The Role of Observations in Climate Science

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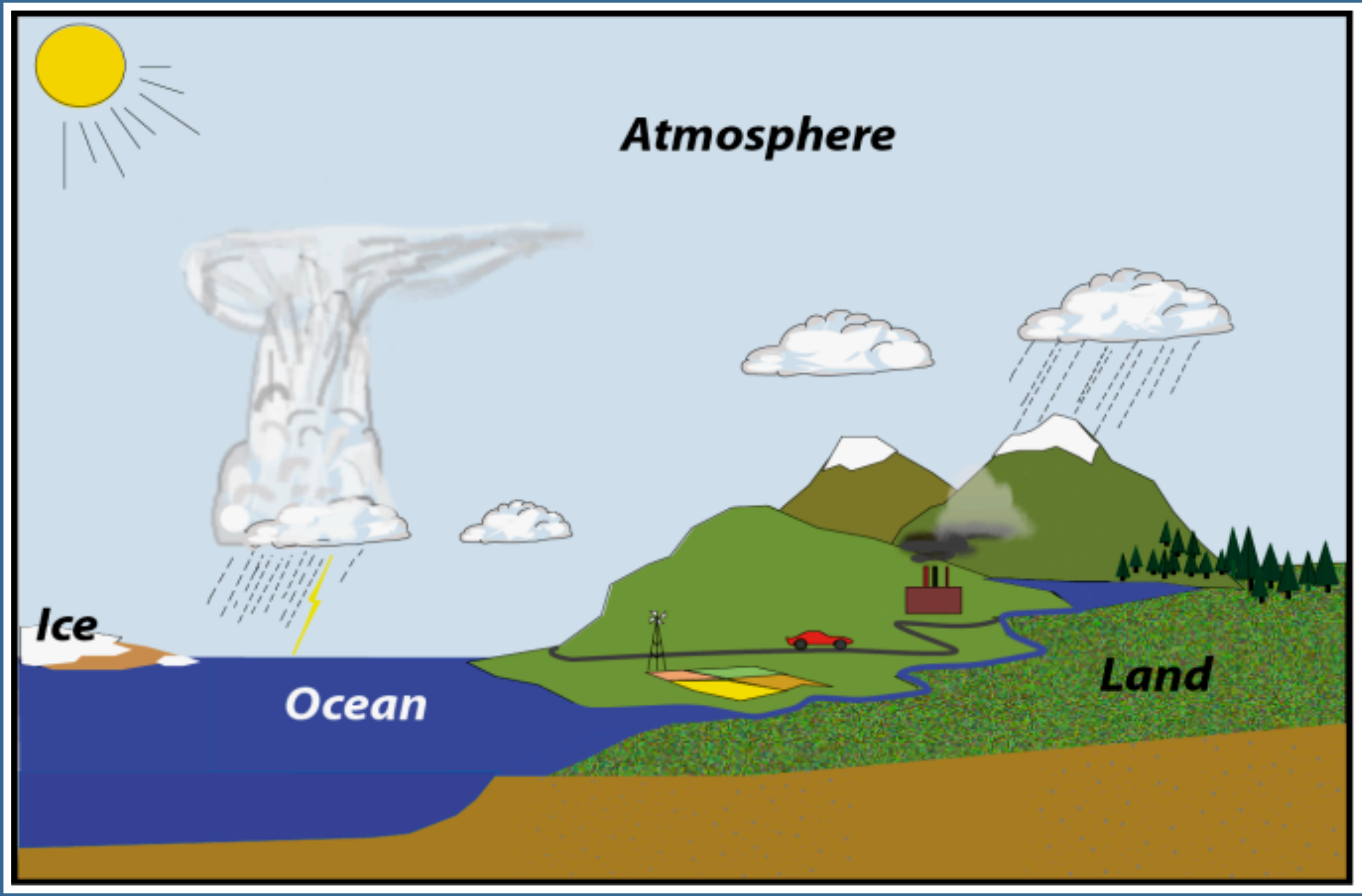
Questions

- What is climate?
- What does it mean to “observe” the climate?
- Why do we need climate observations?
- How do we get climate observations?
- What do we need to do going forward?

The climate system:
Atmosphere, Land, Ocean, Cryosphere



Adapted from: Tom Karl, Kevin Trenberth

Definitions of Climate

- "Climate is what you expect; weather is what you get."
- Complicated provenance: variously credited to:
  - Mark Twain – apparently this is incorrect
  - Robert Heinlein/Lazarus Long in "Time Enough for Love"
  - "Some meteorologists"
  - "Some climate scientists"
  - "Weather forecasters"

Definitions of Climate

- “Climate tells you what clothes to buy, but weather tells you what clothes to wear.”
  - “a middle school student” according to UCAR’s Introduction to Climate (http://www.ucar.edu/learn/1_2_1.htm)

Definitions of Climate

- The background context for weather
  - "Big M, Little c"
- The ensemble of states that the components of the Earth System take on
  - "Big C, Little m"

Definitions of Climate

- Meaningless distinction – depends on what you're looking for.
- What do you see – a vase, or two faces?
  - devised by Edgar Rubin, according to Wikipedia

Definitions of Climate

- *Glossary of Meteorology, Second Edition*
  - "The slowly varying aspects of the atmosphere-hydrosphere-land surface system."
  - Goes on at some length to provide details and context, but this is generally accepted as a good short definition
  - Individual weather events are presumably excluded, but their statistics are a critical aspect of the climate

Definitions of Climate

- In terms of predictability:
  - Climate predictions are (largely) independent of the initial state of the atmosphere
  - Weather predictions are (largely) independent of the boundary conditions represented by the state of the ocean, land surface and cryosphere
  - Border between weather and climate occurs somewhere in the first month, and is very fuzzy

