Lecture 8: Climate Modeling

How to Build a Climate Model

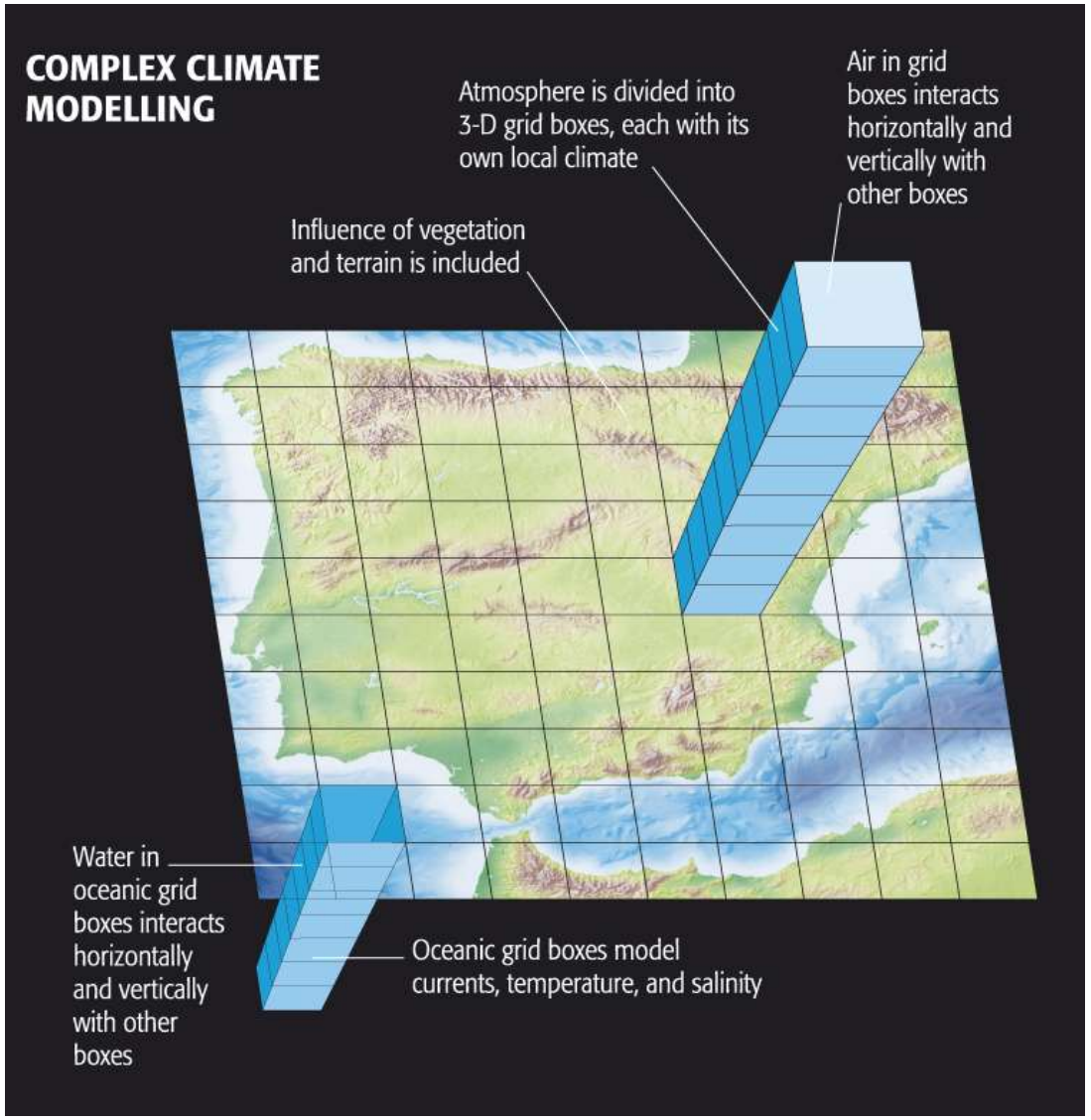
- **The climate** is governed by many complex physical, chemical, and biological processes and their interactions.
- **Building a climate model** needs to consider hydrosphere (ocean water and ice), atmosphere, biosphere, geosphere, and their interactions.
- **Simple climate models**: ignore the 3D structure of Earth, atmosphere, and oceans, and simply focus on the balance between incoming solar energy and outgoing terrestrial energy to determine temperatures on Earth. The following factors must be accounted for:
  - Greenhouse effect.
  - Positive and negative feedback loops.

Complex Numerical Models of Climate

- **A complex climate model is** a computerized representation of Earth including its atmosphere and oceans and various other components, based on a 3D global grid. The model then applies these changes to its virtual world to see what effect they have on the climate.
- **The most complex climate models, referred to as "General Circulation Models (GCMs)"**, take into account the full 3D structure of the atmosphere and oceans, lands, and the surface topography. Not only calculate surface temperatures, but also other important climate variables, such as precipitation, atmospheric pressure, surface and upper-level winds, ocean currents, temperatures, and salinity.

Complex Climate Modeling

- All this is accomplished by **breaking the oceans and atmosphere into many small grid boxes**, and using the underlying physical, chemical, and biological relationships to calculate values for the properties of each box and the interactions between different boxes.



Numerical Modeling of Climate

Hydrodynamic equations:

1. equations of motion
2. thermodynamic equation
3. continuity equation
4. equation of state
5. equations that govern water vapor, phase change, and latent heat.
6. conservation equations of various scalars

Mathematical algorithm for solving hydrodynamic equations

Equations of motion: Newton Law $m \cdot a = F$

For unit mass, $\frac{V_{t+\Delta t} - V_t}{\Delta t} = F_t$

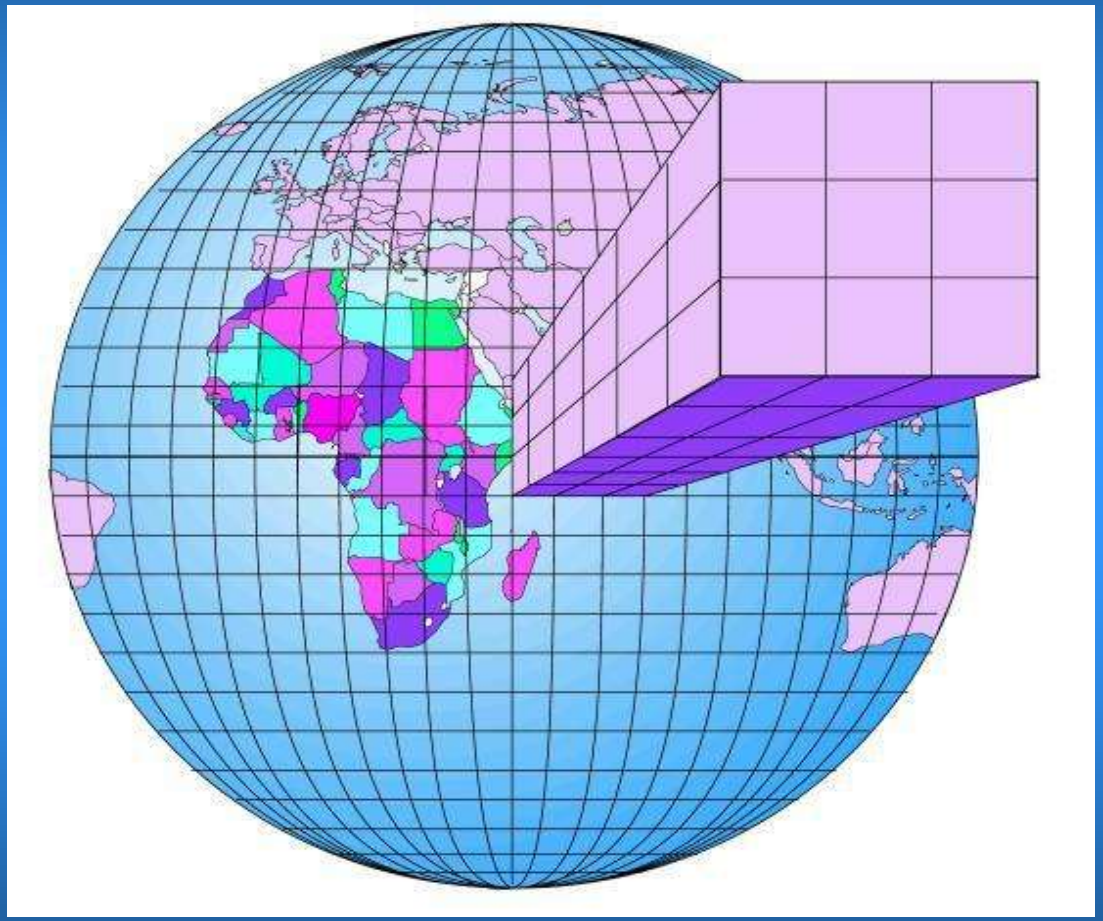
$$V_{t+dt} = V_t + F_t \cdot \Delta t$$

$$V_{t=0} \Rightarrow V_{dt} \Rightarrow V_{2dt} \Rightarrow \cdots\cdots V_t \cdots\cdots$$

Initial value problem

Numerical simulation of climate: Using mathematical algorithms to solve a set of governing equations to predict the future state of the atmosphere based on the data of the past and present state of the atmosphere.

Discretizing governing equations onto model grids



Specifying surface conditions or coupling atmospheric model to oceanic model and land surface model

Historical background

British scientist L. F. Richardson
Weather Prediction by Numerical Process, 1922

Richardson estimated that a work force of 64,000 people would be required just to keep up with the weather at a global basis.

But Richardson did not make a successful numerical forecast.

Filtering meteorological noises

American meteorologist J. G. Charney, 1948
Geostrophic and hydrostatic approximations
Quasi-geostrophic model, 1950,
the first numerical forecast

- Akira Kasahra at the University of Chicago made the first numerical forecast of hurricane movement 1957.

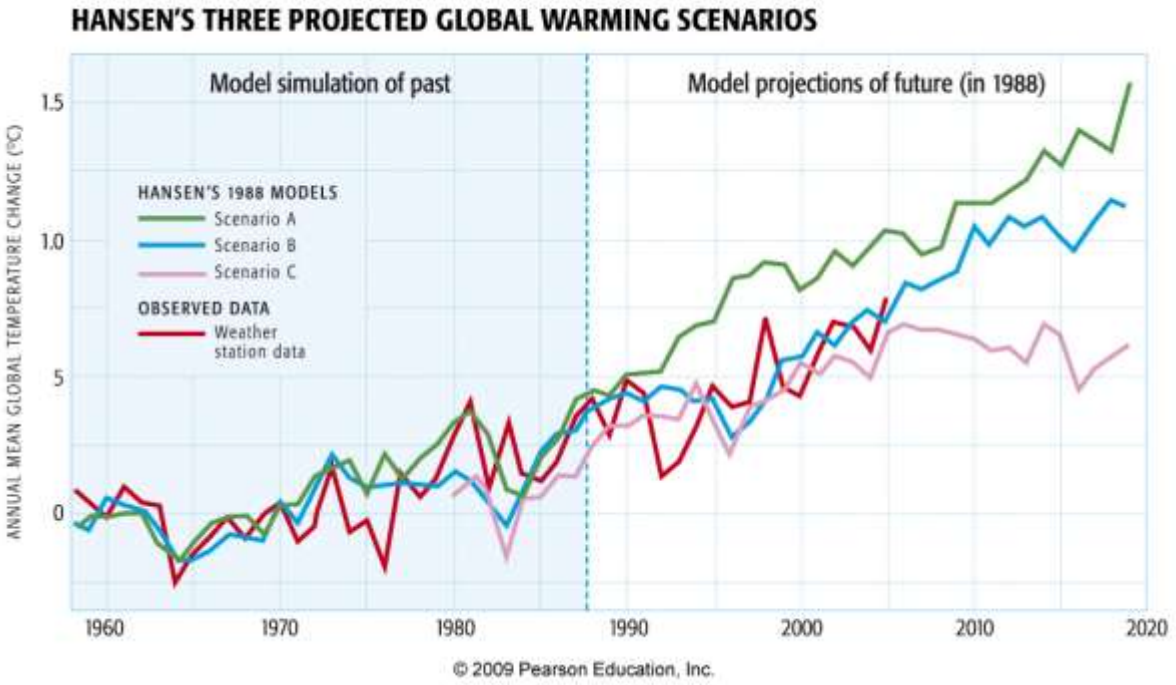
In the 50s, people are optimistic about numerical weather forecast

- **Global observational network of the atmosphere has been established, which can provide more accurate initial fields.**
- **Great success of numerical calculation in other fields, such as calculating the trajectories of planetary orbits and long-range missals.**

- The accuracy of numerical forecast improved dramatically during the 60s, 70s, and 80s.

