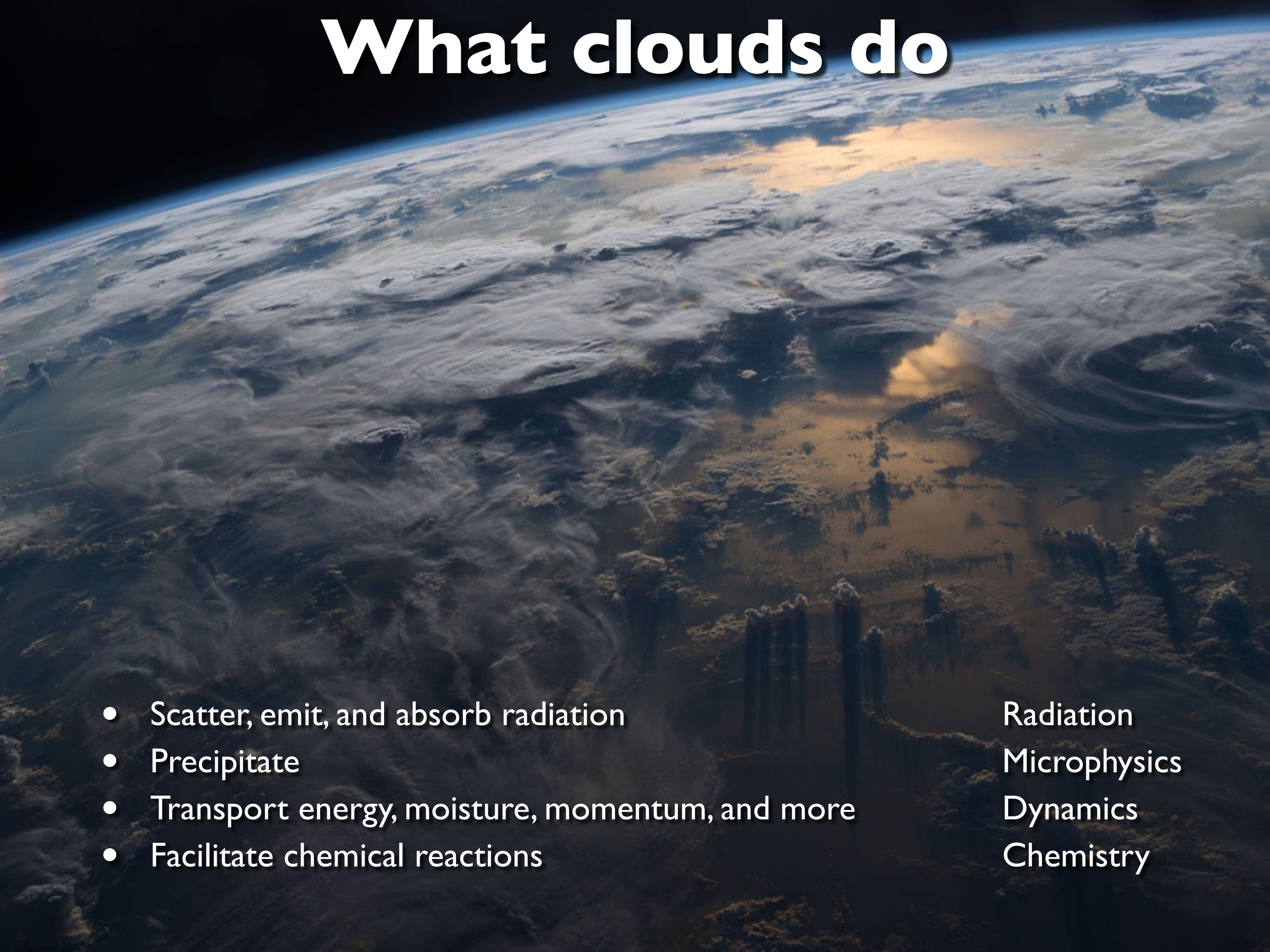
Cloud Parameterizations

David Randall

What clouds do



- Scatter, emit, and absorb radiation — Radiation
- Precipitate — Microphysics
- Transport energy, moisture, momentum, and more — Dynamics
- Facilitate chemical reactions — Chemistry

Cloud regimes

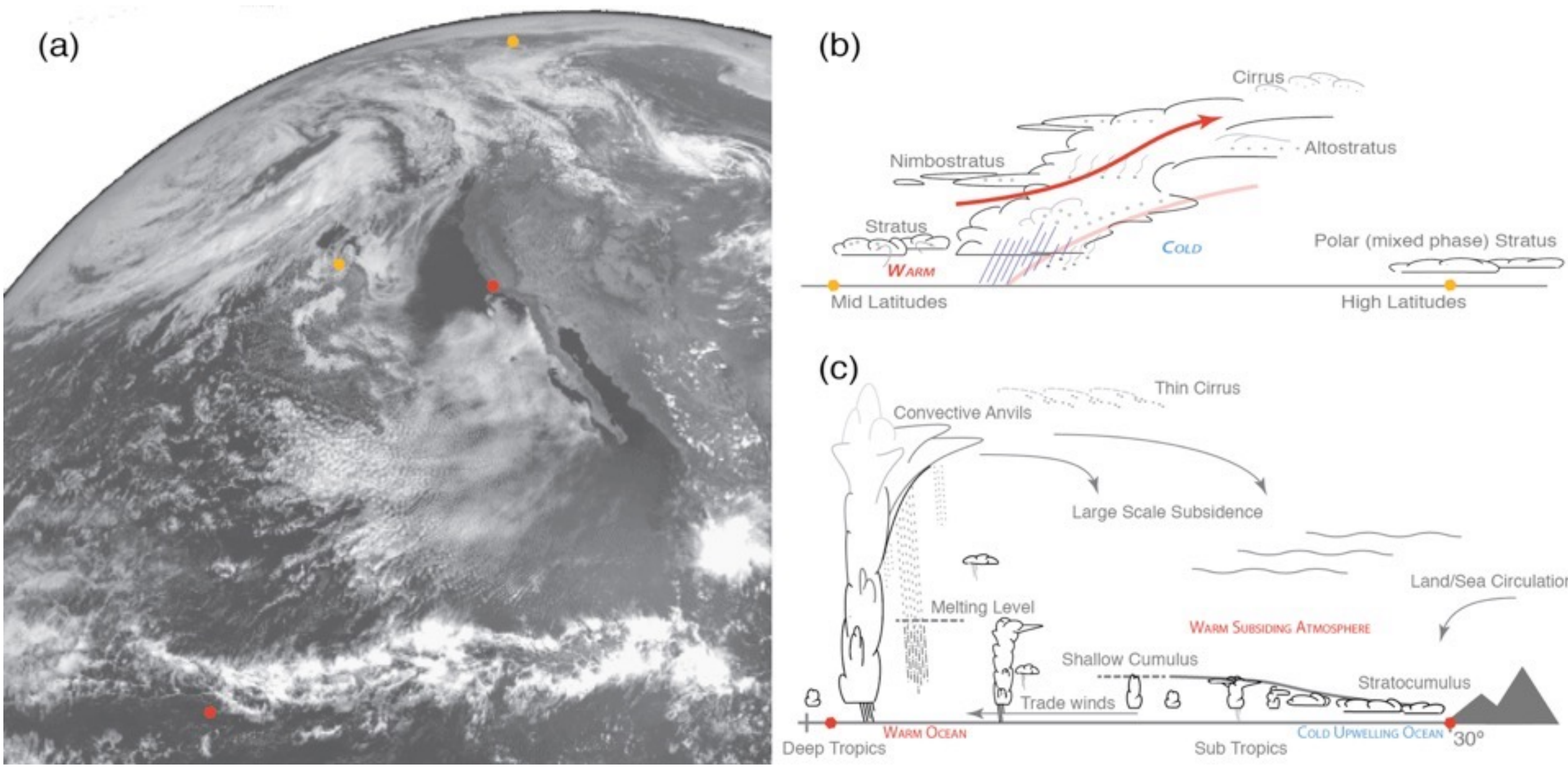


Figure from IPCC AR5

Clouds couple the energy and water cycles

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- Globally:
  - The atmosphere is cooled radiatively and warmed by latent heat release.
  - The surface is warmed radiatively and cooled by evaporation.

Clouds couple the energy and water cycles

- Globally:
  - The atmosphere is cooled radiatively and warmed by latent heat release.
  - The surface is warmed radiatively and cooled by evaporation.
- Locally:
  - The atmosphere is warmed radiatively by precipitating cloud systems.
  - The surface is cooled radiatively by precipitating cloud systems.

A paradox

Globally, stronger precipitation is balanced by stronger radiative cooling of the atmosphere.

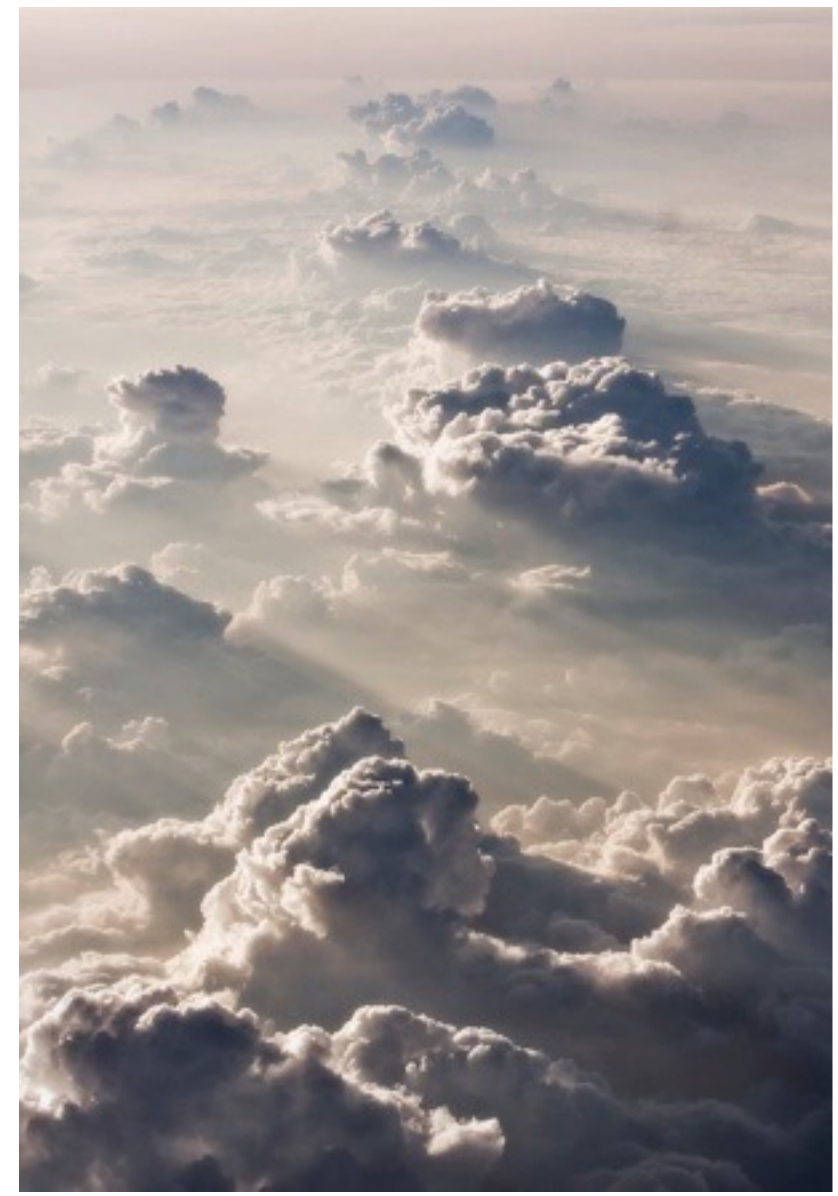
Locally, stronger precipitation leads to weaker radiative cooling of the atmosphere.

Where do clouds fit in models?

- Cumulus parameterization
- Stratiform cloud parameterization
- Boundary layer parameterization

How large-scale modelers have categorized clouds

- Convective clouds
  - Deep
  - Shallow



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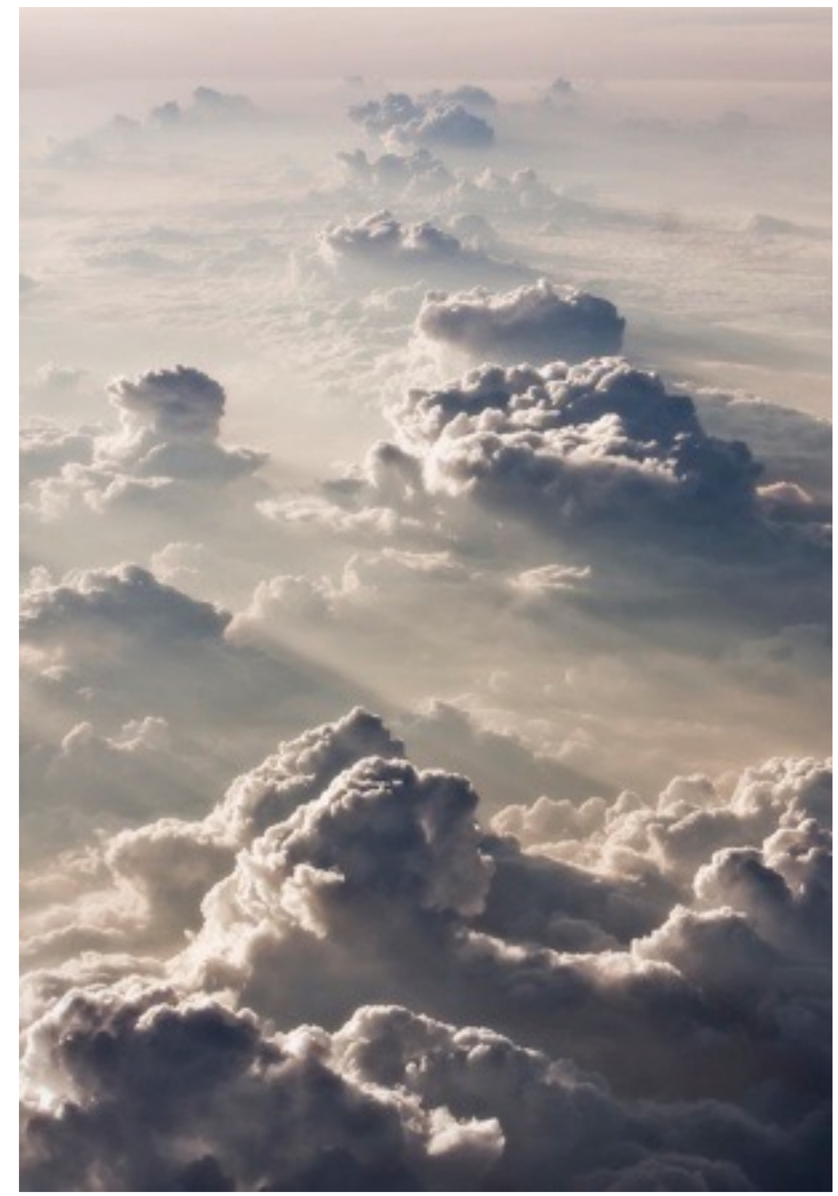
  - Convective detrainment
  - Frontal lifting
  - Orographic lifting



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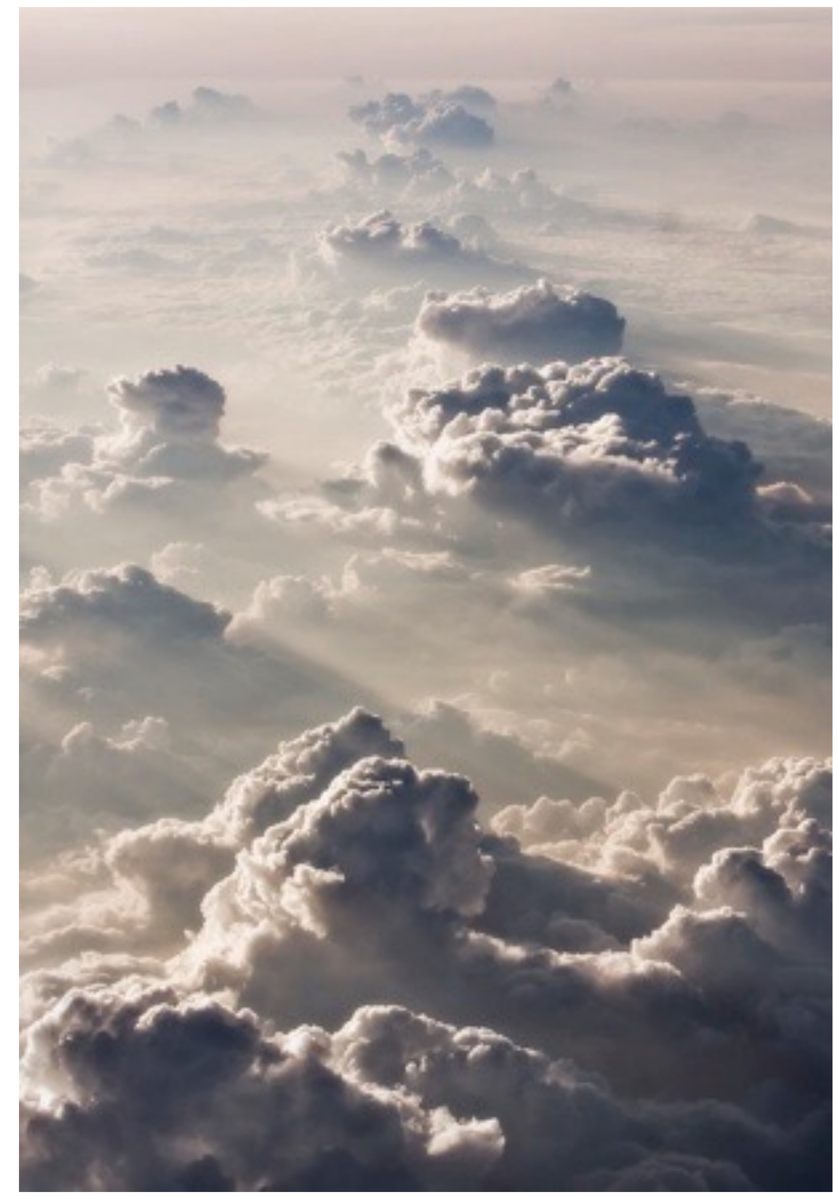
- Marine stratocumulus clouds



Scope

Due to time constraints, I will limit my self to two important cloud types:

- Deep convection
- Marine stratocumulus clouds

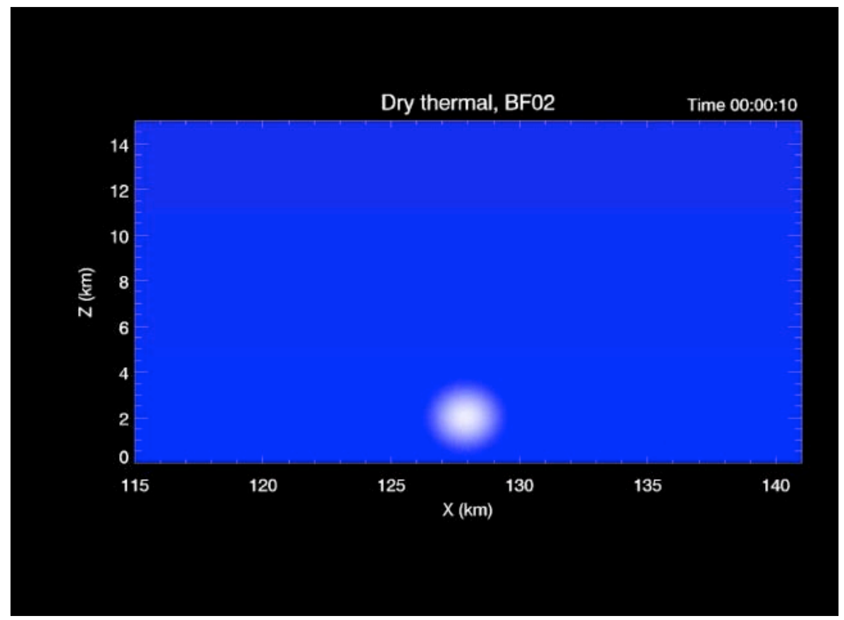
Deep convection

- Conditional instability is necessary but not sufficient.
- Vertical transports are powerful and important.
- The fractional area covered by convective updrafts is very small.

