Parametrizing Cloud Cover in Large-scale Models

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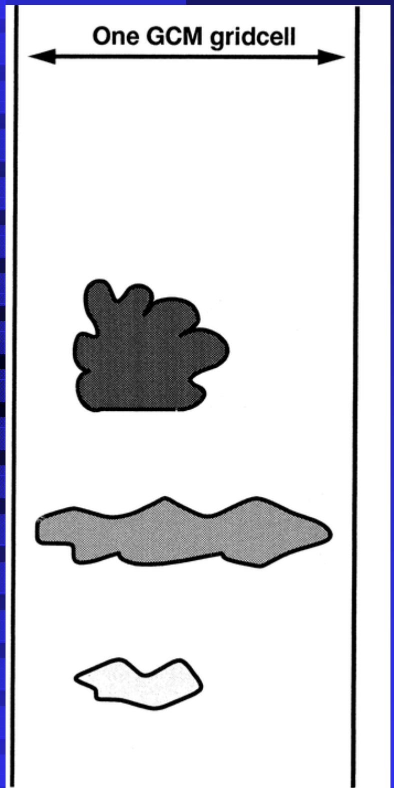
Outline

- Terms, Definitions, and Approaches
- What is sensitive to the parameterization of cloud cover?
- The convective detrainment process
- Advanced methods for statistical cloud parameterization
- When will the cloud cover parameterization go away?

The situation as it has come to be…

Adrian's Clouds

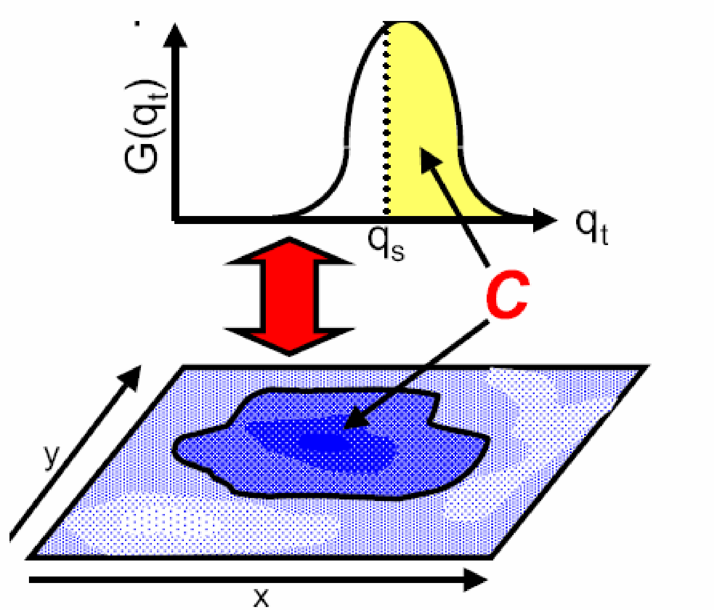


- Clouds cover only a fraction of a large-scale model grid box
- Cloud 'cover' is the horizontal fraction of the area of this grid box at a given level of the atmosphere that is occupied by saturated air
- Large-scale models have 2 means of condensation – 'convective' and 'stratiform'
- Cloud cover parameterization determines the behavior of the 'stratiform' or non-buoyant clouds
- The cloud cover parameterization determines the large-scale condensation (and evaporation)
- The interaction between the parameterizations of stratiform and convective clouds is quite important

Adrian: "It is clear that a utopian perfect microphysical model will render poor results if combined with an inaccurate predictor of cloud cover, due to the incorrect estimate of in-cloud liquid water."

Approach 1: Statistical Cloud Fraction

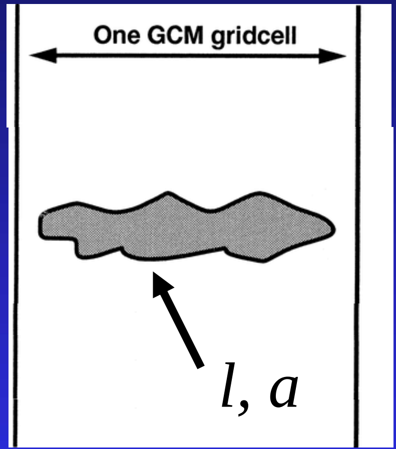
- Assume that you know the distribution of water substance in the grid-box and that it can be characterized by a simple mathematical Probability Distribution Function (PDF)
- Given the saturation specific humidity, the cloud fraction is simply the fraction of the PDF that has total water greater than saturation
- The amount of cloud condensate is simply the excess of saturation under the assumption of no super-saturation



- The challenge is specifying the characteristics of the distribution, for example, the variance
- Simplest method is to relate the variance to the mean value of total water – this is equivalent to a Relative Humidity (RH) cloud scheme
- Prominent users include UK Metoffice and LMD

Approach 2: Prognostic Cloud Fraction/ Condensate (Tiedtke 1993)

- Prognostic equations for cloud condensate *l* and cloud fraction *a*
- Tracers that are advected and diffused and that have parameterized sources and sinks from the physical processes (large-scale condensation, convection, microphysics, etc.)



