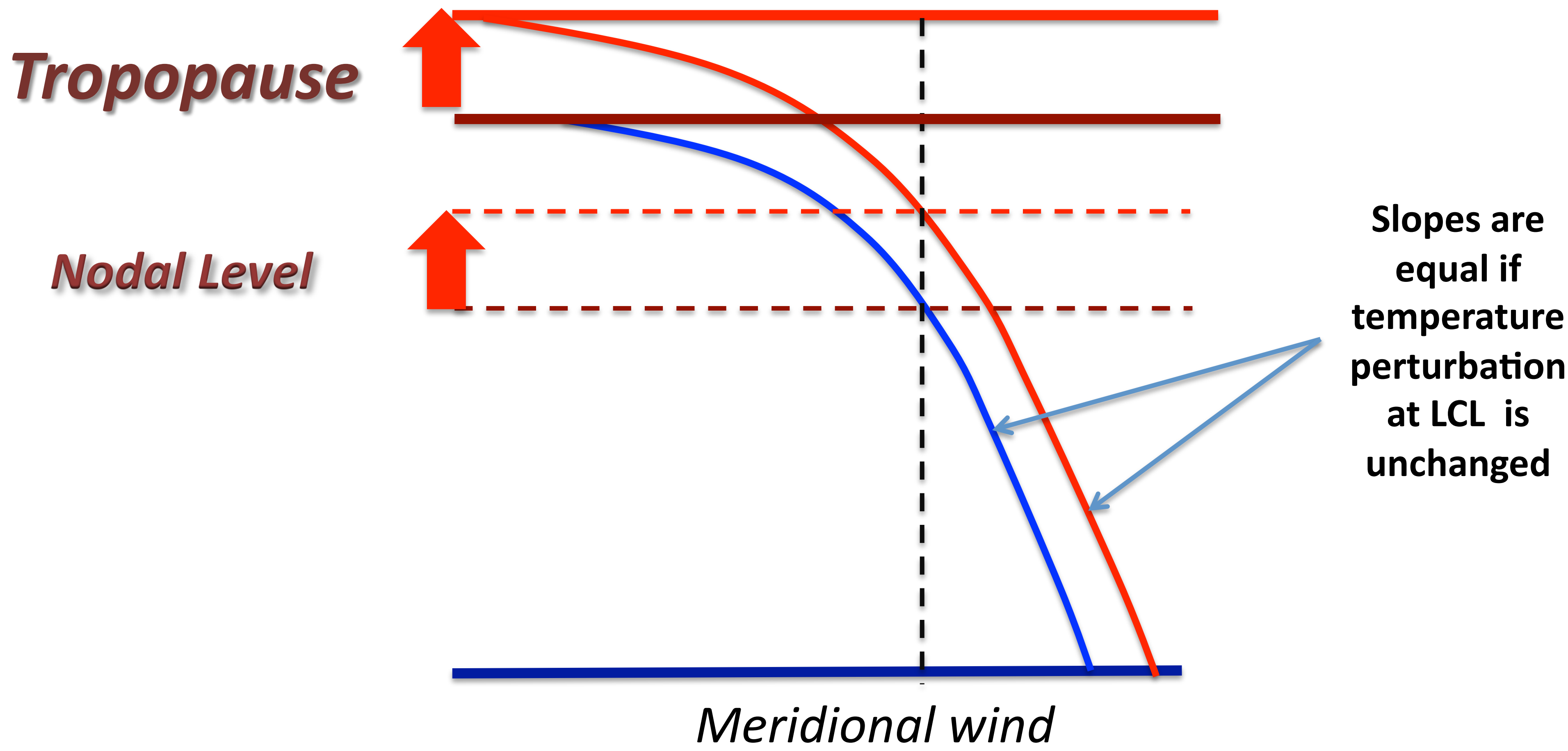
δ < ∂x h* > vs. δ < ωr,h* > over 10N-20N
R2=0.71349
δ < ∂x h* > [%]
δ < ωr,h* > [%]
20
10
0
-10
-20
-20
-10
0
10
20
30



