Atmospheric modeling and the Community Atmospheric Model (CAM)

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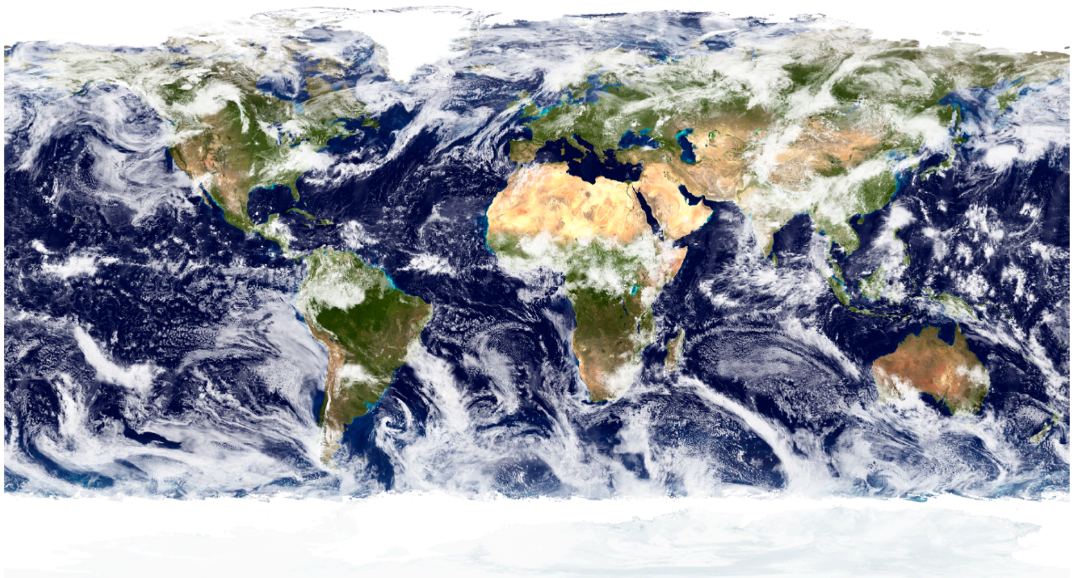
Outline

- Atmospheric modeling framework: equations and grids
- What's a parameterization ?
- The quest of a General Circulation Model at NCAR
- Simulating climate with the Community Atmospheric Model (CAM)

Numerical model of the atmosphere

- Numerical models of the atmosphere are based on the physical laws of fluid.



Source: NASA Earth Observatory

Basic framework =
Spatial grid on which the equations of physics are represented

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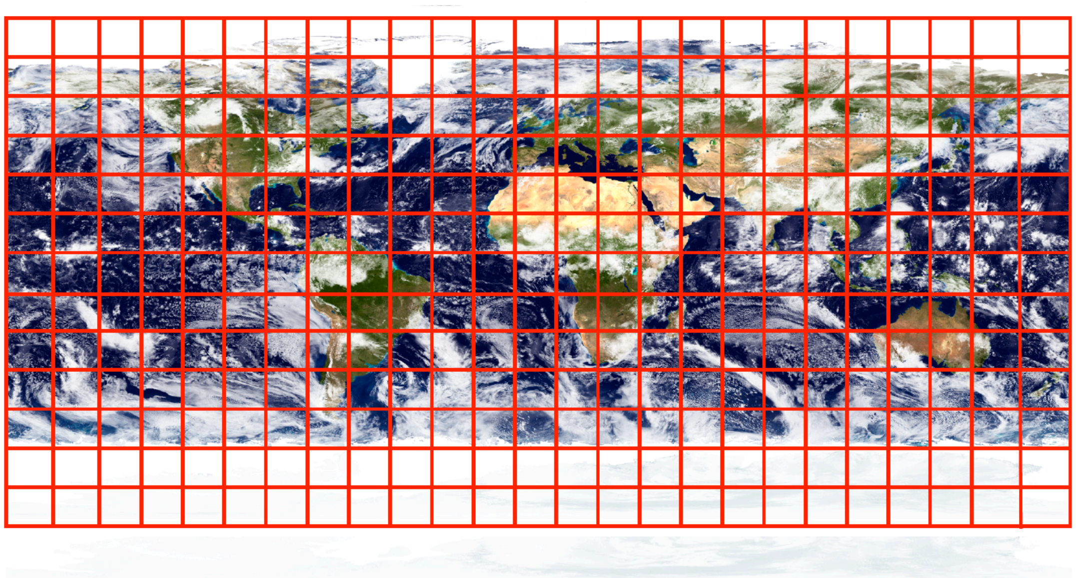


Source: NASA Earth Observatory

Basic framework =
Spatial grid on which the equations of physics are represented

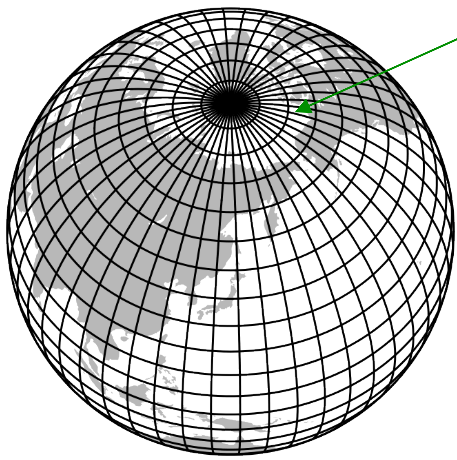
Red lines = lat/lon grid

Grid cell = smallest scale that can be resolved but many important process occurs on sub-grid scales

Courtesy: Peter Lauritzen

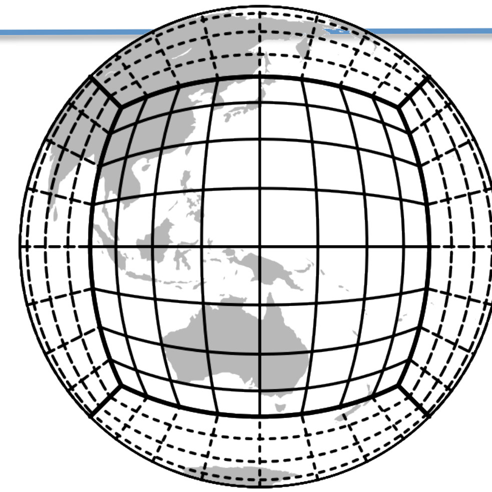
Atmospheric grids

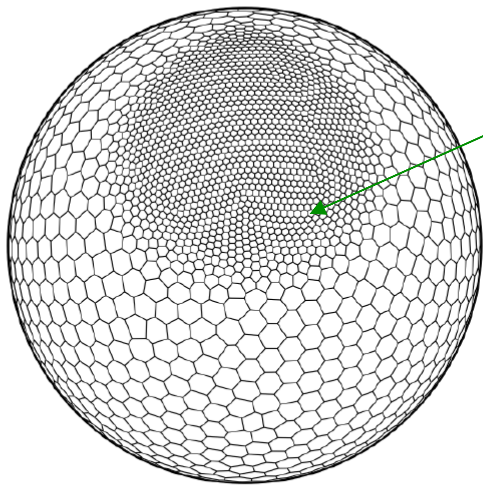
LATITUDE-LONGITUDE GRID



Problem near the poles where longitudes converge

CUBED SPHERE GRID

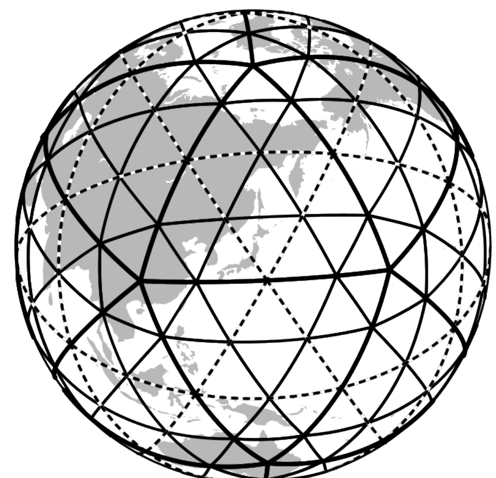


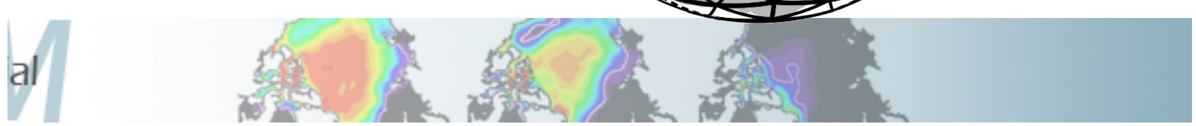


Regional focus

Figure V.1. A variable resolution grid based on a Spherical Centroidal Voronoi Tesselation.

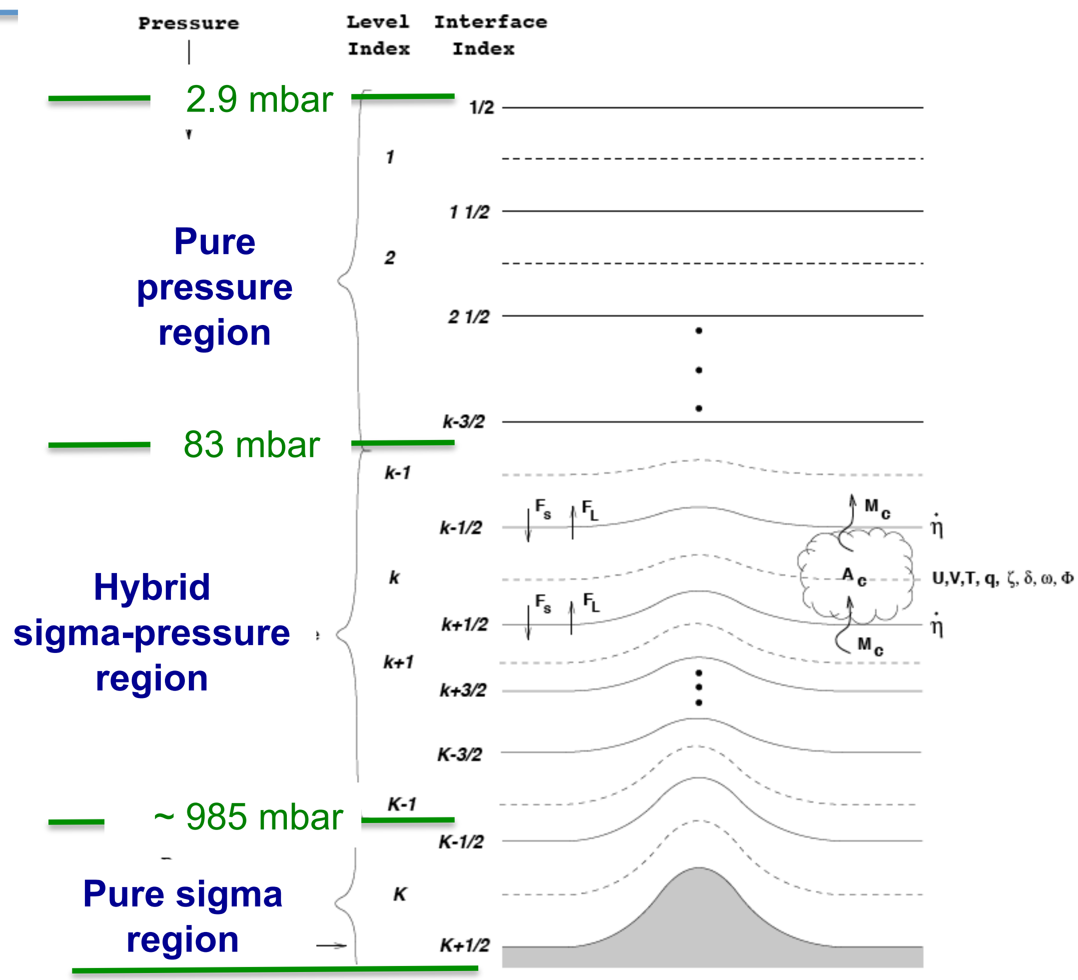
SPHERICAL GEODESIC OR ICOSAHEDRAL GRID





Vertical grid

- Vertical resolution is also important for quality of simulations
- Levels are not equally spaced (levels are closer near surface and near tropopause where rapid changes occurs)
- In CAM: “hybrid” coordinate
  - bottom: sigma coordinate (follows topography)
  - top: pressure coordinate
  - middle: hybrid sigma-pressure



