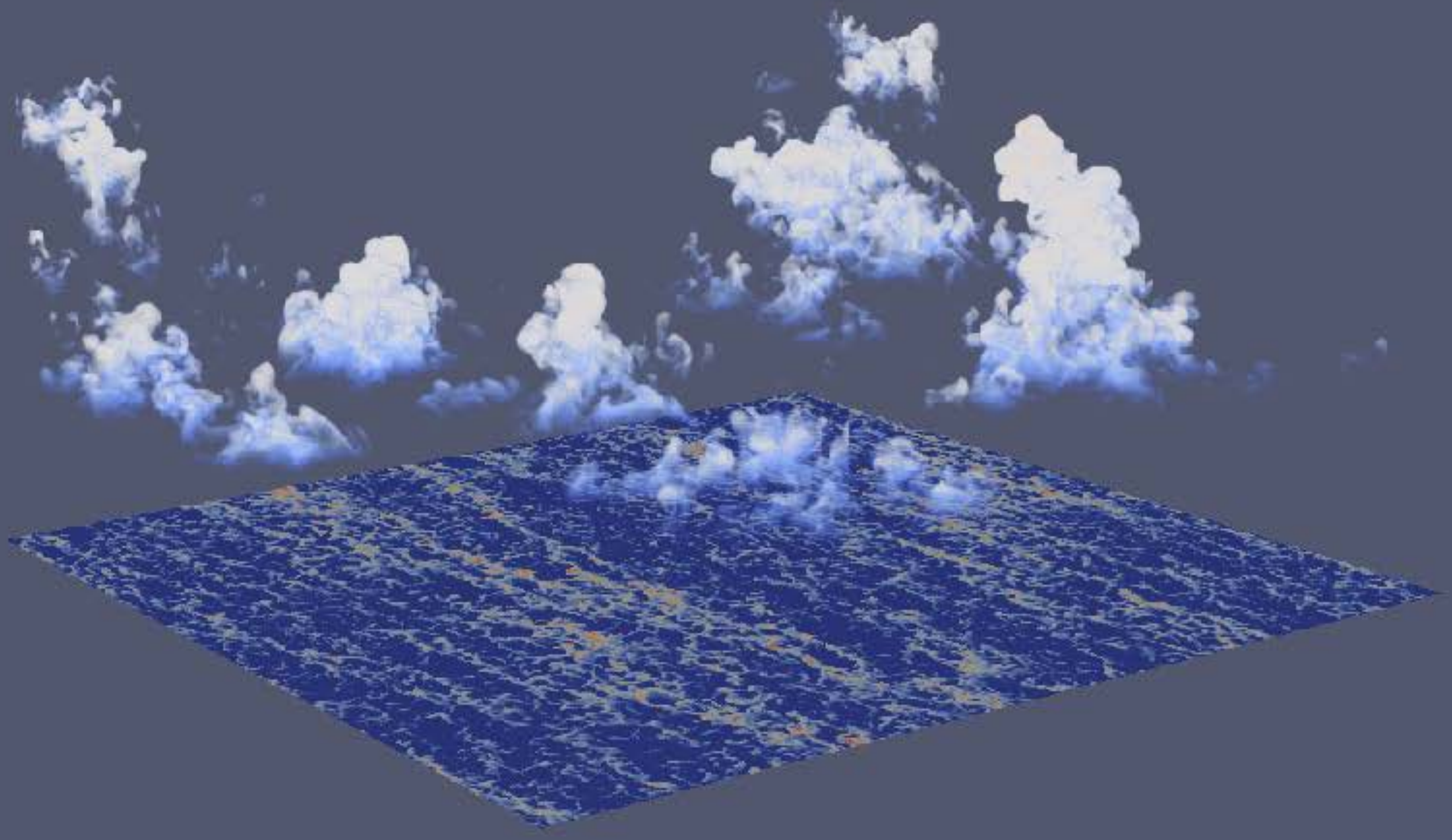
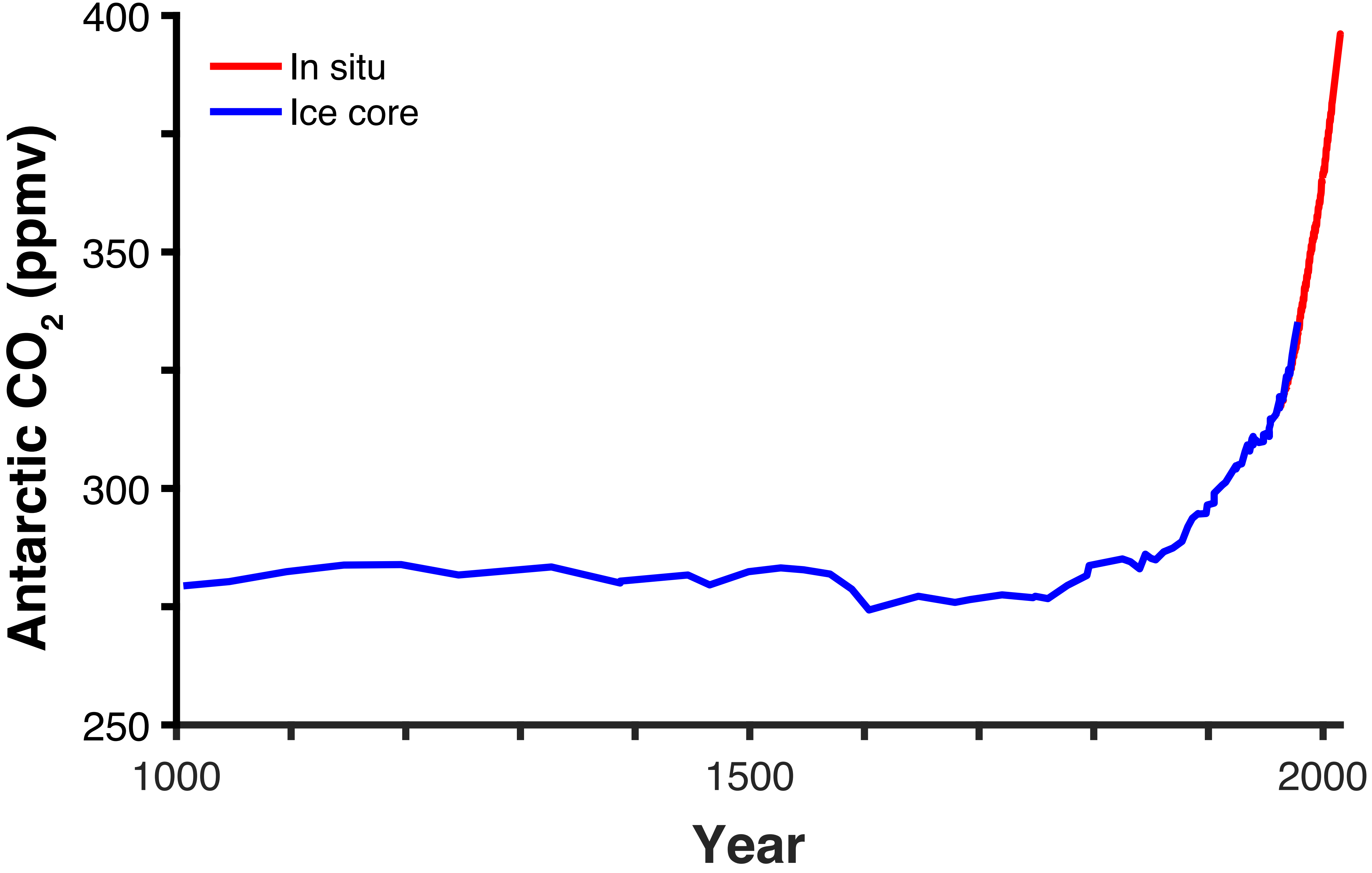


Computing Clouds: Why Turbulent Coherent Structures are Crucial for Predicting Climate Change

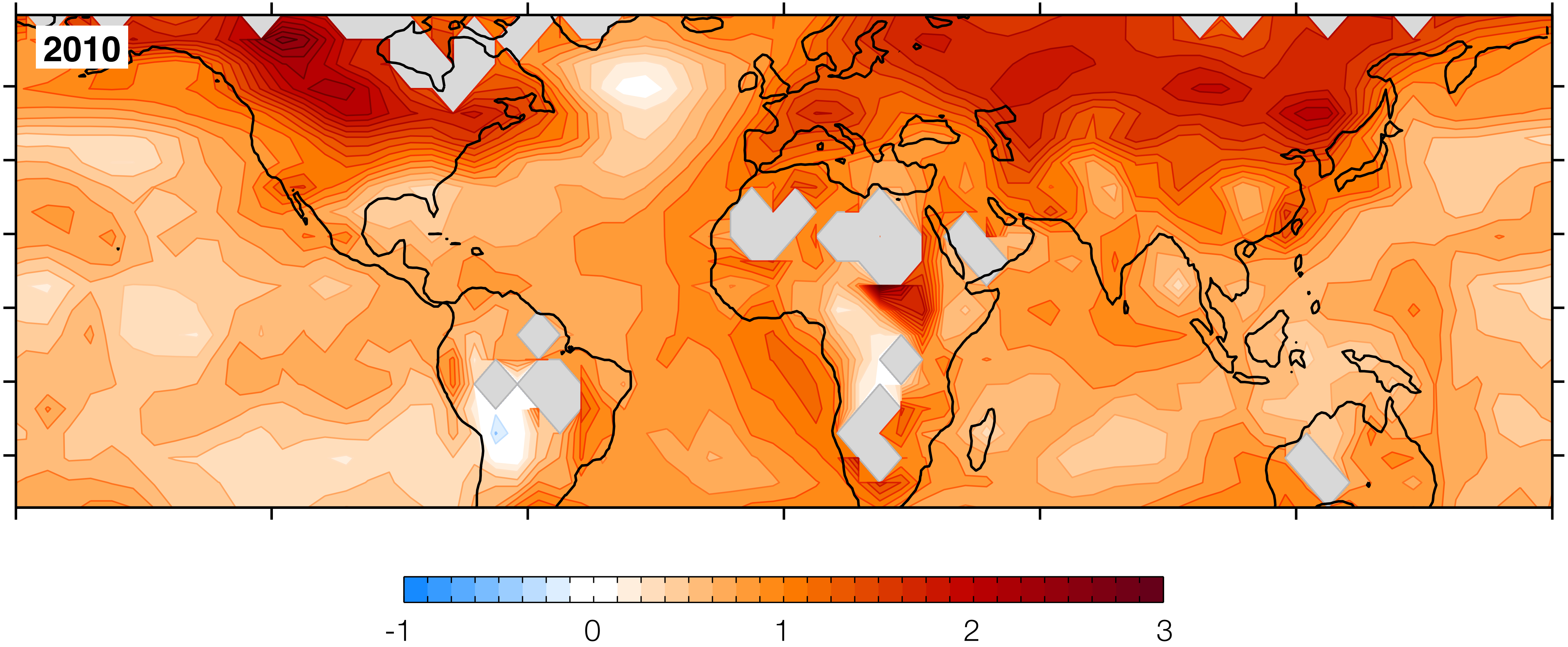
Tapio Schneider
Zhihong Tan
Florent Brient
Kyle Pressel

Atmospheric CO_2 is rising rapidly



Data sources: Etheridge et al. 1998; Keeling et al. 2008

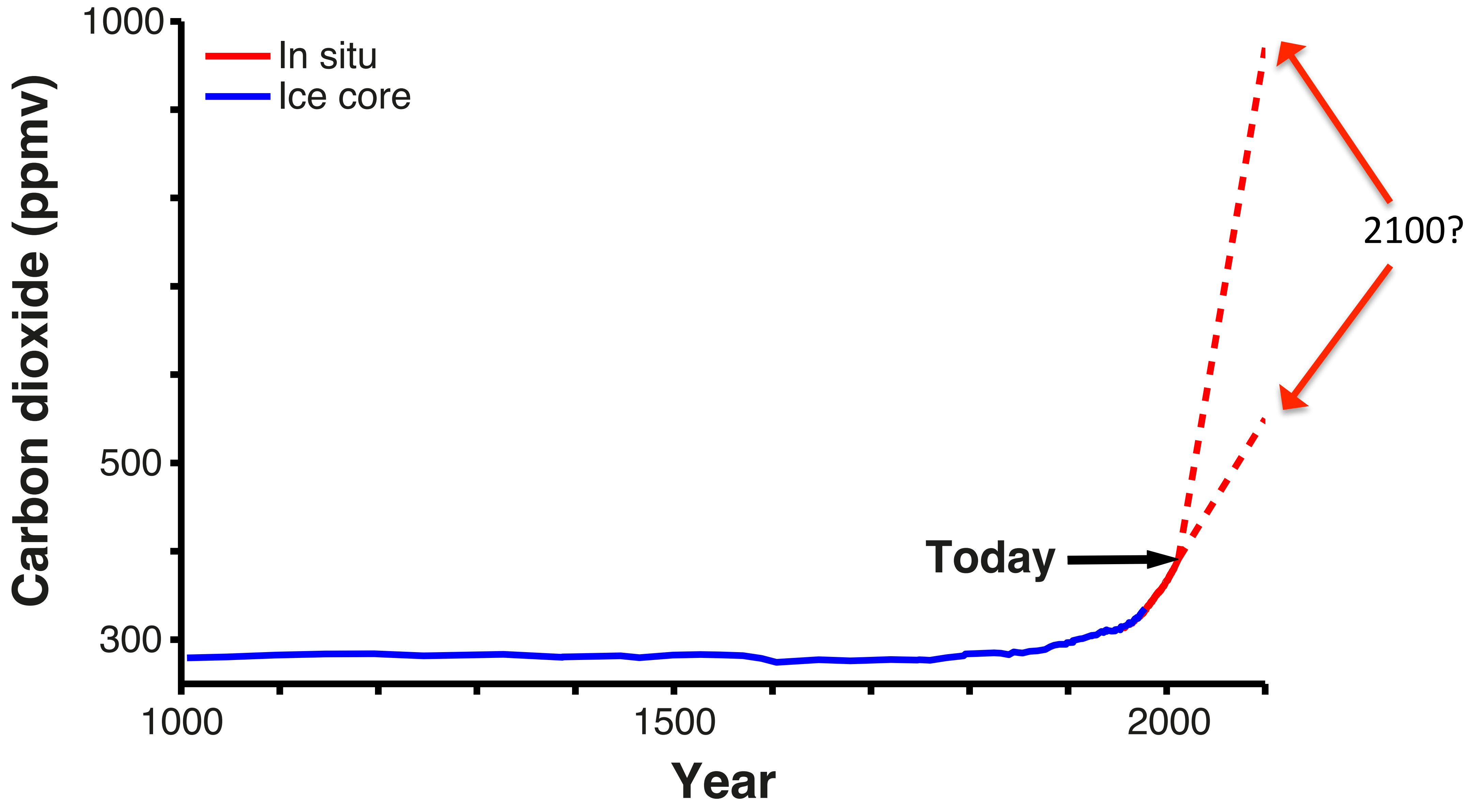
Temperatures are rising along with CO_2



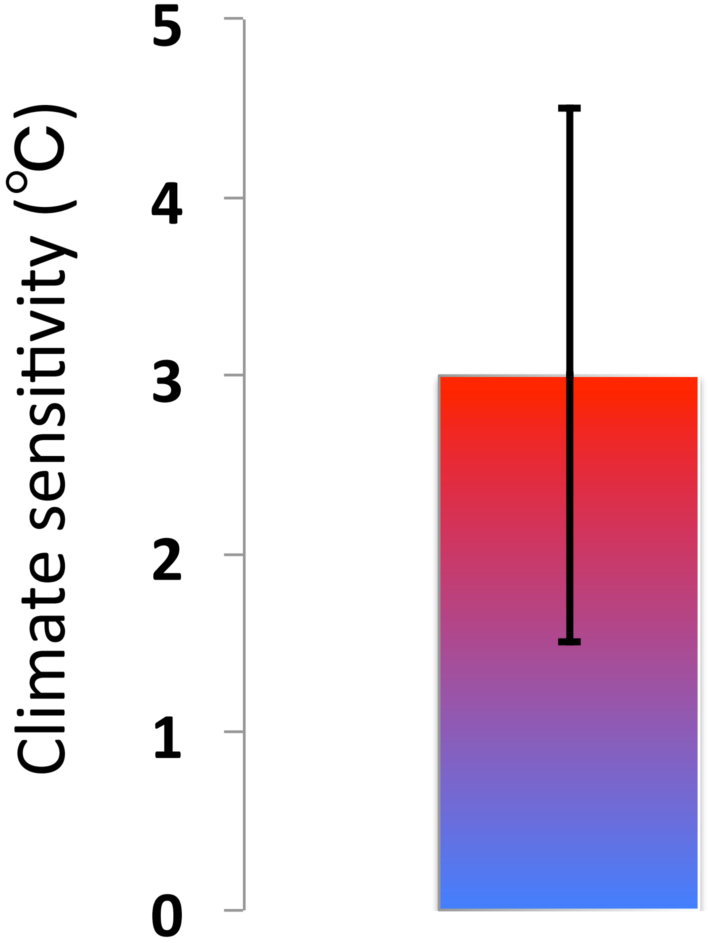
Temperature change (ºC) from 1850s through 2010s

Schneider & Held, J. Climate, 2001; update http://climate-dynamics.org/videos

As CO_2 continues to rise, how warm will it get?