Conditional instability

Gravity wave

Conditional instability

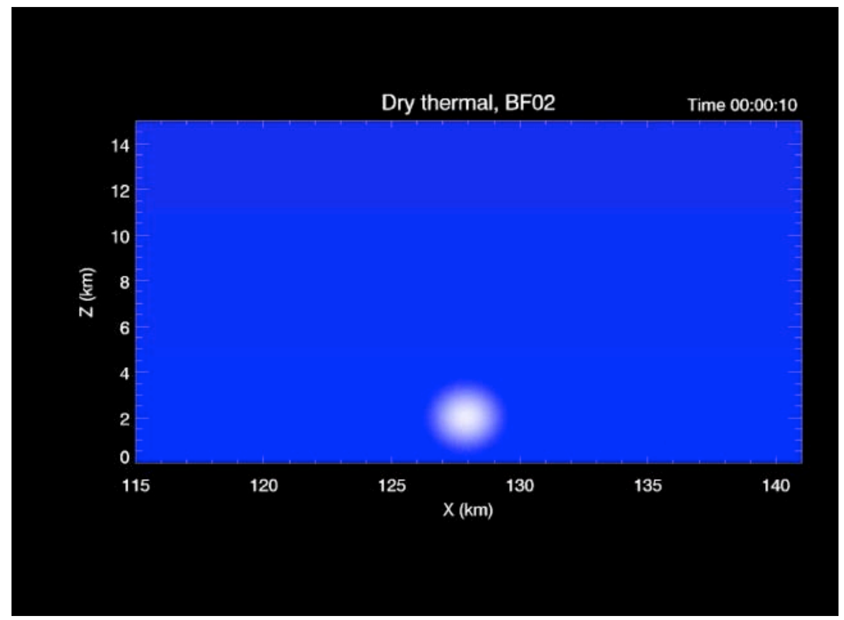


Gravity wave

Dry thermal

Conditional instability

Gravity wave



Dry thermal

Cumulus convection

Heating and drying

$$Q_1 \equiv LC - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho\overline{w's'}) - \frac{1}{\rho}\nabla_H \cdot (\rho\overline{\mathbf{V}_H' s'}) + Q_R$$

$$Q_2 \equiv LC + \frac{L}{\rho}\frac{\partial}{\partial z}(\rho\overline{w'q_v'}) + \frac{L}{\rho}\nabla_H \cdot (\rho\overline{\mathbf{V}_H' q_v'})$$

An overbar represents an average over a grid cell area, at a given height and time.

Vertical flux divergences dominate

Horizontal and vertical fluxes are comparable in magnitude.

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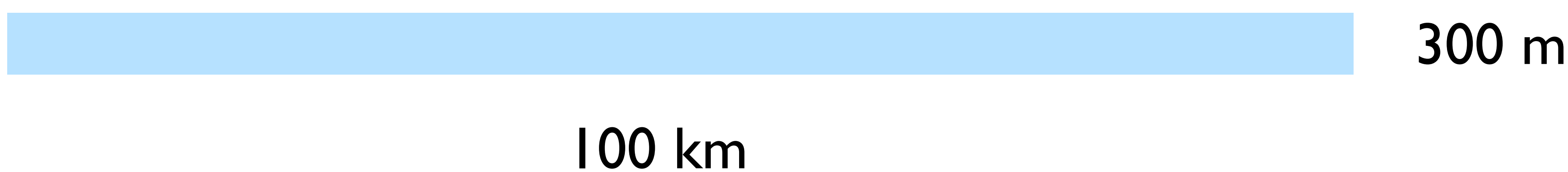
Vertical fluxes converge and diverge over much shorter distances than horizontal fluxes.



Vertical flux divergences dominate

Horizontal and vertical fluxes are comparable in magnitude.

Vertical fluxes converge and diverge over much shorter distances than horizontal fluxes.

300 m

100 km

$$Q_1 \cong LC - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho \overline{w's'}) + Q_R$$

$$Q_2 \cong LC + \frac{L}{\rho}\frac{\partial}{\partial z}(\rho \overline{w'q_v'})$$

Conventional Parameterizations

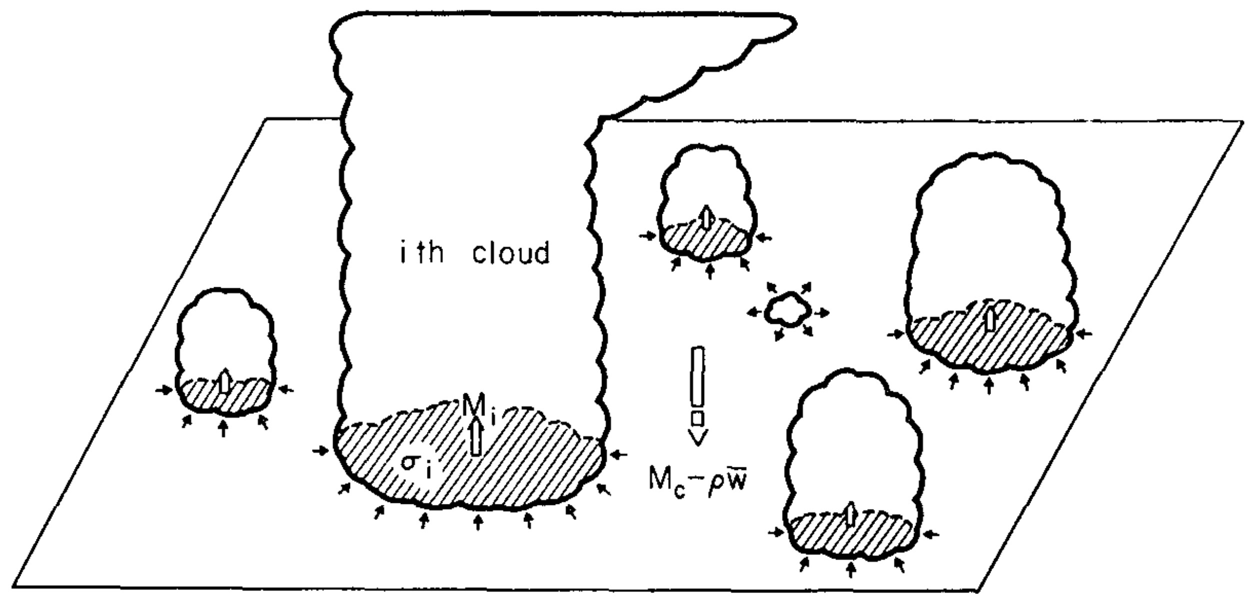
Global circulation

Cloud-scale
&mesoscale
processes

Radiation,
Microphysics,
Turbulence

Parameterized

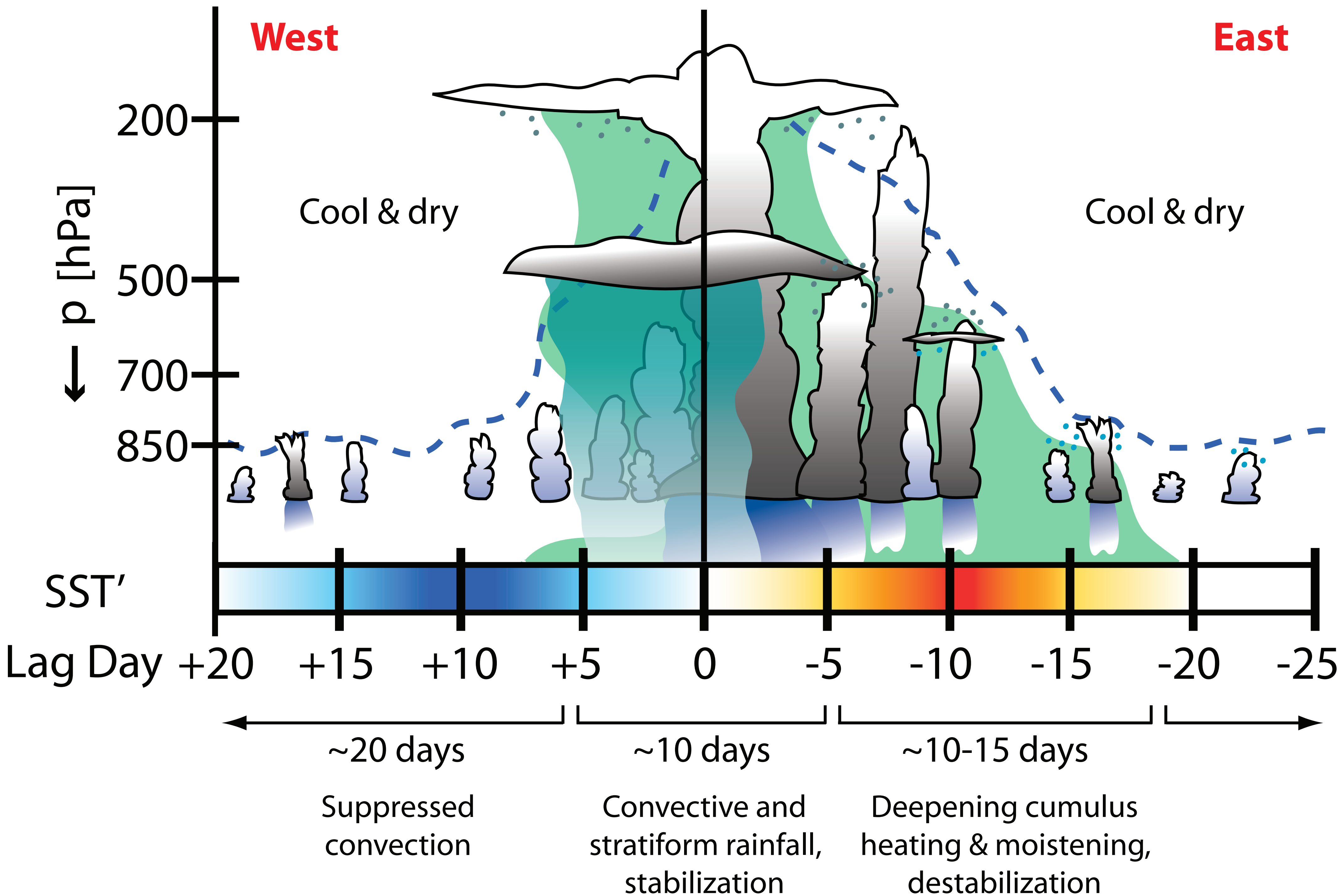
Scale Separation



"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."

-- AS 74

Example of scale separation: The MJO



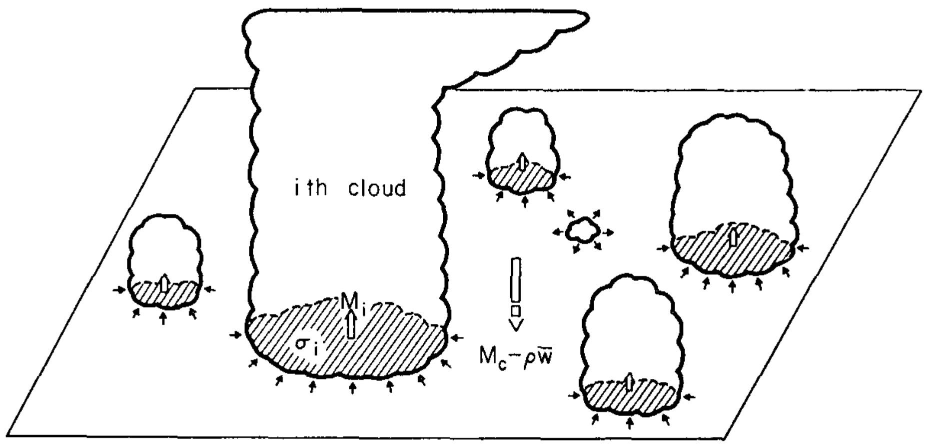
Slide from Jim Benedict

Mass fluxes

$$\sum_{i=1}^{N} \sigma_i = 1$$

$$\sum_{i=1}^{N} \sigma_i w_i = \overline{w}$$

$$\sum_{i=1}^{N} \sigma_i h_i = \overline{h}$$



$$F_h \equiv \rho \overline{wh} - \rho \overline{w}\,\overline{h} = \sum_{i=1}^{N} M_i \left(h_i - \overline{h} \right)$$

$$M_i \equiv \rho \sigma_i \left(w_i - \overline{w} \right)$$

The convective energy clue is proportional to the mass flux.

A key simplifying assumption

$$\boxed{\sigma \ll 1}$$

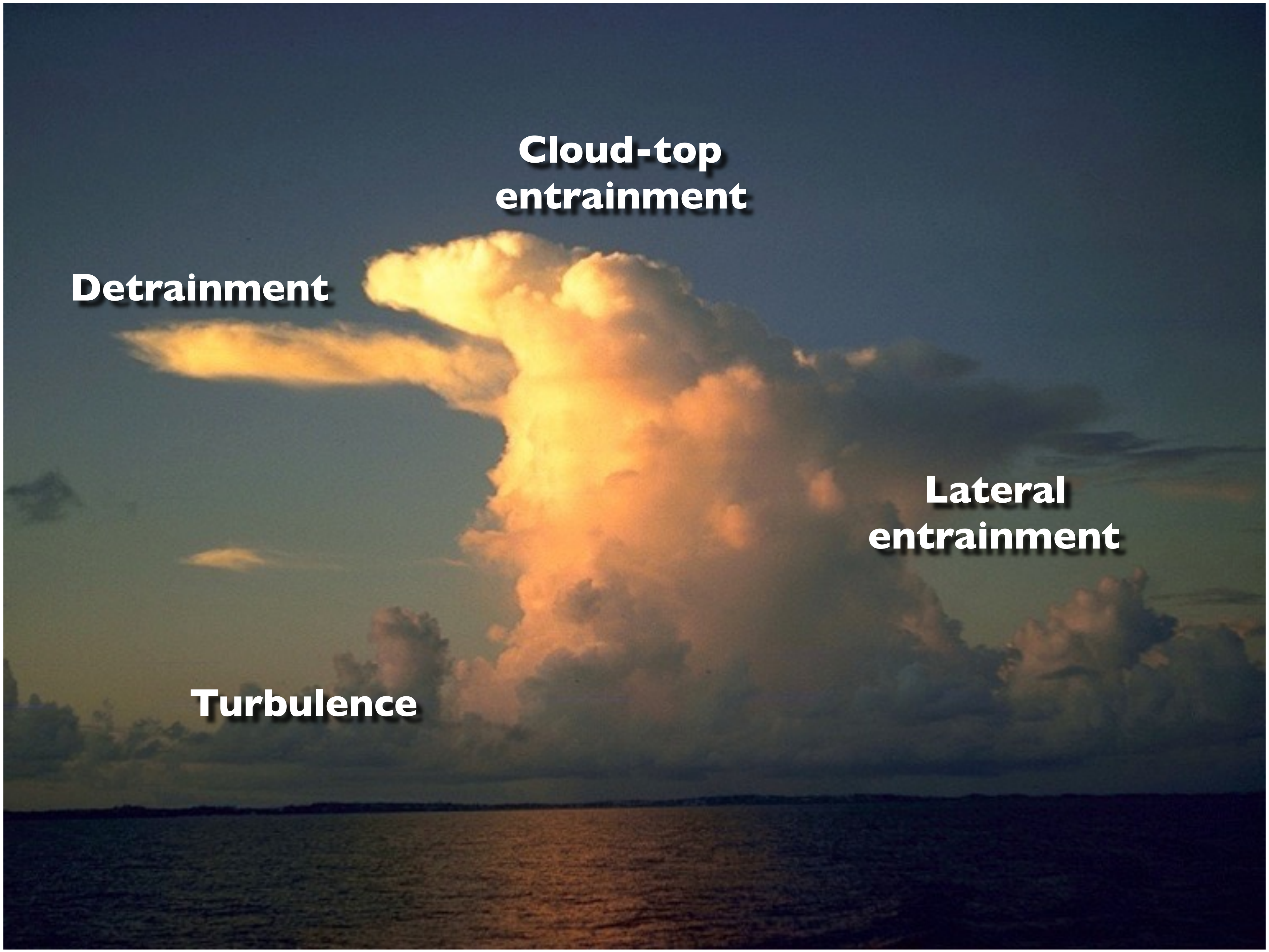
The simple reasons for this observed fact were explained by Jacob Bjerknes in a 1938 paper.

It follows that the "environment" has almost the same thermodynamic properties as the grid-cell average.

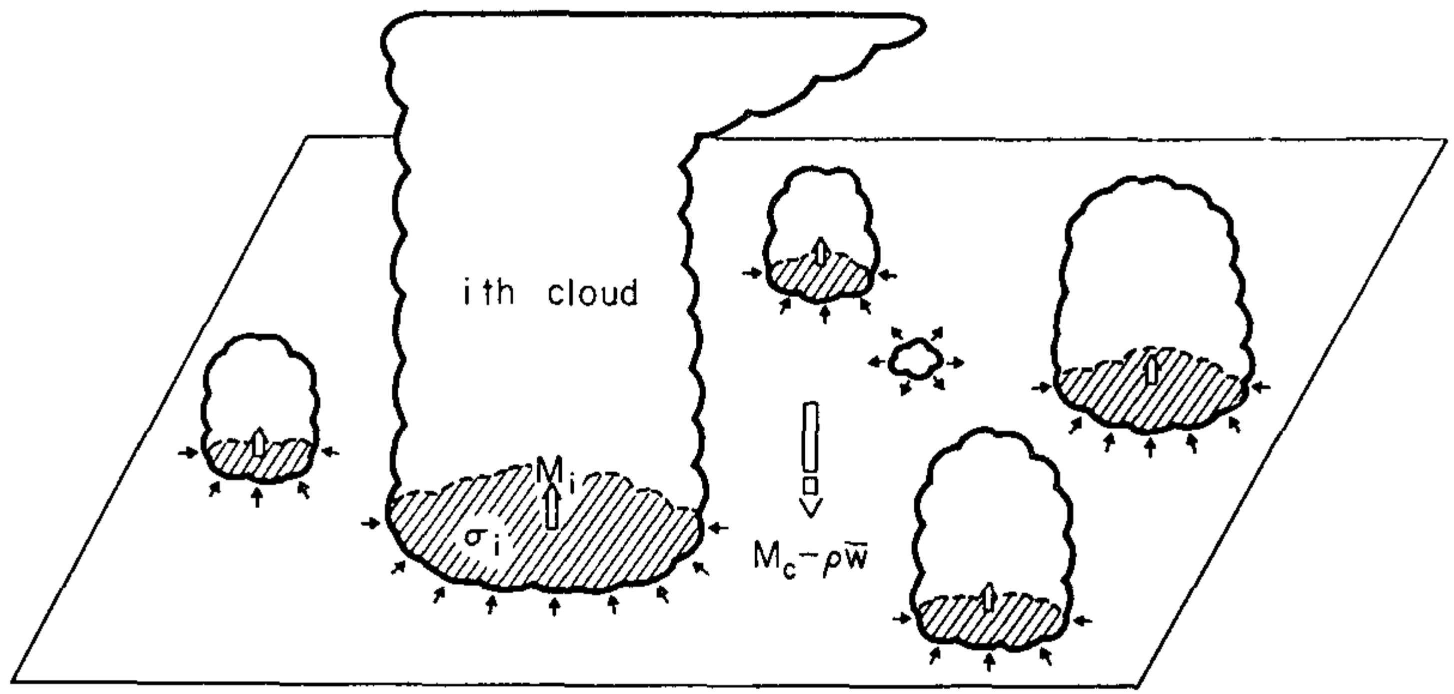
$$\tilde{h} \cong \overline{h}$$

Because this is true, we can equate the heating and drying of the environment with the heating and drying of the grid-scale average, and we can avoid computing sigma.

