Physics Parameterizations in Global Atmospheric Models

CESM Tutorial 2018

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Monday August 6th

Outline

- What are “AGCM Physics”?
- Resolution, subgrid variability
- Parameterizations
- Examples
  - Mass-flux Convection scheme
  - CLUBB
  - More cloud issues
- Future directions

Equations of Motion – explicitly resolved dynamics

Where do the "physics" appear?

$$d\overline{\mathbf{V}}/dt + fk \times \overline{\mathbf{V}} + \nabla\overline{\phi} = \boxed{\mathbf{F}},$$ *(horizontal momentum)*

$$d\overline{T}/dt - \kappa\overline{T}\omega/p = \boxed{Q}/c_p,$$ *(thermodynamic energy)*

$$\nabla \cdot \overline{\mathbf{V}} + \partial\overline{\omega}/\partial p = 0,$$ *(mass continuity)*

$$\partial\overline{\phi}/\partial p + R\overline{T}/p = 0,$$ *(hydrostatic equilibrium)*

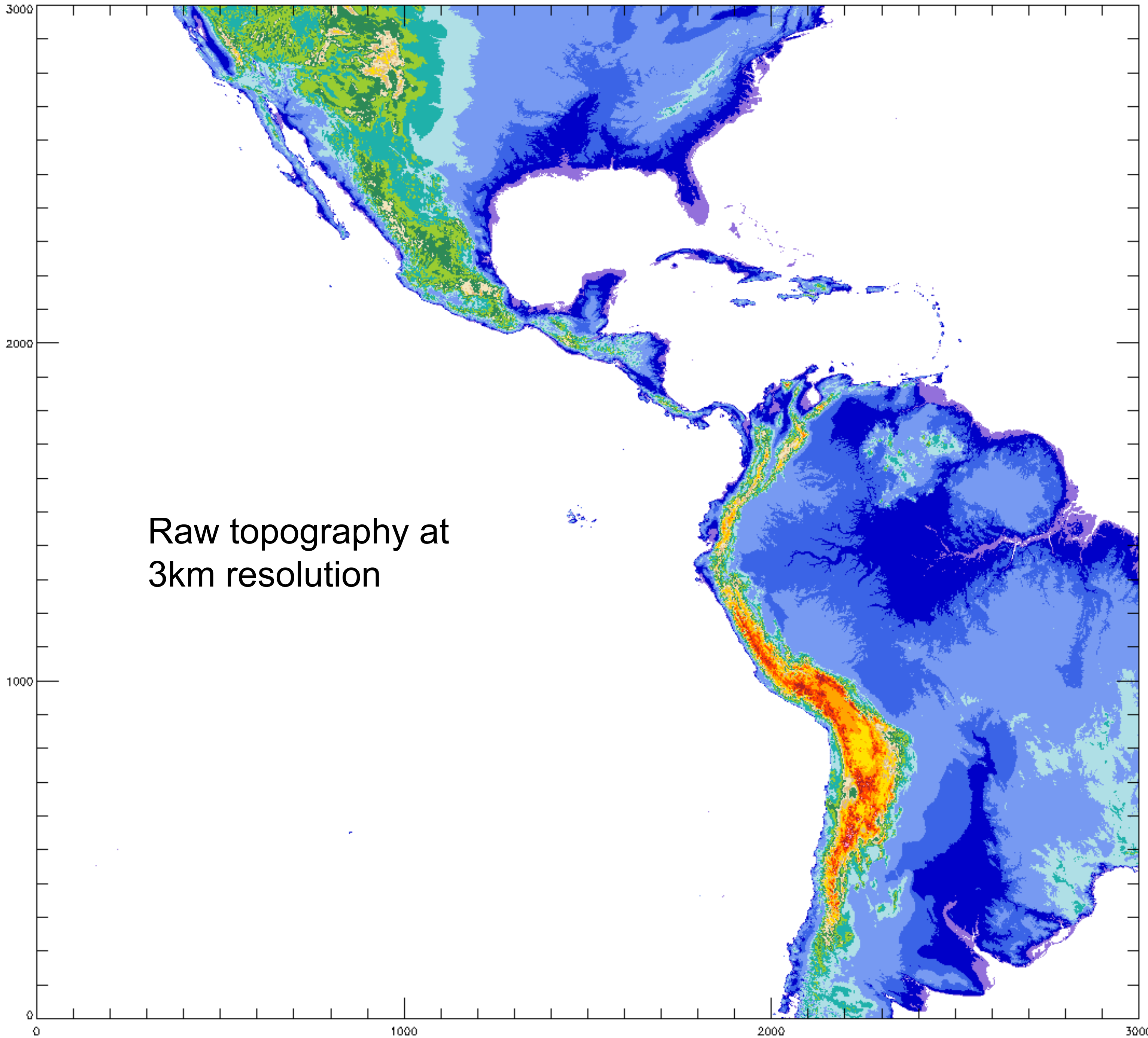
$$d\overline{q}/dt = \boxed{S_q}.$$ *(water vapor mass continuity)*

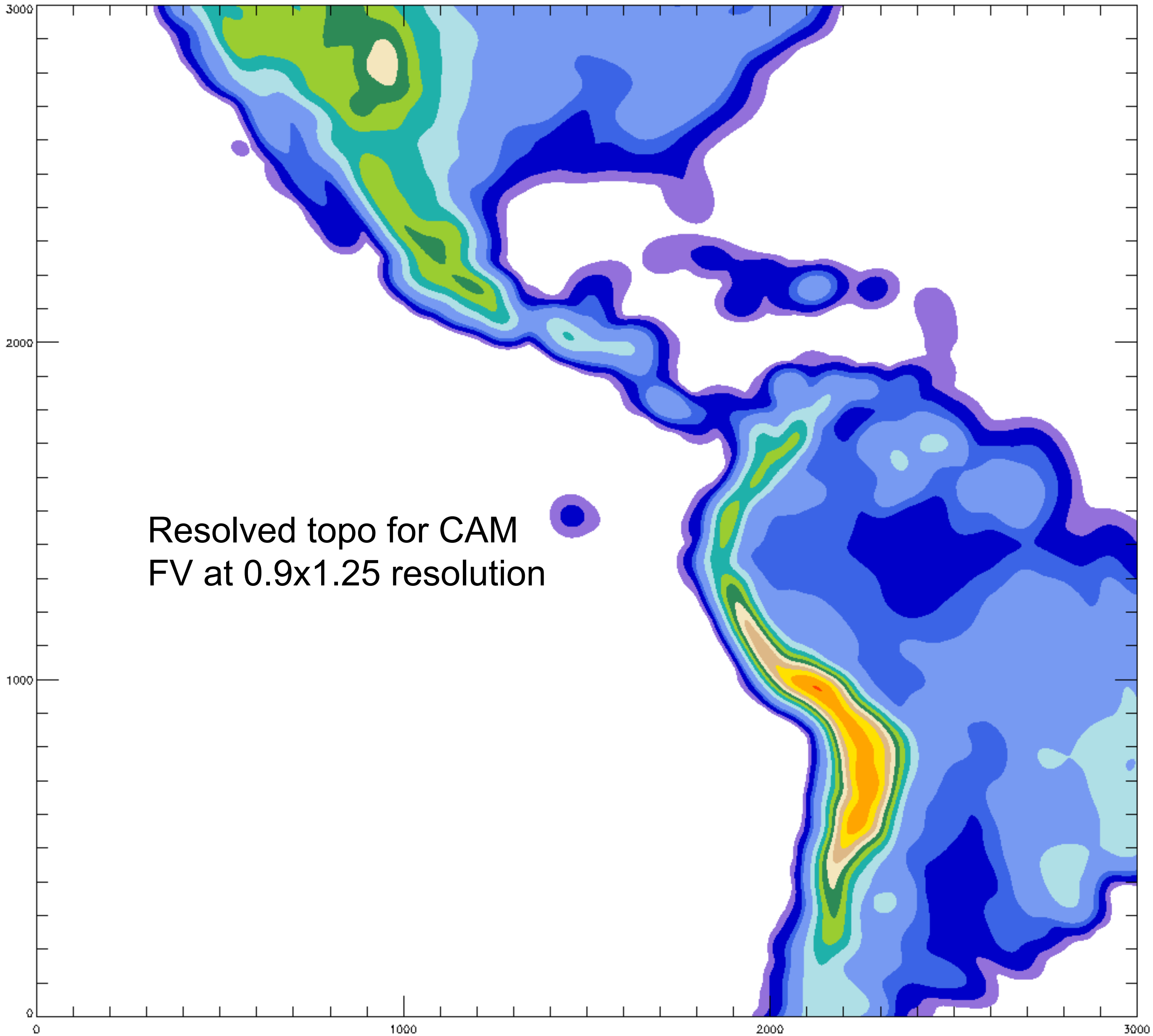
$dq_{\{l,i,r,\ldots\}}/dt =$

F_{QV}, F_{QL}, F_{QI} …? ***(water substance evolution equations, chemistry ...)***

What are the “physics” trying to represent?

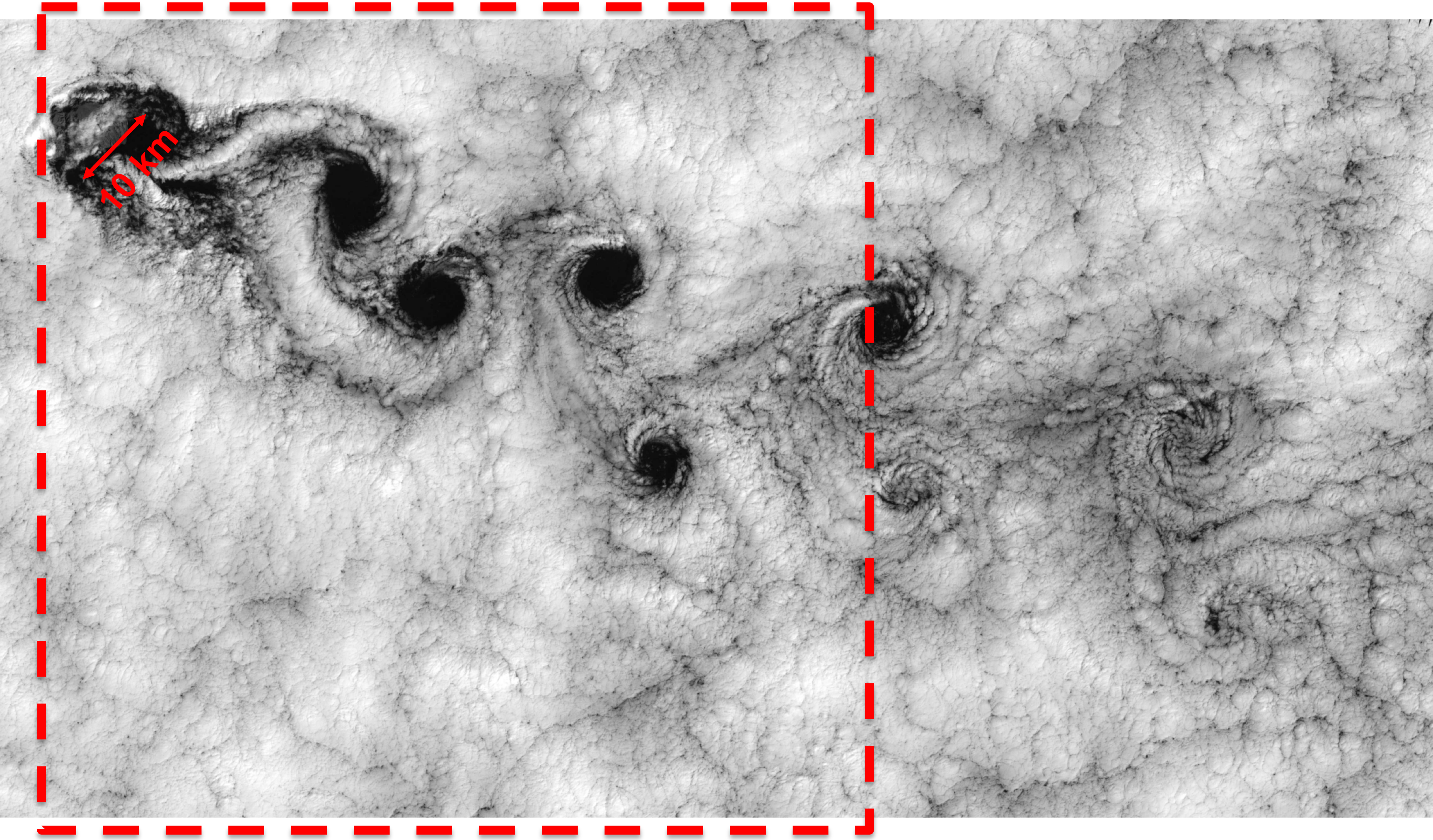
Unresolved motions, sub-grid variability, …. Photons …


Raw topography at
3km resolution
0
1000
2000
3000
0
1000
2000
3000



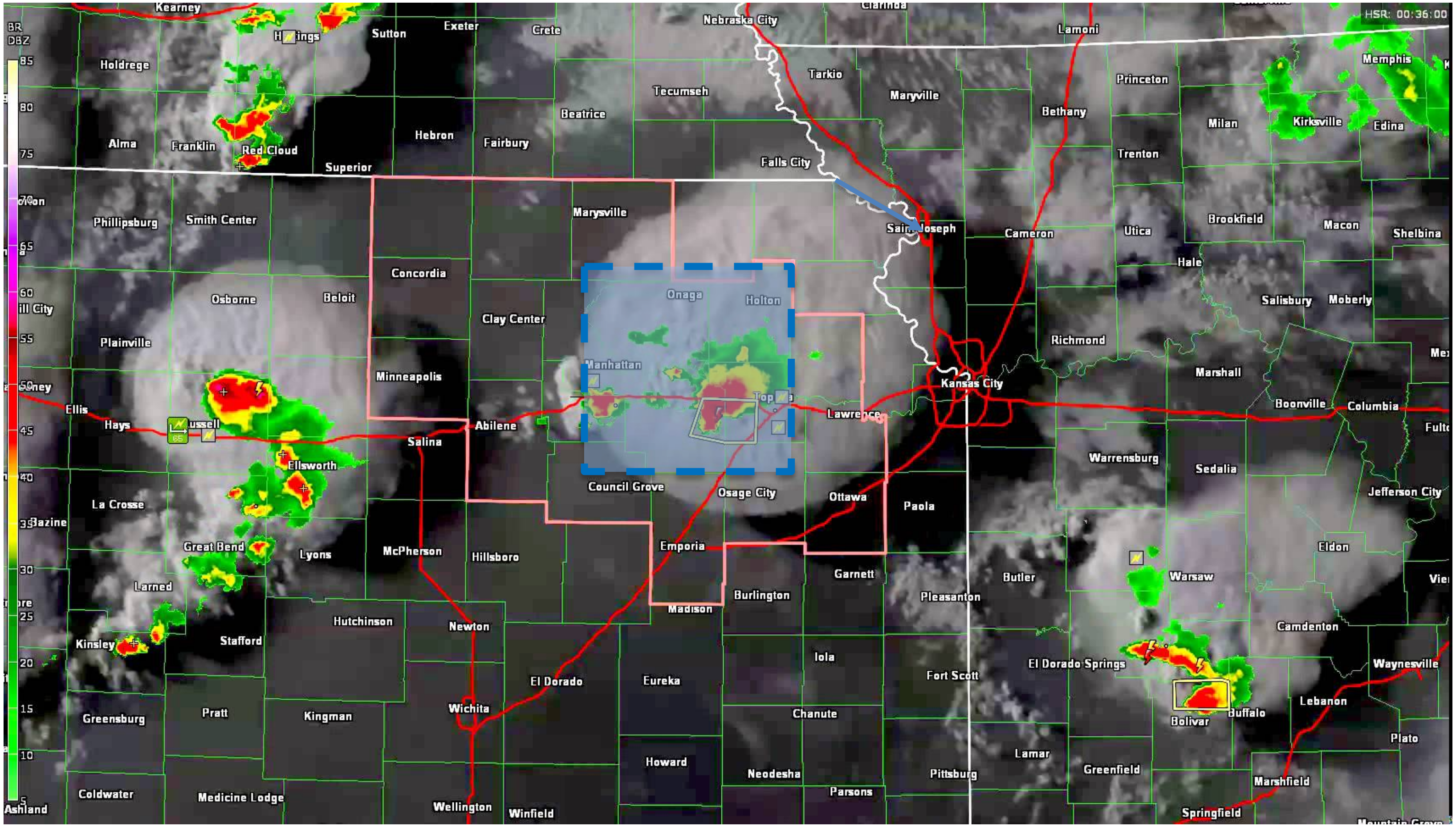
Resolved topo for CAM
FV at 0.9x1.25 resolution
0
1000
2000
3000

Boundary layer clouds



Alejandro Selkirk Island (33S 80W)

Deep Convection



July 15, 2015

OK, so atmospheric models with large grid boxes miss a lot of interesting stuff

....

