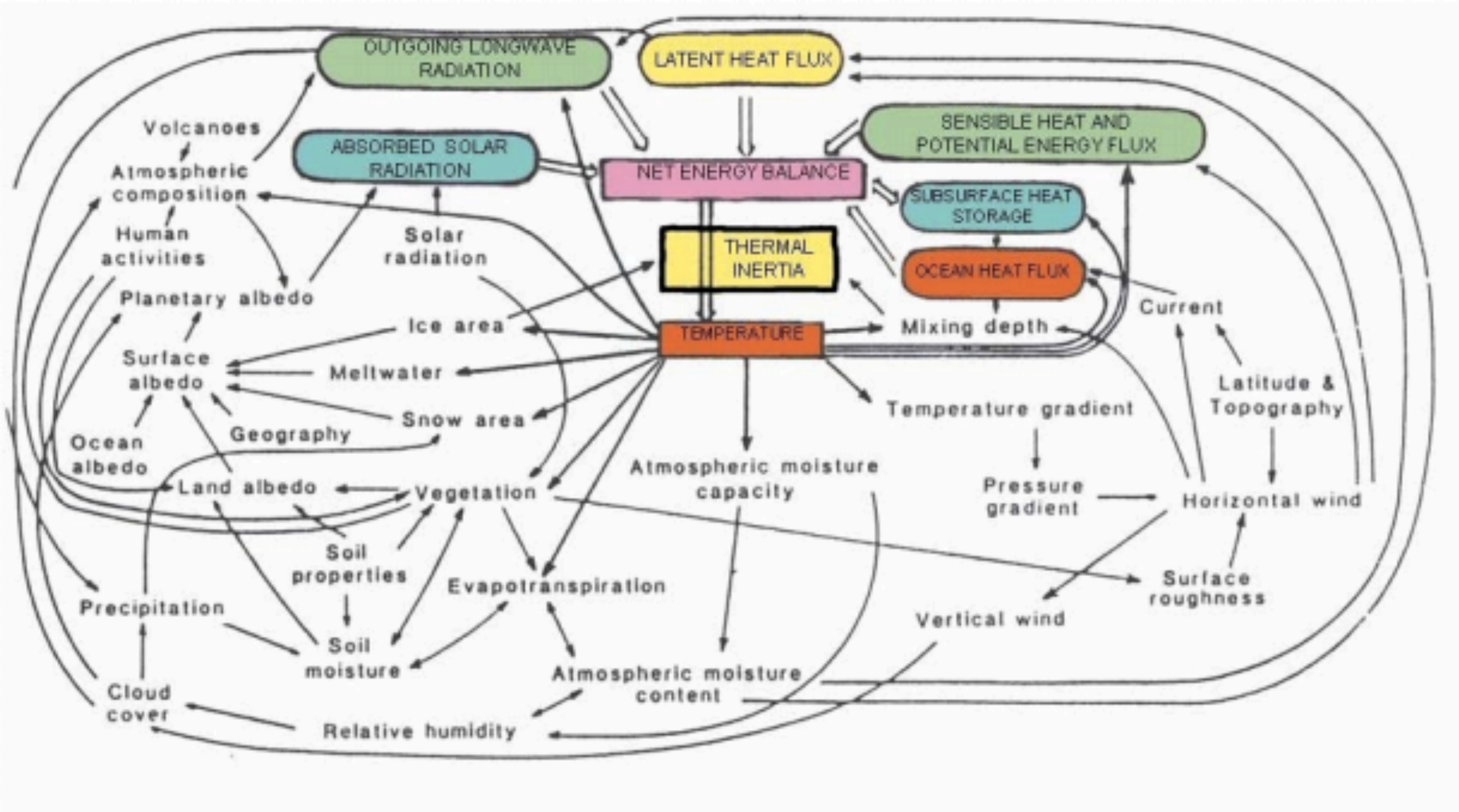
A Climate Modeling Primer

Vasu Misra
Department of Earth, Ocean and Atmospheric Science &
Center for Ocean-Atmospheric Prediction Studies,
Florida State University,
Tallahassee

Outline

- Climate Modeling
- From chaos to Climate Prediction to Climate Projection
- What is IPCC AR4?
- What is IPCC AR5?
- Downscale---Why? How?

Climate modeling



Flow diagram for climate modeling, showing feedback loops. From Robock (1985).

Climate Modeling

Uses

$$\frac{\partial u}{\partial t} = - u \frac{\partial u}{\partial x} - v \frac{\partial u}{\partial y} - \omega \frac{\partial u}{\partial p} + fv - \frac{\partial \phi}{\partial x} + F_x$$

$$\frac{\partial v}{\partial t} = - u \frac{\partial v}{\partial x} - v \frac{\partial v}{\partial y} - \omega \frac{\partial v}{\partial p} - fu - \frac{\partial \phi}{\partial y} + F_y$$

Newton’s second law of motion

$$\frac{\partial \phi}{\partial p} = - \frac{RT}{p}$$

Hydrostatic equation/vertical momentum equation

$$\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} + \frac{\partial w}{\partial p} = 0$$

Mass continuity equation/ conservation of mass

$$\frac{\partial T}{\partial t} = - u \frac{\partial T}{\partial x} - v \frac{\partial T}{\partial y} + \omega\left(\frac{RT}{c_p p} - \frac{\partial T}{\partial P}\right) + \frac{H}{c_p}$$

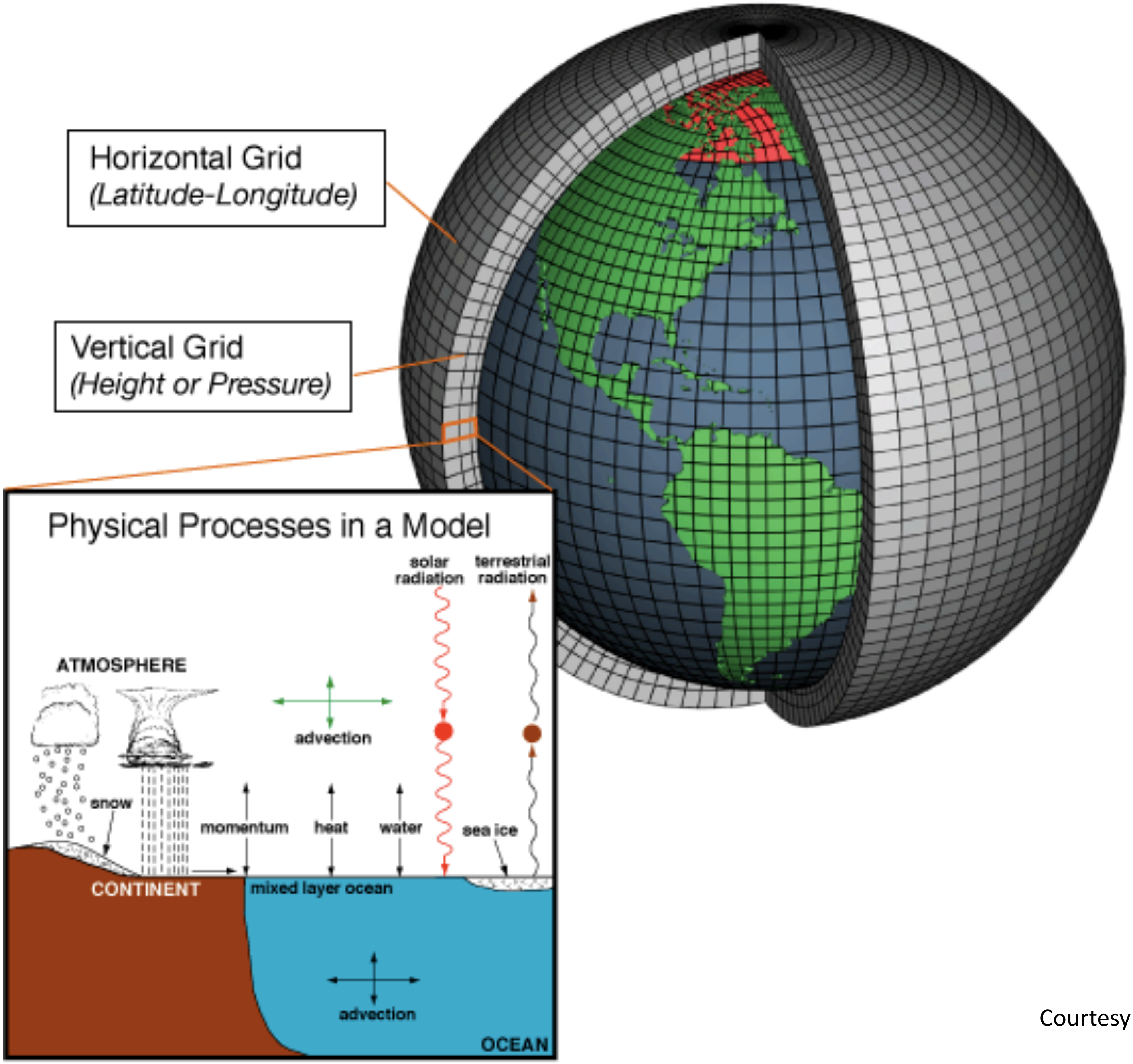
First law of thermodynamics

$$\frac{\partial q}{\partial t} = - u \frac{\partial q}{\partial x} - v \frac{\partial q}{\partial y} - \omega \frac{\partial q}{\partial p} + E - P$$

Conservation of moisture

To describe the motion of the fluids in the climate system (air and water)

Over the years we have added more physics including atmospheric chemistry, ocean biogeochemistry, terrestrial ecosystem of various complexities and continuing to add more……



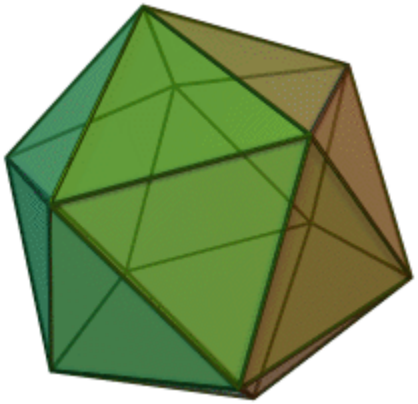
Courtesy: NOAA

Complexities to dynamical core to make the models more accurate and faster to integrate