Large-scale source

$$\left.\frac{\partial l}{\partial t}\right|_{ls} \approx -a\omega \frac{\partial q_s}{\partial T}\left.\frac{\partial T}{\partial p}\right|_{moist-adiabat}$$

$$\left.\frac{\partial a}{\partial t}\right|_{ls} \approx -\frac{(1-a)^2}{2(q_s - q_v)}\omega \frac{\partial q_s}{\partial T}\left.\frac{\partial T}{\partial p}\right|_{moist-adiabat}$$

Convective Scale Source

$$\left.\frac{\partial l}{\partial t}\right|_{conv} = D(l_c - l) + gM_c \frac{\partial l}{\partial p}$$

$$\left.\frac{\partial a}{\partial t}\right|_{conv} = D(1-a) + gM_c \frac{\partial a}{\partial p}$$

- Users: ECMWF, GFDL, New Model UKMet Office

Pros and Cons

Statistical Cloud Approach

Pros

- The PDF is explicit and is more easily be tested with data
- The non-linear effects of microphysics and radiation can be treated appropriately since the sub-grid distribution of cloud condensate is known
- PDF could be used in the prediction of other quantities (e.g. convective triggering)

Cons

- Predicting the shape of the PDF is challenging

Prognostic Cloud Approach

Pros

- Cloud variables are tracked directly – processes such as microphysics that only affect clouds will only affect the cloud variables with this approach but not with the statistical cloud approach

Cons

- There are cases where there is no PDF that can produce the prognosed values of cloud fraction, water vapor and cloud condensate
- If you start with clear sky, when does cloud begin?

Cons or omissions common to both approaches

- Over what scale is the cloud fraction or total water variance measured?
- What is the connection of the sub-grid distribution of other quantities such as the vertical velocity, cloud phase, temperature, cloud droplet number?

What is sensitive to the parameterization of cloud cover?

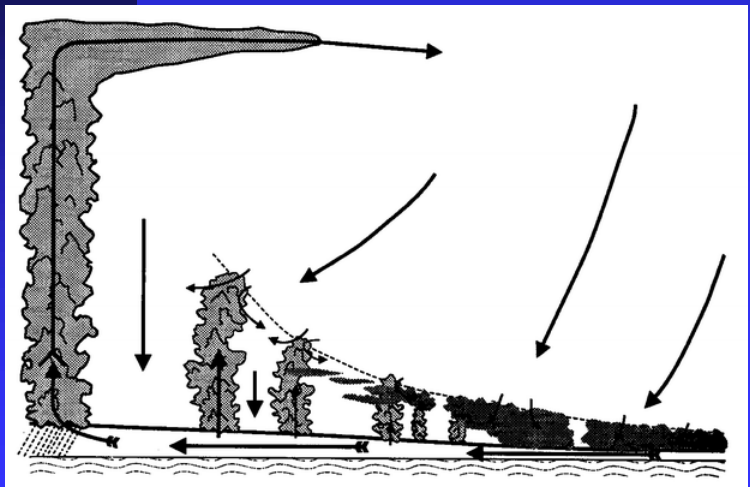
- A sensitivity test is performed that replaces one approach with another using a single model (GFDL)
- Two 6-year integrations with specified sea surface temperatures have been performed
- GFDL AM2 Details:
  - Horizontal resolution of 2 degrees
  - 24 vertical levels
  - Cloud fraction and condensate is predicted using Tiedtke’s prognostic cloud fraction and condensate scheme

Details of the Sensitivity Experiment

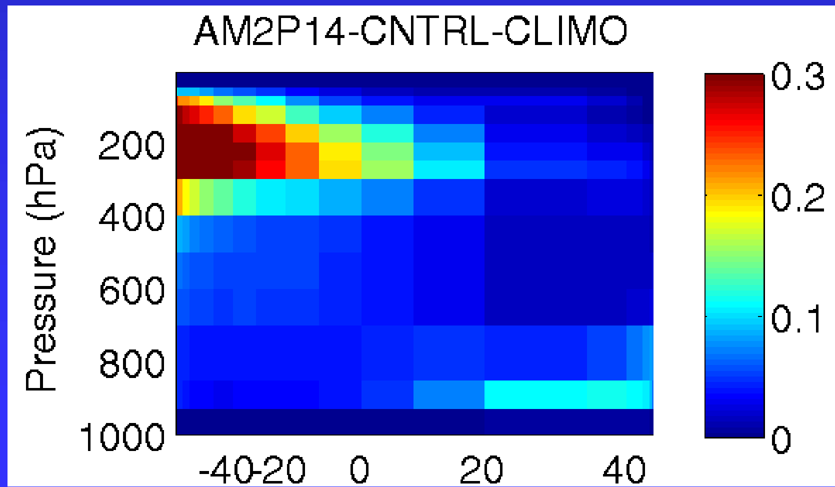
- Sensitivity experiment replaces the prognostic cloud fraction with a statistical cloud scheme
  - The assumed PDF is a symmetric beta distribution whose width is a fixed fraction of total water
  - The fixed fraction is set to a value that yields the same critical relative humidity used in the Tiedtke cloud fraction
  - Radiation is handled with the Monte-Carlo Independent Column Approximation (MCICA)
  - Nothing else including the partitioning between liquid and ice is changed