So What??

Nonlinearity

5 Values of "x" = 1,1,1,2,10

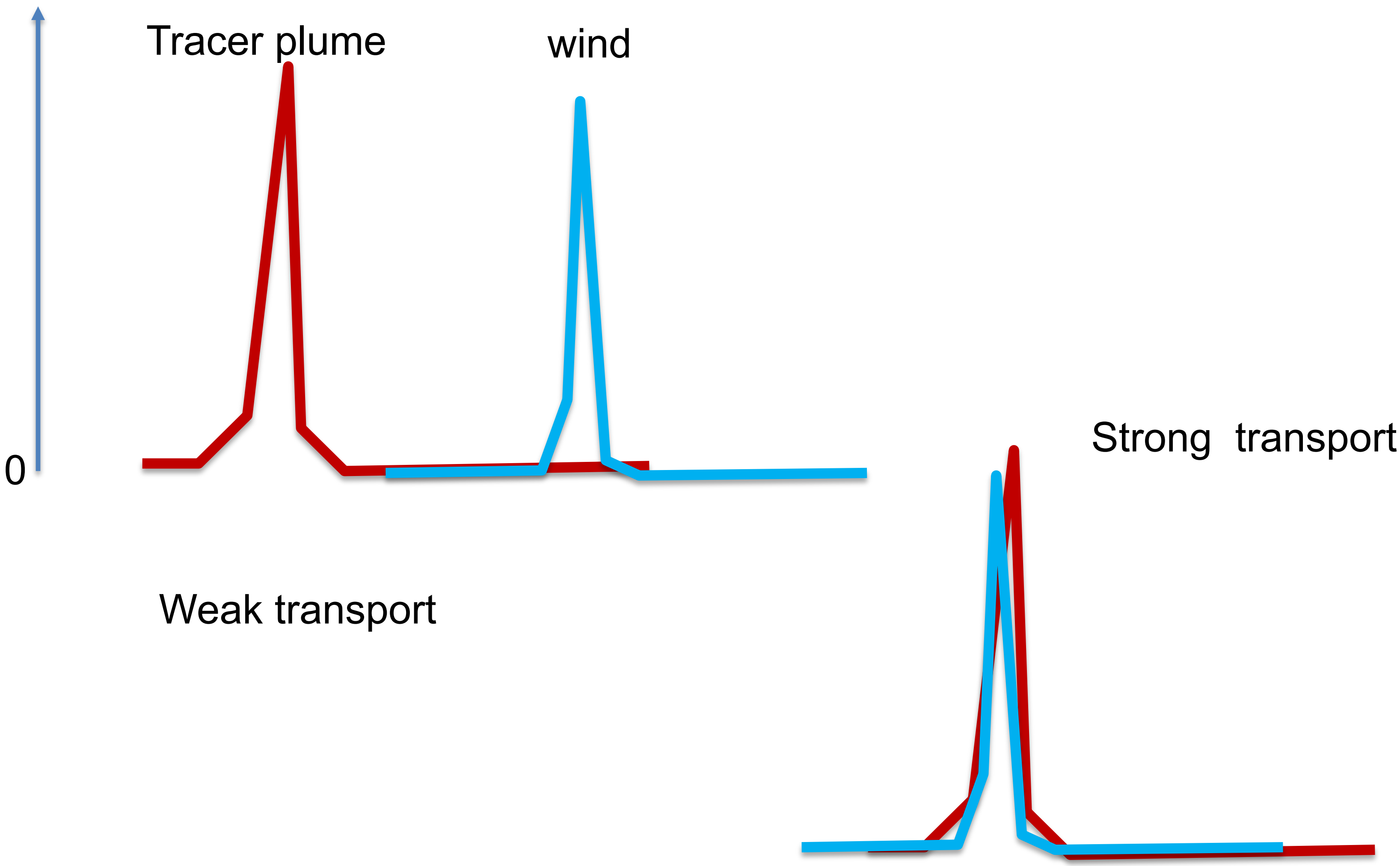
$$M(p) = \left[\frac{1}{5}\sum x^p\right]^{\frac{1}{p}}$$

```
p=1
      M(p)=3.00000

p=2
      M(p)=4.62601

p=10
      M(p)=8.51340
```

Nonlinearity



How do nonlinearities arise?

e.g., Cloud microphysics:

Autoconversion of cloud water to rain

$$P_{l->r} = k{q_l}^a{N_l}^b$$

a ranges from 2 to 4;
b from around -1 to -2

Condensation at RH=1

How do nonlinearities arise?

Fluxes:

$$\partial_t(\rho s) + \partial_x(\rho u s) + \partial_y(\rho v s) + \partial_z(\rho w s) \;=\; P_s$$

$$\partial_t(\rho \bar{s}) + \partial_x(\rho \bar{u}\bar{s}) + \partial_y(\rho \bar{v}\bar{s}) + \partial_z(\rho \bar{w}\bar{s}) =$$
$$\bar{P}_s - \partial_x \rho \overline{u's'} - \partial_y \rho \overline{v's'} - \partial_z \rho \overline{w's'}$$

$\overline{(\;)}$ large−scale horiz. average; $(\;)'$deviation from avg.

"Column physics"

Subgrid horizontal fluxes are typically ignored in atmospheric models

$$\partial_t(\rho\bar{s}) + \partial_x(\rho\bar{u}\bar{s}) + \partial_y(\rho\bar{v}\bar{s}) + \partial_z(\rho w s) =$$
$$\bar{P}_s - \partial_x\rho\overline{u's'} - \partial_y\rho\overline{v's'} - \partial_z\rho\overline{w's'}$$

$$\partial_t(\rho\bar{s}) + \partial_x(\rho\bar{u}\bar{s}) + \partial_y(\rho\bar{v}\bar{s}) + \partial_z(\rho w s) =$$
$$\bar{P}_s - \partial_z\rho\overline{w's'}$$

Column physics don't need to communicate with neighboring grid columns ➔ "embarrassingly parallel"

Summary

- Physics schemes - *"parameterizations"* - need to return tendencies as functions of model grid mean variables
- Tendency calculations may include representation of subgrid variability

How are parameterizations built?

- Basic physics
- Empirical formulations from observations or high-resolution calculations (e.g. LES, CRMs)
- Some simple conceptual model – “cartoon”

Physics Parameterizations needed by an AGCM

- Radiation
    - Clear sky (typically no subgrid variability used)
    - Cloudy
- Surface exchanges
- Boundary Layer Turbulence
- Shallow convection
- Cloud "macrophysics"
- Deep Convection
- Cloud microphysics
- PBL form drag
- Gravity wave drag

Physics Parameterizations in CAM6

- Radiation RRTMG
  - Clear sky (typically no subgrid variability used)
  - Cloudy
- Surface exchanges Similarity theory (Monin-Obukhov …)
- Boundary Layer Turbulence
- Shallow convection
- Cloud "macrophysics"

CLUBB prognostic moments

- Deep Convection Zhang & McFarlane mass flux scheme
- Cloud microphysics Morrison Gettelman 2-moment
- PBL form drag Beljaars et al neutral shear flow over obstacles
- Gravity wave drag Lindzen-type schemes for various sources
- Complex prognostic aerosol model

Mass flux convection schemes in atmospheric models

Convective cloud conceptualized as simple entraining/detraining plume(s)

Thermodynamic Equation

$$\partial_t \rho s + \nabla \cdot \rho \mathbf{u} s + \partial_z \rho w s = \boxed{Q} + \ldots$$

Latent heating

Plume/cloud cont. equation

$$\partial_t \rho \boxed{a} + \partial_z \rho \boxed{a} w_c = \boxed{E} - \boxed{D}$$

Cloud areal fraction

Entrainment

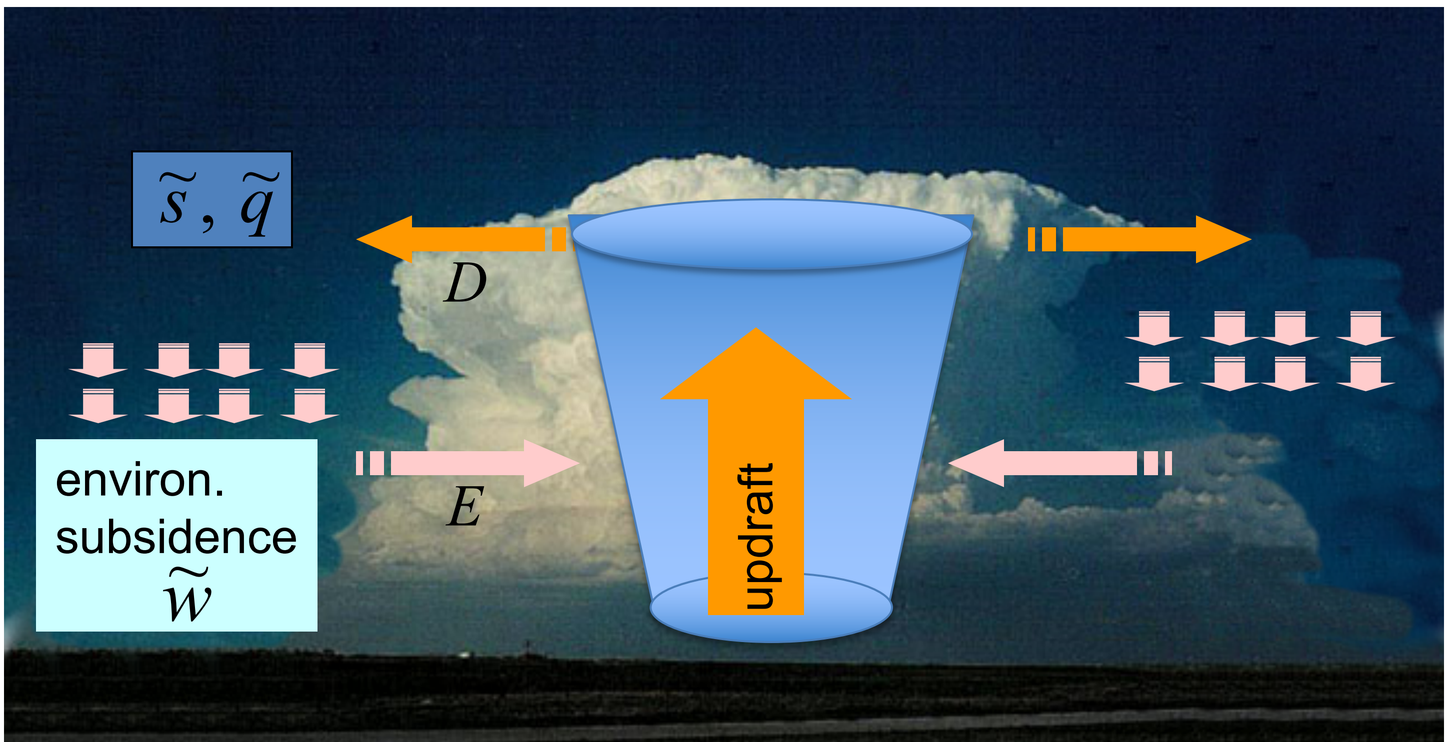
Detrainment

Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = \overline{Q} - \partial_z \overline{\rho w' s'} + \ldots$$

Plume therm. equation

$$\partial_t \rho a s_c + \partial_z \rho a w_c s_c = E\tilde{s} - D s_c + a Q_c$$



Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = aQ_c - \partial_z \overline{\rho w' s'} + \ldots$$

Sub-grid fluxes re-written

$$\partial_z \overline{\rho w' s'} = \partial_z \rho a w_c s_c + \partial_z \rho (1-a) \tilde{w}\tilde{s}$$

compensating subsidence*

$$\Leftrightarrow \rho a w_c = -\rho (1-a) \tilde{w}$$

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = aQ_c - \partial_z \rho a w_c s_c - \partial_z \rho (1-a) \tilde{w}\tilde{s} + \ldots$$

$$\partial_z \rho a w_c s_c = E\tilde{s} - D s_c + aQ_c - \partial_t \rho a s_c$$

Plume therm. equation

Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = aQ_c - \partial_z \overline{\rho w' s'} + \dots$$

Sub-grid fluxes re-written

$$\partial_z \overline{\rho w' s'} = \partial_z \rho a w_c s_c + \partial_z \rho (1-a) \tilde{w} \tilde{s}$$

compensating subsidence*

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$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = \cancel{aQ_c} - \partial_z \rho a w_c s_c - \partial_z \rho (1-a) \tilde{w} \tilde{s} + \dots$$

$$\partial_z \rho a w_c s_c = E\tilde{s} - D s_c + \cancel{aQ_c} - \partial_t \rho a s_c$$

Plume therm. equation

Explicit in-cloud latent heating term drops out

Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = -E\tilde{s} + D s_c + \partial_t \rho a s_c - \partial_z \rho (1-a) \tilde{w} \tilde{s} + \dots$$

Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = -E\tilde{s} + Ds_c + \partial_t \rho a s_c - \partial_z \rho(1-a)\tilde{w}\tilde{s} + \ldots$$

$$-\rho(1-a)\tilde{w} = \rho a w_c \equiv M_c$$

$$a \to 0 \;\Leftrightarrow\; \tilde{s} \to \bar{s}$$

Grid box average therm. equation

$$\partial_t \overline{\rho s} + \overline{\nabla \cdot \rho \mathbf{u} s} + \partial_z \overline{\rho w}\,\overline{s} = \underbrace{-E\bar{s} + Ds_c + \partial_z M_c \bar{s}} + \ldots$$

