Atmospheric modeling II: Physics in the Community Atmosphere Model (CAM)

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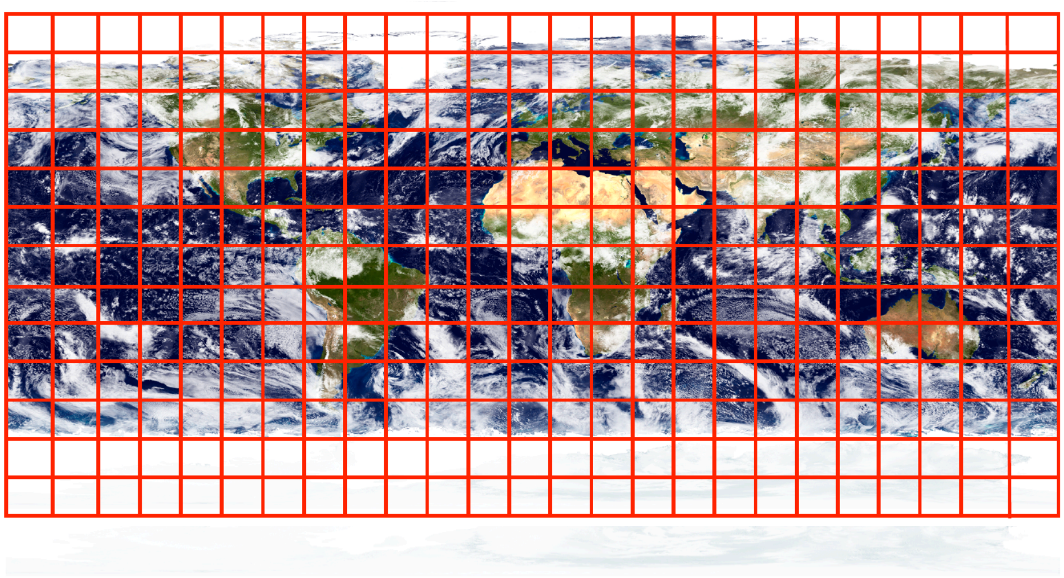
U.S. DEPARTMENT OF ENERGY
Office of Science

Outline

- The hydrostatic primitive equations. Scales of atmospheric processes.
- What’s a parameterization ?
- Overview of the parameterizations in CAM
- From CAM4 to CAM5: improvements and new capabilities in 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

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

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

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

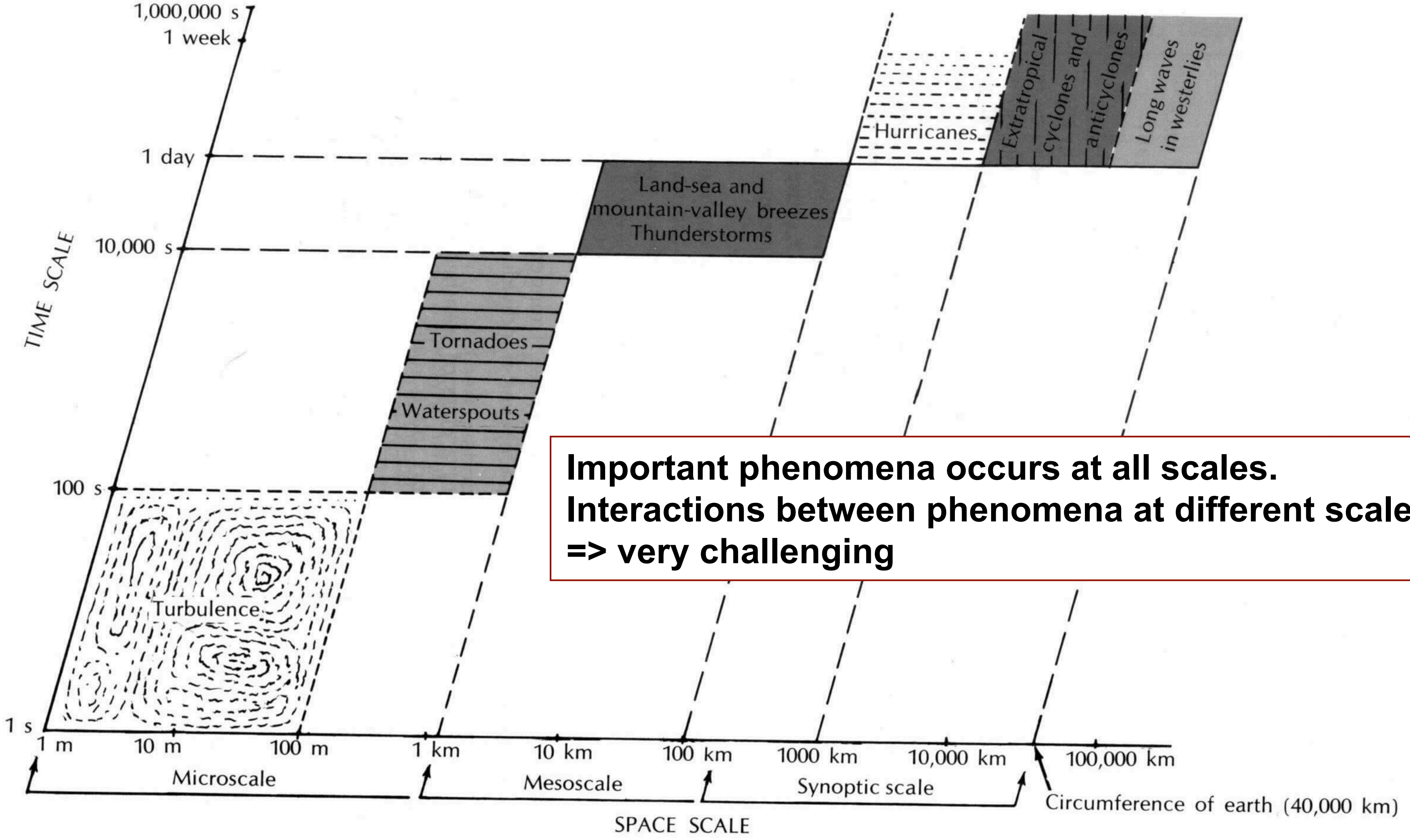
Hydrostatic balance: $\partial\overline{\phi}/\partial p + R\overline{T}/p = 0,$

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

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

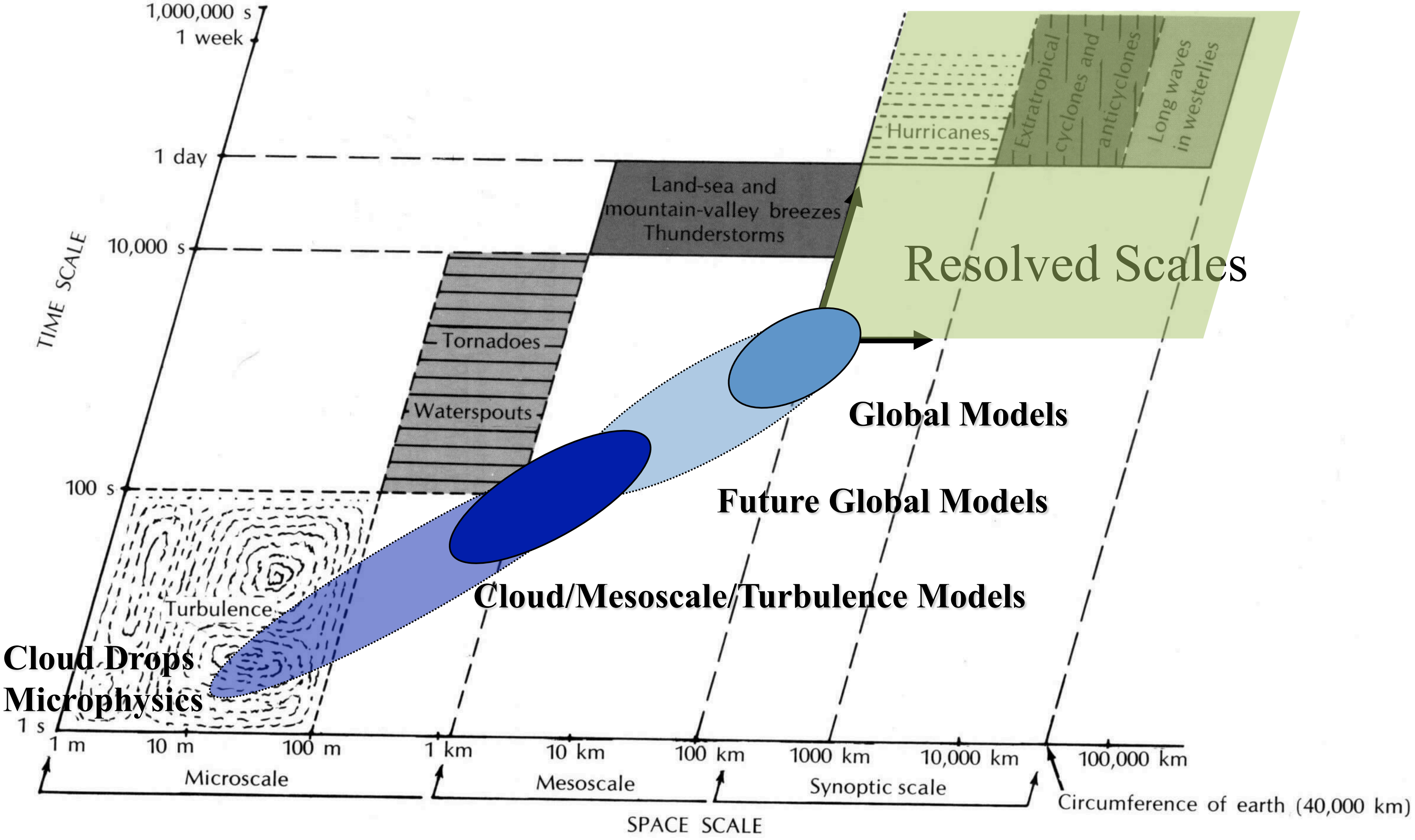
Parameterized processes or “the physics”

Scales of Atmospheric Processes



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

Scales of Atmospheric Processes



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)

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Physical parameterization

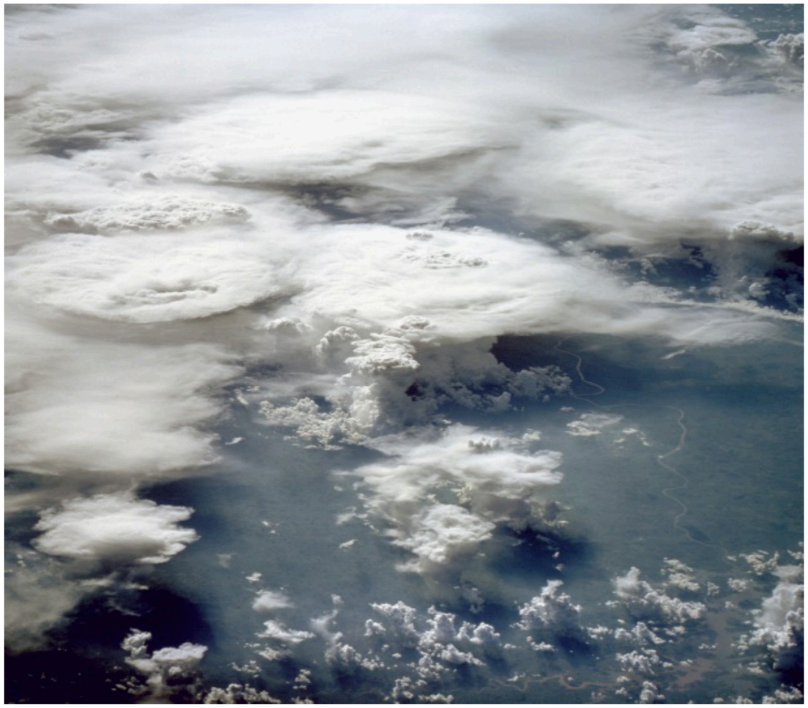
- Parameterization = process of including the effect of unresolved phenomena

