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  - Energy
  - Water
  - Momentum
  - Trace species

What do clouds do?

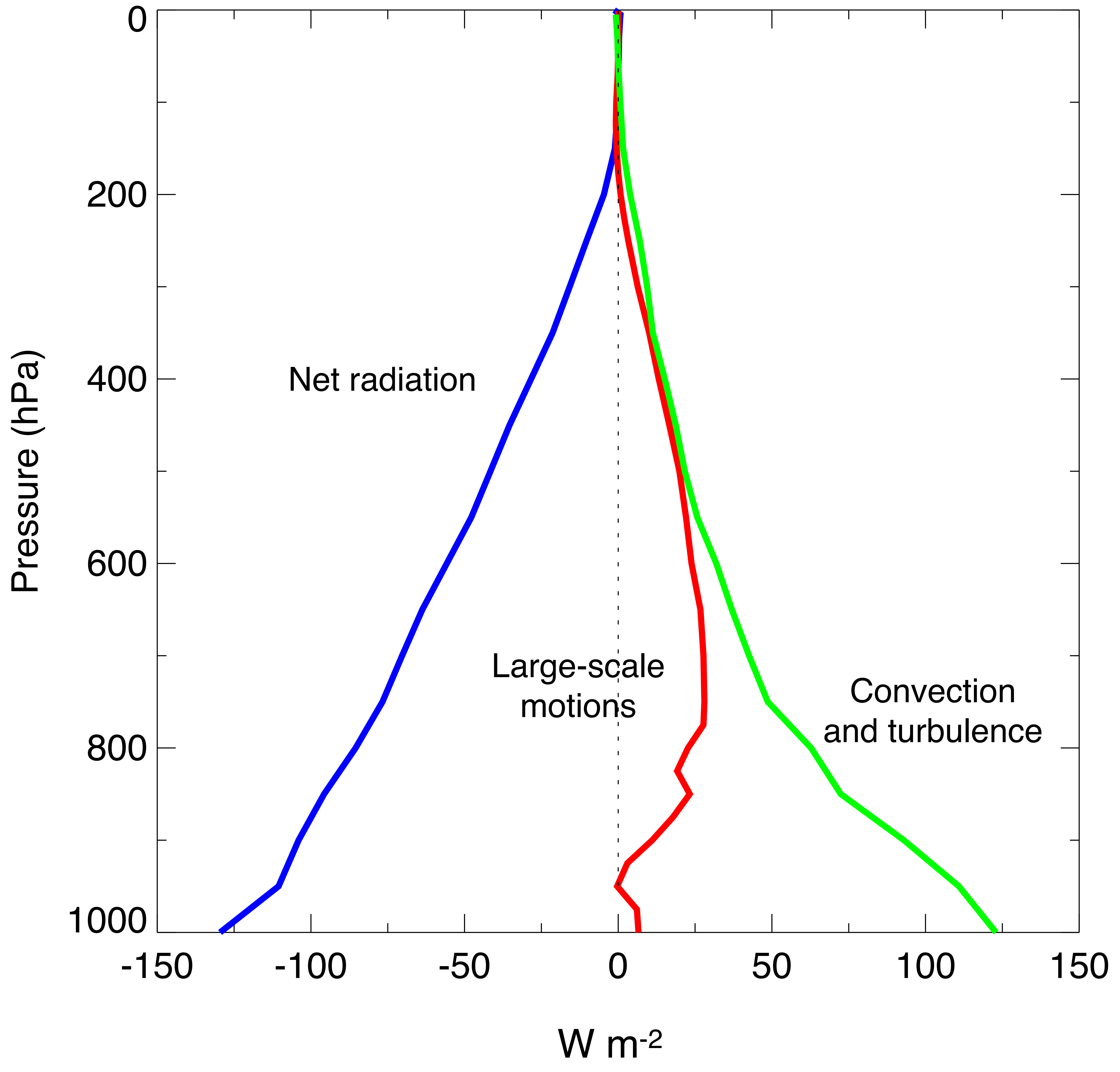
- Scatter, absorb, and emit radiation
- Precipitate
- Transport things vertically
  - Energy
  - Water
  - Momentum
  - Trace species
- Faciliate chemical reactions

Andrew Gettelman talked about microphysics parameterizations.

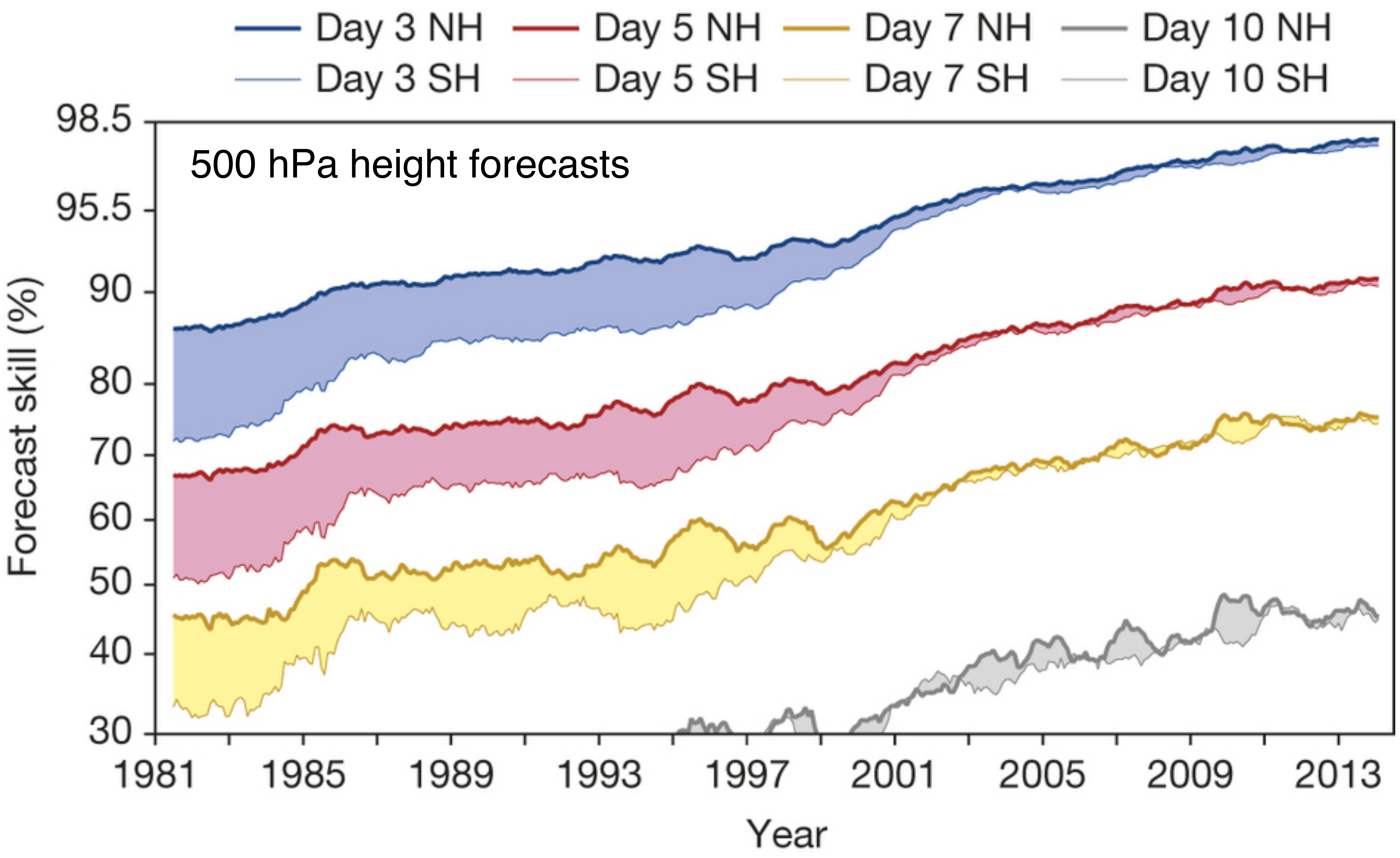
Robert Pincus discussed radiation parameterizations.

I will cover turbulence and convection.

Globally averaged vertical energy flows



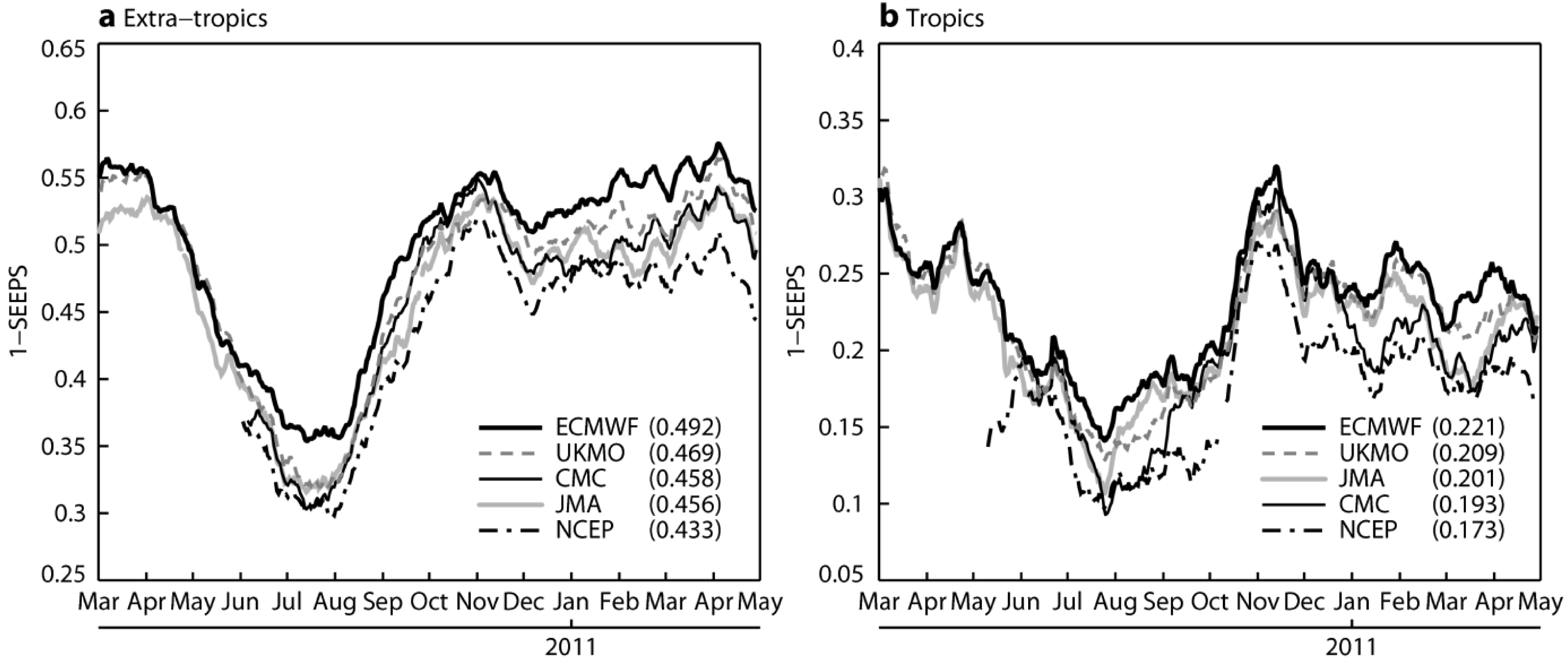
Forecasts have been getting better.



Bauer et al., Nature, 2015

Precipitation forecasting is hard, though.

In these plots, higher values mean more skill.



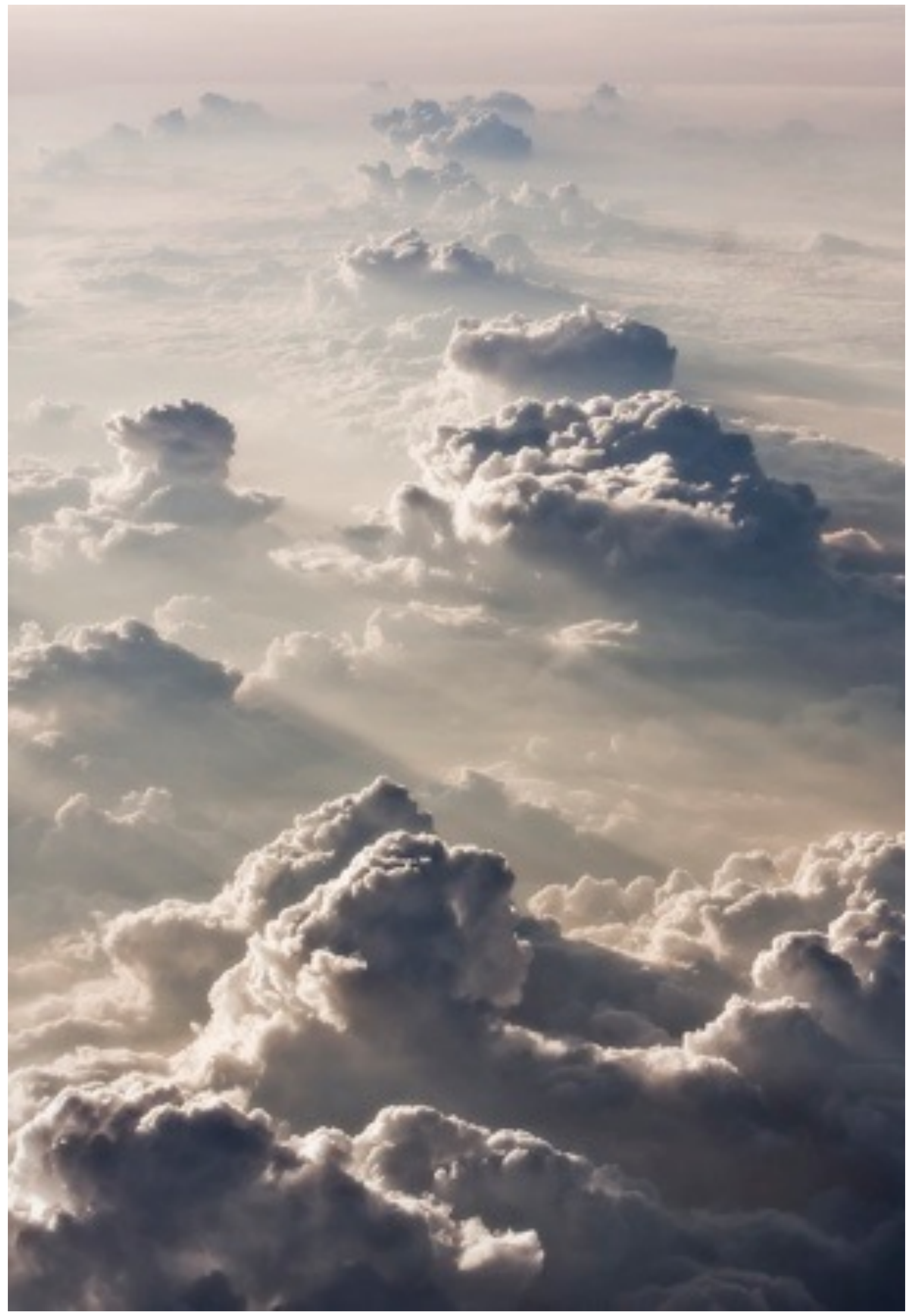
Midlatitude forecasts are less skillful in summer than in winter.

Tropical forecasts are less skillful than midlatitude forecasts.

Haiden et al., 2012

How global modelers have approached clouds

- Convective clouds
  - Deep
  - Shallow



How global modelers have approached clouds

- Convective clouds
  - Deep
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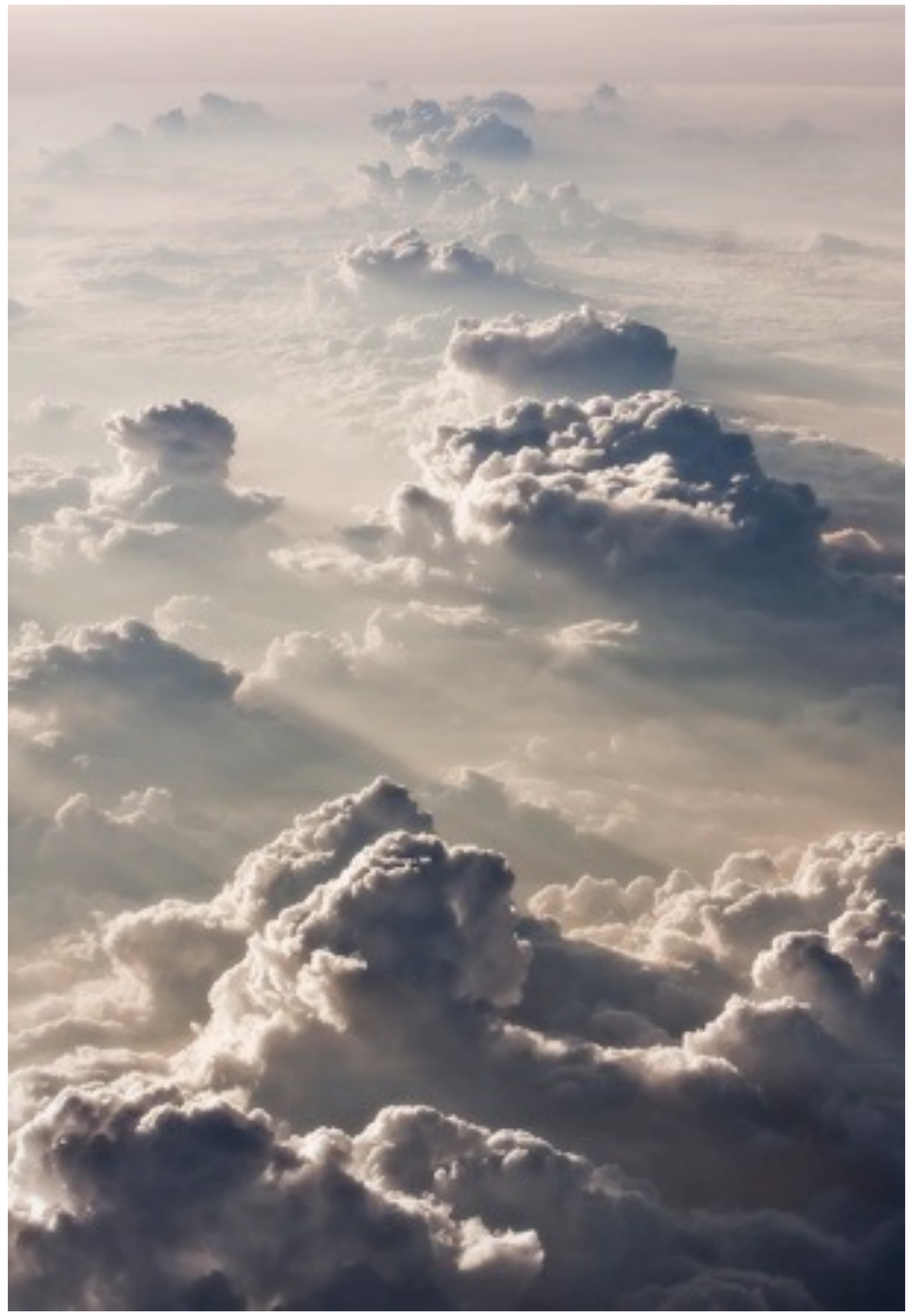
- Stratiform clouds above the boundary layer
  - Convective detrainment
  - Frontal lifting
  - Orographic lifting



How global modelers have approached clouds

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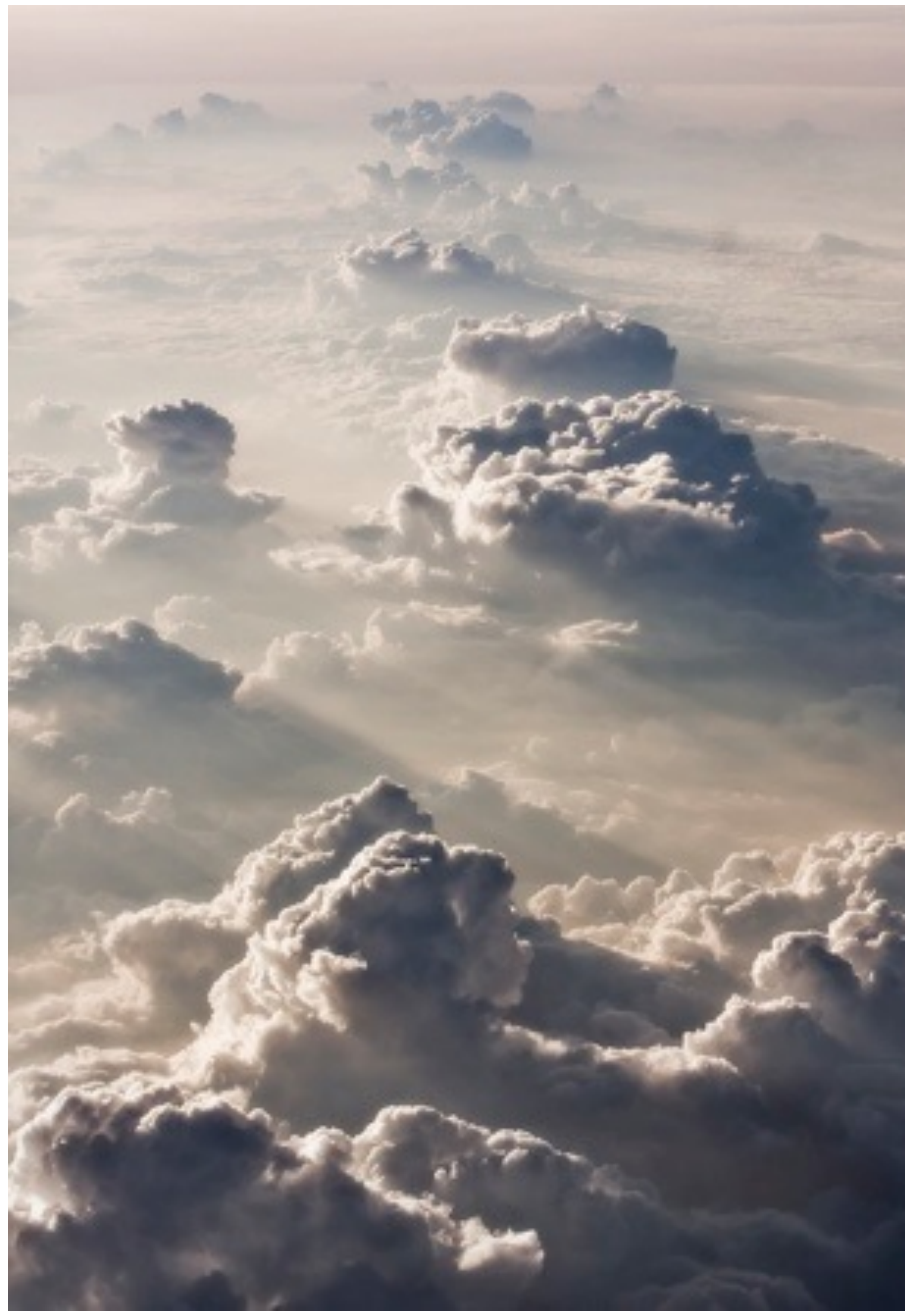
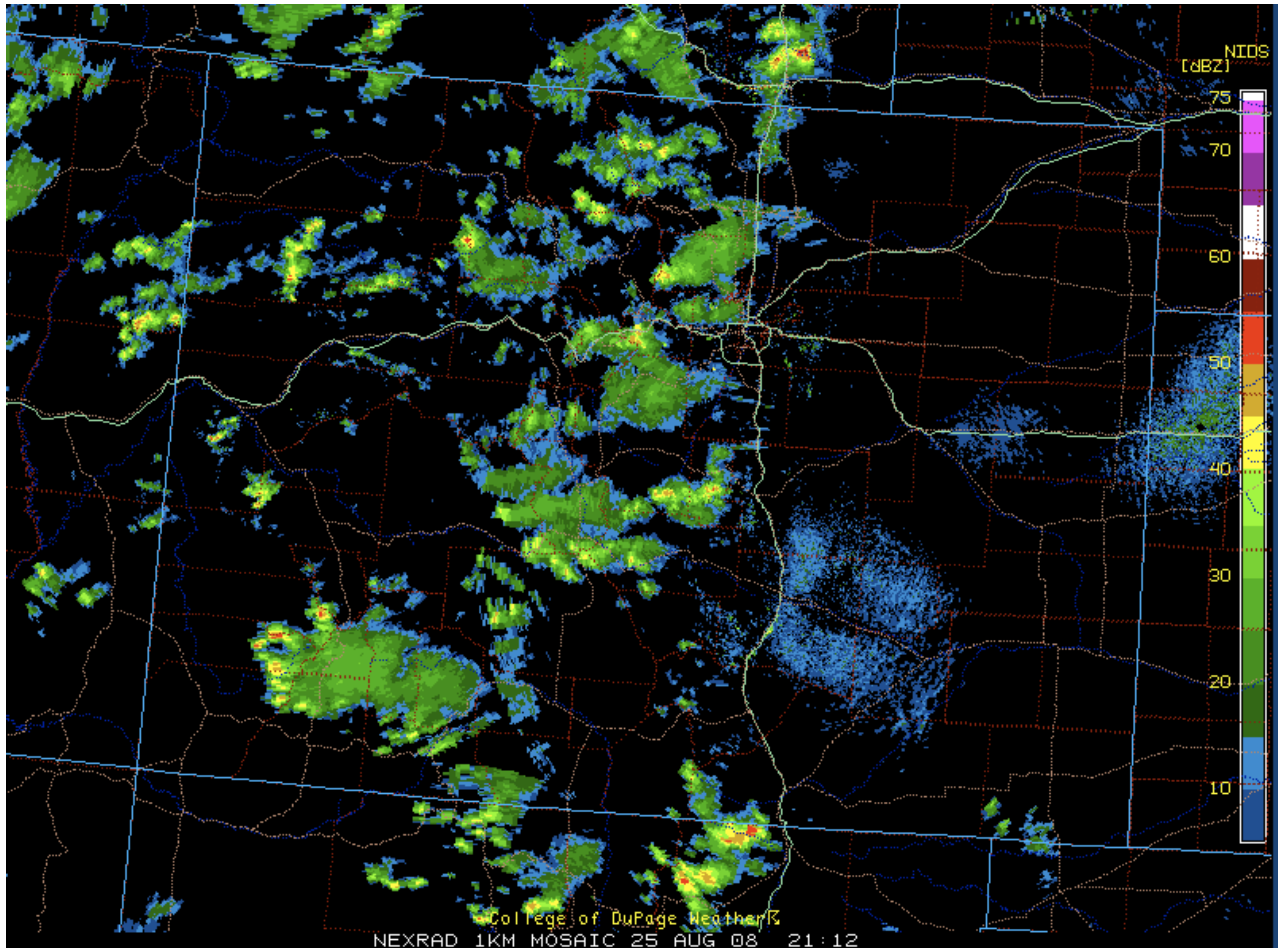
    - Frontal lifting
    - Orographic lifting
- Marine stratocumulus clouds



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.

This is a fundamental issue.

Analogy

	Kinetic theory of gases	*Cloud parameterization*
Players	Molecules	Clouds
Volume	1 cubic cm	1 model grid column
Sample size	A multiple of Avogadro's number $\mathcal{O}(10^{23})$	Dozens to thousands of clouds
Simplifying assumptions	Point-like molecules; Inter-molecular collisions neglected	Small updraft area; Uniform environment; Direct interactions among clouds neglected
Nonequilibrium effects	Brownian motion, etc.	TBD, maybe mesoscale organization

Charney & Eliassen 1964

"The most difficult task … is to describe the turbulent transport properties of the cumulus convection field in statistical equilibrium with the large-scale field of motion."

