Shallow-cloud and turbulence parameterization in CAM6

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This talk will . . .

- Ask, What is the parameterization problem for clouds and turbulence?
- Show a framework for analyzing subgrid variability parameterizations
- Compare extant parameterization approaches
- Describe CAM6's parameterization approach

What is the cloud and turbulence parameterization problem?

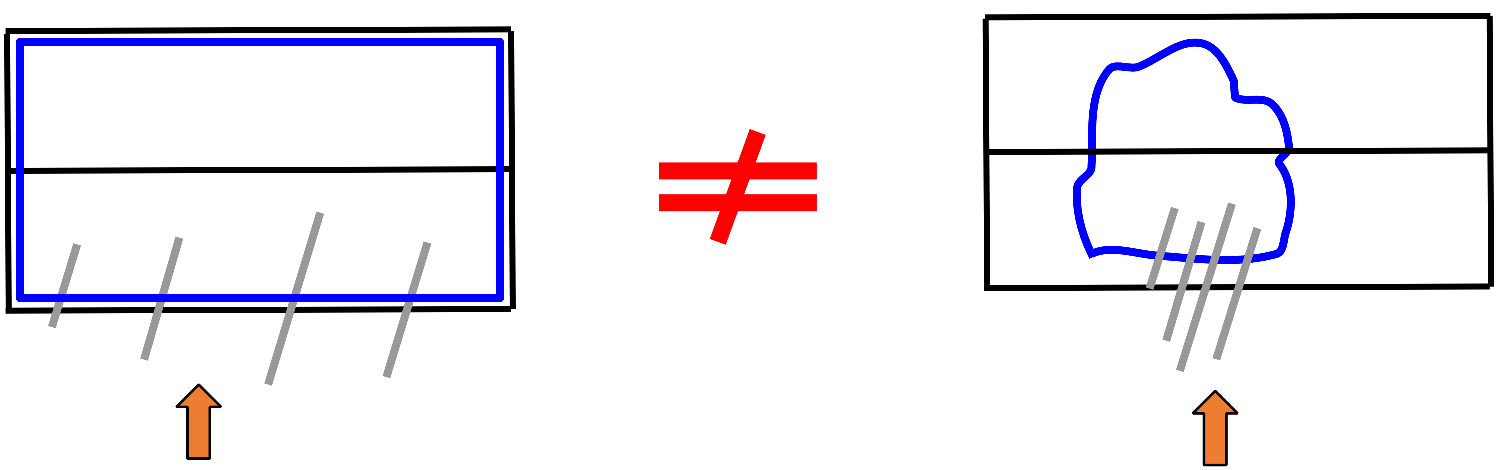
- The problem is to parameterize *subgrid variability* in a large-scale model

- "Large-scale" means 100 km for a climate model or 10 km for a weather forecast model

- Subgrid information is needed
  1) to estimate turbulent fluxes, and
  2) to drive microphysics and radiation

For non-linear process, subgrid variability affects the grid means

For instance, consider the effects of partial cloudiness on drizzle rate:



How an all-or-nothing model handles microphysics

What we would prefer to do

Parameterizing subgrid variability would no longer be necessary if computer power were sufficient to resolve turbulent eddies

It is unlike microphysics parameterization, which will always be needed.

The Reynolds-averaged equations tell us that a parameterization needs to provide subgrid fluxes and averaging information:

$$\frac{\partial \overline{r_t}}{\partial t} = \underbrace{-\overline{w}\frac{\partial \overline{r_t}}{\partial z}}_{ma} \underbrace{-\frac{\partial \overline{w' r_t'}}{\partial z}}_{ta} + \overline{\mathrm{Mphys}}$$

r_t = total water (vapor+liquid)
$theta_l$ = liq water pot temp
w = vertical velocity

$$\frac{\partial \overline{\theta_l}}{\partial t} = \underbrace{-\overline{w}\frac{\partial \overline{\theta_l}}{\partial z}}_{ma} \underbrace{-\frac{\partial \overline{w' \theta_l'}}{\partial z}}_{ta} + \overline{\mathrm{RT}} + \overline{\mathrm{Mphys}}$$

red = predicted by host model, microphysics (Mphys), or radiation (RT)

blue = predicted by cloud/turbulence parameterization

green = subgrid integration driven by cloud parameterization

The Reynolds-averaged equations tell us that a parameterization needs to provide subgrid fluxes and averaging information:

$$\frac{\partial \overline{u}}{\partial t} = \underbrace{-\overline{w}\frac{\partial \overline{u}}{\partial z}}_{\text{mean adv}} \underbrace{-f(v_g - \overline{v})}_{\text{Coriolis/press}} \underbrace{-\frac{1}{\rho_s}\frac{\partial \rho_s \overline{u'w'}}{\partial z}}_{\text{turb adv}}$$

$$\frac{\partial \overline{v}}{\partial t} = \underbrace{-\overline{w}\frac{\partial \overline{v}}{\partial z}}_{\text{mean adv}} \underbrace{+f(u_g - \overline{u})}_{\text{Coriolis/press}} \underbrace{-\frac{1}{\rho_s}\frac{\partial \rho_s \overline{v'w'}}{\partial z}}_{\text{turb adv}}$$