Aspects of Climate Science

- Climate science is “a systematic enterprise that builds and organizes knowledge in the form of testable explanations and predictions about the climate” (adapted from Wikipedia, which must be used with care, but I like it)
- Observations are how we build/organize knowledge
- Theory provides the explanations and predictions
- In the case of climate (like weather), in practice the theory is used to build models, which provide the predictions

Observations and Theory

- All science is based on observations
- If we can't explain the observations with theory, our science is incomplete
  - Description is fine, and fun, but not enough by itself
- For climate, theory is implemented in models
  - For weather, augmented fluid dynamical models of the atmosphere are sufficient for many purposes
  - For climate, must include all the components: atmosphere (including composition and aerosols), ocean, land surface, snow and ice
- Good theory (good models) will reproduce observations and forecast the future well without "much" tuning
  - Obviously the forecast part is tough for long time scales, since we have to wait a long time (too long for practical purposes)

Observations

- There was a time when climate on human scales was thought to be unvarying
  - Climate observations were just the statistics of weather
  - Didn't work for the coupled system
- Climate as the coupled system requires observations of all the component parts
- For some time scales, some aspects can be neglected
  - Global change projections do not depend on the initial state of the atmosphere
  - Seasonal to decadal time scales don't depend on changes in the deep ocean

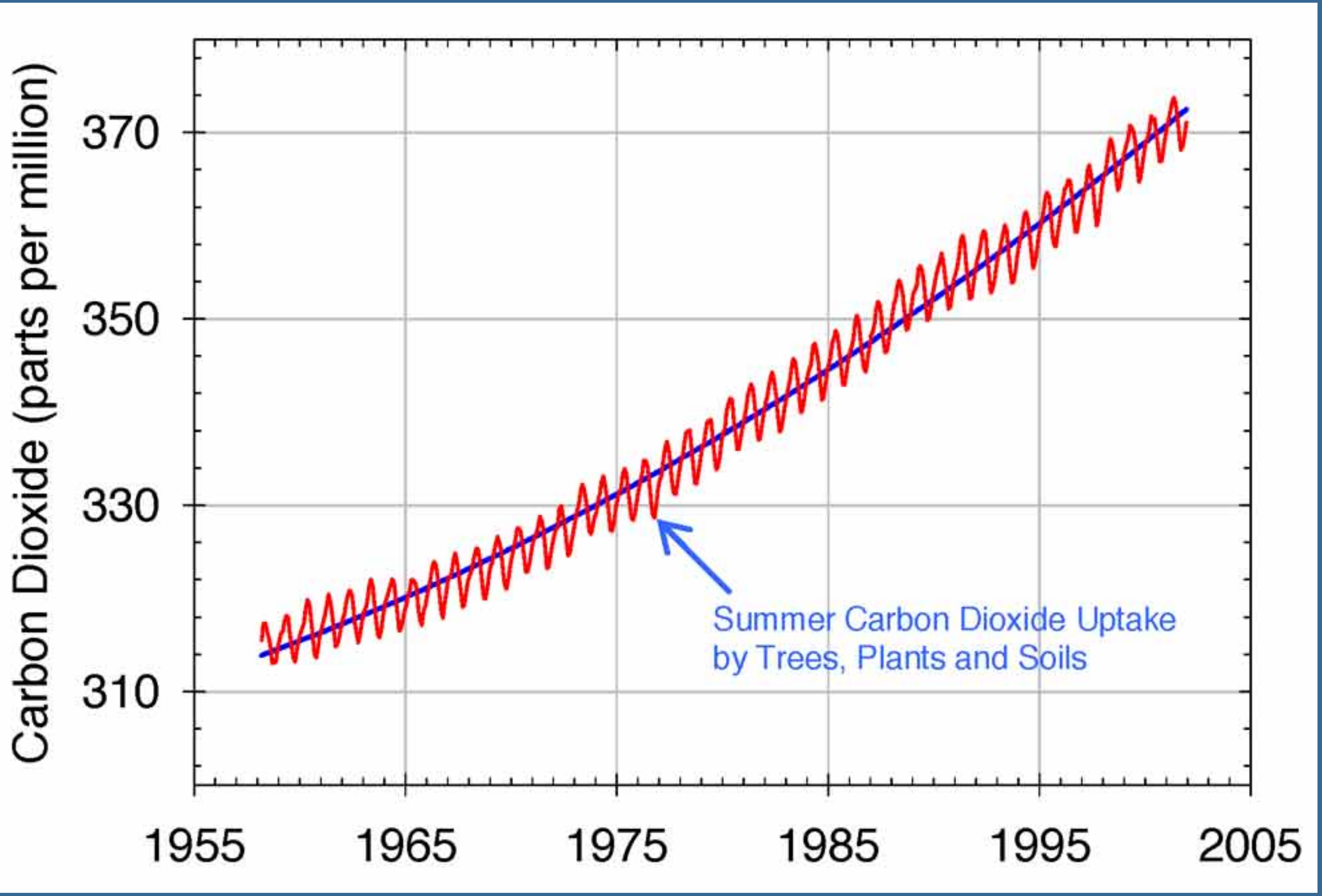
Why Observe the Climate?

- Nowcasting
  - Just like with weather, some aspects of climate variation can be extrapolated from recent conditions
  - El Niño/Southern Oscillation
- Provide historical context for weather forecasts
  - Climatology has always been known to be a useful baseline
- Validating theory/models
  - Particularly crucial for climate models, since waiting for a large set of forecasts to verify is not an option

How Do We Get Climate Observations?