Manabe et al. 1965

"Moist convective adjustment"

"…Because of convective instability, intense grid-scale convection develops exponentially in the area where the lapse rate is unstable. …Therefore, *it is desirable to design a scheme of convection such that the grid-scale convection does not develop*."

"…We used a very simple scheme of convective adjustment depending upon both relative humidity and the lapse rate and successfully *avoided the abnormal growth of grid-scale convection*."

Manabe et al. 1965

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Closure based on release of instability, but without a model of penetrative convection.

Syukuro Manabe &
Anthony J. Broccoli

BEYOND GLOBAL WARMING

How Numerical Models Revealed the Secrets of Climate Change

Syukuro Manabe
Winner of the Nobel Prize in Physics
2021

ON THE HEAT BALANCE IN THE EQUATORIAL TROUGH ZONE

by

HERBERT RIEHL
The University of Chicago

and

JOANNE S. MALKUS
Woods Hole Oceanographic Institution

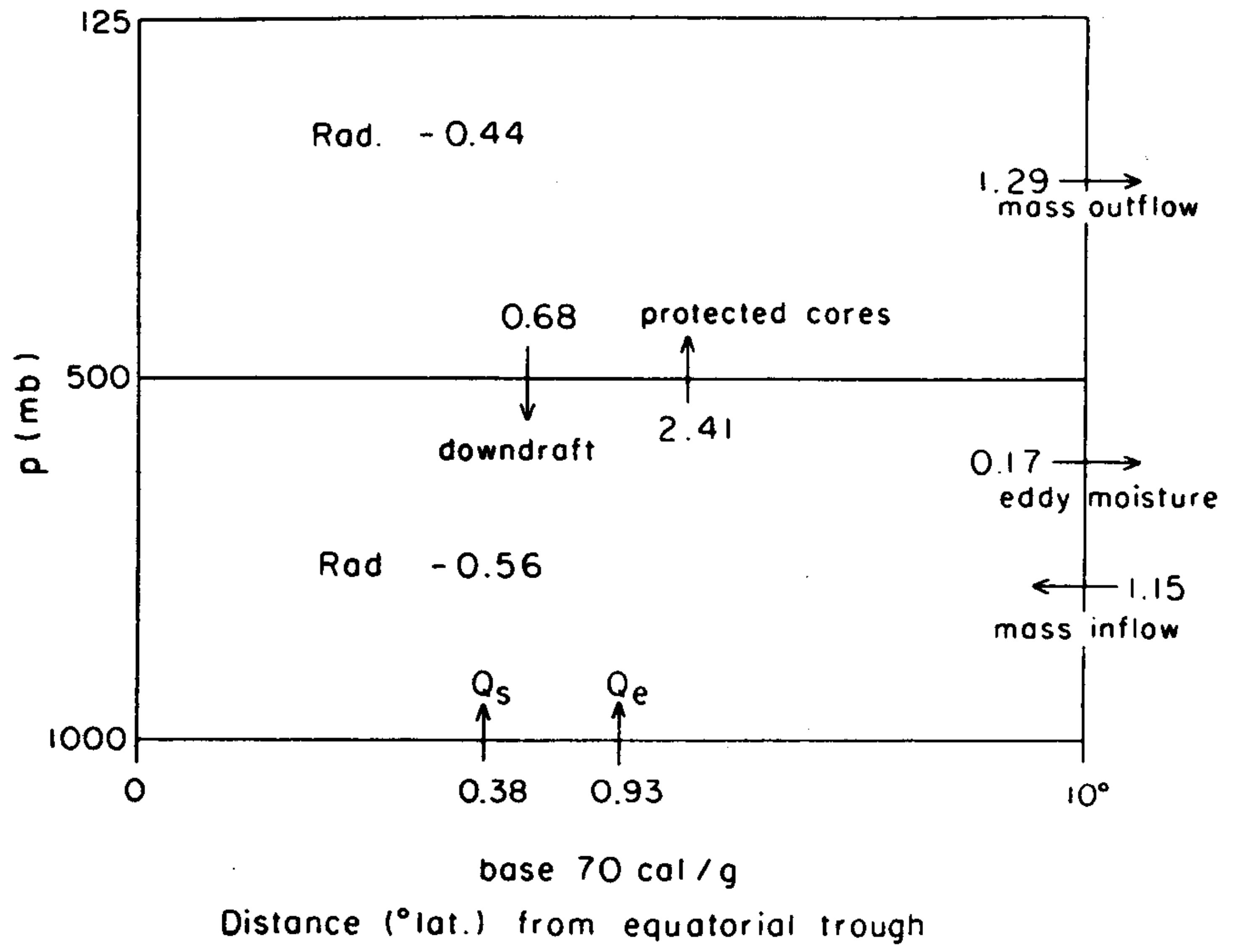


Fig. 18. Heat budget for winter side of equatorial trough zone (unit 10^{15} cal/sec).

Strong, deep, partially upgradient
upward energy transport
by penetrative convection

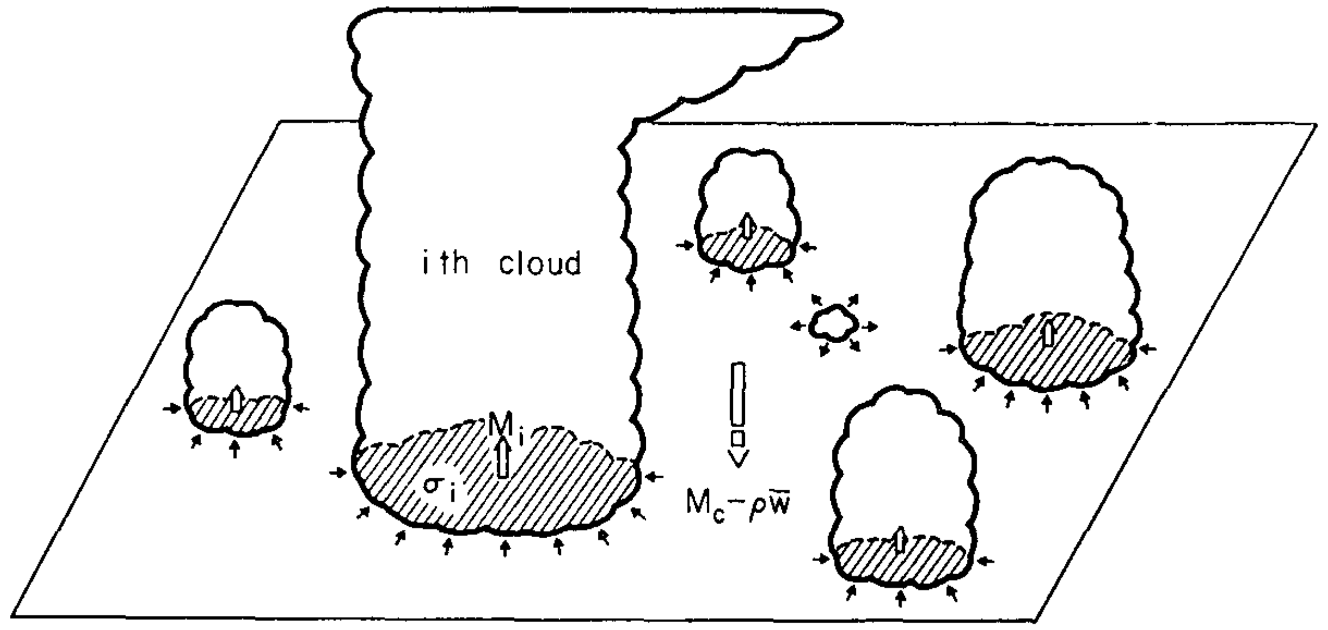
Kuo 1965

"…We shall show that the statistical effect of the convective motions can be included without referring to their details by using a certain averaging process, and then we shall derive the formulas that express the latent heat released by the deep cumulus purely in terms of parameters of large scale quantities."

Kuo used Joanne Malkus's cloud model, but assumed that heating occurred by diffusion from updrafts rather than convective fluxes.

Arakawa & Schubert (1974)

- What they included:
  - A spectrum of updrafts
  - Mass fluxes (ref. AA 1969) — an emphasis on convective *fluxes* of energy, etc.
  - Quasiequilibrium closure
  - Oversimplified but explicit interactions of cumulus clouds with the boundary layer
  - Detrained liquid and ice — which were assumed to immediately return to vapor



They cited a total of 9 papers authored or co-authored by Joanne Simpson.

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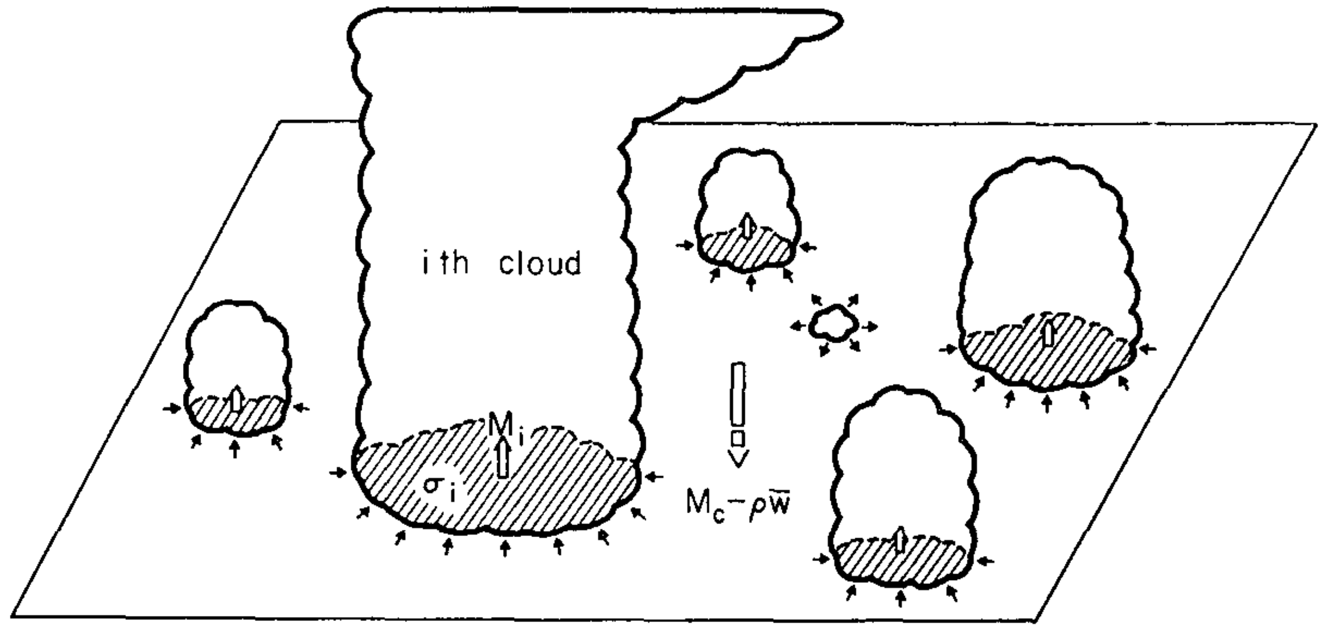
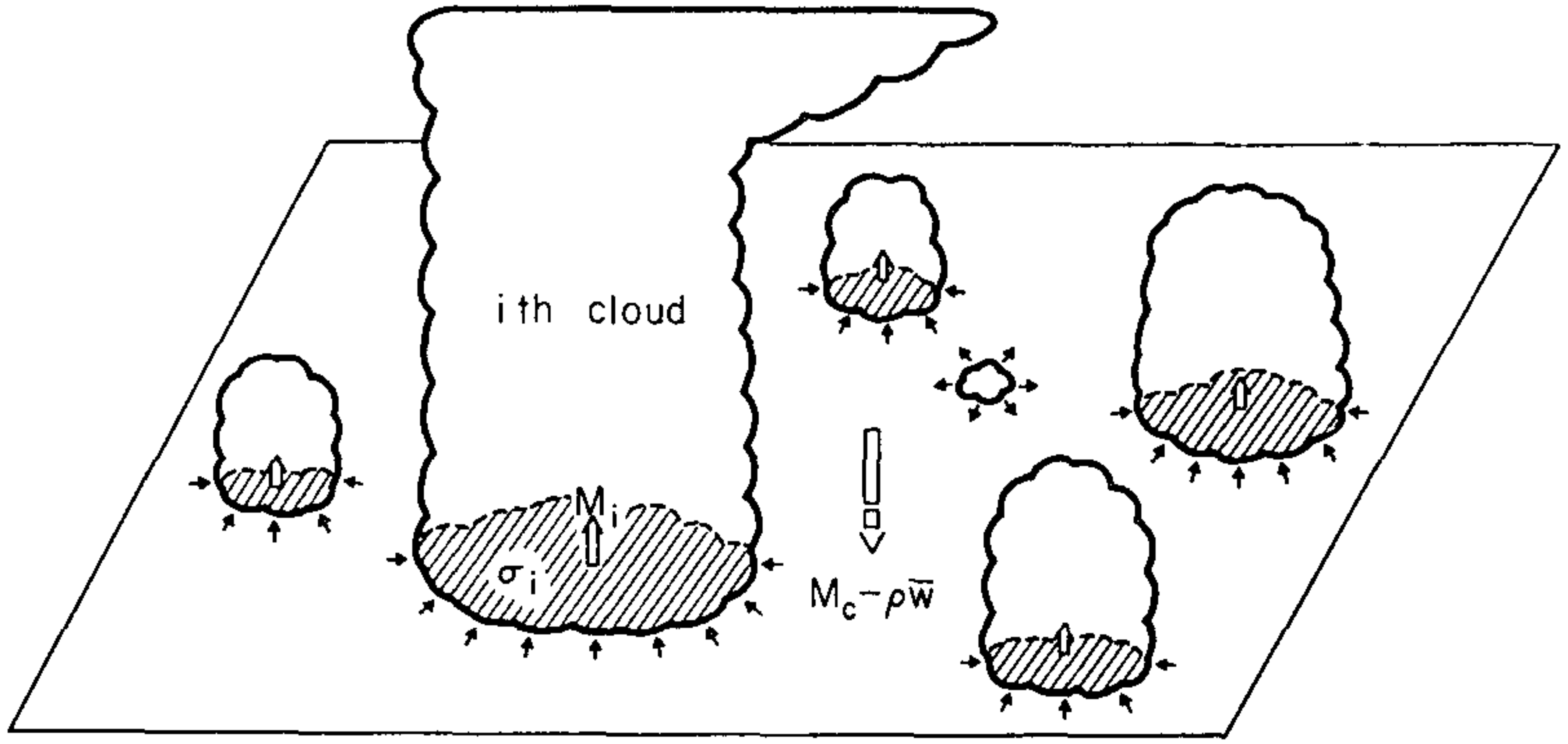


- Two of the many things that they left out:
  - Any real role for stratiform clouds, formed by detrainment or otherwise
  - Downdrafts

They cited a total of 9 papers authored or co-authored by Joanne Simpson.

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."

—Arakawa & Schubert 1974

Reynolds Averaging

It is neither feasible nor desirable to consider in detail all of the small-scale fluctuations that occur in the turbulent boundary layer. For this reason, we ``filter'' or “average'" or “smooth'" the data, and attempt to describe only the resulting *statistics* of the flow. Here we follow the approach of ``Reynolds Averaging,'' which takes its name from Osborne Reynolds, the famous aerodynamicist who invented it in the late 19th century.

Suppose that

$$\frac{\partial}{\partial t}(\rho q) + \nabla \cdot (\rho \mathbf{V} q) = S_q$$

where t is time and S_q is a source of q. The quantity inside the divergence operator is a flux of q due to an advecting mass flux $\rho\mathbf{V}$.

We now *decompose* each of the dependent variables as follows:

$$q = \overline{q} + q', \quad \mathbf{V} = \overline{\mathbf{V}} + \mathbf{V}', \quad S_q = \overline{S_q} + S_q' \ .$$

This is called the “`Reynolds decomposition.” Here an overbar denotes an averaging operator that must be defined defined. Substitution gives

$$\frac{\partial}{\partial t}\left[\rho\left(\overline{q} + q'\right)\right] + \nabla \cdot \left[\rho\left(\overline{q} + q'\right)\left(\overline{\mathbf{V}} + \mathbf{V}'\right)\right] = \overline{S_q} + S_q' \ .$$

Here we have neglected additional terms that arise from variations of the density of the air. We want to *choose* the averaging operator in such a way that the average of this equation reduces to

$$\frac{\partial}{\partial t}(\rho\overline{q}) + \nabla \cdot \left[\rho\left(\overline{q}\,\overline{\mathbf{V}} + \overline{q'\mathbf{V}'}\right)\right] = \overline{S_q} \ .$$

Here the flux divergence term has two parts. The first involves the product of two averages, and the second involves the average of the product of two primes. The quantity $\overline{q'\mathbf{V}'}$ is the flux due to the product of two fluctuations. It can be called the “turbulent flux of q,” assuming that the fluctuations are associated with turbulence. Note, however, that fluctuations can also arise from other things, such as waves.

Some of the Reynolds-averaged equations

$$0 = -\nabla \cdot (\rho \overline{\mathbf{v}}) - \frac{\partial (\rho \overline{w})}{\partial z} \ ,$$

$$\rho \frac{\partial \overline{s}}{\partial t} = -\rho \left(\overline{\mathbf{v}} \cdot \nabla \right) \overline{s} - \rho \overline{w} \frac{\partial \overline{s}}{\partial z} + \overline{Q_R} + \rho L \overline{C} - \frac{\partial F_s}{\partial z} \ ,$$

$$\rho \frac{\partial \overline{q_v}}{\partial t} = -\rho \left(\overline{\mathbf{v}} \cdot \nabla \right) \overline{q_v} - \rho \overline{w} \frac{\partial \overline{q_v}}{\partial z} - \rho \overline{C} - \frac{\partial F_{q_v}}{\partial z} \ ,$$

$$\rho \frac{\partial \overline{l}}{\partial t} = -\rho \left(\overline{\mathbf{v}} \cdot \nabla \right) \overline{l} - \rho \overline{w} \frac{\partial \overline{l}}{\partial z} + \rho \overline{C} - \frac{\partial F_l}{\partial z} - \overline{\chi} \ ,$$

$$\rho \frac{\partial \overline{\mathbf{v}}}{\partial t} = -\rho \left(\overline{\mathbf{v}} \cdot \nabla \right) \overline{\mathbf{v}} - \rho \overline{w} \frac{\partial \overline{\mathbf{v}}}{\partial z} - \nabla \overline{p} - \rho f \mathbf{k} \times \overline{\mathbf{v}} - \frac{\partial \mathbf{F_v}}{\partial z} \ .$$

Here $F_s \equiv \rho \overline{w's'}$, etc.

Mass fluxes I

Reynolds averaging can be written like this

$$\rho\overline{w'h'} = \rho \sum_{j=1}^{J} \left[\sigma_j \left(w_j - \overline{w} \right) \left(h_j - \overline{h} \right) \right] = \sum_{j=1}^{J} \left[M_j \left(h_j - \overline{h} \right) \right] \ ,$$

where

$$M_j \equiv \rho\sigma_j \left(w_j - \overline{w} \right)$$

is a mass flux. This demonstrates that mass fluxes arise purely from Reynolds averaging, and that they involve no approximation for $J \to \infty$. In practice, of course, J must be finite.

Sometimes we also make the approximation

$$M_j \cong \rho\sigma_j w_j \ ,$$

which can be justified when $\overline{w}$ is sufficiently small, which it will be if the grid cell is sufficiently large. The approximate form is expected to fail at high resolution, when $\overline{w}$ can easily be comparable to or even larger than w_j.

We can calculate $\rho\overline{w'h'}$ if the M_j and h_j can be determined somehow.

Mass fluxes II

In principle we could define a mass flux for each square millimeter of a grid cell. This is not a good idea because so much detail is (presumably) unnecessary, and because it would be very impractical to deal with such a large number of mass fluxes. *We need a way to reduce the number of mass fluxes to a manageable value, without losing too much accuracy.*

Suppose that we have a very detailed numerical simulation of the convective turbulence inside a grid cell, and we want to use the *statistics* of the simulation to compute values of σ_j, w_j, and h_j that can be used to obtain an accurate value of $\rho\overline{w'h'}$.

There are at least three ways to do this.

Plumes

Historically, plume models have been used to calculate the h_j, and “mass-flux closures” have been used to determine the M_j. As a result, there is a tendency to associate the mass-flux method with plume models.

Budget for a small patch

$$\frac{\partial}{\partial t}(\rho h) = -\nabla \cdot \left[\rho \mathbf{v} h + \left(\mathbf{F}_h\right)_H\right] - \frac{\partial}{\partial z}\left[\rho w h + \left(F_h\right)_z\right] + \rho S_h$$

Integrate over an area A_j to obtain

$$\frac{\partial}{\partial t}\left(\rho_j h_j A_j\right) = -\oint_C \left[\rho \mathbf{v}_n h + \left(\mathbf{F}_h\right)_n\right] dl - \frac{\partial}{\partial z}\left\{A_j\left(\rho w h\right)_j + A_j\left[\left(F_h\right)_z\right]_j\right\} + \rho_j A_j \left(S_h\right)_j$$

For $h \equiv 1, F_h = 0,$ and $S_h = 0$ this reduces to the continuity equation in the form

$$\frac{\partial}{\partial t}\left(\rho A_j\right) = -\oint_C \rho \mathbf{v}_n \, dl - \frac{\partial}{\partial z}\left[A_j\left(\rho w\right)_j\right]$$

The area A_j is chosen so that the air within it has quasi-uniform properties.

The sum of all the A_j is assumed to fill the grid cell.

Each A_j may consist of multiple disconnected parts.

A simple cumulus cloud model

To go further, we need to know the soundings inside the updrafts. For this purpose, a simple cumulus cloud model is required. We assume that all cumulus clouds originate from the top of the boundary layer, carrying the mixed-layer properties upward. The mass flux changes with height according to

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

Here E is the entrainment rate, and D is the detrainment rate. The in-cloud profile of moist static energy, $h_c(z)$, is governed by

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

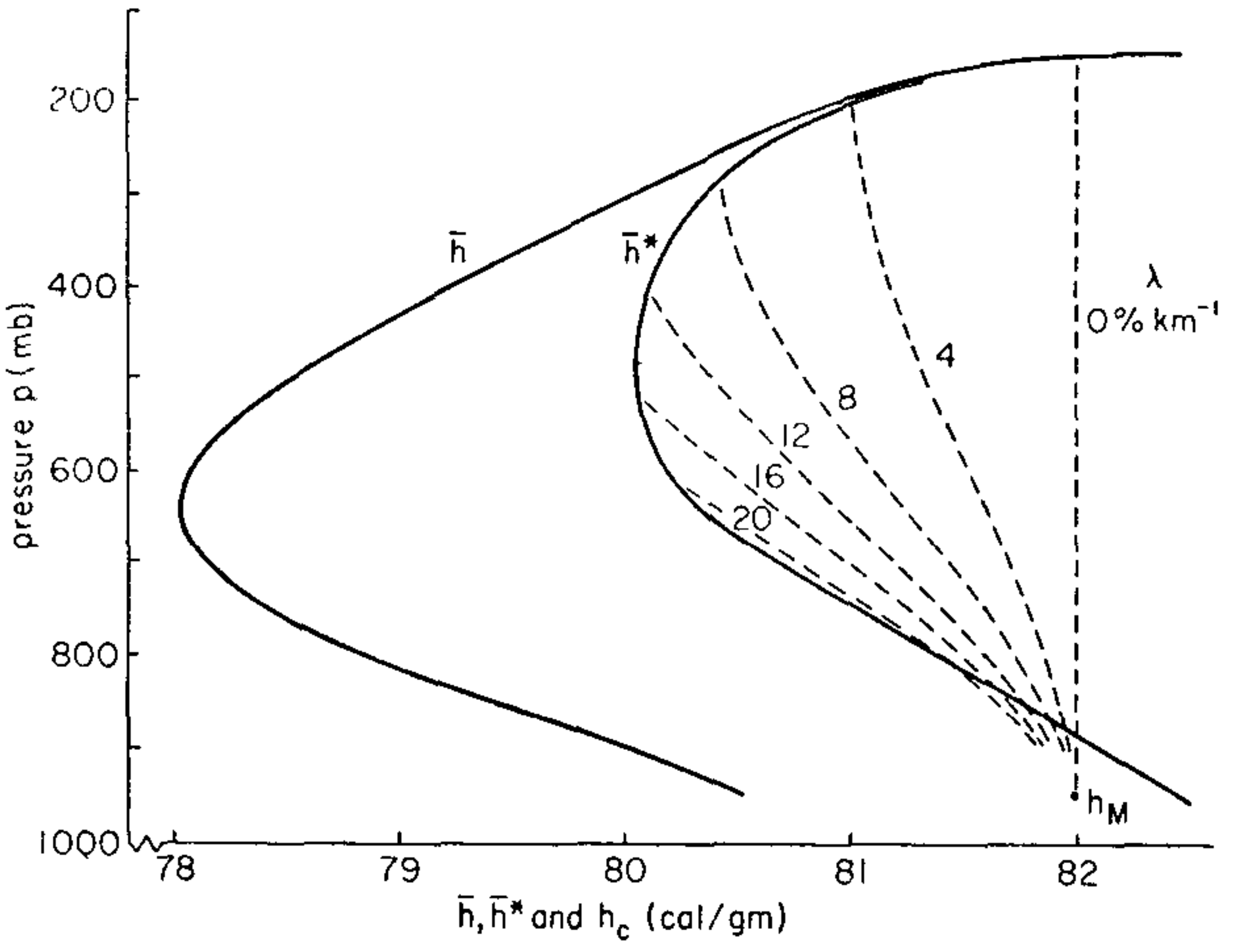
There are no source or sink terms in this equation because the moist static energy is unaffected by phase changes and/or precipitation processes, and we neglect radiative effects.

By combining the two equations above, we can show that

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

Note that h_c is affected by entrainment, which dilutes the cloud with environmental air, but not by detrainment, which expels the cloud's own moist static energy at each level.

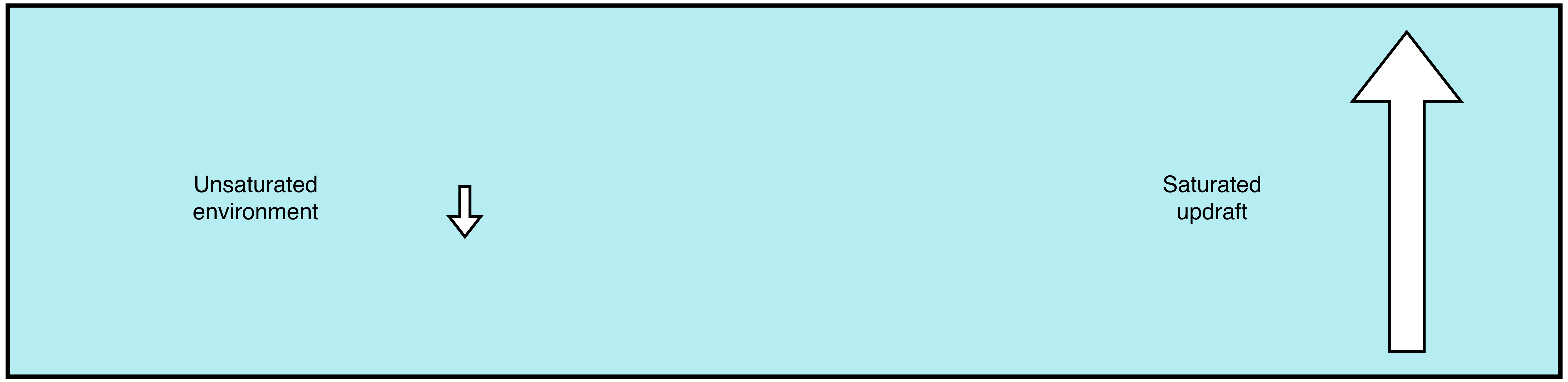
Entrainment reduces buoyancy



The cloud top is usually assumed to be the level of neutral buoyancy.