Cumulus entrainment



Toy updrafts & downdrafts



Entraining plumes

$$\frac{\partial M_c(z)}{\partial z} = E(z) - D(z)$$

Mass budget

$$\frac{\partial}{\partial z}\left[M_c(z)h_c(z)\right] = E(z)\bar{h}(z) - D(z)h_c(z)$$

Moist static energy budget

$$\frac{\partial h_c(z)}{\partial z} = \frac{E(z)}{M_c}\left[\bar{h}(z) - h_c(z)\right]$$

Dilution

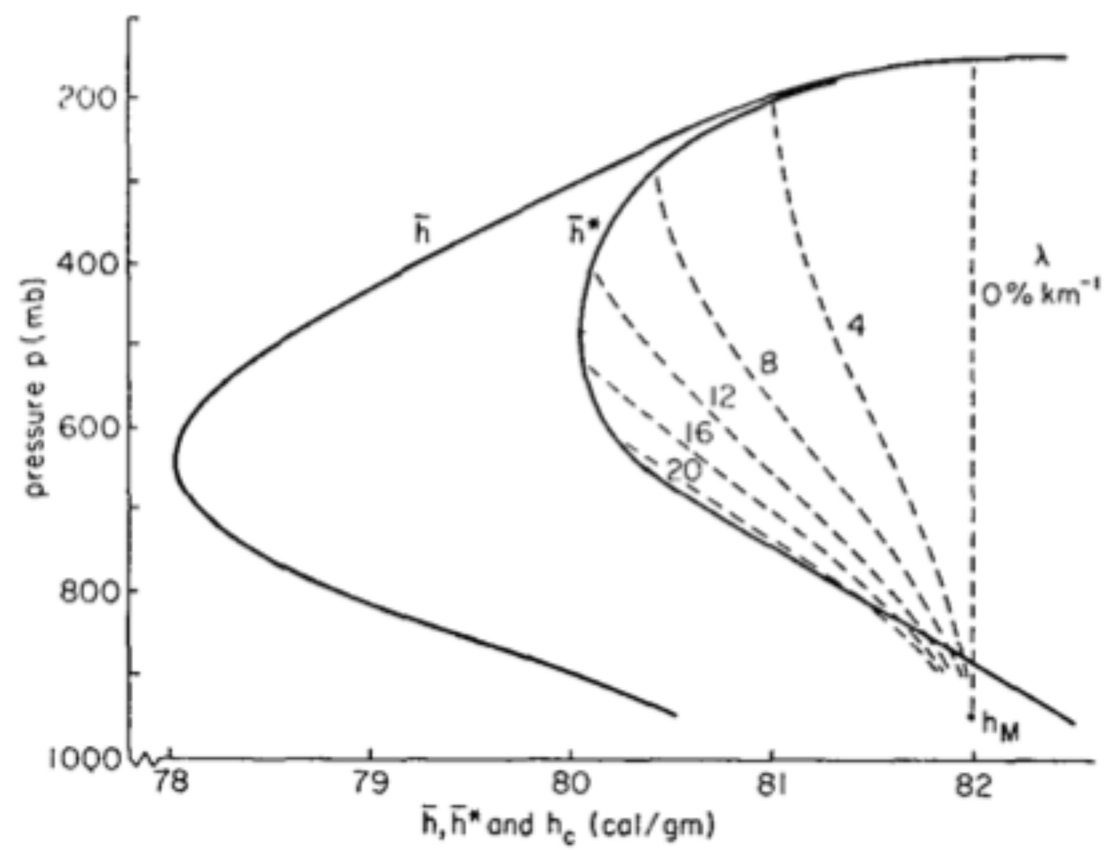


FIG. 6. Vertical profiles of $\bar{h}(p)$, $\bar{h}^*(p)$ and $h_c(p,\lambda)$; $h_c(p,\lambda)$ lines are dashed and labeled with the value of λ in percent per kilometer. Profiles of $\bar{h}$ and $\bar{h}^*$ were obtained from Jordan's (1958) "mean hurricane season" sounding. The top p_B of the mixed layer is assumed to be 950 mb; h_M is assumed to be 82 cal gm^{-1}.

Arakawa & Schubert, 1974

Closure for the mass flux

$$M_c = \rho \sigma w_c$$

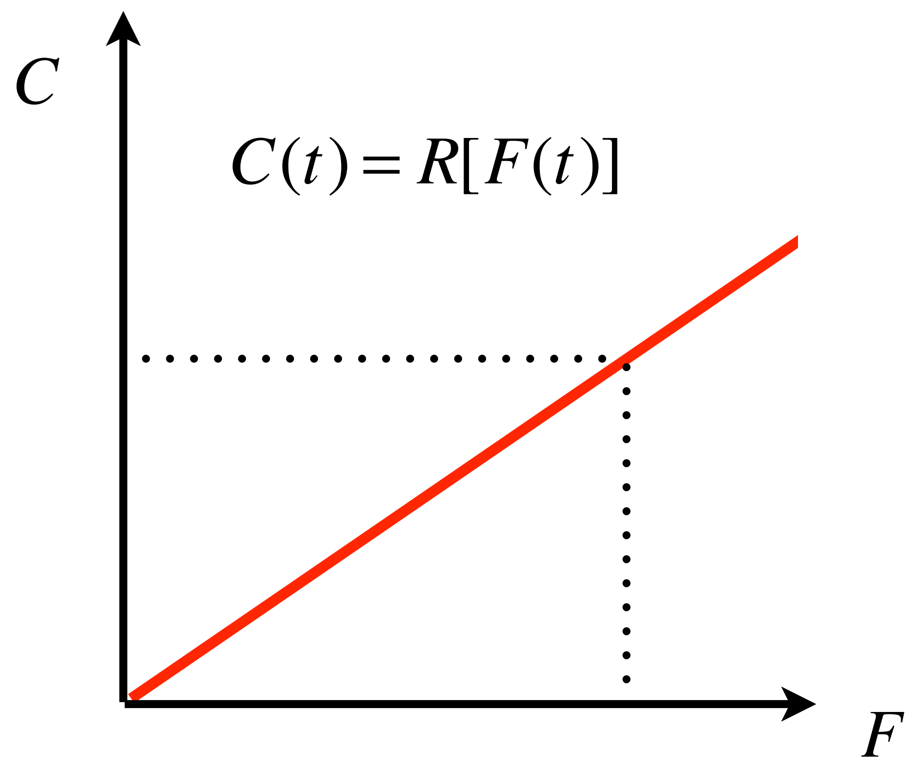
- Convection converts CAPE into convective vertical motion.
- The mass flux is a measure of this motion.
- The mass flux is a measure of the intensity of the convection.
- The "closure" must determine the mass flux.
- If this process is "fast," then CAPE is destroyed as fast as it is generated.
- This "quasi-equilibrium" assumption can be used to determine the mass flux by solving a linear algebraic system.
- A better approach is to choose a mass flux that pushes the CAPE towards zero on a short but finite time scale.
  - "Relaxation", as in relaxed Arakawa-Schubert
  - Prognostic closure

Quasi-Equilibrium

"When the time scale of the large-scale forcing, is sufficiently larger than the [convective] adjustment time, … the cumulus ensemble follows a sequence of quasi-equilibria with the current large-scale forcing. We call this … the quasi-equilibrium assumption."

"The adjustment … will be toward an equilibrium state … characterized by … balance of the cloud and large-scale terms…"

-- AS 74



Quasi-Equilibrium

The offensive player is the large-scale weather regime.

The defensive player is the cloud field.

Sources and sinks of CAPE

- Sources or "*forcing*" -- anything that tends to steepen the lapse rate or moisten the lower troposphere
  - Surface fluxes
  - Radiative cooling aloft
  - Large-scale rising motion
  - Warm advection down low
  - Cold advection aloft

- Sinks -- anything that tends to reduce the lapse rate or dry the lower troposphere
  - Convective warming aloft
  - Convective drying
  - Cooling at low levels due to convective downdrafts
  - Large-scale subsidence
  - Warm advection aloft
  - Cold advection down low

Current issues with conventional cloud parameterizations

- Microphysics
  - How many water species?
  - Role of aerosols?
- Convective entrainment
  - How many cloud "types"?
  - What controls entrainment?
- Convective closures
- Coupling deep convection with the boundary layer
  - Updrafts?
  - Downdrafts?
- Departures from quasi-equilibrium
- Resolution-dependence
- Stochasticity

Parameterize less at high resolution.

Global circulation

Cloud-scale &mesoscale processes

Radiation, Microphysics, Turbulence

Parameterized

Resolve convection?

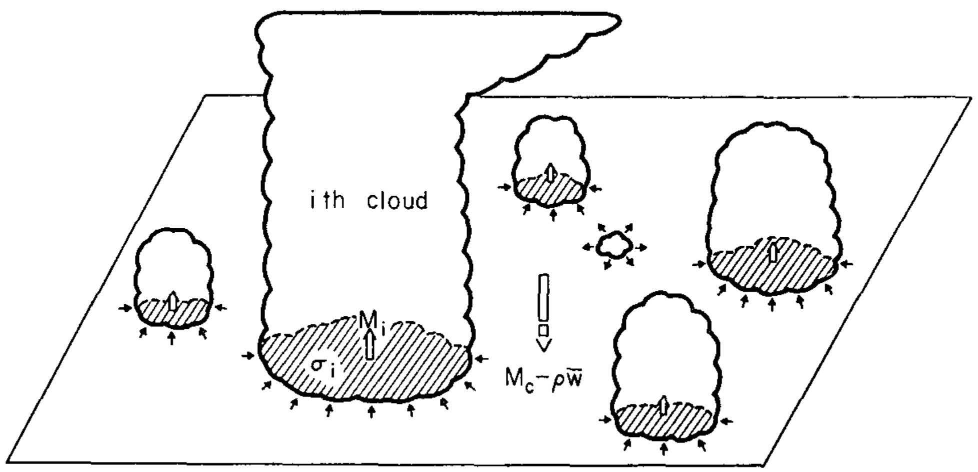
- Modest increases in resolution don't improve the simulation of convective processes. *There is lots of evidence that a horizontal grid-spacing of 4 km or finer is needed.*

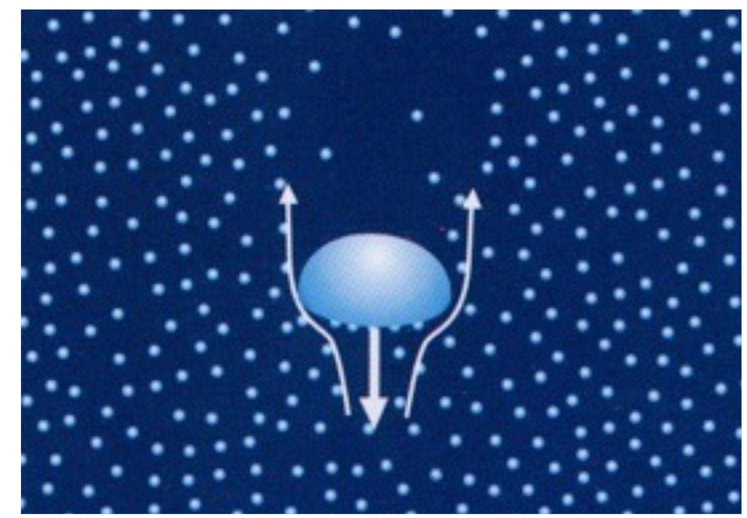
- Even such high-resolution models are very dependent on parameterizations of turbulence and shallow convection, as well as microphysics and radiation.

Three issues with conventional parameterizations at high resolution:

- Convective transports become less important, and microphysics dominates.
- The sample size is too small to enable a statistical treatment.
- The “resolved-scale forcing” varies too quickly to allow quasi-equilibrium.

Heating and drying on coarse and fine meshes





Increasing resolution

GCM

CRM

Parameterizations for low-resolution models are designed to describe the collective effects of ensembles of clouds.

Parameterizations for high-resolution models are designed to describe what happens inside individual clouds.

Average over a cloud system → Individual clouds

Scale-dependence of heating & drying

$$Q_1 - \overline{Q_R} = L\overline{C} - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho\overline{w's'}) - \frac{1}{\rho}\nabla_H \cdot (\rho\overline{\mathbf{v}_H{}'s'}),$$

$$Q_2 = -L\overline{C} - \frac{1}{\rho}\frac{\partial}{\partial z}(\rho\overline{w'q_v{}'}) - \frac{1}{\rho}\nabla_H \cdot (\rho\overline{\mathbf{v}_H{}'q_v{}'}).$$

These quantities are defined in terms of spatial averages.

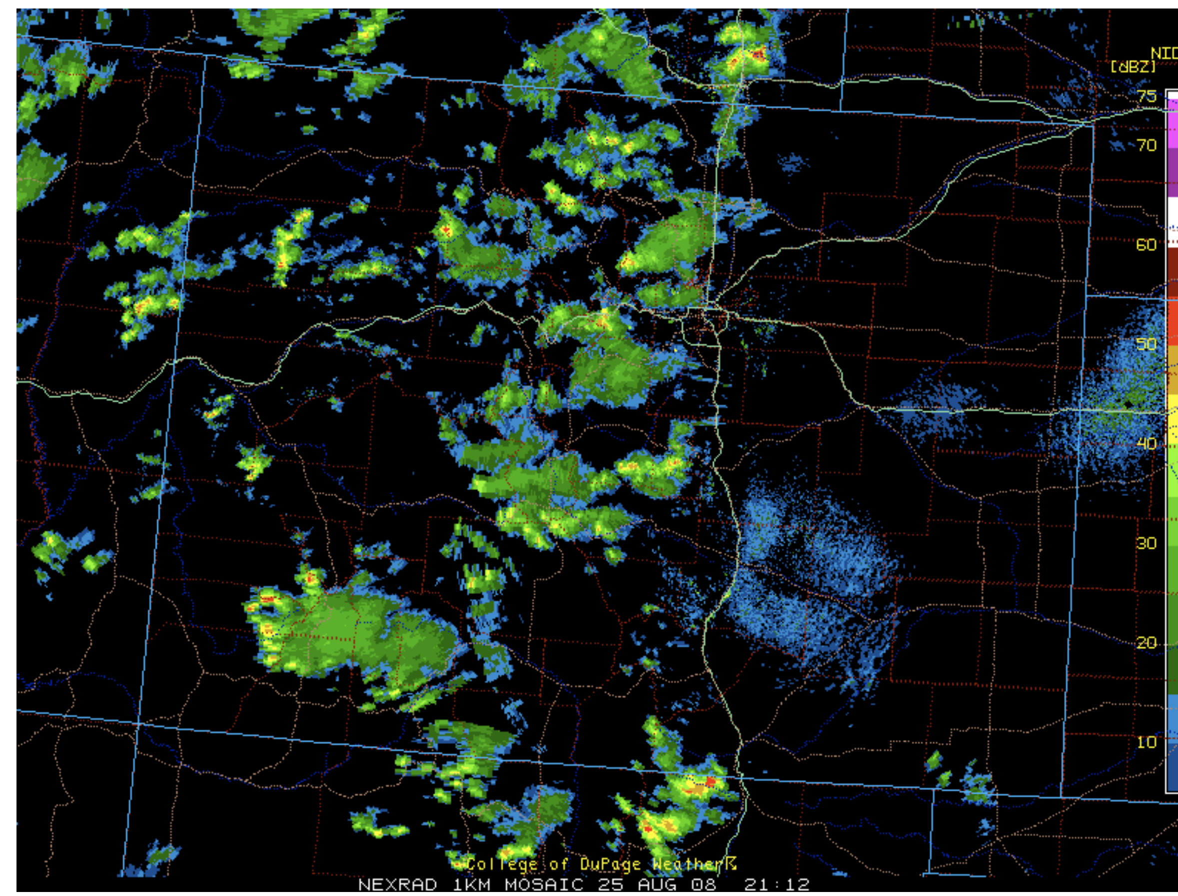
As the averaging length becomes smaller:

- The vertical transport terms become less important. Later horizontal averaging does not change this.
- The horizontal transport terms become more important locally. Horizontal averaging kills them, though.
- The phase-change terms become dominant.

Sample Size

With a grid spacing of 20 km or less, we definitely do not have a statistically meaningful sample of large clouds in each grid column.

