Climate and weather forecasting:
Issues and prospects for prediction of climate on multiple time scales

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Some slides borrowed from others: esp Bill Collins

The Earth

Take a large almost round rotating sphere 8,000 miles in diameter.

Surround it with a murky, viscous atmosphere of many gases mixed with water vapor.

Tilt its axis so that it wobbles back and forth with respect to the source of heat and light.

Freeze it at both ends and roast it in the middle.

Cover most of the surface with a flowing liquid that sometimes freezes and which constantly feeds vapor into that atmosphere as the sphere tosses billions of gallons up and down to the rhythmic pulling of the moon and the sun.

Condense and freeze some of the vapor into clouds of imaginative shapes, sizes and composition.

Then try to predict the future conditions of that atmosphere for each place over the globe.

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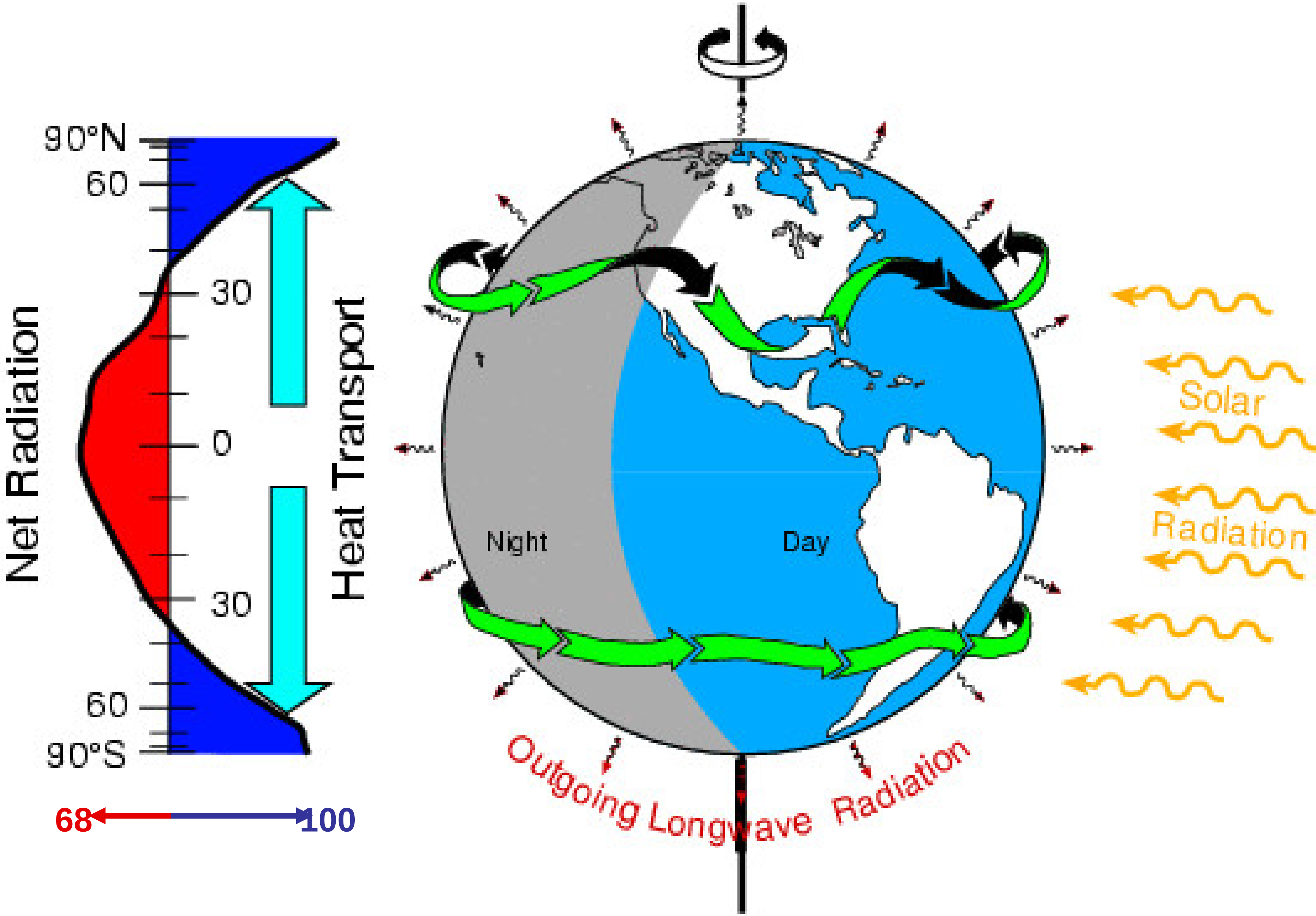
Energy on Earth



Energy on Earth

The incoming radiant energy is transformed into various forms (internal heat, potential energy, latent energy, and kinetic energy) moved around in various ways primarily by the atmosphere and oceans, stored and sequestered in the ocean, land, and ice components of the climate system, and ultimately radiated back to space as infrared radiation.

An equilibrium climate mandates a balance between the incoming and outgoing radiation and that the flows of energy are systematic. These drive the weather systems in the atmosphere, currents in the ocean, and fundamentally determine the climate. And they can be perturbed, with climate change.

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The role of the climate system

Atmosphere: Volatile turbulent fluid, strong winds,
Chaotic weather, clouds, water vapor feedback
Transports heat, moisture, materials etc.
Heat capacity equivalent to 3.4 m of ocean

Ocean: 70% of Earth, wet, fluid, high heat capacity
Stores, moves heat, fresh water, gases, chemicals
Adds delay of 10 to 100 years to response time

Land: Small heat capacity, small mass involved (conduction)
Water storage varies: affects sensible vs latent fluxes
Wide variety of features, slopes, vegetation, soils
Mixture of natural and managed
Vital in carbon and water cycles, ecosystems

Ice: Huge heat capacity, long time scales (conduction)
High albedo: ice-albedo feedback
Fresh water, changes sea level

Antarctica 65 m (WAIS 4-6m), Greenland 7m, other glaciers 0.35m

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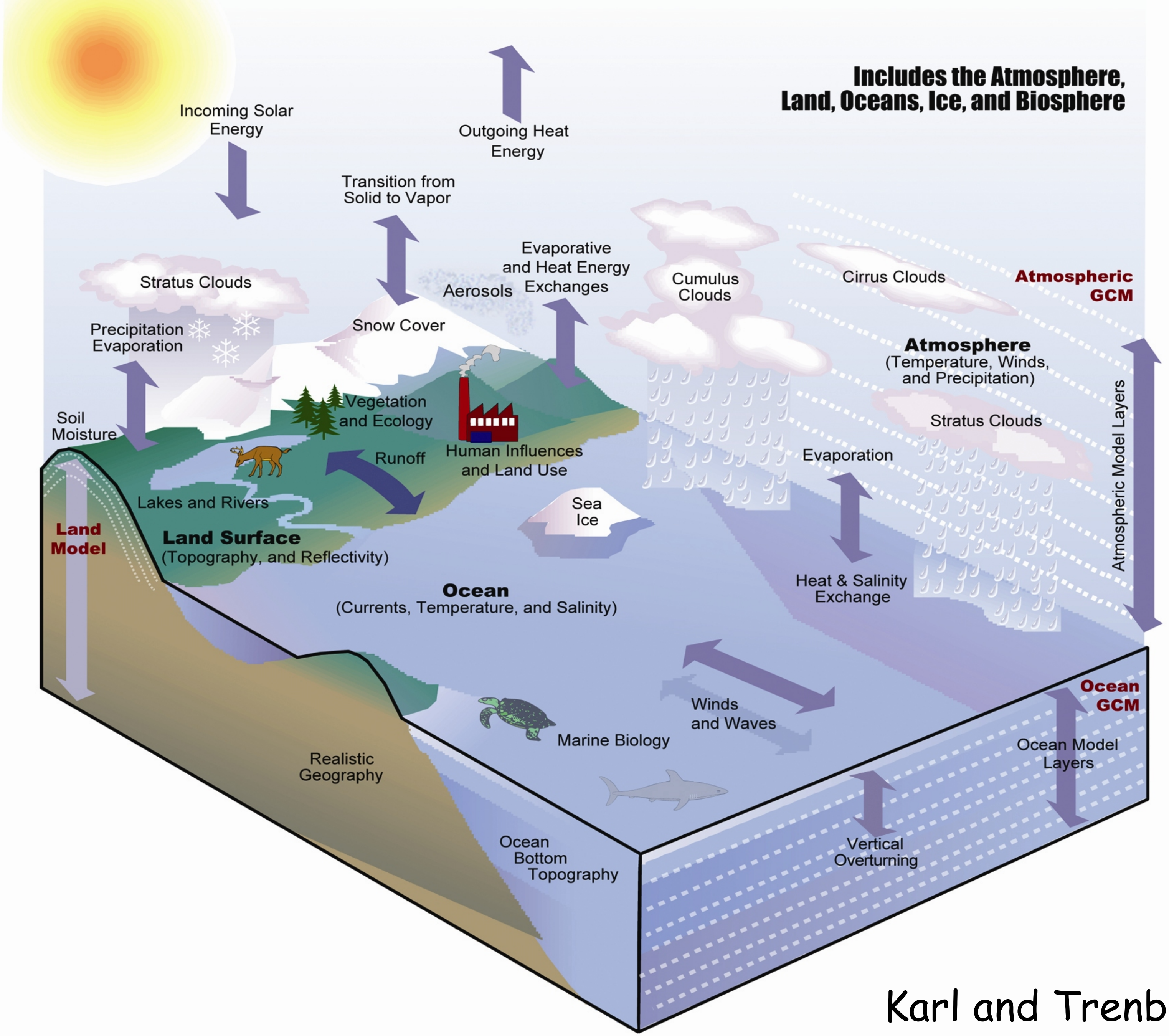
Modeling the Climate System



Karl and Trenberth 2003

Weather and Climate Prediction
is based on solution of the governing physical laws expressed as basic equations:

- Basic gas laws
- Newton's Laws of motion   F = ma: dynamics in 3D
- Conservation of energy: thermodynamics
- Conservation of mass: dry air components, moisture, other species (plus sources and sinks)

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Governing laws: e.g. for the Atmosphere

- ***Momentum equations:***

  $d\underline{\mathbf{V}}/dt = -\alpha\nabla p - 2\Omega\wedge\underline{\mathbf{V}} - g\underline{\mathbf{k}} + F + D_m$

  where $\alpha=1/\rho$ (ρ is density), p is pressure, Ω is rotation rate of the Earth, g is acceleration due to gravity (including effects of rotation), $\underline{\mathbf{k}}$ is a unit vertical vector, F is friction and D_m is vertical diffusion of momentum

- ***Thermodynamic equation:***

  $dT/dt = Q/c_p + (RT/p)\omega + D_H$

  where c_p is the specific heat at constant pressure, R is the gas constant, ω is vertical velocity, D_H is the vertical diffusion of heat and $Q = Q_{rad} + Q_{con}$ is internal heating from radiation and condensation/evaporation;

- ***Continuity equations,*** *e.g. for moisture (similar for other tracers):*

  $dq/dt = E - C + D_q$

  where E is the evaporation, C is the condensation and D_q is the vertical diffusion of moisture

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Slingo

Weather prediction

- Weather prediction is a problem of predicting the future evolution of the atmosphere for minutes to days to perhaps 2 weeks ahead.
- It begins with observations of the initial state (and their uncertainties) and analyses into global fields, then use of a model of the atmosphere to predict all of the future evolution of the turbulence and eddies for as long as is possible.
- Because the atmosphere is a chaotic fluid, small initial uncertainties or model errors grow rapidly in time and make deterministic prediction impossible beyond about 2 weeks.

