Climate Modeling and Downscaling

Types of climate-change experiments: a preview

1) "What-if" sensitivity experiments – increase the optically active gases and aerosols according to an assumed scenario, and compare the model solution with that from a no-change experiment. (IPCC-type experiments)
2) Deterministic initial-value forecasts
3) Feedback sensitivity studies
4) Anthropogenic landscape-changes – impacts on climate
5) Downscaling from AOGCMs, using regional models

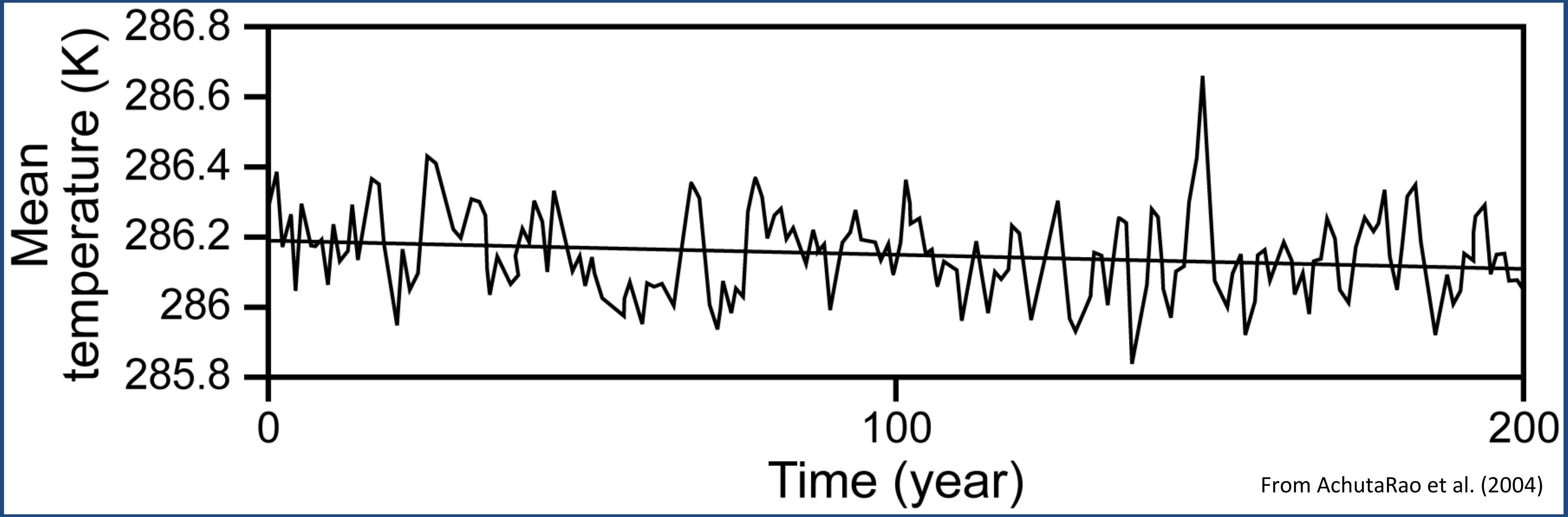
Type 1: IPCC-type Greenhouse-gas-impact studies

- Objective - define the change associated with anthropogenic forcings. Somehow, the natural "internal variability" of the atmosphere should be filtered from the solution.

The concept

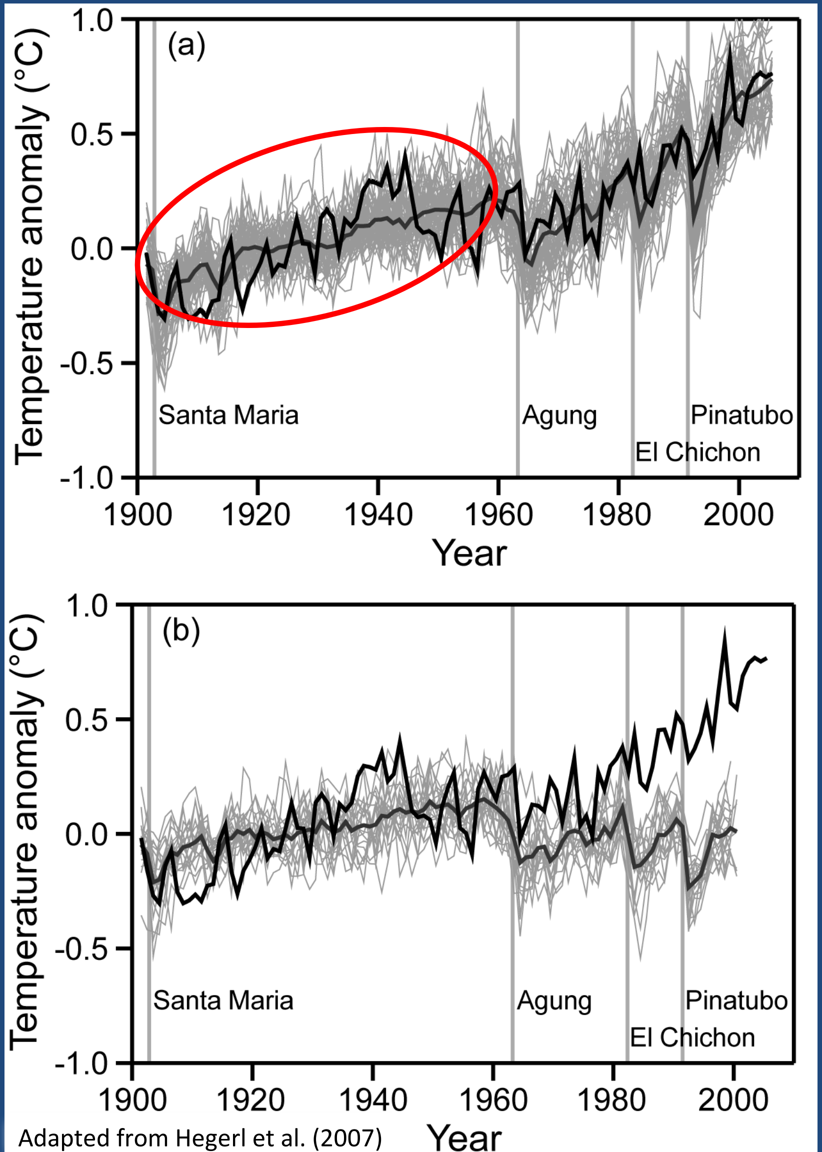
- The change in the global-average (or regional) weather conditions is a sum of
  - the natural (internal) variation of the climate system, that would have occurred without human impacts
  - the climate change that results from the human impact (greenhouse gases, land-surface modification)
- Need to isolate the human impact

Example 1 of internal variability



Global-mean surface air temperature from a simulation by an AOGCM that has no anthropogenic forcing.

Example 2 of internal variability



Adapted from Hegerl et al. (2007)

The solid black line is the observed global average surface air temperature

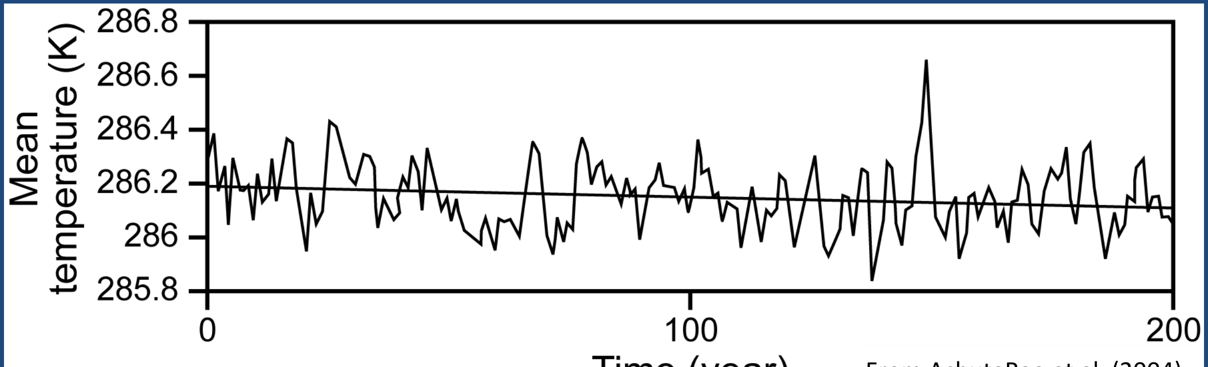
What is the cause of the internal variability?

What is the cause of the internal variability?

- Natural long-time-scale physical processes
  - Deep ocean circulations
  - Land and sea ice
  - Land surface

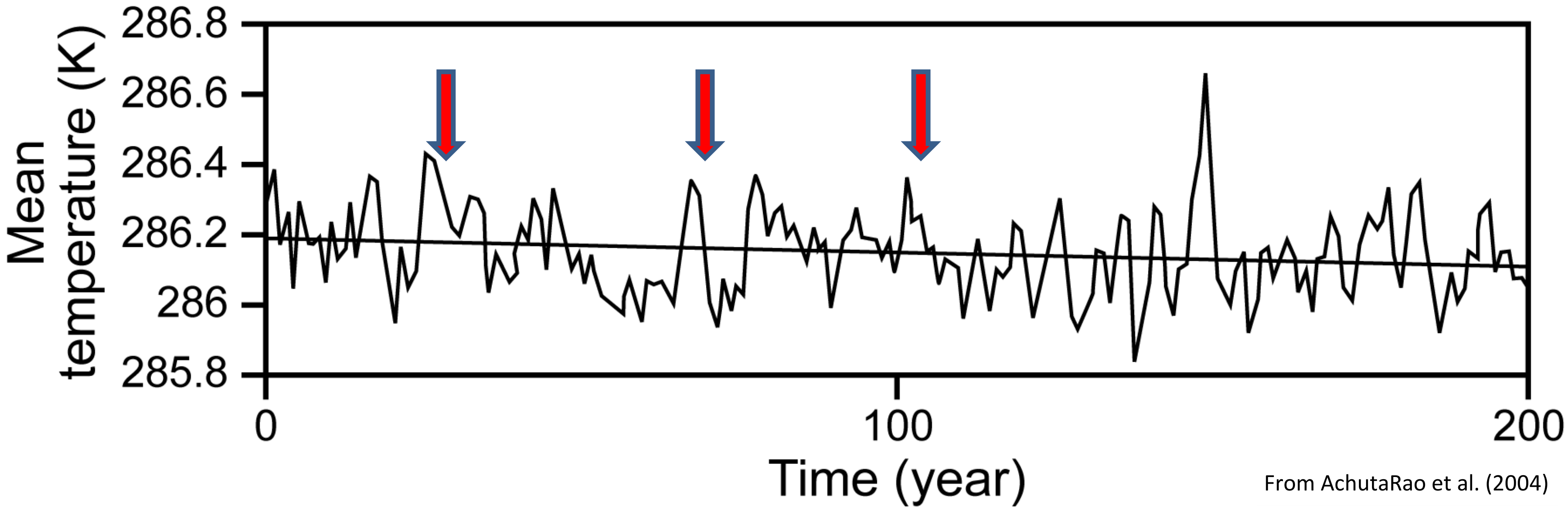
Experimental design for the IPCC-type human-impact studies

- Generate a control run for the present climate - allow possibly thousands of years to spin up, and then run for a couple of hundred years of the present climate (no change in CO_2 or aerosol forcing).



