ATM 265, Spring 2019
Lecture 09
Turbulence, Clouds and Moisture
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Reynold's Averaging

Three forms of the water vapor transport equation:

$$\frac{dq_v}{dt} = 0$$ **(Lagrangian form)**

$$\frac{\partial q_v}{\partial t} + \mathbf{u} \cdot \nabla q_v = 0$$ **(Eulerian form)**

$$\frac{\partial}{\partial t}(\rho q_v) + \nabla \cdot (\rho \mathbf{u} q_v) = 0$$ **(Conservative form)**

Reynold's Averaging

$$\frac{\partial}{\partial t}(\rho q_v) + \nabla \cdot (\rho \mathbf{u} q_v) = 0$$

This equation can be rewritten in split horizontal / vertical form:

$$\frac{\partial}{\partial t}(\rho q_v) + \nabla_h \cdot (\rho \mathbf{u}_h q_v) + \frac{\partial}{\partial z}(\rho w q_v) = 0$$

Introduce Reynold's averages, which represents a division of the field into mean (i.e. resolved) and perturbed (i.e. unresolved or sub-grid) components:

$$\mathbf{u}_h = \overline{\mathbf{u}_h} + \mathbf{u}_h' \qquad q_v = \overline{q_v} + q_v'$$

Rules:

$$\overline{\overline{x}} = \overline{x} \qquad \overline{x'} = 0 \qquad \overline{xy} = \overline{x}\,\overline{y} + \overline{x'y'}$$

Reynold's Averaging

$$\frac{\partial}{\partial t}(\rho q_v) + \nabla_h \cdot (\rho \mathbf{u}_h q_v) + \frac{\partial}{\partial z}(\rho w q_v) = 0$$

$$\mathbf{u}_h = \overline{\mathbf{u}_h} + \mathbf{u}'_h \qquad\qquad q_v = \overline{q_v} + q'_v$$

$$\overline{\frac{\partial}{\partial t}(\rho(\overline{q_v} + q'_v))} + \nabla_h \cdot \overline{(\rho(\overline{\mathbf{u}_h} + \mathbf{u}'_h)(\overline{q_v} + q'_v))} + \frac{\partial}{\partial z}\overline{(\rho(\overline{w} + w')(\overline{q_v} + q'_v))} = 0$$

$$\frac{\partial}{\partial t}(\rho\overline{q_v}) + \nabla_h \cdot (\rho\overline{\mathbf{u}_h}\,\overline{q_v} + \rho\overline{\mathbf{u}'_h q'_v}) + \frac{\partial}{\partial z}(\rho\overline{w}\,\overline{q_v} + \rho\overline{w' q'_v}) = 0$$

Reynold's Averaging

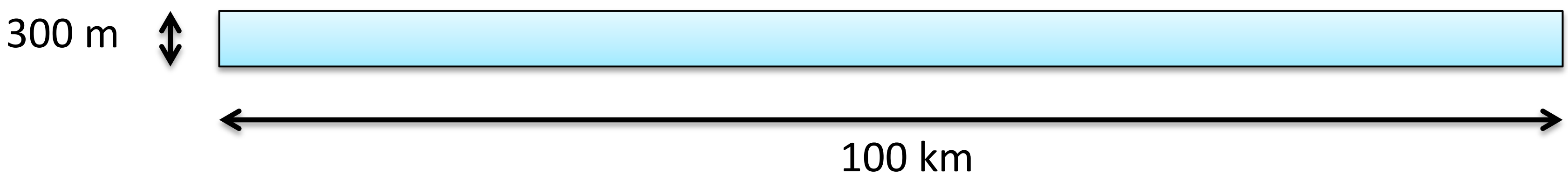
$$\frac{\partial}{\partial t}(\rho\overline{q_v}) + \nabla_h \cdot (\rho\overline{\mathbf{u}_h}\,\overline{q_v} + \rho\overline{\mathbf{u}'_h q'_v}) + \frac{\partial}{\partial z}(\rho\overline{w}\,\overline{q_v} + \rho\overline{w' q'_v}) = 0$$

- Large scale horizontal transport ($\rho\overline{\mathbf{u}_h}\,\overline{q_v}$)
- Horizontal eddy transport ($\rho\overline{\mathbf{u}'_h q'_v}$)
- Large scale vertical transport ($\rho\overline{w}\,\overline{q_v}$)
- Vertical eddy transport ($\rho\overline{w' q'_v}$)

Reynold's Averaging

Observation: Horizontal and vertical fluxes are comparable in magnitude.

But: Vertical fluxes convergence and diverge over much shorter distances than horizontal fluxes.



So: $$\nabla_h \cdot (\rho \overline{\mathbf{u}_h' q_v'}) \ll \frac{\partial}{\partial z} (\rho \overline{w' q_v'})$$

Reynold's Averaging

$$\frac{\partial}{\partial t}(\rho \overline{q_v}) + \nabla_h \cdot (\rho \overline{\mathbf{u}_h}\, \overline{q_v}) + \frac{\partial}{\partial z}(\rho \overline{w}\, \overline{q_v}) + \frac{\partial}{\partial z}(\rho \overline{w' q_v'}) = 0$$

Large scale transport

Vertical eddy transport

Parameterize This!

Kelvin-Helmholtz Instability

Numerical simulation of a Kelvin-Helmholtz instability representing turbulent mixing between two different density fluids. Observe how the small scale mixing acts similar to diffusion.

Source: Wikimedia (http://commons.wikimedia.org/wiki/File:KHI.gif)

Reynold's Averaging

$$\frac{\partial}{\partial t}(\rho\overline{q_v}) + \nabla_h \cdot (\rho\overline{\mathbf{u}_h}\,\overline{q_v}) + \frac{\partial}{\partial z}(\rho\overline{w}\,\overline{q_v}) + \frac{\partial}{\partial z}(\rho\overline{w'q_v'}) = 0$$

