Some observations on boundary layer and convective processes for chemistry and climate models

Philip J. Rasch

(thanks to)

M. Lawrence, K. Emanuel, Jack Kain, Minghua Zhang, D. Zurovac-Jevtic, Jim Hack

"Organized Convection"

Understanding only German, Fritz was unaware that the clouds were becoming threatening.

Paraphrasing from “Observational constraints on Cumulus parameterization” (D. Raymond, 1993) (which I believe represents a consensus view)

- Negative feedbacks exist between convection and the large scale.
- It is not necessary to have a parameterization that is highly accurate. It is sufficient that changes in large-scale forcing result in changes in parameterized convection that are correct in sign and of the right order of magnitude
- Because of negative feedback, this behavior will often force the convective parameterization to do the right thing.

Paraphrase (continued)

- Must:
  - Predict mass flux/heating
  - Detrainment of vapor flux
  - Estimate precipitation production and ice detrainment
- Clouds exit at their level of neutral buoyancy
  - Constrains Θ_v and moisture detrainment
- Close relationship exists between convective heating and vertical mass flux
- Net vertical mass flux is strongly constrained

CAM/SCAM

- Community Atmosphere Model (CAM, formerly CCM) (http://www.cgd.ucar.edu/models/atm-cam)
- Single Column version of full GCM
- Convection
  - Zhang McFarlane (1994)
    - deep, bulk ensemble entraining/detraining plume
    - CAPE reduced with e-folding time scale of 2 hours
    - Downdraft
    - No triggers
  - Hack (shallow, mid-level, “3-level cloud element”)

Three "pictures" of convection are examined

- Standard CAM bulk formulation
- Stochastic mixing model (Emanuel and Zivkovic-Rothman, 1999)
- Much more elaborate plume model (Kain-Fritsch 1990,1993; Kain, 2003)

Neither the model, nor convective schemes were tuned for this exercise!

Raymond, 1993

Kain-Fritsch

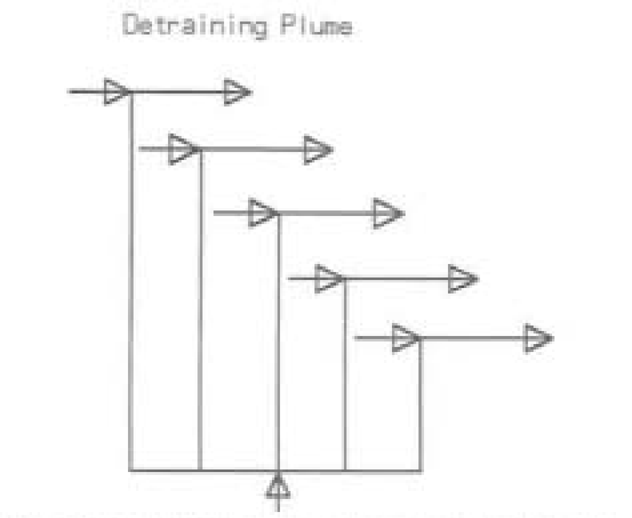


FIG. 2.3. In the detraining plume, subparcels ascending from cloud base mix with environmental air at various heights and exit the cloud.

- Entraining detraining plume with vertical momentum dynamics, triggers, tuning to CRMs'. Entrainment /detrainment functions of buoyancy and humidity.
- Shallow convection. Cloud Base Mass flux depends on TKE (currently prescribed)
- Revised downdraft (favors short, fat downdrafts)
- CAPE always reduced by 90%/timestep. Based on dilute parcel properties
- Tracer studies (Mari and Bechtold, McHenry)

Emanuel Scheme

Raymond, 1993

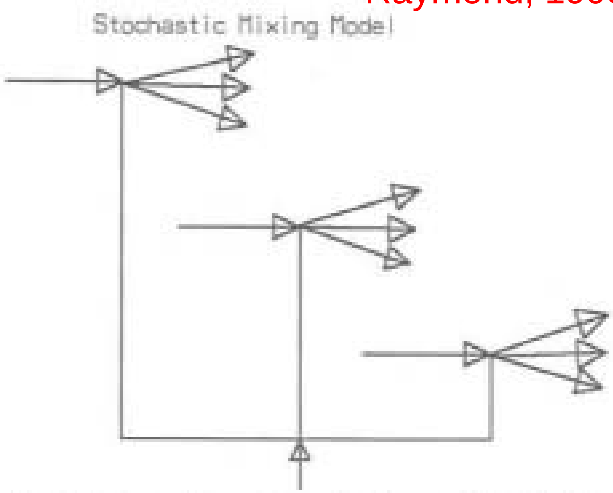


FIG. 2.4. The stochastic mixing model (Raymond and Blyth 1986) differs from the detraining plume model in that different mixing fractions are assumed for different subparcels mixing with environmental air at each level. This results in multiple exit levels for each mixing level.

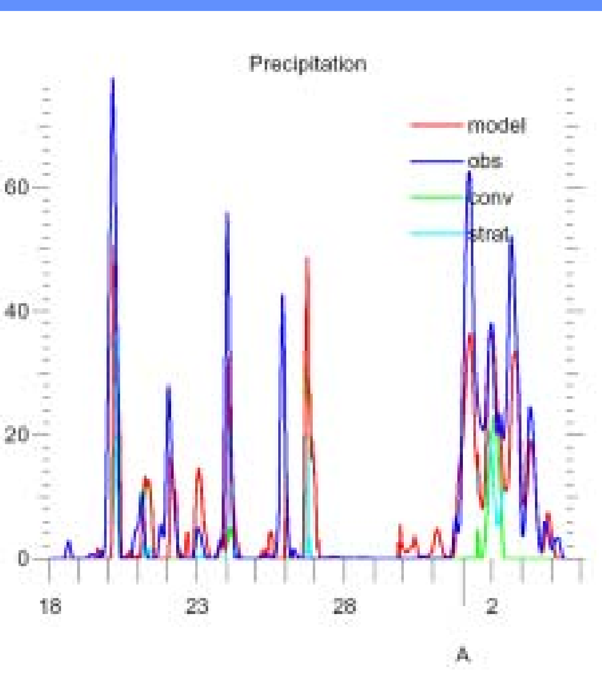
- Stochastic mixing model
- A lot of attention to microphysics
- Strong saturated downdrafts (possibility of non-precipitating cumuli)
- Unsaturated downdrafts
- Entrainment/detrainment functions of buoyancy gradients
- Subcloud-layer quasi-equilibrium closure
- Tracers studies by Wang et al (1996)

First experiments in context of two field programs

- TOGA COARE (pacific warmpool, tropical deep convection)
  - SST prescribed
- ARM-CART (Oklahoma, midlatitude summertime convection)
  - Surface temperature calculated from land model

Precipitation, instantaneous ARM-CART (summer)

Emanuel



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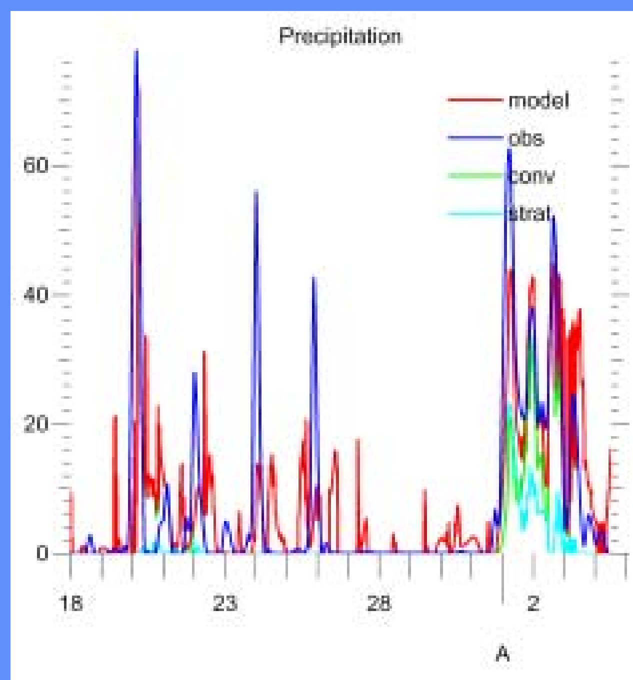
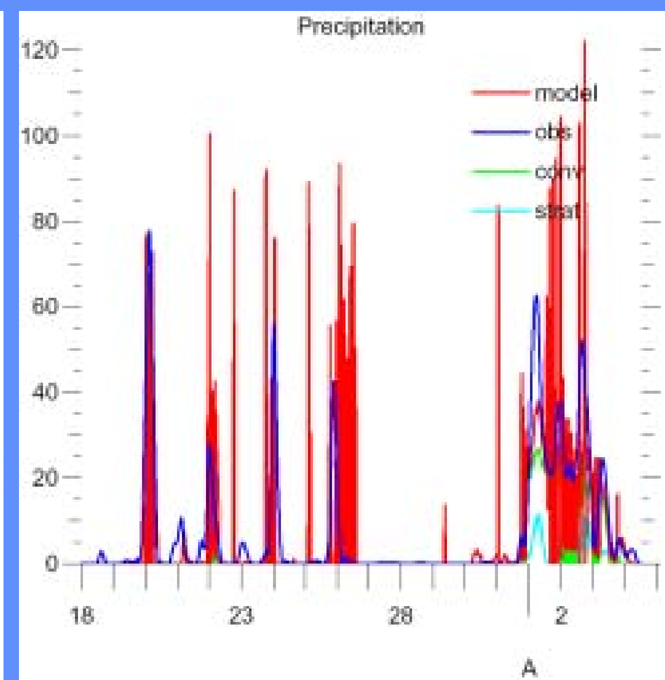
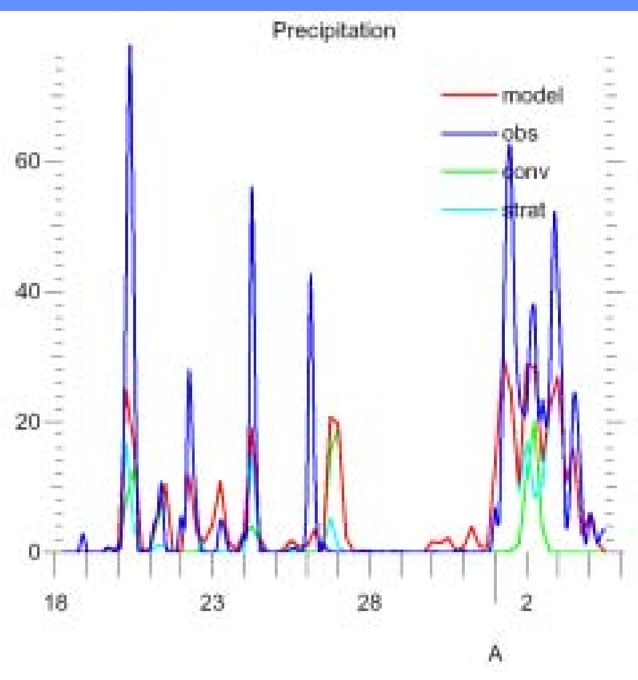


Kain-Fritsch



Precipitation, 3 hour averages ARM-CART (summer)