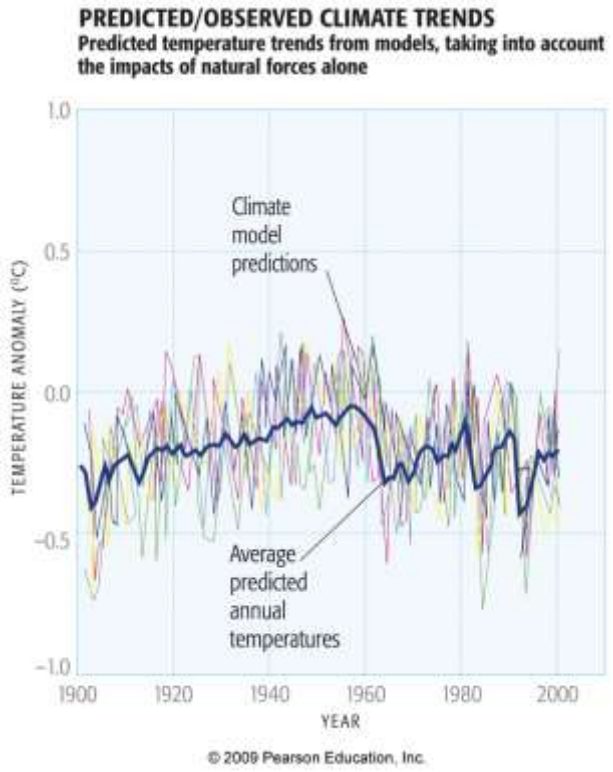
James Hansen – Projections in 1988

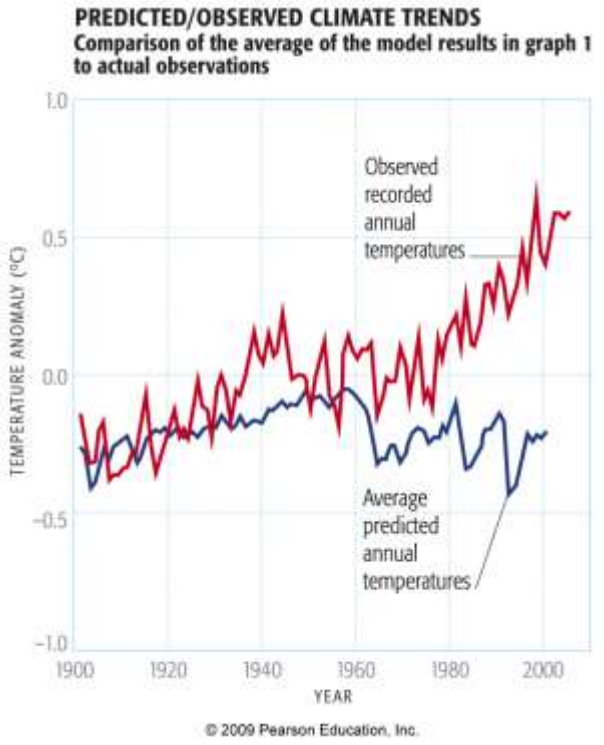
- NASA climatologist Hansen's congressional testimony: he presented projections about likely future warming in terms of 3 possible scenarios.
- Projections Hansen made in 1988 have proven to be a key validation of the models by climate scientists.



Comparing Climate Model Predictions with Observations

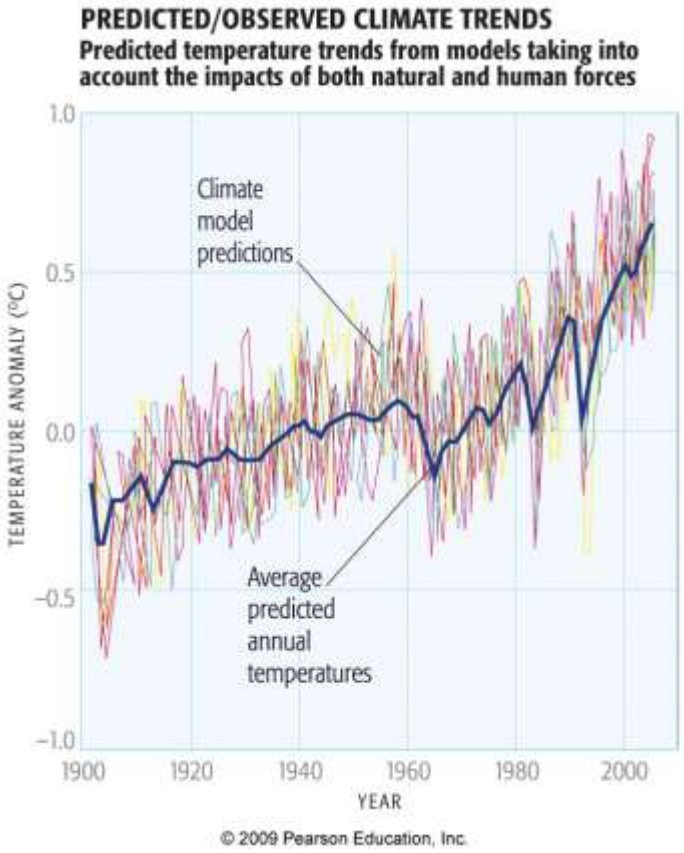
- Taking into account the impacts of natural forces alone
- Two natural factors:
  - Changes in solar energy input: warm and cool
  - Explosive volcanic activity: cool

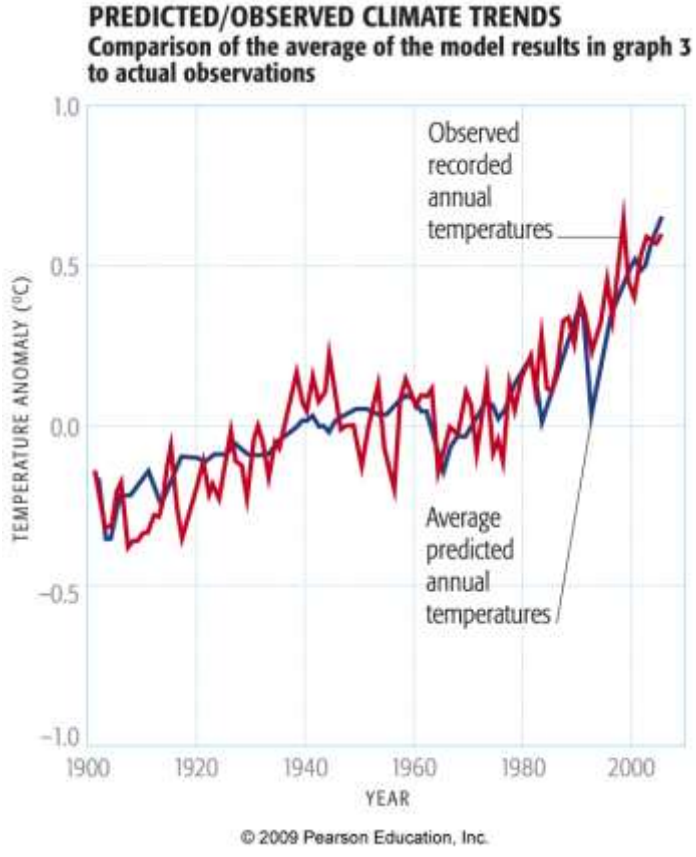




Comparing Climate Model Predictions with Observations

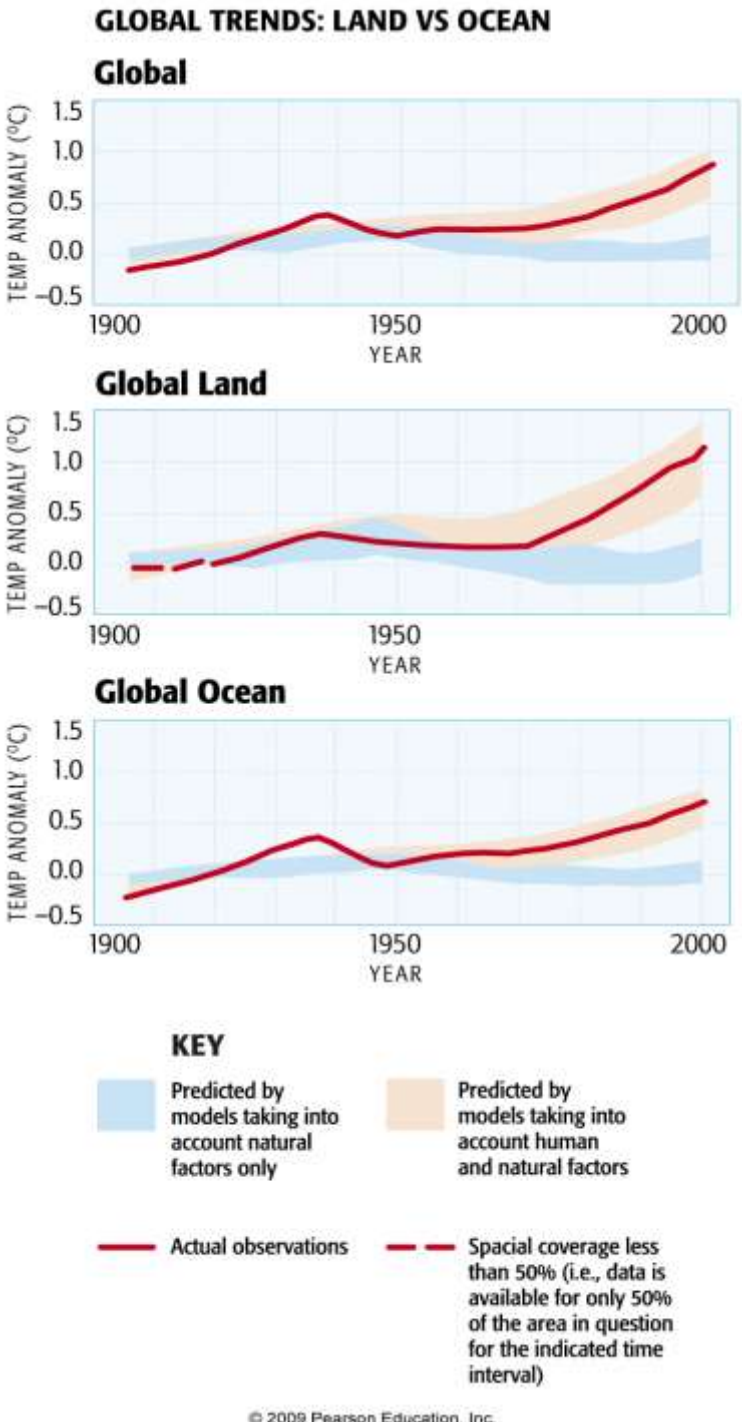
- Including human impacts as well
- Human impacts include:
  - Fossil-fuel burning (Primary impact)
  - Industrial aerosols (secondary impact)





Global Trends: land vs. ocean

- Globally, only the models that take into account both human and natural factors make predictions that look like actual data trends.



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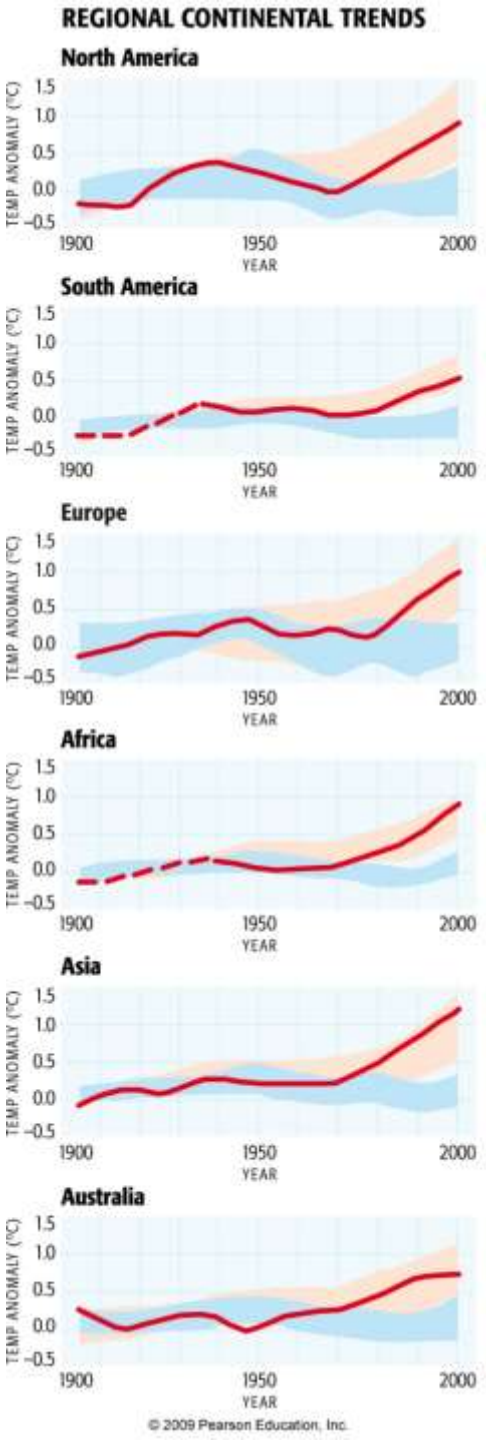
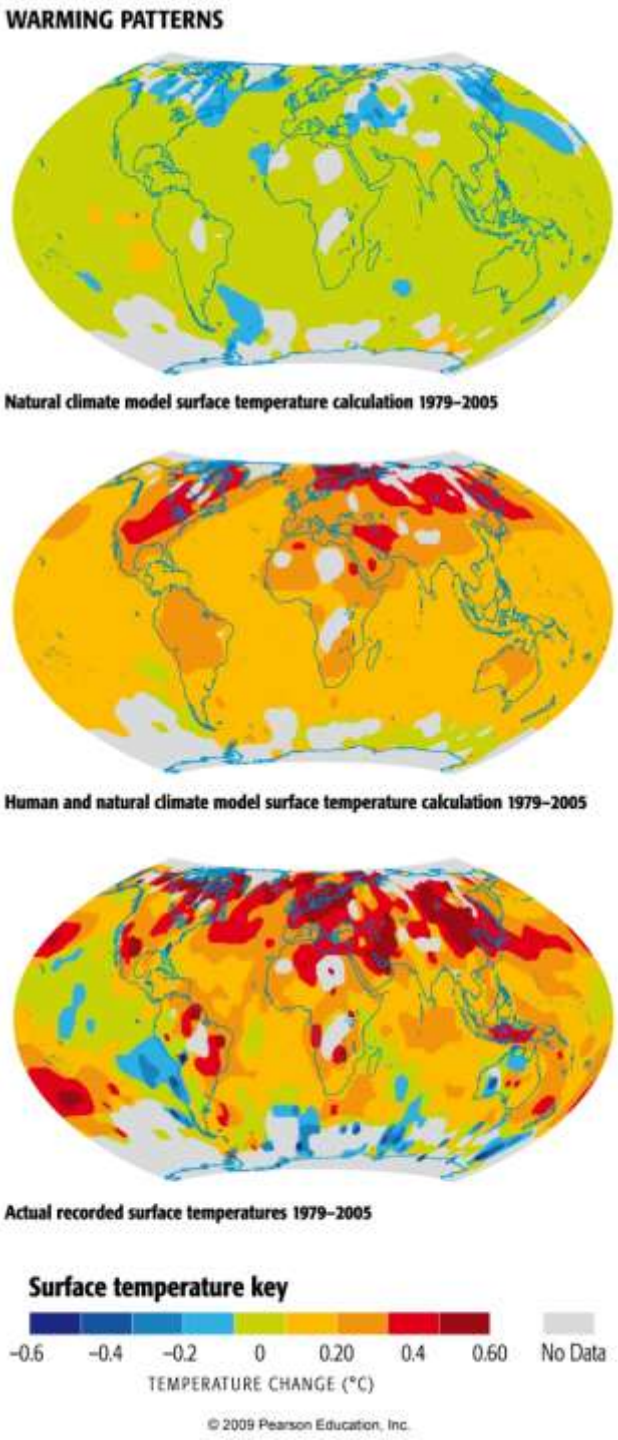
Regional Continental Trends

- Human influences are now having a detectable impact on temperature changes measured in individual regions.