Results

- Surprising at first is how little of the model changes
  - Radiation balance is more or less the same
- Further analysis of these results via ‘Bony’ diagrams which focus on tropical climate



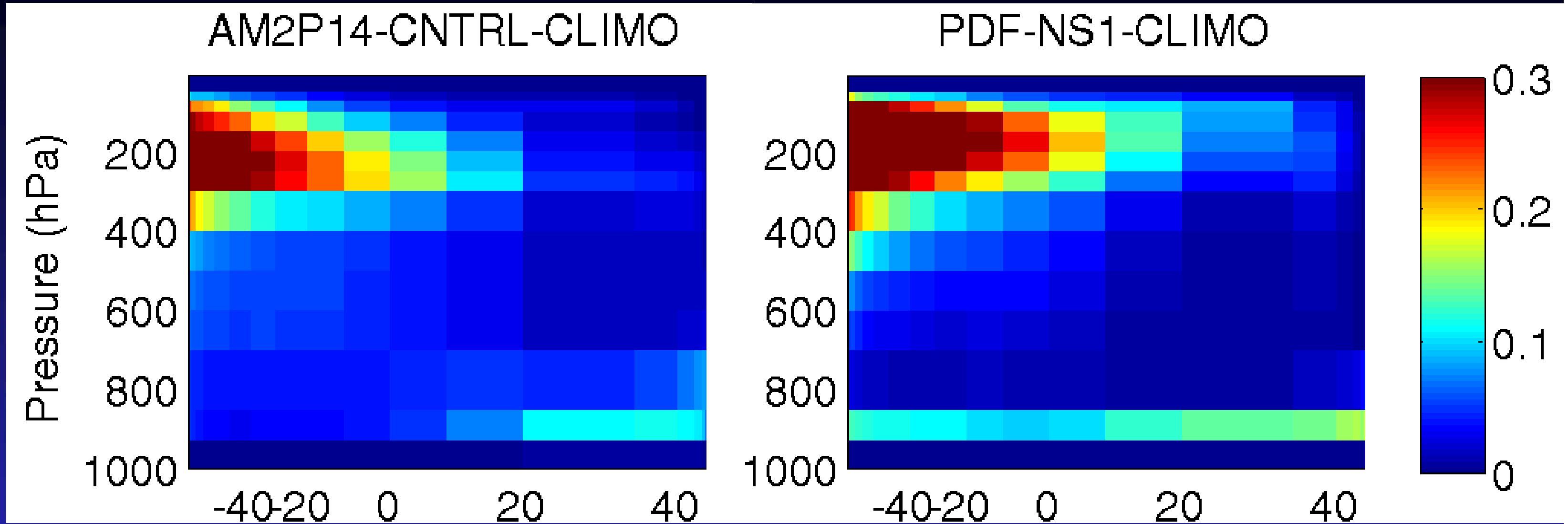
Warm SST *Cold SST*



500 hPa ω (hPa day^{-1})