- 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)

$$\boxed{RH = \frac{e}{e_{sat}} \text{ x } 100}$$

water vapor pressure

saturation water vapor pressure

- 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

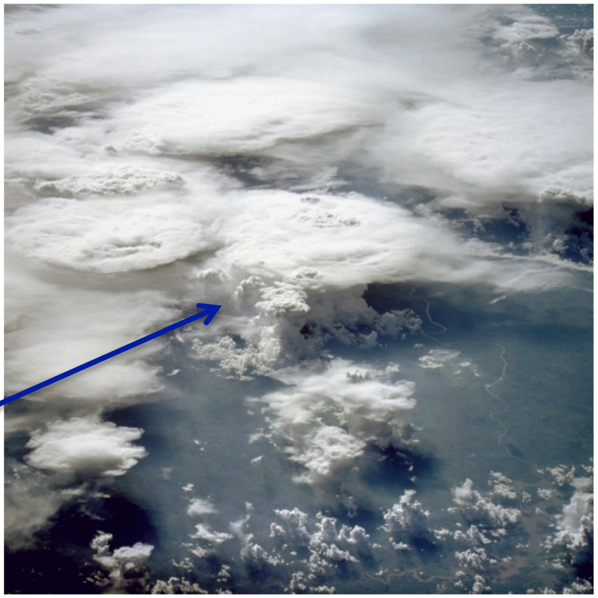
Sub-grid processes

- 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

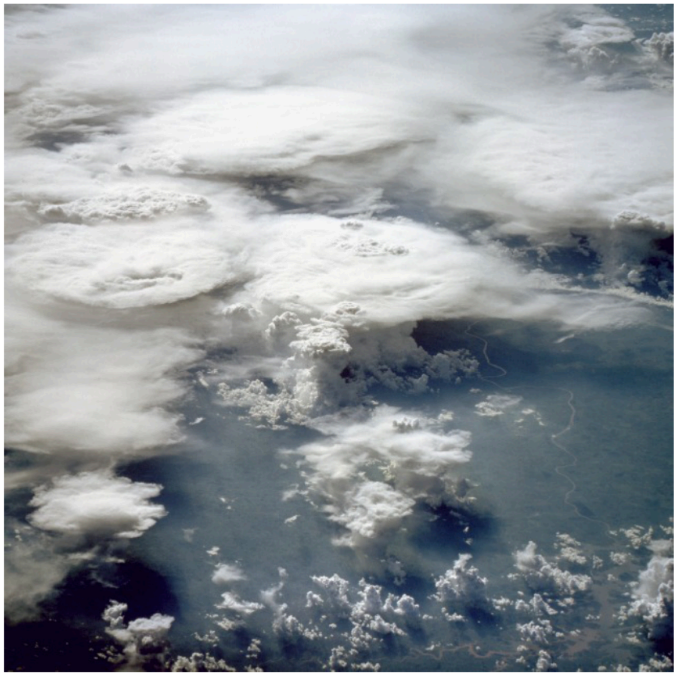
- Locally clouds form when RH = 100%

- 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



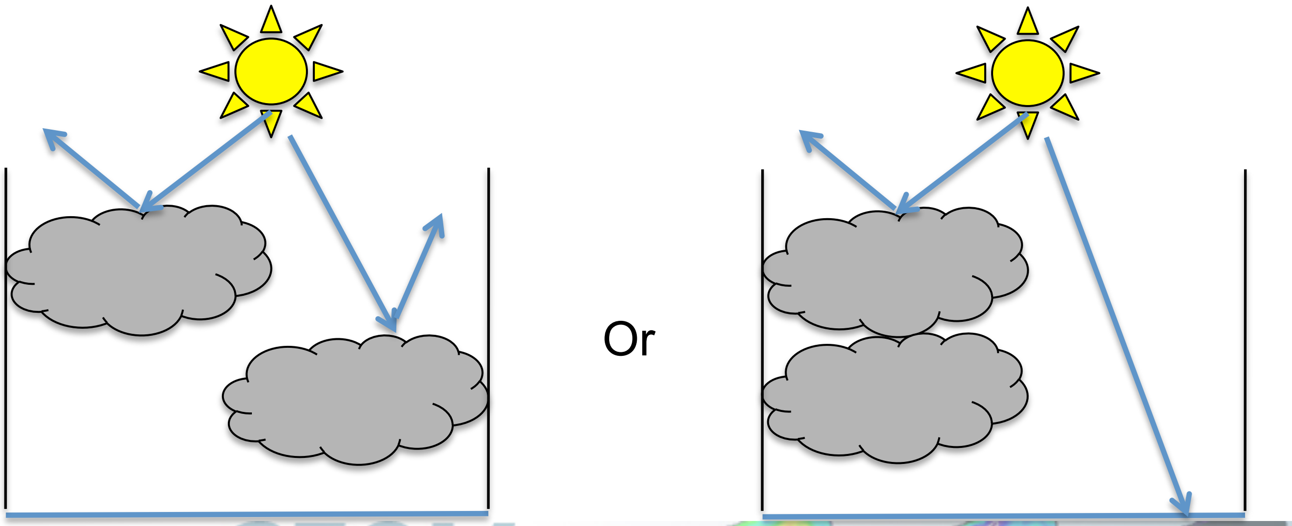
Vertical distribution of clouds

- 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.

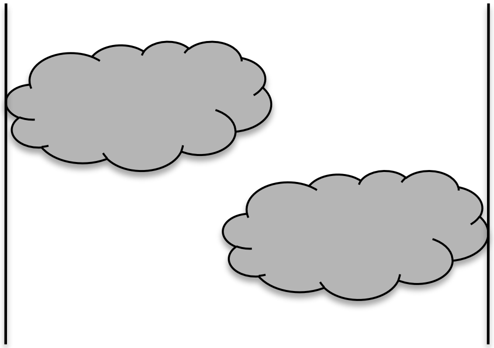
- Now, the question is: *how do we distribute the clouds in the vertical ?*

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



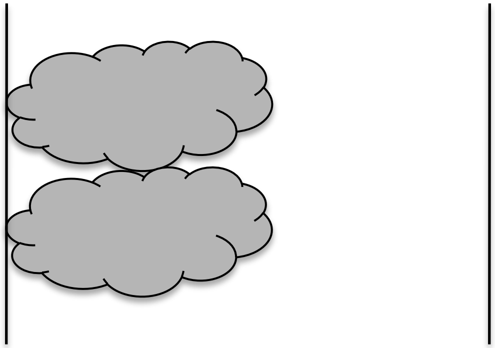
Cloud overlap assumptions

Minimum overlap



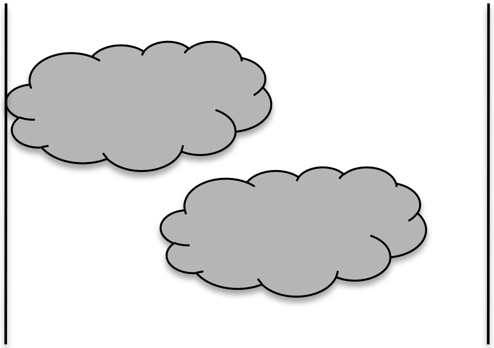
C = C1 + C2

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”*)

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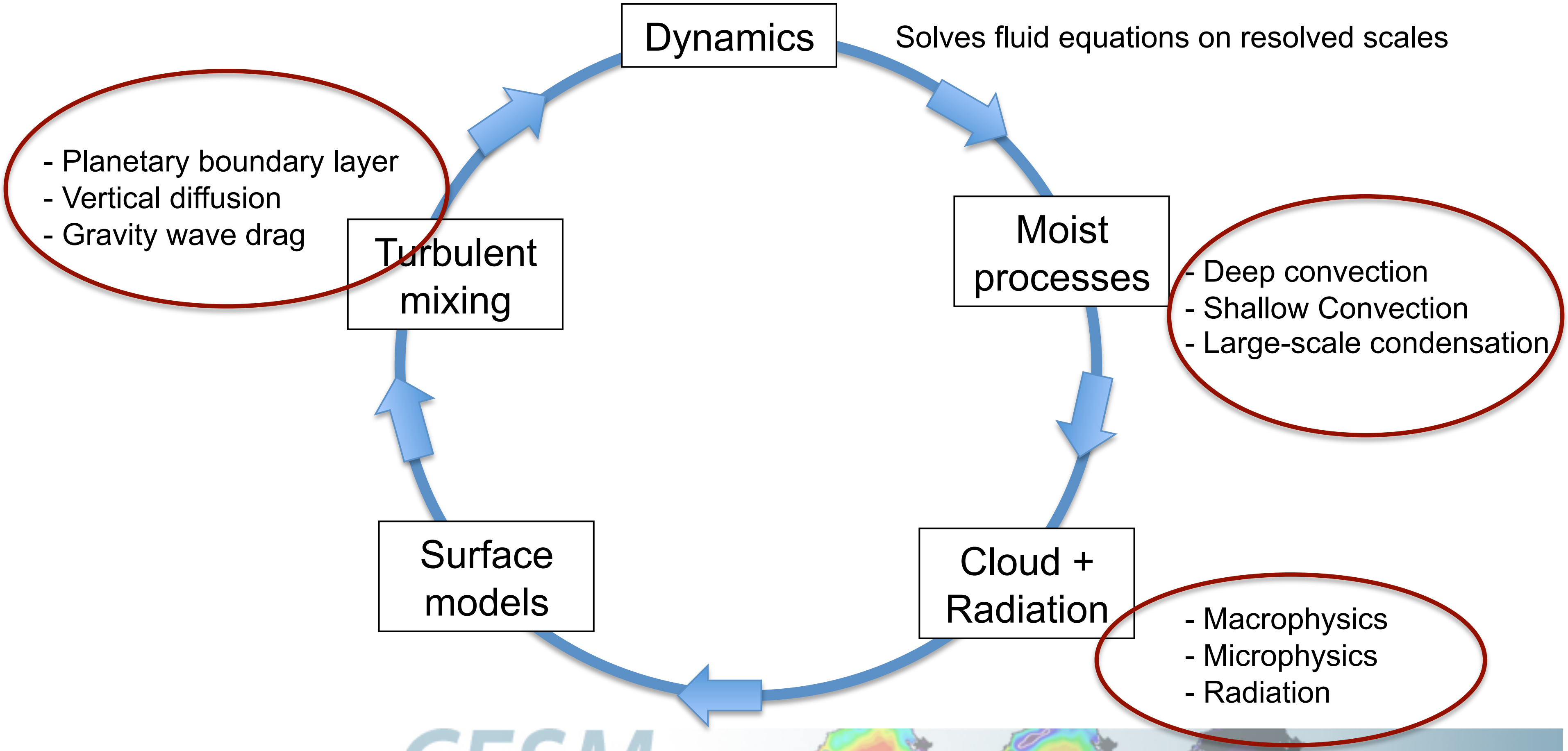
- From CAM4 to CAM5: improvements and new capabilities in CAM.

CAM parameterizations

- In the previous slides, we have built a simple cloud parameterization

- Many other processes are parameterized in CAM.