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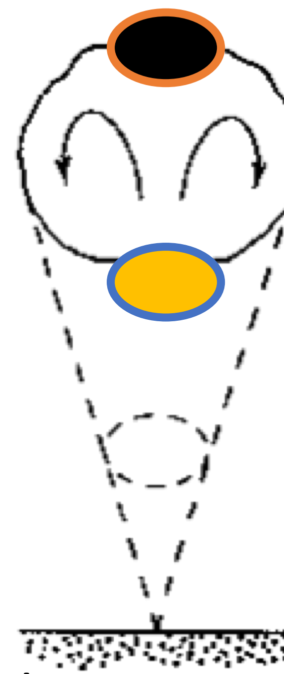
What is the essence of convection? Buoyancy is the source of convection, and transport is needed to move parcels upward.

$$\frac{\partial w'}{\partial t} = -\underbrace{w'}_{+}\underbrace{\frac{\partial w'}{\partial z}}_{-} + \underbrace{\frac{g}{\theta_{v0}}\theta'_v}_{+} + \ldots$$



w' = perturbation vertical velocity

theta$_v$' = perturbation virtual pot. temp.

These are two terms that parameterizations struggle with! One has a derivative and the other has a non-conserved variable.

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Let’s first provide a framework to analyze extant parameterization methodologies

- We’ll take the example of vertical turbulent flux of total water, $\langle w' r_t' \rangle$ (where r_t = vapor plus cloud liquid).

- A framework for analysis is provided by the Reynolds-averaged equation of total water flux.

- Similar equations exist for the fluxes of heat and momentum.

An equation for the flux of total water can be derived from the governing equations:

$$\frac{\partial w' r_t'}{\partial t} = r_t' \frac{\partial w'}{\partial t} + w' \frac{\partial r_t'}{\partial t}$$

Add this . . .

$$\frac{\partial w'}{\partial t} = \underbrace{-\frac{1}{\rho_s}\frac{\partial p'}{\partial z}}_{\text{pressure}} \underbrace{+\frac{g}{\theta_{vs}}\theta_v'}_{\text{buoy prod}} \underbrace{-w'\frac{\partial w'}{\partial z}}_{\text{turb adv}}$$

and this . . .

$$\frac{\partial r_t'}{\partial t} = \underbrace{-w'\frac{\partial \overline{r_t}}{\partial z}}_{\text{turb prod}} \underbrace{-w'\frac{\partial r_t'}{\partial z}}_{\text{turb adv}}$$

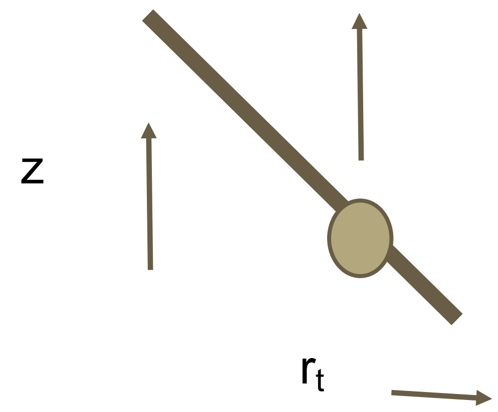
and avg to obtain this:

$$\frac{\partial \overline{w' r_t'}}{\partial t} = \underbrace{-\overline{w'^2}\frac{\partial \overline{r_t}}{\partial z}}_{\text{turb prod}} \underbrace{-\frac{1}{\rho_s}\overline{r_t'\frac{\partial p'}{\partial z}}}_{\text{pressure}} \underbrace{+\frac{g}{\theta_{vs}}\overline{r_t'\theta_v'}}_{\text{buoy prod}} \underbrace{-\frac{\partial \overline{w'^2 r_t'}}{\partial z}}_{\text{turb adv}}$$

brown = closed w/o PDF

The turbulence production term generates flux when there is vertical motion in the presence of a vertical gradient of moisture

$$\underbrace{-\overline{w'^2}\frac{\partial \overline{r_t}}{\partial z}}_{\text{turb prod}}$$



Positive buoyancy, when positively correlated with moisture, generates positive moisture flux

$$\underbrace{+\frac{g}{\theta_{vs}}\overline{r_t'\theta_v'}}_{\text{buoy prod}}$$

Turbulent advection is a flux of the flux

$$\underbrace{-\frac{\partial \overline{w'^2 r_t'}}{\partial z}}_{\text{turb adv}}$$

$$w'^2 r_t' = w'(w' r_t')$$

The pressure term is often parameterized in a simple way:

$$\underbrace{-\frac{1}{\rho_s}\overline{r'_t\frac{\partial p'}{\partial z}}}_{\text{pressure}} = \underbrace{-\frac{\overline{w'r'_t}}{\tau}}_{\text{return2iso}} \underbrace{-C_7\frac{g}{\theta_{vs}}\overline{r'_t\theta'_v}}_{\text{buoy pressure}}$$

This is not a cloud average, but a layer average. It includes all turbulence and clouds within a grid box.

