Applying an economical scale-aware PDF-based turbulence closure model in NOAA NCEP GCMs

Alex Belochitski[1,4], Steven Krueger[2], Peter Bogenschutz[3], Shrinivas Moorthi[4], Robert Pincus[5,6]

[1]UCAR, [2]University of Utah, [3]NCAR, [4]NOAA NCEP EMC, [5]University of Colorado, [6]NOAA ESRL

Photo: Lis Cohen

Assumed PDF Method

- One approach for better representing SGS clouds and turbulence is the Assumed PDF Method, that parameterizes SGS clouds and turbulence in a unified way.

- We assume that there exists a joint PDF of vertical velocity, w, total water (vapor + cloud condensate) mixing ratio, q_t, and liquid water potential temperature, θ_l:

$$\mathbf{P=P(w,\ q_t,}\ \theta_l\mathbf{)}$$

- This will allow us to couple subgrid interactions of vertical motions and boyancy.

Randall et al. (1992)

Applying the Assumed PDF Method

The assumed PDF method contains three main steps that must be carried out for each grid box and time step.

- Prognose means and various higher order moments
- Use these moments to select a particular PDF member from the assumed functional form
- Use the selected PDF to compute many other higher order terms that have to be closed, e.g. buoyancy flux, cloud fraction, sub-grid condensation.

Details of the Assumed PDF Method

$$\overline{\theta_l'^2}, \overline{q_t'^2}, \overline{w'^2}, \overline{w'\theta_l'}, \overline{w'q_t'}, \overline{q_t'\theta_l'}, \overline{w'^3}$$

- Typically requires the addition of several prognostic equations into model (Golaz et al. 2002, Cheng and Xu 2006, 2008) to provide the turbulence moments required to specify the PDF.
- Our approach is called **Simplified Higher-Order Closure** (**SHOC**):
    - Second moments are diagnosed using simple formulations based on Redelsperger and Sommeria (1986) and Bechtold et al. (1995)
    - Third moment of w is diagnosed using algebraic expression of Canuto et al. (2001)
    - All diagnostic expressions for the moments are functions of prognostic SGS TKE.
    - The turbulence length scale is related to the SGS TKE and diagnosed eddy length scales.

Required Modifications to GFS

- SHOC will replace the boundary layer turbulence scheme as well as the shallow convection parameterization (Han and Pan, 2011).
- Large-scale microphysics scheme (Zhao and Carr, 1997) will no longer calculate cloud fraction or the large-scale condensation/evaporation rates.
- A new variable, SGS TKE, will be predicted.
- SHOC was originally implemented in a CRM using the Arakawa C-grid. GFS is a spectral model so all variables are available at every grid point. The prognostic TKE equation code will be modified for efficiency.
- Consistent thermodynamic variables will be used in the SHOC code and GFS.

Progress to Date

Implementation of the prognostic TKE equation is largely complete and is now being tested. In addition to the general plan for step one, the following technical modifications were made:

- The SHOC code was modified to be suitable for use in a global circulation model environment: It was made re-entrant and capable of working with arbitrary physics windows; the code from SHOC and the relevant code from its original host model code were combined into a single package with an explicitly defined interface to facilitate ease of incorporation into a variety of GCMs.

- Time integration of the TKE equation was reformulated in a semi-implicit manner.

- The term related to shear production of TKE was simplified to only include vertical gradients of large-scale horizontal velocity.