- In the atmosphere, no single observation can be a "climate" observation
  - In other components, depends on degree of variability
- Need to take samples in space and time
  - Sampling required depends on variability and accuracy needed
- The samples need to be converted into appropriate statistics
  - Not generally a straightforward problem

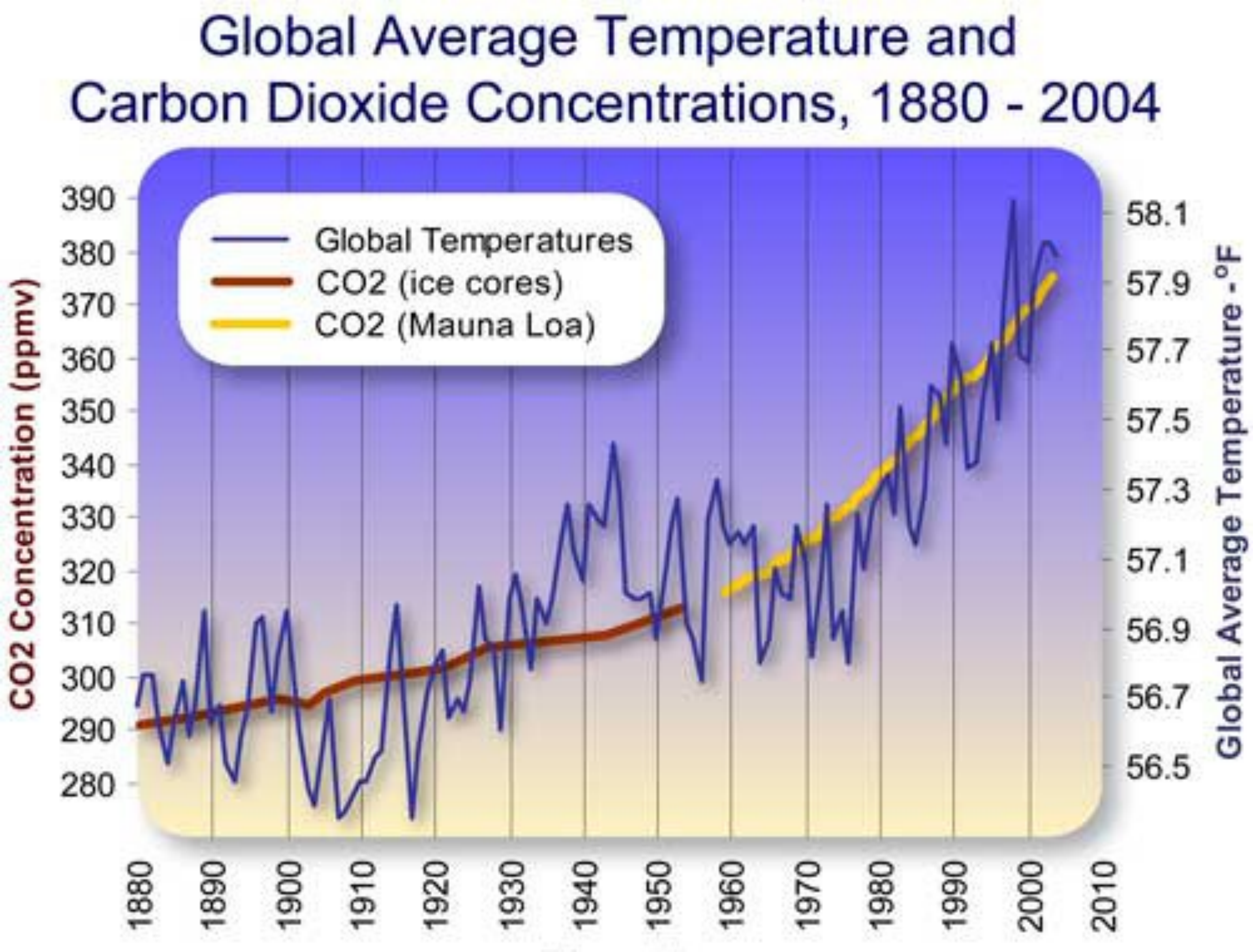
Atmospheric Compostion: Carbon Dioxide



Keeling curve:
Measured at Mauna Loa

- Beginning in the 1950s it was observed that atmospheric composition was changing
- Theoretical calculations (simple models) predicted that doubling CO_2 would lead to a global temperature increase of 2°

Atmospheric Composition: Carbon Dioxide



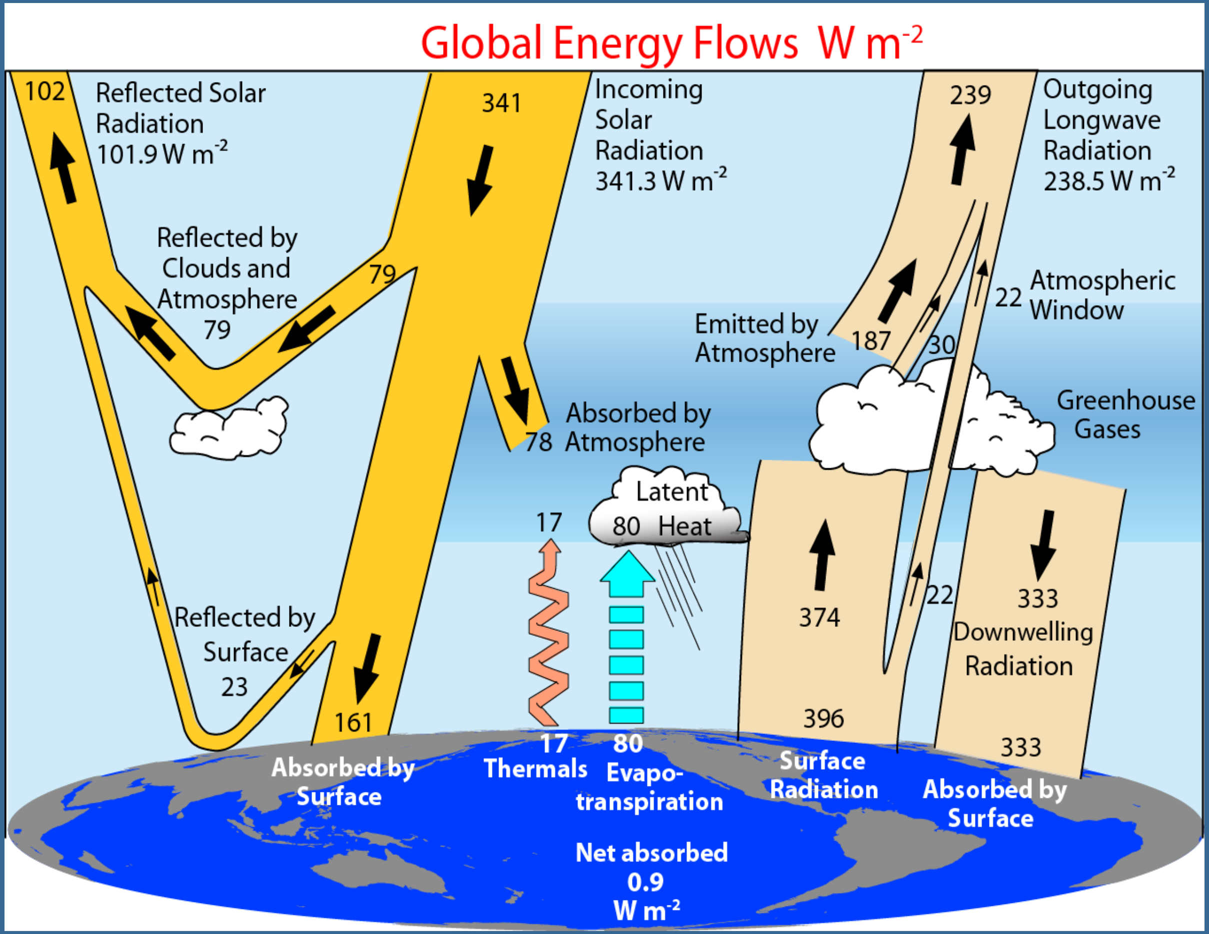
- Observations fairly consistent with theory
- Many of the differences related to atmospheric aerosols that reduced atmospheric transparency (“the human volcano”)