Vertical level structure of CAM 4.0

Vertical grid

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- In CAM: “hybrid” coordinate
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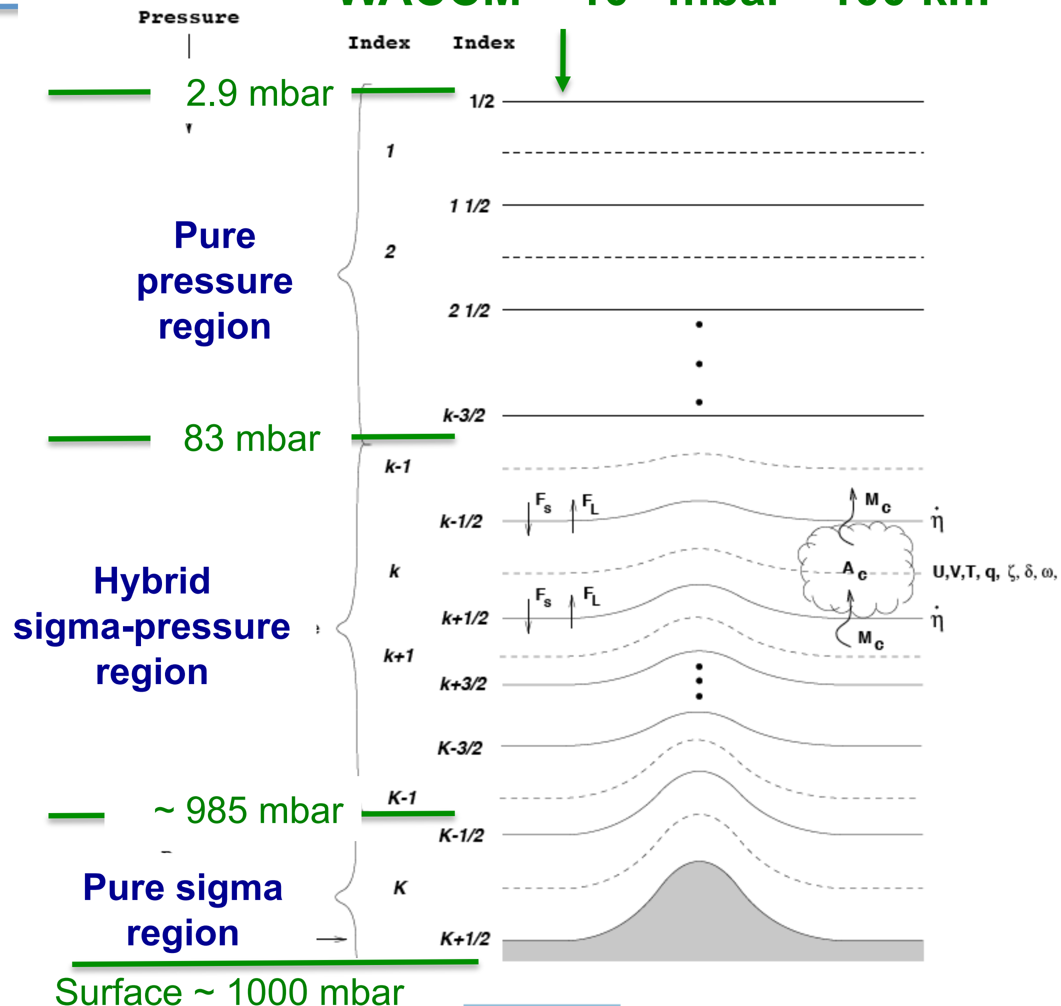
  - top: pressure coordinate
  - middle: hybrid sigma-pressure

Model top:
CAM = 2 mbar - 40 km
WACCM = 10^{-6} mbar - 100 km



Vertical level structure of CAM 4.0

The hydrostatic primitive equations

- Simplified form of the equations of motion: the primitive equations

  - Atmosphere is in hydrostatic balance (good for horizontal grid > 10 km) compression due to gravity is balanced by a pressure gradient force

    (*involves ignoring acceleration in the vertical component of the momentum equations*)

  - Earth is assumed to be spherical and some other small terms in the momentum equations are neglected (*atmosphere is thin compared to its horizontal extent*)

The hydrostatic primitive equations

- Simplified form of the equations of motion: the primitive equations

Momentum conservation: $$d\overline{\mathbf{V}}/dt + fk \times \overline{\mathbf{V}} + \nabla\overline{\phi} = \mathbf{F},$$

Energy conservation: $$d\overline{T}/dt - \kappa\overline{T}\omega/p = Q/c_p,$$

Mass conservation: $$\nabla \cdot \overline{\mathbf{V}} + \partial\overline{\omega}/\partial p = 0,$$

Hydrostatic balance: $$\partial\overline{\phi}/\partial p + R\overline{T}/p = 0,$$

Water vapor conservation: $$d\overline{q}/dt = S_q.$$

The hydrostatic primitive equations

- Simplified form of the equations of motion: the primitive equations

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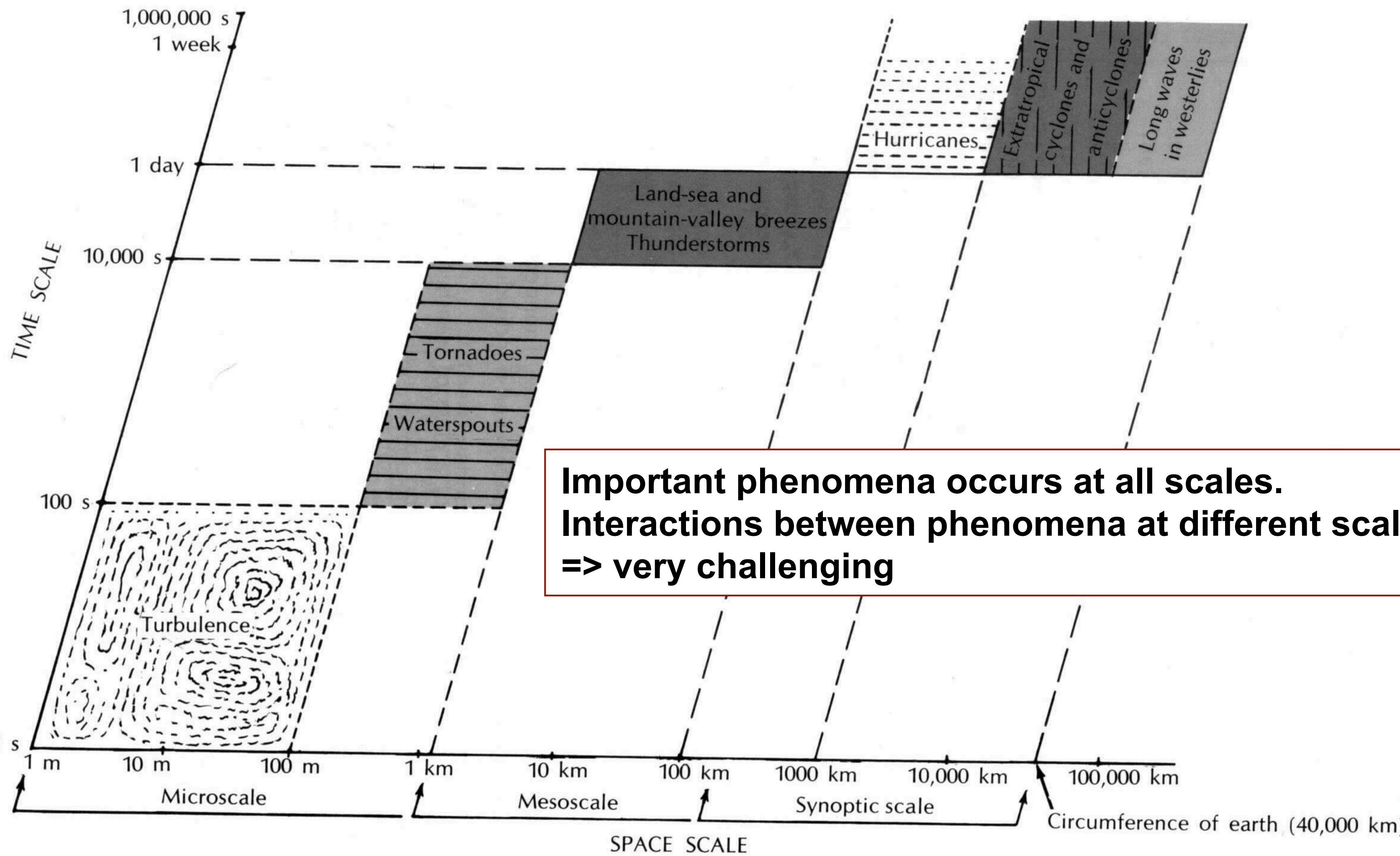
Hydrostatic balance: $\partial\overline{\phi}/\partial p + R\overline{T}/p = 0,$

Water vapor conservation $d\overline{q}/dt = S_q.$

Source and sinks due to phenomena occurring on scales smaller than grid resolution

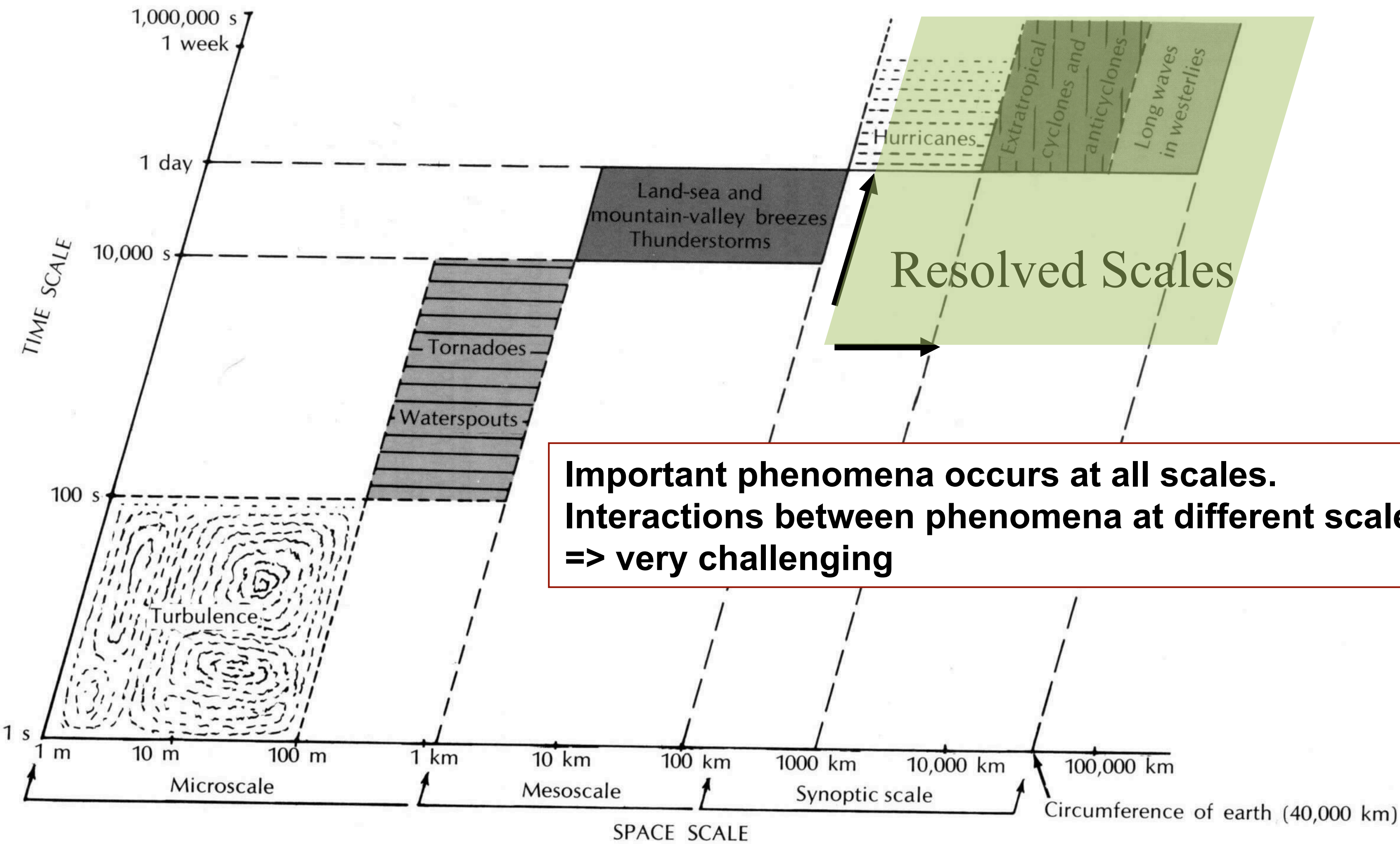
Parameterized processes or "the physics"

Scales of Atmospheric Processes



Important phenomena occurs at all scales.
Interactions between phenomena at different scales
=> very challenging

Scales of Atmospheric Processes



Important phenomena occurs at all scales.
Interactions between phenomena at different scales
=> very challenging

Summary

- Numerical models of the atmosphere are based on the physical laws of fluid.

- Basic framework
  Spatial grid on which the equations of physics are represented.
  Grid cell = smallest scale that can be resolved
  but many important processes occur on sub-grid scales

Roughly speaking:

- The dynamical core solves the governing fluid and thermodynamic equations on resolved scales
- while the parameterization represent the sub-grid scales processes not included in the dynamical core. (Thuburn: 2008)

Outline

- Atmospheric modeling framework: equations and grids
- **What's a parameterization ?**
- The quest of a General Circulation Model
- Simulating climate with the Community Atmospheric Model (CAM)

Physical parameterization

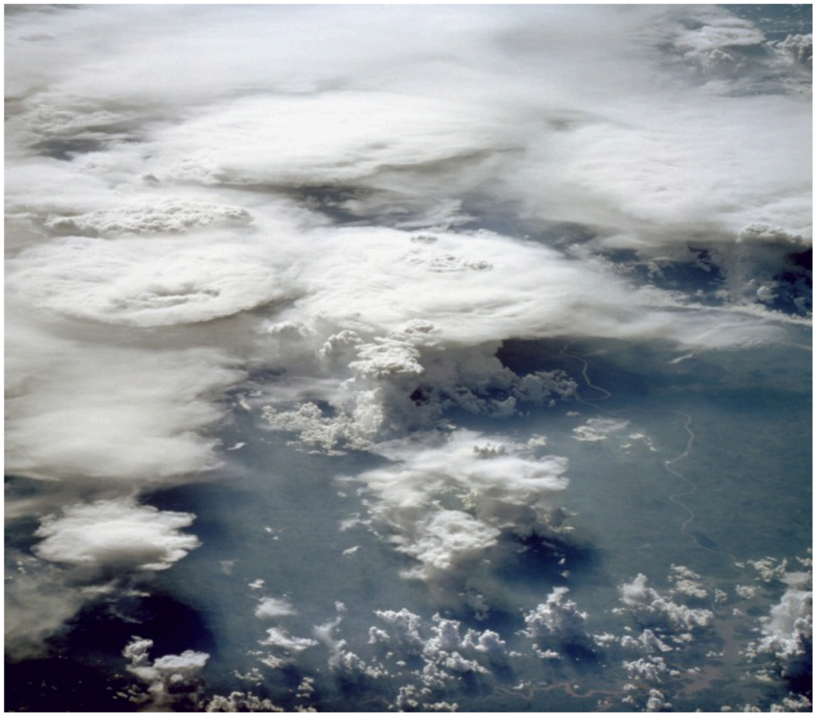
- Parameterization = process of including the effect of unresolved phenomena

- Usually based on:
  - Basic physics (law thermodynamics)
  - Empirical formulation from observations

- Key parameterizations in atmospheric model: radiation, effects of unresolved turbulence and gravity waves, effects of convection on heat, moisture and momentum budgets.