In final form, cumulus forcing is determined entirely by profiles of E, D, and M_c. Key assumptions up to here:

$$-\rho(1-a)\tilde{w} = \rho a w_c \qquad \text{(compensating subsidence);}$$

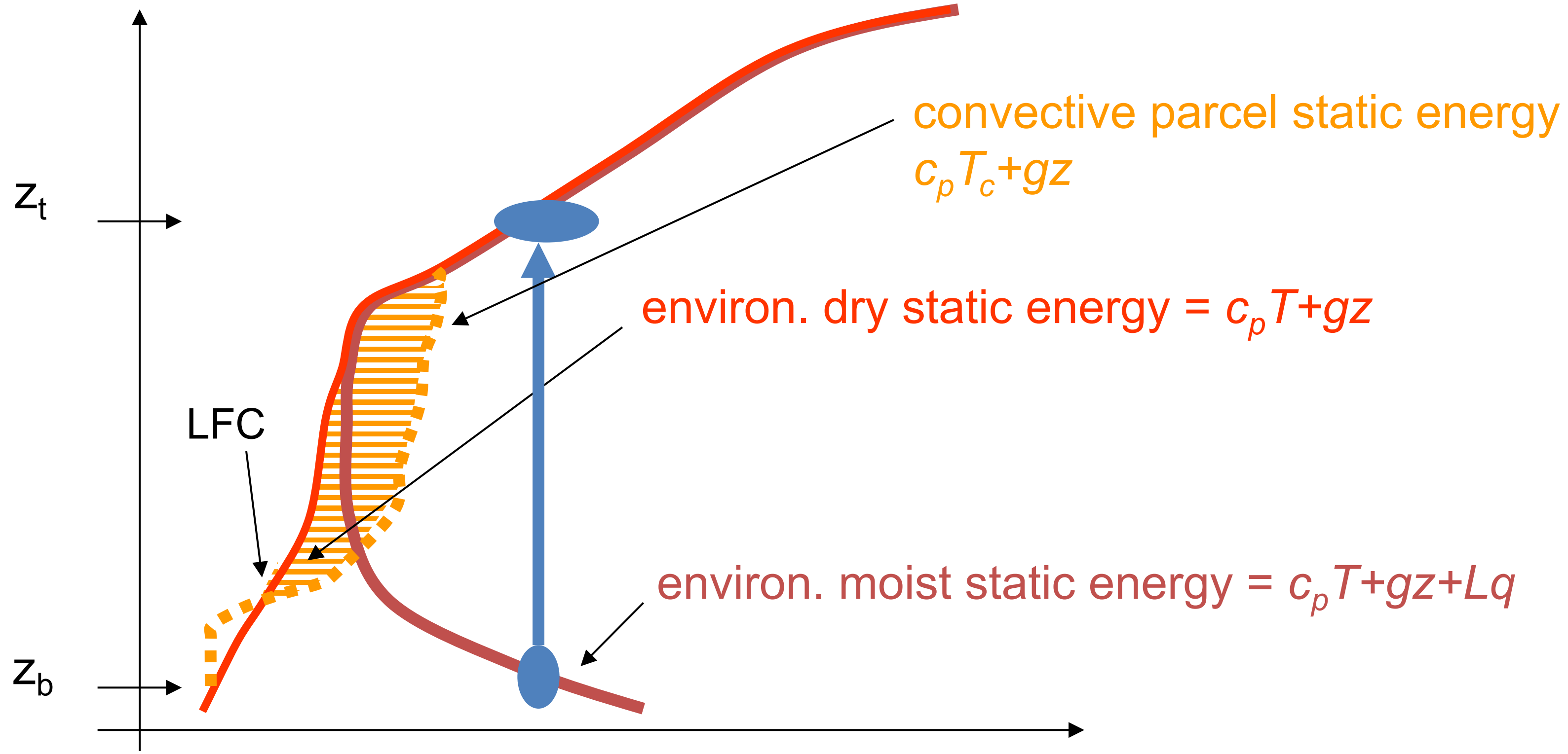
$$a \to 0 \qquad \text{(small areal fraction/negligible storage)}$$

Mass-flux convective parameterizations determine profiles E, D, and M_c based on grid mean quantities and ***assumed plume models***.

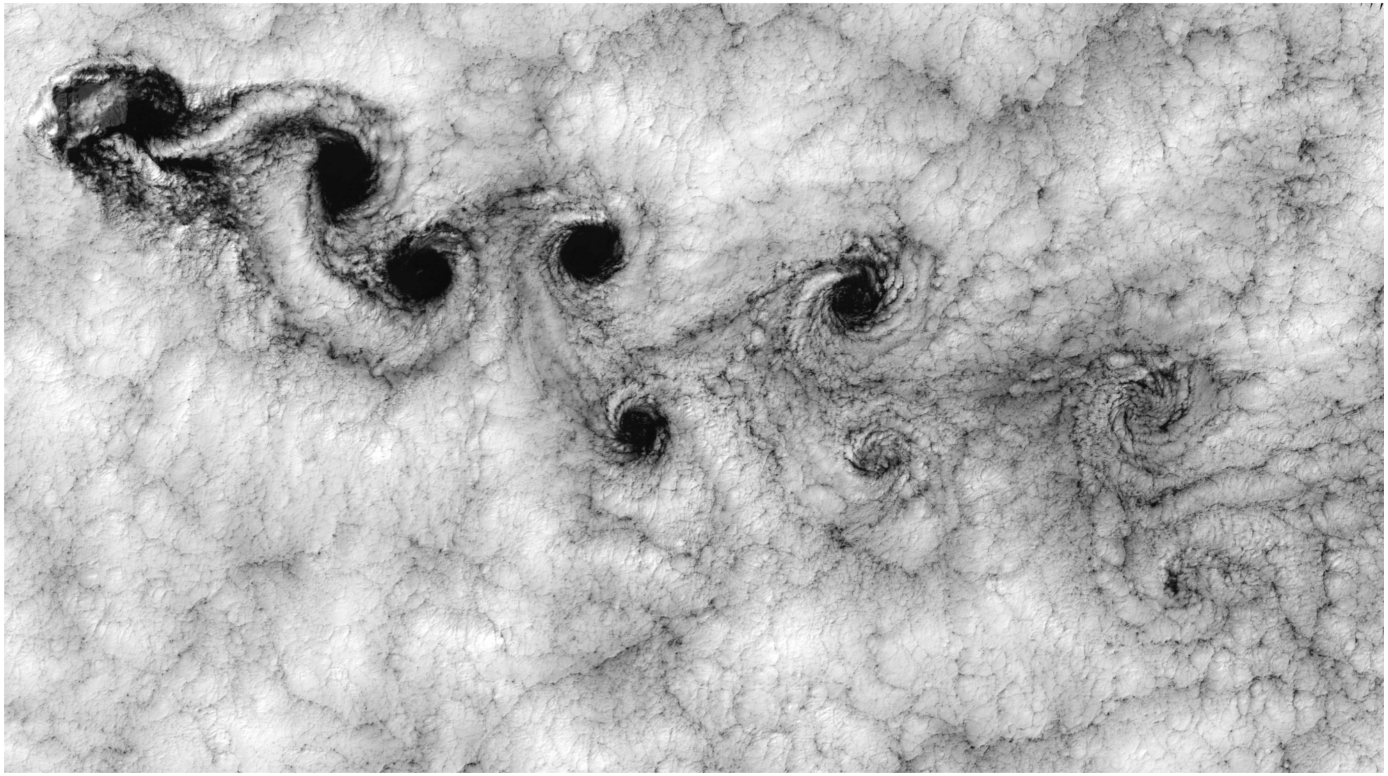
Convective Available Potential Energy is a common control for parameterized convective mass flux in climate models

$$\sim CAPE = g\int_{z_B}^{z_T} \frac{T_c - T}{T}\, dz$$

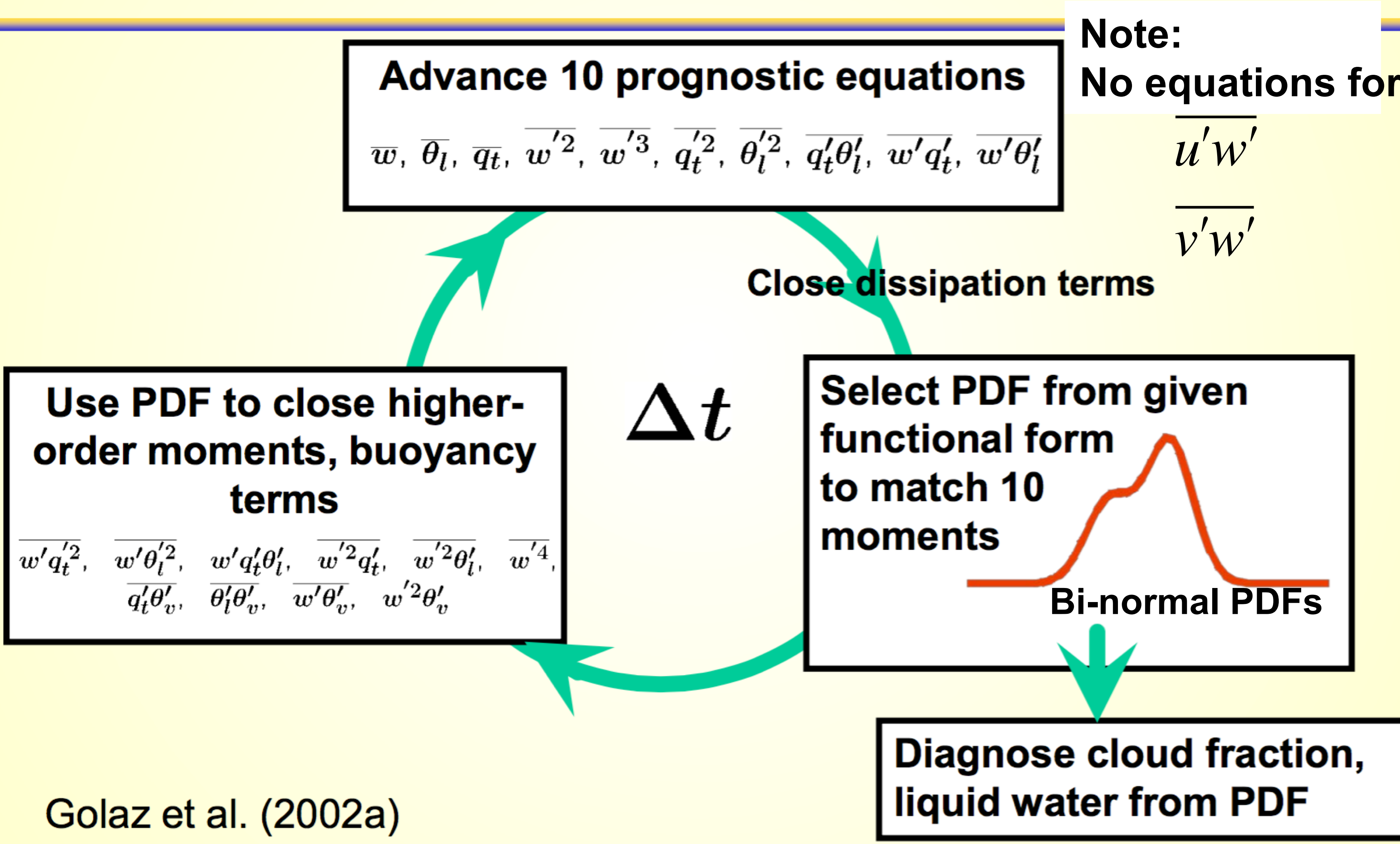
$$M_c(z_b) \sim f(CAPE, \partial_t CAPE)$$



Prognostic higher-order moments for turbulence and shallow convection – Cloud Layers Unified by Bi-normals (CLUBB)



Overview of CLUBB's solution procedure



Golaz et al. (2002a)

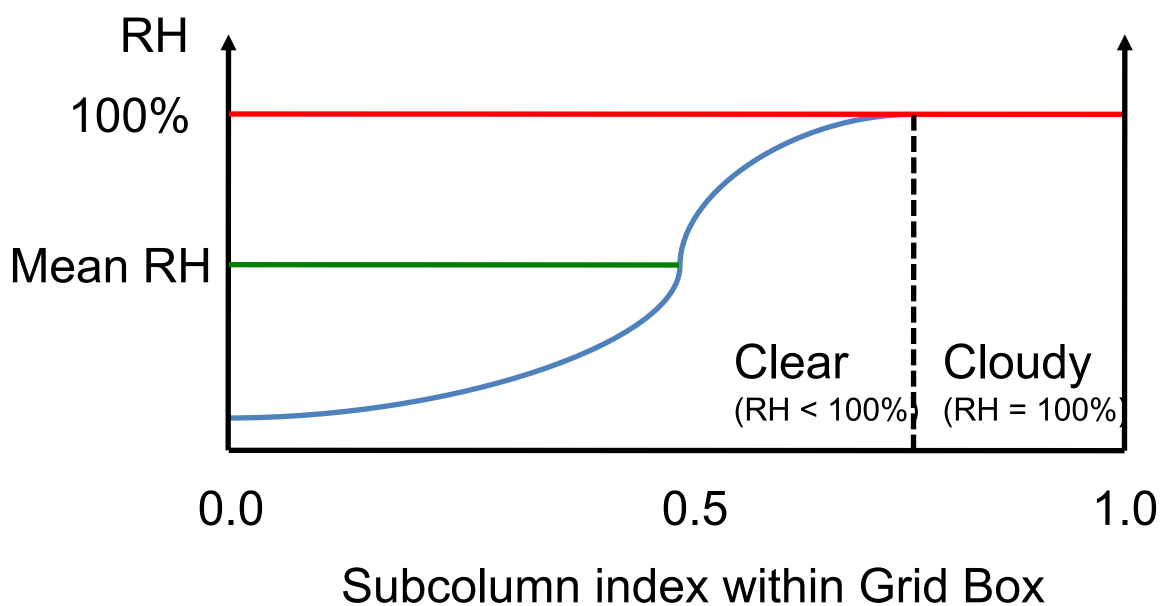
More on Clouds

Stratiform Clouds

Sub-Grid Humidity and Clouds

Liquid clouds form when RH = 100% ($q=q_{sat}$)

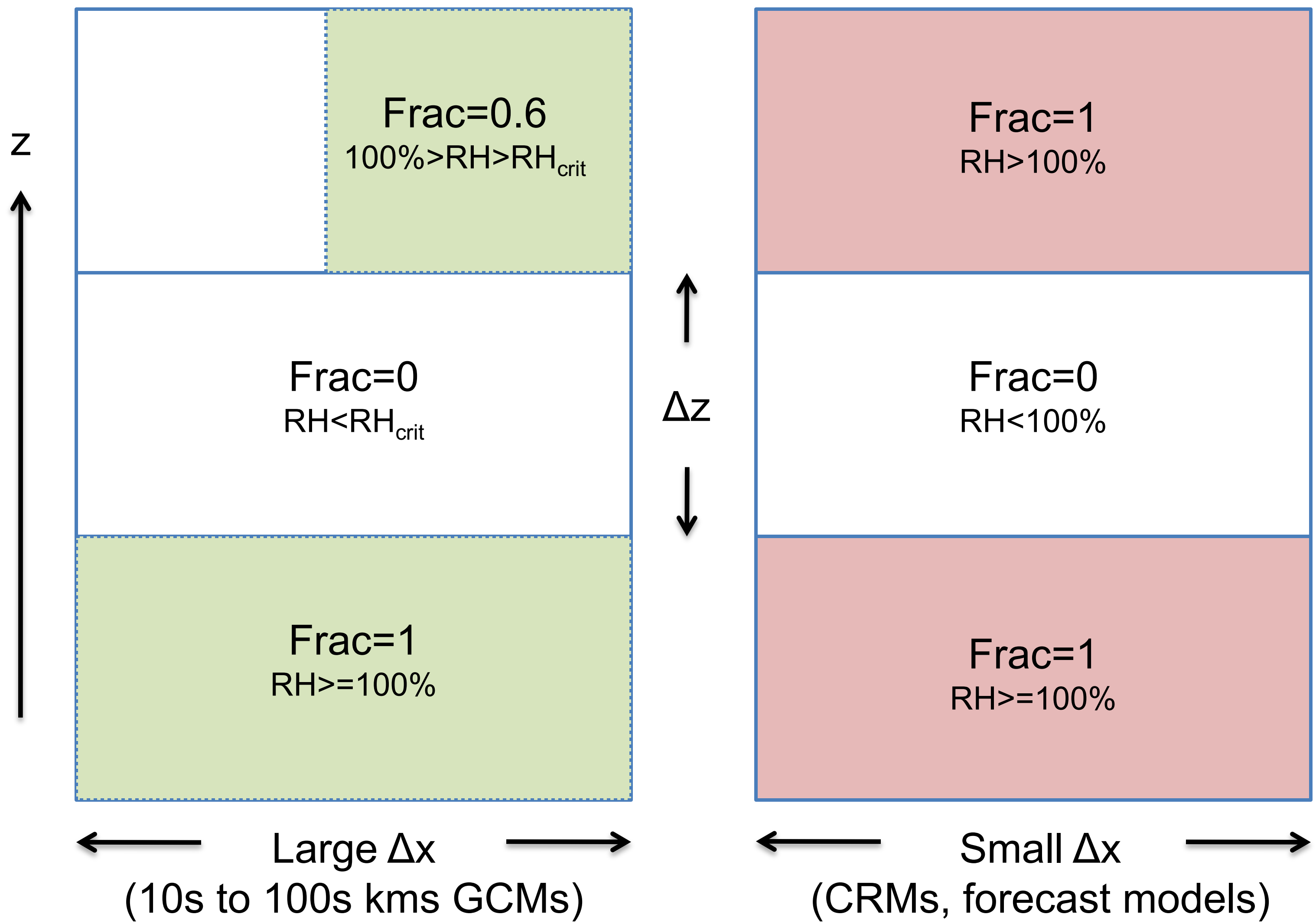
But if there is variation in RH in space, some clouds will form before *mean* RH = 100%