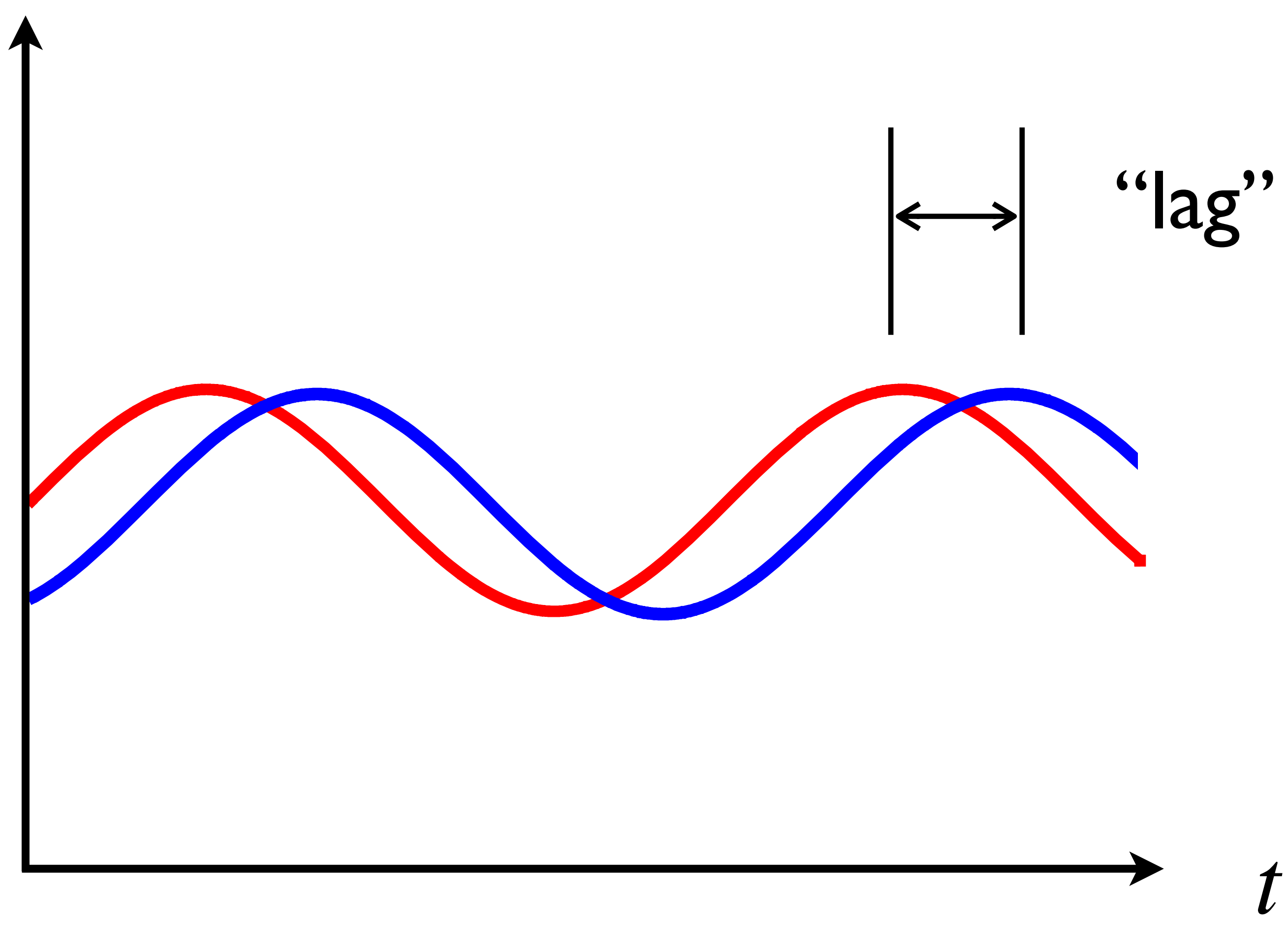
Even with a grid spacing of 200 km, the number of large clouds in a grid column is worryingly small.



A summer afternoon in Colorado

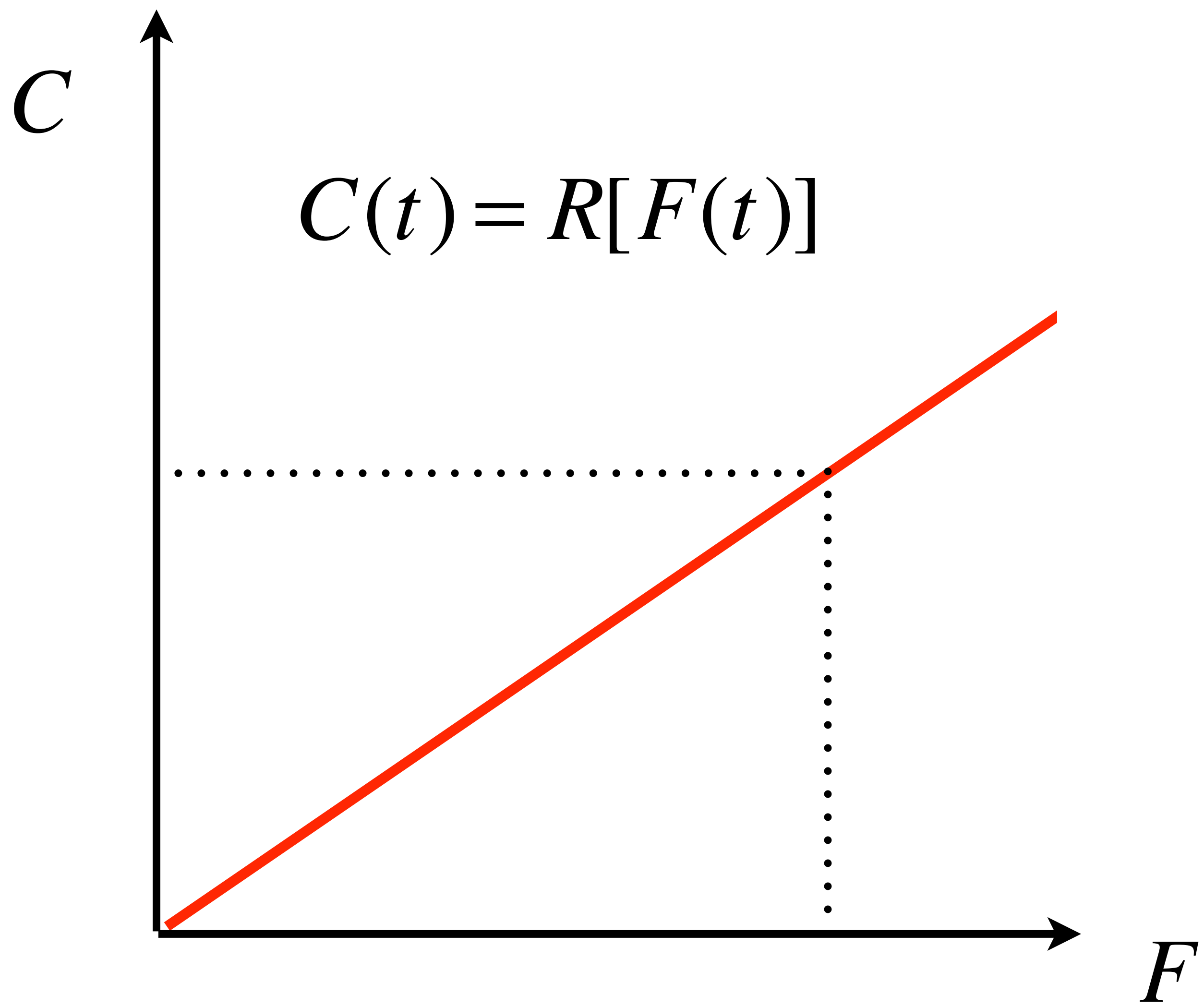
Departure from Quasi-Equilibrium, I: Delayed response

$$C(t) = R[F(t-\tau)]$$

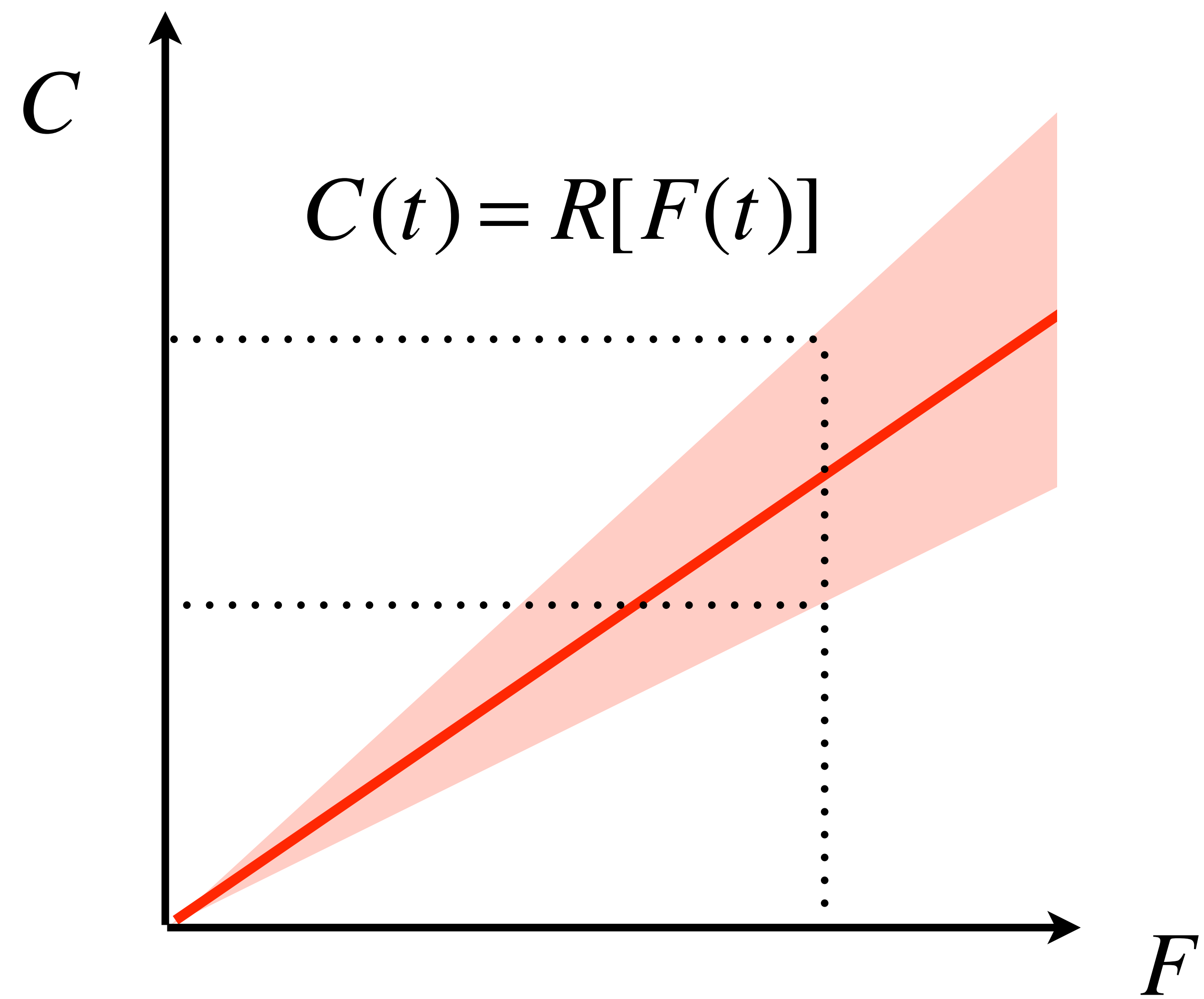


In a rapidly evolving weather regime, equilibrium is not possible (even with a large sample size), but the convection can still be deterministic.

Departure from Quasi-Equilibrium, 2: Stochastic effects



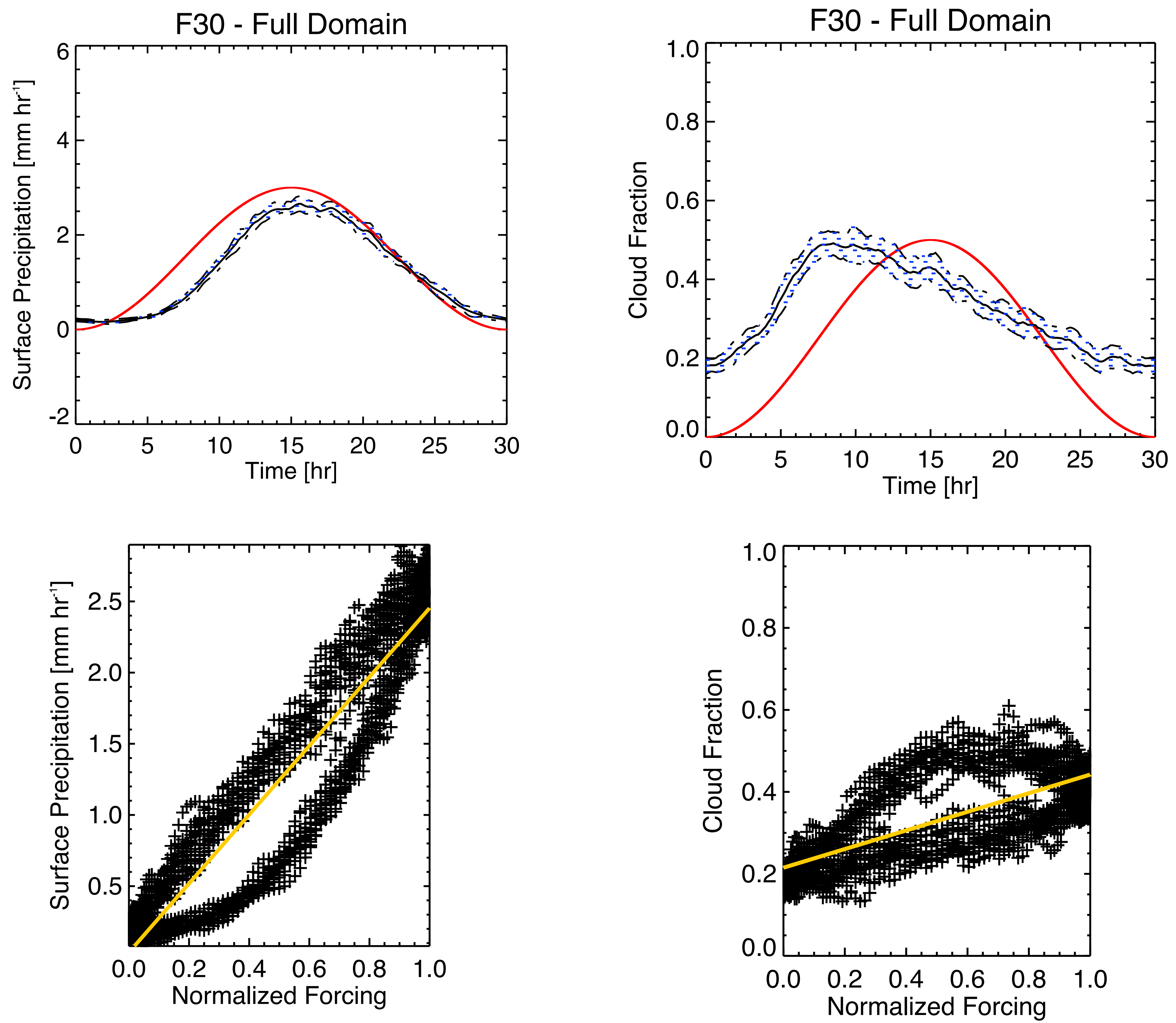
Deterministic convection



Non-deterministic convection

Judith Berner will talk about this.

Lags & Hysteresis



Jones & Randall 2011

Increasing resolution can make things worse.

- Smaller grid cells contain fewer clouds, so the sample-size issue becomes more of a concern.
- Smaller weather systems, which appear on finer grids, have shorter time scales, so lags become more common.

Three Ways to Use Cloud-Resolving Models To Improve Global Models

- Test parameterizations and suggest ideas
- Replace parameterizations
- Become the global model

Global Cloud-Resolving Models

- Uniform global horizontal grid spacing of 4 km or better
- 100 or more layers up to at least the stratopause
- Parameterizations for microphysics, turbulence (including small clouds), and radiation
- Execution speed of at least several simulated years per wall-clock day

Global Cloud-Resolving Models

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This requires roughly 10,000 times as many floating point operations as a "high-resolution" climate simulation of today, with 64-km grid spacing.

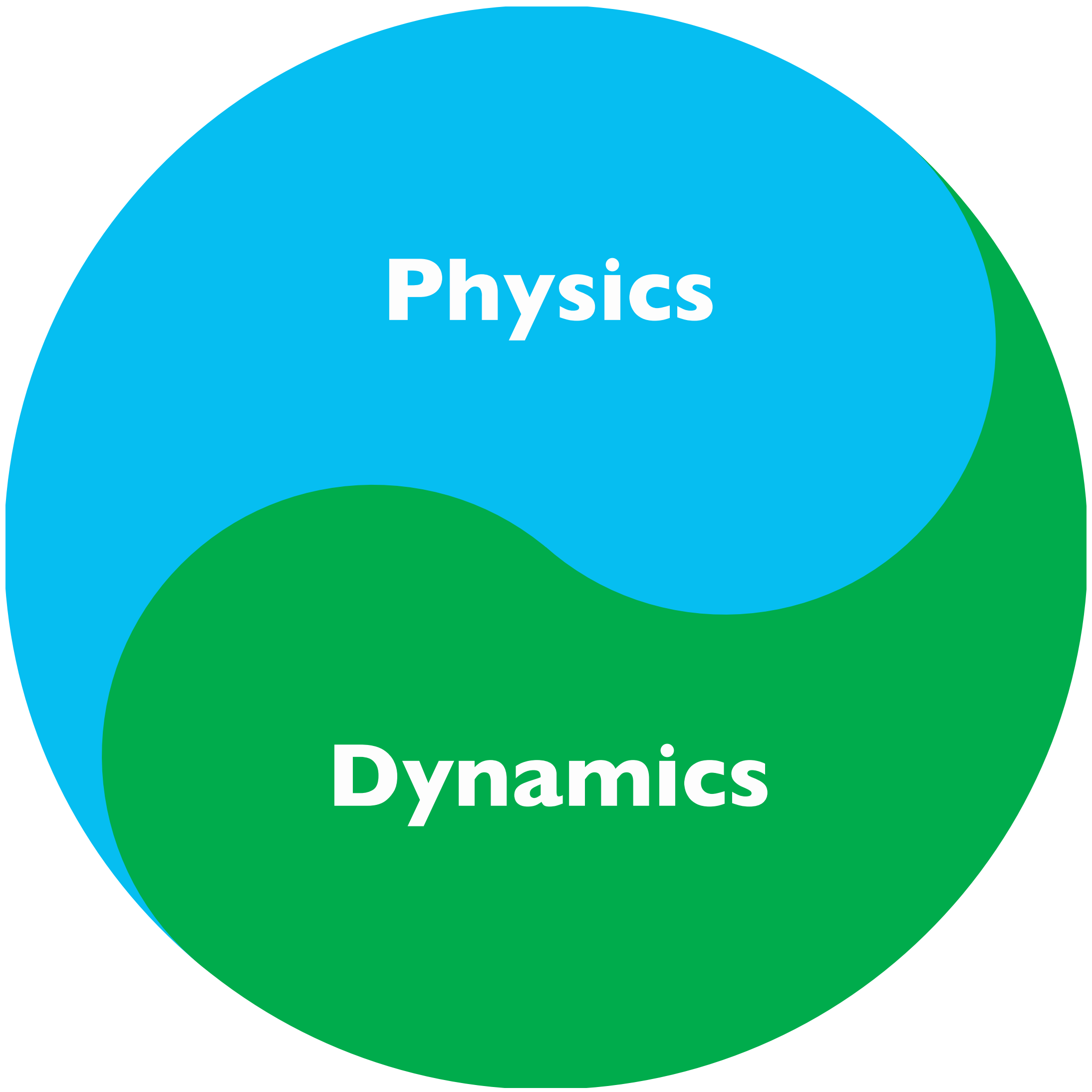
Century-long simulations with GCRMs may be do-able if a substantial fraction of an exaflop machine can be efficiently used by a single simulation.

GCRMs for Operational NWP

- May be feasible in the next few years.
- Need parameterizations for use at high resolution
- Lower resolution models will still be needed, e.g., for ensembles.
- Can the same model be used at both high and low resolution?