Large scale transport

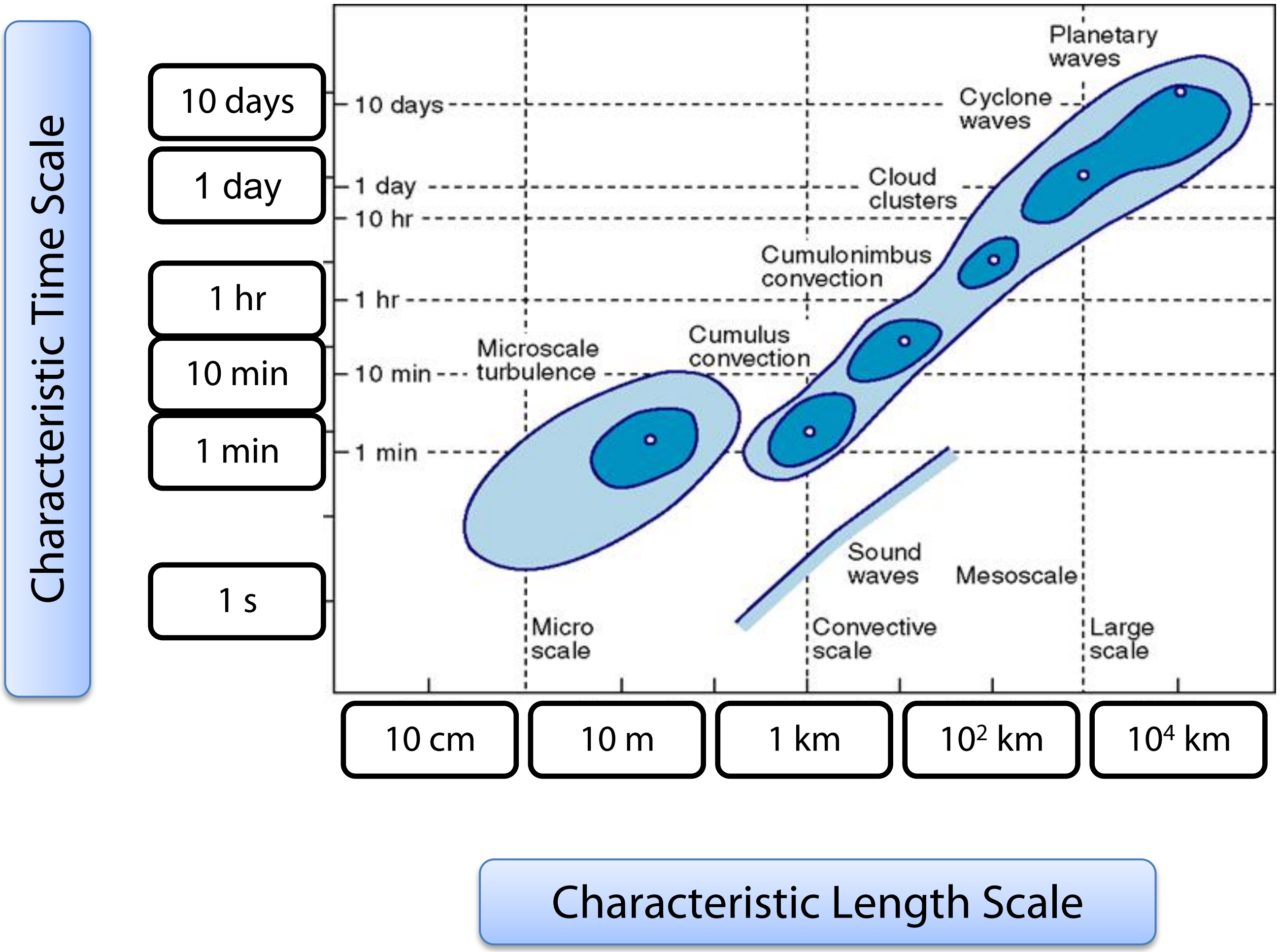
Vertical eddy transport

Parameterize This!

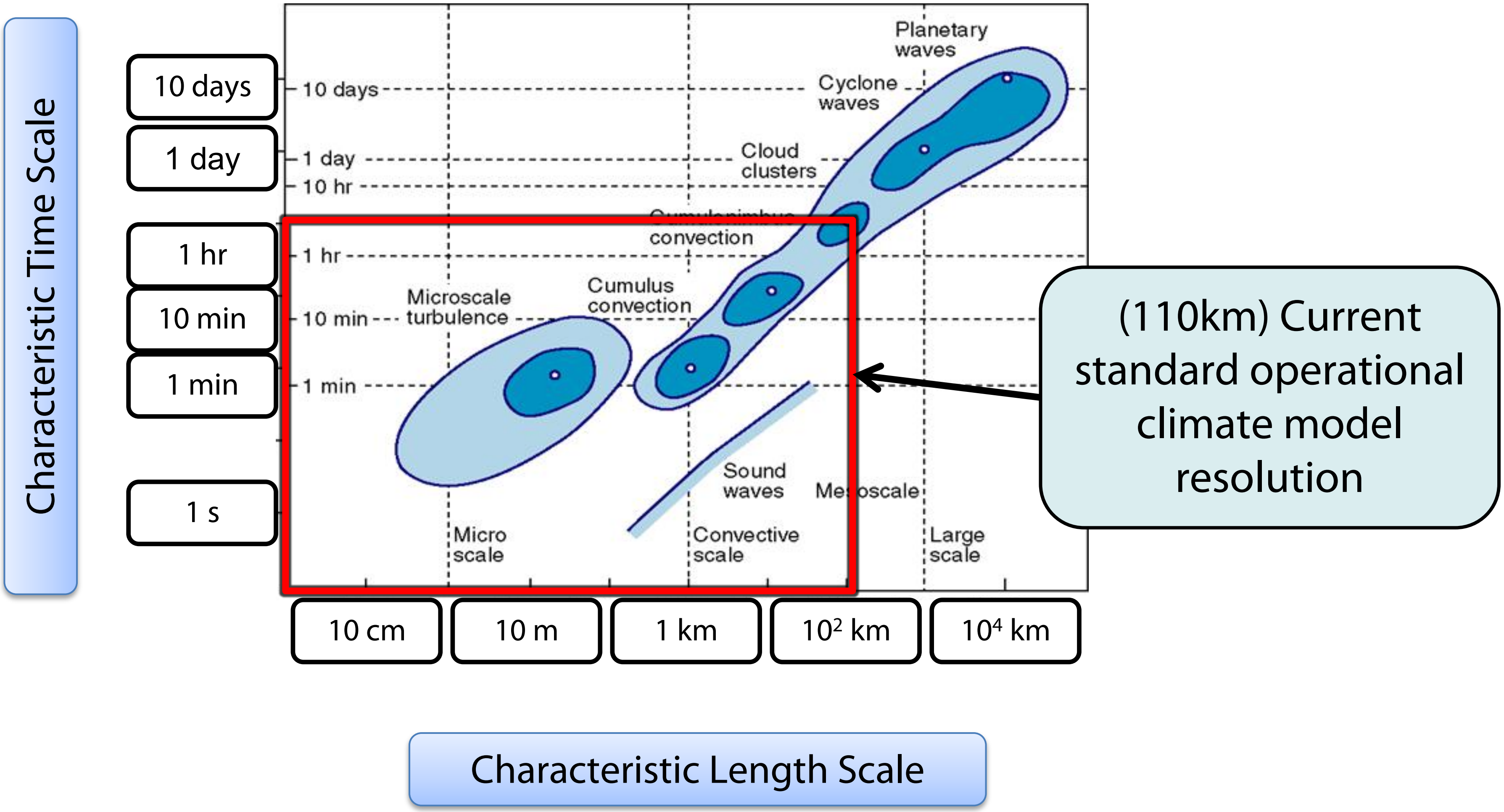
First approximation treatment:

$$\frac{\partial}{\partial z}(\rho\overline{w'q_v'}) \approx \frac{\partial}{\partial z}\left(-\rho K_E \frac{\partial q_v}{\partial z}\right)$$

