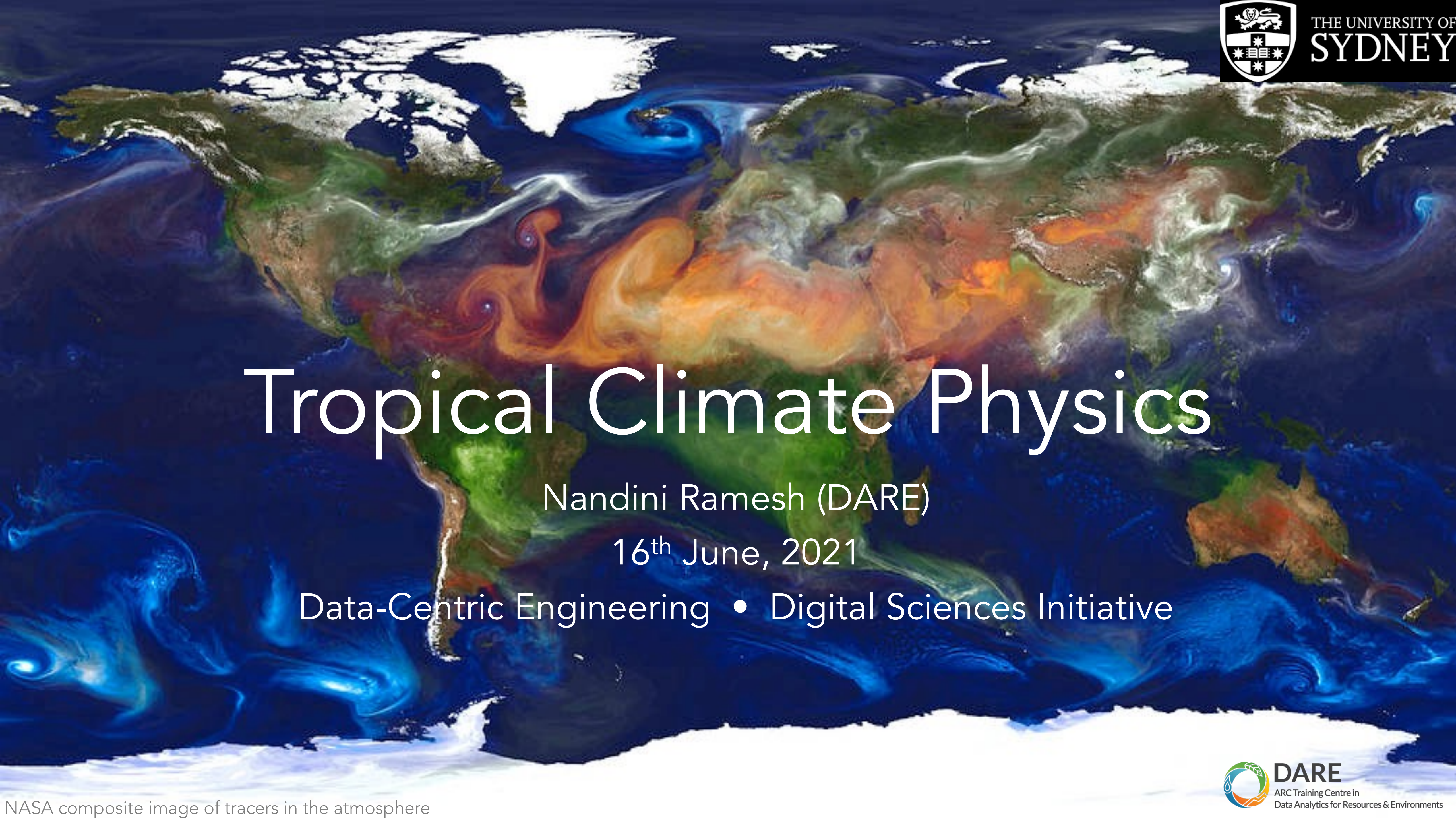
Tropical Climate Physics

Nandini Ramesh (DARE)

16th June, 2021

Data-Centric Engineering • Digital Sciences Initiative



NASA composite image of tracers in the atmosphere

Outline

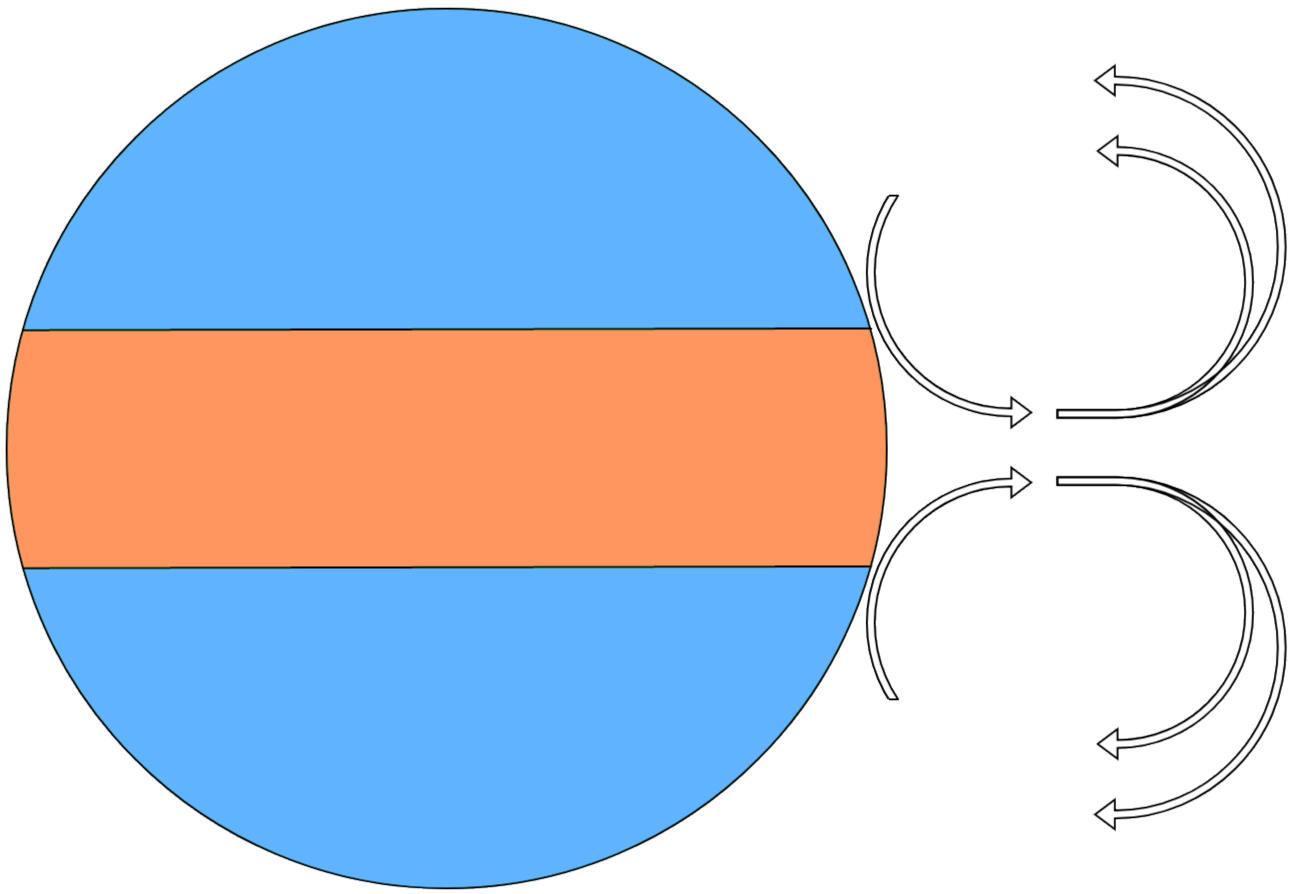
1. A very rapid introduction to climate physics
   (With a tropical rainfall bias)

2. How climate science uses digital twins

3. Two illustrations of my work with digital twins

The Setting

Atmosphere and ocean: fluid flow in a **thin shell** over a spherical, rotating, unevenly-heated planet.

