Understanding the effect of global warming on precipitation extremes: progress and challenges

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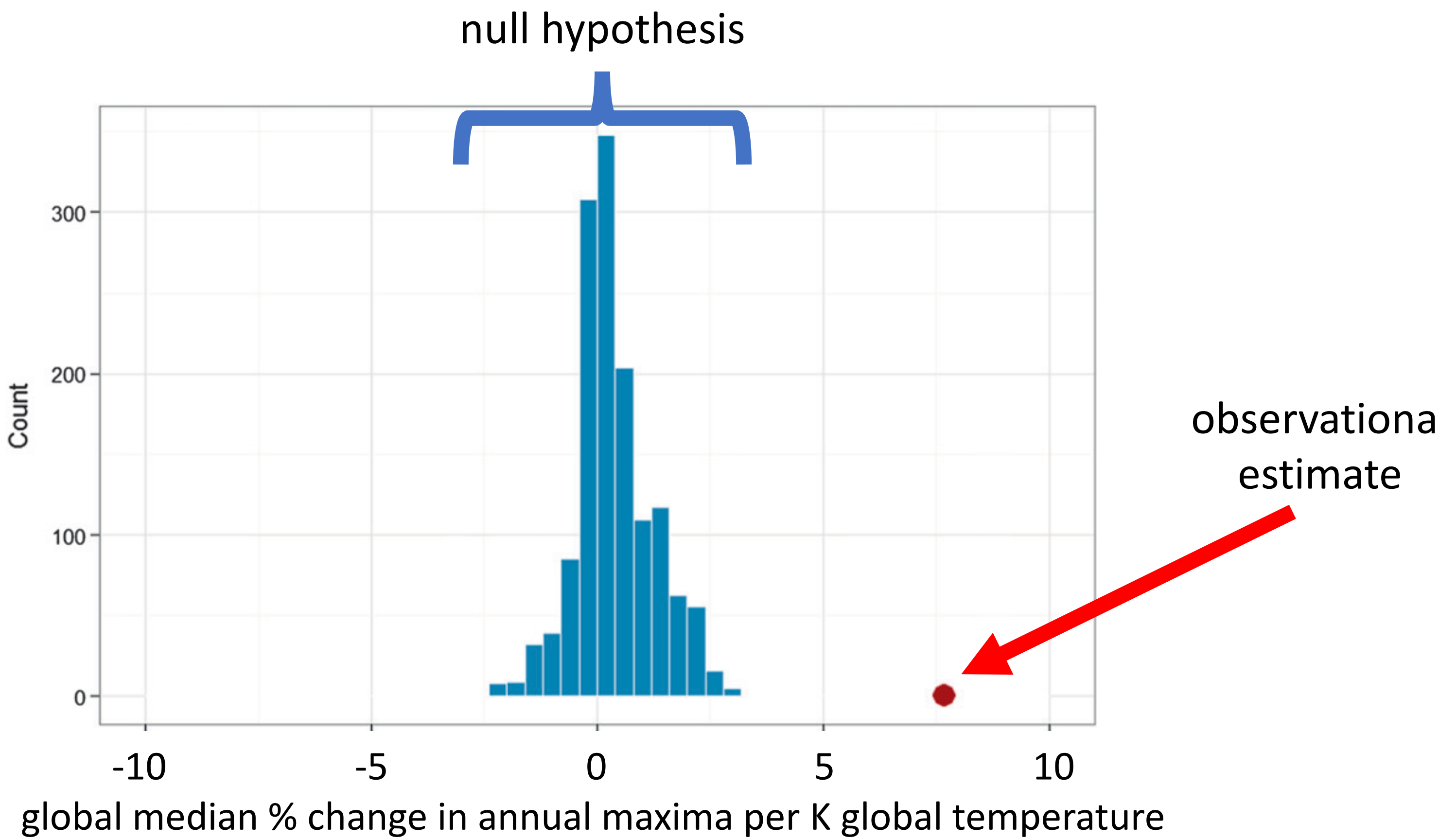
What are precipitation extremes?

- Heaviest rainfall events
- Defined as high percentile of distribution
  - (e.g., annual maximum daily rainfall)
- Range of time and spatial scales of interest

2010 Pakistan floods (photo: UPI)

Are precipitation extremes stronger in a warmer world?

Observations indicate higher global temperature is associated with more intense precipitation extremes



Observational estimate of sensitivity of annual maximum daily precipitation to global-mean temperature (Westra et al., 2013)

Extreme precipitation events over most of the mid-latitude land masses and over wet tropical regions will very likely become more intense and more frequent by the end of this century, as global mean surface temperature increases.

IPCC, AR5, Summary for policymakers

How much will precipitation extremes change in Wollongong by 2100?

- Why do we expect precipitation extremes to increase with warming?

- How can we constrain the magnitude of future changes in precipitation extremes at regional scale

What sets the upper limit on precipitation rates?

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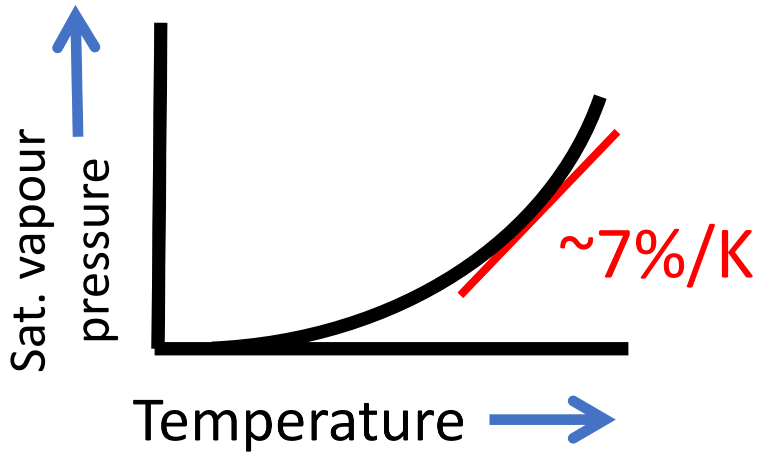
- Heaviest rainfall constrained by available water vapour? (Trenberth, 1999)



“Clausius-Clapeyron relationship”

What sets the upper limit on precipitation rates?