Dynamics
Physics

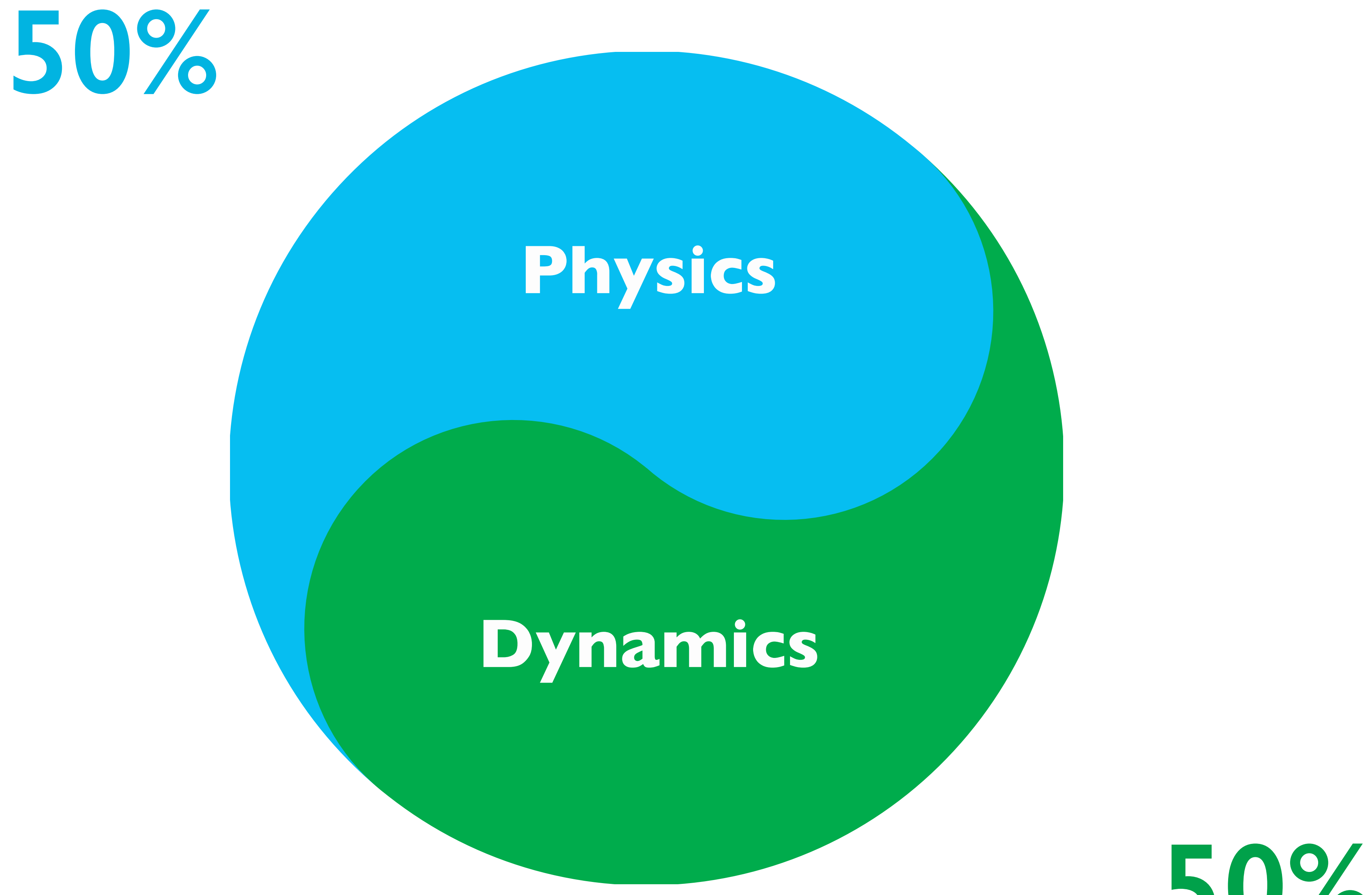
The yin & yang of climate modeling



"Dynamics" refers to fluid dynamics that is explicitly simulated on the grid.

"Physics" refers all other processes, which have to be parameterized.

Where does the computer time go?



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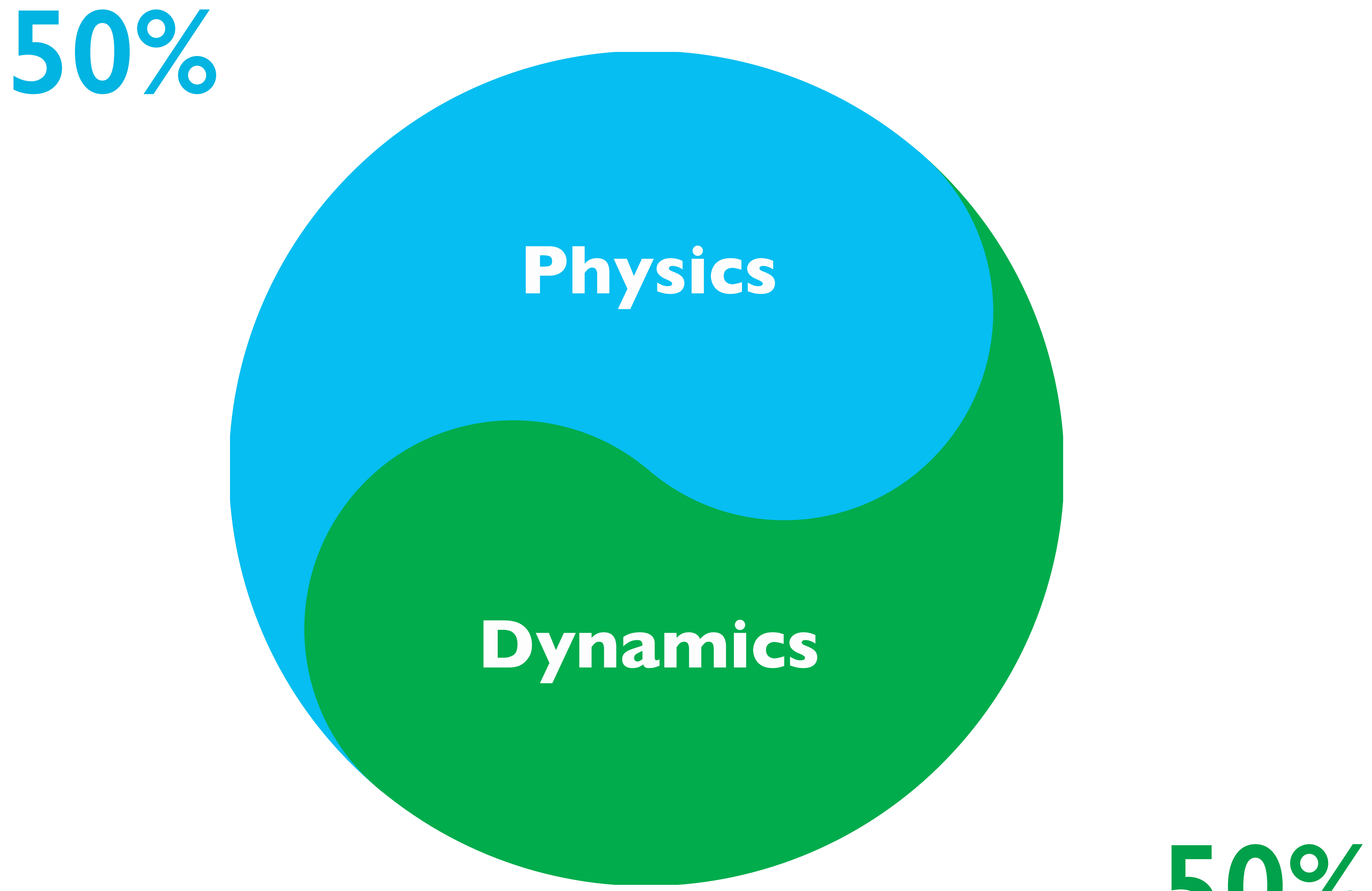
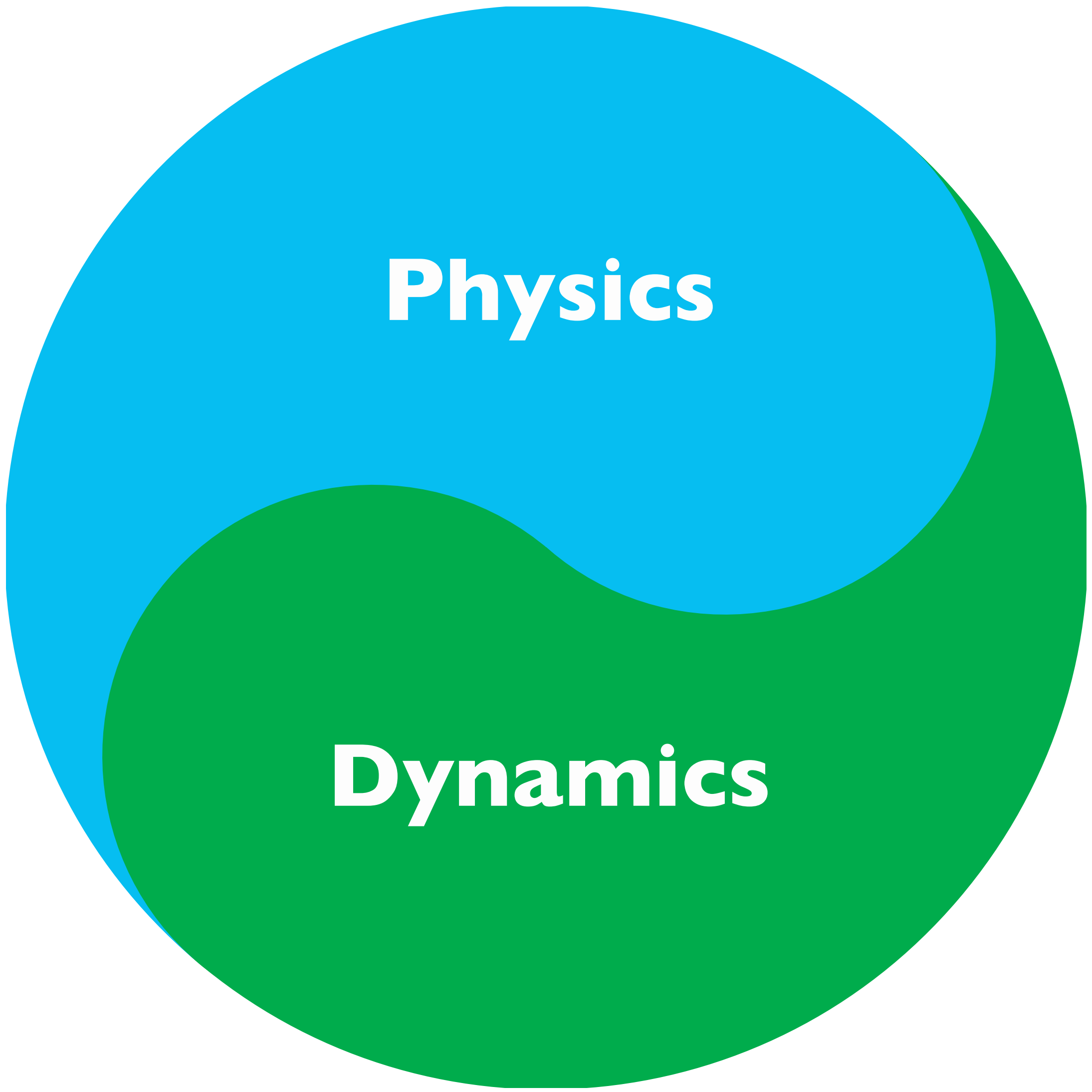


This is changing.

Scaling

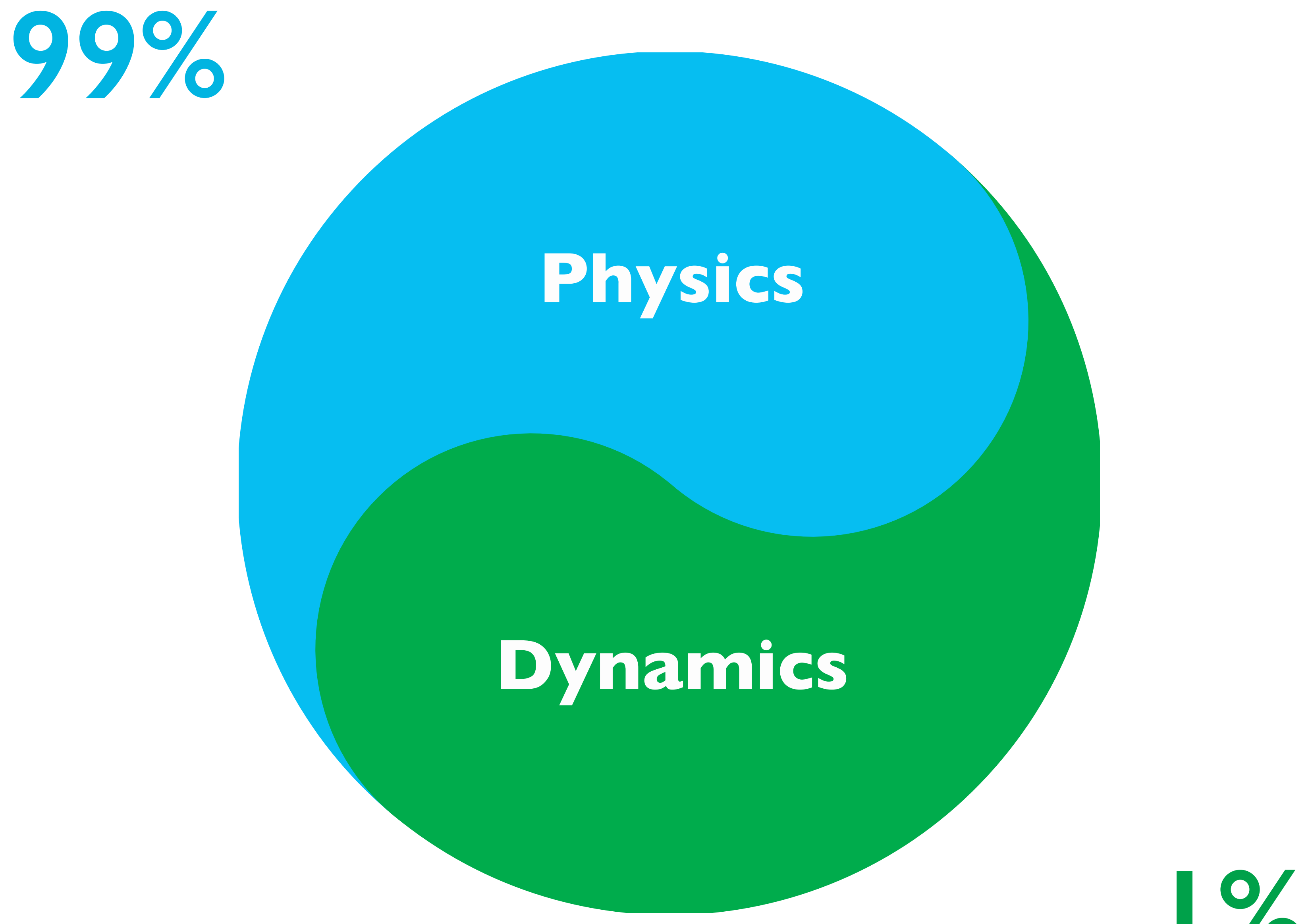
Strong scaling
except for load balancing issues



Weak scaling
except that the time step has to be reduced with higher resolution

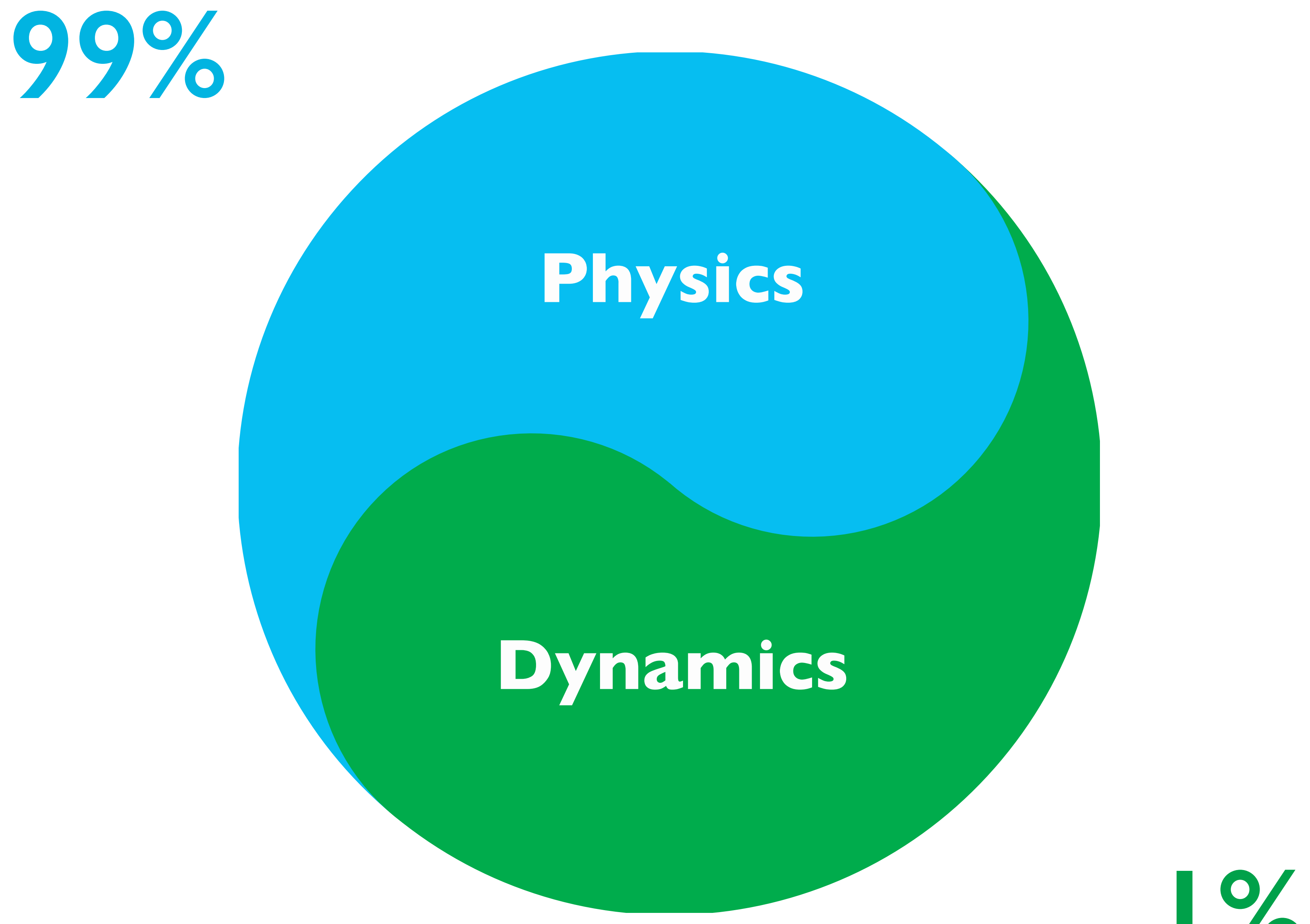
Model architecture should be designed to take advantage of the relatively good scaling of the physics.