Emanuel



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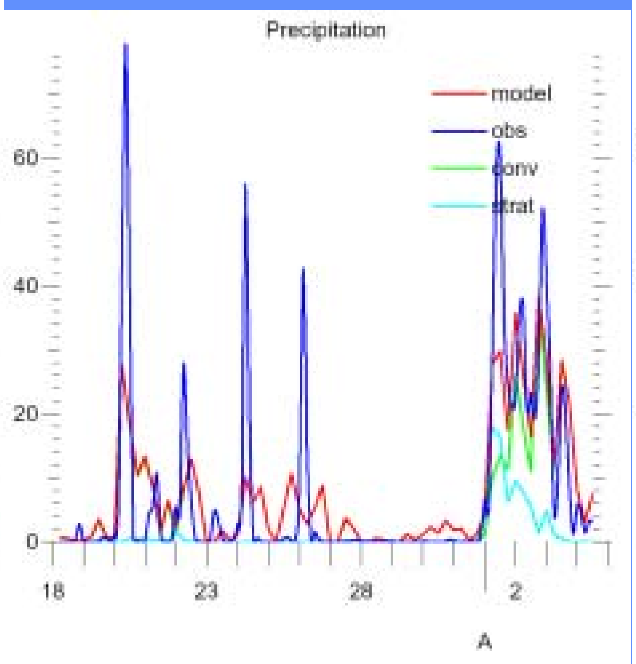
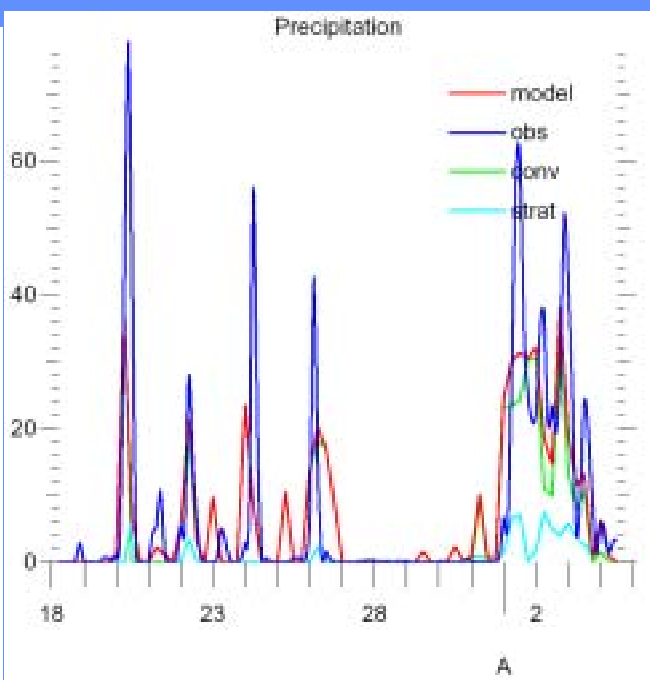
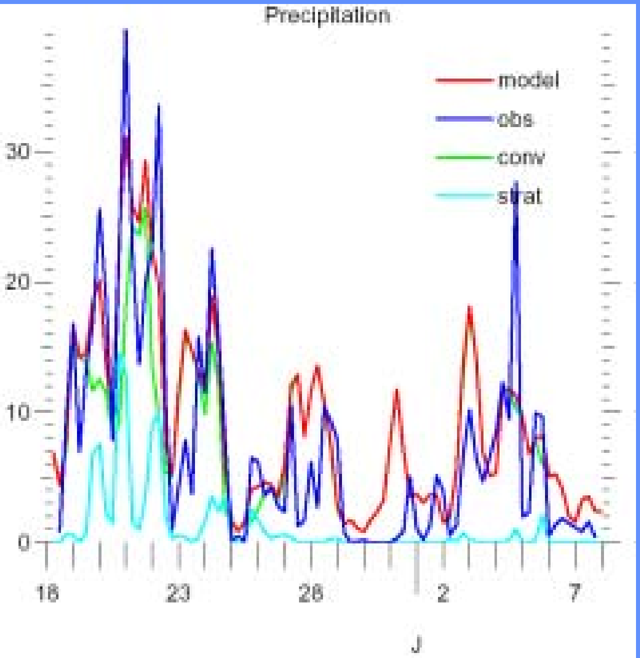


Kain-Fritsch



Precipitation, 3 hour averages TOGA-COARE (Dec-Jan)

Emanuel



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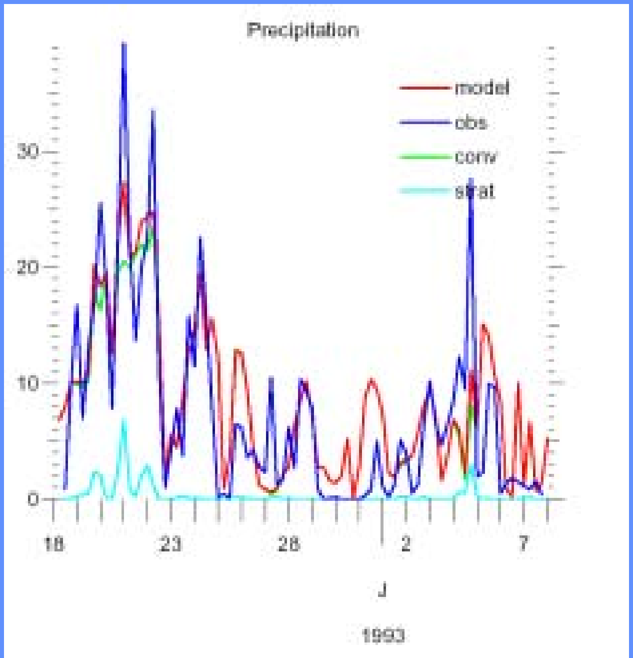
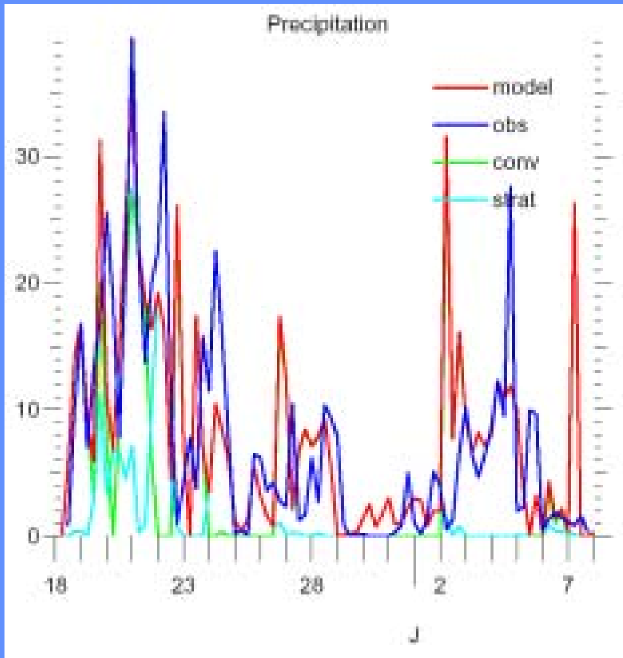
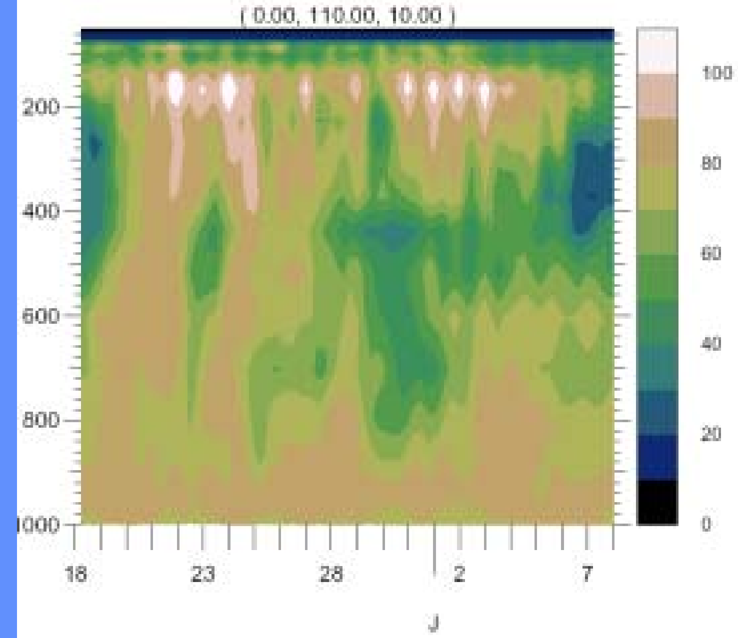


Kain-Fritsch

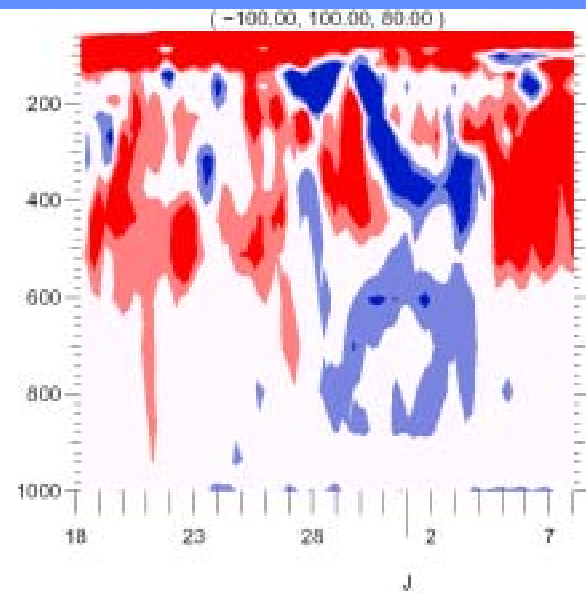


Relative Humidity TOGA-COARE (Dec-Jan)