Dynamics

Solves fluid equations on resolved scales

Moist processes

- Deep convection
- Shallow Convection
- Large-scale condensation

Cloud + Radiation

- Macrophysics
- Microphysics
- Radiation

Surface models

Turbulent mixing

- Planetary boundary layer
- Vertical diffusion
- Gravity wave drag

CAM parameterizations

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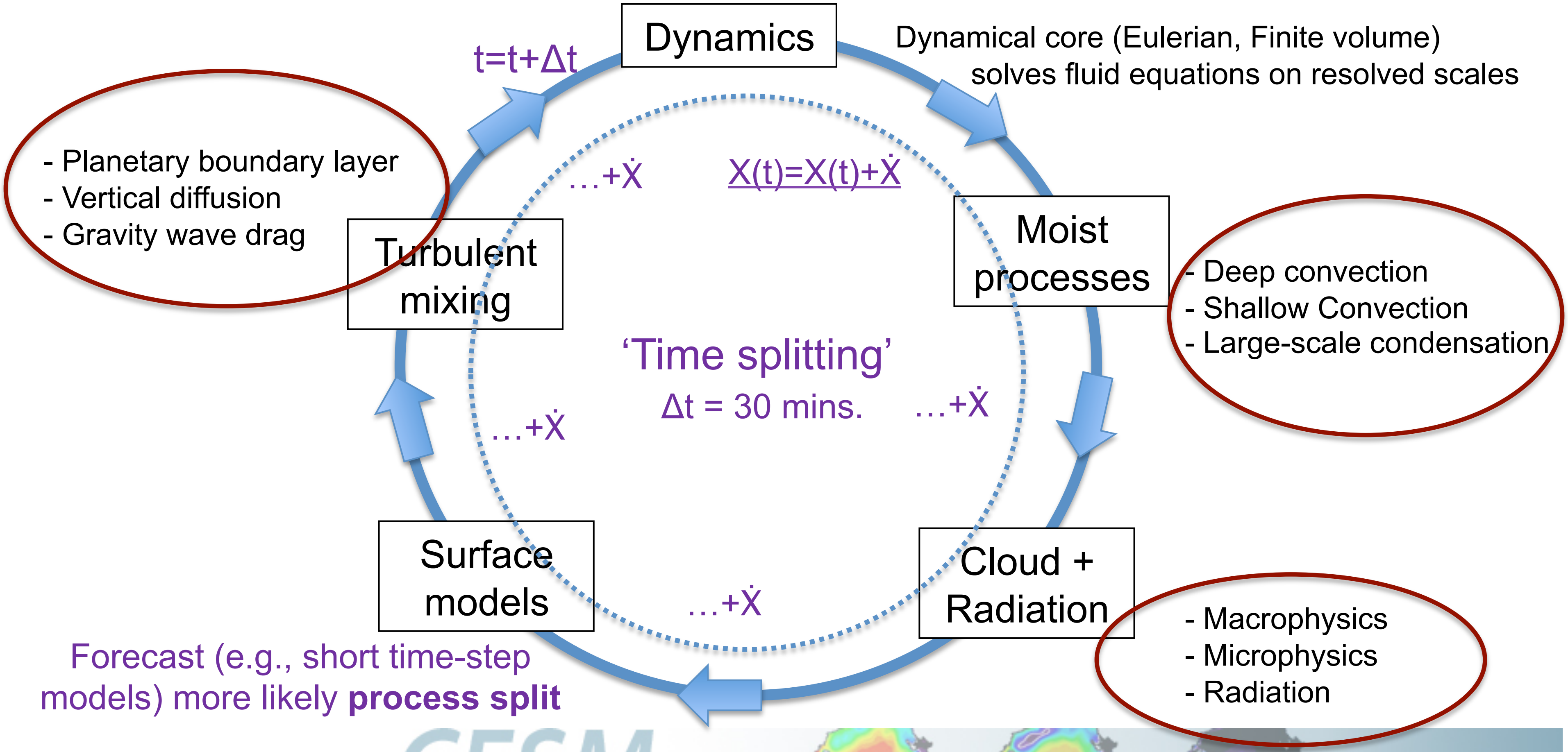

Dynamics

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

Moist processes

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Cloud + Radiation

- Macrophysics
- Microphysics
- Radiation

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t=t+Δt

$X(t)=X(t)+\dot{X}$

…$+\dot{X}$

…$+\dot{X}$

…$+\dot{X}$

…$+\dot{X}$

'Time splitting'

Δt = 30 mins.

Forecast (e.g., short time-step models) more likely **process split**

Clouds: Multiple Categories

Stratiform (large-scale) clouds

- Responds to large-scale relative humidity

  If $RH < RH_t$ => cloud fraction = 0
  If $RH_t \leq RH < 100\%$ => 0 < cloud fraction < 1
  If $RH = 100\%$ => cloud fraction = 1

Shallow convection clouds

- 10 - 100 meters
- Non precipitating (mostly)
- Responds to surface forcing

Deep convection clouds

- 100m – 10km
- Penetrating convection (surface -> tropopause)
- Precipitating
- Responds to surface forcing and conditional instability

Shallow and Deep Convection

Exploiting conservation properties

Common properties

Parameterize consequences of vertical displacements of air parcels

Conserves thermodynamic properties

Unsaturated: Parcels follow a dry adiabat (conserve dry static energy)

Saturated: Parcels follow a moist adiabat (conserve moist static energy)

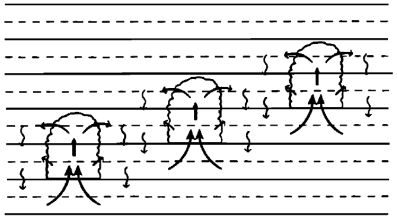
Shallow (10-100 m)	**Deep (100m-10km)**
Parcels remain stable (buoyancy<0)	Parcels become unstable (buoyancy>0)
Shallow cooling mainly	Deep heating
Some latent heating and precipitation	Latent heating and precipitation
Generally a source of water vapor	Generally a sink of water vapor
Small cloud radius - large entrainment	Large cloud radius - small entrainment

Shallow and Deep Convection

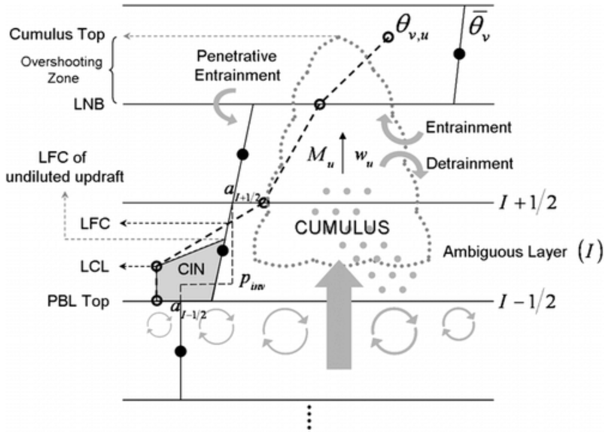
Closure: How much and when?

Shallow

Local conditional instability CAM4



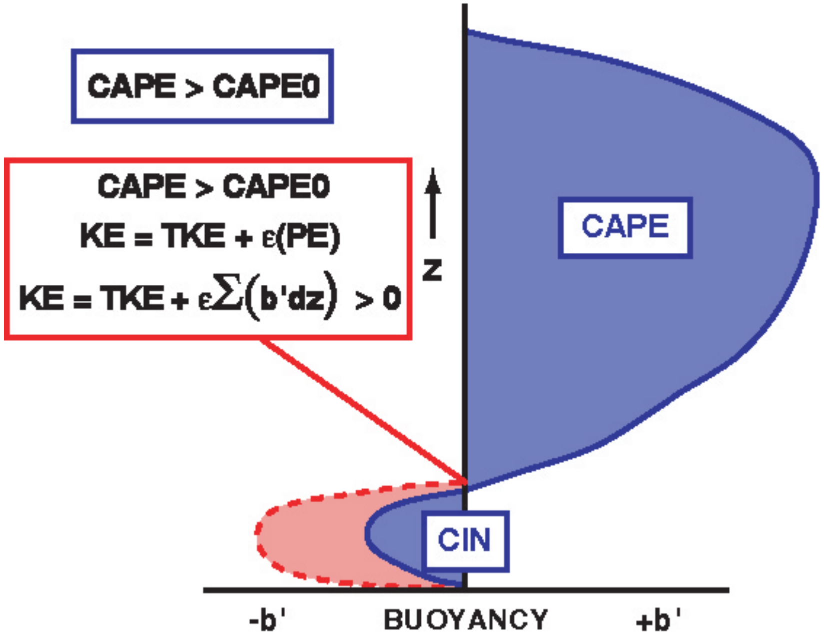
Convective inhibition and turbulent kinetic energy (TKE) CAM5



Deep

Convective Available Potential Energy (CAPE)

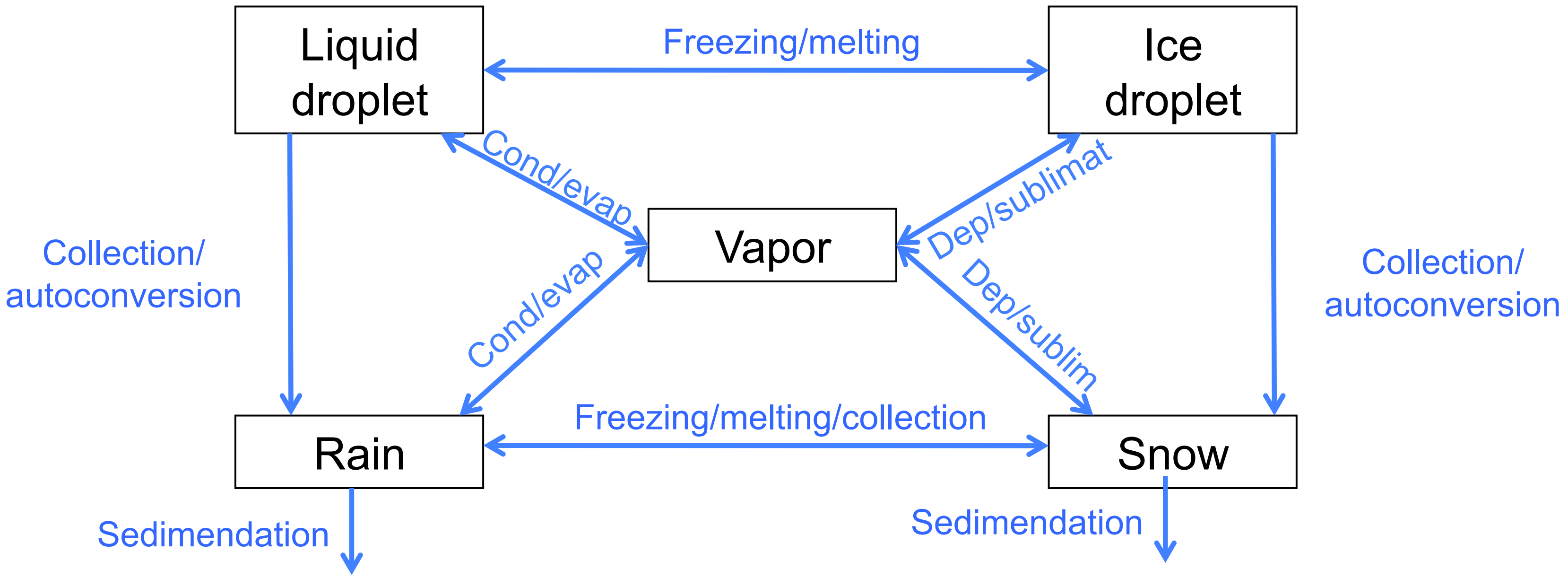
CAPE>CAPE$_{trigger}$ Timescale=1 hour



Shallow and deep convection and stratiform cloud fractions combined for radiation

Cloud Microphysics

- Cloud microphysics are the physical processes that describe the growth, decay, and fallout of condensed particles.