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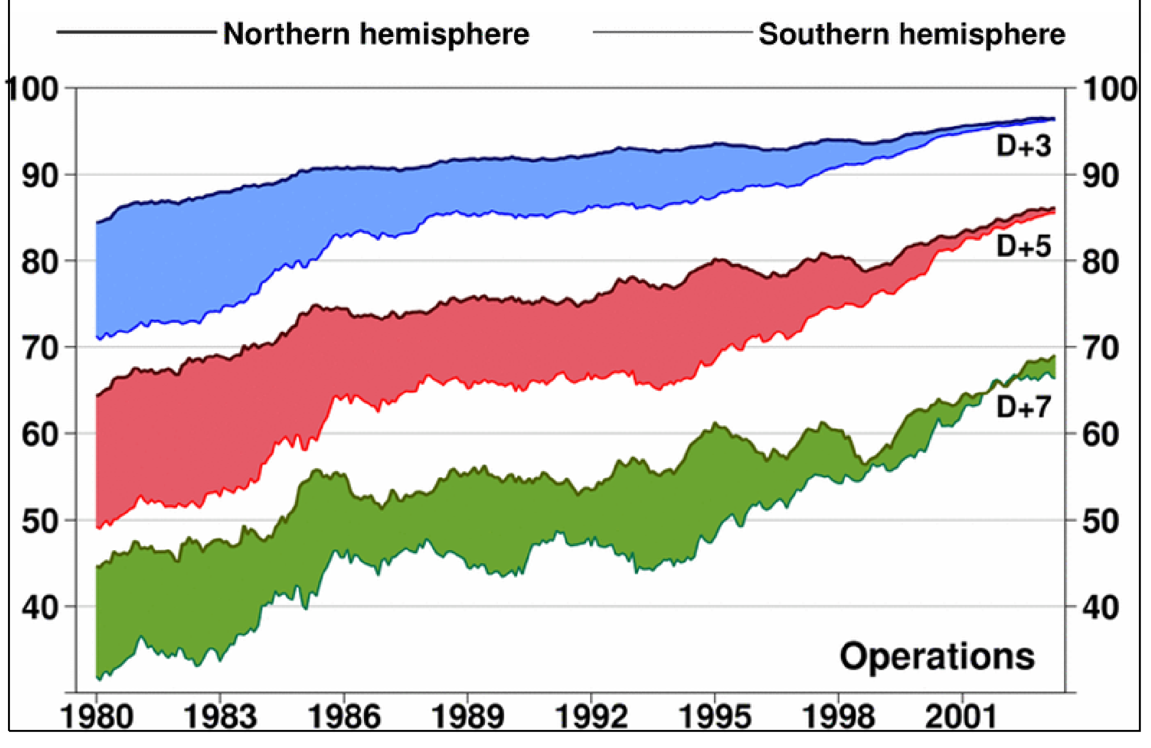
Weather systems: 10 days

This movie was from:

http://www.ssec.wisc.edu/data/comp/latest_cmoll.gif

Forecast skill

Improvement in medium-range forecast skill [Rerun in 2000]



Original forecast

Anomaly correlation of 500 hPa height forecasts

ECMWF

Climate prediction

- Climate prediction is a problem of predicting the patterns or character of weather and the evolution of the entire climate system.
- It is often regarded as a "boundary value" problem. For the atmosphere this means determining the systematic departures from normal from the influences from the other parts of the climate system and external forcings (e.g., the sun).
- The internal components of the climate system have large memory and evolve slowly, providing some predictability on multi-year time scales.
- But because there are many possible weather situations for a given climate, it is inherently probabilistic.
- Human influences are now the main predictable climate forcing.

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Climate prediction

- Models can be run with the same external forcings to the atmosphere but with changes in initial atmospheric state, and ensembles generated to get statistics of the predicted state.
- Averaging over ensembles can also be supplemented by averaging in time, and perhaps averaging in space.
- Ensembles can also be formed using different models (and hence different formulations, especially of parameterizations).

Weather and climate prediction

- As the time-scale of weather is extended, the influence of anomalous boundary forcings grows to become noteworthy on about seasonal timescales.
- The largest signal is El Niño on interannual time scales.
- El Niño involves interactions and coupled evolution of the tropical Pacific ocean and global atmosphere. It is therefore an <u>initial value</u> problem for the ocean and atmosphere.
- In fact all climate prediction involves initial conditions of the climate system, leading to a seamless (in time) prediction problem.

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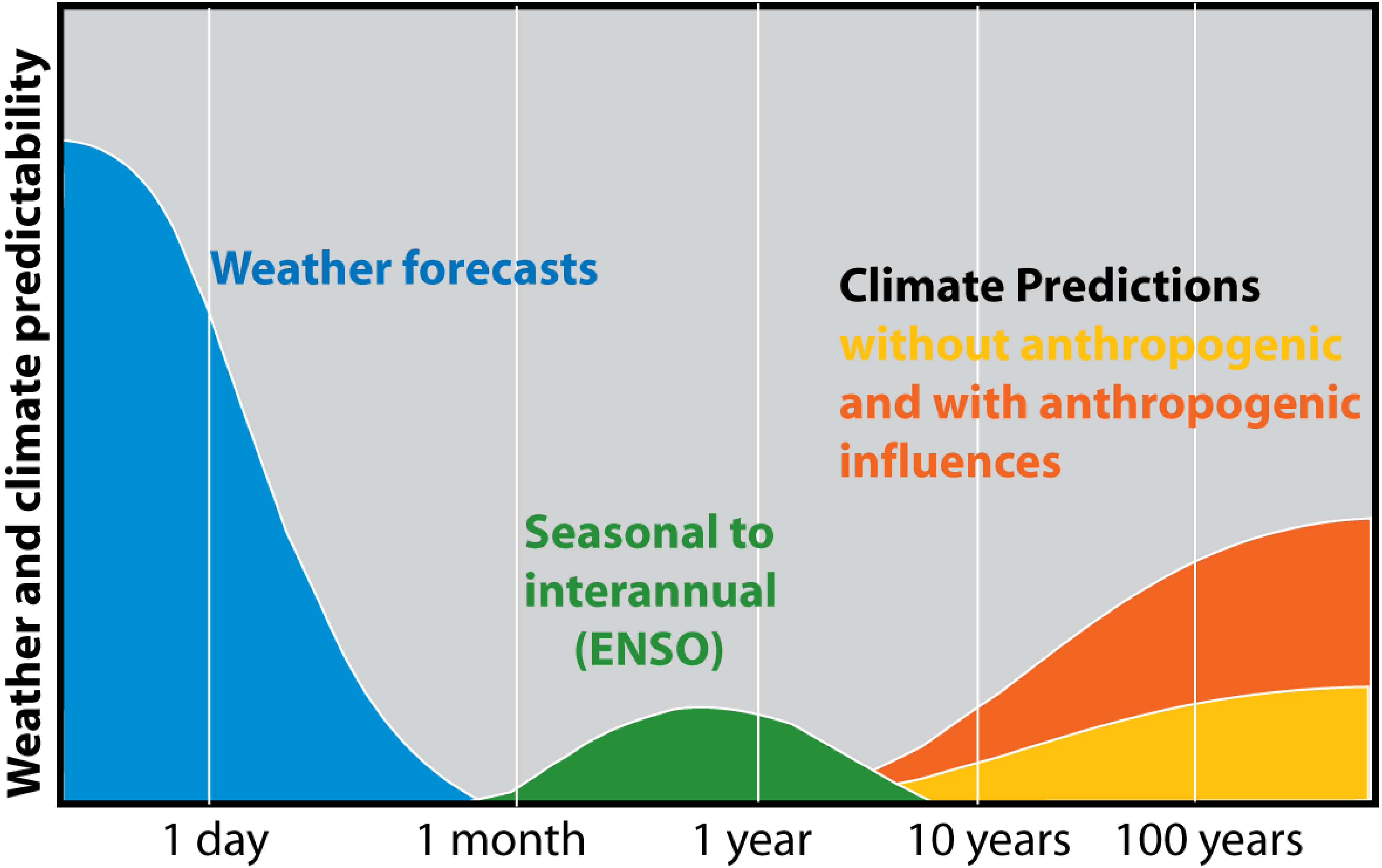
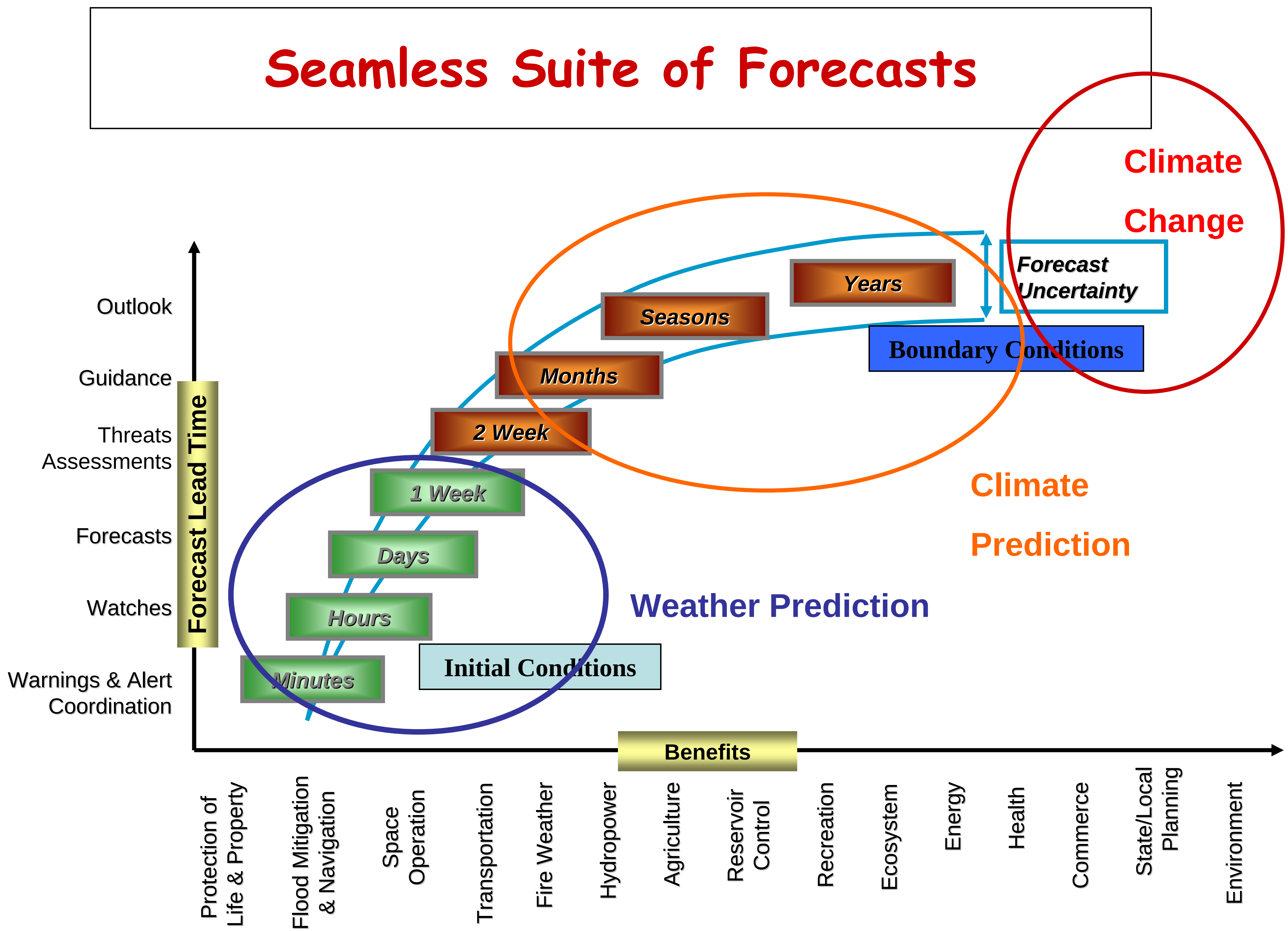
Predictability of weather and climate