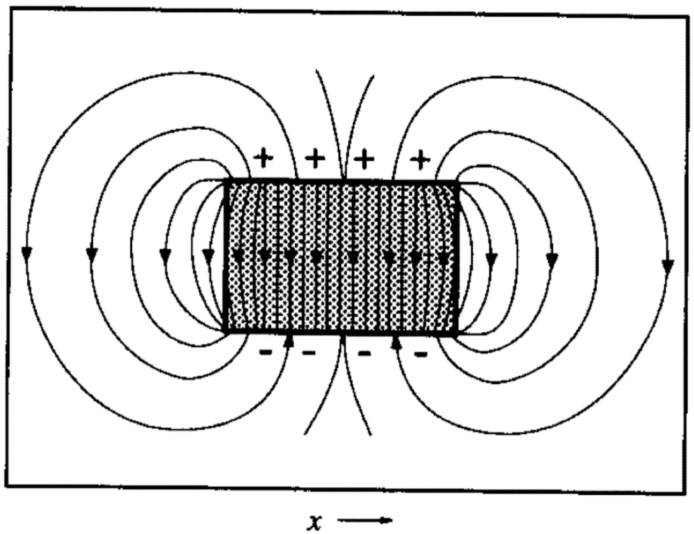
The return-to-isotropy pressure term reduces the magnitude of the flux

$$\underbrace{-\frac{\overline{w'r_t'}}{\tau}}_{\text{return2iso}}$$

Pressure perturbations tend to return the turbulence to an isotropic state in which the variances are non-zero but the fluxes are zero.

The buoyancy force is opposed by a non-hydrostatic pressure force

$$\underbrace{-C_7 \frac{g}{\theta_{vs}} \overline{r_t'\theta_v'}}_{\text{buoy pressure}}$$

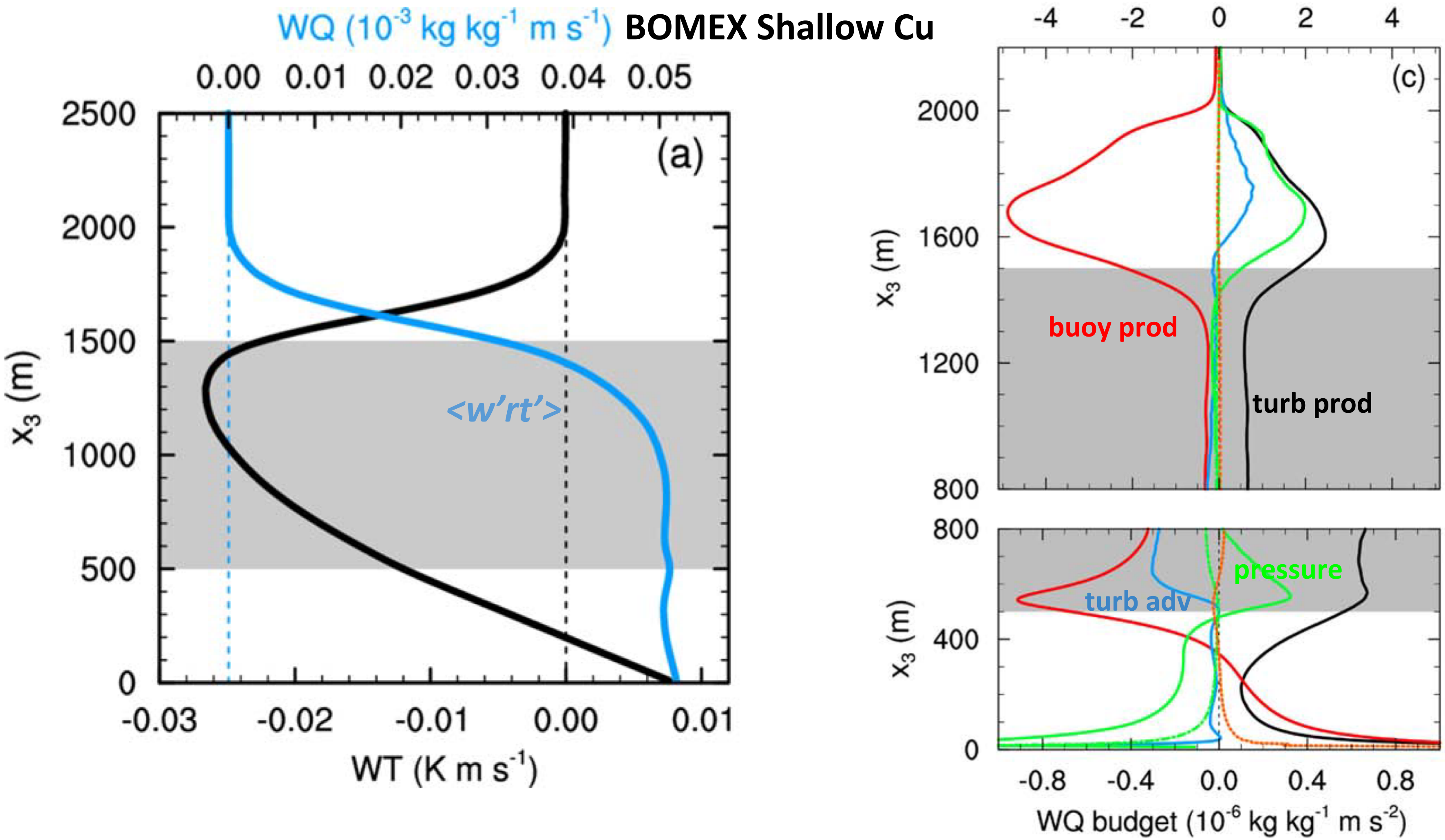


Houze (1993)

Substituting in this parameterization for pressure leaves us with a simplified equation that tells us all the processes that affect moisture flux:

$$\frac{\partial \overline{w'r'_t}}{\partial t} = \underbrace{-\overline{w'^2}\frac{\partial \overline{r_t}}{\partial z}}_{\text{turb prod}} \underbrace{-\frac{\overline{w'r'_t}}{\tau}}_{\text{return2iso}} \underbrace{+(1-C_7)\frac{g}{\theta_{vs}}\overline{r'_t\theta'_v}}_{\text{buoy+pressure}} \underbrace{-\frac{\partial \overline{w'^2r'_t}}{\partial z}}_{\text{turb adv}}$$

None of these terms is negligible!