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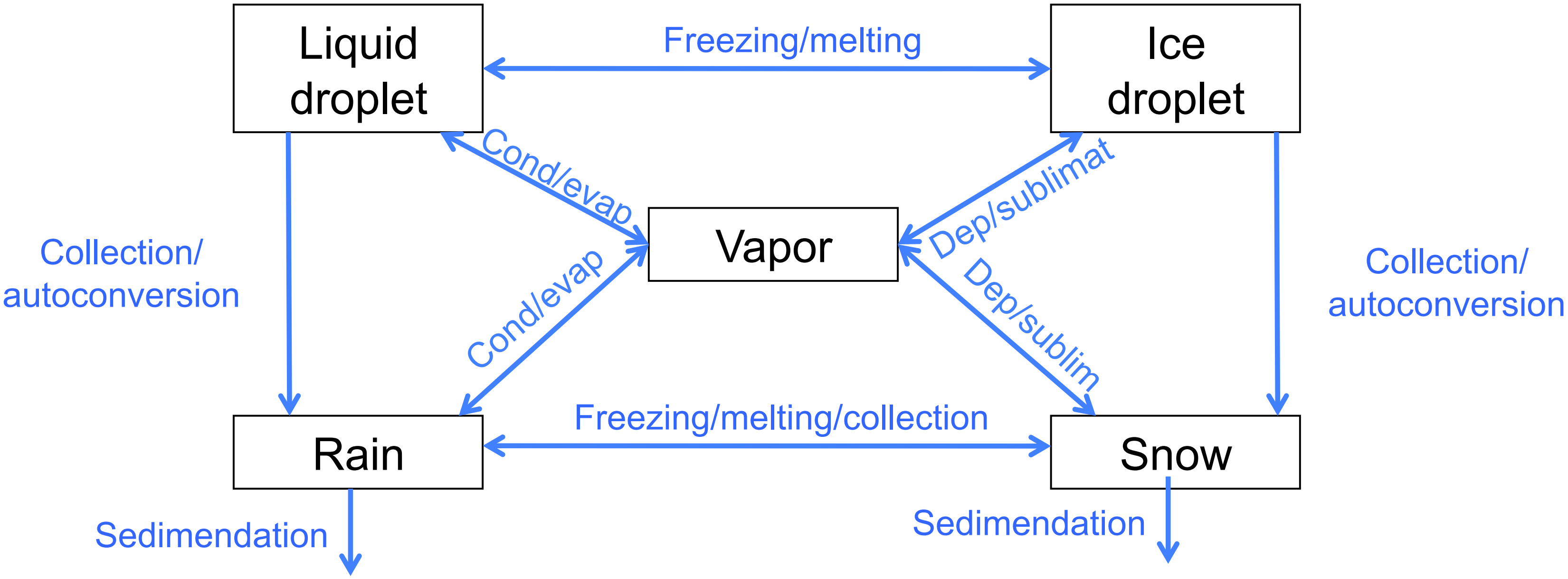


Liquid droplet

Freezing/melting

Ice droplet

Cond/evap

Dep/sublimat

Collection/ autoconversion

Vapor

Collection/ autoconversion

Cond/evap

Dep/sublim

Rain

Freezing/melting/collection

Snow

Sedimendation

Sedimendation

Two types of microphysics parameterization:
- single moment scheme: predicts mass mixing ratio
- double moment scheme: predicts mass mixing ratio and number concentration

Different types of Microphysics

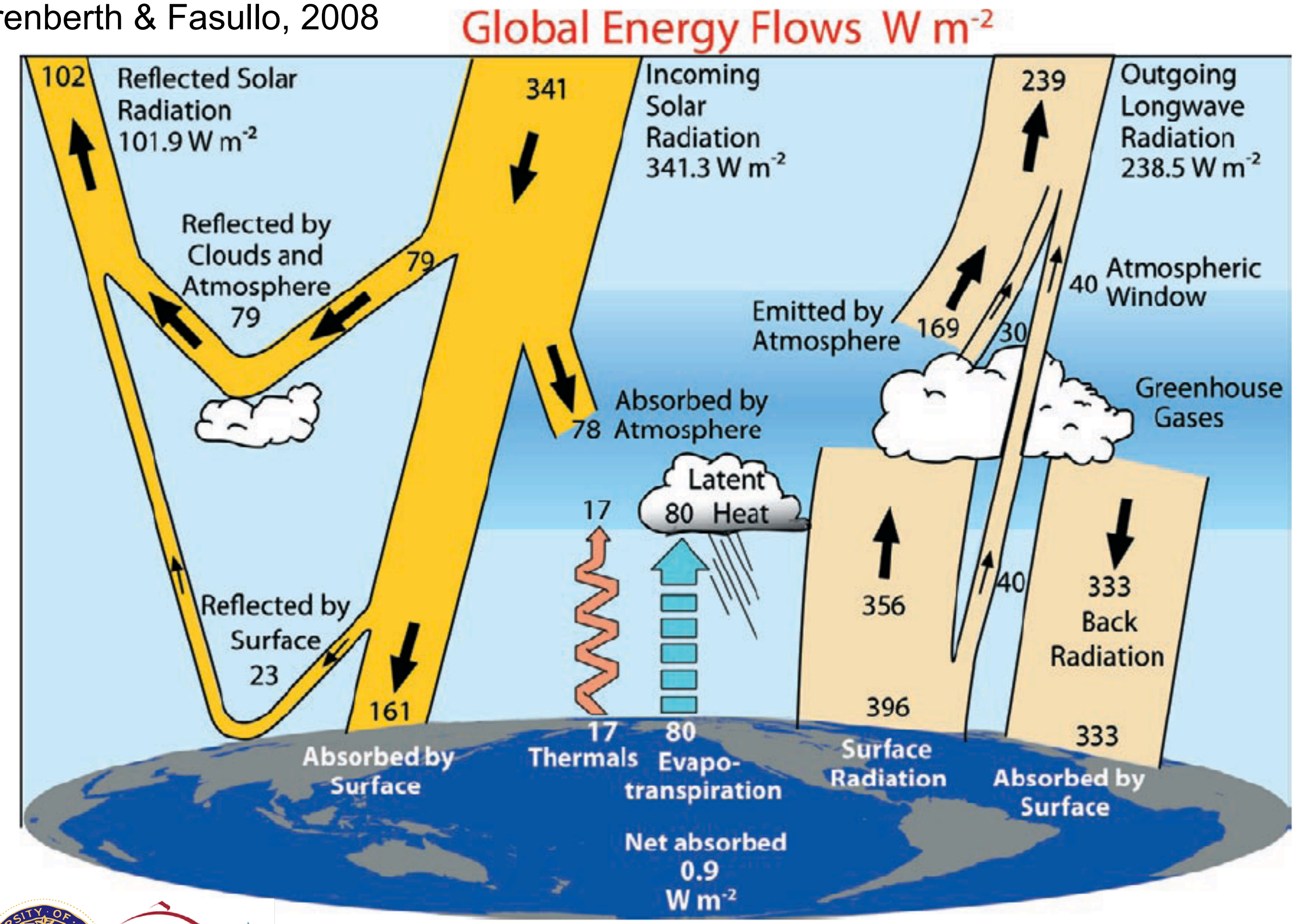
- Bulk Microphysics (CAM4)
  - Mass based only (2 species: liquid and ice)
  - Bulk transformations and processes
  - Specified sizes or size distributions

- 2-moment Microphysics (CAM5)
  - First moment = mass; 2nd moment = number concentration
  - Use an analytic representation of the size distribution and carry around moments of the distribution
  - Size distribution reconstructed from an assumed shape.

Radiation

The Earth's Energy Budget

Trenberth & Fasullo, 2008



Gas	SW Absorption (Wm^{-2})
CO_2	1
O_2	2
O_3	14
H_2O	43

Thanks to: Bill Collins, Berkeley & LBL

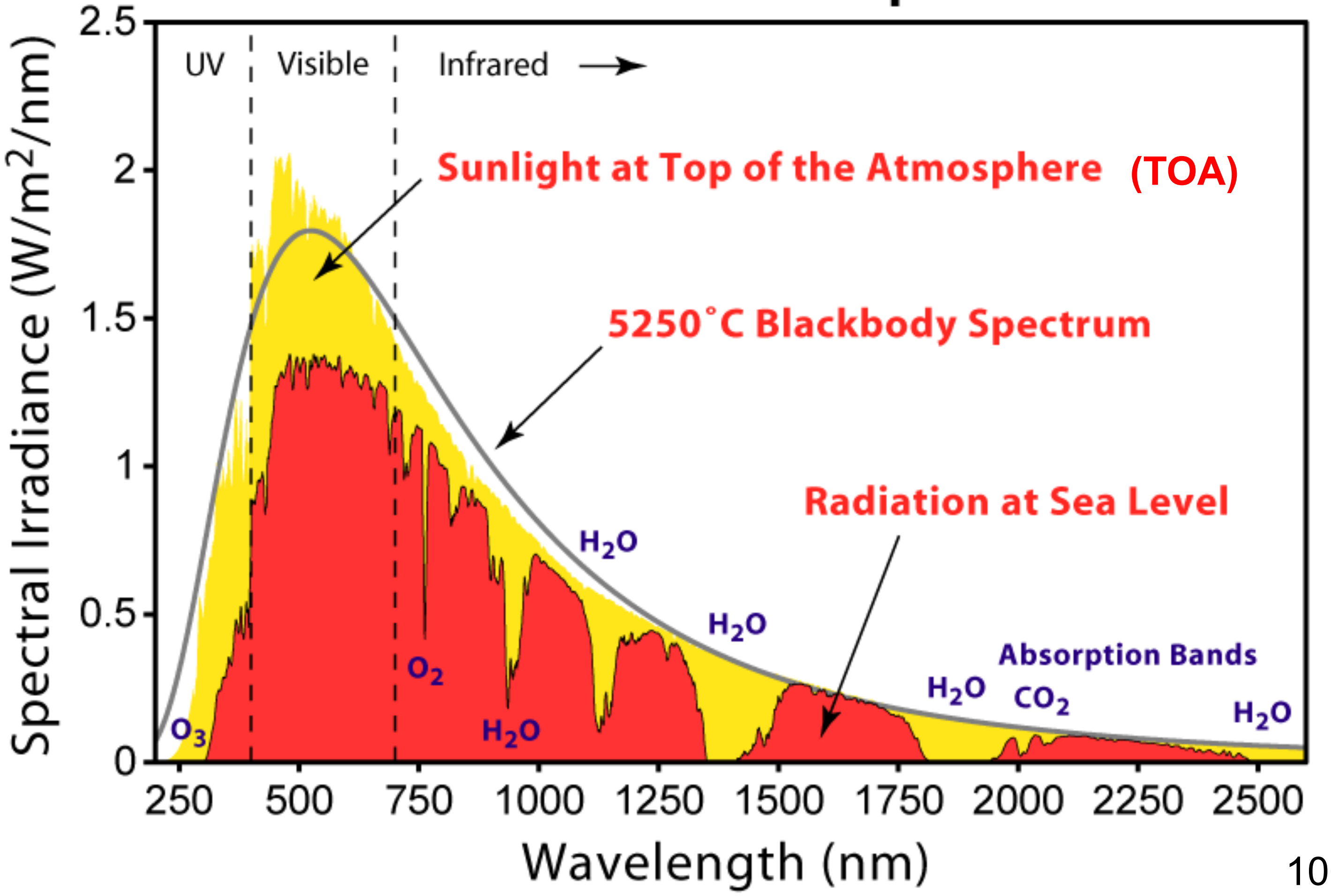
Goals of GCM Radiative Codes

The radiative code must supply:

- the total radiative flux at the surface to calculate the surface energy balance
- the radiative heating and cooling rates at each level of the atmosphere

The parameterization should include the combined effect of absorption and scattering by the radiatively active gases (H_2O, CO_2, O_3…) together with cloud and aerosol.