- Behavior of model is critically dependent of these parameterization processes

Example: Clouds



Courtesy: Andrew Gettelman

Cloud parameterization

- Let’s build a simple parameterization for clouds

- Need some basic theories

  water vapor cannot be supersatured

  at saturation => water vapor condensates

  our theory: Relative Humidity (RH) ≤ 100%

Relative Humidity (RH)

$$RH = \frac{e}{e_{sat}} \times 100$$

water vapor pressure (e)

saturation water vapor pressure (e_{sat})

- Add some rules to define it (‘closure’)

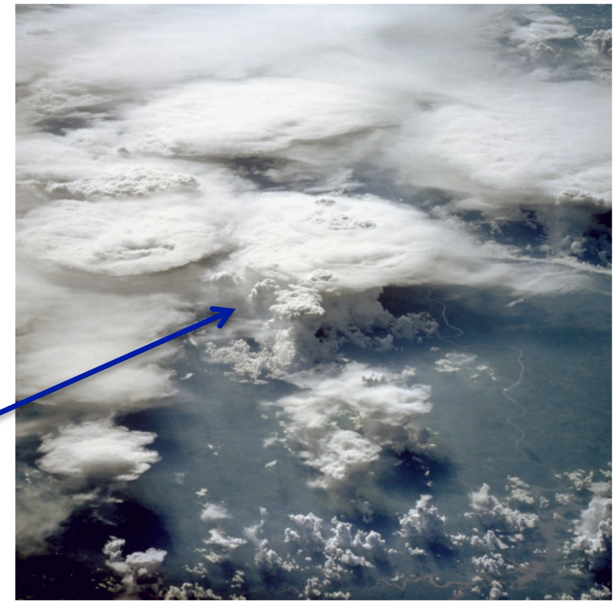
  If RH < 100%: cloud = 0

  If RH = 100%: cloud = 1

- Done ! Now we have a cloud parameterization

Courtesy: Andrew Gettelman

Sub-grid processes



• Our cloud parameterization:

If RH < 100% => cloud = 0

If RH = 100% => cloud = 1

doesn't take into account
sub-grid scale variation of relative humidity

The relative humidity is
not uniform over the grid cell

• Let's take our cloud parameterization one step further and let's introduce:
"Fractional cloudiness" or "cloud macrophysics"

Sub-grid relative humidity (RH) and clouds

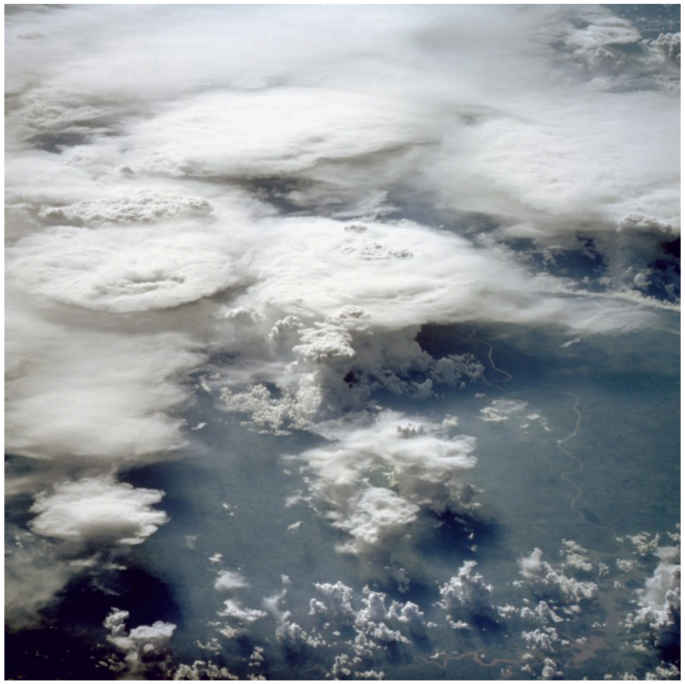
• Locally clouds form when RH = 100%

• But if there is a variation in RH in space, clouds will form before mean RH = 100%

• To take into account sub-grid scale variability of relative humidity, we can use

If RH < 90%   => cloud fraction = 0
If RH [90-100]% => cloud fraction = [0,1]
If RH = 100%   => cloud fraction = 1

NB: 90% is an arbitrary threshold



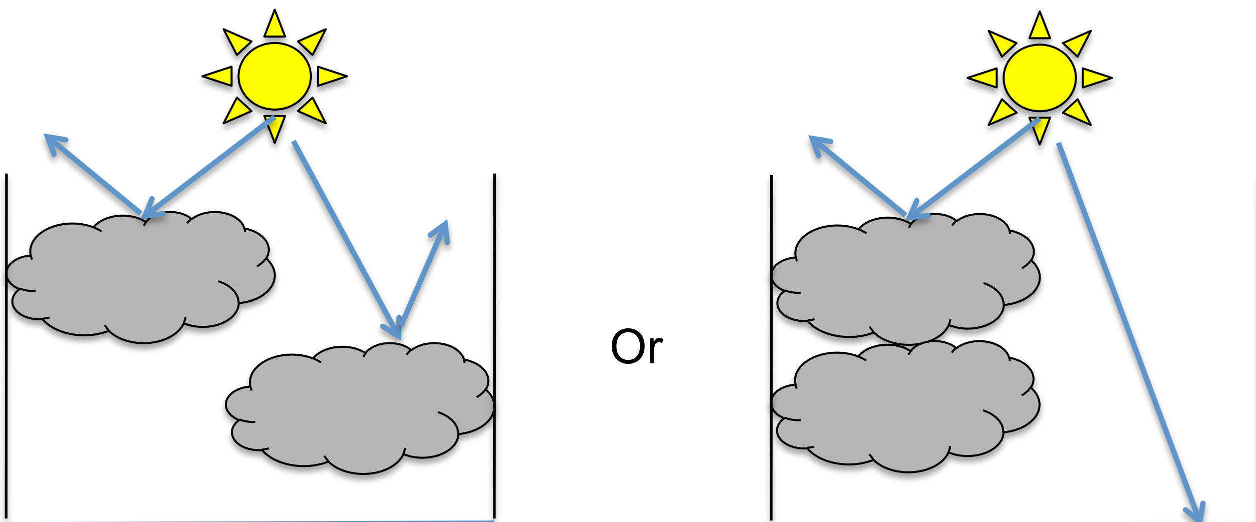
Vertical distribution of clouds

• Now, we have a cloud fraction parameterization that takes into account sub-grid scale variability of relative humidity.

• We can compute the cloud fraction at each level of the model.

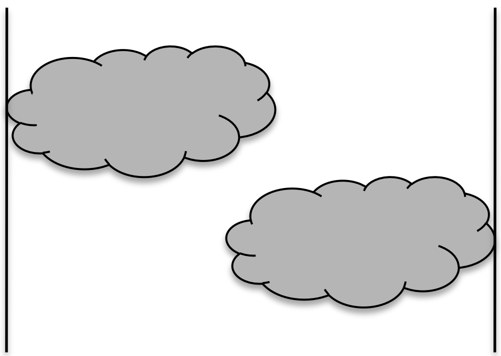
• Now, the question is: *how do we distribute the clouds in the vertical ?*

• For radiation purpose, it is very different to have:



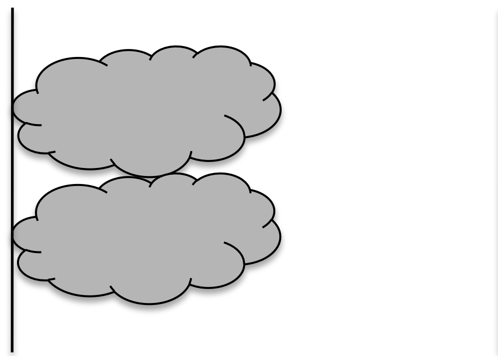
Cloud overlap assumptions

Minimum overlap



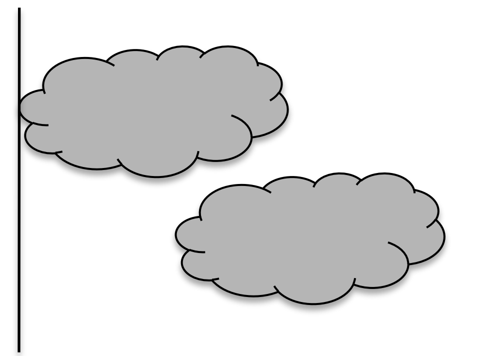
$C = C1 + C2$

Maximum overlap



$C = \max(C1, C2)$

Random overlap

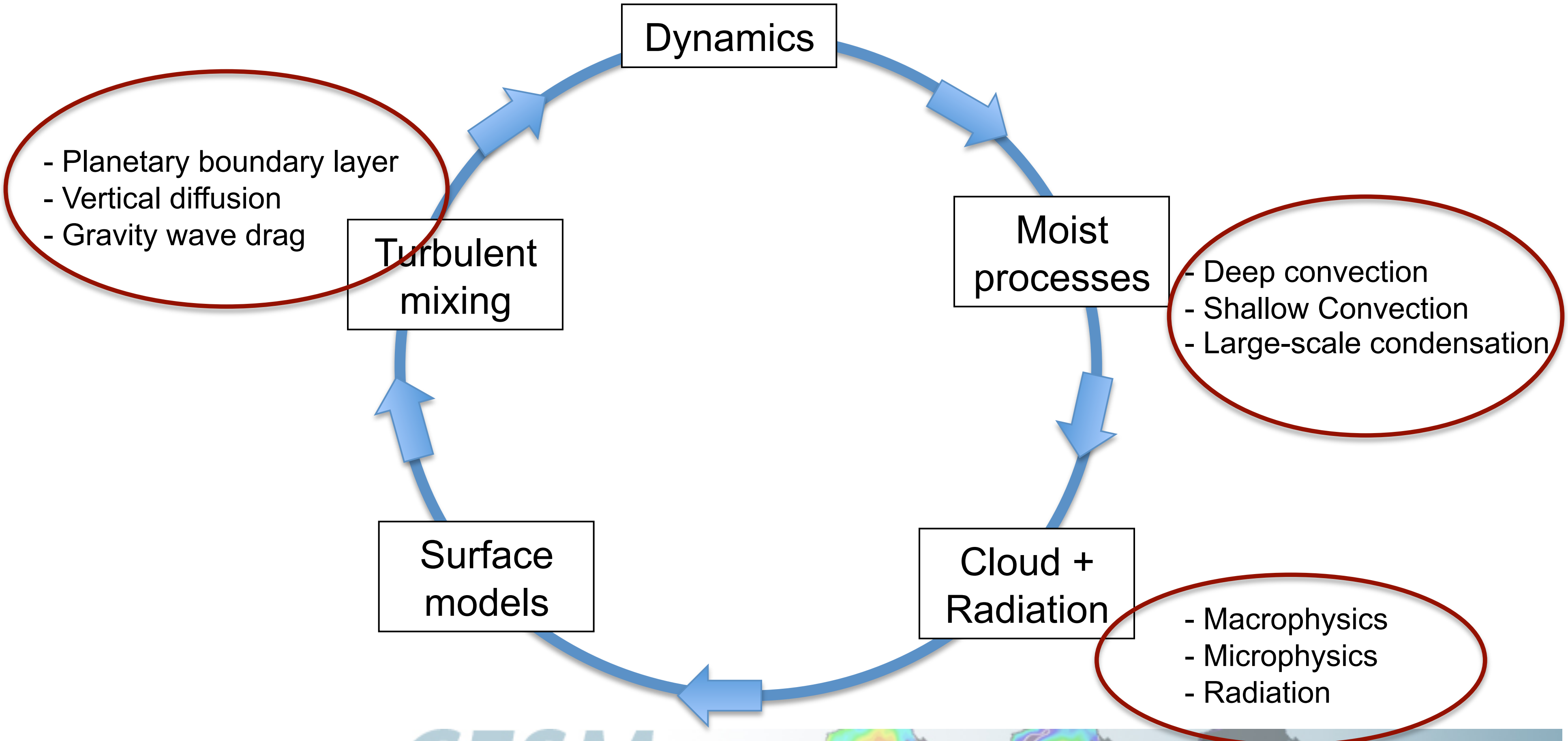


$C = 1 - (1-C1)(1-C2)$

A common assumption in atmospheric models is : **maximum-random overlap**
- maximum overlap for adjacent clouds (*"it is the same cloud"*)
- random overlap for discrete clouds (*"it is two different clouds"*)

CAM parameterizations

- In the previous slides, we have built a simple cloud parameterization
- Many other processes are parameterized in CAM.