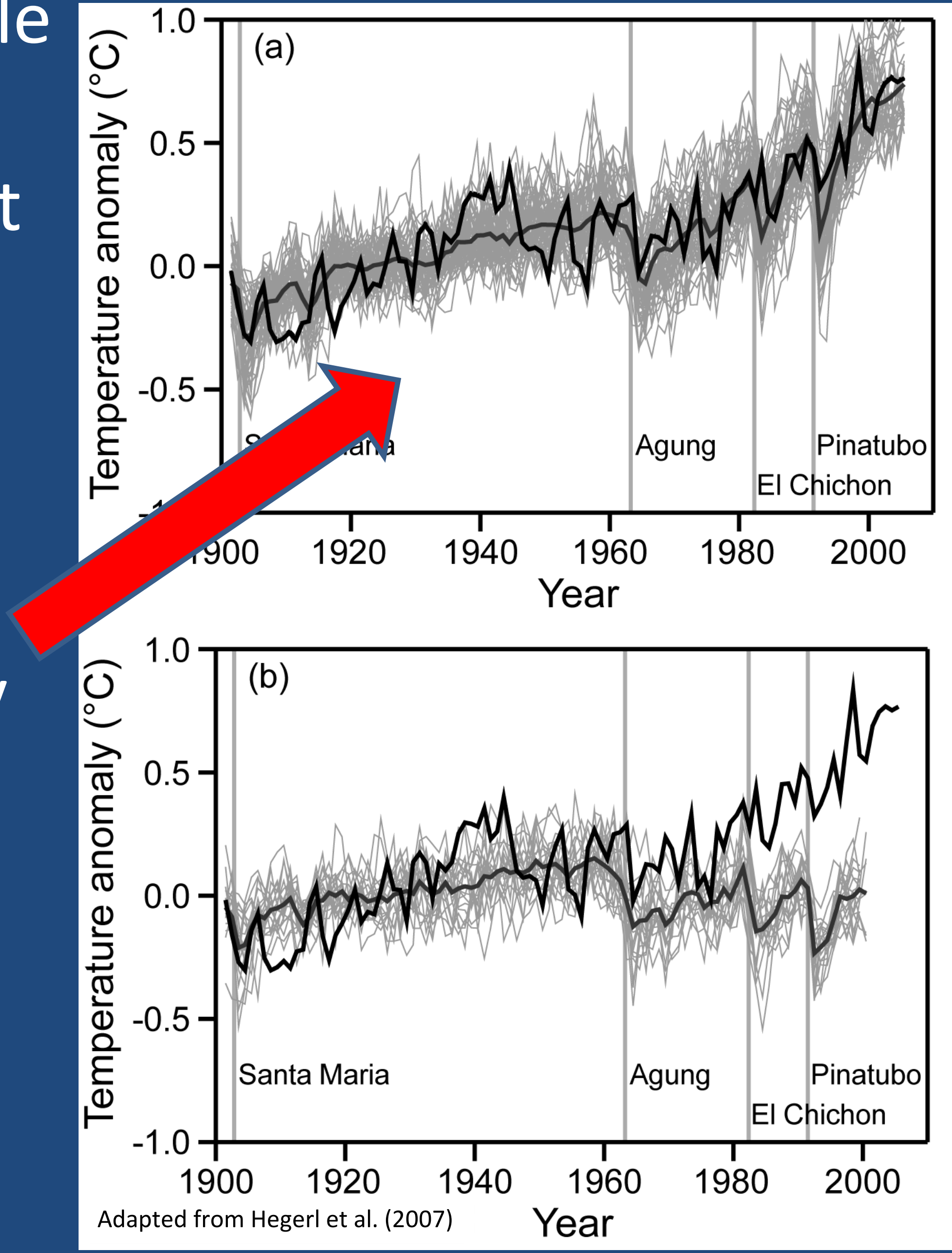
From AchutaRao et al. (2004)

- Begin a future-climate run at any arbitrary time by imposing a ramp up, as a function of time, in CO_2 or aerosol forcing – there are many accepted scenarios.



- Where you start in the internal cycle determines the change.

- Solution - Run an ensemble of simulations using the same model with different start times, and average them – removes most of the effect of the internal variability.
- Or, create an ensemble by running many different AOGCMs (from different organizations and countries) for the same scenario, and average them.



Adapted from Hegerl et al. (2007)

- These are NOT deterministic, initial-value predictions in the sense that we start from an observed state of the physical system – rather we have sensitivity experiments.

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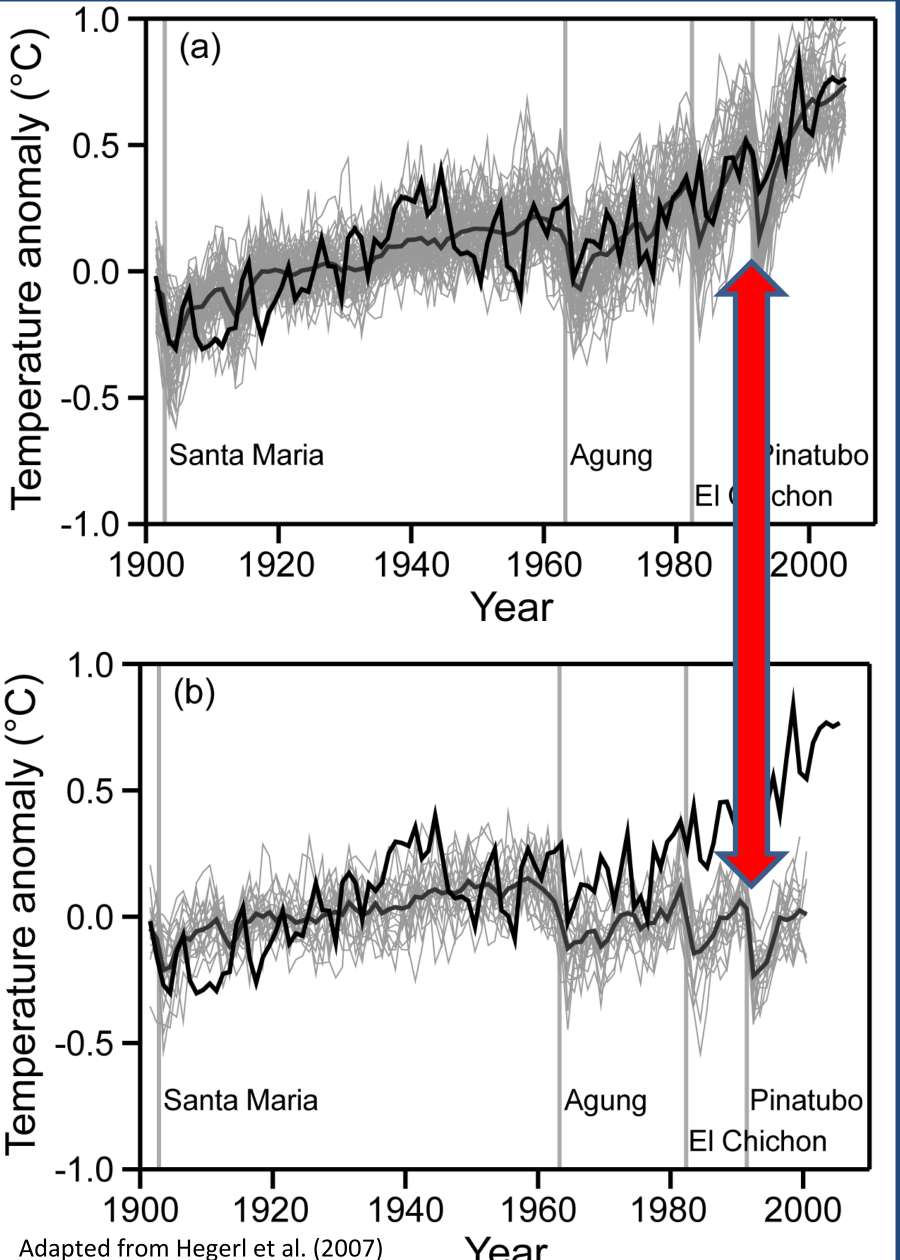

Adapted from Hegerl et al. (2007)

Type 2) Deterministic initial-value forecasts

- Can be used for seasonal to decadal prediction.
- Must initialize all components of the physical system – deep ocean circulations to deep-soil conditions. (How do we do this?)
- This is being done operationally for inter-seasonal prediction – e.g., the NCEP Climate Forecast System (CFS).
- For longer periods (decadal) – major research area.