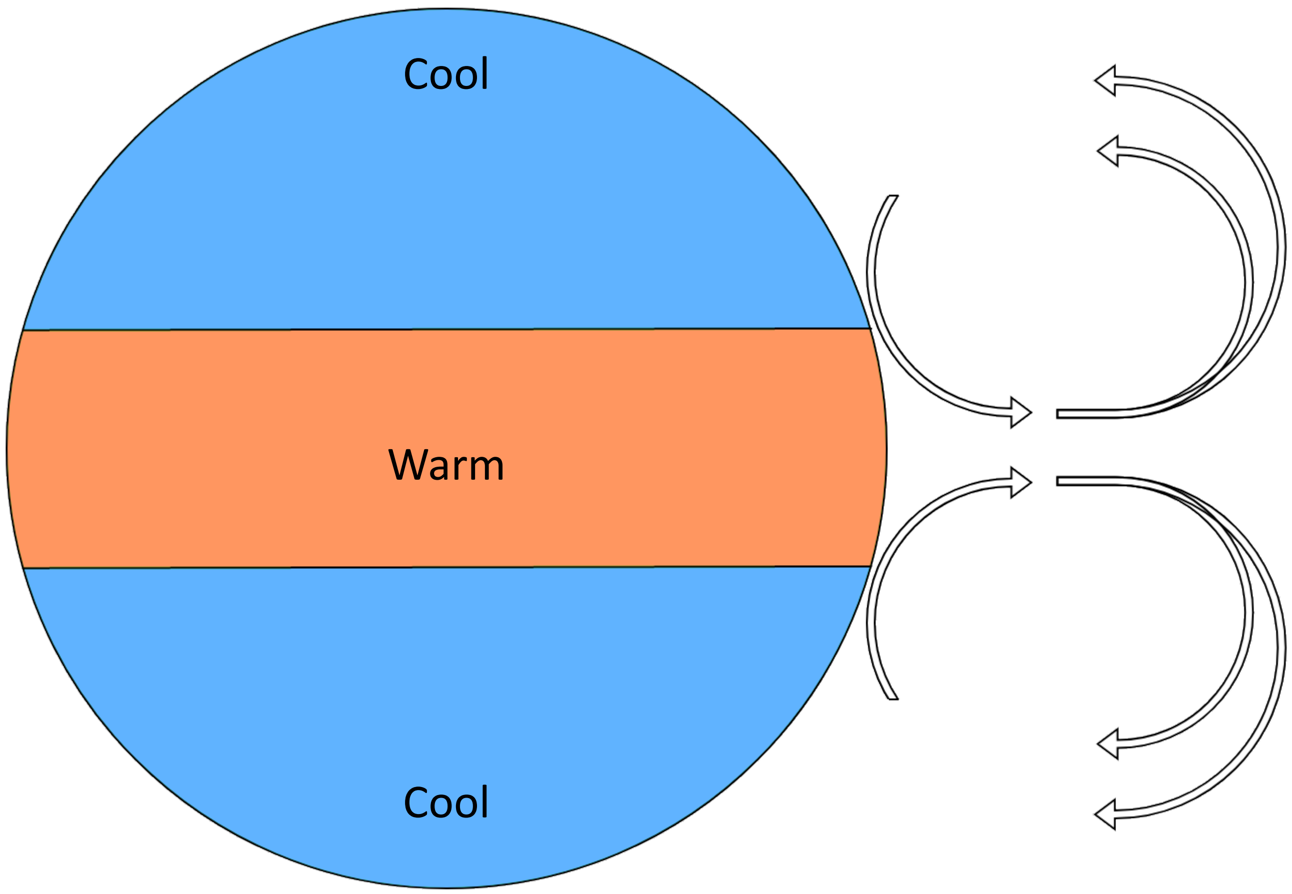


- Atmosphere: ~100 km thick; troposphere only **15 km** at its thickest.
- Ocean is 11 km deep at its deepest, approx. **4 km** in most places.

Compare with radius of Earth: **6371 km**

The Setting

Atmosphere and ocean: fluid flow in a thin shell over a spherical, rotating, **unevenly-heated** planet.

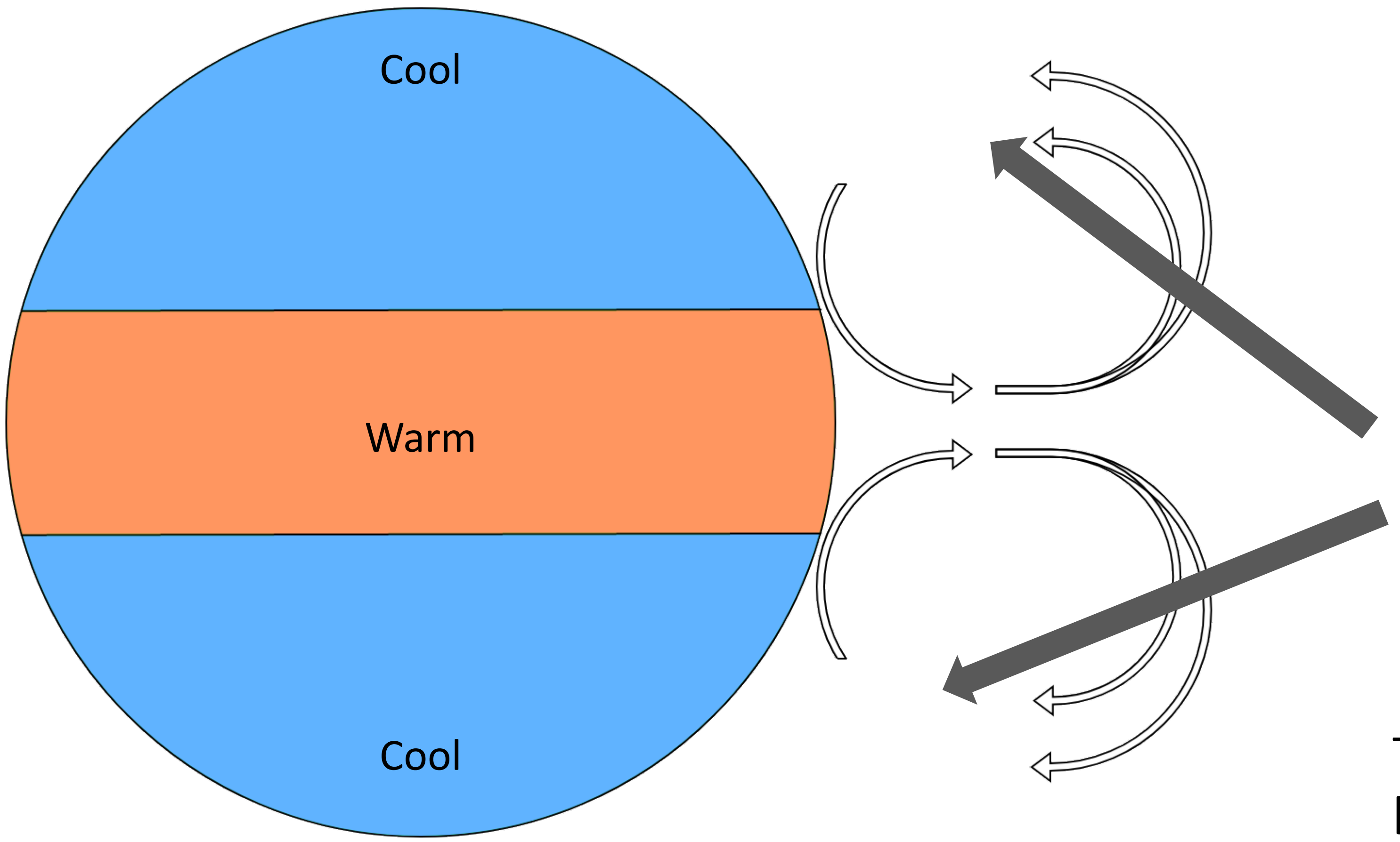


Warm air expands, is more buoyant, rises at low latitudes

Cool air is denser, sinks at higher latitudes

The Setting

Atmosphere and ocean: fluid flow in a thin shell over a **spherical**, **rotating**, unevenly-heated planet.



