Implementation and early tests of a PDF parameterization in WRF

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Outline

1. Describe our subgrid-scale probability density function (PDF) parameterization

2. List disadvantages and advantages of PDF parameterizations

3. Show simulations of marine Sc clouds

The cloud parameterization problem[1]

A parameterization of clouds and turbulence needs to supply subgrid-scale fluxes of heat, moisture, and momentum:

Heat:

$$\frac{\partial \bar{\theta}_l}{\partial t} = -\bar{w}\frac{\partial \bar{\theta}_l}{\partial z} - \frac{\partial}{\partial z}\overline{w'\theta_l'} + \bar{R} + \left.\frac{\partial \bar{\theta}_l}{\partial t}\right|_{ls} \quad (1)$$

Moisture:

$$\frac{\partial \bar{q}_t}{\partial t} = -\bar{w}\frac{\partial \bar{q}_t}{\partial z} - \frac{\partial}{\partial z}\overline{w'q_t'} + \left.\frac{\partial \bar{q}_t}{\partial t}\right|_{ls} \quad (2)$$

Momentum:

$$\frac{\partial \bar{u}}{\partial t} = -\bar{w}\frac{\partial \bar{u}}{\partial z} - f(v_g - \bar{v}) - \frac{\partial}{\partial z}\overline{u'w'} \quad (3)$$

$$\frac{\partial \bar{v}}{\partial t} = -\bar{w}\frac{\partial \bar{v}}{\partial z} + f(u_g - \bar{u}) - \frac{\partial}{\partial z}\overline{v'w'} \quad (4)$$

Red and Magenta = calculated by host model

Blue = calculated by parameterization

[1]According to Peter Stone of MIT.

Our parameterization for clouds and turbulence: CLUBB

CLUBB denotes ``Cloud Layers Unified By Binormals."

CLUBB is a unified, higher-order closure parameterization of subgrid variability. It predicts turbulence, shallow cumulus clouds, stratiform clouds, and deep convective clouds.

In our private copy of WRF, CLUBB replaces both PBL and deep convective schemes.

CLUBB predicts a number of higher-order equations

In CLUBB, the set of prognosed moments includes:

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

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

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

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

$w =$ vertical velocity $\quad q_t =$ total water specific humidity

$\theta_l =$ liquid water potential temperature

These moments predict the fluxes we need and some extra quantities as well.

CLUBB closes many terms using an assumption about the shape of the subgrid probability density function (PDF)

CLUBB use the *Assumed* PDF Method. We *assume* a *functional form* of the PDFs, and determine a *particular instance* of this functional form for each grid box and time step. (The form we assume is a double Gaussian PDF.)

The PDF varies in space and evolves in time.