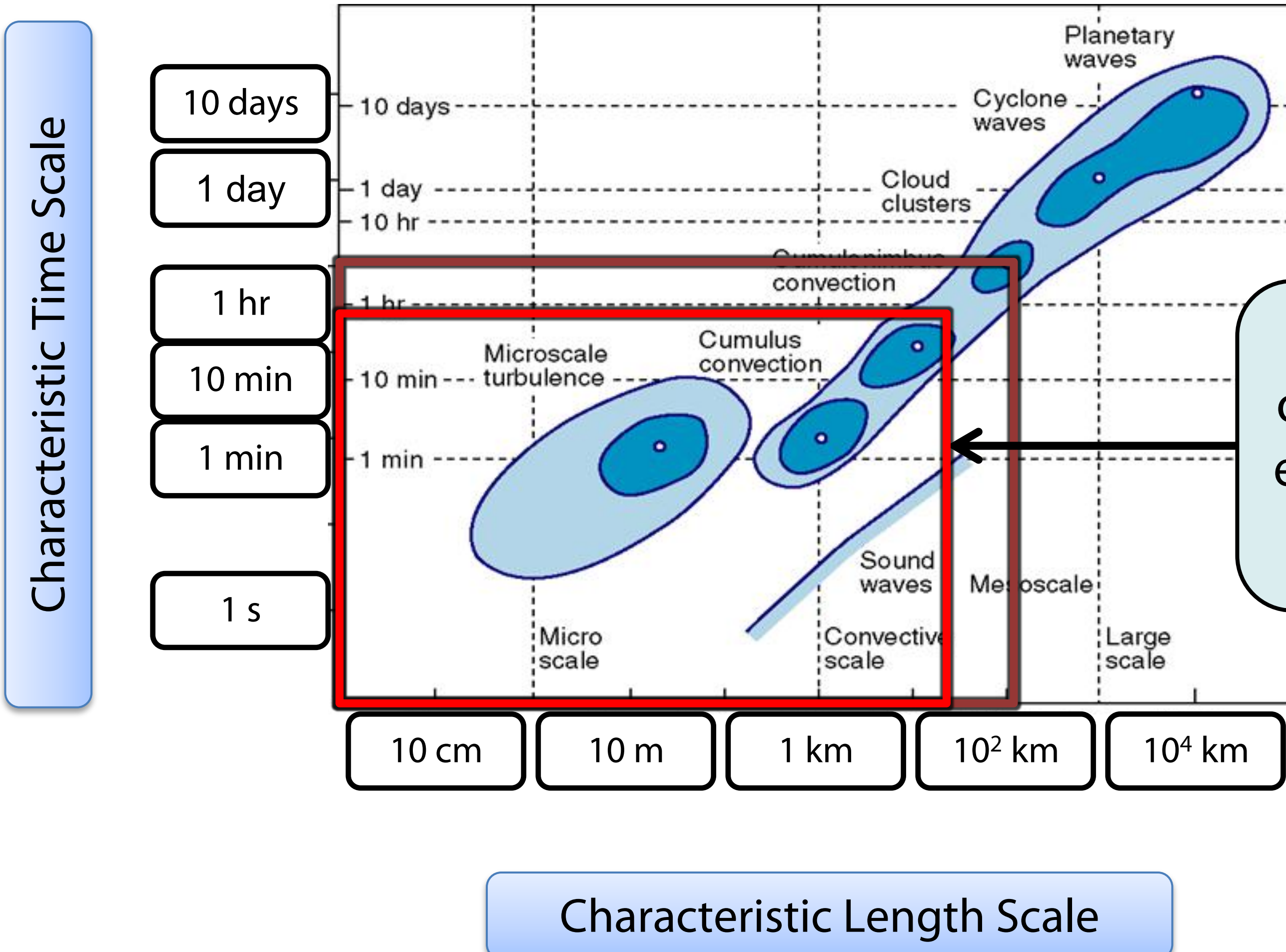
Atmospheric Features by Resolution



Atmospheric Features by Resolution



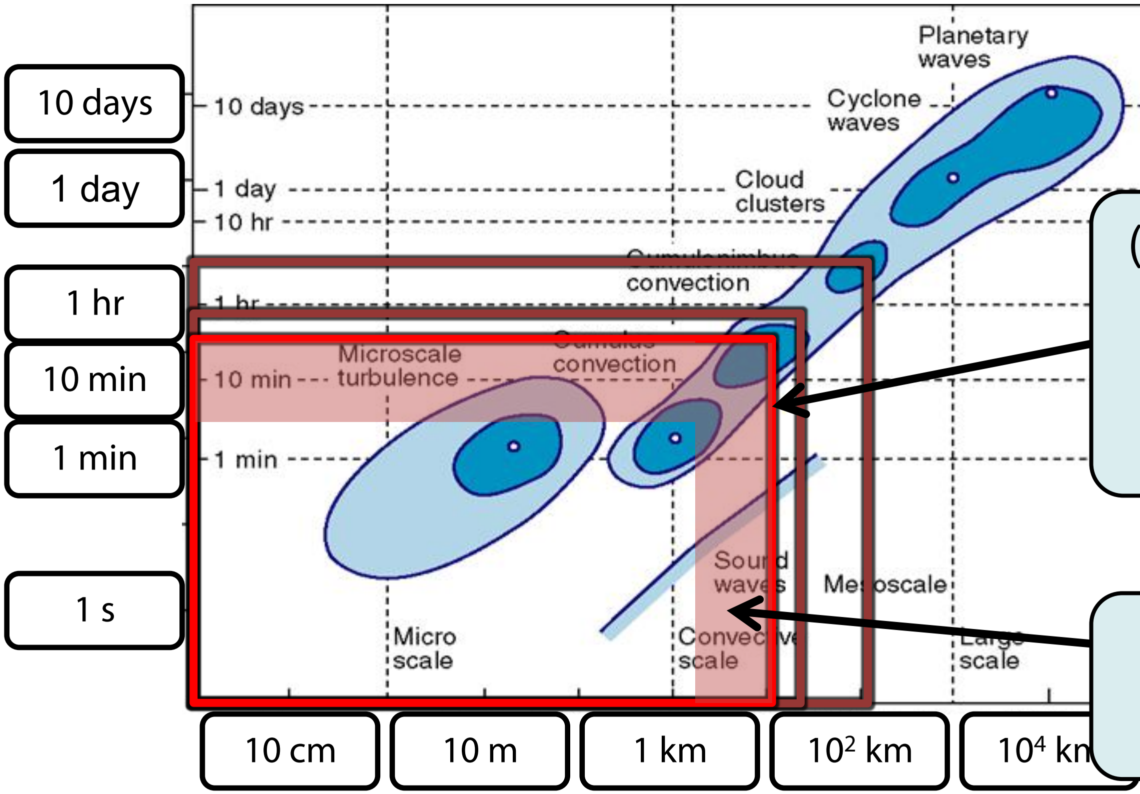
Atmospheric Features by Resolution



(25km) Resolution of tropical cyclones; experimental global climate resolution

Atmospheric Features by Resolution

Characteristic Time Scale

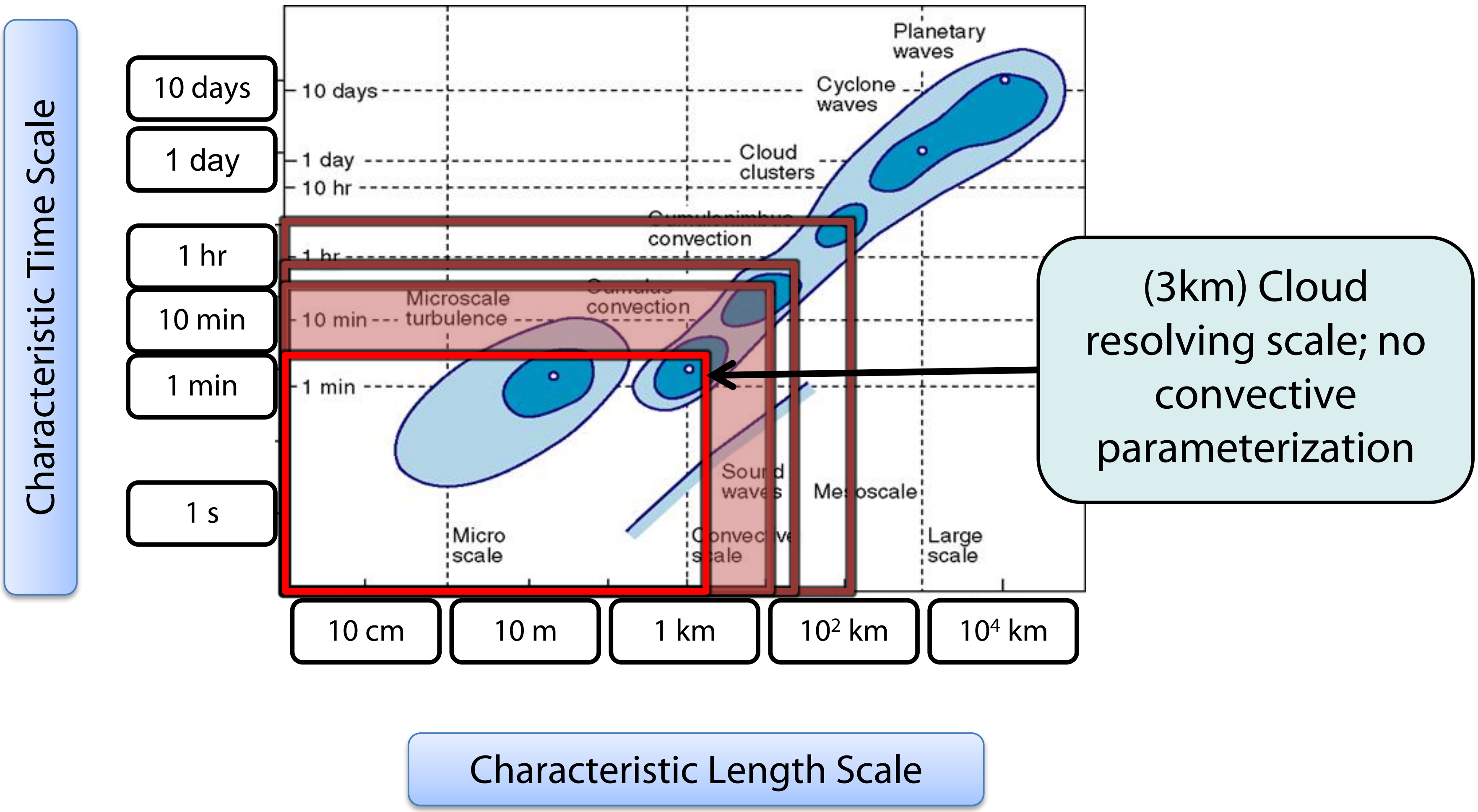


(10km) Transition to non-hydrostatic scales; NWP resolution

"Parameterization No-man's Land"

Characteristic Length Scale

Atmospheric Features by Resolution