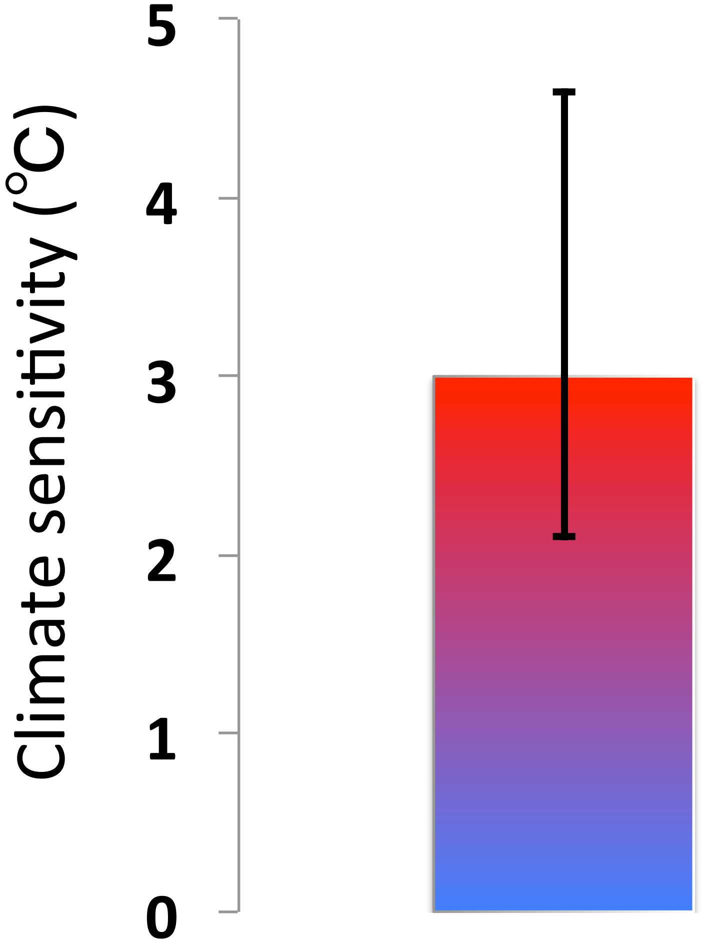
Equilibrium climate sensitivity was uncertain 1979



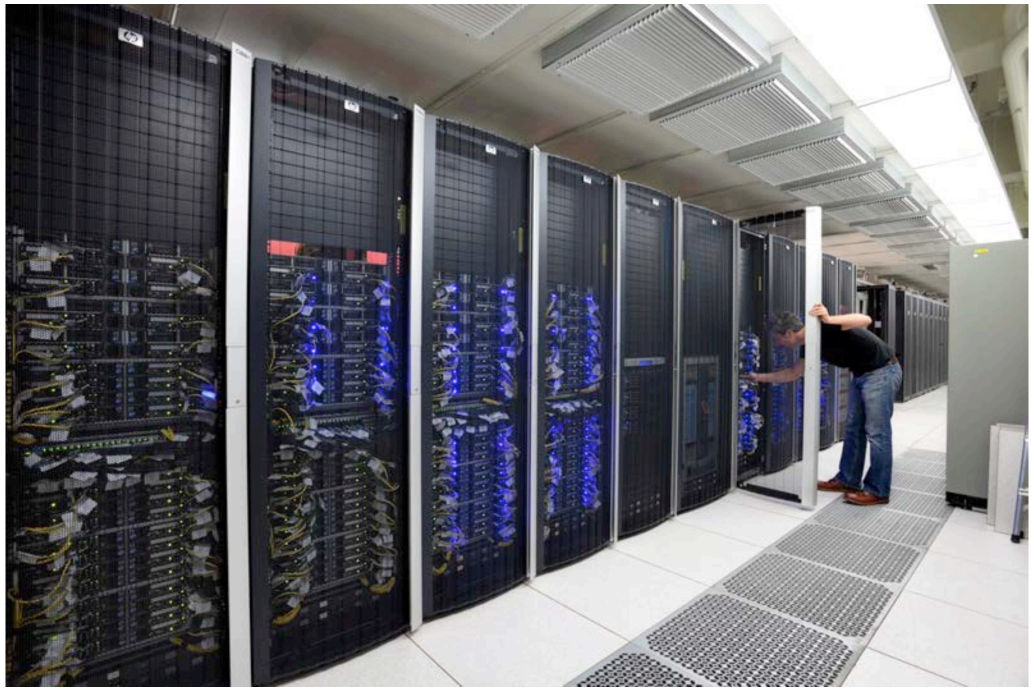

http://webmuseum.mit.edu


http://archive.computerhistory.org

… and still is uncertain in 2016

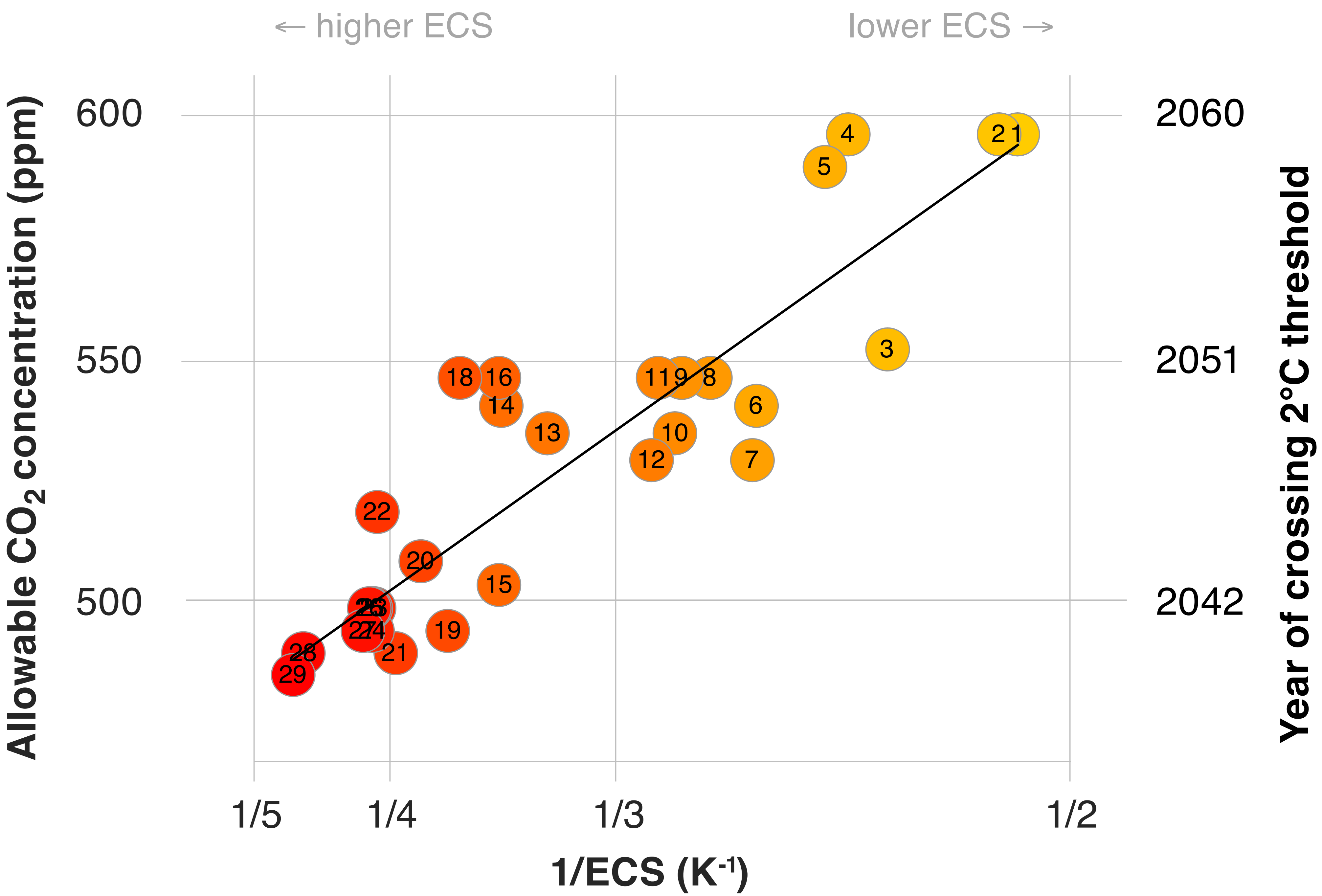


INTERGOVERNMENTAL PANEL ON climate change



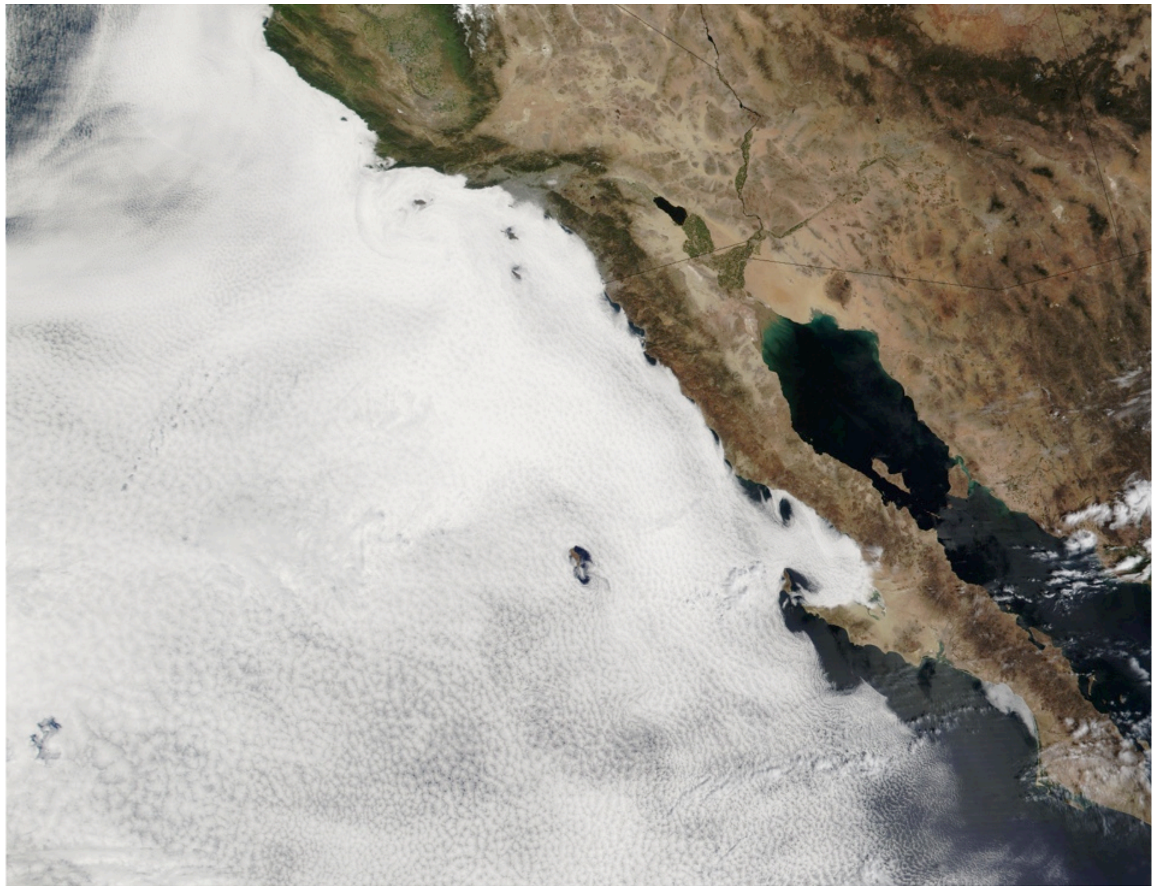
Caltech GPS supercomputer

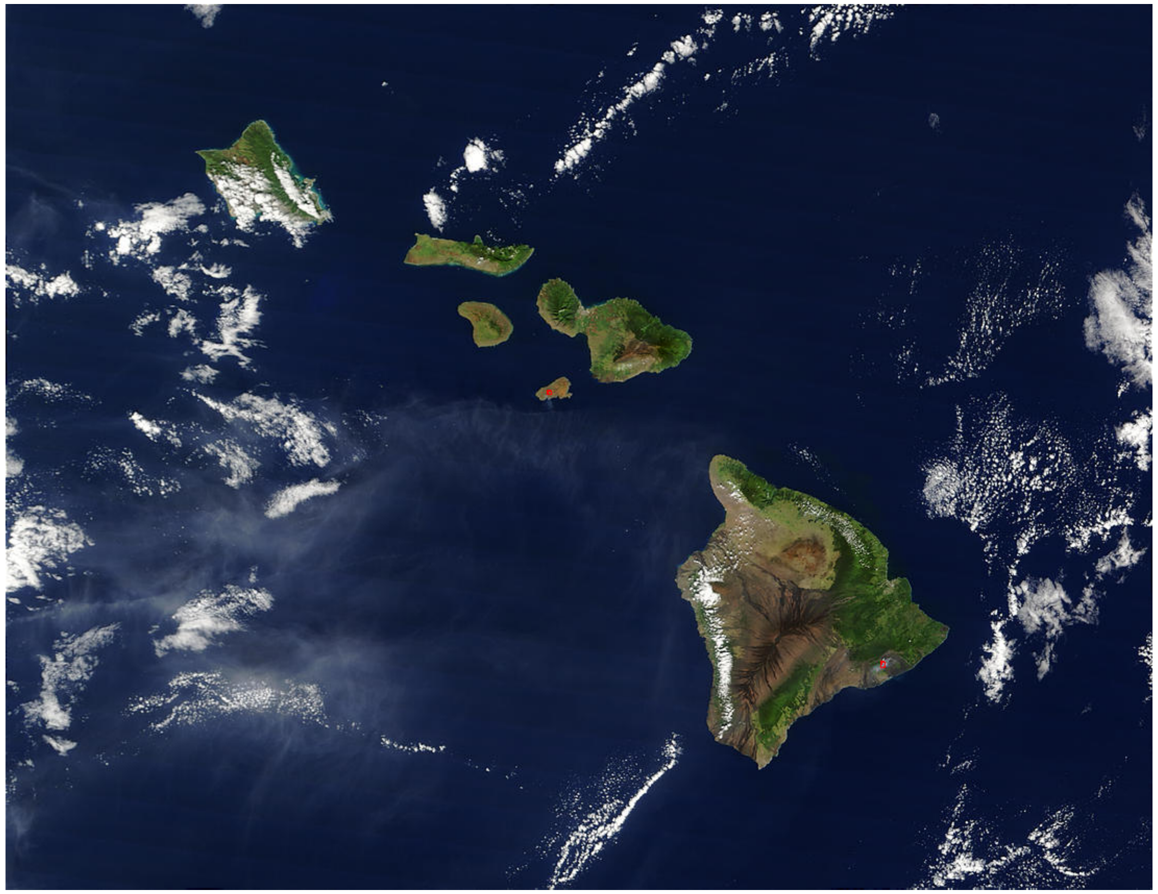
Allowable CO_2 concentration before 2°C threshold is crossed depends strongly on ECS (CMIP5 models)