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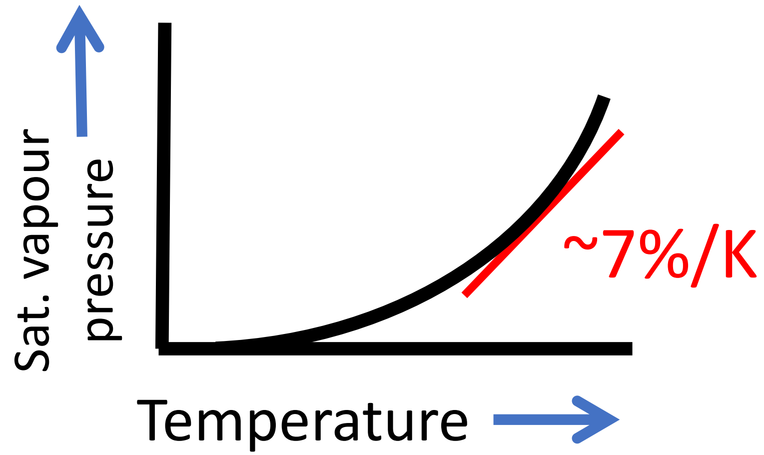
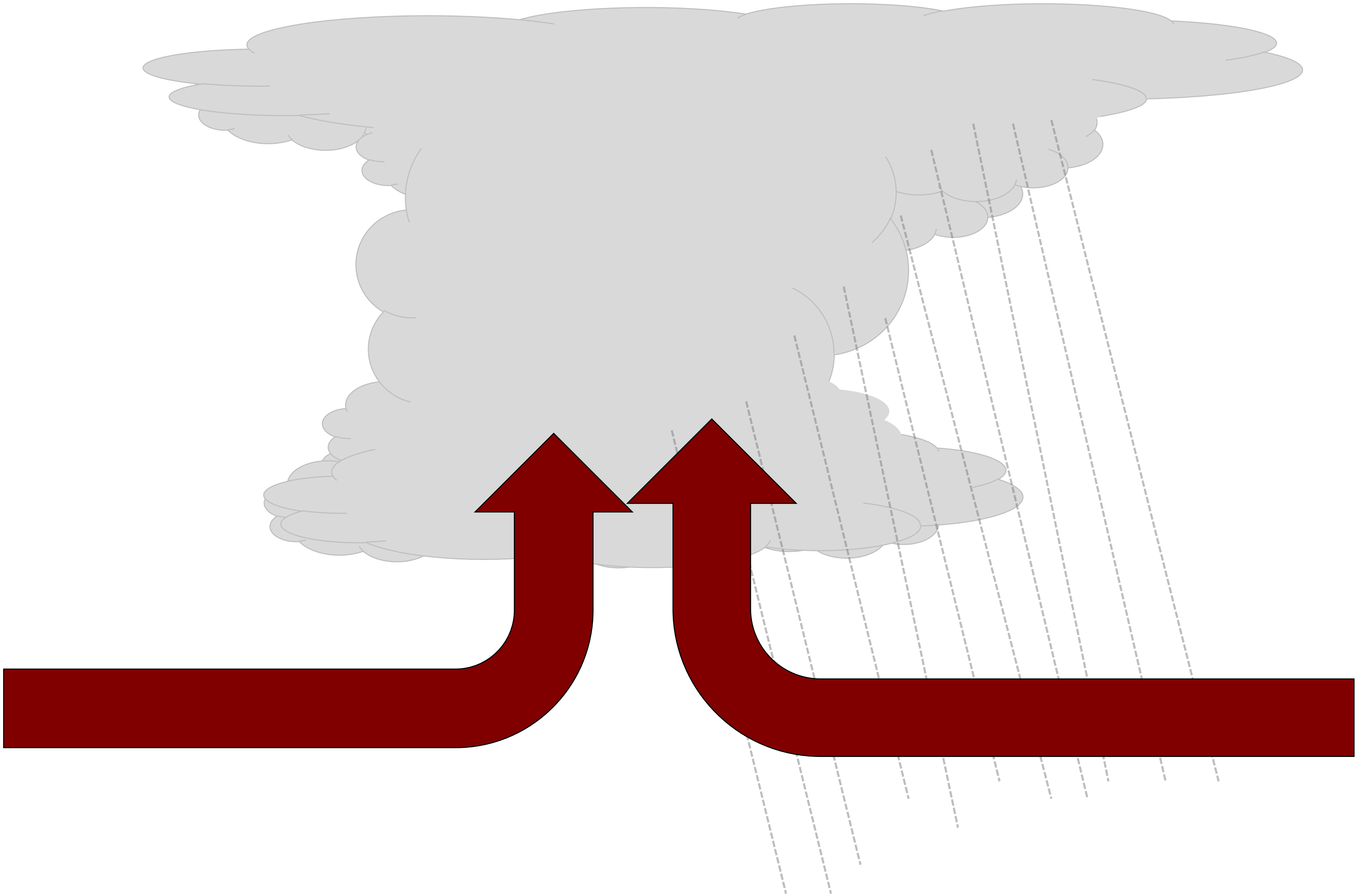


What's wrong with this argument?

