Maritime Convection

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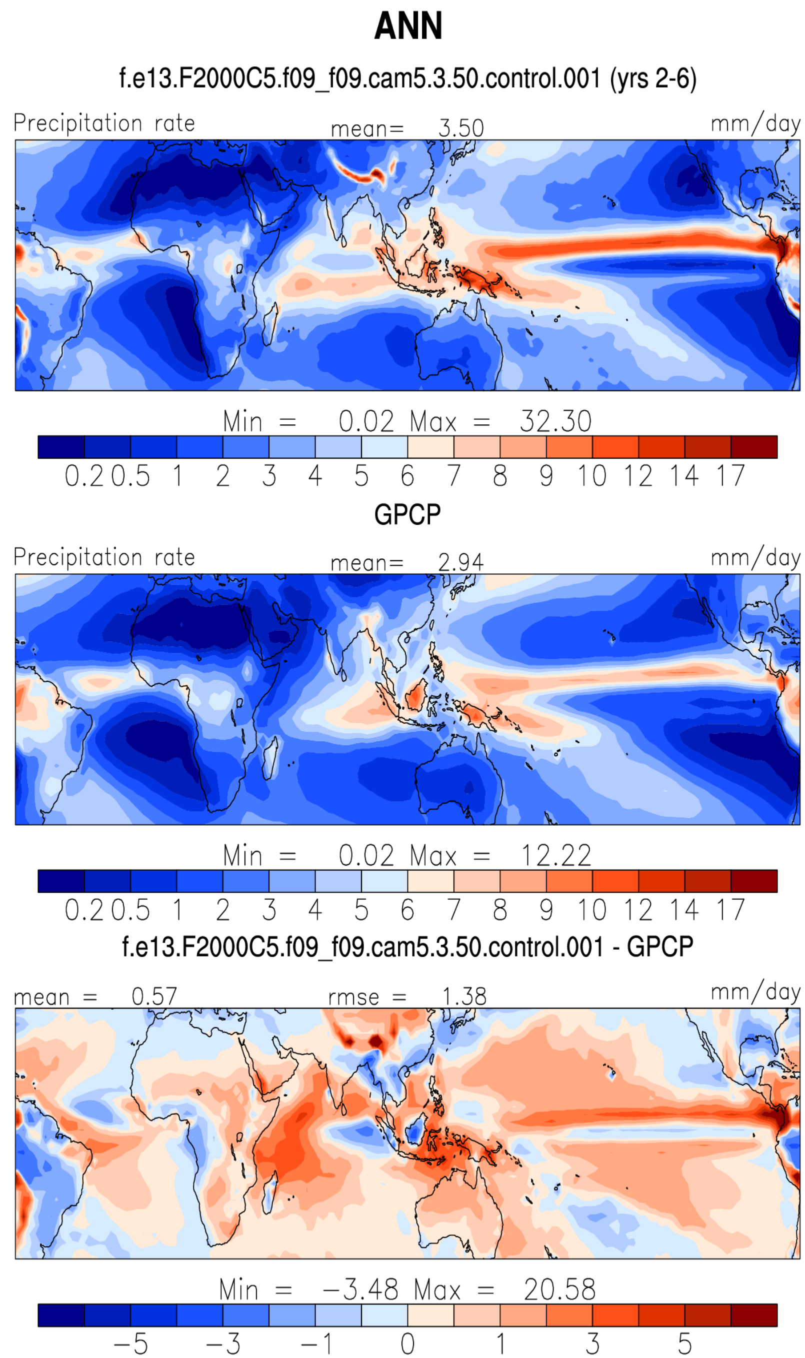
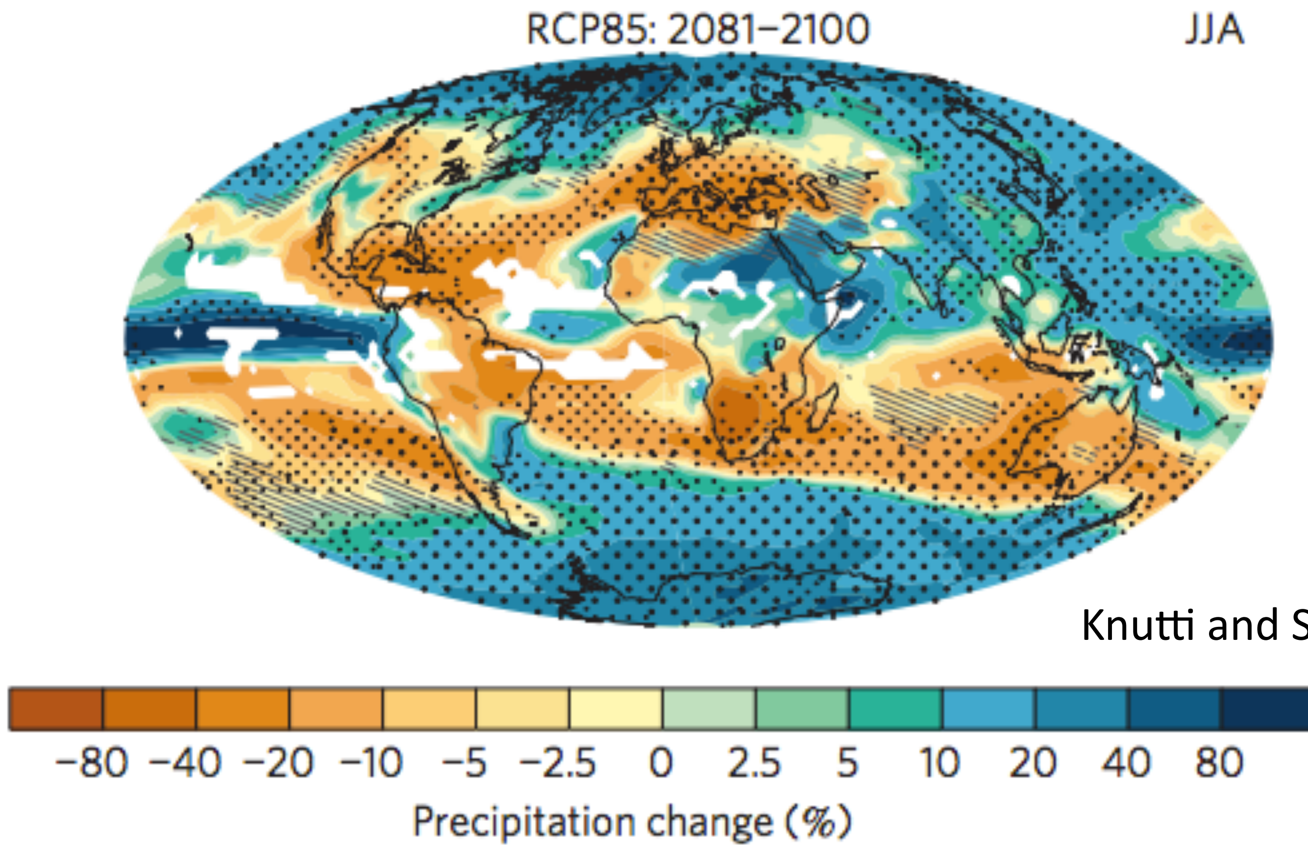
Why Maritime?