Type 3) Feedback sensitivity studies

- Experiments to define the strengths and sign of feedbacks between radiative forcing and climate
- For example, one standard procedure defines the “equilibrium climate sensitivity”
  - Double the CO_2 instantaneously and let the model run to an equilibrium near-surface temperature.
  - The change in the temperature reflects the sensitivity.

Type 4) Anthropogenic landscape changes: impacts on climate

- Can use a global or regional model.
- These are sensitivity studies of the sort that we discussed in the chapter on experimental designs for research – conduct a control simulation and then one with an existing or future anthropogenic change.
- These sensitivity simulations will be longer in duration than the simple ones discussed before

Type 5) Downscaling from AOGCMs, using regional models

- Motivation – response to climate change is often at local level, so information is needed at high spatial resolution.
- Two approaches:
  - Dynamical downscaling – Force the LBCs of a mesoscale model with output from an AOGCM. Do “time slices” to make this computationally tractable. (Risks of time slices?)
  - Statistical downscaling – Statistically relate the small-scale response to the large (AOGCM) scale processes.

Special requirements for AOGCMs used for climate studies/prediction

- Land-surface modeling
  - Carbon sources and sinks
  - Dynamic vegetation models – response to CO_2, T, precipitation
  - Soil layers that extend through a deep layer
  - Plant root dynamics
  - Dust elevation
- Ice modeling
  - Snowpack modules
  - Motion and thickness of land and sea ice
  - Permafrost
  - Polar ice caps

- Water bodies
  - Deep-ocean circulation – have different resolutions and time steps than the atmospheric model.
  - Ocean chemistry
    - Salinity – affects density and saturation vapor pressure
    - CO_2 exchange with the atmosphere
    - Marine biosphere
    - Nutrient input from the atmosphere
  - Wave intensity – affects albedo, evaporation rate, aerosol (salt) source, roughness.
- Physical-process parameterization
  - Small errors may lead to a large cumulative effect; e.g., cloud-errors causing a drift in the temperature.
  - Existing parameterizations are often tuned for the current climate.
  - Different approaches may be needed versus what is used for weather modeling, because of coarser resolution.

- Conservation properties of dynamical cores
  - mass and energy, more-important for long integrations
  - “mass fixer” sometimes used to compensate for mass leaks or sources.
- Initial conditions
  - For IPCC-type GHG impact experiments, and for assessing the impact of projected landscape changes, any realization of the current climate will work.
  - For initial-value simulations, the state of the entire physical system must be initialized.
- Flux corrections
  - To compensate for small errors in the fluxes of heat, water vapor and momentum , artificial corrections have been added to some models.
  - These corrections are non physical.
  - Few contemporary AOGCMs are flux corrected.

Verification of AOGCMs for past or present climates

- Why is success with the current climate not a guarantee that the model will be able to replicate a future climate?

Verifying recent versus past climates: relative advantages

- Recent/present climate (e.g., the last 100 years)
  - Conventional observations are available for verification.
  - External forcings are known (volcanic eruptions, aerosols, orbital and solar properties)
  - Climate changes have been small, compared to what has been experienced over longer periods.

- Past (paleo) climates
  - Must rely on proxy information to define the climate conditions for verification, and for the external forcings.
  - Time periods are too long to simulate with full-physics models.
  - Significant changes took place.

First verify climate models with individual weather events

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- Why?

First verify climate models with individual weather events

- The climate signal results from the aggregate effect of individual weather events and their simulated properties – e.g., cyclone tracks and intensities.
- These individual events should be simulated well in order to get the climate right.
- Even if the current climate statistics look right, they may be "right" for the wrong reason…unless you look at individual events.

Testing of climate models at the "individual-component" level

- Climate models are obviously much more complex than NWP models…with many more "components".
- Thus, to the extent that individual components can be tested in isolation, the more confidence we can have in the entire system.

Metrics for climate model verification

- Global-mean quantities – e.g., temperature
- Composite global indices, based on many variables
- Spatial patterns of variables (e.g., annual precip, SLP)
- Replication of specific features/processes – e.g., ENSO, diurnal cycle of precip
- Regional extremes

Verification of global-average climate statistics

- Challenge – What variable(s) best represent climate, and can serve as metrics of the overall errors in the simulations?
- There are many possible variables associated with the atmosphere, hydrosphere, cryosphere, lithosphere and biosphere.
- Some studies simply use global-mean temperature, and others use a “composite index”.

An example of a composite index from simulations of current climate

- Simulations were from three Climate Model Inter-comparison Projects (CMIP)
  - CMIP1 – mid 1990s
  - CMIP2 – early 2000s
  - CMIP3 – late 2000s (based on IPCC AR4)
- Verification was based on a synthesis of reanalyses and observations, to create annual-mean climatologies from 1979-1999.
- Calculating a model-performance index

$$e_{vm}^2 = \sum_n w_n(\bar{s}_{vmn} - \bar{o}_{vn})^2 / \sigma_{vn}^2$$

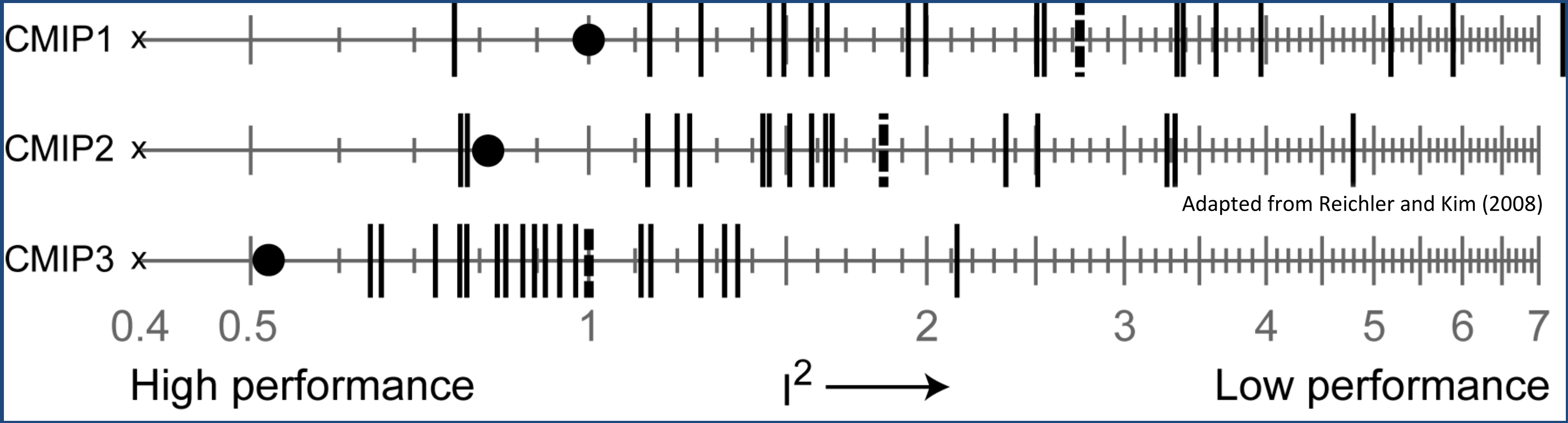
$$I_{vm}^2 = e_{vm}^2 / \overline{e_{vm}^2}^m$$

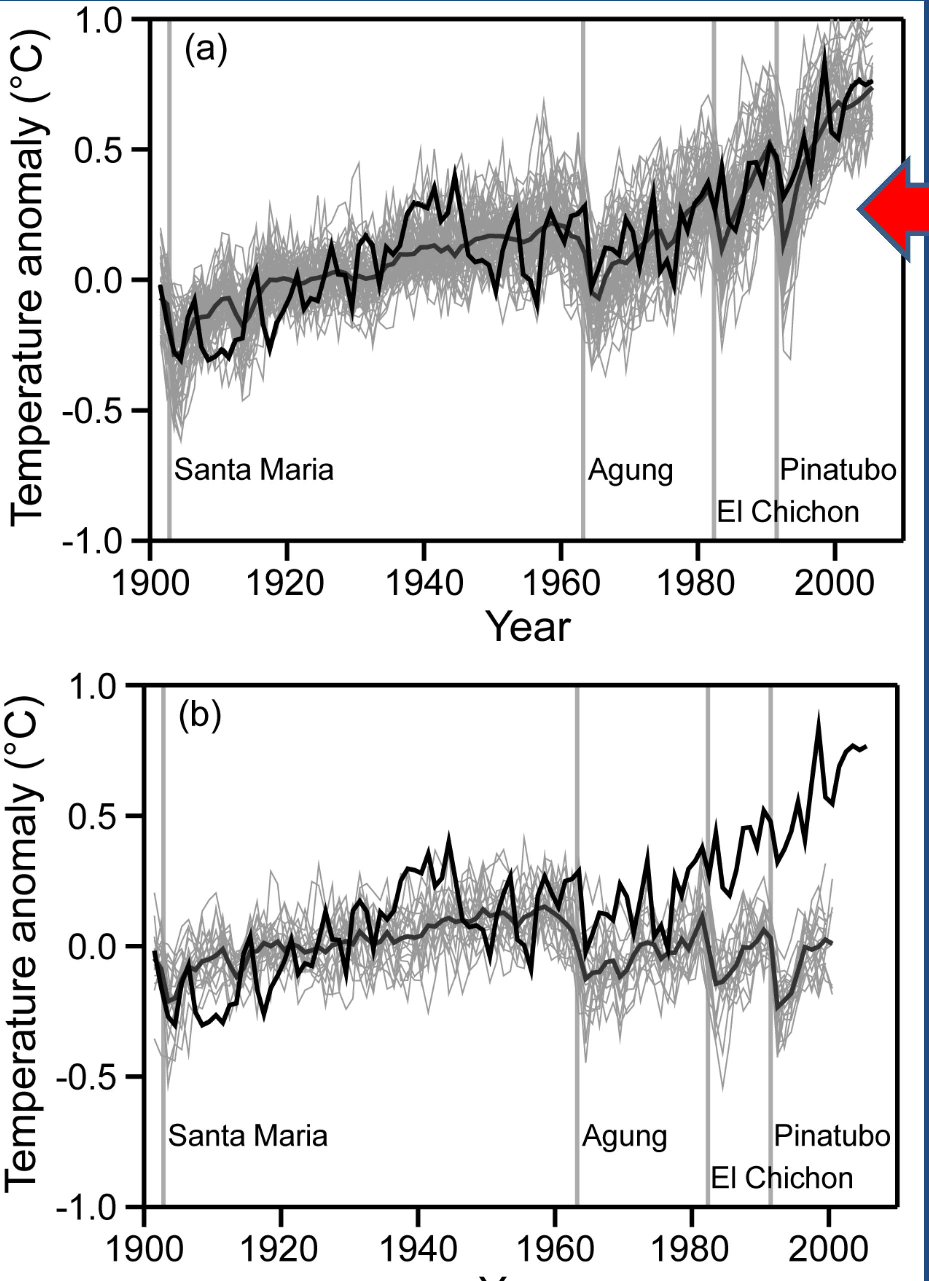
$$I_m^2 = \overline{I_{vm}^2}^v$$

- e^2: normalized error variance
- s: simulated annual climatological mean
- o: observed annual climatological mean
- w: weights
- σ: interannual variance based on observations
- I: overall performance index
- Subscripts
    - v: variable
    - m: model
    - n: grid point