Obs



Emanuel



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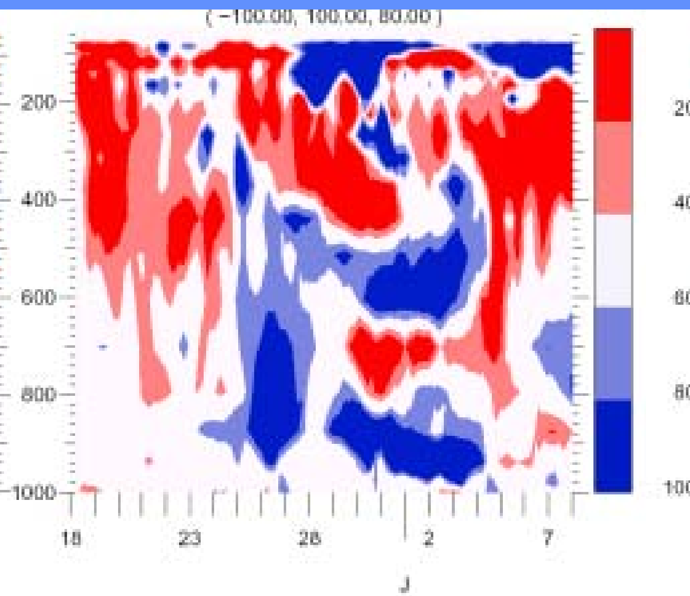
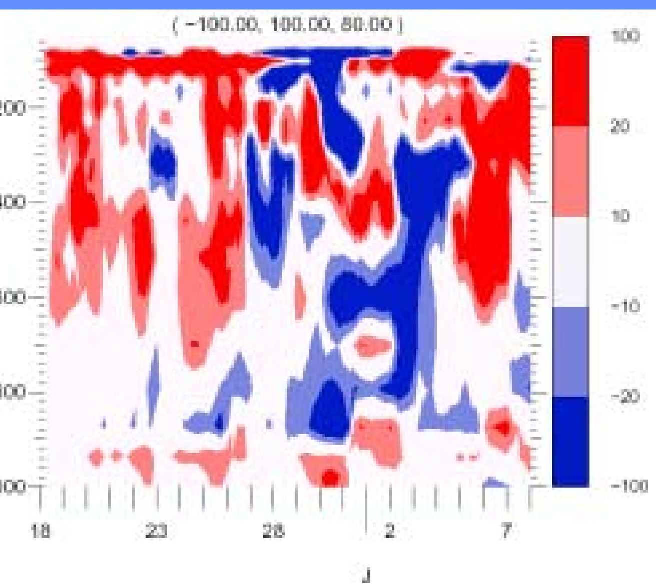
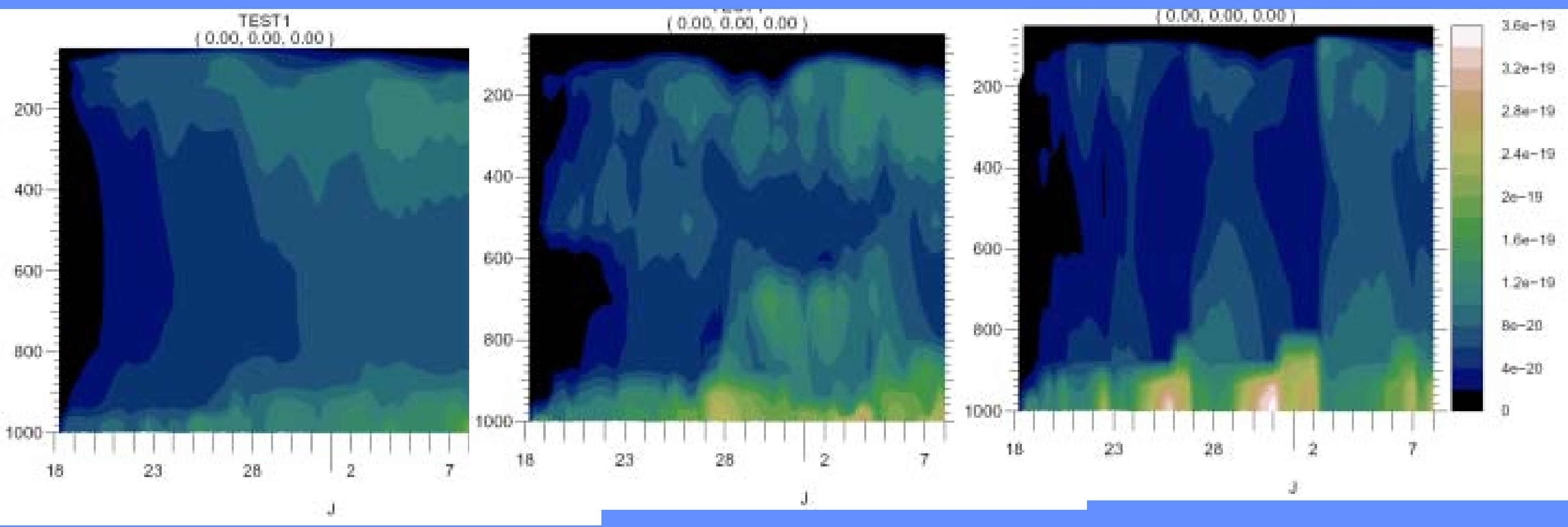


Kain-Fritsch



Radon-like SurfaceTracer TOGA-COARE (Dec-Jan)

Emanuel Standard Kain-Fritsch



Upper Tropospheric Ozone-like Tracer TOGA-COARE (Dec-Jan)

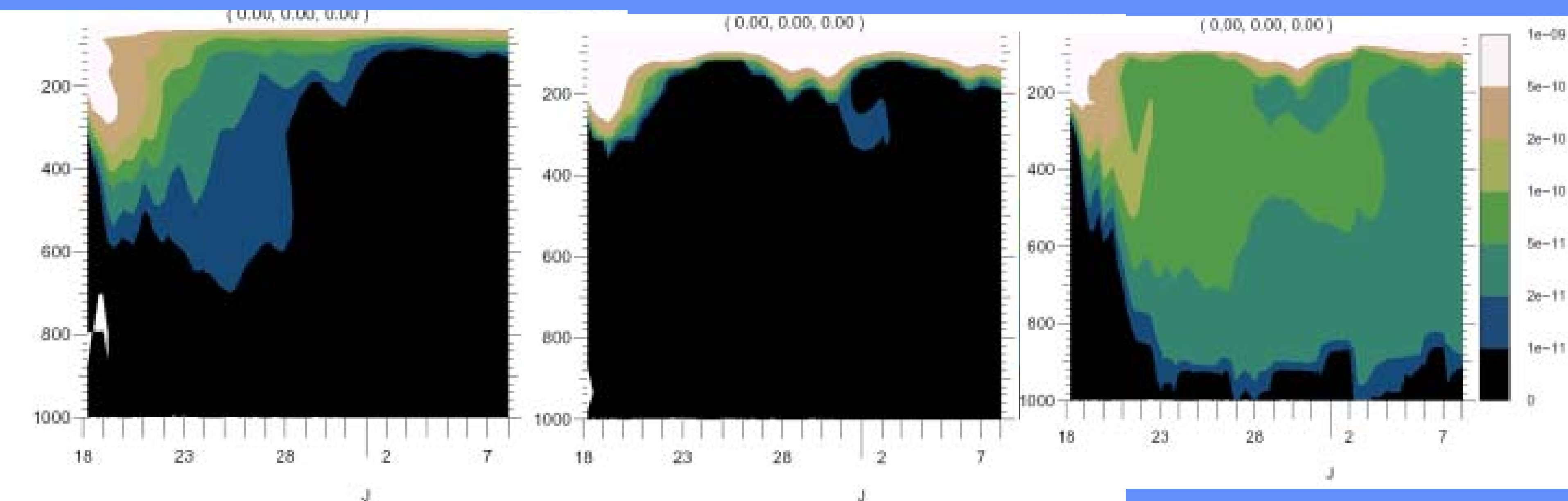
1 above 200 hPa

0 below

Emanuel

Standard

Kain-Fritsch



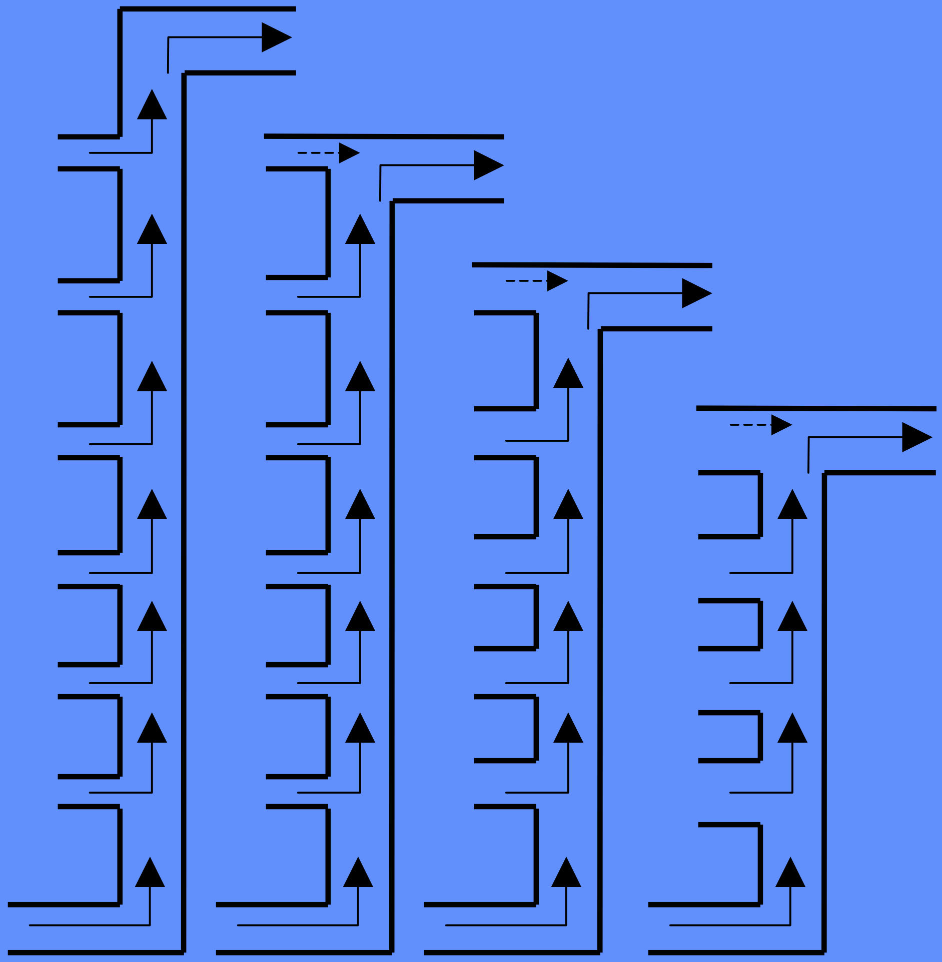
Summary

- Convective mass fluxes are very different in parameterizations
- Heat and water vapor are, in a sense “easy” compared to gaseous and aerosol tracers.
- Tracers reveal substantial differences between parameterizations.
- Tracers can help constrain uncertainties in choice of parameterization
  - Compare with observations
  - Compare with cloud resolving models
- Radon? CO? Methyl Iodide? Others (HC, Halogenated gases)?