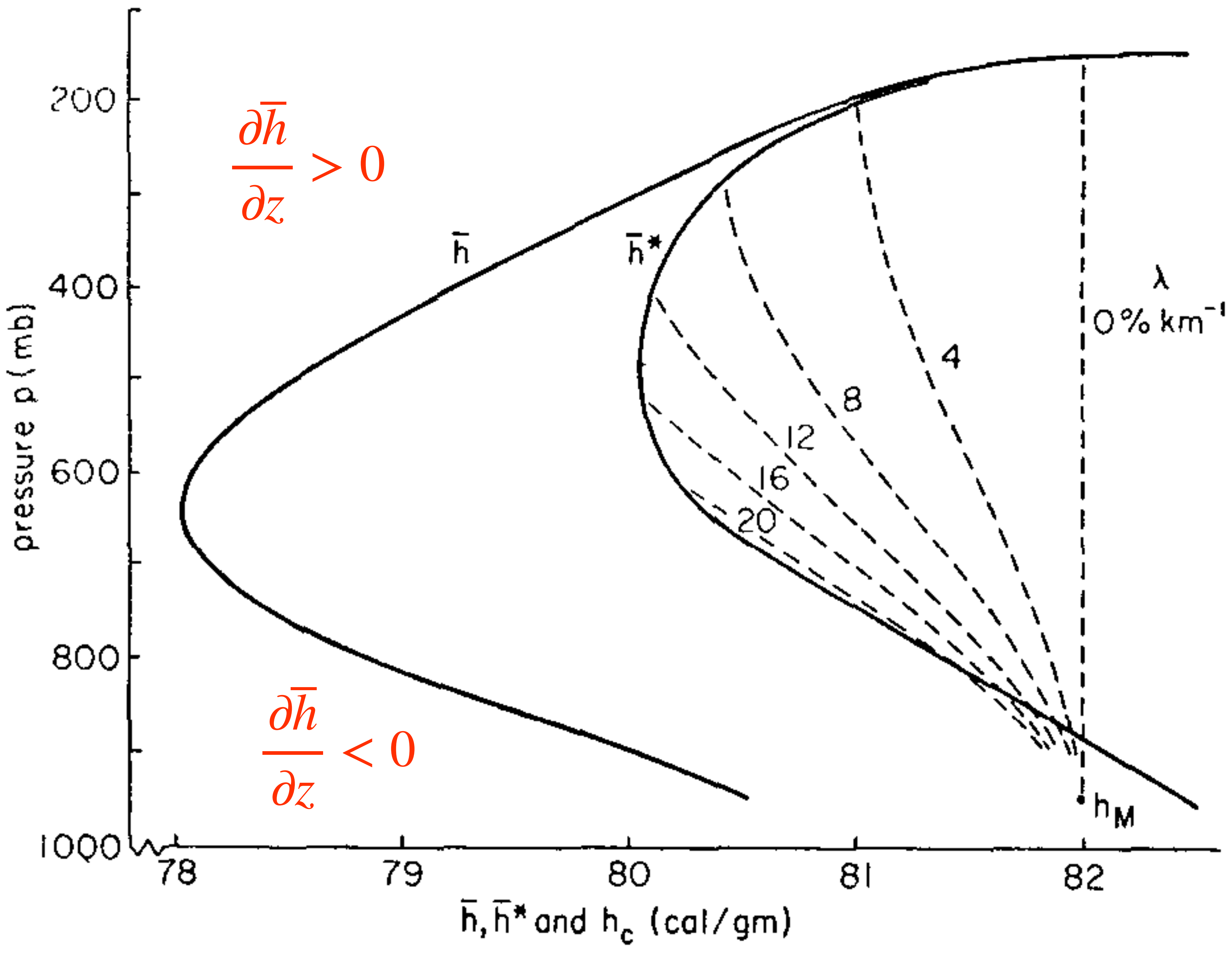
The small σ limit

It is observed that convective updrafts occupy only a small fraction (~1%) of a “large-scale” area, so that $\sigma_j \ll 1$ for all updrafts. The reasons for this are well understood.



Also, when $\sigma_j \ll 1$ for all updrafts, it makes sense to define an “environment” in which $h \cong \overline{h}$.

Up-Gradient Fluxes



Here the dashed lines show in-cloud soundings h_i with different entrainment rates.

$$\rho \overline{w'h'} = \rho \sum_{i=1}^{N} \left[\sigma_i \left(w_i - \overline{w} \right) \left(h_i - \overline{h} \right) \right]$$

In this example, fluxes are down-gradient in the lower troposphere and up-gradient in the upper troposphere.

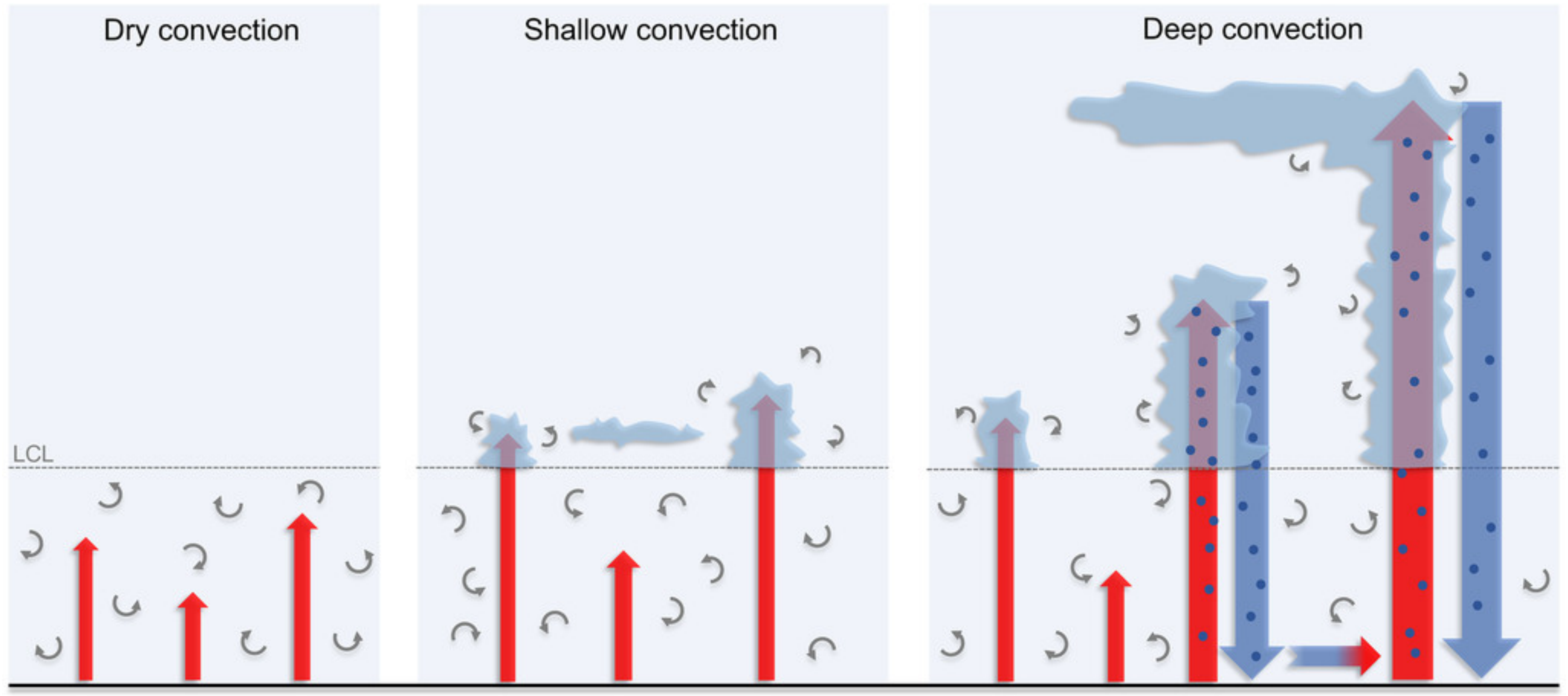
Down-gradient fluxes are expected when the eddy's depth is shallow compared to the depth over which $\partial \overline{h} / \partial z$ changes sign.

Deeper, "penetrative" eddies can produce up-gradient fluxes.

Conclusion: Up-gradient fluxes are not "mysterious."

Plumes can be generalized using the EDMF (Eddy-Diffusivity Mass-Flux) approach.

$$\rho \overline{w'h'} = \rho \sum_{i=1}^{N} \left[\sigma_i \left(w_i - \overline{w} \right) \left(h_i - \overline{h} \right) \right] - K \frac{\partial \overline{h}}{\partial z}$$

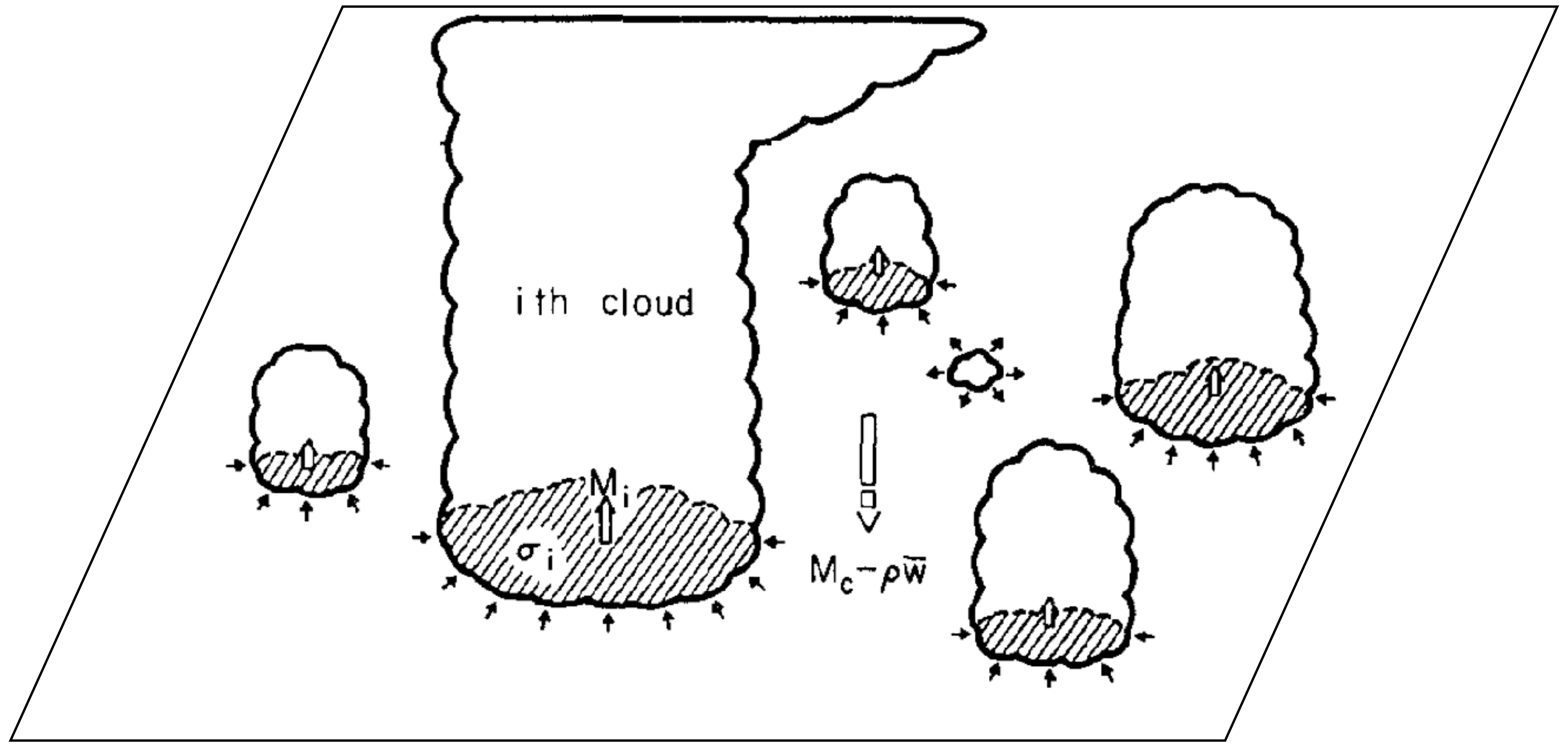


Here the mass-flux term represents the flux produced by the deep, "penetrative" eddies, and the eddy-diffusion represents the shallow "turbulent" eddies.

Siebesma, A.P., P.M.M. Soares, and J. Teixeira, 2007: A Combined Eddy-Diffusivity Mass-Flux Approach for the Convective Boundary Layer. *J. Atmos. Sci.*, 64, 1230-1248.

Suselj, K., Kurowski, M. J., & Teixeira, J. (2019). A Unified Eddy-Diffusivity/Mass-Flux Approach for Modeling Atmospheric Convection, *J. Atmos. Sci.*,, 76(8), 2505-2537.

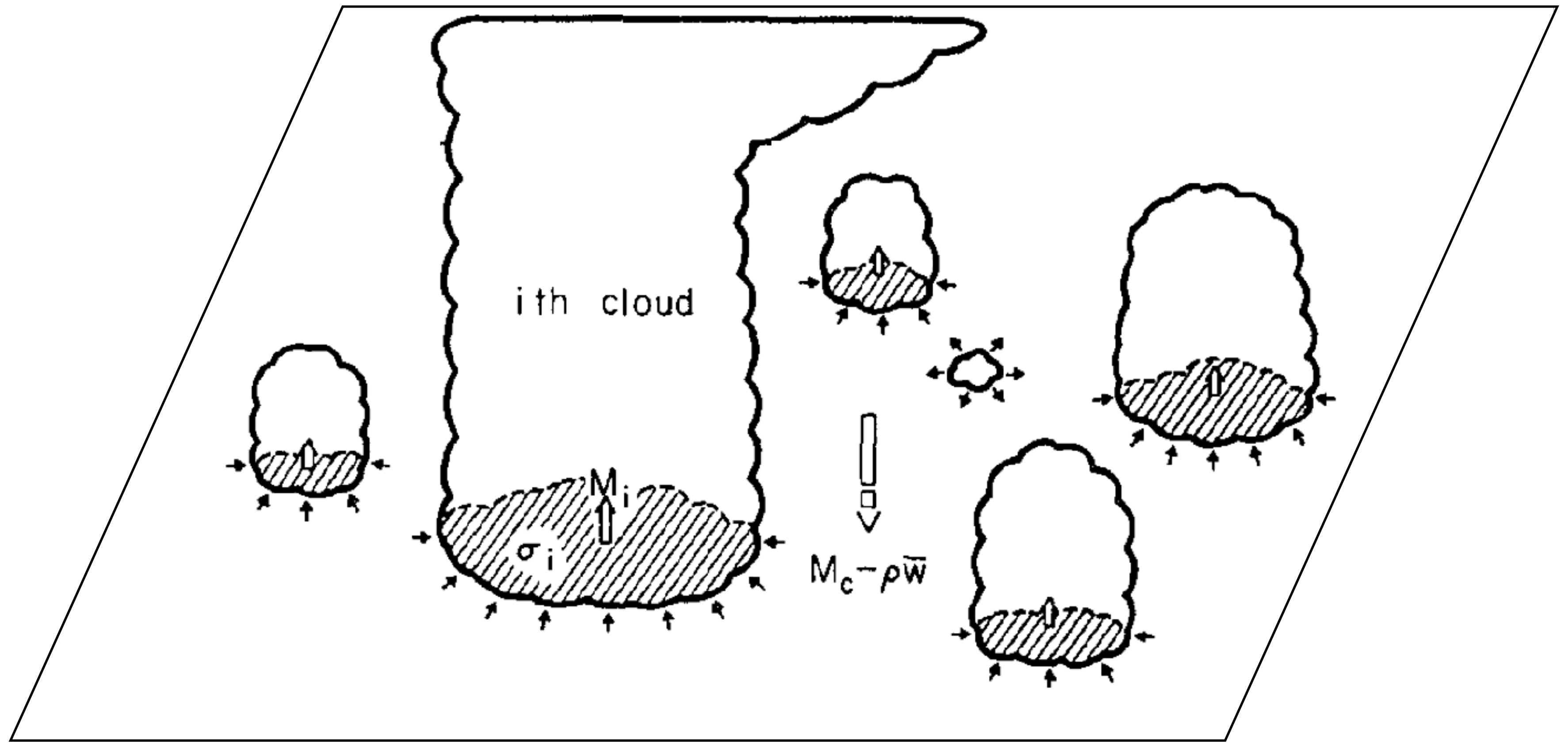
Plumes are idealizations.



Updrafts
Downdrafts
Environment

The real sky is not this tidy.

Plumes are idealizations.



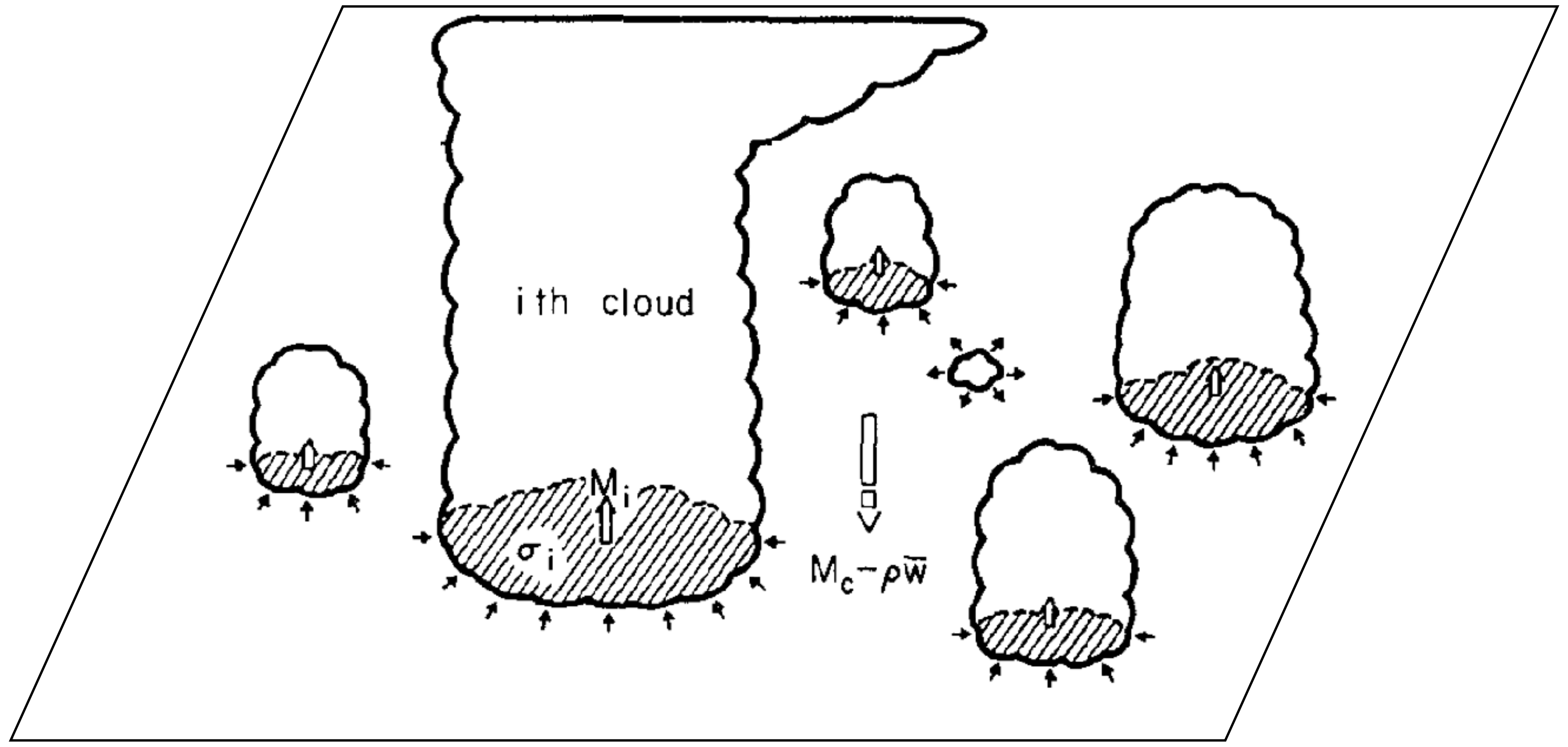
Updrafts
Downdrafts
Environment

The real sky is not this tidy.

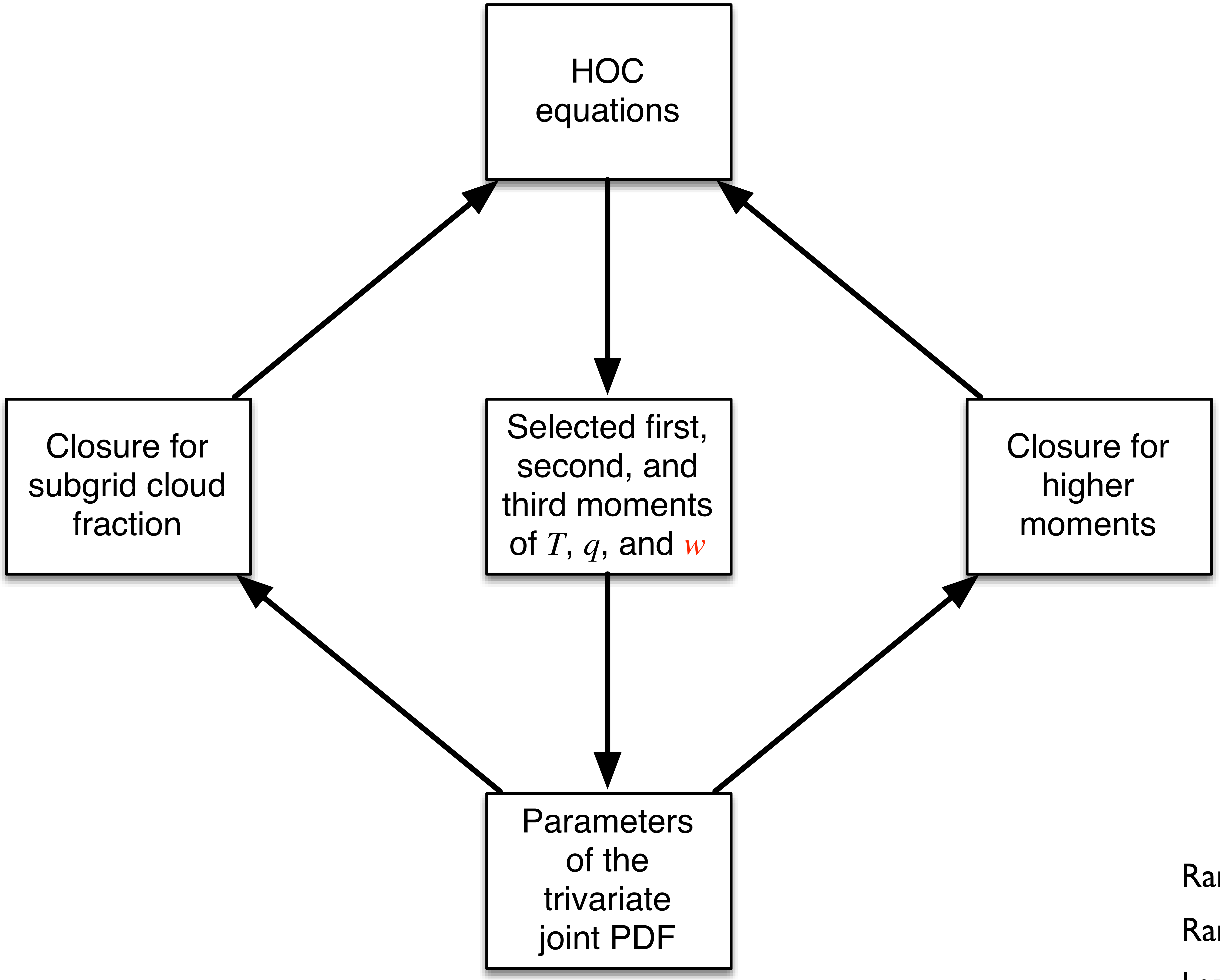
Chess pieces on a board with pre-assigned roles

Plumes are not very flexible.