Global warming Patterns

- Actual observations (bottom map) correspond closely with model predictions that take into account the impacts of both natural and human forces (middle map).



- But unfortunately, improvement of climate models slowed nearly to a standstill beginning around 90s.

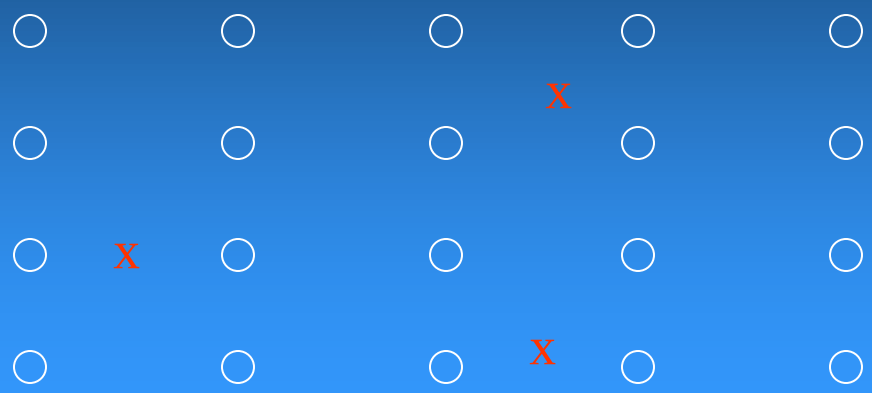
Why?

Challenges of numerical simulation of climate

- Insufficient observations – leading to inaccurate initial conditions;
- Chaotic nature of the atmospheric and oceanic system;
- Inherent deficiency of numerical models with limited resolution that fails to resolve sub-grid physical processes.

1. Initial conditions

a. Traditional approach: objective analysis and data initialization



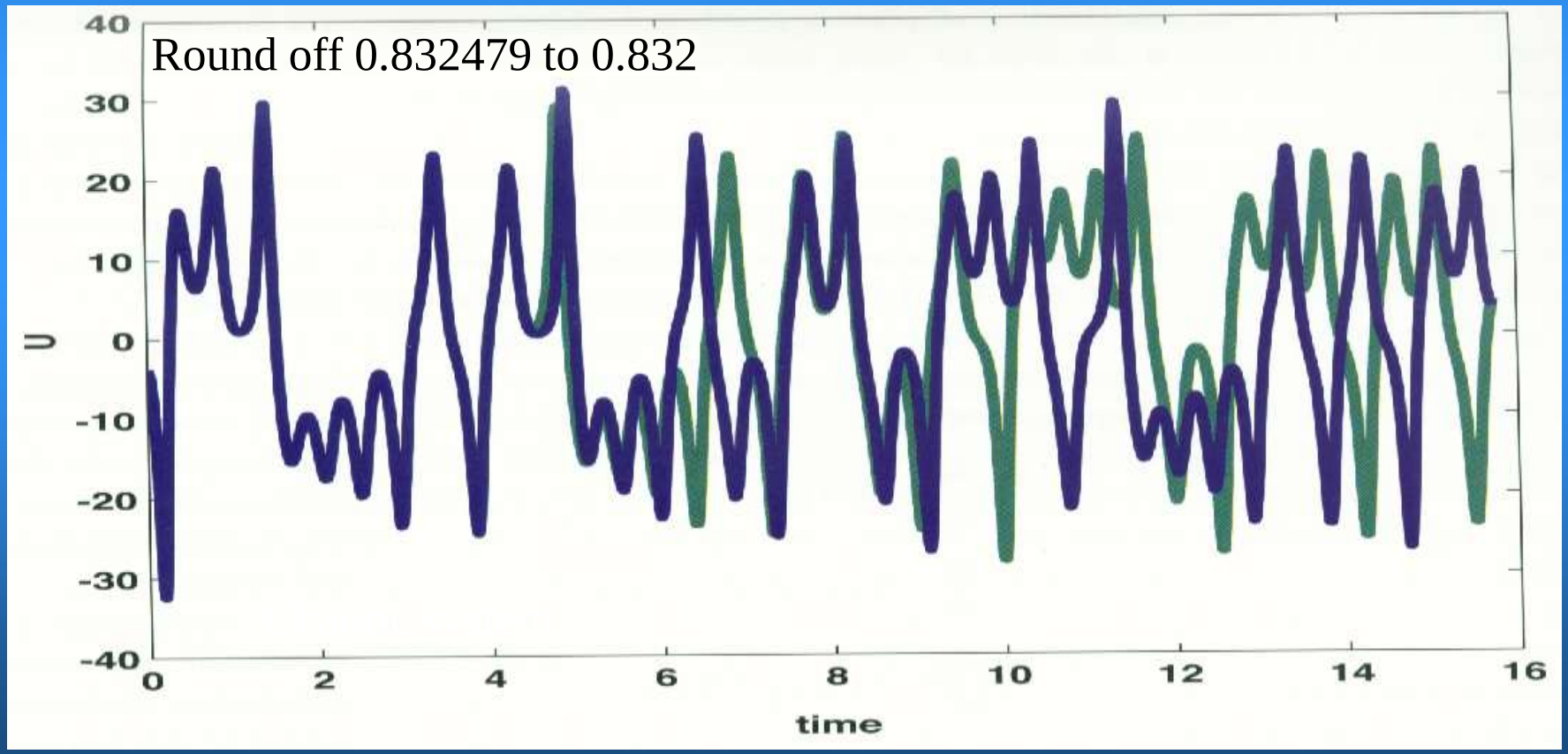
1. Objective analysis: Irregular observational data is converted onto regular model grid points using certain interpolation schemes. Such objectively analyzed data may contain noise .

2. Data initialization: Objectively analyzed data are further modified in a dynamically consistent way.

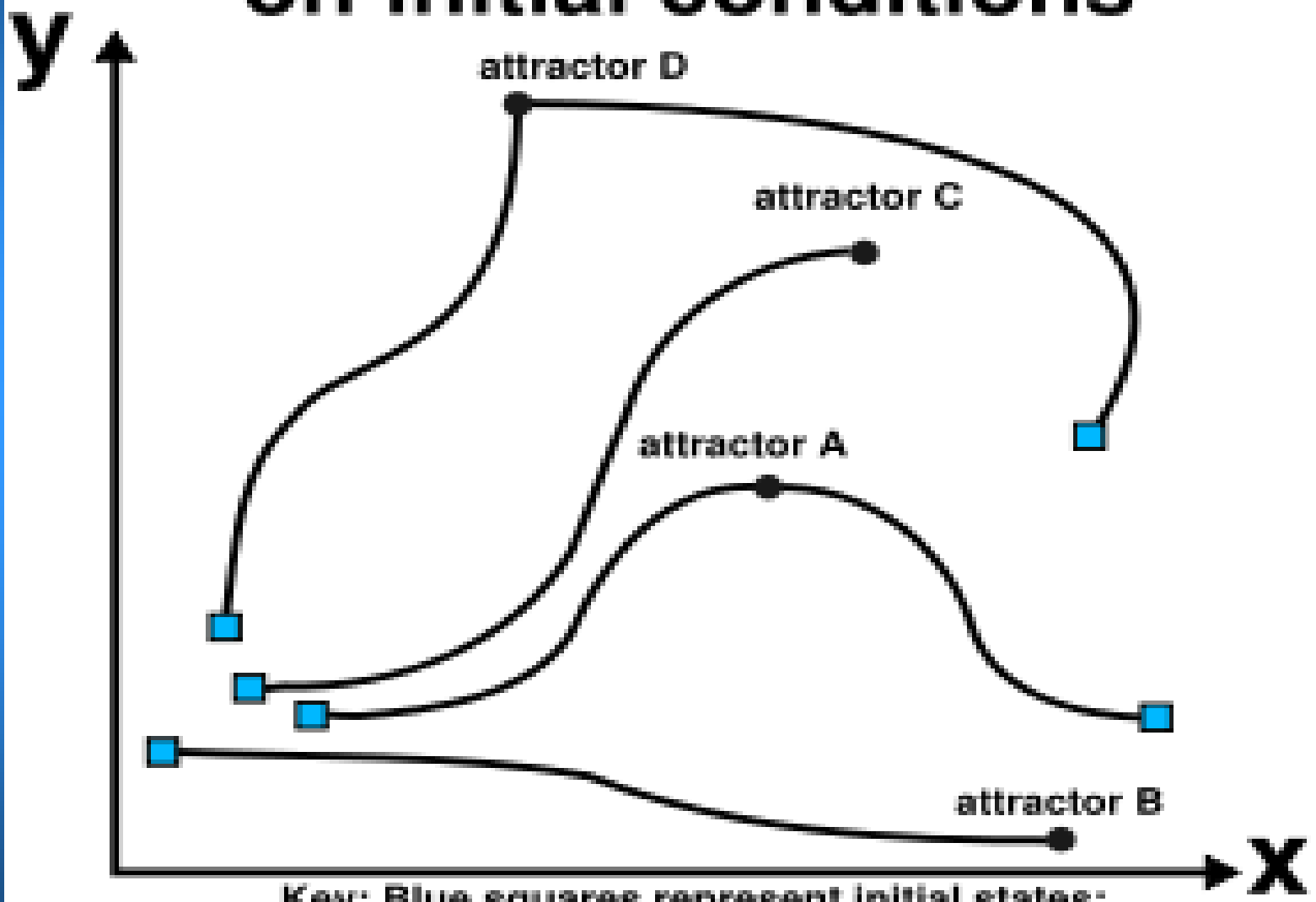
3. Data assimilation: Separate objective analysis and data initialization are combined together into an integrated one to obtain a best estimate of the state of the atmosphere at the analysis time using all available information.

2. Chaotic nature of the atmospheric and oceanic system: Sensitive dependence on initial conditions, butterfly effect

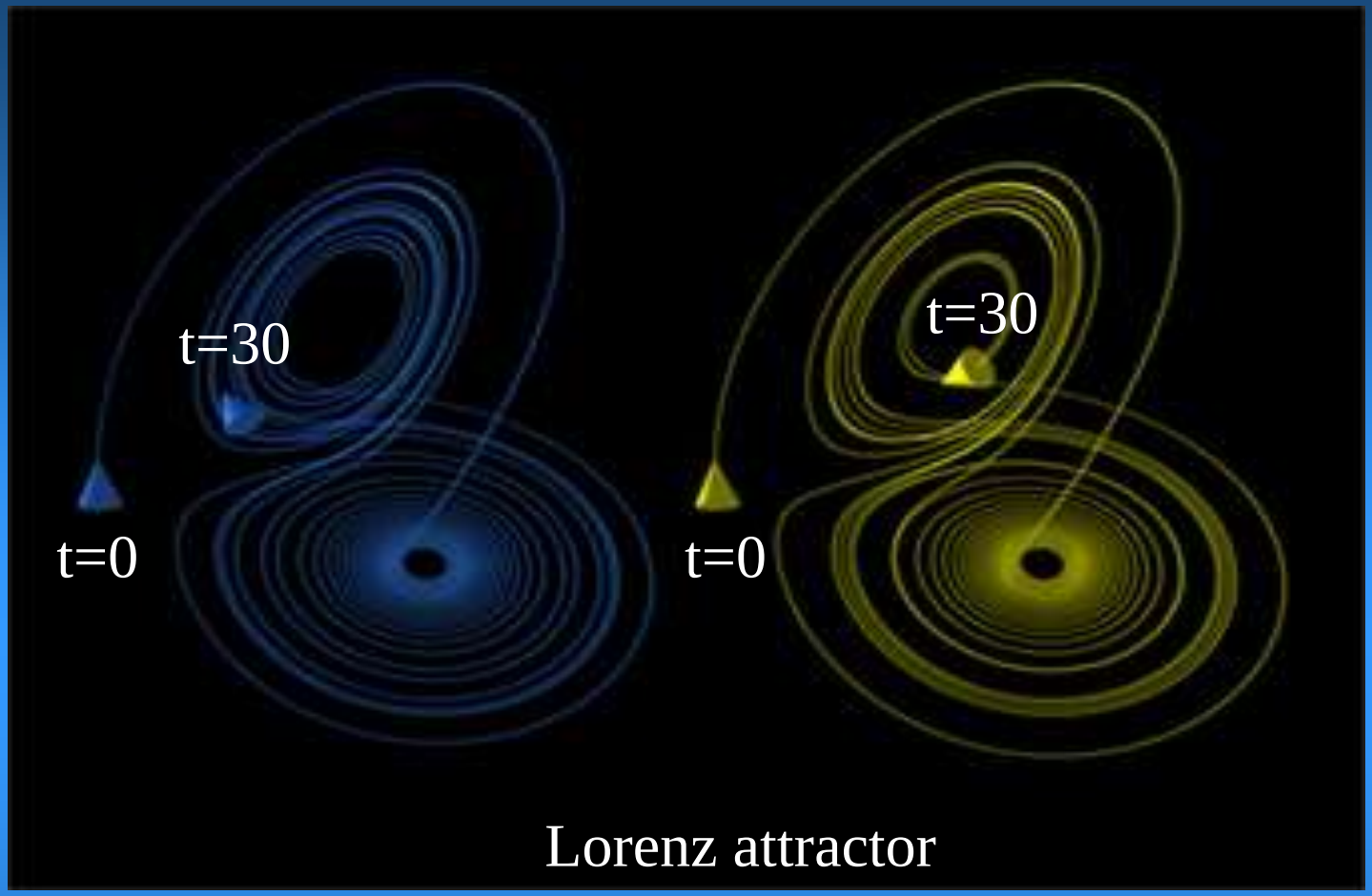
Edward N. Lorenz (a professor at the MIT) equations:



Sensitive dependency on initial conditions

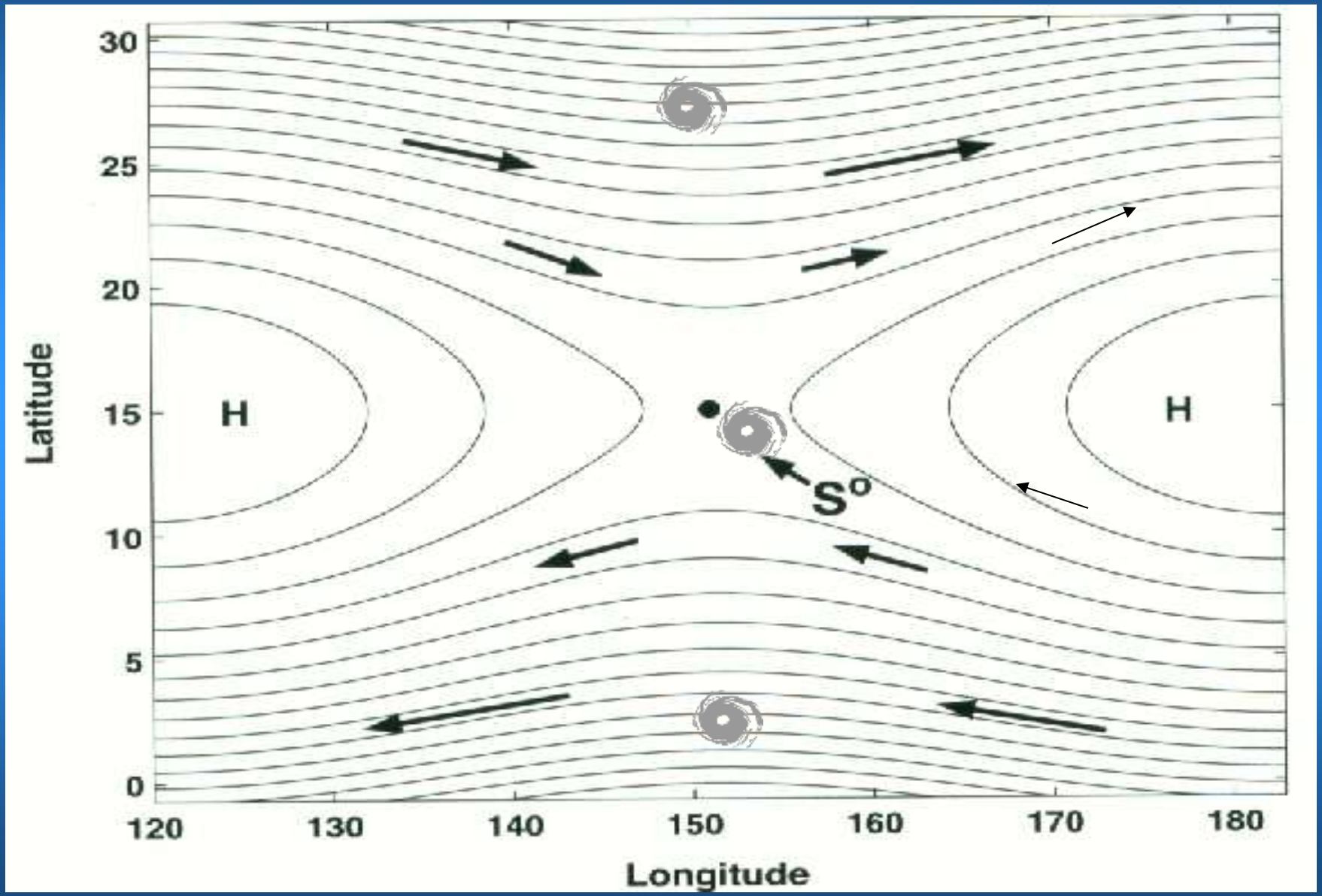


Key: Blue squares represent initial states; black circles represent equilibria

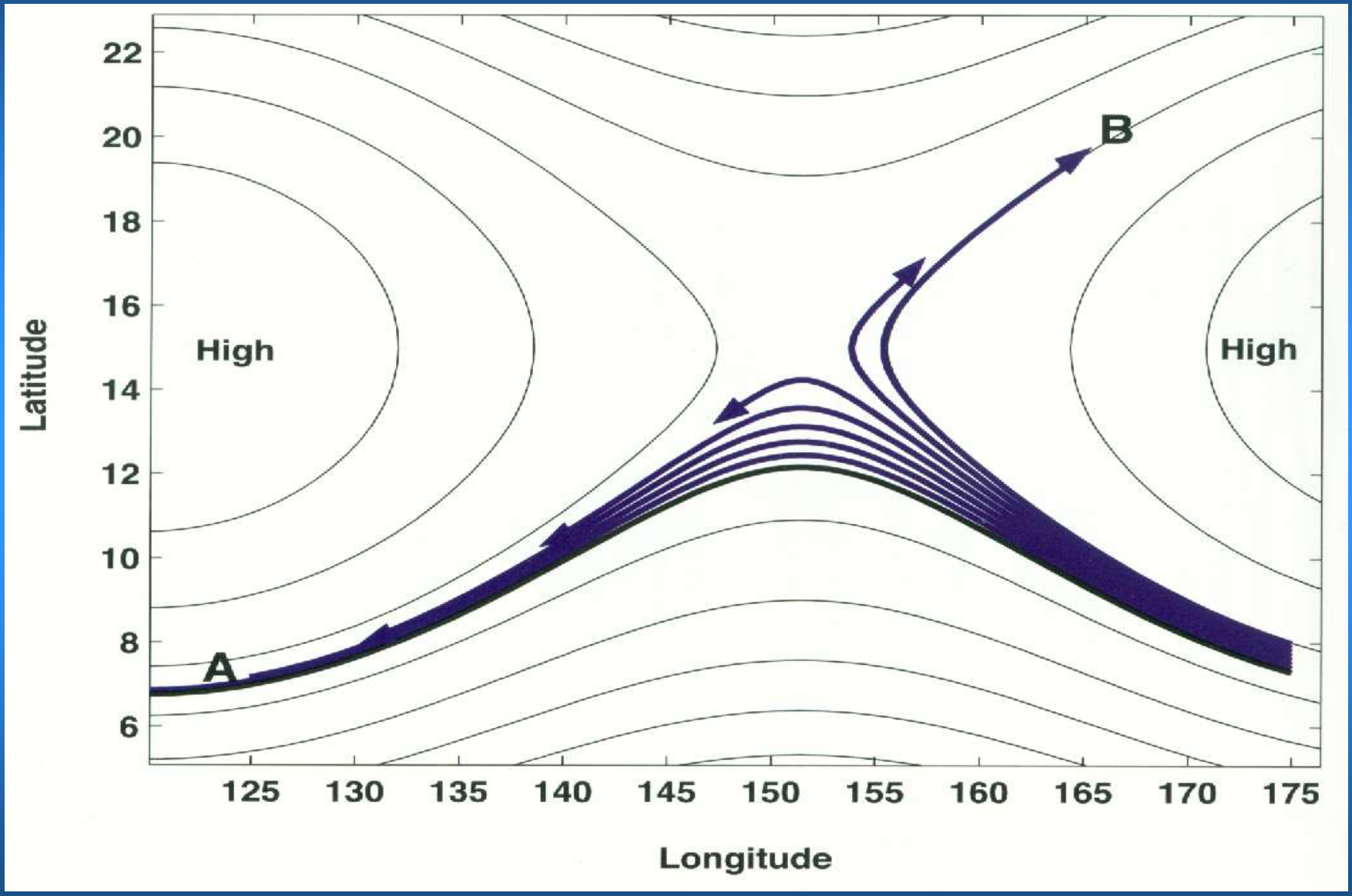


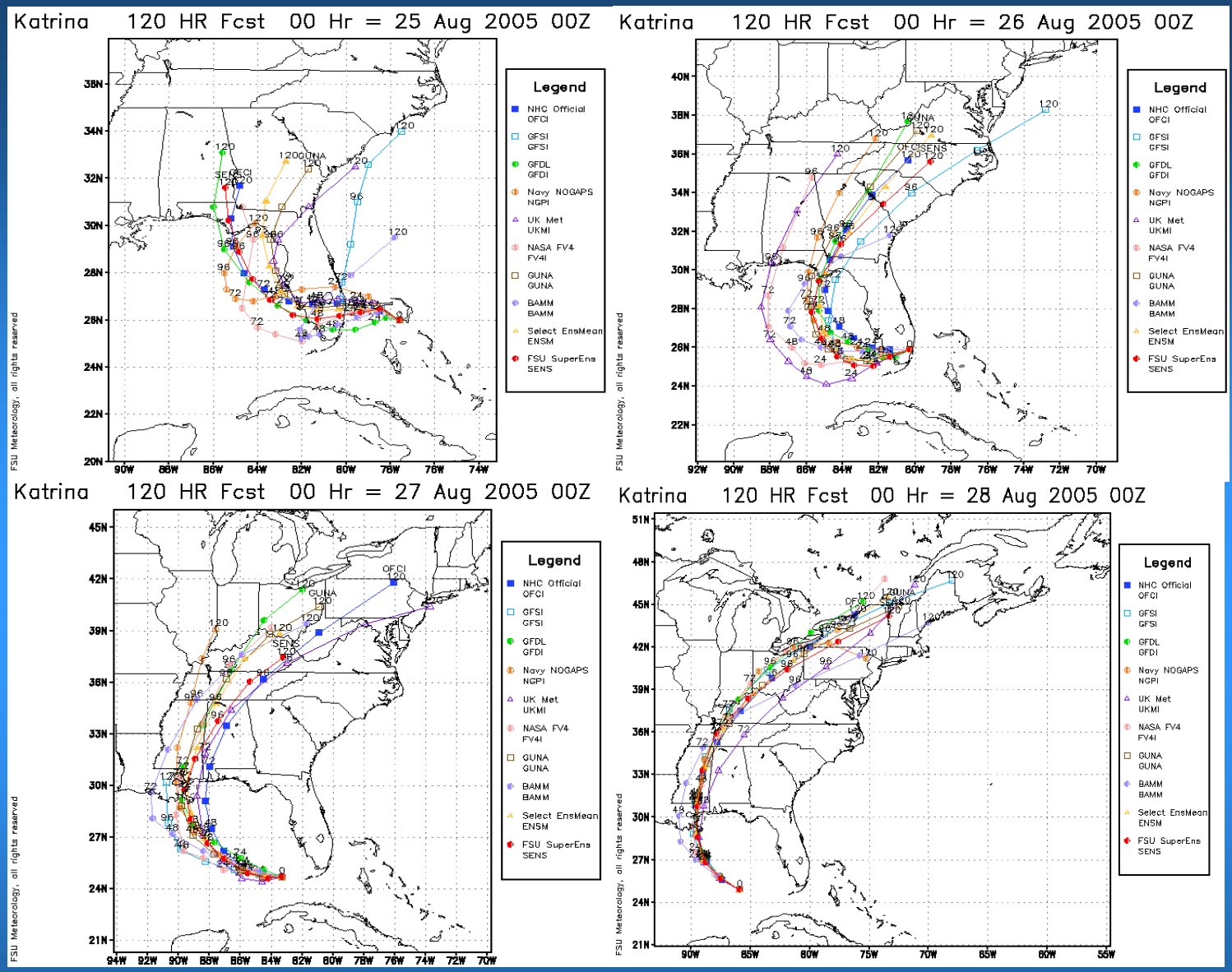
The Lorenz attractor starting at two initial points that differ only by 10^{-5} of initial position in the x-coordinate. Initially, the two trajectories seem coincident, but the final positions at t=30s are no longer coincident.

This scenario can really wreak havoc with hurricane track forecast



Ensemble forecasting





Ensemble simulation: (1) one model, different initial conditions

(2) same initial condition, many models

IPPC simulations

Ensemble Prediction

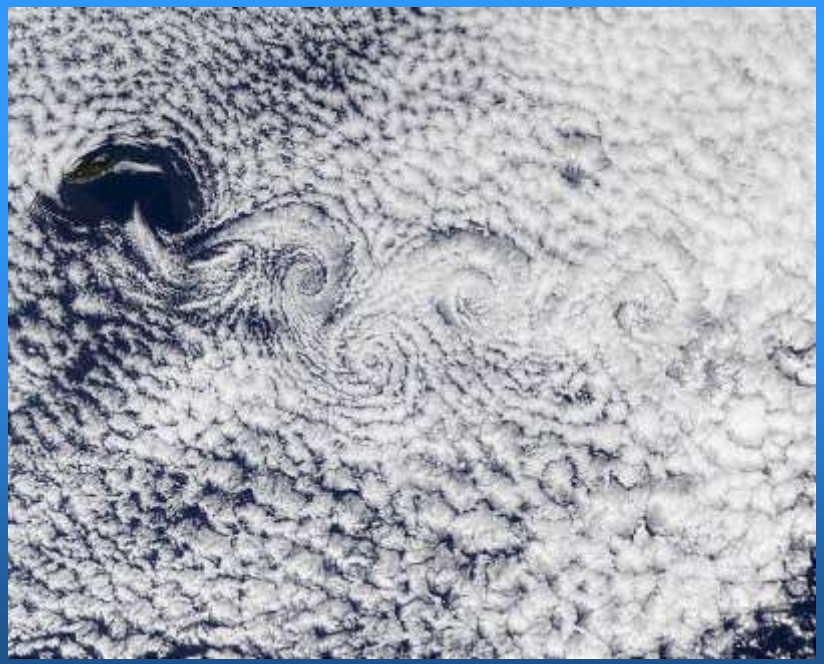
Ensemble forecasting is a method used by modern operational forecast centers to account for uncertainties and errors in the forecasting system which are crucial for the prediction errors due to the chaotic nature of the atmospheric dynamics (sensitive dependency on initial conditions). Many different models are created in parallel with slightly different initial conditions or configurations. These models are then combined to produce a forecast that can be fully probabilistic or derive some deterministic products such as the ensemble mean.