Assumed Distribution function of Humidity in a grid box with sub-grid variation

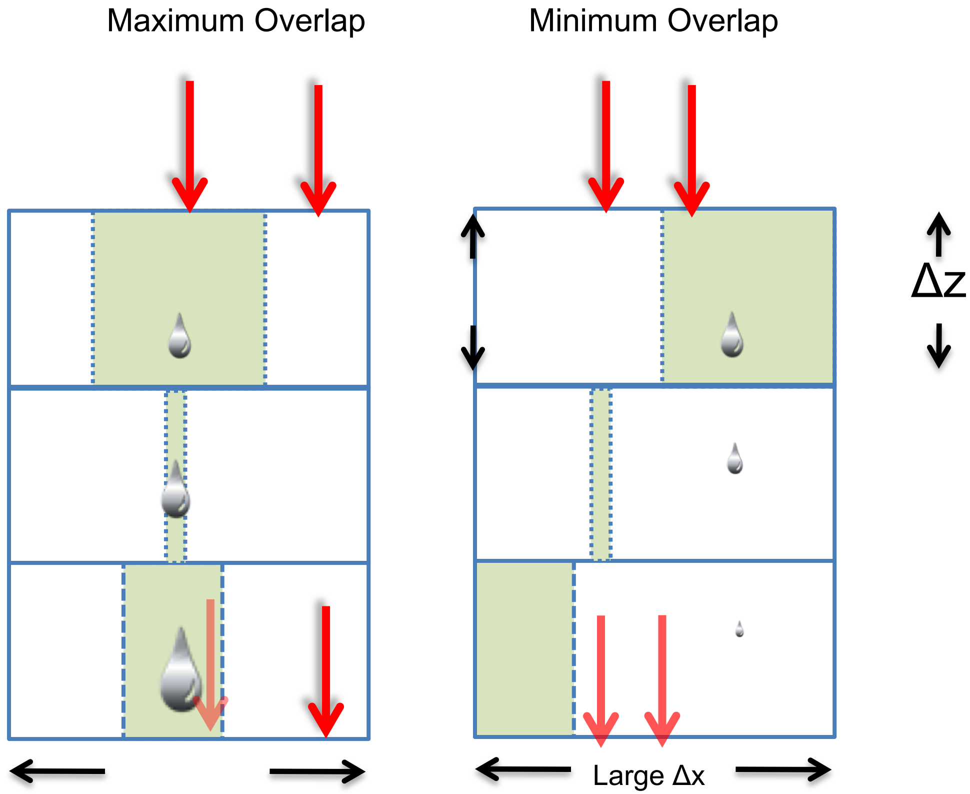
Fractional Cloud Cover

Cloud_Frac=f(RH,w,water,aerosols,time,…)



The Cloud Overlap Challenge

Radiation and micro/macro-physics impact



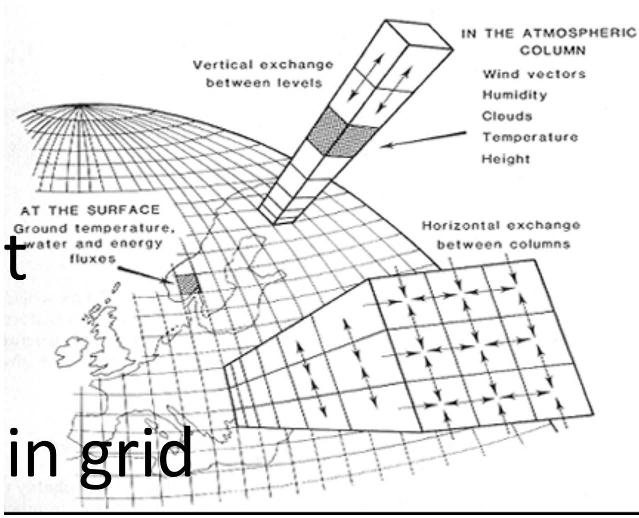
- Contiguous cloudy layers maximally overlapped in CAM
- Non-contiguous layers randomly overlapped

Parameterizations

High level design

1. Inputs and effects totally contained within single columns
   - Single grid point structures are believed
2. Most (many common) schemes do not possess a "memory"
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)

1,2 and 3 begin to cause trouble as resolution increases and time-steps decrease



Parameterizations

High level design

Process splitting versus time splitting (CAM)

Process splitting:

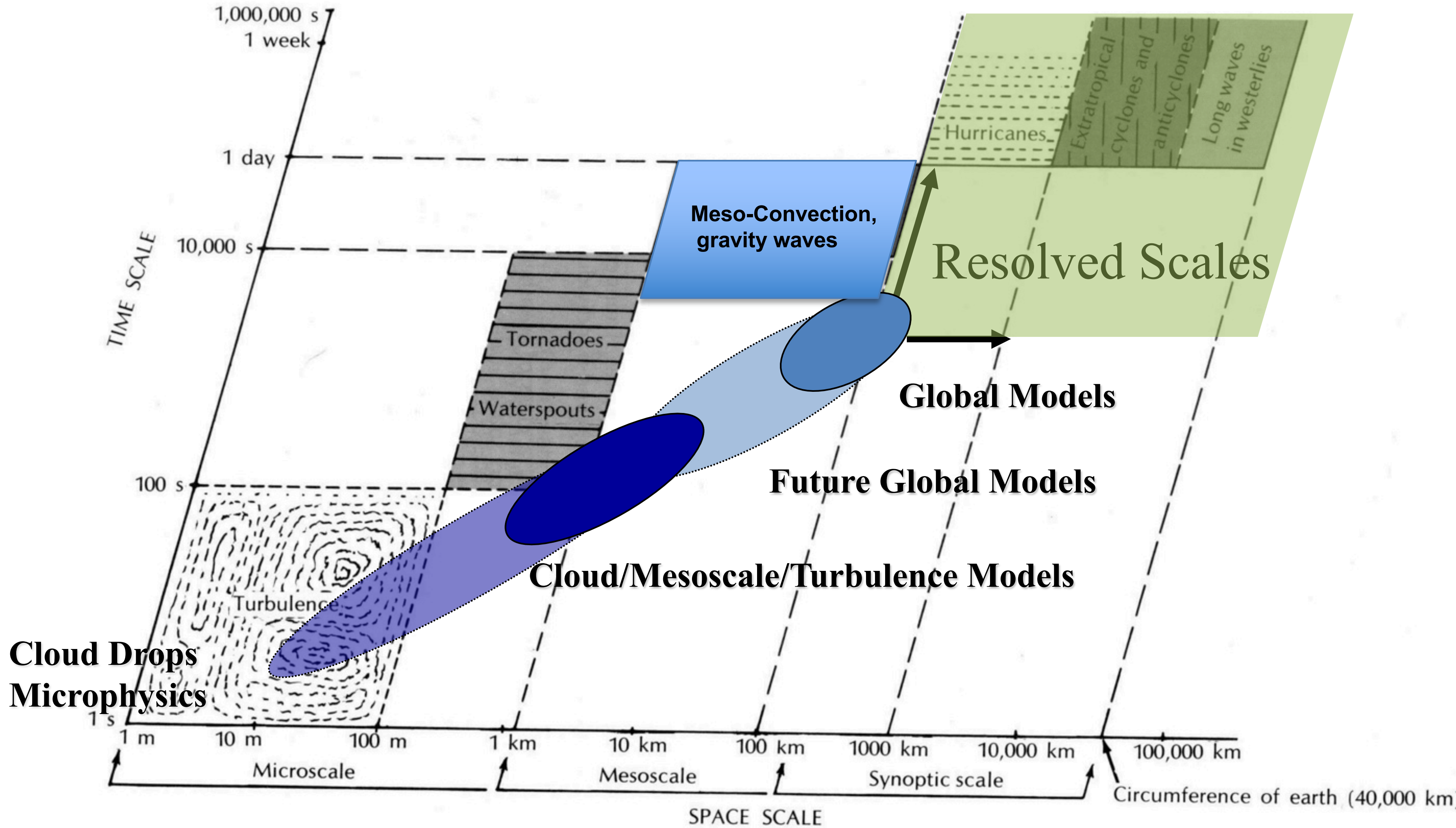
- All parameterizations work on same state. Provide tendencies for unified update

Time splitting

- Parameterizations update state as they work and pass updated state to next param.

Scales of Atmospheric Processes

Determines the formulation of the model



Future Directions for Physics in Models?

What do we need to consider?

As grid-sizes and time steps decrease, parameterizations may need to communicate across space and time

As grid-sizes and time steps decrease, resolved scales may not contain enough information to close parameterizations

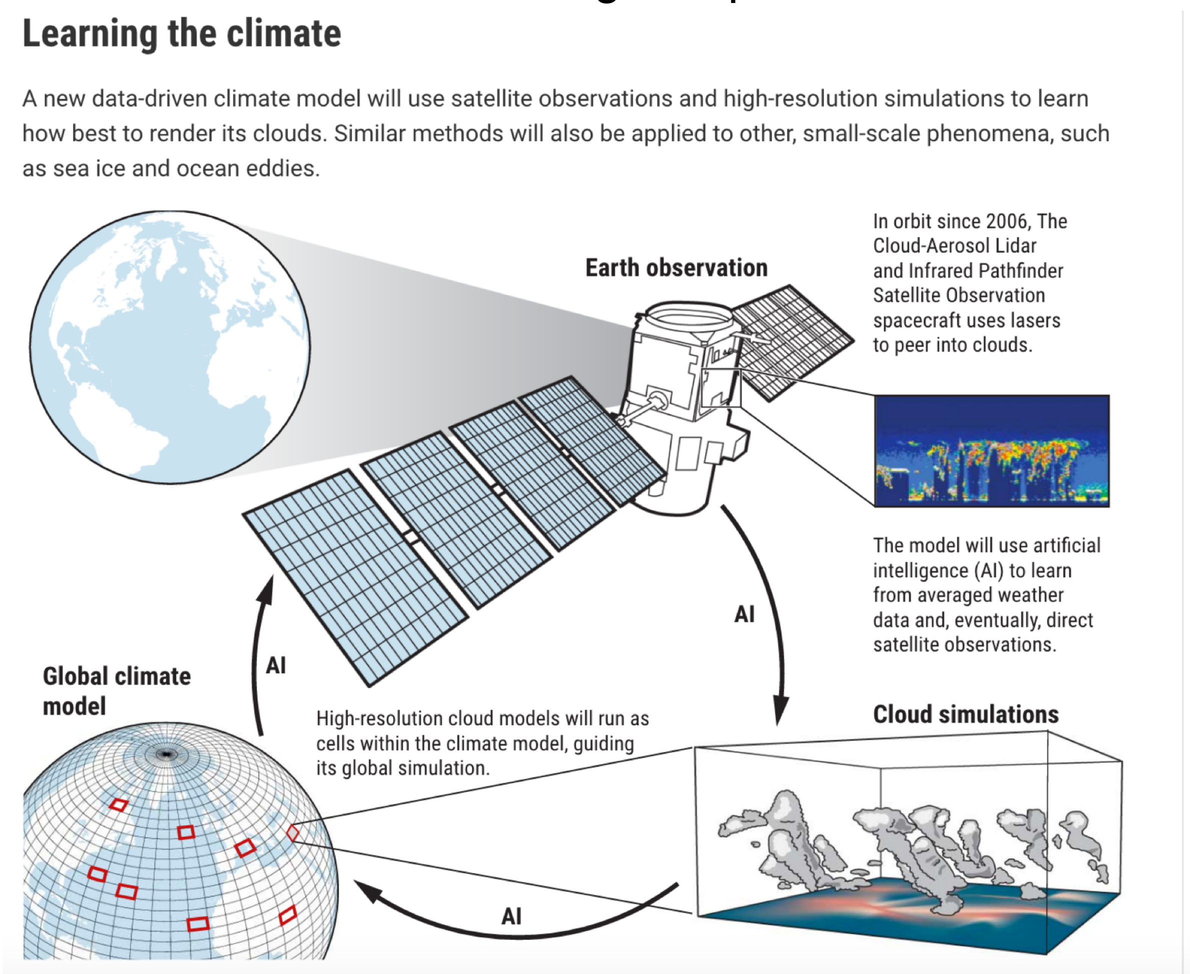
- Stochastic elements?
- Life-cycles of processes?

At any resolution, better sub-grid representations are needed

- Subcolumns?

Future Directions for Physics in Models?

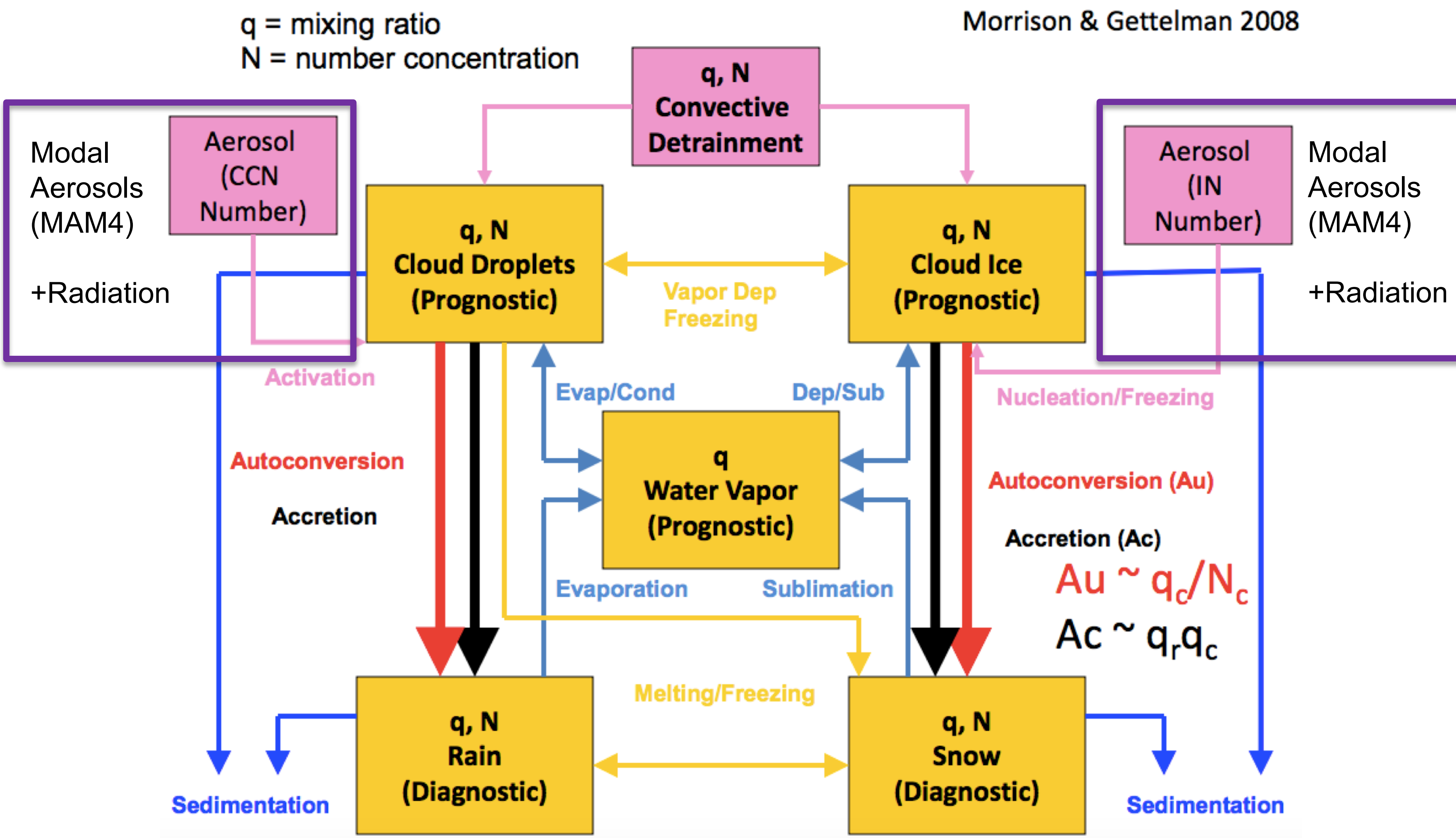
Science insurgents plot a climate model driven by artificial intelligence
By Paul VoosenJul. 26, 2018 , 2:00 PM
http://www.sciencemag.org/news/2018/07/science-insurgents-plot-climate-model-driven-artificial-intelligence



Questions?