Convective Transport Formulations

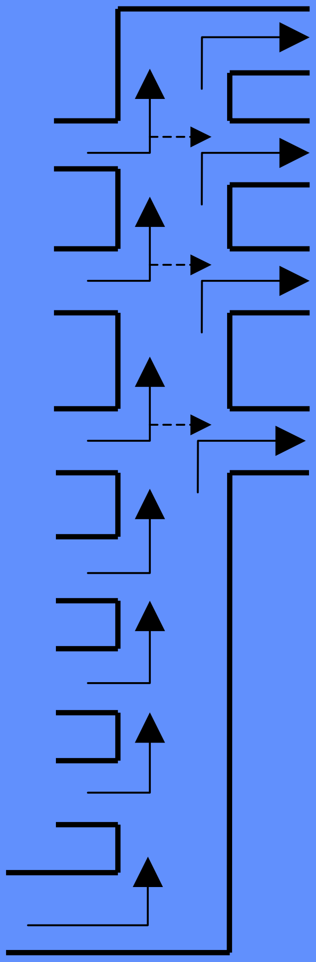
(Lawrence & Rasch, 2004 submitted)

Plume Ensemble



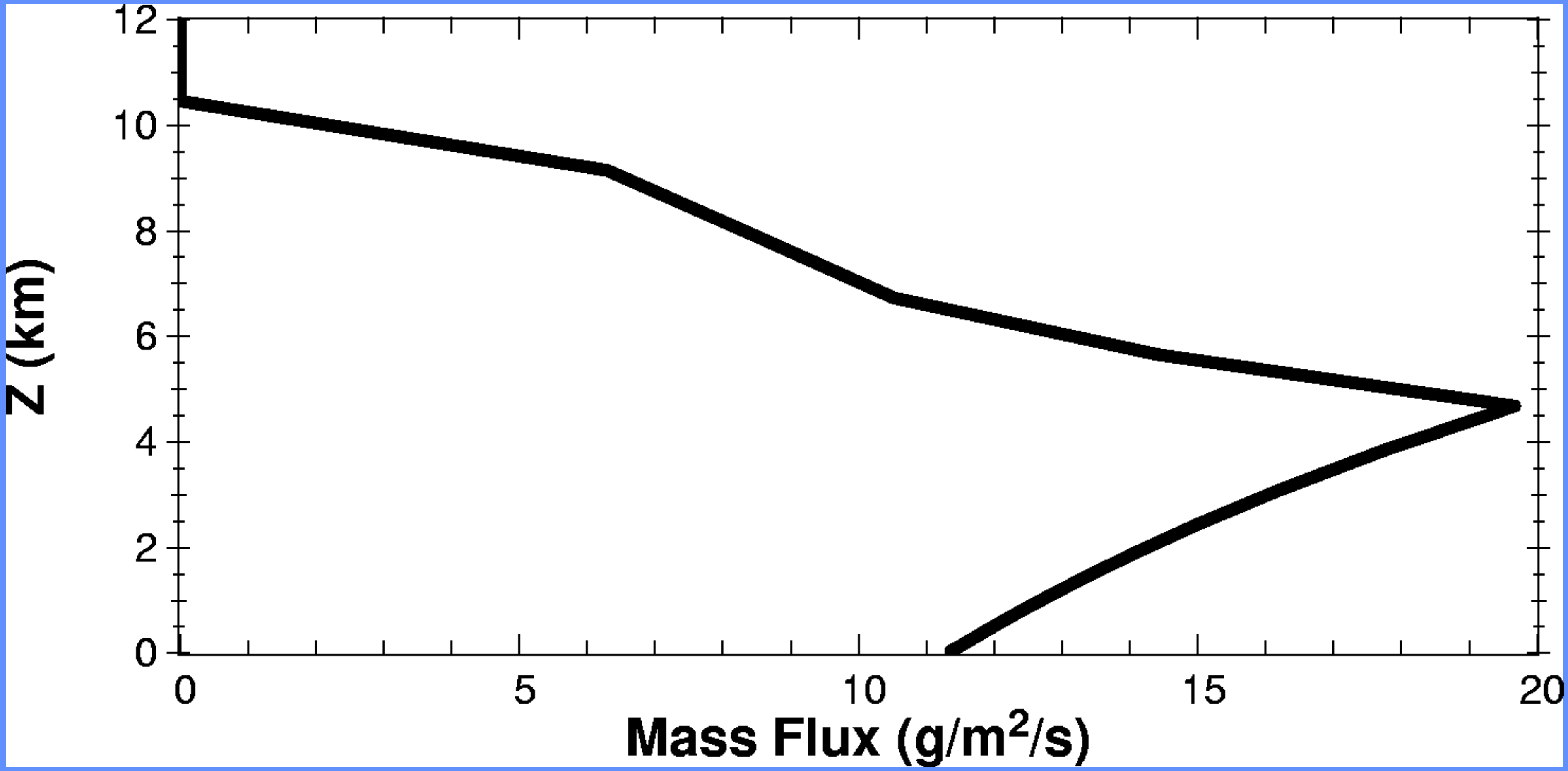
Arakawa and Schubert, 1974; Lord et al., 1982; Hack et al., 1984; Grell, 1993

Bulk



Yanai et al., 1973; Tiedtke, 1989; Grell, 1993; Pan and Wu, 1995; Zhang and McFarlane, 1995

Decomposition of a Bulk Mass Flux Profile into a set of Discrete Plumes (Sub-Ensembles)



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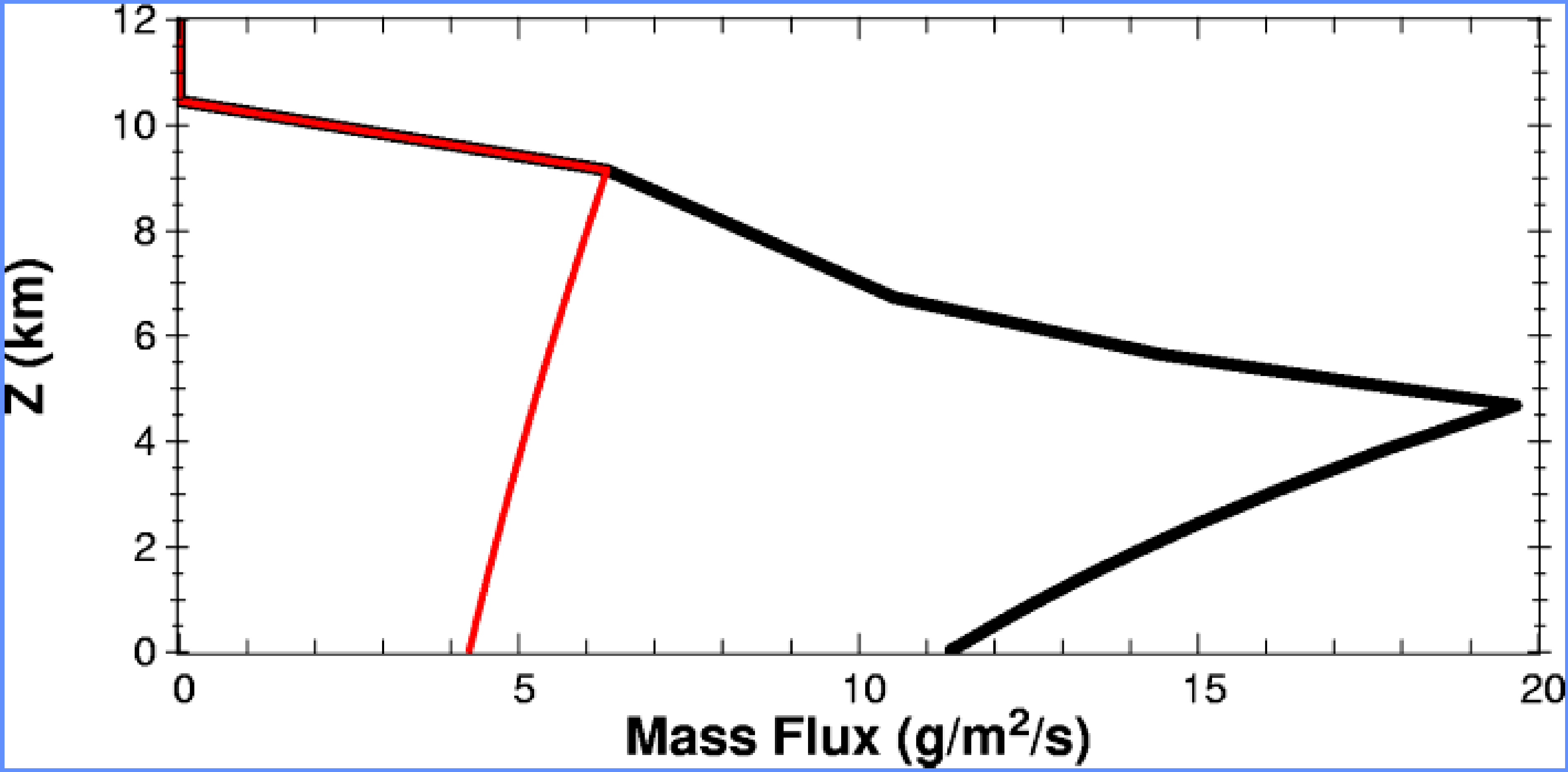