3. Limited model resolution: how to represent sub-grid physical processes in models

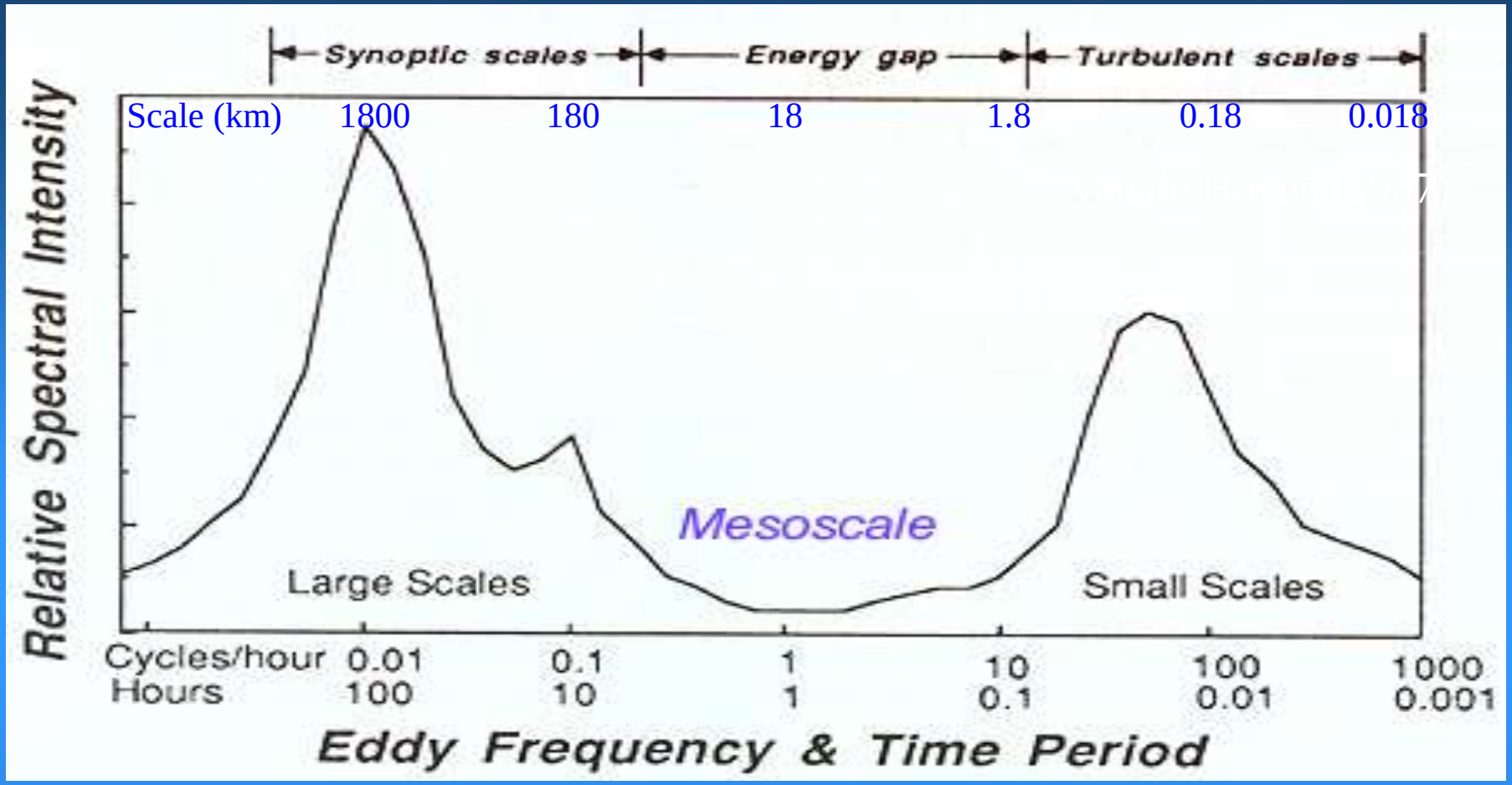
clouds turbulence

Grid size of climate models: ~50 – 100/200 km

~10 km



~100 m – a few km



Parameterization

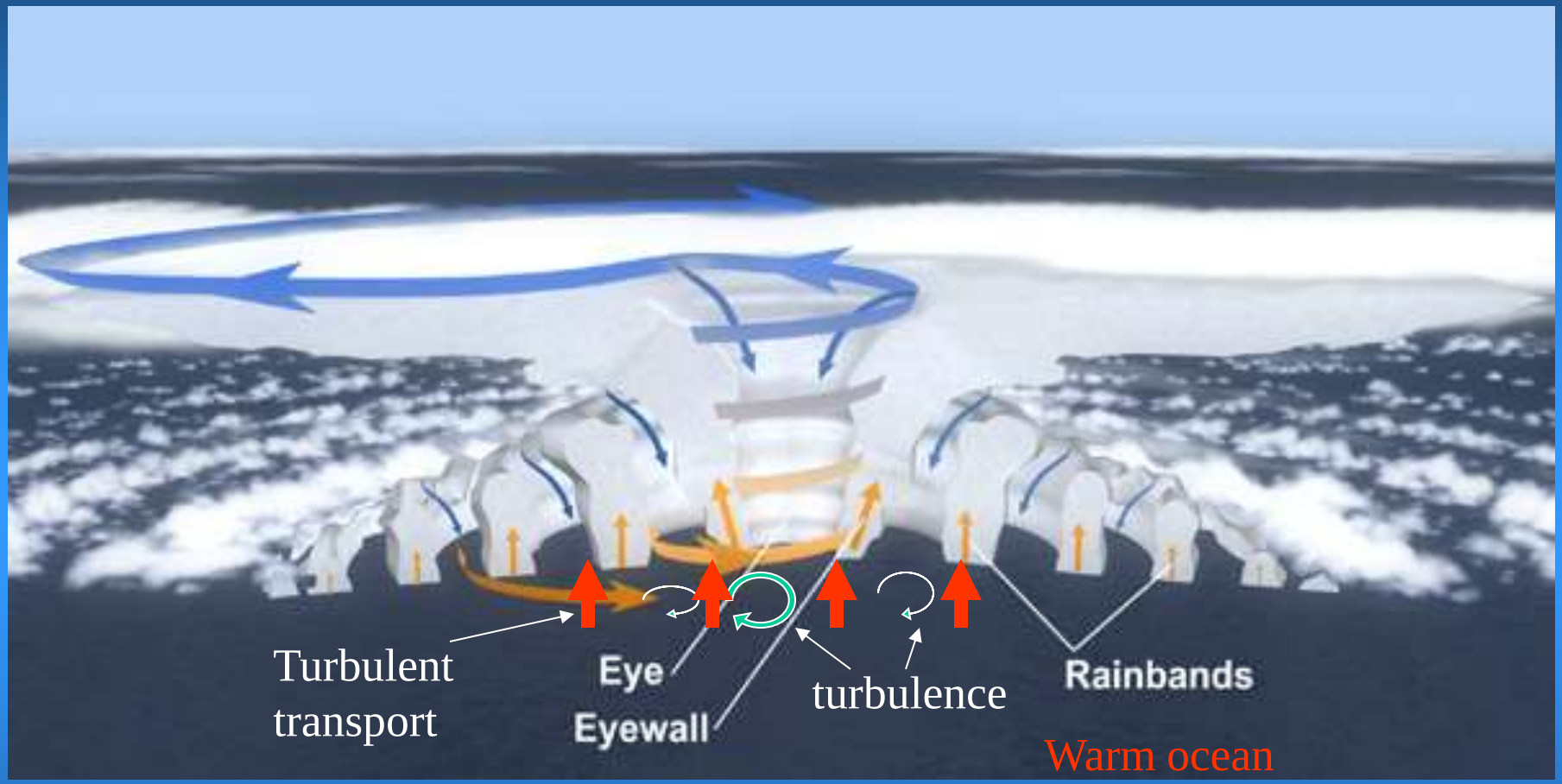
cloud properties =

$f(\overline{U}, \overline{V}, \overline{W}, \overline{T}, \overline{Q})$

$\overline{U}, \overline{V}, \overline{W}, \overline{T}, \overline{Q}$

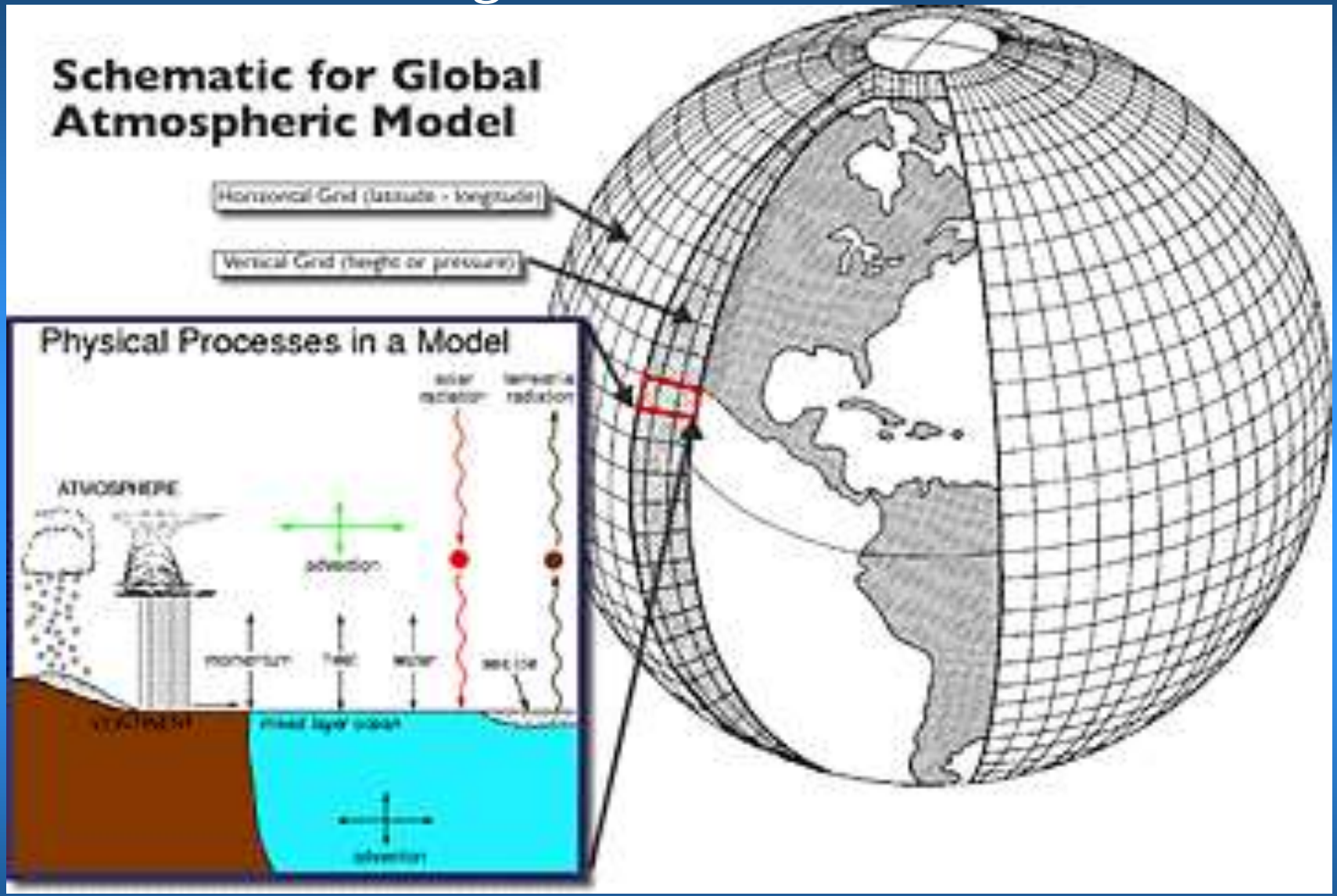
Representation of sub-grid physical processes in terms of model resolved quantities