The composite indices

- Vertical lines – individual model performance
- Dashed lines – average performance
- X – Performance of the NCEP-NCAR reanalysis
- Solid circles – Performance of the multi-model ensemble mean



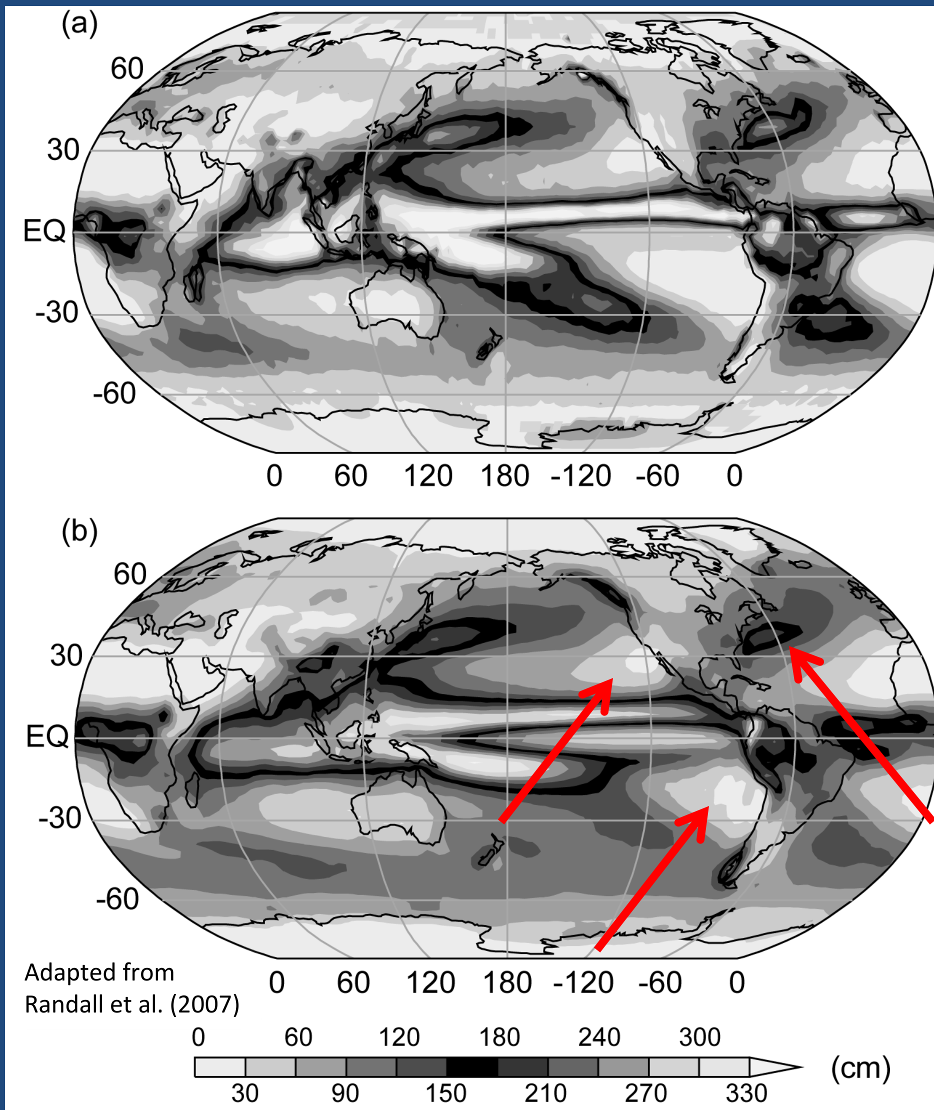


Adapted from Hegerl et al. (2007)

Another example –

Qualitative verification of ensemble-mean global-average near-surface temperature for the last century

Verification of specific processes and regional features – current climate

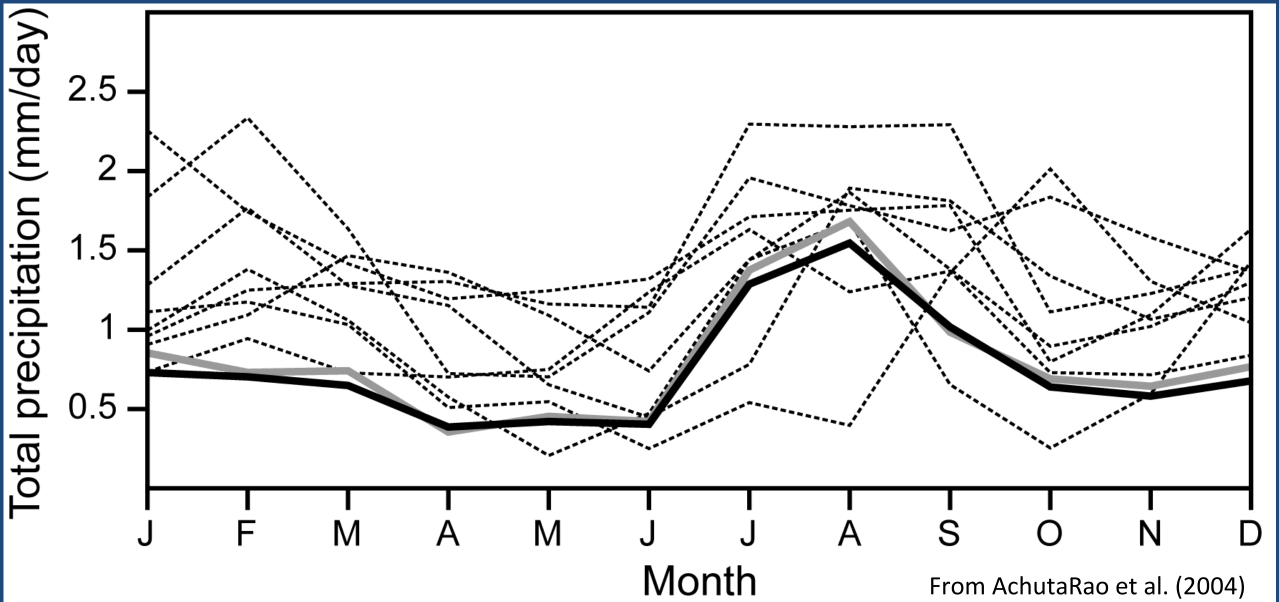


Adapted from Randall et al. (2007)

- Annual-mean precipitation
  - a) analysis of obs
  - b) CMIP3 simulation

An example of a quantitative regional verification

- CMIP2 comparison
- Precipitation in the southwestern US
- Overall annual cycle is captured, but there is much variation from model-to-model.
- Heavy lines – analyses of precipitation



From AchutaRao et al. (2004)

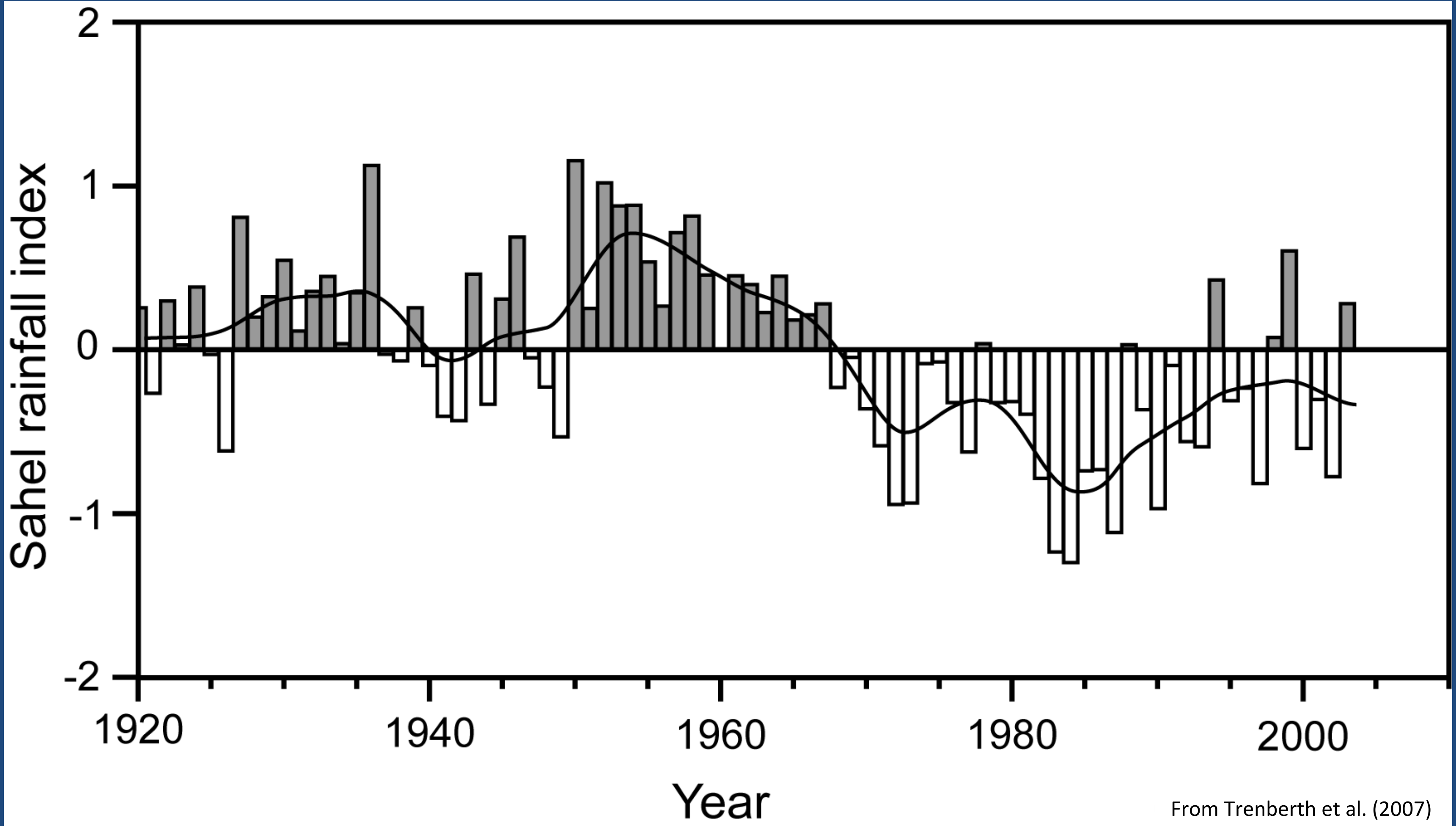
Modeling extreme values in new climate regimes

