Understanding Temperature Distributions from a Dynamical Perspective

IMSI Confronting Global Climate Change

Climate and Weather Extremes

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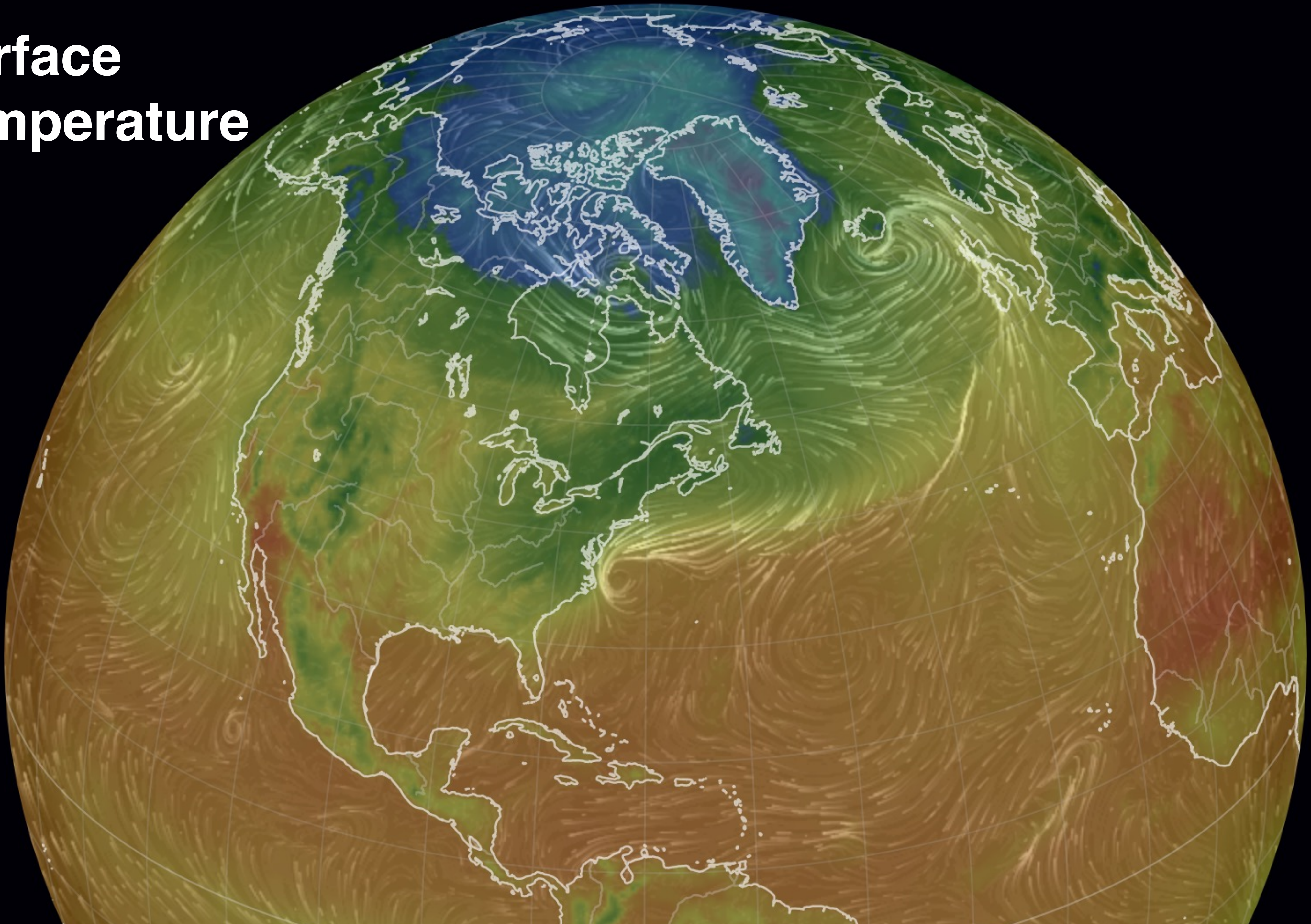
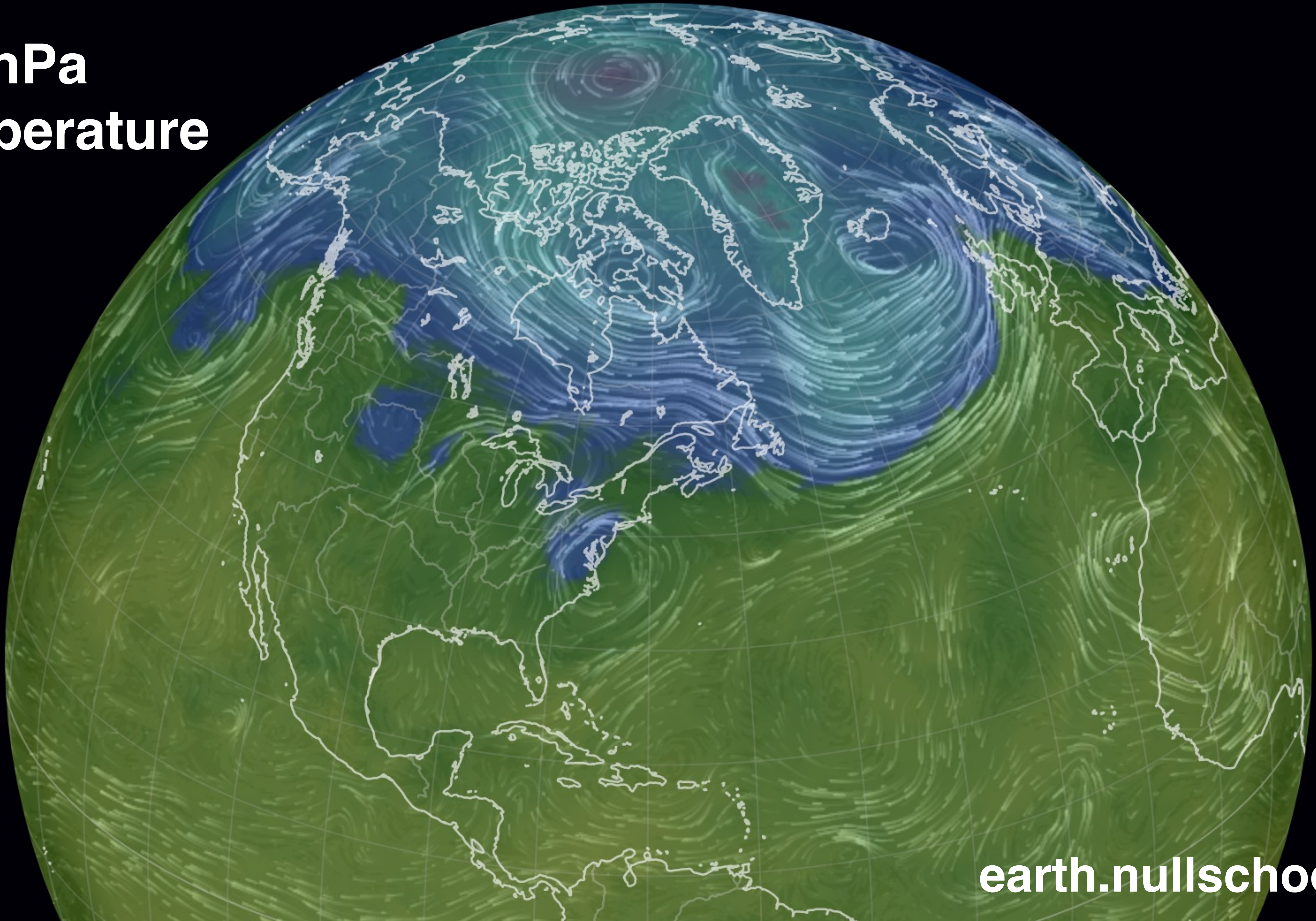
Surface Temperature



700 hPa Temperature



earth.nullschool.net

1) What processes set the shape of temperature distributions?

2) What changes might we expect in the future?

Begin with the equation that describes the evolution of any tracer:

$$\underbrace{\frac{\partial \theta}{\partial t}}_{\text{Local tendency}} = \underbrace{-\mathbf{v} \cdot \nabla \theta}_{\text{advection}} + \underbrace{\dot{\theta}}_{\textbf{everything else}}$$

It can be shown that, with a first order Taylor expansion:

$$\left\langle \frac{\partial \theta}{\partial t} \right\rangle^e \approx -\left\langle \mathbf{v} \bullet \nabla \theta \right\rangle^e - \left\langle \frac{\theta - \theta_0}{\tau} \right\rangle^e$$

Local tendency **at temperature quantile e**

Advection **at *temperature* quantile e**

First order Taylor expansion of **everything else**, evaluated at temperature quantile e

Assume that the distribution is not changing much over the time-period of interest

$$\cancel{\left\langle \frac{\partial \theta}{\partial t} \right\rangle}^e = -\left\langle \mathbf{v} \cdot \nabla \theta \right\rangle^e - \left\langle \frac{\theta - \theta_0}{\tau} \right\rangle^e$$

Small compared to other terms, even though there is a trend

Rearrange to obtain

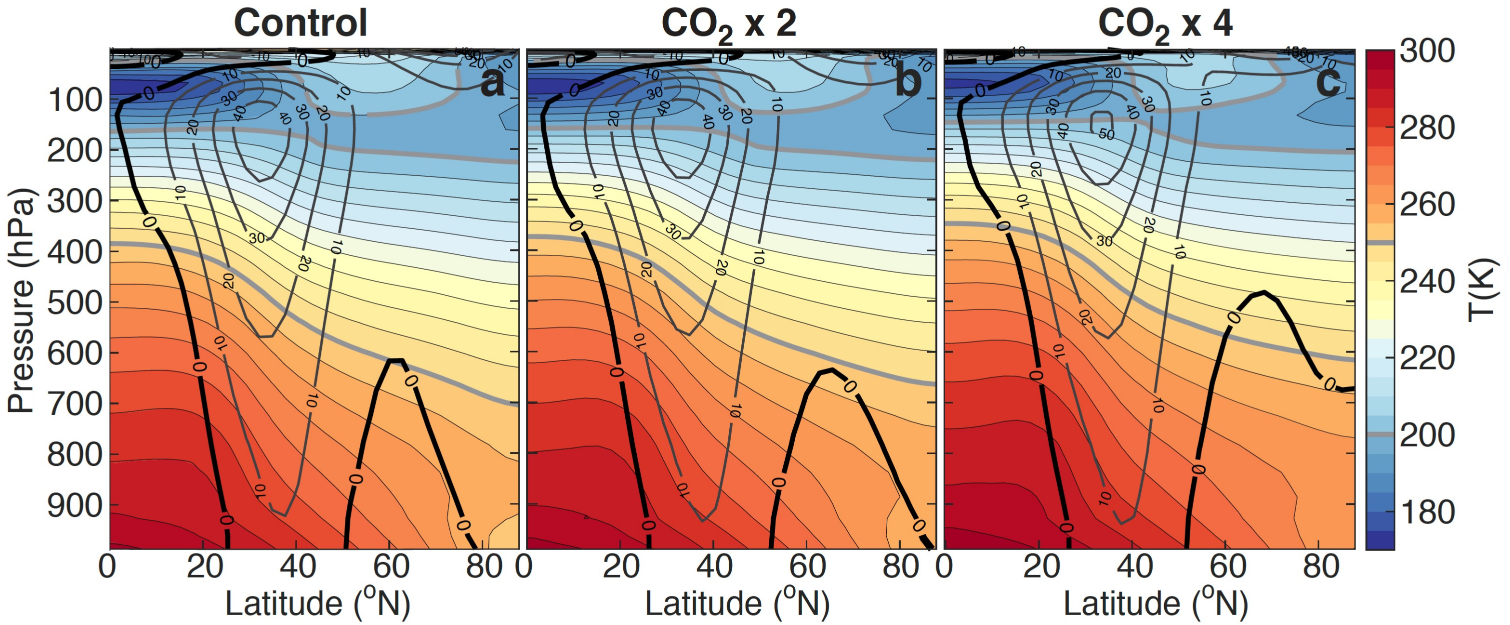
$$\langle \theta \rangle^e = -\tau \left\langle \mathbf{v} \cdot \nabla \theta \right\rangle^e + \theta_0$$