EXTRA SLIDES

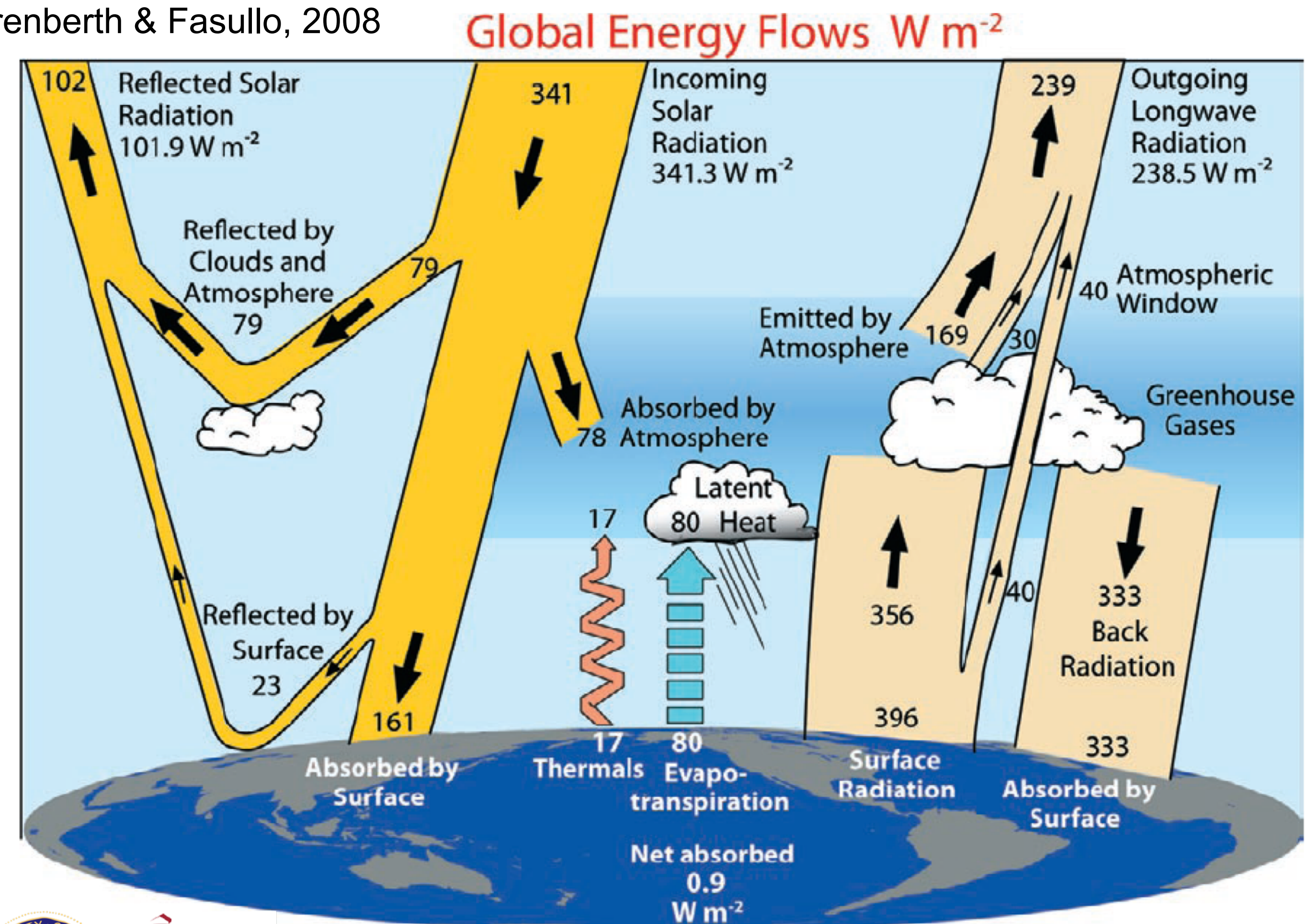
CAM5 Microphysics



Radiation

The Earth's Energy Budget

Trenberth & Fasullo, 2008

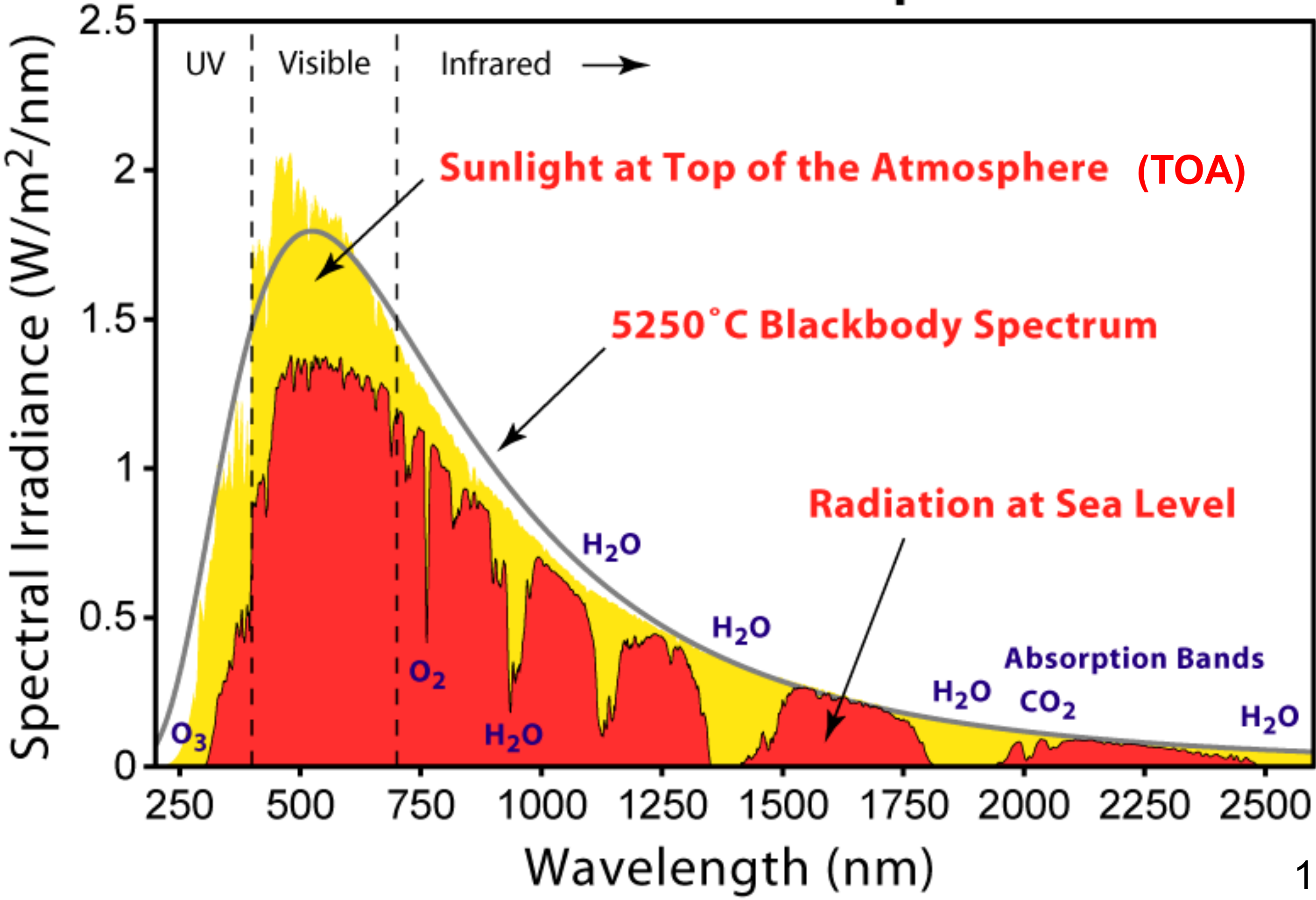


Gas	SW Absorption (Wm^{-2})
CO_2	1
O_2	2
O_3	14
H_2O	43

+Condensed species: Clouds & Aerosols

Bill Collins, Berkeley & LBL

Solar Radiation Spectrum

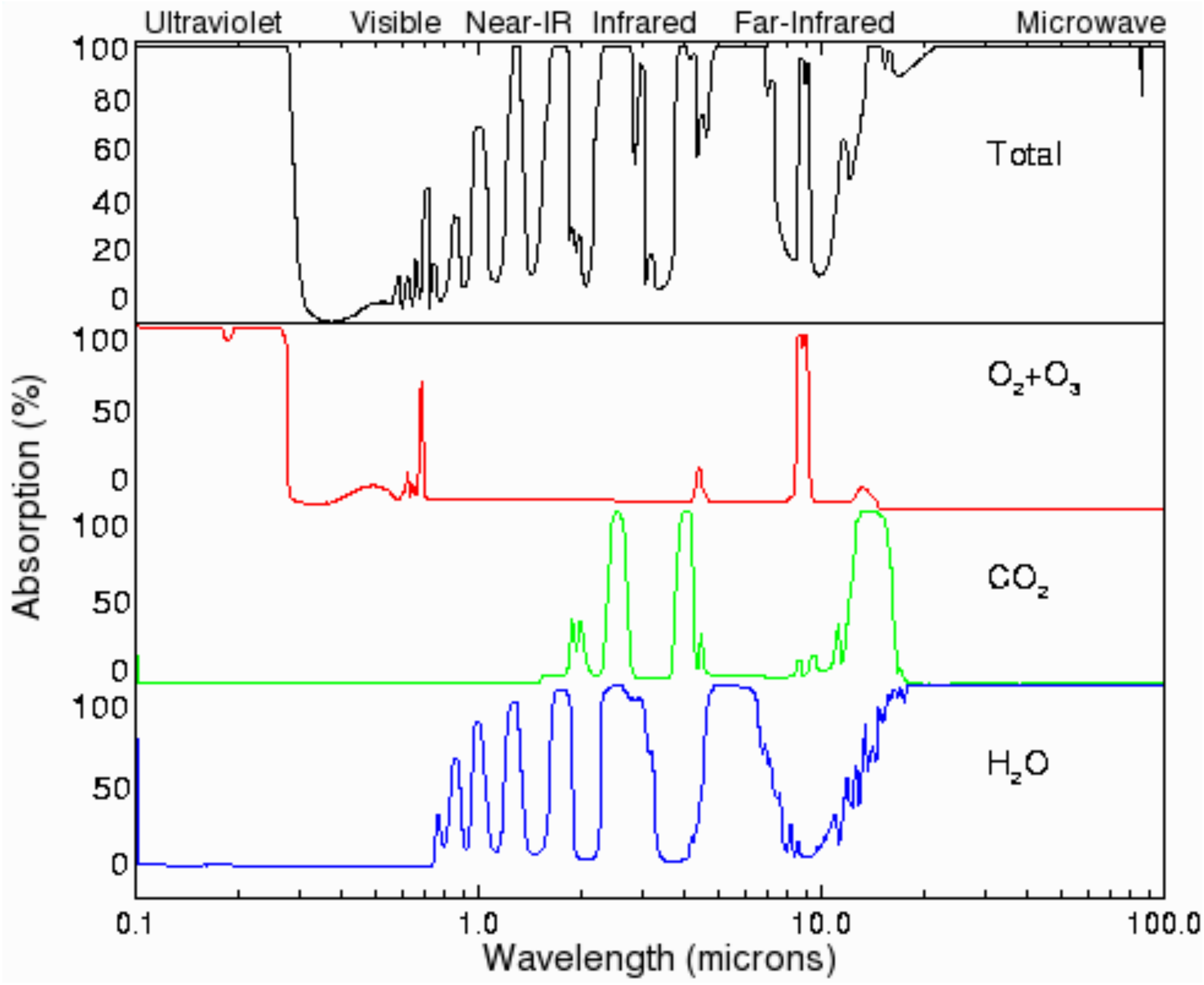


1000nm = 1μm

Input at TOA, Radiation at surface

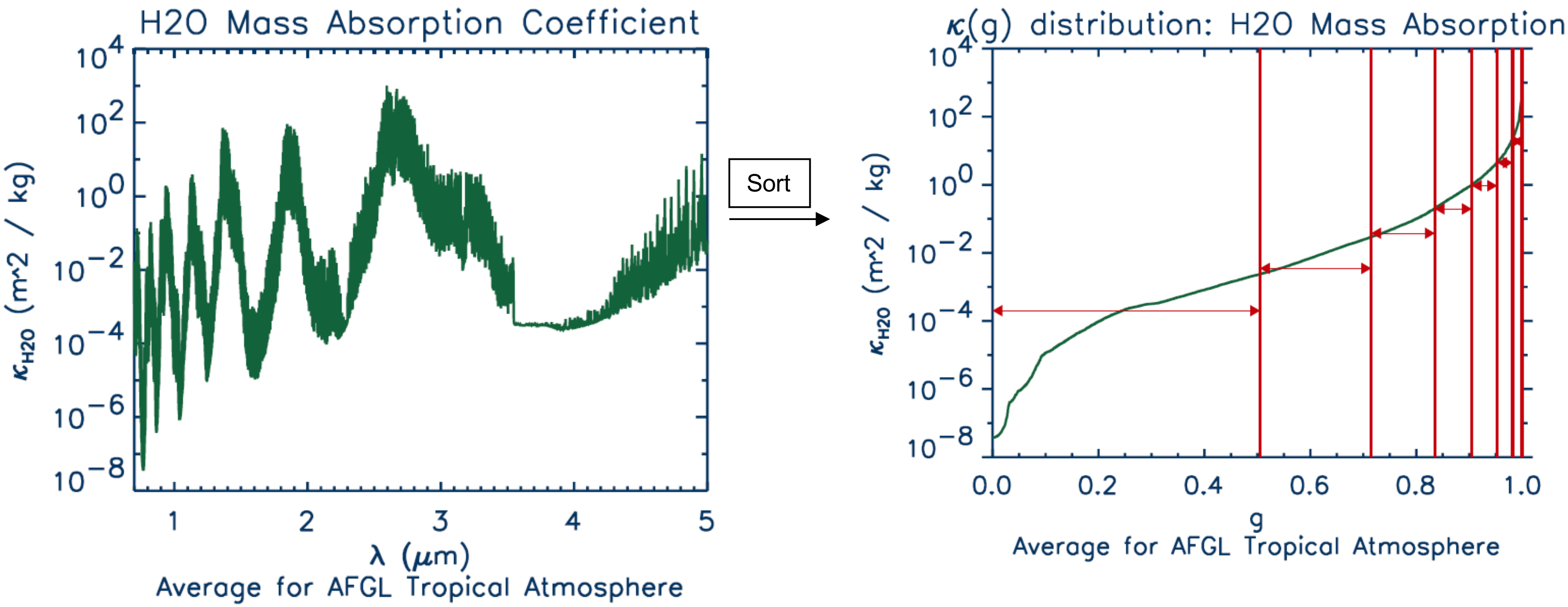
From: 'Sunlight', Wikipedia

IR absorption



1000nm = 1μm

k-distribution Band Models



• Line-by-line calculations

•Very expensive/slow, accurate

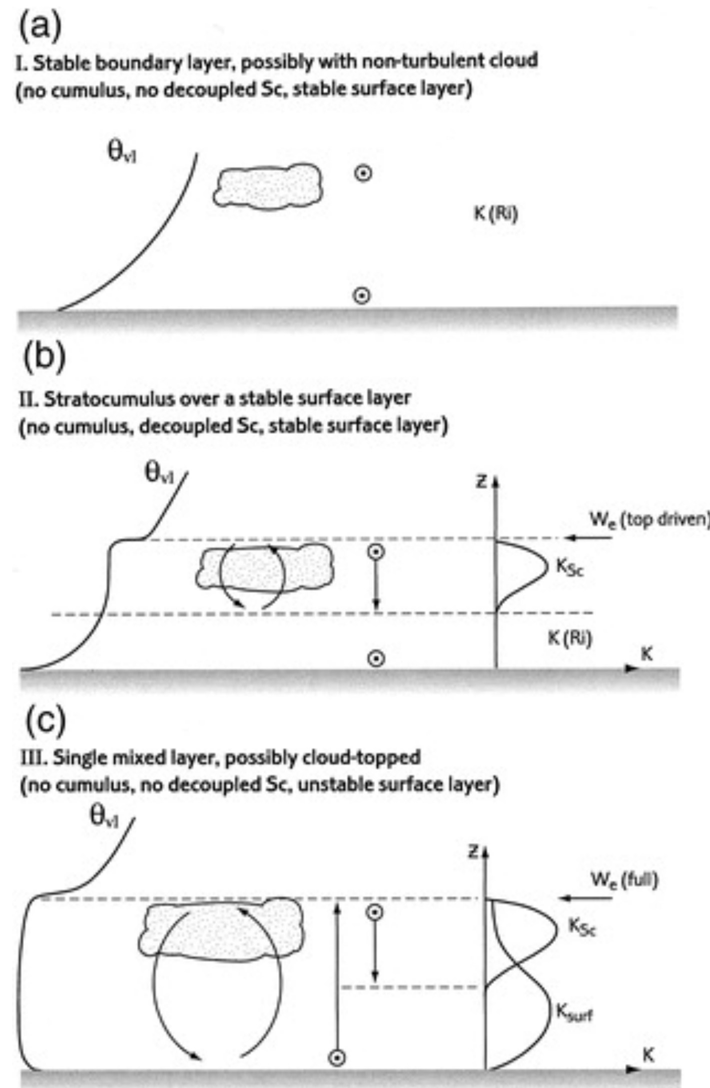
• k-distribution band model, sort absorption coefficients by magnitude

• **Cheaper/fast, less accurate**

Planetary Boundary Layer (PBL)

Regime dependent representations

- Vital for near-surface environment (humidity, temperature, chemistry)
- Exploit **thermodynamic conservation** (liquid virtual potential temperature θ_{vl})
- **Conserved** for rapidly well mixed PBL
- **Not conserved** for stable PBL
- Critical determinant is the presence of turbulence
- **Richardson number** $$\mathrm{Ri} = \frac{g\beta}{(\partial u/\partial z)^2},$$
- <<1, flow becomes turbulent