Schneider et al. *Nature Climate Change*, 2017

Climate sensitivities scatter because of low clouds



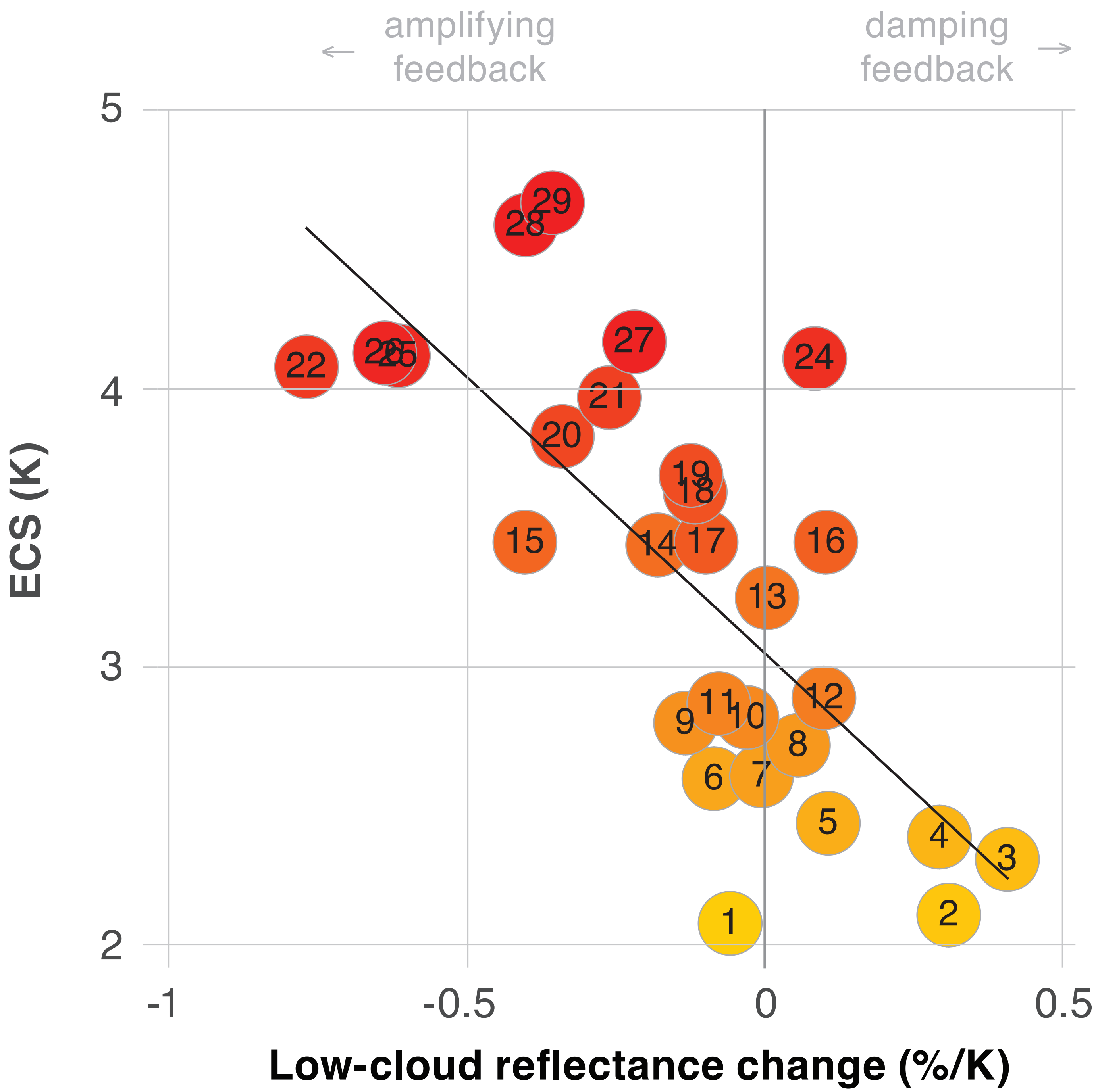


http://eoimages.gsfc.nasa.gov

Stratocumulus: colder

Cumulus: warmer

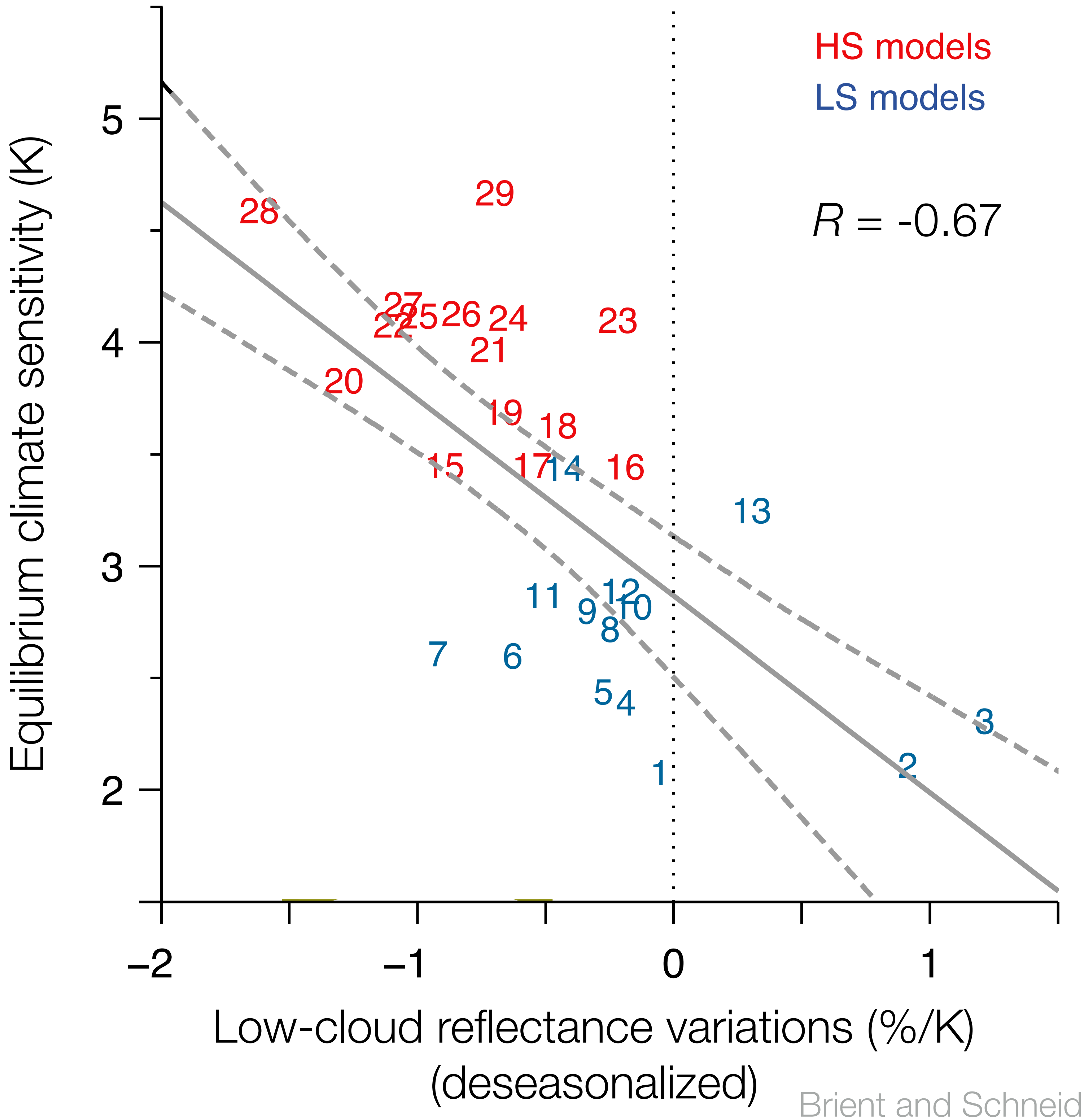
Majority of ECS variance across models is accounted for by low-cloud reflectance feedback



Schneider et al. *Nature Climate Change*, 2017

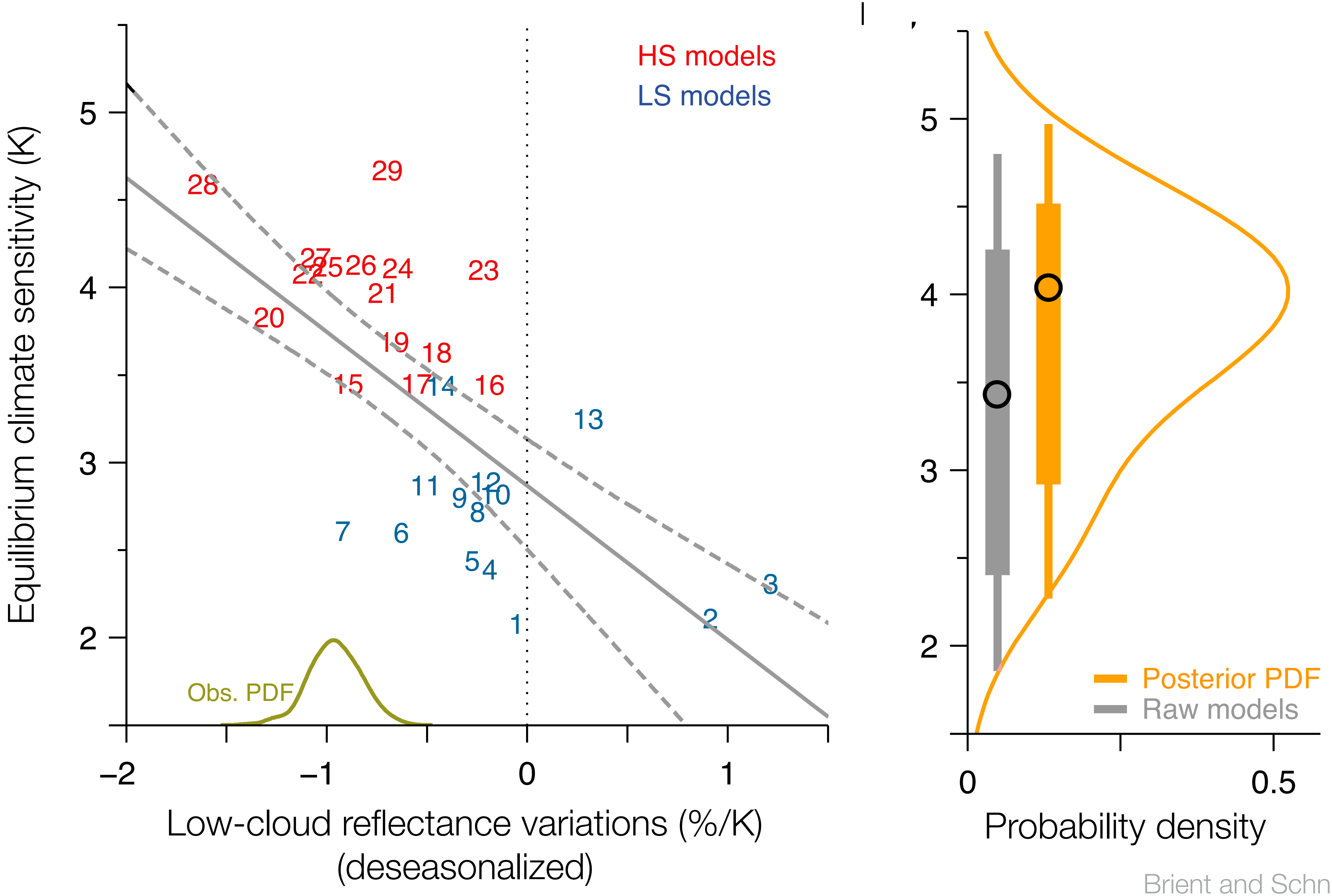
Can observations reduce the uncertainties in cloud feedbacks?

ECS correlates with *natural* reflectance *variations*



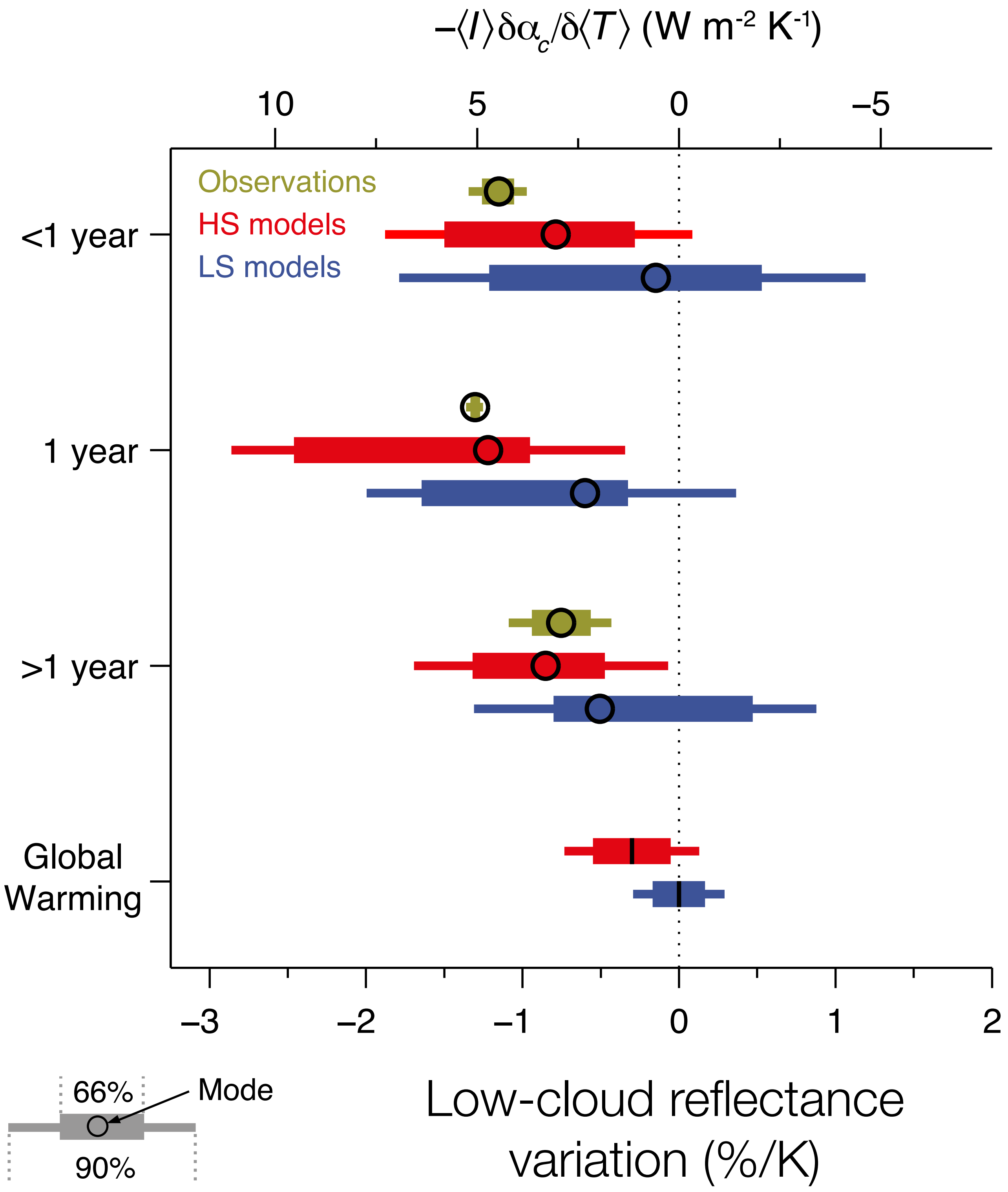
Brient and Schneider 2016; see also Qu et al. 2015

This allows us to constrain ECS (somewhat)



Brient and Schneider 2016

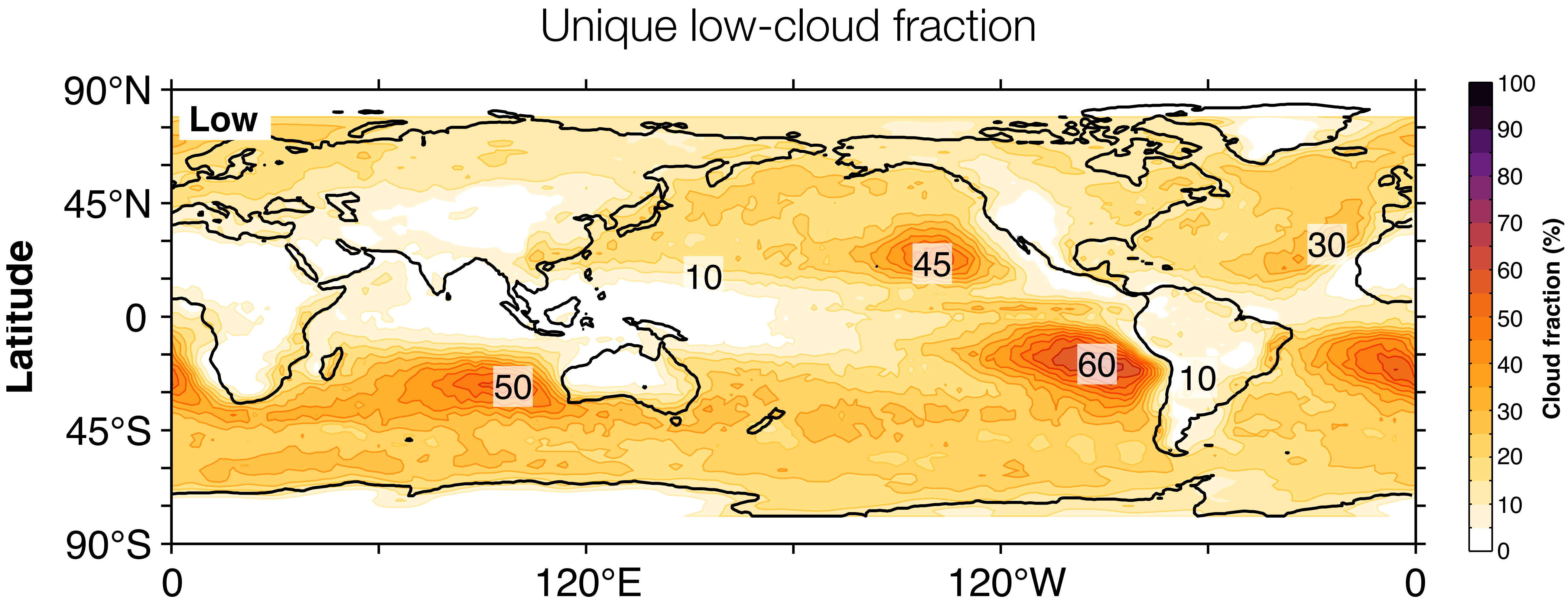
Observations point to robustly positive shortwave feedback of low clouds, but models differ widely