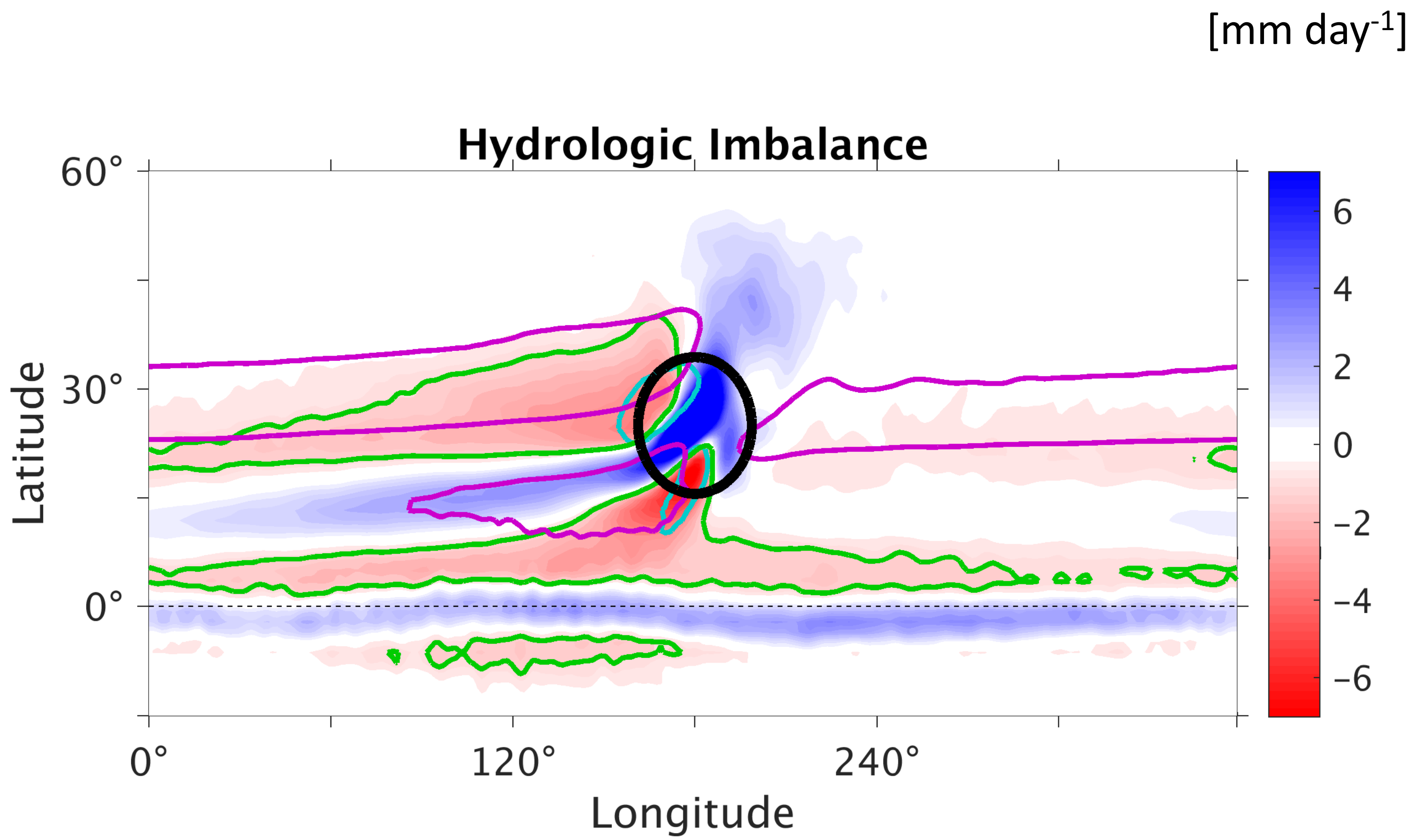
ω at 500hPa for JJAS [s−1]
Sverd. ωbc at 500hPa for JJAS [s−1]
δ ω at 500hPa for JJAS [s−1]
Sverd. δ ωbc at 500hPa for JJAS [s−1]
Latitude
Longitude
80
60
40
20
0
−20
−40
−60
−180
−90
0
90
180
0.1
0.05
0
−0.05
−0.1