Steps in the Assumed PDF Method

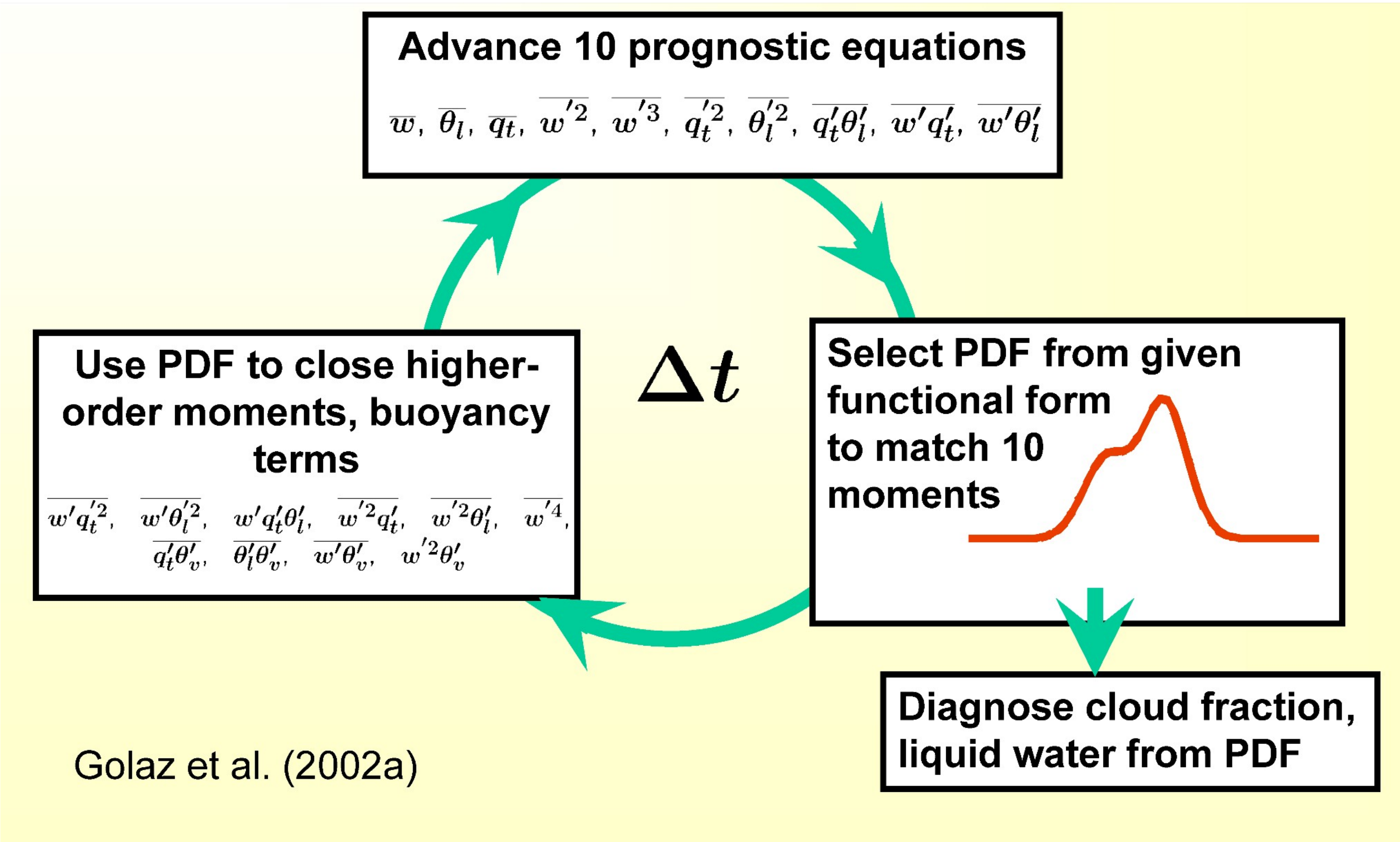
The Assumed PDF Method contains 3 main steps that must be carried out for each grid box and time step:

(1) Prognose grid box means and various higher-order moments.

(2) Use these moments to select a particular PDF instance from the assumed functional form.

(3) Use the selected PDF to compute average of various higher-order terms that need to be closed, e.g. buoyancy flux, cloud fraction, etc.

Schematic of the Assumed PDF method



What are some *disadvantages* of the assumed PDF method?

Disadvantage 1 of the PDF approach: Complexity

The code base for a PDF parameterization is larger than that for a mass-flux scheme.

The problem of complexity can be ameliorated to some extent by good software engineering.

Disadvantage 2 of the PDF approach: Computational cost

The PDF method prognoses many higher-order moments. Therefore, it is expensive.

Optimization of the code can reduce the runtime of PDF parameterizations to some extent.

What are some potential *advantages* of the assumed PDF method over other types of cloud parameterization, e.g. mass-flux schemes?

Parameterization problem: Lack of memory

Some convective parameterizations respond instantly to instability (e.g. CAPE). That is, the parameterizations are diagnostic, rather than prognostic.

In nature, however, deep convection evolves gradually from shallow convection. Lack of memory of whether shallow convection has occurred is part of the reason that deep convection sometimes onsets prematurely in parameterizations.

The PDF approach: Including memory

All of CLUBB's higher-order moment equations contain a time-tendency term.

Therefore, CLUBB need not respond instantaneously to changes in CAPE. This allows the possibility of gradual onset of deep convection.

Parameterization problem: Inappropriate formulation in the terra incognita

At grid spacings between 1 and 10 km, convection is partly resolved and partly subgrid scale. Therefore, these grid spacings are "terra incognita" for parameterizations.

Many parameterizations assume that cloudy updrafts occupy a small fraction of a grid column, but this assumption is no longer true at finer grid spacings.