Brient and Schneider 2016

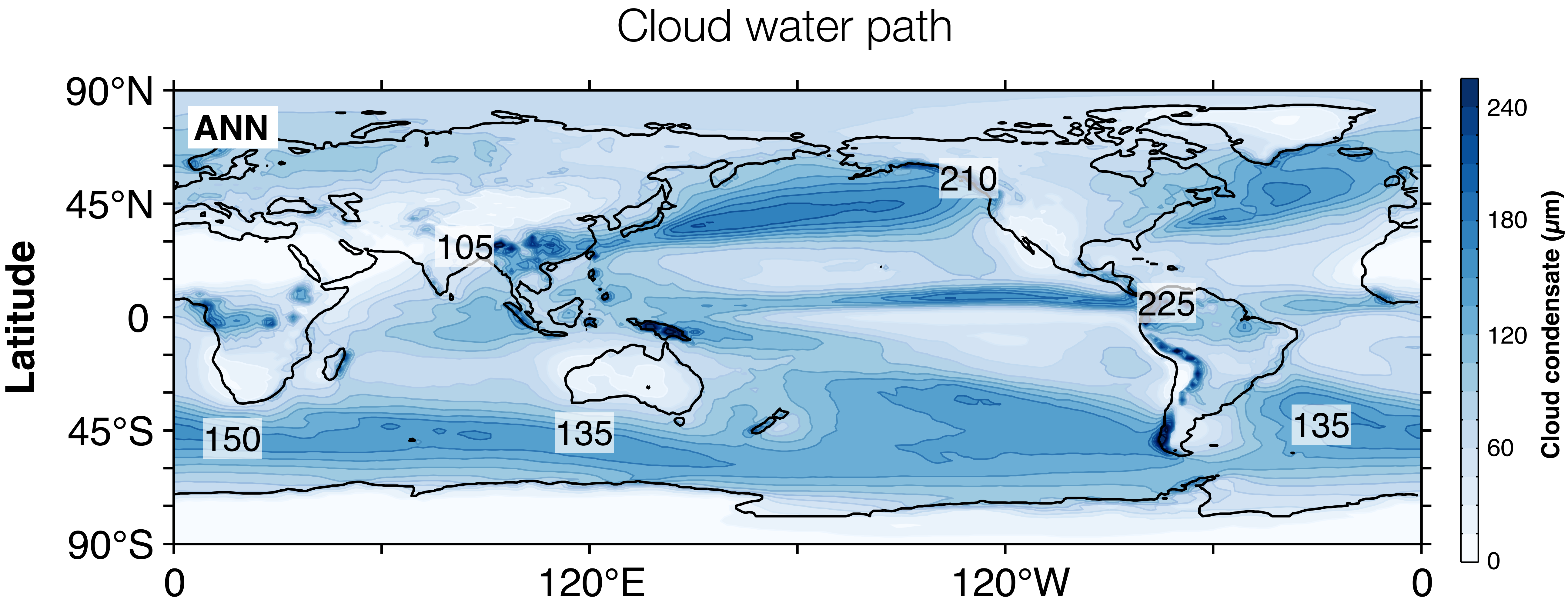
Why are low clouds difficult for climate models, and how can we make progress?

Low clouds are important because they cover large areas



Based on CloudSAT-CALIPSO data for 2006-2011 from Kay & Gettelmann 2009

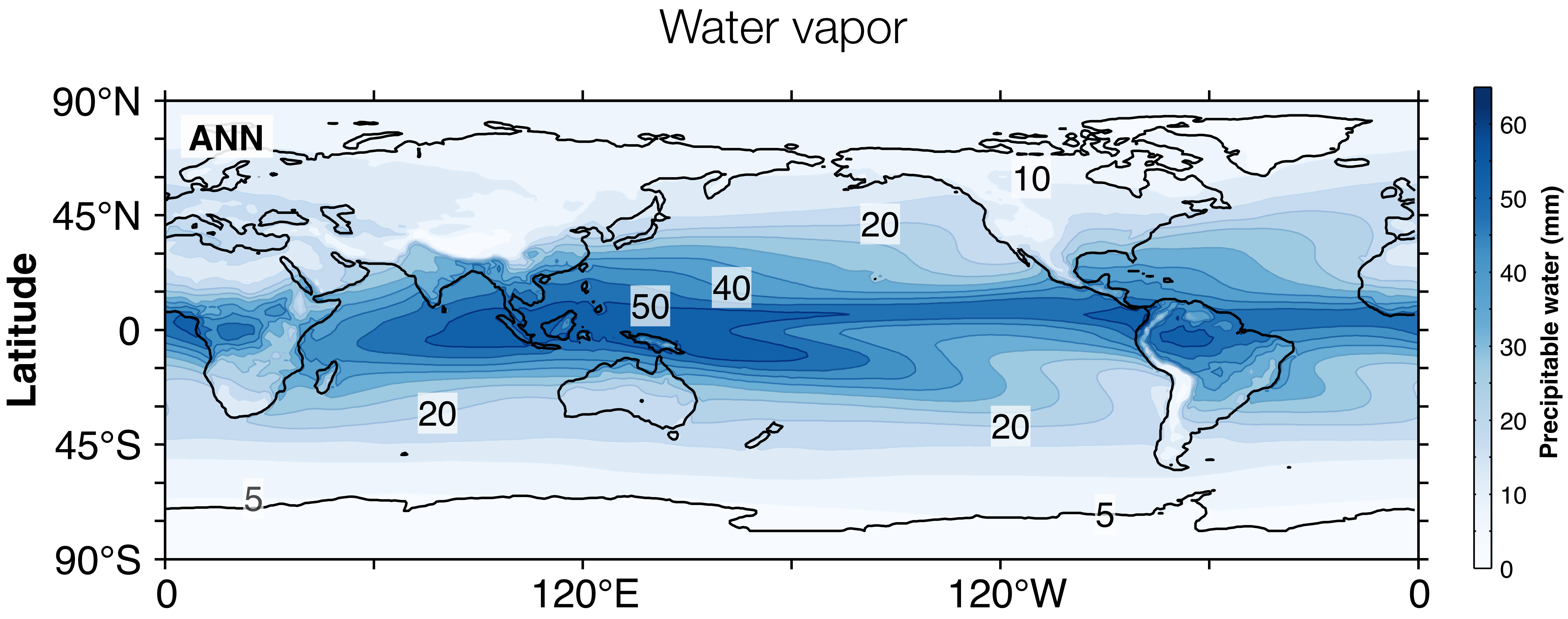
But there is very little water in them



Global-mean 0.1 mm

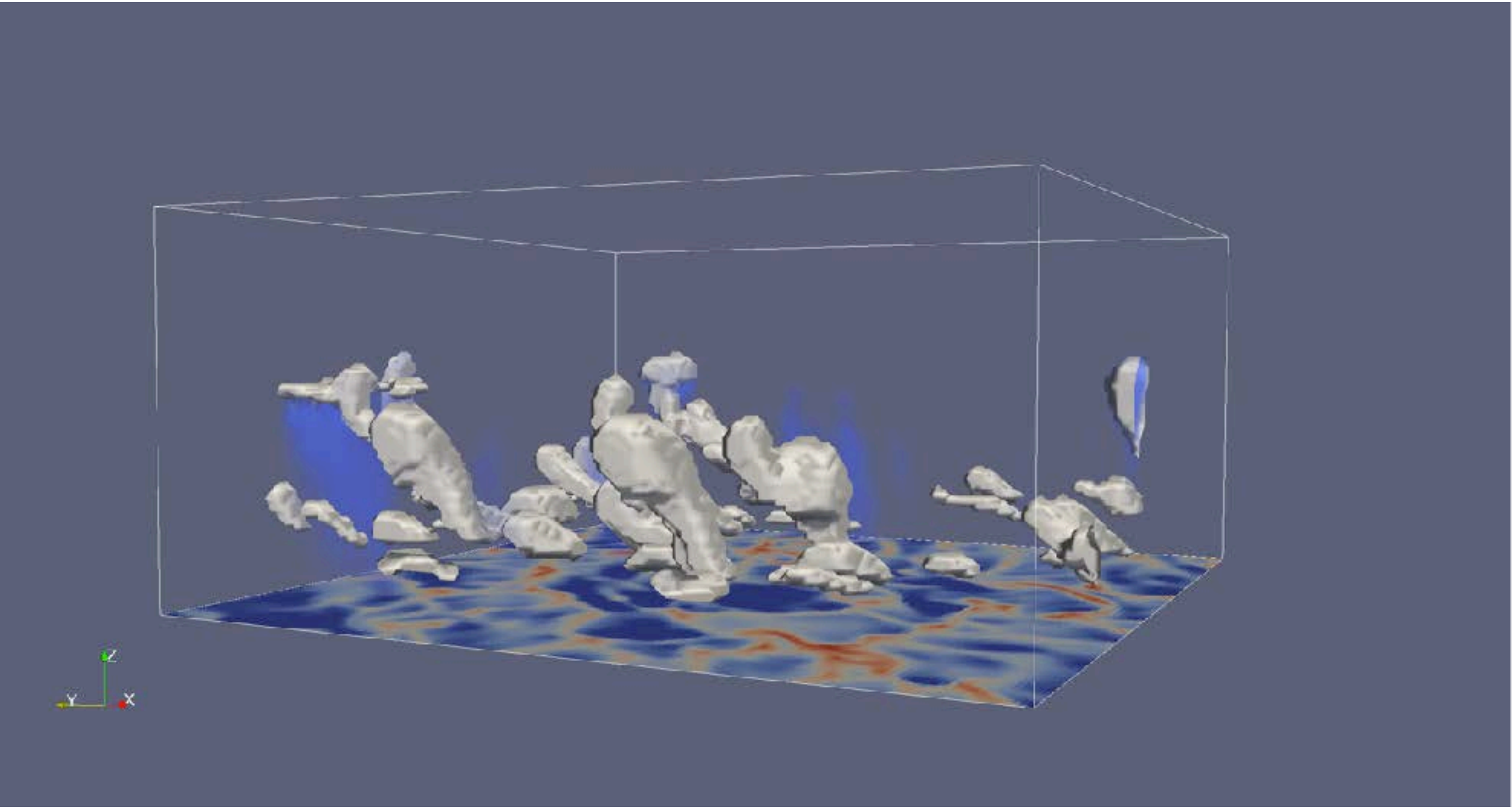
Based on CloudSAT-CALIPSO data for 2006-2011 from Kay & Gettelmann 2009

Most atmospheric water is vapor



Global-mean 25 mm

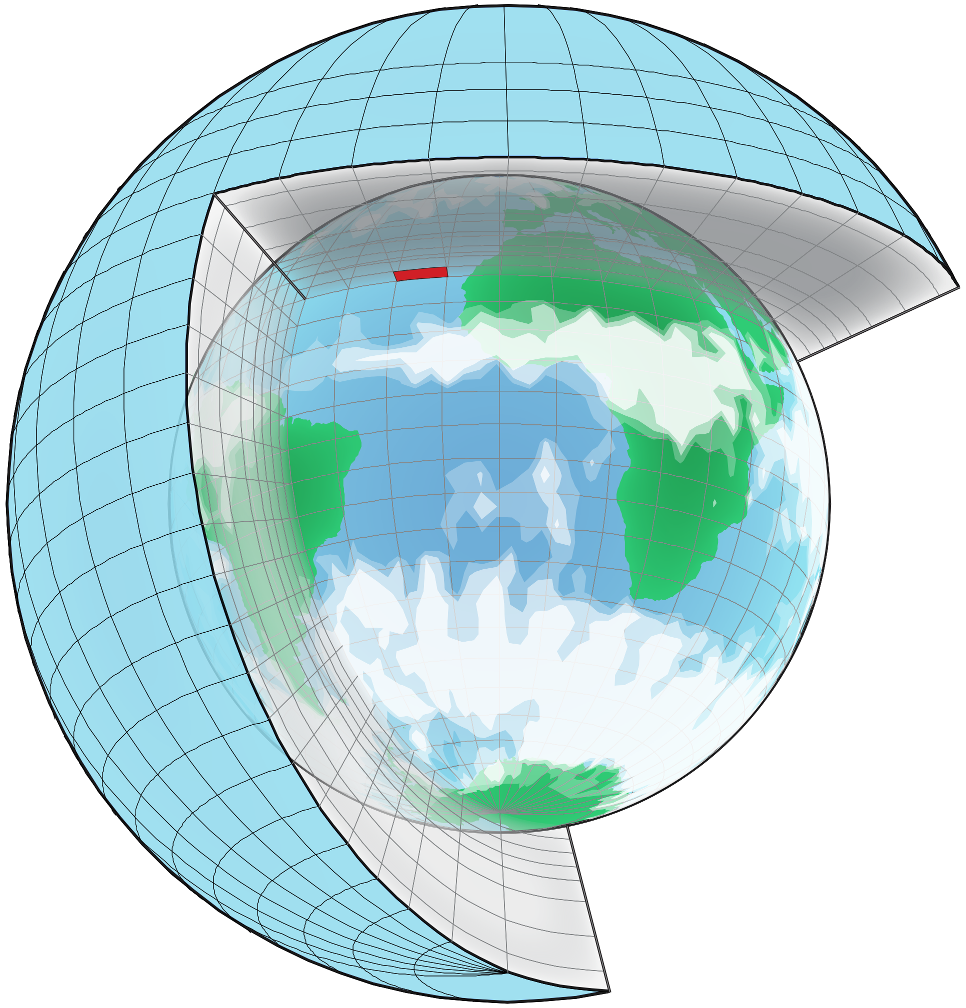
Clouds form where small residual of water condenses in coherent turbulent updrafts



Large-eddy simulation of tropical cumulus

Simulation with PyCLES (Pressel et al. 2015)