- Simpler boundary conditions
- Still significant difficulties simulating, even with specified SST
- Problems compound with ocean

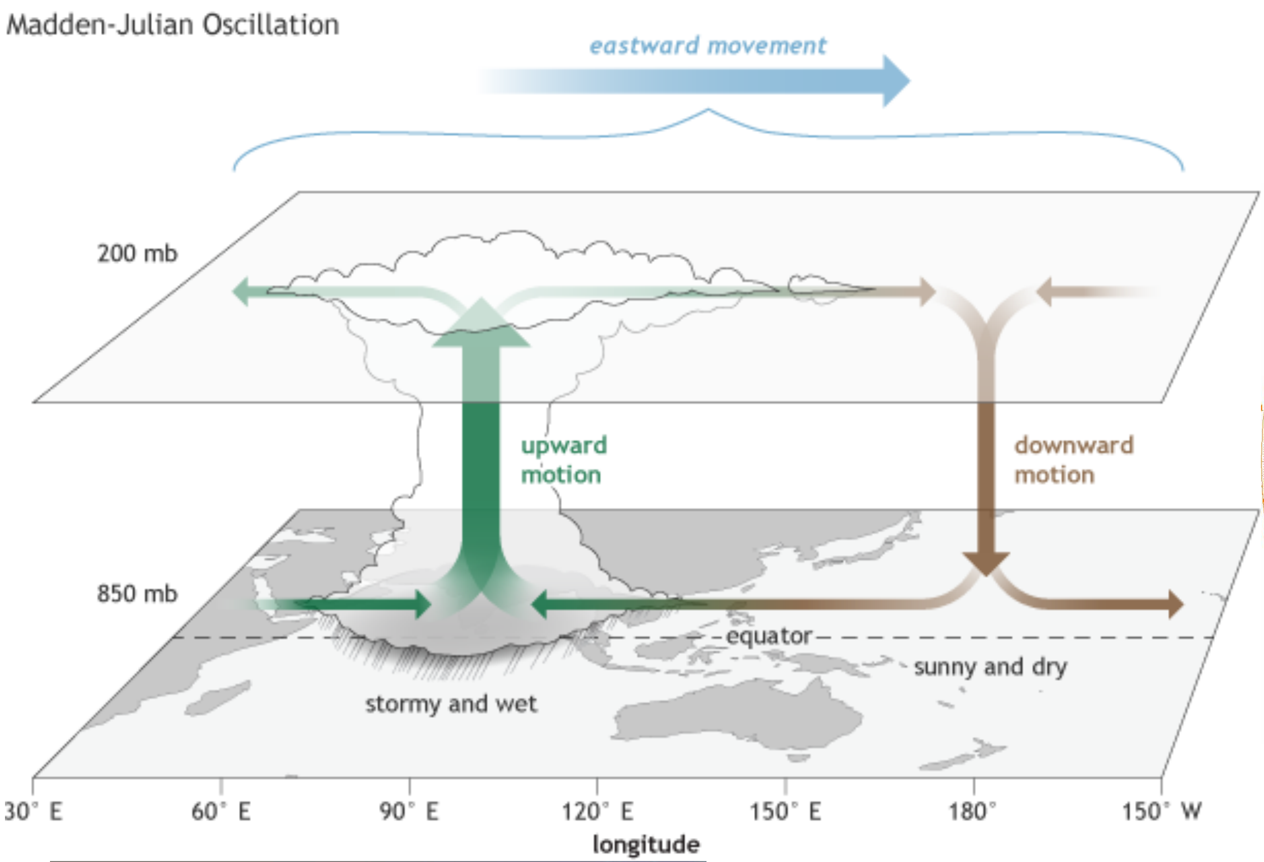


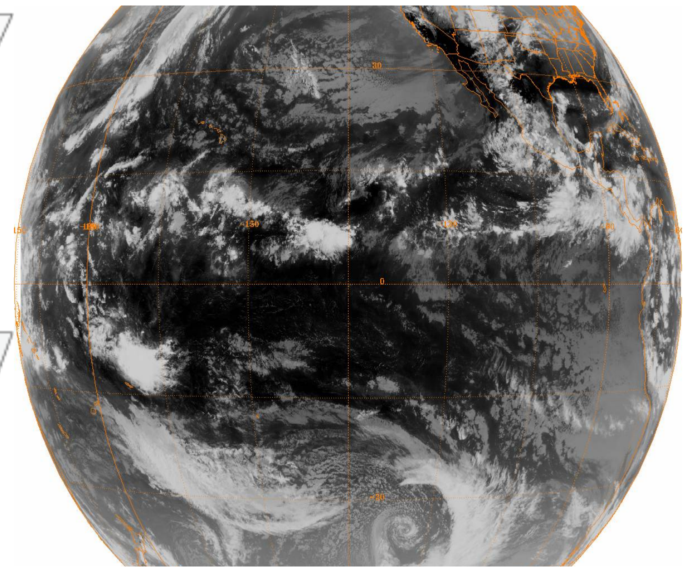
Substantial uncertainties in how tropical rainfall will change with climate