- Built-in vertical structures
- Assumed cloud-base levels
- No time-dependence



A second way: HOC



Randall JAS 1987

Randall, Shao, and Moeng, JAS 1992

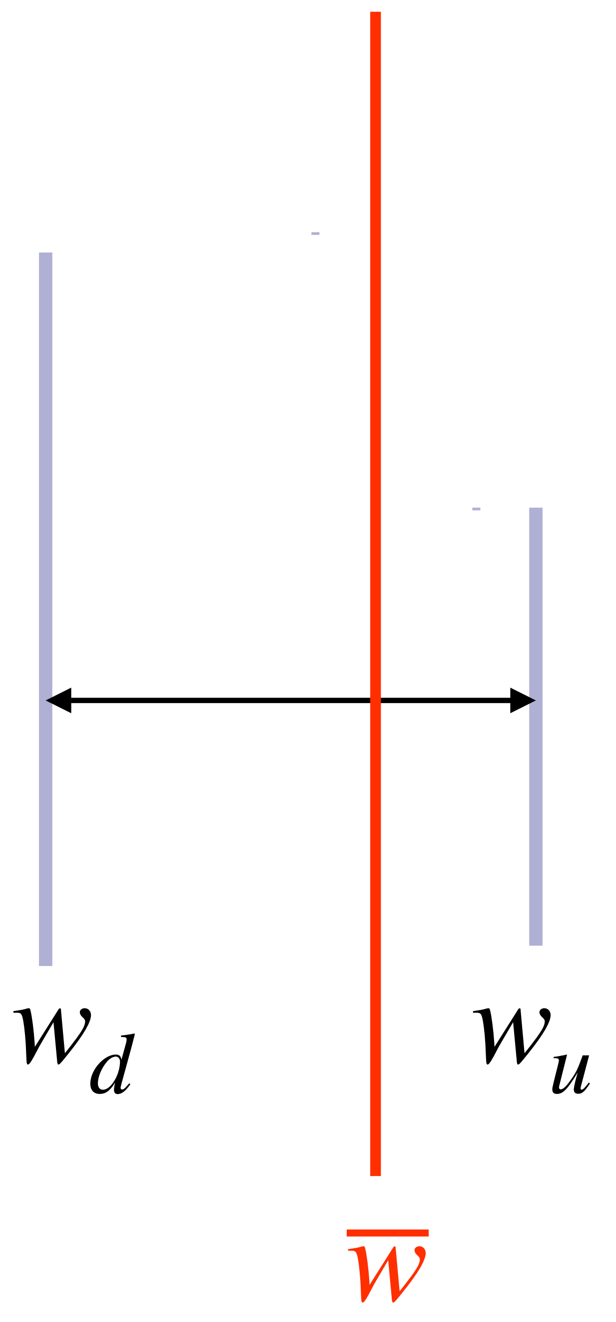
Lappen and Randall, JAS 2001

Simple case of two delta functions

Mean (first moment):
$\overline{w} = \sigma w_u + (1 - \sigma)\, w_d$

Variance (second moment about the mean):
$\overline{w'^2} = \sigma (1 - \sigma)\, (\delta w)^2$ where $\delta w \equiv w_u - w_d$

Mass flux:
$M_c = \sigma (1 - \sigma)\, \delta w$



Two delta functions

Mass flux for the case of two delta functions

Means: $\overline{h} = \sigma h_u + (1-\sigma)\, h_d$ and $\overline{w} = \sigma w_u + (1-\sigma)\, w_d$

Flux of h: $\rho\overline{w'h'} = \rho\left[\sigma\left(w_u - \overline{w}\right)\left(h_u - \overline{h}\right) + (1-\sigma)\left(w_d - \overline{w}\right)\left(h_d - \overline{h}\right)\right]$

But $h_u - \overline{h} = (1-\sigma)\left(h_u - h_d\right)$ and $h_d - \overline{h} = -\,\sigma\left(h_u - h_d\right)$,

so $\rho\overline{w'h'} = \rho\left[\sigma(1-\sigma)^2\left(w_u - w_d\right)\left(h_u - h_d\right) + \sigma^2(1-\sigma)\left(w_u - w_d\right)\left(h_u - h_d\right)\right]$,

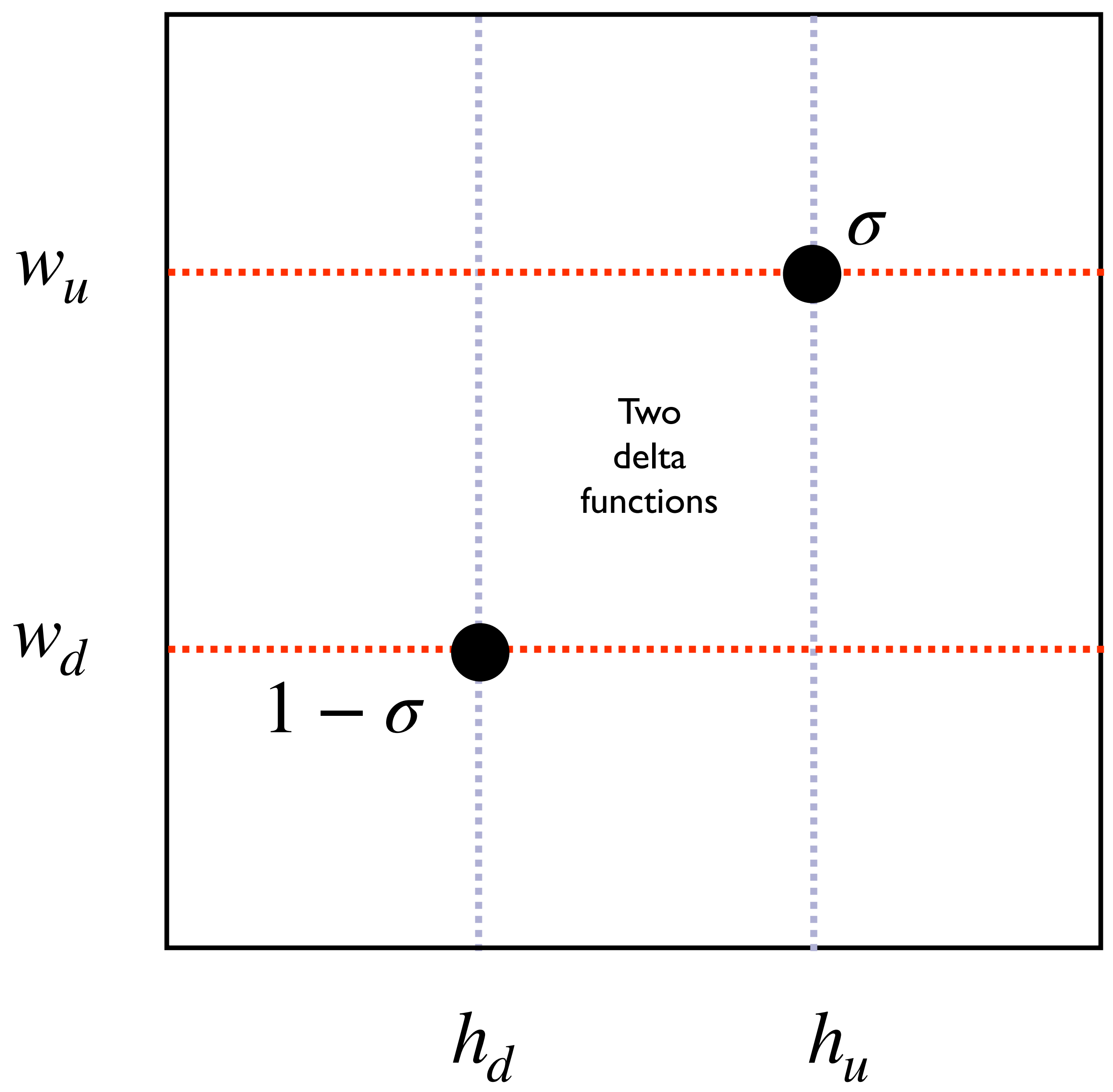
which simplifies to

$$\rho\overline{w'h'} = \rho\sigma(1-\sigma)\left(w_u - w_d\right)\left(h_u - h_d\right).$$

The flux of *any* h is proportional to

$$M \equiv \rho\sigma(1-\sigma)\left(w_u - w_d\right),$$

which is called the "mass flux." The mass flux goes to zero if $\sigma \to 0$ or $\sigma \to 1$. Why?



How to solve

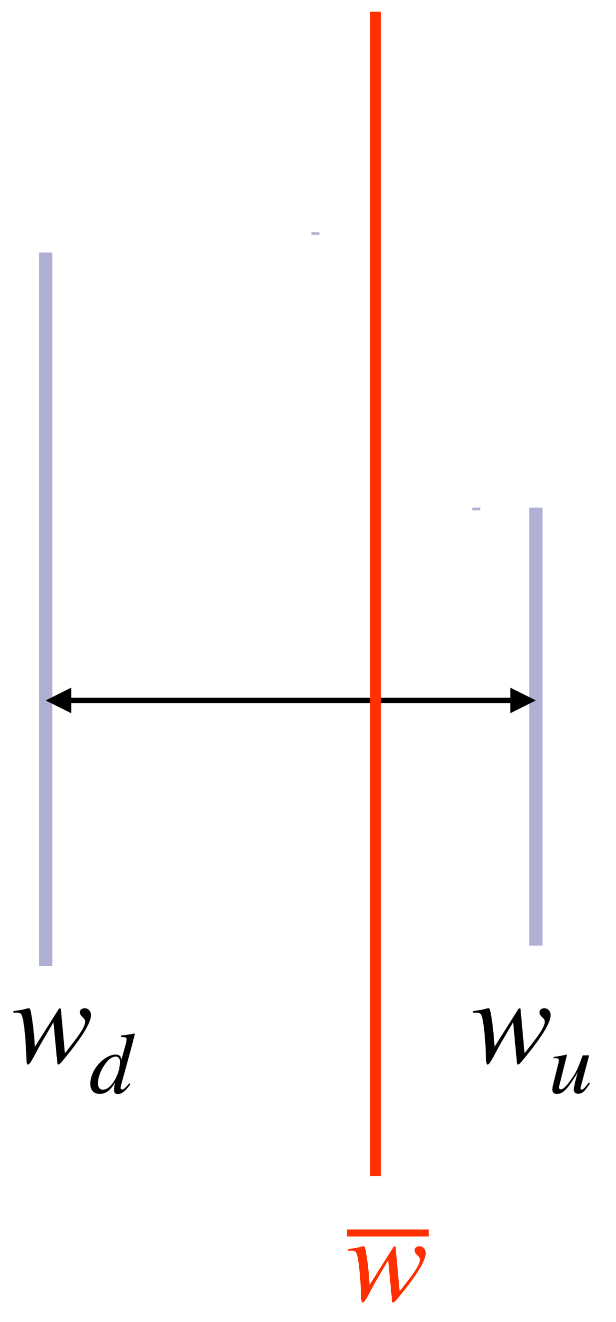
$$\delta w = \pm \sqrt{\frac{\overline{w'^2}}{\sigma(1-\sigma)}}$$

$$\overline{w'^3} = \sigma(1-\sigma)(1-2\sigma)\left[\frac{\overline{w'^2}}{\sigma(1-\sigma)}\right]^{3/2}$$

Skewness $S_w \equiv \frac{\overline{w'^3}}{\left(\overline{w'^2}\right)^{3/2}} = \frac{1-2\sigma}{\sqrt{\sigma(1-\sigma)}}$

$$\sigma = \frac{1}{2}\left(1 \pm \frac{S_w}{\sqrt{4+S_w^2}}\right)$$

$$\delta w = \mp \sqrt{\overline{w'^2}\left(4+S_w^2\right)}$$



If we know $\overline{w'^2}$ and $\overline{w'^3}$, we can calculate σ and δw.

From σ, δw, and $\overline{w}$, we can calculate w_u and w_d.

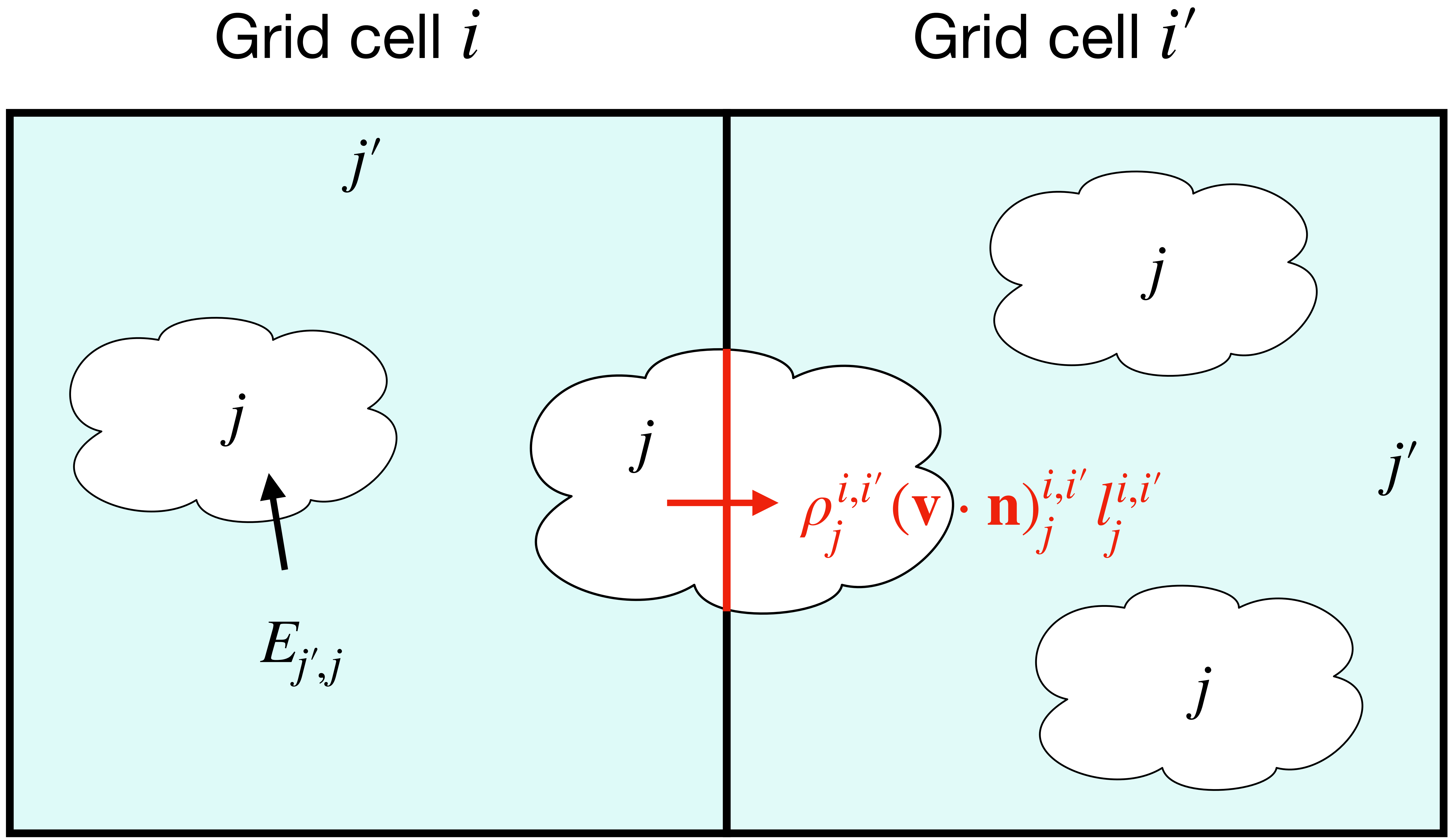
In this way, the predicted moments determine the distribution.

A third way: The multi-fluid model

$$\frac{\partial}{\partial t}\left(\rho_j h_j^i A_j\right) = -\oint_C \left[\rho \mathbf{v}_n h + \left(\mathbf{F}_h\right)_n\right] dl - \frac{\partial}{\partial z}\left\{A_j\left(\rho w h\right)_j + A_j\left[\left(F_h\right)_z\right]_j\right\} + \rho_j A_j \left(S_h\right)_j$$

$$\frac{\partial}{\partial t}\left(\rho A_j\right) = -\oint_C \rho \mathbf{v}_n \, dl - \frac{\partial}{\partial z}\left[A_j\left(\rho w\right)_j\right]$$

Inter-cell and intra-cell mass fluxes



$$E^i_{j',j} = -\,E^i_{j,j'}$$

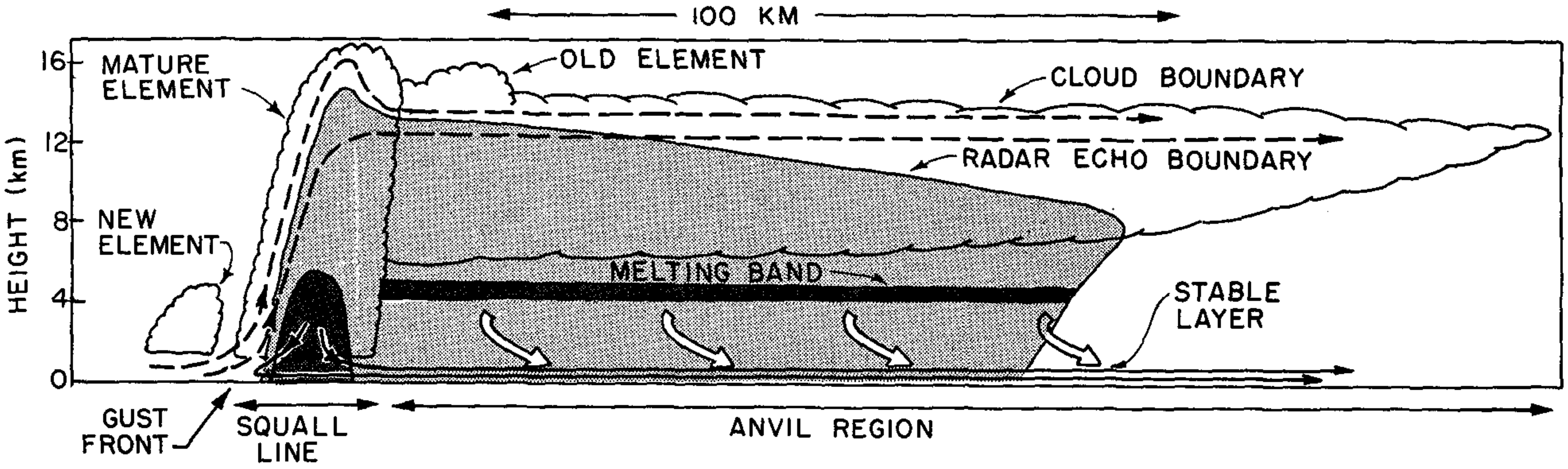


Fig. 2. Schematic cross section through squall-line system. Streamlines show flow relative to the squall line. Dashed streamlines show updraft circulation, thin solid streamlines show convective-scale downdraft circulation associated with mature squall-line element, and wide arrows show mesoscale downdraft below the base of the anvil cloud. Dark shading shows strong radar echo in the melting band and in the heavy precipitation zone of the mature squall-line element. Light shading shows weaker radar echoes. Scalloped line indicates visible cloud boundaries.

Stratiform clouds matter,
and not just for radiation.

The Role of Convective-Scale Precipitation Downdrafts in Cumulus and Synoptic-Scale Interactions

RICHARD H. JOHNSON[1]

National Hurricane and Experimental Meteorology Laboratory, NOAA, Coral Gables, Fla. 33124

(Manuscript received 9 February 1976, in revised form 16 June 1976)

Fifty years later, downdrafts still present many issues.

A Scheme for Representing Cumulus Convection in Large-Scale Models

KERRY A. EMANUEL

Center for Meteorology and Physical Oceanography, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Manuscript received 11 April 1990, in final form 10 April 1991)

“The equilibrium water vapor content of the environment depends sensitively on the processes that determine the amount of cloud water remaining in detraining air.”

Q. J. R. Meteorol. Soc. (2001), **127**, pp. 53–72

Estimation of entrainment rate in simple models of convective clouds

By DAVID GREGORY*
European Centre for Medium-Range Weather Forecasts, UK

(Received 17 March 2000; revised 26 July 2000)

Cumulus clouds are turbulent.

Entrainment is a turbulent process.
Its importance was recognized already by Henry Stommel (1947).

Constraints on Cumulus Parameterization from Simulations of Observed MJO Events

ANTHONY D. DEL GENIO

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JINGBO WU, AUDREY B. WOLF, AND YONGHUA CHEN

Department of Applied Physics and Applied Mathematics, Columbia University, New York, New York

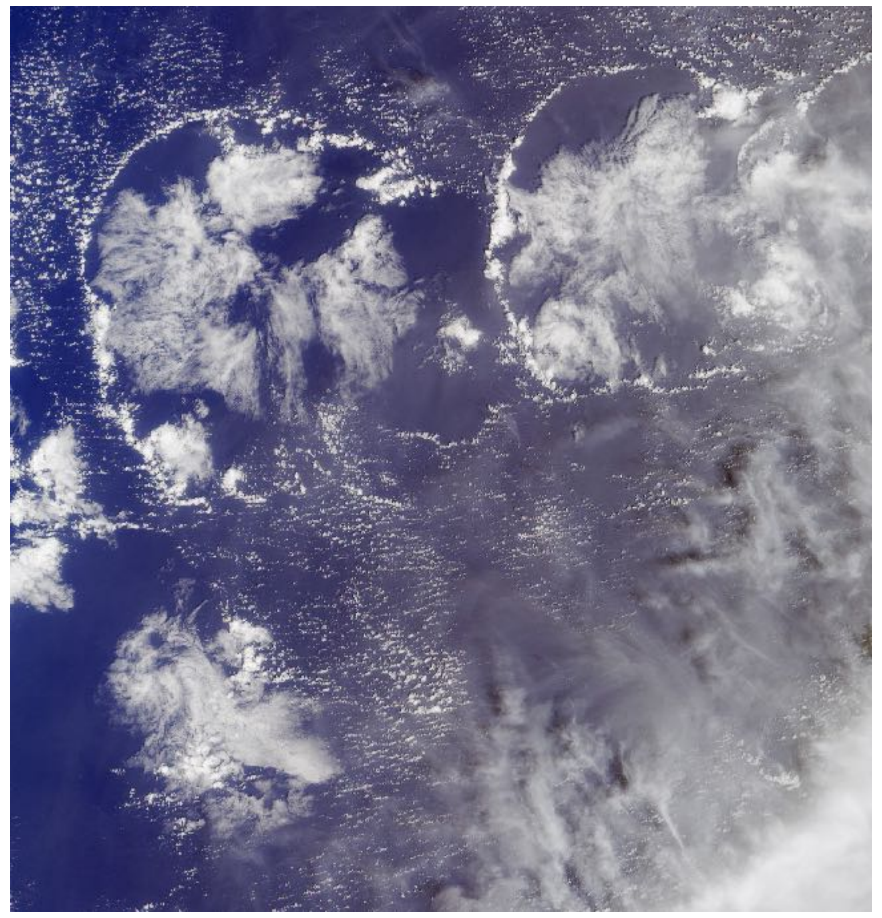
MAO-SUNG YAO

Trinnovim LLC, Institute for Space Studies, New York, New York

DAEHYUN KIM

Department of Atmospheric Sciences, University of Washington, Seattle, Washington

(Manuscript received 6 December 2014, in final form 15 April 2015)



Cold pools

Convective momentum transport

664 MONTHLY WEATHER REVIEW VOLUME 115

The Consistent Parameterization of the Effects of Cumulus Clouds on the Large-Scale Momentum and Vorticity Fields

STEVEN K. ESBENSEN
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LLOYD J. SHAPIRO
Hurricane Research Division, AOML/NOAA, Miami, FL 33149

EDWARD I. TOLLERUD
Weather Research Program, ERL/NOAA, Boulder, CO 80303

(Manuscript received 31 July 1986, in final form 18 September 1986)

Q. J. R. Meteorol. Soc. (1992), **118**, pp. 819–850 551.515.41

Organized convective systems: Archetypal dynamical models, mass and momentum flux theory, and parametrization

By MITCHELL W. MONCRIEFF
National Center for Atmospheric Research, Boulder, Colorado 80307–3000, U.S.A.*

(Received 17 April 1991; revised 20 May 1992)

What determines the convective mass flux?

Closures

A "closure" determines the intensity of the convection.

Quasi-Equilibrium Closure

"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

Sources and sinks of buoyancy

Let $A = A\left(T, q, \lambda\right)$ be a generalized measure of the CAPE.

Then $\left(\dfrac{\partial A}{\partial t}\right)_{\lambda} = \dfrac{\partial A}{\partial T}\dfrac{\partial T}{\partial t} + \dfrac{\partial A}{\partial q}\dfrac{\partial q}{\partial t}$

Substitute for circled quantities

$$\left(\frac{\partial A}{\partial t}\right)_{\lambda} = \int_0^{\lambda_{max}} K(\lambda, \lambda') M_c(\lambda') \, d\lambda' + F(\lambda)$$

Convective terms
(Response)

Non-convective terms
(Forcing)

From Wayne's dissertation

$$\frac{\partial A(\lambda)}{\partial t} = a(z_B,\lambda)\,\rho_B\,\frac{\partial s_{vM}}{\partial t} + b(z_B,\lambda)\,\rho_B\,\frac{\partial h_M}{\partial t} + c(z_B,\lambda)\,\rho_B\,\frac{\partial h_M}{\partial t}$$

$$-\rho_B\,\frac{\partial z_B}{\partial t}\Bigg\{-\alpha(z_B)\Delta s_v - d(z_B,\lambda)L\left(\frac{\partial \ell(z,\lambda)}{\partial z}\right)_{z=z_B}$$

$$+\lambda\left[\frac{A(\lambda)}{\rho_B} + a(z_B,\lambda)\Delta s_v + b(z_B,\lambda)\Delta h + c(z_B,\lambda)\Delta h\right]\Bigg\}$$

$$+\int_{z_B}^{z_D(\lambda)} \eta(z,\lambda)\left\{-\alpha(z)\frac{\partial \bar{s}_v(z)}{\partial t} + \lambda\left[a(z,\lambda)\frac{\partial \bar{s}_v(z)}{\partial t} + b(z,\lambda)\frac{\partial \bar{h}(z)}{\partial t}\right]\right\}\rho(z)\,dz$$

$$+\int_{z_B}^{z_D(\lambda)} \eta(z,\lambda)\left\{\lambda\left[c(z,\lambda)\frac{\partial \bar{h}(z)}{\partial t} + d(z,\lambda)\frac{1}{1+\gamma(z)}\frac{\partial}{\partial t}\left(\bar{h}^*(z)-\bar{h}(z)\right)\right]\right\}\rho(z)\,dz$$

The quasi-equilibrium approximation

Drop the time-rate-of-change term:

$$0 \cong \int_0^{\lambda_{max}} K(\lambda, \lambda') M_c(\lambda') \; d\lambda' + F(\lambda)$$

Solve for $M_c(\lambda)$.

$$R + F \cong 0$$

In order for this approach to work, we have other be able to separate the convective response from the non-convective forcing.

A more basic issue:

A more basic issue:

Can we really separate the forcing from the response?

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- Surface fluxes are influenced by deep convection.

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- Surface fluxes are influenced by deep convection.
- Stratiform precipitation is influenced by deep convection.
- Radiatively active stratiform clouds are influenced by deep convection.

Randall and Pan (1993, p. 143):

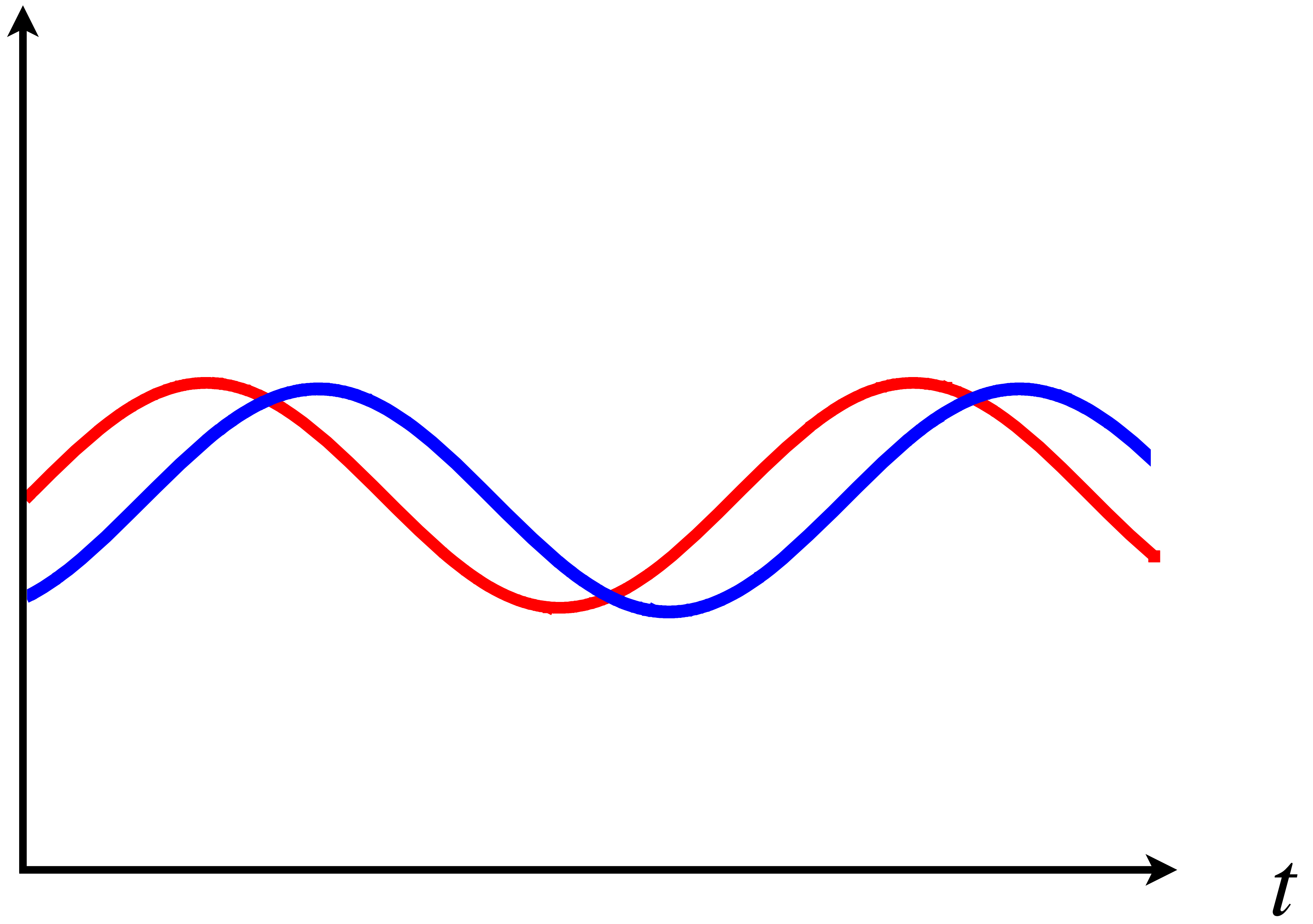
"… it is not always clear which processes are convective and which are not."