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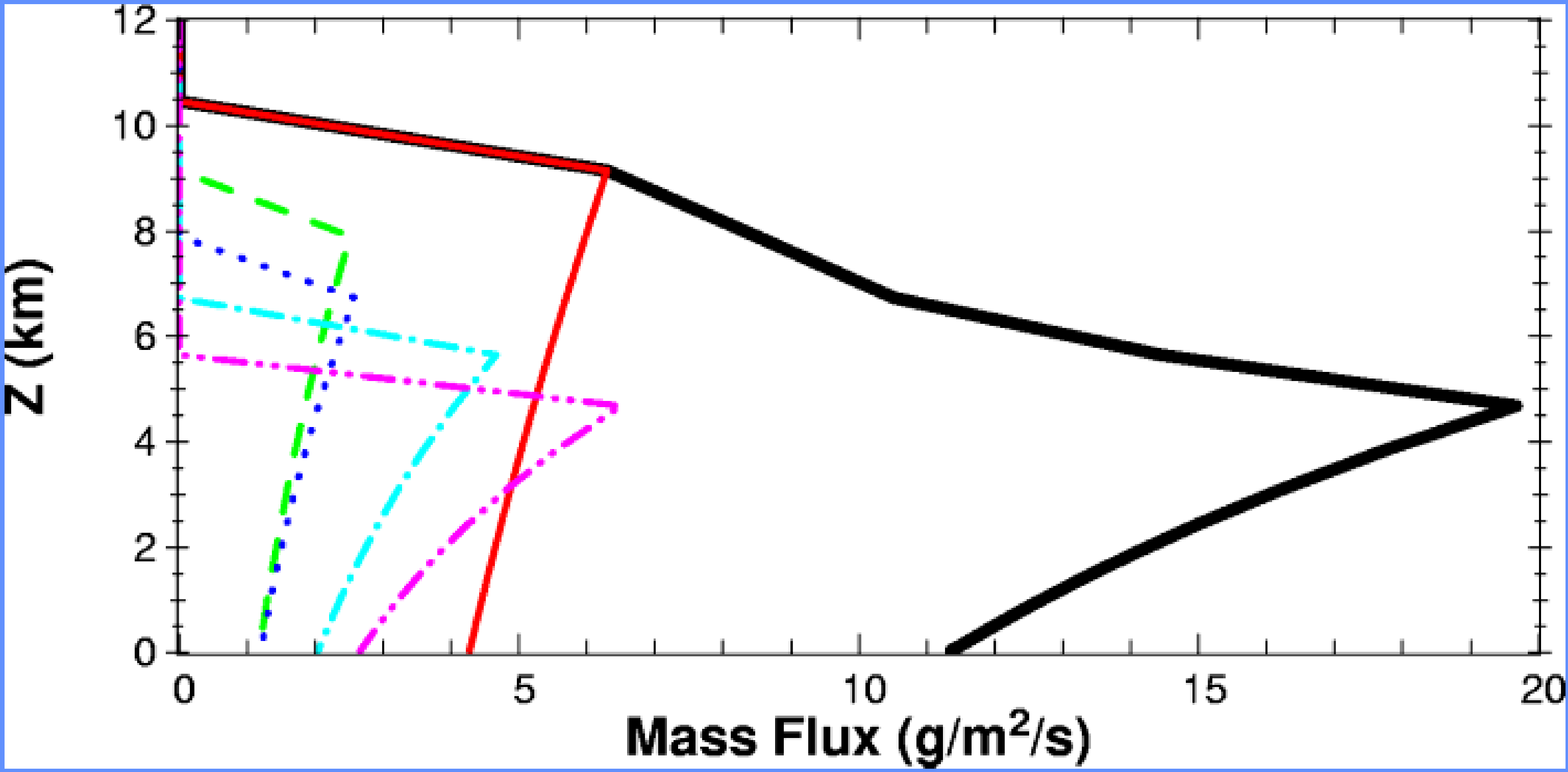
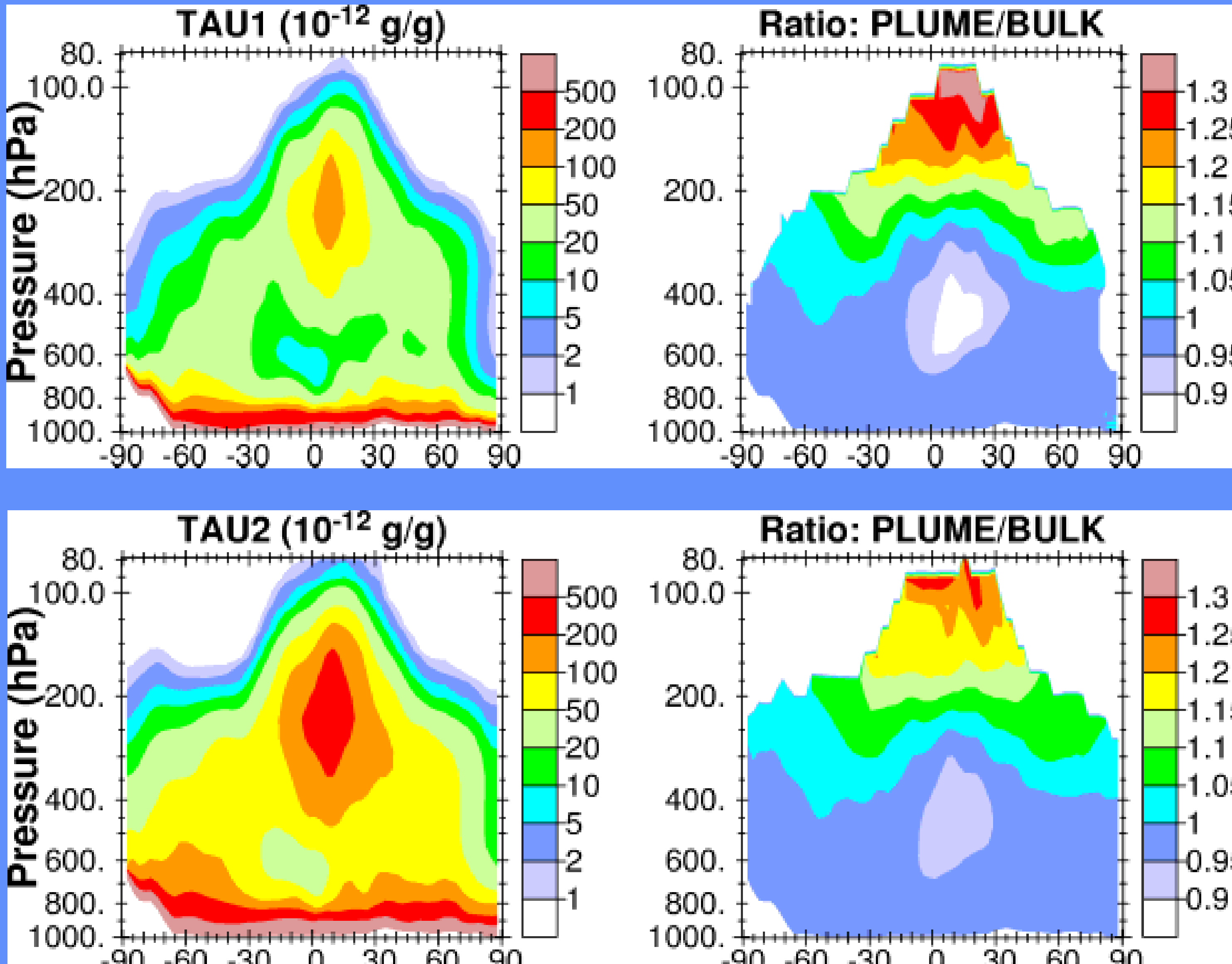