Hurricane boundary layer turbulent processes



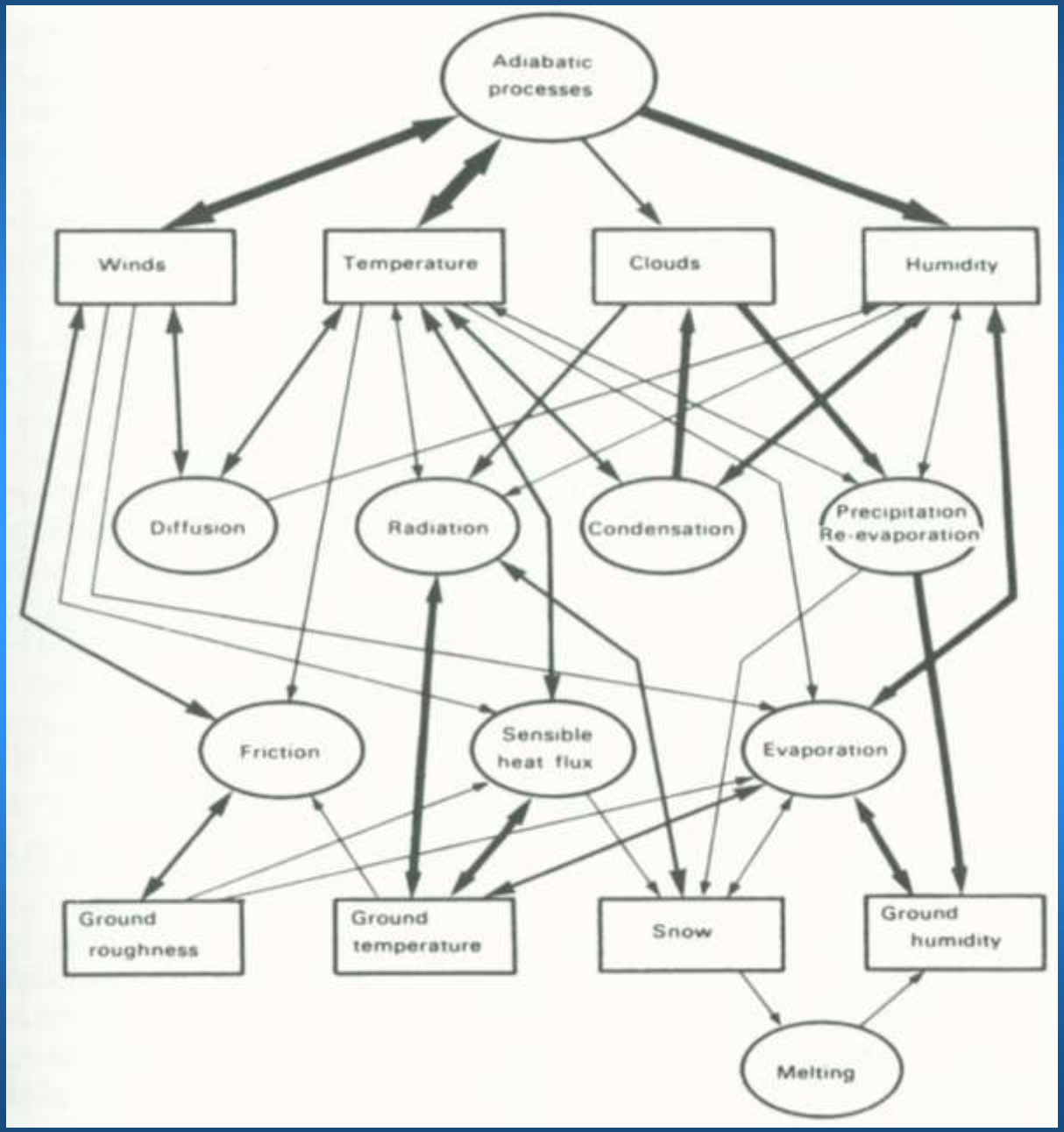
Do the parameterizations realistically represent the energy transported by the turbulence in numerical models?

Climate modeling



State-of-the-art climate models now include the interactive representations of the ocean, the atmosphere, the land, the hydrologic and cryospheric processes, terrestrial and oceanic carbon cycles, and atmospheric chemistry.

Physical parameterization



1. Boundary layer process (turbulence)

2. Moist convection process

3. Cloud microphysics and precipitation

4. Radiation

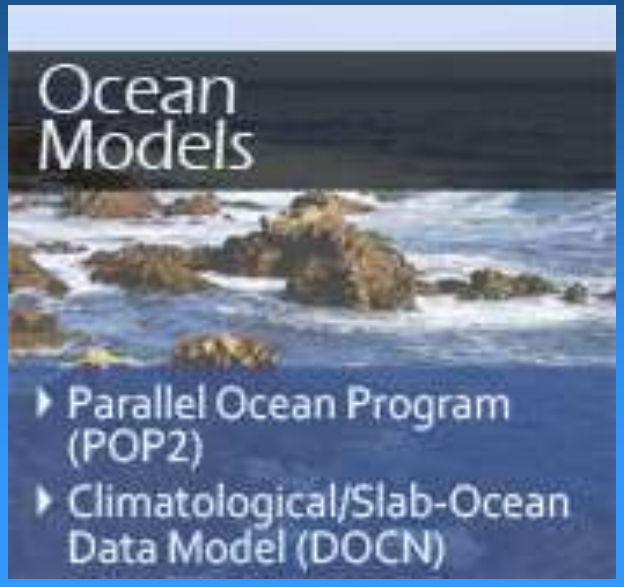
Atmospheric model components:

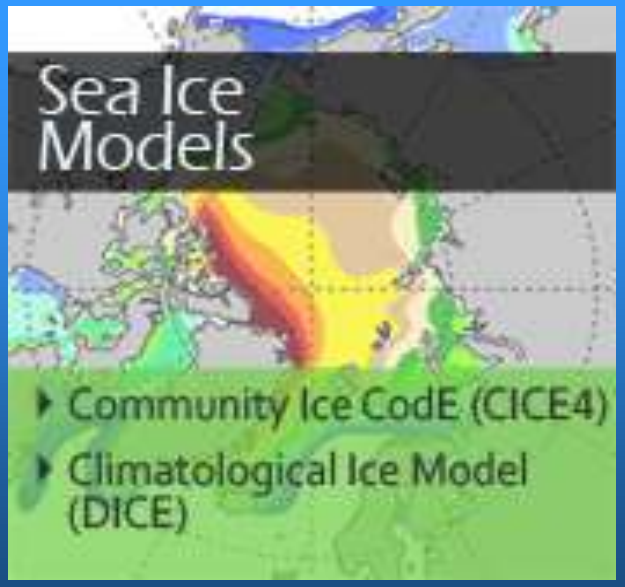
1. Initialization package
2. Dynamic core
3. A suite of parameterizations
4. Coupler with other components in the climate system, such as ocean, land, sea ice, …
5. Post-processing package

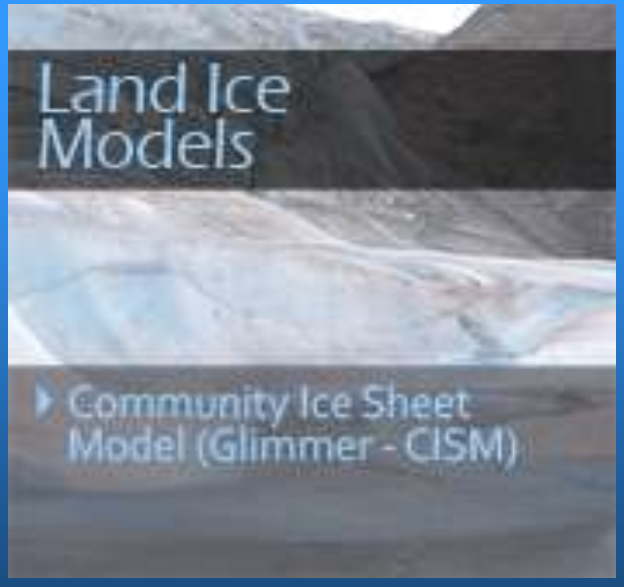
National Center for Atmospheric Research Community Earth System Model

Version	Release	Description
CESM 1.0.3	June 2011	
CESM 1.0.2	December 2010	Notable improvements
CESM 1.0.1	September 2010	
CESM 1.0	June 2010	
CCSM 4.0	April 2010	Notable improvements
CCSM 3.0	June 2004	Notable improvements. Numerous multi-century control runs have been conducted at low, medium, and high resolutions and are available to the general public for examination and analysis.
CCSM 2.0.1	October 2002	Provides an incremental improvement over CCSM2.0. A number of minor problems were fixed, forcing datasets were updated, and a lower-resolution paleo version (T31/gx3v4) of the model was included.
CCSM 2.0	May 2002	All components have been upgraded. Target architectures were IBM SP, SGI Origin 2000, and Compaq/alpha. A multi-century control run was presented at the annual CCSM Workshop in June, 2002.
CCSM 1.4	July 2000	This version introduces further improvements to the code, build procedures, and run scripts. This code distribution will run on Cray machines and SGI Origin 2000 machines.
CCSM 1.2	July 1998	This version introduces a choice of two atm/lnd resolutions, T31 and T42, and two ocn/ice resolutions, 3x3 and 2x2 degree. Also, the atm and lnd models are now separate components. This code distribution runs on NCAR Cray machines.
CCSM 1.0	June 1996	This was the first public release of the CCSM software. This code and corresponding control runs were presented at the firest CSM Workshop in May 1996.

NCAR CESM 1.0







http://www.cesm.ucar.edu/models/cesm1.0/

Cloud-Aerosol-climate feedback

Cloud formation

Two processes, acting together or individually, can lead to air becoming saturated: cooling the air or adding water vapor to the air. But without cloud nuclei, clouds would not form.