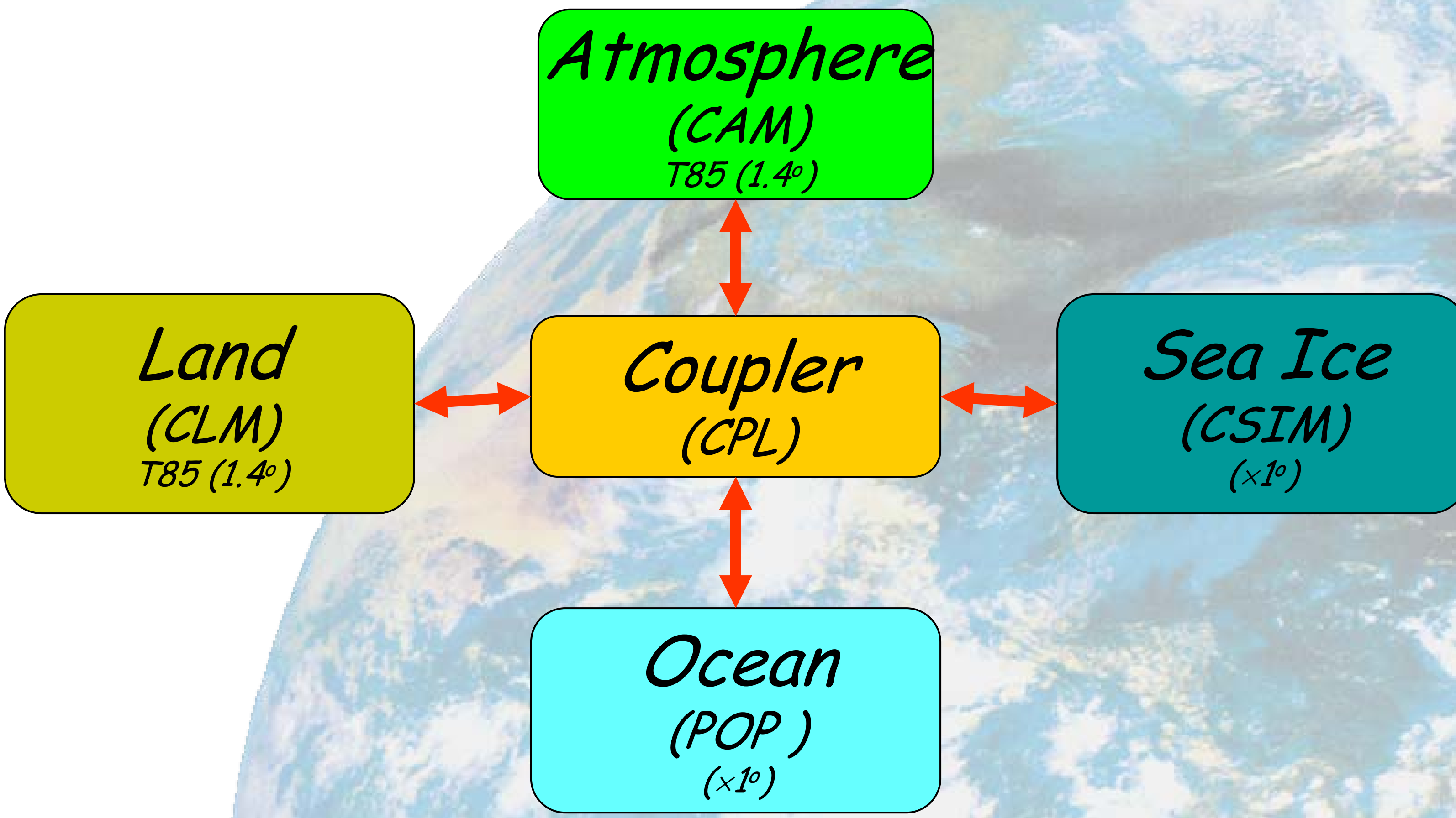




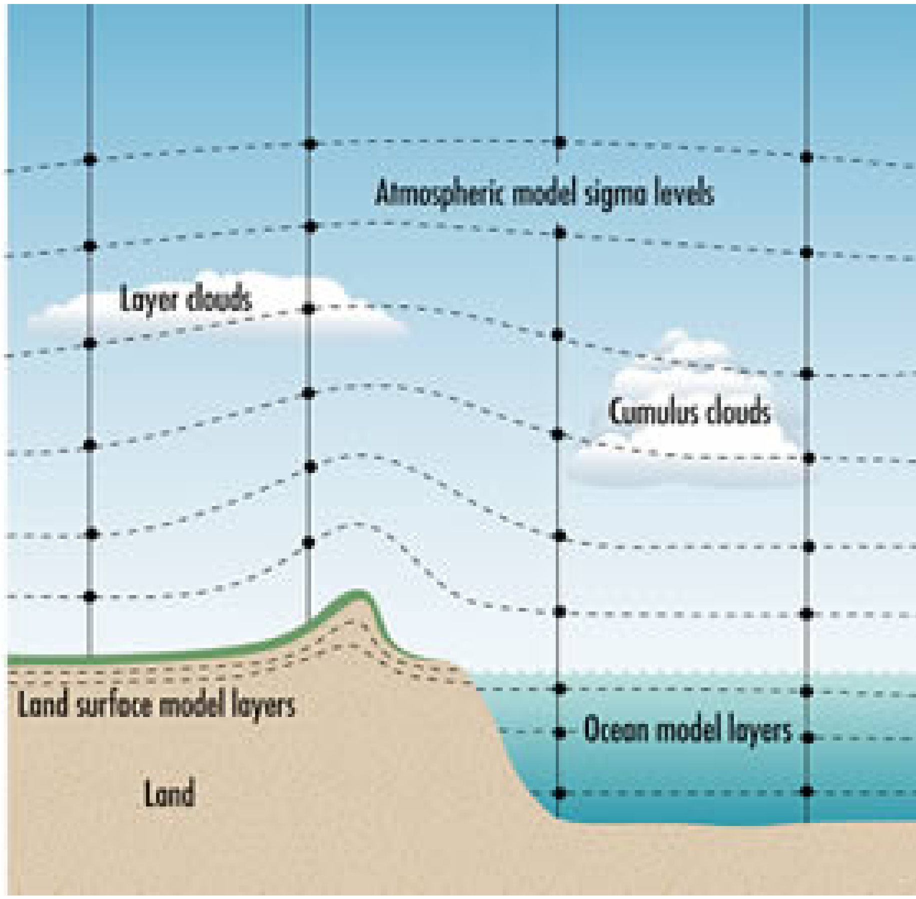
Seamless Suite of Forecasts
Climate Change
Forecast Uncertainty
Years
Seasons
Boundary Conditions
Months
2 Week
1 Week
Days
Hours
Minutes
Initial Conditions
Climate Prediction
Weather Prediction
Forecast Lead Time
Outlook
Guidance
Threats Assessments
Forecasts
Watches
Warnings & Alert Coordination
Benefits
Protection of Life & Property
Flood Mitigation & Navigation
Space Operation
Transportation
Fire Weather
Hydropower
Agriculture
Reservoir Control
Recreation
Ecosystem
Energy
Health
Commerce
State/Local Planning
Environment

Configuration of NCAR CCSM3

(Community Climate System Model)

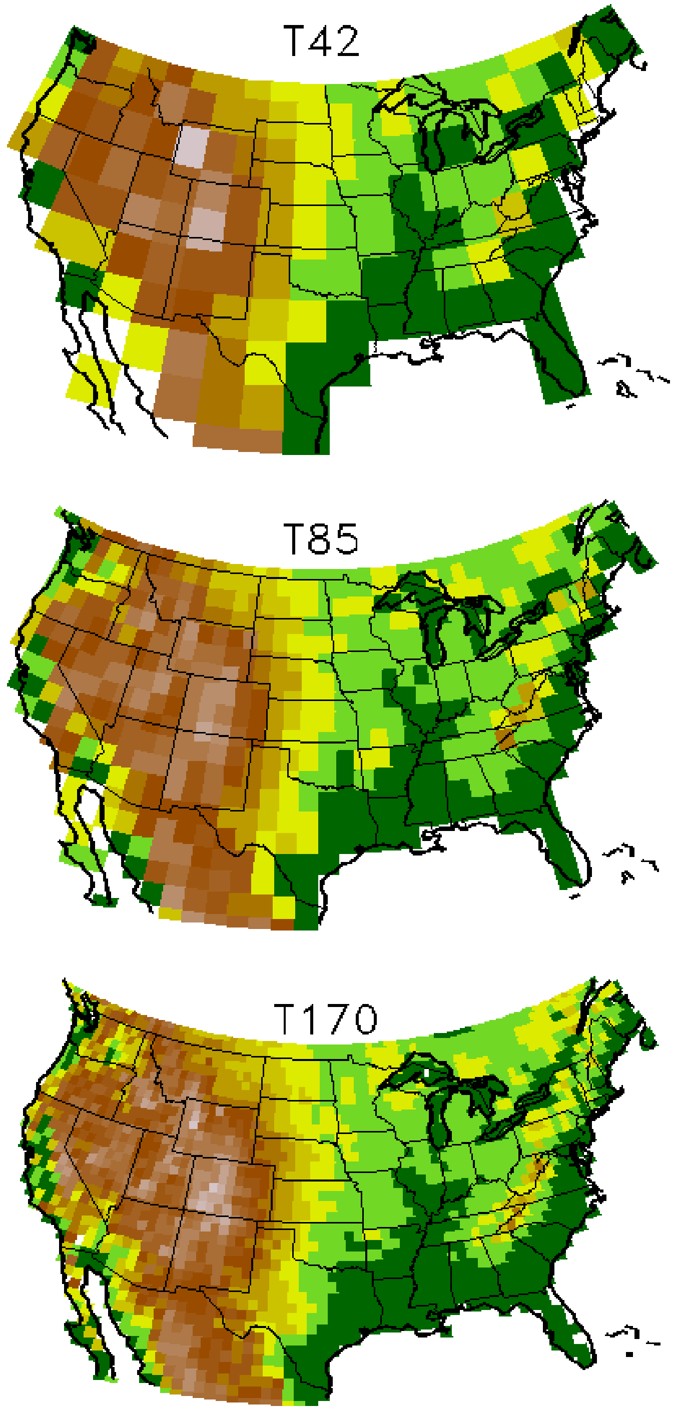


Model discretization



Horizontal Discretization of Equations

The partial differential governing equations are discretized using about 30 to 60 vertical layers and a horizontal grid ranging in size from 2.8° latitude (300 km) (T42 spherical harmonic spectral depiction) to 1/3° latitude (35 km) (T341).



Strand

Billions of variables

At T341 resolution:

There are about 1000x500 points x60 levels

For about 10 variables for the atmosphere

= 300,000,000 independent predictors

Which step forward in time on about 5 minute intervals.

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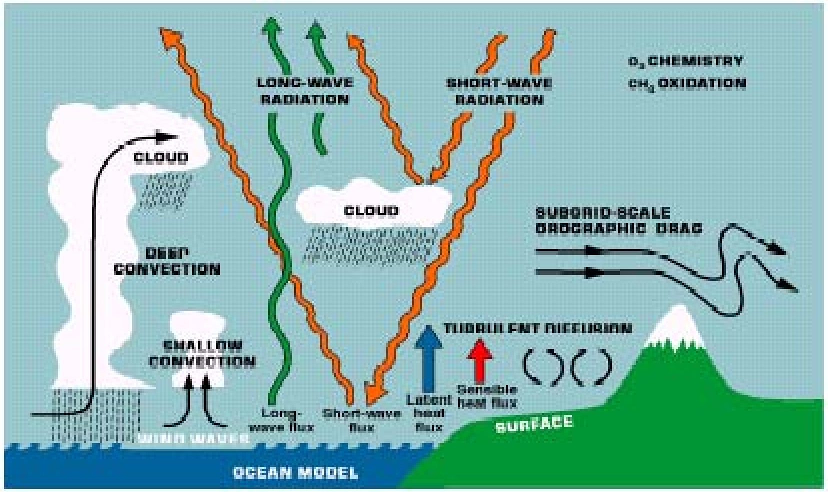
Physical Parameterizations