Warm air expands, is more buoyant, rises at low latitudes

Cool air is denser, sinks at higher latitudes

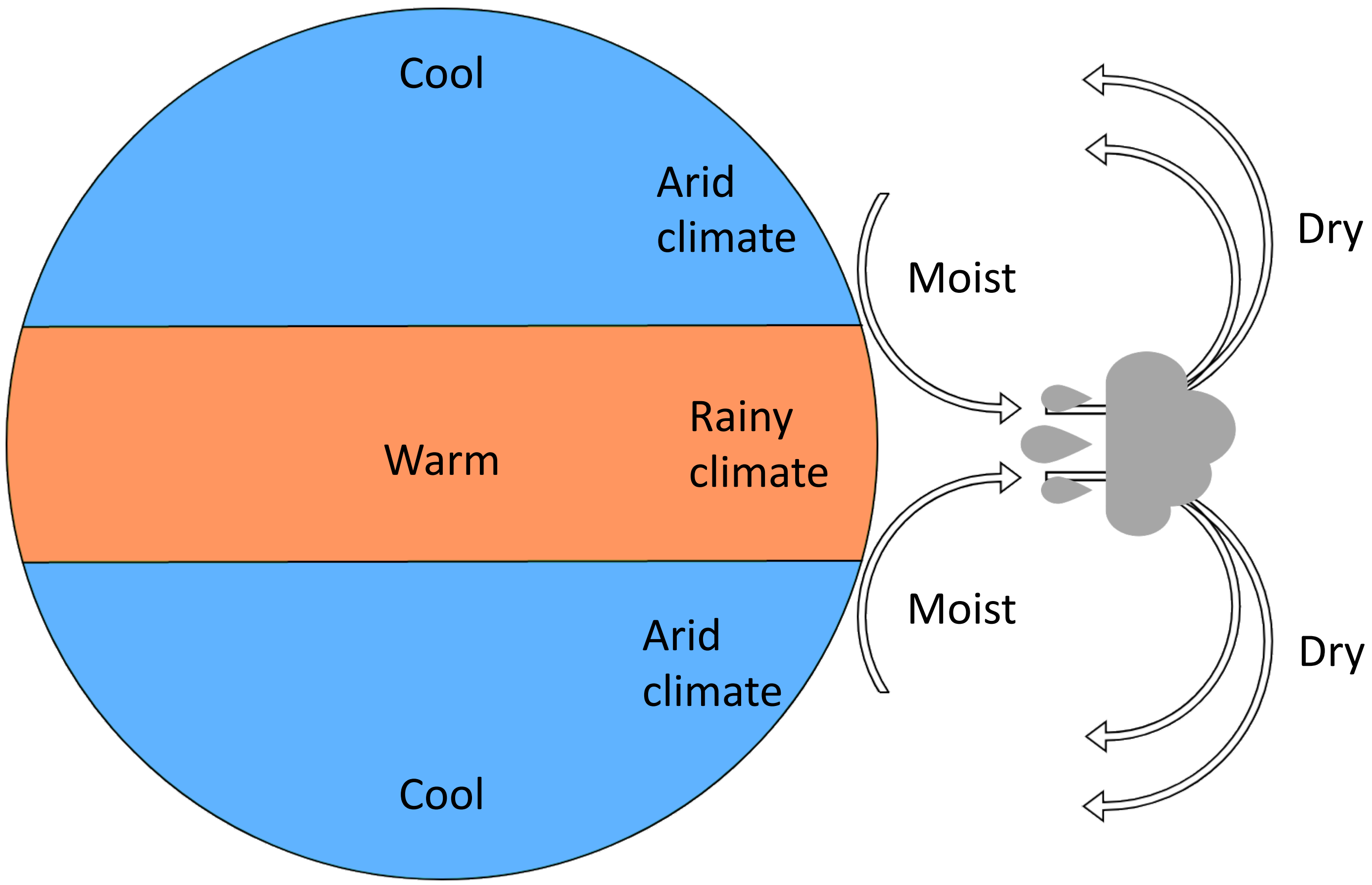
Rotation & spherical shape make these flows unstable beyond 30-40º N/S, so these cells end at these latitudes.

These cells are called the

Hadley Circulation.

The Setting

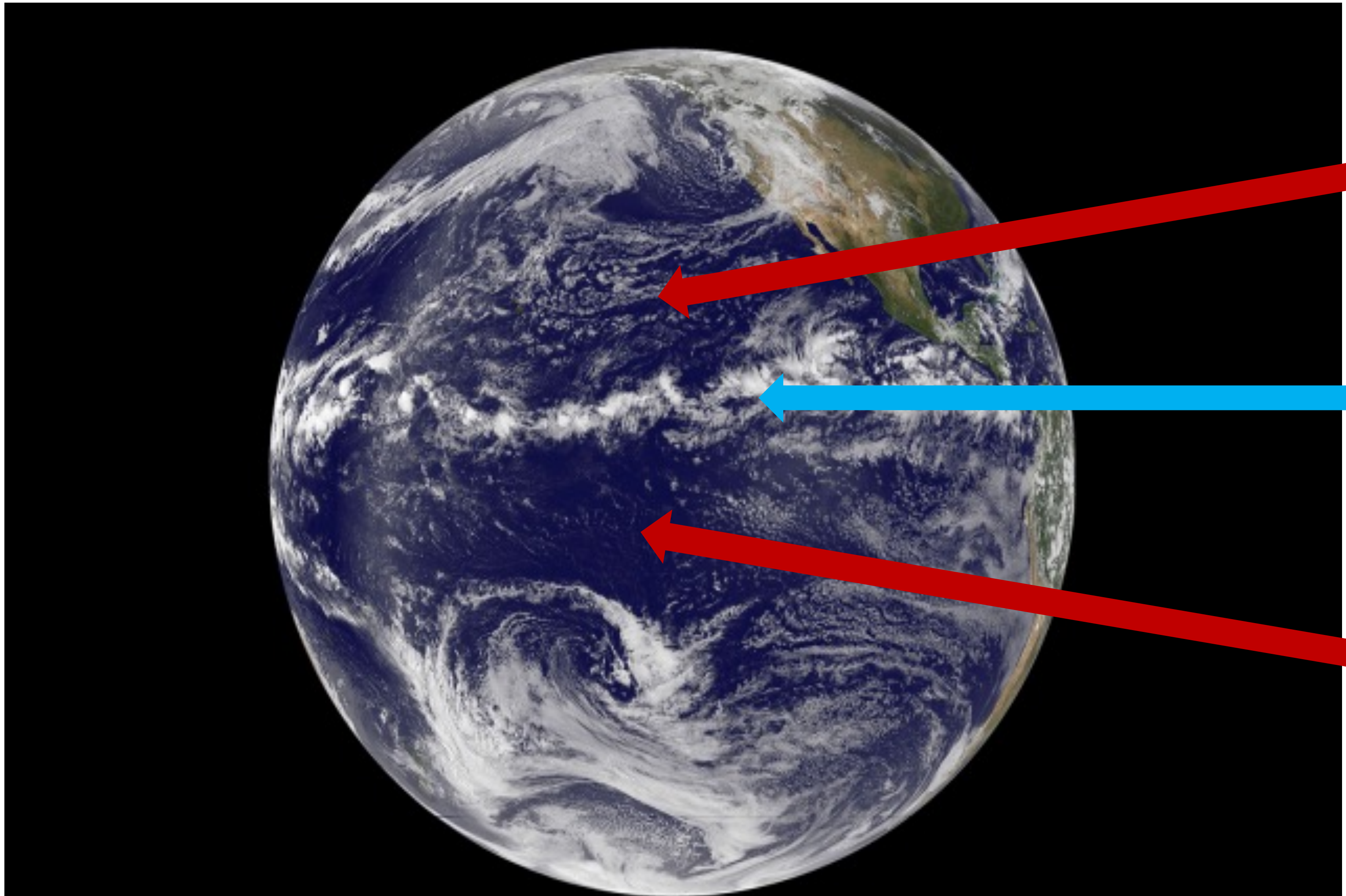
Atmosphere and ocean: fluid flow in a thin shell over a spherical, rotating, unevenly-heated planet **with moisture**.



Warm, **moist**, air expands, is more buoyant, rises at low latitudes.
Moisture condenses and rains out as rising air cools.

Cool, **dry**, air is denser, sinks at higher latitudes.
These areas experience desert-like climates.