Climate models are too coarse to resolve updrafts

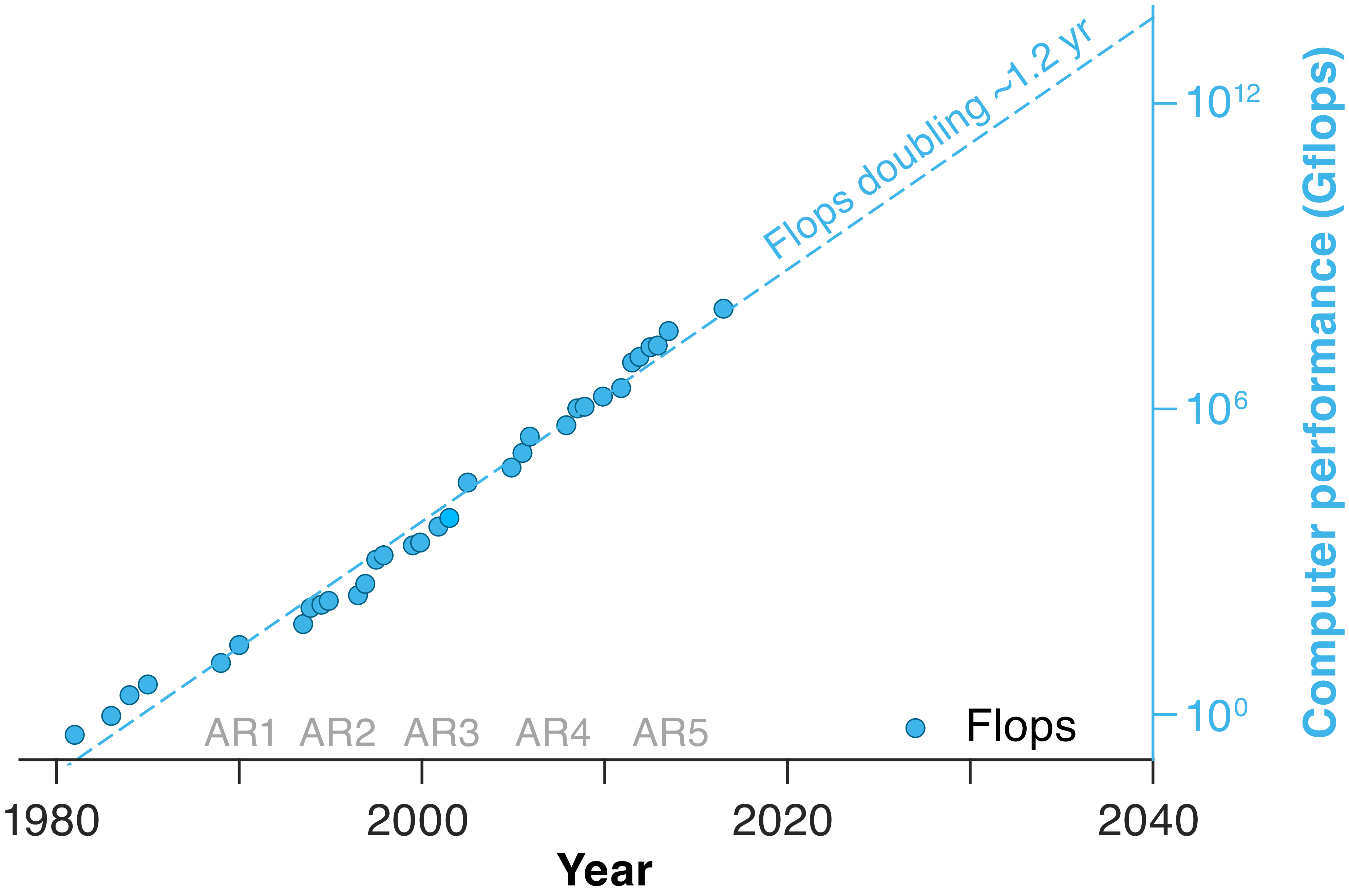


Global model:
~100 km resolution

NASA MODIS

Cloud scales: ~10 m

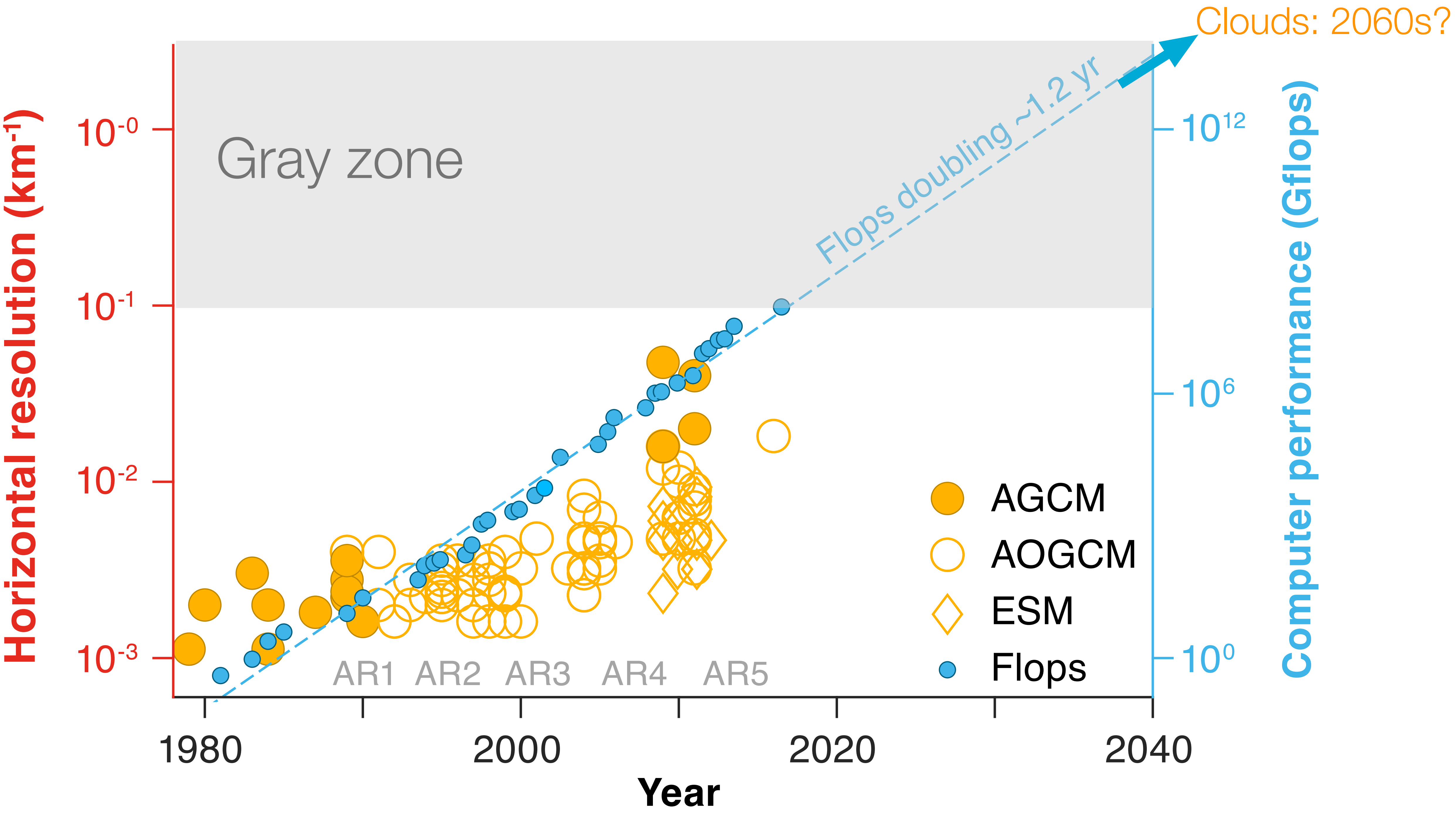
When will faster computers resolve clouds globally?



Peak performance of fastest computer

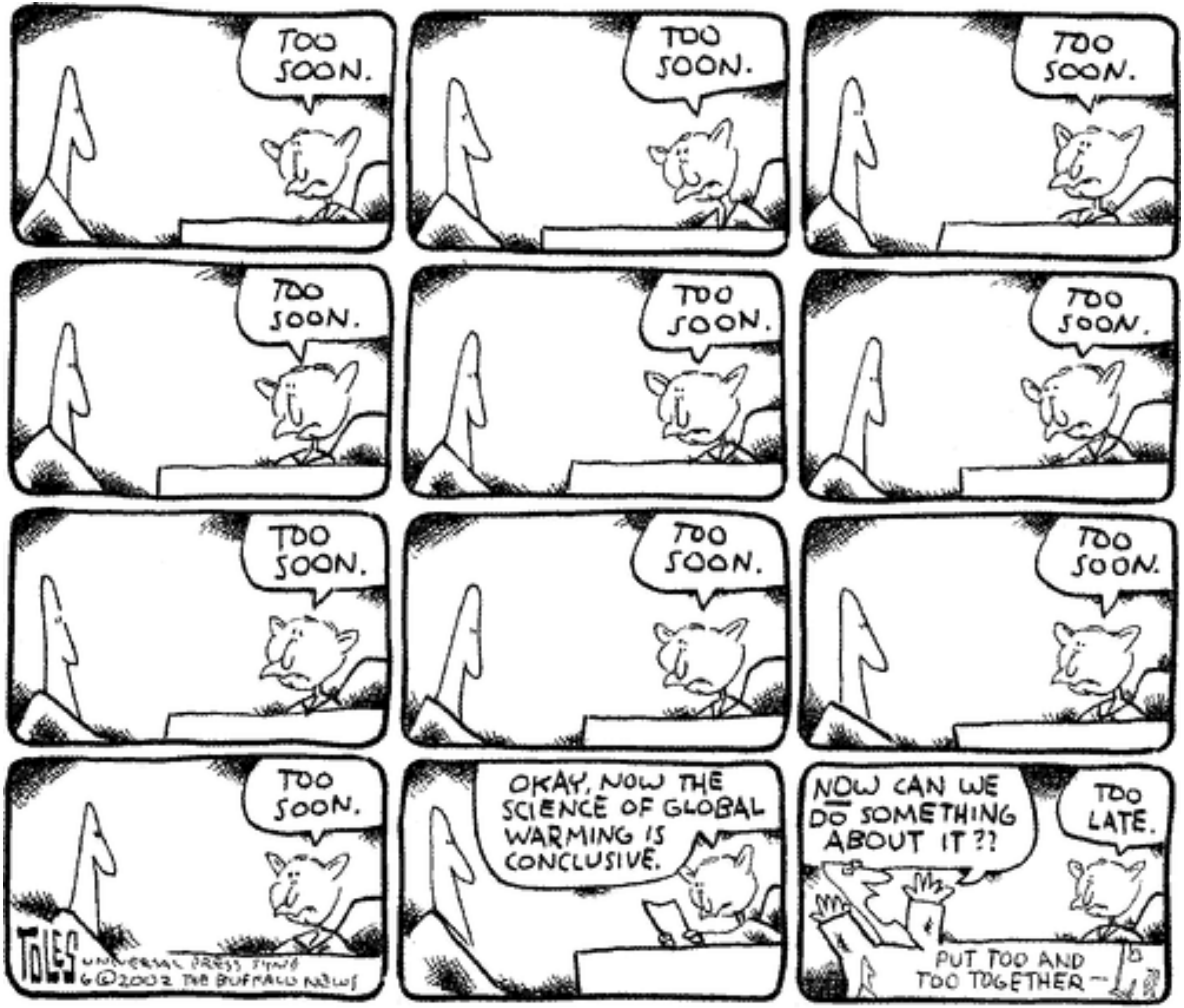
Schneider et al. *Nature Climate Change*, 2017

Global cloud resolving models not before 2060



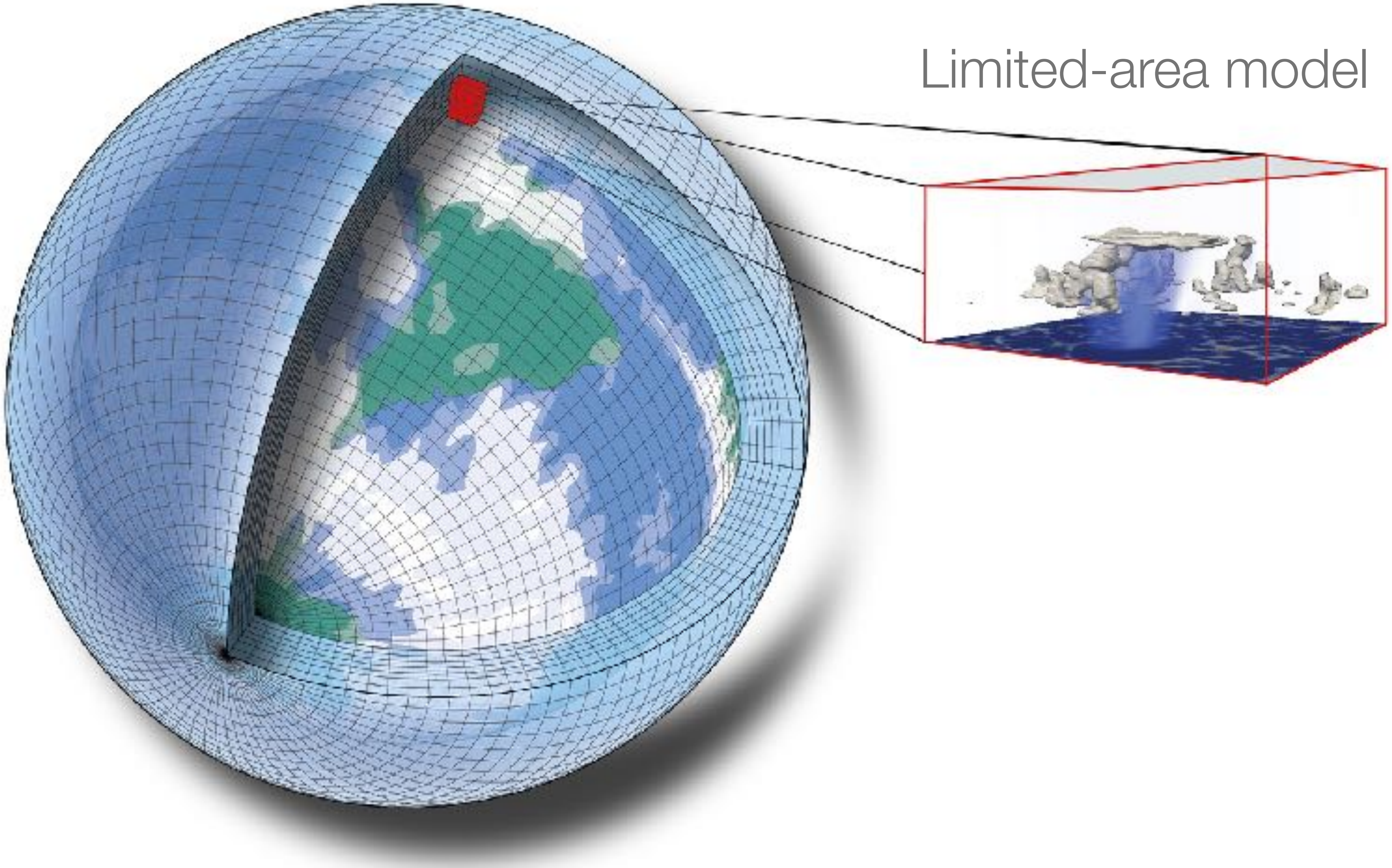
Climate model resolution

Schneider et al. *Nature Climate Change*, 2017


TOO SOON.
TOO SOON.
TOO SOON.
TOO SOON.
TOO SOON.
TOO SOON.
TOO SOON.
TOO SOON.
TOO SOON.
TOO SOON.
OKAY, NOW THE SCIENCE OF GLOBAL WARMING IS CONCLUSIVE.
NOW CAN WE DO SOMETHING ABOUT IT?!
TOO LATE.
PUT TOO AND TOO TOGETHER—
TOLES
UNIVERSAL PRESS SYND
6 ©2002 THE BUFFALO NEWS