Heavy precipitation events draw in moisture from their surroundings!



Instead, consider the dynamics of precipitation extreme events themselves

$$P_e = \epsilon \times \omega \times q_s$$

extreme precipitation rate

efficiency

large-scale upward motion

(vertical gradient of) saturation humidity

Humidity is not the only factor controlling precipitation extremes

e.g., O'Gorman & Schneider (2009); Muller & O'Gorman (2011); Singh & O'Gorman (2014)

Precipitation extremes under warming

$$\frac{\delta P_e}{P_e} \approx \frac{\delta \epsilon}{\epsilon} + \frac{\delta \omega}{\omega} + \frac{\delta q_s}{q_s}$$

microphysical

dynamical

thermodynamical

Simple thermodynamic scaling for precipitation extremes

- If ϵ and ω remain constant:

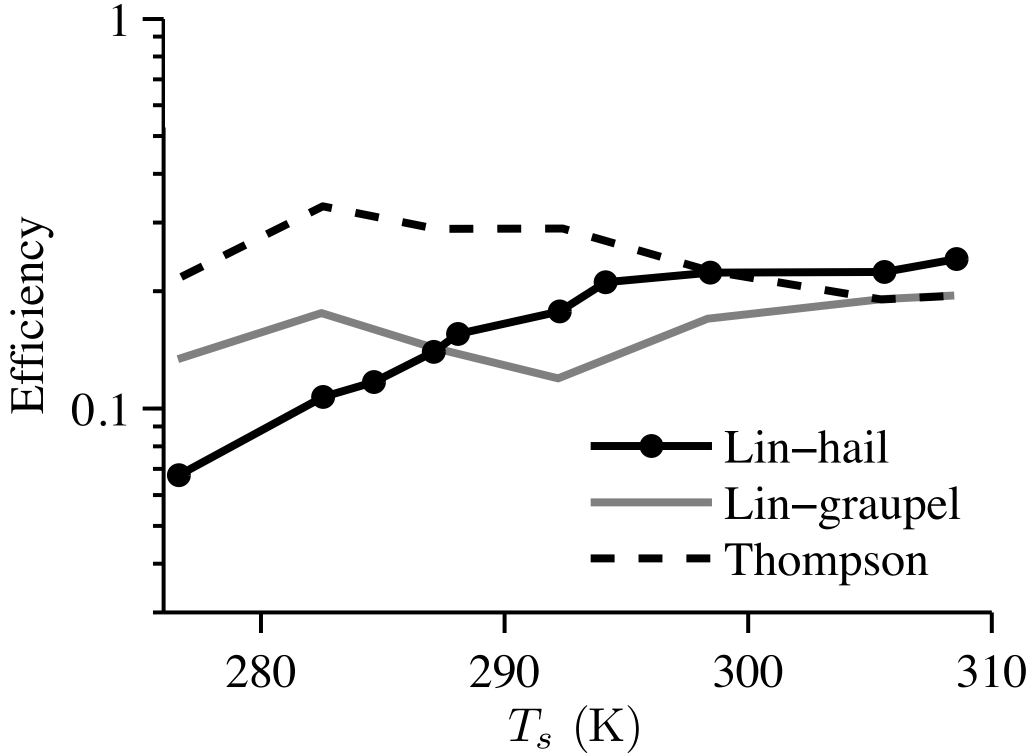
$$P_e \propto q_s$$

- Precipitation extremes increase at roughly 4-7%/K
- Similar to Clausius-Clapeyron scaling

Do we expect precipitation extremes to scale with moisture content after all?

Efficiency potentially important for convective-scale extremes

- ϵ represents the efficiency of turning large rates of column net-condensation into large precipitation rates



Measure of ϵ for simulations of RCE at different surface temperatures (Singh & O'Gorman., 2014)