On Earth



NOAA GOES & NASA Visualization Studio

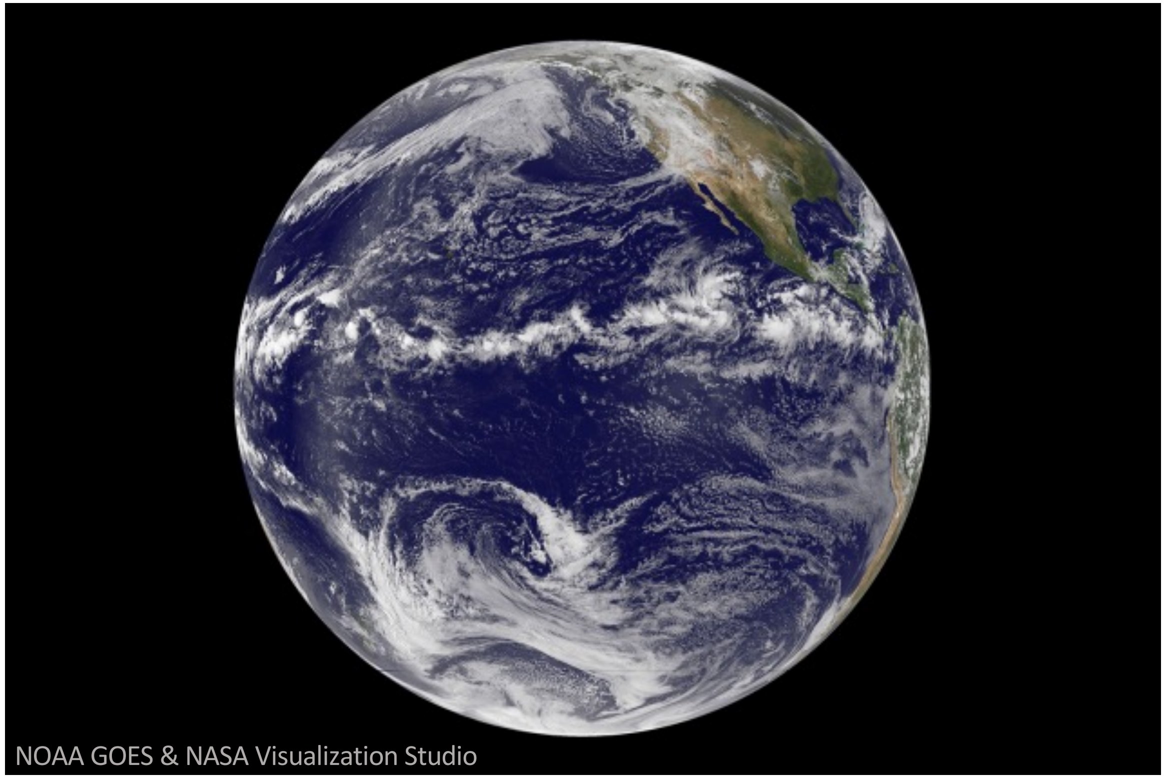
Clear skies, dry climate, sinking air

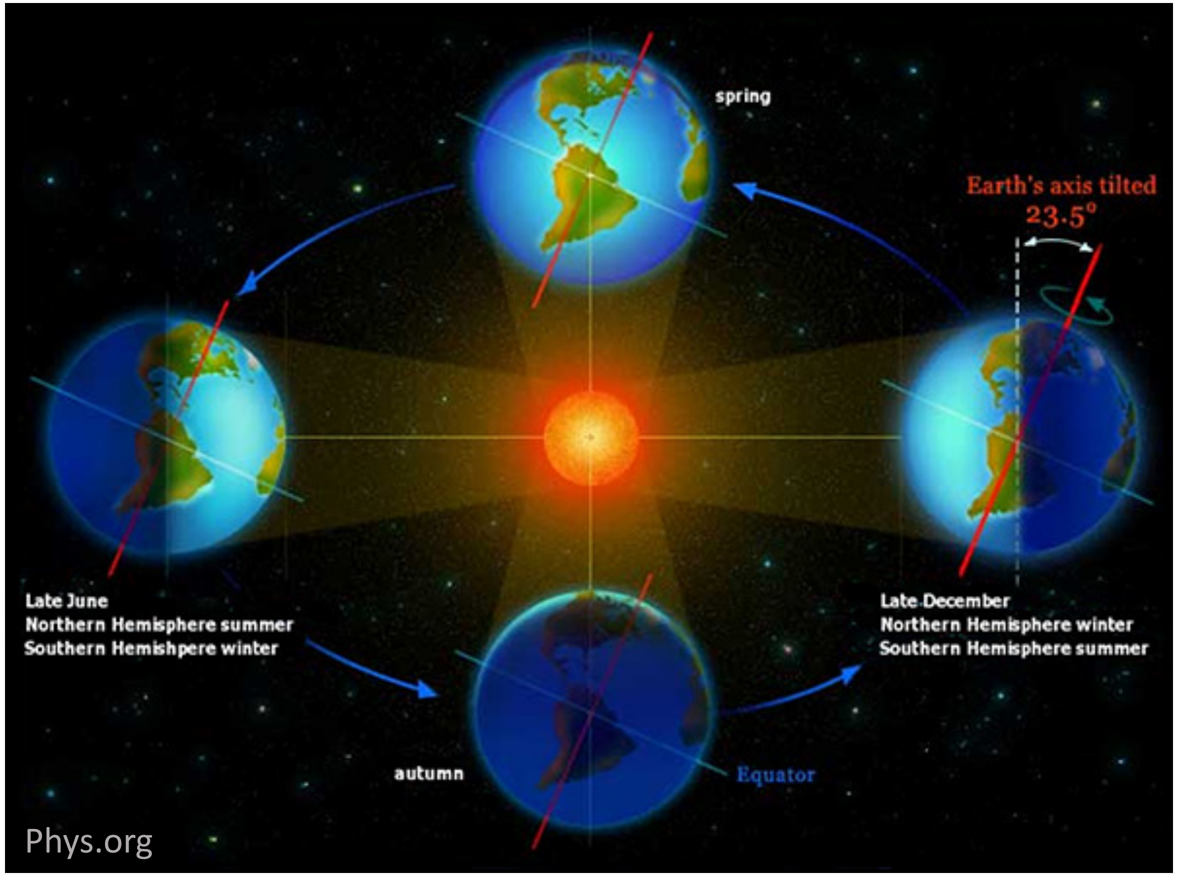
Band of intense tropical rainfall (Inter-Tropical Convergence Zone or ITCZ)

Clear skies, dry climate, sinking air

Seasons on Earth

As the latitude of maximum incoming energy changes with the seasons, the ITCZ shifts north/south.