- CAM4: Gradient Ri # + non-local transport (Holtslag and Boville, 1993)
- CAM5: TKE-based Moist turbulence (Park and Bretherton, 2009)



How do we parameterize this menagerie of small-scale flows in a global model???

Subgrid momentum fluxes

Momentum Equation

$$\partial_t \rho \mathbf{u} + \ldots + \partial_z \rho w \mathbf{u} = -\nabla p - \rho \nabla \phi + \mathbf{F} + \ldots, \quad \rho \text{ is atmospheric density}$$

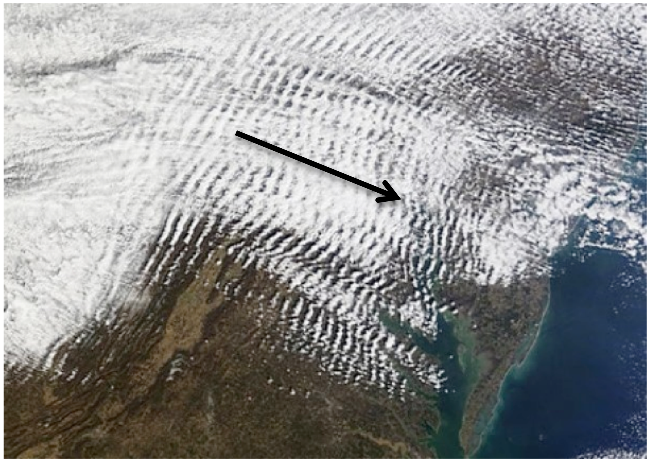
Grid box average momentum equation

$$\partial_t \bar{\rho} \bar{\mathbf{u}} + \ldots + \partial_z \bar{\rho} \bar{w} \bar{\mathbf{u}} = -\nabla \bar{p} - \bar{\rho} \nabla \bar{\phi} - \partial_z \overline{\rho u' w'}\, \mathbf{i} - \partial_z \overline{\rho v' w'}\, \mathbf{j} + \bar{\mathbf{F}}$$

Vertical derivatives of zonal and meridional subgrid vertical momentum fluxes produce drag forces

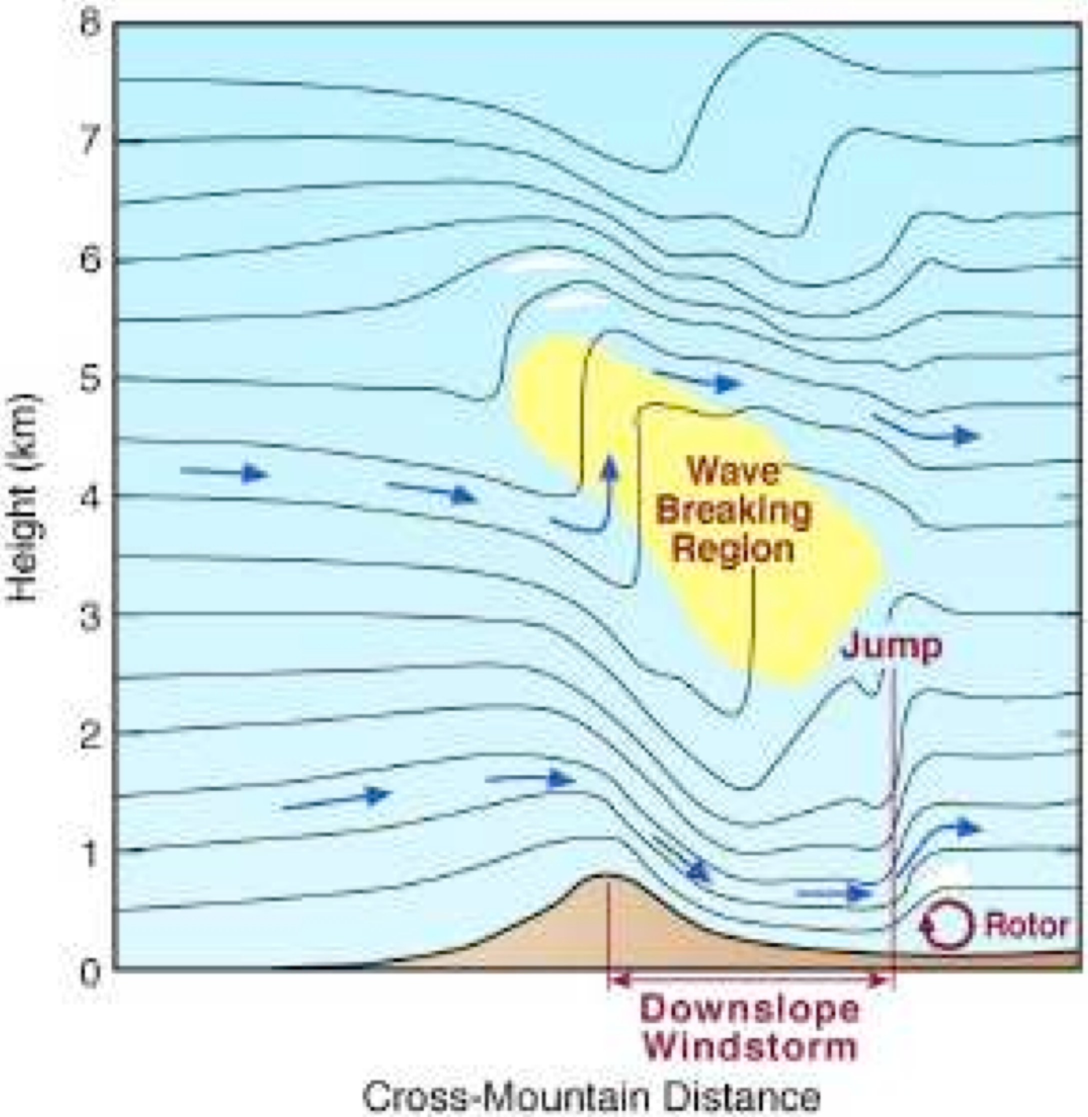
Subgrid momentum fluxes

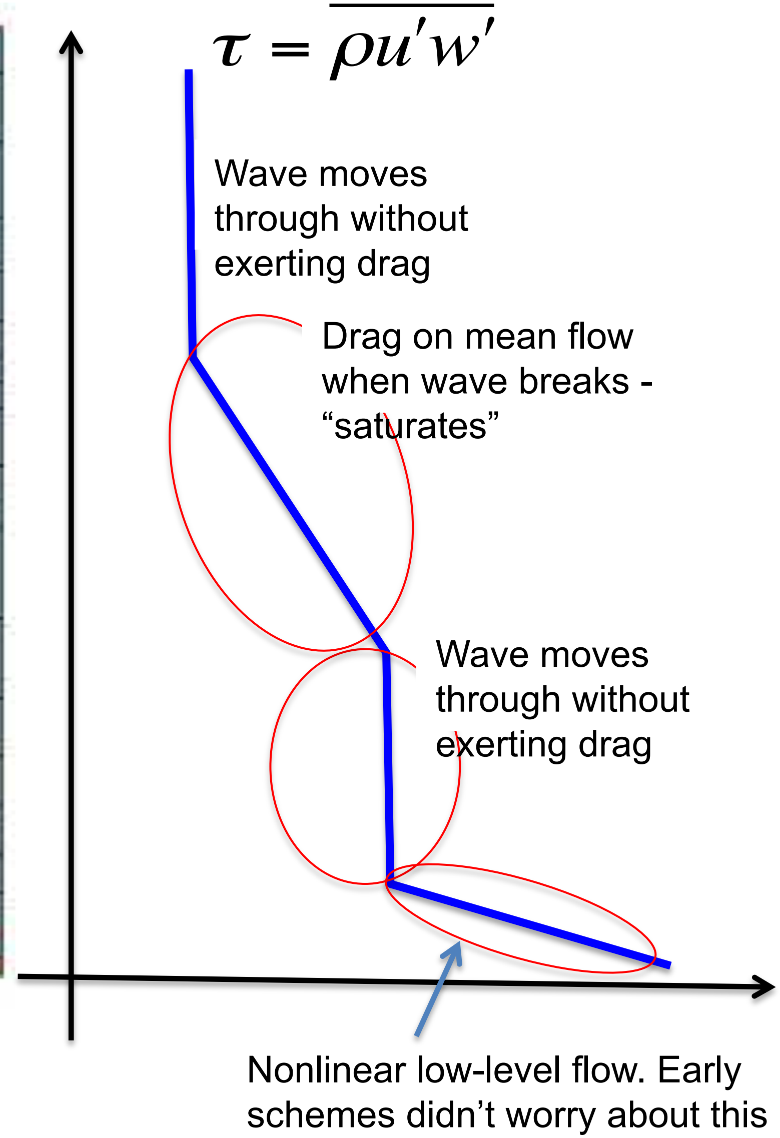
Let's turn into coordinates where "x" is perpendicular to wave cres



Our job is then to calculate

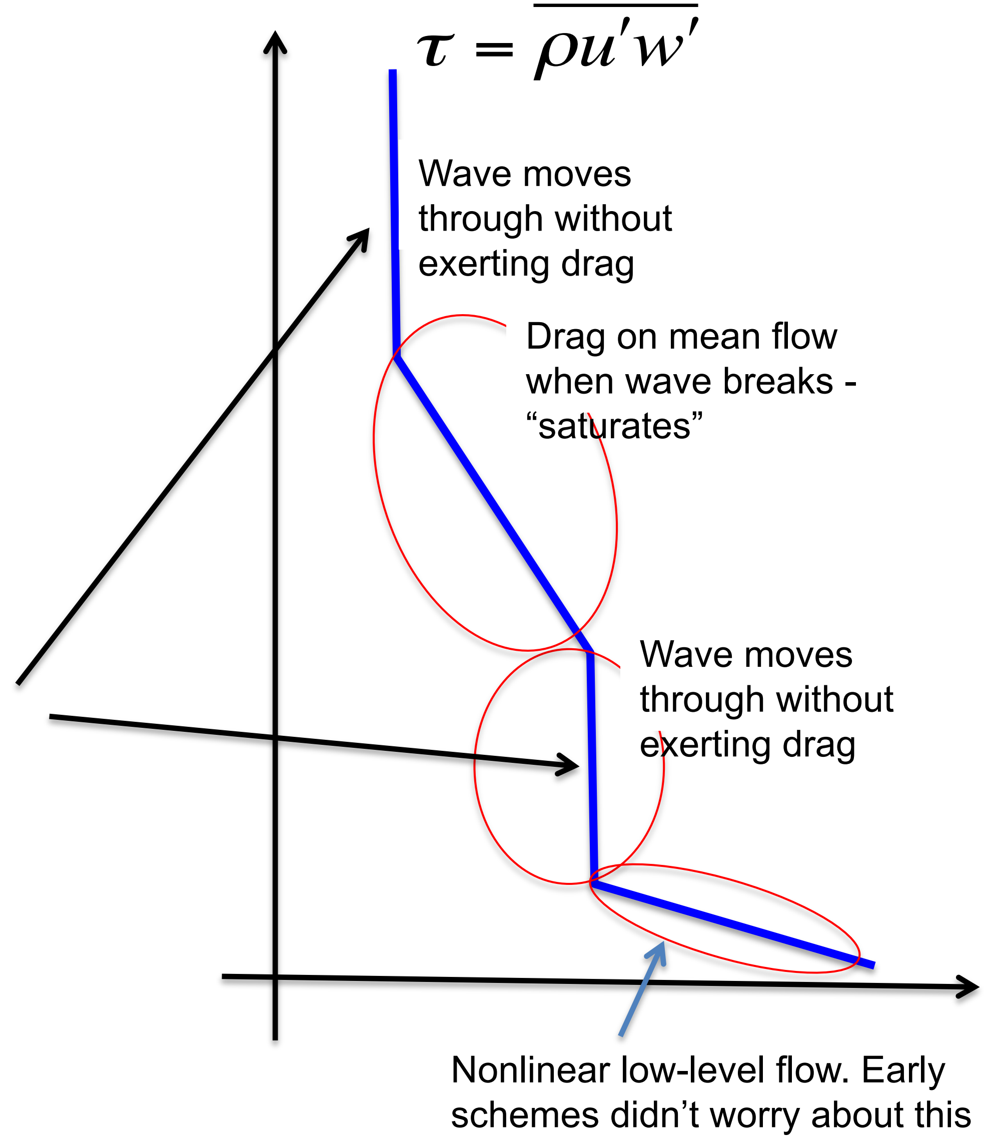
$$\tau = \overline{\rho u' w'}$$





Complex wave pattern conceptualized as 2D monochromatic wave controlled by “saturatio