- These are often more important than mean values.
- Heavy rains, temperature, wind, drought, stronger storms in general.
- European project – Modeling the Impact of Climate Extremes (MICE)

Seasonal to multi-year initial-value predictions

- Must forecast anthropogenic impacts and internal variability.

Internal variability in the Sahel



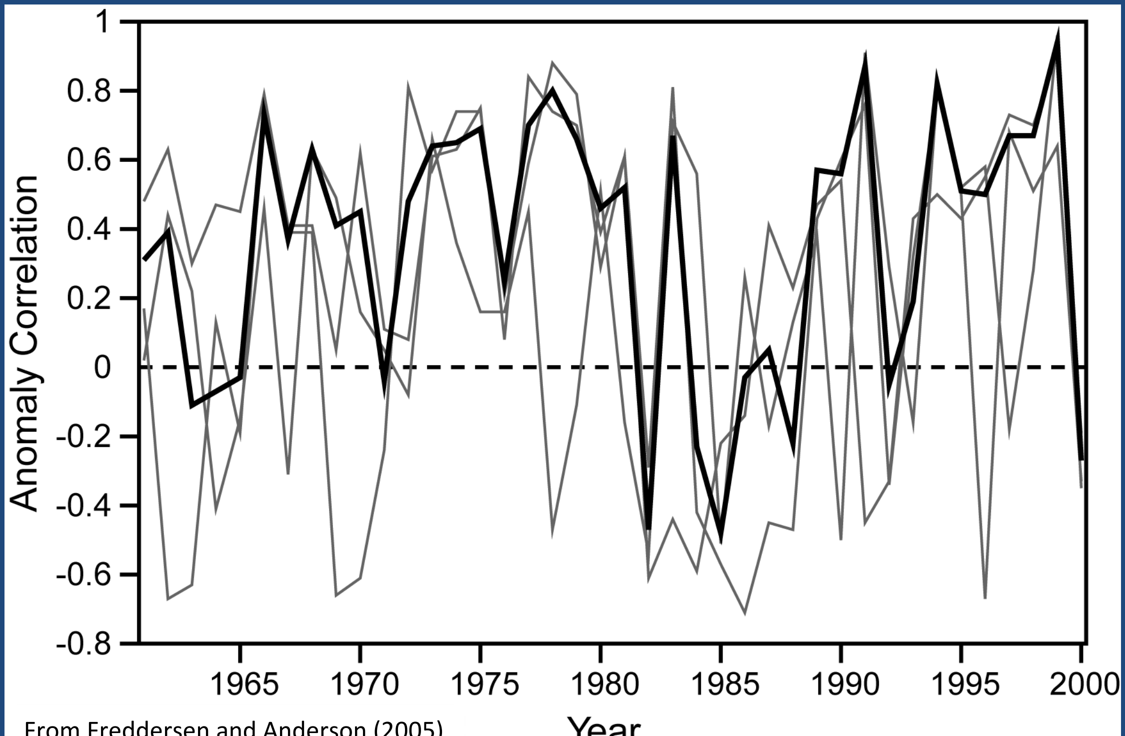
From Trenberth et al. (2007)

Seasonal to multi-year initial-value predictions

- Must forecast anthropogenic impacts and internal variability.
- Major modeling requirements
  - Accurate models of the entire physical system: atmosphere, ocean, ice, land
  - Initial conditions for the atmosphere, ocean, ice, land (using data assimilation)
  - Method for ensemble prediction
  - Method for correcting for the systematic error

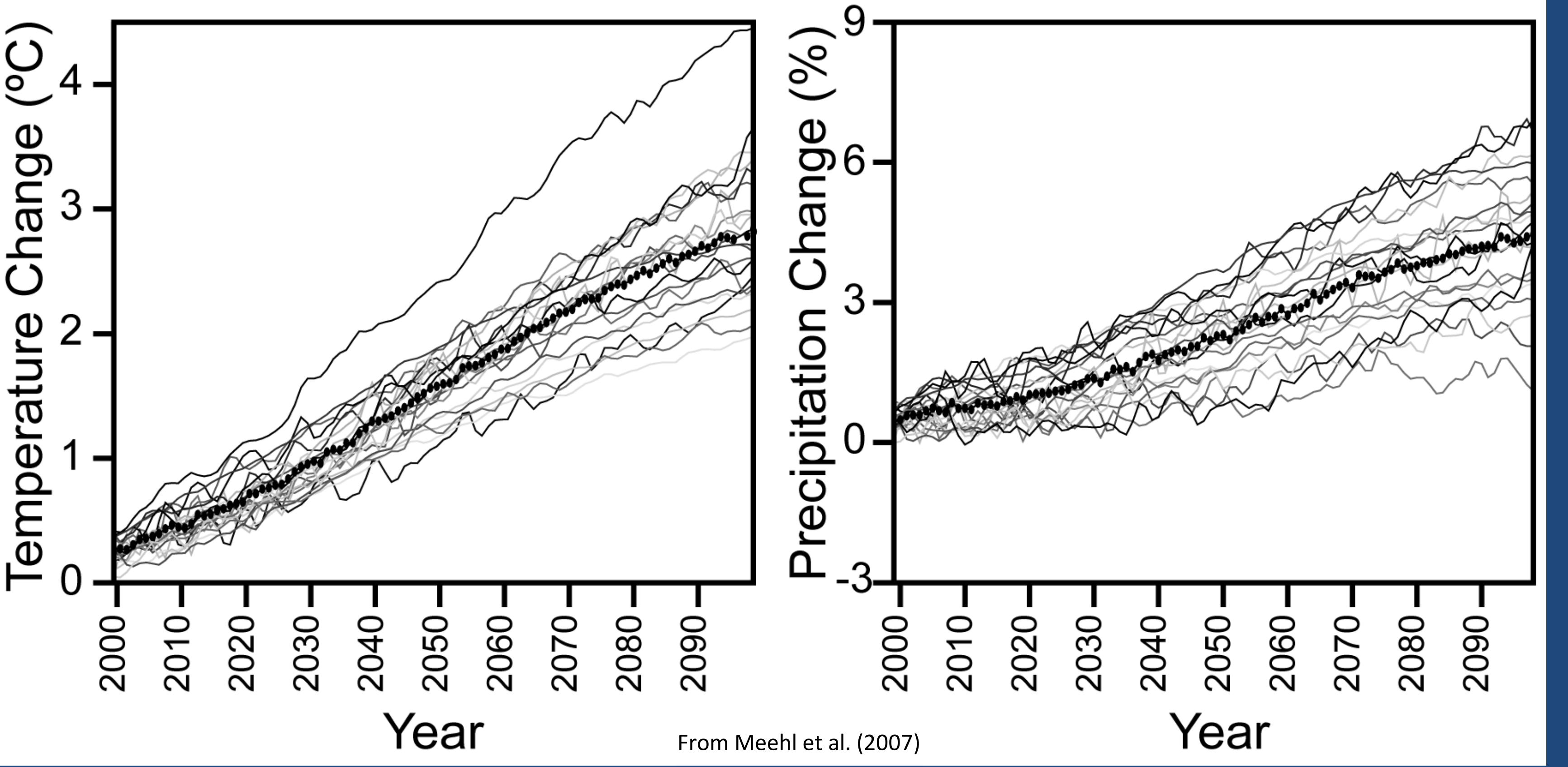
Ensemble climate simulation - example

- 2-month predictions
- 40-years of forecasts
- Europe: July, August, September
- Three models – gray lines