Solar Radiation Spectrum

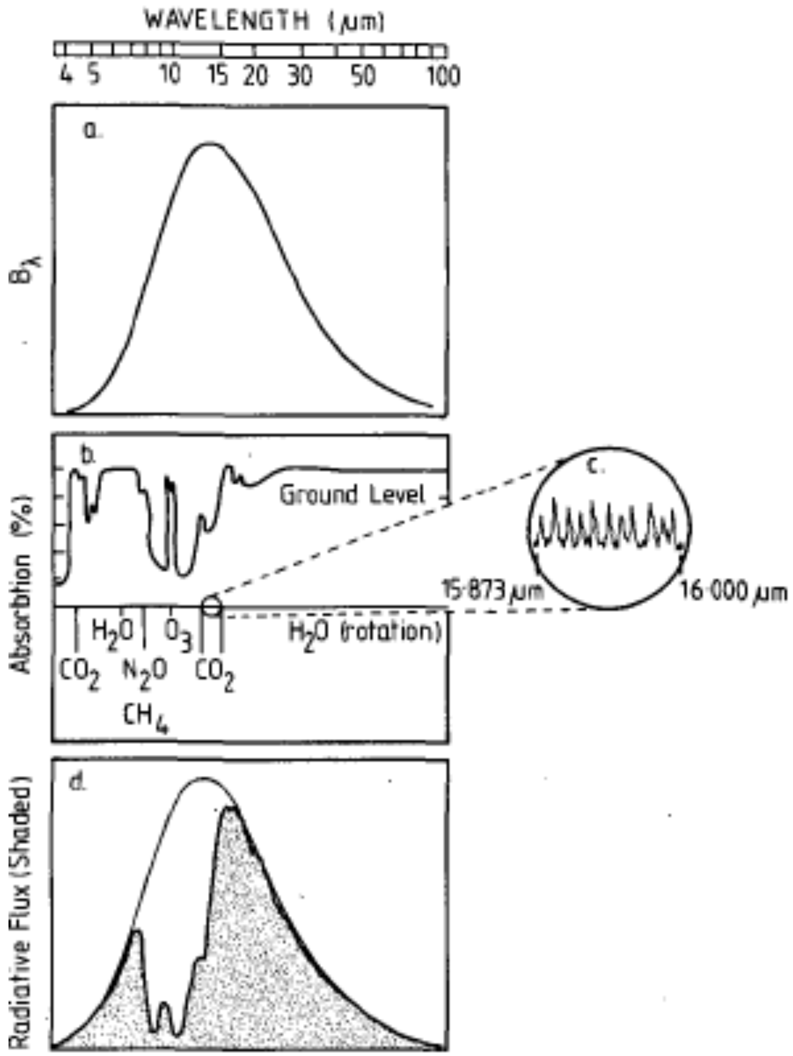


1000nm = 1mm

Input at TOA, Radiation at surface

From: ‘Sunlight’, Wikipedia

Longwave radiation



The normalized blackbody emission spectra for the Earth (255K)

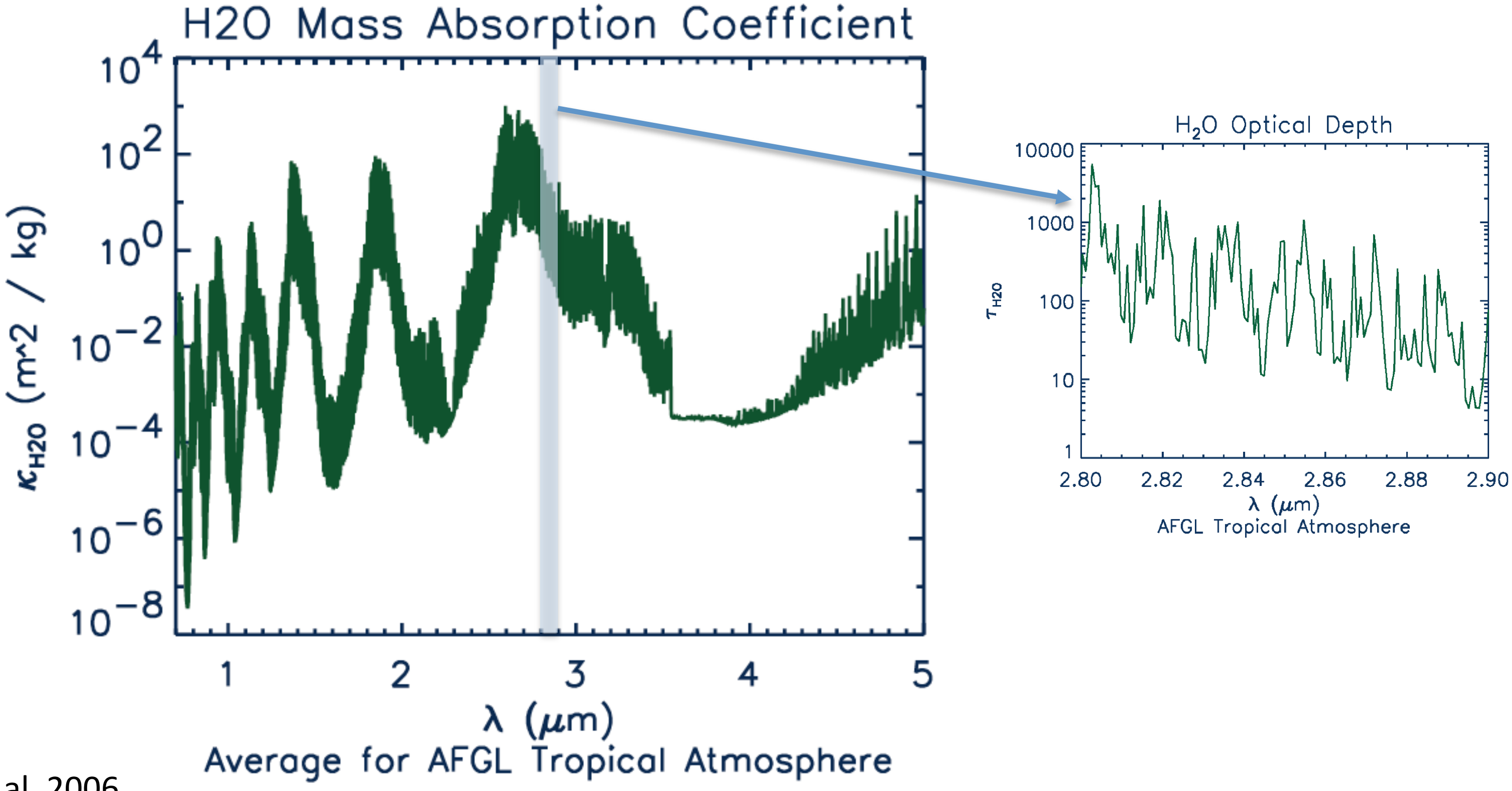
Fraction of radiation absorbed while passing from the surface to the top of the atmosphere.

Longwave radiative flux at the top of the atmosphere

Challenge of radiative parameterization

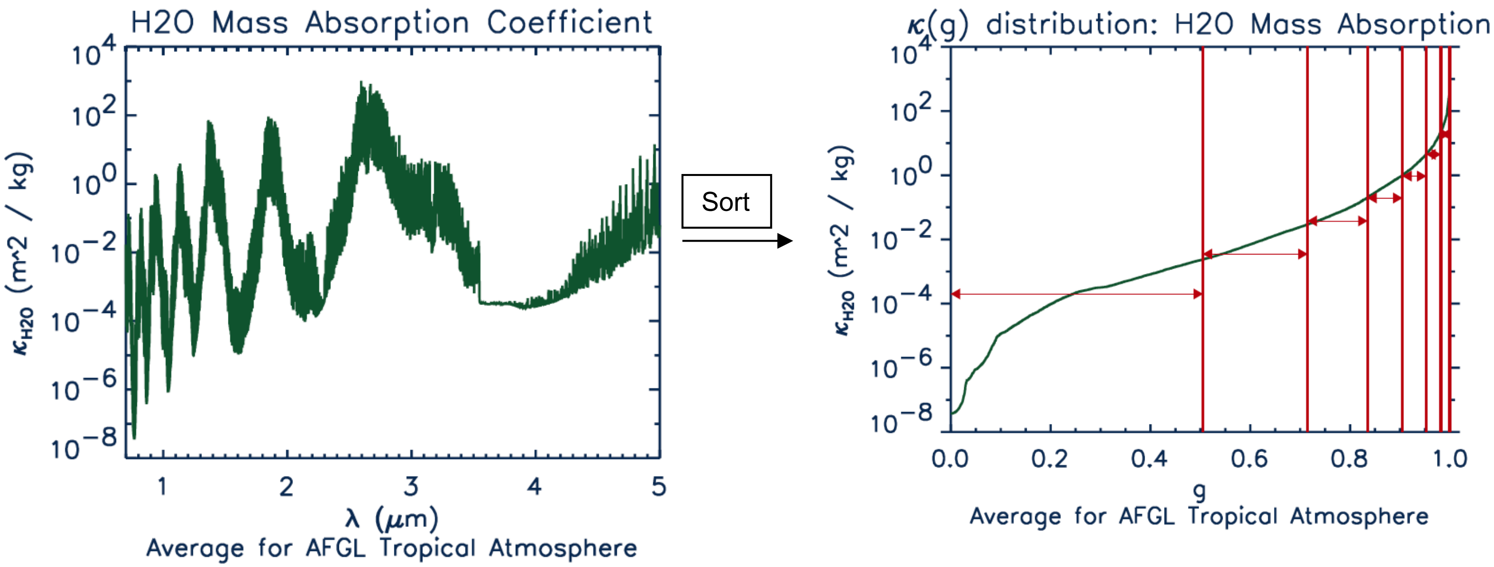
Radiatively active gases (H_2O, CO_2, O_3): large number of spectral lines (10^5-10^6)

Absorption coefficient: 12 orders of magnitude at different wavelengths



Collins et al, 2006

k-distribution Band Models



$$\boxed{T(u) = \frac{1}{\lambda_2 - \lambda_1} \int_{\lambda_1}^{\lambda_2} \exp[-\kappa(\lambda) u] \, d\lambda}$$

$$\boxed{\hat{T}(u) \simeq \sum_{i=1}^{N} \exp[-\hat{\kappa}_i u] \; \delta g_i}$$

- In the k-distribution band model, the absorption coefficients are sorted by magnitude.
- The transmission integral is easier to approximate in this sorted form.

CAM5 Radiation Code

- Rapid Radiative Transfer Model for GCM's ('RRTMG')
  - correlated K-code
  - validated against line-by-line models
- Radiation code is expensive (~50% of total) even when calculated once every hour

Planetary Boundary Layer (PBL)

- The PBL is the lowest part of the troposphere where winds, temperatures and humidity are strongly influenced by the surface.

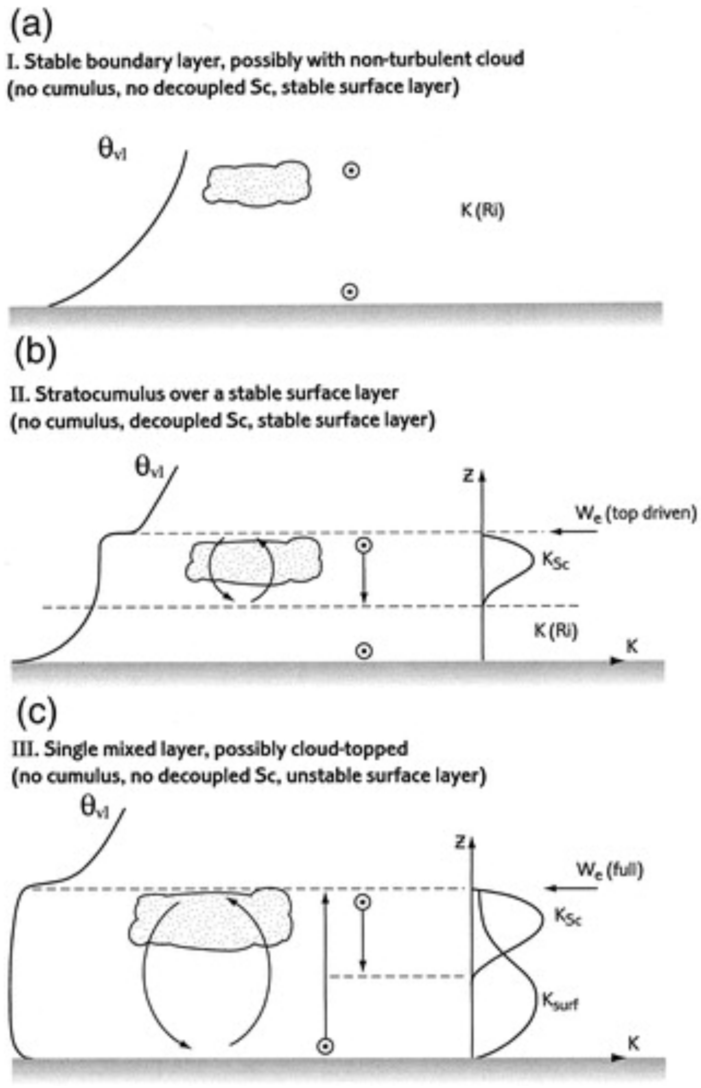
- PBL parameterization should be able to handle many different turbulence regimes.

- CAM4: non-local transport scheme

- optimized for simulation of dry convective and nocturnal PBL over land.