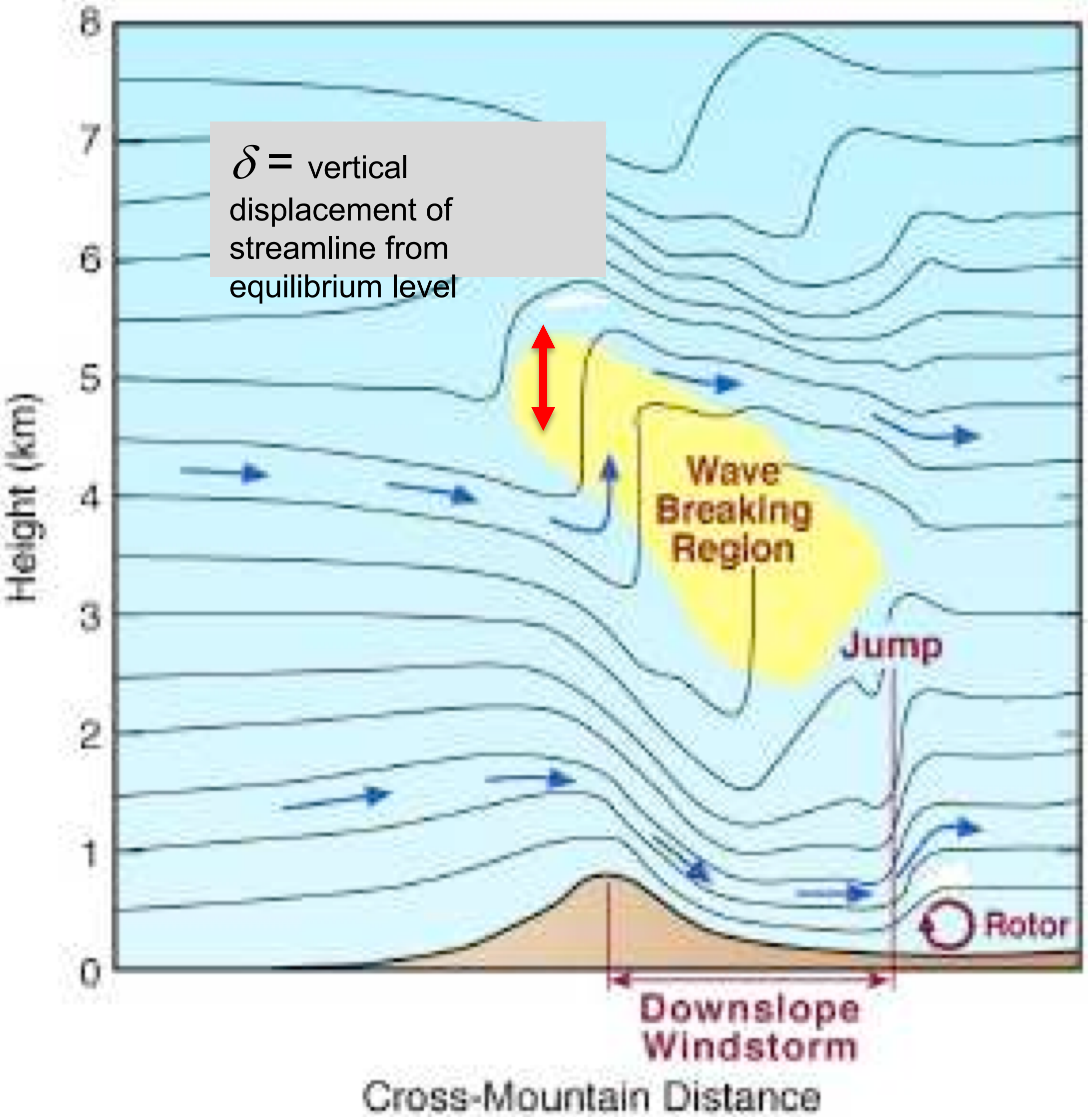
Lindzen, R. S. (1981). Turbulence and stress owing to gravity wave and tidal breakdown. *Journal of Geophysical Research*, *86*(C10), 9707-9714.

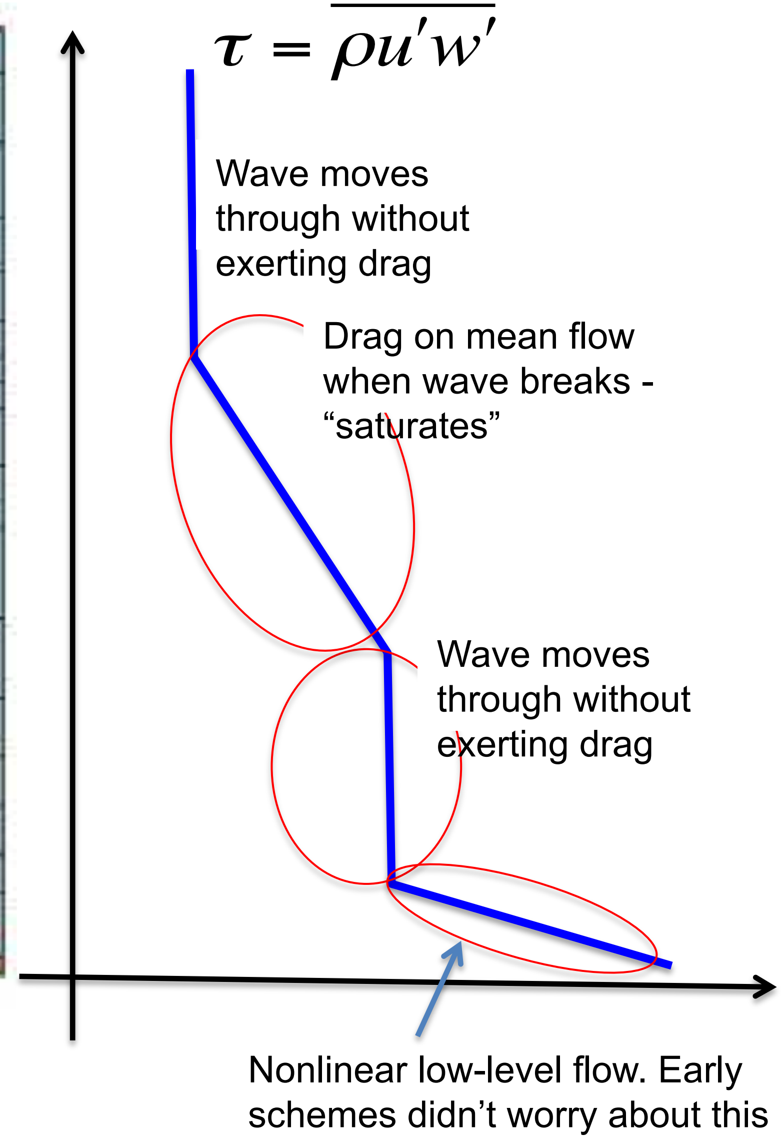


Eliassen-Palm theorem:
Non-dissipating waves have conserve τ as they propagate vertically

Complex wave pattern conceptualized as 2D monochromatic wave controlled by "saturatio

Lindzen, R. S. (1981). Turbulence and stress owing to gravity wave and tidal breakdown. *Journal of Geophysical Research*, *86*(C10), 9707-9714.





How do we calculate τ based on topographic information?

Orographic gravity wave momentum flux based on δ and gravity wave dispersion relationships

$$u' = N\delta$$

$$w' = k\bar{U}\delta$$

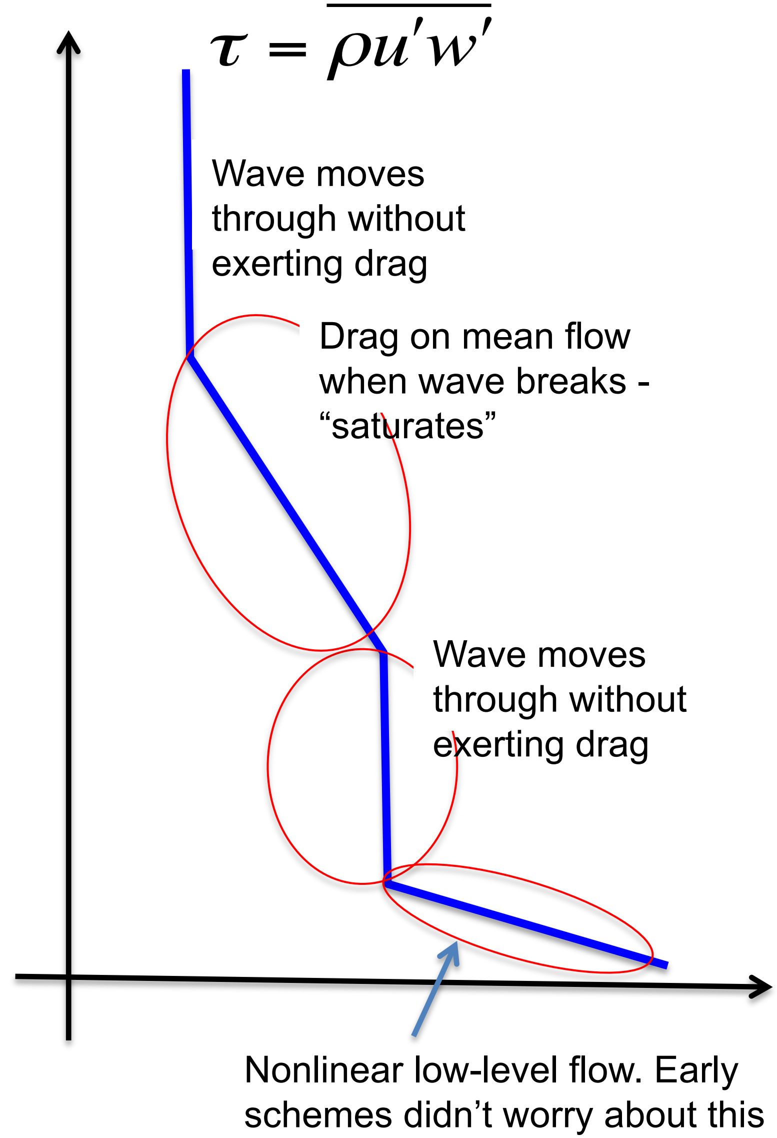
so momentum flux becomes

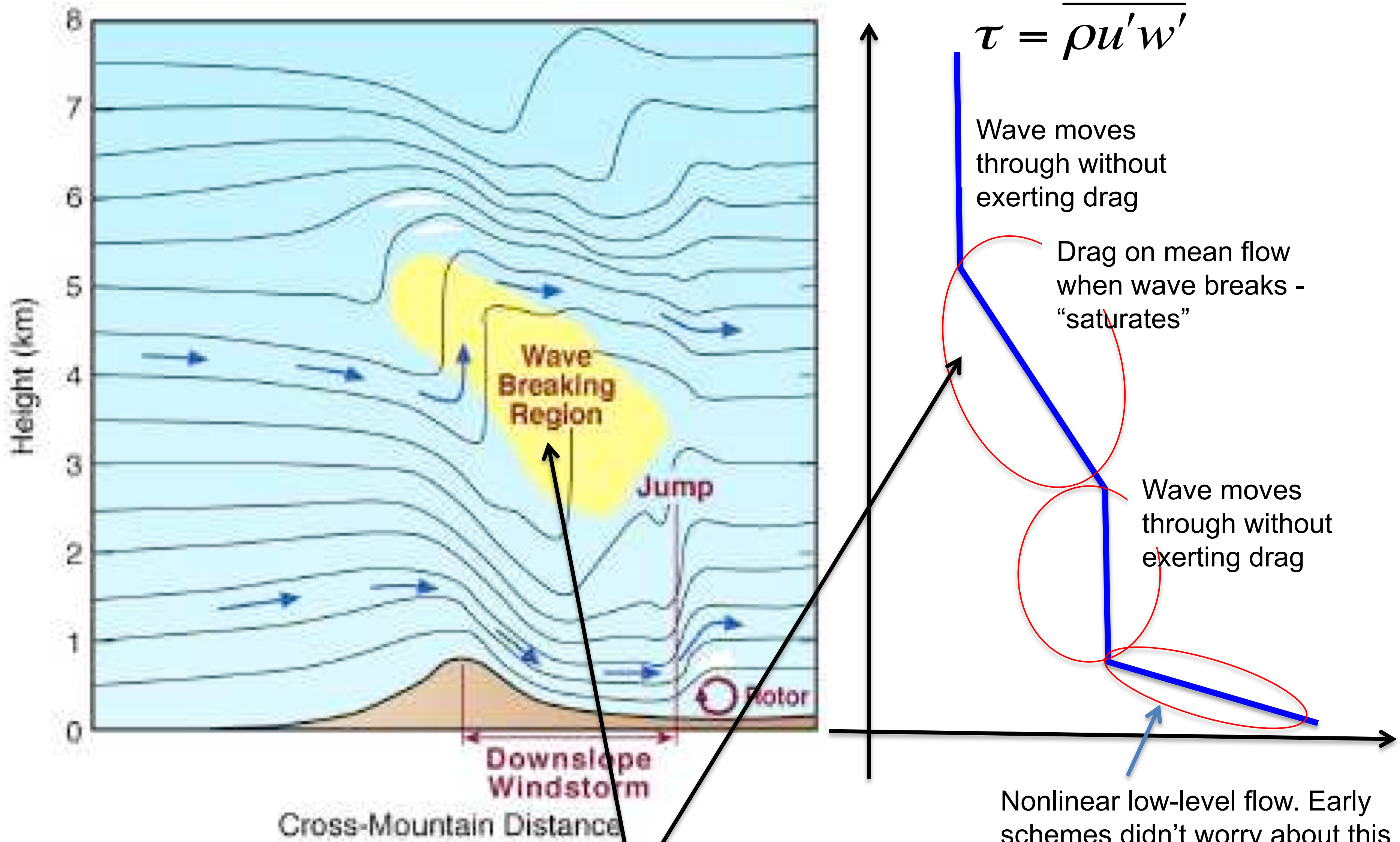
$$\tau \approx C\rho k\bar{U}N\delta^2$$