What the technology wants us to do

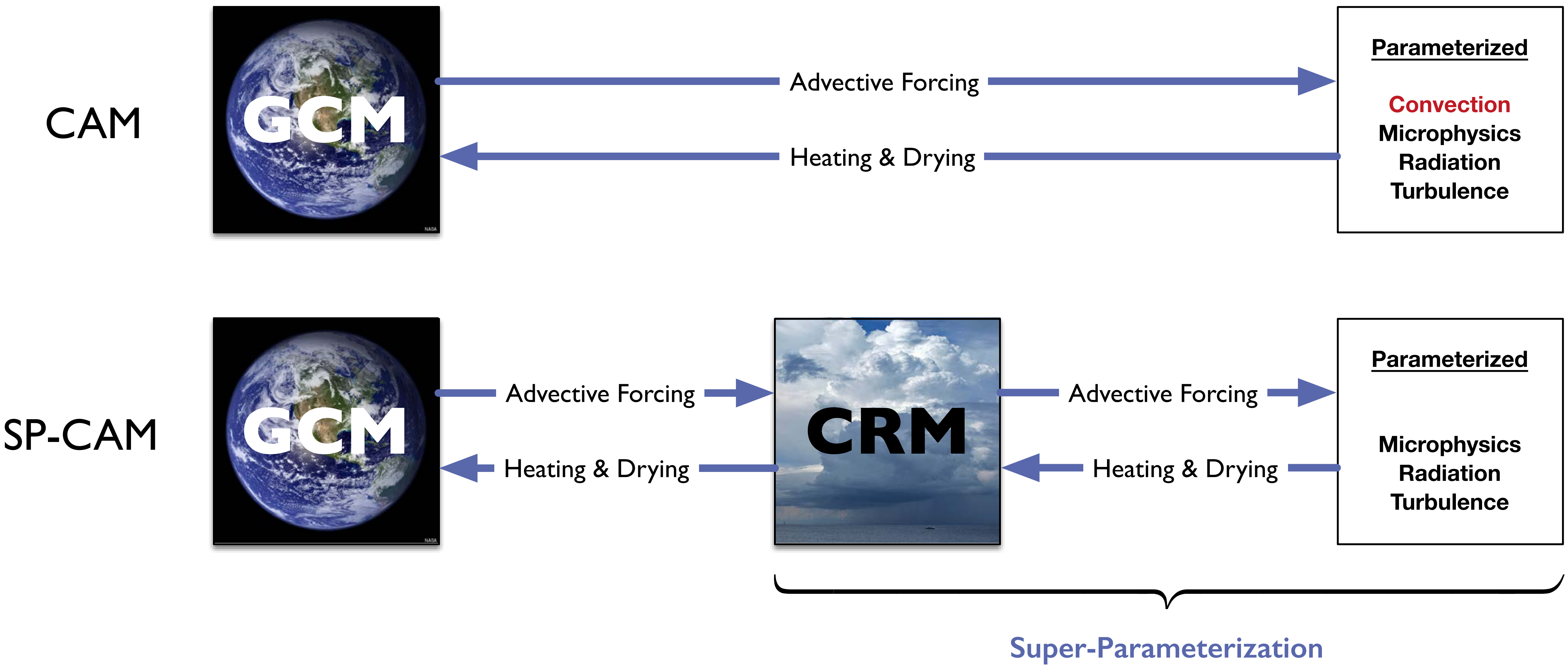


- Moderate increases in the resolution of the poorly scaling dynamical core
- Major increases in the realism of the better-scaling physics

“Super-parameterization” does this.

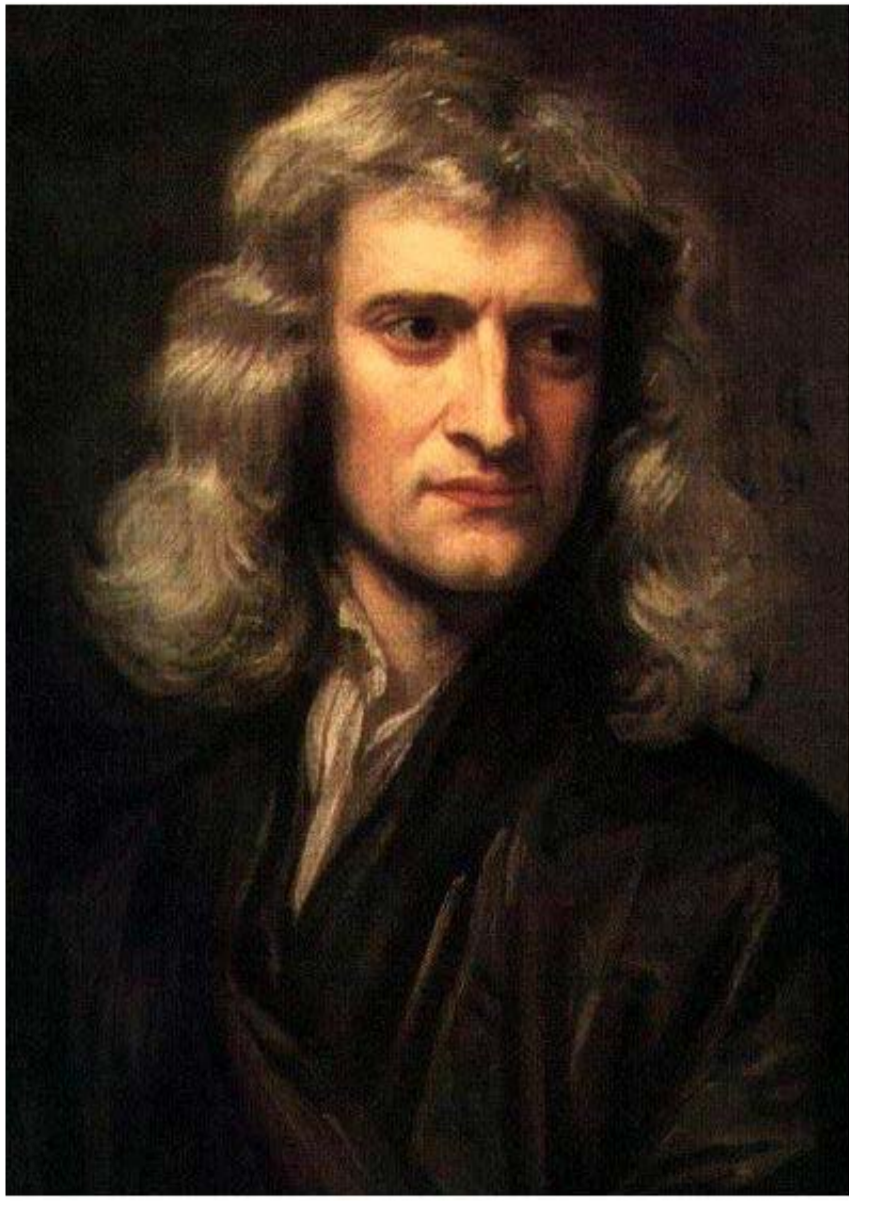


What is super-parameterization?



What's different?

- The equation of motion
  - No closure assumptions
  - No triggers
  - Mesoscale organization
- CRM memory
  - Delay in convective response
  - Sensitive dependence on initial conditions
- Almost embarrassingly parallel:
  MUCH more computation, but no increase in communication
- Short CRM "physics" time steps, much longer GCM dynamics time steps



The SP-CAM produces realistic variability on a wide range of time scales.

- Diurnal cycle (especially papers by Mike Pritchard et al.)
- MJO
- Monsoon fluctuations
- ENSO

http://www.cmmap.org/research/pubs-mmf.html

Extreme Precipitation Events

SP-CAM can simulate strong precipitation.

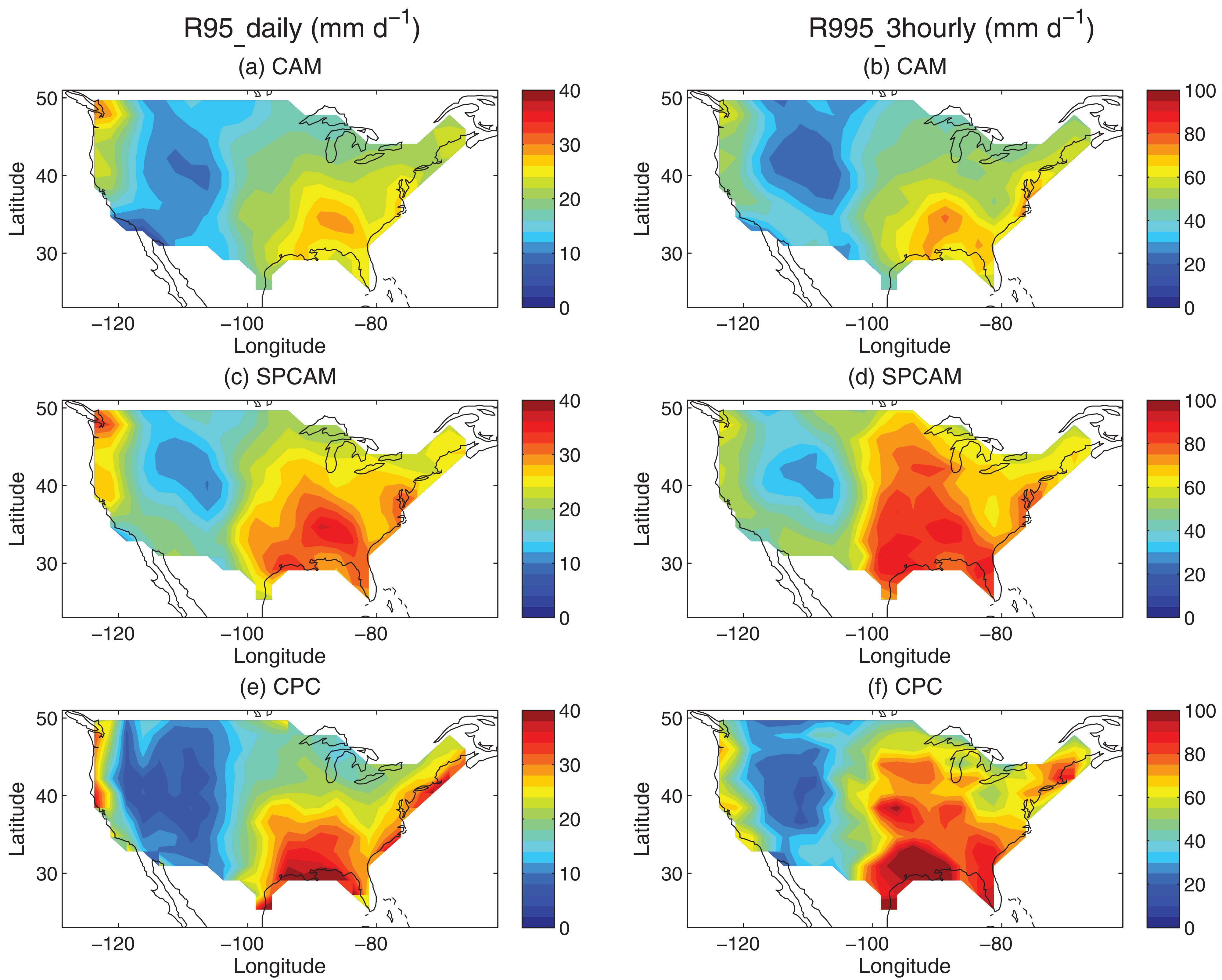


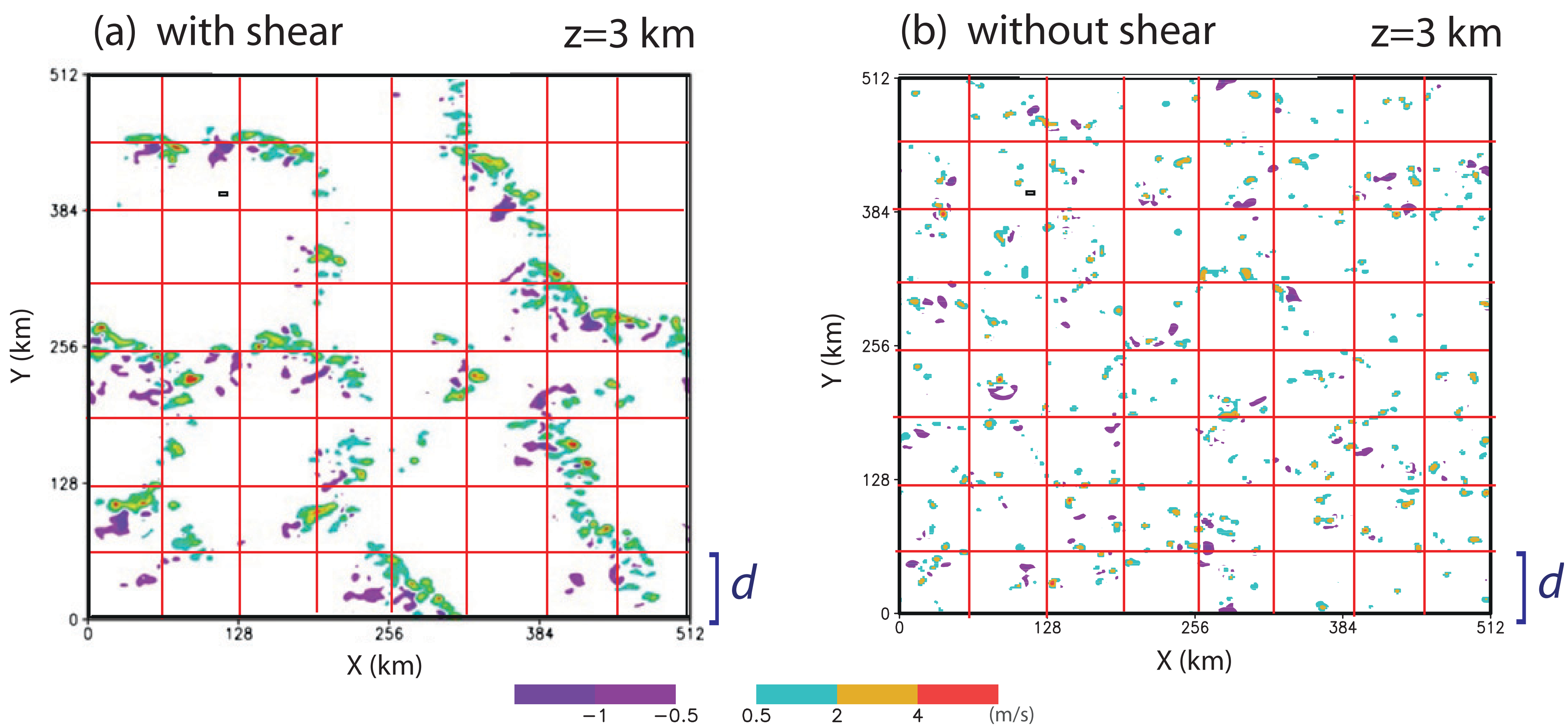
Figure 3. Simulated and observed U.S. extreme precipitation: 95th percentile daily precipitation for (a) CAM, (c) SP-CAM, (e) CPC; and 99.5th percentile 3-hourly precipitation for (b) CAM, (d) SP-CAM, (f) CPC.

Li et al., 2012

“Scale-Aware” Parameterizations?

- Equations and code unchanged as grid spacing varies from 100 km to 1 km
- From simulation of an ensemble of clouds to simulation of the interior of a single cloud

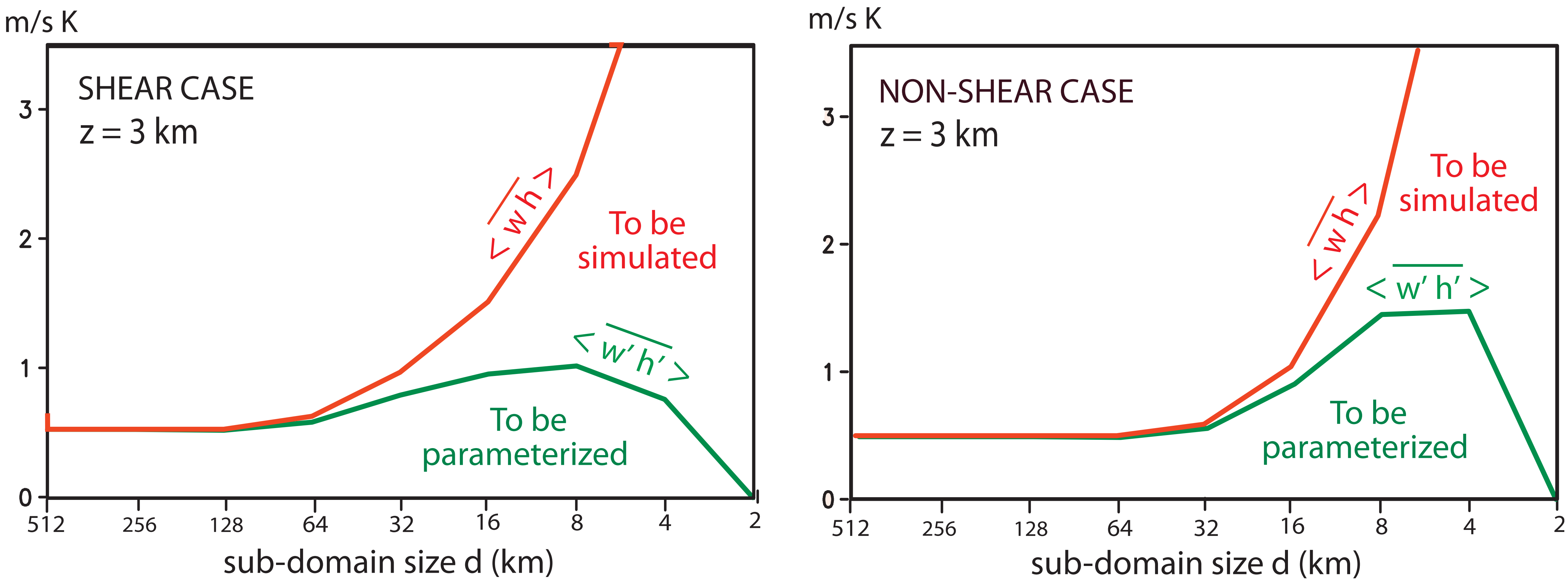
CRM subdomains



Small subdomain = “high resolution GCM”

Arakawa & Wu 2013

Total vs subgrid fluxes



Data only from subdomains where convection is active

Arakawa & Wu 2013

Recall our simplifying assumption

$$\boxed{\sigma \ll 1}$$

This assumption is not viable when the horizontal grid spacing of a model is comparable to the width of an individual convective cloud.

$$M_c = \rho \sigma w_c$$

Instead of a closure on the mass flux, make a closure on sigma.