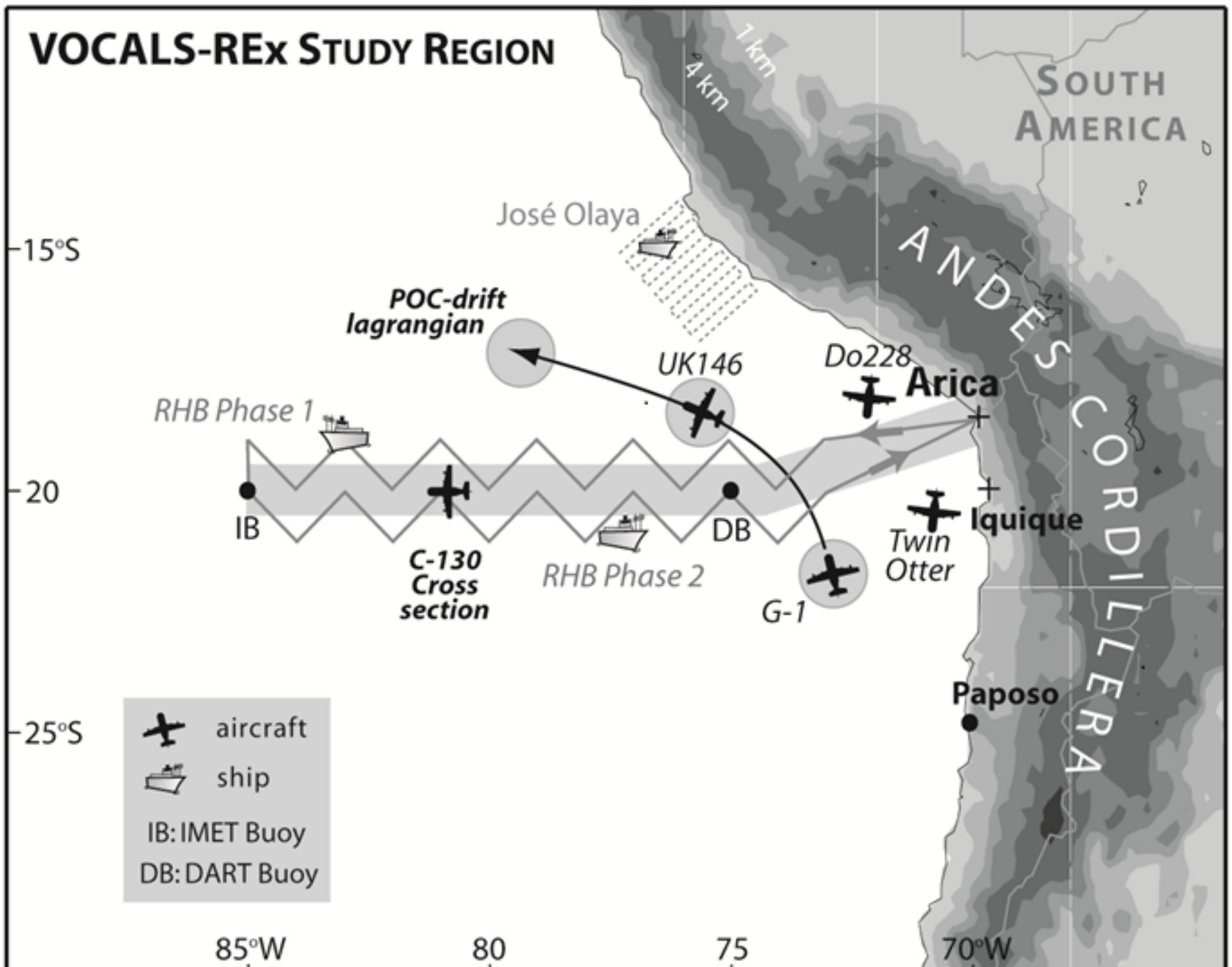
(Wyngaard 2004; Gerard 2007)

The PDF approach: Formulation in the terra incognita

Because CLUBB does not employ a mass-flux scheme, it needs to make no assumption about the fraction of a grid box that is occupied by updrafts or environmental air.

From a PDF point of view, the key difference between small and large grid boxes is that in nature, smaller volumes encompass less variance of cloud and turbulence.