Temperature at a quantile can be expressed as a linear function of the temperature advection at that quantile

Apply this to an idealized aquaplanet model with full radiation

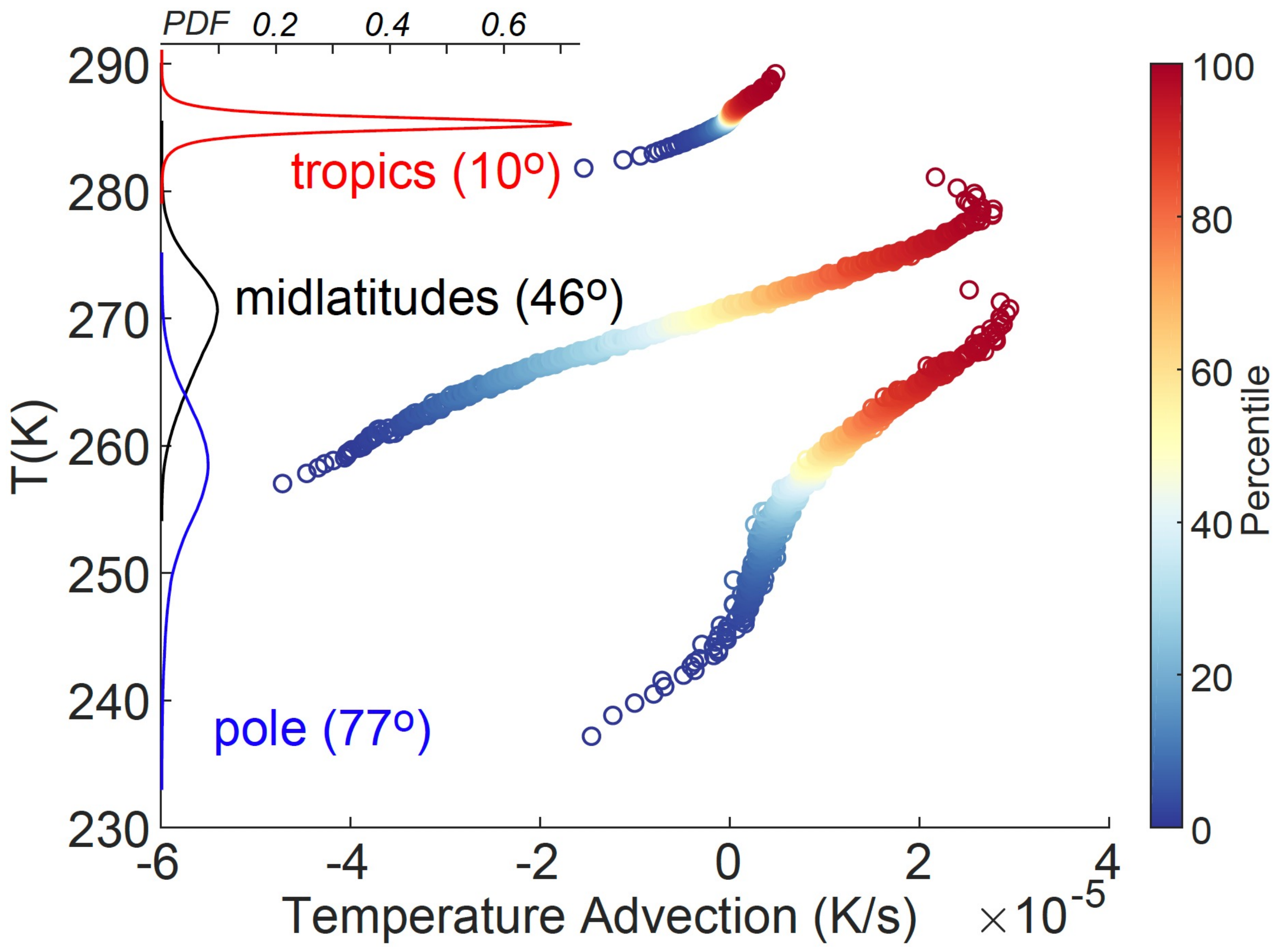
Idealized model: solves equations of motion + thermodynamic equation. Includes a full radiative transfer treatment and a simple treatment of moisture

No clouds; when air is saturated, the moisture just falls out as rain



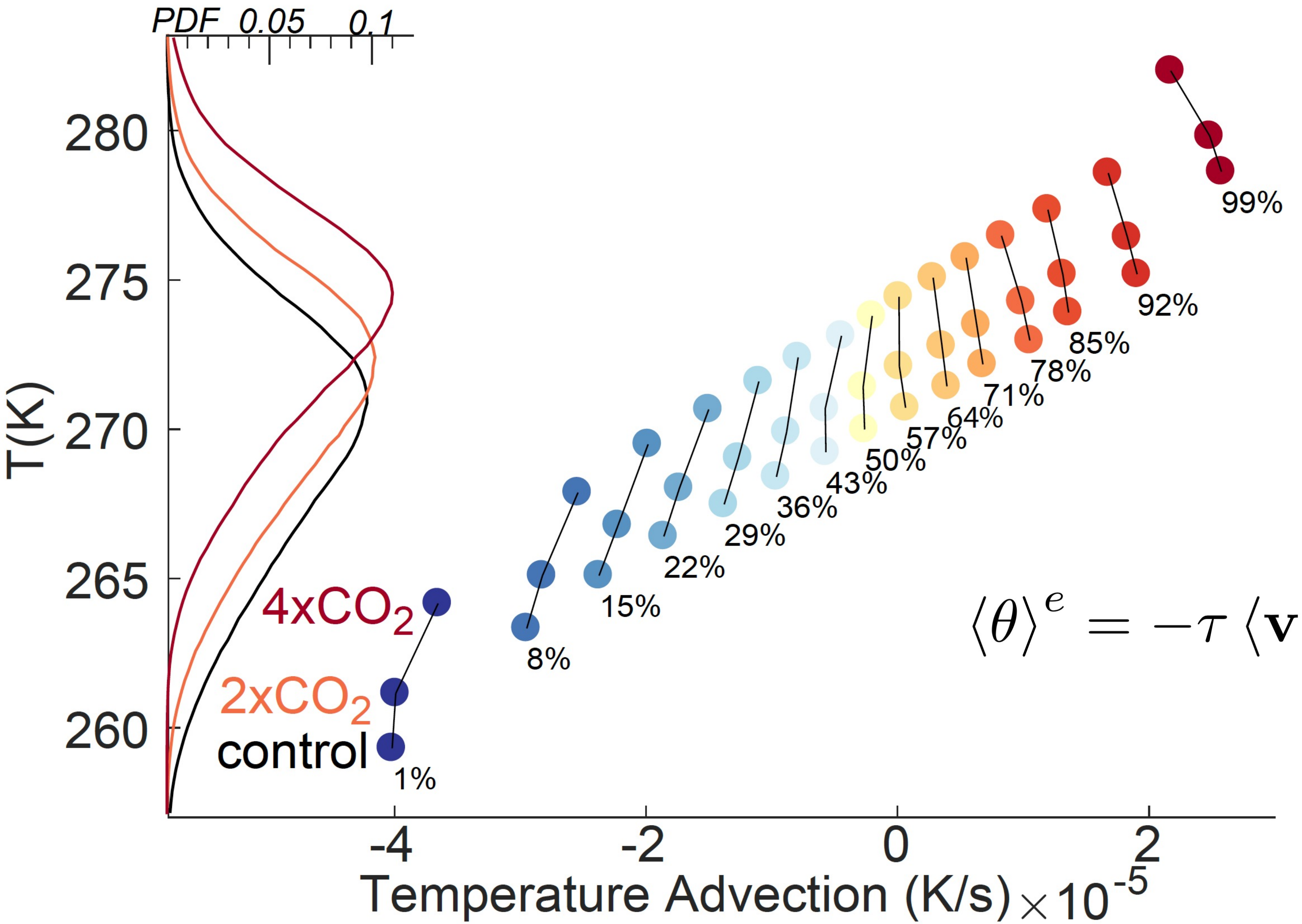
No continents
No hemispheric asymmetry
Every point at the same latitude is equivalent
*= **large** sample size for statistics*

Clear relationship between temperature and horizontal temperature advection



$$\langle \theta \rangle^e = -\tau \langle \mathbf{v} \cdot \nabla \theta \rangle^e + \theta_0$$

Warming does not affect all quantiles equally



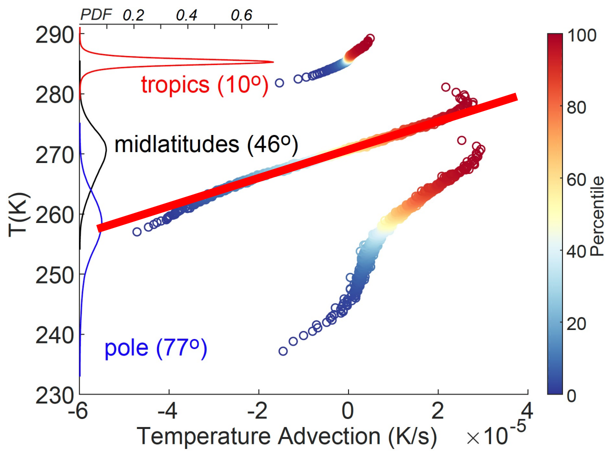
$$\langle\theta\rangle^e = -\tau\left\langle \mathbf{v}\cdot\nabla\theta\right\rangle^e + \theta_0$$