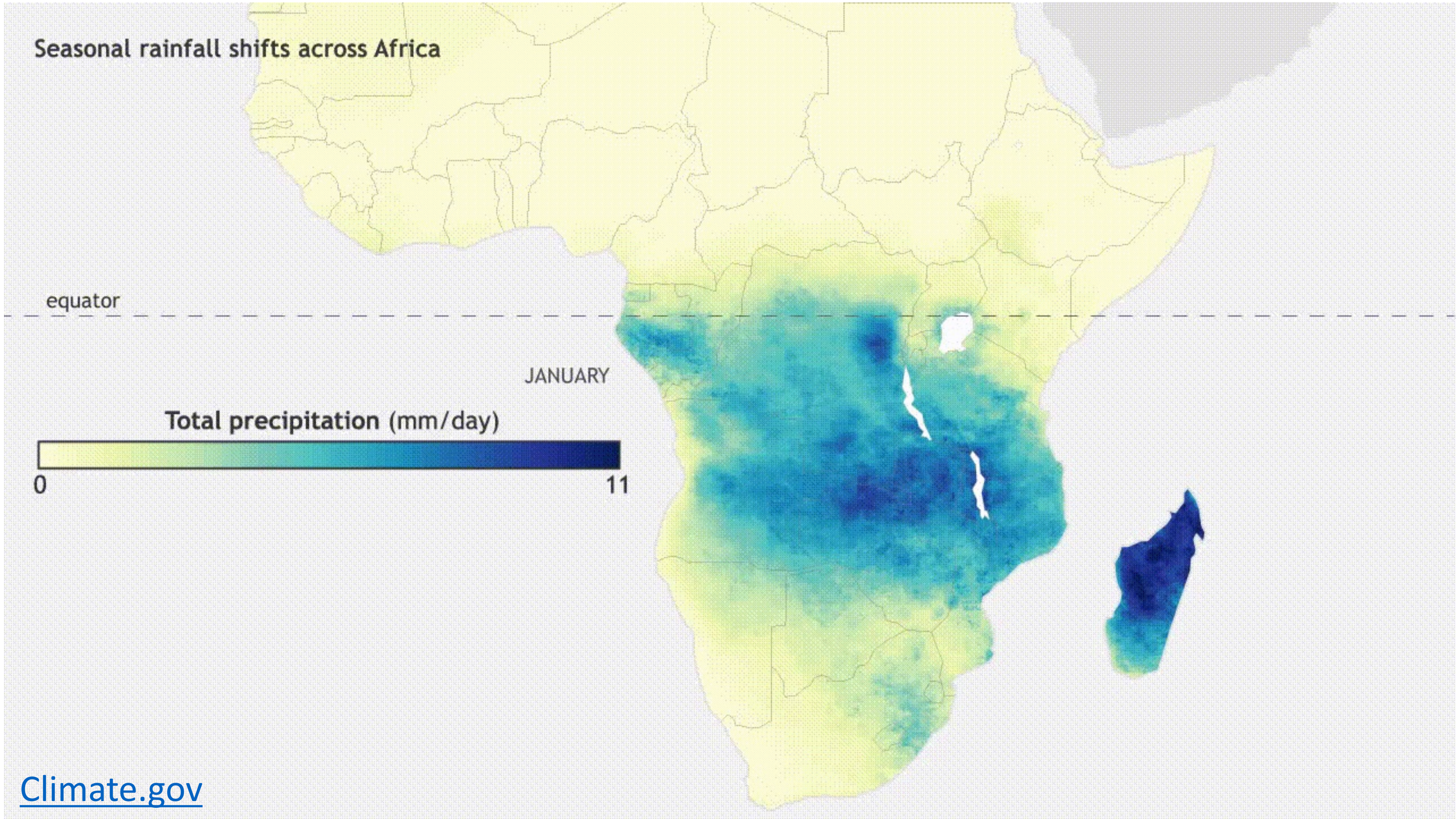




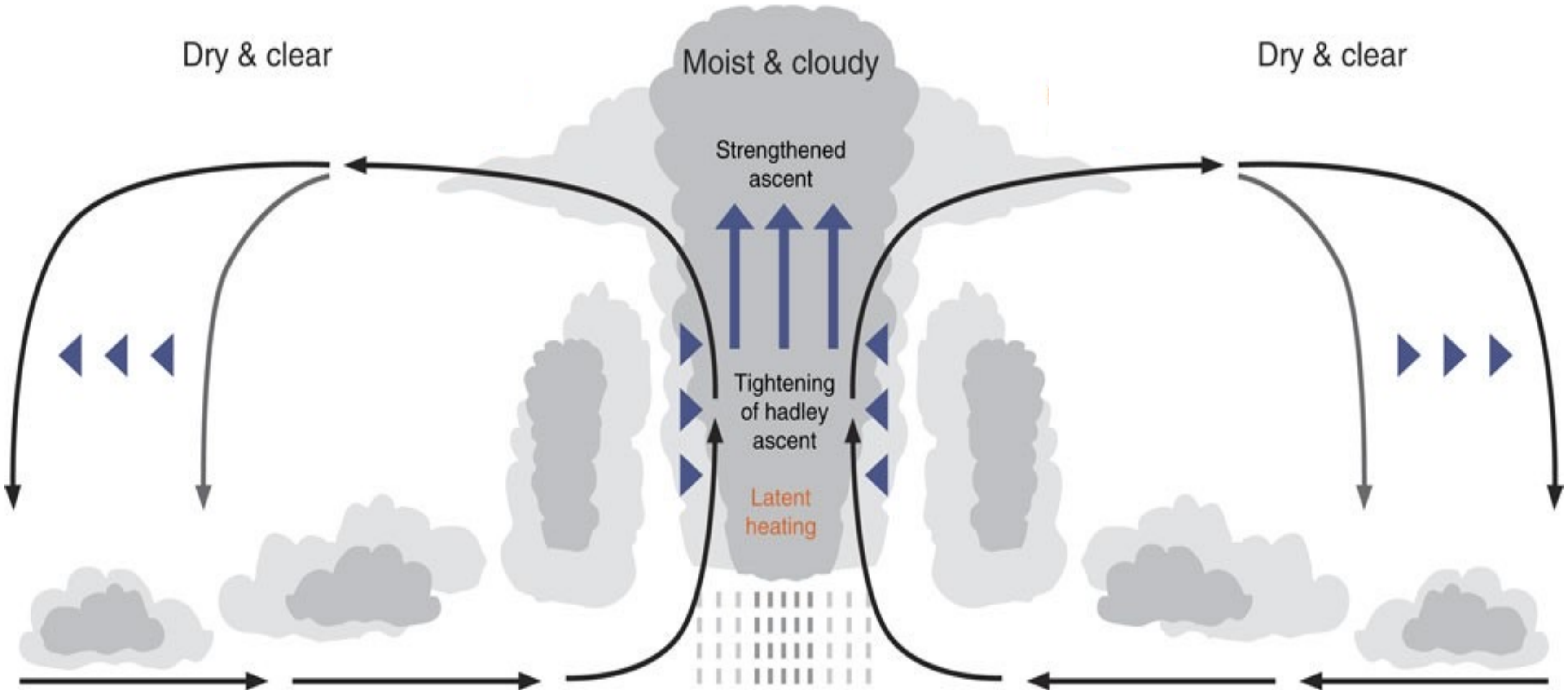
Large-scale patterns affect local rainfall

The belt of intense tropical rainfall moves north and south with the seasons.

To predict rainfall at a particular location on timescales longer than a few days, we need to predict the evolution of these patterns.



Climate change and the Hadley circulation



Su et al. 2017

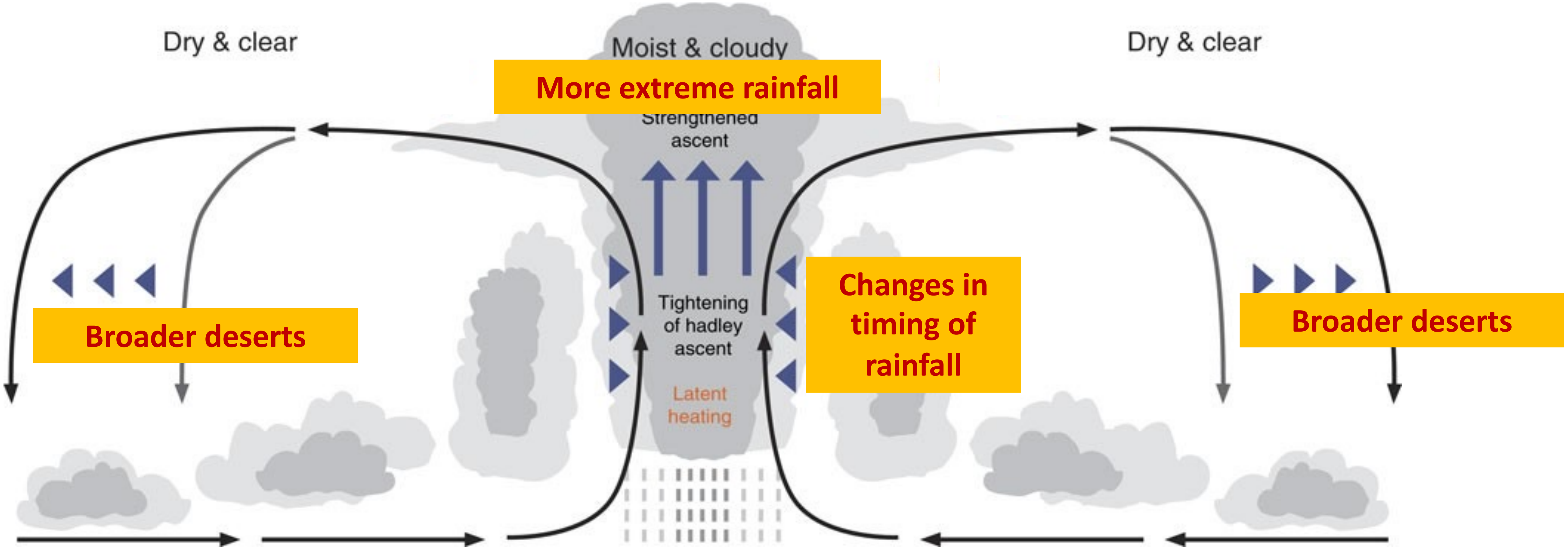
Climate change will result in:

- A reduced equator-to-pole gradient in temperature
- An increase in the water vapor content of the atmosphere

We need to understand the net effects of opposing influences.

Changes in wetness/dryness over much of the world will be governed by changes in this circulation pattern.

Climate change and the Hadley circulation



Su et al. 2017

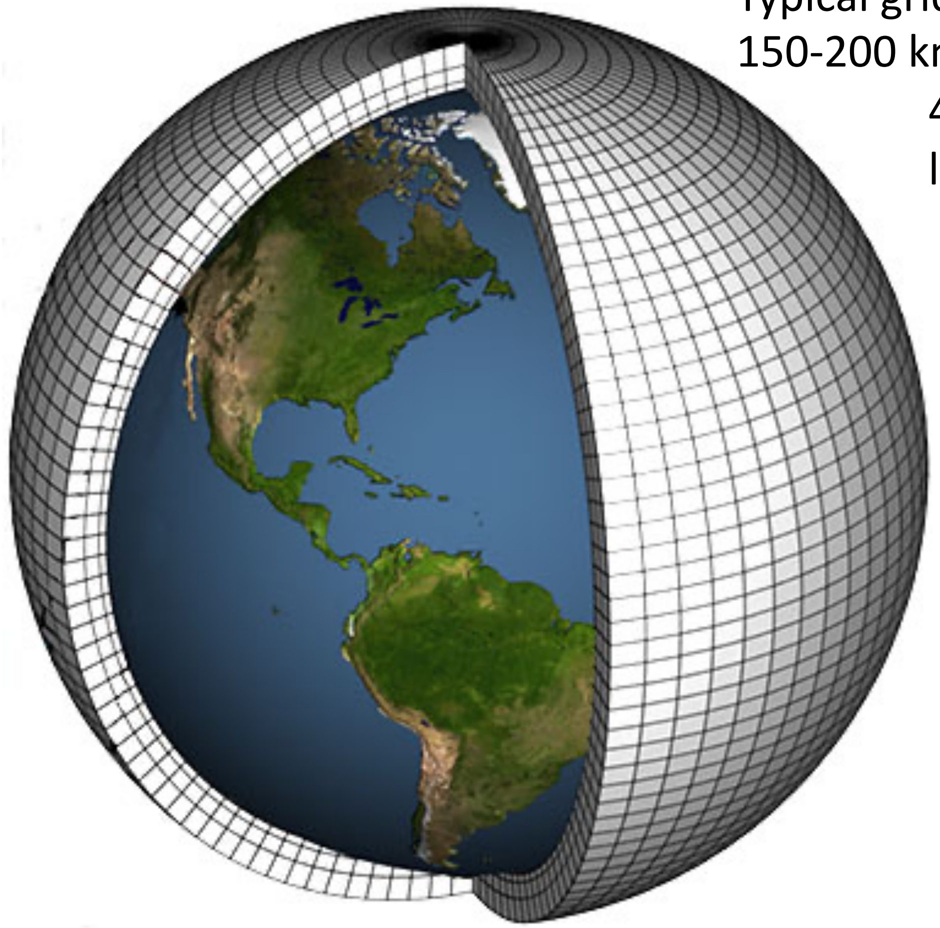
Changes in wetness/dryness over much of the world will be governed by changes in this circulation pattern.

Geophysical Fluid Dynamics: Constructing a General Circulation Model (GCM)

- Flow in 2 layers of fluid (ocean, atmosphere) in a thin shell on a rotating sphere.
- Tracers: Salt makes ocean water denser, water vapor makes air lighter.
- Externally forced by spatially uneven sunlight, changing over time
- Irregularly-shaped continents and topography produce spatially uneven surface conditions (temperature, moisture, and roughness)

Typical grid resolution: 150-200 km

40 vertical levels



Llnl.gov

The Primitive Equations

We construct digital twins of the Earth system by numerically solving these equations on a latitude-longitude-height grid, stepping forward in time.