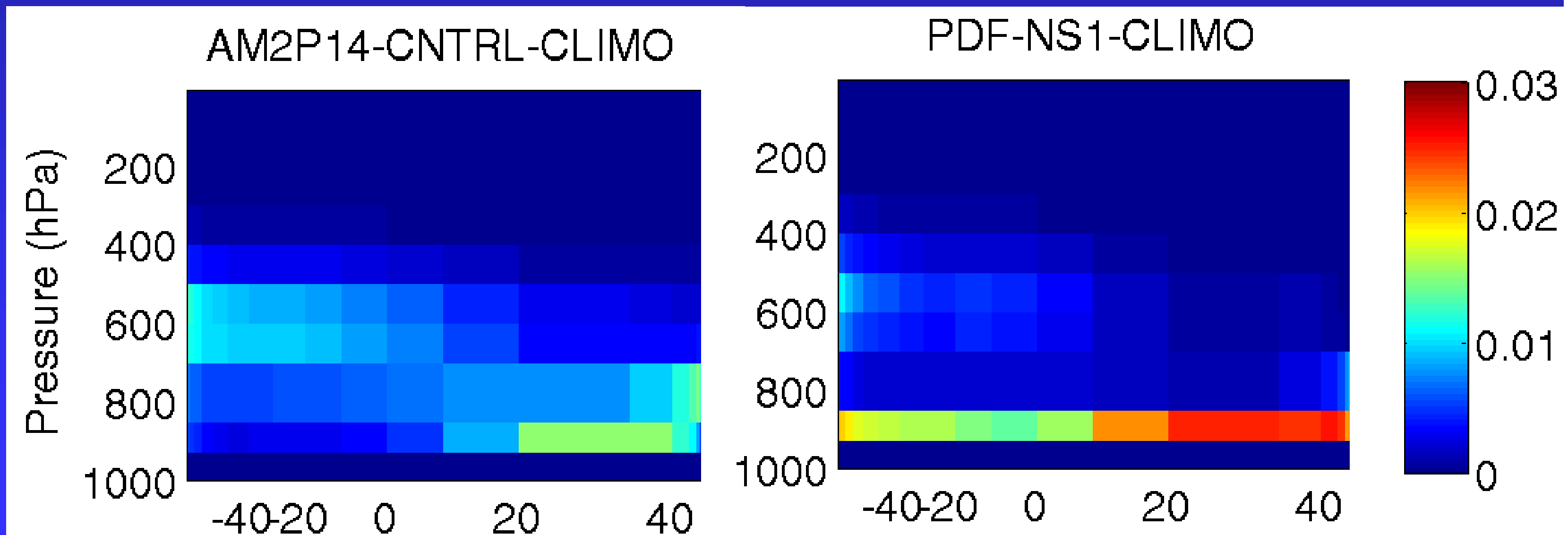
AM2 Cloud Fraction

Cloud Fraction



Cloud Liquid

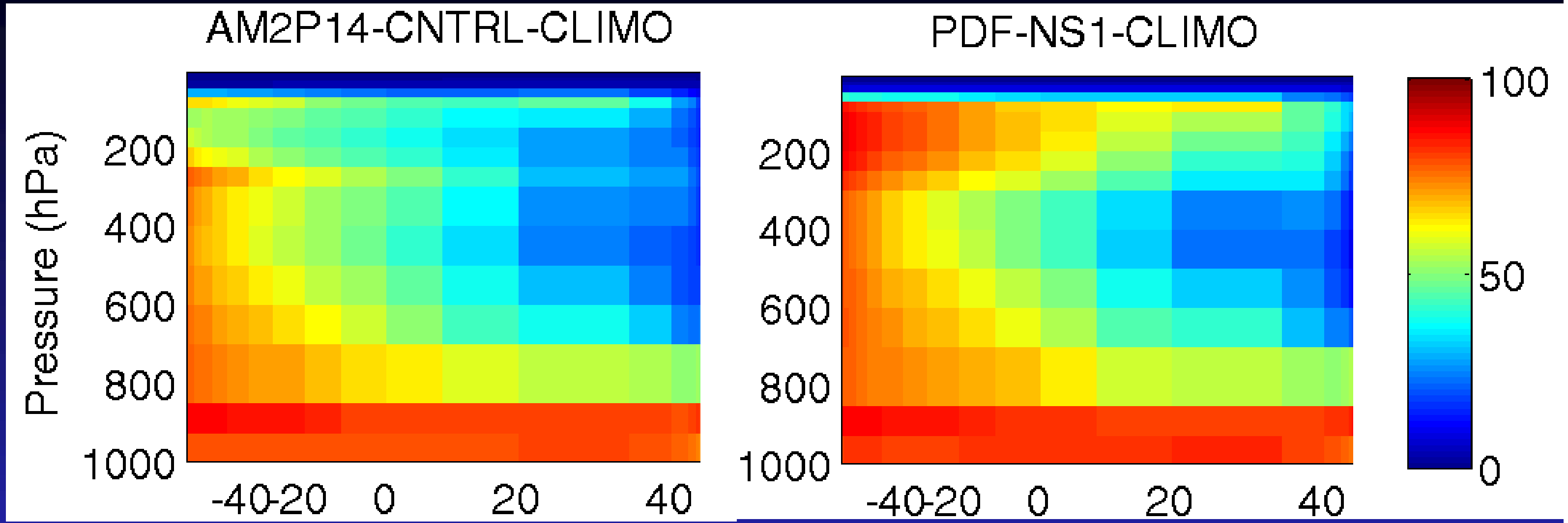
(g/kg)



500 hPa ω (hPa day⁻¹) *500 hPa ω (hPa day⁻¹)*

Relative Humidity

(%)