Icosahedron

12 vertices

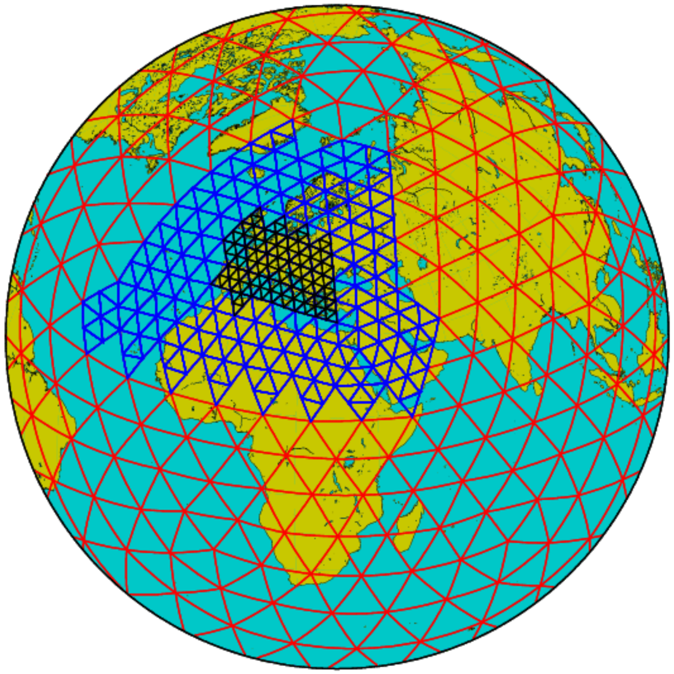
20 equilateral triangles



Example for local grid refinement

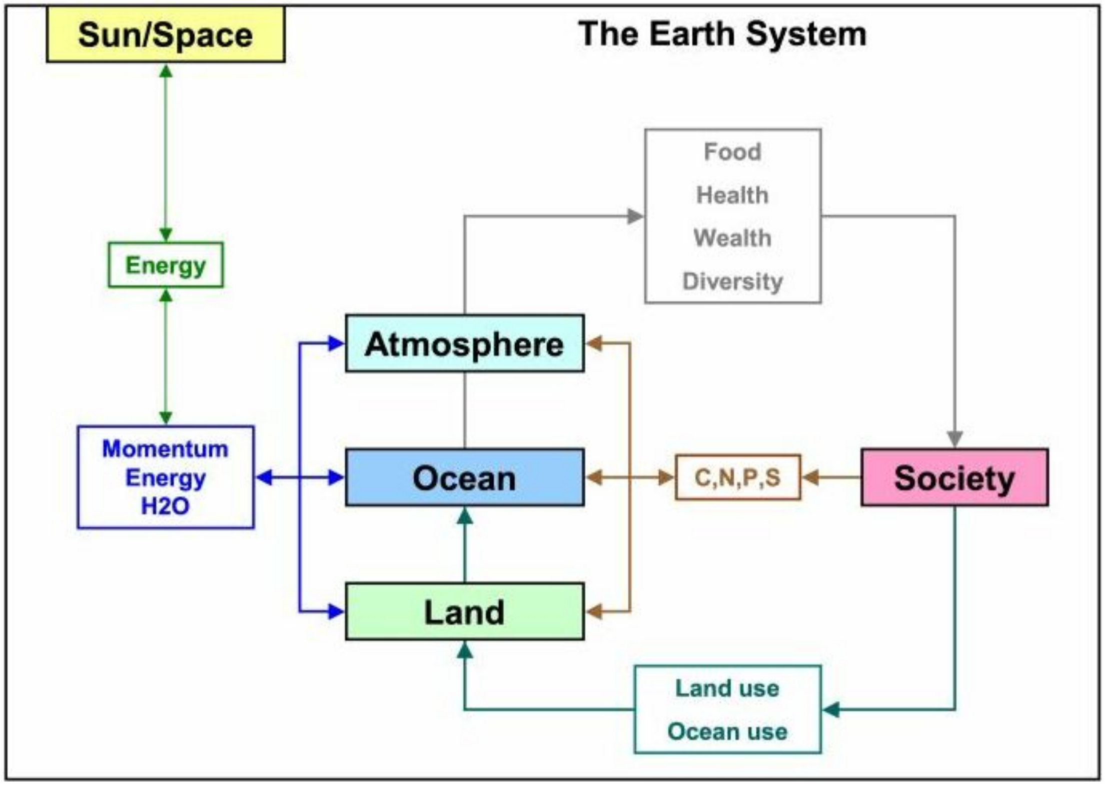
- Quasi uniform base grid:
  icosahedron edge → 6 cell edges

- 2 step refinement in a lat-lon region over Europe by bi-section of edges:
  1 triangle → **4** → **16**



Courtesy: M. A. Giorgetta/ MPI & DWD

A modern schematic view of a Earth System Model



Dynamical cores are at the base of the general circulation models and their properties determine the quality of the solutions

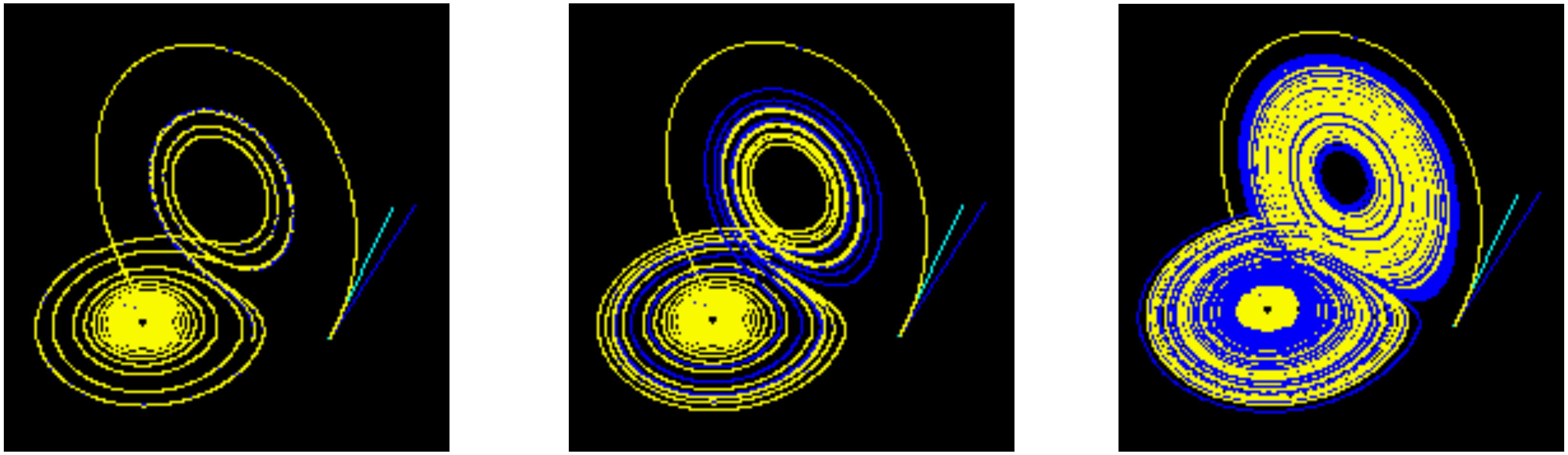
Courtesy: M. A. Giorgetta/ MPI & DWD

Lorenz model

- The Lorenz model is defined by three nonlinear differential equations giving the time evolution of the variables *X(t), Y(t), Z(t)*

  $dx / dt = a (y - x)$
  $dy / dt = x (b - z) - y$
  $dz / dt = xy - c z$

- One commonly used set of constants is $a = 10$, $b = 28$, $c = 8 / 3$. Another is $a = 28$, $b = 46.92$, $c = 4$. "a" is sometimes known as the **Prandtl** number and "b" the **Rayleigh** number.
- They never reach a steady state. Instead it is an example of deterministic chaos. As with other chaotic systems the Lorenz system is sensitive to the initial conditions, two initial states no matter how close will diverge.

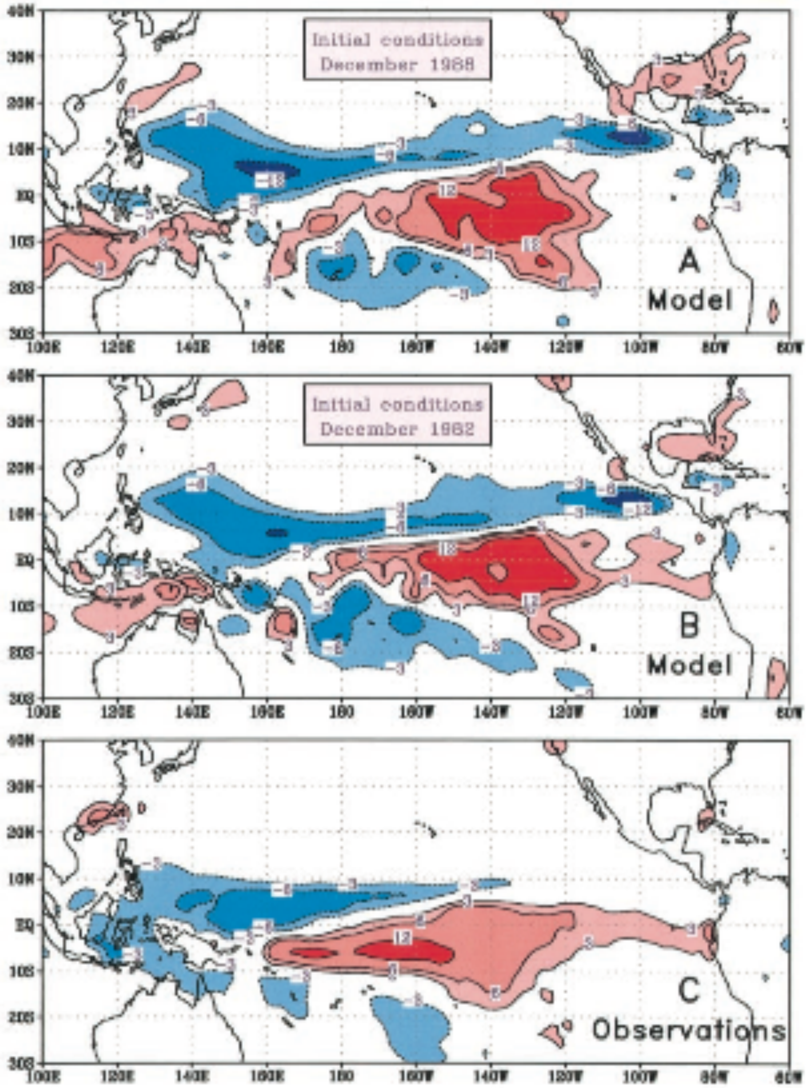


3-D evolution of the 2 trajectories starting at two initial points
Initial conditions were only by 10^{-5} in the x-coordinate.

Predictability in the Midst of Chaos: A Scientific Basis for Climate Forecasting

J. Shukla

Seasonal mean rainfall for December-January-February 1982-83



Atmospheric initial conditions of December 1982 forced with SST anomalies of 1982

Atmospheric initial conditions of December 1988 forced with SST anomalies of 1982

Observed rainfall for December-January-February 1982-83

Message: The atmospheric anomalies are a slave of the boundary conditions (SST)
➔You can predict mean seasonal climate beyond NWP range

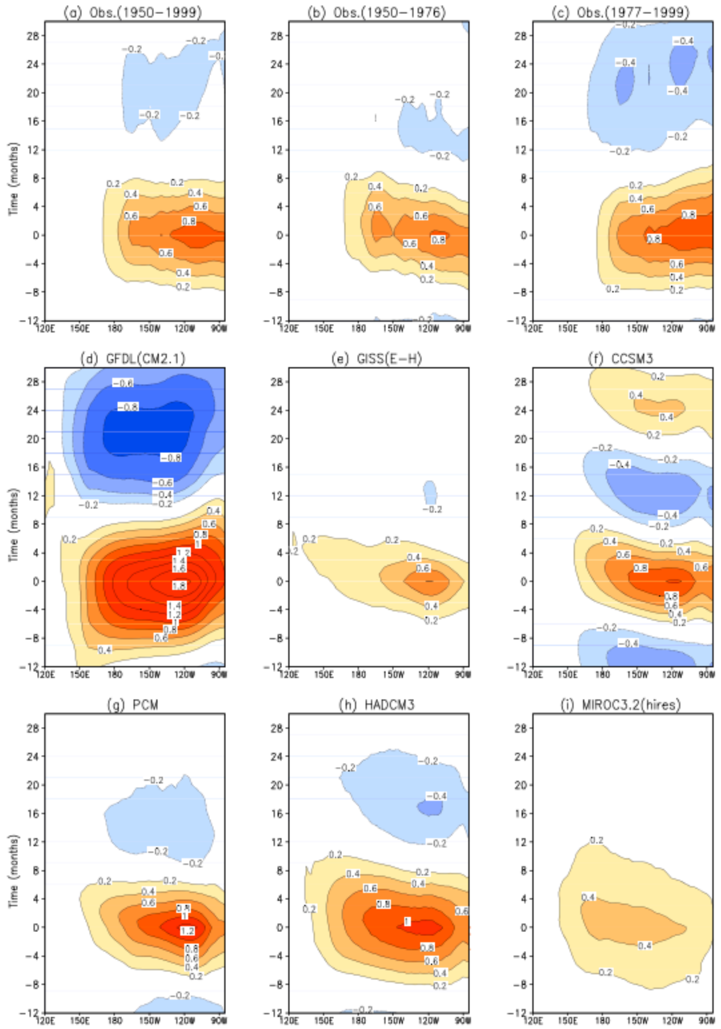
Subtle distinction

- Prediction: can be either verified or will be verified in the short future
- Projection: cannot be verified or will be verified when the projection in itself becomes irrelevant!