- CAM5: TKE-based moist turbulence

- designed for stratocumulus marine boundary layer



(a)

I. Stable boundary layer, possibly with non-turbulent cloud (no cumulus, no decoupled Sc, stable surface layer)

(b)

II. Stratocumulus over a stable surface layer (no cumulus, decoupled Sc, stable surface layer)

(c)

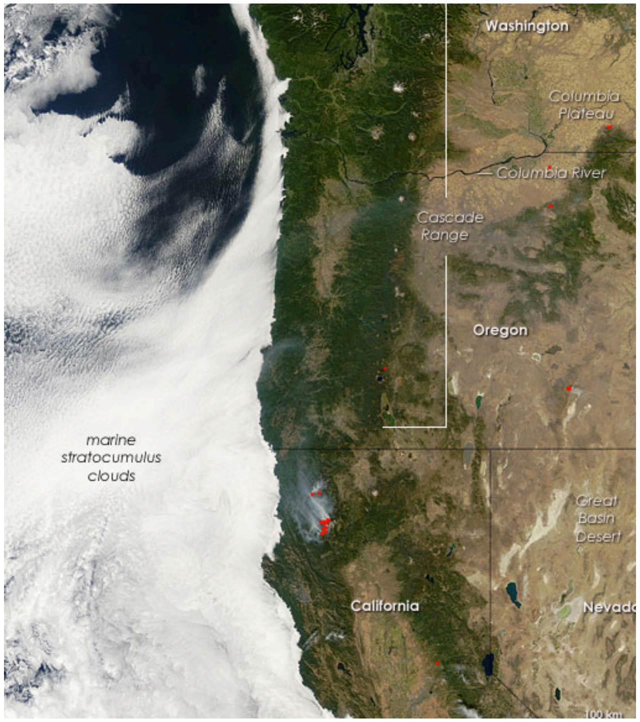
III. Single mixed layer, possibly cloud-topped (no cumulus, no decoupled Sc, unstable surface layer)

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

entrainment at cloud top

Strong longwave cooling at cloud top

Possible decoupling

drizzle

turbulence

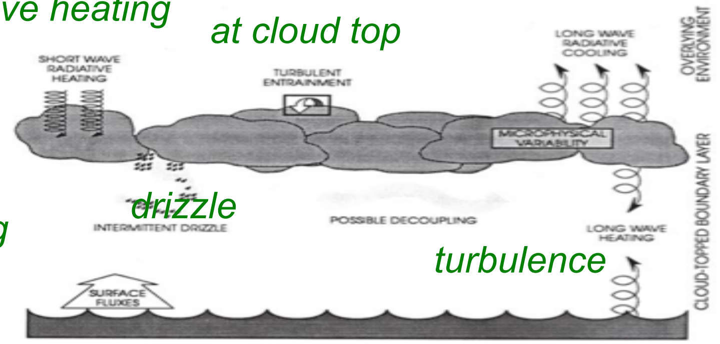


FIG. 1. The interplay of physical processes associated with stratocumulus cloud layers.

A few hundreds meters

CAM5 represents stratocumulus better

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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

Parameterizations from CAM4 to CAM5

Major improvements in CAM5

- A new moist turbulence scheme explicitly simulates stratus-radiation-turbulence interactions
- 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 (**aerosol indirect effect**)

Sea-Surface Temperature errors

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

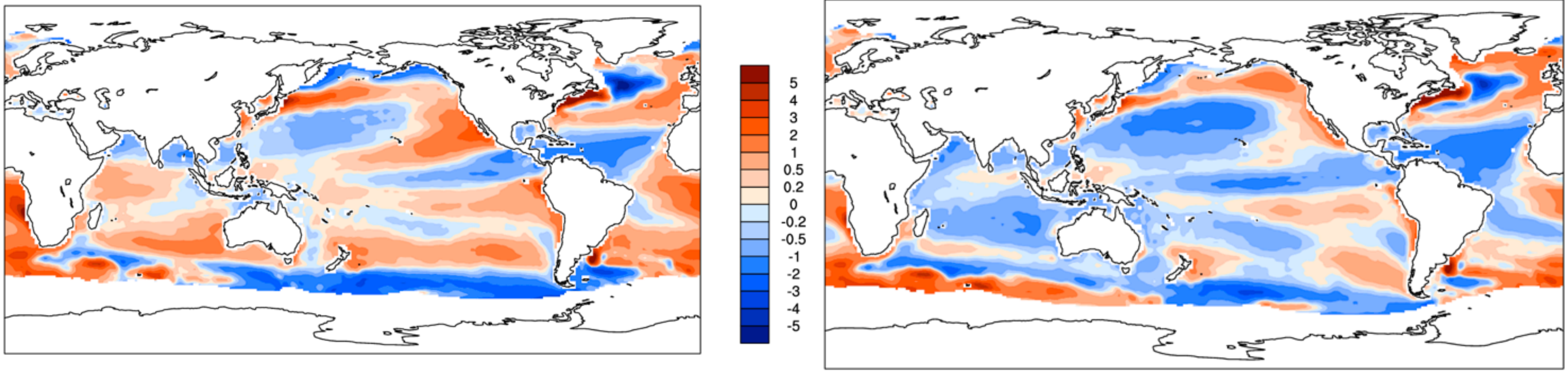
- Root Mean Square Errors (RMSE) reduced in CAM5.1

CESM with CAM4

Mean = 0.18
RMSE = 1.07

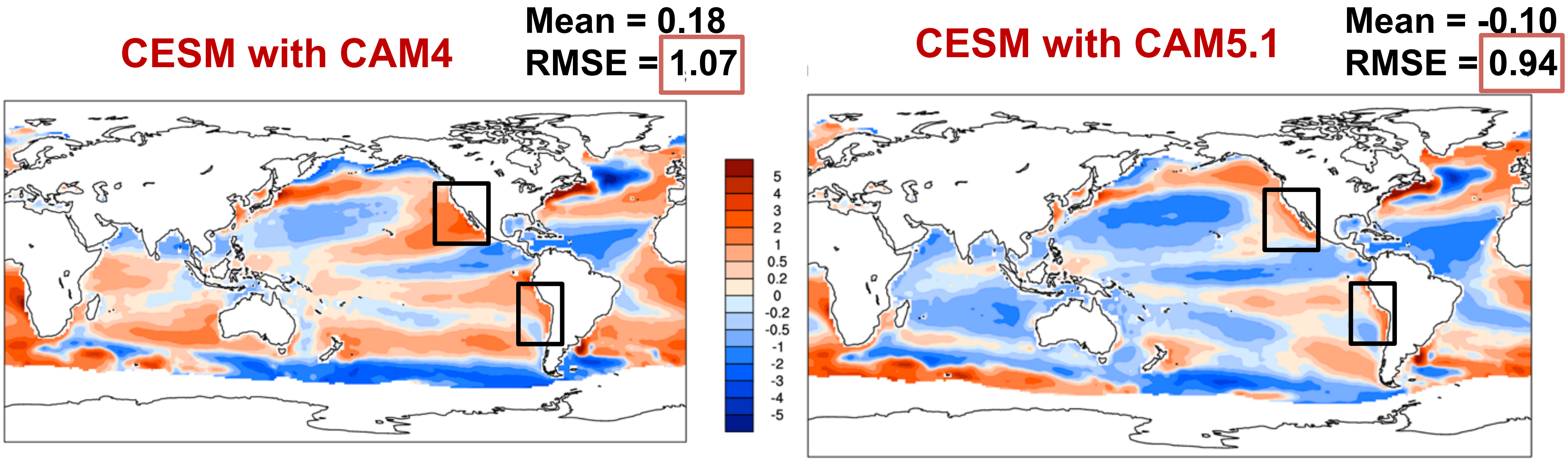
CESM with CAM5.1

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)



CESM with CAM4

Mean = 0.18
RMSE = 1.07

CESM with CAM5.1

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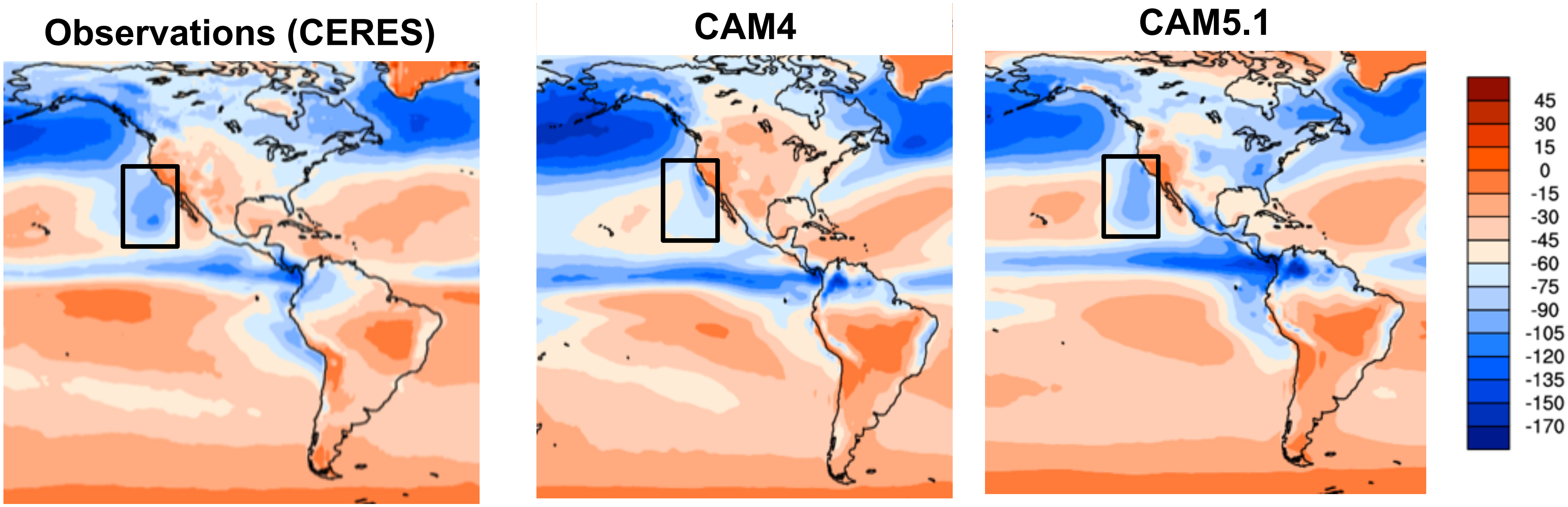
RMSE = 0.94

Californian stratocumulus

Shortwave cloud forcing (W/m^2) = $\textbf{Net SW}_{\textbf{all sky}} - \textbf{Net SW}_{\textbf{clear sky}}$
- Tells us something about the cloud cooling effect
- The more negative, the more cooling effect


Observations (CERES)