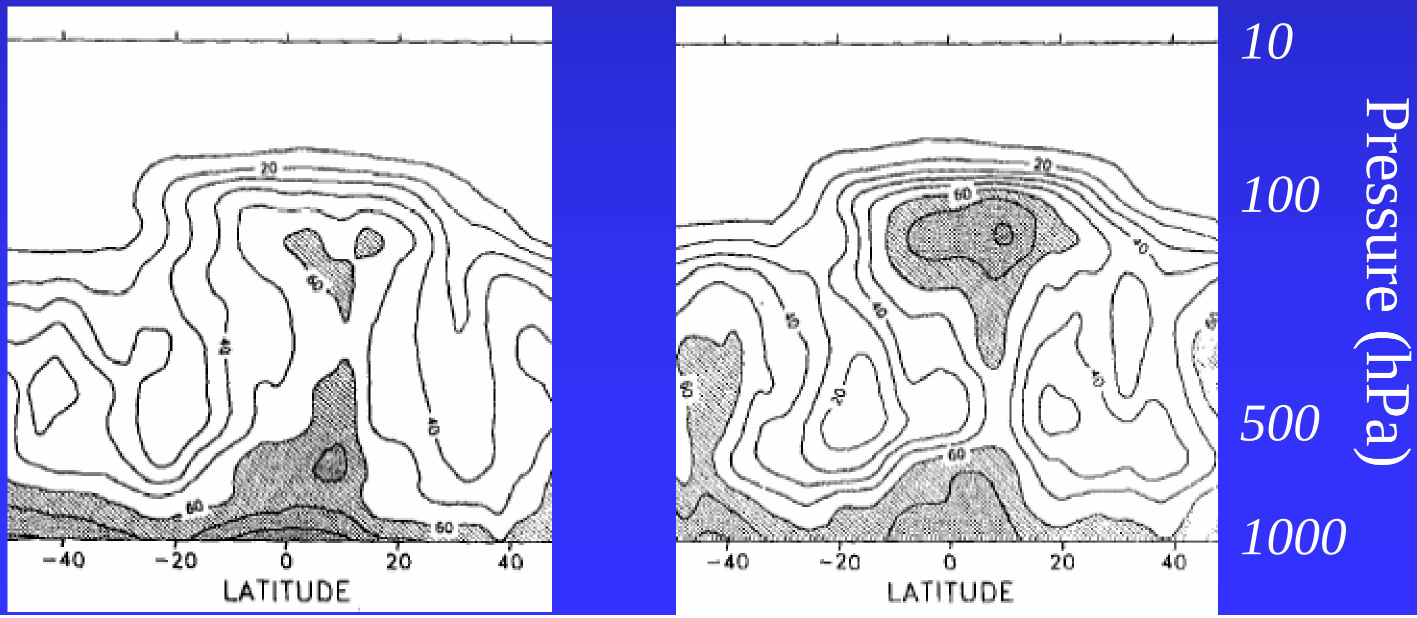
500 hPa ω (hPa day^{-1}) 500 hPa ω (hPa day^{-1})

Tiedtke (1993)

Prognostic Cloud Diagnostic Cloud

Relative Humidity

(%)



Climate Sensitivity

- Cloud feedback remains a largely unsolved problem as evinced by the continuing wide spread in simulated feedbacks by climate models
- Understanding of differences between models is hampered by the complexity of feedbacks simulated and the large-structural differences between models
- Based on slab simulations with the latest IPCC models, Webb et al. (2006) noted that climate sensitivity was higher in models with PDF cloud schemes – *Is this a coincidence?*

Climate Sensitivity Analysis

- ‘Cess’ Experiments in which the sea surface temperature was raised by 2K globally are a cheap way to assess how (some) feedbacks change
- Two Cess experiments – one for the control model and one for the model with PDF cloud scheme – were performed