Uncertainty in climate projections

- There are 2 kinds of uncertainty:
- The first kind refers to that from multi-model spread. Has remained large since the first IPCC assessment report
- The second kind refers to biases in models (erroneous diurnal cycles, MJO, QBO, ENSO). More “treacherous” than first kind—there is no current method to quantify, let alone reduce this uncertainty on projections

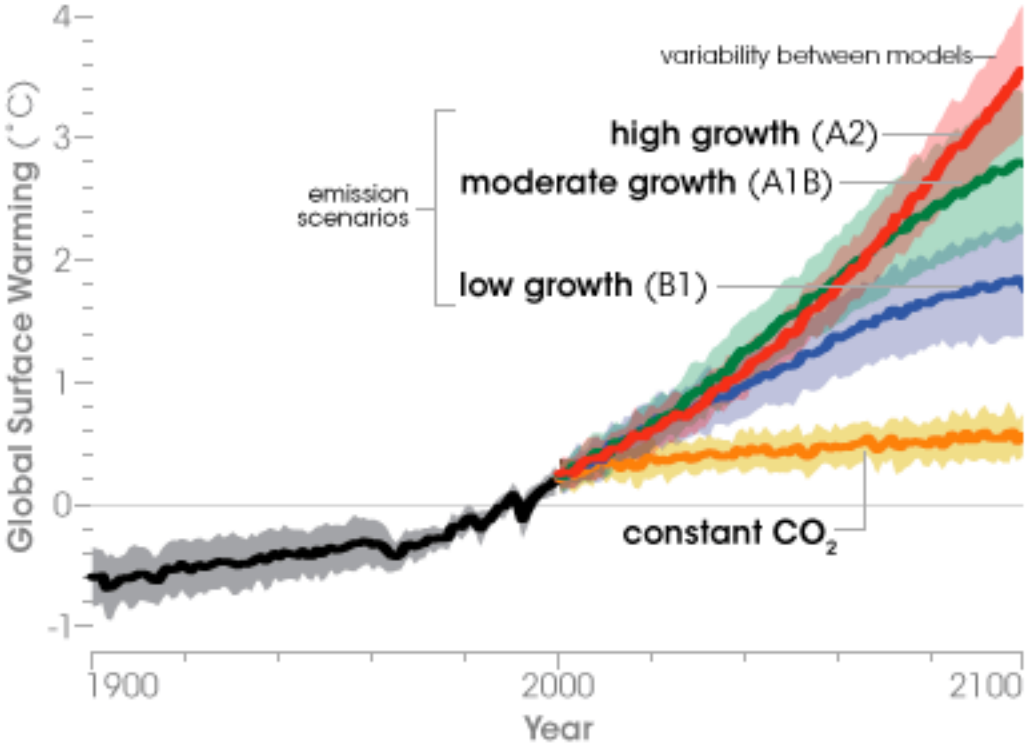
Uncertainty of second kind
(Nino3 SST index regressed on equatorial Pacific SST at different lead/lag over a 42-month period)



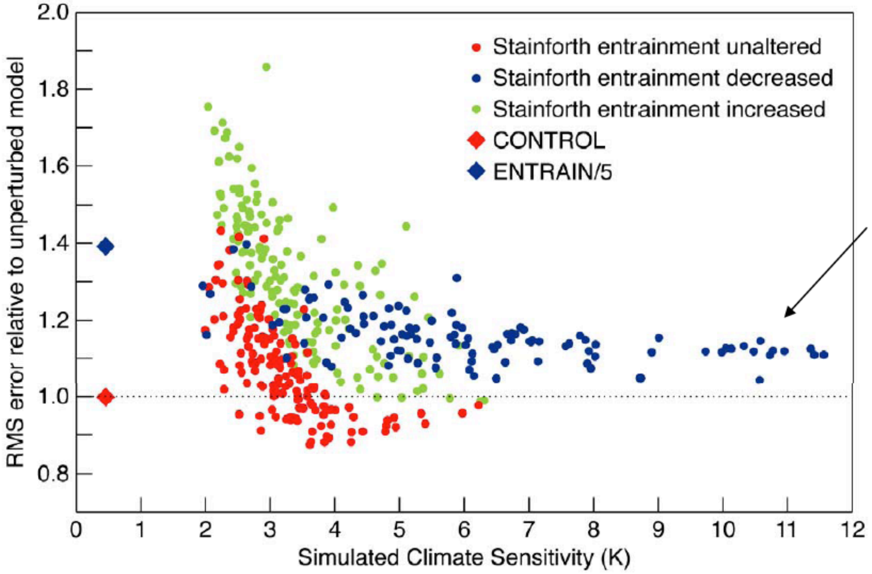
Courtesy:Joseph and Nigam

Message: None of the models are anywhere close to observations in their rendition of ENSO

Uncertainty of first kind



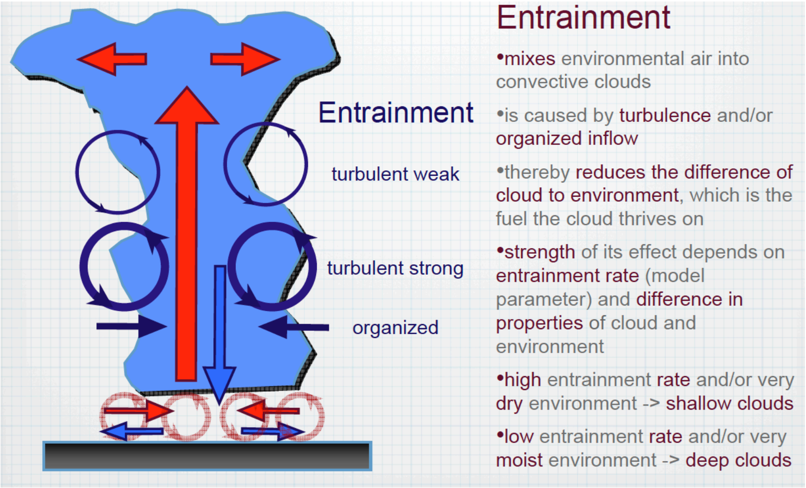
Climate: Error vs Sensitivity



Highest climate sensitivity for low convective entrainment models

fast physics!

Climate sensitivity is the change in global mean surface air temperature to change in radiative forcing.



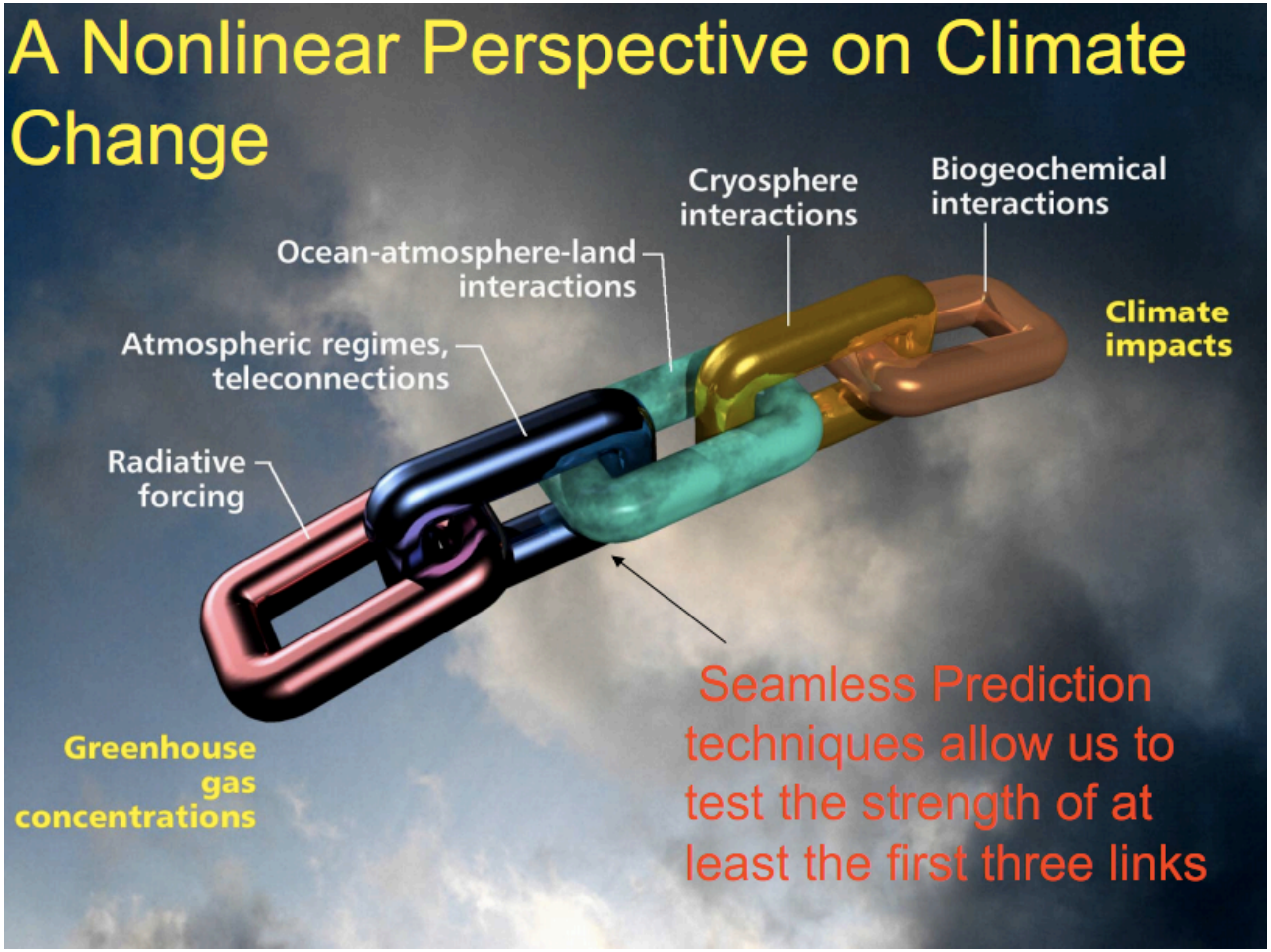
Entrainment

- mixes environmental air into convective clouds
- is caused by turbulence and/or organized inflow
- thereby reduces the difference of cloud to environment, which is the fuel the cloud thrives on
- strength of its effect depends on entrainment rate (model parameter) and difference in properties of cloud and environment
- high entrainment rate and/or very dry environment -> shallow clouds
- low entrainment rate and/or very moist environment -> deep clouds

Message: Fast physics, like deep convection (thunderstorms) are critical to model's projection➔ Numerical weather prediction models can be used to assess climate model uncertainty

Courtesy Tim Palmer, ECMWF

A paradigm shift from a reduced to a seamless modeling system



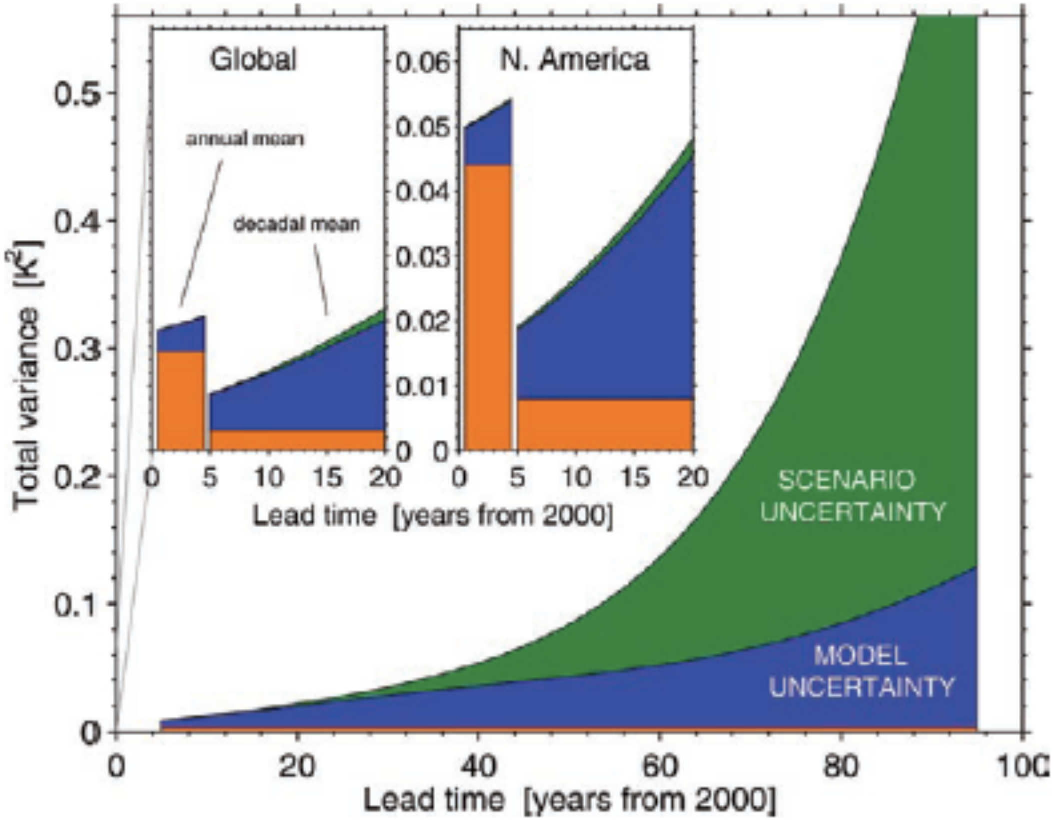
A Nonlinear Perspective on Climate Change

Seamless Prediction techniques allow us to test the strength of at least the first three links