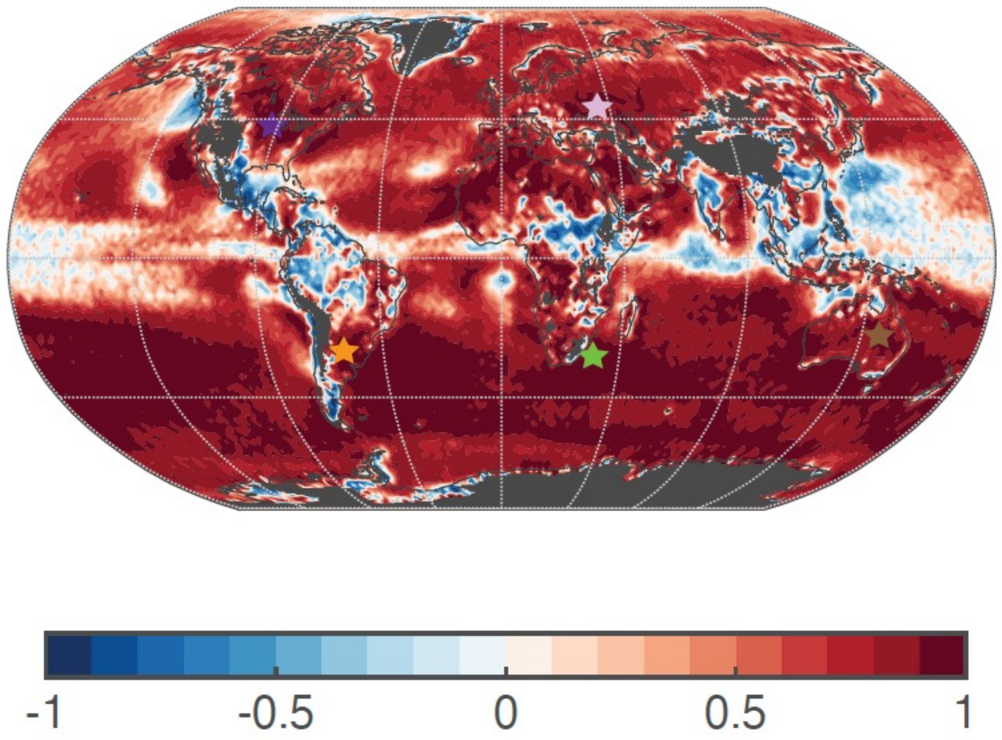
How well does this apply more generally?

Where can horizontal temperature advection explain the shape of the temperature distribution?

Linear least squares r values for JJA (better in DJF) for the fit between temperature at a given quantile and temperature advection at that temperature quantile

$$\langle\theta\rangle^{e} = -\tau\,\langle\mathbf{v}\cdot\nabla\theta\rangle^{e} + \theta_0$$

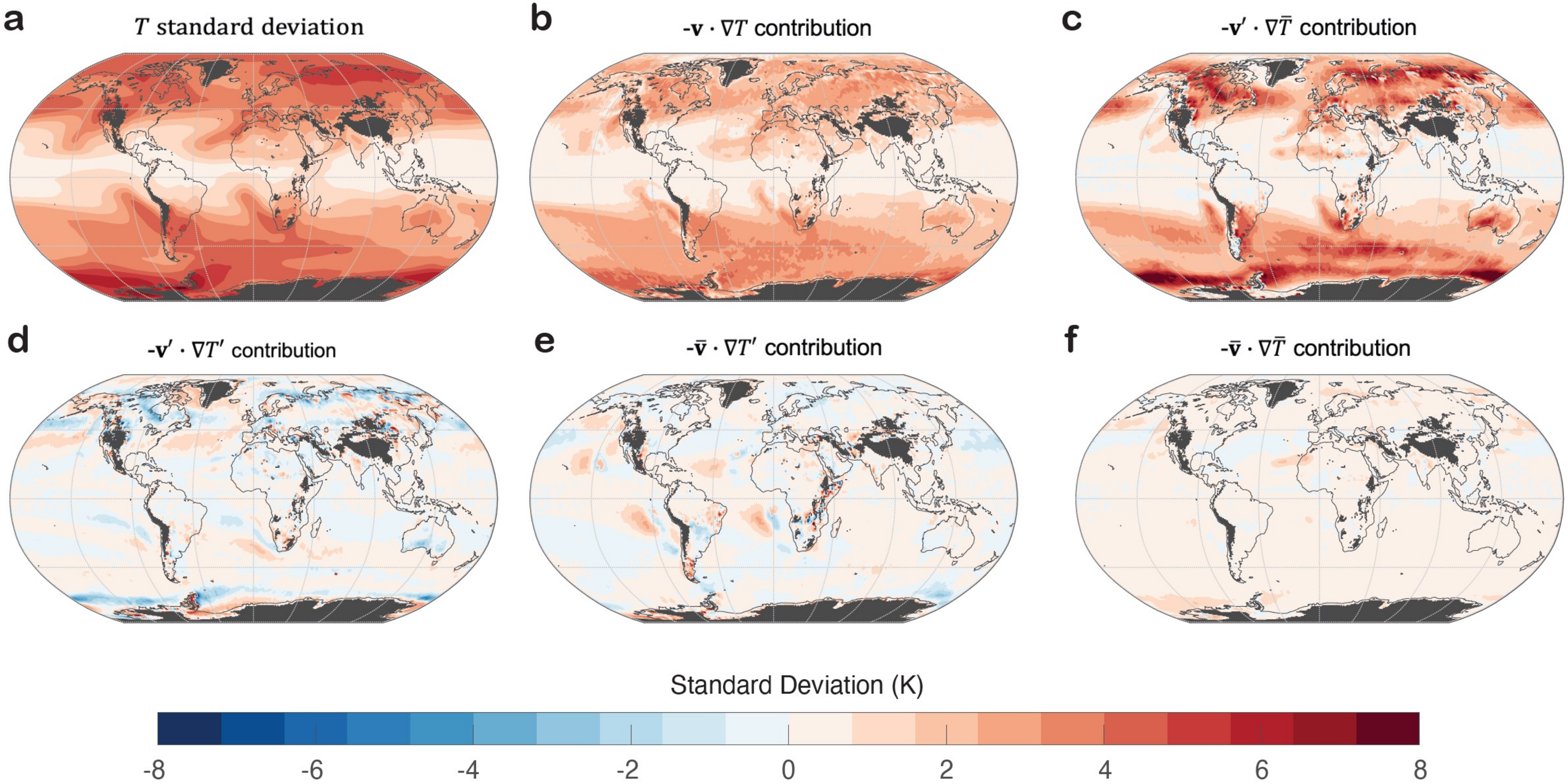




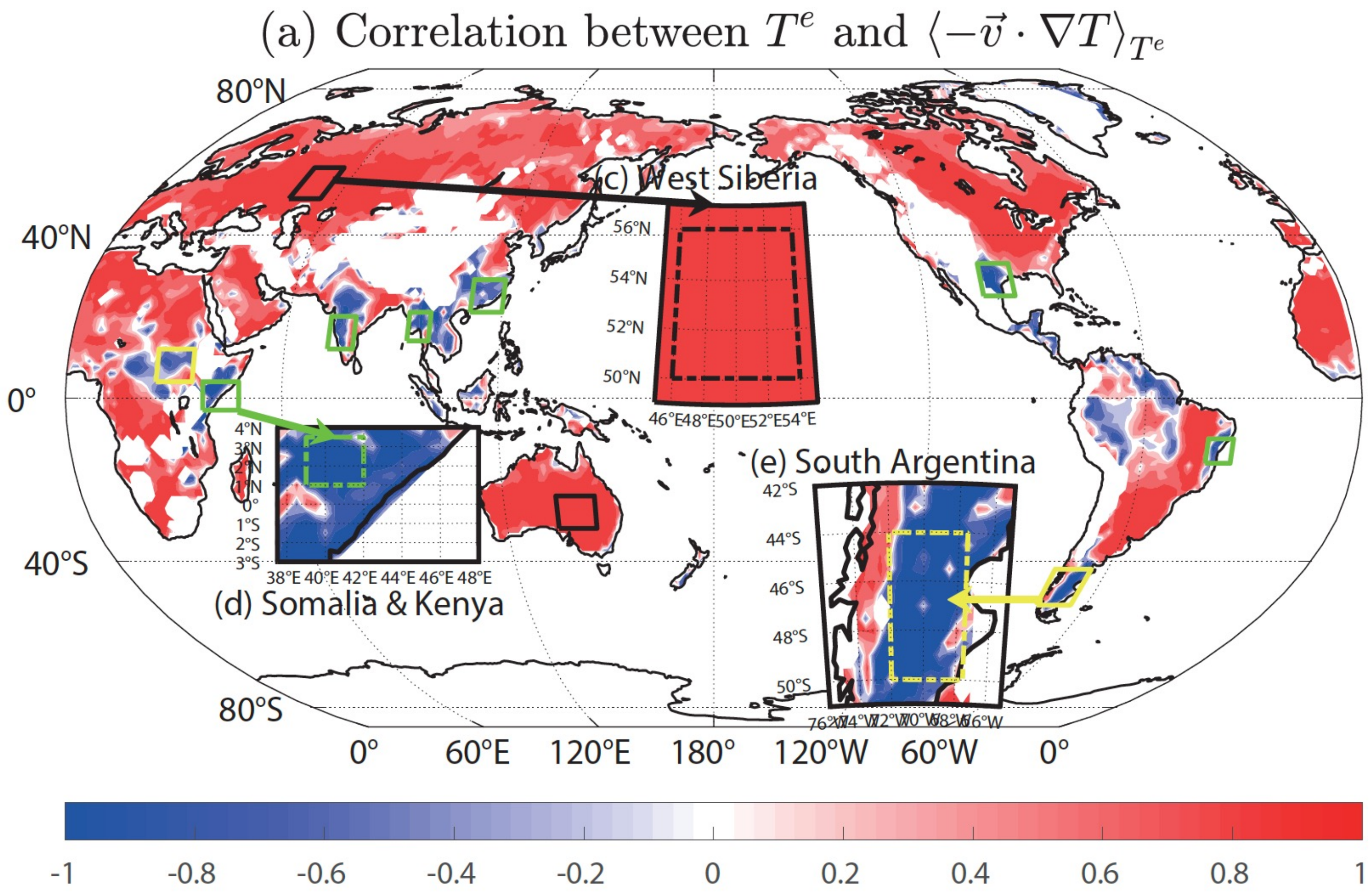
How much does advection matter for variance?

$$\sigma^2_{-\mathbf{v}\cdot\nabla T} = \left(\frac{1}{2}\cdot(T_w + T_c)\right)^2 = \left(\frac{1}{2}\cdot\tau\cdot((-\mathbf{v}\cdot\nabla T)_w + (-\mathbf{v}\cdot\nabla T)_c)\right)^2$$

Follows from Tamarin-Brodsky et al. 2020



What about places where correlation is not positive? What else is going on?