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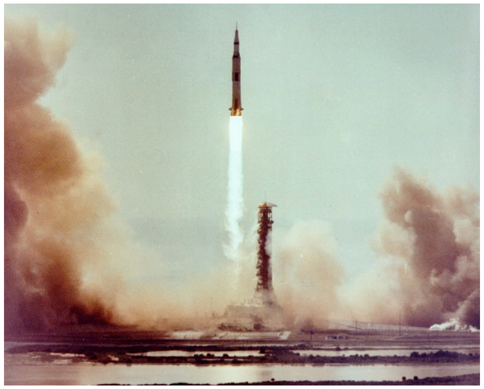
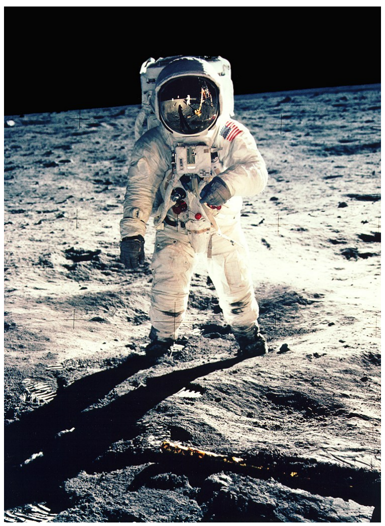
- **The quest of a General Circulation Model at NCAR**
- The Community Atmospheric Model

The late 60s were exciting times



Apollo 11 landed the first man on the moon on July 20, 1969.



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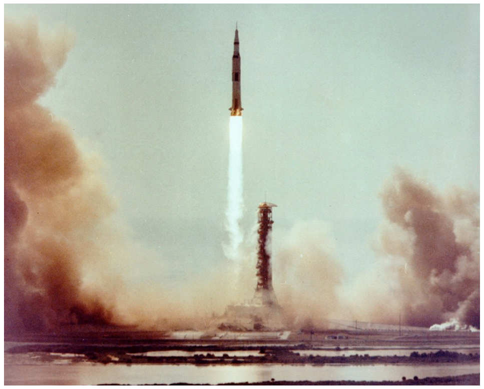

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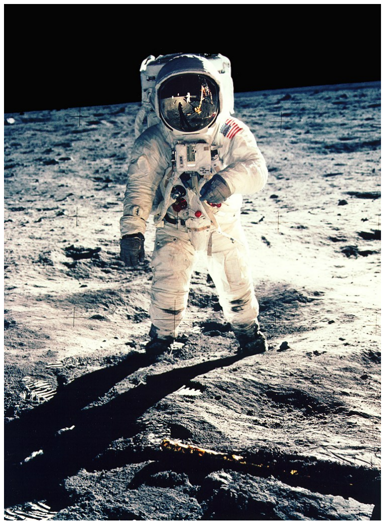


Warren Washington is looking at model output onto microfilm

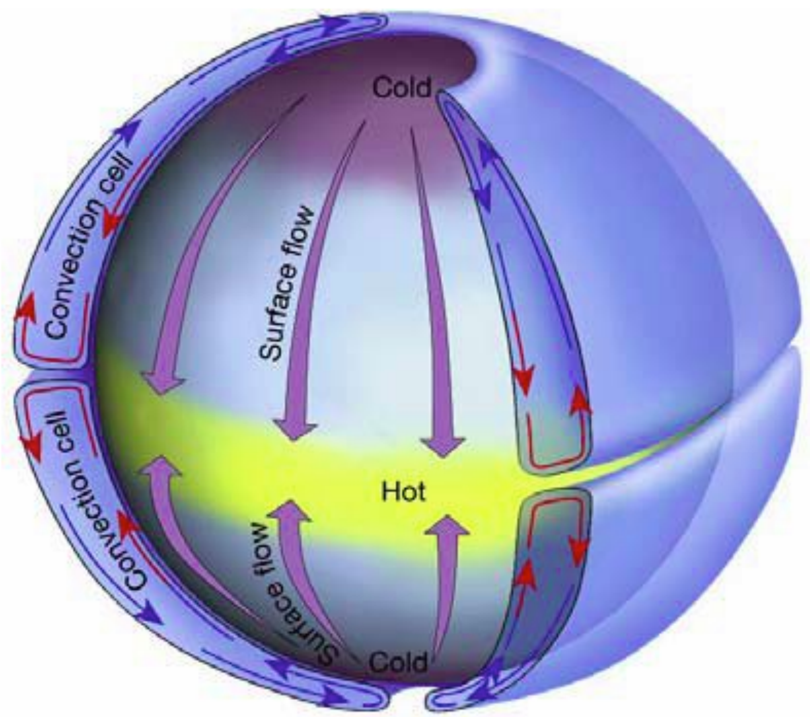
Two young NCAR scientists were among the pioneers into the quest for a GCM

Akira Kashara is retrieving data stored onto nine-track magnetic tapes.