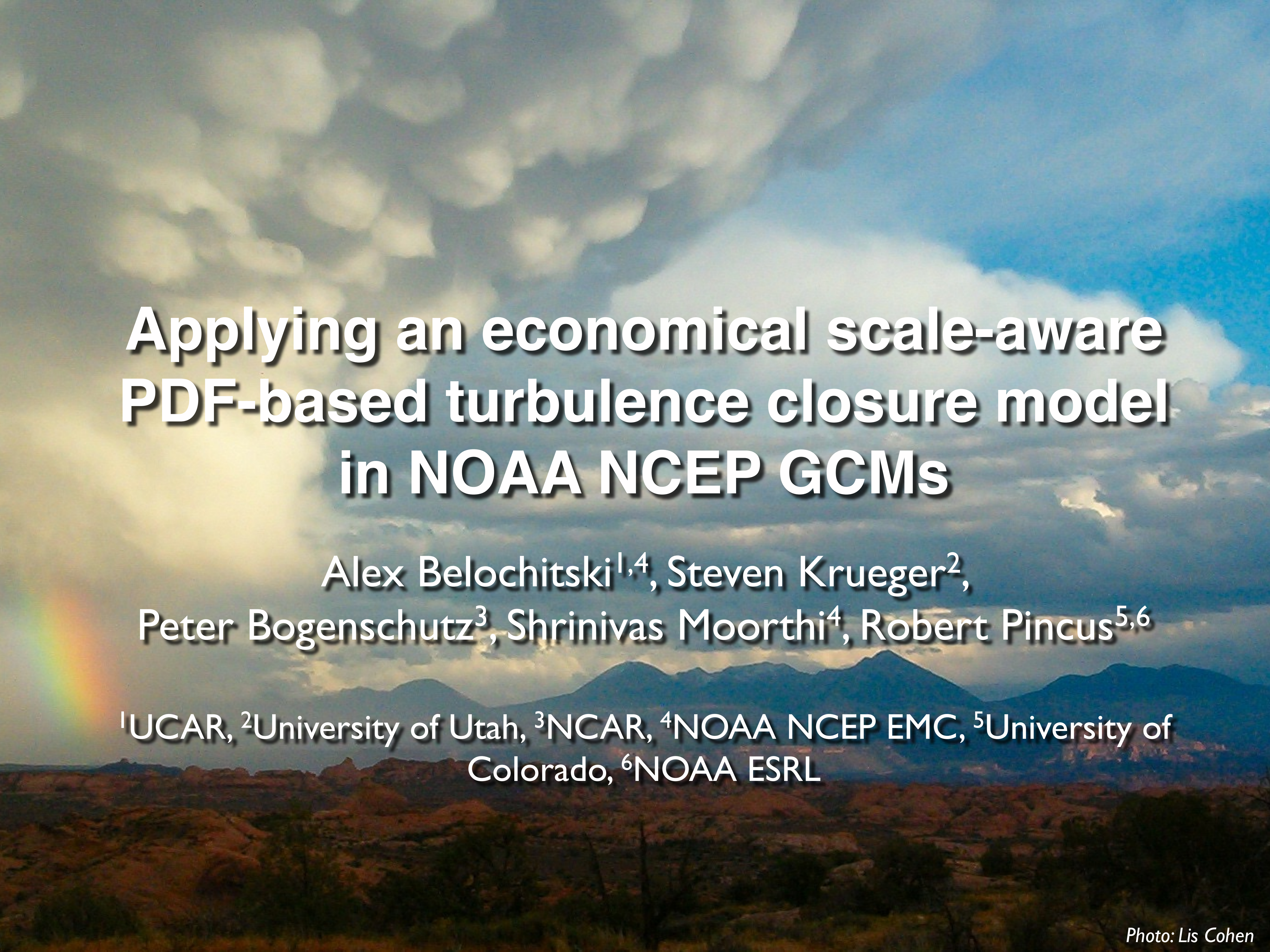

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