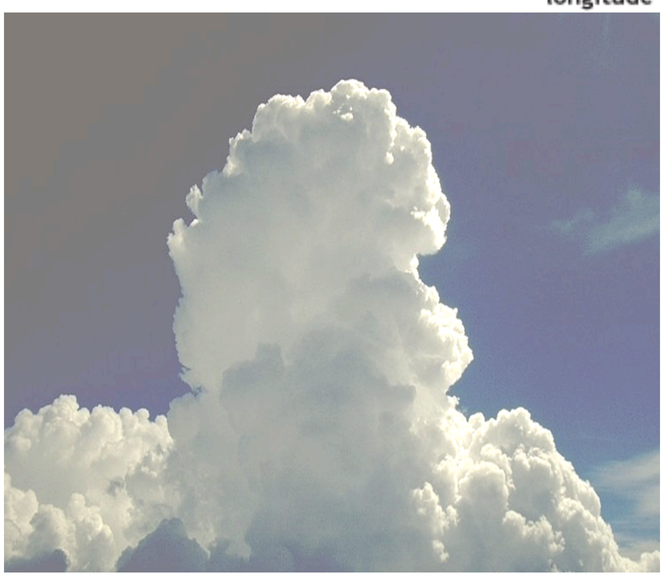


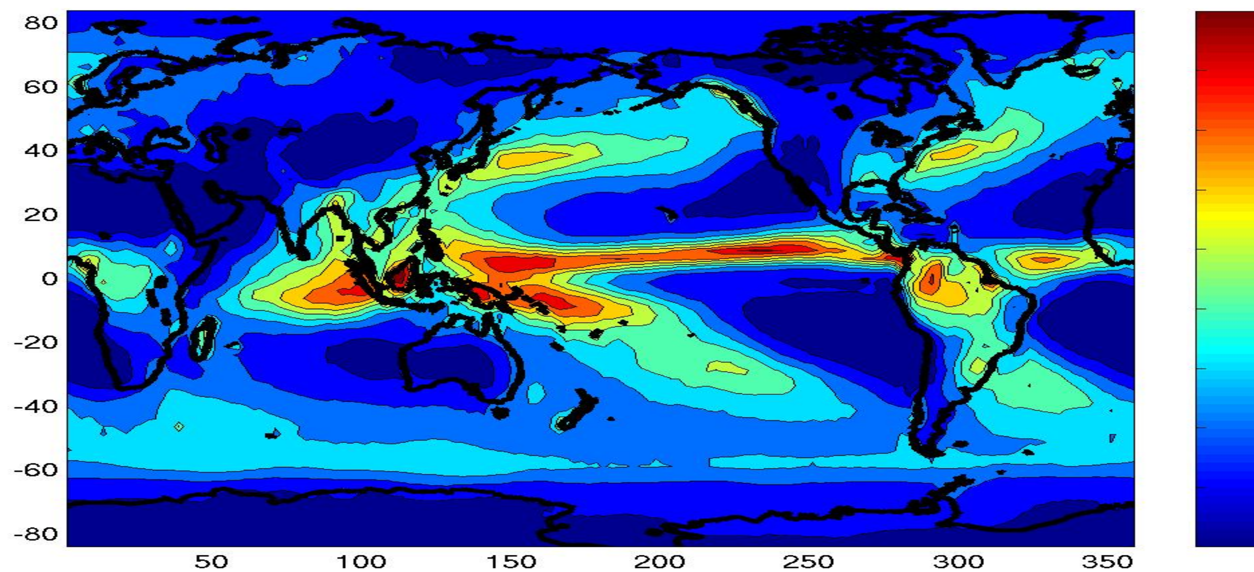
Knutti and Sedlacek (2012)

Stipling marks robust changes, white areas mark uncertain sign of changes


Madden-Julian Oscillation
eastward movement
200 mb
upward
motion
downward
motion
850 mb
equator
sunny and dry
stormy and wet
30° E
60° E
90° E
120° E
150° E
180°
150° W
longitude






80
60
40
20
0
-20
-40
-60
-80
50
100
150
200
250
300
350

Prediction issues underlie uncertainties about how convection works

Key scientific frontiers:

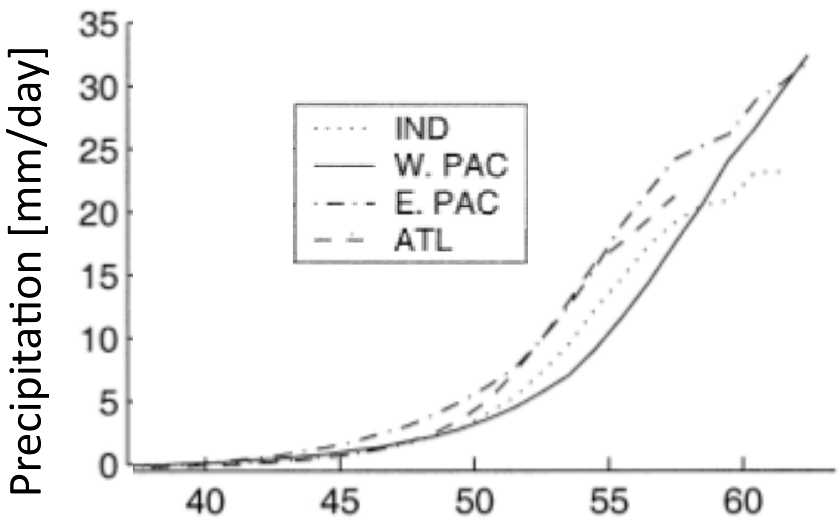
- Factors controlling the form and distribution of convection
- Effect of convection on the environment
- Response of convection to climate change

All of this is also relevant for continental convection

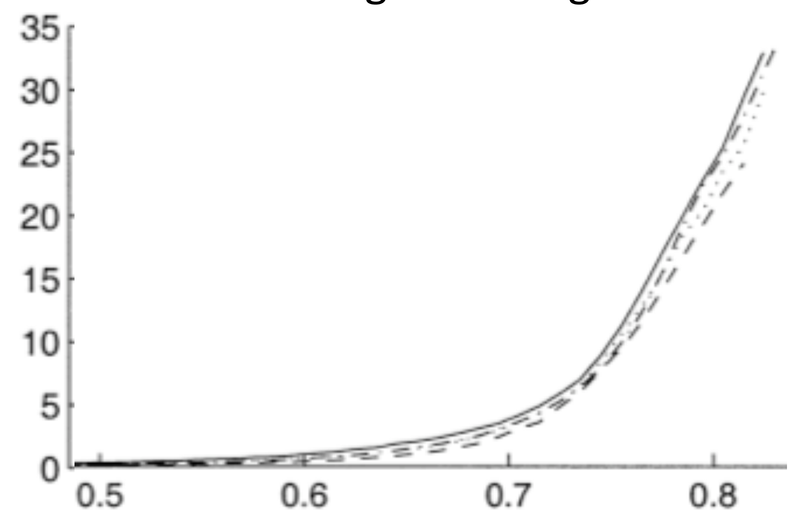
Factors controlling the form and distribution of convection:

To reason about convection, useful to reason about column-integrated moisture

Satellite (SSMI) daily 2 x 2 degree averaged data



Column water vapor



Column (bulk) rel. humidity

=

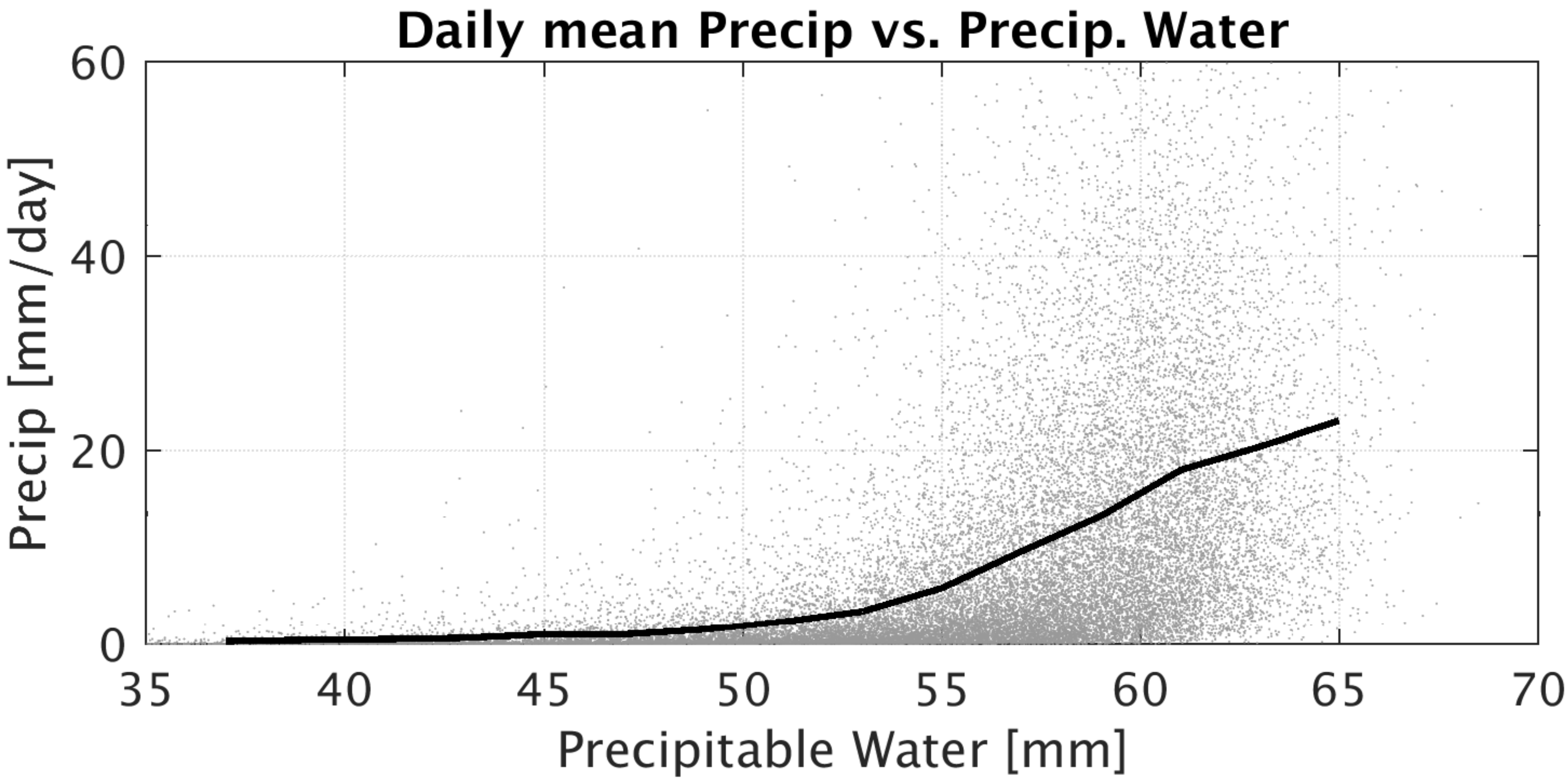
WVP / Saturation WVP (WVP if atmosphere were fully saturated)

From Bretherton, Peters & Back (2004)

Interpretation: combination of cause & effect

If we can understand moisture evolution, can understand a lot about convection

… though relationship has a fair amount of noise



so going beyond this is also important

Scientific questions related to moist static energy budgets motivate measurements

- Some measurements exist (e.g. TOGA COARE, dropsonde arrays, satellite data)
- Example of use of satellite data here
- More/better measurements needed to answer open questions

Dry static energy budget describes intensity of convection

$$s = c_p T + gz \quad \alpha \ln\theta$$

Yanai et al (1973)

$$\frac{\partial s}{\partial t} = \nabla \cdot s\vec{v} + L(c - e) + g\frac{\partial}{\partial p}\left(F^{s}_{turb} + F_{rad}\right) + S_h$$

Local s tendency

Advection

Latent heating

Convergence of radiative, turbulent fluxes

Dry Static Energy = Enthalpy + Geopotential

Vertically integrate over mass, assume steady to state to get the following:

$$\nabla \cdot \langle s\vec{v} \rangle = LP + \Delta F_{rad} + F^{s}_{turb}$$

Latent heating varies more than radiative, turbulent fluxes

To reason about moisture, we look at moist static energy (MSE) budget

MSE roughly conserved during moist adiabatic processes

$$h = \Phi + C_p T + Lq$$

Potential Temperature Moisture

To reason about moisture, we look at moist static energy (MSE) budget

MSE roughly conserved during moist adiabatic processes

$$h = \Phi + C_p T + Lq$$

$$\frac{\partial h}{\partial t} = -u\frac{\partial h}{\partial x} - v\frac{\partial h}{\partial y} - \omega\frac{\partial h}{\partial p} + g\frac{\partial}{\partial p}\left(F_{turb}^{h} + F_{rad}^{h}\right) + S_h$$

Integrate vertically over pressure...

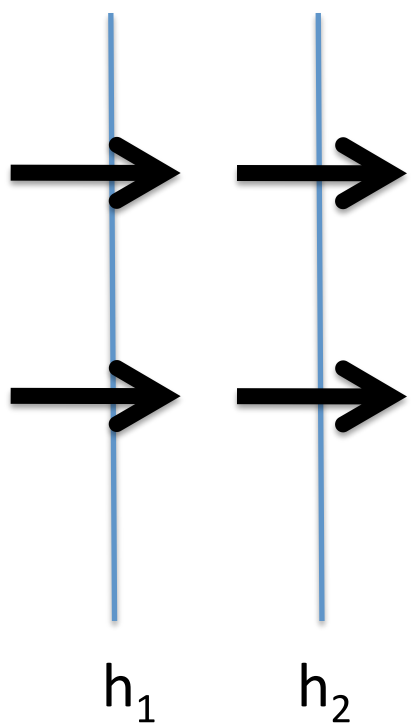
$$\left\langle \frac{\partial h}{\partial t} \right\rangle = \left\langle -u\frac{\partial h}{\partial x} - v\frac{\partial h}{\partial y} \right\rangle + \left\langle h\frac{\partial \omega}{\partial p} \right\rangle + LE + H + \langle Q_r \rangle$$

Horizontal advection + Horizontal divergence of MSE

Flux divergence

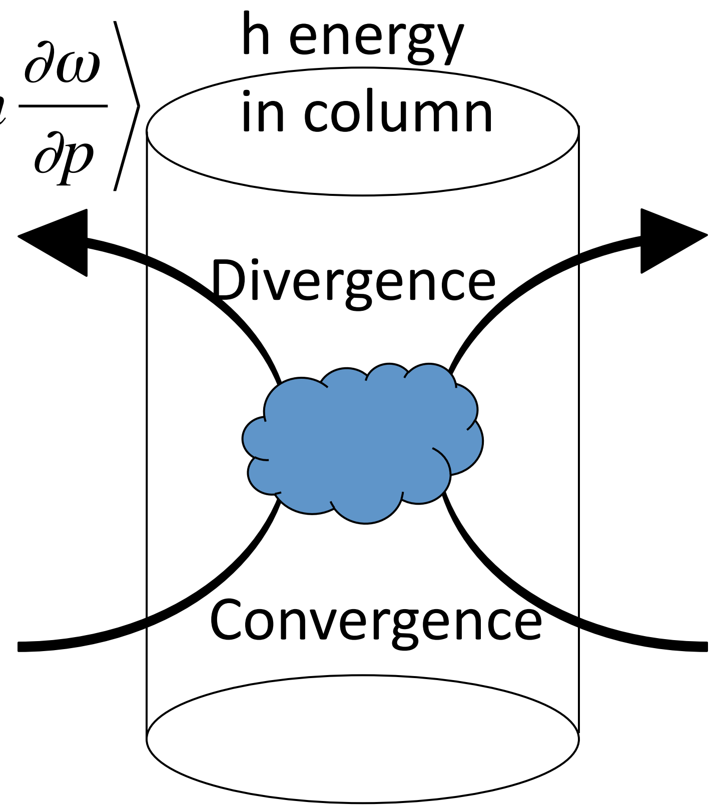
$$\left\langle \frac{\partial h}{\partial t} \right\rangle = \left\langle -u\frac{\partial h}{\partial x} - v\frac{\partial h}{\partial y} \right\rangle + \left\langle -\omega \frac{\partial h}{\partial p} \right\rangle + LE + H + \langle Q_r \rangle$$