An expression for the temperature budget at each percentile that includes more processes

Based on equivalent potential temperature, which is conserved in moist adiabatic processes

Horizontal humidity advection

Vertical humidity advection

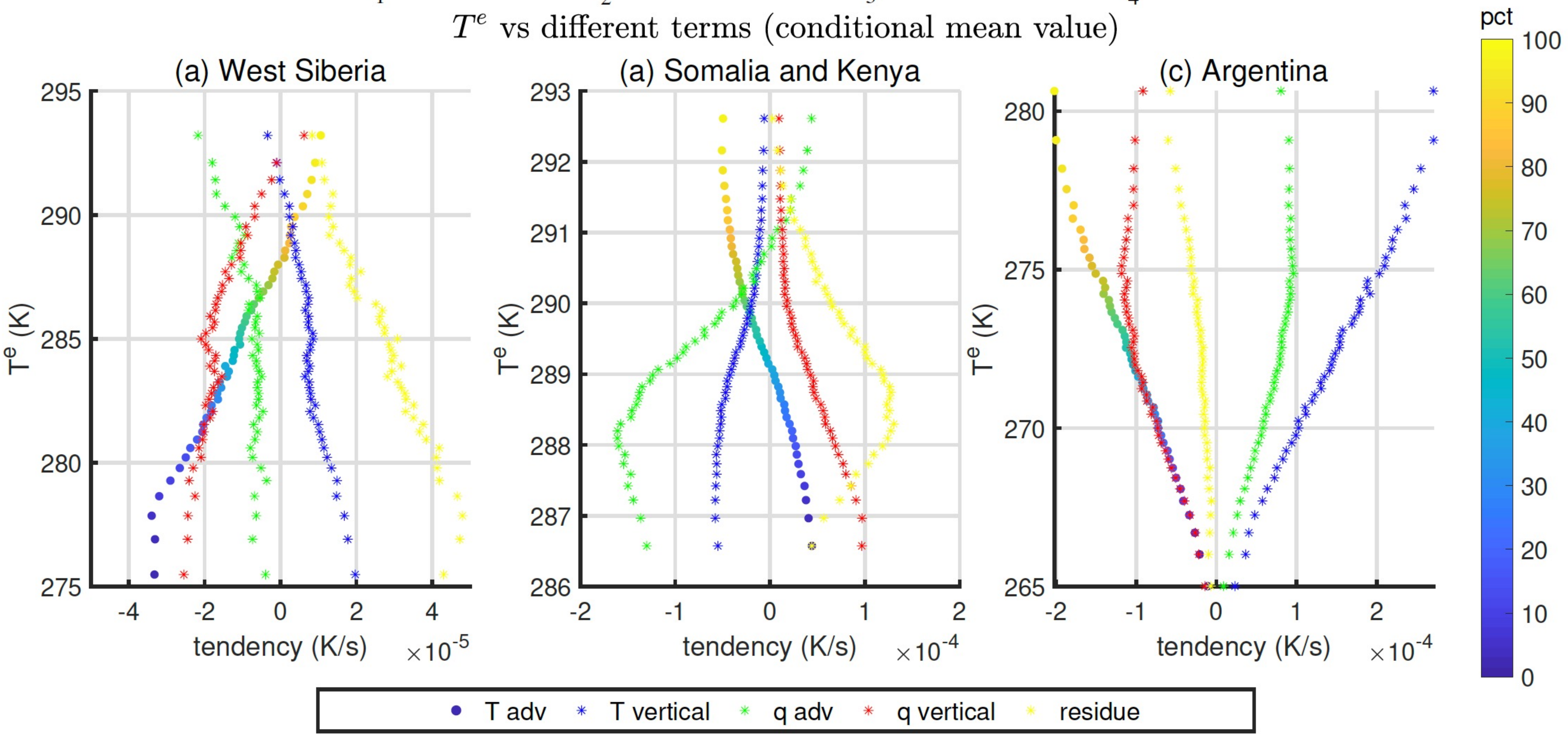
$$\underbrace{\left(\frac{p_0}{p}\right)^{\frac{R_d}{c_p}} \langle -\vec{v} \cdot \nabla T \rangle_{T^e}}_{1} + \underbrace{\frac{L_v}{c_p} \langle -\vec{v} \cdot \nabla q \rangle_{T^e}}_{2} + \underbrace{\left(\frac{p_0}{p}\right)^{\frac{R_d}{c_p}} \langle -\omega \frac{\partial T}{\partial p} + \omega \frac{\kappa T}{p} \rangle_{T^e}}_{3} + \underbrace{\frac{L_v}{c_p} \langle -\omega \frac{\partial q}{\partial p} \rangle_{T^e}}_{4} + \underbrace{R_{T^e}}_{5} = 0,$$

Horizontal temperature advection

Vertical temperature advection

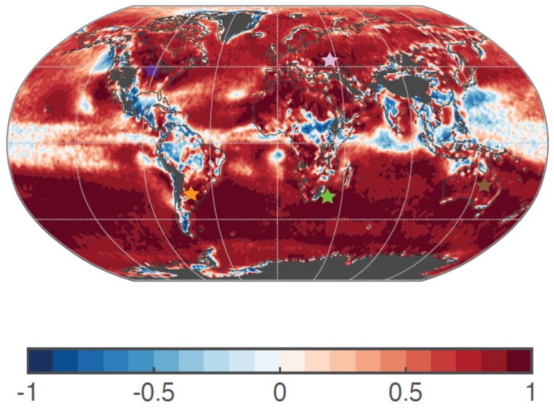
Residual is still **everything else**, but everything else is much more limited. Radiation and sensible heat flux (not latent heat because we use equivalent potential temperature)

$$\underbrace{\left(\frac{p_0}{p}\right)^{\frac{R_d}{c_p}}\langle -\vec{v}\cdot\nabla T\rangle_{T^e}}_{1} + \underbrace{\frac{L_v}{c_p}\langle -\vec{v}\cdot\nabla q\rangle_{T^e}}_{2} + \underbrace{\left(\frac{p_0}{p}\right)^{\frac{R_d}{c_p}}\left\langle -\omega\frac{\partial T}{\partial p}+\omega\frac{\kappa T}{p}\right\rangle_{T^e}}_{3} + \underbrace{\frac{L_v}{c_p}\left\langle -\omega\frac{\partial q}{\partial p}\right\rangle_{T^e}}_{4} + \underbrace{R_{T^e}}_{5} = 0,$$



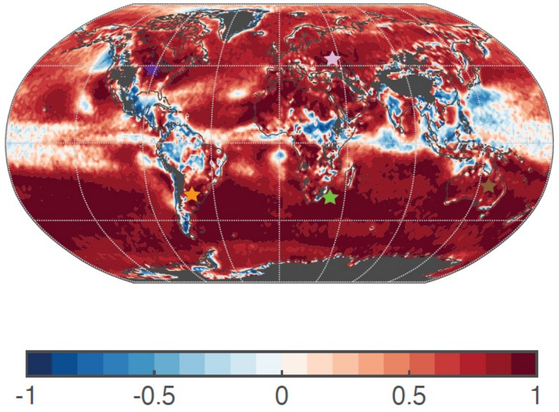
Summary of Part I:
We derive a new expression for examining the temperature distribution

We use a very simple treatment to understand the contribution of horizontal temperature advection. Most places it's large.

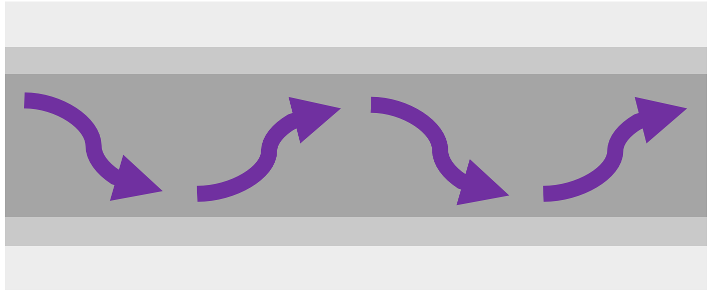


We include moisture to look at places where it likely matters

Part II: Are midlatitude heatwaves caused by quasi-resonant amplification (QRA) of Rossby waves?

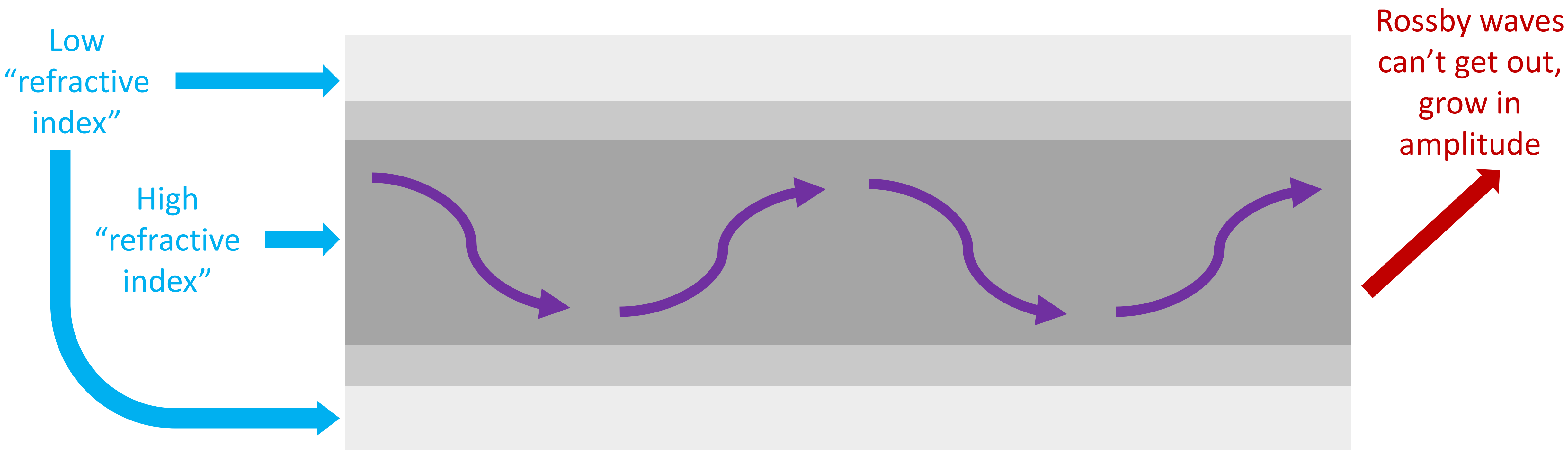


- Rossby waves (RWs): $\mathcal{O}(10^3 - 10^4\ \mathrm{km})$
- Barotropic vorticity eqn:
- Waveguide:



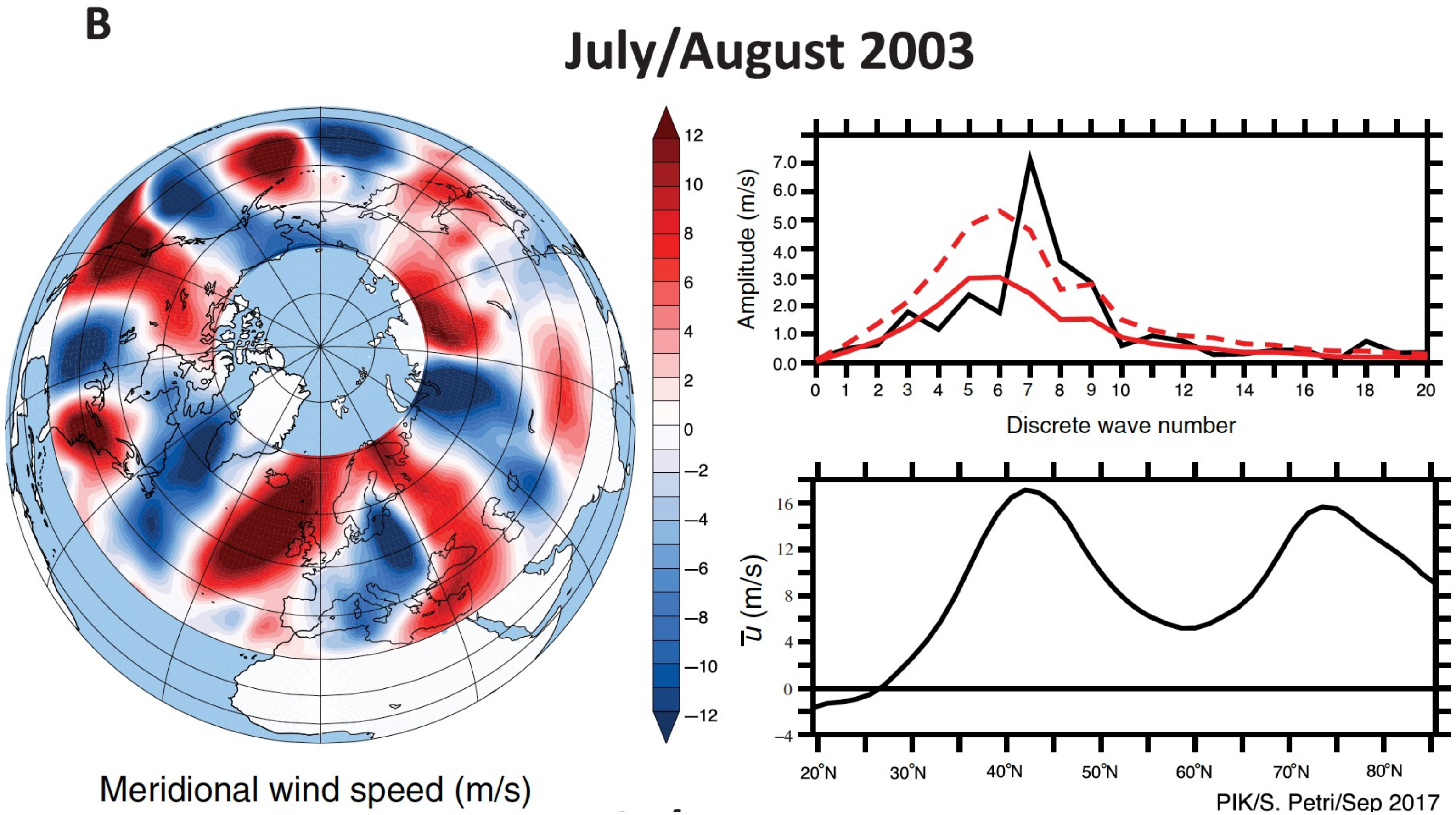
- Importance: *(Petoukhov et al. 2013)*
  1. Waveguide + forcing → trapped stationary RW
  2. Large-amplitude RW → surface extreme weather

Quasi-Resonant Amplification of Rossby Waves



Explained in Pethoukov et al. 2013

Heat waves may be associated with double jet structures



Mann et al. 2018

And the details of the double jet have been used to look at future changes in heat waves

SCIENCE ADVANCES | RESEARCH ARTICLE

CLIMATOLOGY

Projected changes in persistent extreme summer weather events: The role of quasi-resonant amplification

Michael E. Mann[1]*, Stefan Rahmstorf[2,3], Kai Kornhuber[2], Byron A. Steinman[4], Sonya K. Miller[1], Stefan Petri[2], Dim Coumou[2,5]

Persistent episodes of extreme weather in the Northern Hemisphere summer have been associated with high-amplitude quasi-stationary atmospheric Rossby waves, with zonal wave numbers 6 to 8 resulting from the phenomenon of quasi-resonant amplification (QRA). A fingerprint for the occurrence of QRA can be defined in terms of the zonally averaged surface temperature field. Examining state-of-the-art [Coupled Model Intercomparison Project Phase 5 (CMIP5)] climate model projections, we find that QRA events are likely to increase by ~50% this century under business-as-usual carbon emissions, but there is considerable variation among climate models. Some predict a near tripling of QRA events by the end of the century, while others predict a potential decrease. Models with amplified Arctic warming yield the most pronounced increase in QRA events. The projections are strongly dependent on assumptions regarding the nature of changes in radiative forcing associated with anthropogenic aerosols over the next century. One implication of our findings is that a reduction in midlatitude aerosol loading could actually lead to Arctic de-amplification this century, ameliorating potential increases in persistent extreme weather events.

Does this mechanism actually hold?
- Does the waveguide cause heat waves?

- LOTS of assumptions in the *Petoukhov et al. 2013* theory

- Most important equation:

$$a^2 l^2 = k_s^2 - k^2$$

Dimensionless zonal wavenumber (specified)

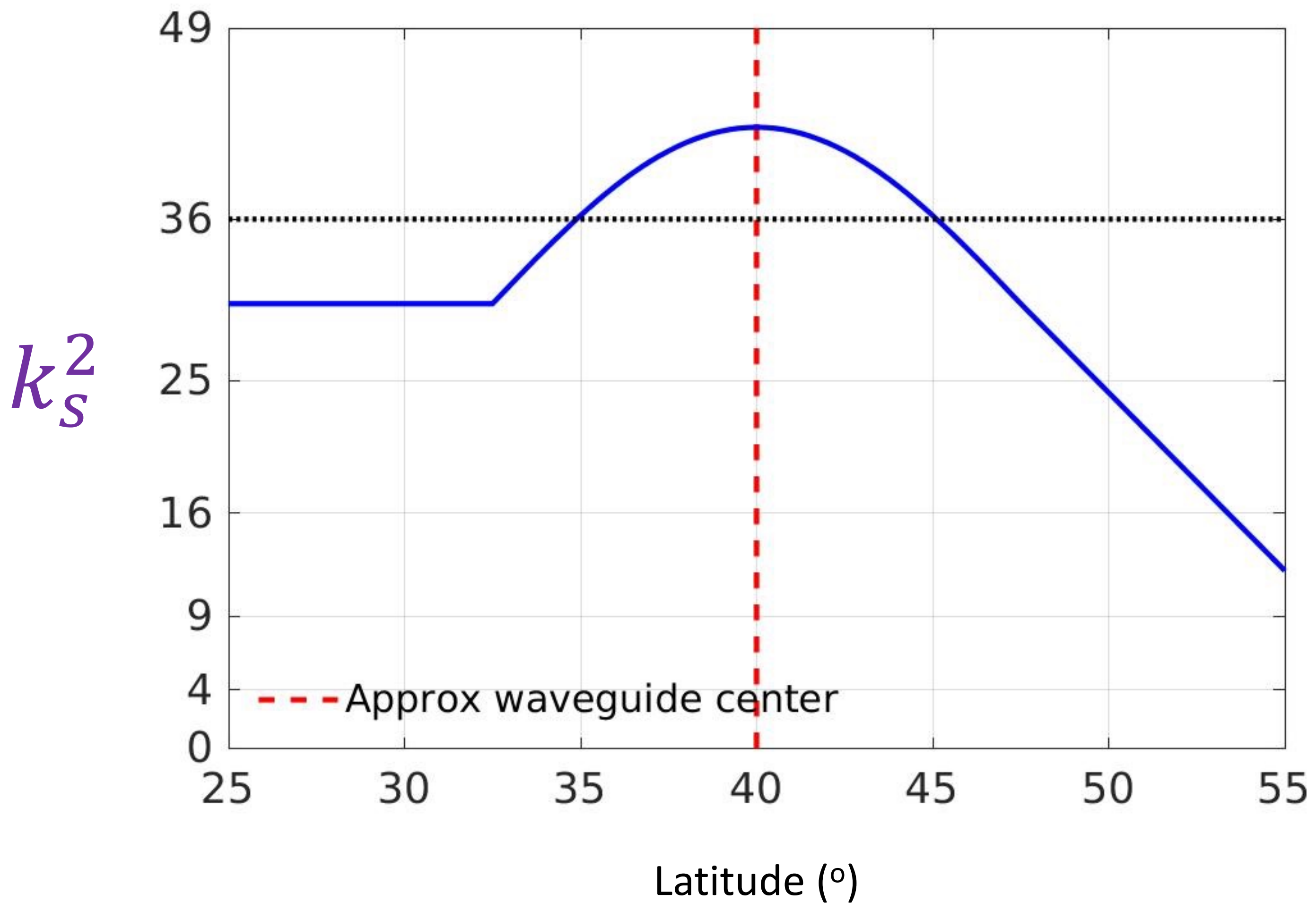
Earth radius

Meridional wavenumber

Stationary wavenumber (function of U)

- Need $l^2 > 0$ to propagate → k_s^2 maxima can trap waves

Simple example stationary wavenumber profile



$$a^2 l^2 = k_s^2 - k^2$$

Should trap $k=6$, but not waves $k \leq 5$ or $k \geq 7$

Testing quasi-resonant amplification

- Plan
  1. Make idealized GCM climate with $k=6$ waveguide
  2. Attempt to force $k=6$ wave
  3. Compare to *Petoukhov et al. 2013*

- Model improvements
  1. Zonally symmetric T_{eq}
  2. Flat topography
  3. Specified heating to excite wave

We create a mean state that has a wave-6 waveguide

Idealized GCM: simple physics, realistic mean flow

Following *Chang 2006* + related works:

1. GFDL spectral dynamical core (T42, ~2.8^o Gaussian grid)

2. Simple physics

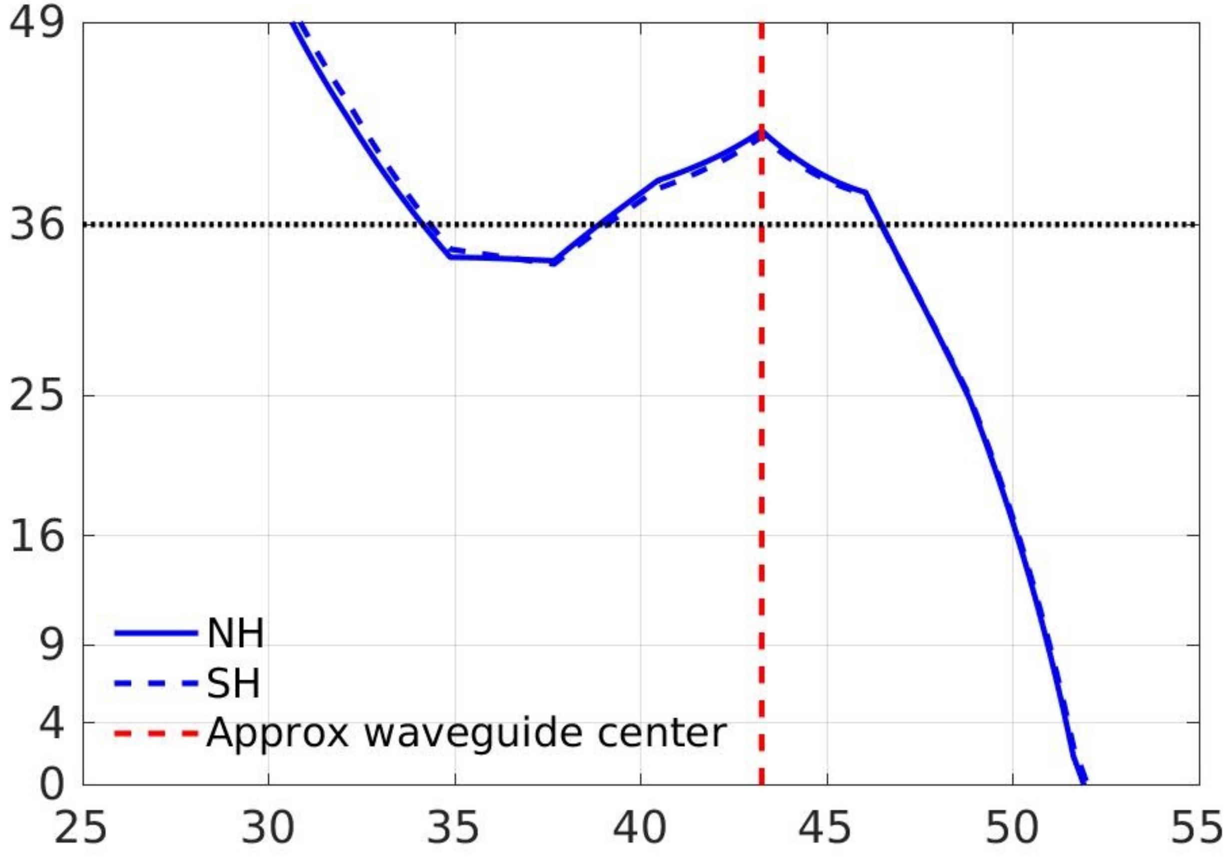
Heating $\left.\frac{\partial T}{\partial t}\right|_Q = \frac{T_{eq} - T}{\tau_Q}$ **Friction** $\left.\frac{\partial \vec{u}}{\partial t}\right|_F = -\frac{\vec{u}}{\tau_F}$

3. Realistic mean flow

$$\underbrace{T_{eq}^{i+1}}_{\text{New } T_{eq}} = \underbrace{T_{eq}^{i}}_{\text{Old } T_{eq}} - \frac{1}{3}\underbrace{\left(\bar{T}^i - T_{target}\right)}_{T \text{ error when model runs w/ old } T_{eq}}$$

Yes, we can create a waveguide

k_s^2

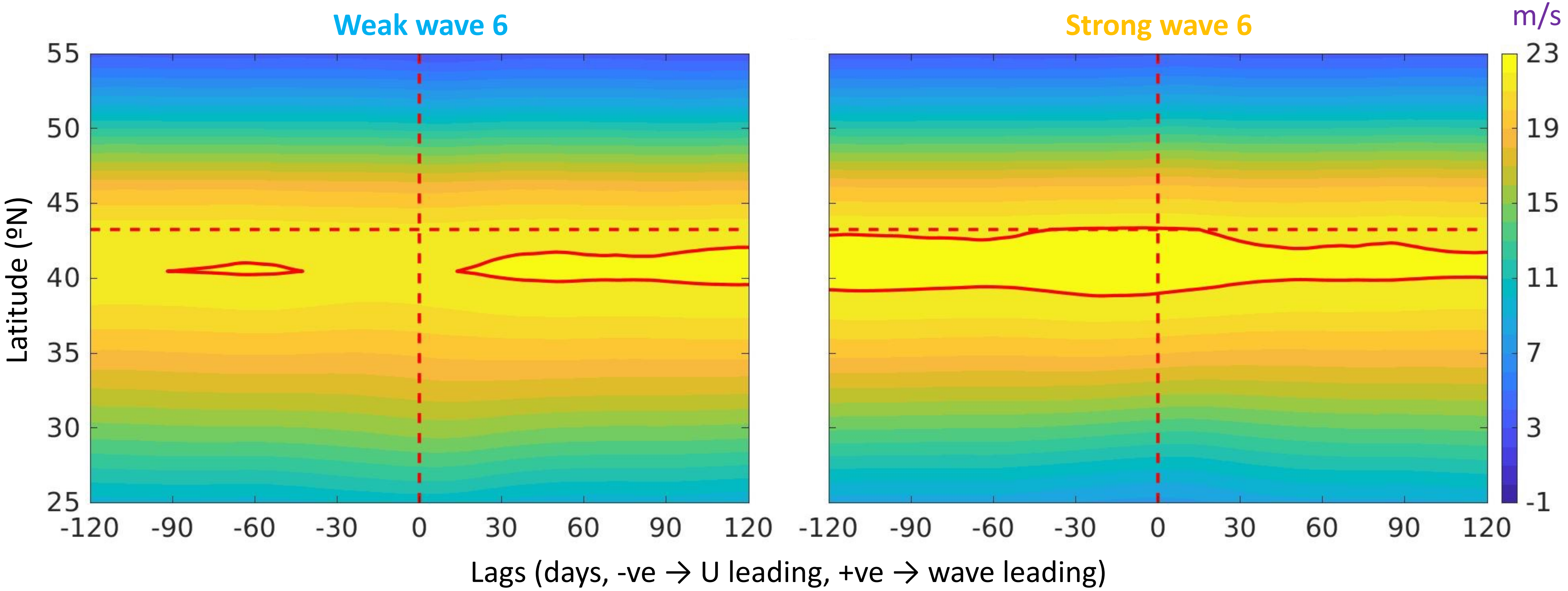


Latitude (º)

- U evaluated at 300 hPa
- 2700-day means

The zonal jet varies with wave 6 amplitude …

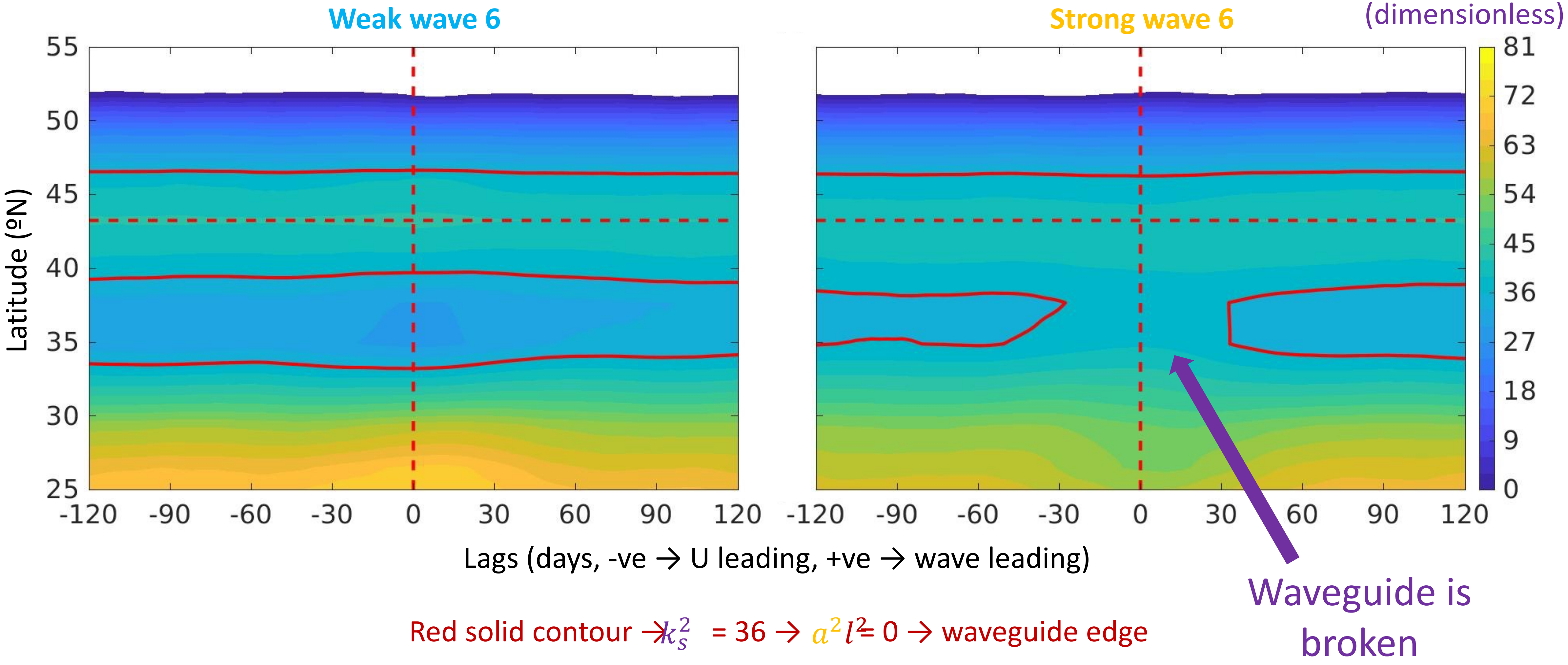
- Composites over 41 30-day means apiece, based on 300 hPa v



Red solid contour → 22 m/s

… as do the waveguide properties (?!)

- Plotted quantity is k_s^2



Red solid contour → k_s^2 = 36 → $a^2 l^2 = 0$ → waveguide edge

Summary of Part II:

We recreate the conditions that are theoretically favorable for Rossby wave quasi-resonant amplification in an idealized model

The strongest wave-6 occurs when the waveguide is broken (for ~ a month on either side of the event!)

QRA does not actually work in a simple model

Conclusions

We derive a new expression for examining the temperature distribution – like using composite analysis for every location and every quantile

Midlatitude temperature distributions are reasonably well explained by horizontal temperature advection
- This makes QRA plausible

QRA doesn’t seem to work even in a simple model.