Parameterizations: High level design

Source: Rich Neale, Julio Bacmeister

1. Inputs and effects totally contained within single columns
   - Single grid point structures are believed

2. Most (may common) schemes do not possess a "memory"
   - Calculations only on instantaneous state of the system

3. Assume sufficient space-time volume in grid means for "good" statistics

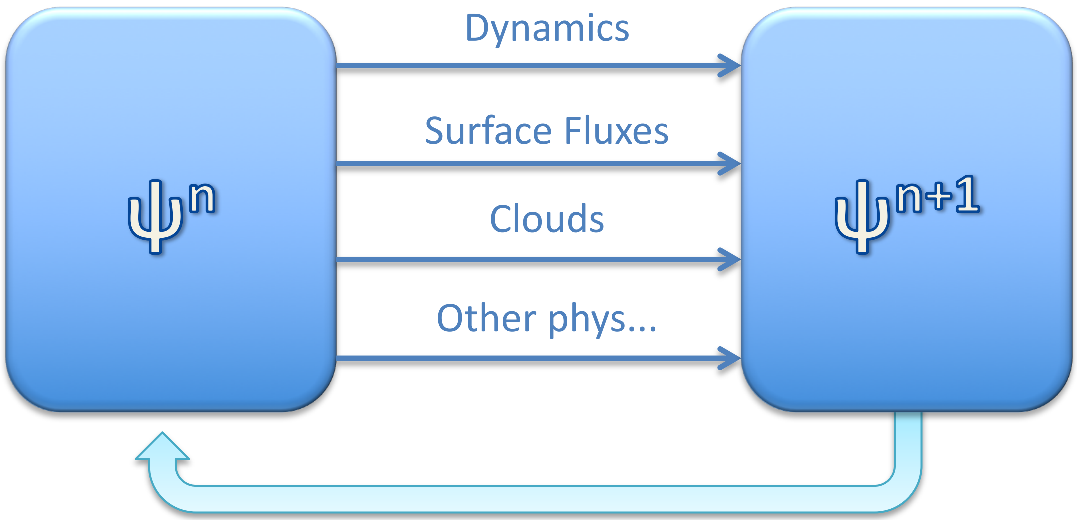
4. For climate should be mass, momentum and energy conserving (limiters and fixers may be needed)