CAM4

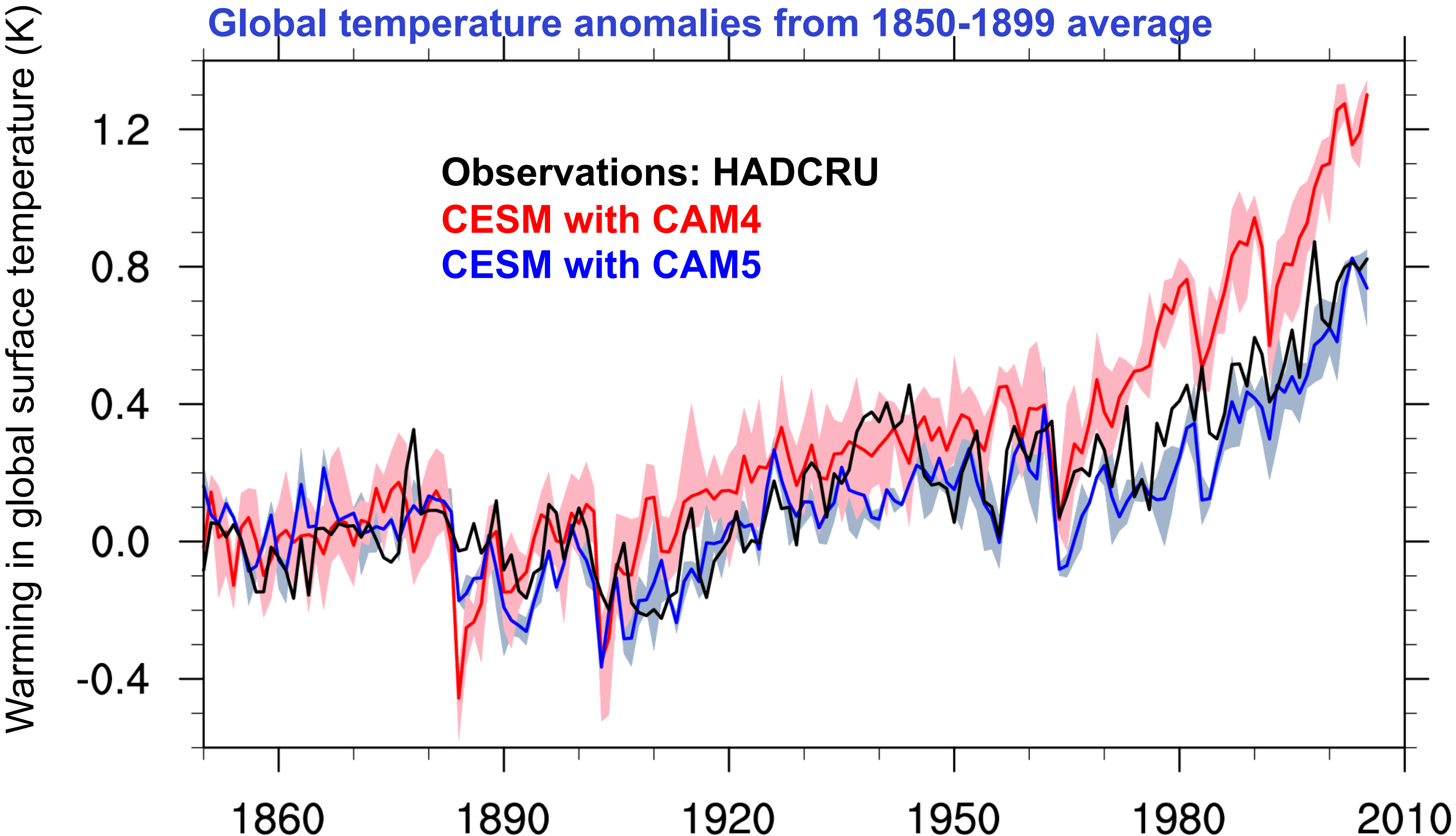
CAM5.1

Cooling effect on the ocean

Not enough cooling and cloud too close to the coast

Major improvement

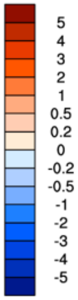
Warming over the 20th century



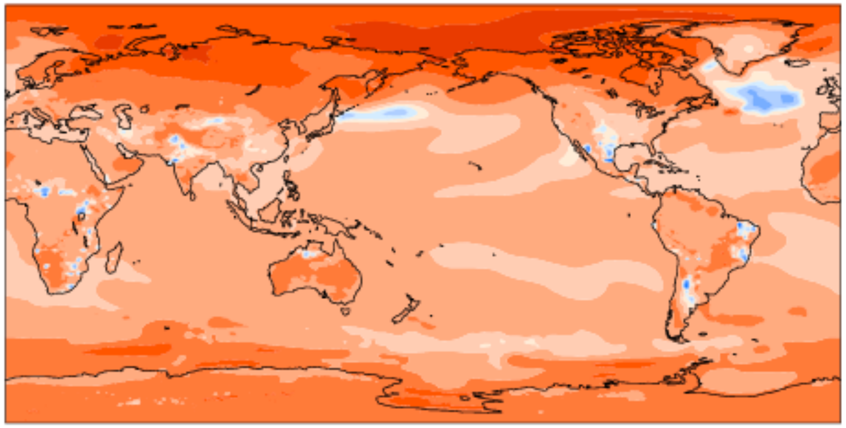
Warming over the 20th century

- Warming over 20th century:

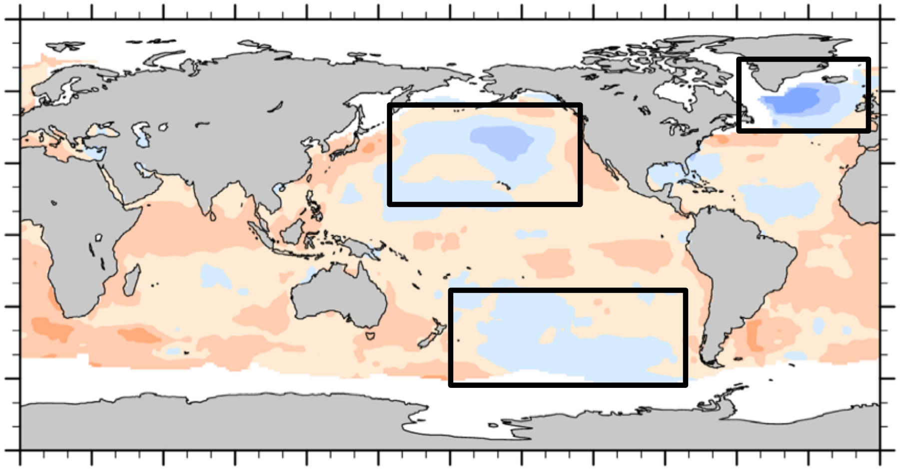
$TS^{\text{(present day)}} - TS^{\text{(preindustrial)}}$