Changing wind in lower troposphere

B: change vertical structure keeping magnitude of temperature perturbation at LCL invariant

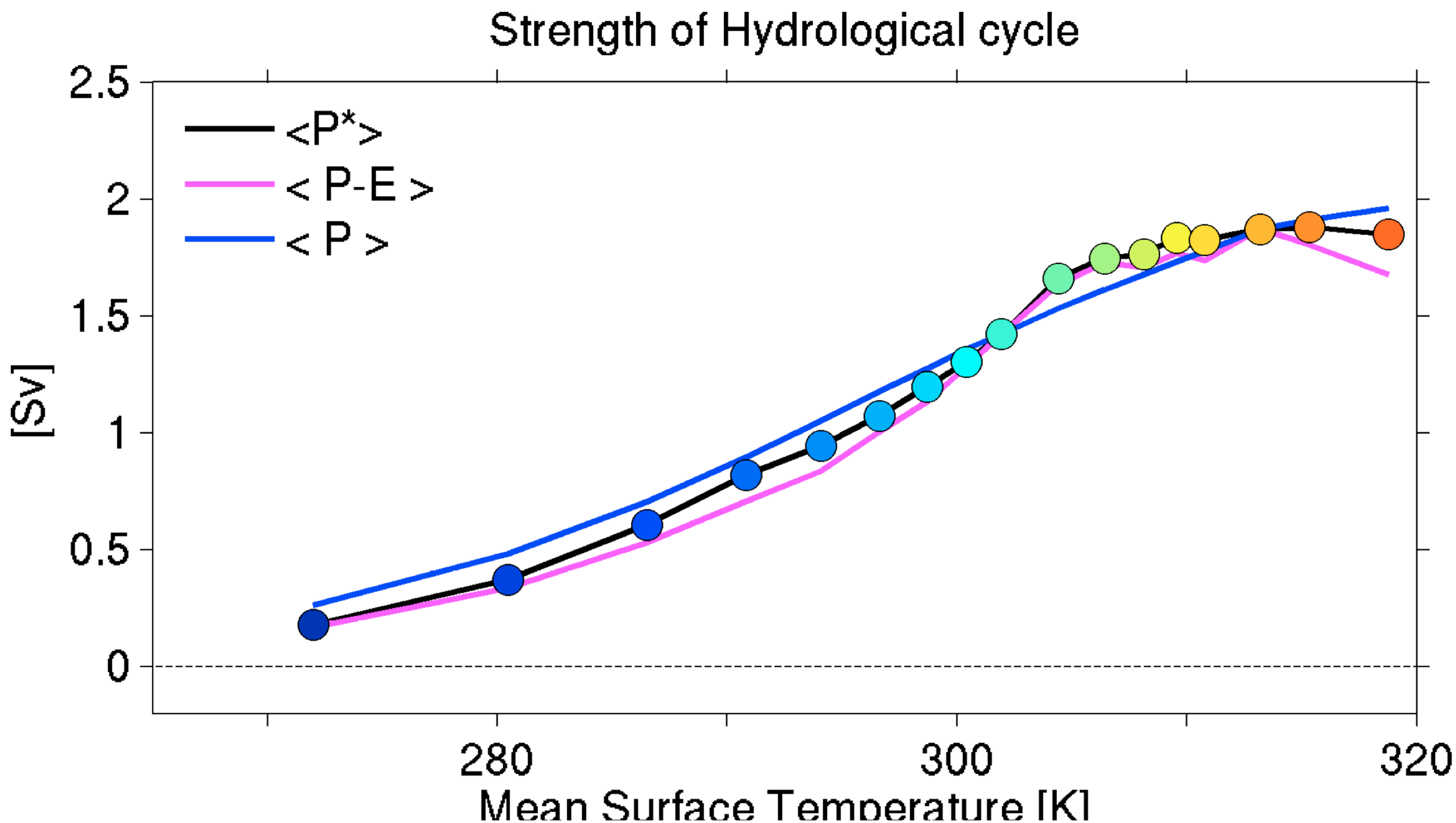


Wet zones near heating zone, enhanced dryness to the west.