Efficiency potentially important for convective-scale extremes

- ϵ represents the efficiency of turning large rates of column net

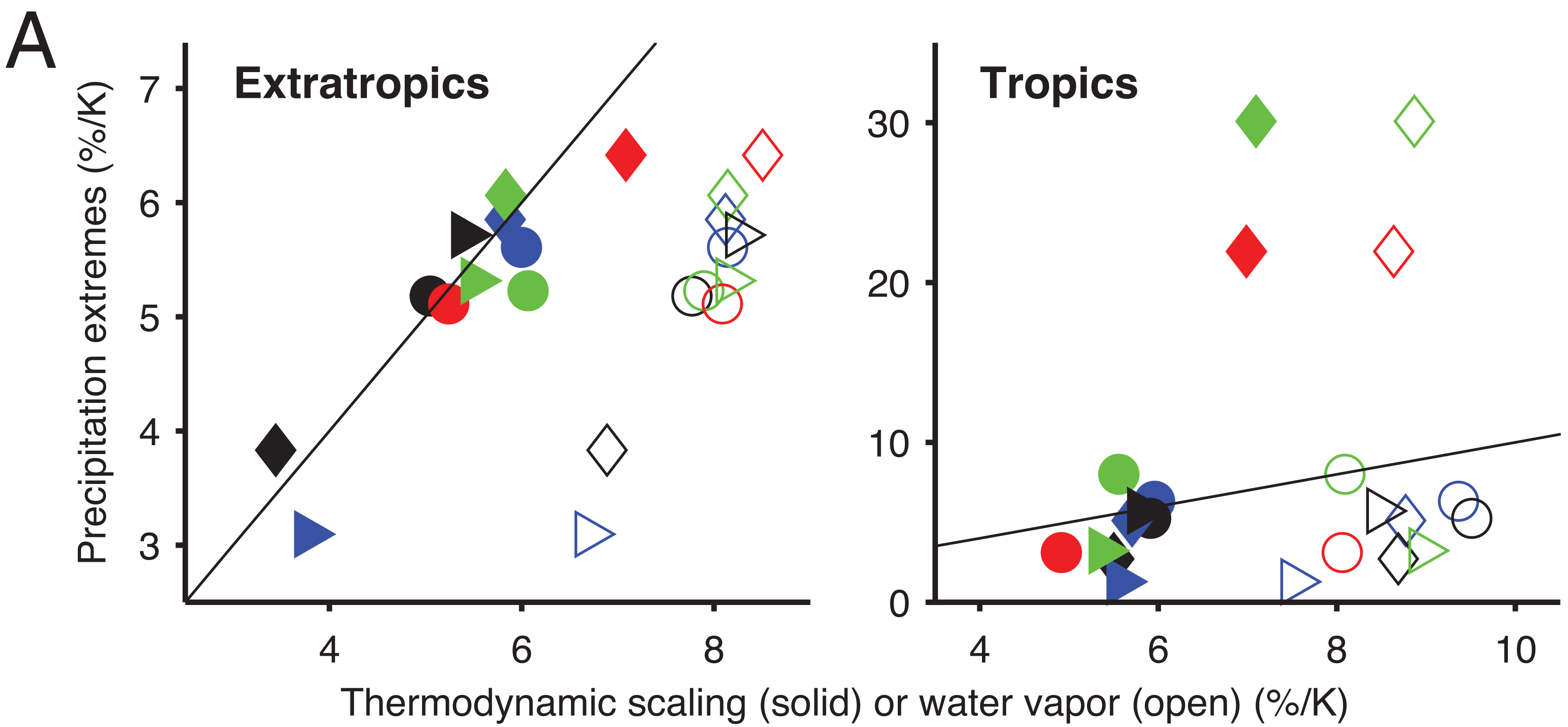
At large time and space scales (e.g., daily extremes at GCM-gridbox scale) changes in efficiency unimportant for changes in precipitation extremes

But dynamics are important!

T_s (K)

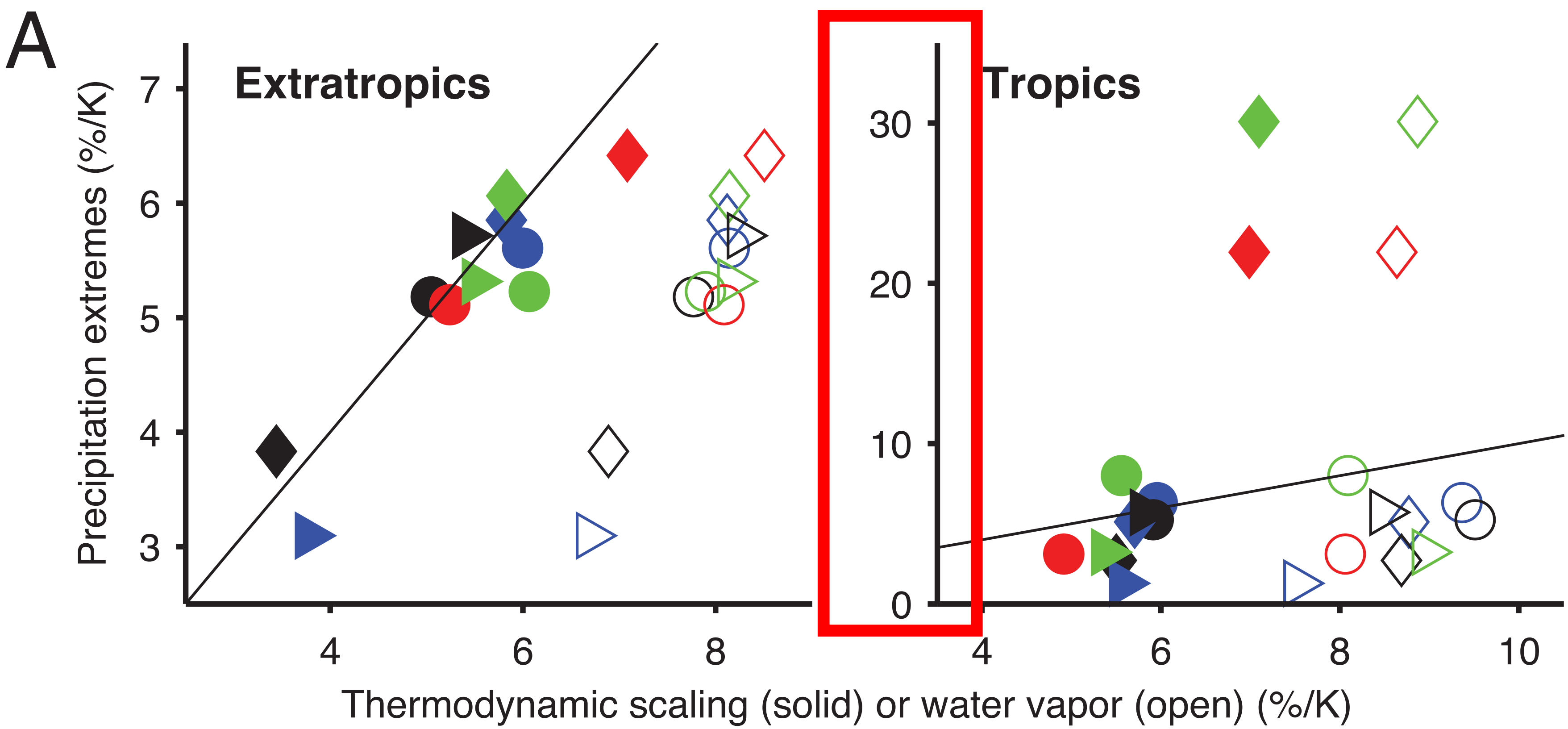
Measure of ϵ for simulations of RCE at different surface temperatures (Singh & O'Gorman., 2014)