1, 2 and 3 cause trouble as resolution increases and time-step decreases

Dynamics-Parameterization Coupling

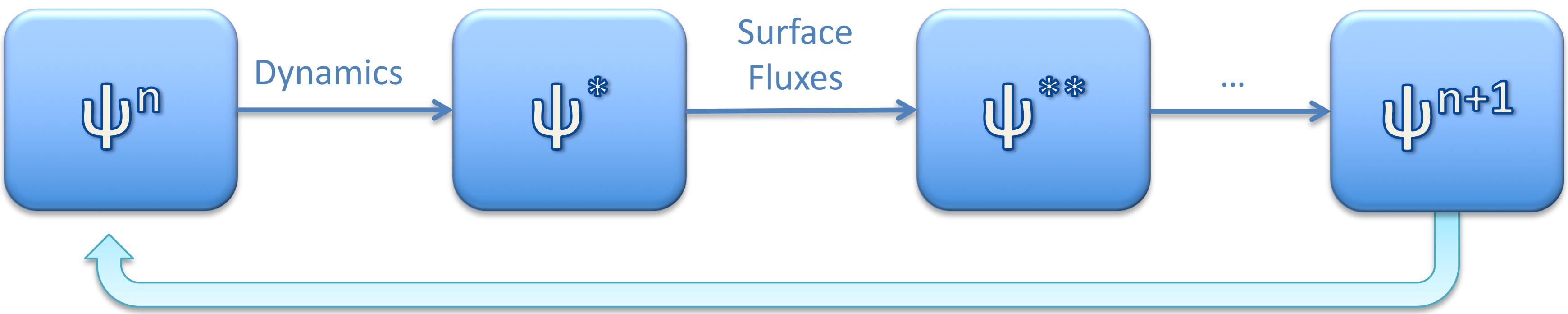
Process Split

All parameterizations work on the same state, provide tendencies for update



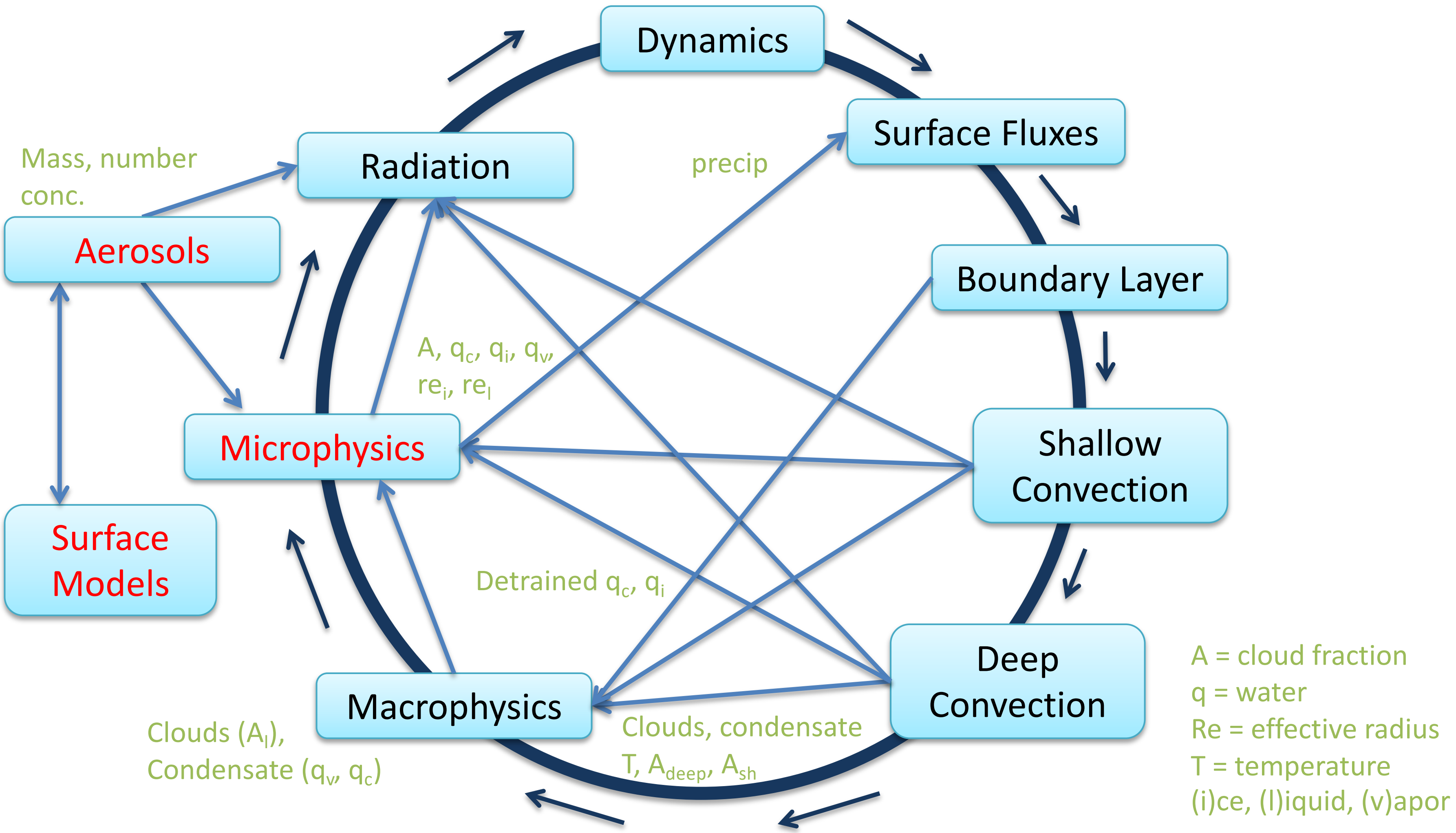
Time Split

Parameterizations update state as they work



CAM Time Step

Source: Rich Neale, Julio Bacmeister



Large Scale Condensation

Large-Scale Condensation

Condensation rate: $$\frac{\partial q_v}{\partial t} = -C$$

Heating due to condensation: $$\frac{\partial T}{\partial t} = \frac{L}{c_p} C$$

Where L is the latent heat of vaporization and c_p is the specific heat of dry air. The saturation specific humidity is determined via Claussius-Clapeyron:

$$q_{sat}(T,p) \approx \epsilon \frac{e_s(T)}{p} \approx \frac{\epsilon}{p} e_0^* \exp\left[-\left(\frac{L}{R_v}\right)\left(\frac{1}{T} - \frac{1}{T_0}\right)\right]$$

In the atmosphere, we never observe $q_v > q_{sat}$ so it is reasonable to assume that condensation occurs nearly instantaneously as a mechanism to reduce the water vapor to saturation.

Large-Scale Condensation

Approximate adjustment as follows:

$$q_v^{n+1} = q_v^n + \Delta q_v \qquad T^{n+1} = T^n + \Delta T$$

Where from the last slide we have:

$$\Delta T = -\frac{L}{c_p}\Delta q_v \qquad \Delta q_v = q_{sat}(T^{n+1}, p) - q_v^n$$

Note:

- In this formulation pressure does not change
- Saturated specific humidity must be evaluated at final temperature, since it's at this stage that we need to ensure $q_v \leq q_{sat}$

Large-Scale Condensation

To solve this set of nonlinear equations, we approximate saturation pressure at new temperature via first-order Taylor series:

$$q_{sat}(T^{n+1}, p) \approx q_{sat}(T, p) + \frac{dq_{sat}}{dT} \Delta T$$

Then solve:

$$T^{n+1} = T^n + \frac{L}{c_p} \left(\frac{q_v^n - q_{sat}(T, p)}{1 + \frac{L}{c_p} \frac{dq_{sat}}{dT}} \right)$$

$$q_v^{n+1} = q_v^n - \left(\frac{q_v^n - q_{sat}(T^n, p)}{1 + \frac{L}{c_p} \frac{dq_{sat}}{dT}} \right)$$

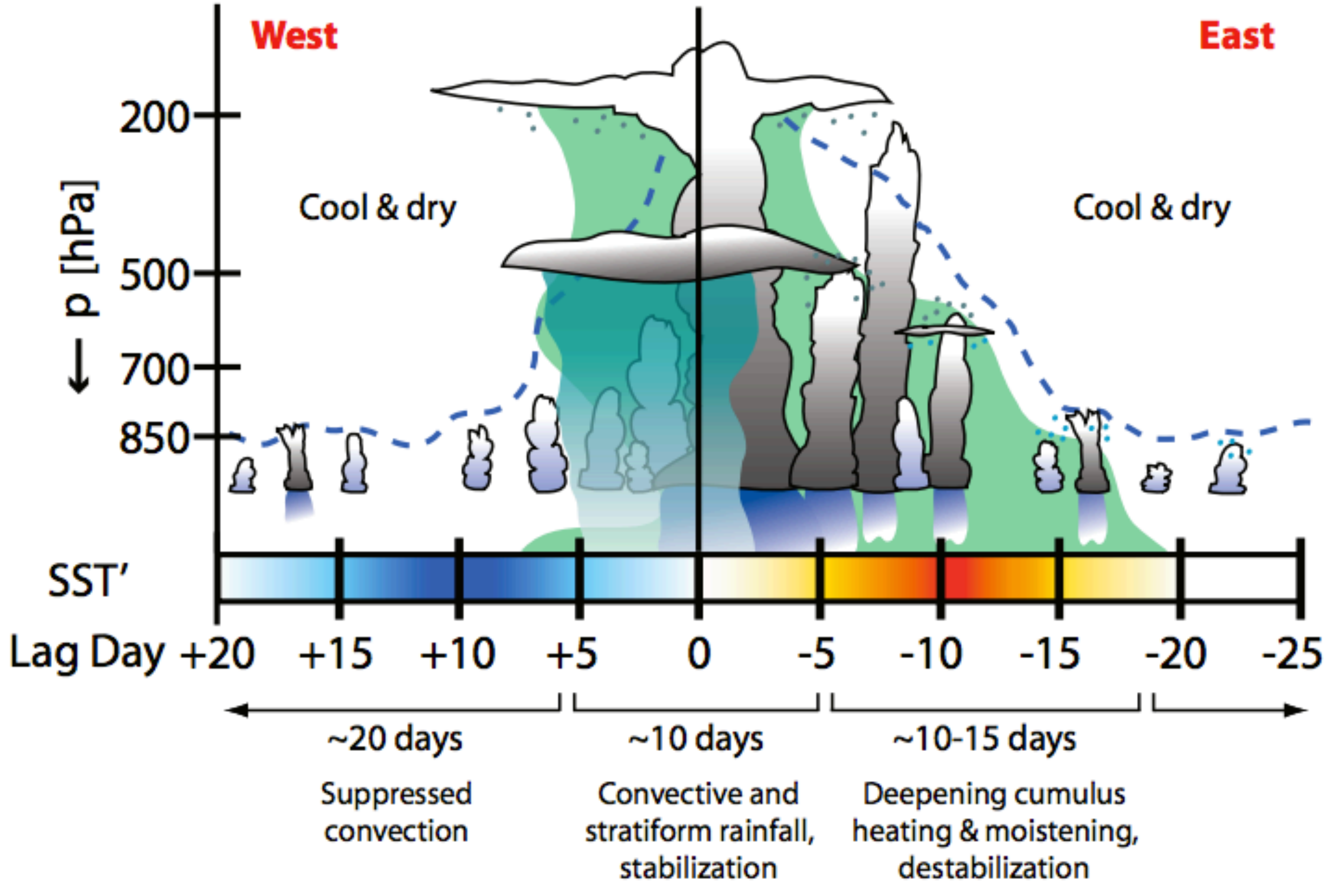
Condensation rate:

$$C = \frac{1}{\Delta t} \left(\frac{q_v^n - q_{sat}(T^n, p)}{1 + \frac{L}{c_p} \frac{dq_{sat}}{dT}} \right)$$

Cloud Parameterizations

Clouds

Source: Jim Benedict



Clouds

Source: David Randall

The treatment of clouds in global atmospheric models is arguably the biggest source of uncertainty.

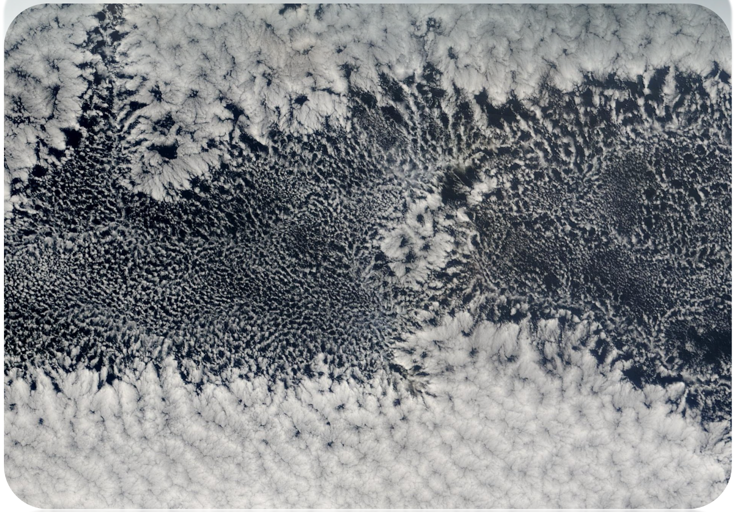
Convective Clouds →

- Deep
- Shallow

Stratiform clouds above the boundary layer

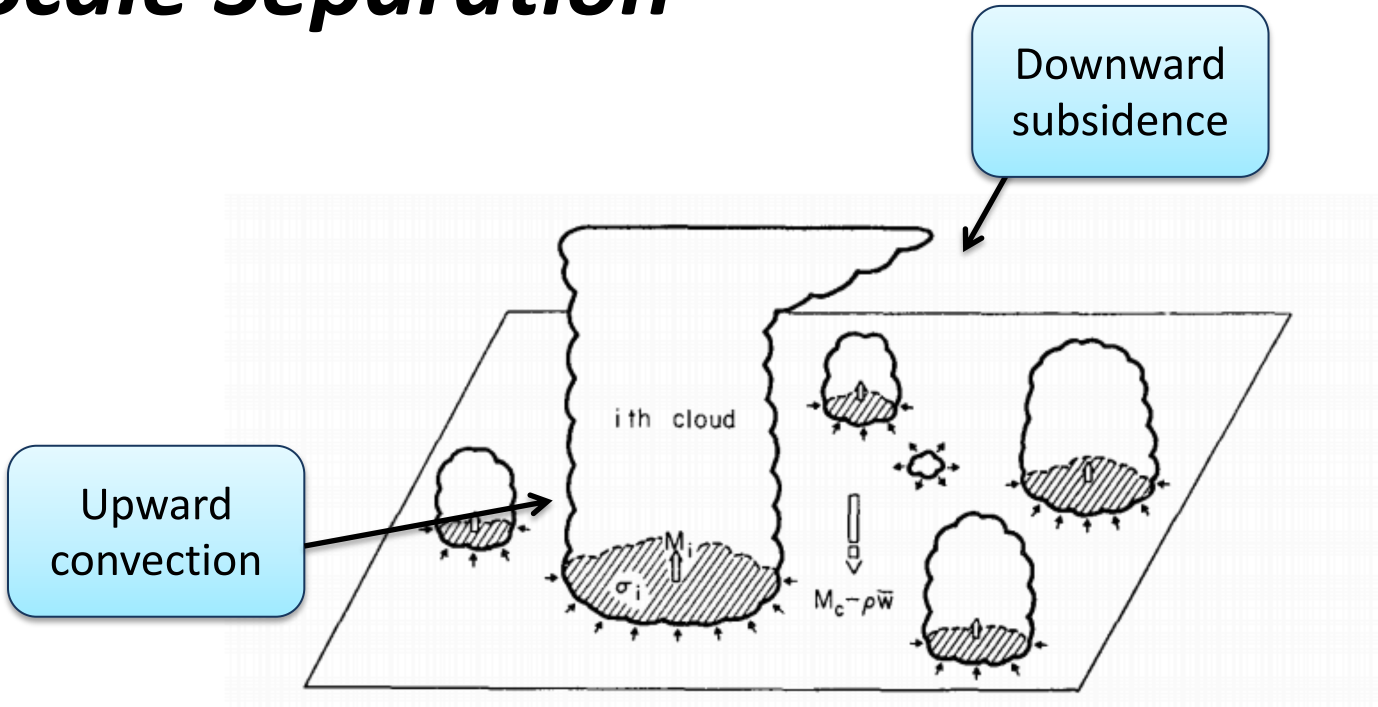
- Convective detrainment
- Frontal lifting
- Orographic lifting