Randall, D. A., and D.-M. Pan, 1993: Implementation of the Arakawa-Schubert cumulus parameterization with a prognostic closure. In *The Representation of Cumulus Convection in Numerical Models,* a Meteorological Monograph published by the American Meteorological Society, K. Emanuel and D. Raymond, Eds., pp. 137-144.


Forcing
Response
VILLANOVA
5
UCONN
13

Delayed response

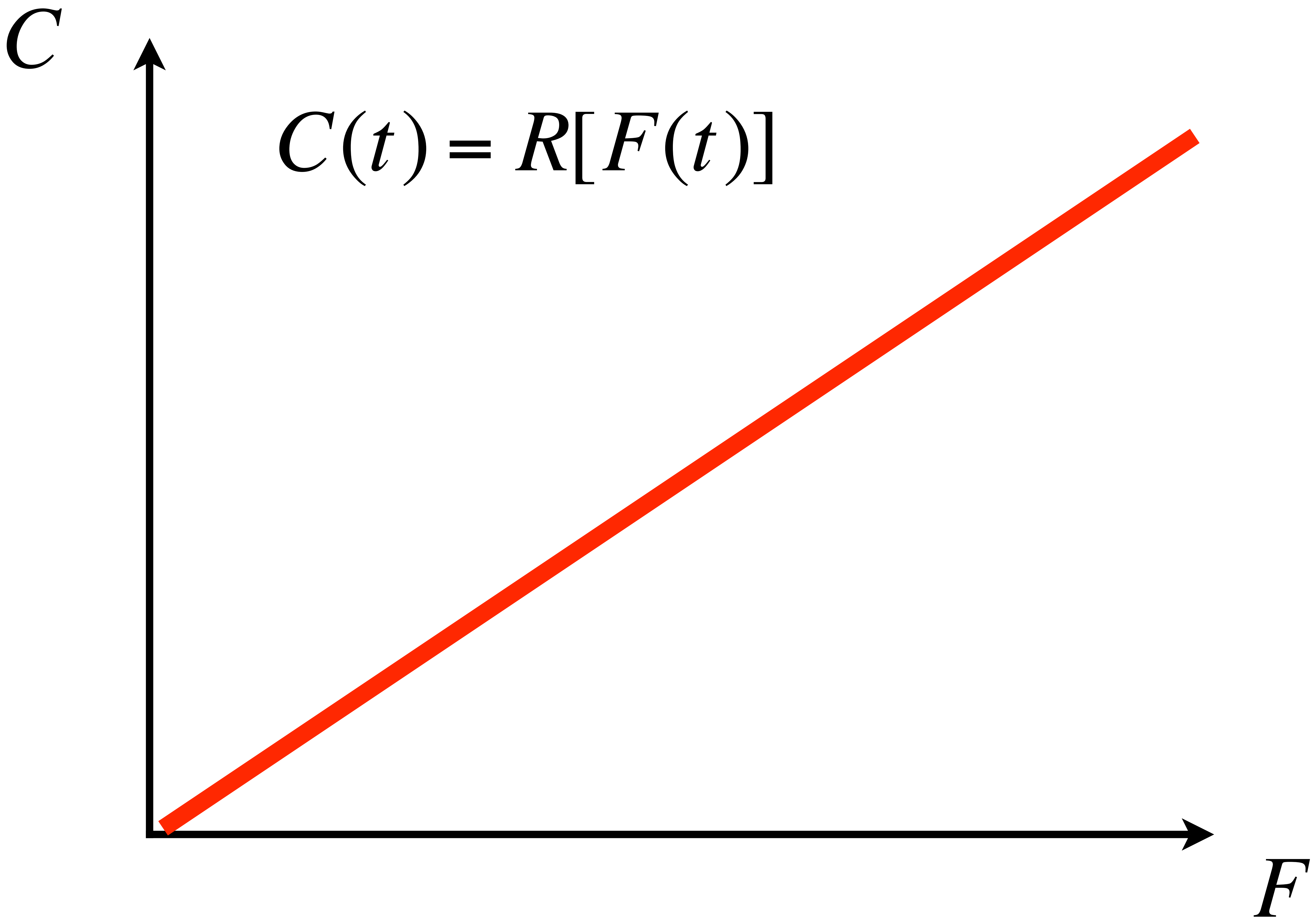
$C(t) = R[F(t - \tau)]$



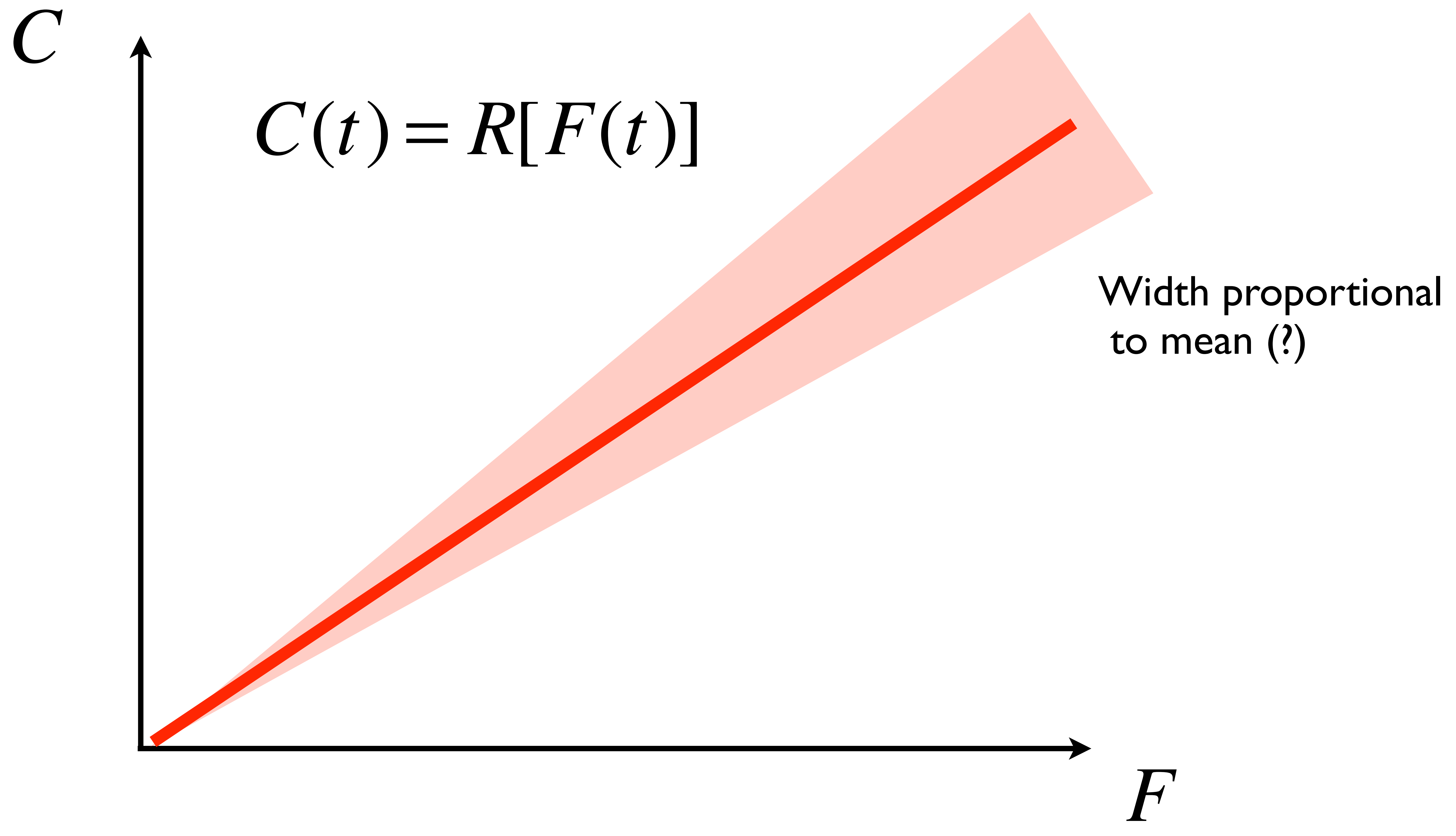
C can't keep up with F.

With rapidly changing conditions, equilibrium is not approximated (even with a large sample size), but the convection can still be deterministic.

Deterministic parmeterization



Stochasticity



With a small sample size but slowly changing conditions, we get non-deterministic, non-equilibrium behavior.

Stochastic closure

Q. J. R. Meteorol. Soc. (1999), **125**, pp. 2887–2908

Stochastic representation of model uncertainties in the ECMWF Ensemble Prediction System

By R. BUIZZA*, M. MILLER and T. N. PALMER
European Centre for Medium-Range Weather Forecasts, UK

(Received 18 August 1998; revised 19 March 1999)

Roberto
Buizza

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Roberto
Buizza

Robert
Plant

George
Craig

Judith
Berner

Prognostic closure

$$\left(\frac{\partial A}{\partial t}\right)_{\lambda} = \int_0^{\lambda_{max}} K(\lambda, \lambda')\, M_c(\lambda')\ d\lambda' + F(\lambda)$$

Example #1 of a prognostic closure: Prognostic CKE

$$\frac{\partial K}{\partial t} = B - \frac{K}{\tau_{dis}}$$

Predict the vertically integrated cumulus kinetic energy (CKE) for each cloud type.

$$B = \left(M_c\right)_B A$$

Here $\left(M_c\right)_B$ is the cloud base convective mass flux, and A is the CAPE.

$$K = \alpha \left(M_c\right)_B^2$$

A closure assumption that relates K to $\left(M_c\right)_B$

$$2\alpha \left(M_c\right)_B \frac{\partial}{\partial t} \left(M_c\right)_B = \left(M_c\right)_B A - \frac{\alpha \left(M_c\right)_B^2}{\tau_{dis}}$$

Substitution gives this.

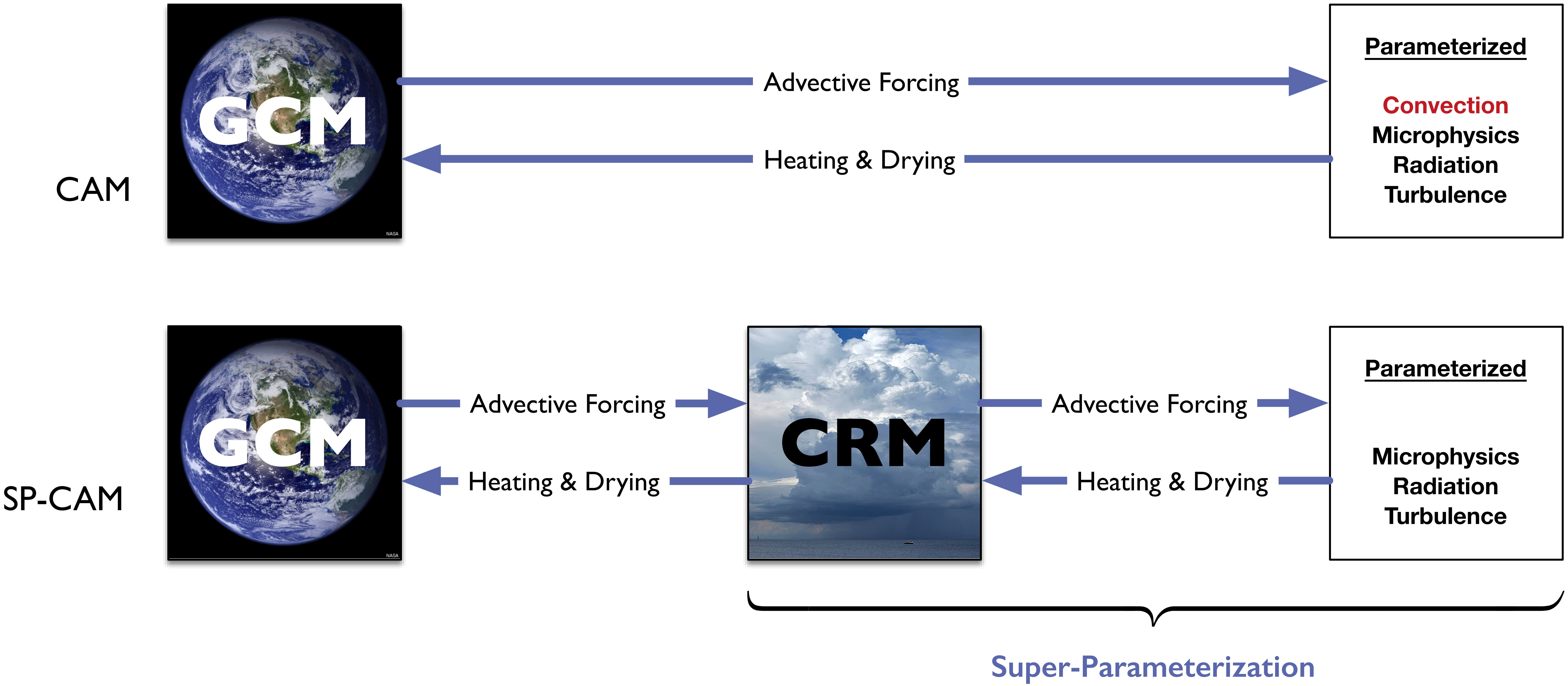
$$\frac{\partial}{\partial t} \left(M_c\right)_B = \frac{A}{2\alpha} - \frac{\left(M_c\right)_B}{2\tau_{dis}}$$

Simplification gives this.

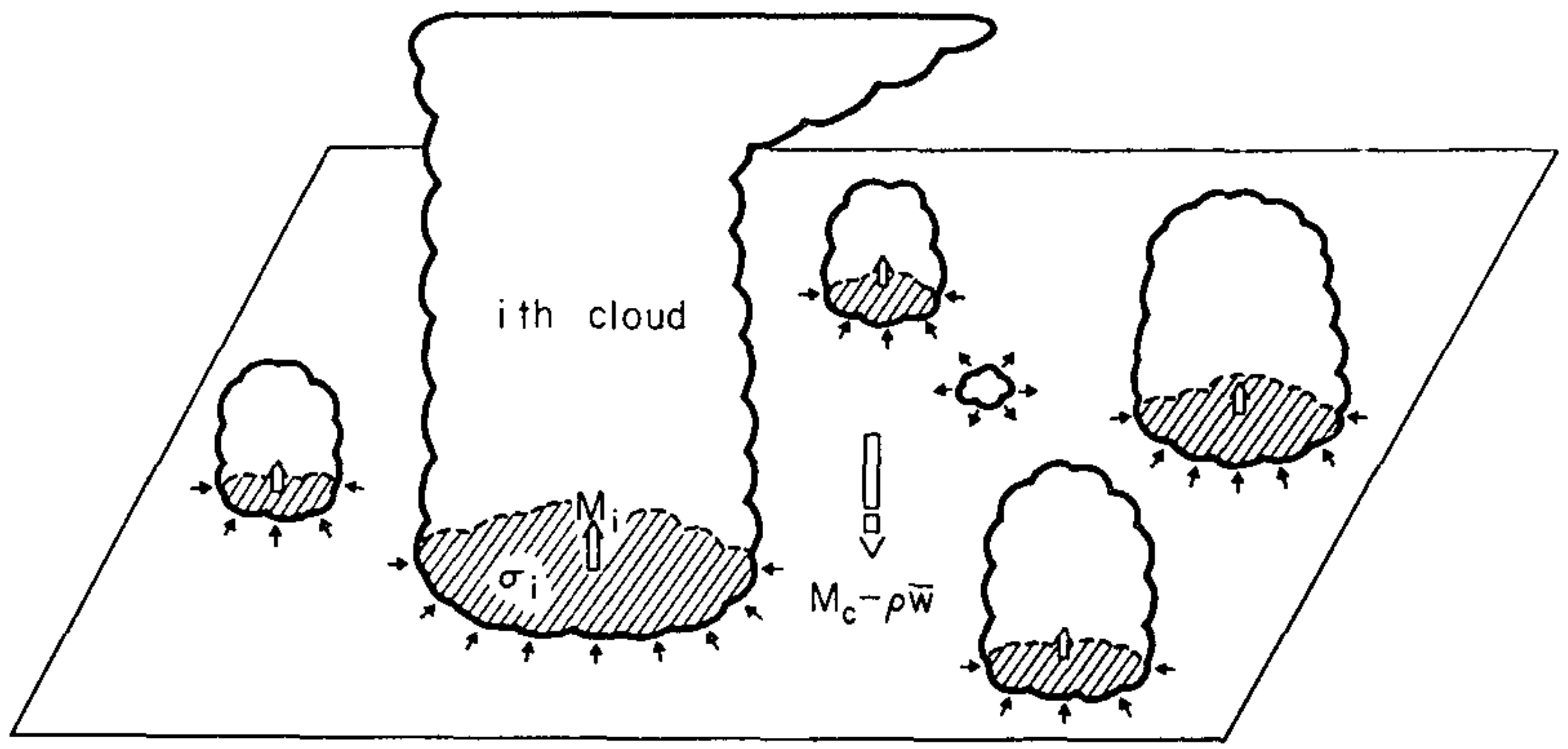
$$\left(M_c\right)_B = A\tau_{dis}/\alpha$$

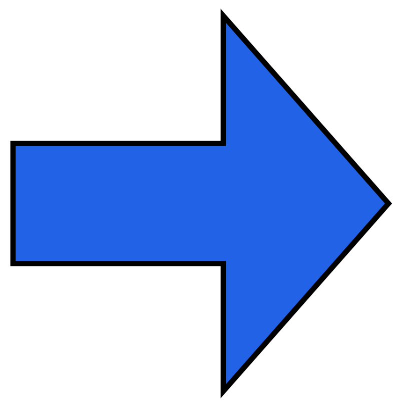
Equilibrium solution

Example #2 of a prognostic closure: Super-Parameterization

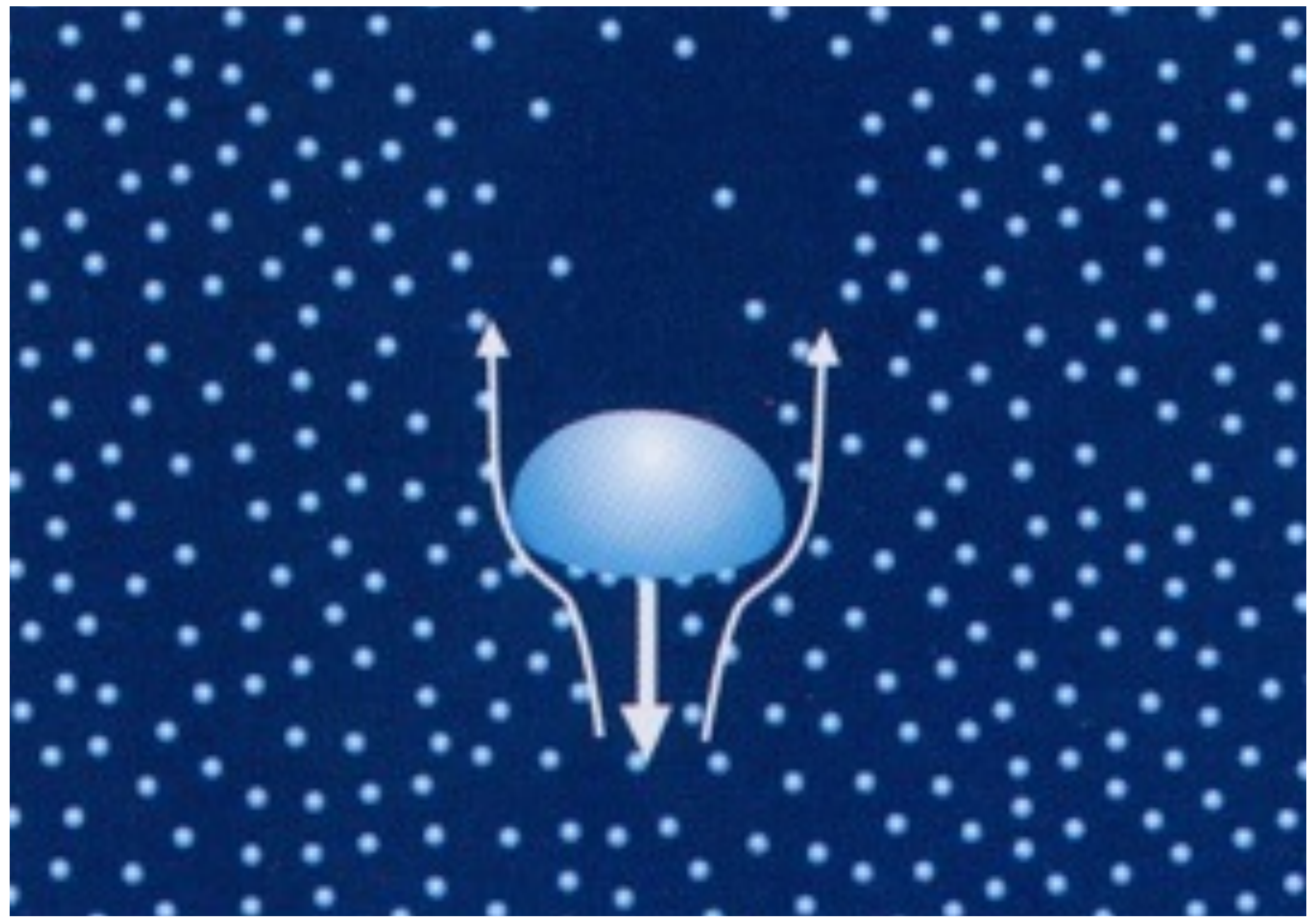


Parameterized processes on coarse and fine meshes





Increasing resolution



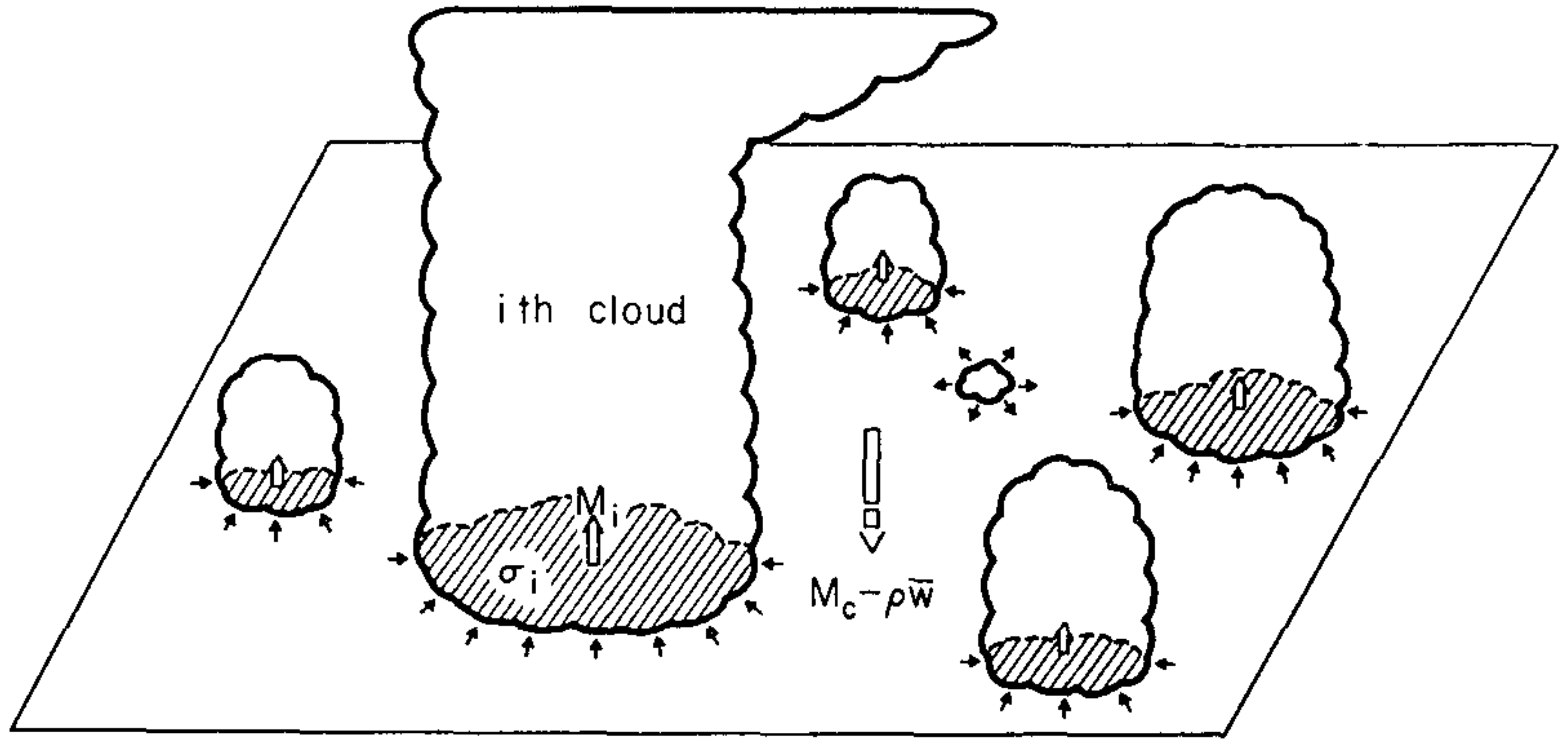
GCM

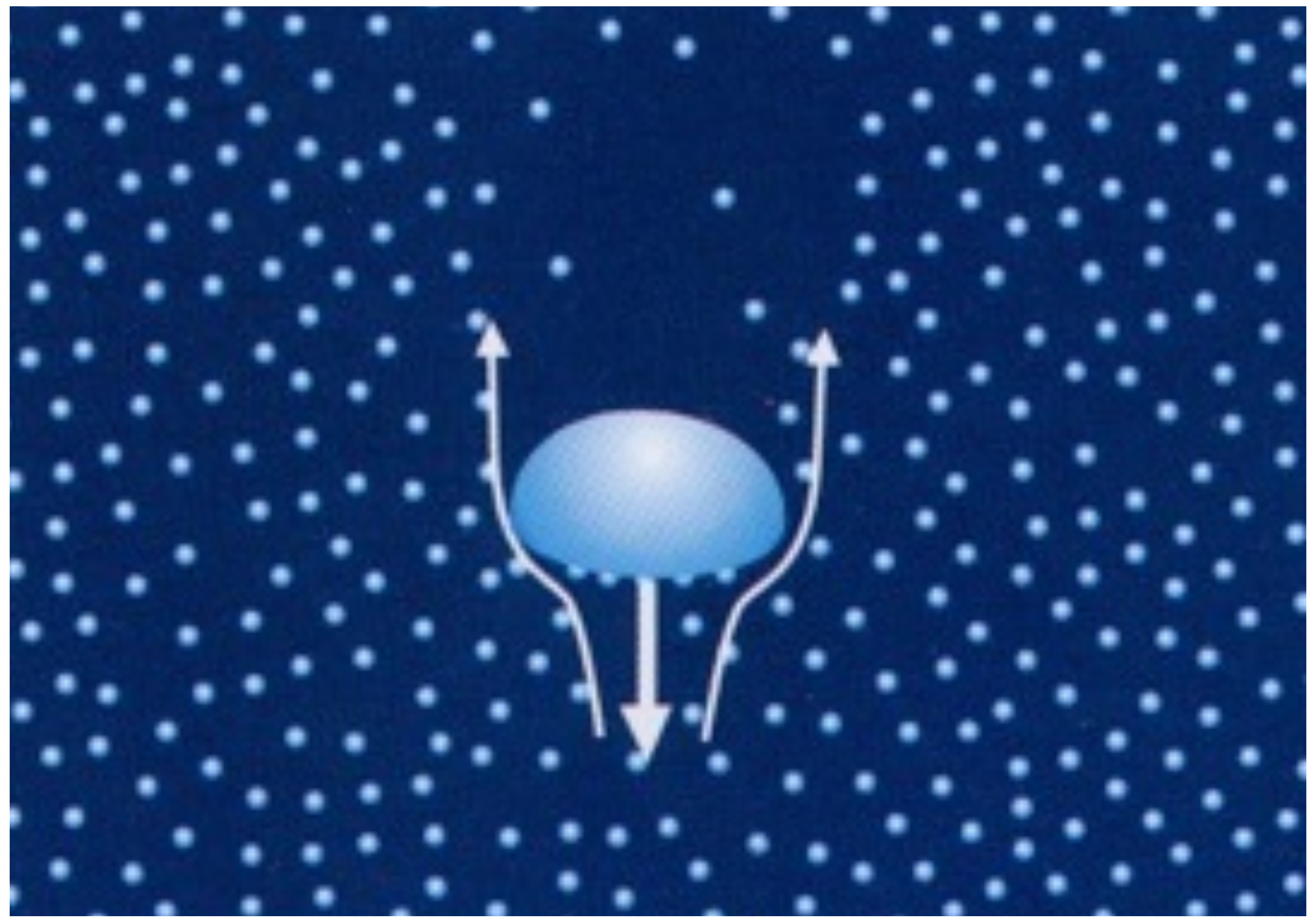
Parameterizations for low-resolution models are designed to describe the collective effects of ensembles of clouds.