Tracer Results with MATCH-MPIC

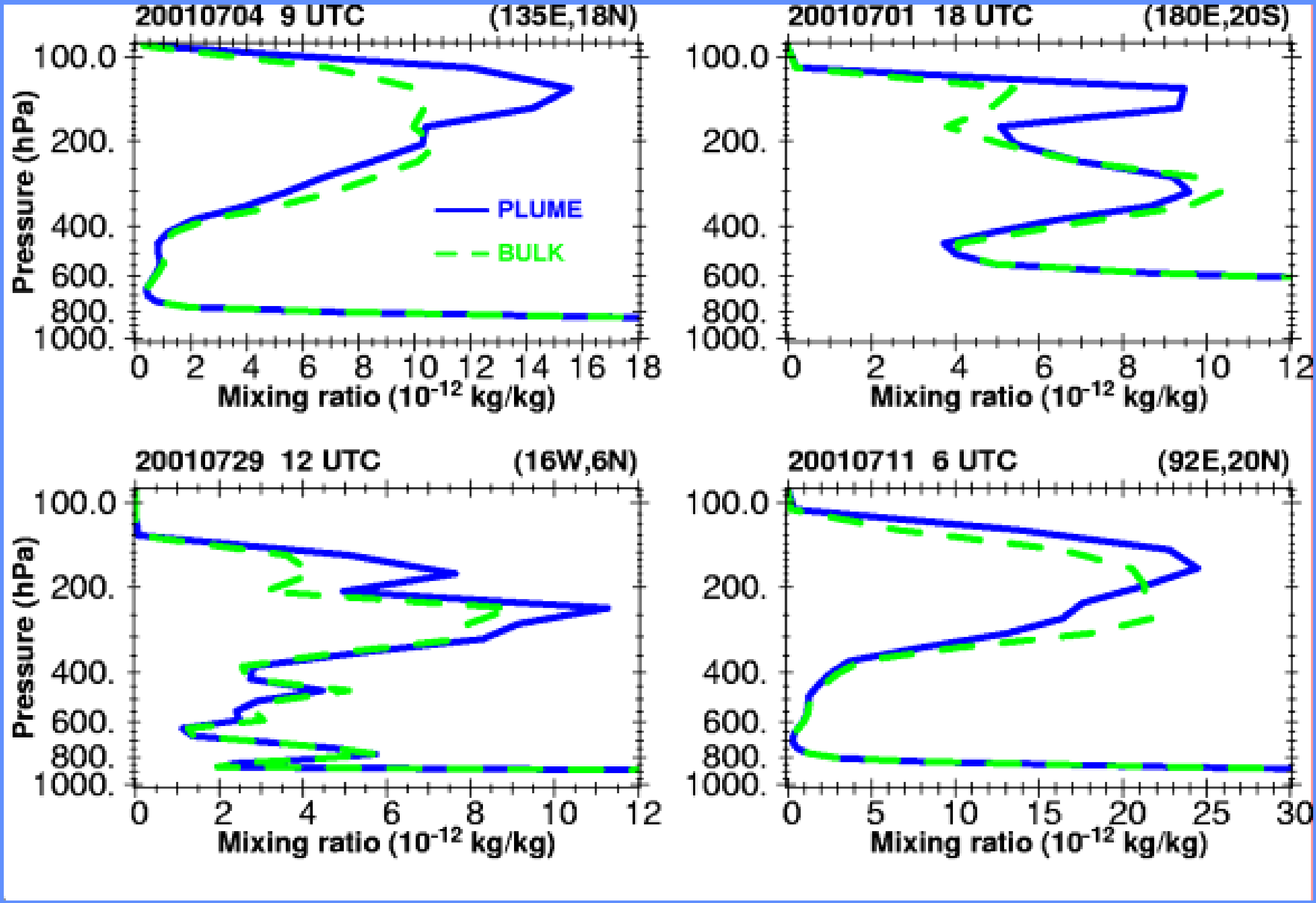
$\tau = 1$ d

$\tau = 2$ d



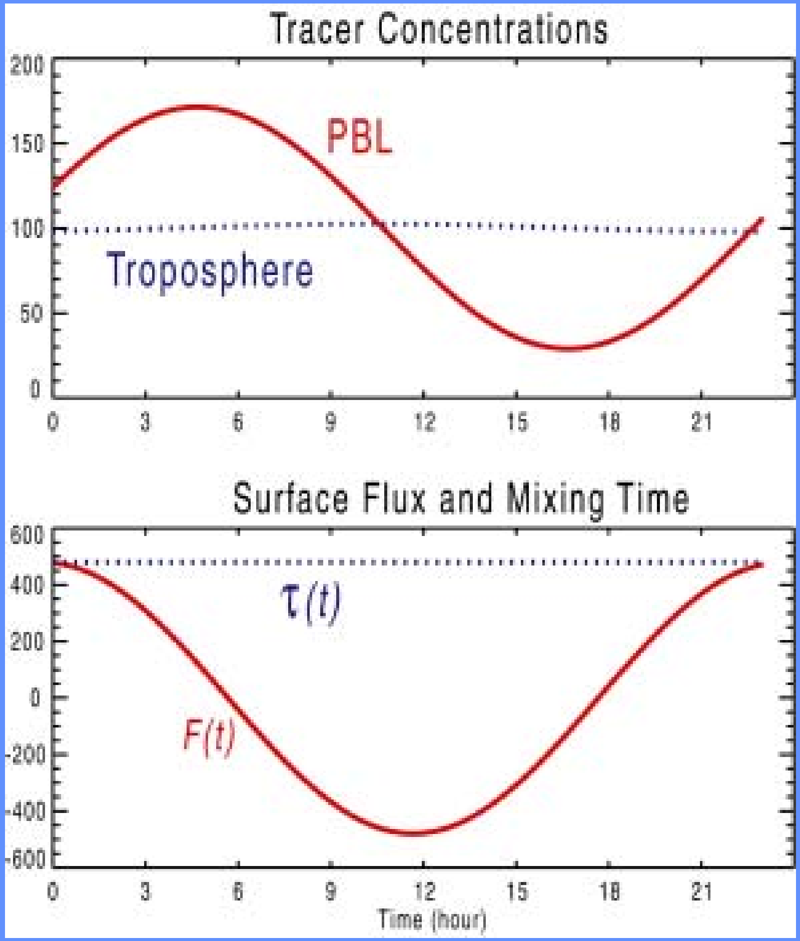
Zonal Mean, July 2001

Selected Individual Profiles



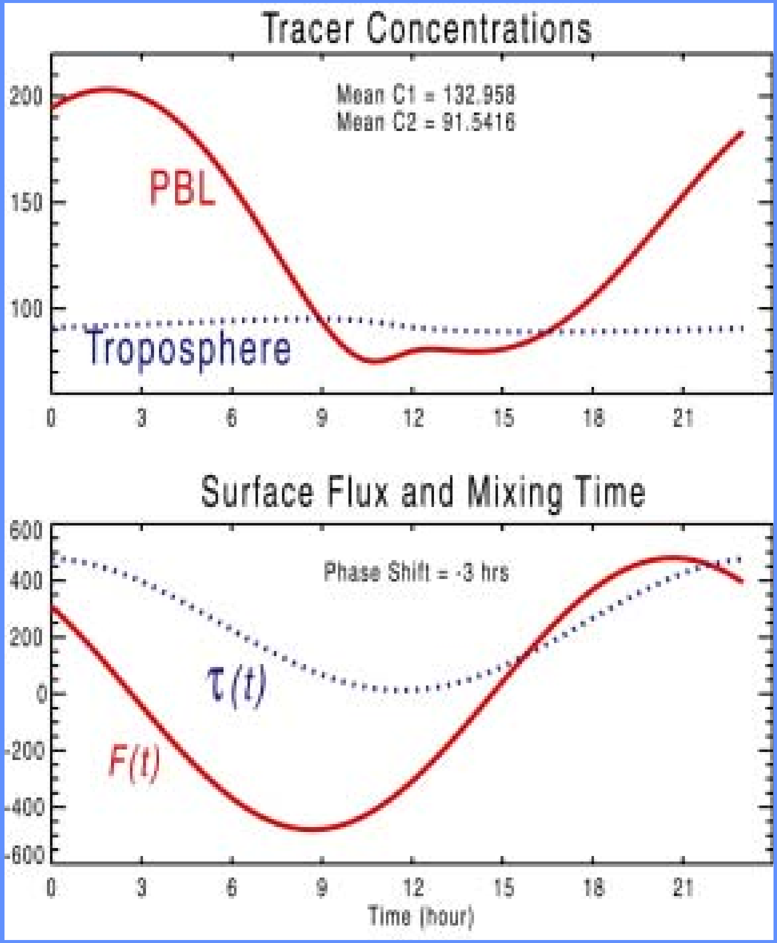
Statistics also examined (e.g., 5% of all profiles in convectively active columns have differences exceeding 50% for τ = 1 d tracers) c/o Scott Denning

Two-Box Model: No Rectification



- **Sinusoidal surface fluxes**
- **Mixing time scale is constant**
- **Result is a sinusoidal diurnal cycle of PBL concentration**
- **Damped sinusoidal variations in the troposphere are out of phase with PBL**

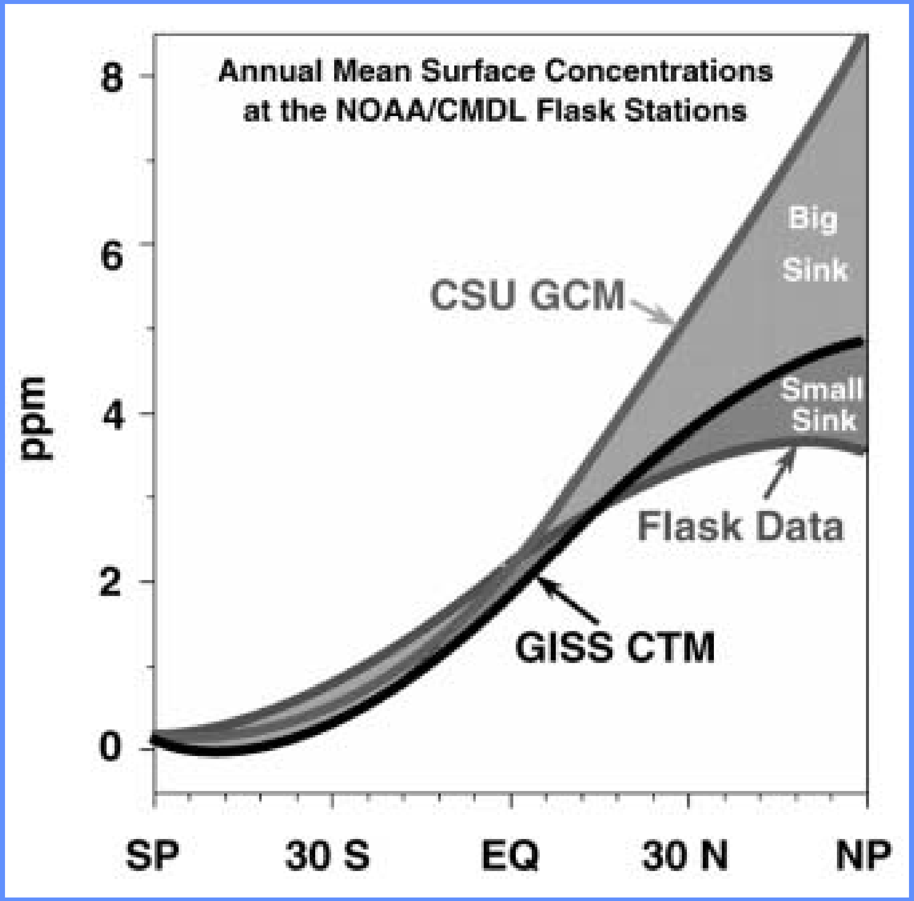
Two-Box Rectifier Forcing



- **Diurnal cycles of flux and mixing are correlated**
- **Classic "rectified" signal**
- **Phase lag maximizes rectification … reflects tracer "capacity" of PBL**
- **Diurnal mean in lower box is 133% of global mean**

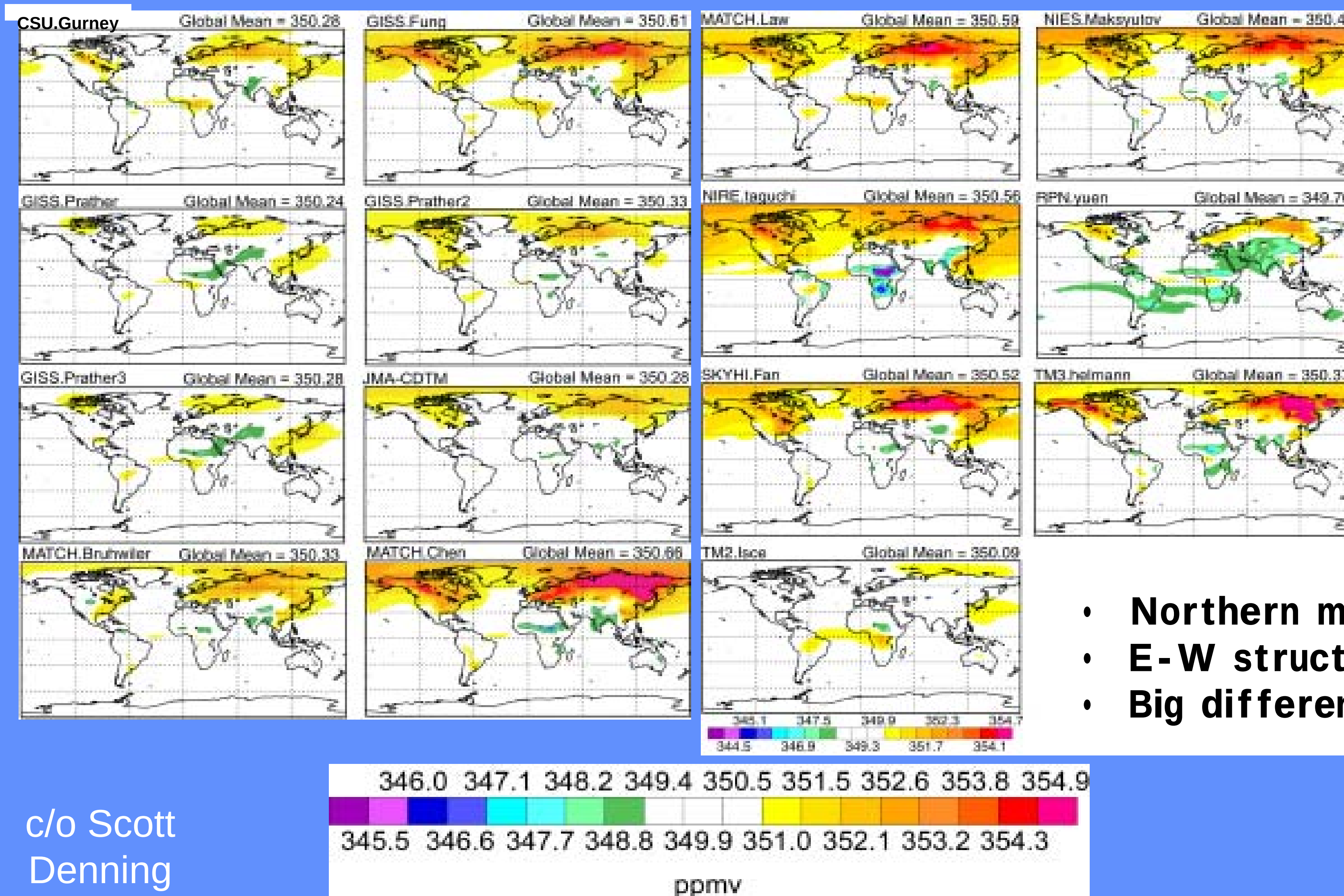
c/o Scott Denning

Gradients Imply Sinks



- **Simulated N-S gradients (polynomial fit to flask stations)**
- **Fossil plus ocean plus balanced biosphere (no terrestrial sinks)**
- **Meridional gradient mismatch between simulations and data indicates magnitude of inferred sink**