References:

Linz, M., Chen, G., Zhang, B., & Zhang, P. (2020). A framework for understanding how dynamics shape temperature distributions. *Geophysical Research Letters*, 47, e2019GL085684. https://doi.org/10.1029/2019GL085684

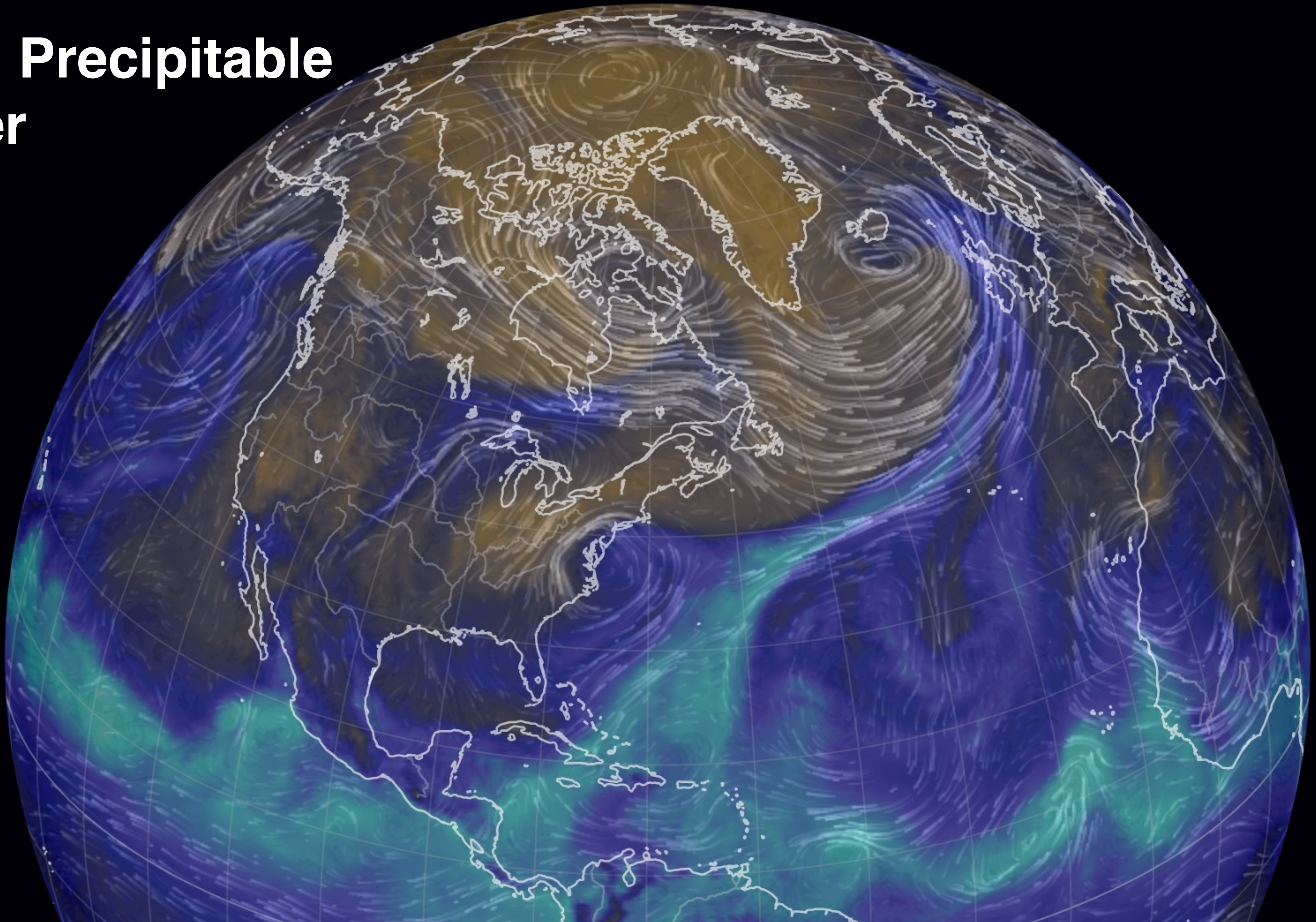
Zhang, B., Linz, M., & Chen, G. (2022). Interpreting Observed Temperature Probability Distributions Using a Relationship between Temperature and Temperature Advection, *Journal of Climate*, *35*(2), 705-724. https://journals.ametsoc.org/view/journals/clim/35/2/JCLI-D-20-0920.1.xml

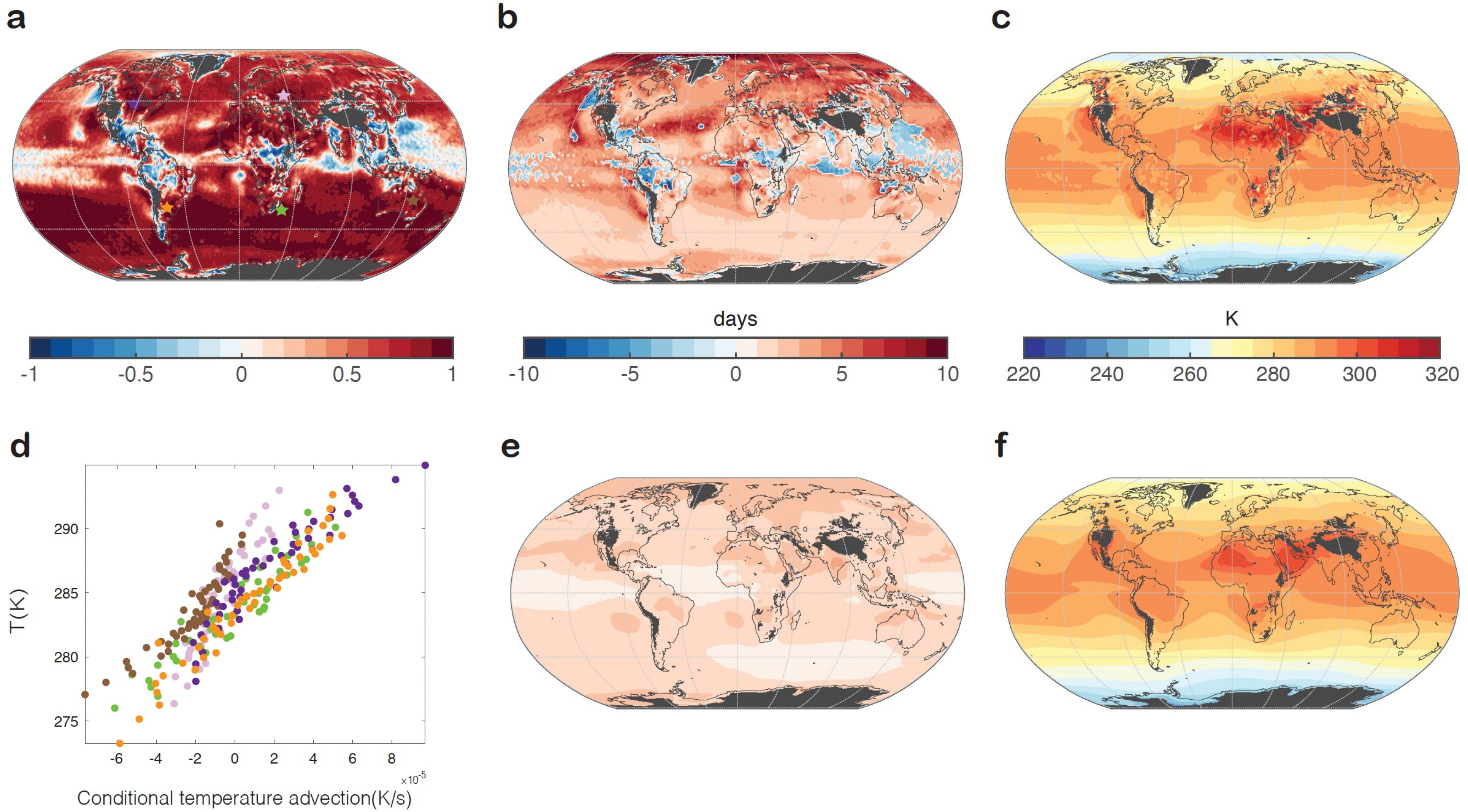
Quan, H., Linz, M., Zhang, B., Chen, G., and Bourguet, S.: How Do Different Processes Shape Temperature Probability Distributions? A Percentile-averaged Temperature Tendency Decomposition. Submitted to Journal of Climate

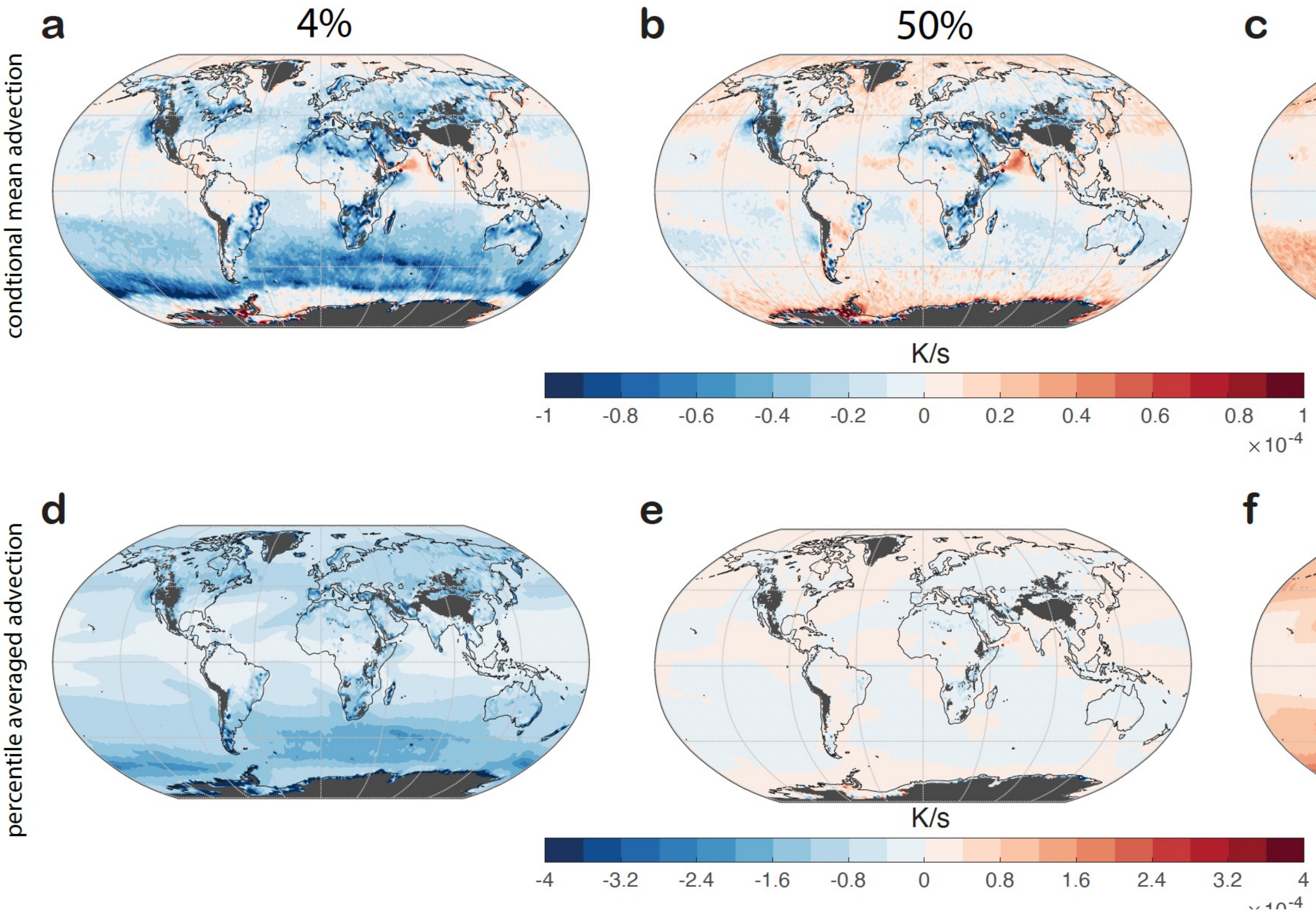
Mooring, T. and Linz, M. An Examination of Quasiresonant Amplification of Rossby Waves in an Idealized Climate Model. in prep. (will be submitted in November)