CRM

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

Parameterized processes on coarse and fine meshes





Increasing resolution

GCM

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

CRM

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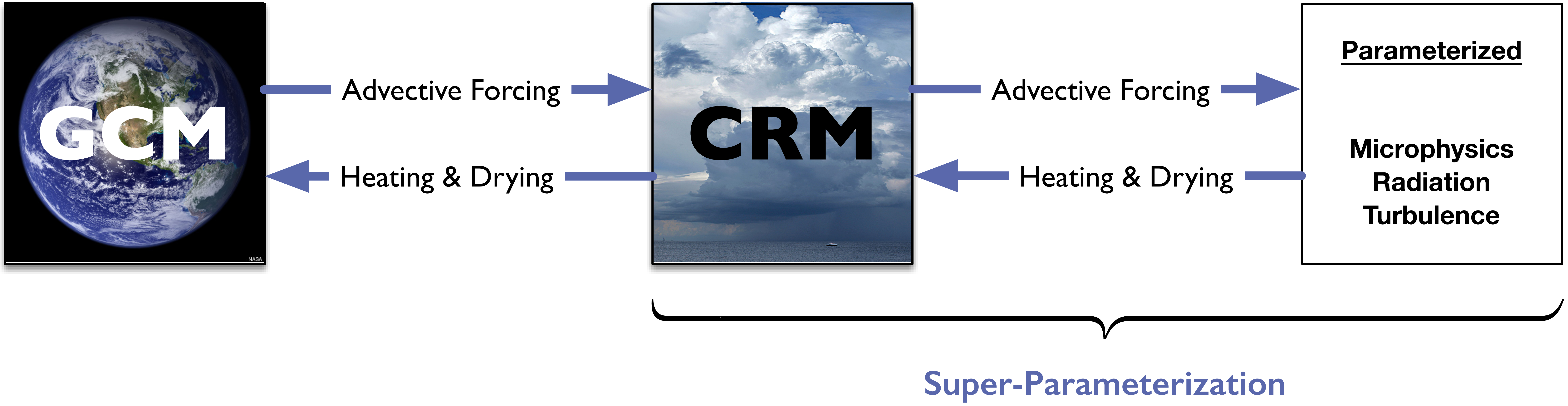
Expected values --> Individual realizations

Super-Parameterization



- Each CRM runs continuously.
- The CRMs do not communicate with each other, so the model is embarrassingly parallel.
- The width of the CRM domain is not tied to the GCM grid size, so a super-parameterization is *not* resolution-independent.

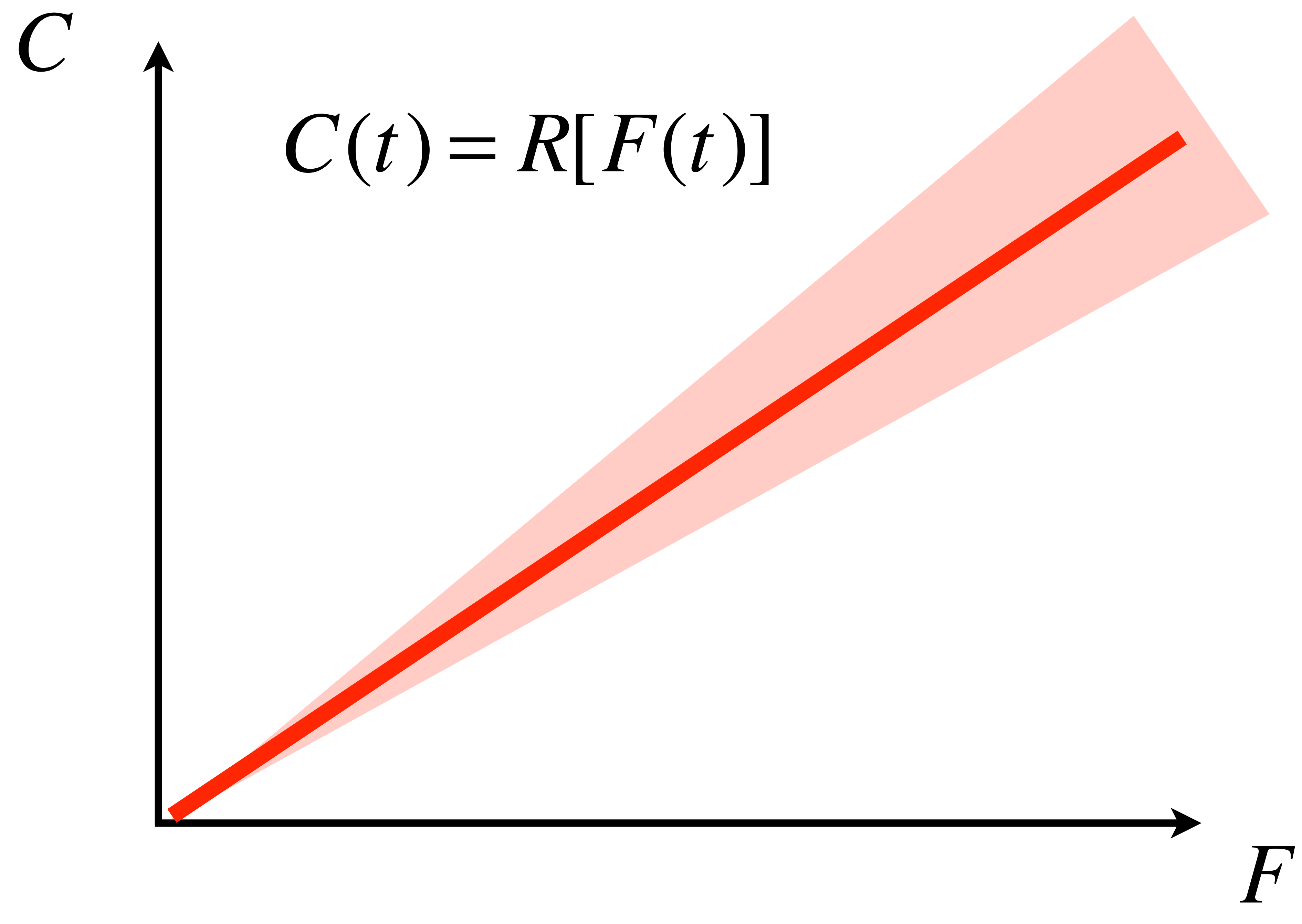
What’s different?

- 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

Superparameterization is a fancy (and expensive) prognostic closure.

A prognostic closure can be sensitivity dependent on its initial conditions, and can therefore behave chaotically.

This means that prognostic parameterizations can "automatically" be stochastic parameterizations.



Reasons to use prognostic closure

- There is no need to distinguish between forcing and response.
- The convection has a memory and can respond with some delay.
- Prognostic closure is simpler and computationally faster.
- Because a prognostic parameterization can be *sensitively dependent on its initial conditions*, it can behave stochastically.

Reasons to use prognostic closure

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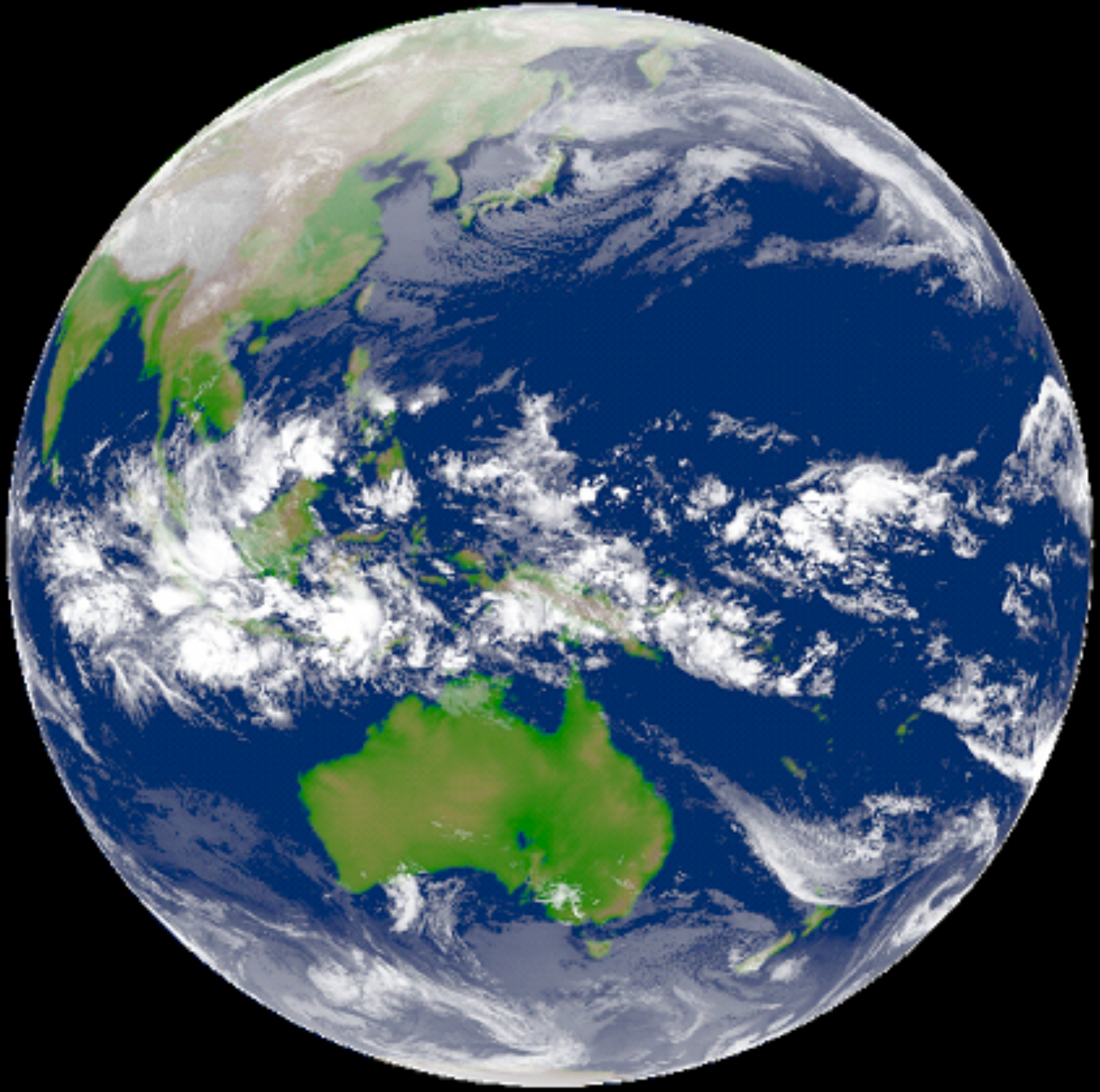
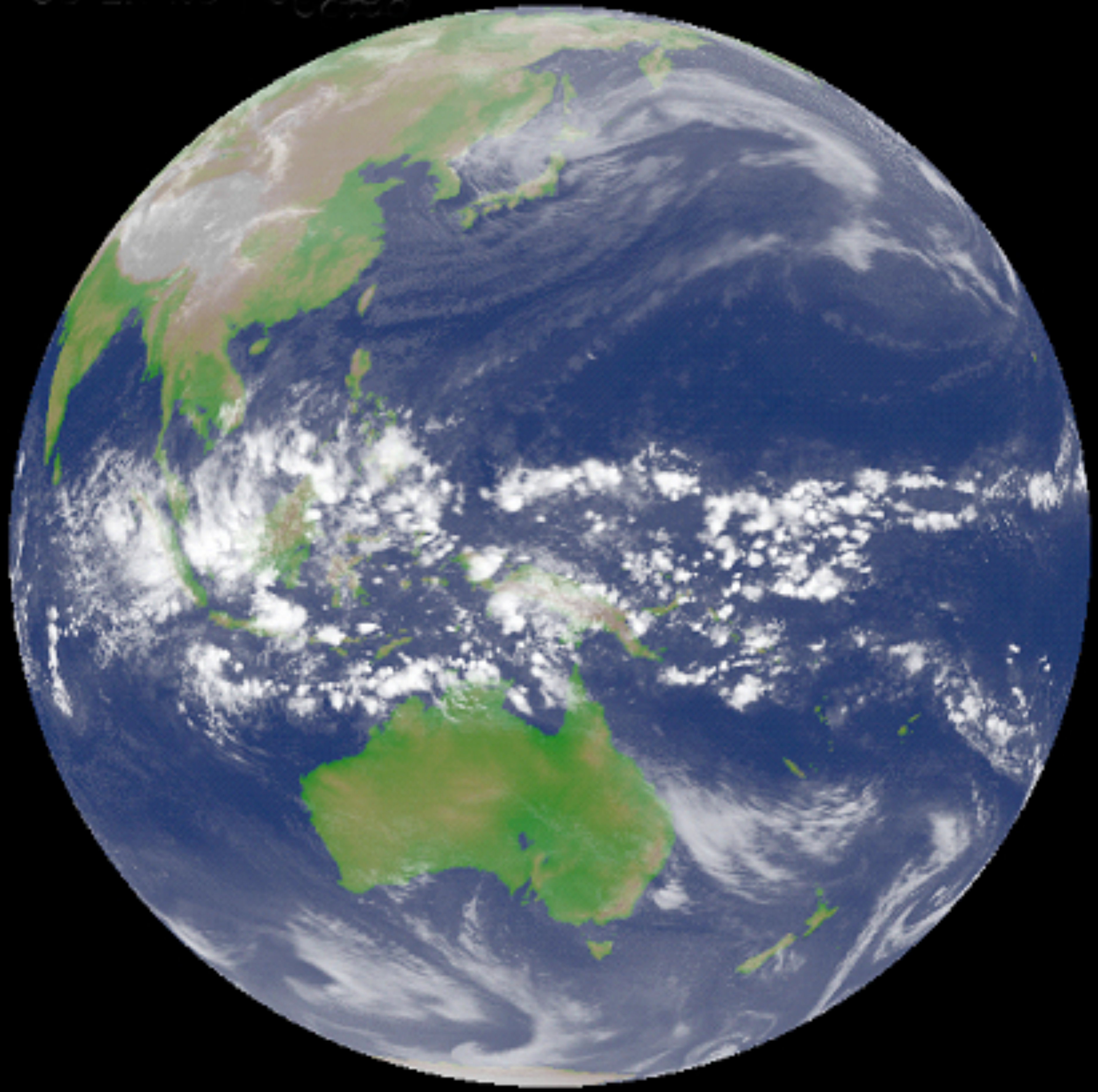
Global Cloud Resolving Models





Slide from Hiro Miura

The Grey Zone

Scales larger than $10\ \delta x$ are well resolved.

Subgrid-scales are not resolved at all, and therefore must be parameterized.

Scales close to the grid spacing are “represented” but not well resolved.
They should be “partially parameterized.”

Crossing the grey zone

There has always been a grey zone.

With $\delta x = 400$ km, the smaller synoptic scales are in the grey zone.

With $\delta x = 40$ km, the meso scales are in the grey zone.

With $\delta x = 4$ km, thunderstorms are in the grey zone.

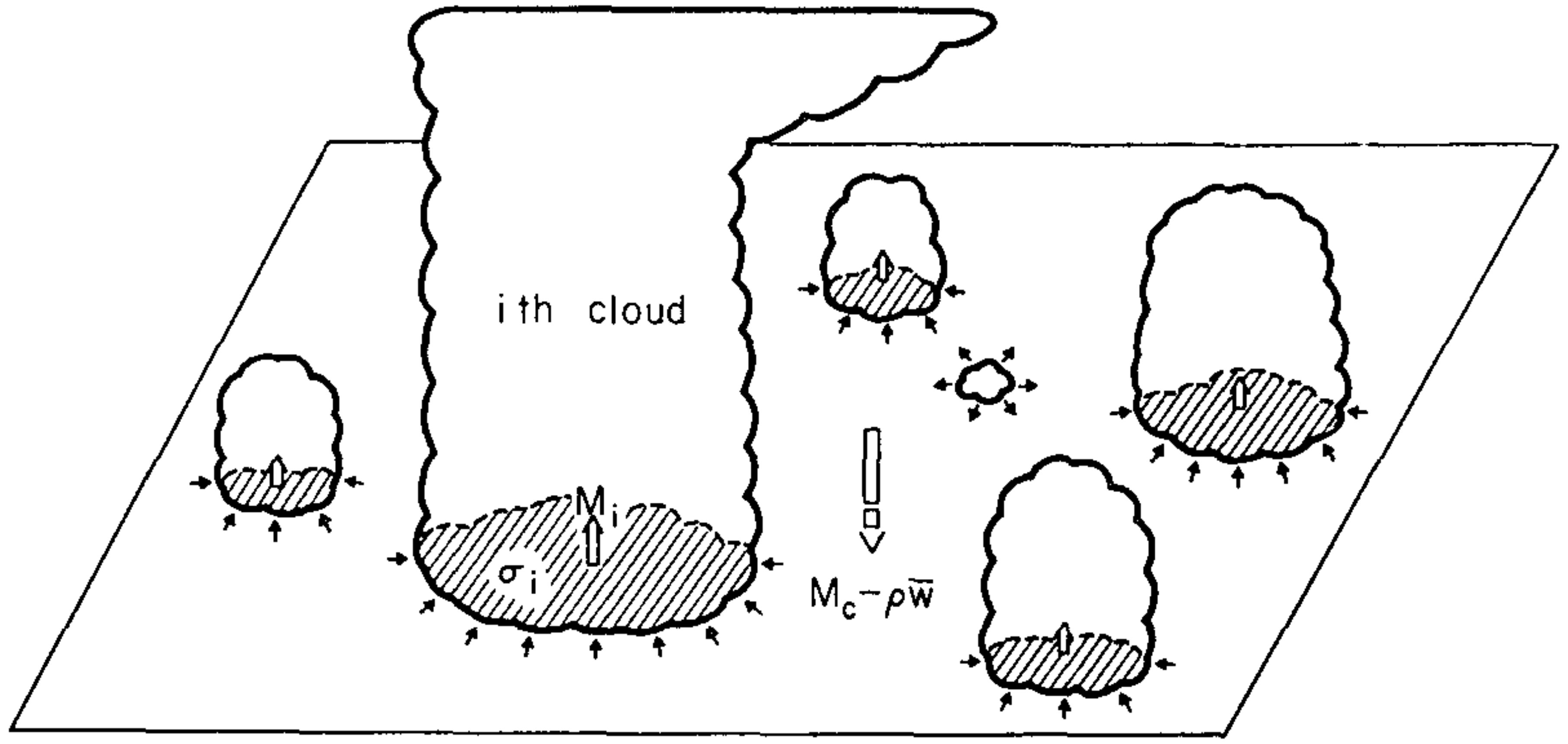
With $\delta x = 0.4$ km, turbulence is in the grey zone.

Two Grey-Zone issues

- Resolution
- Sample size

Resolution-independent parameterizations

Low resolution



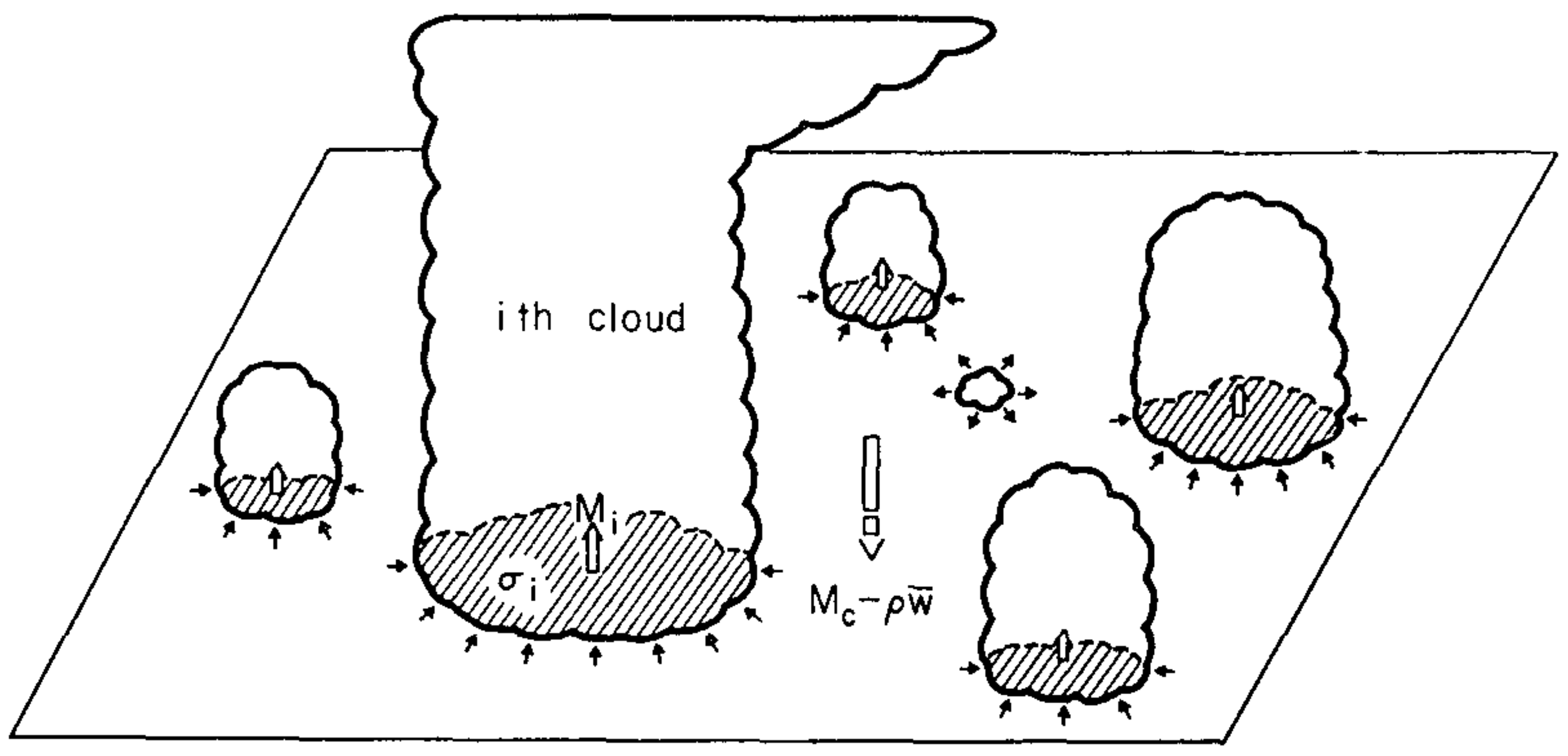
Updrafts occupy a small fraction of each grid cell.

Quasi-equilibrium closure is useful.

Convective transport occurs on the *subgrid* scale.