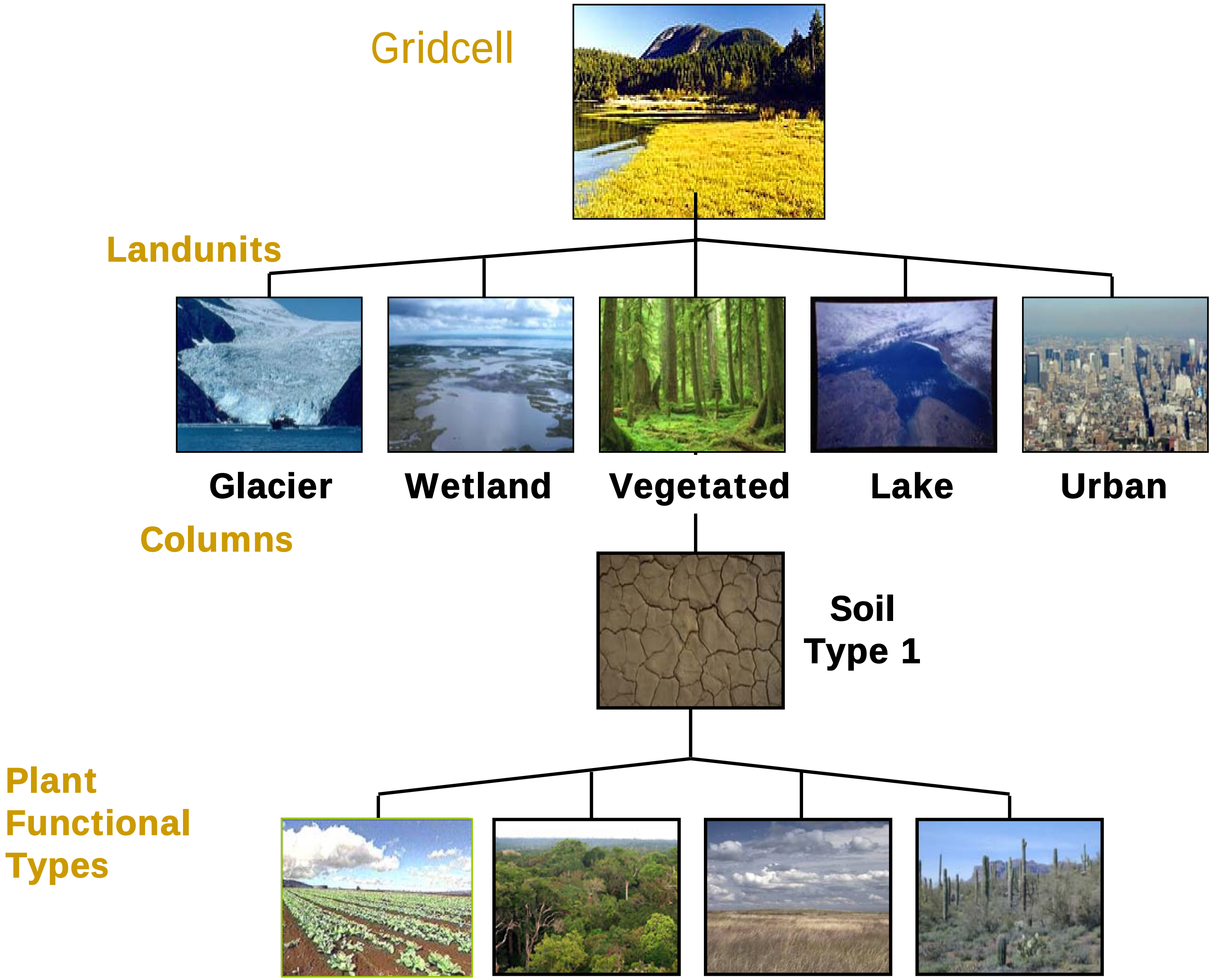
Processes not explicitly represented by the basic dynamical and thermodynamic variables in the equations (dynamics, continuity, thermodynamic, equation of state) on the grid of the model **need to be included by *parameterizations*** (3 kinds).

1. **Processes on smaller scales** than the grid not explicitly represented by the resolved motion;
   - Convection, boundary layer friction and turbulence, gravity wave drag
   - All involve the vertical transport of momentum and most also involve the transport of heat, water substance and tracers (e.g. chemicals, aerosols)
2. **Processes that contribute to internal heating**
   - Radiative transfer and precipitation
   - Both require cloud prediction
3. **Processes not included**
   - (e.g. land surface processes,
   - carbon cycle,
   - chemistry, aerosols, etc)



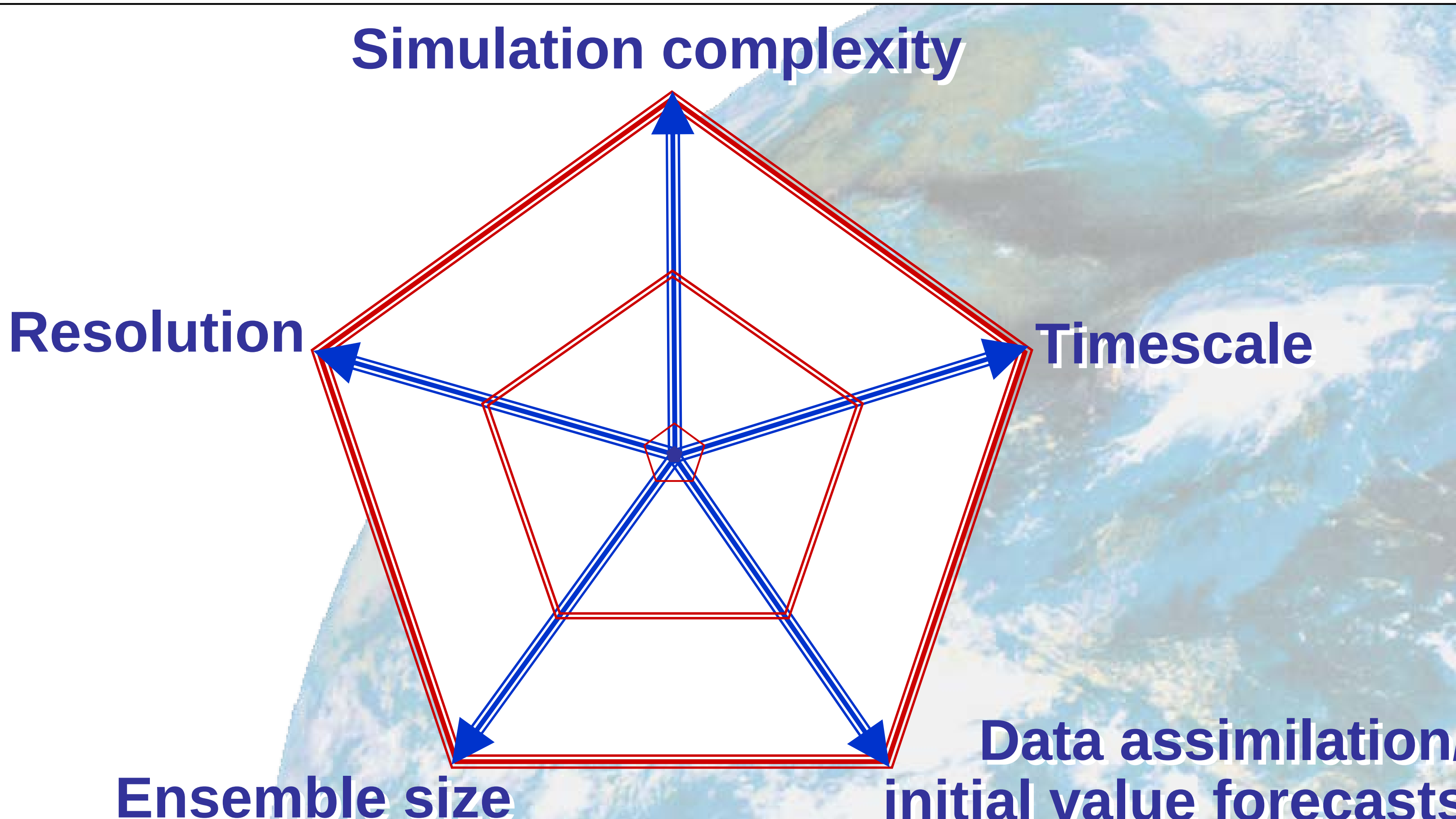
Slingo

Subgrid Structure of the Land Model



5 Dimensions of Climate Prediction

(Tim Palmer, ECMWF)



All require much greater computer resource and more efficient modeling infrastructures

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Progress in NWP and climate modeling

There have been no *revolutionary* changes in weather and climate model design since the 1970s.

- Same dynamical equations, with improved numerical methods
- Comparable resolution
- Similar parameterizations
- A modest extension of the included processes

And the models are somewhat better.

Meanwhile, computing power is up by a factor of a million.

- Model resolution has increased.
  - Horizontal resolution has quadrupled (at most).
  - The number of layers has tripled.
- More processes have been introduced.
- Parameterizations have become a little more elaborate.

Factor of 1000

- Longer runs
- More runs: ensembles

Factor of 1000

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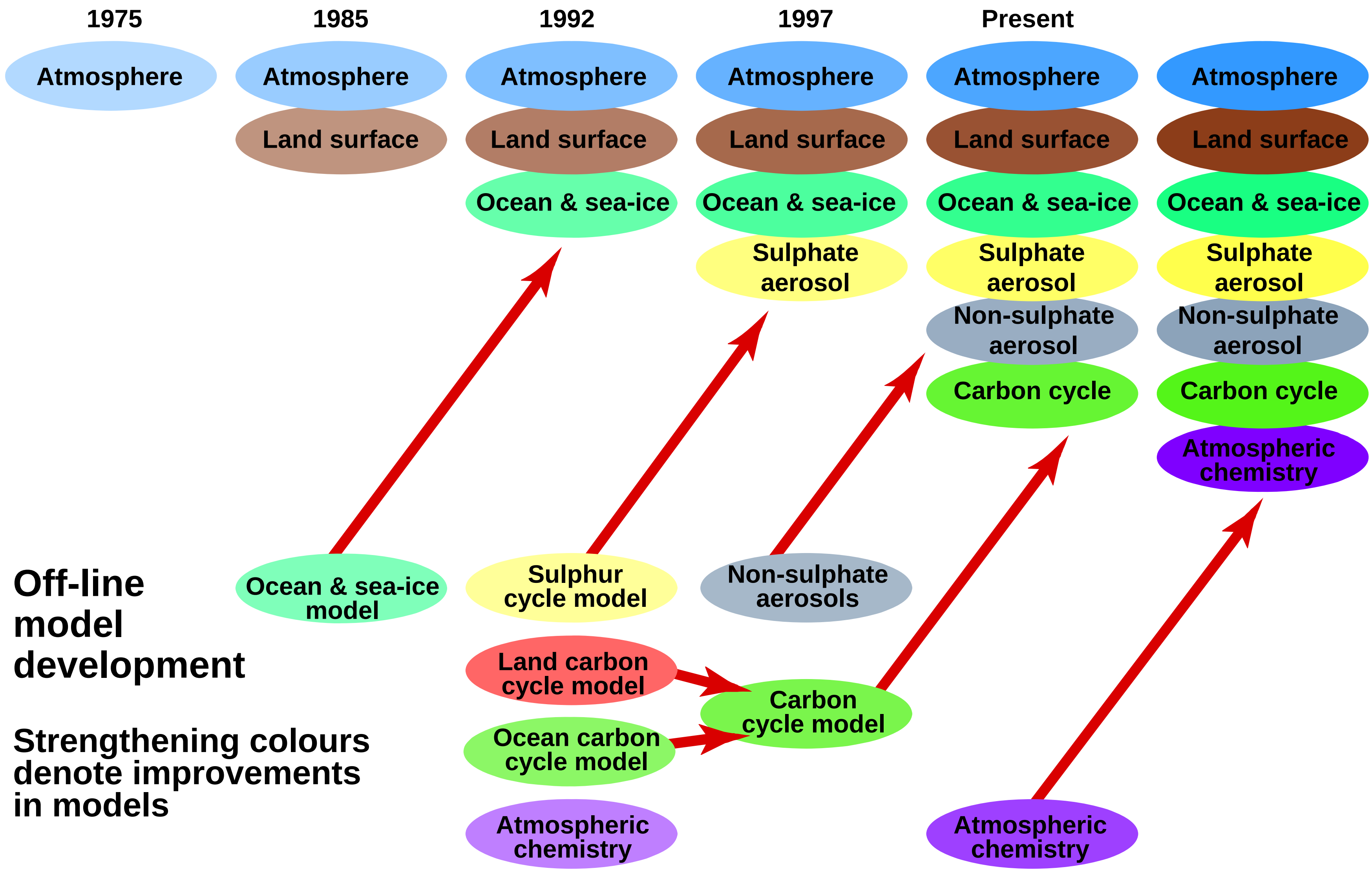
Adapted from D. Randall (CSU)

Towards Comprehensive Earth System Models
Past present and future



"Products" of Global Climate Models

- **Description of the physical climate:**
  - Temperature
  - Water in solid, liquid, and vapor form
  - Pressure
  - Motion fields (winds)

- **Description of the chemical climate:**
  - Distribution of aerosols
  - Evolution of carbon dioxide and other GHGs
  - Coming soon: chemical state of surface air

- **Space and time resolution (CCSM3):**
  - 1.3 degree atmosphere/land, 1 degree ocean/ice
  - Time scales: hours to centuries

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CCSM simulation

Animations from CCSM CAM3 at T341 (0.35° global grid) with observed SST and sea ice (1997) distributions. The land surface is fully interactive. The animations illustrate fine-scale transient variability in the deep tropics that is not seen in lower resolution configurations of the atmospheric model (e.g., typhoons).