A test case: The VOCALS field experiment studied marine Sc that occurred near deep convection over land



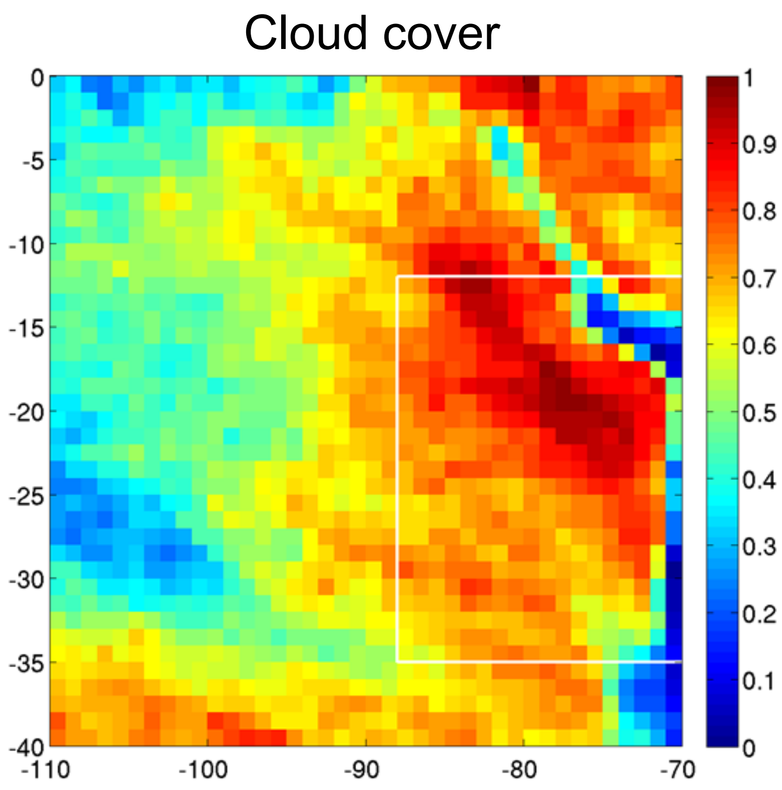
Courtesy
Rob Wood

WRF-CLUBB is participating in Matt Wyant's model intercomparison of the VOCALS clouds

- We simulate a month-long period during Oct/Nov 2008.
- In the plots that follow, we use coarse (50-km) grid spacing and a one-minute timestep.
- One deficiency of these simulations is that they don't (yet) feed cloud fraction from CLUBB to the microphysics.

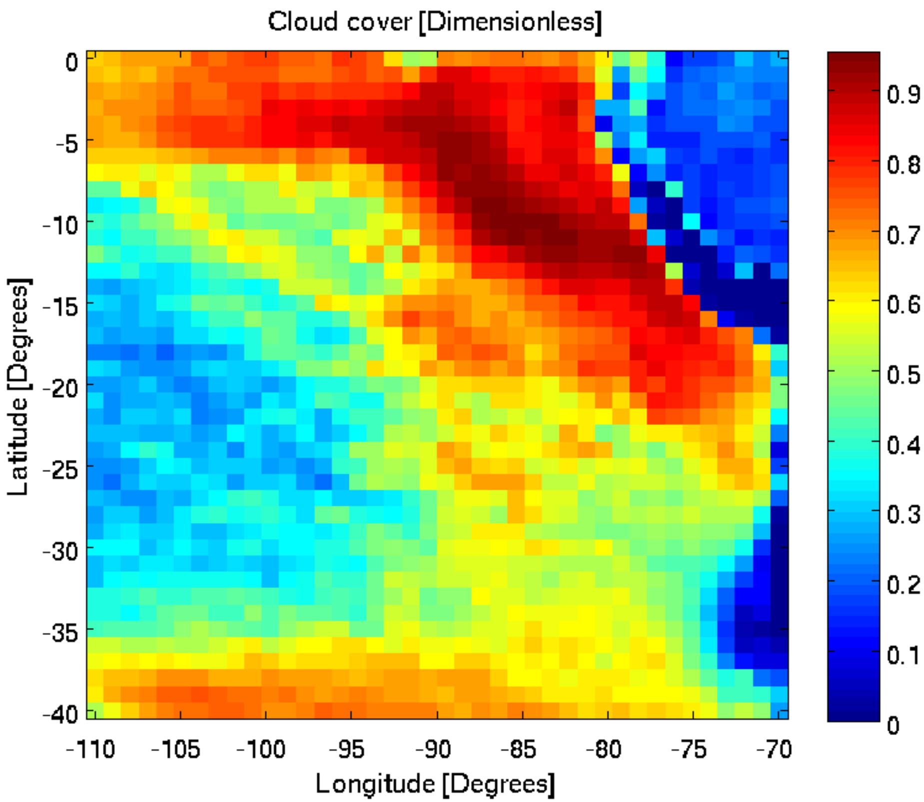
WRF-CLUBB produces Sc cloud, but places the cloud maximum too far north