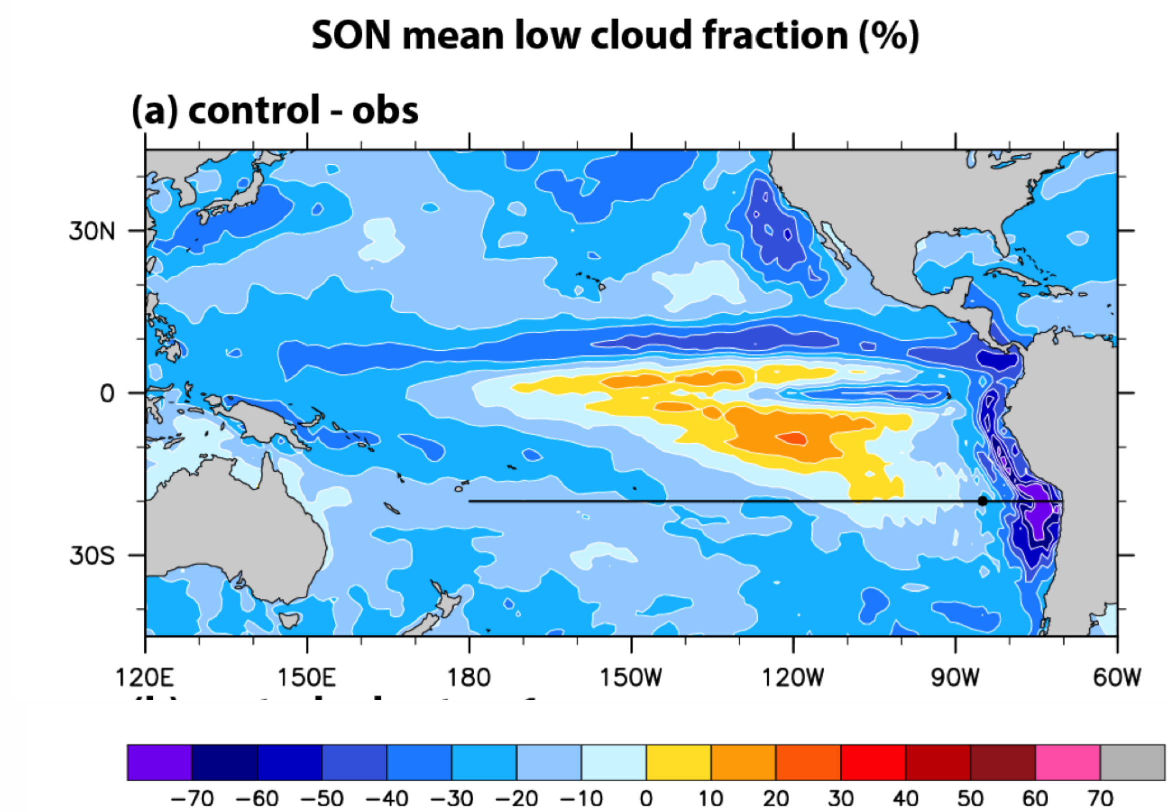
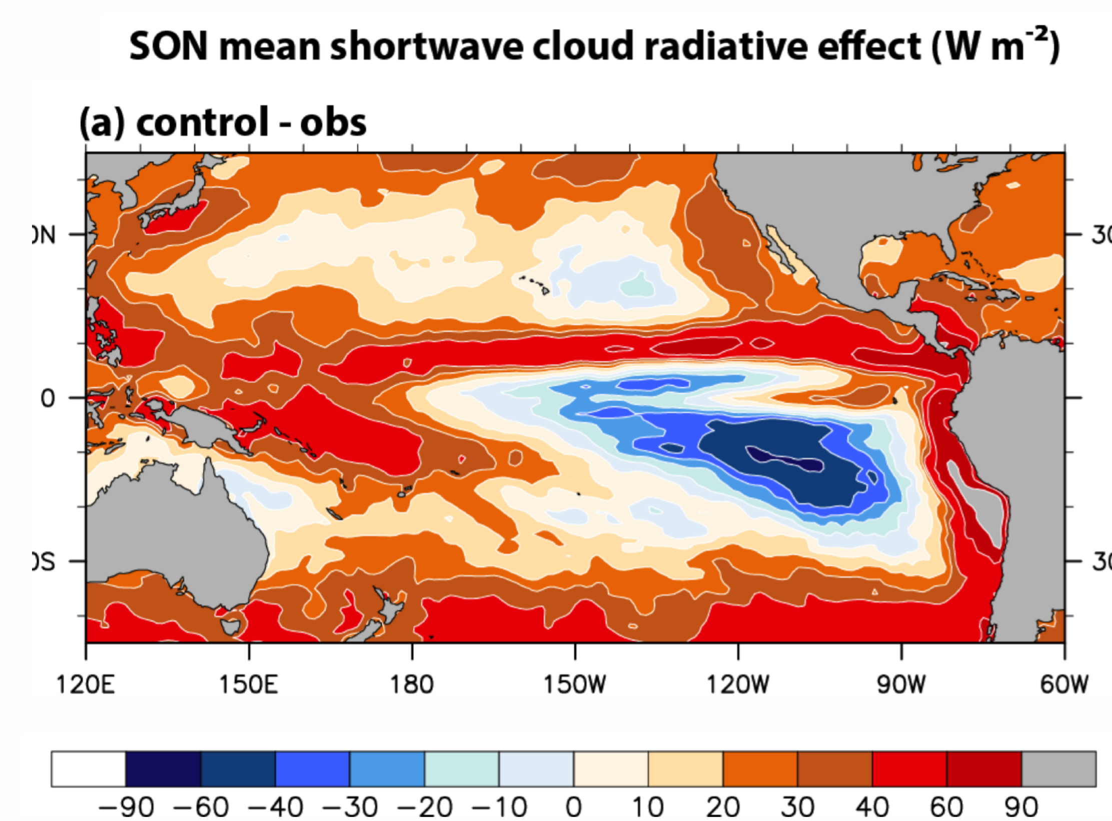
Photo: Lis Cohen