Global Results

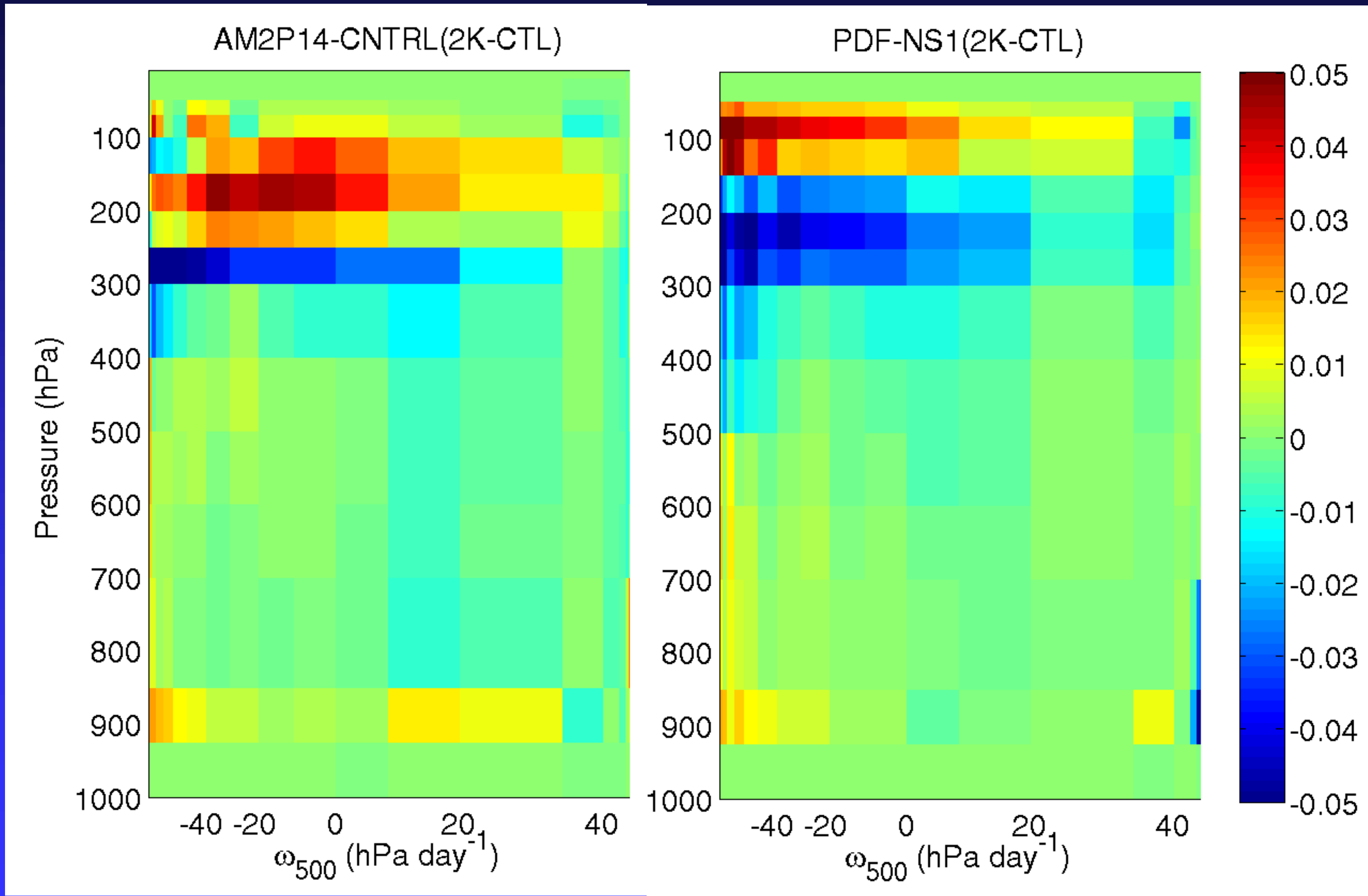
- Climate Sensitivity Parameter (ΔTs/G)

	AM2: w/ Tiedtke clouds	AM2 w/ PDF clouds
λ All-sky (K W^{-1} m^2)	0.61	0.58
λ Clear-sky (K W^{-1} m^2)	0.60	0.73

- Cloud Feedback Parameter (ΔCRF/G)

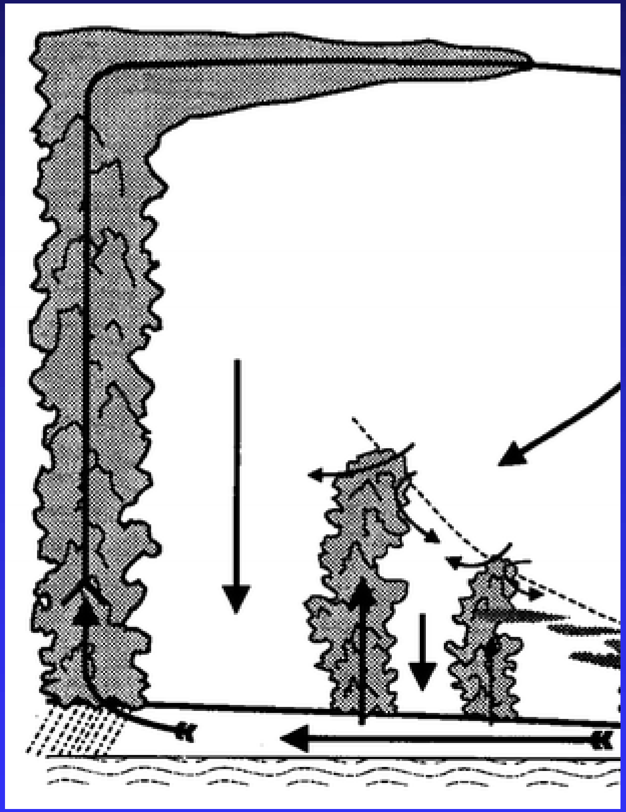
	AM2 w/ Tiedtke clouds	AM2 w/ PDF clouds
ΔLWCF/G Longwave Cloud Forcing	0.28	0.24
ΔSWCF/G Shortwave Cloud Forcing	-0.26	-0.46