- Horizontal Advection



- Horizontal divergence

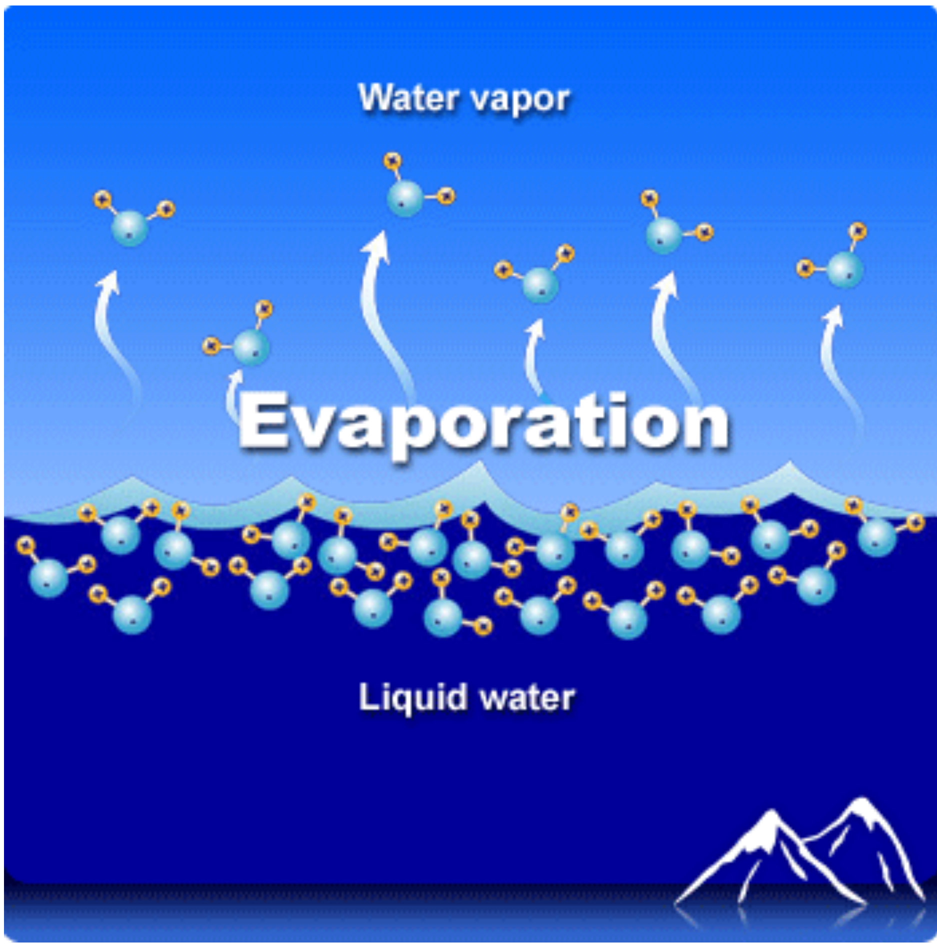
$$= \left\langle h \frac{\partial \omega}{\partial p} \right\rangle$$



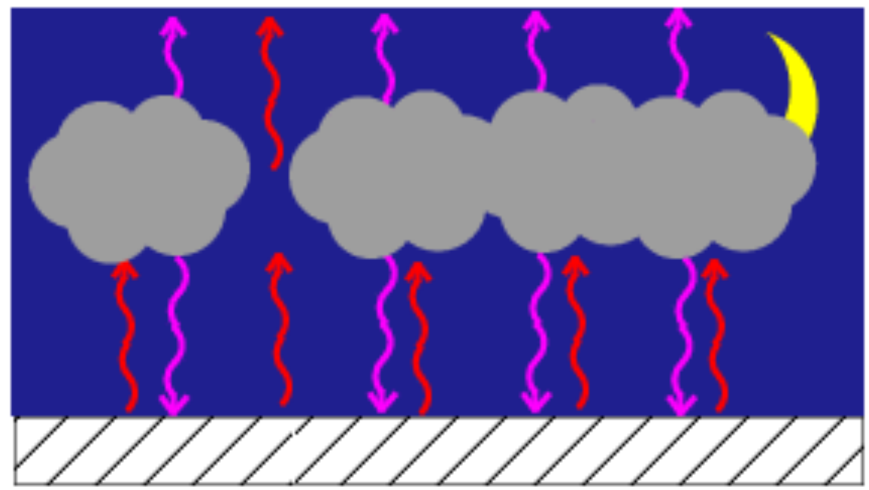
Difficult to constrain, especially vertical structure details

$$\left\langle \frac{\partial h}{\partial t} \right\rangle = \left\langle -u\frac{\partial h}{\partial x} - v\frac{\partial h}{\partial y} \right\rangle + \left\langle -\omega \frac{\partial h}{\partial p} \right\rangle + LE + H + \langle Q_r \rangle$$

Diabatic terms:



- Radiation (cooling)



Column MSE budget equation approximates moisture tendency

$$h \equiv s + Lq$$

s : DSE
q : Mixing ratio

$\langle s' \rangle \ll \langle Lq' \rangle$ due to large Rossby radius

- Column MSE budget equation:

$$\frac{\partial \langle h \rangle}{\partial t} = -\nabla \cdot \langle h\mathbf{v} \rangle + \langle Q_R \rangle + S$$

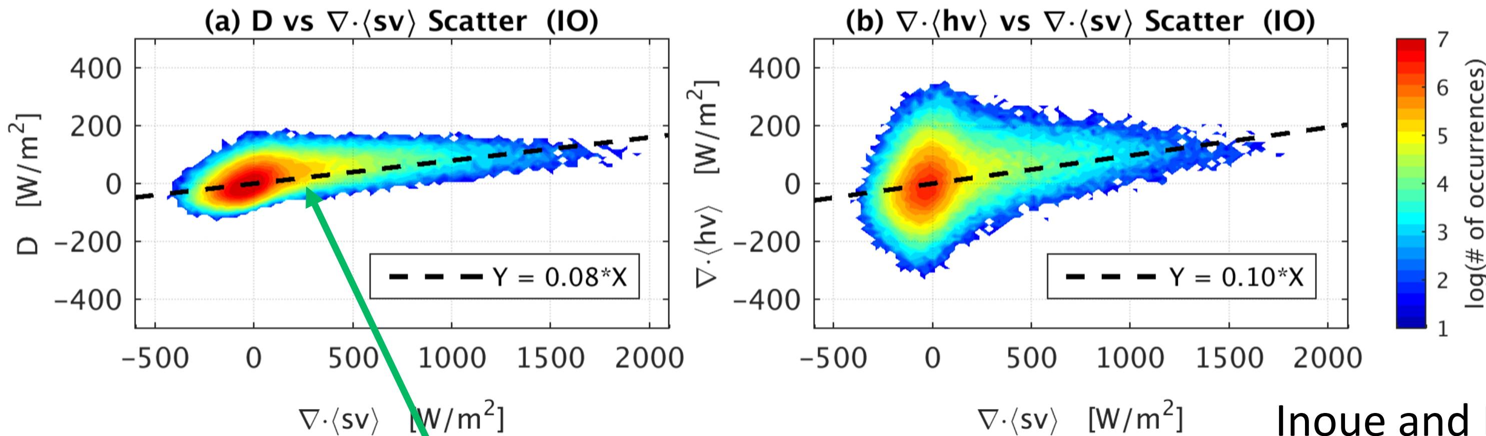
$\langle Q_R \rangle$: Column radiative heating