MODIS satellite obs



Courtesy Matt Wyant and Rob Wood

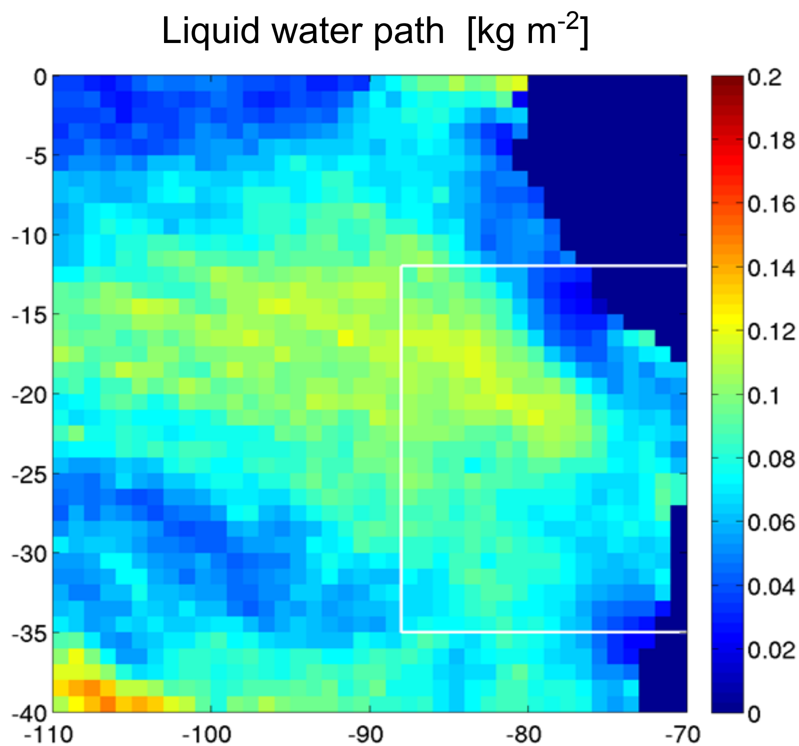
WRF-CLUBB



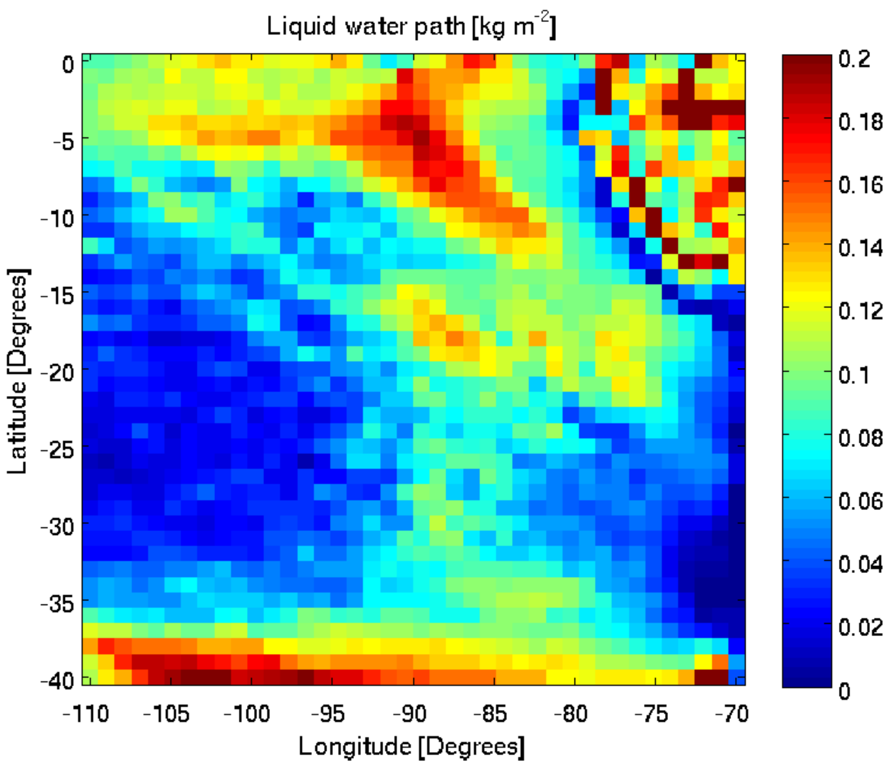
run035, 50km, GFS forcings, l_mp_clubb_pdf=false