- Observing atmospheric composition (except for particulates and water vapor) is relatively easy since relatively few samples are needed
  - Sixty sites used currently
- Surface temperature is another story:
  - Big local changes and big changes over short time periods – good sampling necessary
  - Oceans in particular are a challenge
  - Global temperature time series have been constructed by several groups with consistent results – character of the variations over past century are not in doubt
- What about model validation?
  - CO_2 change is a forcing – must be imposed
  - Temperature change in models is fairly well simulated
  - Projections for end of 21^{st} century are of 2-5° warming in global mean temperature

Other Climate Observations

- Precipitation: global analyses (GPCP, CMAP) constructed using satellite estimates and gauge observations
  - Just over 30 years available now; considerable uncertainty
  - Statistical reconstructions back to 1900 being tested
- Sea Level: satellite and tide gauge observations used
  - Short time scales – tides, waves – filtered out
  - Tough to separate isostatic changes from warming influence
    - Two warming components: thermal expansion, melting of land-based ice/snow
- Atmospheric Water Vapor: satellite and radiosonde observations are available
  - Theory: increasing surface temperatures result in increasing total atmospheric water vapor; robust result in coupled models
  - Observations appear to confirm, but (my) confidence is a bit lower than for temperature

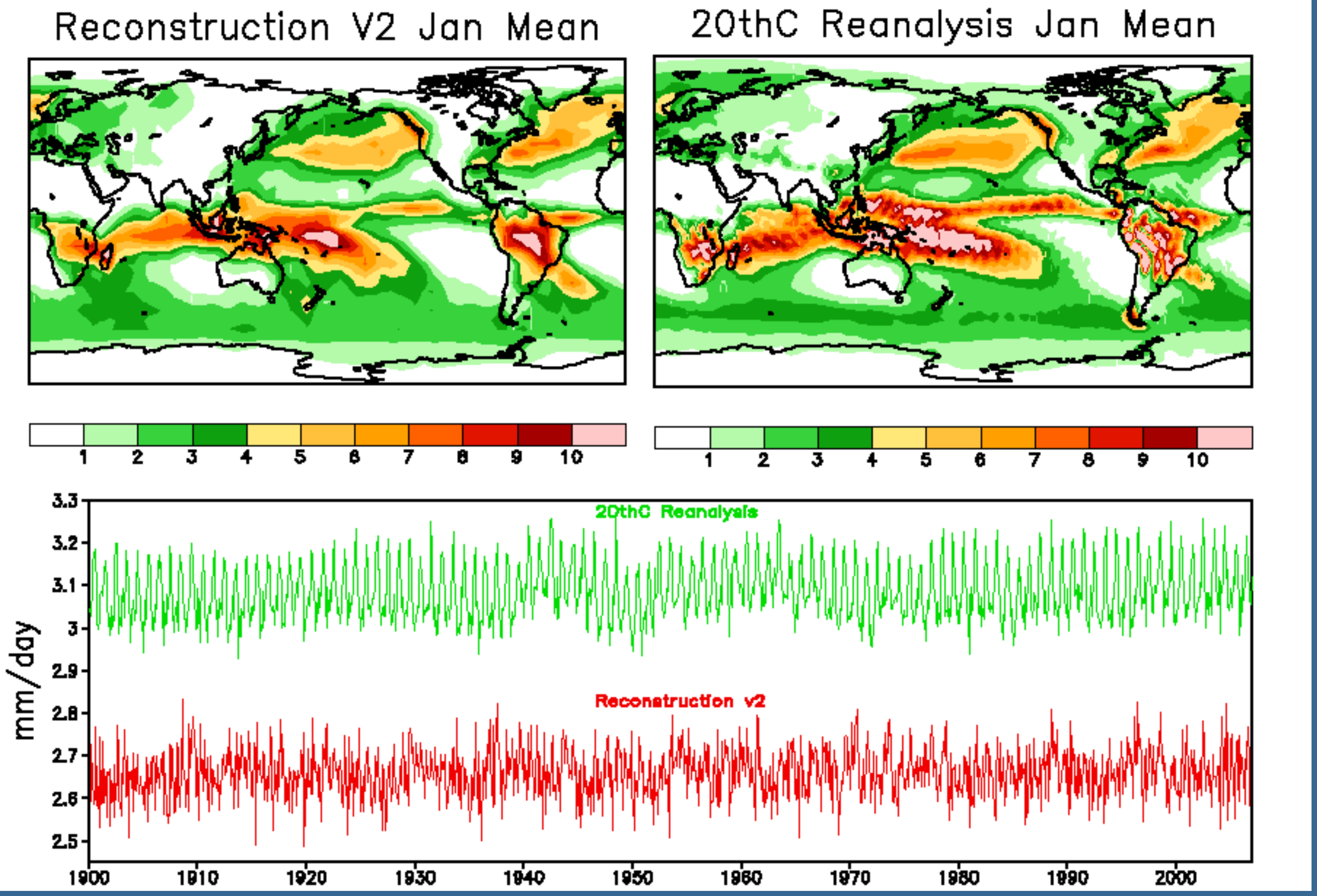
- This piecemeal approach has been useful, but is clearly incomplete
  - Need more complete context for regional anomalies in temperature and precipitation (e.g. March 2012)
  - We would like to be able to calculate the full water and energy budgets