The atmospheric meridional circulation

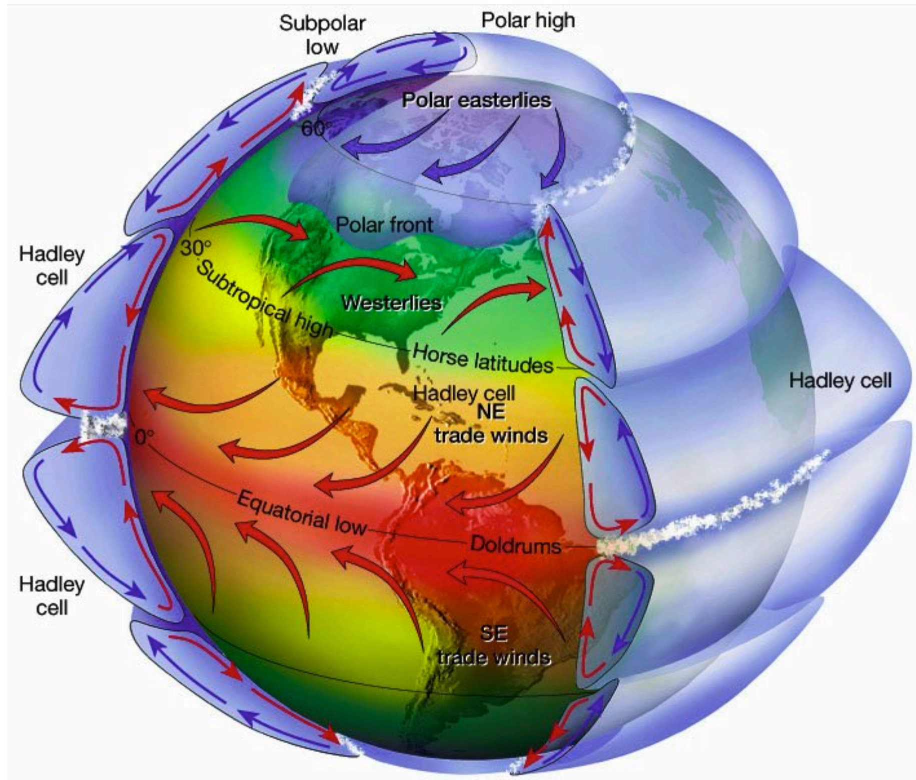
Non-spinning planet

Convective cell due to unequal heating by the sun

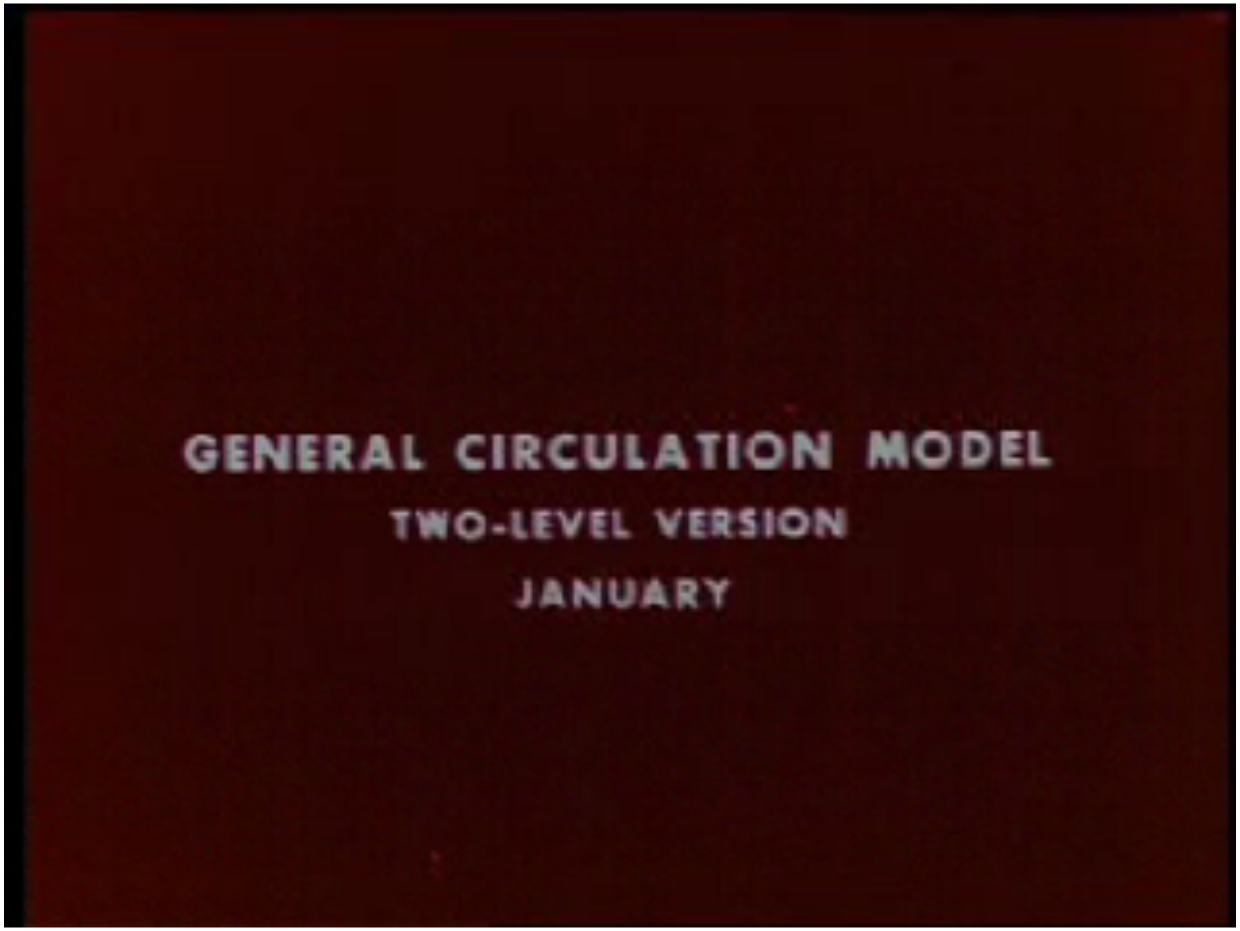


Spinning planet: Coriolis effect

Three-cell model: Hadley cell, the Ferrell Cell and the Polar Cell

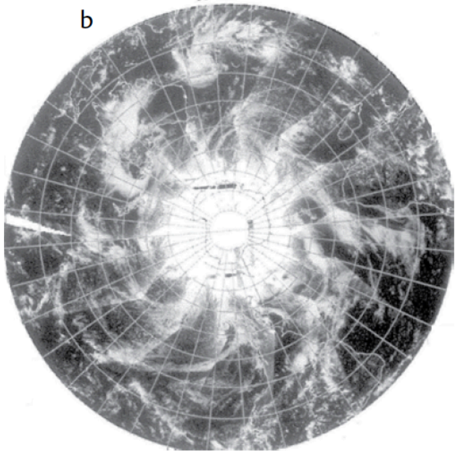


1969: two layer model at 5 degree



Start:
isothermal atmosphere

After 2 weeks:
baroclinic instability

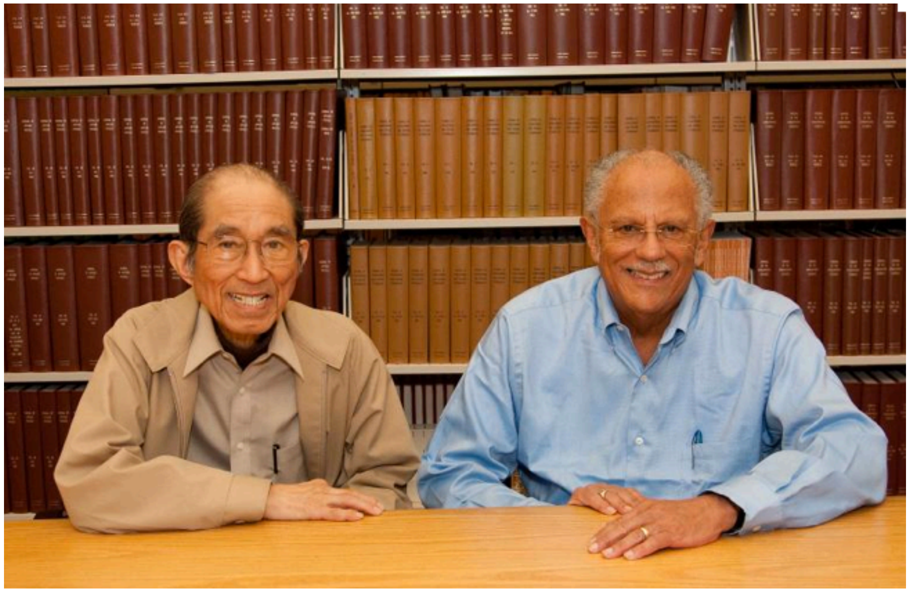


Typical three-cell
meridional circulation

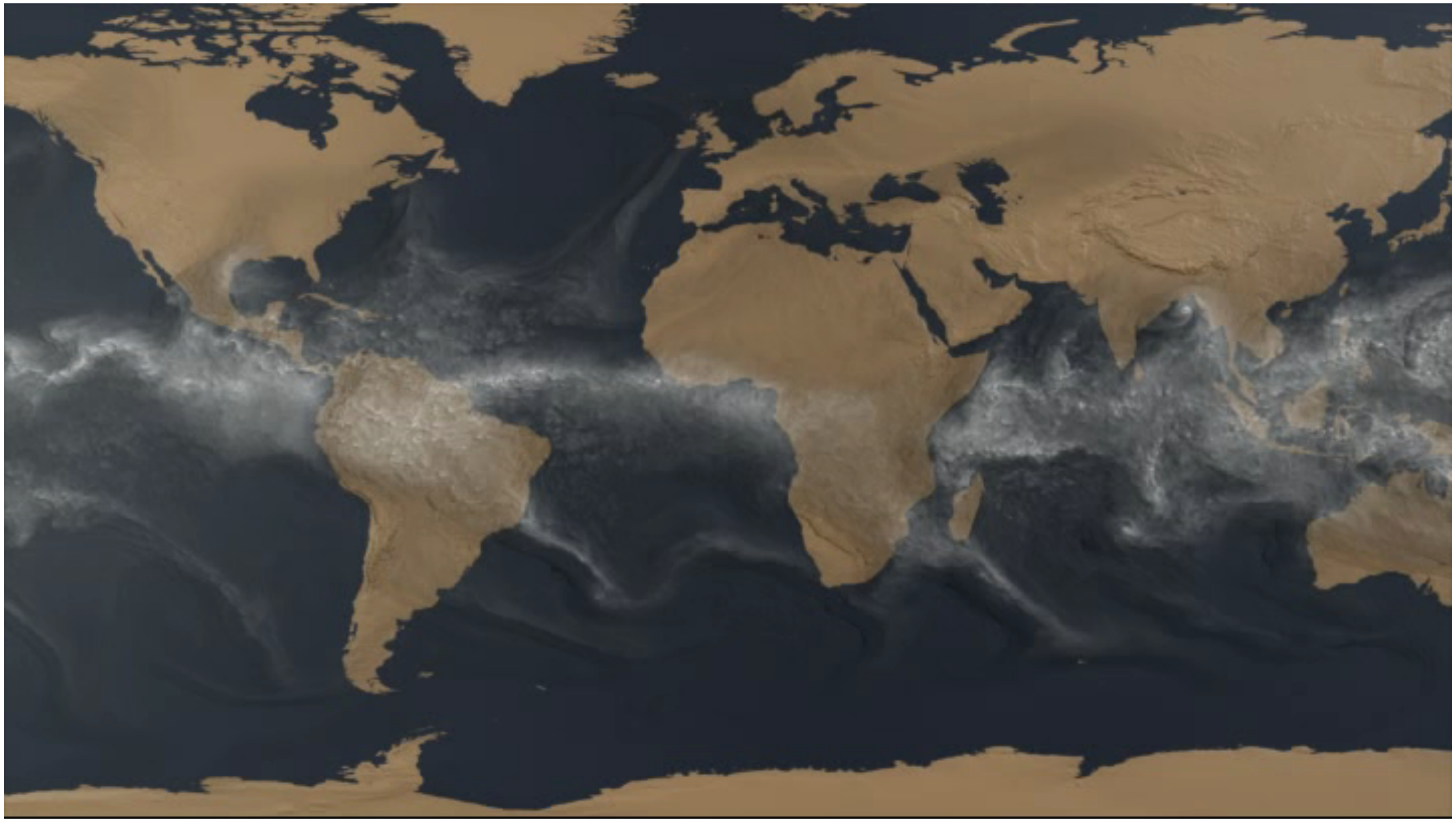
Courtesy: Warren Washington

40 years later…

- We moved away from microfilms and magnetic tapes
- Our pioneers are doing well



Precipitable water in CAM4 (1/8 degree)



Columns=3x10^6

Simulation:
67,000 cores

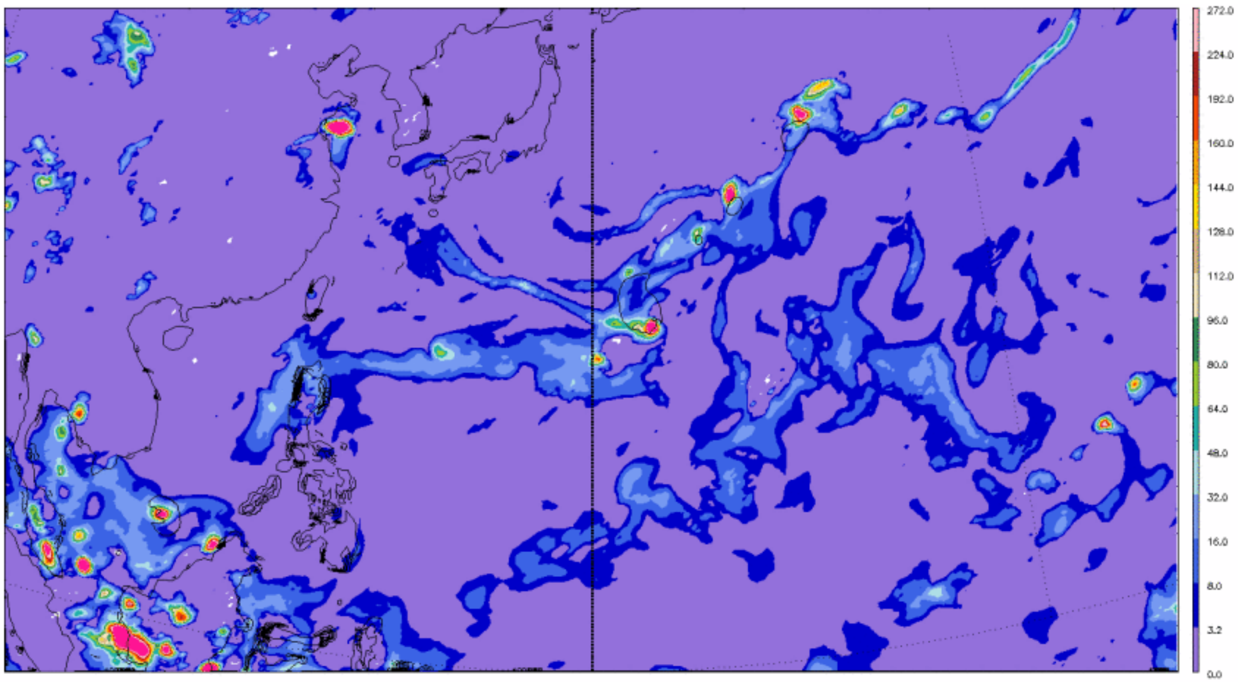
At this resolution, hurricanes and typhoons become visible

Courtesy: Mark Taylor

CAM5 1/4 degree: Fujiwara effect

Two cyclones rotate around each other for a few days and eventually merge, observed mostly in Pacific ocean region.

West Pacific Basin: Sept 1 to Sept 17, 2005



Courtesy, Julio Bacmeister

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The Community Atmospheric Model (CAM)

Model	CAM3	CAM4	CAM5
Release	**June 2004**	**April 2010**	**June 2010**
Shallow Convection	Hack (1994)	Hack (1994)	Park et al. (2009)
Deep Convection	Zhang and McFarlane (1995)	Neale et al. (2008)	Neale et al. (2008)
Microphysics	Rasch and Kristjansson (1998)	Rasch and Kristjansson (1998)	Morrison and Gettelman (2008)
Macrophysics	Rasch and Kristjansson (1998)	Rasch and Kristjansson (1998)	Park et al. (2011)
Radiation	Collins et al. (2001)	Collins et al. (2001)	Iacono et al. (2008)
Aerosols	Bulk Aerosol Model	Bulk Aerosol Model BAM	Modal Aerosol Model Ghan et al. (2011)
Dynamics	Spectral	Finite Volume	Finite Volume

= New parameterization

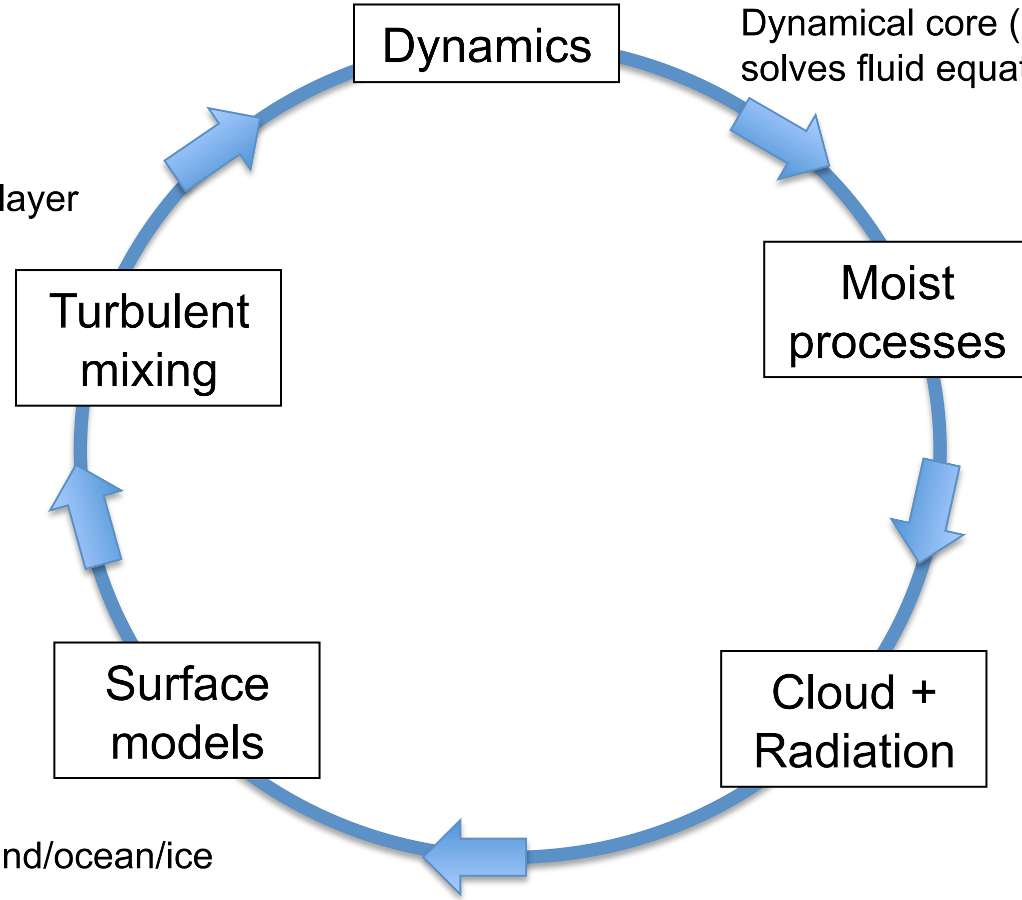
The new little one: CAM5.1

If you are planning to use CAM5 physics, it is recommended to use CAM5.1 when it becomes available

CAM workflow

Dynamical core (Eulerian, Finite volume) solves fluid equations on resolved scales

- Planetary boundary layer
- Vertical diffusion
- Gravity wave drag



- Deep convection
- Shallow Convection
- Large-scale condensation

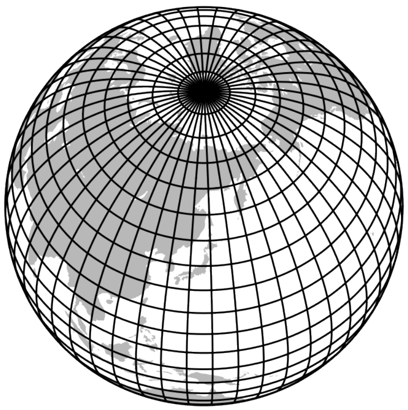
- Macrophysics
- Microphysics
- Radiation

Surface fluxes from land/ocean/ice
- from full models
- from specified surface conditions (Ex: Sea Surface Temperature)

Dynamical cores in CAM

CAM3 (2004)

- Eulerian dynamical core
- Latitude/longitude grid

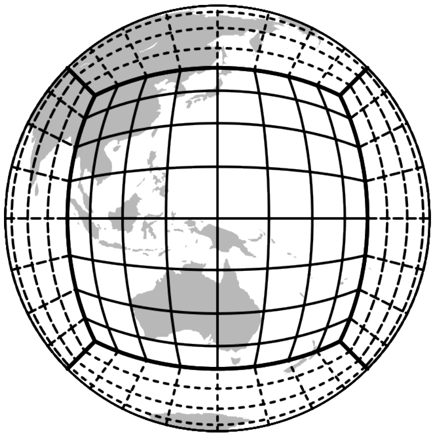


CAM4 and CAM5 (2010)

- Finite volume dynamical core
- Latitude/longitude grid

CAM5.2 (coming in late 2011)

- will likely use spectral element dynamical core
- HOMME (High-Order Method Modeling Environment)
- designed for fully unstructured grids (currently based on cubed sphere grid)



How well does CAM simulate the climate ?