WRF-CLUBB produces too much liquid to the north and south

MODIS



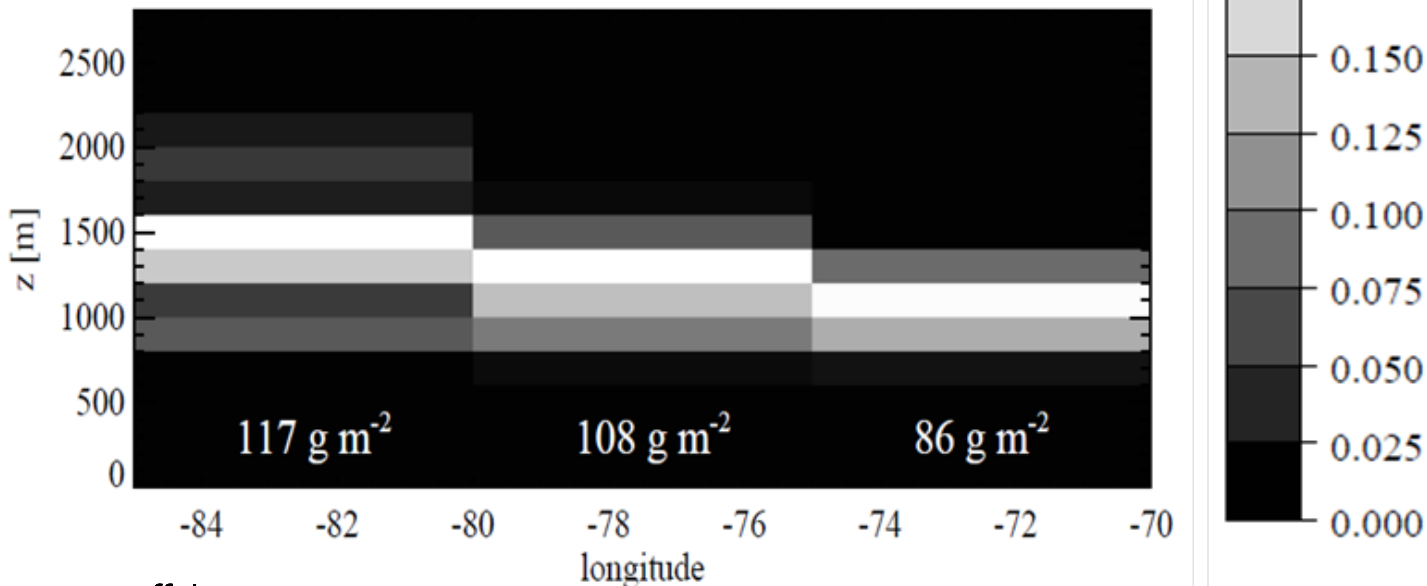
WRF-CLUBB



run035, 50km, GFS forcings, l_mp_clubb_pdf=false

WRF-CLUBB produces clouds that deepen offshore, but WRF-CLUBB's cloud-top height is too low near the coast