$S \equiv LE + H$: Surface fluxes

$$\frac{\partial \langle Lq \rangle}{\partial t} \cong -\nabla \cdot \langle h\mathbf{v} \rangle + D$$

$D \equiv \langle Q_R \rangle + S$: Diabatic source

We can simplify column MSE equation



Inoue and Back, 2017
Satellite data

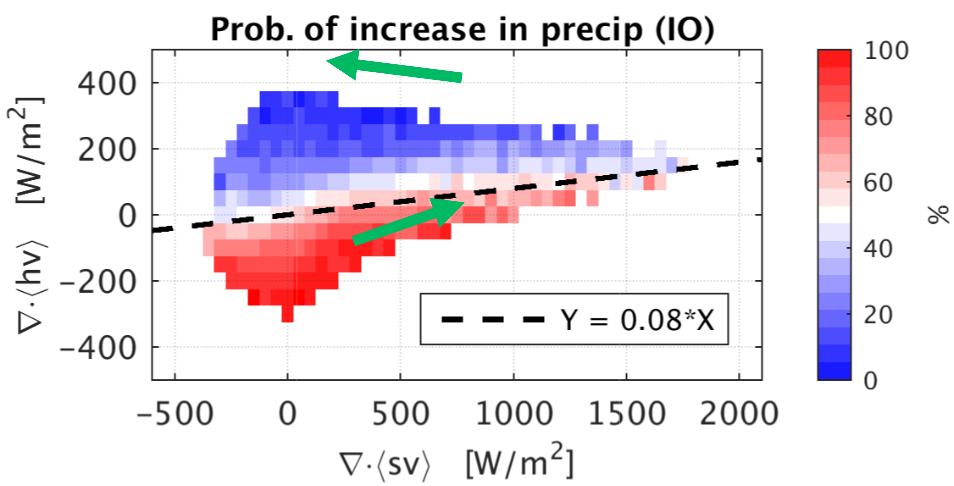
Characteristic GMS (Inoue and Back 2015)

$$D \cong \gamma * \nabla \cdot \langle s\mathbf{v} \rangle$$

$$\frac{\partial \langle Lq \rangle}{\partial t} \cong -\nabla \cdot \langle h\mathbf{v} \rangle + \gamma \nabla \cdot \langle s\mathbf{v} \rangle$$

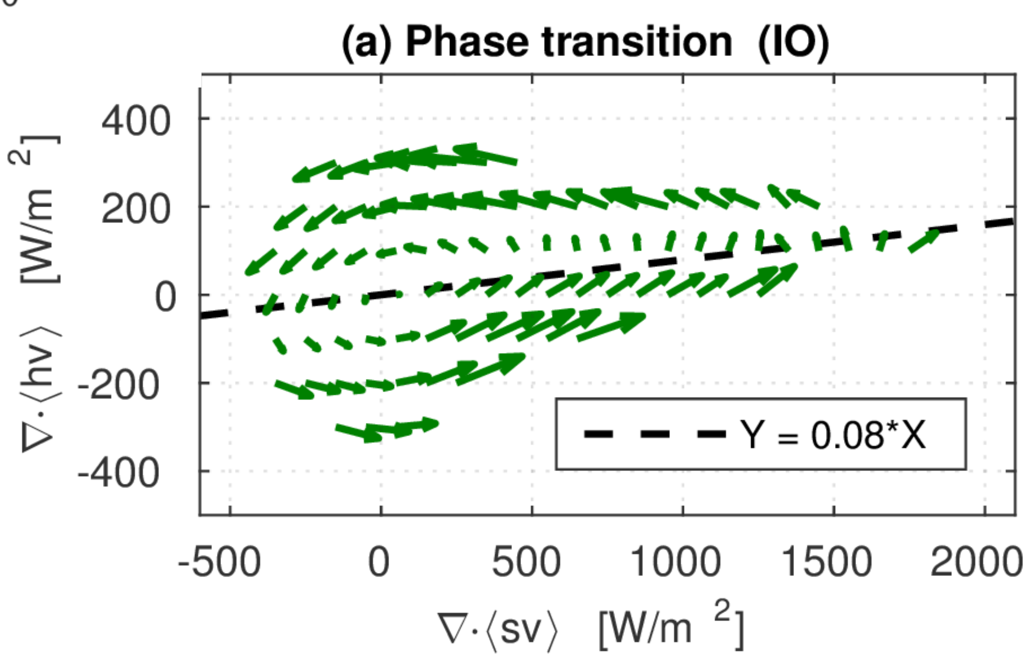
Note that mean slopes are physically important and quite different for satellite data versus field campaign data (factor of 2 higher in field campaign data)

Flux divergences tell us about whether precipitation is increasing/decreasing



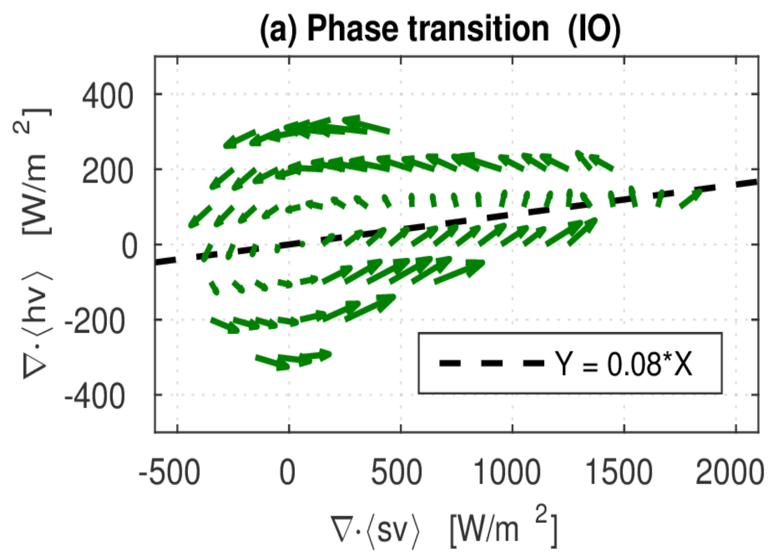
Inoue and Back, 2017
Satellite data, assumptions make diagnostic rather than prognostic