Rectifier Response Functions



- **Northern max**
- **E-W structure**
- **Big differences!**

c/o Scott Denning

Simulated annual mean surface CO_2 response to seasonal forcing c/o Dai et al

Local Time of precip max

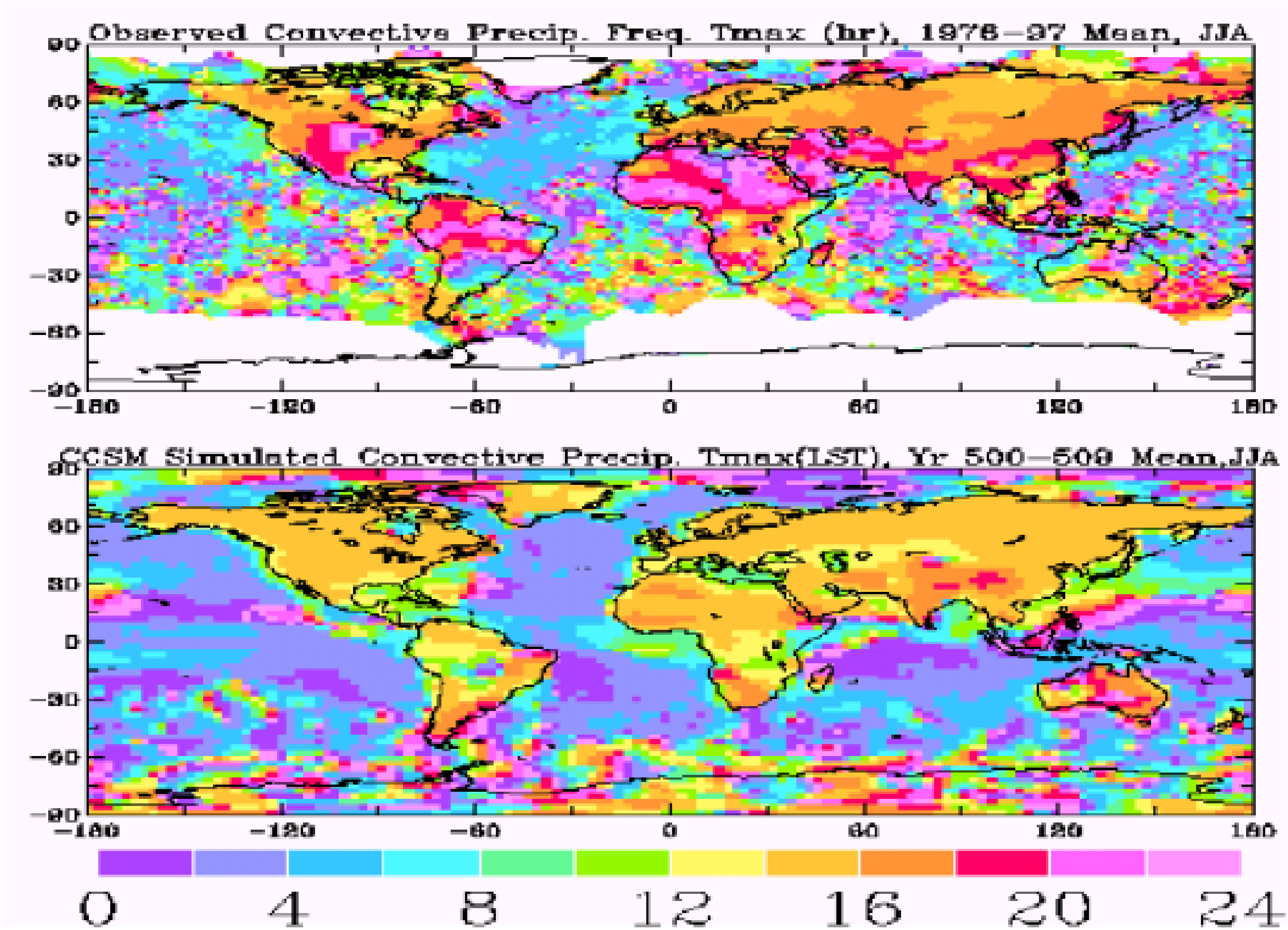
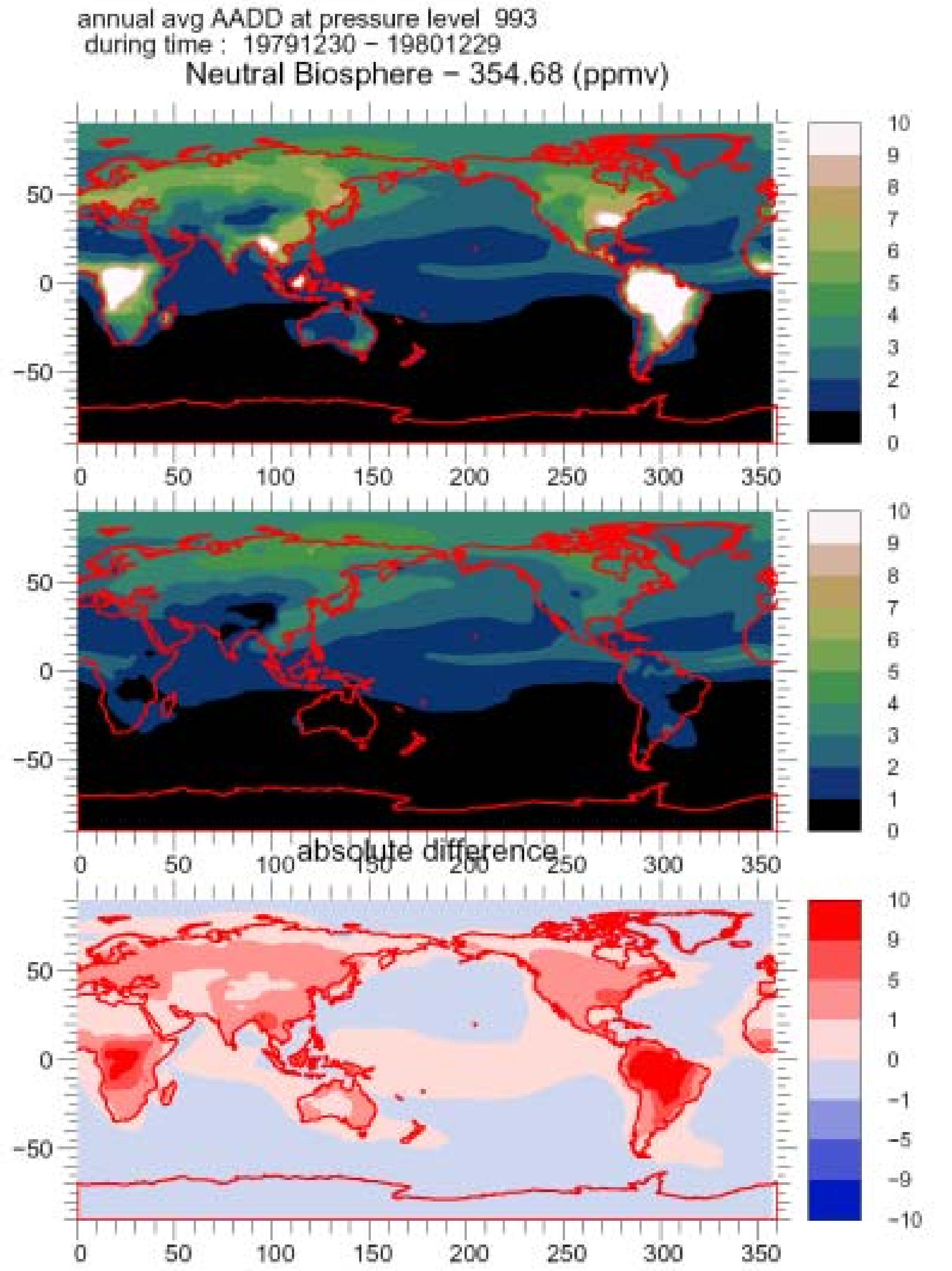


Fig. 8: The local solar time (hr) of the maximum of the diurnal harmonic of JJA convective precipitation frequency based on weather reports (*top*, from Dai 2001b) and of JJA convective precipitation in the CCSM (*bottom*).

Surface Concentration anomaly

Diurnal Source

Seasonal Source

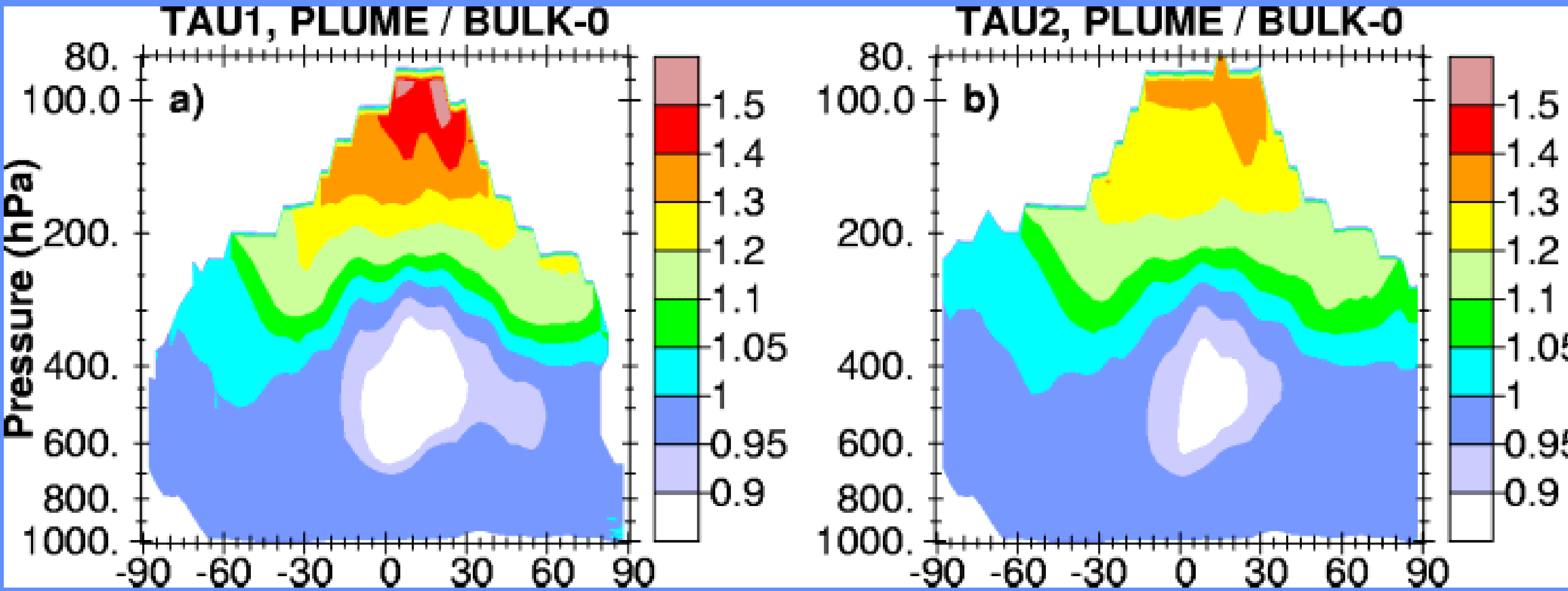


Summary

- Still numerous uncertainties in
  - Intensity/time scale of transport
  - Interactions with environment
  - “picture of convection”
  - Correlations with source/sink

End of talk

Tracer Results with MATCH-MPIC



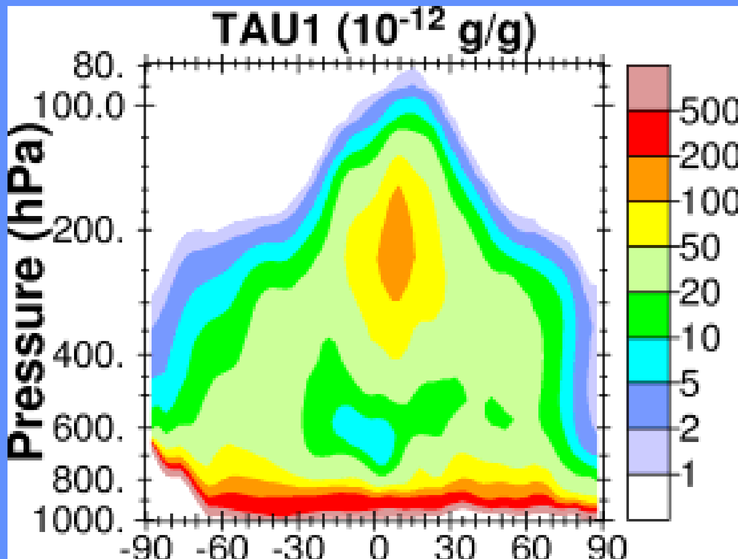
Zonal Mean, July 2001

Paraphrasing from “Observational constraints on Cumulus parameterization”