Contours: **P-E ≤ -1.5 mm day^{-1} in cold (Ts=291K, cyan), reference (Ts=302K, green) and warm (Ts=311K, magenta) climates**

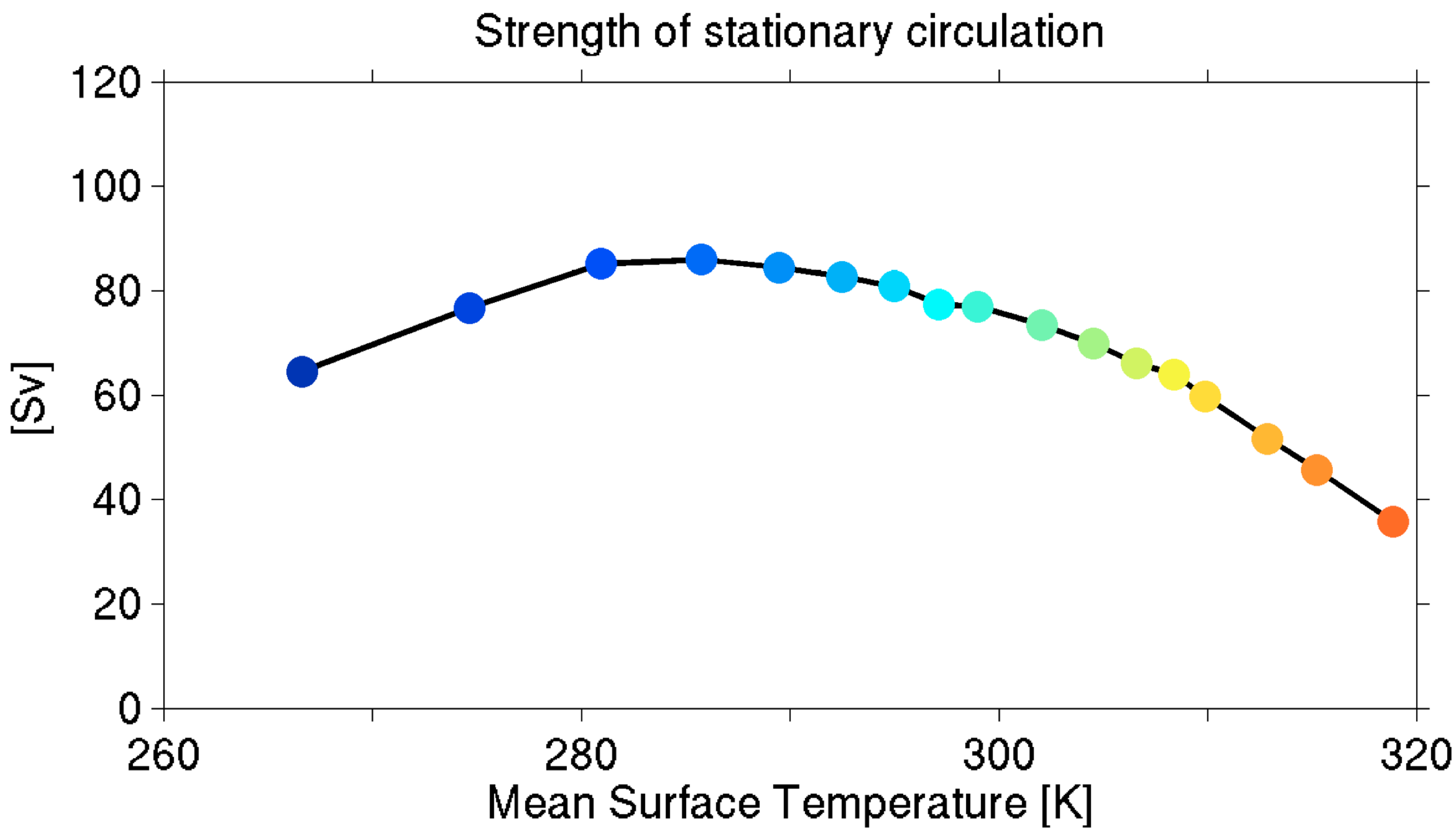
Hydrologic imbalance (P-E) scales with stationary precipitation (P*) over a wide range of climate change