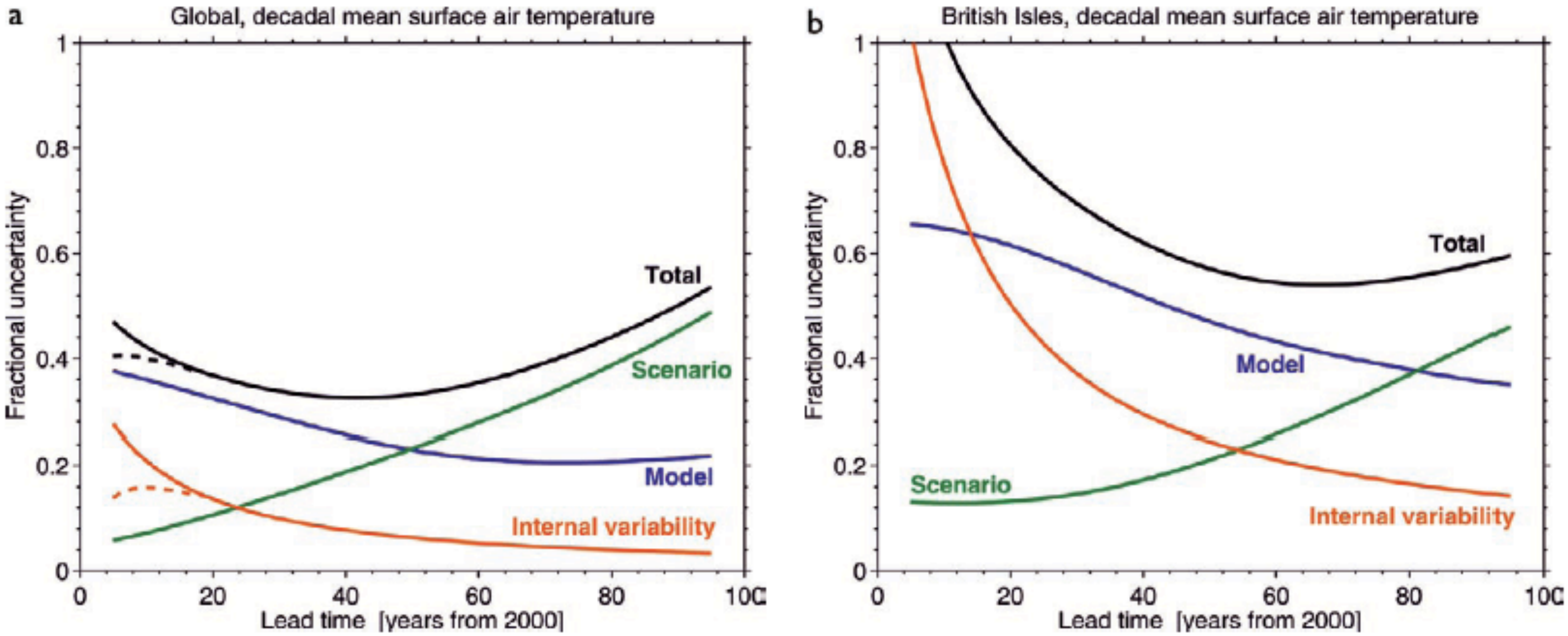
Seamless prediction allows the insights and constraints of Numerical Weather Prediction to be brought to bear on quantifying and reducing these uncertainties.

Courtesy: T. Palmer/ECMWF

Sources of uncertainty of regional climate change



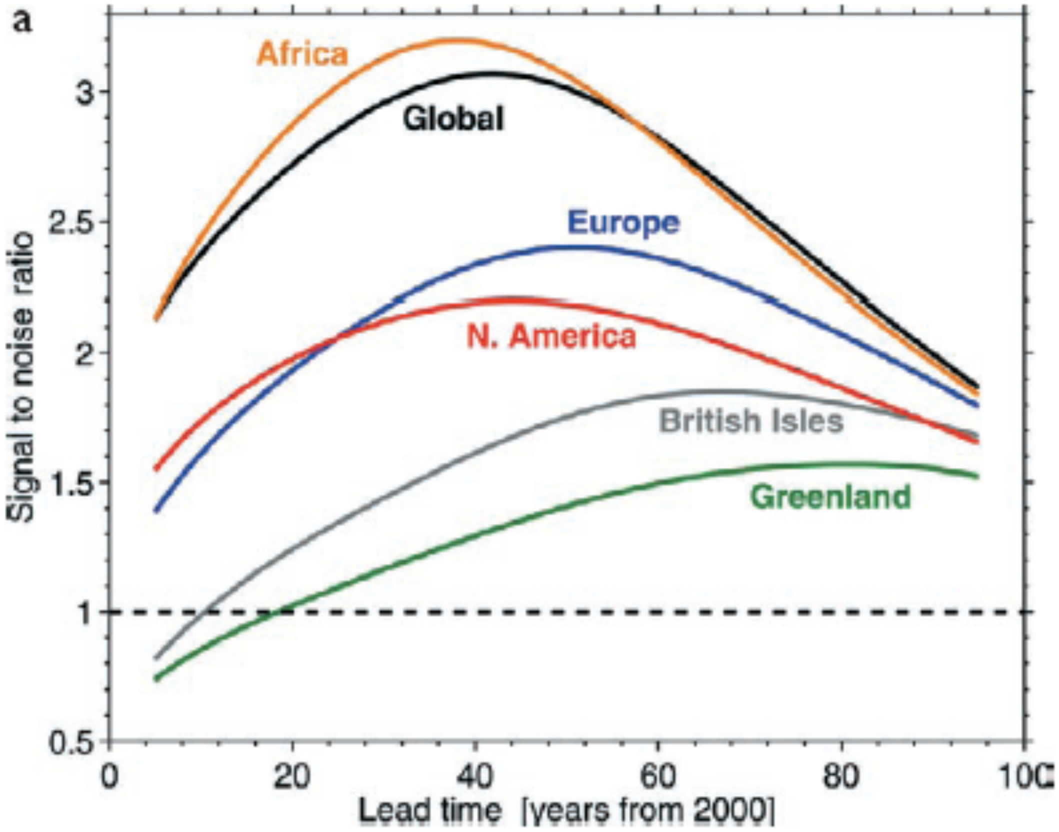
Hawkins and Sutton 2009



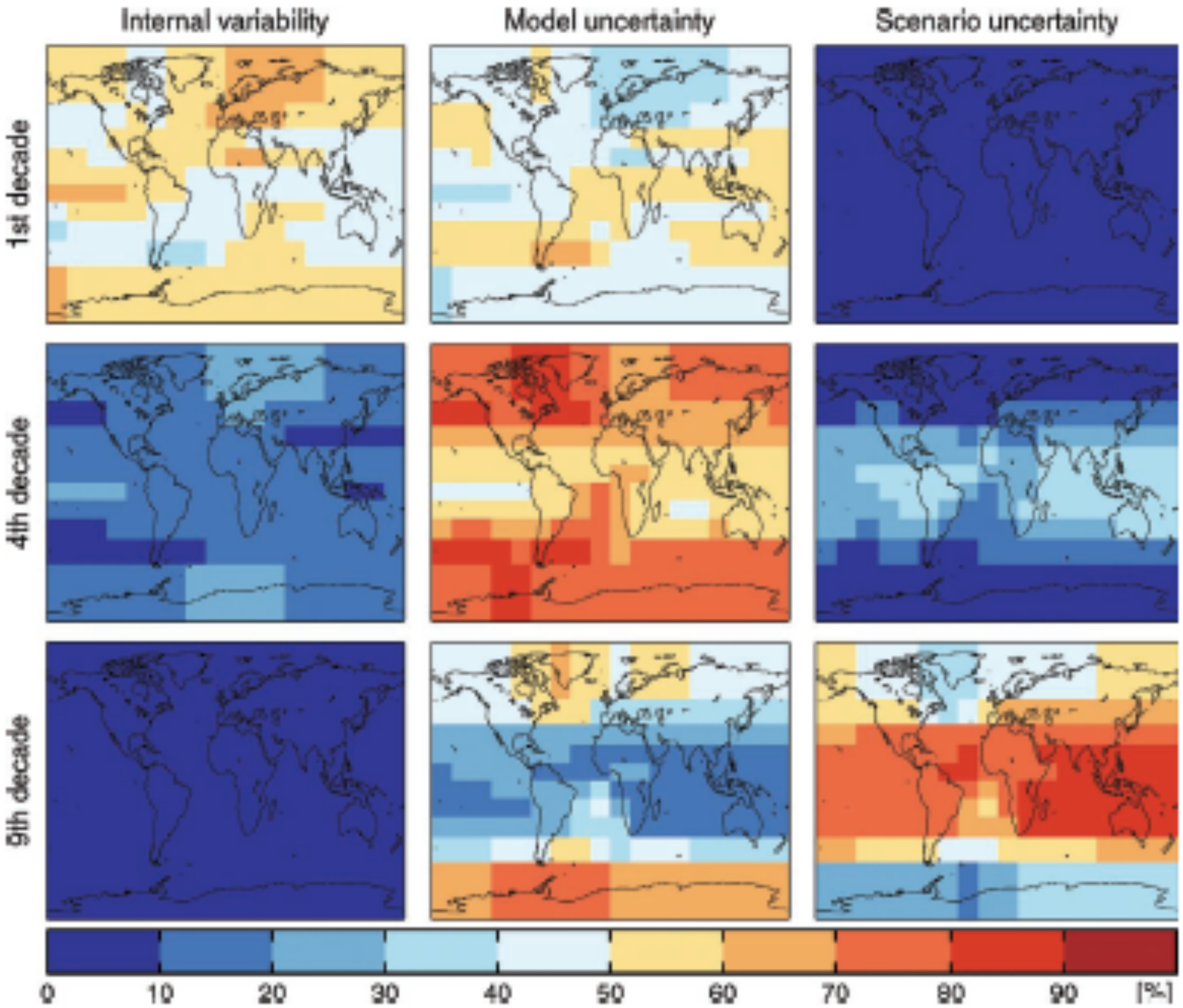
Fractional uncertainty: Ratio of prediction uncertainty [90% confidence level] and expected mean change.

Hawkins and Sutton 2009

Signal to Noise Ratio



Hawkins and Sutton 2009



Hawkins and Sutton 2009

Emission estimates

Special Report on Emissions Scenarios (SRES) prepared by IPCC for AR4 is based on scenario assessments up to 2000.

Scenario Families are: A1 [A1F1, A1B, A1T], A2, B1, B2

A1: integrated world

A2: Divided world

B1: integrated and eco friendly

B2: Divided and eco friendly

SRES overstate income differences in past and present and overestimate future economic growth in developing countries.