Heinze et al. (2015)

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Given the flux-equation framework, let's analyze the following parameterization approaches:

1. Simple downgradient diffusion
1. Downgradient diffusion with a stability correction
1. Eddy diffusion with a counter-gradient term
1. Mass-flux
1. CAM6's approach (CLUBB)

Should we develop a unified parameterization with a single, complex equation set, or combine a set of simpler parameterizations?

Each approach introduces complexity in its own way.

A unified equation set must contain enough physics to model a variety of cloud types. Using separate schemes for separate regimes introduces complexity into the interactions between schemes.

Approach 1: Simple downgradient diffusion can be derived by retaining only the turbulence production and return-to-isotropy terms:

$$0 = \underbrace{-\overline{w'^2}\frac{\partial \overline{r_t}}{\partial z}}_{\text{turb prod}} \underbrace{-\frac{\overline{w'r_t'}}{\tau}}_{\text{return2iso}}$$

$$\overline{w'r_t'} = -\overline{w'^2}\tau\frac{\partial \overline{r_t}}{\partial z} \equiv -K\frac{\partial \overline{r_t}}{\partial z}$$

This approach is used by, e.g., the SHOC parameterization (Bogenschutz and Krueger 2013)

Simple downgradient diffusion omits the buoyancy and flux-of-flux terms

However, Bogenschutz and Krueger (2013) find that “typically used downgradient diffusion for low-order closure (LOC) models appears to function well if the right amount of SGS TKE can be predicted.“

But downgradient diffusion cannot model upgradient fluxes.

Approach 2: Buoyancy may be incorporated into downgradient diffusion

An approximation of the buoyancy terms is incorporated into the eddy diffusivity through so-called "stability functions" (Mellor and Yamada 2.5 level model).

Still cannot model upgradient fluxes

Still ignores flux-of-flux term

Approach 3: Add upgradient term (usually for heat equation)

$$\overline{w'\theta_l'} = -K\left(\frac{\partial \theta_l}{\partial z} - \gamma\right)$$

$$K = \overline{w'^2}\tau$$

The upgradient term is important because it allows the possibility of cumulus-like “non-local” fluxes.

Approach 3a: Deardorff (1972) interprets the upgradient term as a way to incorporate buoyancy:

$$\gamma \equiv \frac{g}{\theta_0} \frac{\overline{\theta_l' \theta_v'}}{\overline{w'^2}}$$

Still need a way to close <*theta*$_l$*’ theta*$_v$*’*> in Cu clouds.

Still need a way to account for turbulent advection.

Approach 3b: Holtslag and Moeng (1991) interprets the upgradient term as a way to include the flux-of-flux term:

$$\gamma \equiv b \frac{w_*^2 \theta_{l*}}{\overline{w'^2} z_i}$$

This representation of the flux-of-flux term contains no derivative operator, as in the governing equations.

Still need a way to handle the buoyancy term.

Approach 4: Mass-flux schemes contain a term with a vertica derivative that is analogous to the flux-of-flux term:

$$\frac{\partial \rho \sigma \overline{r_t}^{\,\mathrm{cld}}}{\partial t} = -\frac{\partial M \overline{r_t}^{\,\mathrm{cld}}}{\partial z} + E \overline{r_t}^{\,\mathrm{env}} - D \overline{r_t}^{\,\mathrm{cld}} - \overline{\mathrm{Precip}}^{\,\mathrm{cld}}$$

In a mass-flux scheme, a vertical derivative does appear.

However, mass-flux averages over convective clouds, not the entire layer. Hence, it is unclear how to interface a mass-flux scheme with an eddy-diffusivity scheme.

However, mass-flux averages over convective clouds, not the entire layer. Hence, it is unclear how to interface a mass-flux scheme with an eddy-diffusivity scheme.

Also, the terms in higher-order closure don’t correspond one to one with the terms in an eddy- diffusivity/mass-flux approach.

Note that the buoyancy production term in the total water equation is negative!

Approach 4: In CAM6's mass-flux closure, a buoyancy term appears, but it is hard to relate to the moisture flux equation

$$M \propto \mathrm{CAPE}/\tau_{\mathrm{convection}}$$

$$\mathrm{CAPE} = g \int_{z_{\mathrm{cloud\ base}}}^{z_{\mathrm{cloud\ top}}} \frac{\theta_{v,\mathrm{parcel}} - \theta_{v,\mathrm{environment}}}{\theta_{v,\mathrm{environment}}}\, dz$$

Instead, the buoyancy appears in the CAPE closure.

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The approach of CAM6 is to include both the buoyancy and flux-of-flux terms

Keeping all the terms is part of the “higher-order” closure approach used by CAM6.