Boundary layer clouds in global circulation models (GCMs)

- GCMs have horizontal grid sizes of tens of km or more.
- Most cloud-scale circulations are not resolved by GCMs and have to be heavily parameterized.
- Representation of coastal Sc and the off-coast transition from Sc to trade-wind Cu has been a long standing challenge.
- Operational GFS has substantial biases in the low cloud fraction vs CloudSat/CALIPSO, and in low cloud radiative forcing vs CERES2
- Representations of SGS (subgrid-scale) circulations in GCMs can be improved!





Fletcher et al (2014)

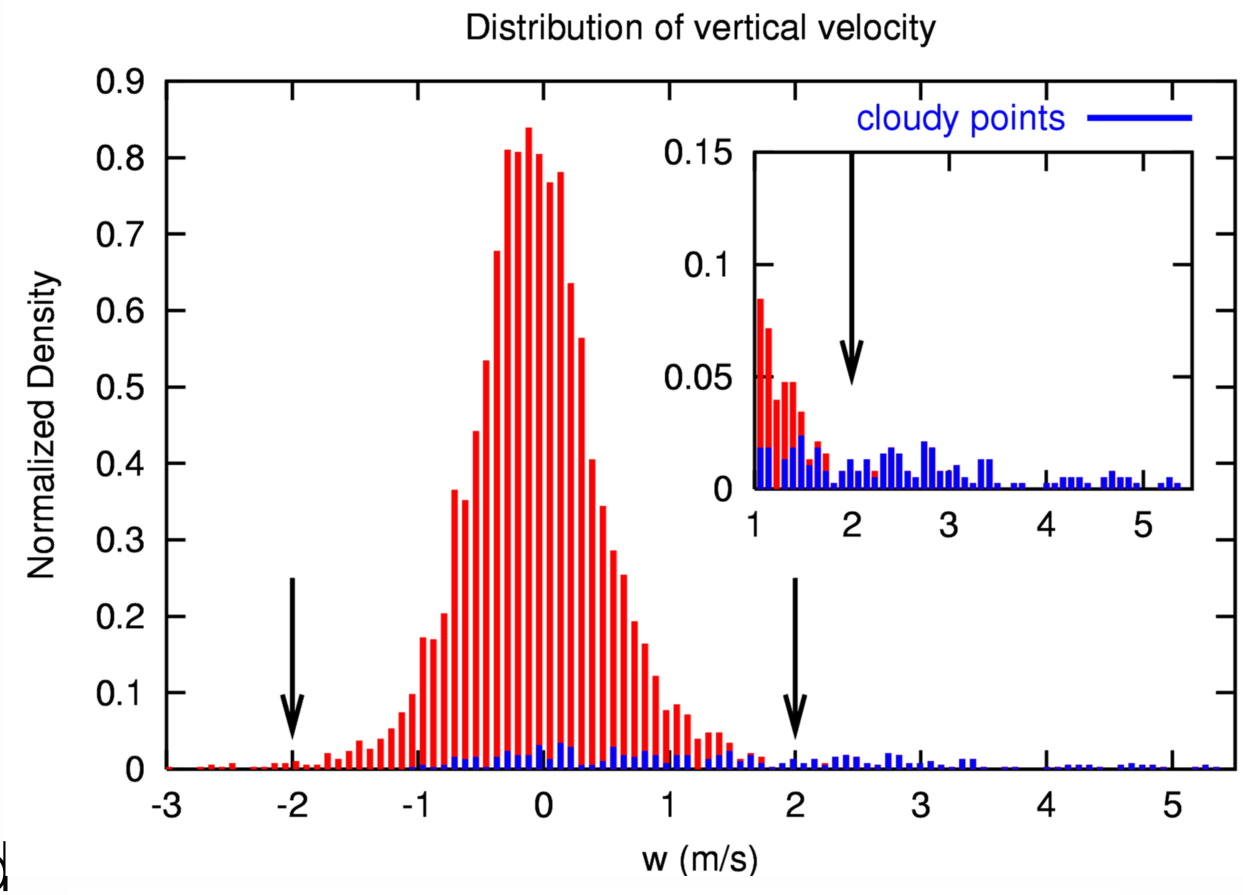
Which PDF to choose?