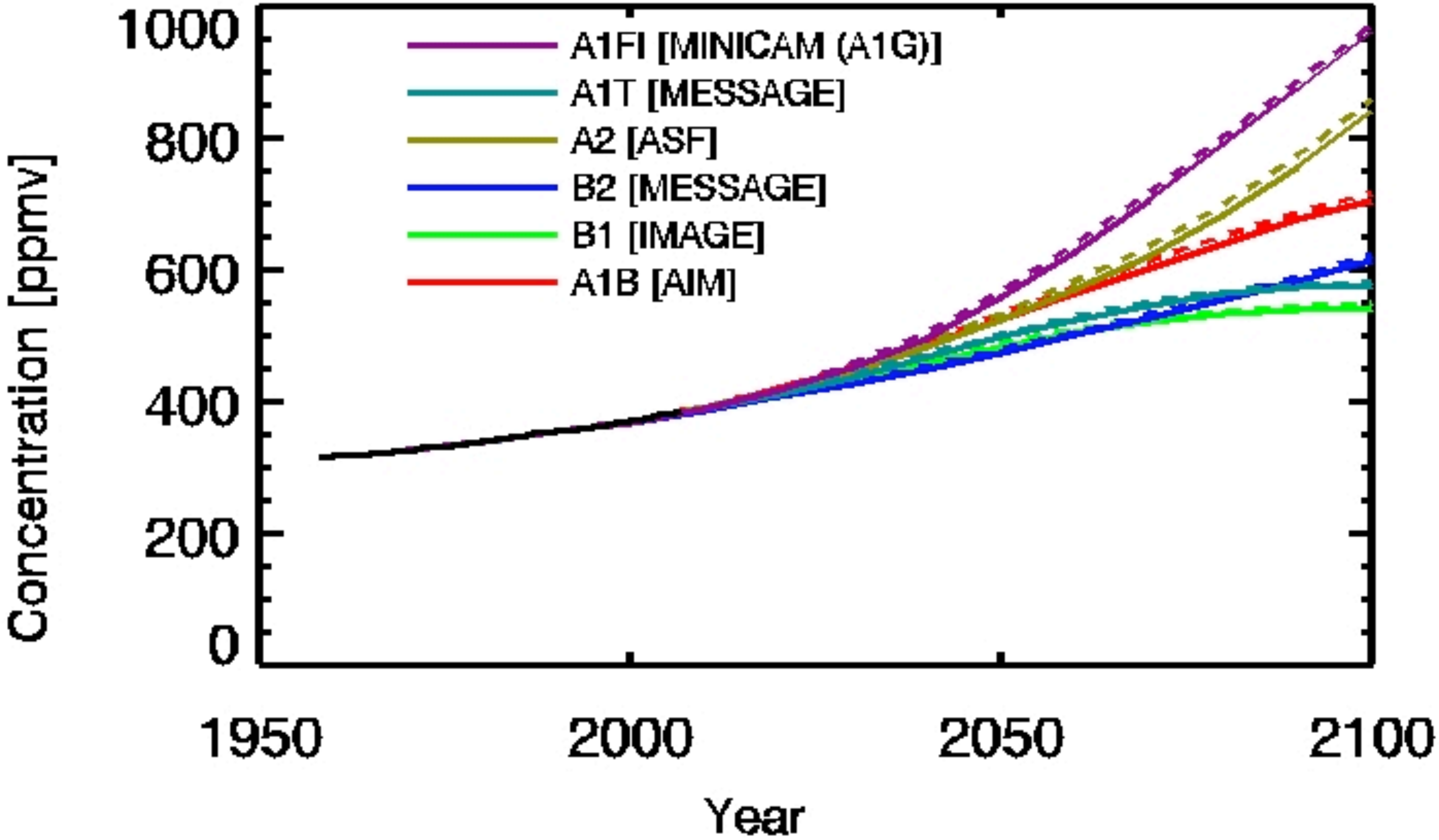
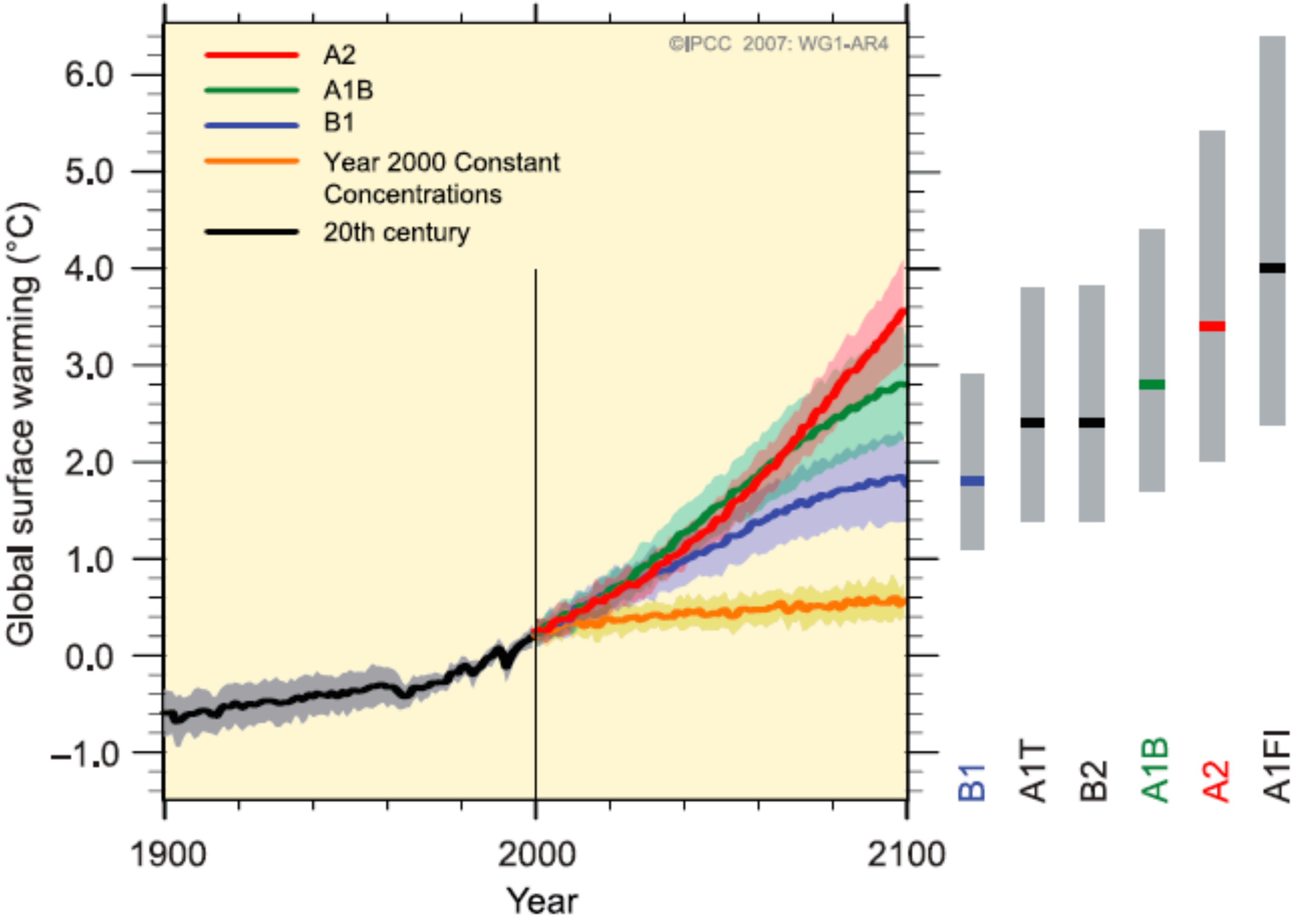


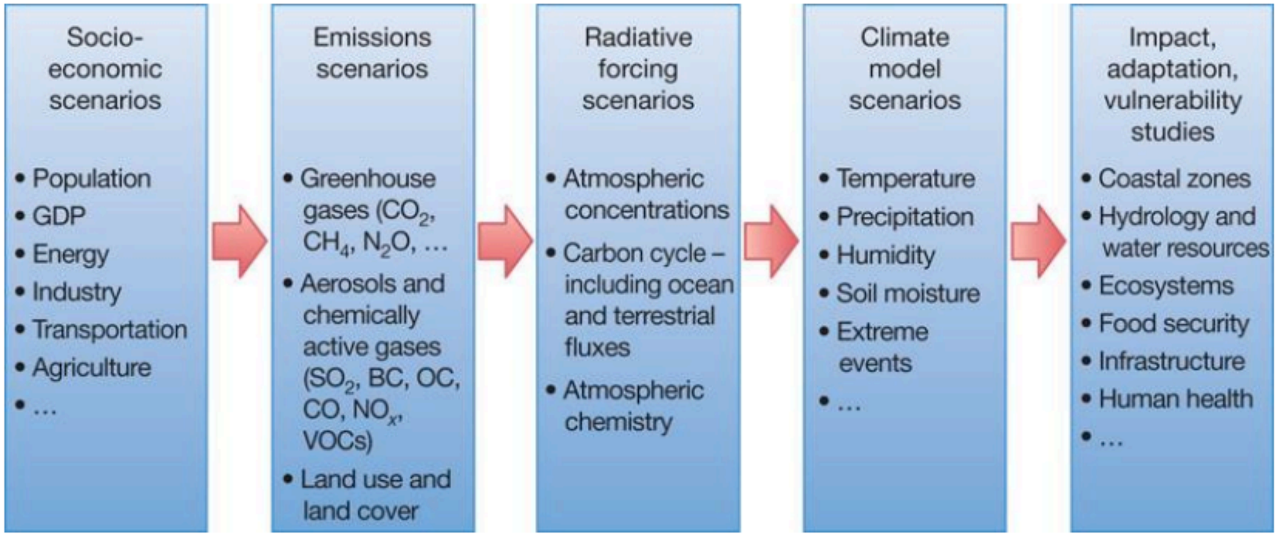
Figure 1: Atmospheric CO2 concentrations as observed at Mauna Loa (black line) and projected under the 6 SRES marker and illustrative scenarios. Two carbon cycle models (see Box 3.7 in IPCC, 2001) are used for each scenario: BERN (solid lines) and ISAM (dashed).

MULTI-MODEL AVERAGES AND ASSESSED RANGES FOR SURFACE WARMING



From AR4 to AR5

- Historically IPCC stimulated scenario development by convening authors and modelers, provided terms of reference, approved scenarios through intergovernmental process that took several years



Socio-economic scenarios
- Population
- GDP
- Energy
- Industry
- Transportation
- Agriculture
- …

Emissions scenarios
- Greenhouse gases (CO_2, CH_4, N_2O, …
- Aerosols and chemically active gases (SO_2, BC, OC, CO, NO_x, VOCs)
- Land use and land cover

Radiative forcing scenarios
- Atmospheric concentrations
- Carbon cycle – including ocean and terrestrial fluxes
- Atmospheric chemistry

Climate model scenarios
- Temperature
- Precipitation
- Humidity
- Soil moisture
- Extreme events
- …

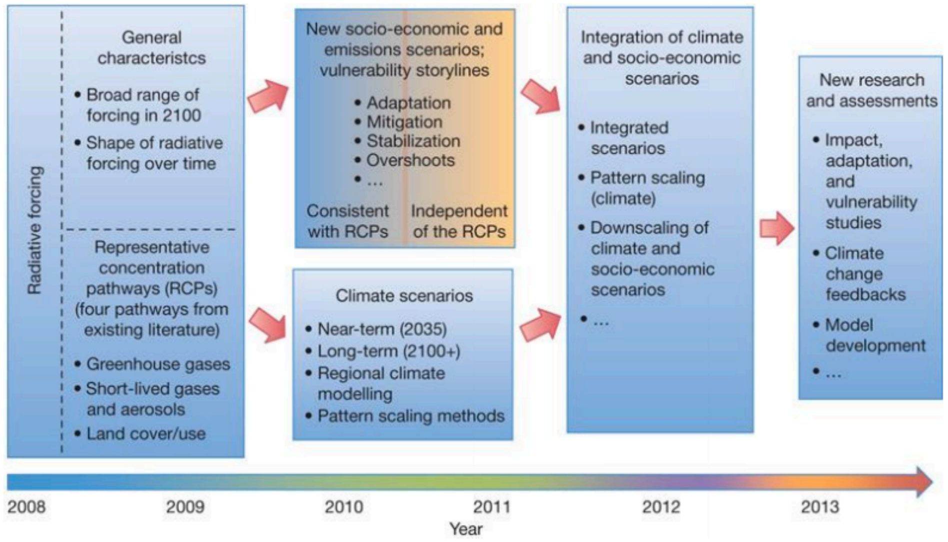
Impact, adaptation, vulnerability studies
- Coastal zones
- Hydrology and water resources
- Ecosystems
- Food security
- Infrastructure
- Human health
- …

(Moss et al., Nature 2010)

- IPCC AR5 is limiting its role to catalyzing and assessing the large and growing scenario literature. Research community is incharge of the scenario development.
- The AR5 will build on the Reference Concentration Pathways (RCP's) which for the first time will include scenarios that explore approaches to climate change mitigation in addition to the traditional 'no climate policy' scenarios

The new scenario process in AR5

New: Parallel process



Radiative forcing

General characteristcs

- Broad range of forcing in 2100
- Shape of radiative forcing over time

Representative concentration pathways (RCPs) (four pathways from existing literature)

- Greenhouse gases
- Short-lived gases and aerosols
- Land cover/use

New socio-economic and emissions scenarios; vulnerability storylines

- Adaptation
- Mitigation
- Stabilization
- Overshoots
- …

Consistent with RCPs

Independent of the RCPs

Climate scenarios

- Near-term (2035)
- Long-term (2100+)
- Regional climate modelling
- Pattern scaling methods

Integration of climate and socio-economic scenarios

- Integrated scenarios
- Pattern scaling (climate)
- Downscaling of climate and socio-economic scenarios
- …

New research and assessments

- Impact, adaptation, and vulnerability studies
- Climate change feedbacks
- Model development
- …

2008 2009 2010 2011 2012 2013

Year

(Moss et al., Nature 2010)

Selection of four Representative Concentration Pathways, RCPs:

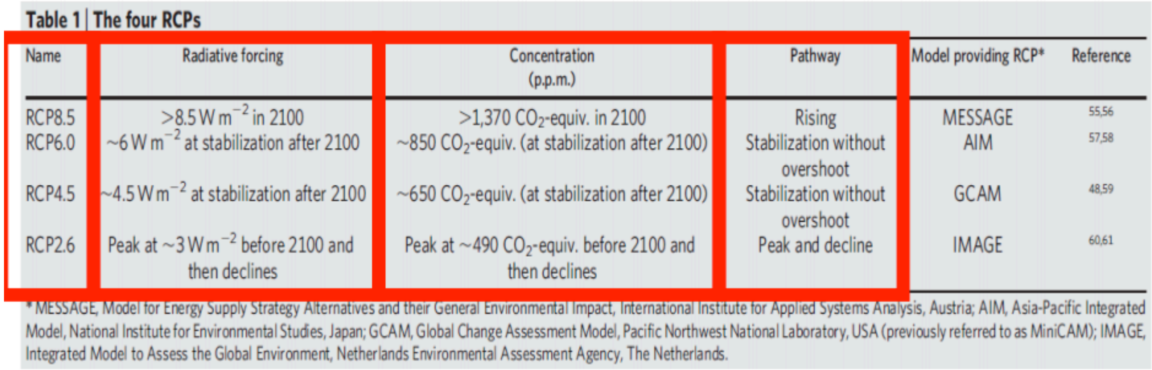


Table 1 | The four RCPs

Name	Radiative forcing	Concentration (p.p.m.)	Pathway	Model providing RCP*	Reference
RCP8.5	>8.5 W m^{-2} in 2100	>1,370 CO_2-equiv. in 2100	Rising	MESSAGE	55,56
RCP6.0	~6 W m^{-2} at stabilization after 2100	~850 CO_2-equiv. (at stabilization after 2100)	Stabilization without overshoot	AIM	57,58
RCP4.5	~4.5 W m^{-2} at stabilization after 2100	~650 CO_2-equiv. (at stabilization after 2100)	Stabilization without overshoot	GCAM	48,59
RCP2.6	Peak at ~3 W m^{-2} before 2100 and then declines	Peak at ~490 CO_2-equiv. before 2100 and then declines	Peak and decline	IMAGE	60,61