Courtesy James J. Hack, Julie M. Caron, and John E. Truesdale

1) Outgoing longwave radiation at top of atmosphere, which illustrates high clouds for January
2) Column integrated water vapor plus precipitation, Jan to June

The links to the two movies have been removed, as they are large in volume:

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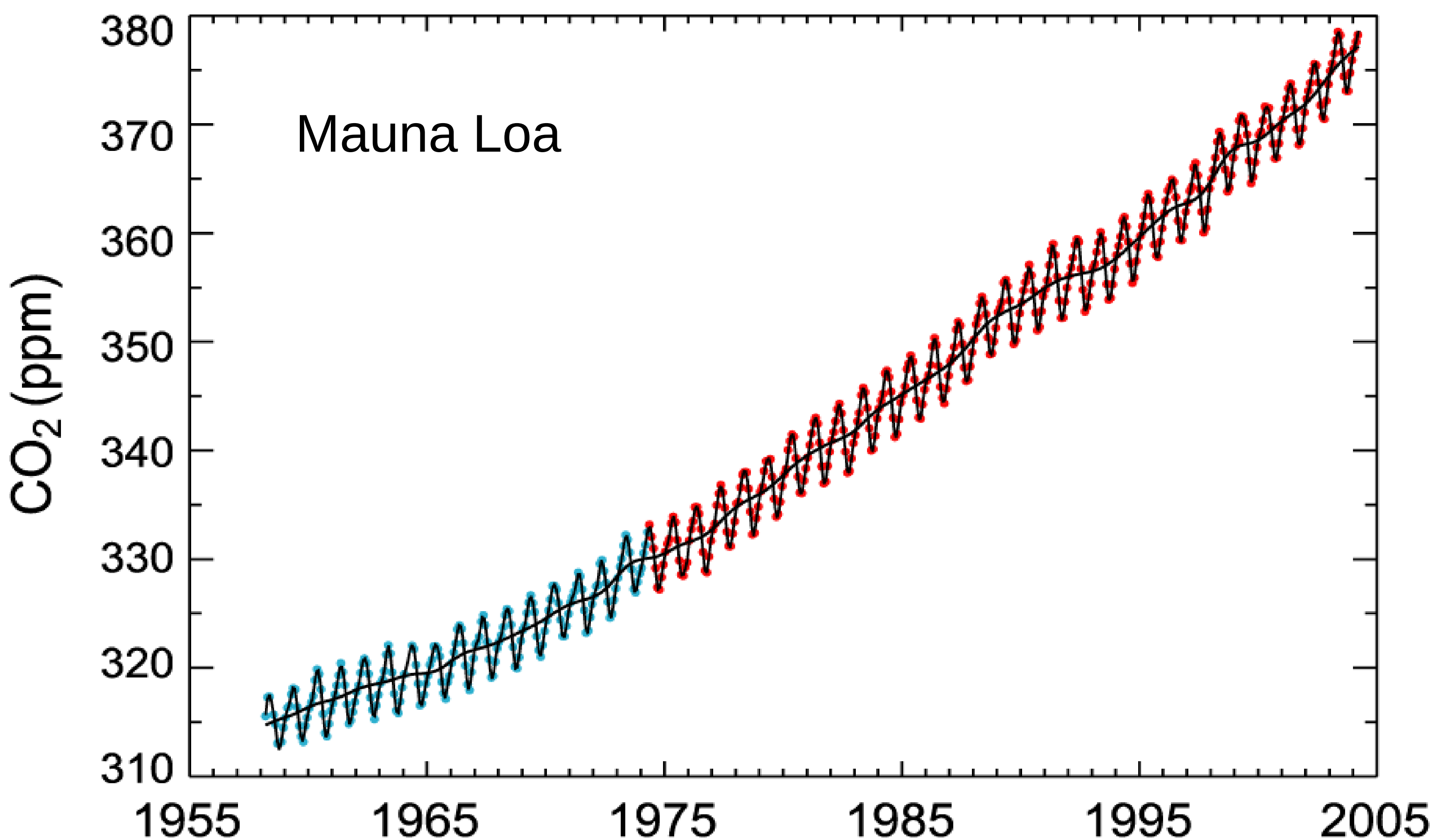
Global warming is happening!

Anthropogenic Climate Change



Carbon dioxide data from NOAA.
Data prior to 1973 from C. Keeling, Scripps Inst. Oceanogr.

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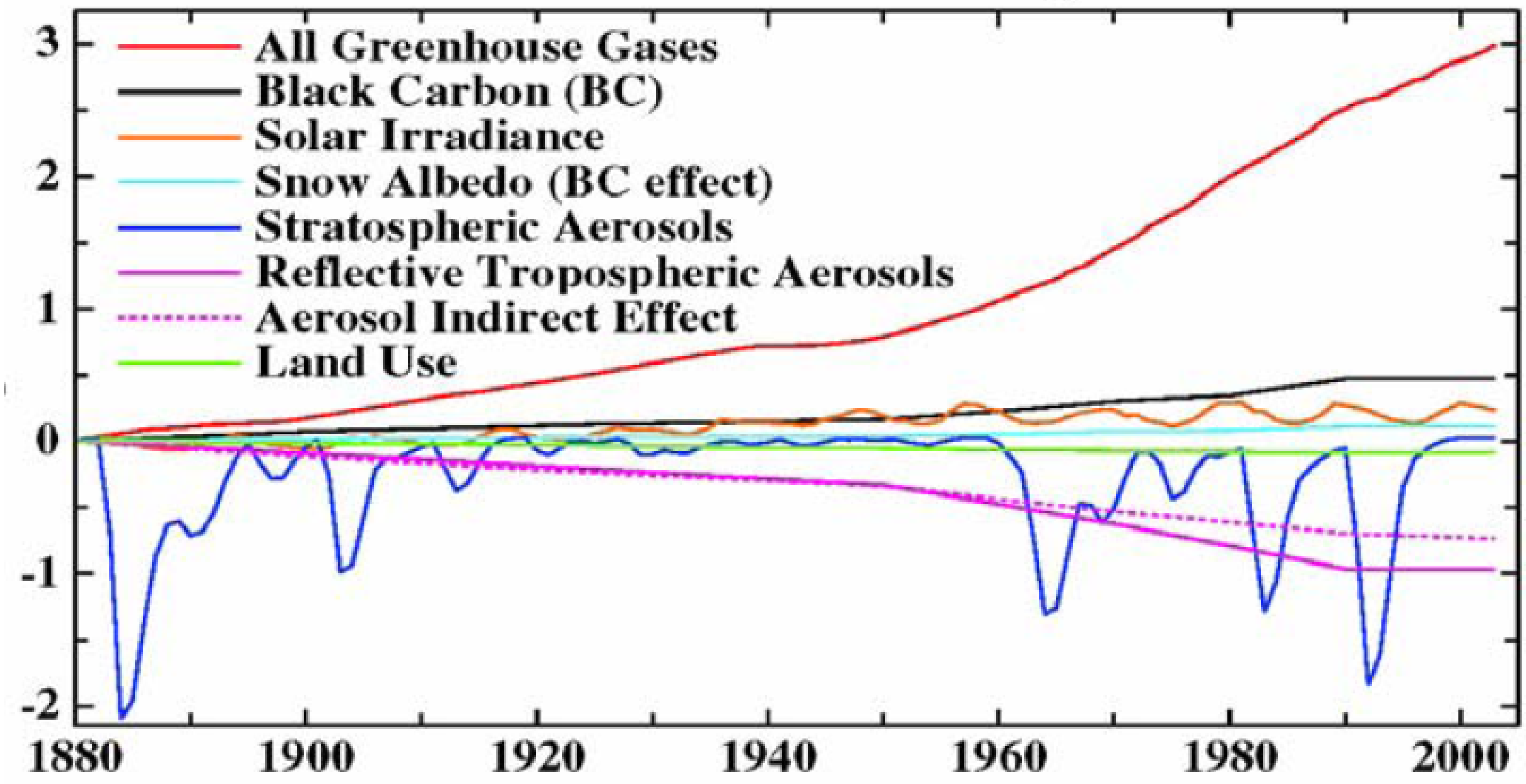
Anthropogenic climate change

- The recent IPCC report has clearly stated that "**Warming of the climate system is unequivocal**" and it is "very likely" caused by human activities.

- Moreover, most of the observed changes are now simulated by models over the past 50 years adding confidence to future projections.

Photo Credit/Crédit photographique: Dan Crosbi

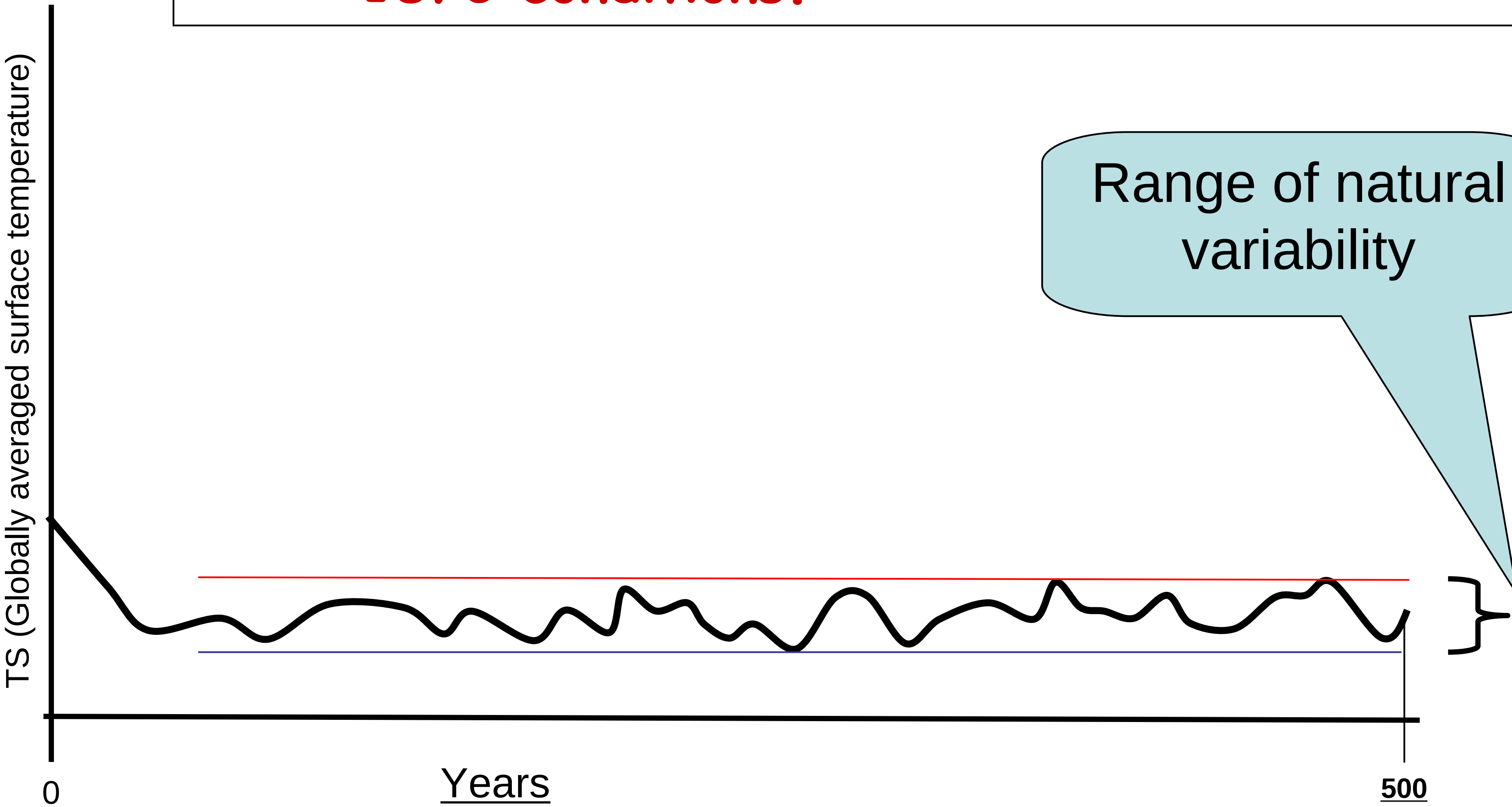
Climate forcing agents over time



Climate forcings used to drive the GISS climate model.