Tamarin-Brodsky, T., et al. Changes in Northern Hemisphere temperature variability shaped by regional warming patterns Nature Geoscience 2020

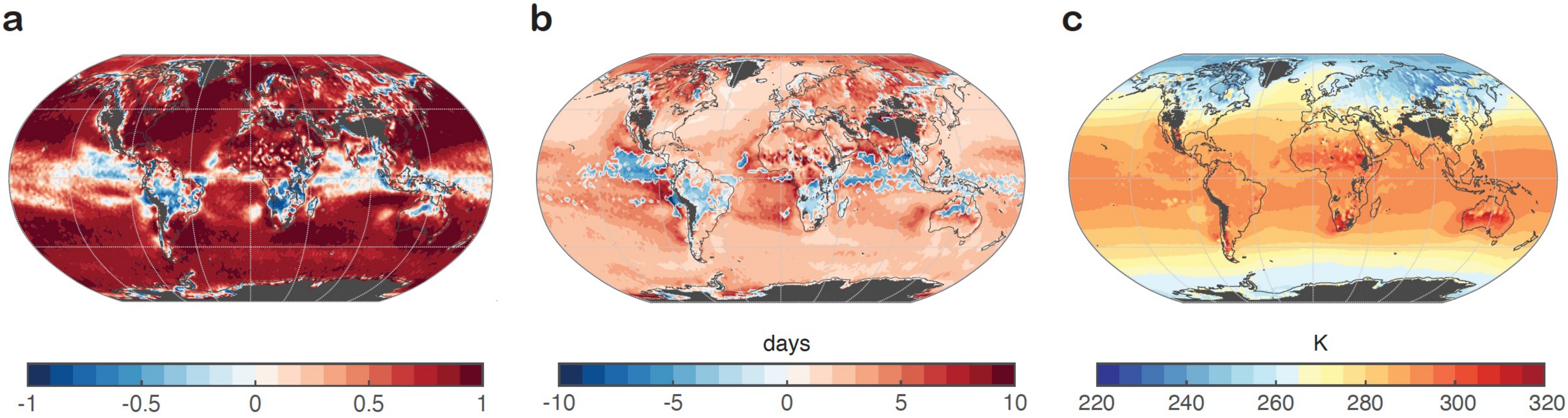
Total Precipitable Water




a
b
c
days
K
-1
-0.5
0
0.5
1
-10
-5
0
5
10
220
240
260
280
300
320
d
e
f
T(K)
290
285
280
275
-6
-4
-2
0
2
4
6
8
$\times 10^{-5}$
Conditional temperature advection(K/s)


a
4%
b
50%
c
96%
condional mean advection
K/s
-1
-0.8
-0.6
-0.4
-0.2
0
0.2
0.4
0.6
0.8
1
$\times 10^{-4}$
d
e
f
percentile averaged advection
K/s
-4
-3.2
-2.4
-1.6
-0.8
0
0.8
1.6
2.4
3.2
4
$\times 10^{-4}$

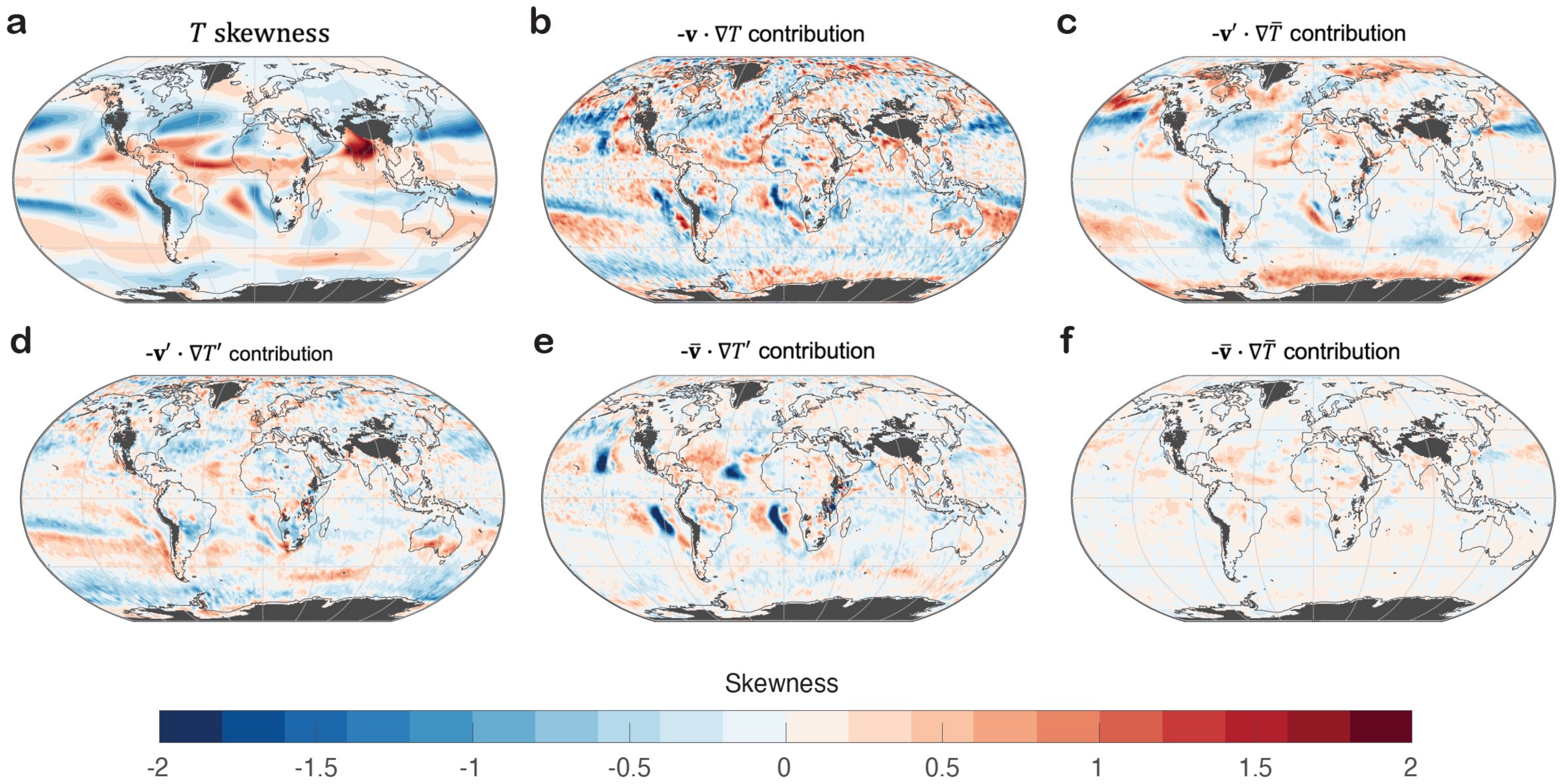
$$\langle\theta\rangle^{e} = -\tau\,\langle\mathbf{v}\cdot\nabla\theta\rangle^{e} + \theta_0$$

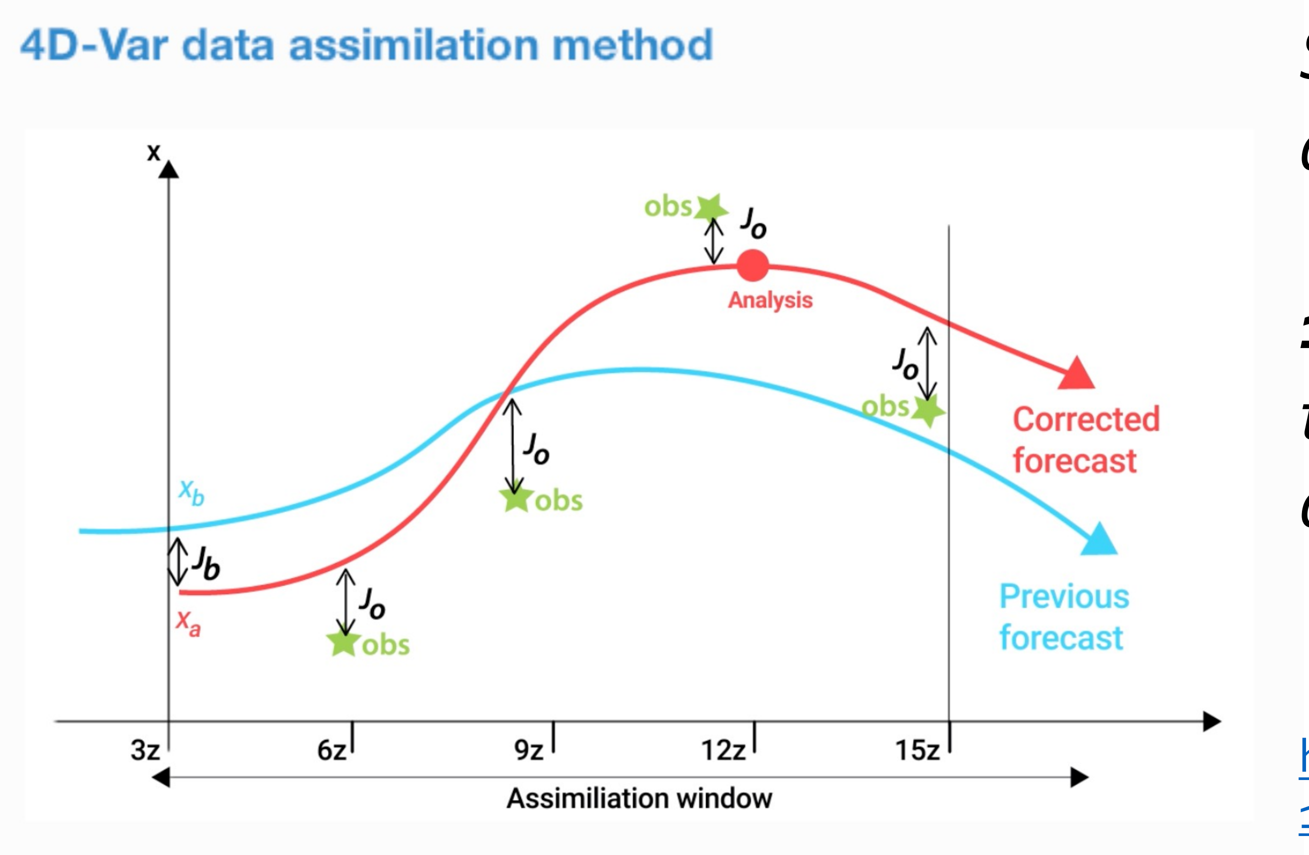


How much does advection matter for skewness?

$$S_{-\mathbf{v}\cdot\nabla T} = \frac{T_w - T_c}{\frac{1}{2}(T_w + T_c)} = \frac{\tau \cdot ((-\mathbf{v}\cdot\nabla T)_w - (-\mathbf{v}\cdot\nabla T)_c)}{\sigma_T}$$

Follows from Tamarin-Brodsky et al. 2020





Schematic of state of the art assimilation from ECMWF.

***150 million** model values (like temperature) are adjusted during this process.*

https://www.ecmwf.int/assets/elearning/da/da1/story_html5.html