(.)*: time-mean, zonally asymmetric component

<.>: Area integral over regions of positive sign

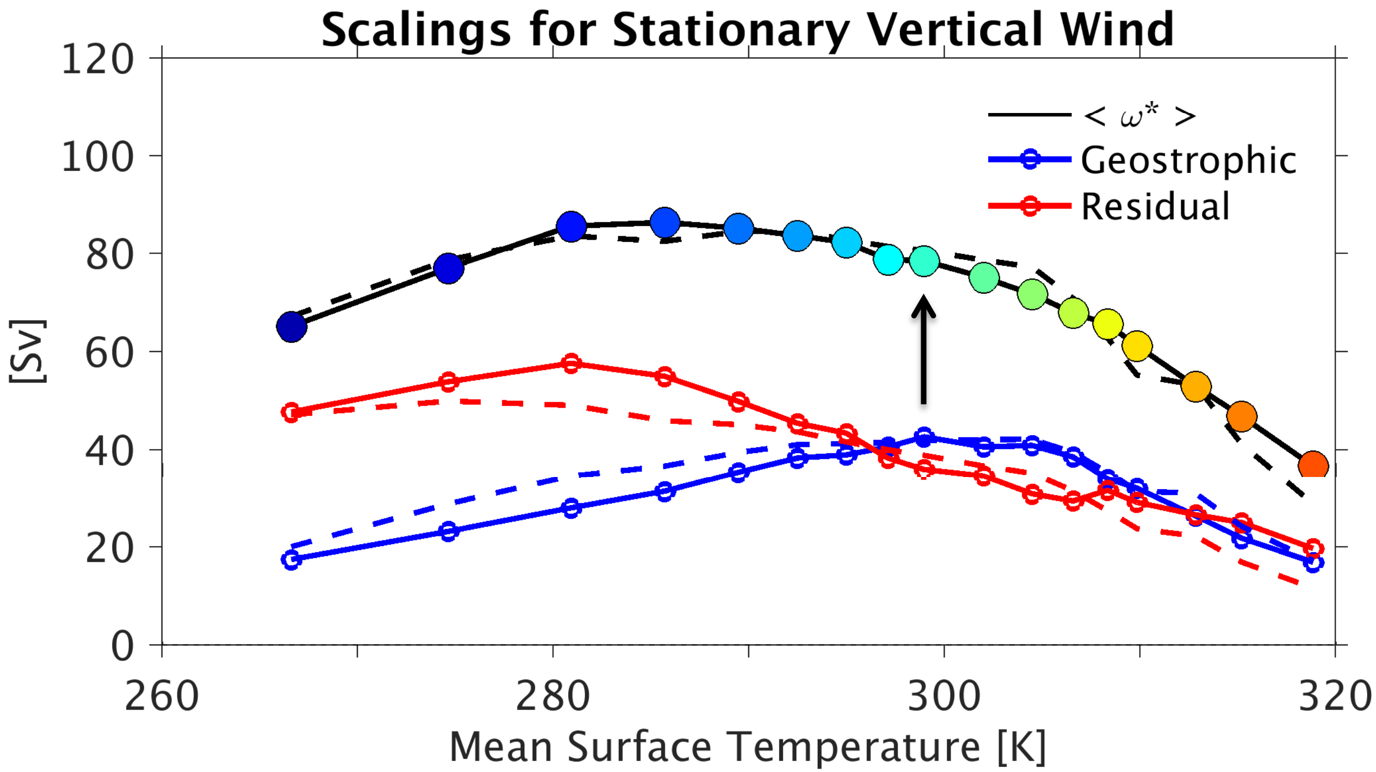
Circulation change is non-monotonic with global warming



Bulk stationary vertical wind evaluated at level of maximum

How to explain this non-monotonicity?