The needed averages are really integrals over the subgrid probability density function (PDF):

Buoyancy term:

$$\overline{r_t'\theta_v'} = \int_{\theta_l'=-\infty}^{\theta_l'=\infty} \int_{r_t'=-\infty}^{r_t'=\infty} \int_{w'=-\infty}^{w'=\infty} r_t'\theta_v' \, P(w', r_t', \theta_l') \, dw' \, dr_t' \, d\theta_l'$$

Turbulent advection term:

$$\overline{w'^2 r_t'} = \int_{\theta_l'=-\infty}^{\theta_l'=\infty} \int_{r_t'=-\infty}^{r_t'=\infty} \int_{w'=-\infty}^{w'=\infty} w'^2 r_t' \, P(w', r_t', \theta_l') \, dw' \, dr_t' \, d\theta_l'$$

But then CAM6 needs to estimate the PDF for closure

To constrain the shape of the PDF, we need to predict more moments, e.g., variance of theta_l.

This brings us to a description of CAM6's parameterization, CLUBB

CLUBB = Cloud Layers Unified By Binormals

CLUBB is a parameterization of clouds and turbulence.

Recall the parameterization problem for subgrid variability:

$$\frac{\partial \overline{r_t}}{\partial t} = \underbrace{-\overline{w}\frac{\partial \overline{r_t}}{\partial z}}_{ma} \underbrace{-\frac{\partial \overline{w'r_t'}}{\partial z}}_{ta} + \overline{\mathrm{Mphys}}$$

$$\frac{\partial \overline{\theta_l}}{\partial t} = \underbrace{-\overline{w}\frac{\partial \overline{\theta_l}}{\partial z}}_{ma} \underbrace{-\frac{\partial \overline{w'\theta_l'}}{\partial z}}_{ta} + \overline{\mathrm{RT}} + \overline{\mathrm{Mphys}}$$

$$\frac{\partial \overline{u}}{\partial t} = \underbrace{-\overline{w}\frac{\partial \overline{u}}{\partial z}}_{\text{mean adv}} \underbrace{-f(v_g - \overline{v})}_{\text{Coriolis/press}} \underbrace{-\frac{1}{\rho_s}\frac{\partial \rho_s \overline{u'w'}}{\partial z}}_{\text{turb adv}}$$

$$\frac{\partial \overline{v}}{\partial t} = \underbrace{-\overline{w}\frac{\partial \overline{v}}{\partial z}}_{\text{mean adv}} \underbrace{+f(u_g - \overline{u})}_{\text{Coriolis/press}} \underbrace{-\frac{1}{\rho_s}\frac{\partial \rho_s \overline{v'w'}}{\partial z}}_{\text{turb adv}}$$

CLUBB’s inputs and outputs:

Inputs:

1) Grid-mean (red) fields.
2) Higher-order moments, including the four blue fluxes.

Outputs:

1) Updated values of the higher-order moments (CLUBB is prognostic).
2) Information about the PDF, which is needed for the green-bar integrals.

Primary steps performed by CLUBB in order to advance one time step:

1) Advance higher-order moments one time step.
2) Given the updated moments, diagnose the subgrid PDF.
3) Close some terms via integration over the PDF.
4) Close pressure and dissipation terms using classical closures.

A CLUBB-SILHS time step,
illustrating the main calculations and flow of information