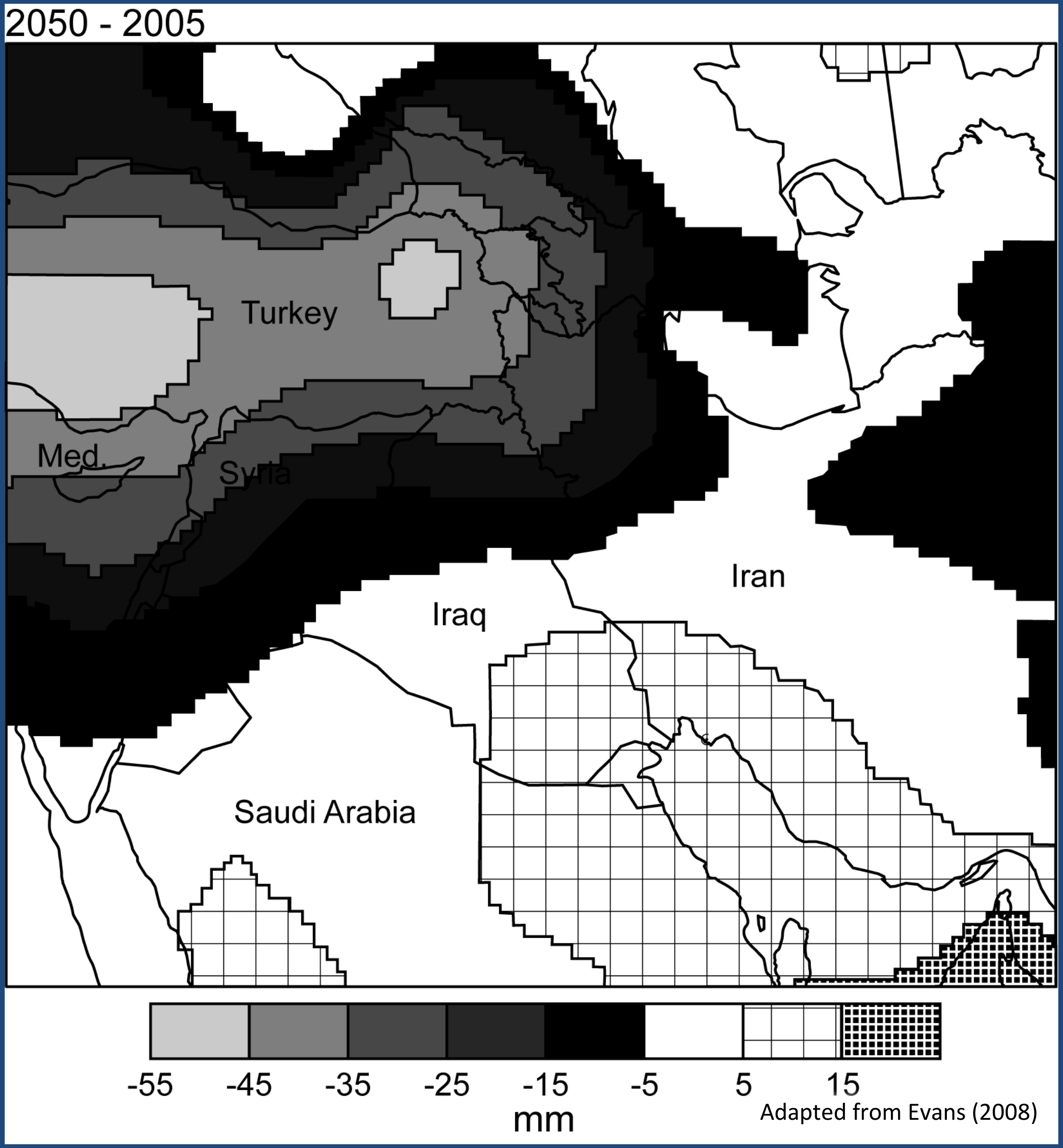


From Freddersen and Anderson (2005)

IPCC AR4 ensemble



From Meehl et al. (2007)



Global AR4 ensemble prediction – local focus

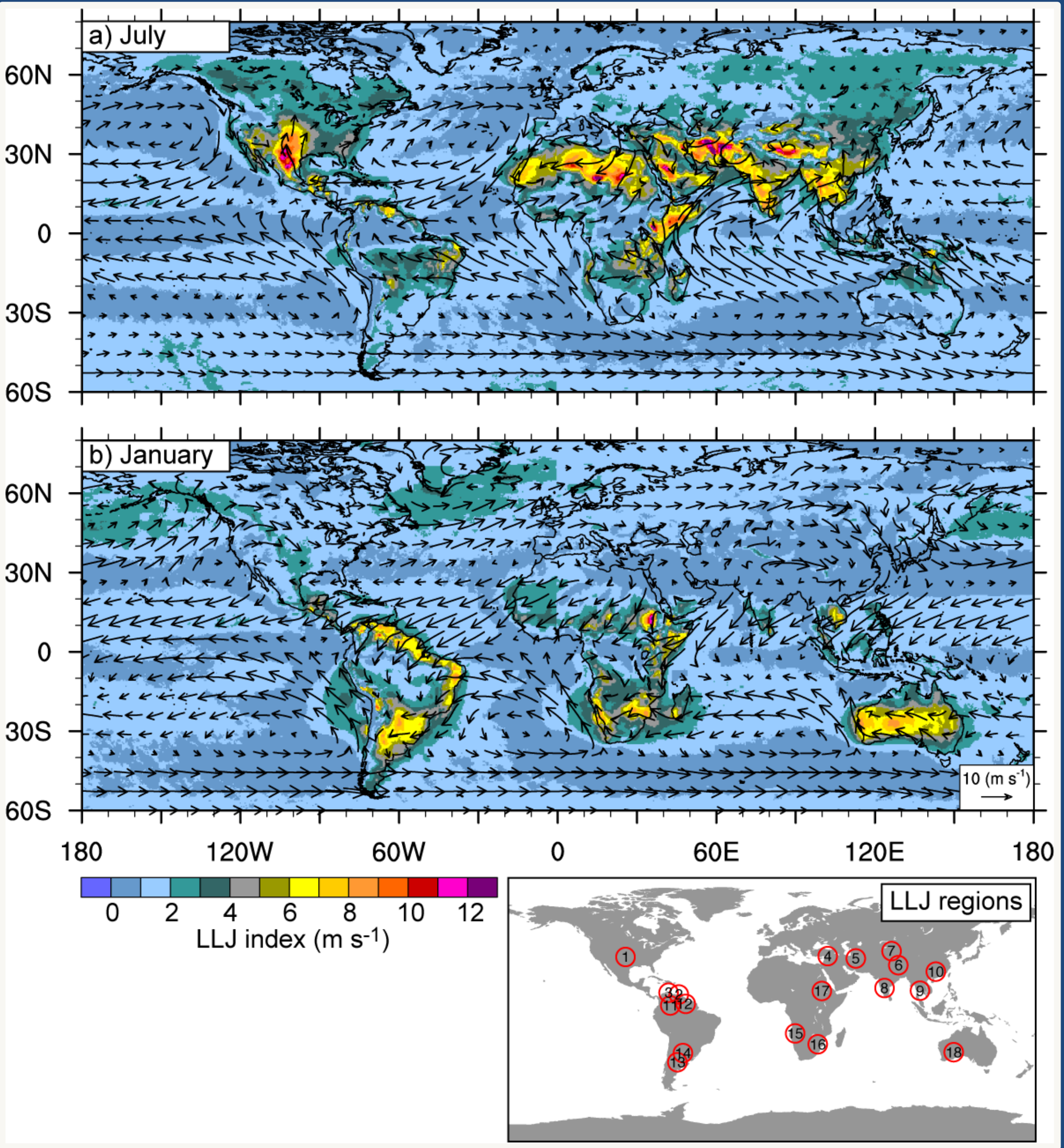
Reanalyses of the current global climate

- Generated and archived by ECMWF, NCEP, etc.
- Specialized reanalyses – for example

High-temporal-frequency output

Arrows = Mean 500- m-AGL winds at local midnight, plotted every 20th grid point.

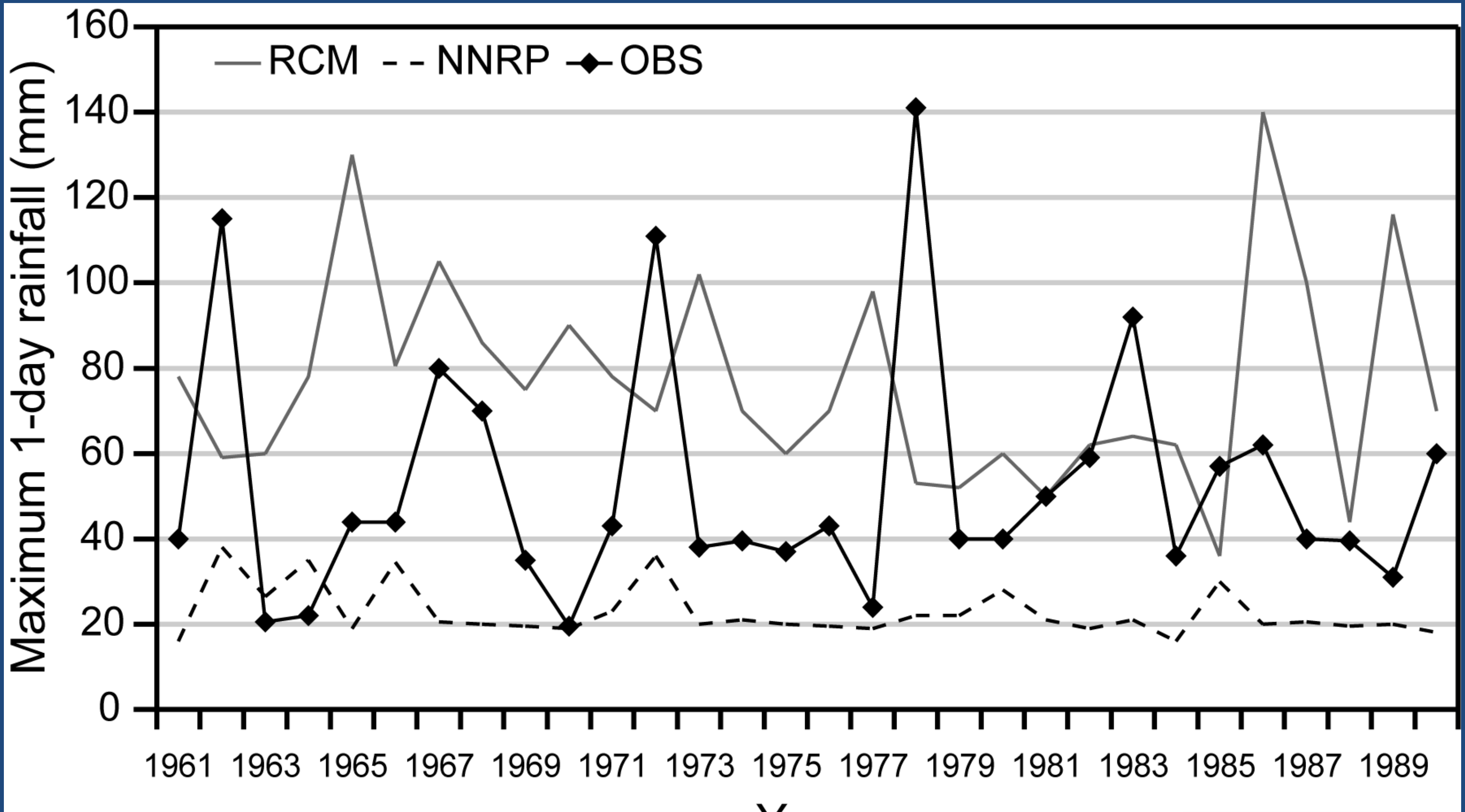
Rife et al. (2010)
Monaghan et al. (2010)