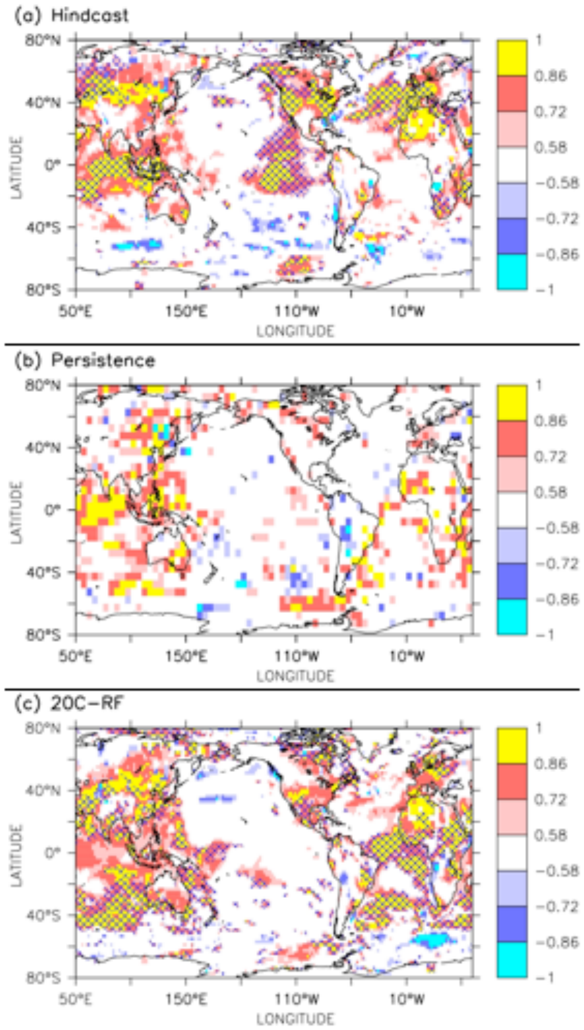
* MESSAGE, Model for Energy Supply Strategy Alternatives and their General Environmental Impact, International Institute for Applied Systems Analysis, Austria; AIM, Asia-Pacific Integrated Model, National Institute for Environmental Studies, Japan; GCAM, Global Change Assessment Model, Pacific Northwest National Laboratory, USA (previously referred to as MiniCAM); IMAGE, Integrated Model to Assess the Global Environment, Netherlands Environmental Assessment Agency, The Netherlands.

(Moss et al., Nature 2010)

All the RCP data is available from: http://www.iiasa.ac.at/

Decadal prediction in AR5

- Decadal prediction is predicated by the fact that it is an initial value problem (initializing the deep ocean temperature, salinity and circulation) can display skill out to 10 years.
- AR5 will employ these Earth System Models for decadal prediction---highly experimental in nature, and the fidelity of these predictions are at this time totally unknown, however the anticipation of its success is high.



Correlation (significant values are hashed) of predicted ten-year surface air-temperature with corresponding observations.

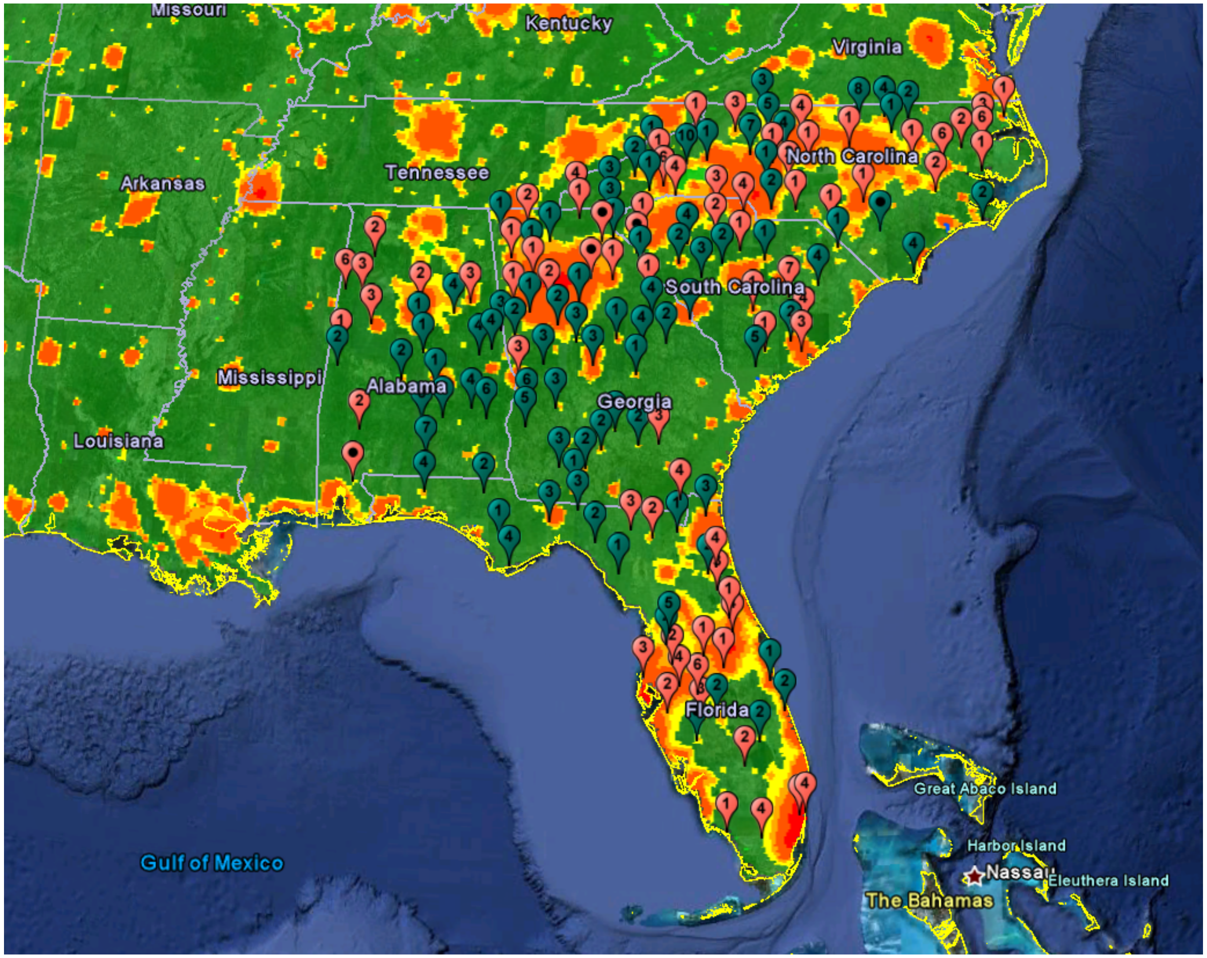
Courtesy N. Keenlyside; Kiel Univ

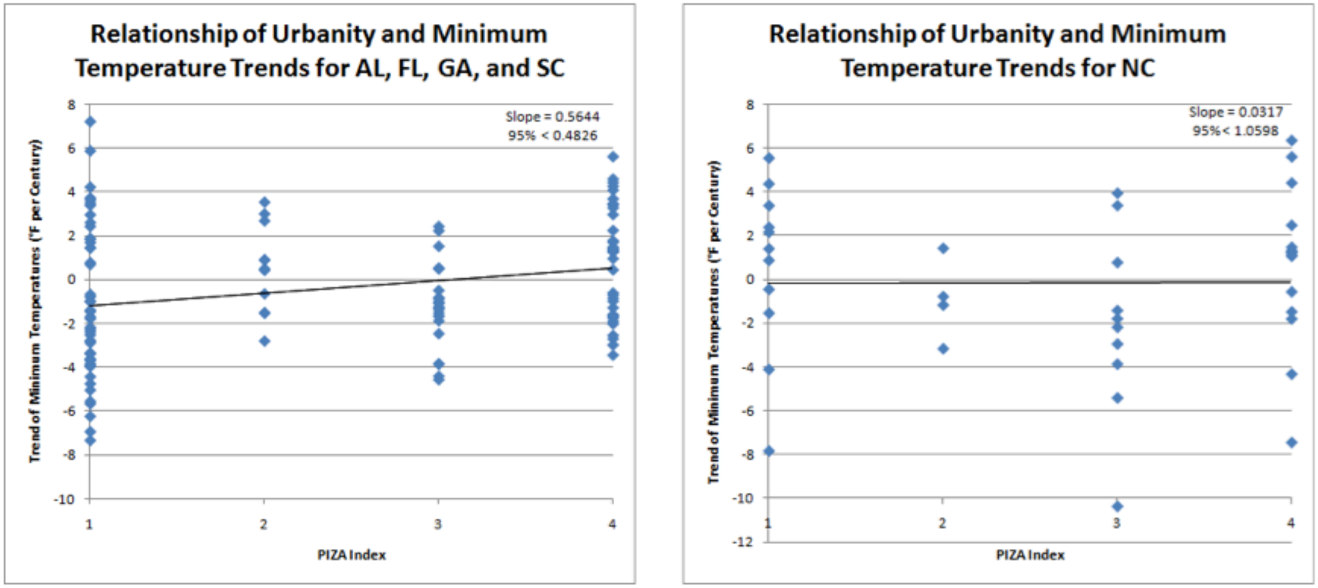
Downscale—Why?

- Regional projections are necessary for planning adaptation/mitigation strategies---they will vary from region to region
- Rising global mean temperatures have some regions cooling while other regions warming at different rates.
- There are benefits to some places to global warming!

T_{Min}/PIZA

(Population Interaction Zones for Agriculture from USDA-Economic Research Service 2005)