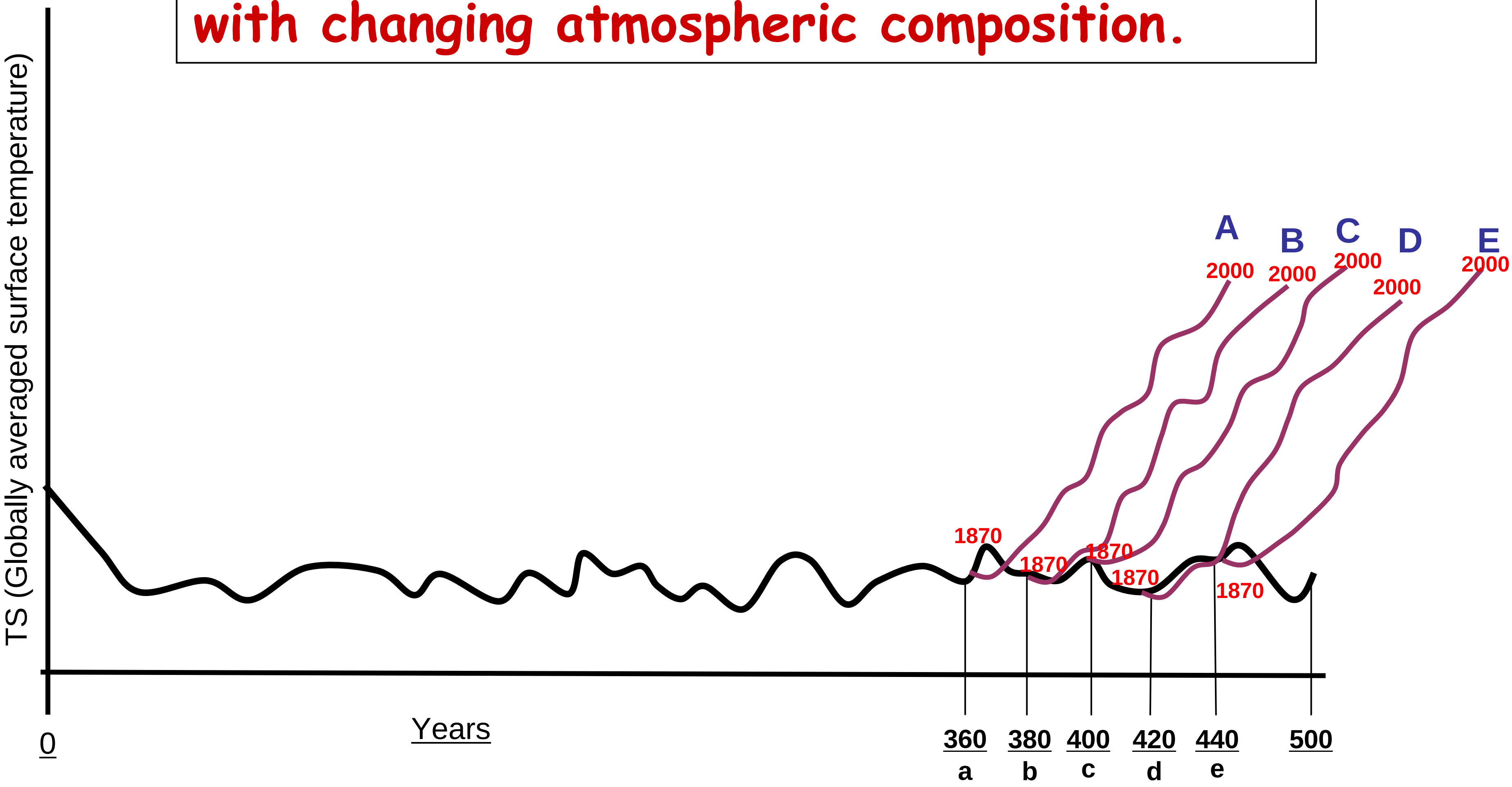
Source: Hansen et al., Science, 308, 1431, 2005.

Schematic of the T85 control run at constant 1870 conditions.



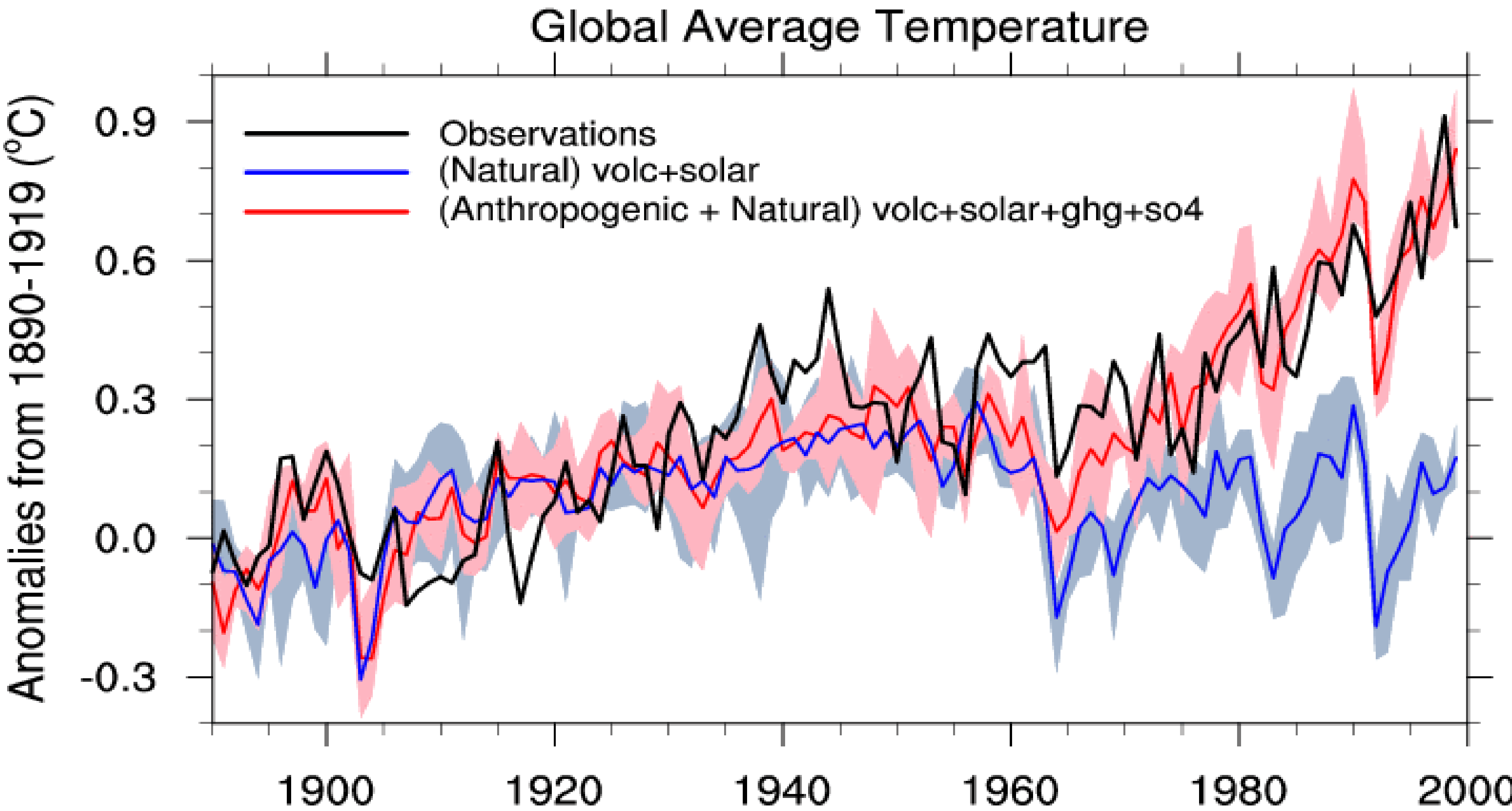
After spinup, the global mean temperature fluctuates naturally from interactions among climate system components

Schematic of the 5-member 1870-2000 historical run ensemble; with changing atmospheric composition.



After the run has stabilized, values every 20 years are used as initial conditions as if 1870 but now with new forcings.

Natural forcings do not account for observed 20th century warming after 1970

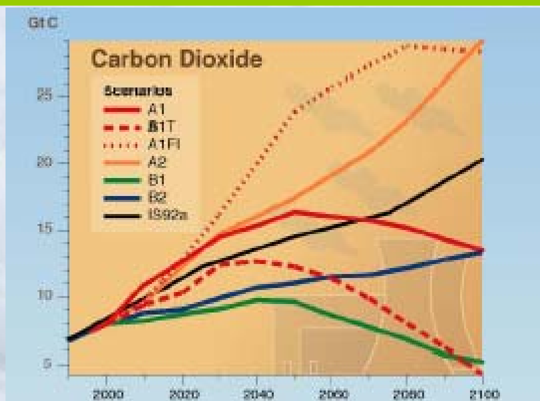


Meehl et al, 2004: J. Climate.

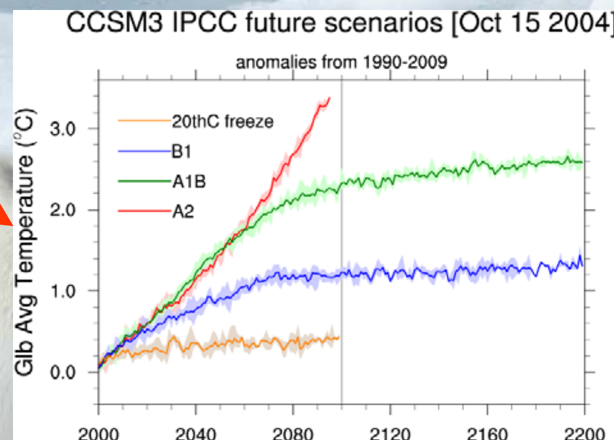
Climate Simulations for the IPCC AR4

(IPCC = Intergovernmental Panel on Climate Change)