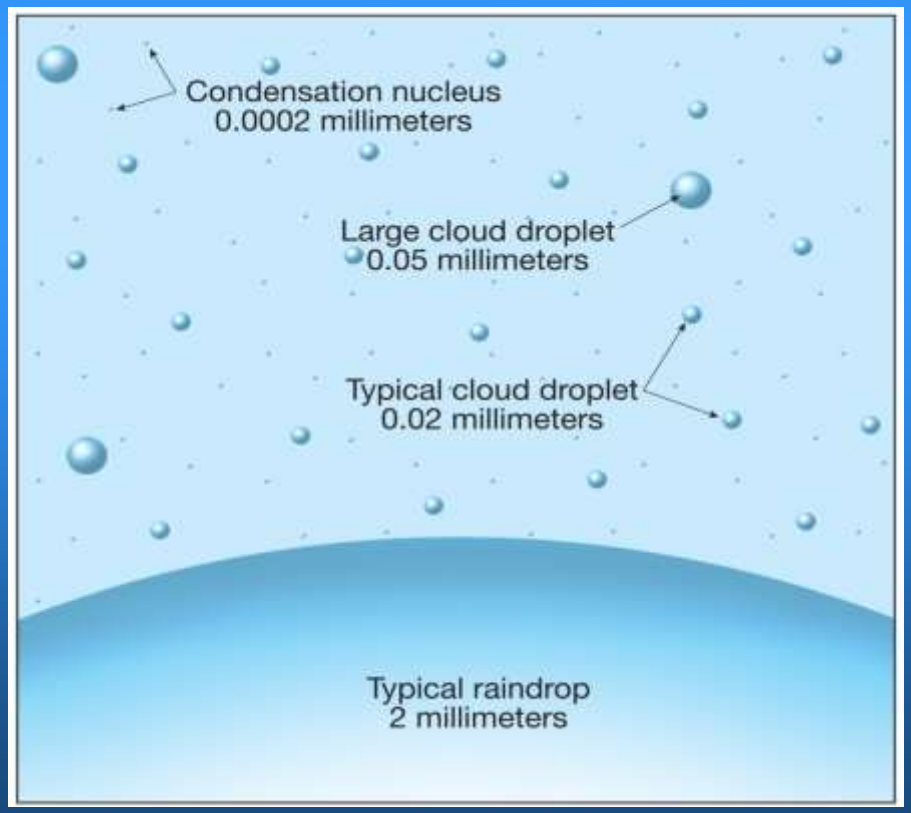
without cloud nuclei

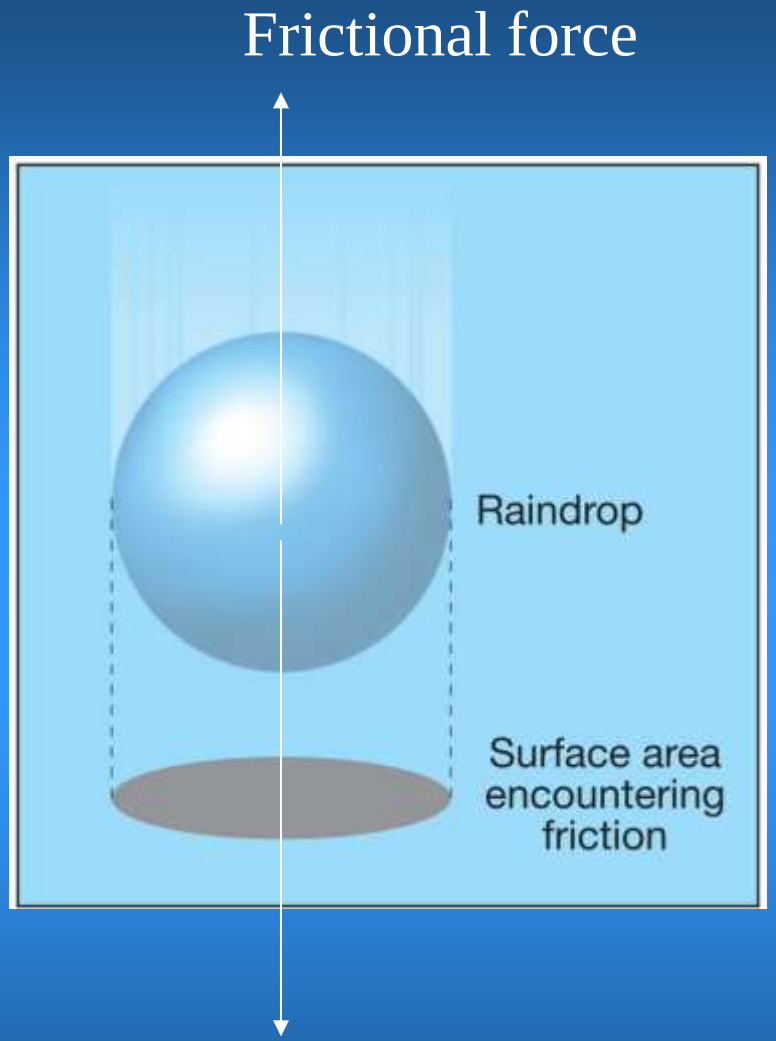
with cloud nuclei

How precipitation forms

Frictional force = Gravitational force

Terminal velocity

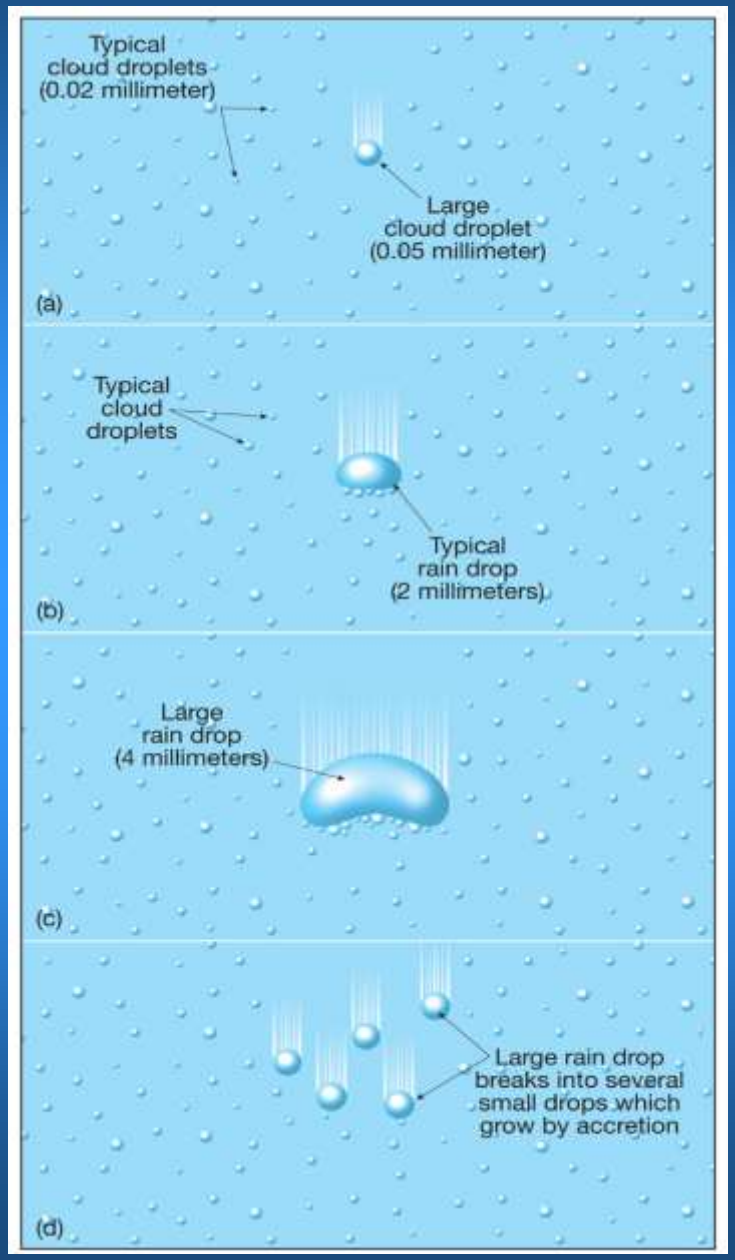




Collision-Coalescence Process

-Larger drops fall faster than smaller drops, so as the drops fall, the larger drops overtake the smaller drops to form larger drops until rain drops are formed.

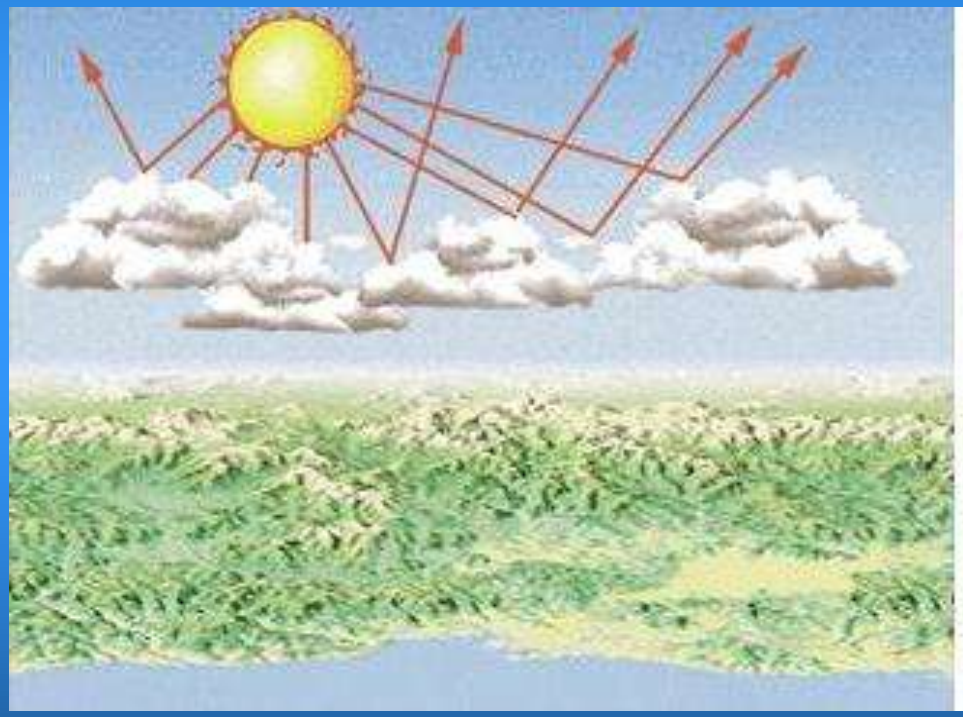
-In a cloud with cloud droplets that are tiny and uniform in size:
-The droplets fall at a similar speed and do not Collide.
-The droplets have a strong surface tension and never combine even if they collide.

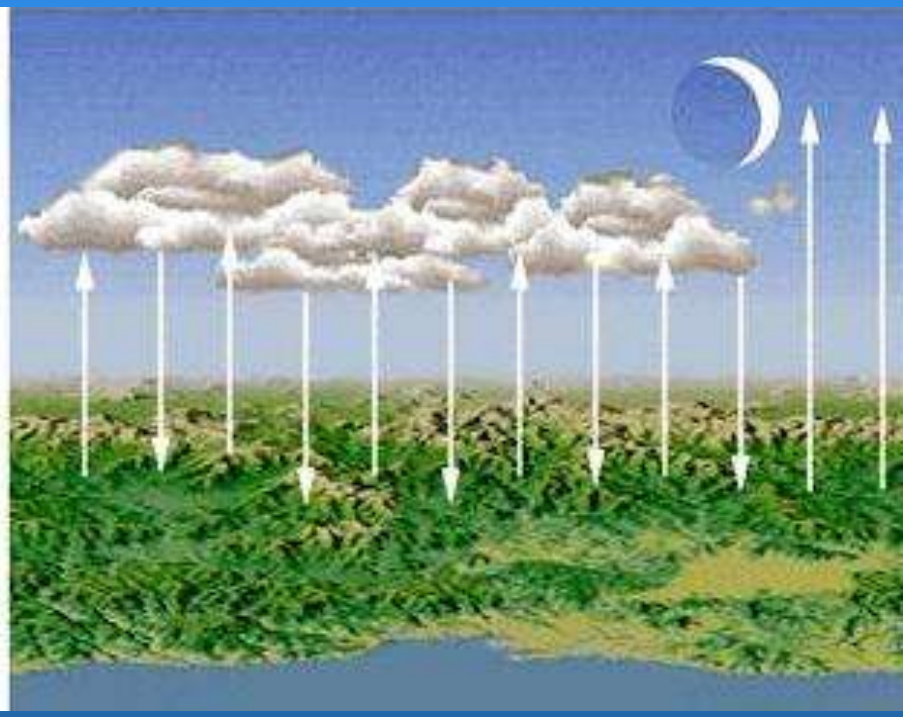


Impact of clouds on climate

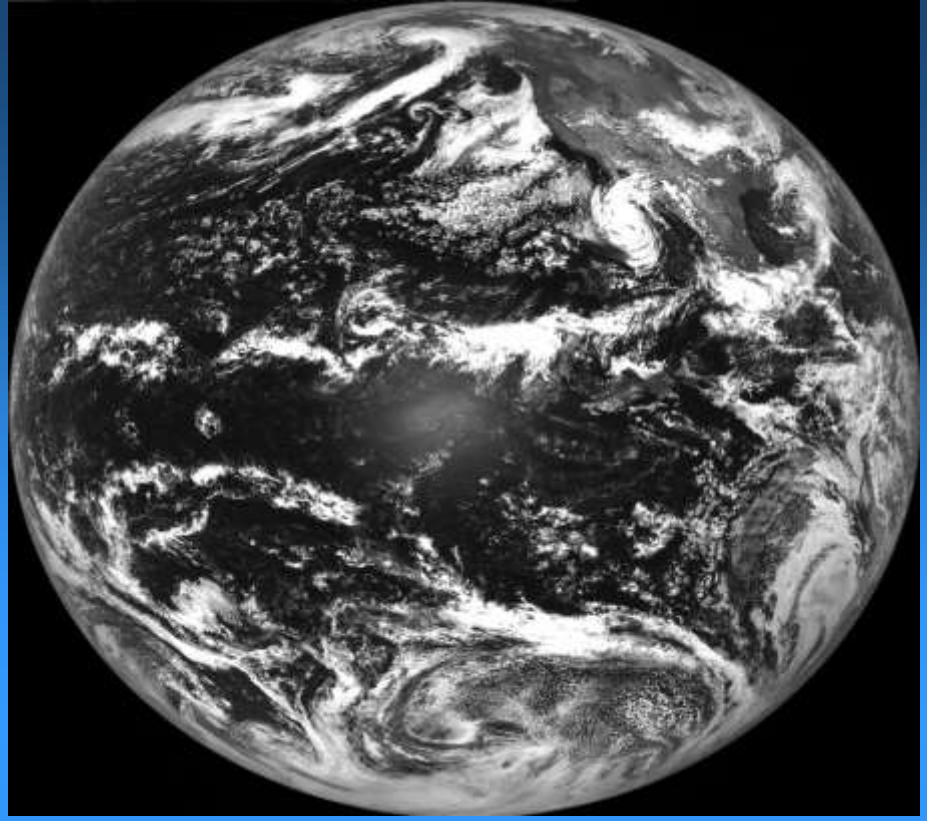
Cooling effect

Warming effect

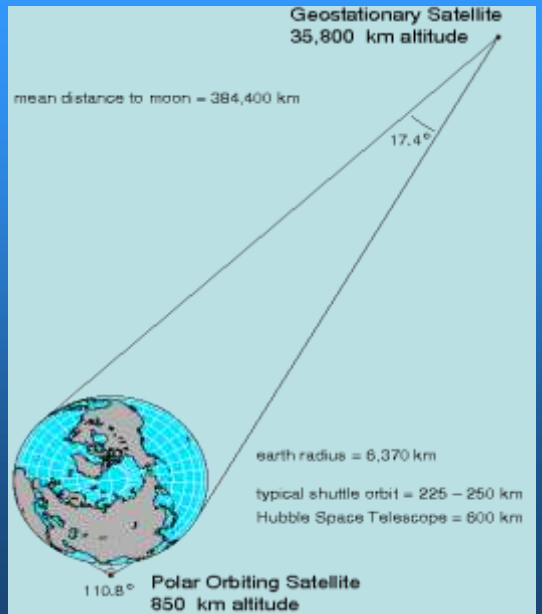




Satellite View of Clouds



Geostationary Satellites



Polar orbit satellite

NASA: The Earth Radiation Budget Experiment (ERBE)

It measures the energy budget at the top of the atmosphere.

Energy budget at the top of atmosphere (TOA)

Incoming solar radiation 340 W/m2

Incoming solar radiation 340 W/m2

Reflected SW radiation
Q1= 50 W/m2

Reflected SW radiation
Q= 100 W/m2

Fictitious climate system

shortwave cloud forcing
dQ=Q1-Q=-50 W/m2 (cooling)

Present climate system

No clouds

Emitted LW radiation
F1= 270 W/m2

Emitted LW radiation
F= 240 W/m2

with clouds

longwave cloud forcing
dF=F1-F=30 W/m2 (warming)

SW cloud forcing = clear-sky SW radiation – full-sky SW radiation

LW cloud forcing = clear-sky LW radiation – full-sky LW radiation

Net cloud forcing (CRF) = SW cloud forcing + LW cloud forcing

Current climate: CRF = -20 W/m2 (cooling)

But this does not mean clouds will damp global warming! The impact of clouds on global warming depends on how the net cloud forcing changes as climate changes.

Direct radiative forcing due to doubled CO2, G = 4 W/m2

$$\lambda = \frac{\Delta \mathrm{CRF}}{\mathrm{G}}$$

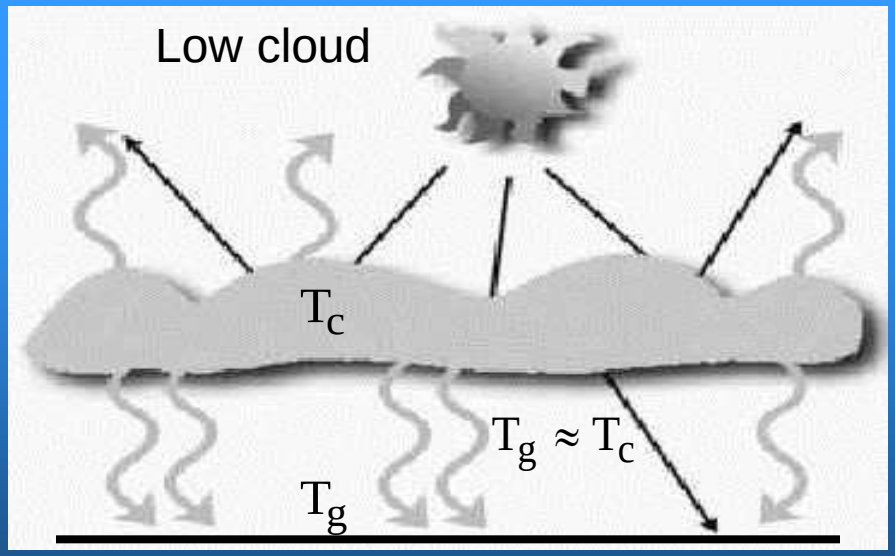
$\lambda > 0 \rightarrow$ positive cloud feedback

$\lambda = 0 \rightarrow$ zero cloud feedback

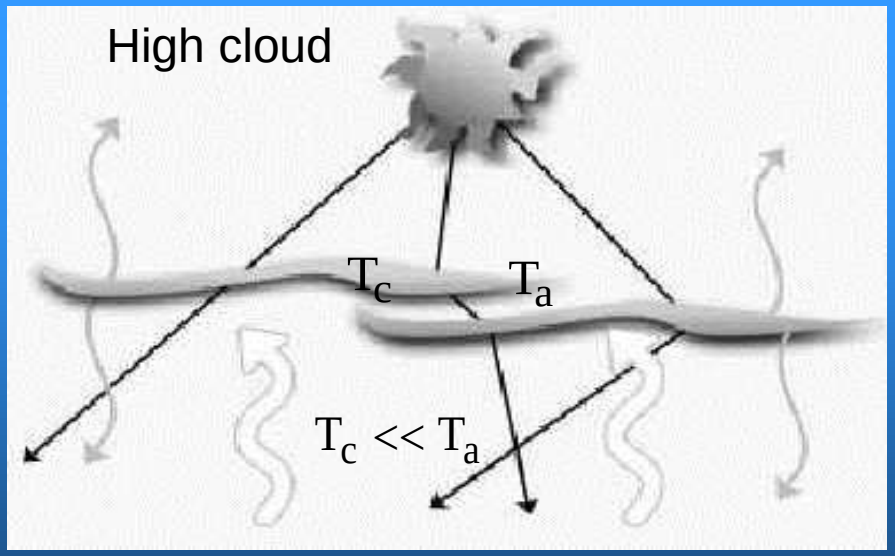
$\lambda < 0 \rightarrow$ negative cloud feedback

e.g. If the net cloud forcing changes from -20 W/m2 to -16 W/m2 due to doubling CO2, the change of net cloud forcing $\Delta CRF = -16 - (-20) = 4\ W/m^2$ will add to the direct CO2 forcing. The global warming will be amplified by a fact of 2.