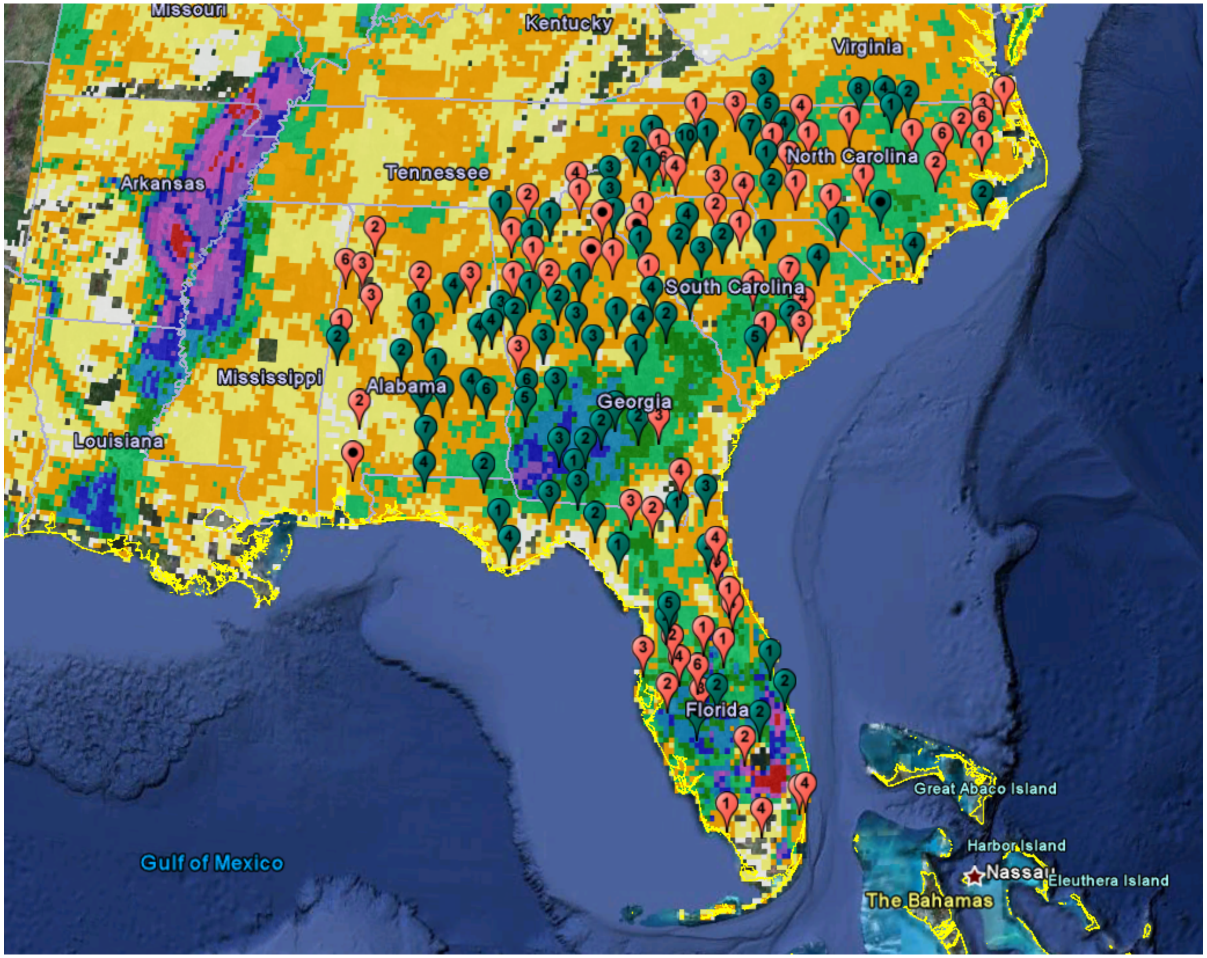




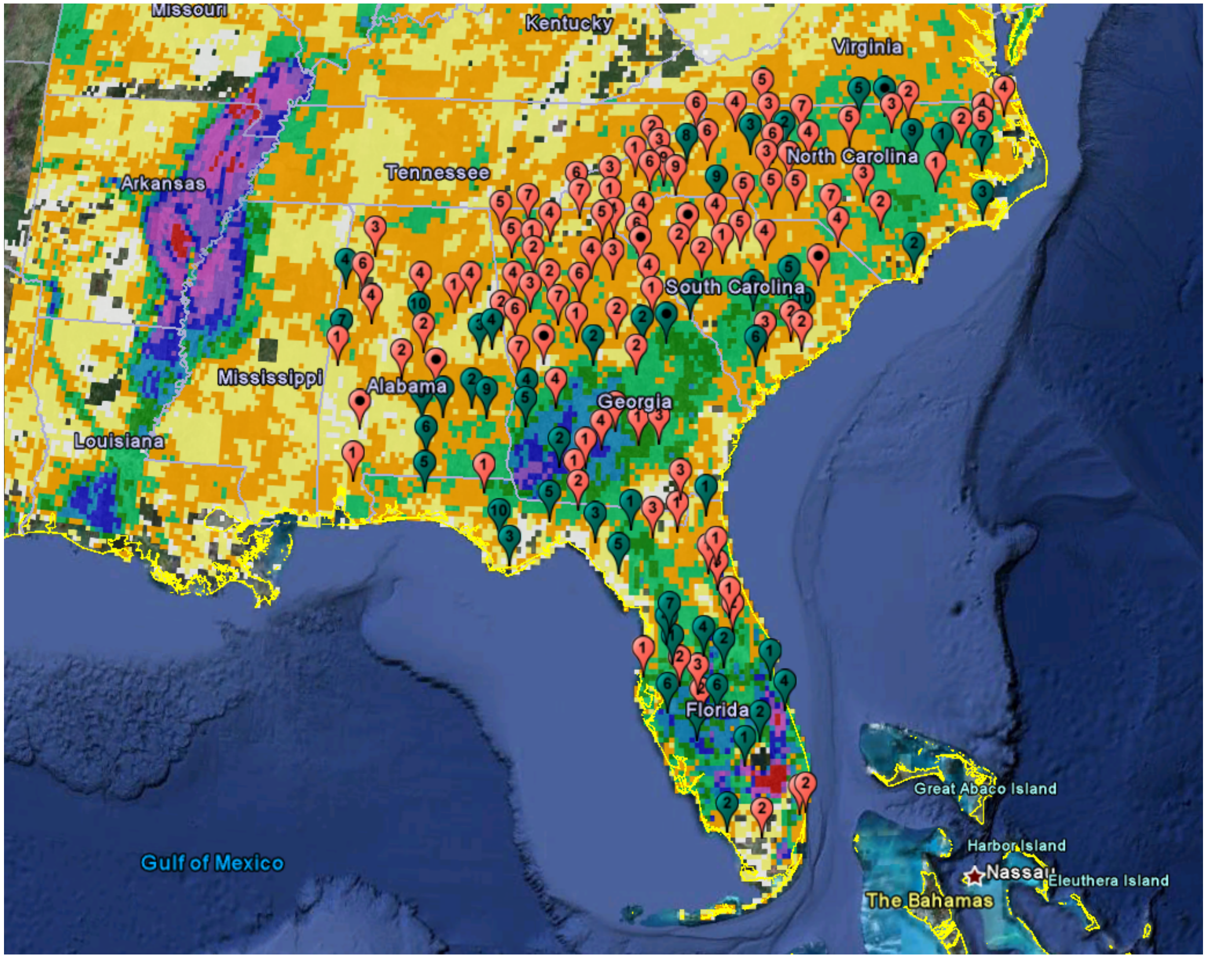
The scatter plot of the linear trends (in ^{0}F/century) of T_{min} over a) Florida, Alabama, Georgia, South Carolina, b) North Carolina with PIZA index. The slope and its 95% confidence level obtained from a Monte Carlo approach is shown on the right top corner.

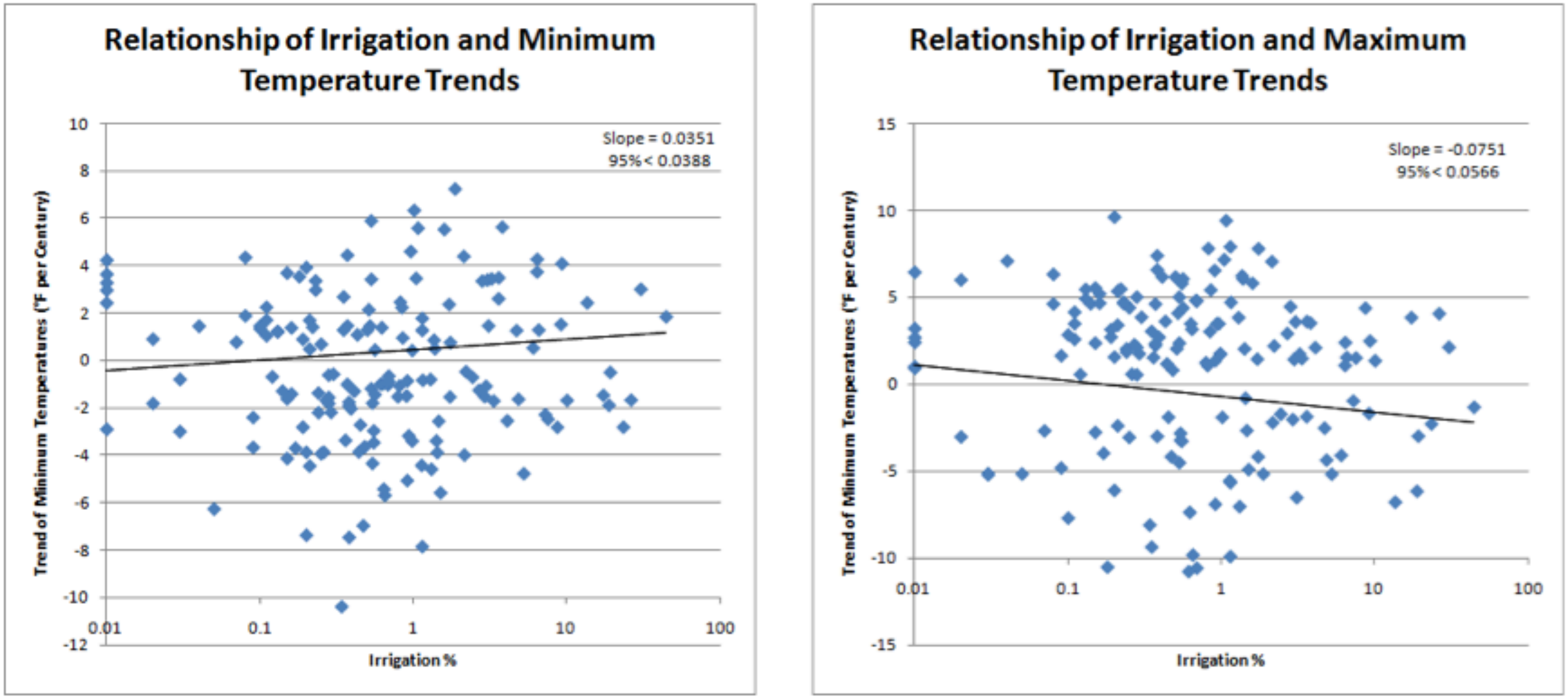
The urban heat island effect: Heat capacity and conductivity of building and paving materials allow for more heat to be absorbed during the day in urban areas than in rural areas. The heat then becomes available at night (when T_{min} is usually observed) to partially compensate for the nocturnal upwelling long-wave radiation loss leading to a rise in T_{min} temperature.

T_{Min}/irrigation
(From UN FAO AQUASTAT global water and agriculture information system)



T_{Max}/irrigation





The scatter plot of the linear trends (in ^{0}F/century) over Florida, Alabama, Georgia, South, and North Carolina of a) T_{min} and b) T_{max} with the irrigation data. The slope and its 95% confidence level obtained from the Monte Carlo approach is shown on the right top corner.

Under light wind conditions at night, with wetter soil having higher heat capacity can lead to higher T_{min} temperature. At daytime irrigation raises evaporation, changing the Bowen ratio and thereby cooling T_{max} temperature.

Downscale—How?

Statistical: Hinges on historical statistical relationships; deduce local variables from large-scale GCM circulations using empirical techniques and calibrating with observations. Pros: cheap, found to be effective in some places for some variables

Cons: Requires stationary time series, changes in observations from change in location/instruments etc can easily jeopardize the methodology

Dynamical (Regional climate model and Variable Resolution Model): Use primitive equations to generate climate at very high resolution for regional domains. Pros: Consistent with known dynamics and physics for atmospheric motion and variability

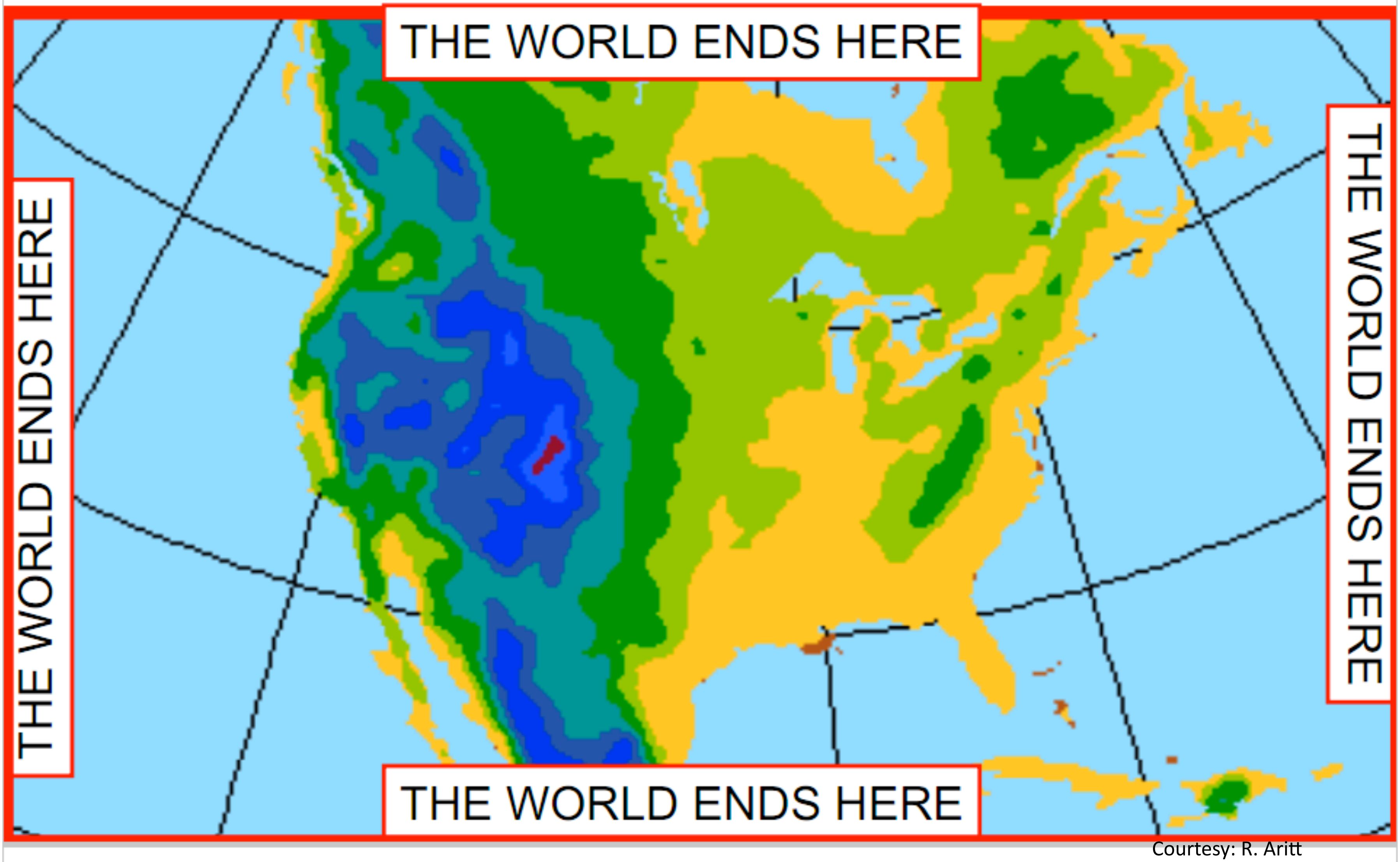
Cons: Expensive, a slave of the coarser model (although variable resolution model can be a resolution to this issue)