Combining 1st baroclinic mode theory and linear vorticity budget provides a quantitative prediction for ω*



Frictional:

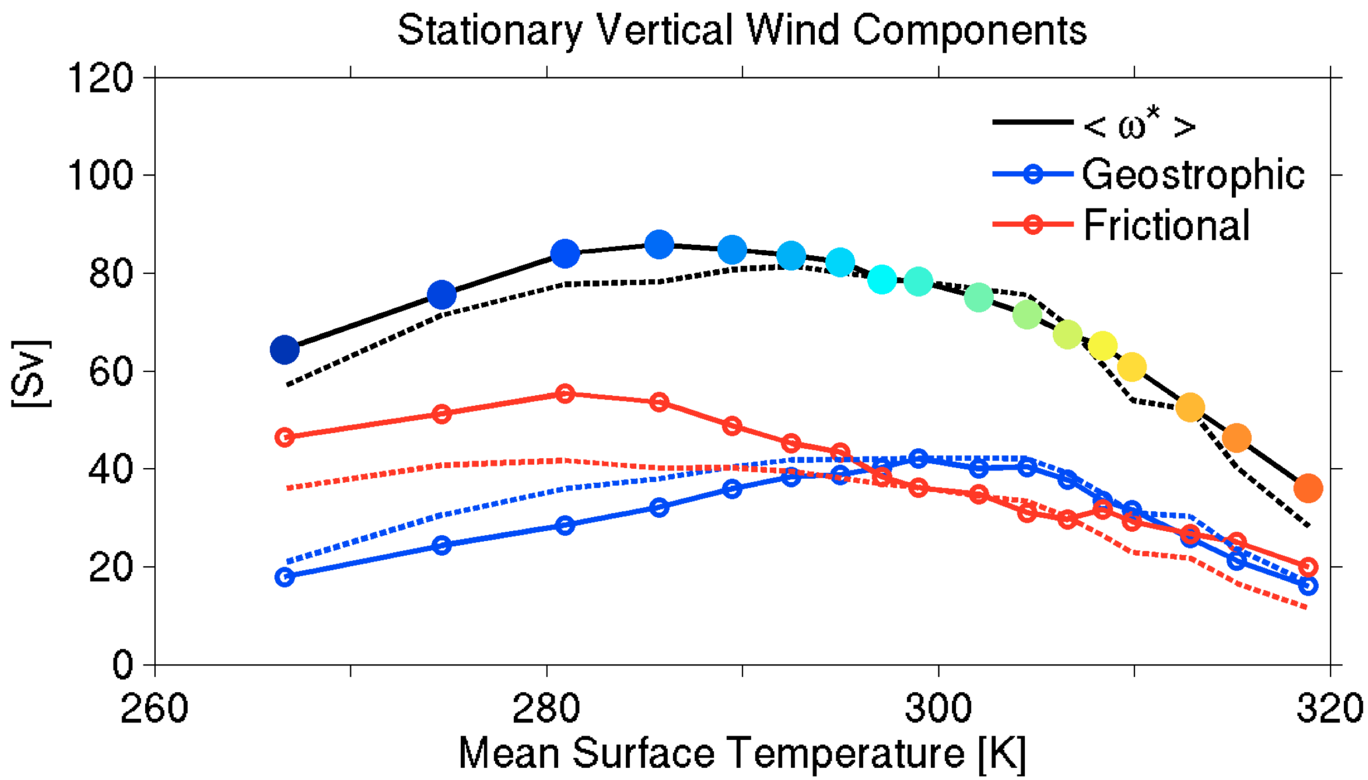
Geostrophic:

V_1: horizontal wind mode

Ω_1: vertical wind mode

- Slide 1: lat-lon panel of omega_star, omega_star Sv_BC [ensemble-mean or 1 GCM simulation]
- Slide 2: average over 10-20N, show good correlation between Sv_BC and total updraft; show vertical profile of Sv_BC.
- Slide 3: decompose correlation into coefficient and mode.

1st baroclinic mode theory provides a qualitative understanding of stationary circulation changes



Despite its simplicity, our mechanism accounts remarkably well for non-monotonic change in strength!

How about for more comprehensive GCM simulations?