Empirical



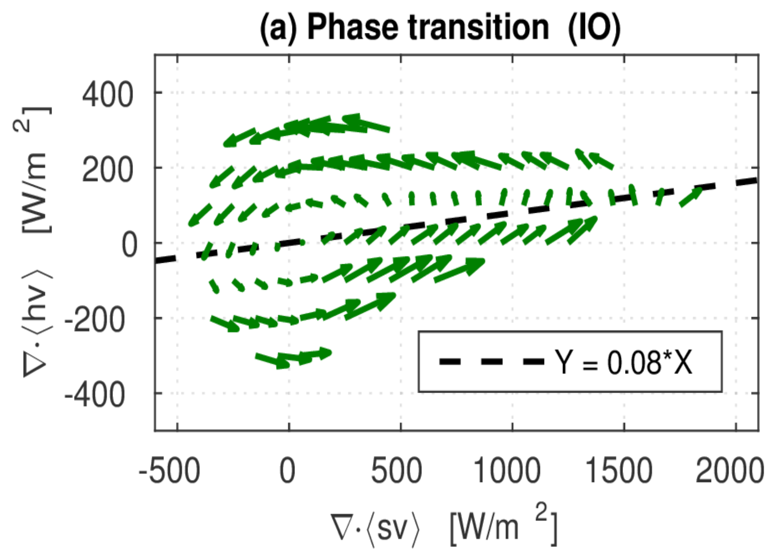
- phase positions in the plane predict subsequent evolution of convection
- Sloped line varies more slowly

Moisture growth/ decay influenced by flux divergence of moist static energy



- Questions to be answered:
  - How does flux divergence of moist static energy depend on environment
  - What controls life-cycle of convective systems?
  - How does convection influence environment? y-axis changes over time

Mean slope of relationship (characteristic gross moist stability, dashed line), determines mean precip response to diabatic sources



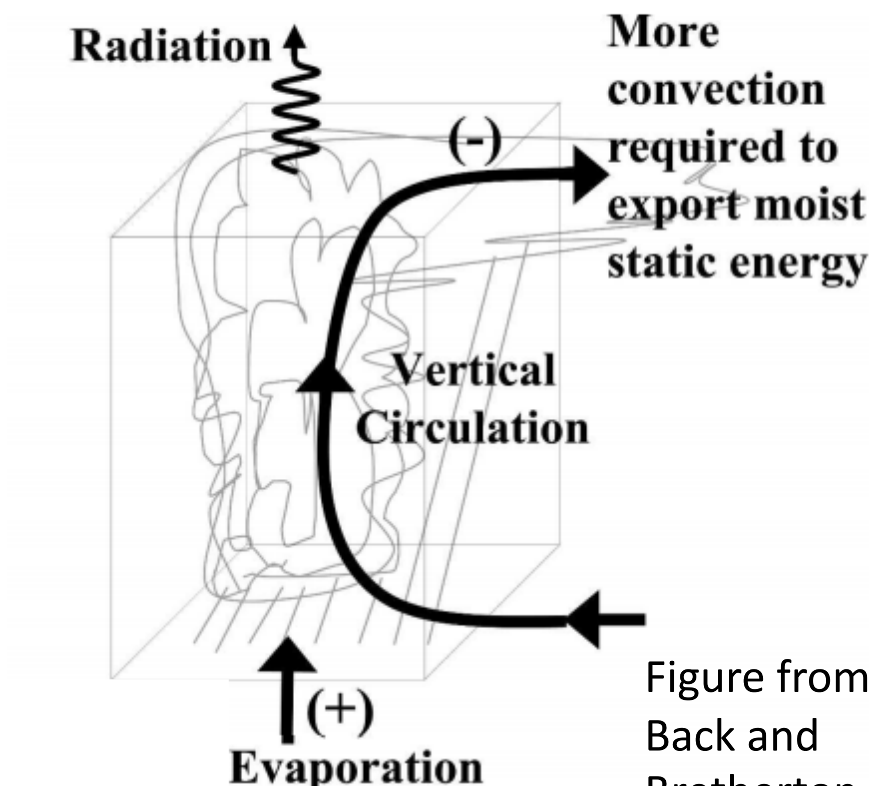


Figure from Back and Bretherton 2005

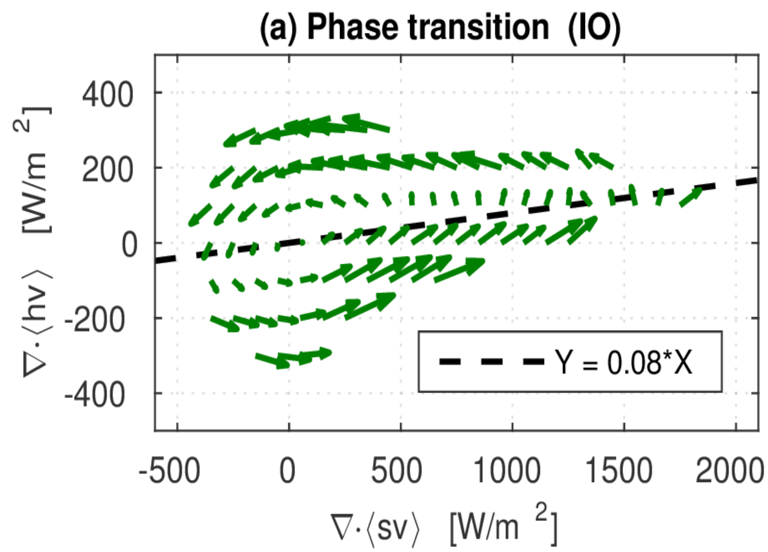
In time-mean:

$$\gamma = \frac{D}{\nabla \cdot \langle s\vec{v} \rangle} = \frac{\nabla \cdot \langle h\vec{v} \rangle}{\nabla \cdot \langle s\vec{v} \rangle}$$

$$LP \approx \frac{\langle Q_R \rangle + S}{\gamma} - \langle Q_R \rangle$$

Gamma likely varies by factor of 2 between field campaign and satellite data (Inoue and Back 2017)

Mean slope of relationship (characteristic gross moist stability, dashed line), determines mean precip response to diabatic sources



- Questions to be answered by field work
  - How does mean slope depend on environment?
  - What controls the time/space evolution of this quantity?