6-6-02

What we can do now



Use global and limited-area models in hierarchical framework

It’s also the golden age of observations from space

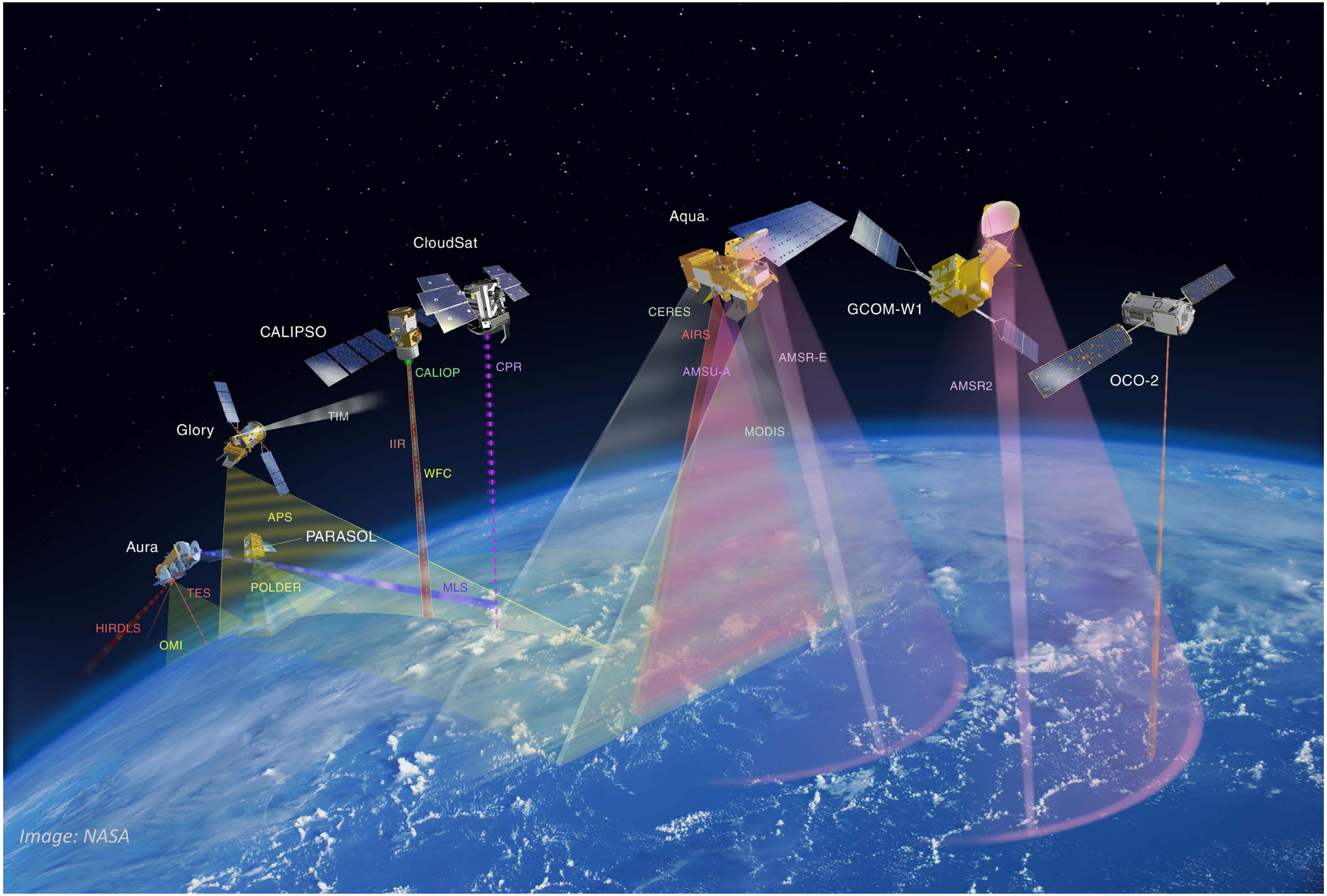
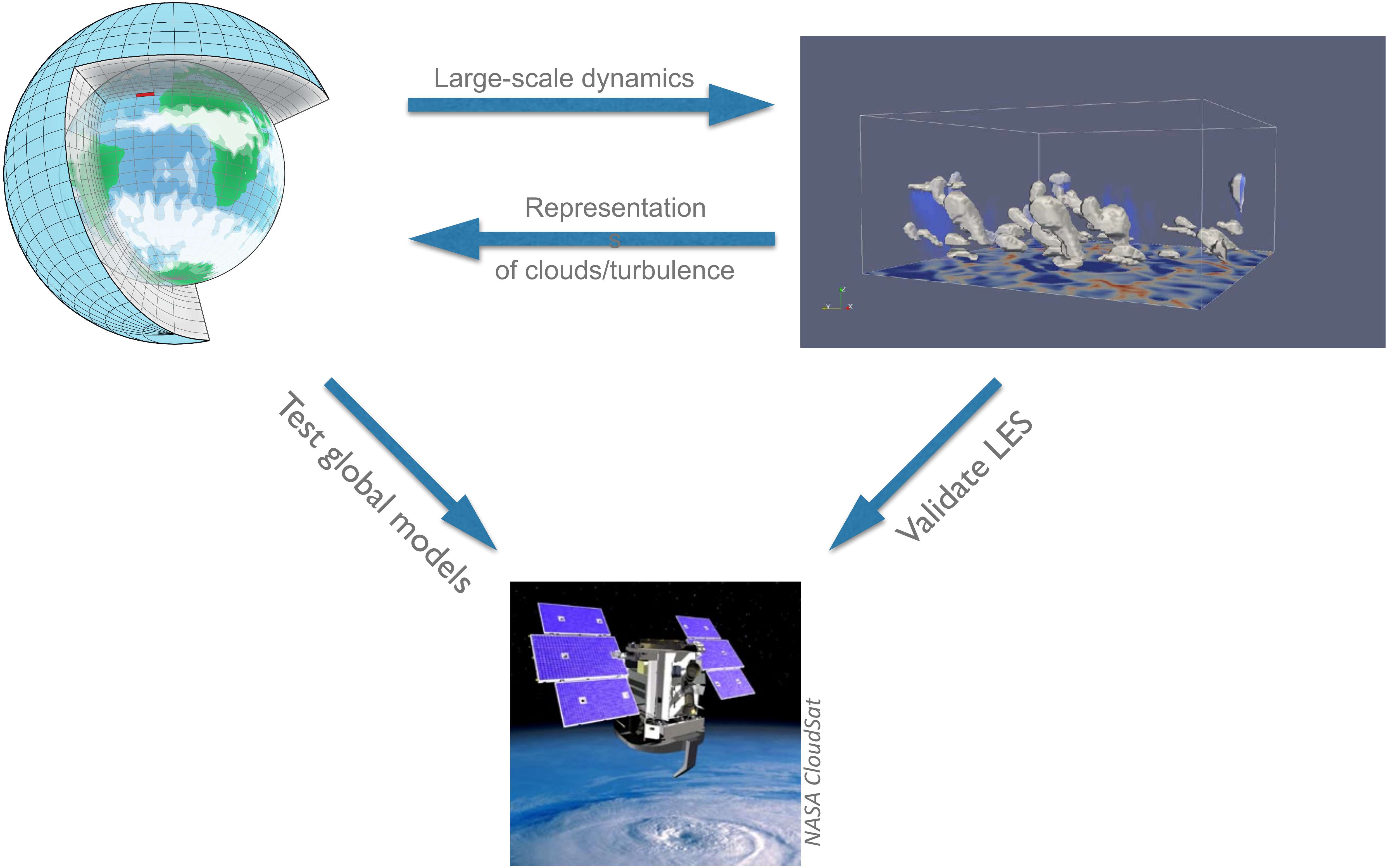


Image: NASA

Develop new representations of clouds and turbulence with model hierarchy and new data



Large-scale dynamics

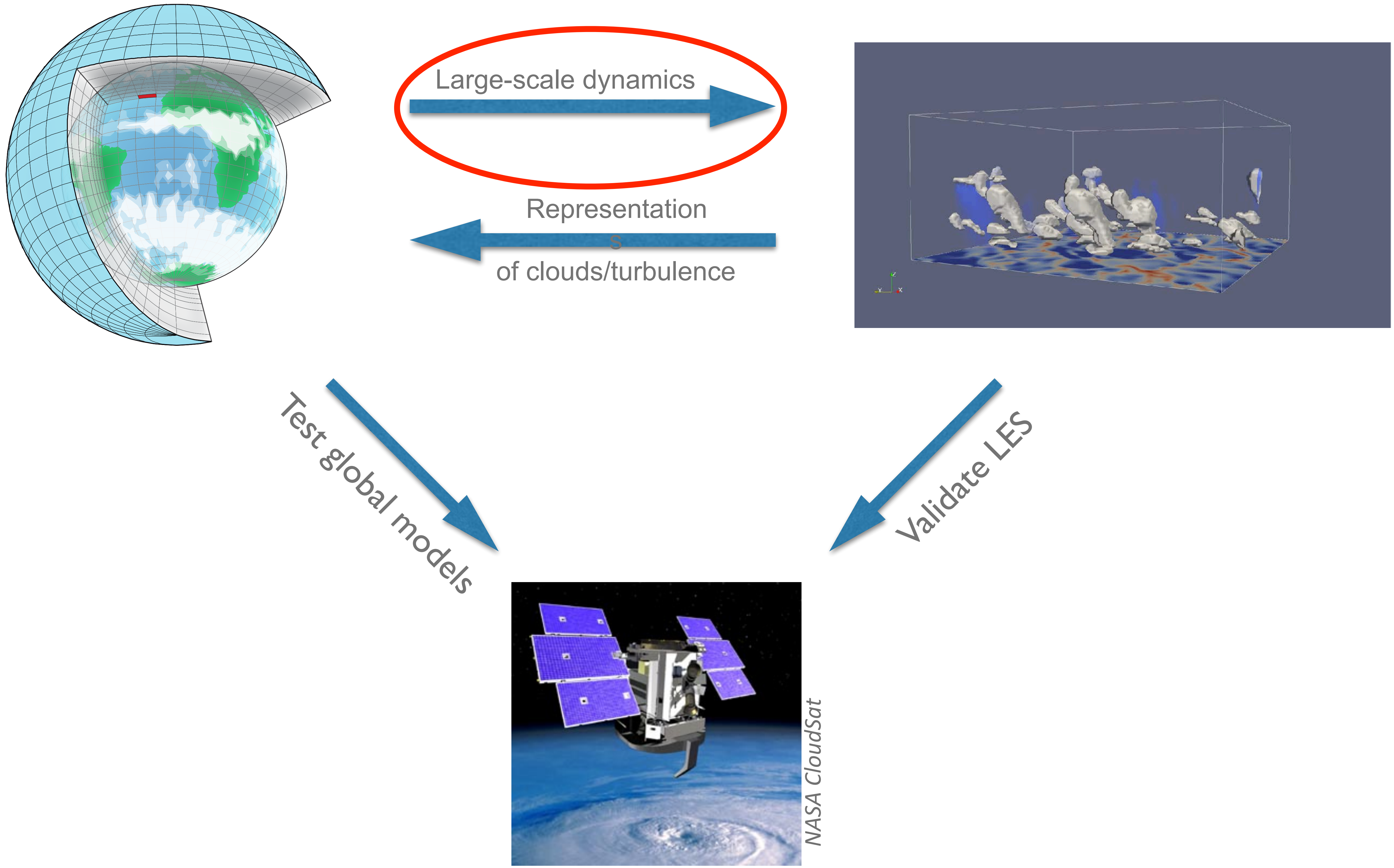
Representations of clouds/turbulence

Test global models

Validate LES

NASA CloudSat

Develop new representations of clouds and turbulence with model hierarchy and new data



Large-scale dynamics

Representations of clouds/turbulence

Test global models

Validate LES

NASA CloudSat

What’s difficult about driving limited-area models? Why not simply prescribing surface temperatures?

- Need to respect energy balance to get surface fluxes right
- E.g., with fixed SST, evaporation

$$E \propto e_s - e = e_s(1\text{-}RH)$$

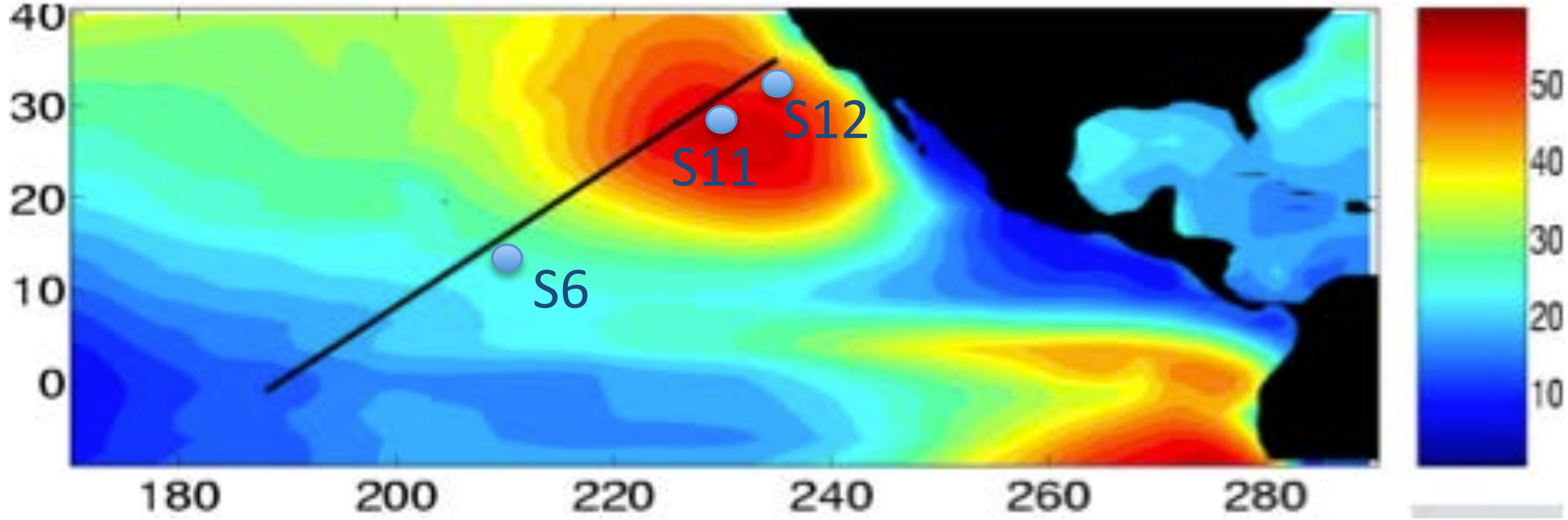
increases exponentially with SST (Clausius-Clapeyron). This distorts buoyancy flux.

Impossible in reality!

We can probe the cloud response with LES

- Python Cloud Large Eddy Simulation (*PyCLES*, Pressel et al. 2015)
  - Closed budgets of specific entropy (s) and total water (q_t)
  - Discontinuity-capturing (WENO) advection schemes
- Include *radiative transfer* in LES, couple it to *slab ocean*, and drive it with
  - horizontal fluxes of heat and water
  - mean vertical velocities
  - relaxation to moist adiabat in free troposphere

Perform LES of low clouds at subtropical sites



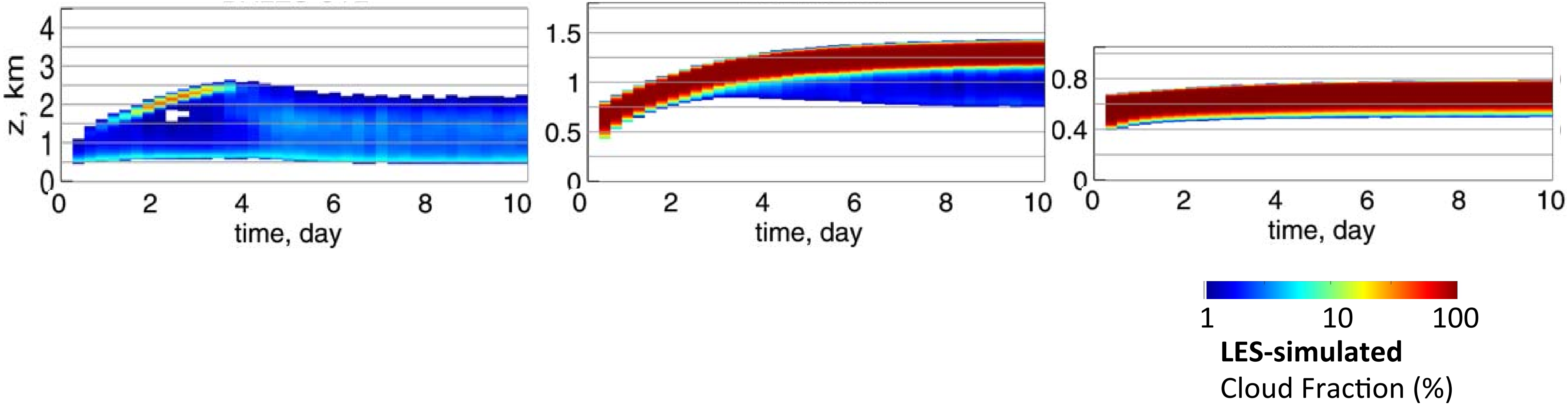
*Teixeira et al. 2011: **Observed** Low Cloud Fraction*

(same sites as in CGILS)

S6: Cumulus (Cu)

S11: Sc-over-Cu

S12: Stratocumulus (Sc)