Conservation of Mass

$$\frac{\partial \omega}{\partial p} + \boldsymbol{\nabla} \cdot \boldsymbol{v} = 0$$

Conservation of Momentum

$$\frac{d\boldsymbol{v}}{dt} + f\boldsymbol{k} \times \boldsymbol{v} + \boldsymbol{\nabla}\phi = F$$

Conservation of Energy

$$\frac{dT}{dt} - \frac{\kappa T \omega}{p} = \frac{Q}{c_p}$$

Conservation of Tracers (water vapor/salt)

$$\frac{dq}{dt} = S_q$$

Hydrostatic balance

$$\frac{\partial \phi}{\partial p} + \frac{RT}{p} = 0$$

The Primitive Equations

We construct digital twins of the Earth system by numerically solving these equations on a latitude-longitude-height grid, stepping forward in time.

Conservation of Mass

$$\frac{\partial \omega}{\partial p} + \boldsymbol{\nabla} \cdot \boldsymbol{v} = 0$$

Only horizontal velocity; aspect ratio means we can often neglect vertical

Conservation of Momentum

$$\frac{d\boldsymbol{v}}{dt} + f\boldsymbol{k} \times \boldsymbol{v} + \boldsymbol{\nabla}\phi = F$$

Conservation of Energy

$$\frac{dT}{dt} - \frac{\kappa T \omega}{p} = \frac{Q}{c_p}$$

Conservation of Tracers (water vapor/salt)

$$\frac{dq}{dt} = S_q$$

Hydrostatic balance

$$\frac{\partial \phi}{\partial p} + \frac{RT}{p} = 0$$

The Primitive Equations

We construct digital twins of the Earth system by numerically solving these equations on a latitude-longitude-height grid, stepping forward in time.

Conservation of Mass

$$\frac{\partial \omega}{\partial p} + \boldsymbol{\nabla} \cdot \boldsymbol{v} = 0$$

Conservation of Momentum

$$\frac{d\boldsymbol{v}}{dt} + f\boldsymbol{k}\times\boldsymbol{v} + \boldsymbol{\nabla}\phi = F$$

Conservation of Energy

$$\frac{dT}{dt} - \frac{\kappa T \omega}{p} = \frac{Q}{c_p}$$

Pressure co-ordinate used in the vertical

Conservation of Tracers (water vapor/salt)

$$\frac{dq}{dt} = S_q$$

Hydrostatic balance

$$\frac{\partial \phi}{\partial p} + \frac{RT}{p} = 0$$

The Primitive Equations

We construct digital twins of the Earth system by numerically solving these equations on a latitude-longitude-height grid, stepping forward in time.

Conservation of Mass

$$\frac{\partial \omega}{\partial p} + \boldsymbol{\nabla} \cdot \boldsymbol{v} = 0$$

Conservation of Momentum

$$\frac{d\boldsymbol{v}}{dt} + f\boldsymbol{k}\times\boldsymbol{v} + \boldsymbol{\nabla}\phi = F$$

Sub grid-scale turbulent motion

Conservation of Energy

$$\frac{dT}{dt} - \frac{\kappa T \omega}{p} = \frac{Q}{c_p}$$

Energy from small-scale processes, phase changes, greenhouse gases, etc

Conservation of Tracers (water vapor/salt)

$$\frac{dq}{dt} = S_q$$

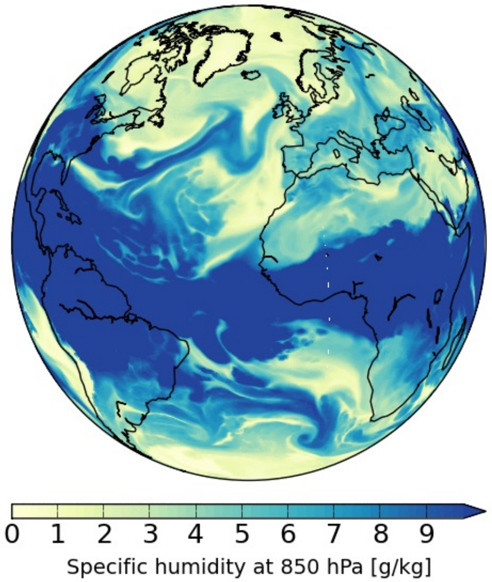
Precipitation/Evaporation or Ice formation/melt, other sources and sinks

Hydrostatic balance

$$\frac{\partial \phi}{\partial p} + \frac{RT}{p} = 0$$

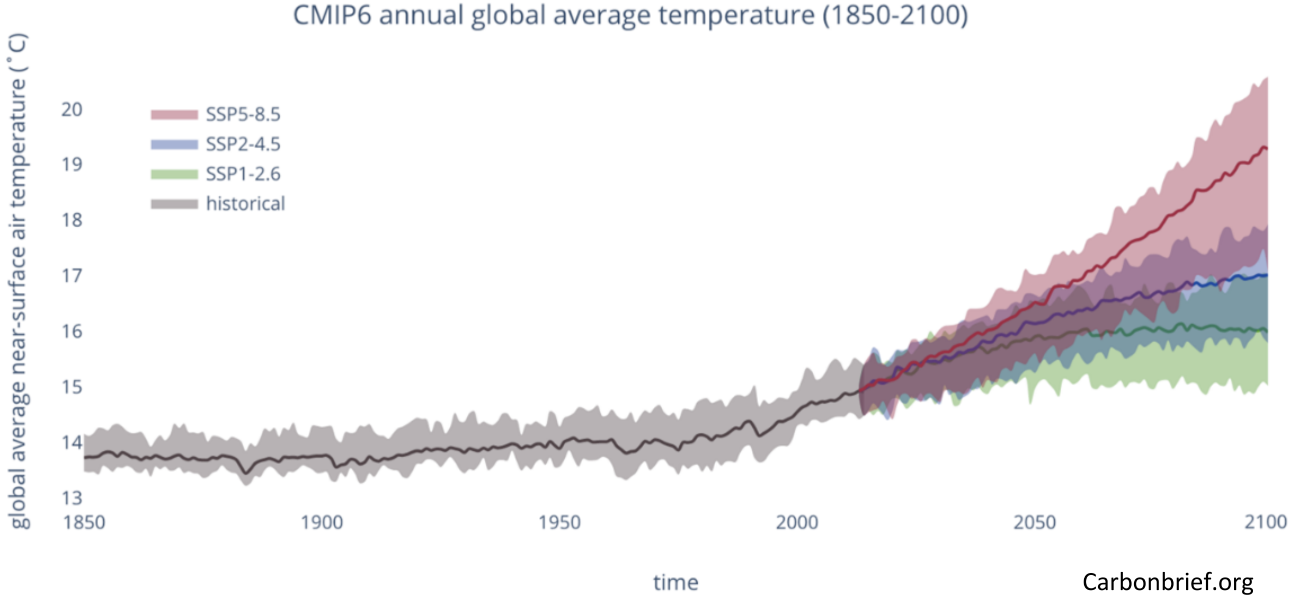
Designing Digital Twins of the Earth

- Conducted by large, interdisciplinary teams of researchers – usually at national research orgs
- Code is open-source and publicly available, extensively validated
- Every few years, an UN-coordinated set of experiments is performed to validate the various digital twins (49) and produce directly comparable output
- Includes simulations of possible climate change scenarios



Output from a climate model simulation from CEDA, UK Met Office

CMIP
The World Climate Research Programme's Coupled Model Intercomparison Project