Climate downscaling

- Approaches
  - Dynamical and statistical
  - Spatial and temporal
  - Current climate and future climate

Example of the benefit of downscaling: Current-climate, spatial, dynamic

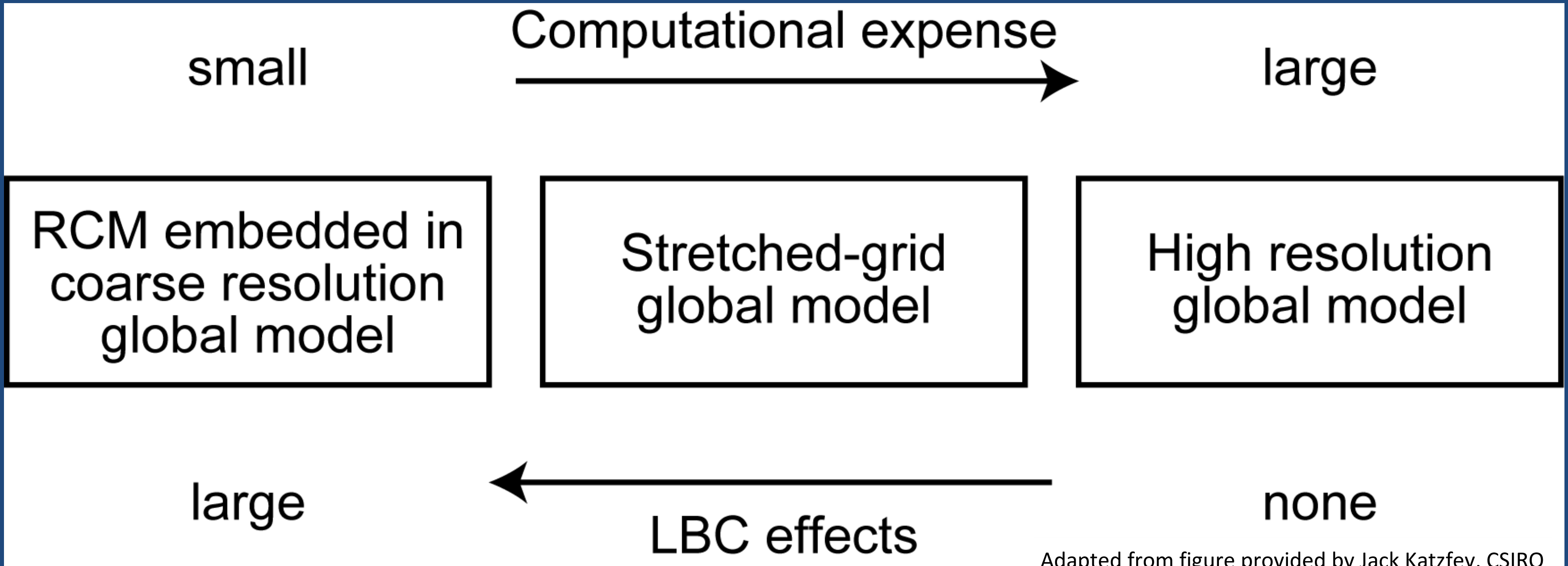


From Hanson et al. (2007)

Dynamical climate downscaling methods

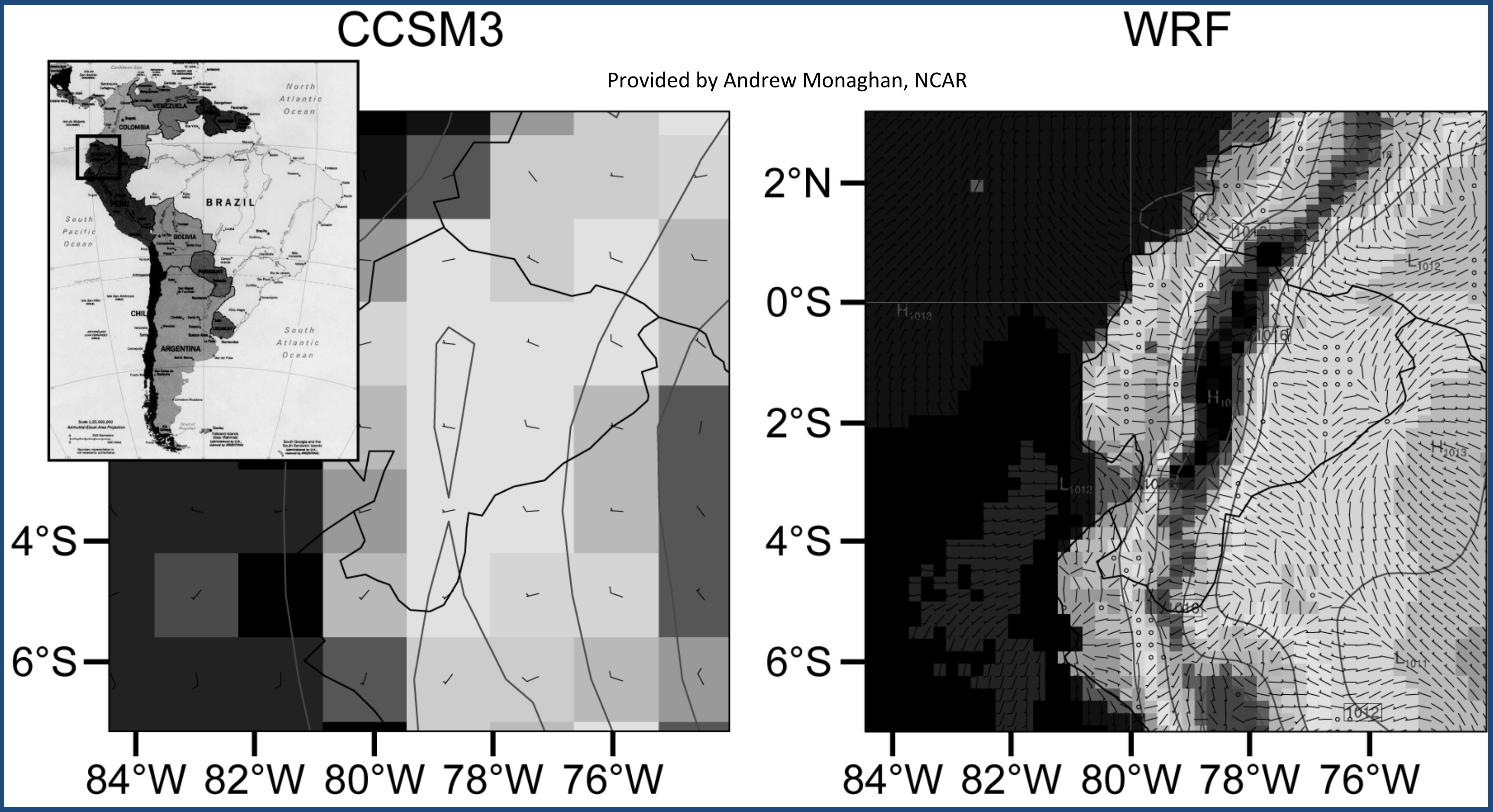
- Limited-area models (Regional Climate Models – RCMs) – define LBCs from AOGCM forecasts, or from reanalyses.
- Global stretched-grid AGCMs (shown before)
- Uniformly high-resolution AGCMs