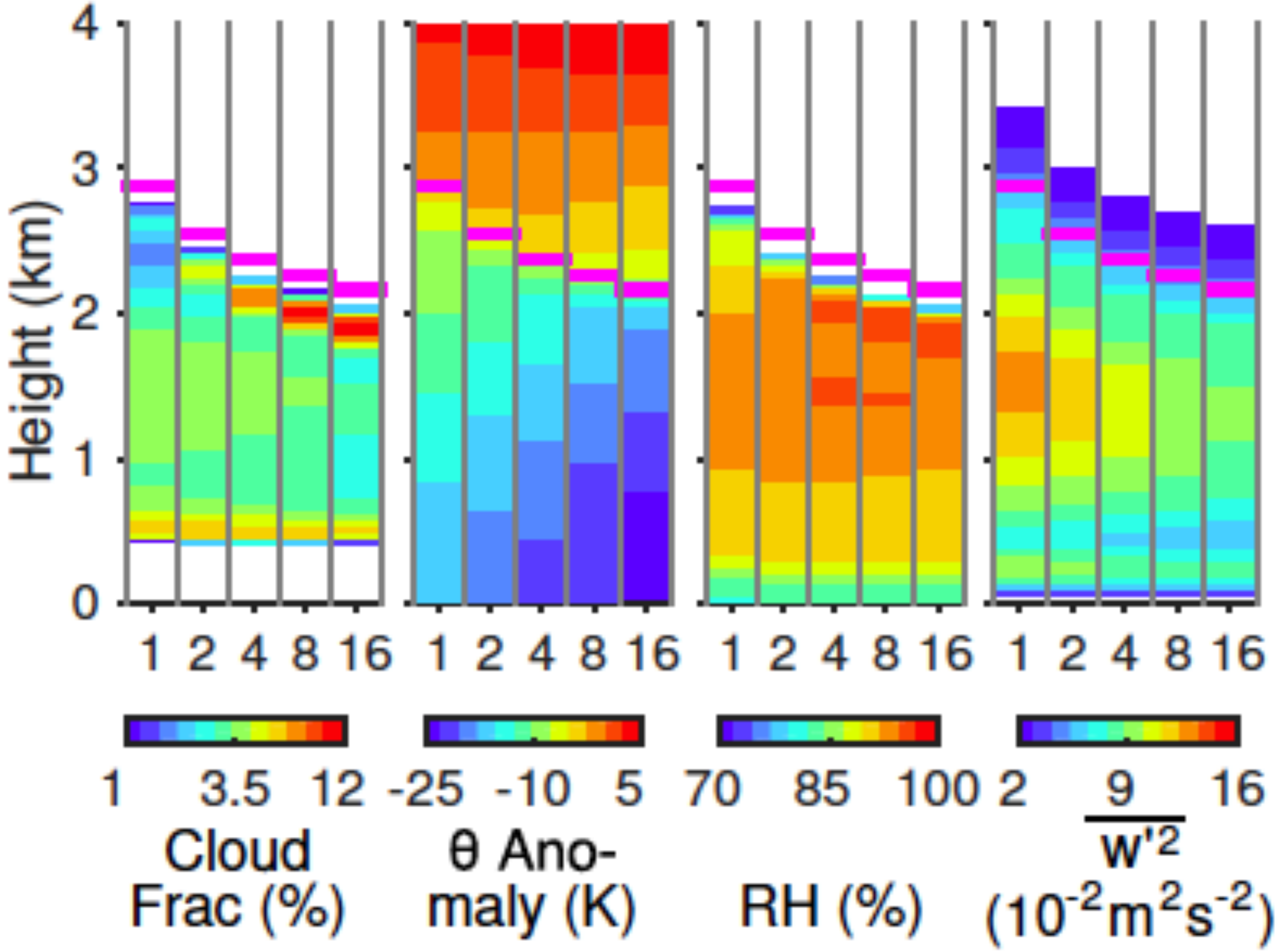


LES-simulated Cloud Fraction (%)

Tan et al. JAMES, in press

Turbulence weakens, cumulus clouds thin under warming (but may form anvils)

CO2, temperature increase →

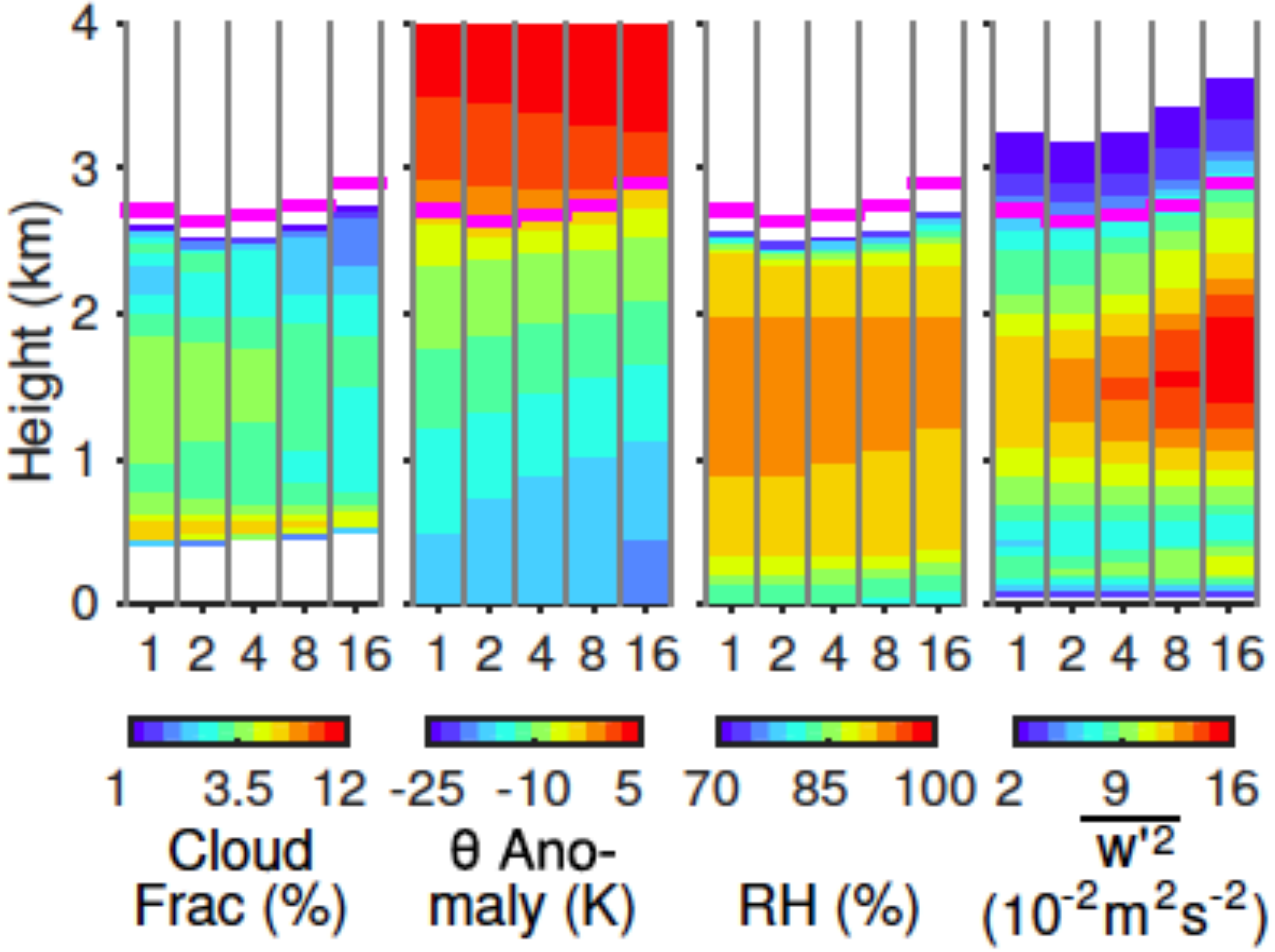


Inversion shallows, turbulence weakens

Tan et al. JAMES, in press

Contrast: Cu response with prescribed temperature

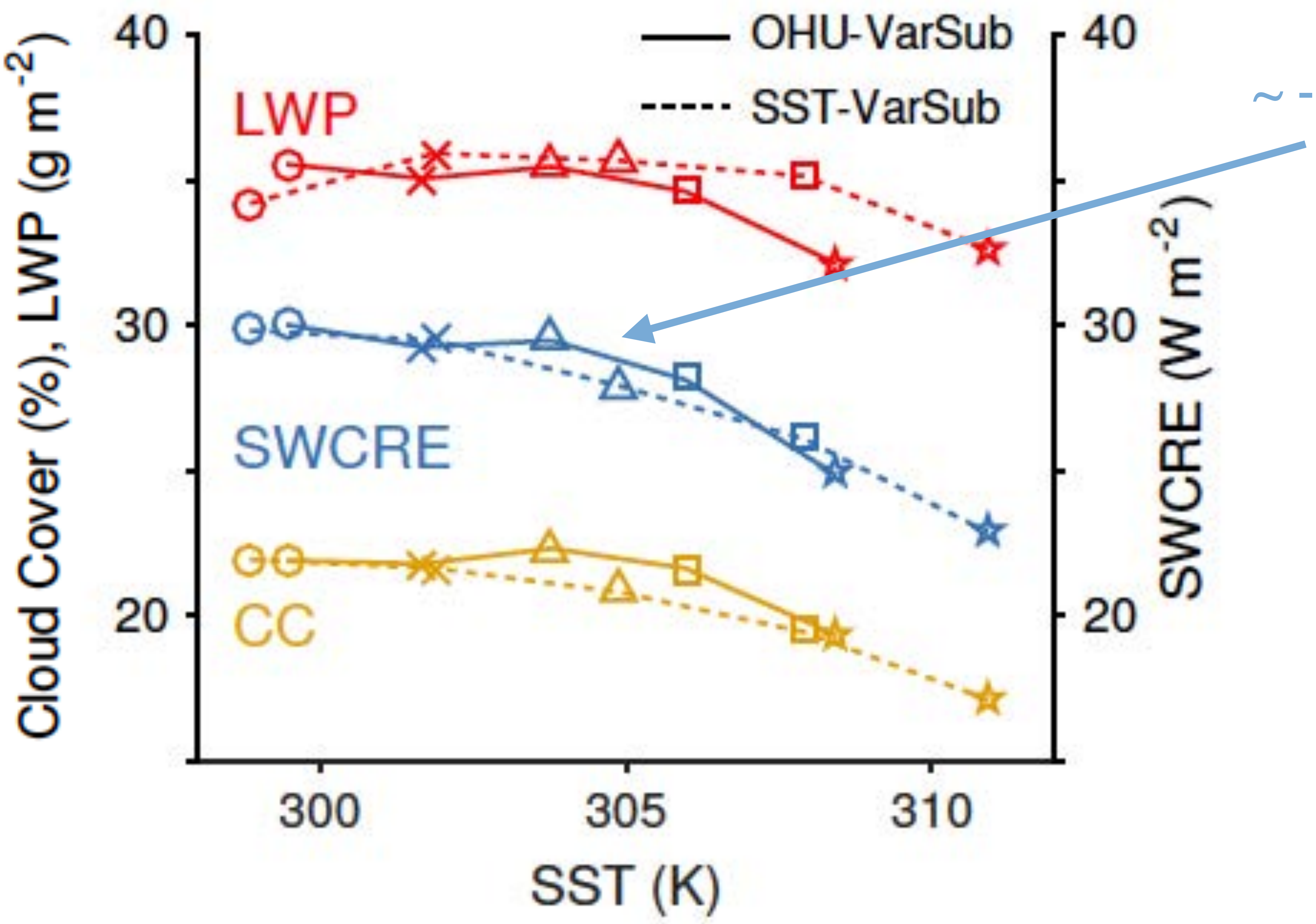
CO2, temperature increase →



Inversion stays same, turbulence strengthens

Tan et al. JAMES, in press

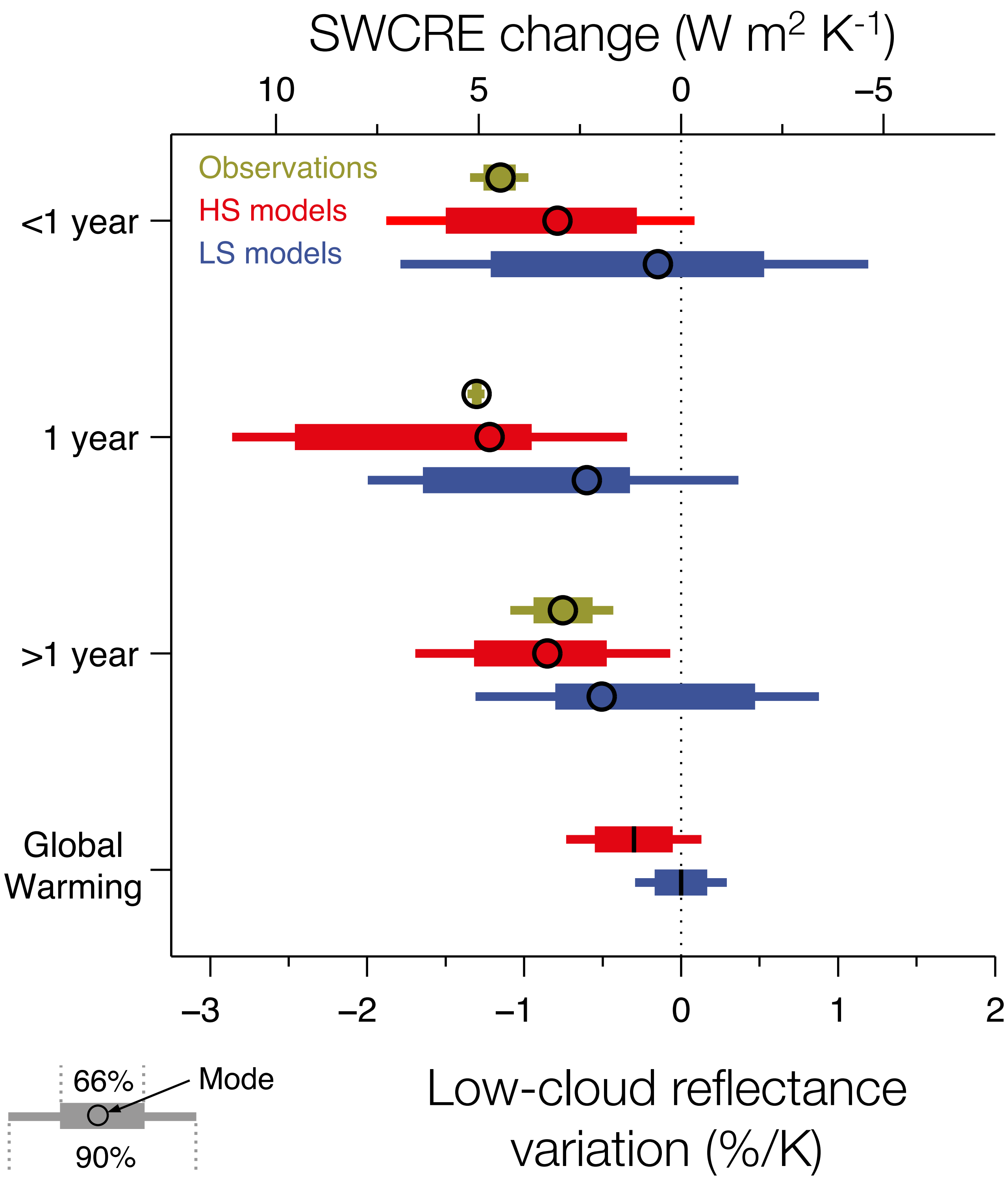
Cloud reflectance decreases under warming



~ - 0.6 W m^2/K

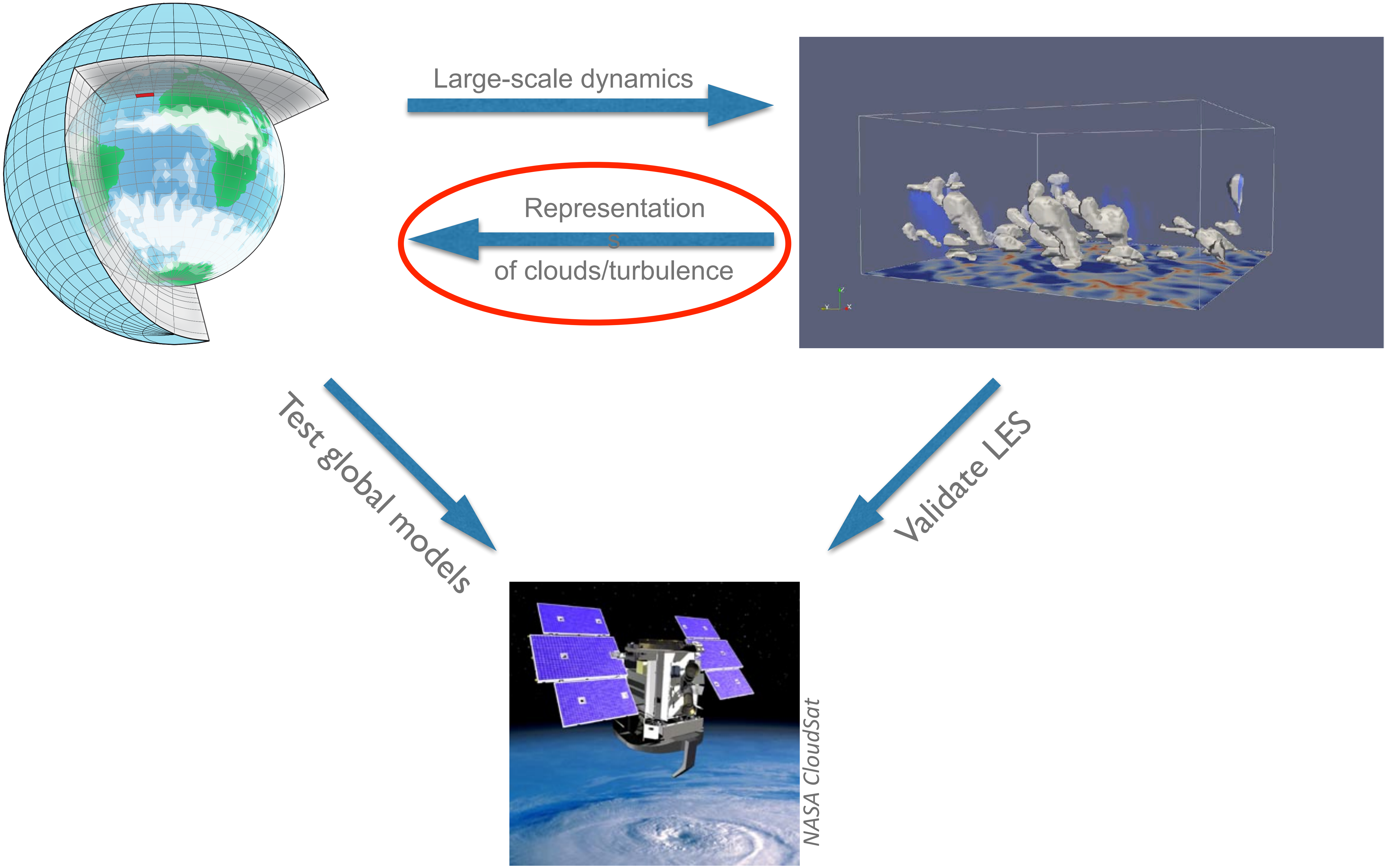
Tan et al. JAMES, in press

SW CRE decrease in LES is broadly consistent with higher-sensitivity climate models