Marine stratocumulus clouds →



Scale Separation

Source: David Randall



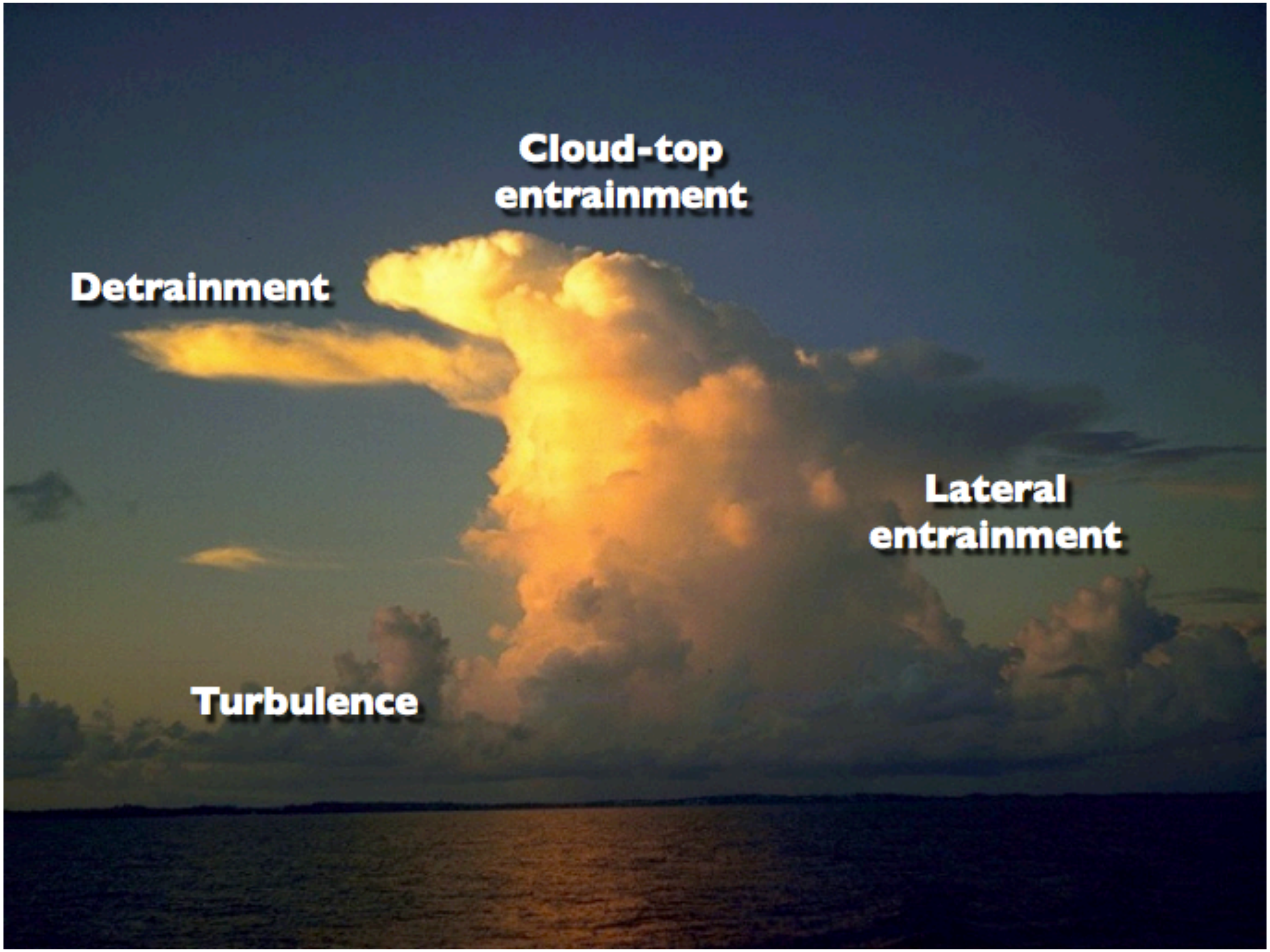
"Consider a horizontal area … large enough to contain an ensemble of cumulus clouds, but small enough to cover only a fraction of a large-scale disturbance. The existence of such an area is one of the basic assumptions of this paper."

- Arakawa and Schubert (1974)

The inclusion of both convective updrafts and large-scale subsidence in each grid cell is an assumption of most modern convective parameterizations.

Cumulus Entrainment

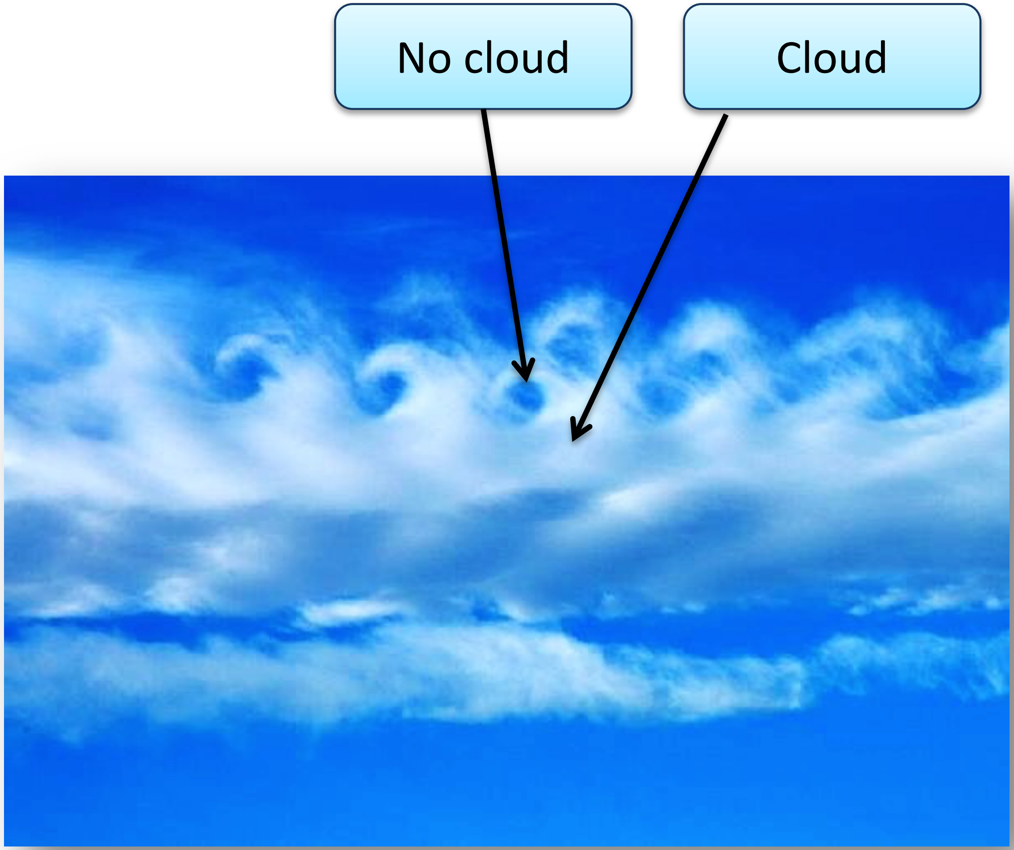
Source: David Randall



What is Entrainment?

Source: David Randall

Entrainment is the active annexation of quiet fluid by turbulence.



Clouds don't entrain

Turbulence entrains

Clouds are turbulent

Clouds: Outstanding Issues

Source: David Randall

The treatment of clouds in global atmospheric models is arguably the biggest source of uncertainty.

Microphysics

- How many water species?
- Aerosols?