Resolution-independent parameterizations

Low resolution



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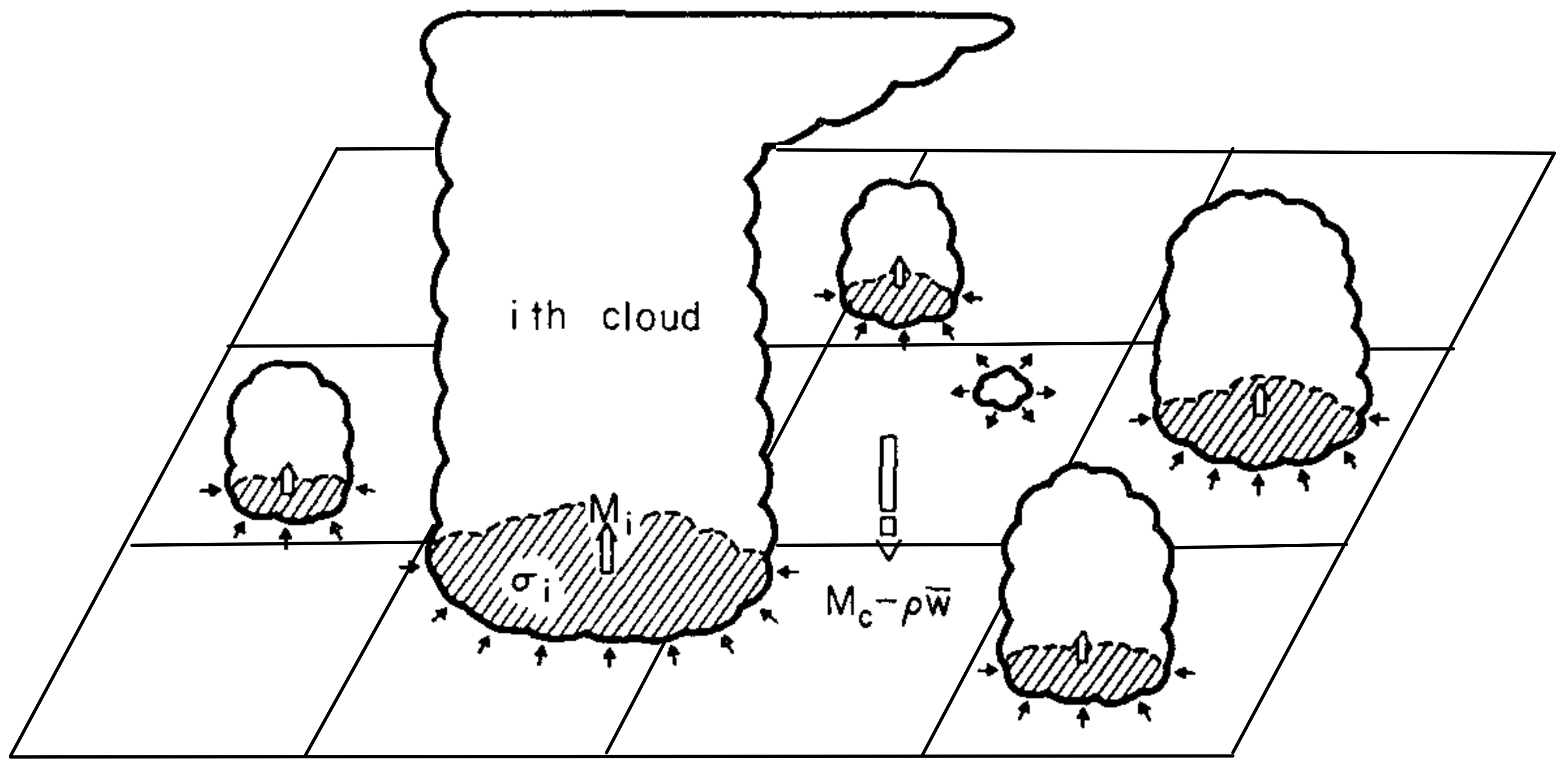


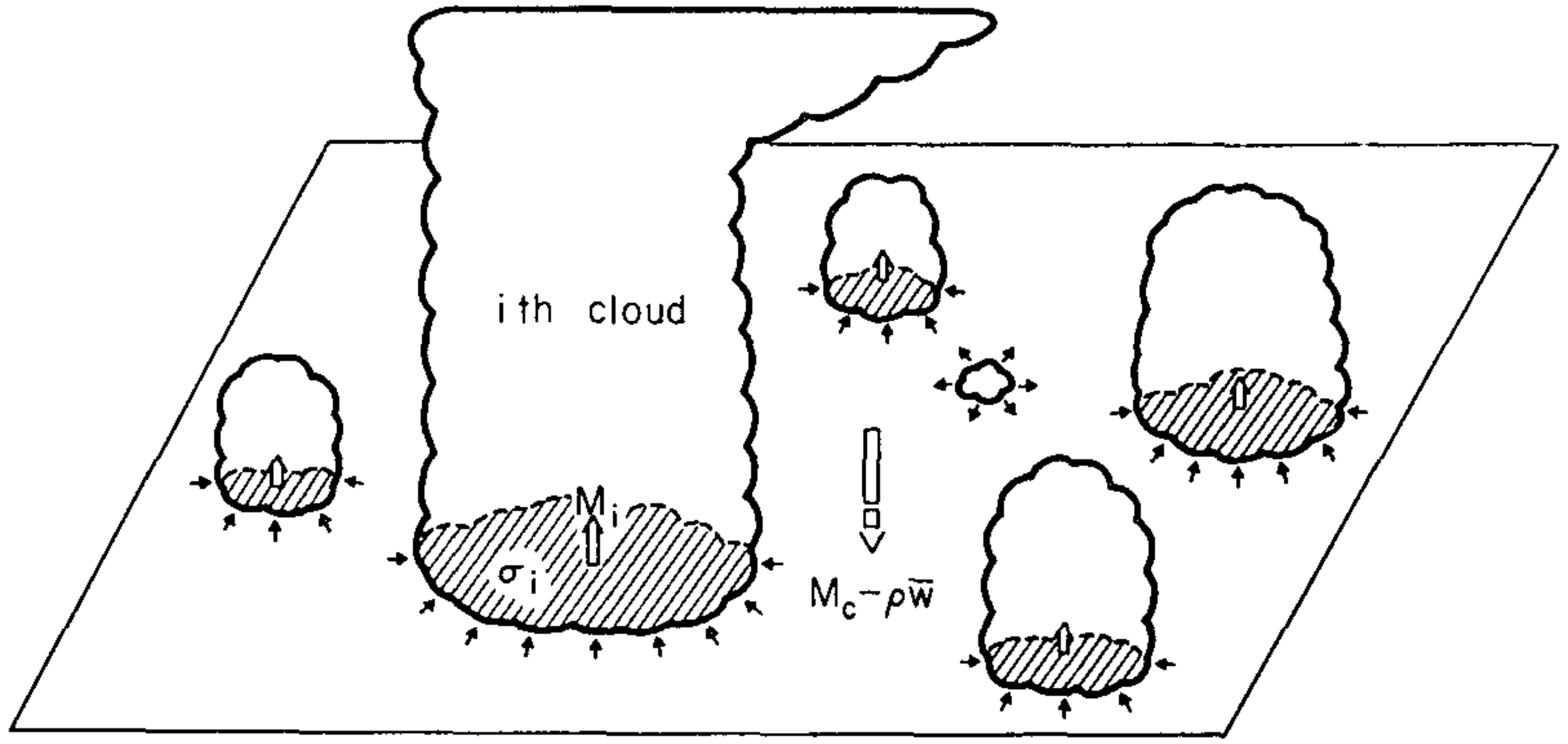
Some grid cells are filled by updrafts.

Quasi-equilibrium breaks down.

Convective transport occurs on the *grid* scale.

Resolution-independent parameterizations

Low resolution



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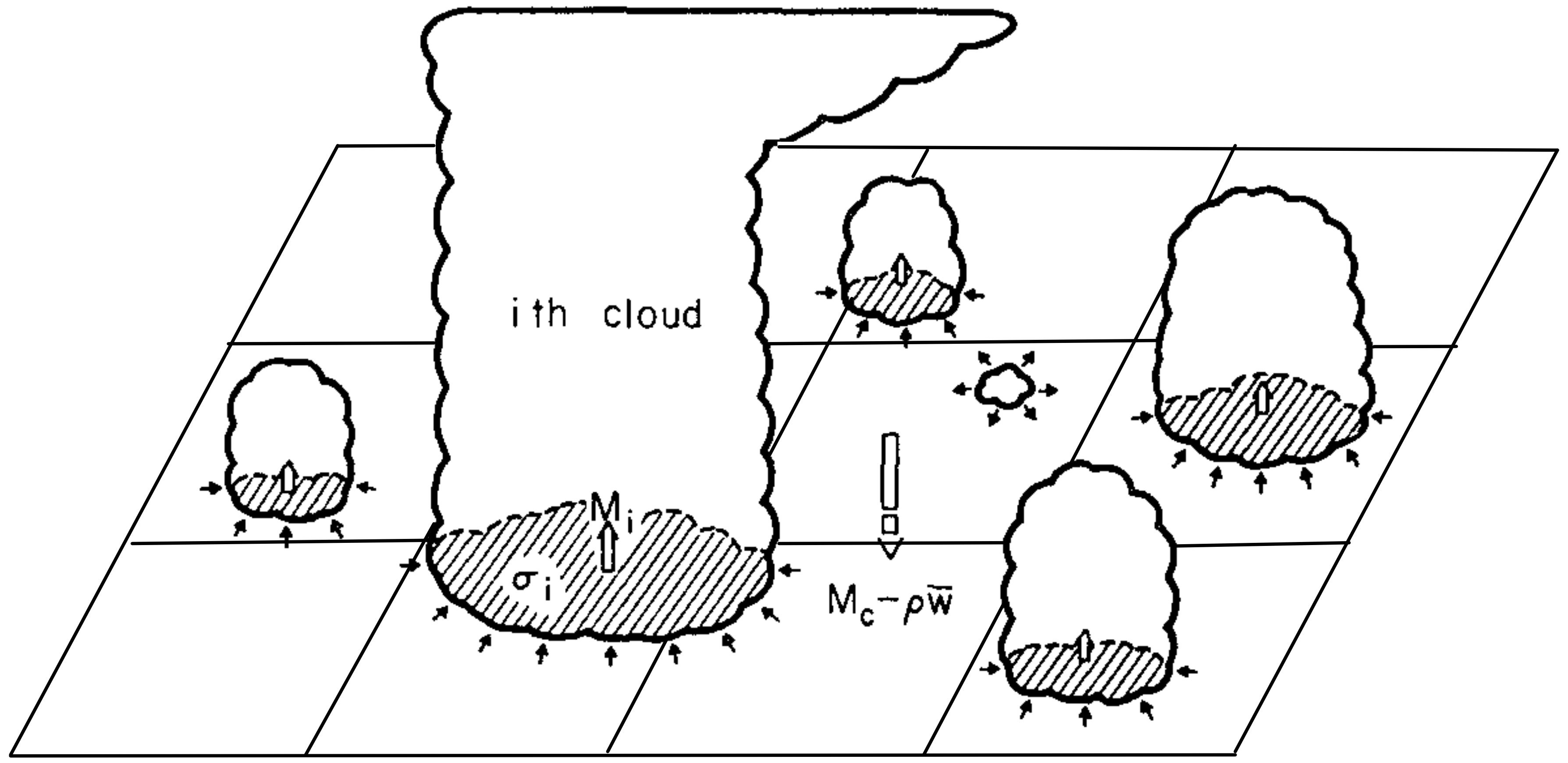


Some grid cells are filled by updrafts.

Quasi-equilibrium breaks down.

Convective transport occurs on the *grid* scale.

In principle, a model that uses resolution-independent parameterizations should converge to the Navier-Stokes equations as $\delta x \to 0$.

Resolution-independent models

A resolution-independent model can be run with a grid spacing of 100 km or 100 m, and everything in between.

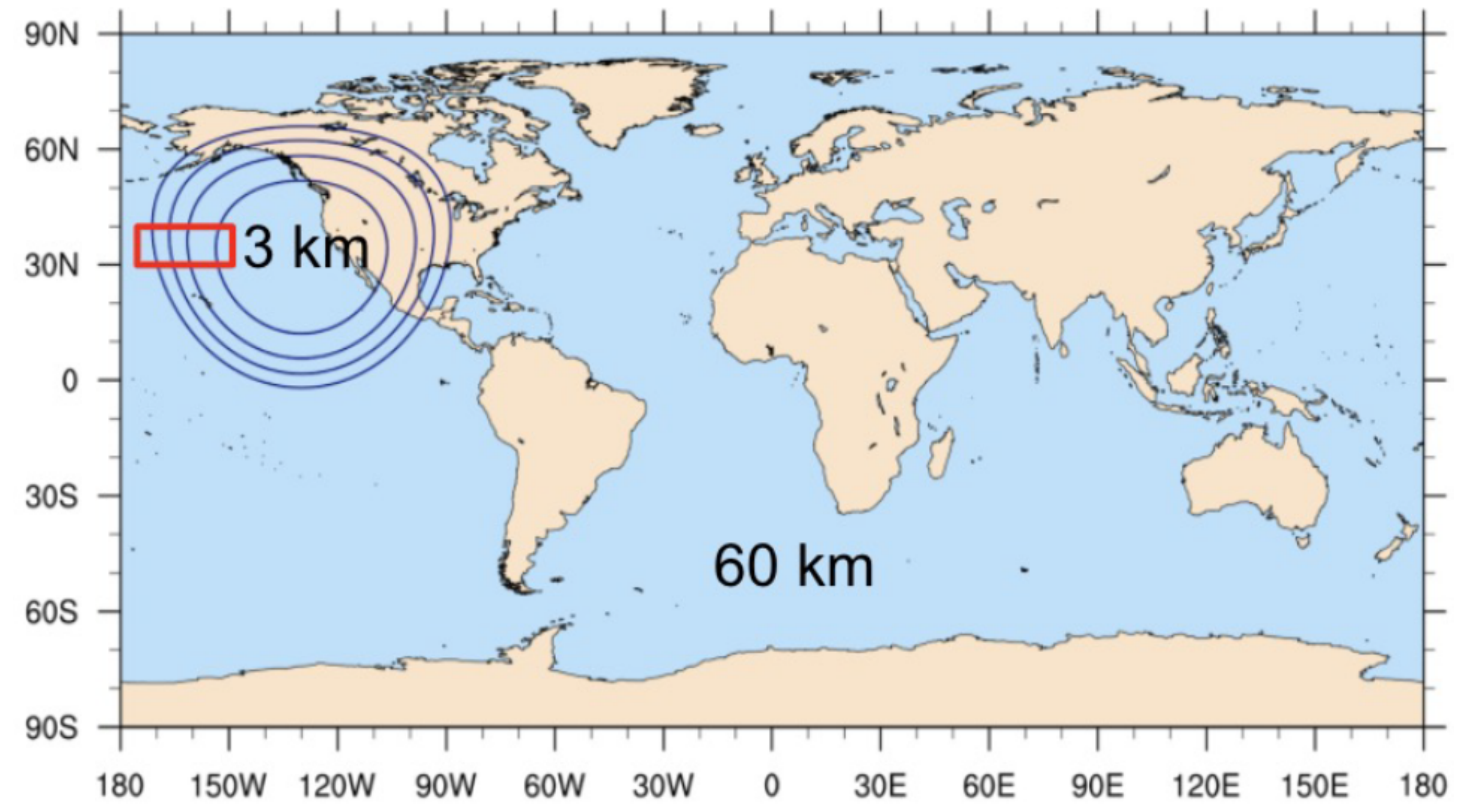
- One set of equations
- One code
- One set of values for the adjustable parameters

A resolution-independent model would be a very useful tool, in a practical sense.

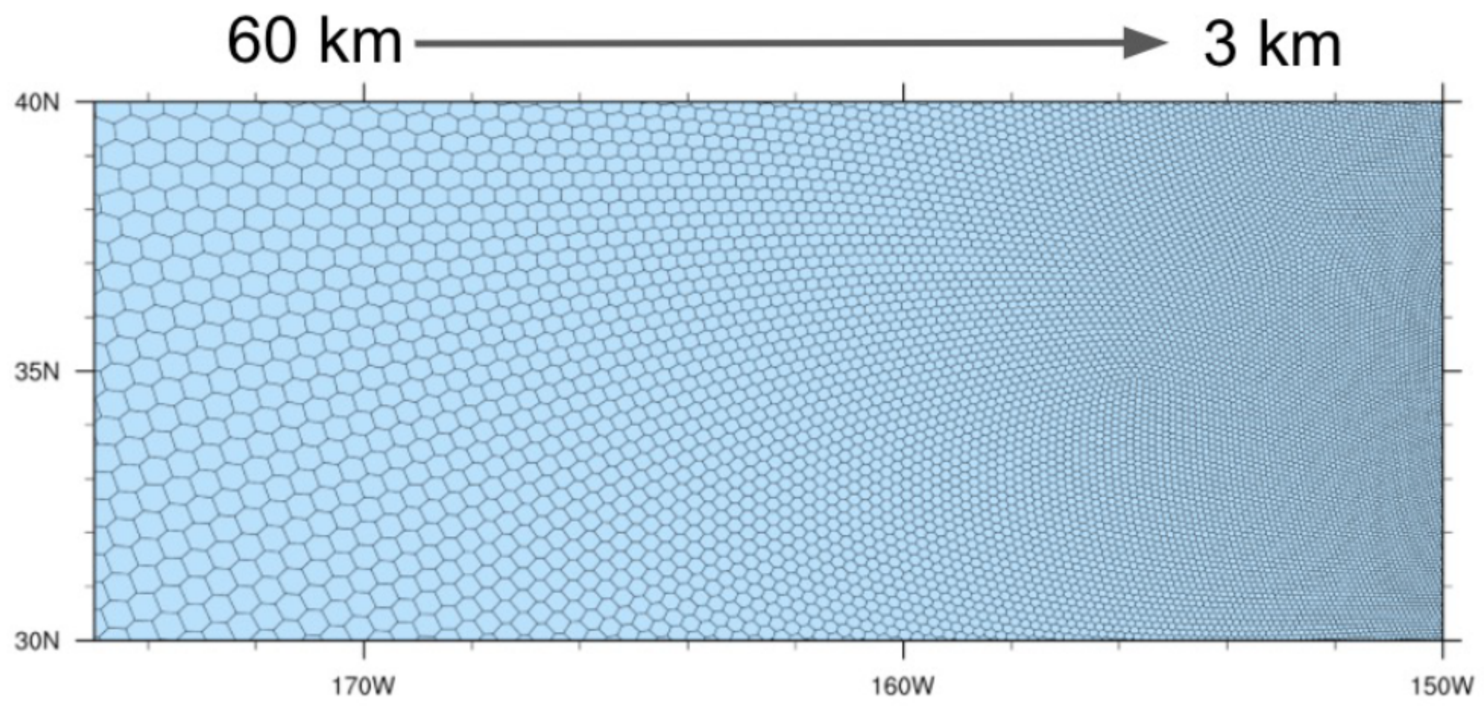
In the process of developing (or trying to develop) a resolution-independent model we will learn a lot.

Resolution-independent parameterizations must be

- Prognostic
  - The current state depends on the past history.
  - Processes are not in equilibrium.
  - Life cycles can play out on scales just below the grid scale.
- Non-local
  - The state of a single column is not sufficient to determine what is happening there.
  - Eddies can be advected or propagate between grid columns.
- Very flexible
  - Deep convection must be parameterized on coarse grids.
  - Shallow convection and turbulence must be parameterized on fine grids.



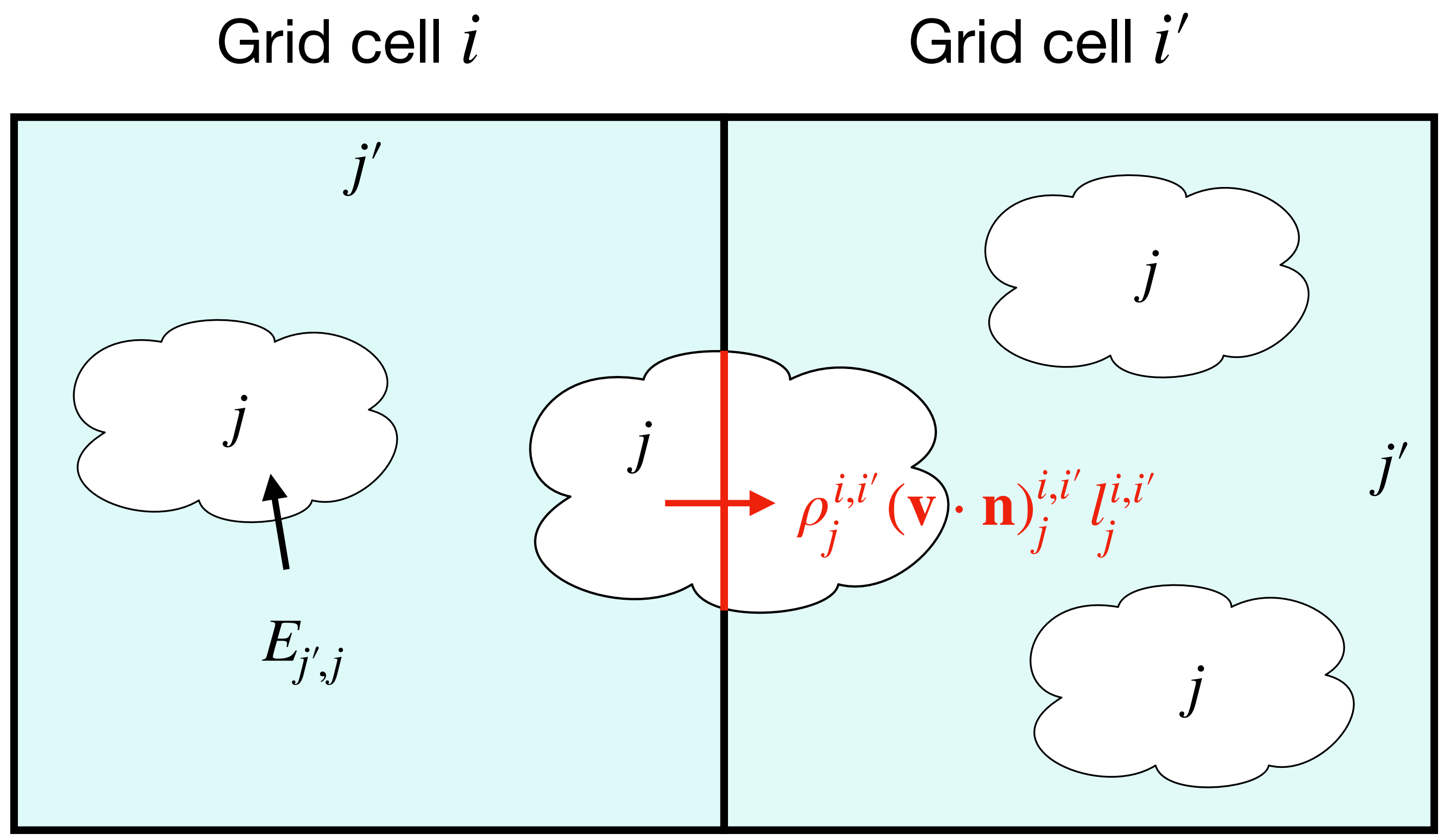
(a) Grid mesh configuration in 60-3km experiments



(b) Unstructured spherical centroidal Voronoi mesh with smooth-transition mesh densities

Figures from Xingying Huang

The multi-fluid approach looks promising.



A way to study this issue:
Periodic "forcing" in a domain of specified size

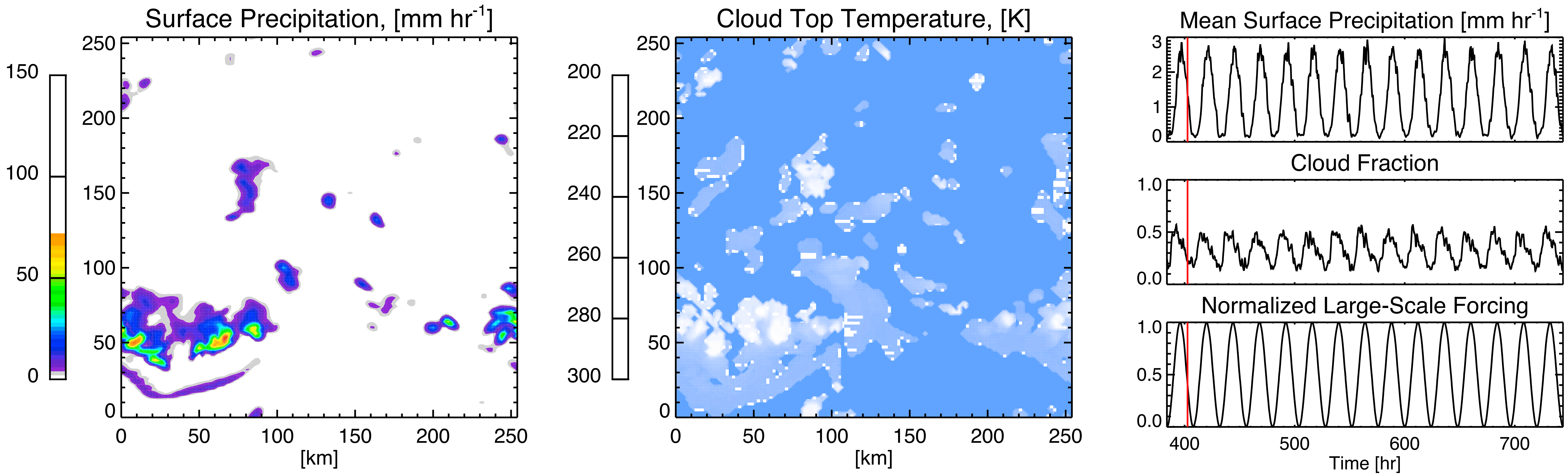
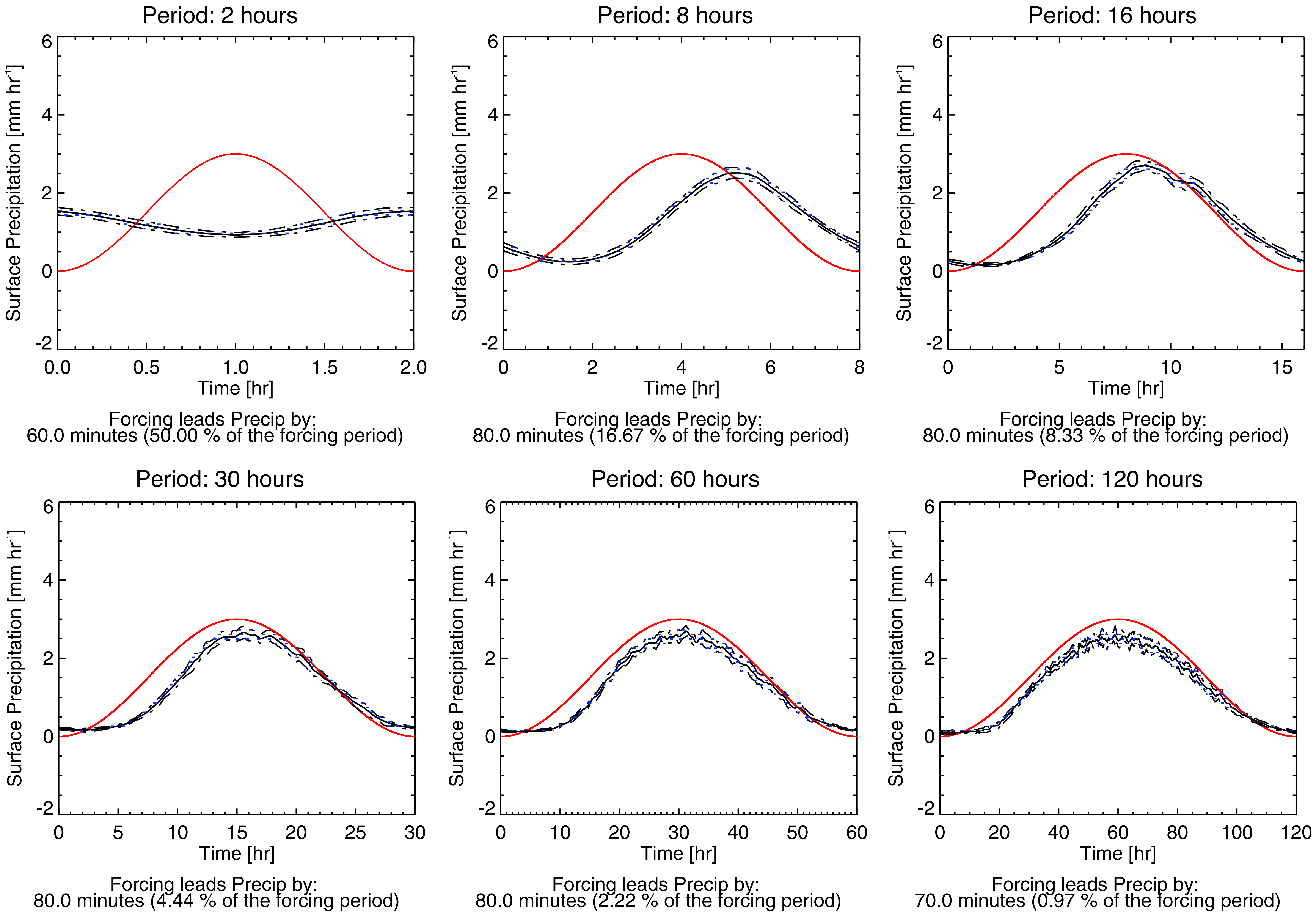


Figure 5. Snapshots and time series from F24.