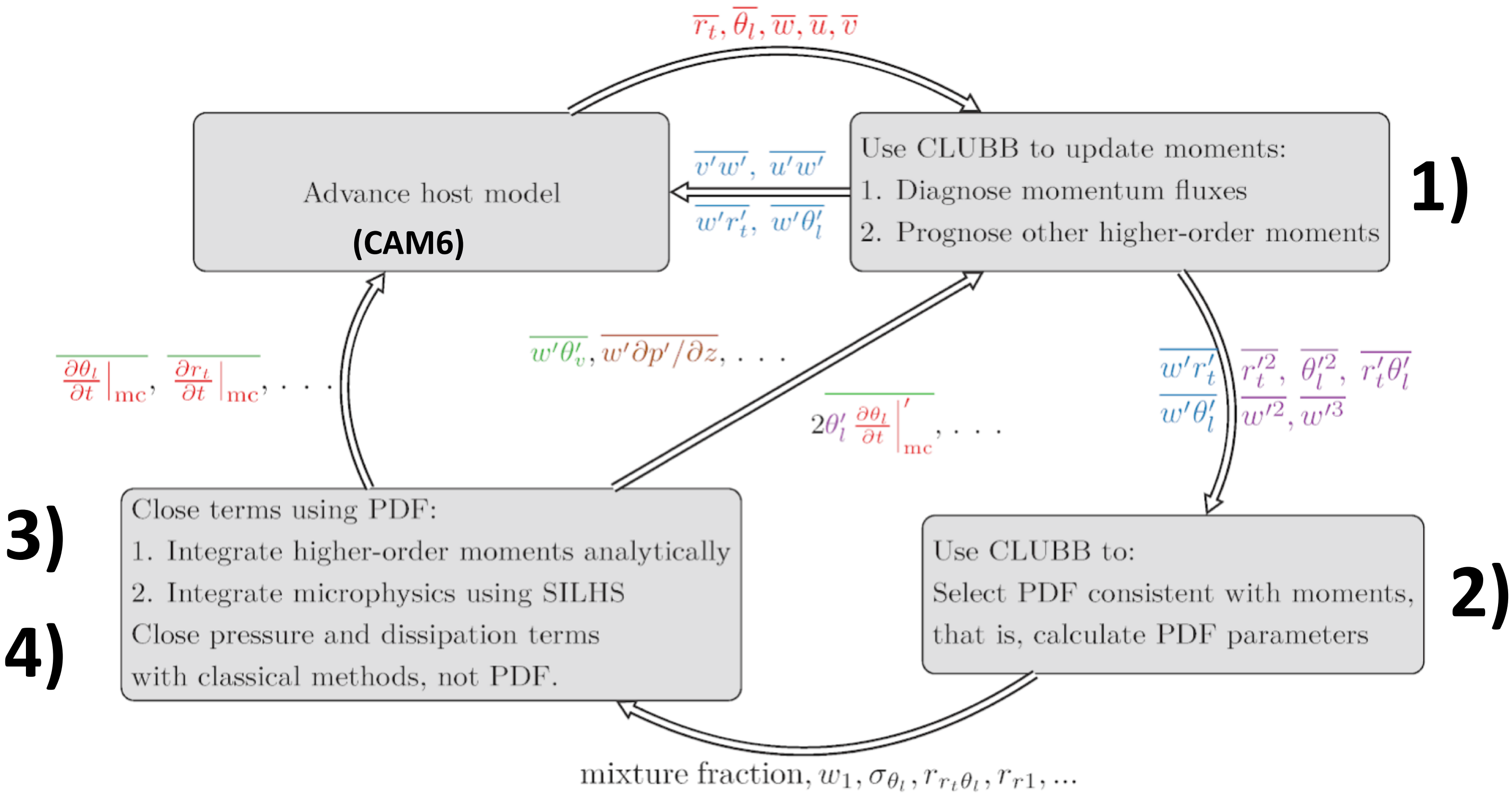


Figure 2.1: The main calculations performed in a CLUBB-SILHS time step. Arrows labelled with variables depict inputs and outputs. This schematic depicts the flow of information within CLUBB-SILHS, not the strict ordering of the sequence of calculations. Although it is not depicted in the schematic, CLUBB, SILHS, and microphysics are often substepped together in a loop several times during a single host model time step.

This is CLUBB's set of prognostic higher-order equations. It can be thought of as an extension to the dynamical core.

$$\text{Means}: \quad \frac{\partial \overline{u}}{\partial t} = \ldots \quad \frac{\partial \overline{v}}{\partial t} = \ldots \quad \frac{\partial \overline{r_t}}{\partial t} = \ldots \quad \frac{\partial \overline{\theta_l}}{\partial t} = \ldots$$

$$\text{2nd}-\text{order}: \quad \frac{\partial \overline{w' r_t'}}{\partial t} = \ldots \quad \frac{\partial \overline{w' \theta_l'}}{\partial t} = \ldots \quad \frac{\partial \overline{w'^2}}{\partial t} = \ldots$$

$$\frac{\partial \overline{r_t'^2}}{\partial t} = \ldots \quad \frac{\partial \overline{\theta_l'^2}}{\partial t} = \ldots \quad \frac{\partial \overline{r_t' \theta_l'}}{\partial t} = \ldots$$

$$\text{3rd}-\text{order}: \quad \frac{\partial \overline{w'^3}}{\partial t} = \ldots$$

$$w = \text{vertical velocity} \qquad r_t = \text{total water mixing ratio}$$

$$\theta_l = \text{liquid water potential temperature}$$

The dissipation and pressure terms are closed using classical closures

Turbulent dissipation is parameterized by Newtonian damping.

Pressure terms are handled by a combination of Newtonian damping and directly counteracting the buoyant generation of turbulence.

What about the remaining terms, such as turbulent transport? CLUBB closes them by integrating over the PDF of subgrid variability.

Use of a PDF closure reduces the number of equations that we need to prognose.

It also ensures a consistent closure for all terms closed using the PDF.

CLUBB assumes the shape of the subgrid PDF

CLUBB uses the Assumed PDF Method. It assumes a functional form of the PDFs, and determines a particular instance of this functional form for each grid box and time step.

E.g., Manton and Cotton (1977)

The subgrid PDF includes several variables

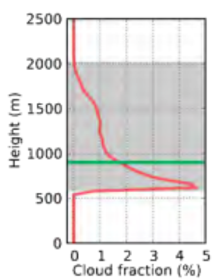
CLUBB uses a multi-dimensional PDF of vertical velocity, total water mixing ratio, and liquid water potential temperature:

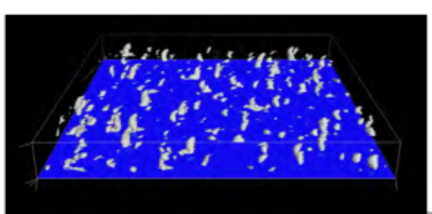
$$P(w, r_t, \theta_l)$$

CLUBB's PDF is ***multivariate***. It is not a set of separate univariate PDFs.