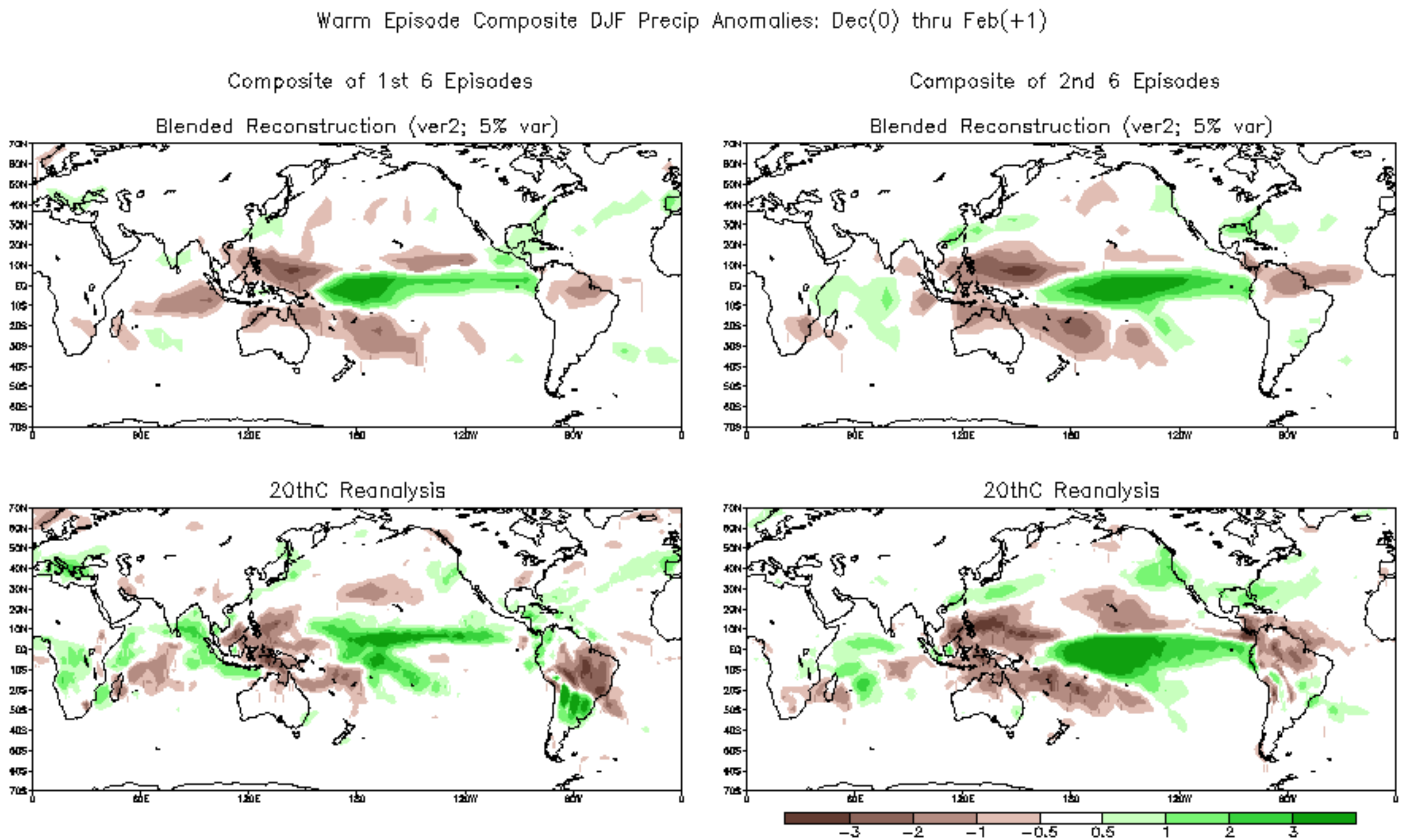
2000-2005 Adapted from Trenberth et al 2009

Completing the Picture

- Land Surface: satellite observations and models
  - NASA EOS and other research satellites have greatly improved the state of land surface understanding
  - GRACE depicts changes in surface/subsurface water
- Ocean: satellite and in-situ observations
  - Satellites providing topography, sea state and salinity at surface
  - Moored and drifting buoys, particularly TAO and Argo, improving knowledge of internal variations
- Cryosphere: satellite helpful
- Atmosphere: problem has much in common with NWP initialization
  - Must somehow combine/integrate all of the atmospheric observations into complete fields
  - Objective analysis/data assimilation required
  - Reanalysis uses constant system to minimize artifacts