Carbonbrief.org

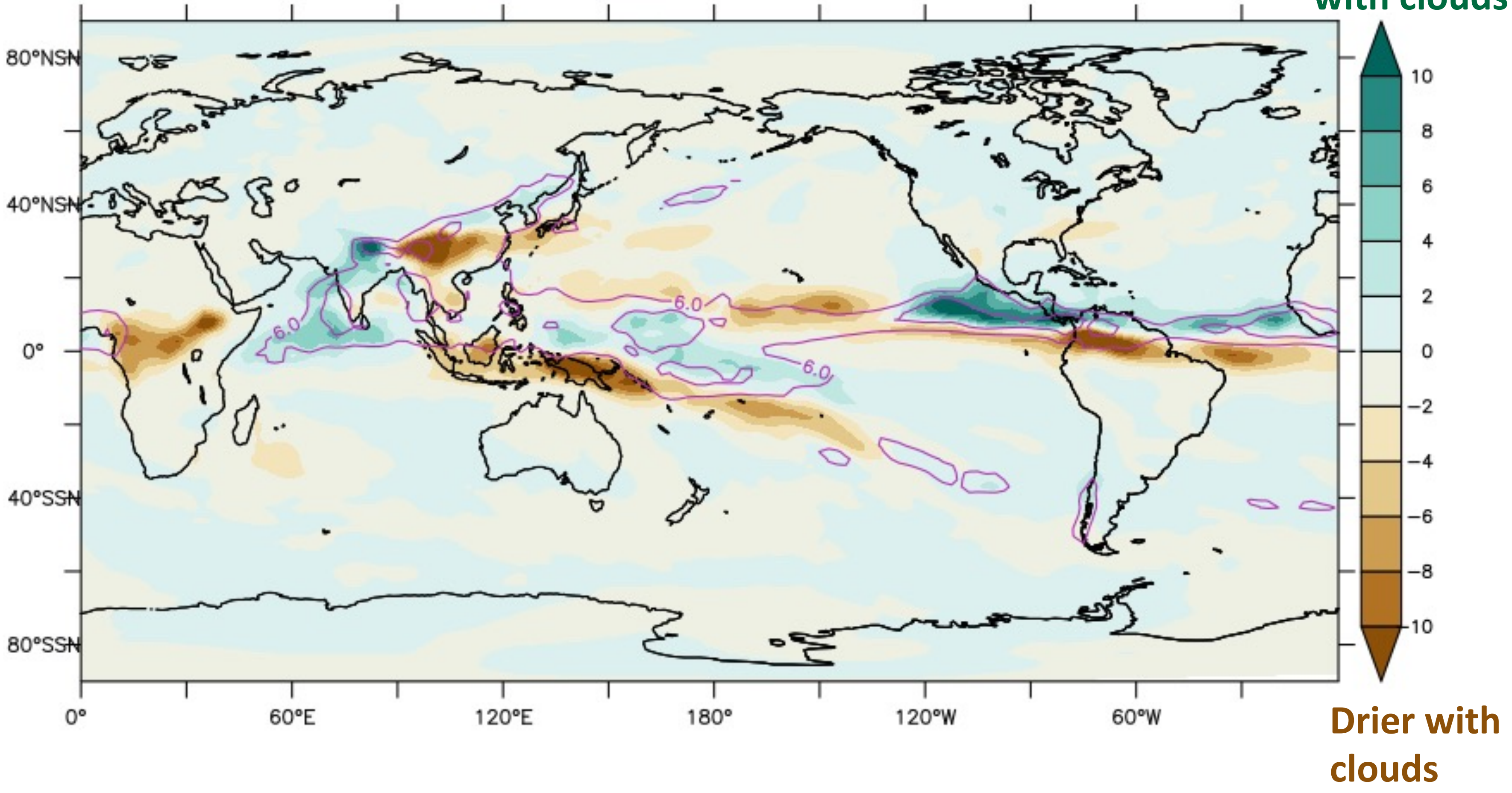
An Experiment: What if Clouds were Transparent?

- **From observations: build a hypothesis.** My hypothesis is that cloud cover acts to accumulate energy (and thereby rainfall) over South Asia.

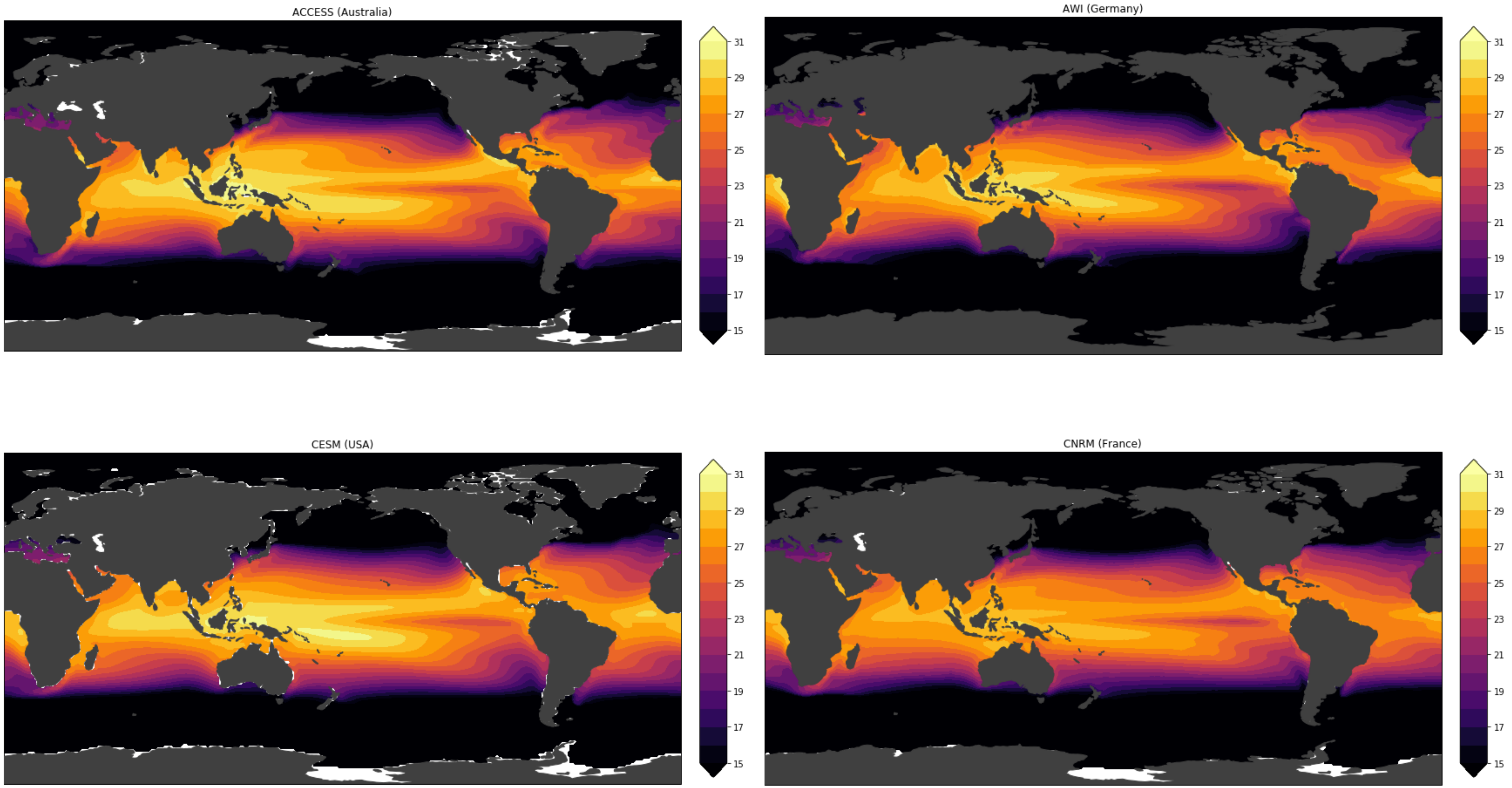
- **Experiment: Change the code** so there is no light reflected back to space, or heat reflected back to Earth, by tropical clouds

- Purple: rainfall in control run (mm/day)

Rainfall in Control Minus Experiment (Northern Summer)



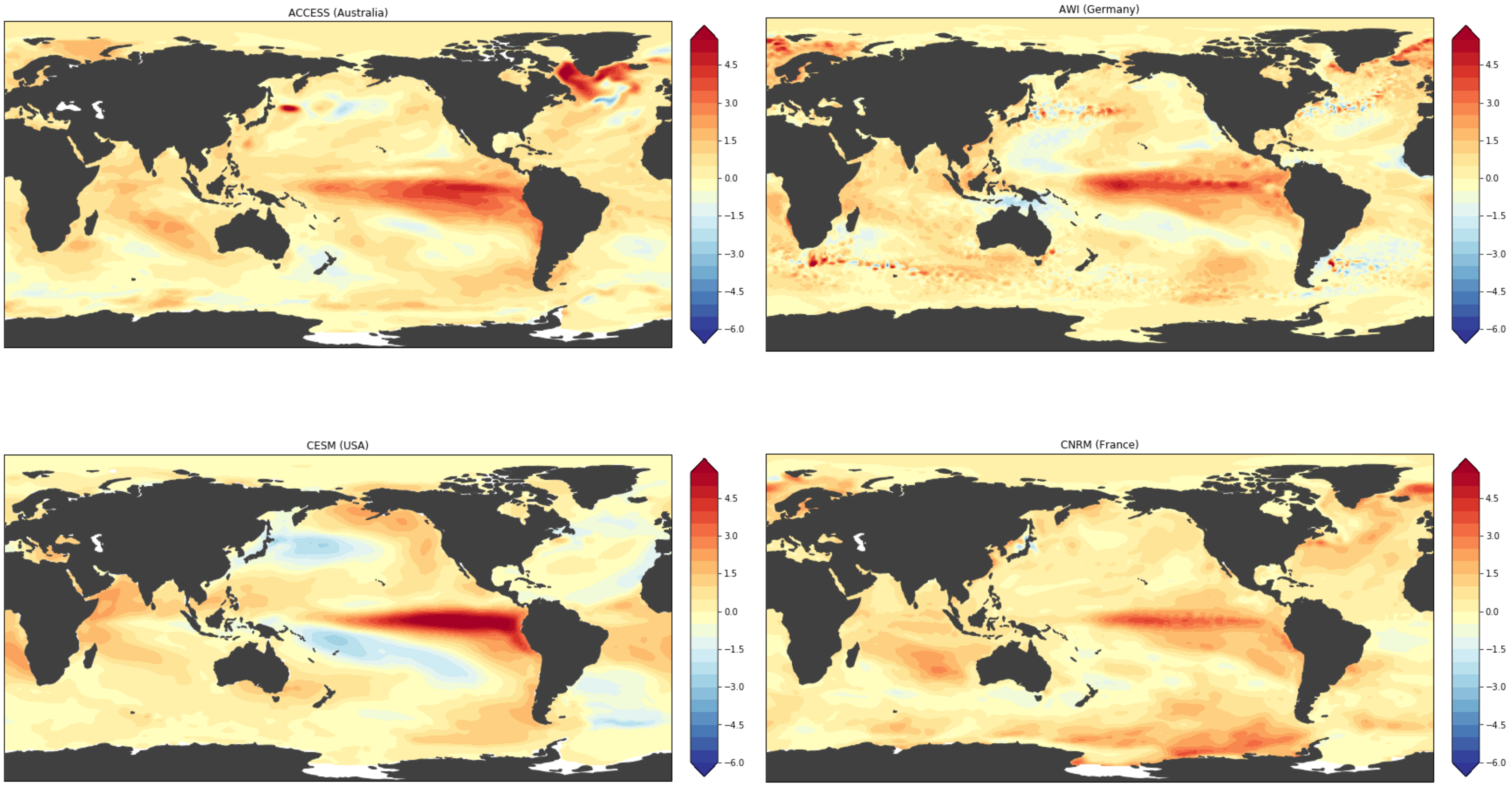
Using CMIP Data: Interpreting El Niño Changes