PDFs in cumulus clouds do not look like delta functions nor single Gaussians:

LES of shallow cumulus clouds (BOMEX)





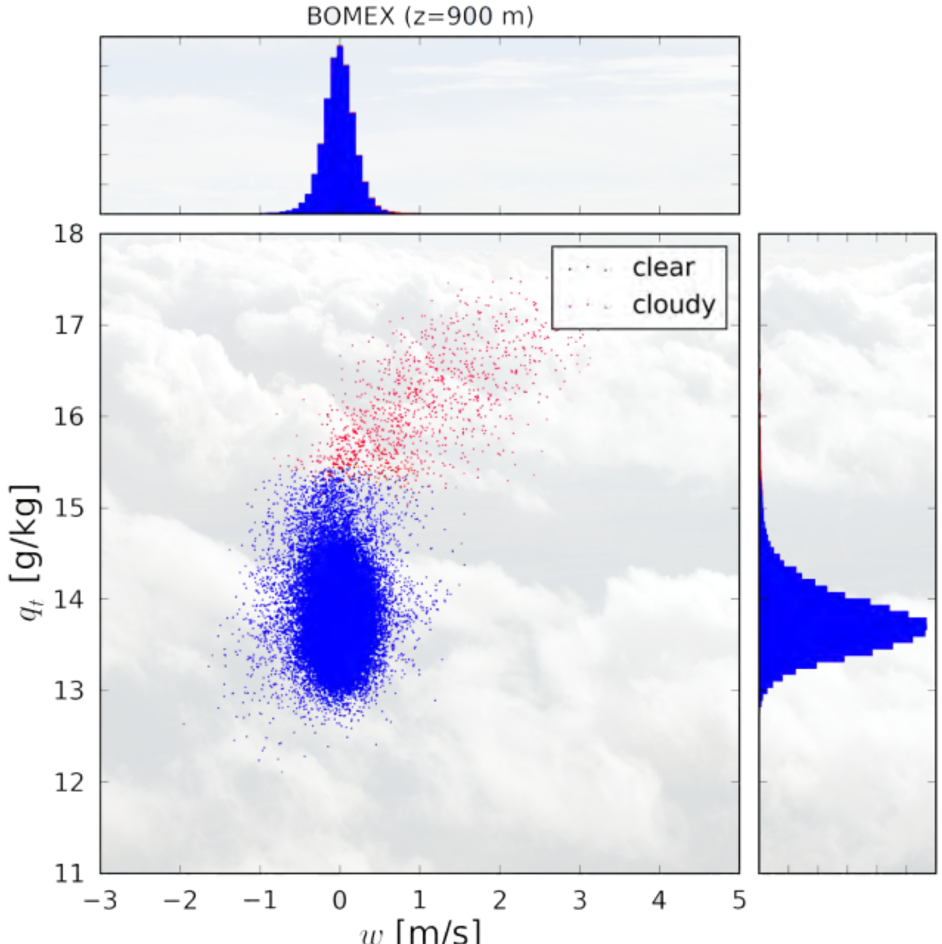


Fig. by C. Golaz

CLUBB uses a Double Gaussian PDF functional form

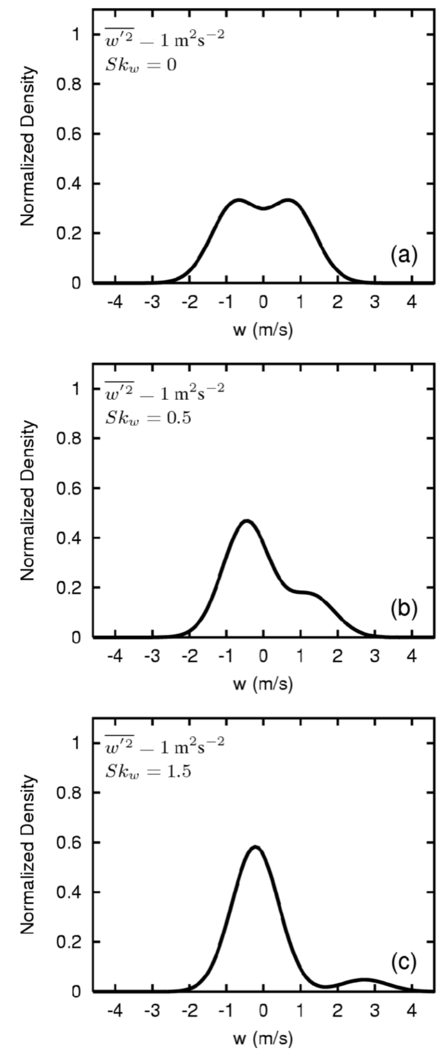
A double Gaussian PDF is the sum of two Gaussians. It satisfies three important properties:

(1) It allows both negative and positive skewness.

(2) It has reasonable-looking tails.

(3) It can be multi-variate.

We do not use a completely general double Gaussian, but instead restrict the family in order to simplify and reduce the number of parameters.



CLUBB’s PDF oozes

The subgrid PDF evolves with time and space as the meteorological conditions (i.e. higher-order moments) change.

It is not a prescribed, climatological PDF.

Broad philosophy: CLUBB tries to emulate aspects of what a LES model does, but using horizontally averaged eqns

CLUBB attempts to be a ***1D LES emulator***.

Like Large-Eddy Simulation (LES), CLUBB starts with the governing equations and spatially filters them.

Unlike LES, CLUBB's equations are averaged to form a 1D (single-column) model.

Like LES, CLUBB has memory, but only of prior timestep.

Unlike LES, CLUBB has no representation of horizontal spatial structure of clouds (e.g. clumping in space).

Can a higher-order closure parameterization handle “non-local” transport?

Like LES, CLUBB contains vertical derivatives (*d/dz*), more so than vertical integrals.

Like LES, CLUBB can represent “non-local” processes, such as cumulus transport. In nature and LES, “non-local” transport is composed of a series of local transport events. Whether we deem it non-local depends on model time step. However, cloud top propagates more slowly than the air within updrafts.