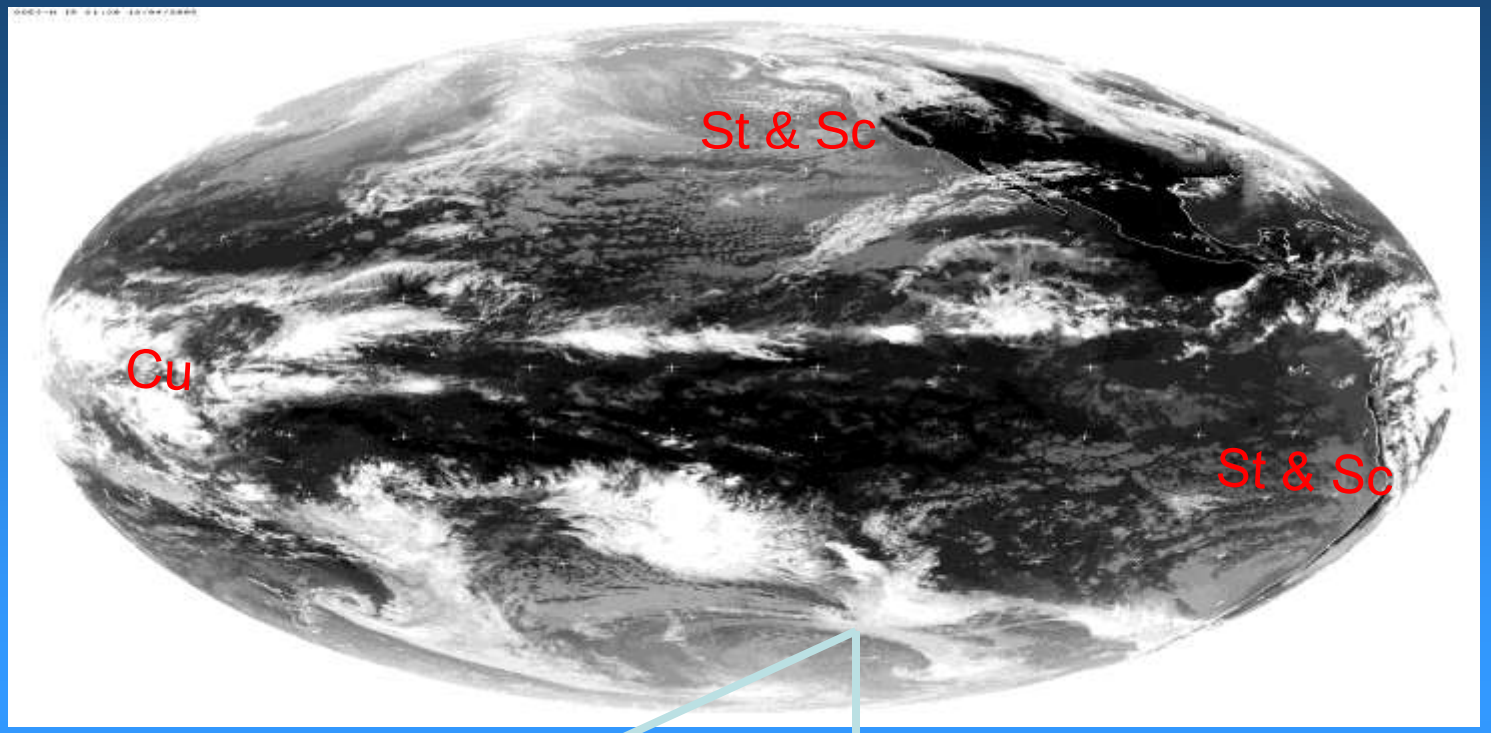
Cloud radiative effects depend on cloud distribution, height, and optical properties.

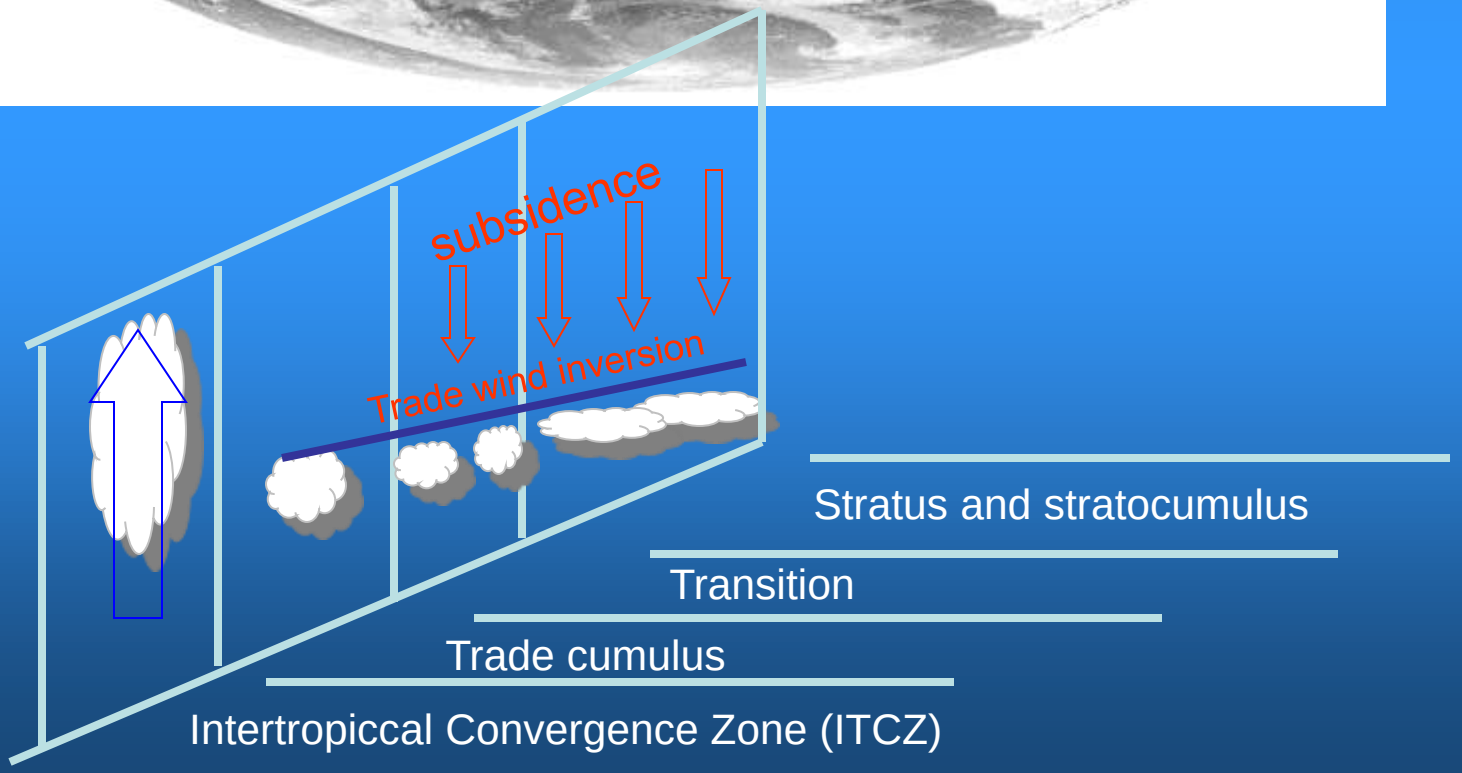


SW cloud forcing dominates

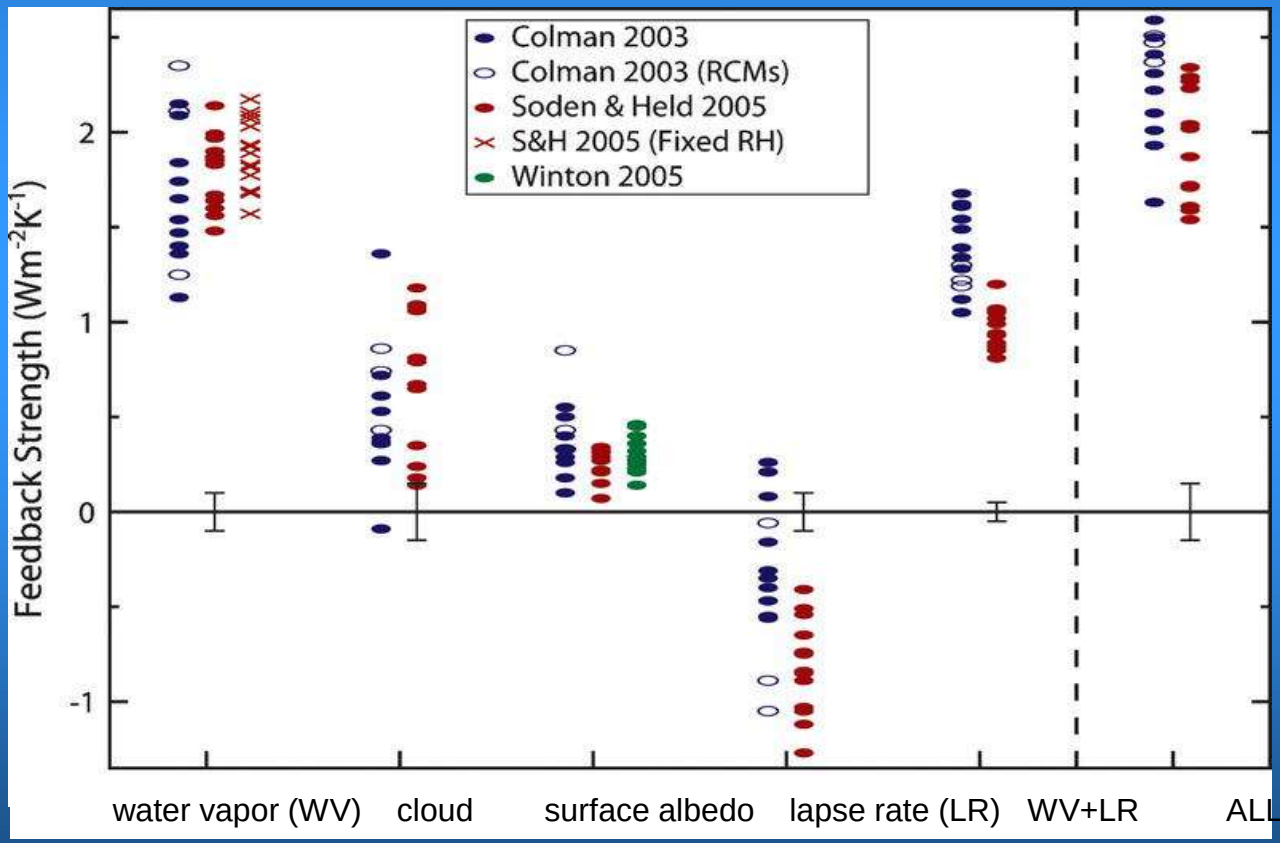


LW cloud forcing dominates


St & Sc
Cu
St & Sc


subsidence
Trade wind inversion
Stratus and stratocumulus
Transition
Trade cumulus
Intertropiccal Convergence Zone (ITCZ)

In GCMs, clouds are not resolved and have to be parameterized empirically in terms of resolved variables.



1. water vapor feedback

$1.80 \pm 0.18\ \mathrm{Wm^{-2}K^{-1}}$

2. lapse rate feedback :

$-0.84 \pm 0.26\ \mathrm{Wm^{-2}K^{-1}}$

3. cloud feedback :

$0.69 \pm 0.38\ \mathrm{Wm^{-2}K^{-1}}$

4. Albedo feedback :

$0.26 \pm 0.08\ \mathrm{Wm^{-2}K^{-1}}$

Aerosol feedback

Aerosols: Small particles (mostly sulfate and nitrate) suspended in the atmosphere by industrial activity (such as coal combustion) or volcanic activity.

Unlike the well-mixed greenhouse gases, industrial aerosols resides in the lower atmosphere for only a short amount of time, and therefore must constantly be produced in order to have a sustained climate impact.

The impacts of aerosols are more regionally limited and variable than those of greenhouse gases.

Direct aerosol effect: scattering, reflecting, and absorbing solar radiation by particles.

Aerosol feedback

Direct aerosol effect: scattering, reflecting, and absorbing solar radiation by particles. --cooling

Primary indirect aerosol effect: cloud reflectivity is enhanced due to the increased concentrations of cloud droplets caused by anthropogenic cloud condensation nuclei (CNN). --cooling

Secondary indirect aerosol effect:

1. Certain aerosols act like greenhouse gases. –warming
2. Greater concentrations of smaller droplets in polluted clouds reduce cloud precipitation efficiency by restricting coalescence and result in increased cloud cover, thicknesses, and lifetime. --warming

3. Changed precipitation pattern could further affect CCN distribution and the coupling between diabatic processes and cloud dynamics.