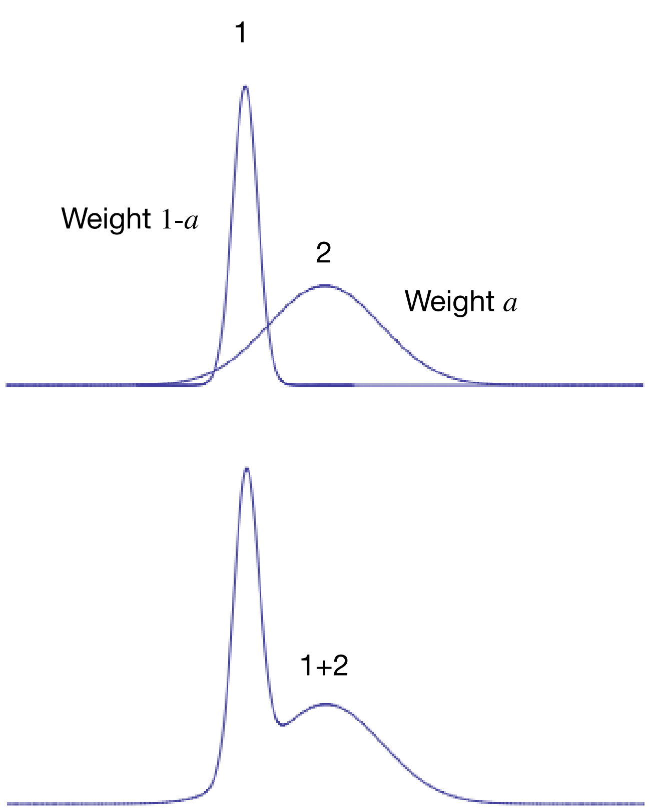
- Larson et al (2002), Bogenschutz et al (2010) showed that in precipitating and non-precipitating trade-wind cumulus, continental cumulus, stratocumulus and stratocumulus-to-cumulus transition regimes, PDFs of w, T, and q are either single- or bi-modal.

- These PDFs are approximated by trivariate double Gaussians for w, T, and q. The first Gaussian can be thought of as representing cloud-free environment, and the second, the clouds.

- After some further simplifying assumptions, the moments required to specify the parameters of the PDFs are:

$$\overline{w},\ \overline{w'^2},\ \overline{w'^3},\ \overline{\breve{\theta}_l},\ \overline{\breve{\theta}_l'^2},\ \overline{q_t},\ \overline{q_t'^2},\ \overline{w'q_t'},\ \overline{w'\theta_l'},\ \overline{q_t'\breve{\theta}_l'}$$





Randall (2013)

We use trivariate double Gaussians, for $w, T,$ and q.

Plan for Implementation in GFS

- Add a prognostic TKE equation to GFS:
  - Use the scalar advection code already present in GFS.
  - Calculate eddy diffusivity and viscosity using SGS TKE.
  - Parametrize shear production, SGS advection and pressure perturbation terms as down-gradient diffusion using these eddy diffusivities.
  - Parametrize TKE dissipation using the new turbulent length scale developed for SHOC.
  - Output and analyze TKE and eddy diffusivity and viscosity fields.
  - At this stage, SHOC does not feed back anything to the GFS.

- Add the assumed PDF component of SHOC to GFS:
  - Use the new eddy diffusivity and viscosity to diagnose moments of the subgrid PDF.
  - Calculate parameters of the assumed PDF.
  - Calculate SGS cloud fraction, SGS condensation, turbulent fluxes and third moment of vertical velocity using the assumed PDF.
  - Output and analyze these fields.
  - At this stage, SHOC still runs non-interactively.

Plan for Implementation in GFS (2)

- Couple SHOC to GFS
  - Pass eddy diffusivity and viscosity, SGS cloud fraction, and cloud water/ice computed by SHOC to GFS.
  - Test, tune and evaluate the resulting model using the standard procedure used at EMC (including cycled data assimilation/forecast tests).

- Implement in the NCEP Coupled model
  - Test, tune and evaluate for climate applications, including seasonal prediction and coupled climate runs.

- All initial testing and tuning will be performed on Gaea.