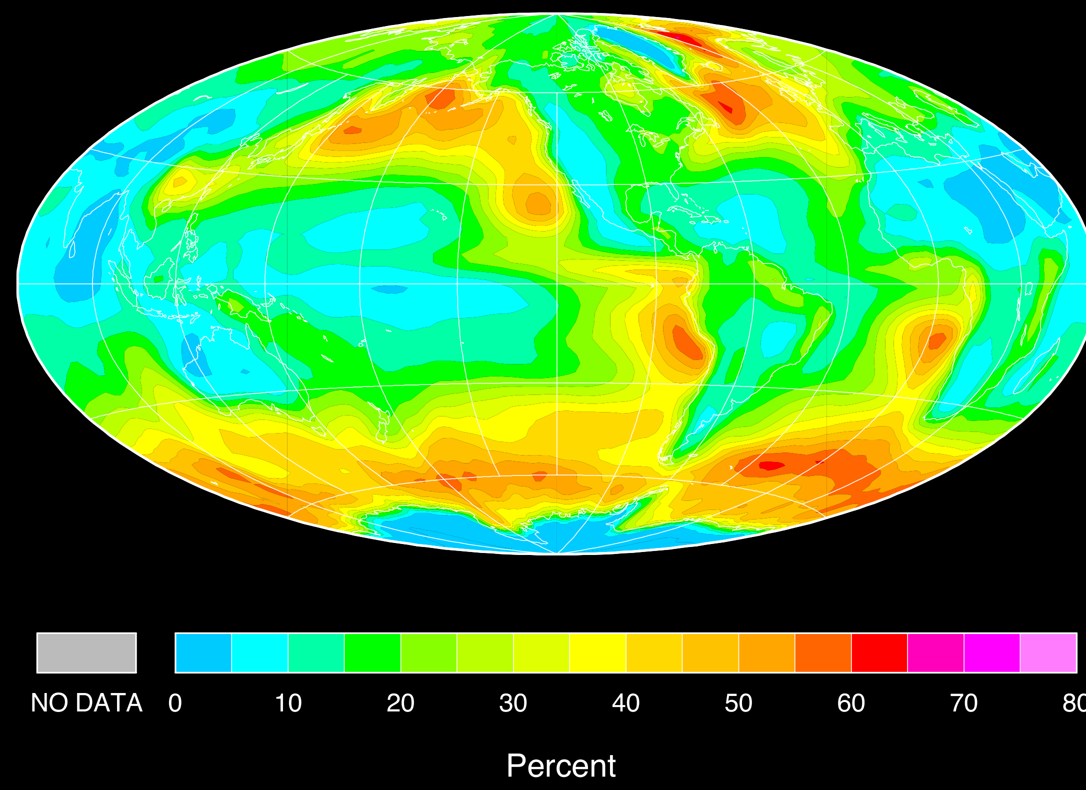
This illustrates how a CRM can be used to study the resolution-dependence of the “subgrid” convection.

Marine stratocumulus clouds

Wimpy clouds, but important & difficult

- Marine stratocumulus cloud layers are typically just a few hundred meters deep.
- They are capped by a strong inversion that is even thinner.
- The in-cloud turbulence is driven mainly by very strong radiative cooling confined to an extremely thin layer.
- It is virtually impossible to explicitly resolve these features in a large-scale model.

Annual ISCCP C2 Inferred Stratus Cloud Amount



Annual ERBE Net Radiative Cloud Forcing

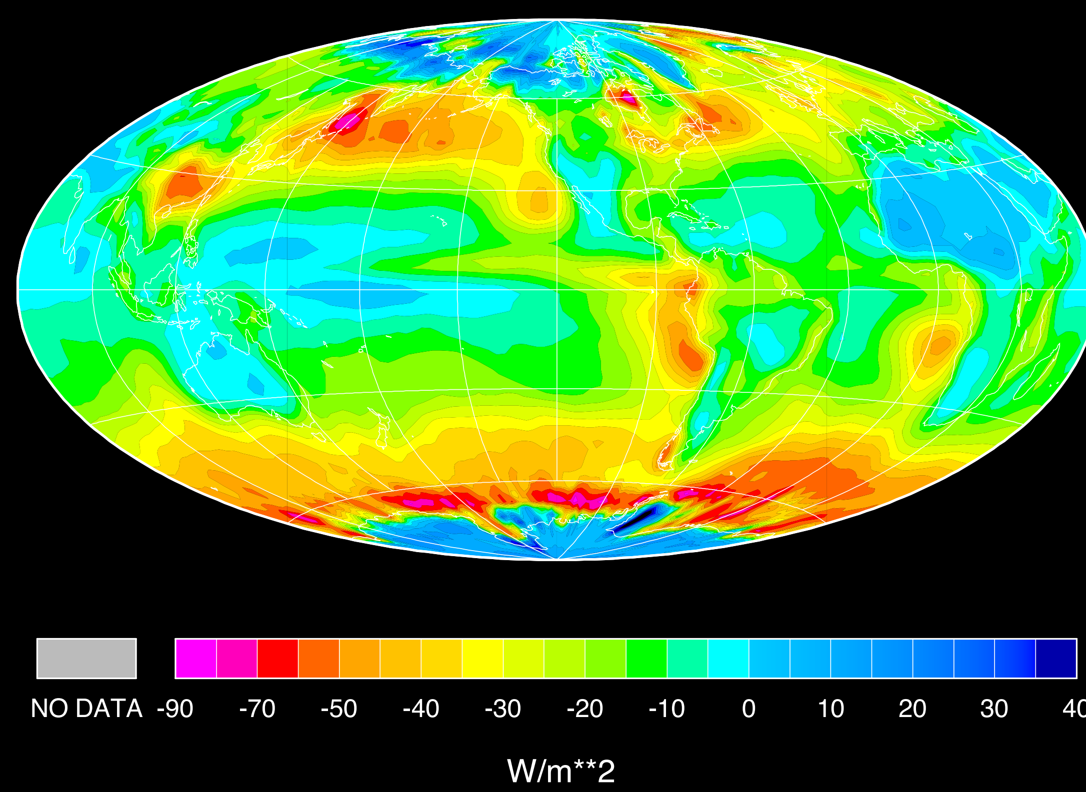


Figure from Norris & Leovy

“Models of cloud-topped mixed layers”

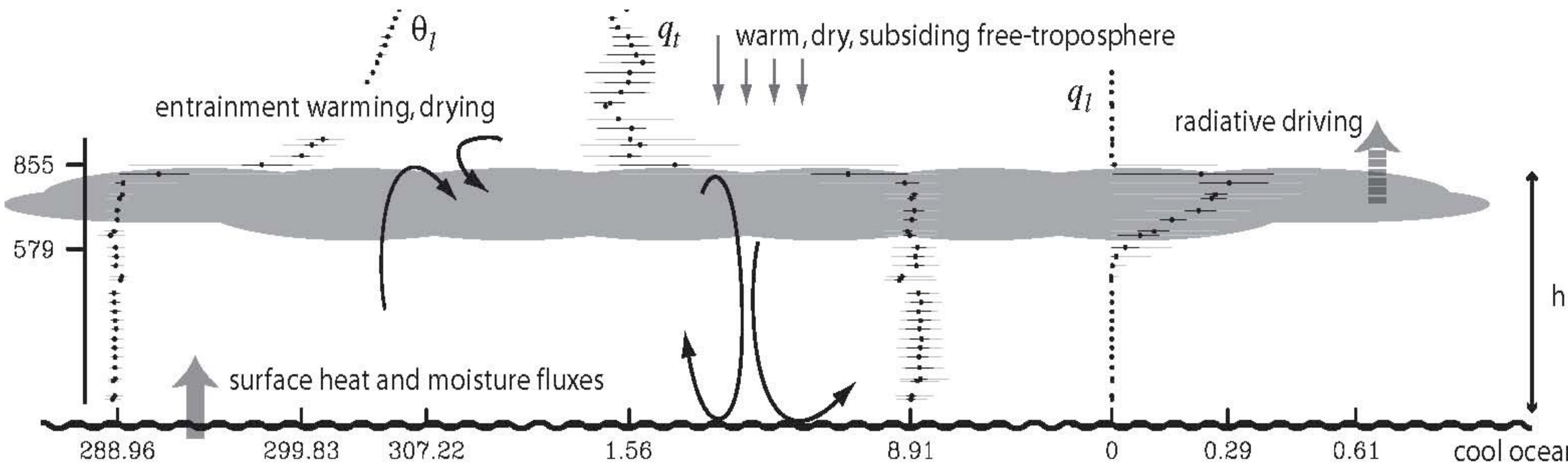


Figure from Bjorn Stevens

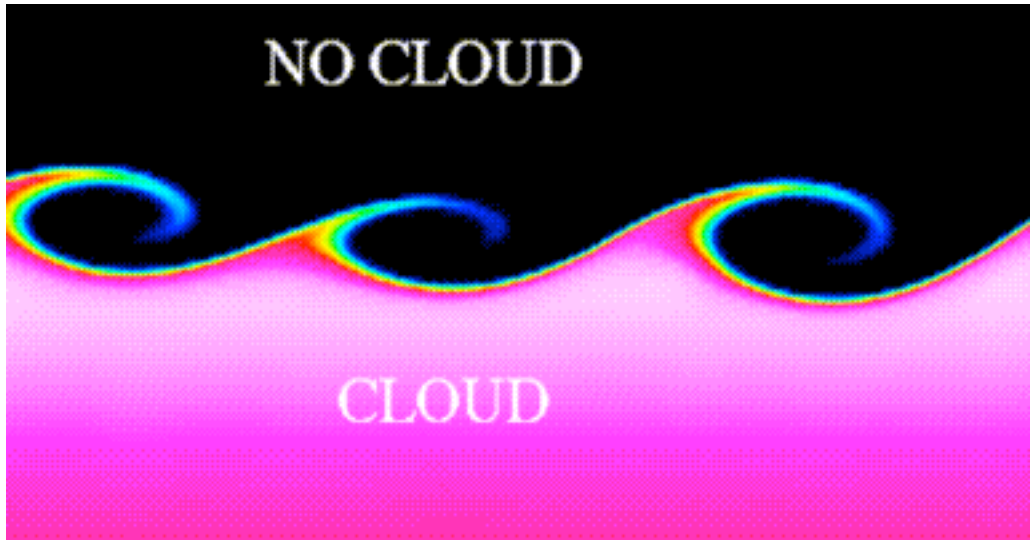
What is entrainment?

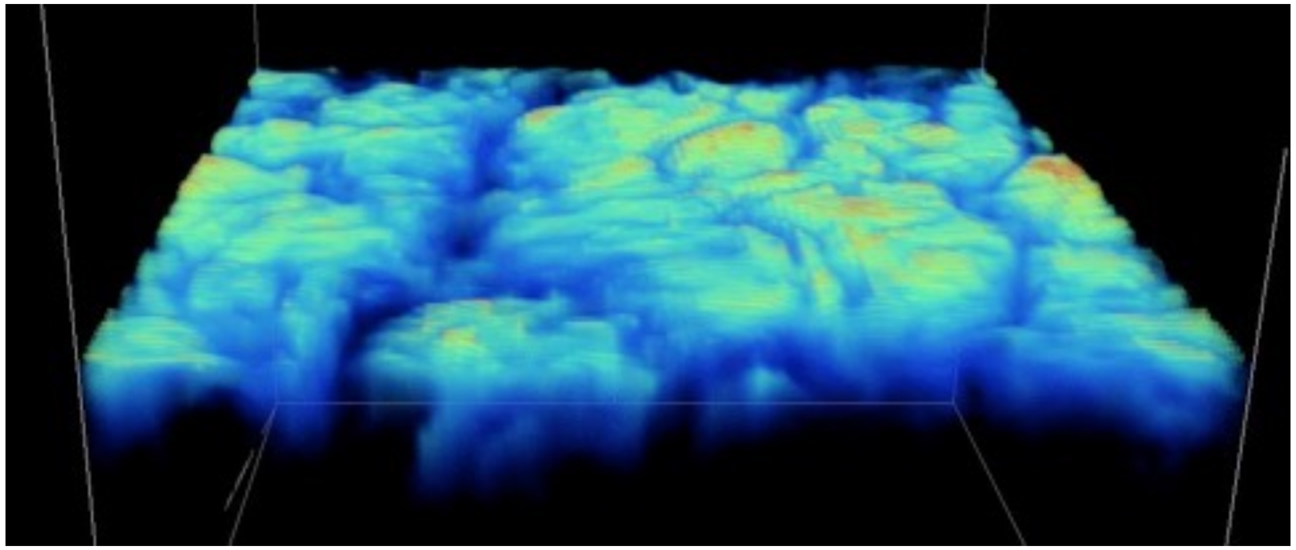
Clouds don't entrain.

Turbulence entrains.

Clouds are turbulent.

Entrainment is the active annexation of quiet fluid by turbulence.





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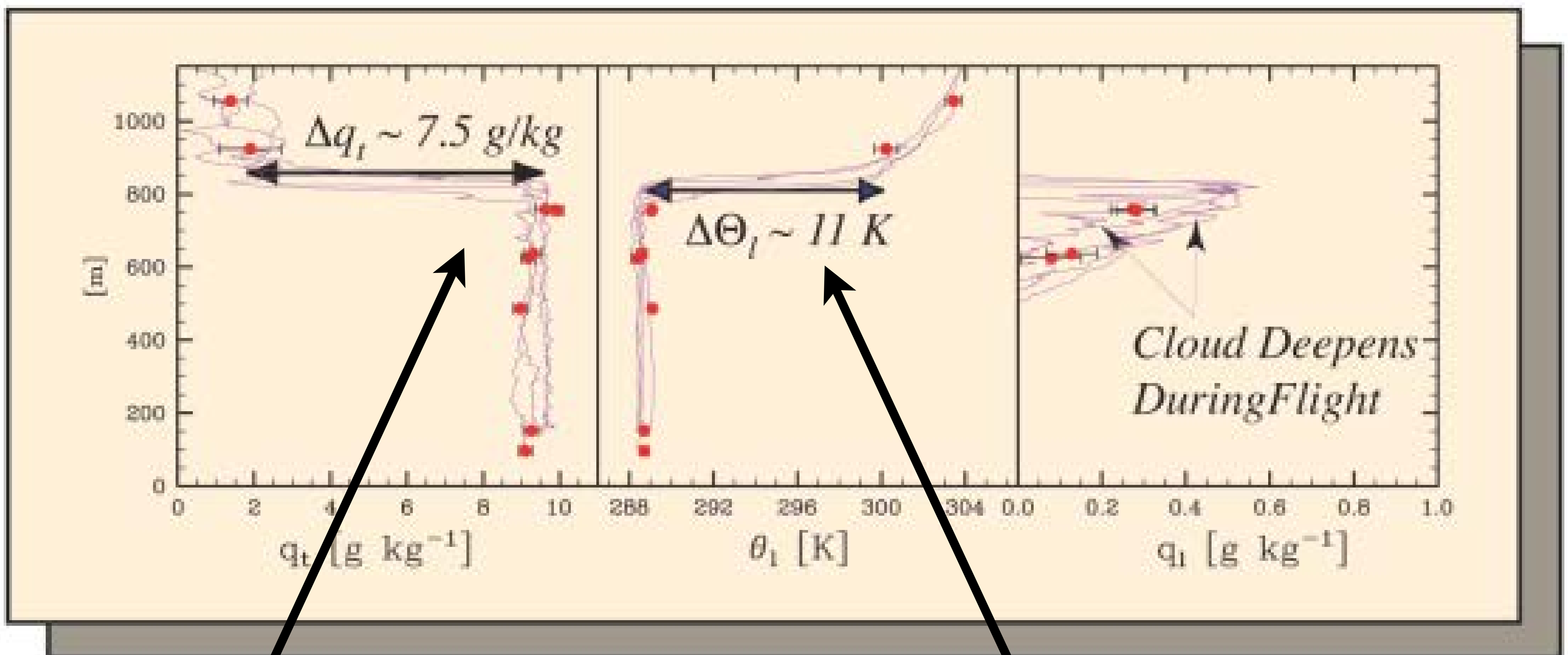
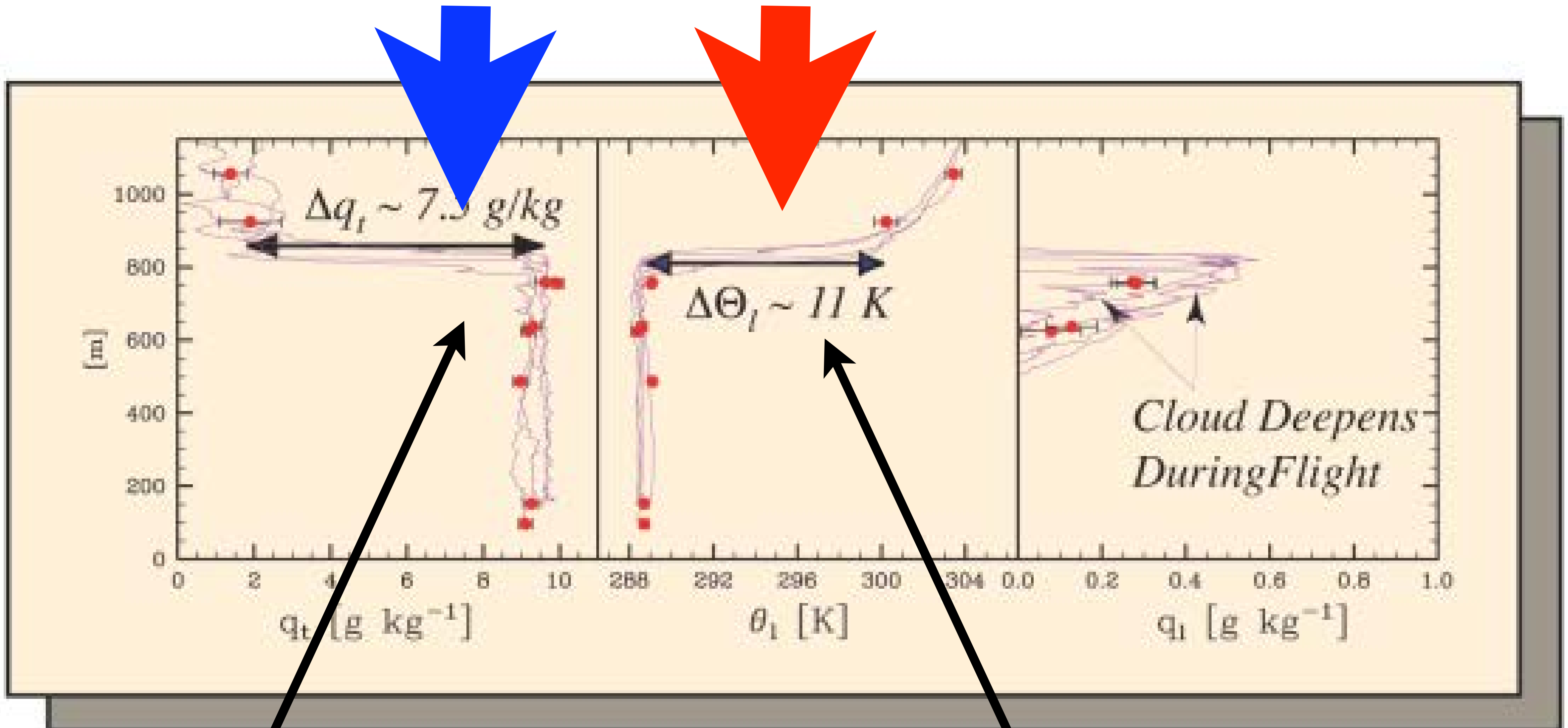


$$(F_{qt})_B = -E\Delta q_t$$

$$(F_{\theta_l})_B = -E\Delta\theta_l + \Delta R$$

Figure from Stevens et al. (2003)

"Models of cloud-topped mixed layers"