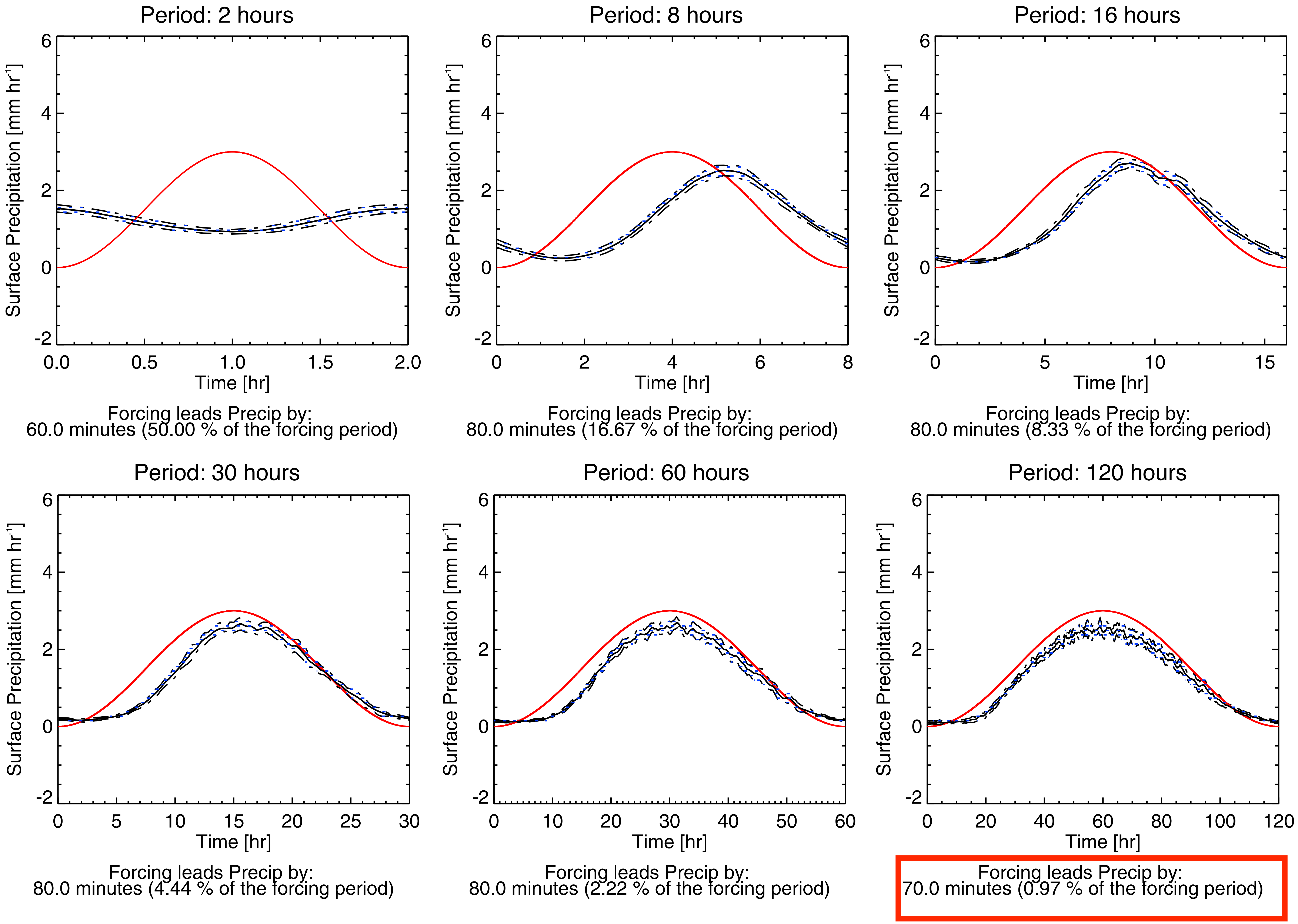
Jones & Randall 2010

Dependence on forcing period



Jones & Randall 2010

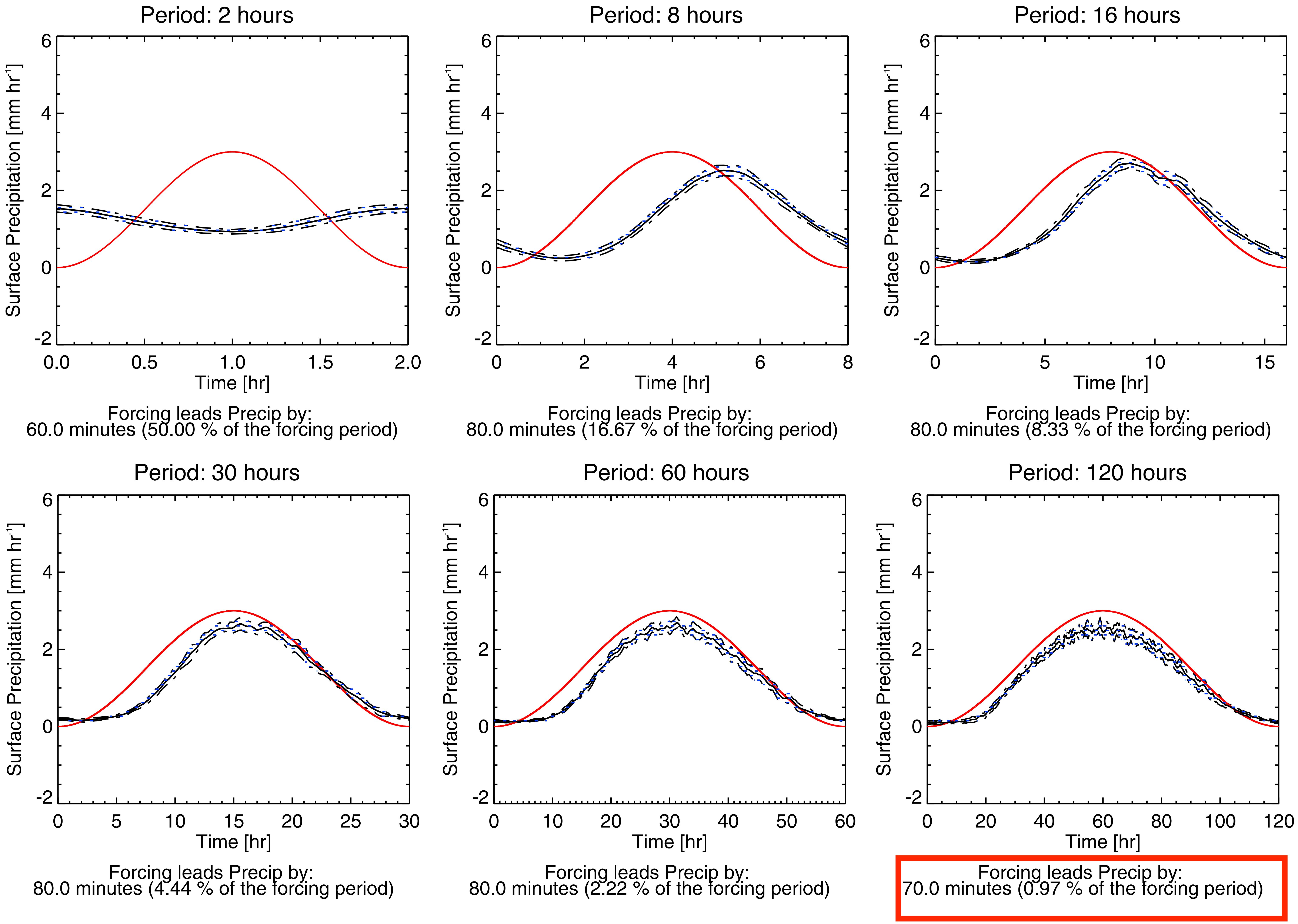
Dependence on forcing period



Adjustment time
~ one hour

Jones & Randall 2010

Dependence on forcing period



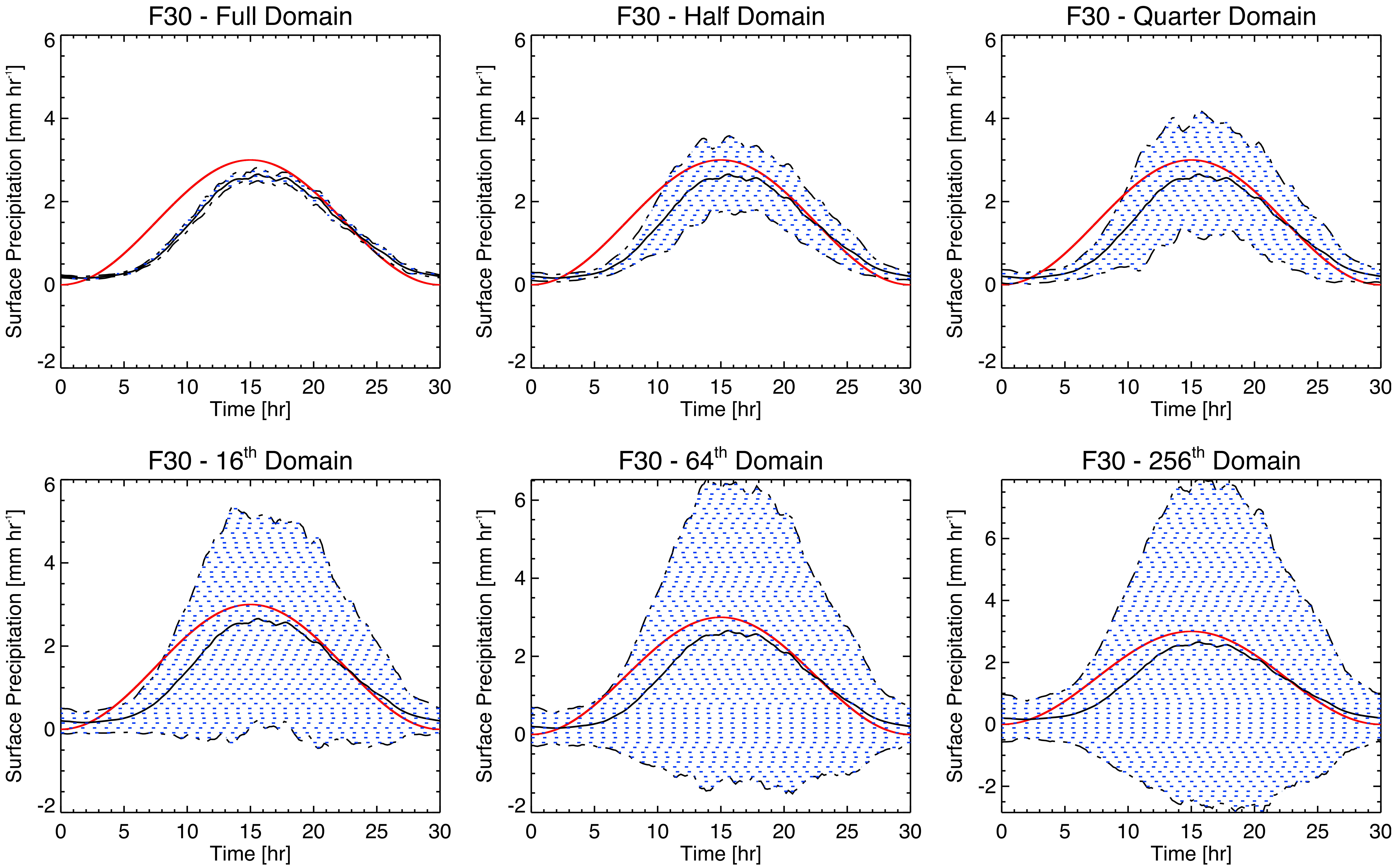
The hatching shows plus/minus one standard deviation

Adjustment time ~ one hour

Jones & Randall 2010

Dependence on domain size

Forcing period 30 hours, and full domain 250 km wide



Jones & Randall 2010

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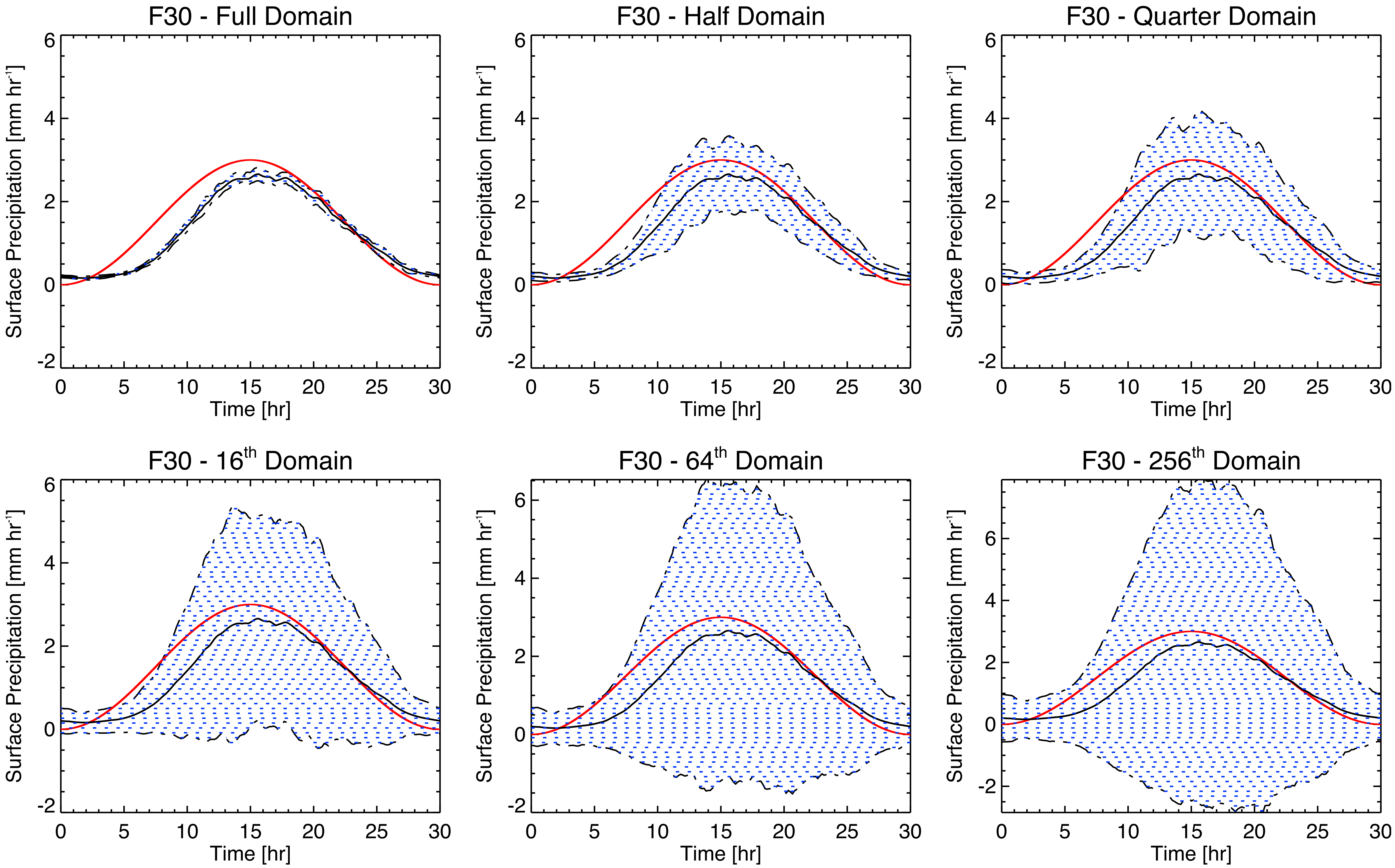

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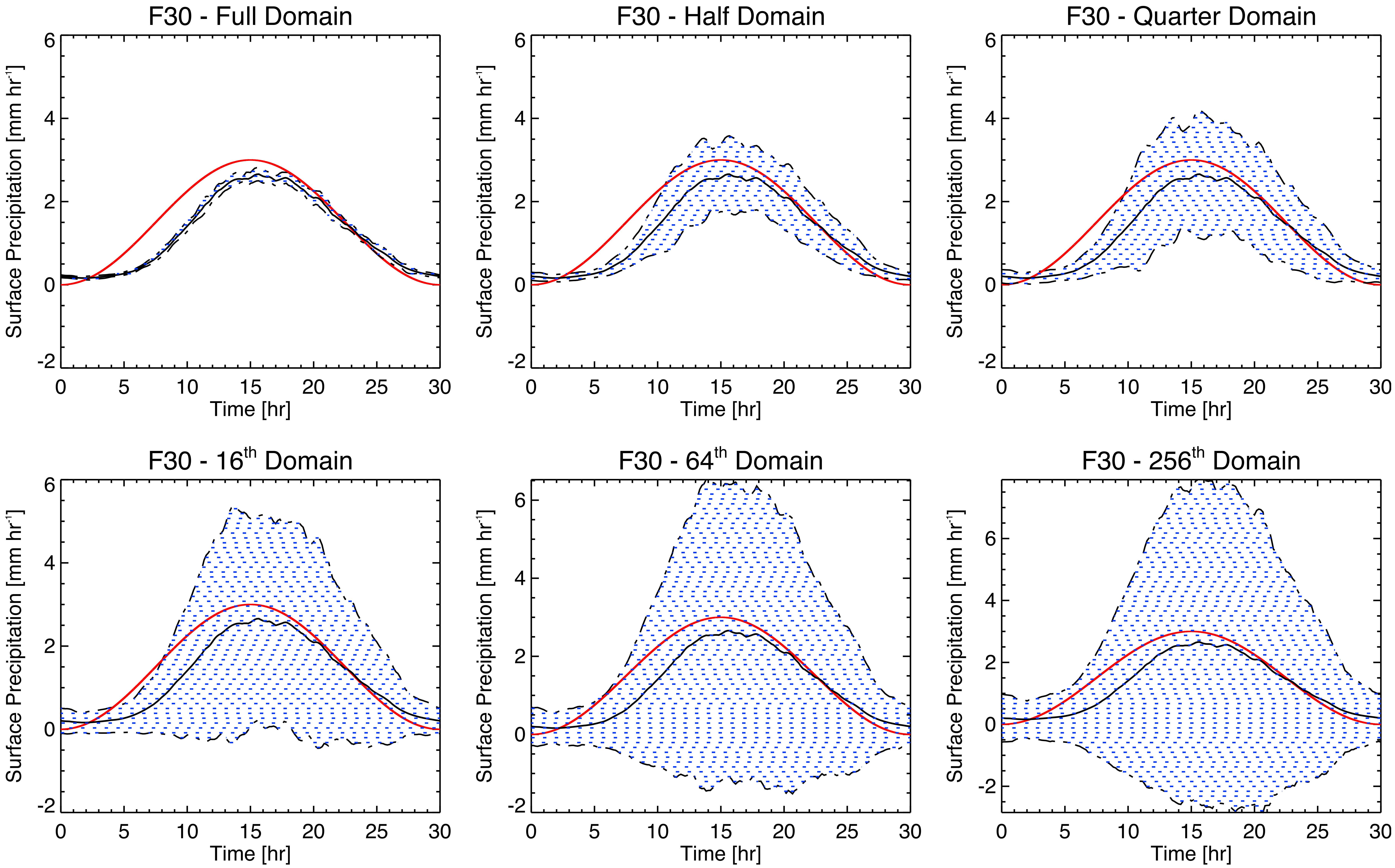


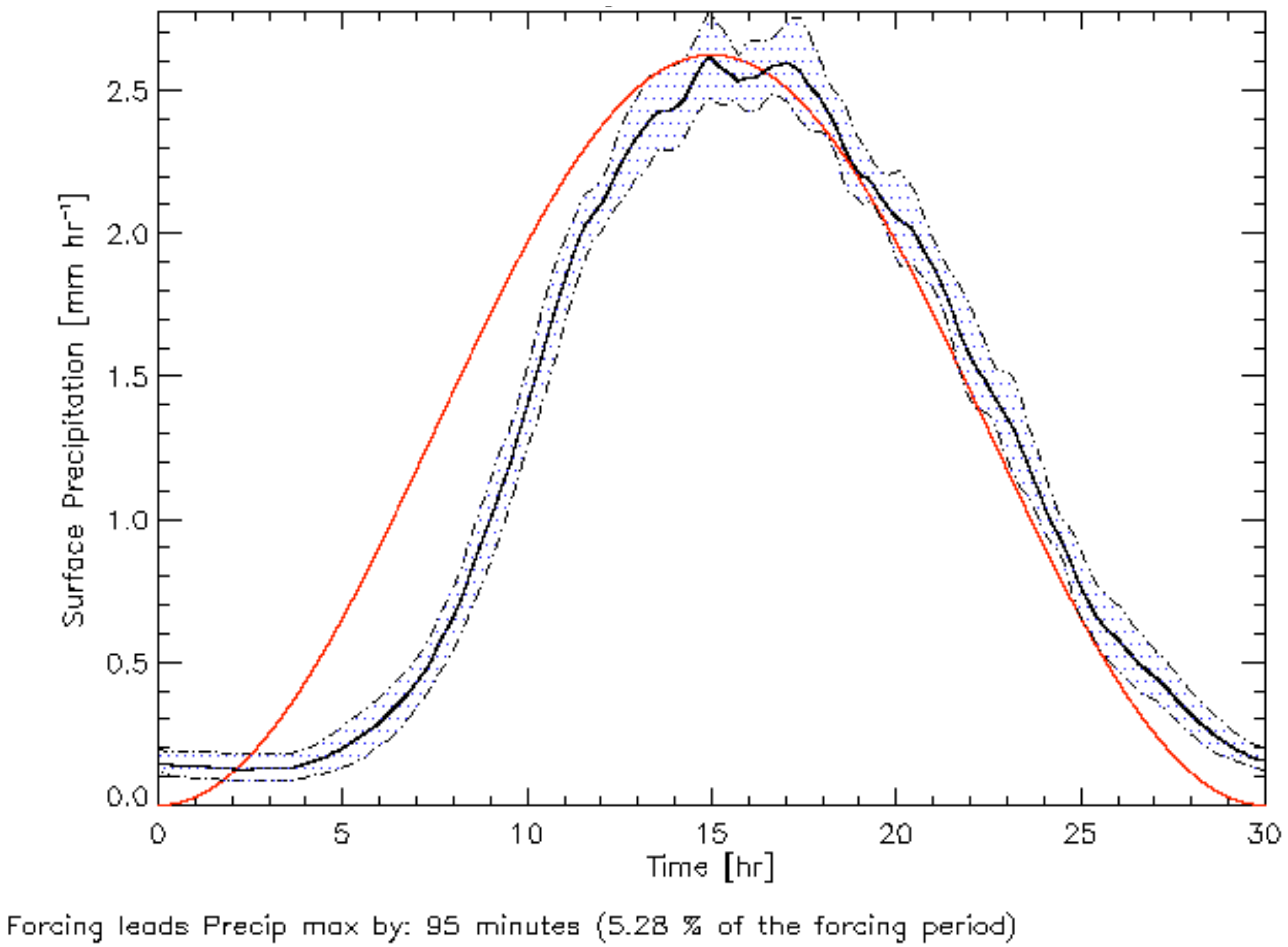
The blue curve shows the average over the entire domain, and is the same in all six panels.

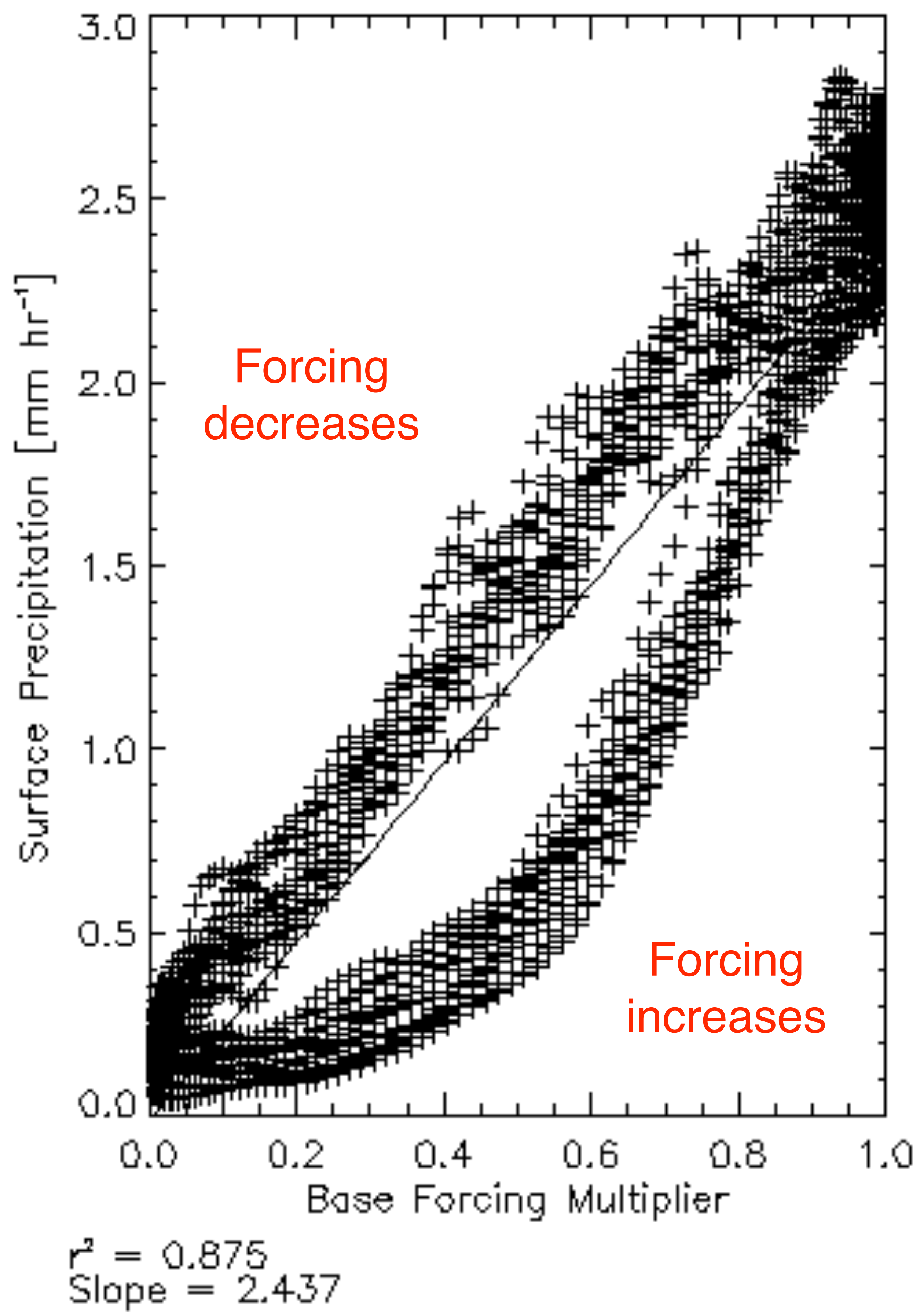
The hatching shows plus/minus one standard deviation

Jones & Randall 2010

Both problems at once

Forcing period 30 hours





Jones & Randall 2010

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

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

What should a cumulus parameterization do?

- Remove grid-scale convective instability
- Transport energy etc. by updrafts
- Interact with stratiform clouds
- Transport energy etc. by downdrafts
- Include realistic microphysical processes
- Include turbulent processes such as entrainment
- Interact with the boundary layer
- Interact with the mean wind, through momentum transport and mesoscale organization
- Produce aggregation
- Remember its own recent past history
- Behave chaotically
- Work for any grid spacing
- Provide explanatory power