Dynamical Downscaling

- Regional models allow use of finer grid spacing than global models.
  - Regional = "not global"
- Benefits of finer grid spacing:
  - Numerical: $\frac{dy}{dx} = \lim_{\Delta x \to 0} \frac{\Delta y}{\Delta x}$
  - Better representation of terrain, coasts, land surface characteristics.
  - Simulate atmospheric structures that are too small even to exist at coarser resolution.
- But: we have a problem…

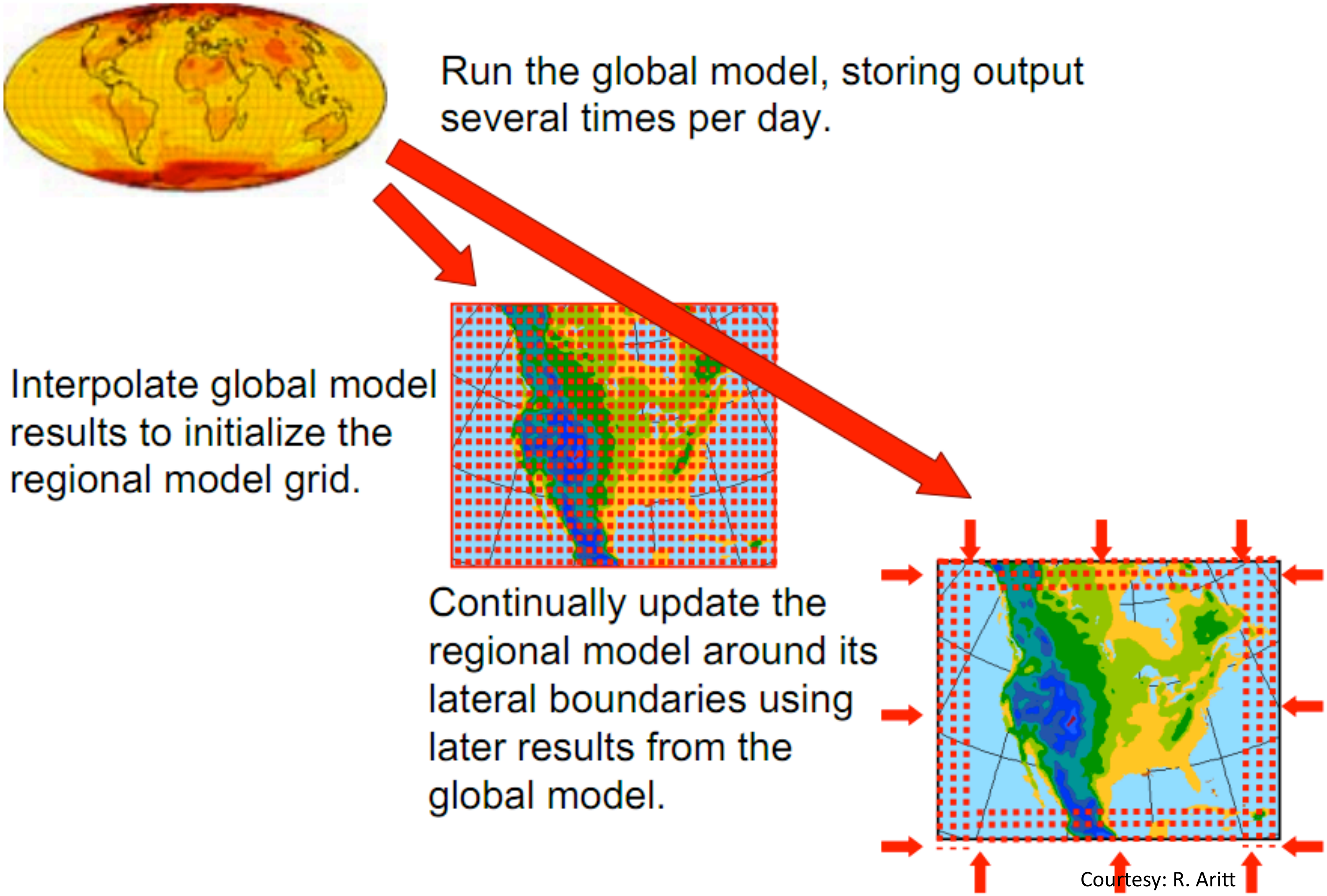
Courtesy R. Aritt

Regional models don't know about the world outside unless we tell them.



Courtesy: R. Aritt

Dynamical Downscaling



Run the global model, storing output several times per day.

Interpolate global model results to initialize the regional model grid.

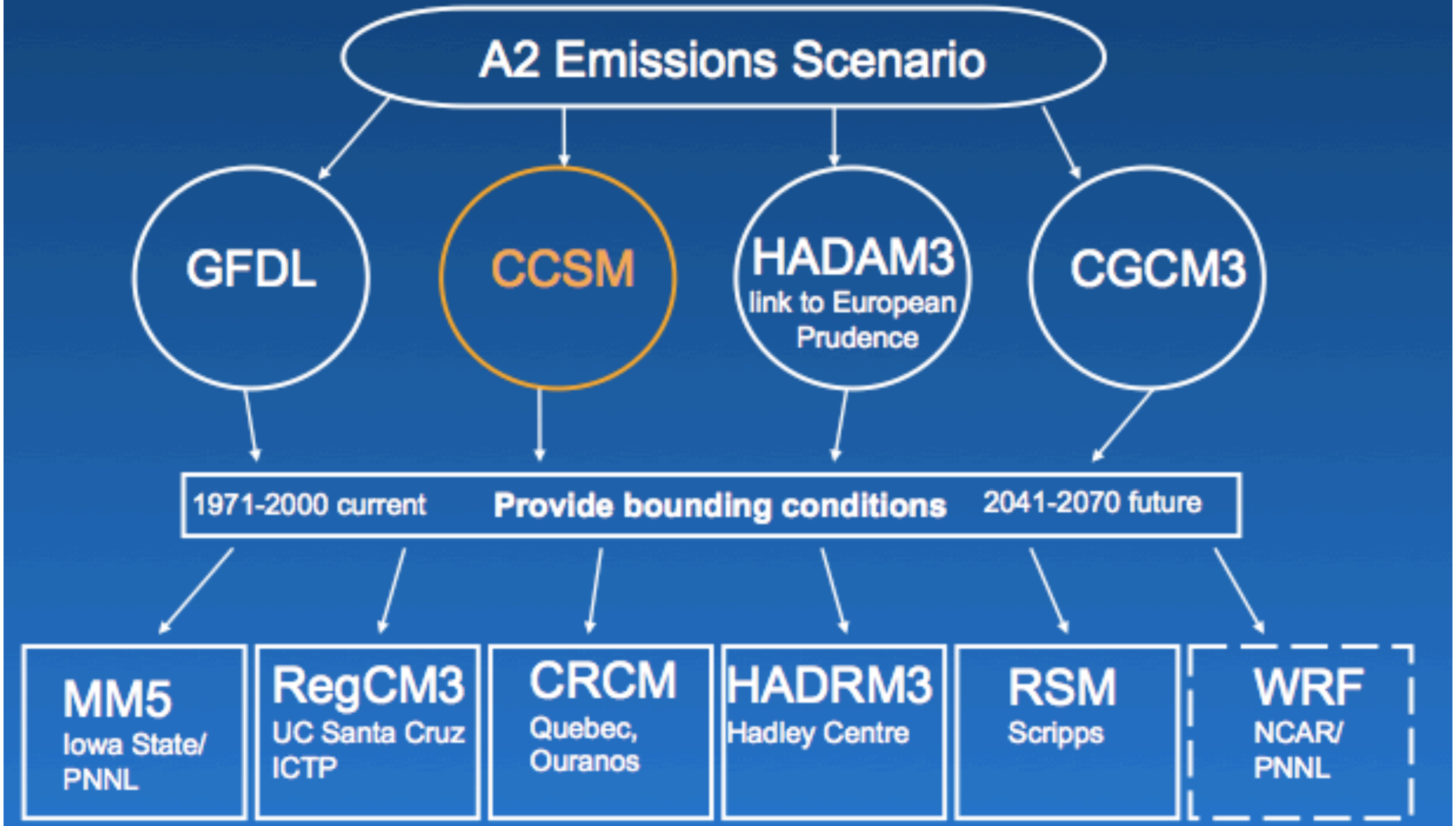
Continually update the regional model around its lateral boundaries using later results from the global model.

Courtesy: R. Aritt

Comparisons between dynamical and statistical methods

- A few studies published
- Sporadic: done over some geographic locations
- Mainly done for simulating/predicting present century climate anomalies:
- Statistical and dynamical methods estimate interannual variability with similar skill
- Significant scope for improvement in future
- Climate change feedbacks are not always captured by statistical methods
- Models fail to reproduce some observed predictor/ predictand relationships

NARCCAP PLAN



A2 Emissions Scenario

GFDL

CCSM

HADAM3
link to European Prudence

CGCM3

1971-2000 current **Provide bounding conditions** 2041-2070 future

MM5
Iowa State/
PNNL

RegCM3
UC Santa Cruz
ICTP

CRCM
Quebec,
Ouranos

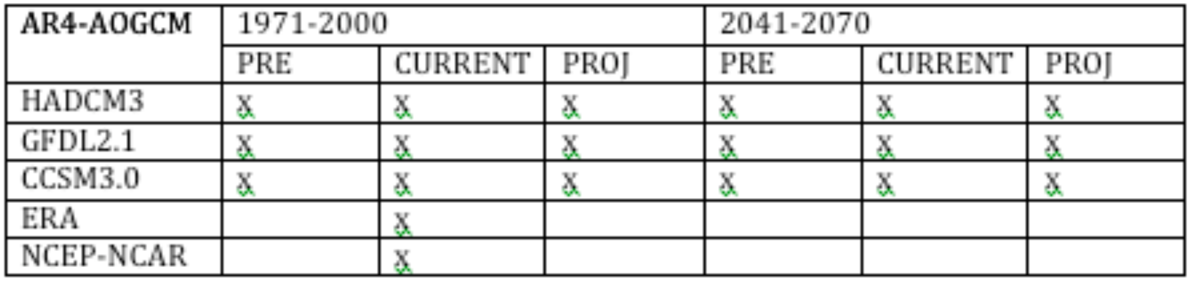
HADRM3
Hadley Centre

RSM
Scripps

WRF
NCAR/
PNNL

Proposed Experiments

- Period: 1971-2000 & 2041-2070 (A2 scenario)
- 3 AOGCMs: HADCM3, CCSM3.0, GFLD2.1
- 2 Reanalysis: ERA & NCEP-NCAR
- LCLUC: pre-industrial, industrial, & projected



AR4-AOGCM	1971-2000			2041-2070		
	PRE	CURRENT	PROJ	PRE	CURRENT	PROJ
HADCM3	X	X	X	X	X	X
GFDL2.1	X	X	X	X	X	X
CCSM3.0	X	X	X	X	X	X
ERA		X				
NCEP-NCAR		X				

Questions we are trying to seek answers for:

- What is the uncertainty of changing climate over Florida that we are dealing with?
- What are the possible sources of this uncertainty?—what is the potential role of land cover and land use change?
- What are the mechanisms/features (e.g. seabreeze, modulation of seasonal cycle [length of the season]) by which local climate will change based on forced large-scale changes?