ΔCloud Fraction



The Convective Detrainment Process

- With the PDF scheme, if the pre-existing relative humidity (and thus cloud fraction) is low, all of the cloud condensate detrained evaporates. Because $l_c \sim q_s$, this is a large-source of additional water vapor
- For the prognostic cloud fraction, the condensate enters a stratiform cloud which (if there is no pre-existing cloud) has the same in-cloud condensate mass as it did in the convection. This condensate can then form precipitation and fall out of the level that it was detrained at before the cloud dissipates



- Thus the PDF scheme with no explicit connection to convection has a lower effective total water precipitation efficiency and you end with greater humidity (and in the end cloud)

Advanced Methods for Statistical Cloud Parameterization

- Bony and Emanuel (2001) uses a lognormal PDF whose shape is adjusted so that the in-cloud condensate diagnosed from the PDF equals that that is diagnosed in the convection scheme and large-scale condensation schemes
- Teixeira and Hogan (2002) use the steady version of the prognostic cloud fraction to propose a diagnostic cloud parameterization that could be used in PDF cloud scheme
- Cusack (1999) sets the width of the PDF to the horizontal variance that is resolved by neighboring grid-boxes of large-scale model (this is a nice down-scale approach – assumes a power law distribution of variance)

Advanced Methods for Statistical Cloud Parameterization

- Prognostic Variance (Tompkins 2002)

$$\frac{\partial q'^2}{\partial t} + V \bullet \nabla q'^2 = S_{conv}(q'^2) + S_{turb}(q'^2) + S_{micro}(q'^2) + S_{meso}(q'^2)$$

- Turbulence source term is well-known
- Convective source term (Klein et al. 2005)

$$S_{conv}(q'^2) = D(q_{t,conv} - q_t)^2 + D(q'^2{}_{conv} - q'^2) + gM_c \frac{\partial q'^2}{\partial p}$$

- Microphysics is a challenge

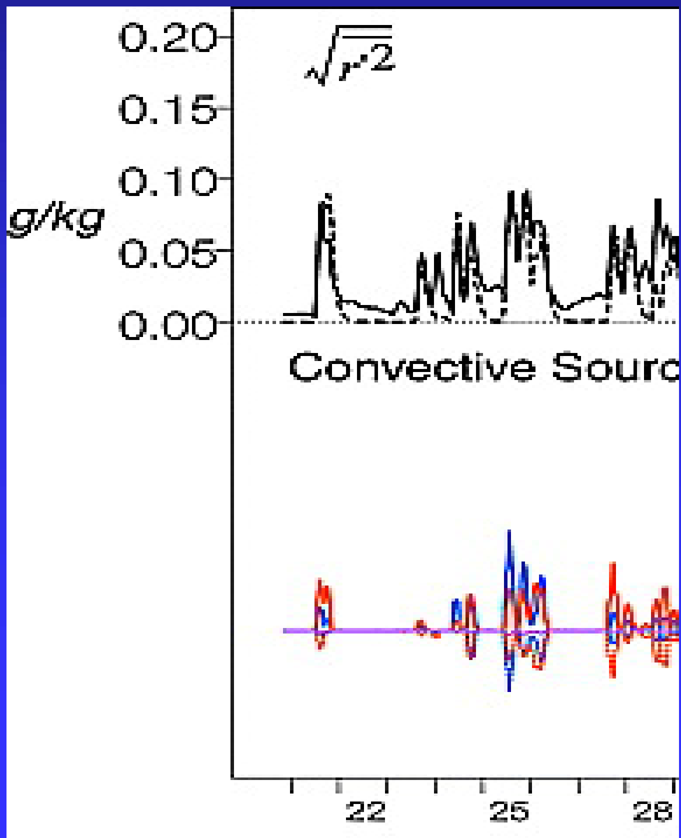
$$S_{micro}(q'^2) = -2\overline{G'_p q'} = -2G_p \sqrt{q'}$$

Monte Carlo approaches? (Larson 2006)

Variance Budget Example

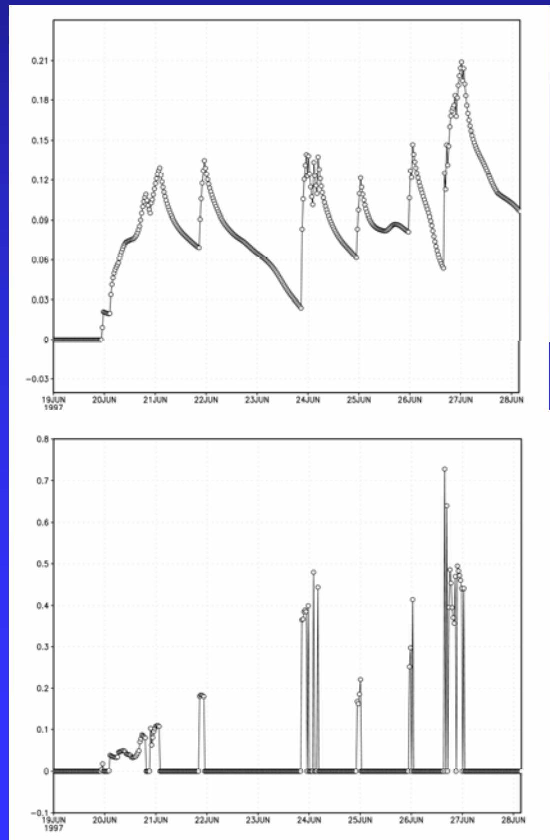
Cloud Resolving Model at the Cirrus Detrainment Level

Single Column Model for the Same Time



$\sqrt{q'^2}$

$S_{conv}(q'^2)$



When will the cloud cover parameterization go away?