Brient and Schneider 2016

Develop new representations of clouds and turbulence with model hierarchy and new data



Large-scale dynamics

Representations of clouds/turbulence

Test global models

Validate LES

NASA CloudSat

Cloud/boundary layer turbulence schemes in current GCMs have unphysical discontinuities

- **Deep convection (coherent)**: Often mass flux schemes (e.g., Arakawa & Schubert1974, Tiedtke 1989; Arakawa & Wu 2013)

- **Shallow convection (coherent)**: Often also mass flux schemes, but with discontinuously different parameters (e.g., entrainment rates)

- **Boundary layer turbulence (more isotropic)**: Often diffusive; difficult to match with cloud layer (e.g.,Troen & Mahrt 1986)

Parametric and structural discontinuities for processes with common (e.g., dry) limits

We use drafts/environment decomposition to develop unified representation of all SGS turbulence

Use adiabatically conserved variables $\phi = \{\theta_l, q_t\}$; partition fluxes into updraft, environment, and (later) downdraft components (Siebesma & Cuijpers 1995):

$$\overline{w'\phi'} = a_u\overline{w'\phi'}_u + (1-a_u)\overline{w'\phi'}_e + a_u(1-a_u)(w_u - w_e)(\phi_u - \phi_e)$$

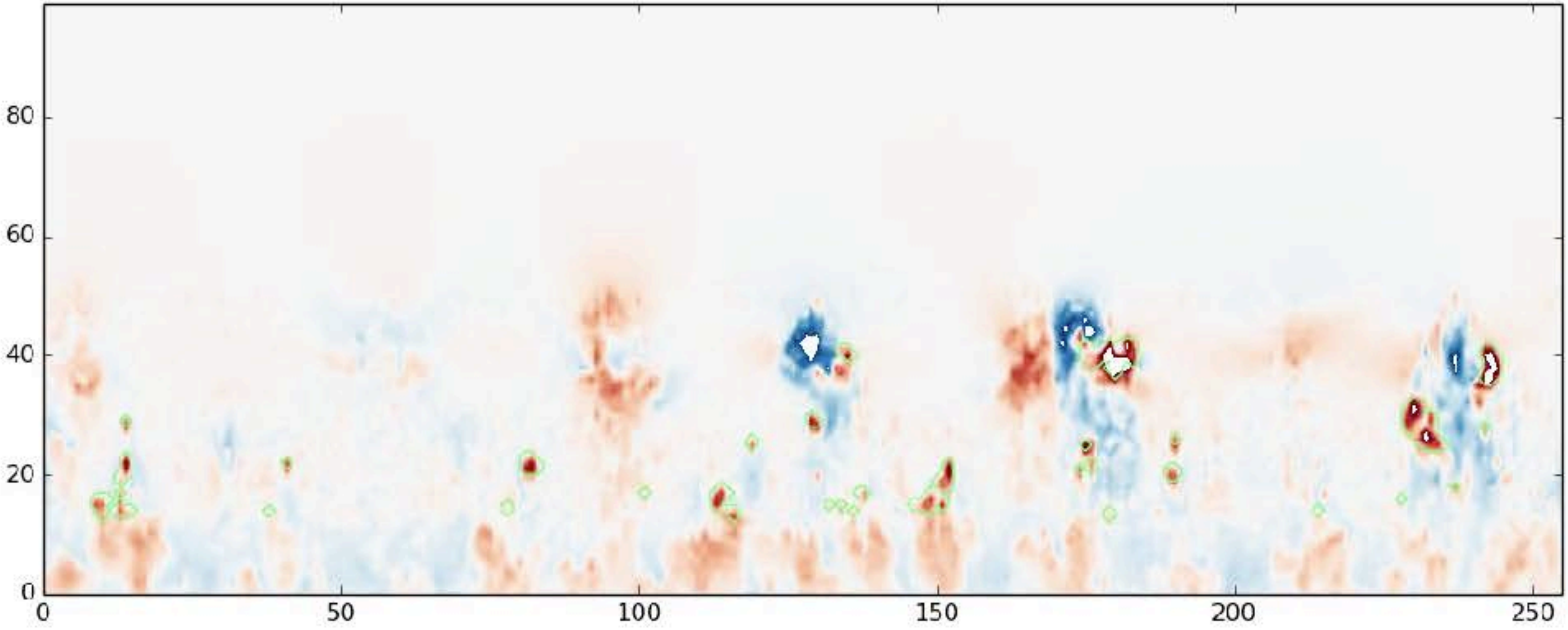
If updraft area fraction a_u is small and $w_e \approx 0$:

$$\overline{w'\phi'} = \overline{w'\phi'}_e + a_u w_u(\phi_u - \bar{\phi})$$

1st term focus in BL schemes, 2nd (mass flux) in convection. Keep both!

Phenomenology of turbulence motivates drafts/environment decomposition (BOMEX, shallow Cu)

Colors: vertical velocity (red up, blue down); green contours: cloud condensate



(Kyle Pressel, code available at climate-dynamics.org)

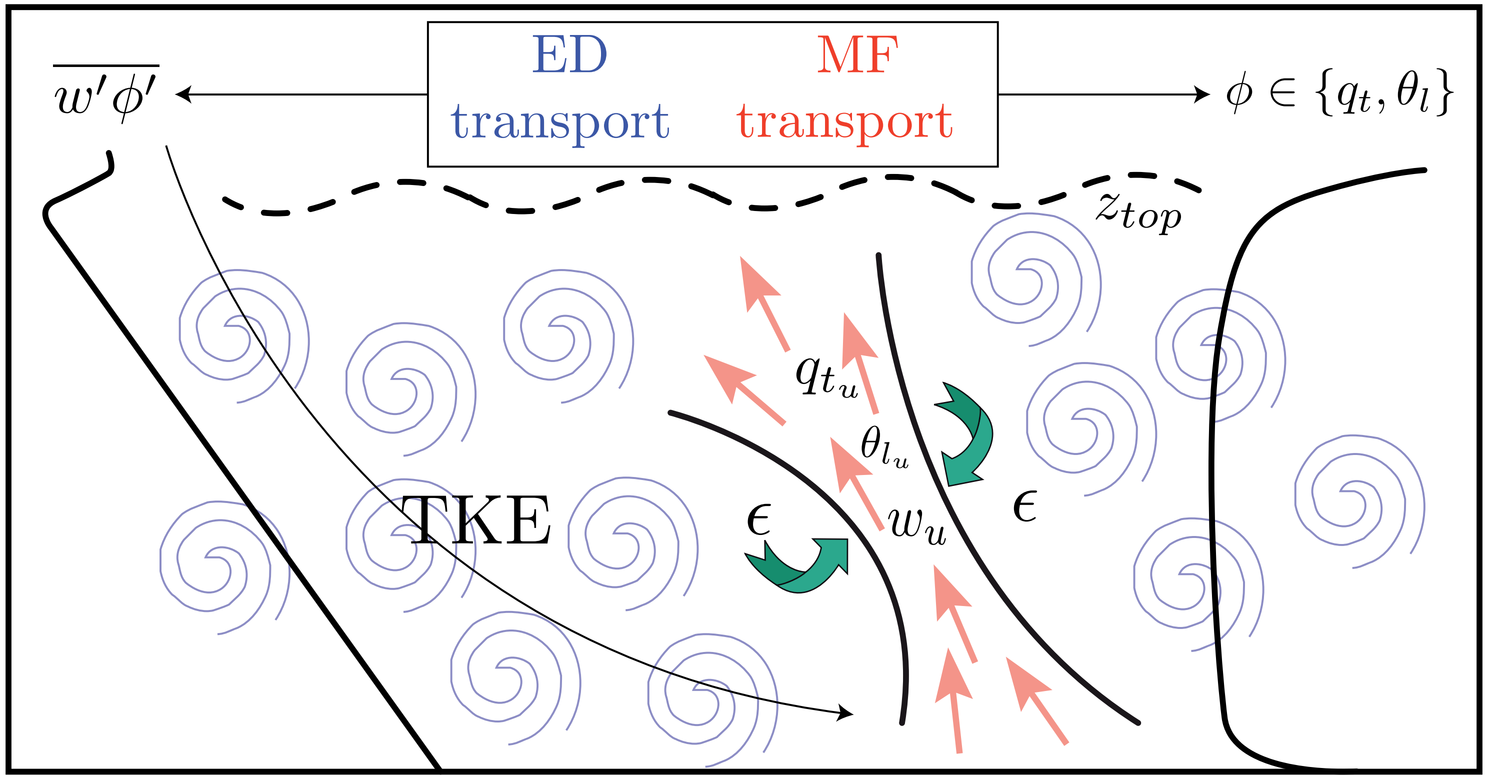
Eddy diffusion/mass flux scheme

Turbulent flux of conserved variables (Siebesma & Teixeira 2000)

$$\overline{w'\phi'} \approx -K(z)\frac{\partial\bar{\phi}}{\partial z} + M(z)(\phi_u - \bar{\phi})$$

ED term
(environment)

MF term
(updraft)



(Witek et al. 2011)

Structure of new EDMF scheme

Draft equations (continuous form, index ‘i’ represents the ith draft):

Vertical velocity w^i: $$\frac{\partial w^i}{\partial t} + \frac{1}{2}\frac{\partial (w^i)^2}{\partial z} = aB_u^i + b\epsilon_i w^i (w^n - w^i)$$

Area fraction a_i: $$\frac{\partial(\rho a_i)}{\partial t} + \frac{\partial(\rho a_i w^i)}{\partial z} = \rho a_i w^i(\epsilon^i - \delta^i)$$

Tracer ϕ^i: $$\rho a_i \frac{\partial \phi^i}{\partial t} + \rho a_i w^i \frac{\partial \phi^i}{\partial z} = \rho a_i w^i \epsilon^i (\phi^n - \phi^i) + \rho a_i S_\phi^i$$

$\phi = \theta_l$ or q_t

B_u: draft buoyancy

ε: entrainment rate

δ: detrainment rate

S: source terms

Grid-mean equations (continuous form, index ‘n’ represents environment):

Tendency due to MF: $$M^i = \rho a_i (w^i - w^T), \quad \left.\frac{d\phi^T}{dt}\right|_{MF} = -\frac{1}{\rho}\frac{\partial}{\partial z}\sum_{i\neq n}\Big(M^i(\phi^i - \phi^n)\Big)$$

Tendency due to ED: $$\left.\frac{d\phi^T}{dt}\right|_{ED} = \frac{1}{\rho}\frac{\partial}{\partial z}\Big((\rho a_n K)\frac{\partial \phi^n}{\partial z}\Big)$$

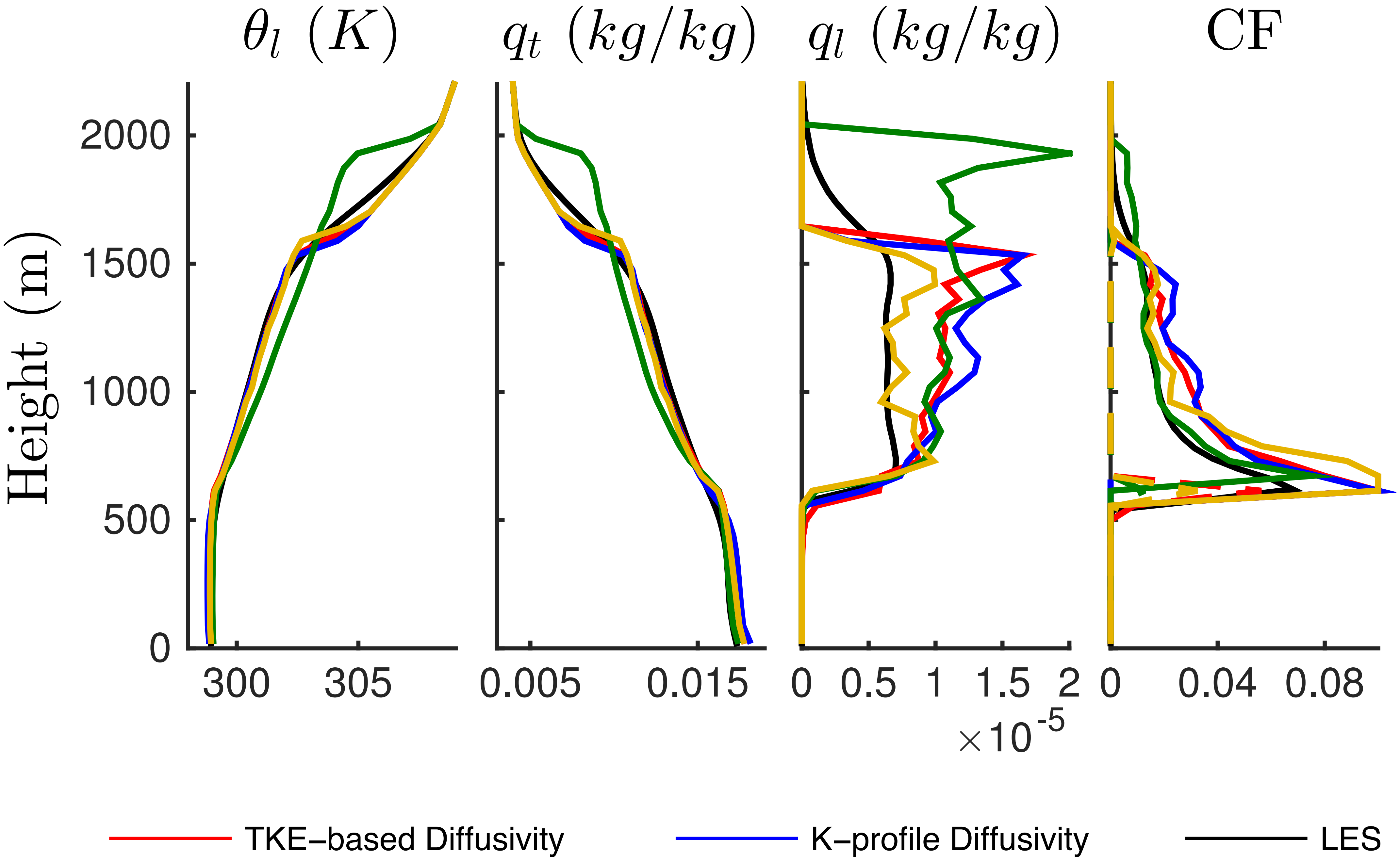
K: eddy diffusivity

Total: $$\left.\frac{d\phi^T}{dt}\right|_{EDMF} = \left.\frac{d\phi^T}{dt}\right|_{MF} + \left.\frac{d\phi^T}{dt}\right|_{ED} + \left.\frac{d\phi^T}{dt}\right|_{S}, \quad \left.\frac{d\phi^T}{dt}\right|_{S} = S_\phi^T = \sum_{i\neq n}(a_i S_\phi^i) + a_n S_\phi^n$$

Treats updraft/downdraft/environment decomposition consistently, at second order (e.g., TKE), and allows variable draft fractions (requires prognostic equations)

(Zhihong Tan)

This works quite well for cumulus clouds (BOMEX)



Currently working on machine-learning approaches to estimate closure parameters in hierarchical EDMF scheme

Summary

- Models produce widely varying low-cloud feedbacks, driving climate sensitivity spread
- Observations point to robustly positive low-cloud feedback, making climate sensitivity < 2.3 K very unlikely
- LES with closed energy budget show that Cu-layer generally shallows, cloud feedback is robustly positive
- Stratocumulus may hold surprises as climate warms beyond $2\times CO_2$
- Unified parameterization based on EDMF framework holds promise, needs to be fleshed out further