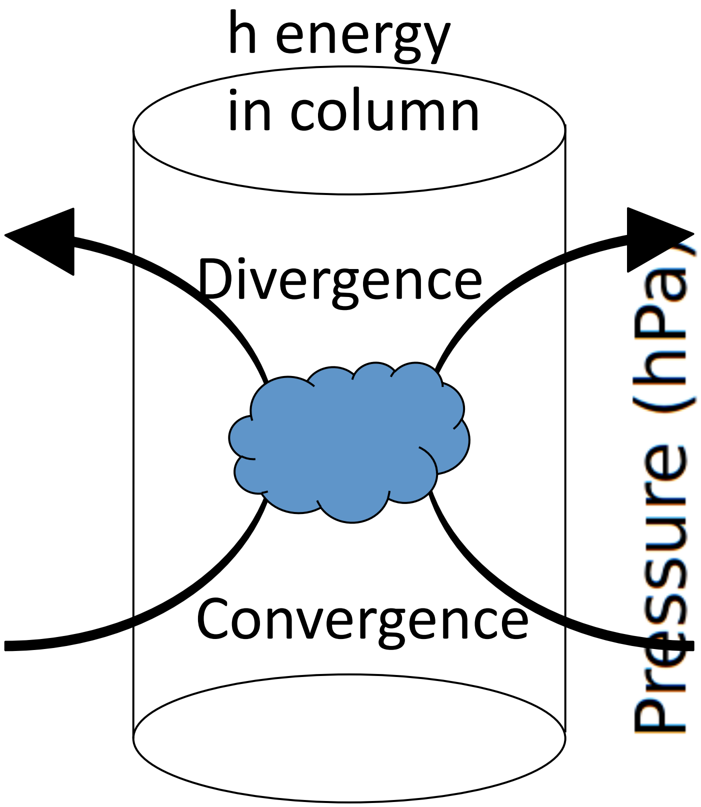
So what do we need to measure?

- Environment: moisture, T profiles, sea surface temperature
- Dry static energy budget
  - Radiative cooling profiles, surface fluxes
  - Flux divergence of dry static energy
    - Horizontal divergence key
  - Diabatic heating profiles
- Moist static energy budget, in addition
  - Surface evaporation
  - Flux divergences
    - Horizontal winds, horizontal moisture gradients
    - Profiles of horizontal divergence, moisture profile

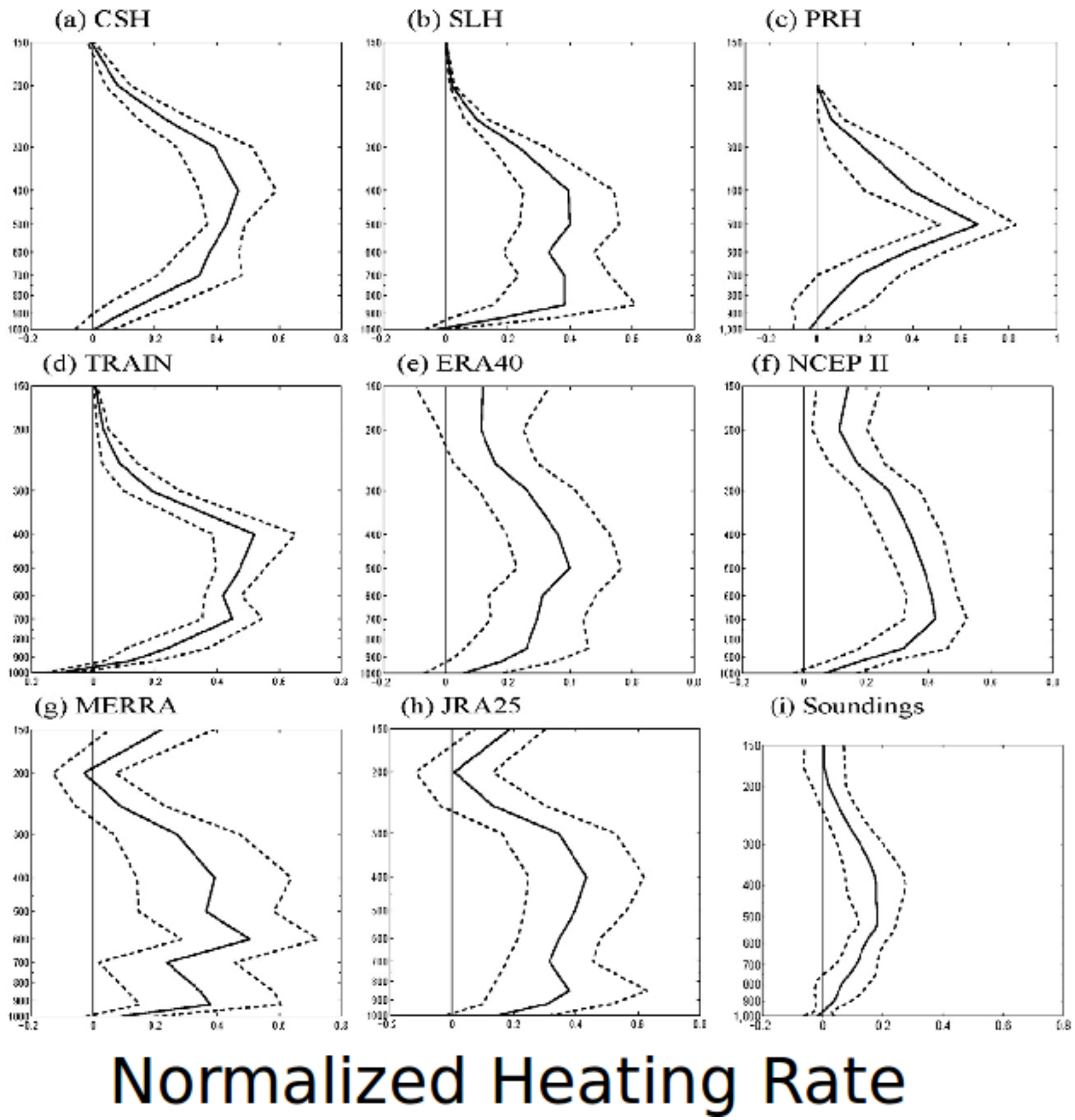
Historical measurement methods

- Gold standard: radiosonde array, surface flux measurements
- Alternatives:
    - Dropsondes arrays
    - Variational analysis using radar data
    - Satellite estimates
    - Remote sensing

Horizontal divergence hard to estimate



Sounding array scales



Adapted from Hagos et al (2010)

Challenges:

- Horizontal divergence profiles
  - In situ dropsonde/radiosonde data expensive, but crucial
- Vertical resolution for remote sensing

Prediction issues underlie uncertainties about how convection works

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Effect of convection on the environment

- Cloud resolving models likely to be essential part of figuring this out
  - Need to be validated/improved by comparison with observations
  - Forcing comes from large-scale moist static energy/dry static energy budgets
- Key additional measurements (smaller scales):
  - Structure, depth, and intensity of convective cells
  - Modification of surface fluxes by convection, downdrafts, gustiness
  - Vertical mass fluxes, water substance and moist static energy detrainment on mesoscale
  - Effects of clouds on long-wave and shortwave radiation
  - Cumulus momentum transports

Effect of convection on the environment Measurement technology

- Airborne doppler radar
- Vertically pointing doppler cloud and precipitation radar
- Measurement of cloud water and ice particle types and concentrations

Effect of convection on the environment Challenges:

- Variability of convection large, so extensive studies needed
  - Expensive, but crucial
- Diurnal cycle challenging

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Response of convection to climate change

- All previously discussed measurements will be important
- Leverage natural variability in existing climate to understand effects of climate change?
- Extensive modeling/theory necessary

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