IPCC Emissions Scenarios



Climate Change Simulations



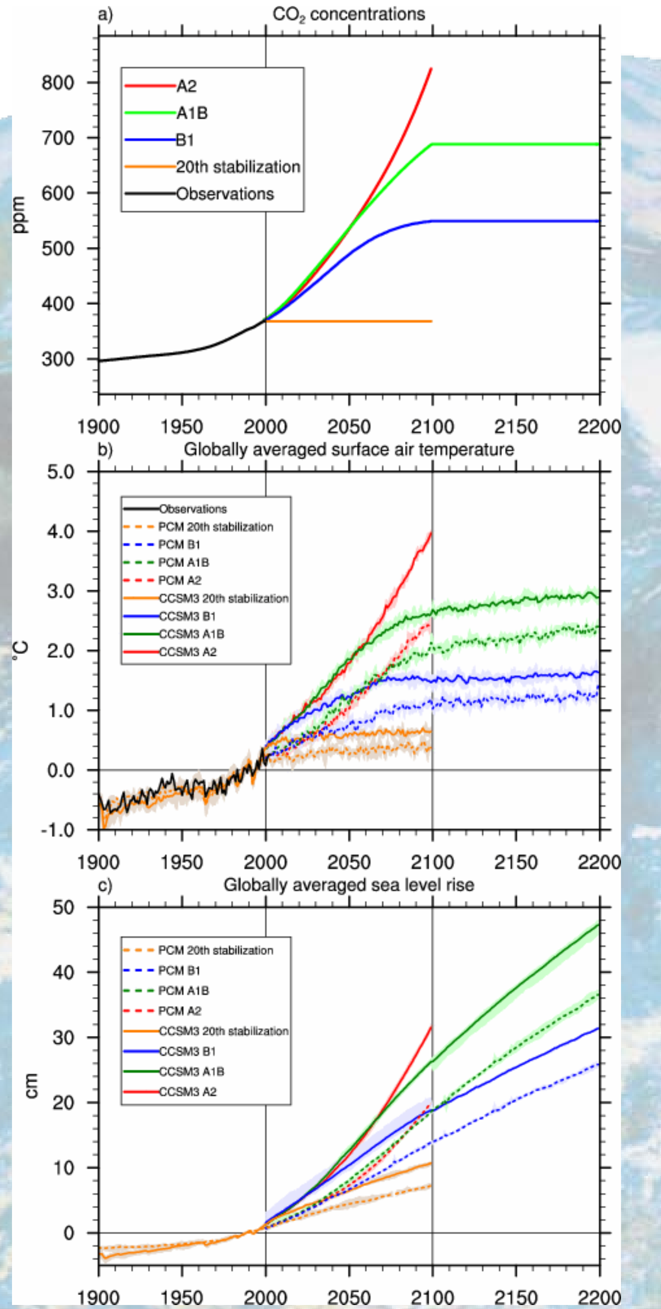
IPCC 4th Assessment

2007

NCAR: Bill Collins

NCAR IPCC Fourth Assessment Report Simulations

- NCAR Community Climate System Model (CCSM-3).
- Open Source
- 8-member ensembles
- 11,000 model years simulated
- “T85” - high resolution
- ~1 quadrillion operations/sim. year
- Rate of simulation: 3.5 sim. yr/day
- Data volume for IPCC: ~110 TB
- Development effort: ~1 person-century



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IPCC does not make predictions

- IPCC uses models to make "what if" **projections** based on possible emissions scenarios
- These supposedly provide decision makers with ideas for which paths might be more desirable
- There is no estimate as to which emissions scenario is more likely or best (no forecast)
- The models are not initialized
- What is used is the **change** from today's model conditions (not today's actual conditions)
- Advantage: removes model bias
- Disadvantage: it is not a forecast

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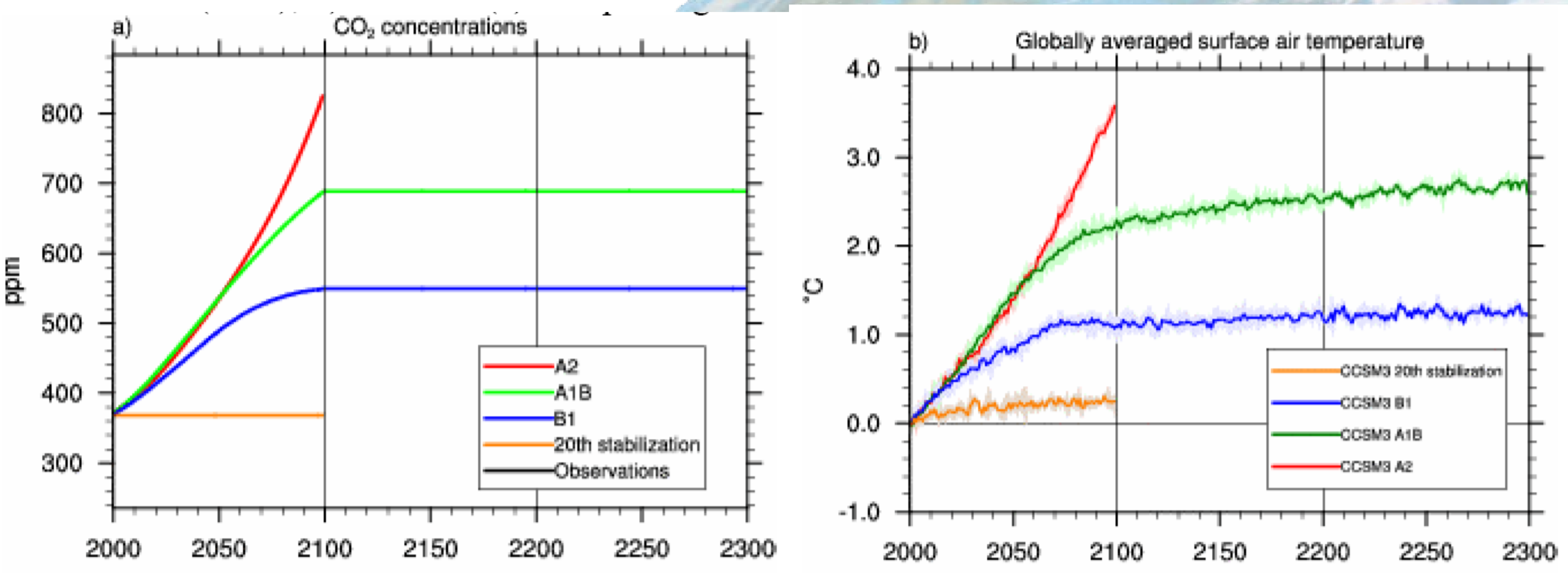
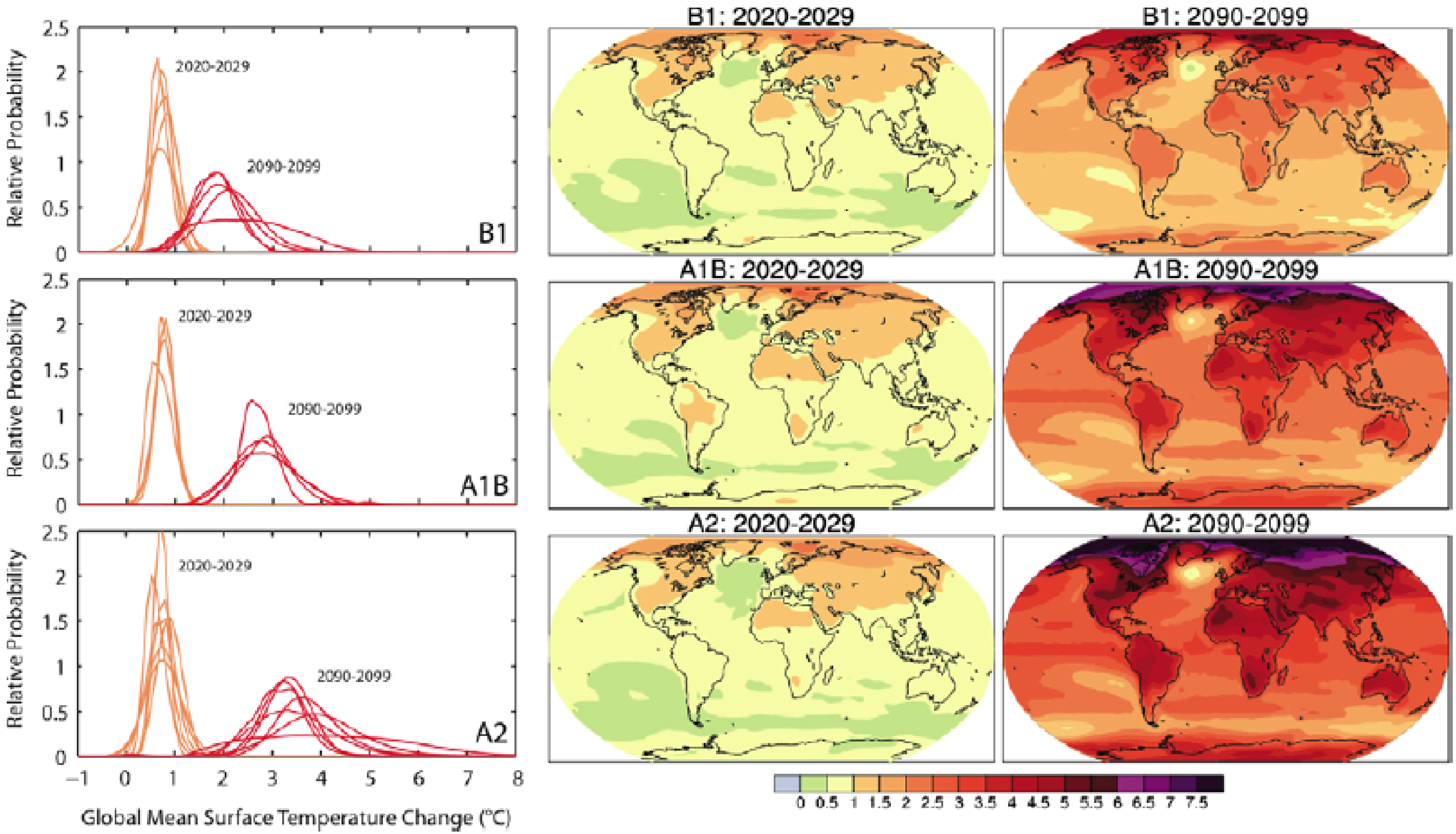
Projections for Global Surface Temperature



Meehl et al, 2005

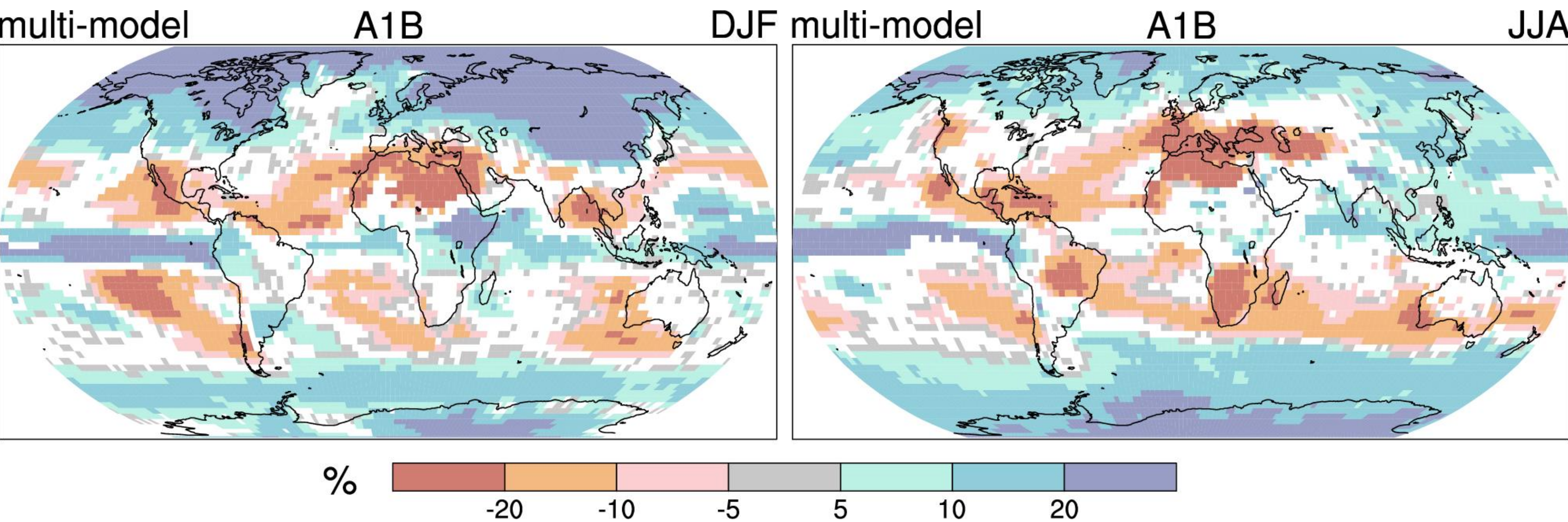
Temperature projections



Probability distribution functions of global mean T get wider as time progresses. Differences are still clear among different future emissions scenarios, however, by 2090s. From IPCC (2007).