LBC effects for the different approaches

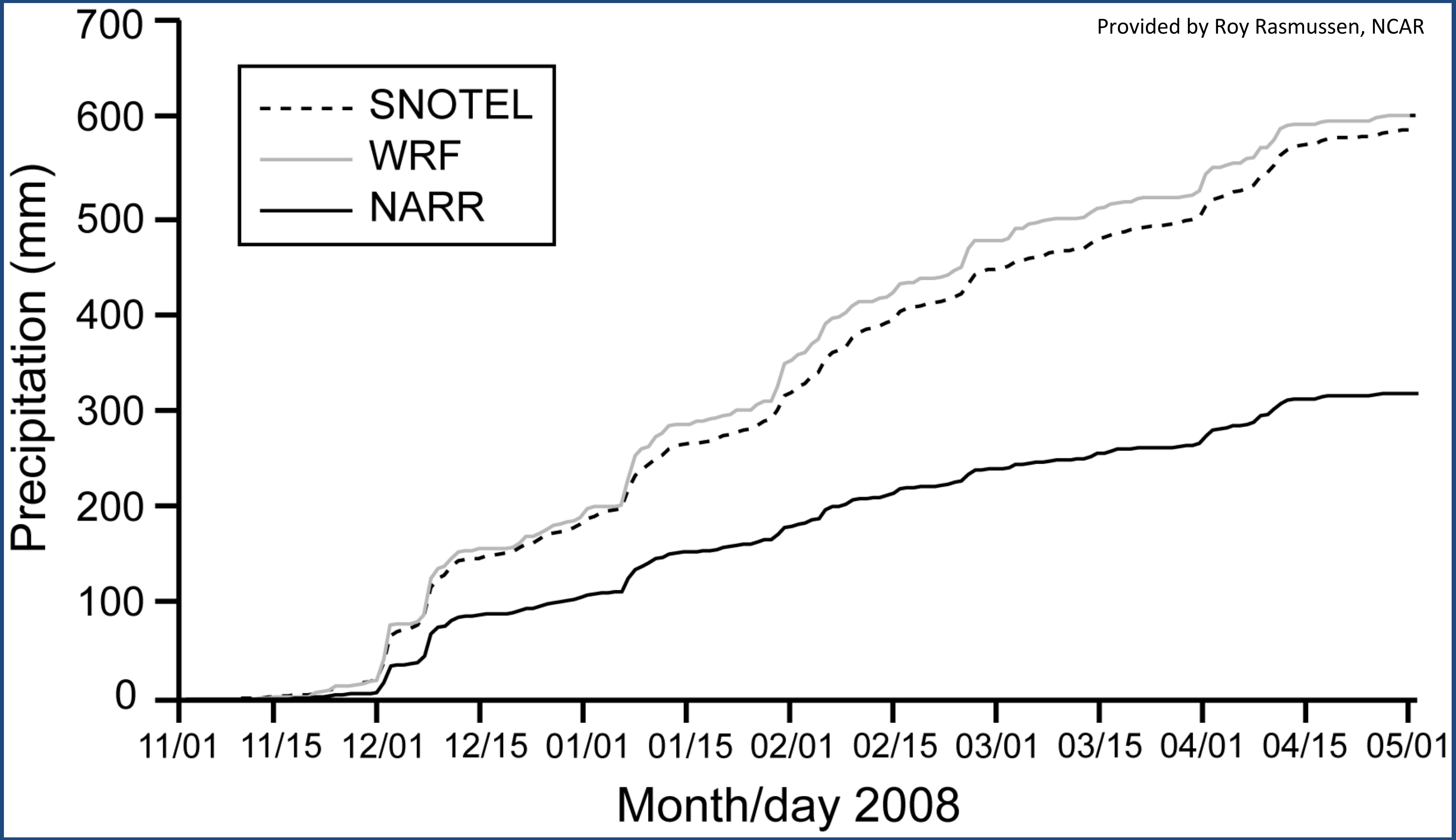


Adapted from figure provided by Jack Katzfey, CSIRO

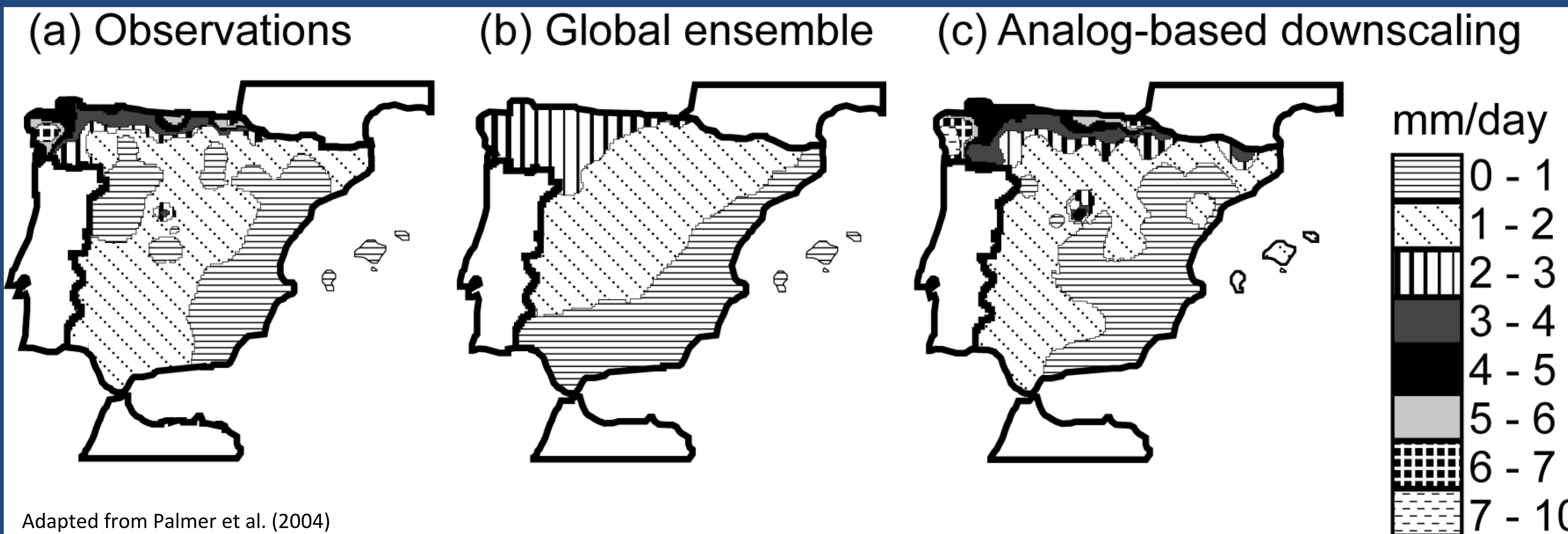
Example of future-climate downscaling with RCM



Example of current-climate downscaling with a LAM



An example of the benefit of statistical downscaling for February-April precipitation



Adapted from Palmer et al. (2004)

Benefit of high resolution for current-climate downscaling

(Total accumulation of 10 Nov 2008 – 22 Mar 2009)

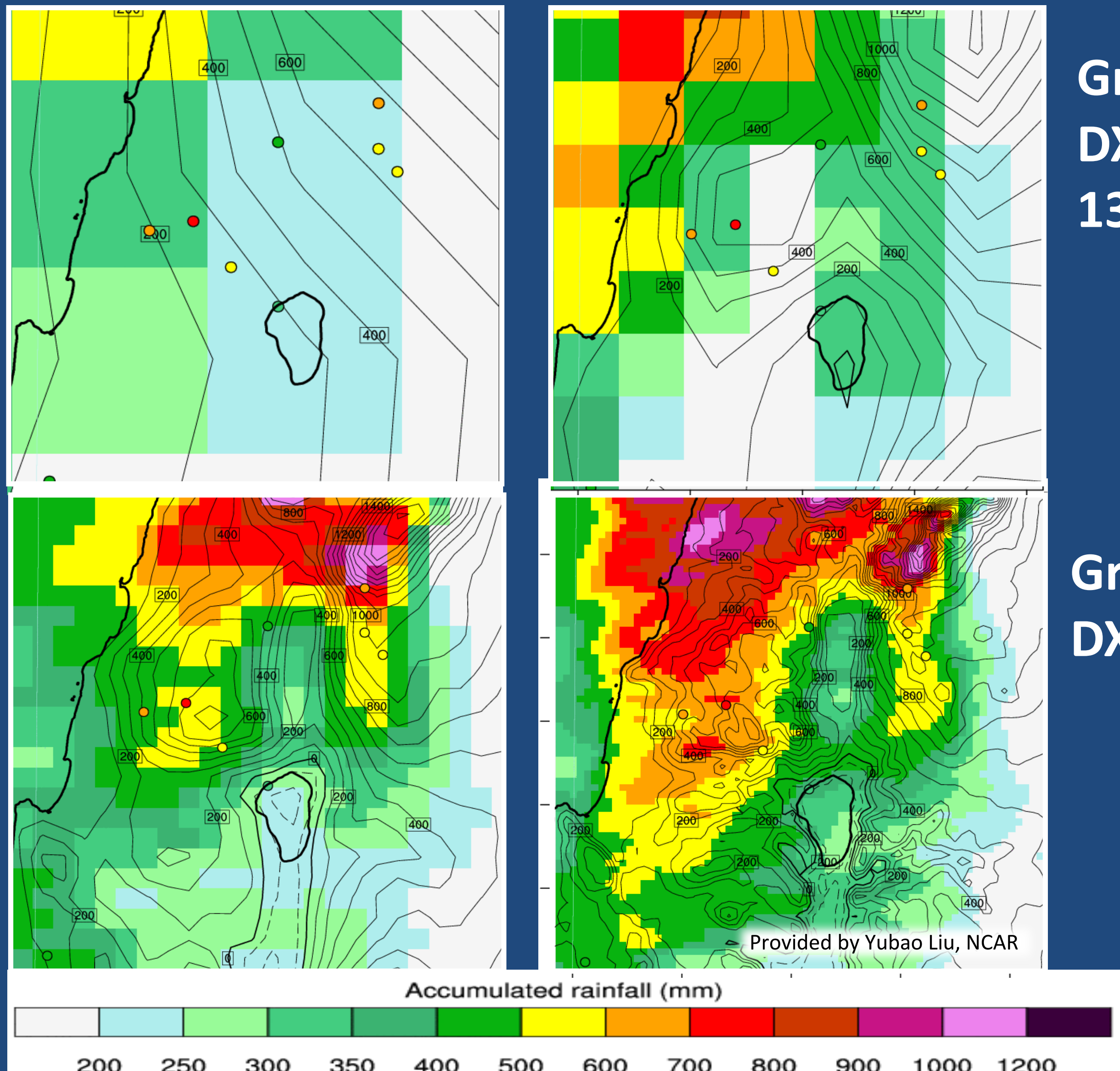
Grid 1
DX:
40.5km

100x100 km^2

Grid 2
DX:
13.5km

Grid 3
DX:4.5km

Grid 4
DX:1.5km



Modeling the climate impacts of anthropogenic landscape changes – sensitivity studies

- Urbanization
- Deforestation and advancement of agriculture
- Irrigation
- Drying of lakes