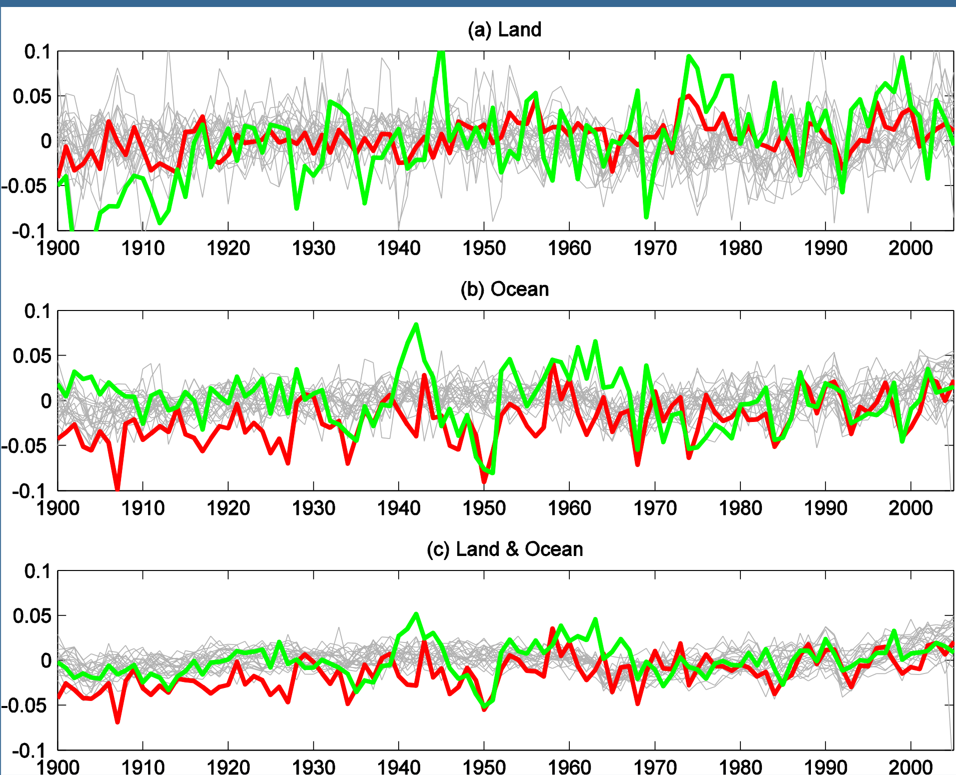

Reconstruction V2 Jan Mean
20thC Reanalysis Jan Mean
1 2 3 4 5 6 7 8 9 10
1 2 3 4 5 6 7 8 9 10
20thC Reanalysis
Reconstruction v2
mm/day
3.3
3.2
3.1
3
2.9
2.8
2.7
2.6
2.5
1900 1910 1920 1930 1940 1950 1960 1970 1980 1990 2000

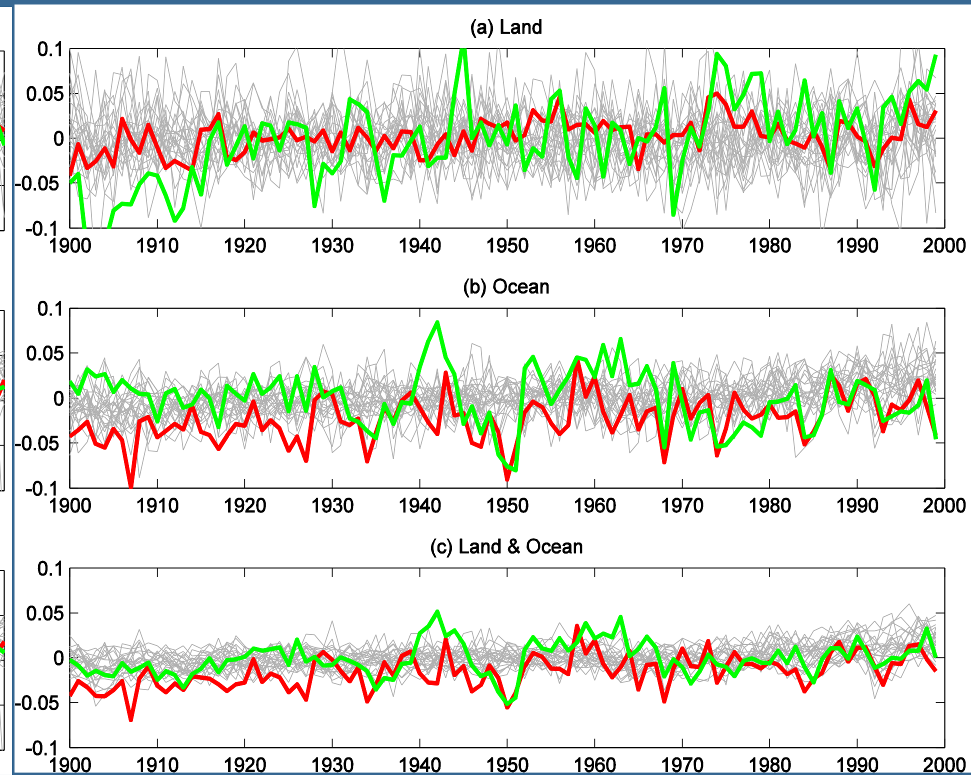
How does the ENSO signal vary between first and second half of the Century?