Can a higher-order closure parameterization model handle vertically correlated plumes?

Recall the Reynolds-averaged equation: The key quantity to parameterize is the turbulent fluxes.

Assumptions about the convective structure are needed only insofar as they help parameterize the fluxes.

CLUBB parameterizes the flux of flux by integrating over the subgrid PDF. The resulting form resembles a mass-flux formulation:

$$\overline{w'^2 r_t'} \approx \frac{1}{(1-\tilde{\sigma}_w^2)} \frac{\overline{w'^3}}{\overline{w'^2}} \overline{w' r_t'}.$$

Larson and Golaz (2005)

This term is proportional to the skewness of *w*. It is only large in skewed, i.e. cumulus, layers.

sigma$_w$ is the mixture component width and is proportional to CLUBB's gamma_coef.

Two drawbacks of CLUBB:

1) Computational cost.

1) Complexity, especially code complexity.

CAM6 produces a smoother transition from Sc to Cu, as would be expected of a unified scheme

CAM5 **Model-obs for low cloud amount** **CAM6**

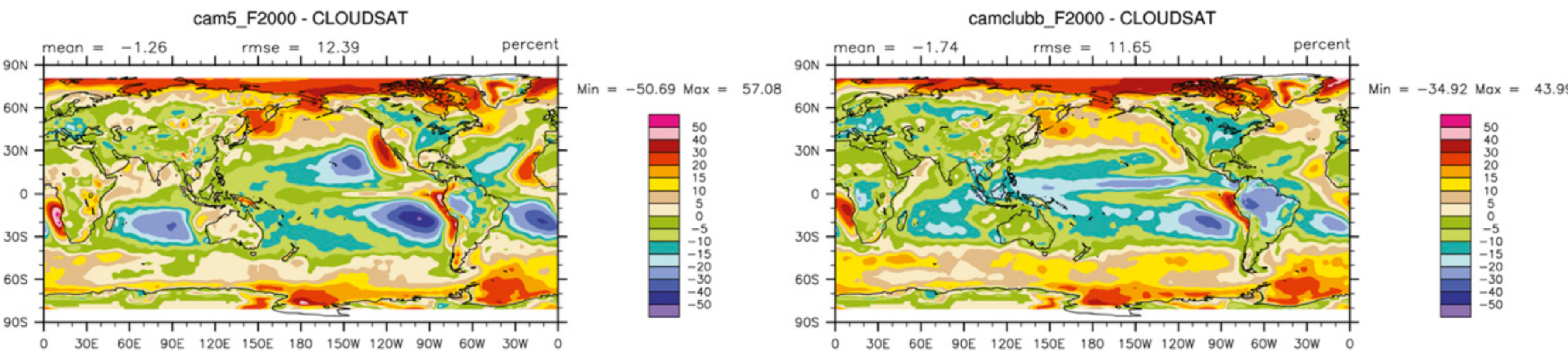


FIG. 2. Differences between 5-yr model simulation for (left) CAM5 and (right) CAM–CLUBB and observations (*CloudSat–CALIPSO*) for the low cloud amount.

Bogenschutz et al. (2013)

The short-wave cloud forcing (SWCF) between CAM6 and CAM5 differs most in continental deep convective regions (?!)

CAM5 **Model-obs for SWCF** **CAM6**

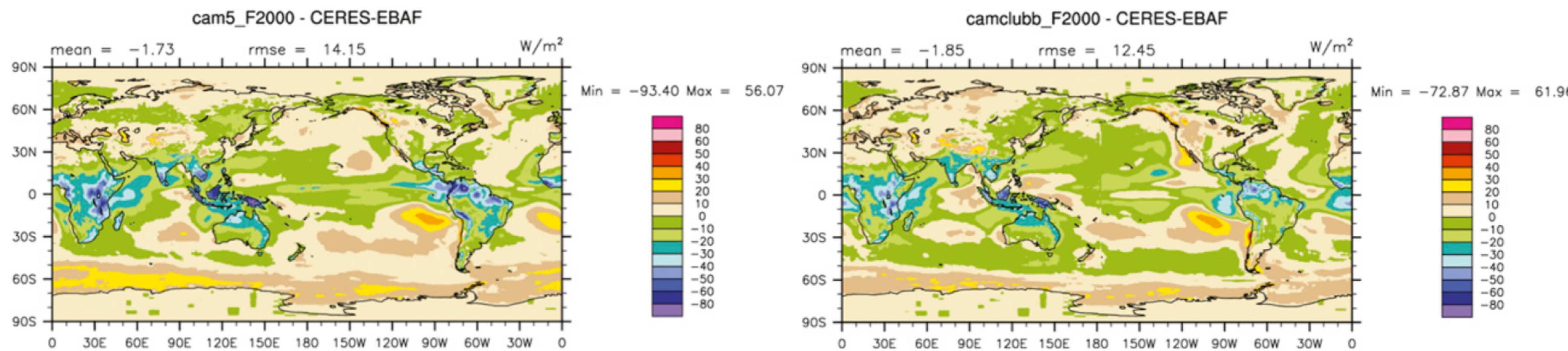


FIG. 4. Differences between 5-yr model simulation for (left) CAM5 and (right) CAM–CLUBB and observations CERES-EBAF for SWCF.

Bogenschutz et al. (2013)