Convective entrainment

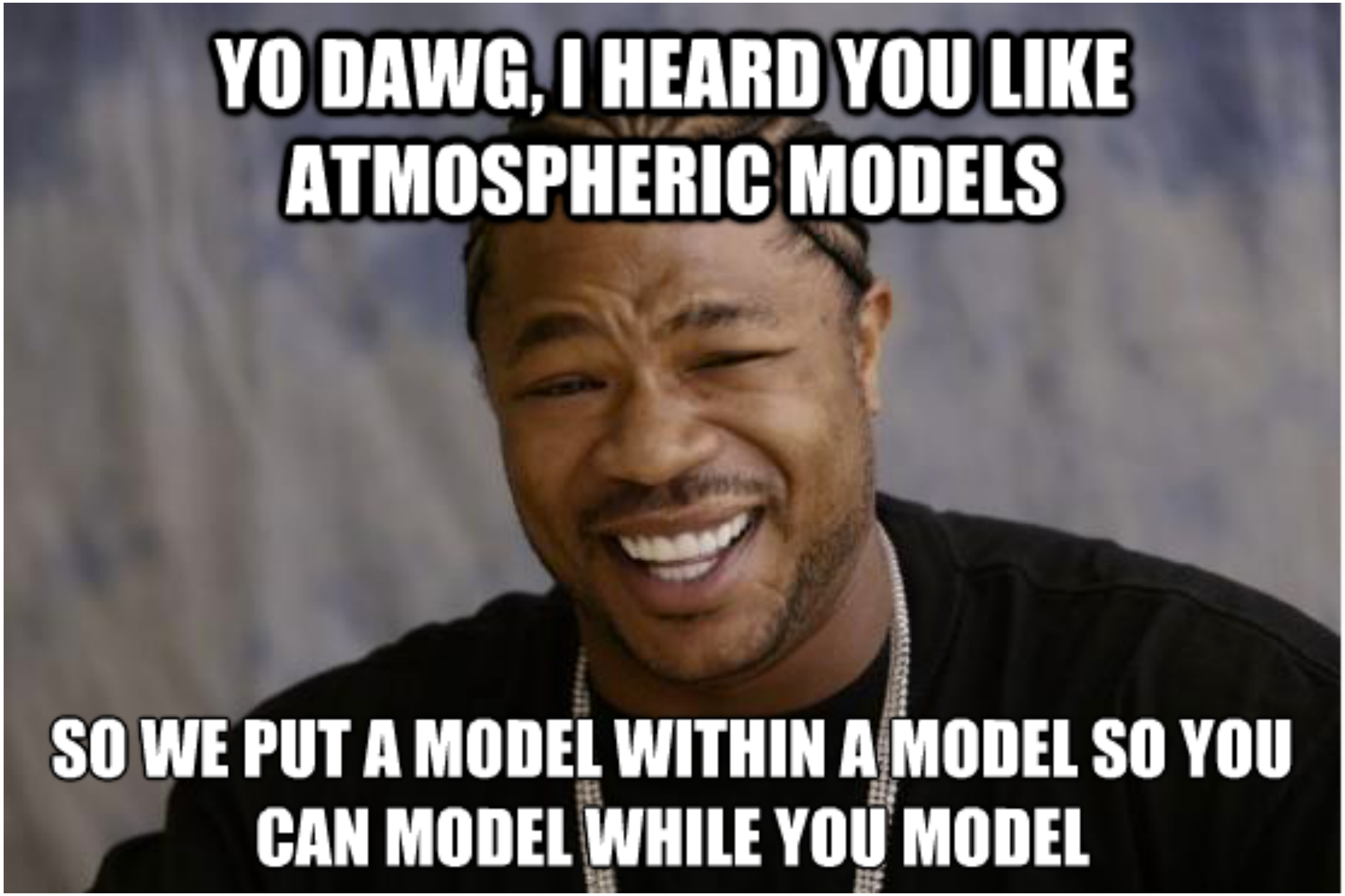
- How many cloud "types"?
- What controls entrainment?

Convective closures

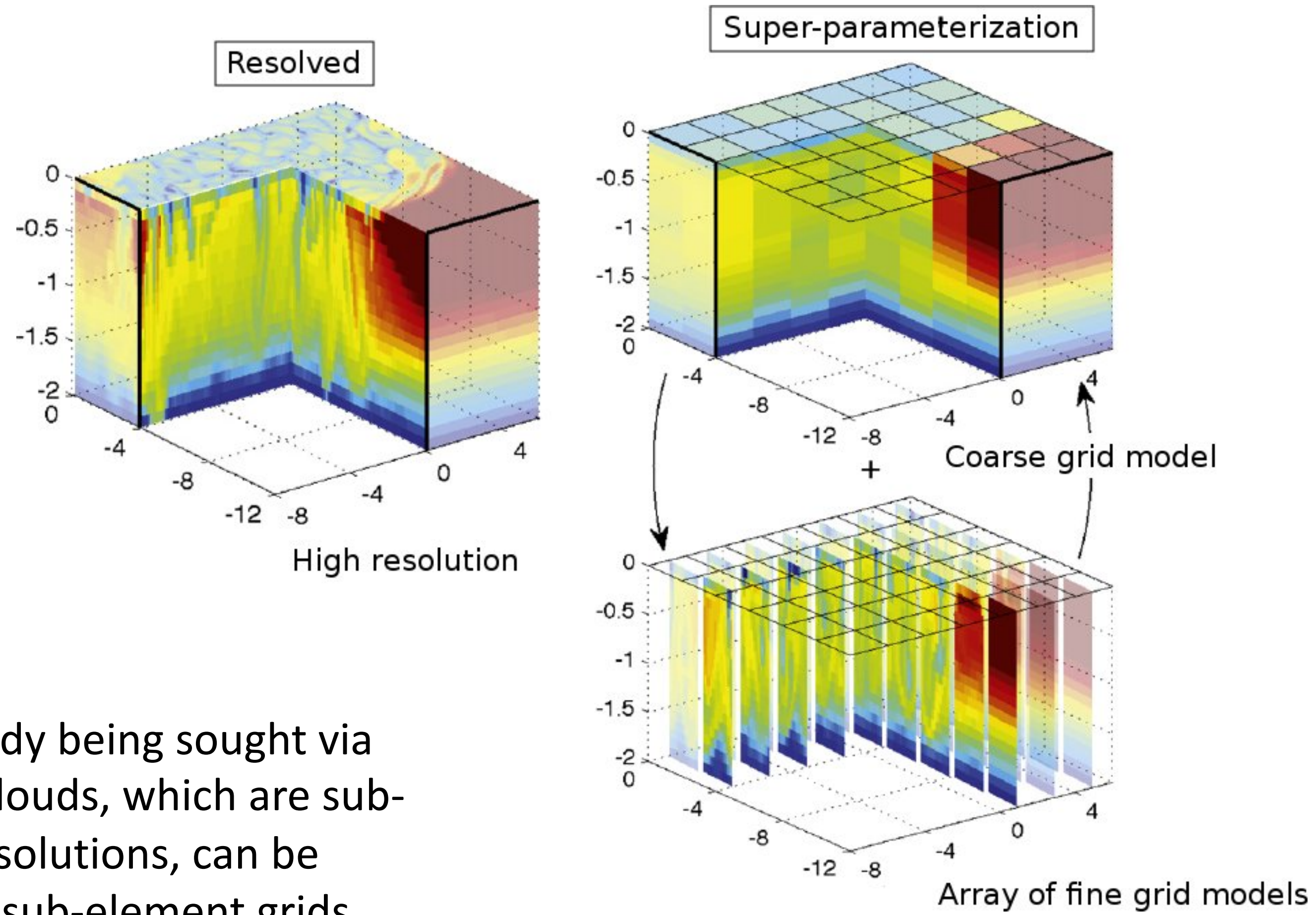
Coupling deep convection with the boundary layer

- Updrafts?
- Downdrafts?

Super-Parameterizations



Super-Parameterizations



High resolution is already being sought via alternative avenues. Clouds, which are sub-gird-scale at current resolutions, can be resolved on finer scale sub-element grids.

Cloud Fraction Challenge

Source: Rich Neale, Julio Bacmeister