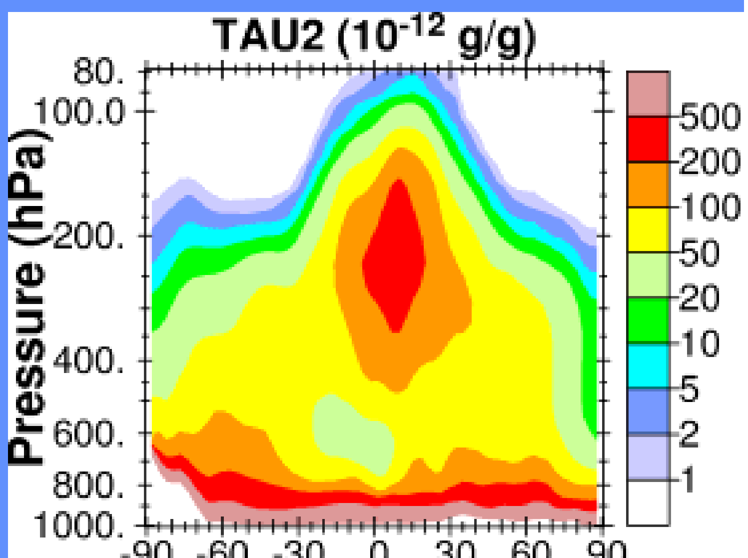
- A satisfactory parameterization of moist convection
  - Will be base on physical theory
  - Need not yield highly accurate results in a situation without feedback, but
  - Must be valid over a broad range of conditions.
  - Responds to changes in forcing

Tracer Results with MATCH-MPIC

$\tau = 1$ d



$\tau = 2$ d



Zonal Mean, July 2001

Paraphrase continued

- Cumulus cloud often reach their level of undilute neutral buoyancy
- Downdrafts can be important, may equal or exceed the updraft mass flux, interact with microphysics, have different roles is cumulus and cumulonimbus

Mass fluxes are quite different for various classes of convection

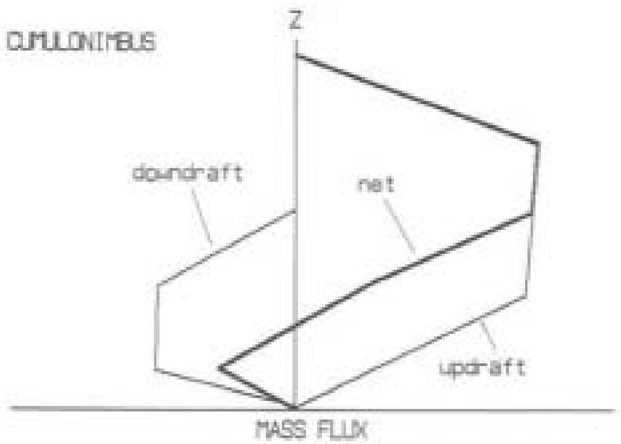


FIG. 2.6. Example of possible vertical mass flux profiles for a cumulonimbus cloud. Significant precipitation-induced downdrafts are confined to below the midlevel equivalent potential temperature minimum, causing the peak vertical mass flux to be above this level.

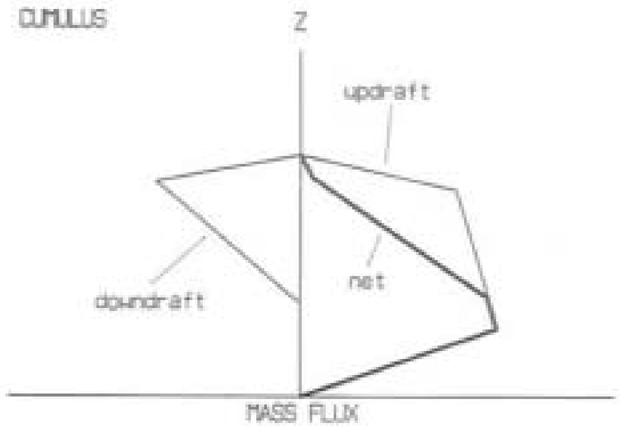


FIG. 2.5. Example of possible vertical mass flux profiles for a non-precipitating cumulus cloud. In the upper regions evaporative cooling of cloud material results in downdrafts that are comparable in strength to the updrafts. The net vertical mass flux is thus close to zero there.

Raymond, 1993

Bulk versus stochastic models of convection

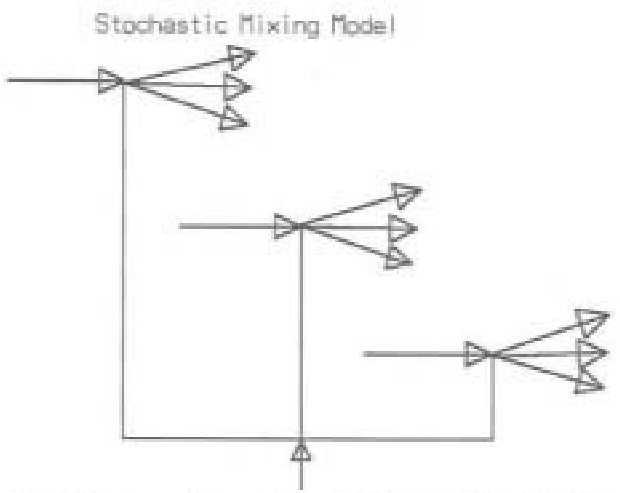


FIG. 2.4. The stochastic mixing model (Raymond and Blyth 1986) differs from the detraining plume model in that different mixing fractions are assumed for different subparcels mixing with environmental air at each level. This results in multiple exit levels for each mixing level.

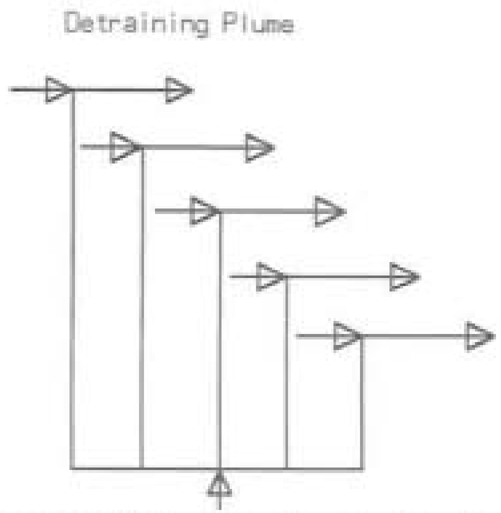
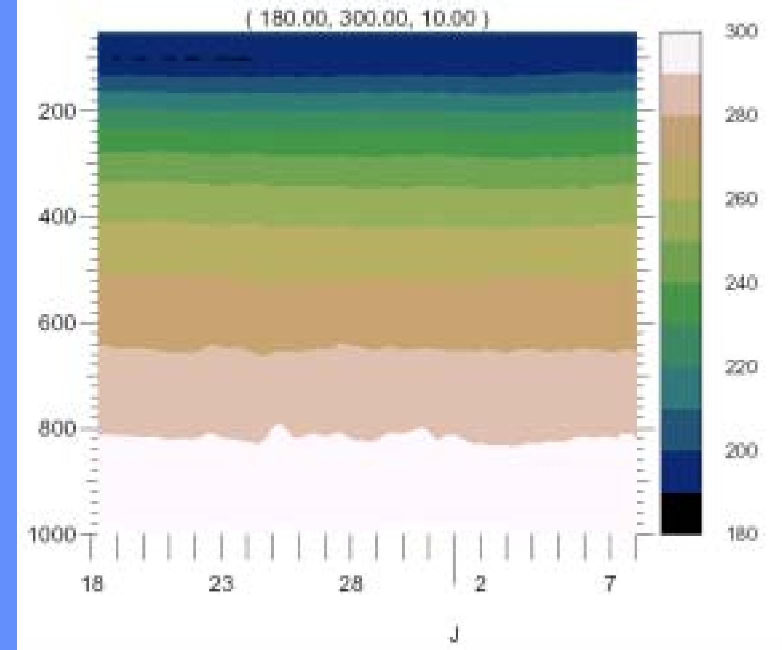


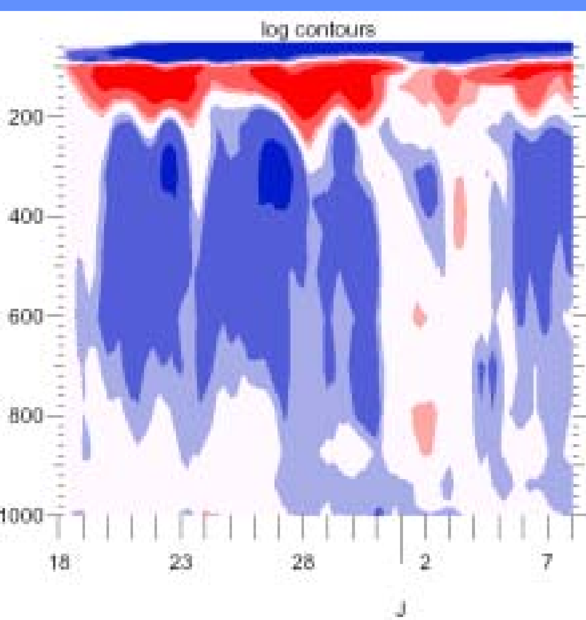
FIG. 2.3. In the detraining plume, subparcels ascending from cloud base mix with environmental air at various heights and exit the cloud.

Temperature Obs TOGA-COARE (Dec-Jan)

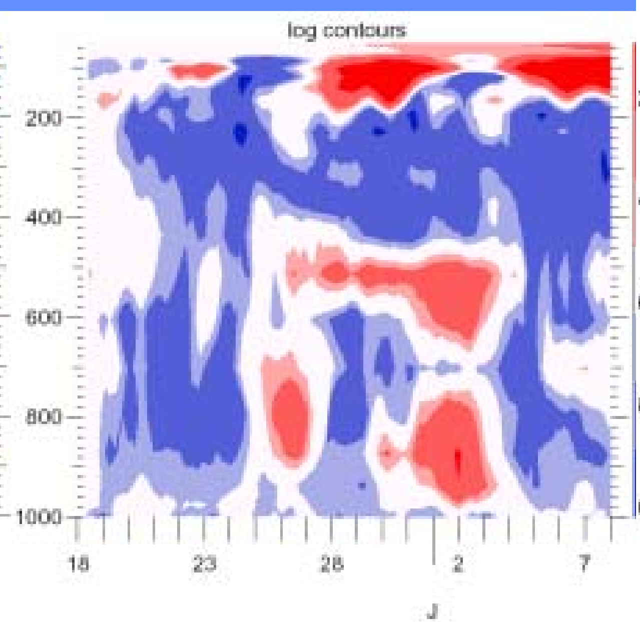
(errors significantly larger than Emanuel and Zivkivic-Rothman)



Emanuel



Standard



Kain-Fritsch