Centennial Trends in Global Mean Precipitation

- Temperature trend is 0.79° over the century
- Reconstructed, reanalyzed and simulated (ensemble mean) precipitation tend to show increasing trend (significance unclear) over same period
- The precipitation data are nearly independent of one another:
  - Simulations are from CMIP5 (left, 22 models) and CMIP3 (right, 24 models) coupled simulations
  - Reanalysis (green) used observed SST and SLP; no oceanic positive trend
  - Reconstruction (red) used GPCP EOFs and gauge observations
  - Models have somewhat less variability than “observations”



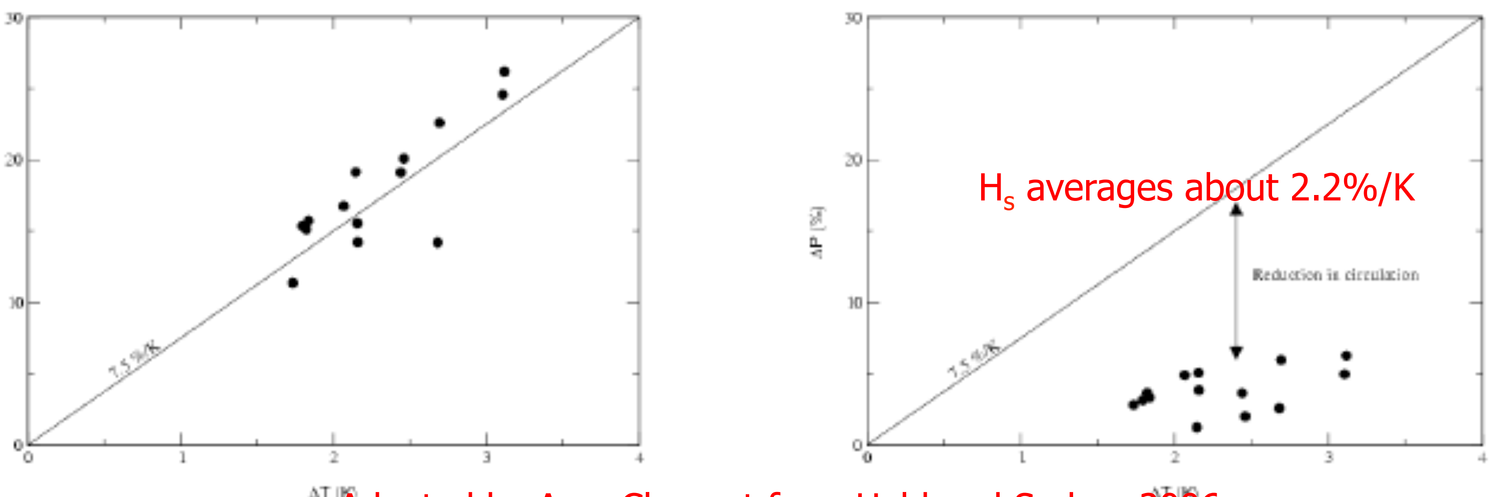


Sensitivity of Global Hydrological Cycle

- Analogous to climate sensitivity, which is change in global mean T for some specified change in radiative forcing
- H_S = % change in mean global P per unit change in mean global T

Water vapor increases with surface temperature at a rate predicted by C-C in climate models

Precipitation increases at a slower rate implying a weaker circulation

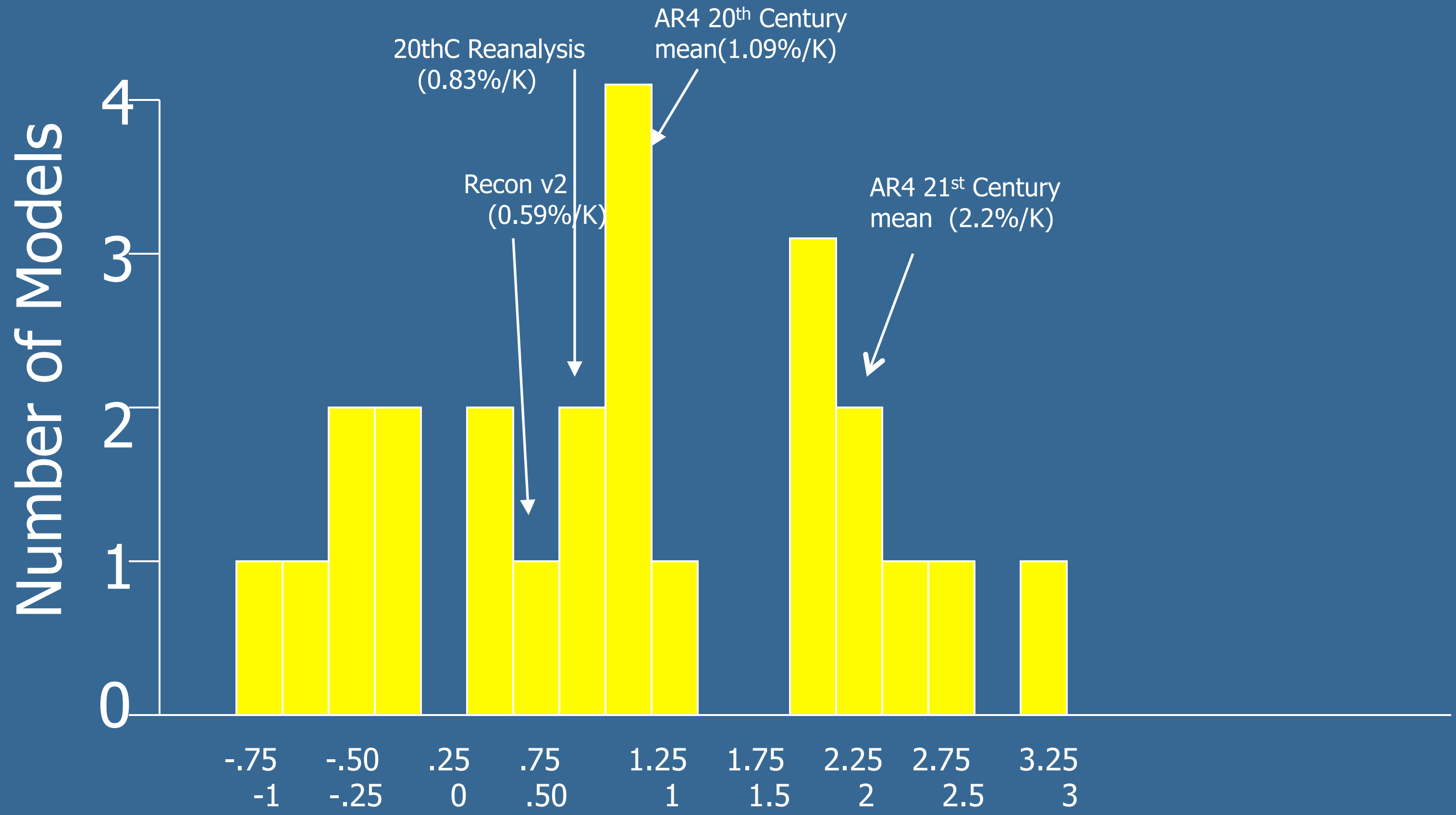


Adapted by Amy Clement from Held and Soden, 2006

IPCC AR4 models under the A1b scenario. Differences are 2080-2100 minus 2020-2000