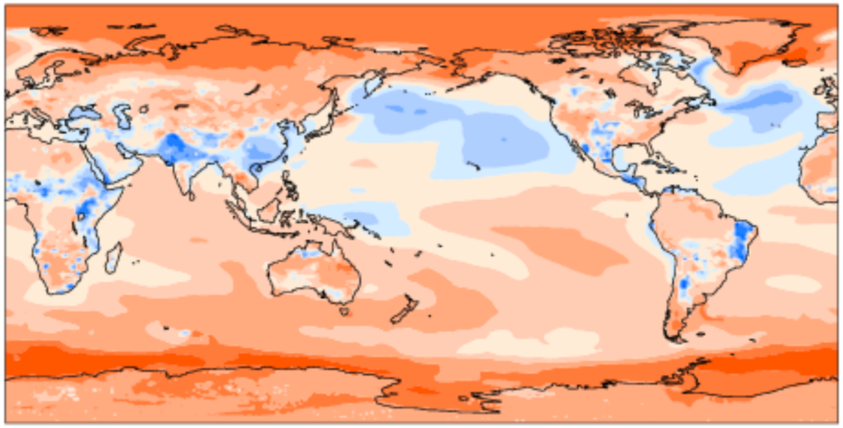
CESM with CAM4 **Mean = 0.84**



Hurrell SSTs dataset



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

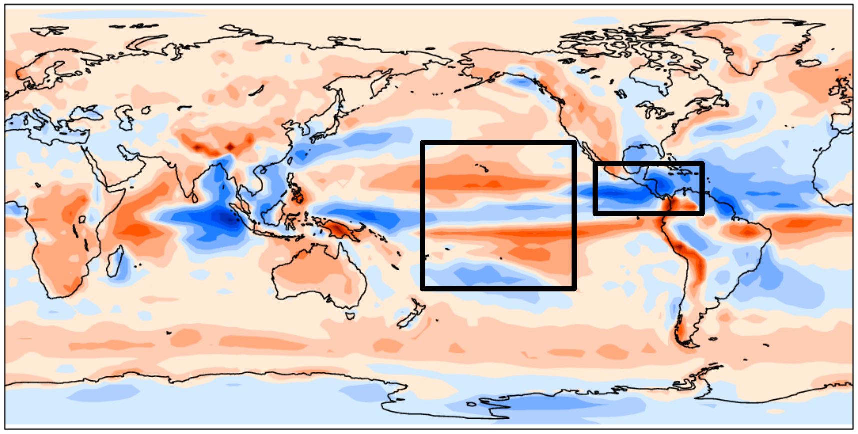


Precipitation errors

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

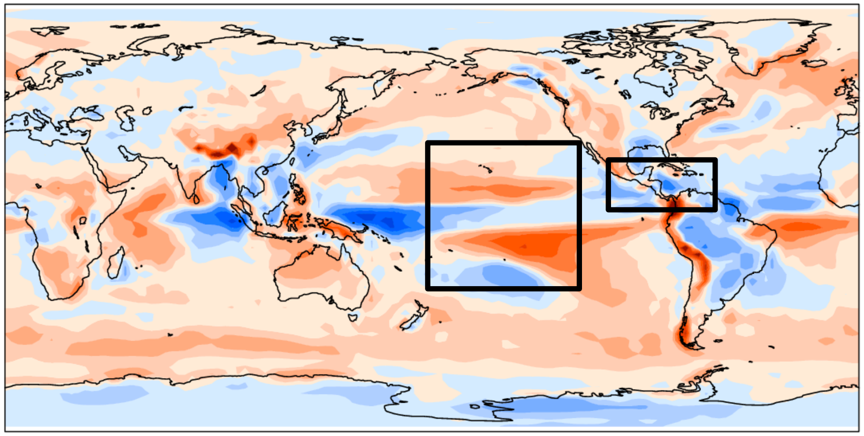
CESM with CAM4

Mean = 0.27
RMSE = 1.09

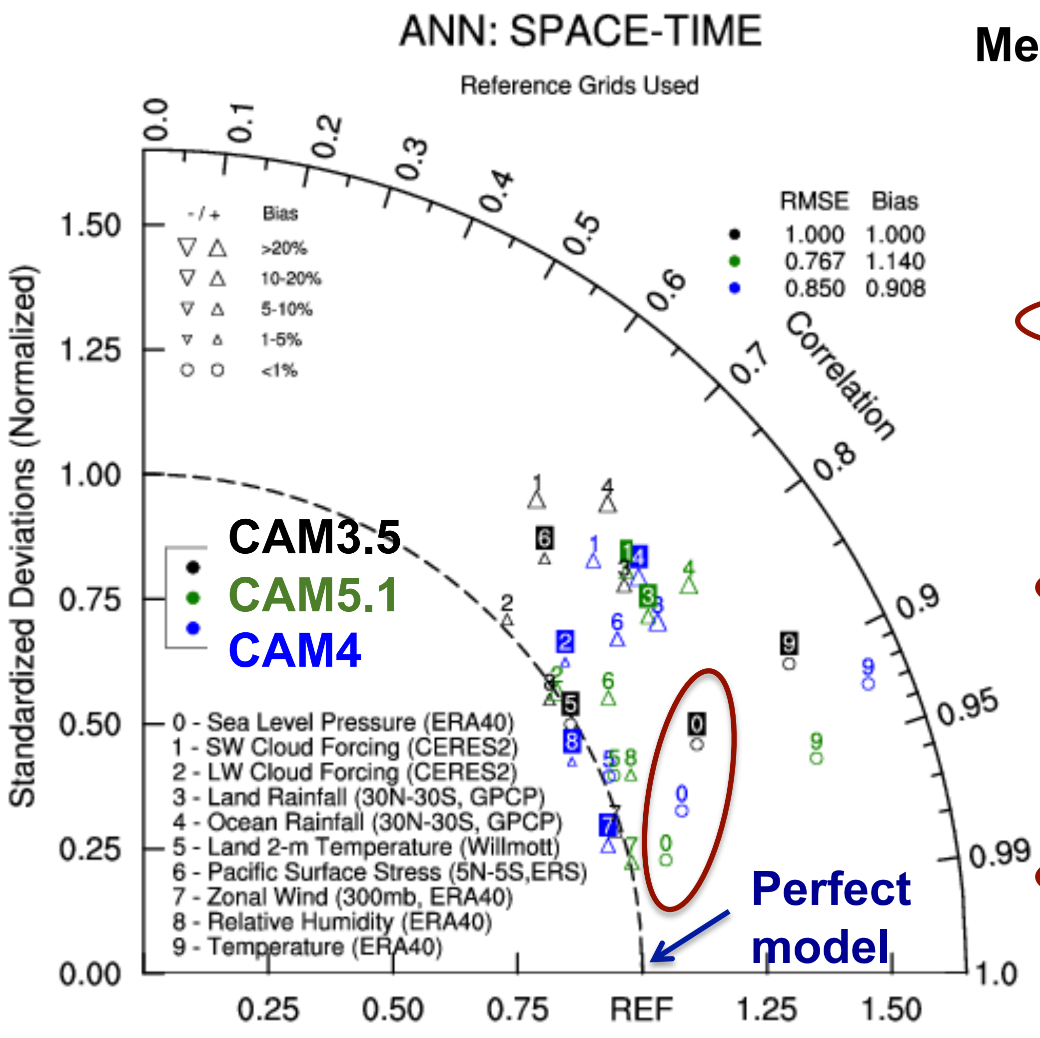


CESM with CAM5.1

Mean = 0.34
RMSE = 1.06



Taylor diagrams



Perfect model

Metric to assess model improvement

CAM3.5 – 2deg

Bias = 1.0

RMSE = 1.0

CAM4

Bias = 0.91

RMSE = 0.85

CAM5.1

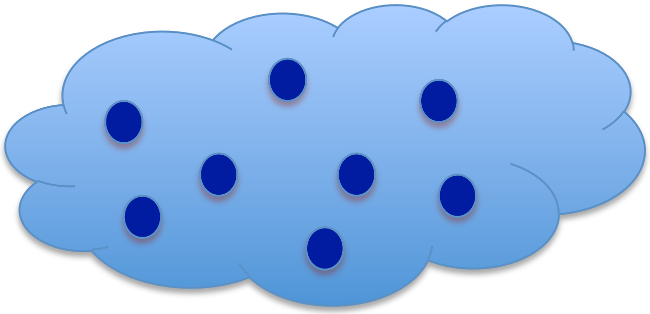
Bias = 1.14

RMSE = 0.77

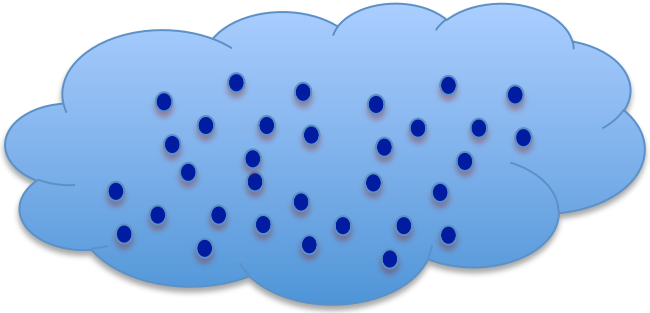
Aerosol and cloud formation

- 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



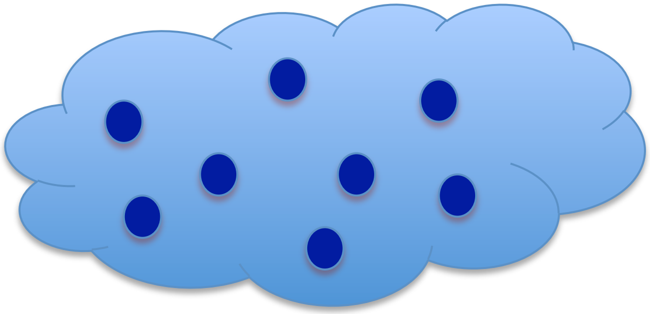
Aerosol and cloud formation

- 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



Polluted air (many CCNs)
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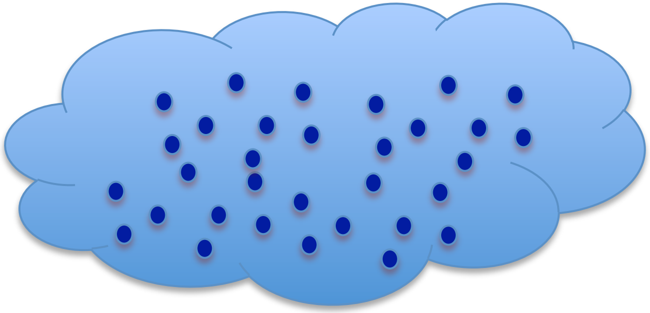


Aerosol: direct and indirect effect

Direct effect

- aerosols scatter and absorb solar and infrared radiation

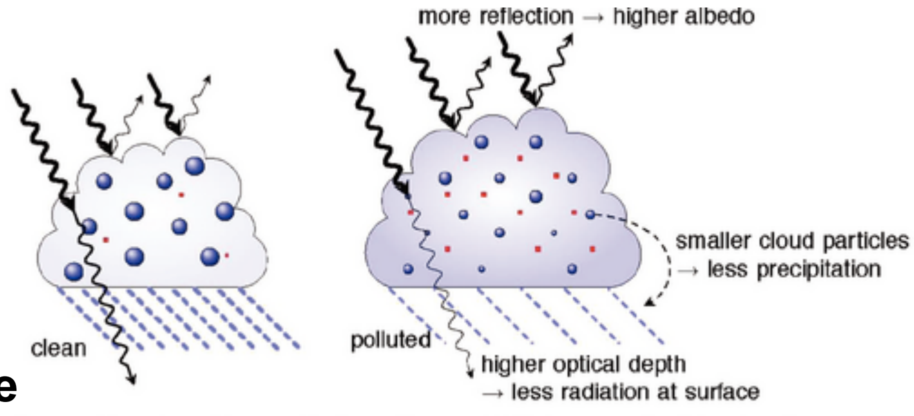
Indirect effect

If aerosol number increases

=> cloud with many small droplets

=> higher albedo (cooling effect on surface)

=> Less precipitation



Aerosols have a cooling effect on climate

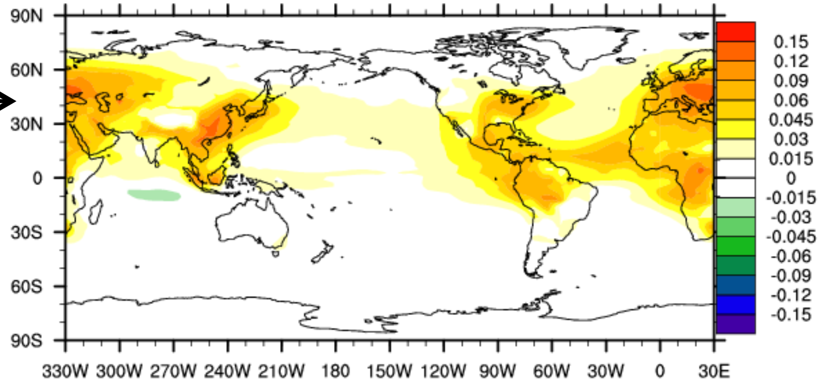
	Direct effect W/m2	**Indirect effect W/m2**
CAM5.1	**-0.21**	**-1.01**
IPCC values	**-0.5 [-0.9 to -0.1]**	**-0.7 [-1.8 to -0.3]**

Impact of aerosol changes

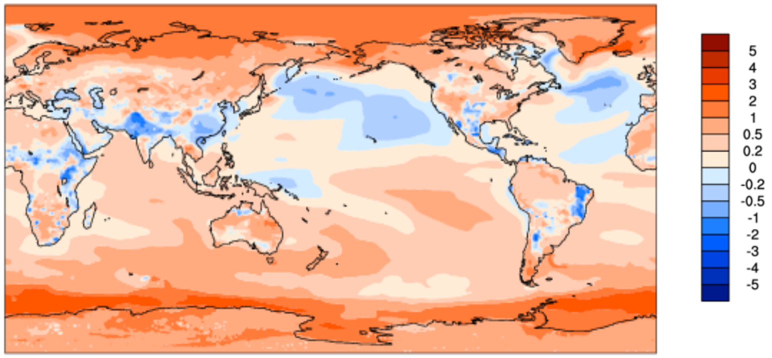
Changes over the 20th century in CESM-CAM5

- 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.

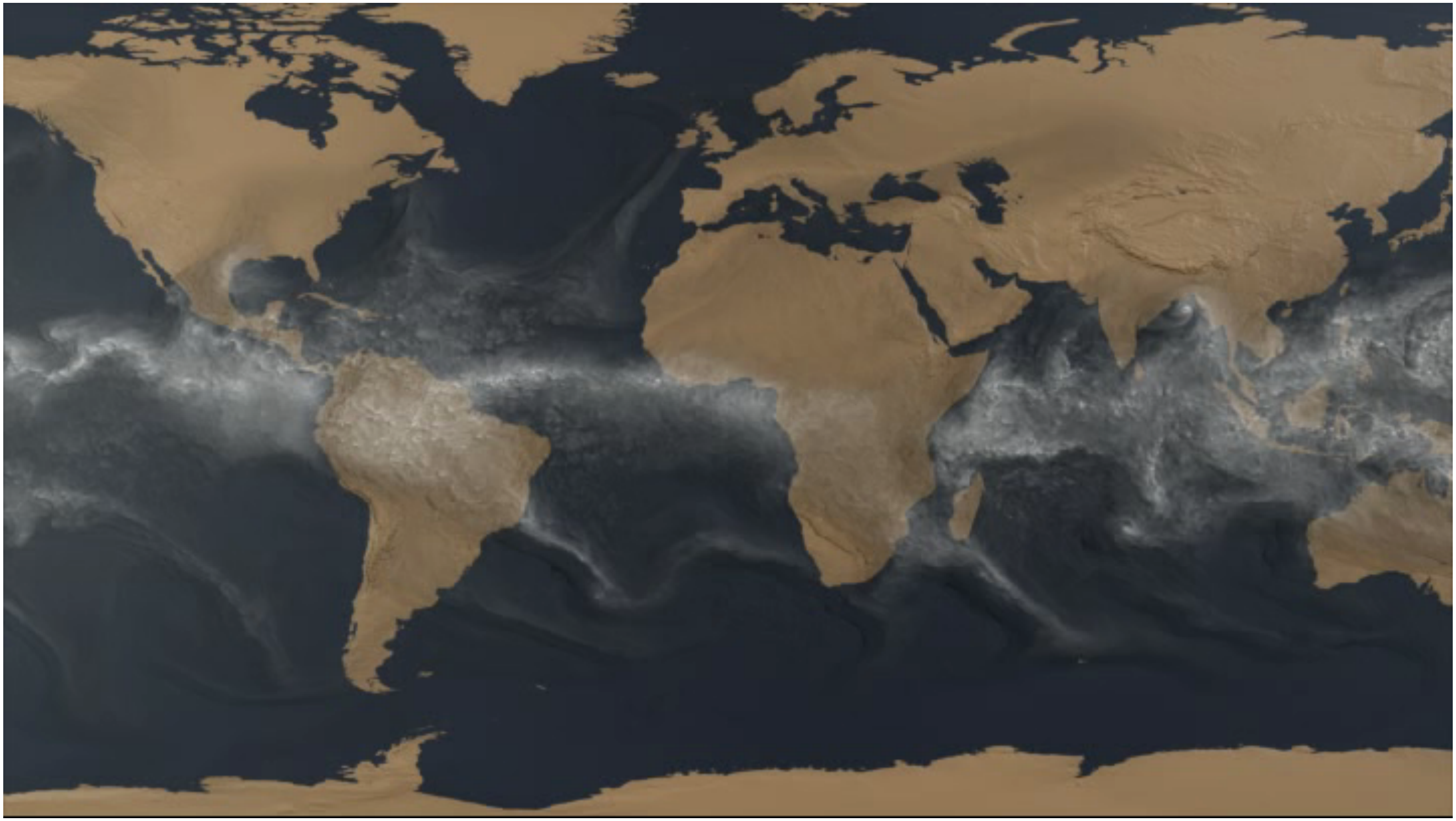
New parameterization have enabled a significant expansion in the research problems that can be addressed within the CESM (for instance we can examine the role of aerosol indirect effect, which was not previously possible).

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.

Summary

- GCMs physics=unresolved processes=parameterization
- Parameterization = approximating reality
  - Starts from and maintains physical constraints
  - Tries to represent effects of smaller ‘sub-grid’ scales
- Fundamental constraints (mass & energy conservation) are our friends
- Clouds are incredibly hard: lots of scales, lots of phase changes, lots of variability
- Clouds are coupled to radiation (also hard) = biggest uncertainties (in future climate)

Thanks



Courtesy: Mark Taylor