• Simulations of the present-day climate and of the 20th century simulations with CAM4 and CAM5 (surface temperature, cloud, precipitation, Taylor diagrams)

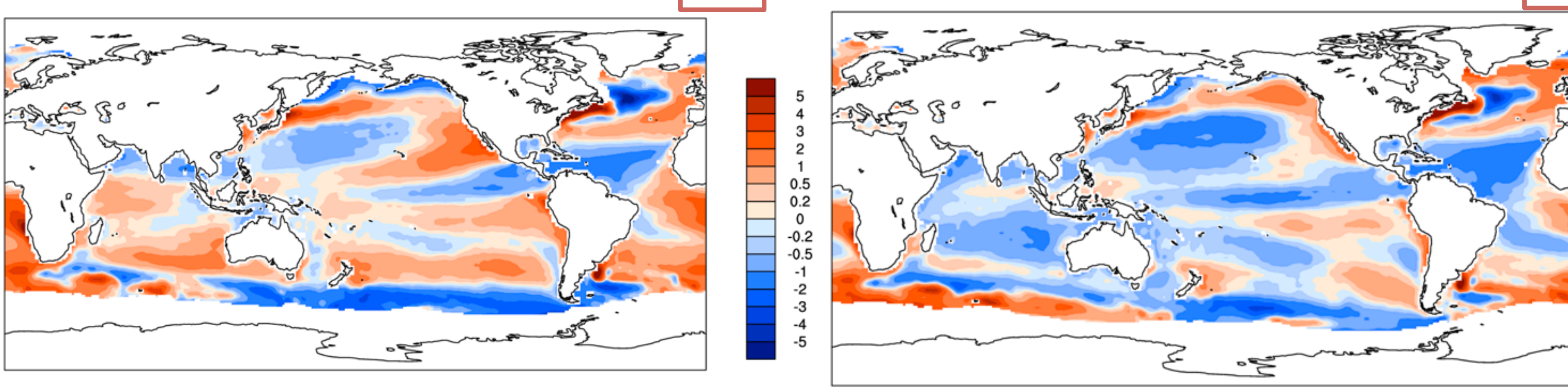
• New capabilities in CAM5: simulate cloud-aerosol interactions

Sea-Surface Temperature errors

- Sea Surface Temperature (SSTs) errors compared to Hurrell dataset
  We use: Error = Model – Dataset
- Root Mean Square Errors (RMSE) reduced in CAM5.1

CESM with CAM4 — **Mean = 0.18**, **RMSE = 1.07**

CESM with CAM5.1 — **Mean = -0.10**, **RMSE = 0.94**



Sea-Surface Temperature errors

- Sea Surface Temperature (SSTs) errors compared to Hurrell dataset
  We use: Error = Model – Dataset

- Root Mean Square Errors (RMSE) reduced in CAM5.1

- Error in stratocumulus regions (Eastern ocean)

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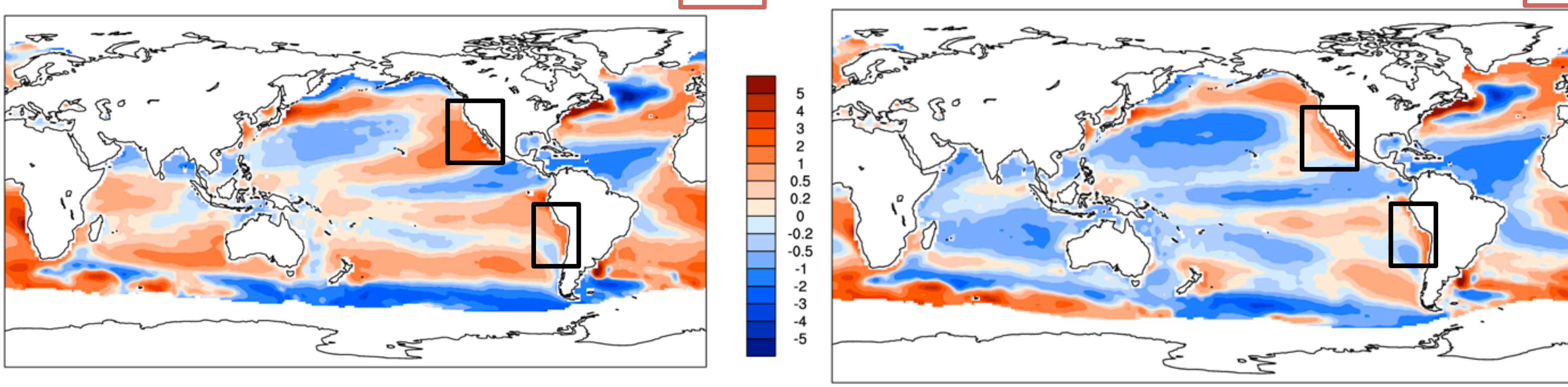
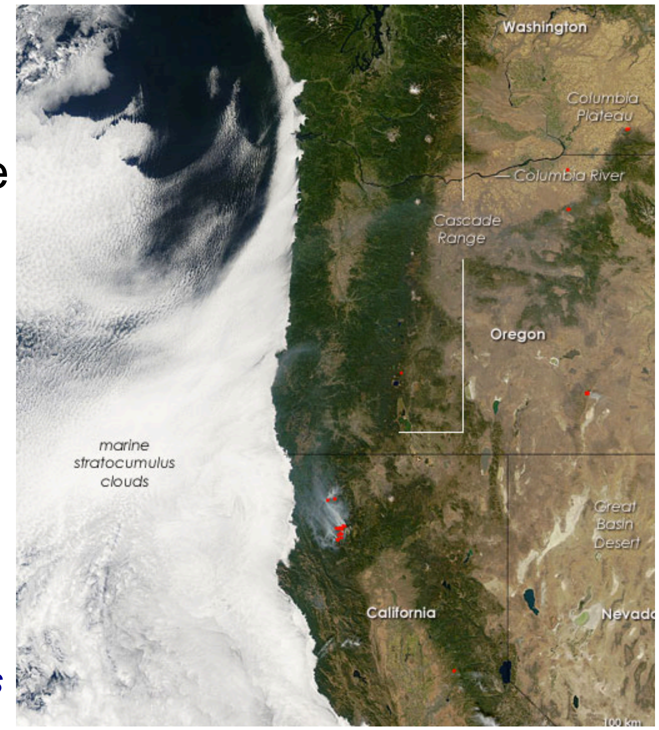


Stratocumulus

- Thin clouds that forms over cold oceans
  (Think "San Francisco")

- Very reflective => strong cooling effect on the surface

- Very difficult to parameterize (very thin and maintained by a blend of complex processes)



Daily cycle of shortwave heating

entraiment at cloud top

Strong longwave cooling at cloud top

Possible decoupling

drizzle

turbulence

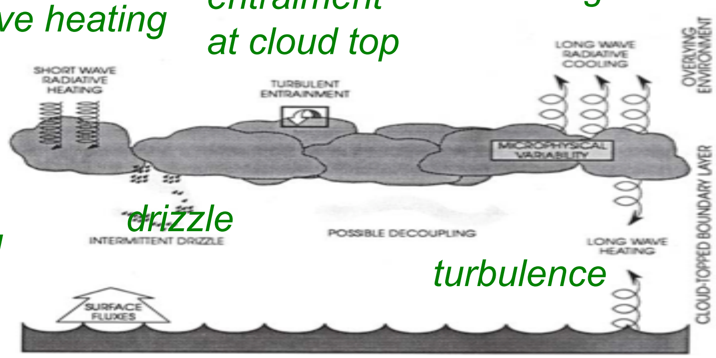


FIG. 1. The interplay of physical processes associated with stratocumulus cloud layers.

A few hundreds meters

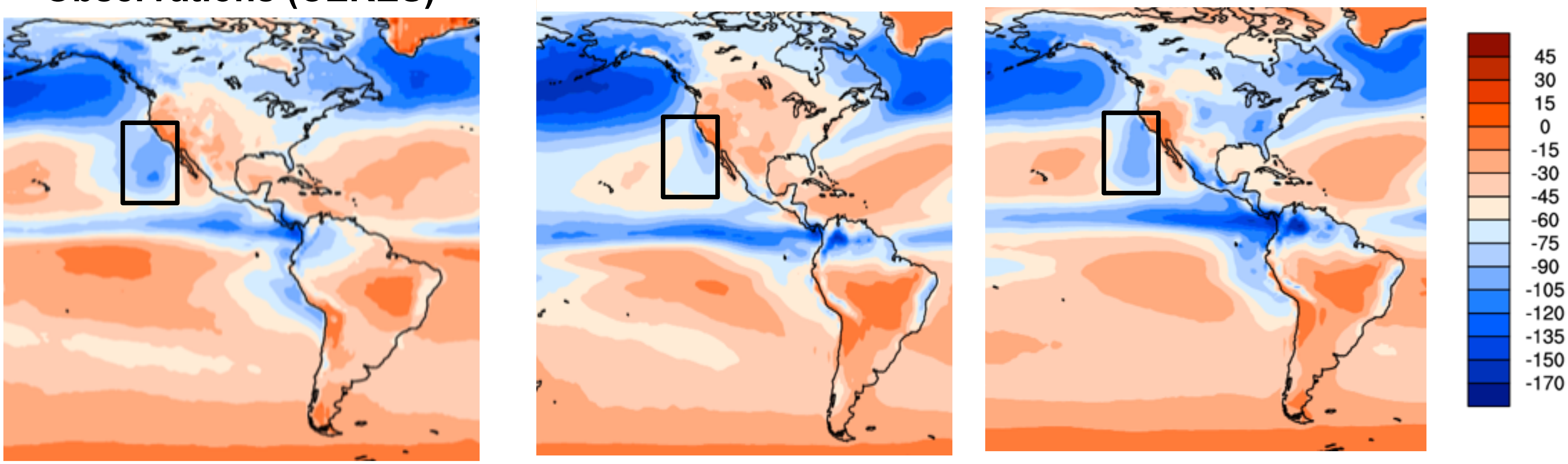
CAM5 represents stratocumulus better

Californian stratocumulus

Shortwave cloud forcing (W/m^2) = **Net** $\mathbf{SW_{all\ sky}}$ **- Net** $\mathbf{SW_{clear\ sky}}$

- Tells us something about the cloud cooling effect
- The more negative, the more cooling effect

Observations (CERES) | **CAM4** | **CAM5.1**

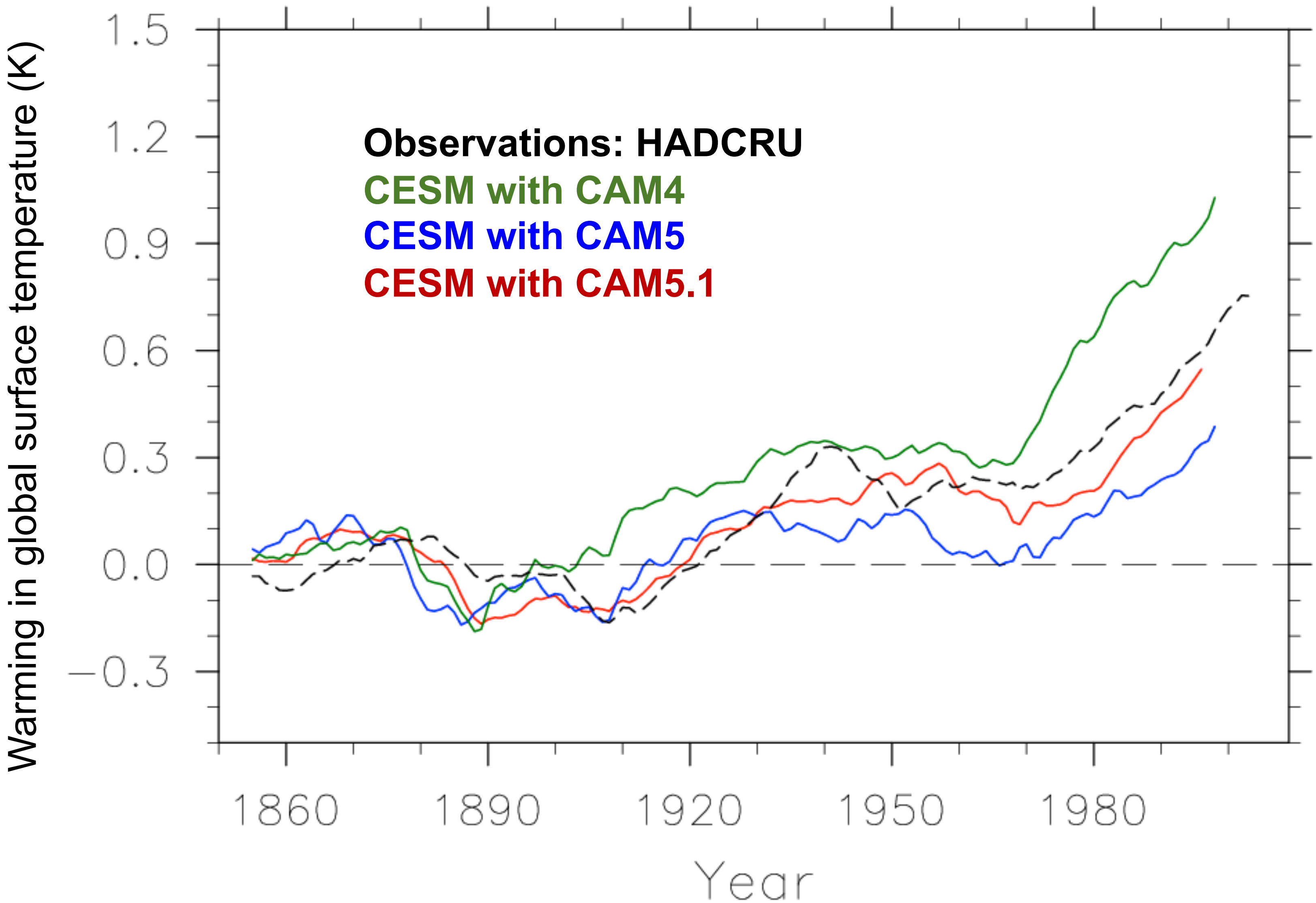


Cooling effect on the ocean

Not enough cooling and cloud too close to the coast

Major improvement

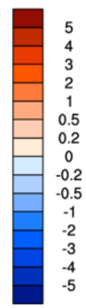
Warming over the 20th century



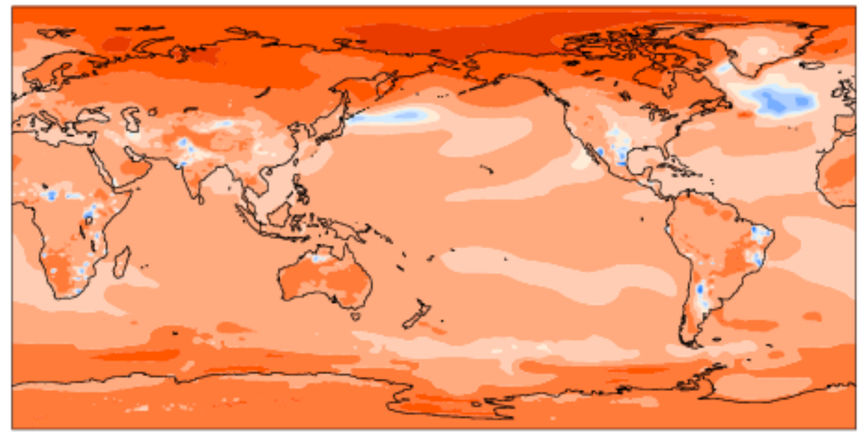
Warming over the 20th century

- Warming over 20th century:

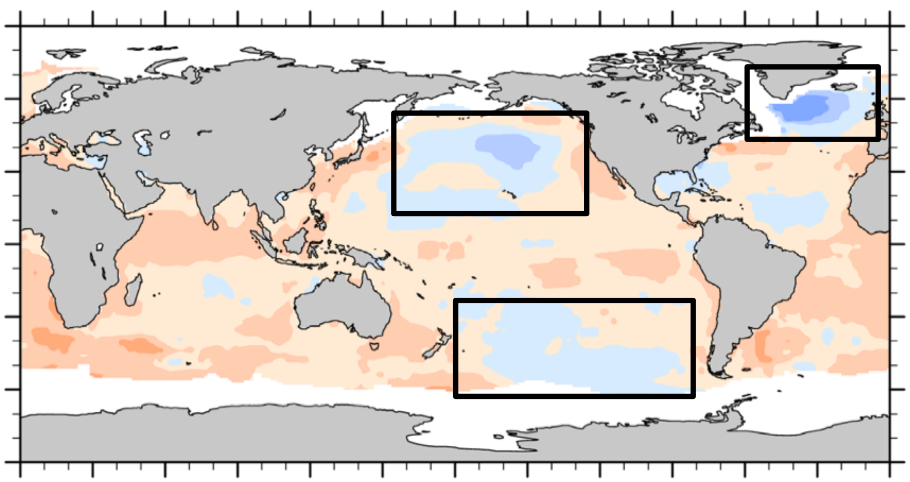
$TS^{(\text{present day})} - TS^{(\text{preindustrial})}$



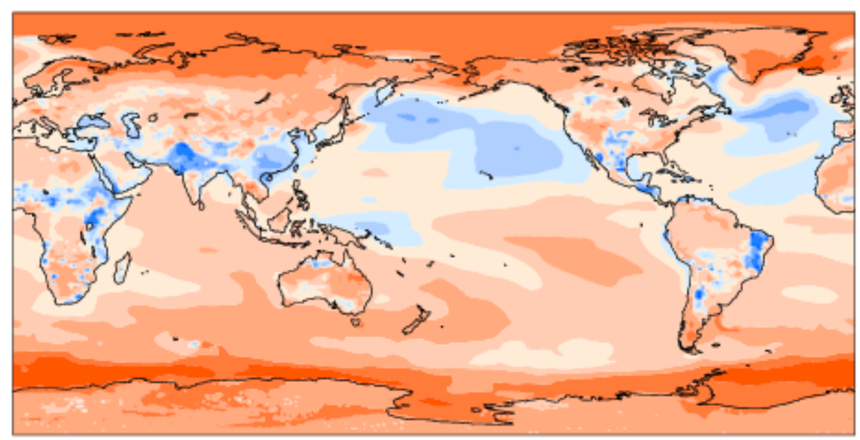
CESM with CAM4 **Mean = 0.84**



Hurrell SSTs dataset



CESM with CAM5.1 **Mean = 0.35**

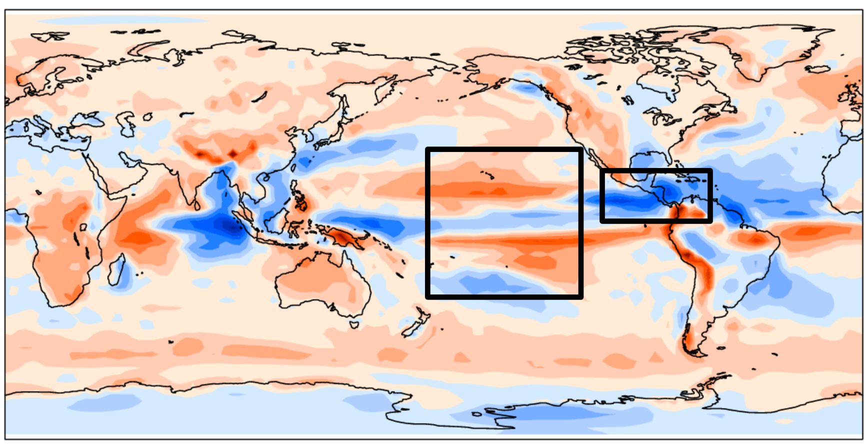


Precipitation errors

- Precipitation errors: Model - CMAP dataset (Xie-Arkin)
- Local improvements but globally, no significant improvement with CAM5.1
  (twin ITCZ still present)

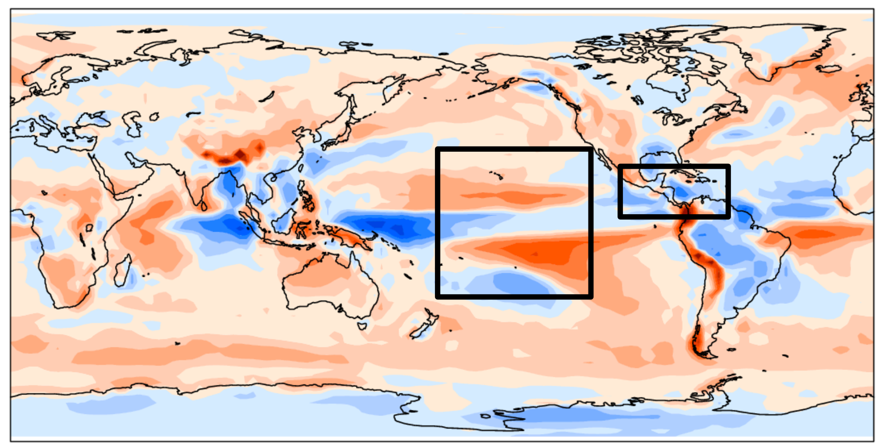
CESM with CAM4

Mean = 0.27
RMSE = 1.09

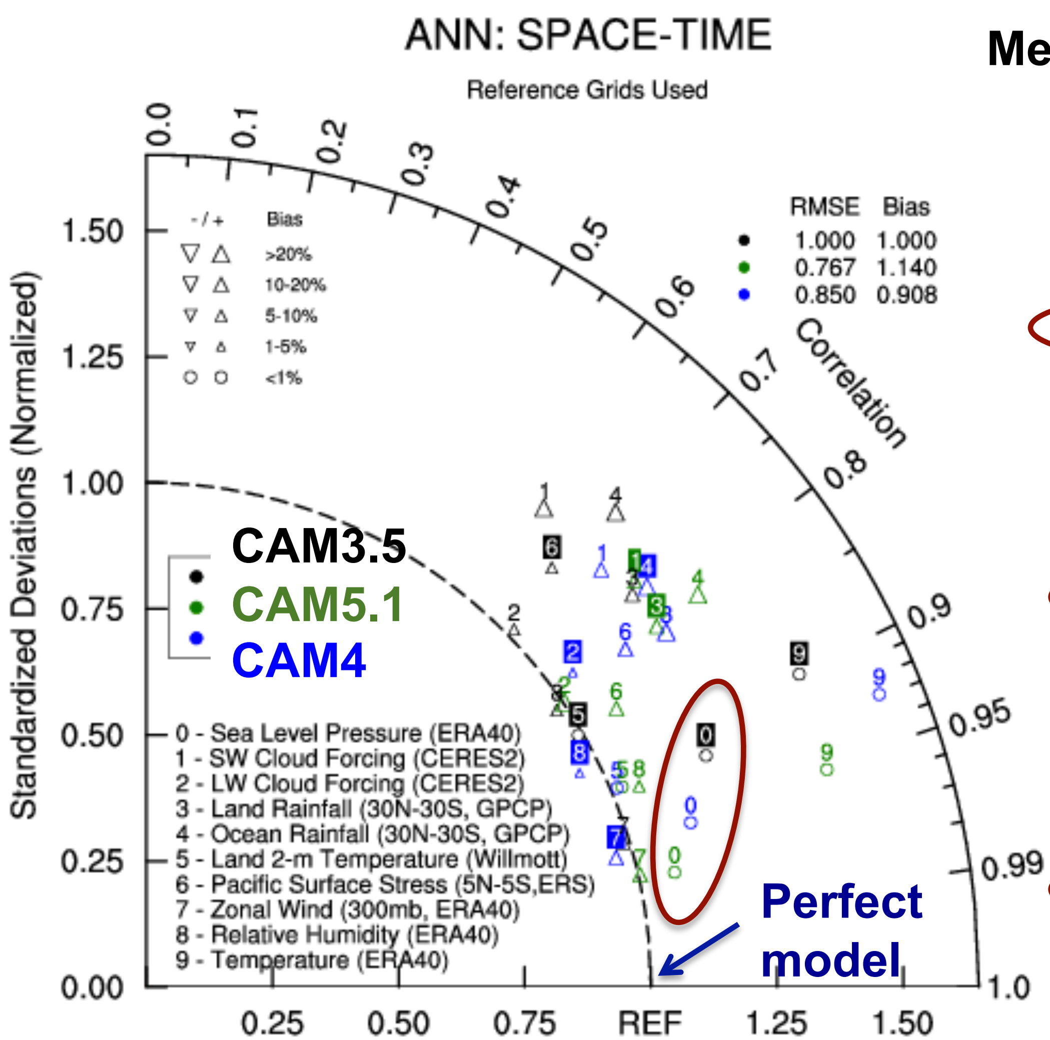


CESM with CAM5.1

Mean = 0.34
RMSE = 1.06



Taylor diagrams



Metric to assess model improvement

CAM3.5 – 2deg

Bias = 1.0
RMSE = 1.0

CAM4

Bias = 0.91
RMSE = 0.85

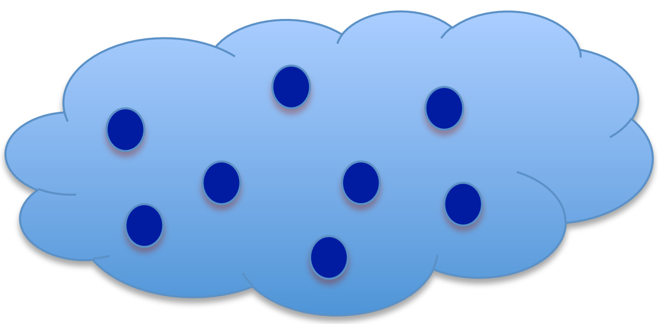
CAM5.1

Bias = 1.14
RMSE = 0.77

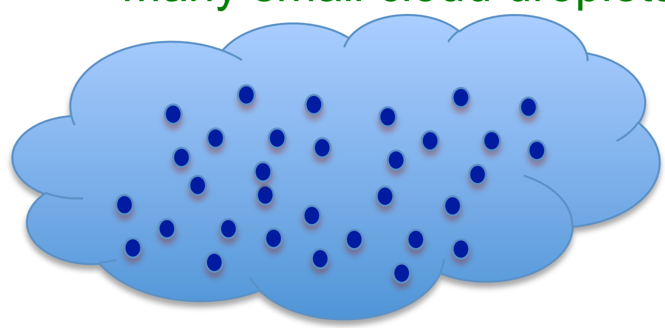
Aerosol and cloud formation

- Formation of cloud droplets requires Cloud Condensation Nuclei (CCN)
  Without CCNs, cloud droplets would form at supersaturation around 400%
- Many aerosols can act as CCN (dust, sea-salts, black carbon, sulfate,..)
- Cloud-aerosol interactions

Pristine air (few CCN)
Few big cloud droplets



Polluted air (many CCNs)
Many small cloud droplets



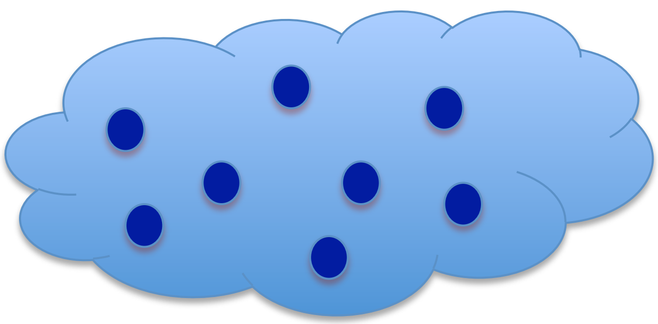
Aerosol and cloud formation

- Formation of cloud droplets requires Cloud condensation nuclei (CCN)
  Without CCNs, cloud droplets would form at supersaturation around 400%

- Many aerosols can act as CCN (dust, sea-salts, black carbon, sulfate,..)