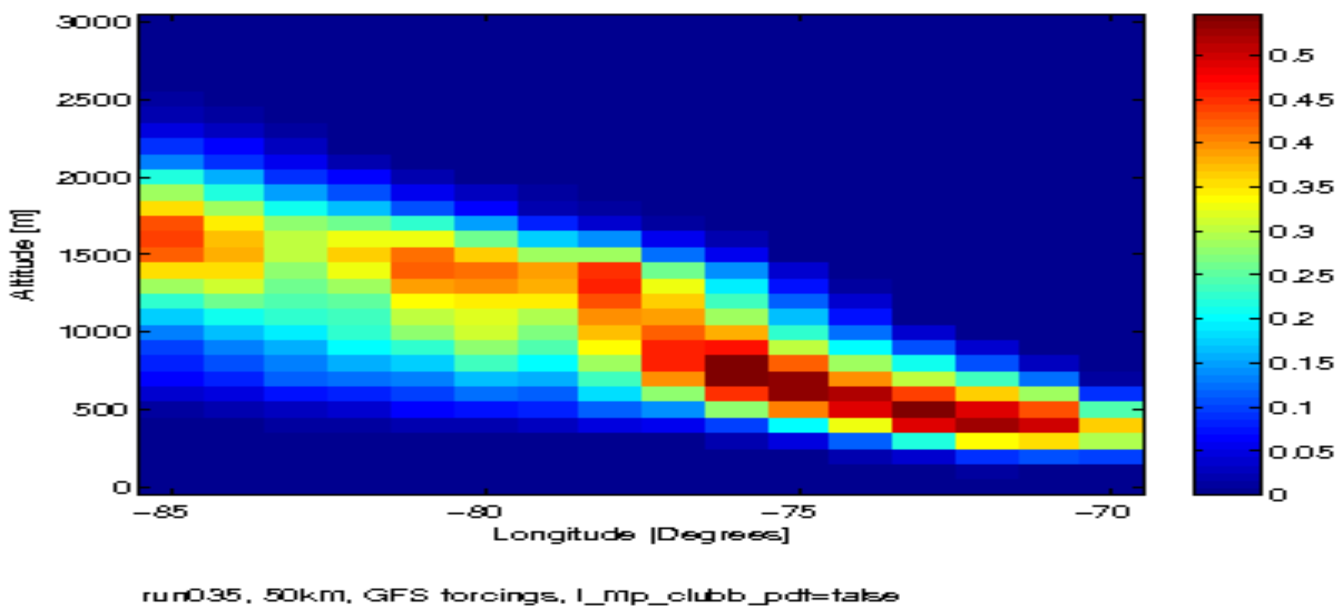
Observed cloud cross section along 20 degrees south