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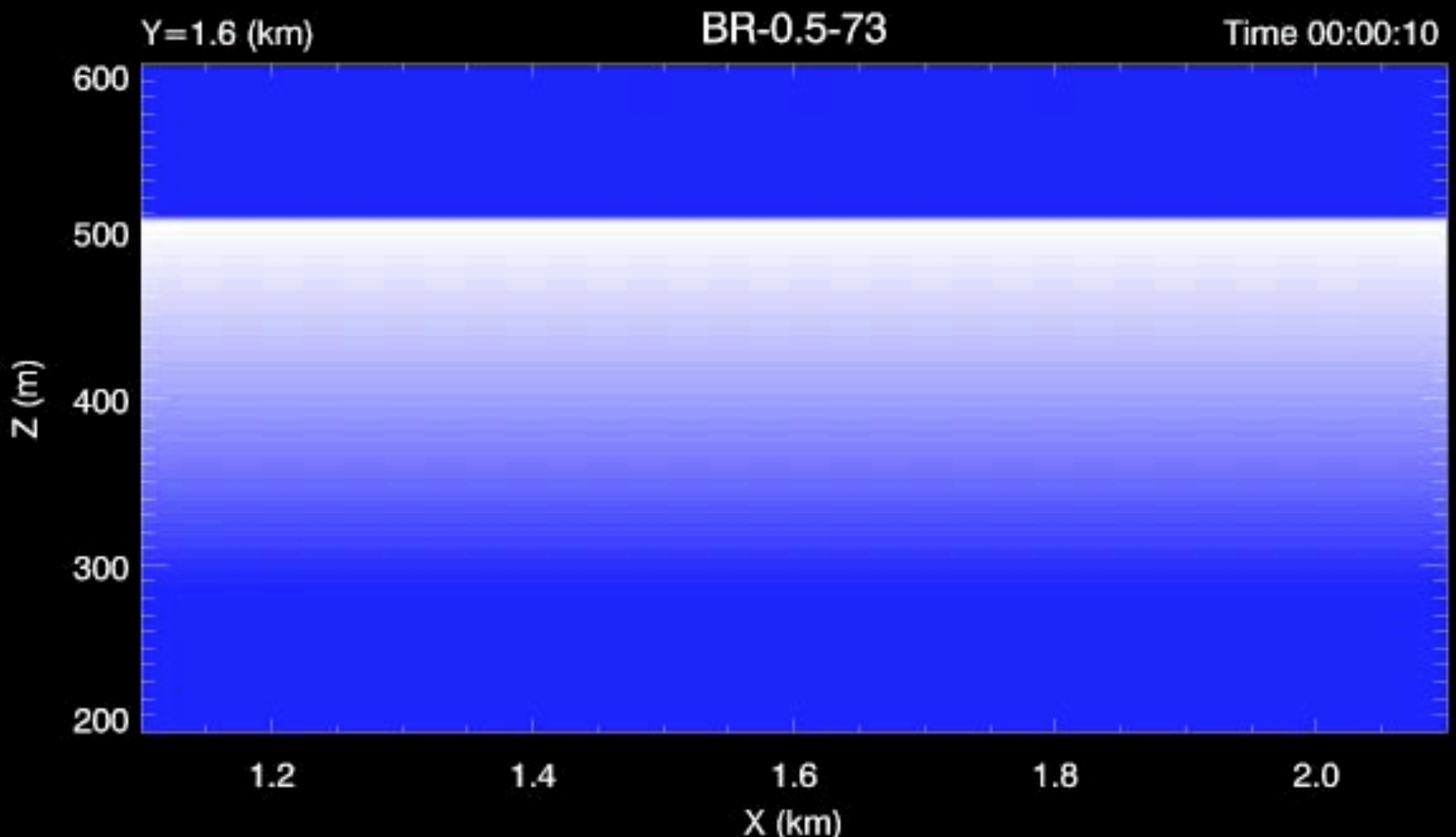
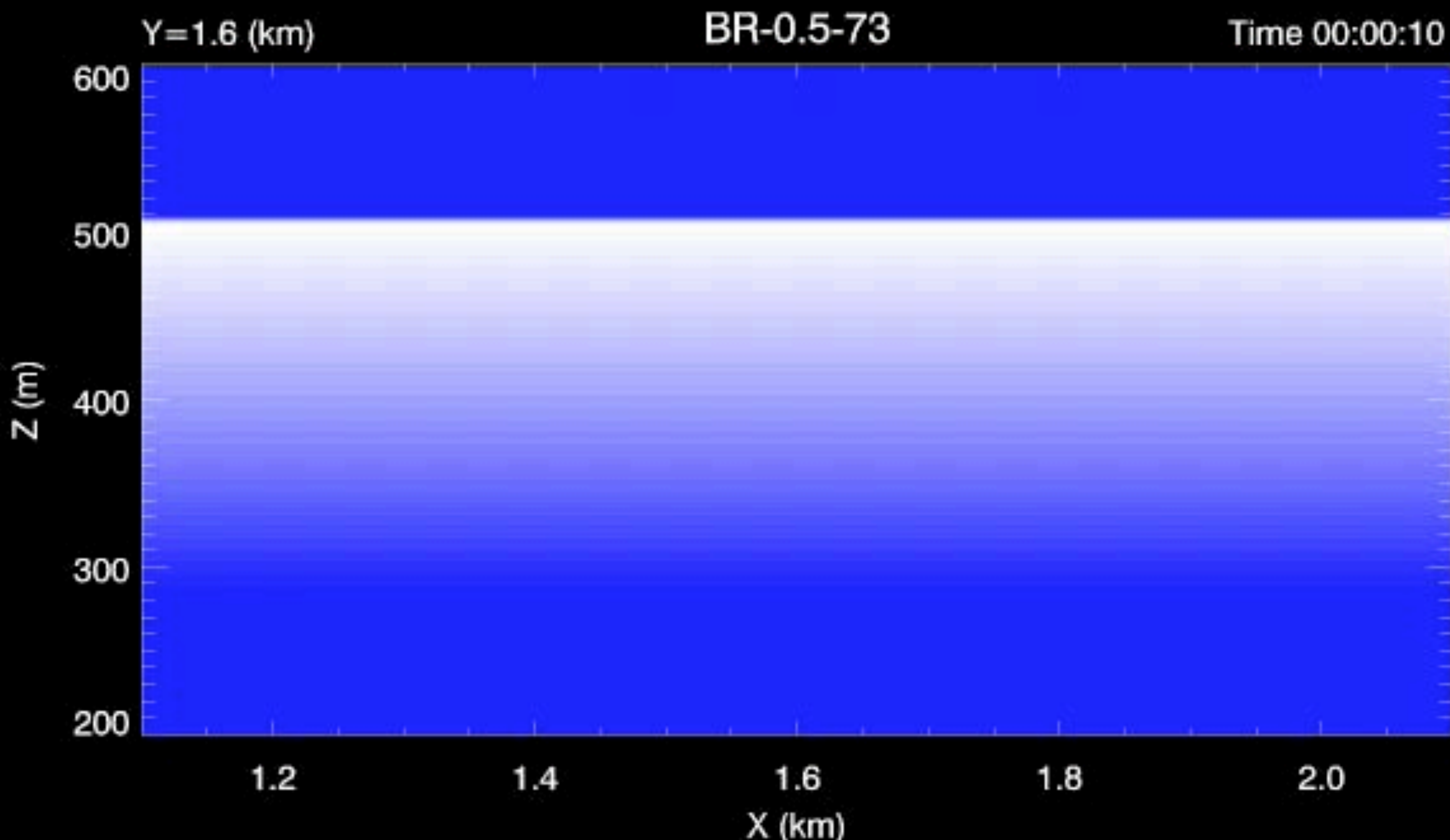
Entrainment driven by cloud-top evaporation



Movie by Tak Yamaguchi

Entrainment driven by cloud-top evaporation



Movie by Tak Yamaguchi

Why are Sc clouds so prevalent over the eastern subtropical oceans?

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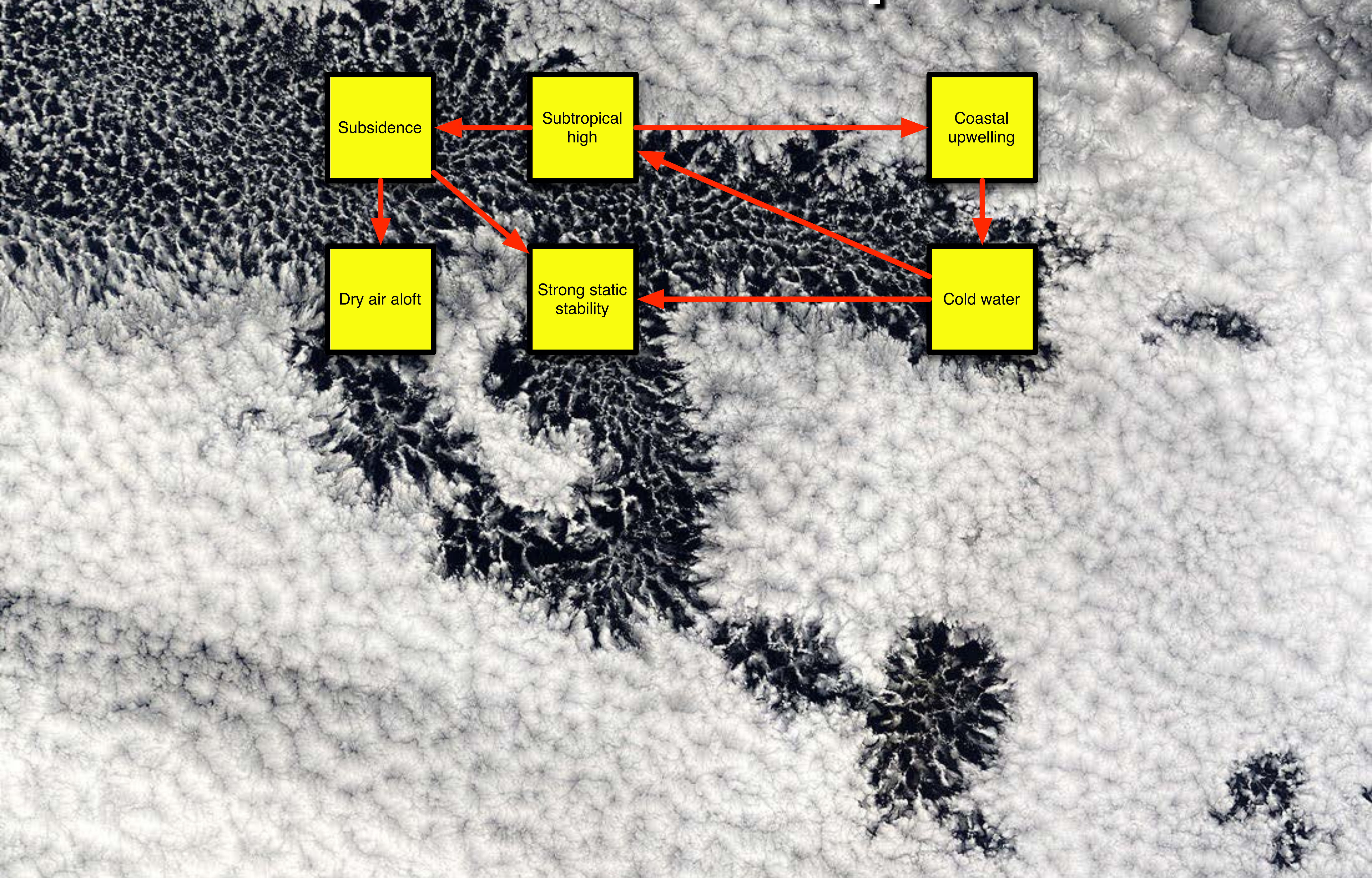

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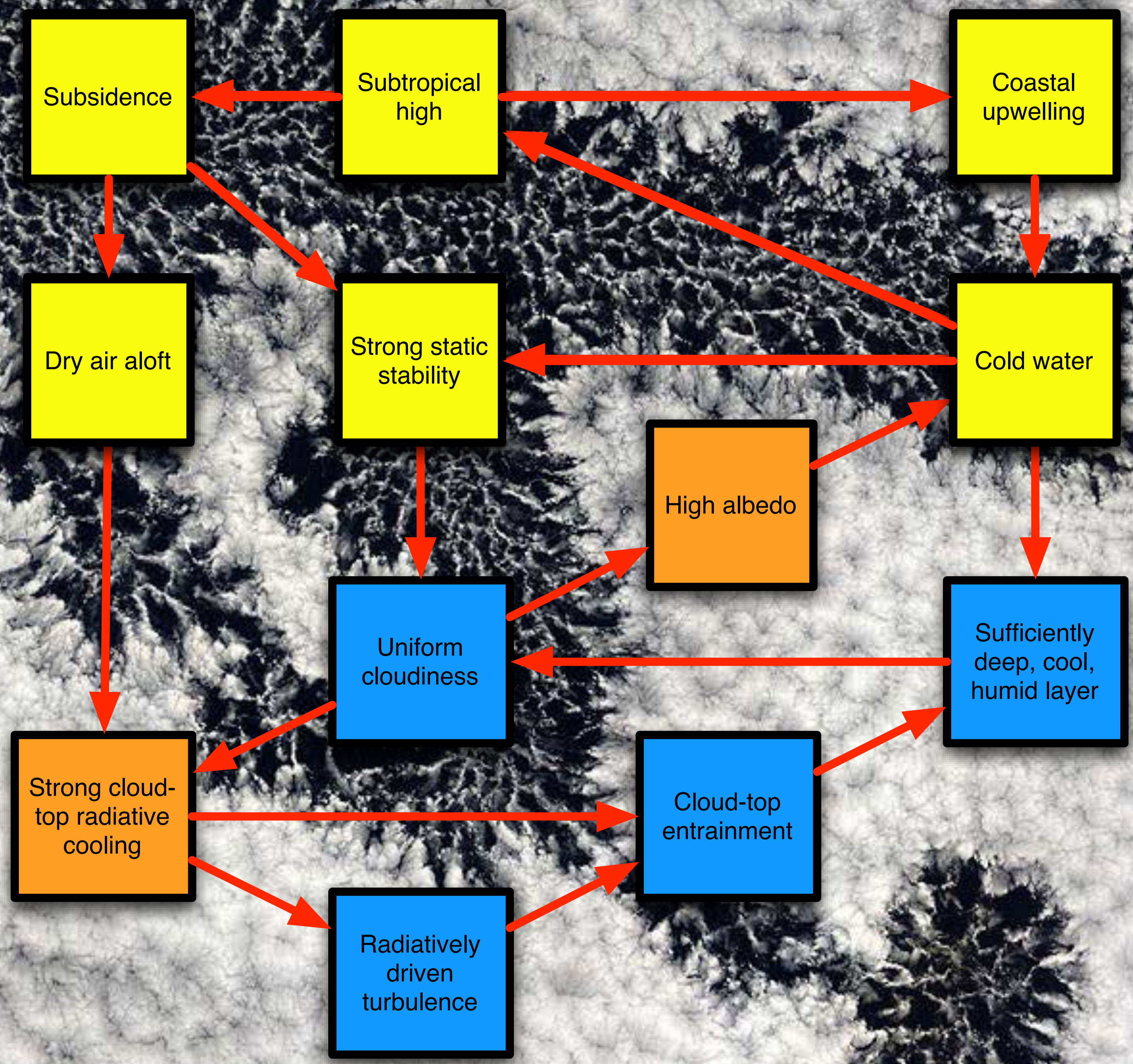
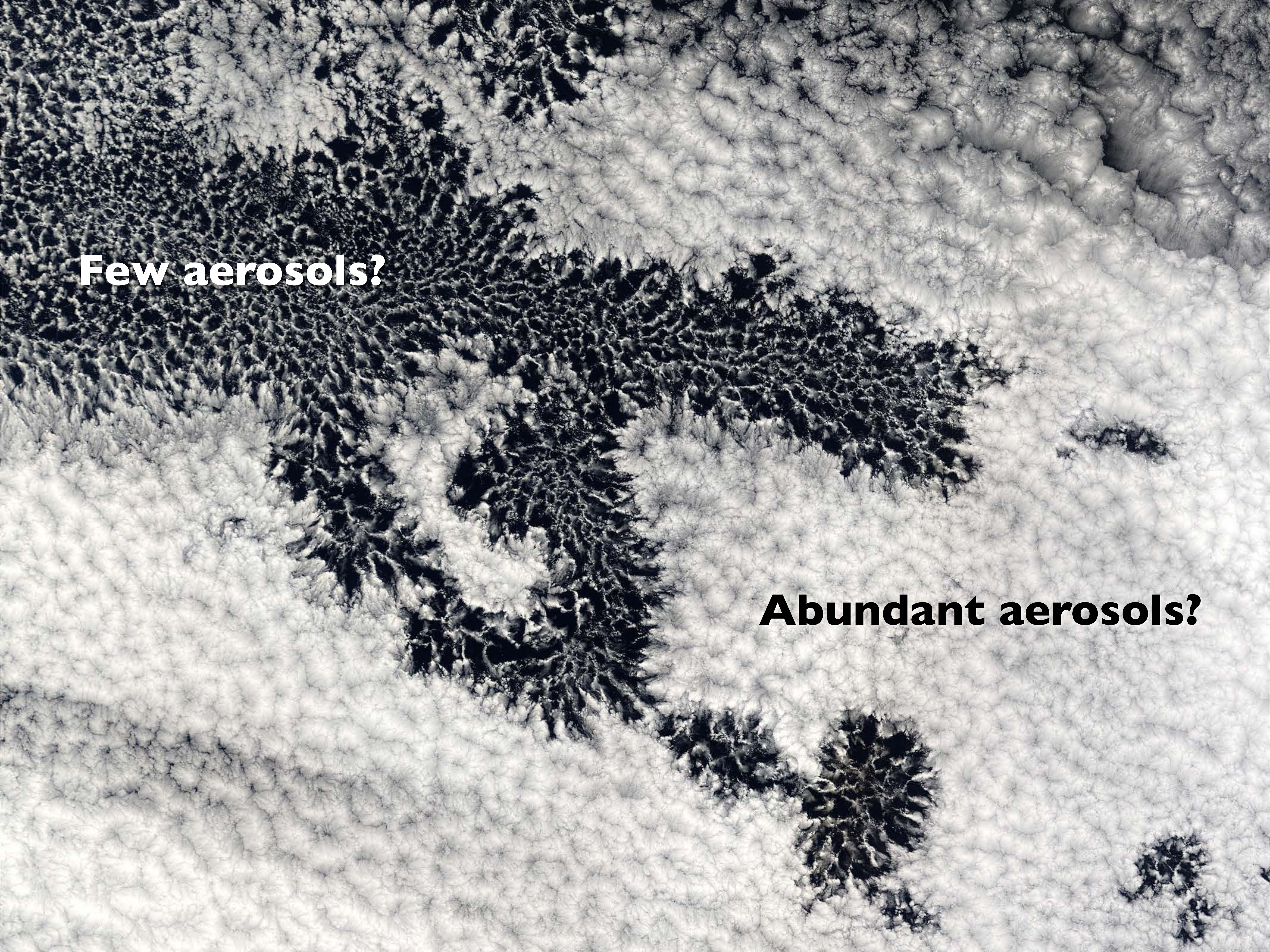


What about aerosols?

- Aerosols have direct radiative effects.
  - Scattering
  - Absorption
- Some aerosols can nucleate clouds.
- However, the availability of nuclei is rarely if ever a key limiting factor preventing cloud formation.
- In fact, the distribution of cloudiness is primarily determined by dynamical processes on a wide range of scales.
- The number of nuclei can strongly influence the cloud particle size distribution.
  - This matters for the cloud optical properties.
  - It also matters for precipitation formation.
  - It may influence cloud organization


Few aerosols?
Abundant aerosols?

Conclusions

- Clouds matter for radiation, precipitation, vertical transports, and chemistry.
- Convection parameterizations rely on the fact that the fractional area covered by updrafts is very small.
- The convective mass flux can be determined by assuming that CAPE is consumed as fast as it is generated.
- Stratocumulus clouds are radiatively important, but don't rain much.
- Stratocumulus clouds are hard to vertically resolve, and also physically complicated.