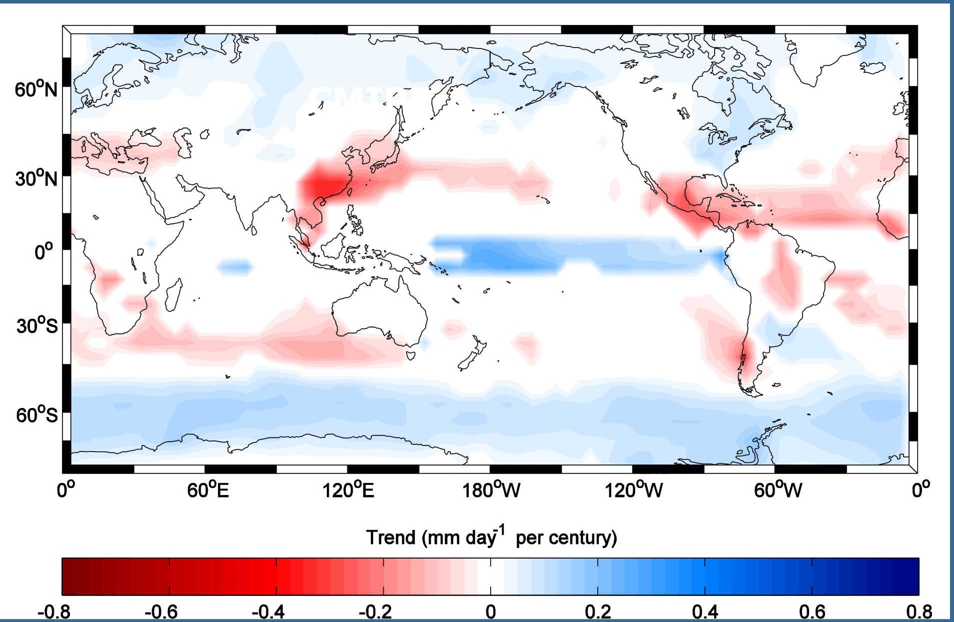
- Using CRU observed temperature change over 1900-2000:
  - Reanalysis H_S = 0.83 %/K
  - Reconstruction H_S = 0.59 %/K
  - AR4 ensemble mean H_S = 1.09 %/K

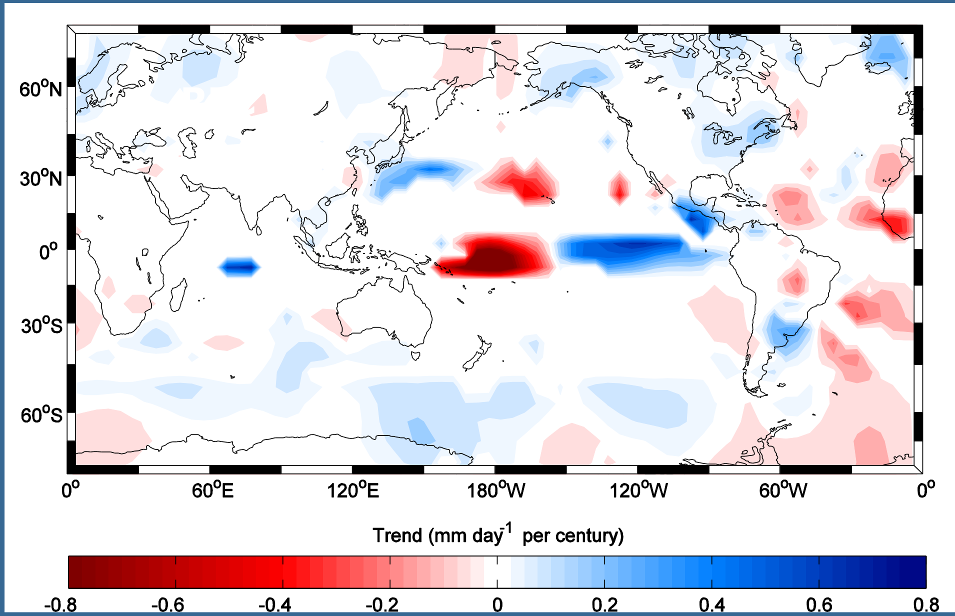
Hydrological Cycle Sensitivity over the 20th Century for 24 Individual CMIP3 Models



Both reconstruction and reanalysis are close to the model ensemble mean value and well within the overall spread

Trend in CMIP5





Spatial distribution of the linear trend in annual precipitation from 22 CMIP5 simulations (left panel) and from the reconstruction (right).

Only significant trends in the models are shown, and the reconstruction values are shown for the same locations

The Future of Climate Observations

- The future of the climate matters to all of us
  - Credible observations are crucial
- Observing systems must be sustained
  - Since we need to project changes, we have to have sufficient continuity to verify model projections of changes
  - Both satellite and earth-based systems are required
- Climate analysis (Earth System Analysis) essential
  - Required to calculate many “essential climate variables”
  - Current dependence on NWP-derived analysis systems is problematic
  - Have to understand better the changes due to changing observing systems
  - Climate analysis system can provide feedback to optimize observing system development
- Must continue to advance Earth System model development
  - Essential to “confront models with data”