This slide showed a movie of the temperature changes projected for 2000 to 2300.

Projected Patterns of Precipitation Change 2090-2100



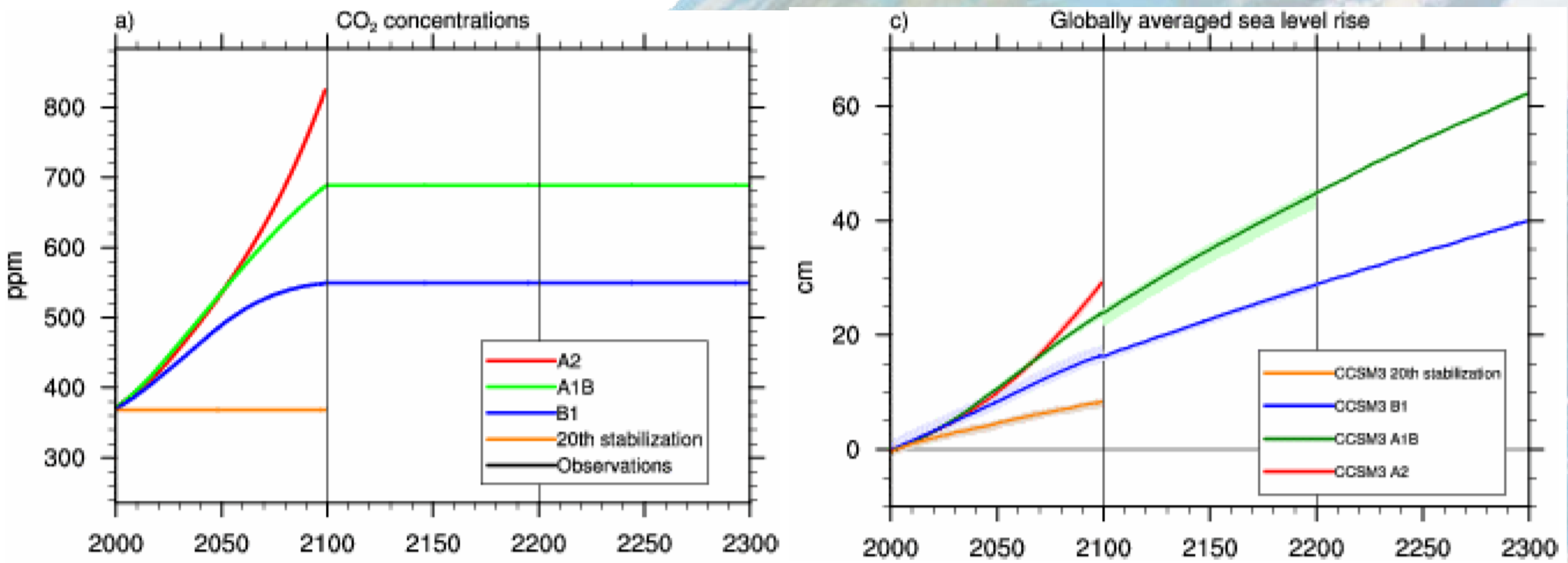
Precipitation increases very likely in high latitudes

Decreases likely in most subtropical land regions

This continues the observed patterns in recent trends

Summary for Policymakers (IPCC AR4)

Projections for Global Sea Level

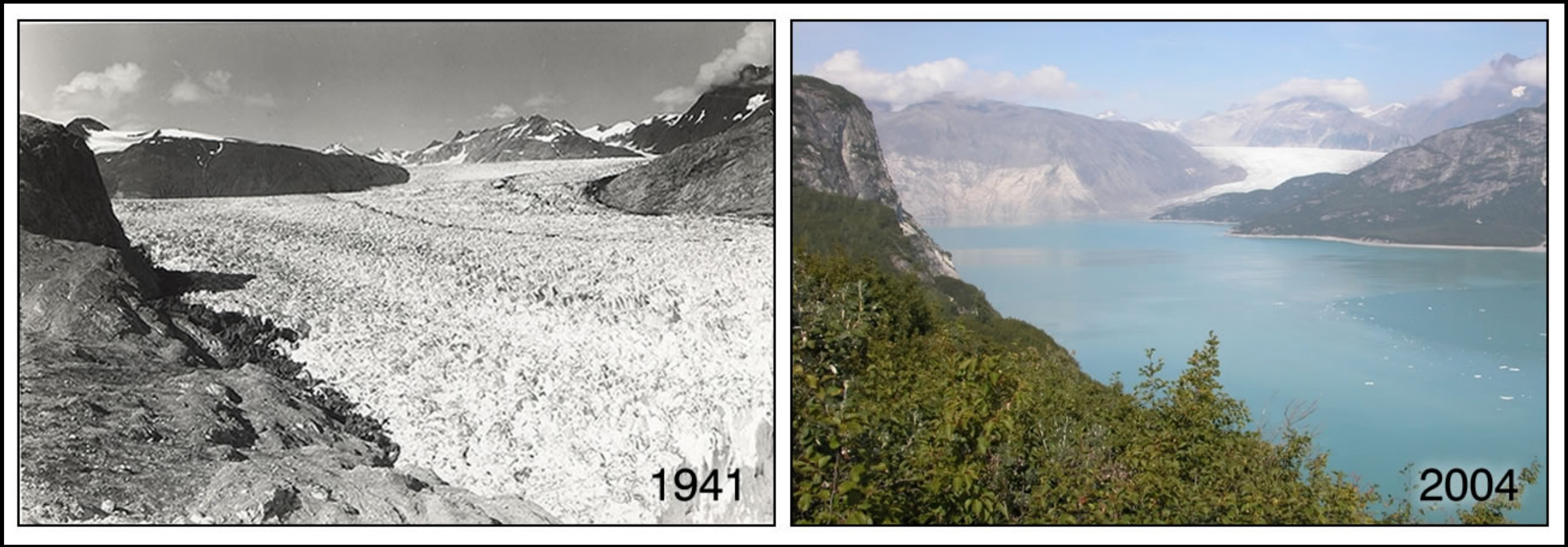


Meehl et al, 2005

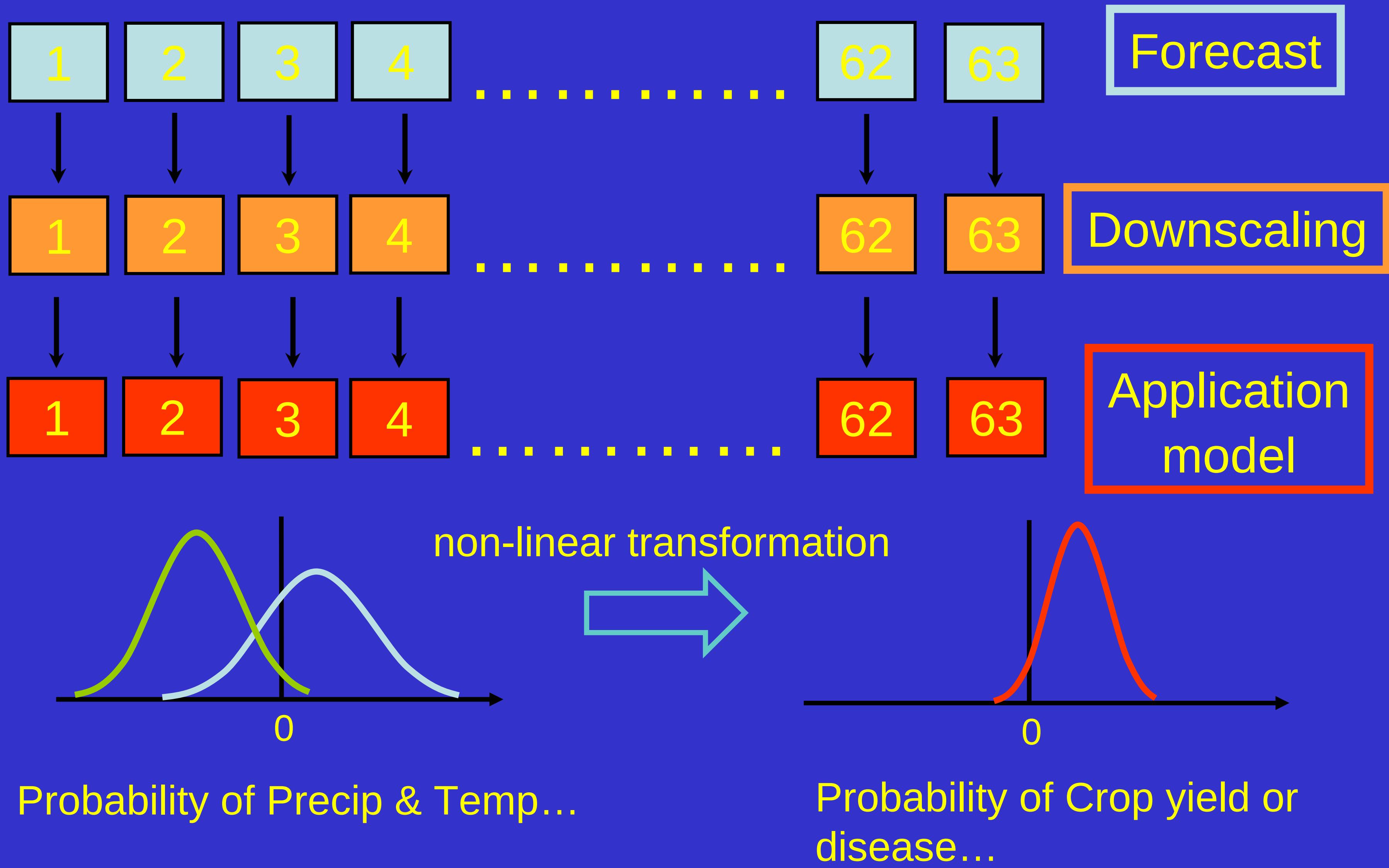
Arctic Summer Sea Ice simulation CCSM: 1900 to 2049

The movie has been removed: it is available at

http://www.ucar.edu/news/releases/2006/arcticvisuals.shtml



End-to-end Forecast System



Future needs: A climate information system

- Observations: in situ and from space
- Data processing and analysis
- Data assimilation and model initialization
- Better, more complete models
- Ensemble predictions: many time scales
- Statistical models: applications
- Information: regional, sectoral

Forecast for 2020 (in 2019)?

New **environmental** forecast products will be feasible

Melting permafrost

Major fires

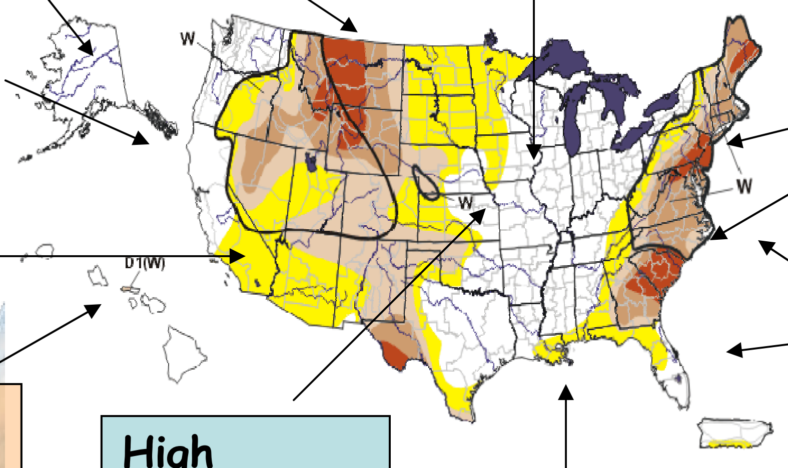
Agricultural production at 50%, blowing dust

Major fisheries regime change likely

Health warning: Limit outdoor activities; expect brownouts

Air quality alerts: 75% of days

Swimming and Fishing prohibited



Frequent flooding and Asian dust threats continue

High danger of toxic CO2 releases

Expect fisheries downturn; health threats

21 Tropical storms: 10 above normal

African bacteria alerts

Possible Threats for Summer 2020:

Drought, hot, dry & unhealthy

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