In model projections, thermodynamic contribution dominates in the extratropics



Sensitivity of 99.9th percentile of precipitation to surface temperature in CMIP5 models (O'Gorman & Schneider, 2009)

But no agreement in changes to tropical precipitation extremes



Sensitivity of 99.9th percentile of precipitation to surface temperature in CMIP5 models
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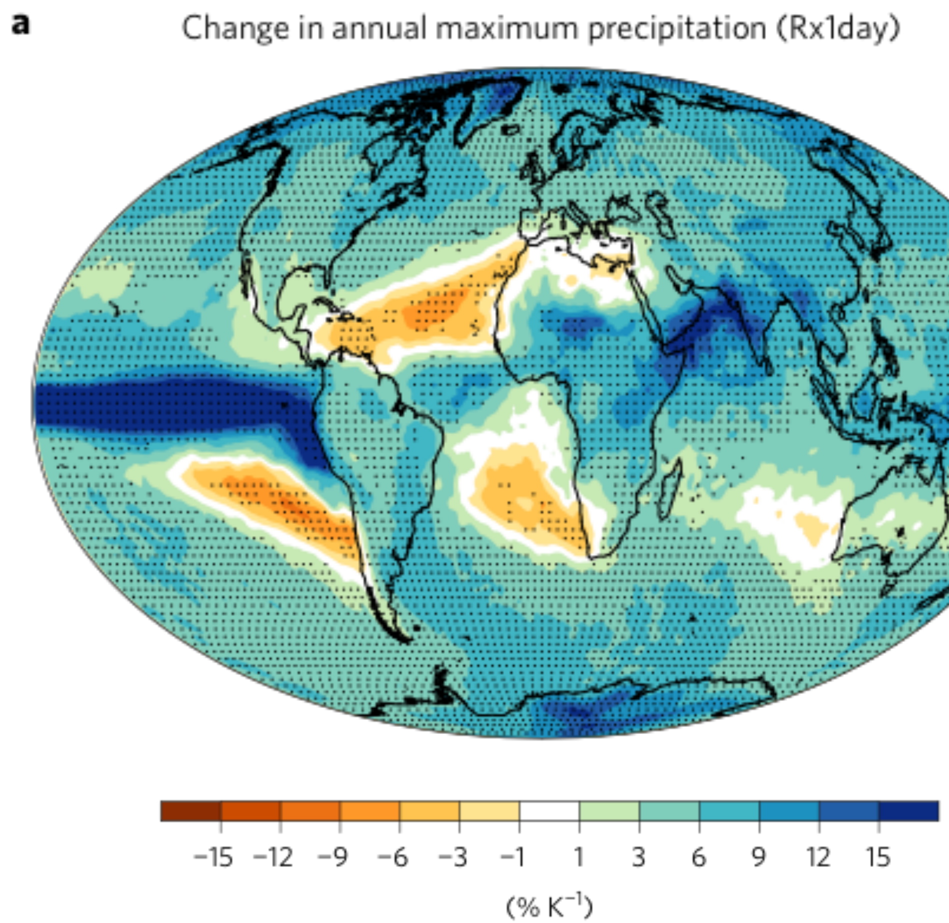
What sets the spatial pattern of changes to precipitation extremes with warming?



Multi-model mean over 22 CMIP5 models. Stipling where 80% of models agree on sign. (Pfahl et al. 2015)