Comparing output from digital twins from 4 different modeling centers: Time-averaged ocean temperatures

Example #2

Using CMIP Data: Interpreting El Niño Changes



Deviation from the mean during an El Niño event:

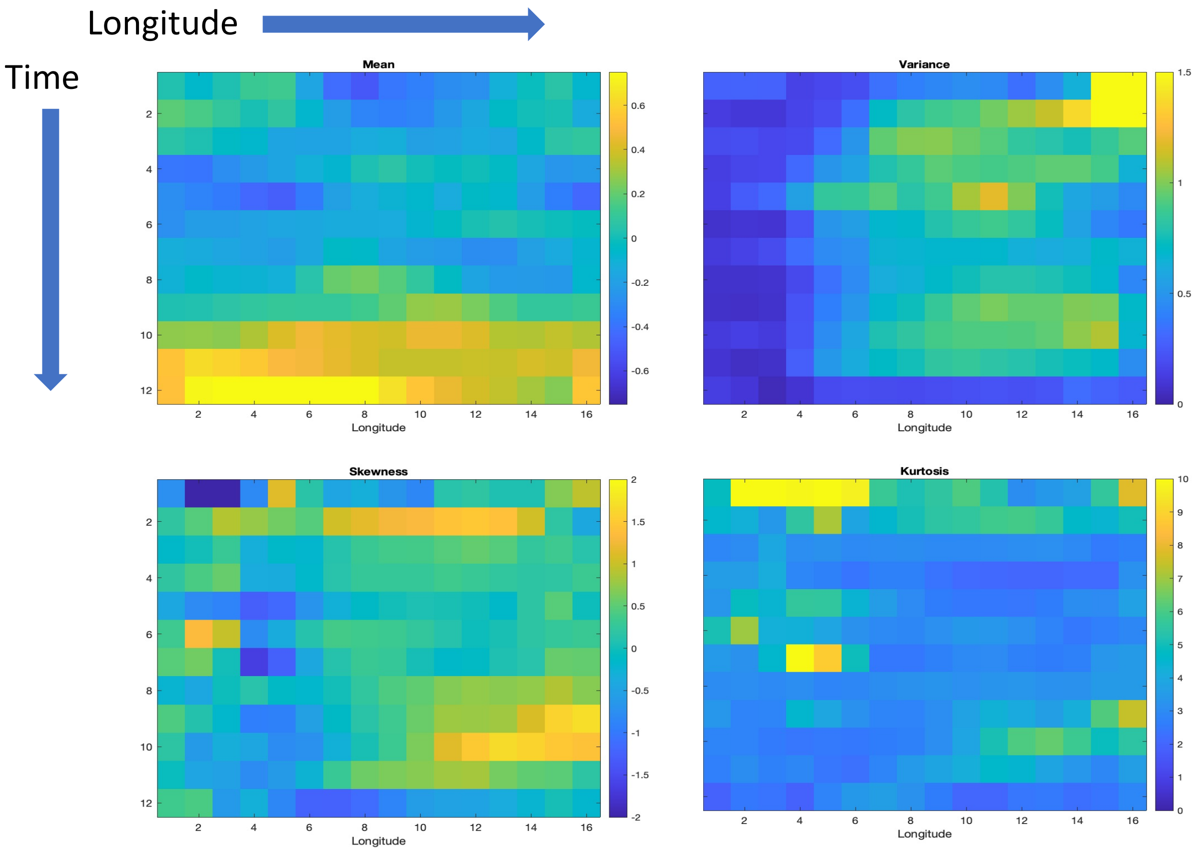
How do we assess which is closest to reality?

Which makes the most reliable predictions?

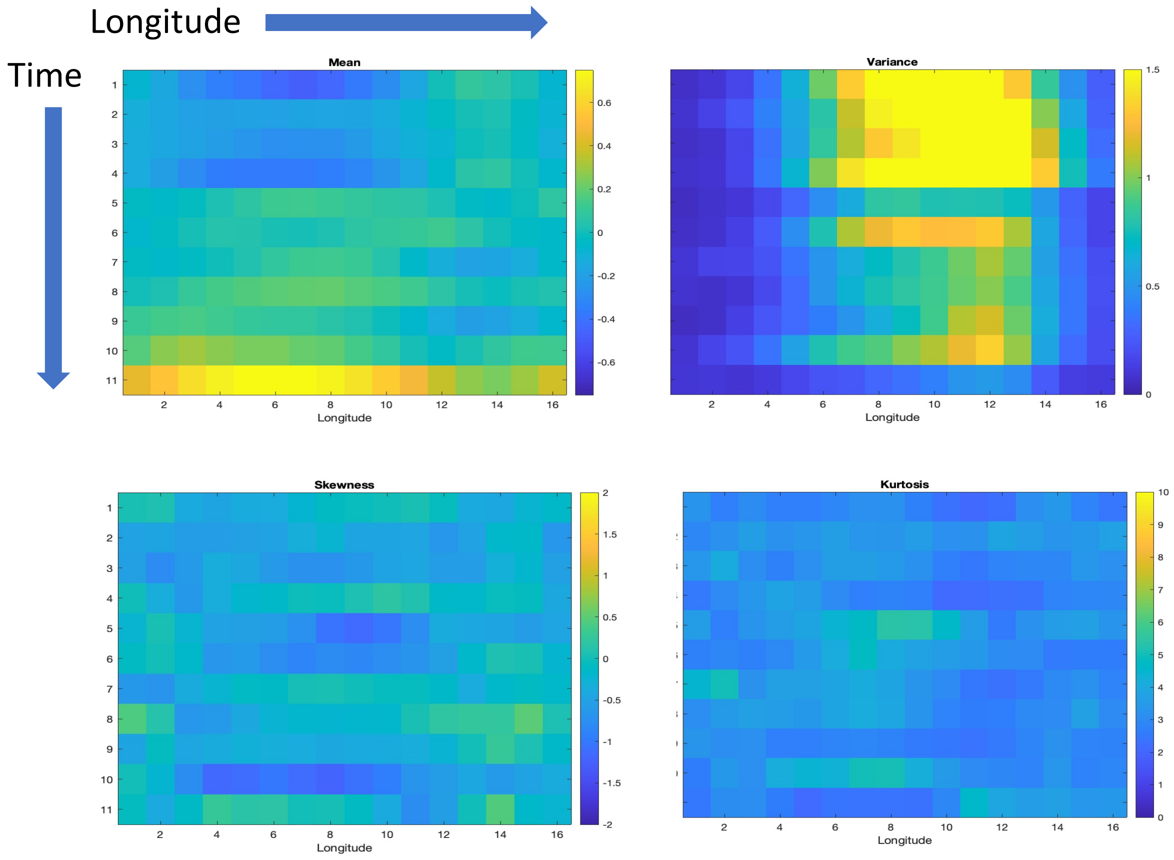
Using CMIP Data: Interpreting El Niño Changes

Modelling the distribution of sea surface temperatures to arrive at metrics for the reliability of digital twins' forecasts

Mean, Variance, Skewness and Kurtosis of the **observed** sea surface temperatures over time



Mean, Variance, Skewness and Kurtosis of the **simulated** sea surface temperatures over time



Summary

- Climate physics is an applied **fluid dynamics + thermodynamics** problem; **numerical simulations** are used extensively
- The Earth's ocean and atmosphere are constrained by the setting to have certain **large-scale spatial patterns**
- **Small deviations** from these spatial patterns have **large societal impacts**!

- Digital twins are developed and compared systematically around the world; petabytes of output are publicly available
- ***How do we interpret the output from imperfect digital twins intelligently?***