- Cloud-aerosol interactions **=> This is something CAM5 is able to represent**

Pristine air (few CCN)
Few big cloud droplets



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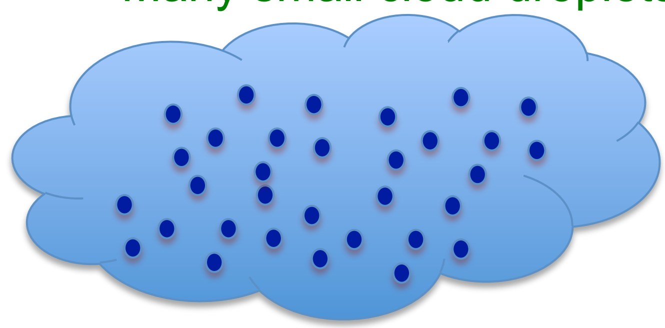
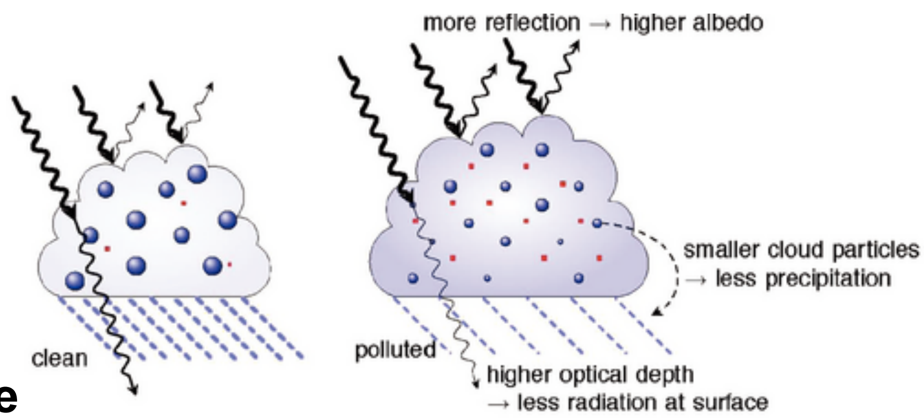


Aerosol: direct and indirect effect

Direct effect
- aerosols scatter and absorb solar and infrared radiation

Indirect effect
If aerosol number increases
=> cloud with many small droplets
=> higher albedo (cooling effect on surface)
=> Less precipitation



Aerosols have a cooling effect on climate

	Direct effect W/m2	Indirect effect W/m2
CAM5.1	-0.21	-1.01
IPCC values	-0.5 [-0.9 to -0.1]	-0.7 [-1.8 to -0.3]

Impact of aerosol changes

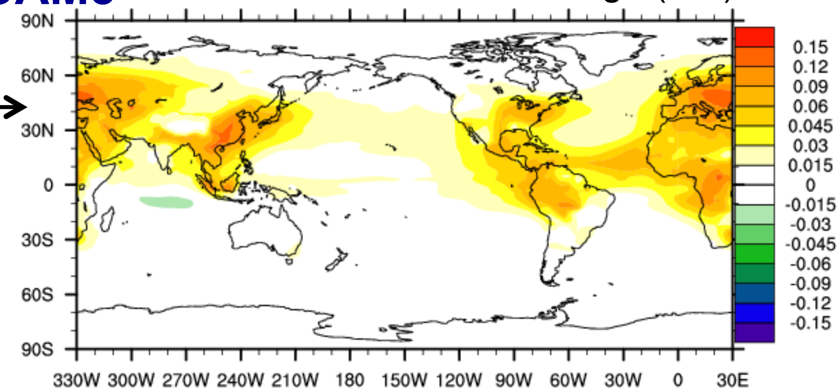
Changes over the 20th century in CESM-CAM5

- Increased aerosol burdens in SE Asia, Europe, NE America

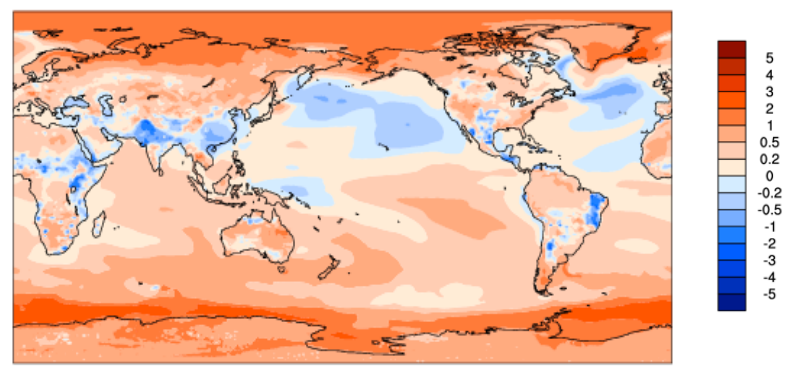
- Aerosol have a cooling effect on climate

- Significant regional modulation of the general global warming trend

Total aerosol change (OD)



Surface temperature changes



CAM5 is able to address many science questions related to the impact of anthropogenic emissions on climate that were not previously possible.

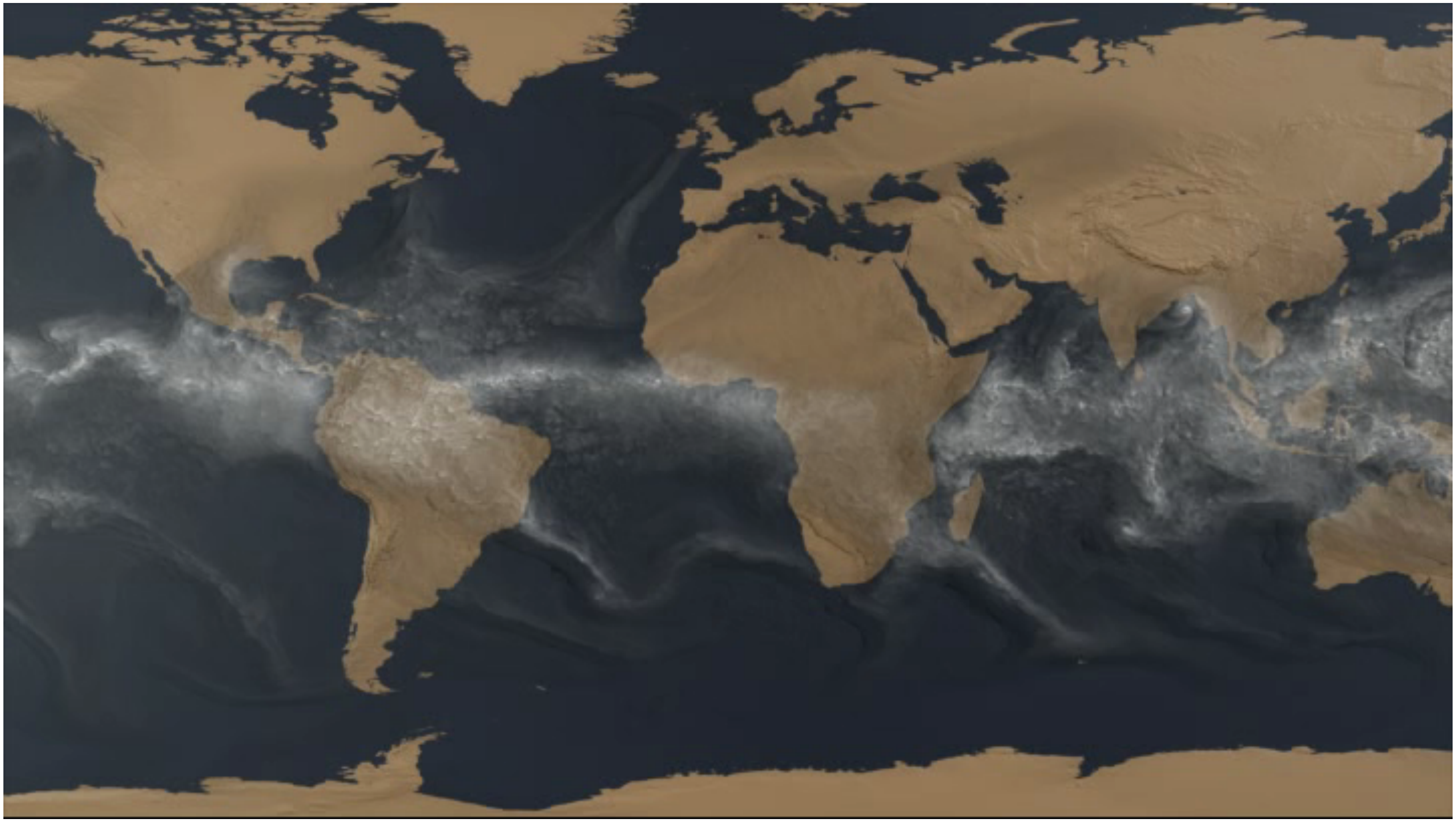
CAM5 physics and beyond…

The CAM5 physics represents a major step forward in the representation of atmospheric physical processes and simulating their climate impacts.

New parameterization have enabled a significant expansion in the research problems that can be addressed within the CESM (for instance we can examine the role of aerosol indirect effect, which was not previously possible).

With the need to provide climate information at ever increasing resolution future model development will aim to provide scale-invariant parameterizations of physical processes, allowing the smoothest transition to high resolution.

Thanks



Courtesy: Mark Taylor

Extra slides

2011 and beyond…

Much remains to be learned from CAM5 both in terms of understanding the many interactions among the new cloud-aerosol processes and their response to near-term climate change and these will be the main focus of research over the coming year.

With the need to provide climate information at ever increasing resolution further model development will aim to provide scale-invariance for the representation of physical processes, allowing the smoothest transition to high resolution.

In particular we aim to perform model parameterizations at or near the cloud-scale regardless of model resolution to give seamless behavior across different model resolutions.

With regional climate modeling in mind CAM5 will soon include the capability to locally refine the model grid in order to provide the highest resolution, but still within the framework of global climate model simulations.

Parameterizations from CAM4 to CAM5

Major improvements in CAM5

- A new moist turbulence scheme explicitly simulates stratus-radiation-turbulence interactions (aerosol indirect effect)
- A new shallow convection scheme uses a realistic plume dilution equation and closure => accurate simulation of spatial distribution of shallow convection
- The revised cloud macrophysics scheme imposes full consistency between cloud fraction and cloud condensate.
- Stratiform microphysical processes are represented by a prognostic, two-moment formulation for cloud droplet and cloud ice, and liquid mass and number concentrations.

Parameterizations from CAM4 to CAM5 (cont)

- The radiation scheme has been updated to the Rapid Radiative Transfer Method for GCMs (RRTMG) and employs an efficient and accurate correlated-k method for calculating radiative fluxes and heating rates.

- The 3-mode modal aerosol scheme has been implemented and provides internally mixed representations of number concentrations and mass for Aitkin, accumulation and course aerosol modes.

- These major physics enhancements permit new research capability for assessing the impact of aerosol on cloud properties. In particular, they provide a physically based estimate of the impact of anthropogenic aerosol emissions on the radiative forcing of climate by clouds.

Climate sensitivity

- Change in SST at equilibrium due to a doubling of CO_2
- Sensitivity is obtained from SOM simulations
- Q_{flux} is obtained from a 50-year period of a well-balanced 1850 fully coupled simulation

CAM4 = 3.17 K
CAM5.1 = 4.04 K

Californian stratocumulus deck (JJA)

Shortwave cloud forcing = Net $SW_{all\ sky}$ - Net $SW_{clear\ sky}$

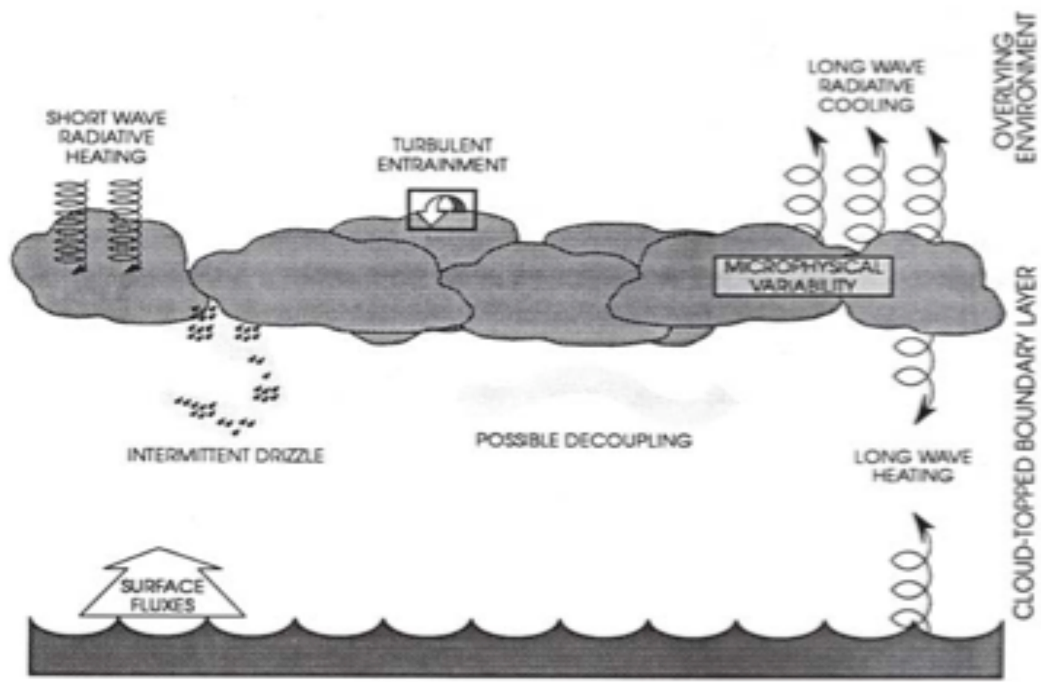


FIG. 1. The interplay of physical processes associated with stratocumulus cloud layers.

Hidden dangers with parameterizations

Even the simplest things are often empirical or have hidden assumptions

Let's take our simple cloud model:

- Cloud fraction = f(RH) so that locally, we have a cloud if RH > 100%

- In the literature, we can find equations for saturation vapor pressure
  $e_{sat} = f(T)$
  These equations are empirical fits from laboratory experiment

- Few experiments exist below -20C!

- e_{sat} itself may be uncertain