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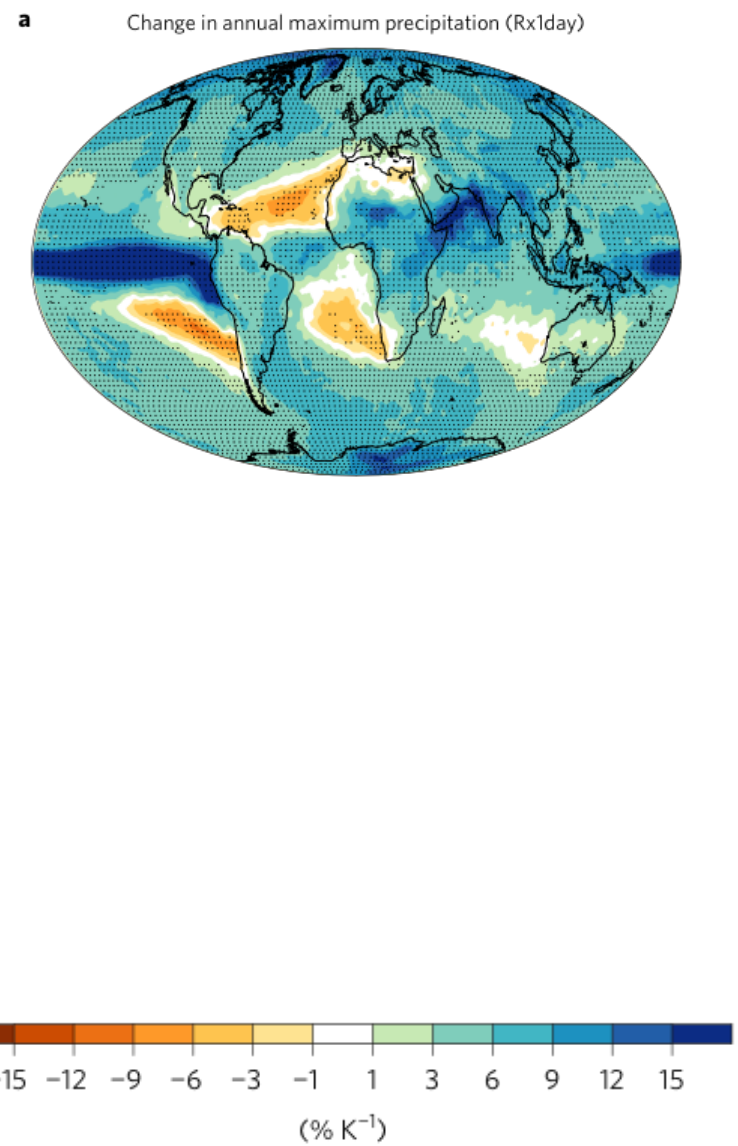
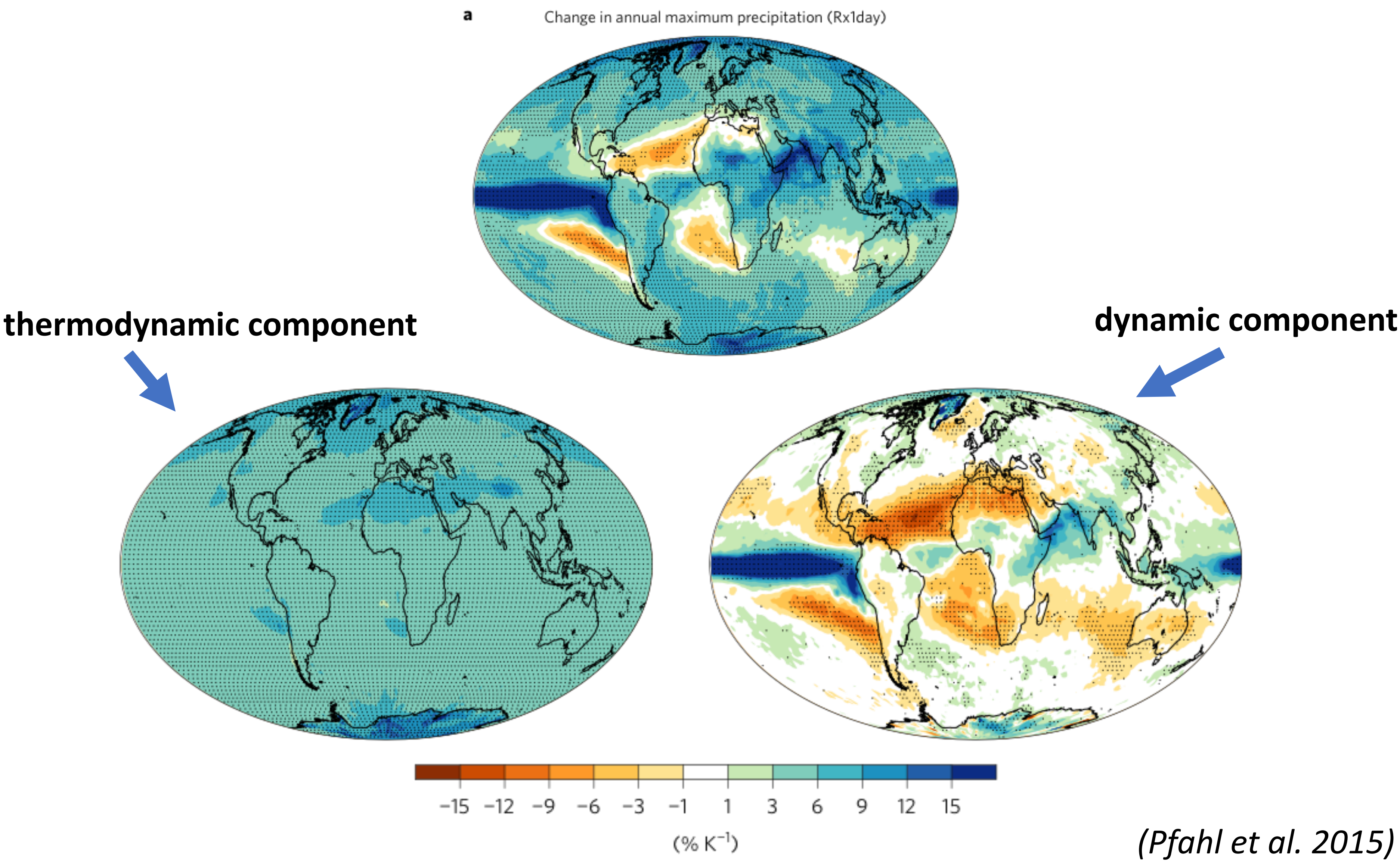


(Pfahl et al. 2015)

Spatial pattern determined by dynamic component



(Pfahl et al. 2015)

What can we say about precipitation extremes?

- Thermodynamic component gives large and robust increase in precipitation extremes

- But dynamic component may also be large in the tropics, and on regional scales
  - magnitude and spatial pattern of changes remain uncertain

Understanding changes in precipitation extremes requires understanding how large-scale upward motion will change under warming

How can we constrain future changes in (tropical) precipitation extremes?