- Some mesoscale and most cloud resolving models ignore the cloud fraction problem entirely, although they may still have a cumulus parameterization
- Why does the cloud fraction parameterization exist?
  - Is it to account for mesoscale variability in cloud fields?
  - Is it to account for the evolution of cloud after cloudy mass has been detrained from updrafts?
- Note that you could ignore the coupling between convection and large-scale but still represent the radiative effects of convective clouds (e.g. towers) through a McICA approach

Convective Detrainment Example

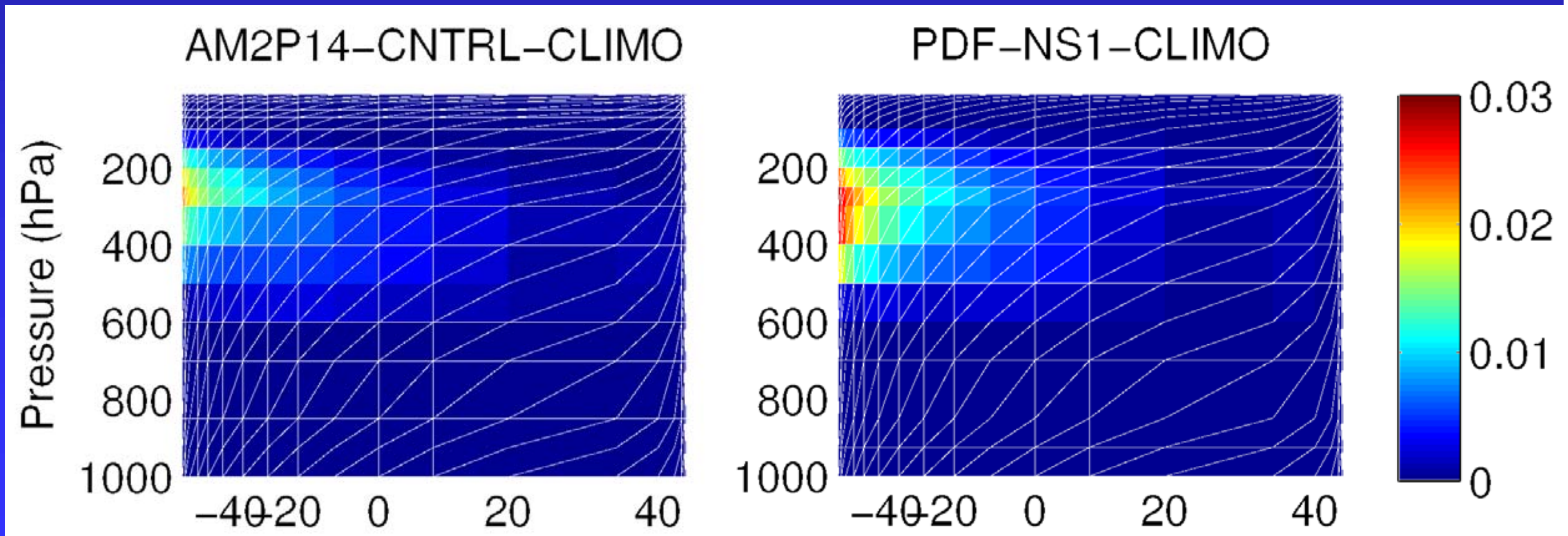
- If you want to do a better simulation of this phenomenon, you want the volume of air detrained in one step to be compatible to the horizontal resolution of the grid box and the time scale of the processes that affect cloud water (e.g. horizontal mixing and microphysical processes) be long relative to the time step (i.e. the processes are resolved)
- Basically this is saying that you want to simulate explicitly convection before the cloud fraction problem goes away

When will the cloud cover parameterization go away?

- However would the cloud errors be worse if you went to an all or nothing scheme (or a very simple PDF scheme) at the very high resolution of the ECMWF model?
- What fraction of upward moisture tranport is currently resolved versus parameterized?
- Would this simplification facilitate the incorporation of more complicated microphysics? And/or facilitate Data-Assimilation?

Cloud Ice

(g/kg)



500 hPa ω (hPa day^{-1})   *500 hPa ω (hPa day^{-1})*

Cloud Optical Thickness Histograms