Intuitively obvious that δ at source level is related to mountain heights

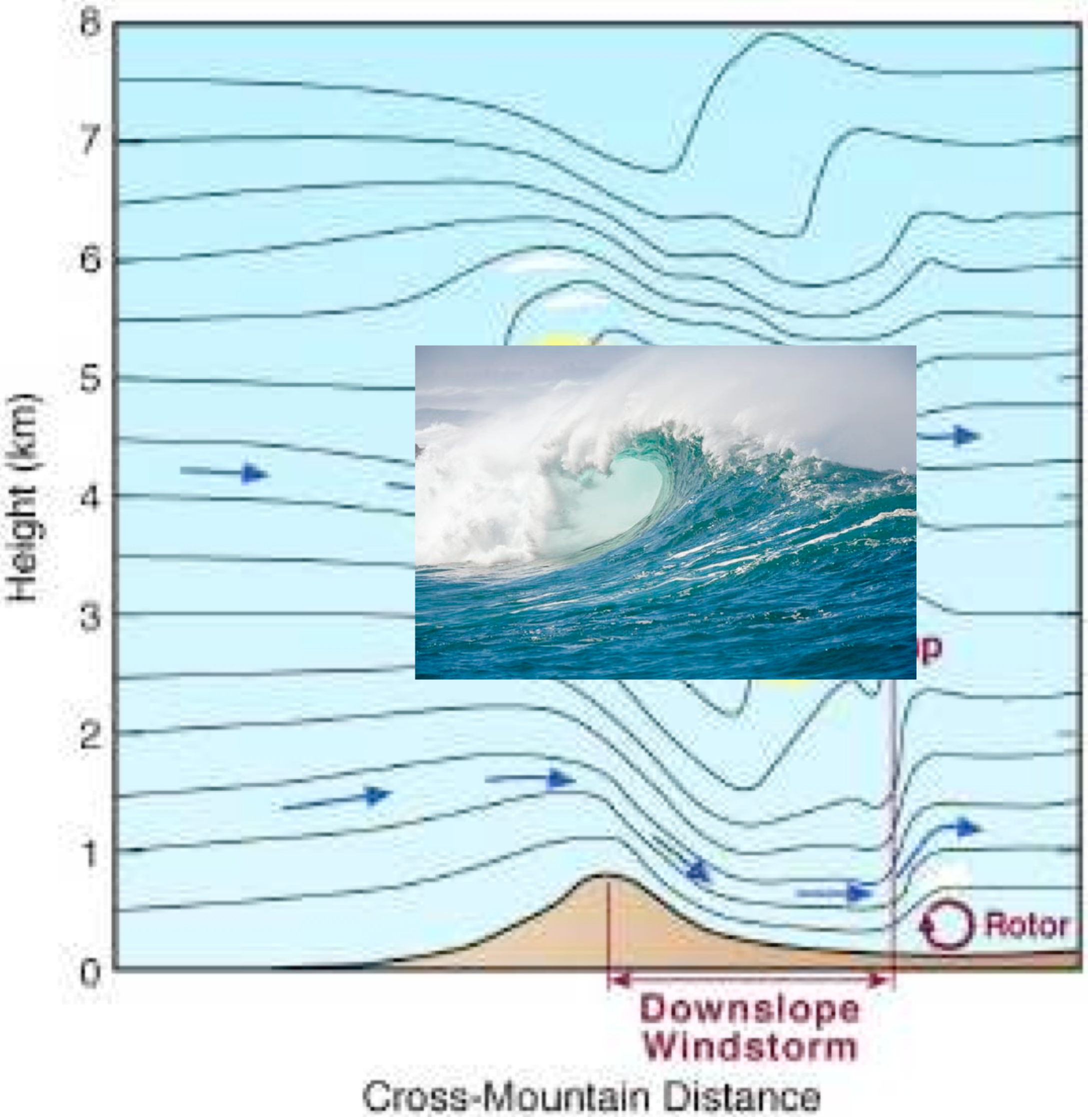
Not so obvious how to get δ from topographic data:

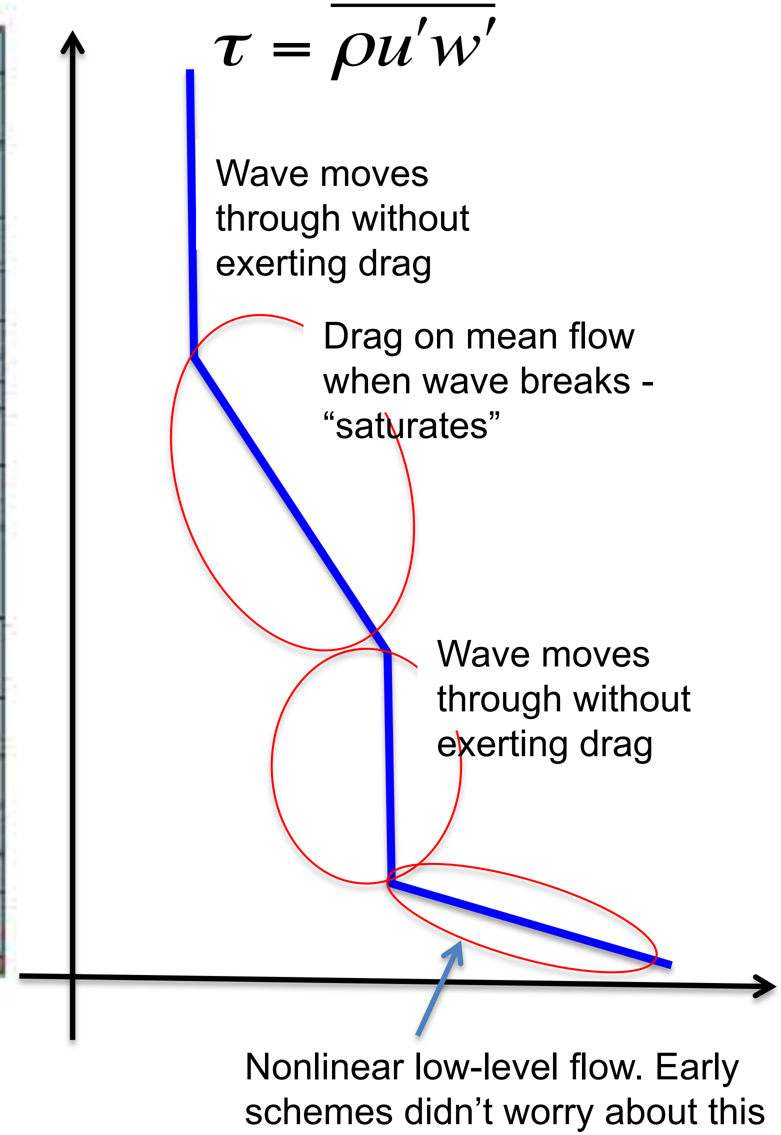
- RMS of subgrid topo?
- Residuals left after smoothing ?





What about **“Saturation”,** i.e.,wave breaking??





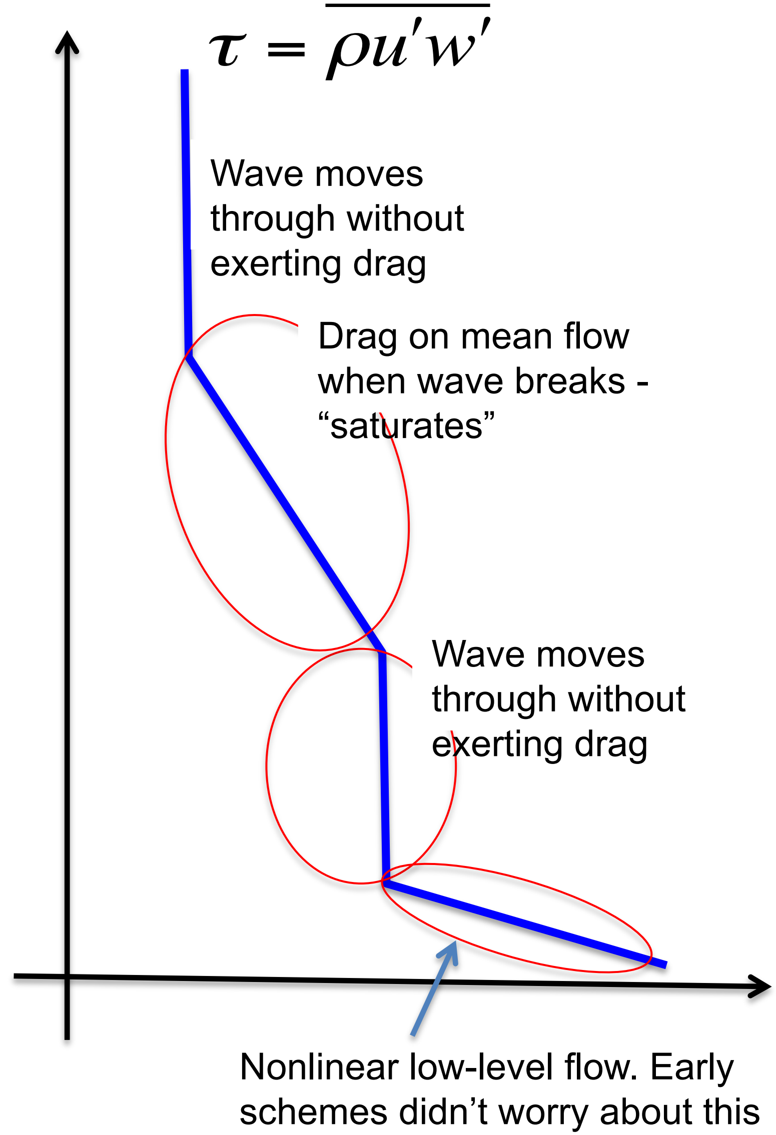
Gravity wave saturation/breaking occurs when streamlines are vertical or overturning ➔local convective instability

“Saturation hypothesis” holds that turbulence continually shaves off just enough energy to keep breaking wave exactly at edge of instability (vertical streamlines), i.e.,

Spilling breaker

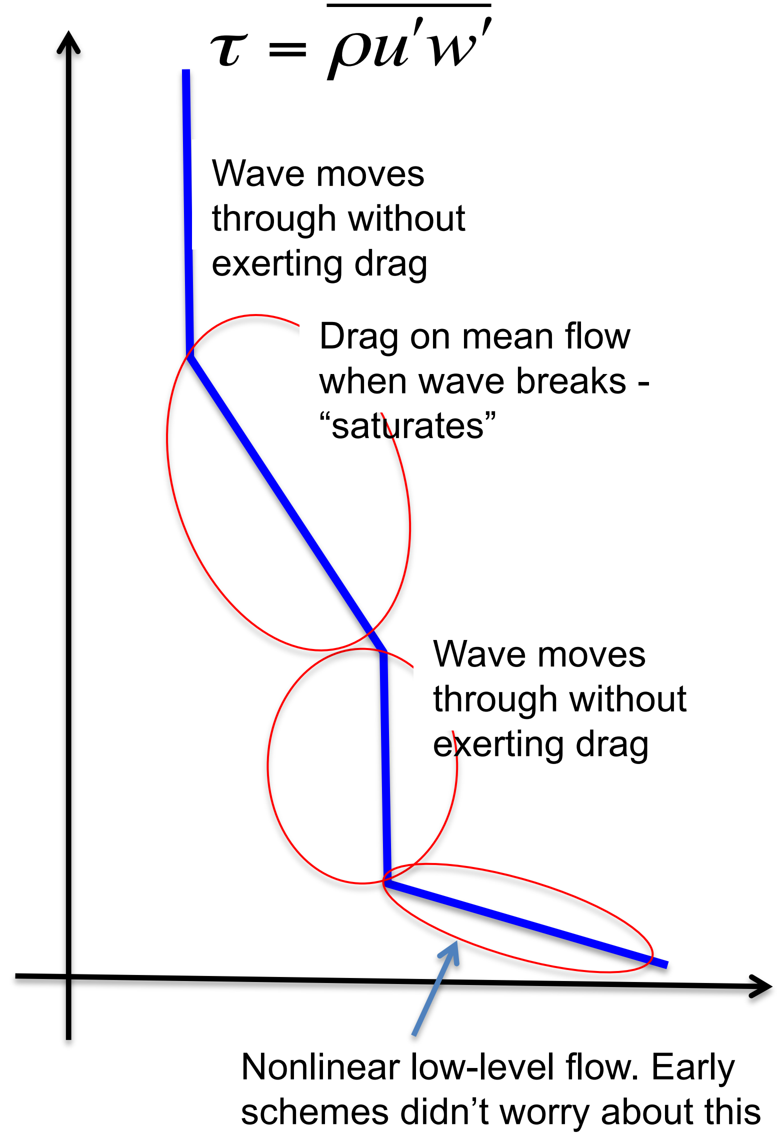
NOT

Plunging breaker



Is saturation hypothesis actually true? Probably sometimes. Not bad first g

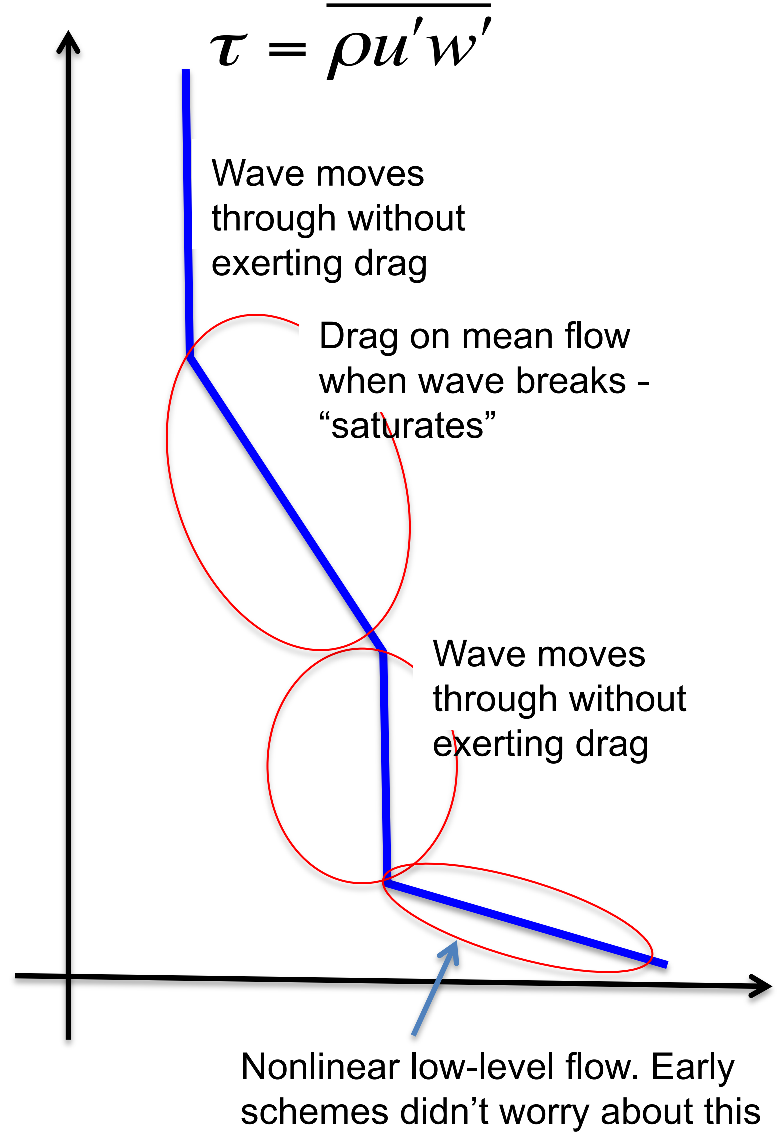
So when do gravity wave streamlines become vertical?



So when do gravity wave streamlines become vertical?

You guessed it. When

$$\delta = \frac{\bar{U}}{N}$$



At this point you have most of what you need to calculate wave momentum flux

Pseudocode:

1) Estimate $\delta(LM)$ from topography dataset

2) Calculate $\tau(LM)=\rho kUN\delta^2$

3) Advance to level above: $\tau(L-1)=\tau(L)$

4) Infer $\delta(L-1)$

5) Test for $\delta(L-1)>U/N$

if ***no*** go to 3)

if ***yes*** set $\delta(L-1)=U/N$ recalculate $\tau(L-1)$ and go to 3)