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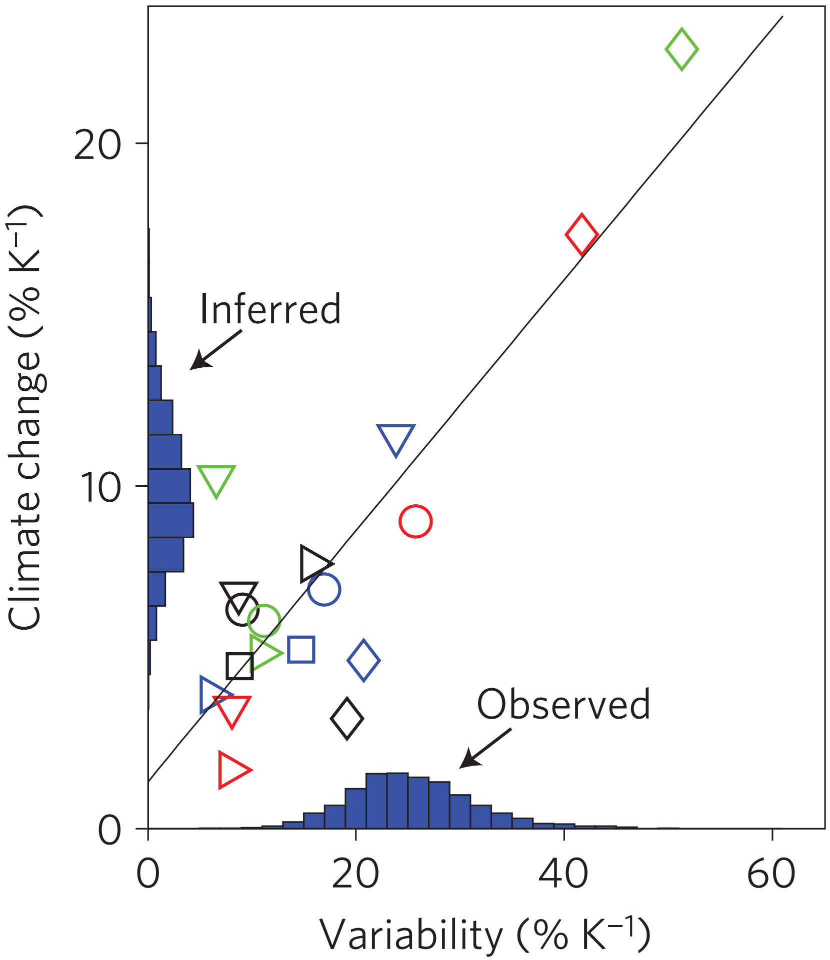
<u>Problem:</u>

Grid-scale vertical velocity relies on interaction between convection and large scale

- poorly simulated in global models
- No guarantee that good simulation of control climate leads to good simulation of changes

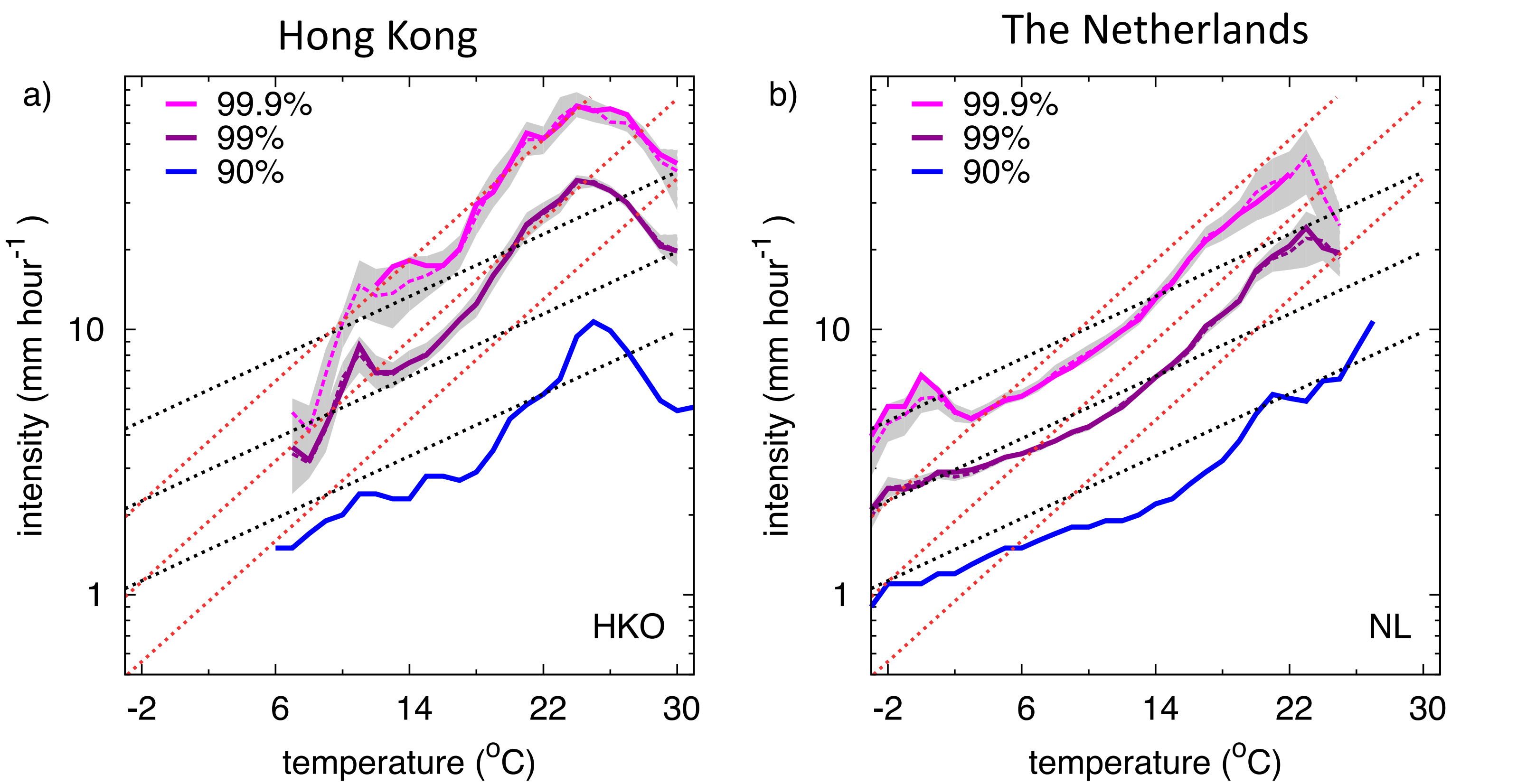
Direction I: Observational constraints

Combine GCMs and observations of variability to derive an “emergent constraint” on precipitation extremes



Tropical-mean changes in precipitation extremes across 18 models (O’Gorman 2012)

Could this be applied on smaller scales?