offshore

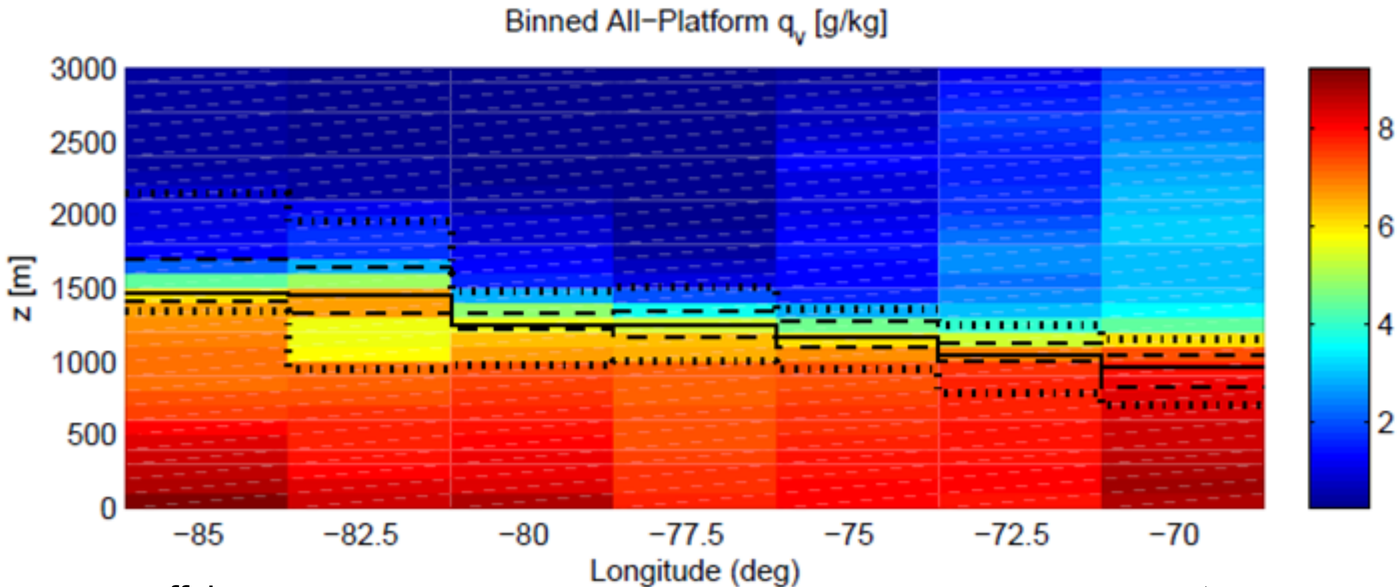
near coast

Modeled Cloud fraction



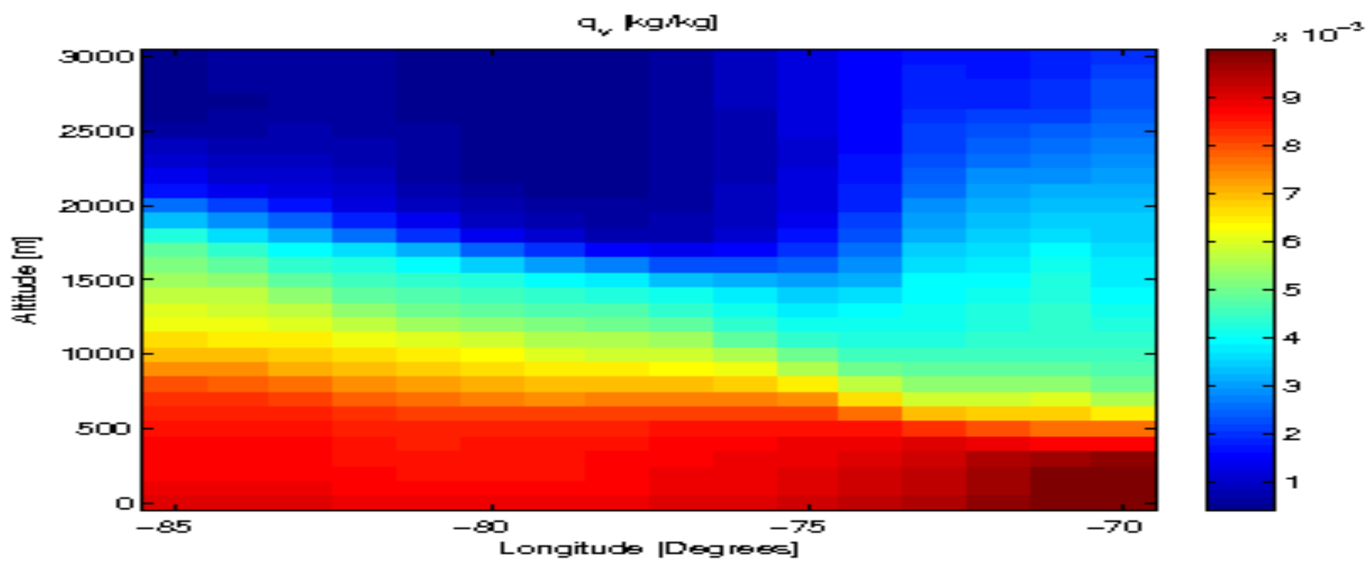
WRF-CLUBB's cloud-top water vapor gradient isn't as sharp as observations

Aircraft-observed water vapor mixing ratio [g/kg]



offshore near coast

WRF-CLUBB water vapor mixing ratio [kg/kg]



run035, 50km, GFS forcings, l_mp_clubb_pdf=false

Conclusions

- We've implemented a PDF parameterization ("CLUBB") in WRF
- We've tested the parameterization for marine Sc. The simulations still need work, but nonetheless the results are encouraging.

Thanks for your time!

Parameterization problem: Inconsistent results as the horizontal grid spacing is refined

Ideally, cloud parameterizations would produce similar results when used at different grid spacing. Insensitivity to resolution is needed especially for simulations with nested grids (e.g., Warner and Hsu 2000).

The PDF approach: Vary dissipation with grid box size

Making the length scale a function of the grid spacing is a simple way of progressively reducing CLUBB's fluxes as resolution increases. As the grid spacing approaches the scale at which convection is resolved, CLUBB lets the resolved scales take over, as desired (Larson et al. 2012).