(Lenderink et al., 2011)

Can these results be used to reason about global warming?

Could this be applied on smaller scales?

Bao et al. (2017) showed (award winning work!) that climate response different to variability

Missing: physical model connecting variability to climate change

Can these results be used to reason about global warming?

Direction II: Theoretical constraints

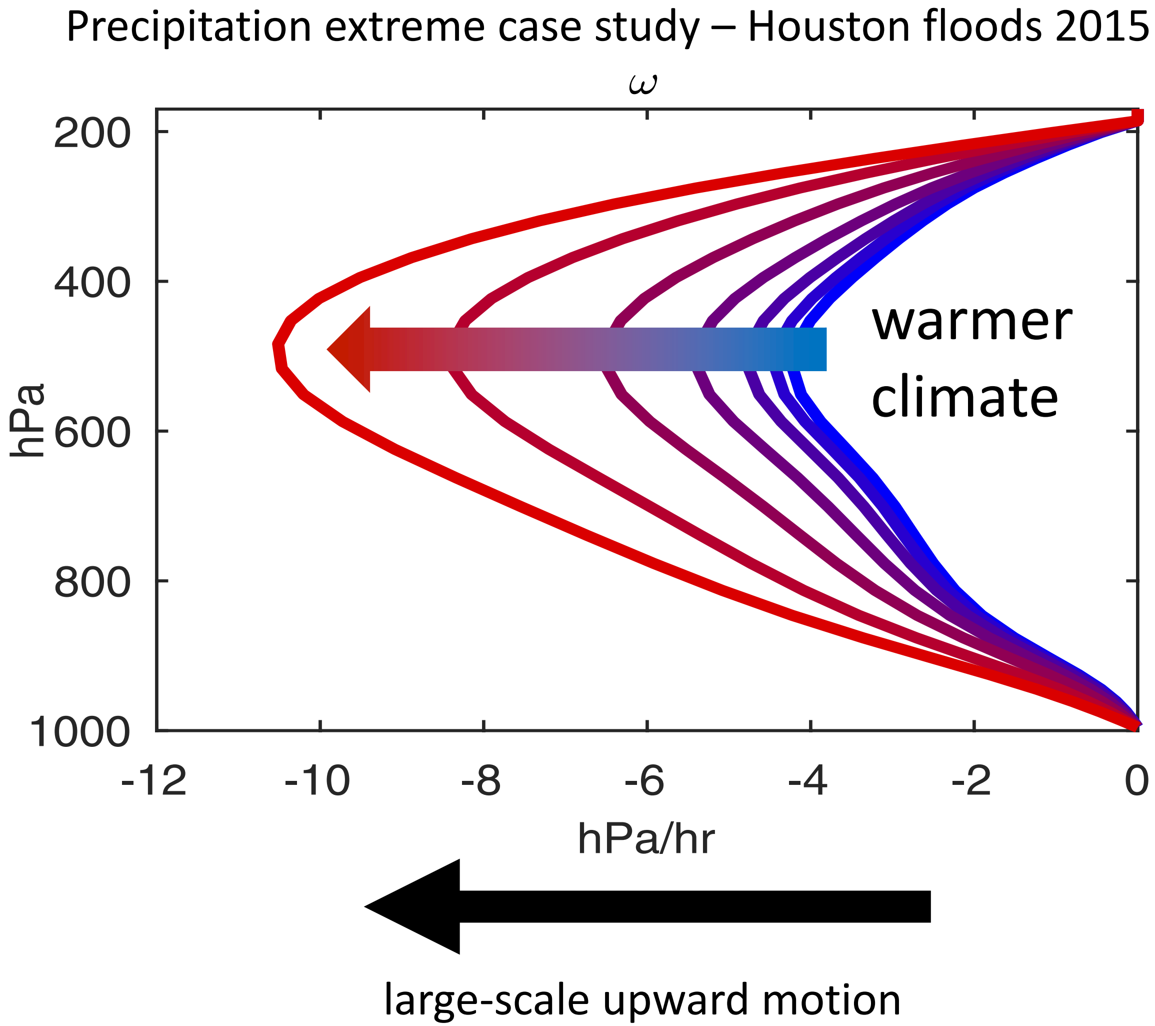
- Use QG-omega equation to reason about changes to upward motion (e.g., Tandon et al., 2018)

$$\frac{N^2}{f^2}\nabla_h^2\omega + \partial_{pp}\omega = \mathcal{F}(\zeta, T, Q)$$

convective heating

- Can use CRM to calculate the convective heating

Precipitation extreme case study – Houston floods 2015



Nie et al. (2018)

Direction III: Regional-scale simulations with cloud permitting models

- Some studies find super-CC scaling in convective precipitation extremes (Kendon et al., 2014) while others do not (Ban et al., 2015)

- May depend on region, model or boundary conditions

- Much work to be done…

Climate change will very likely cause increases in precipitation extremes across the globe

- To understand magnitude and spatial pattern need to predict changes to the dynamics (woo!)

- Need to combine observations, theory, and high-resolution models (along with GCMs) to achieve this