Current Perspectives on Deep Convection, Upper Troposphere, and Lower Stratosphere from General Circulation Models and Cloud-System-Resolving Models

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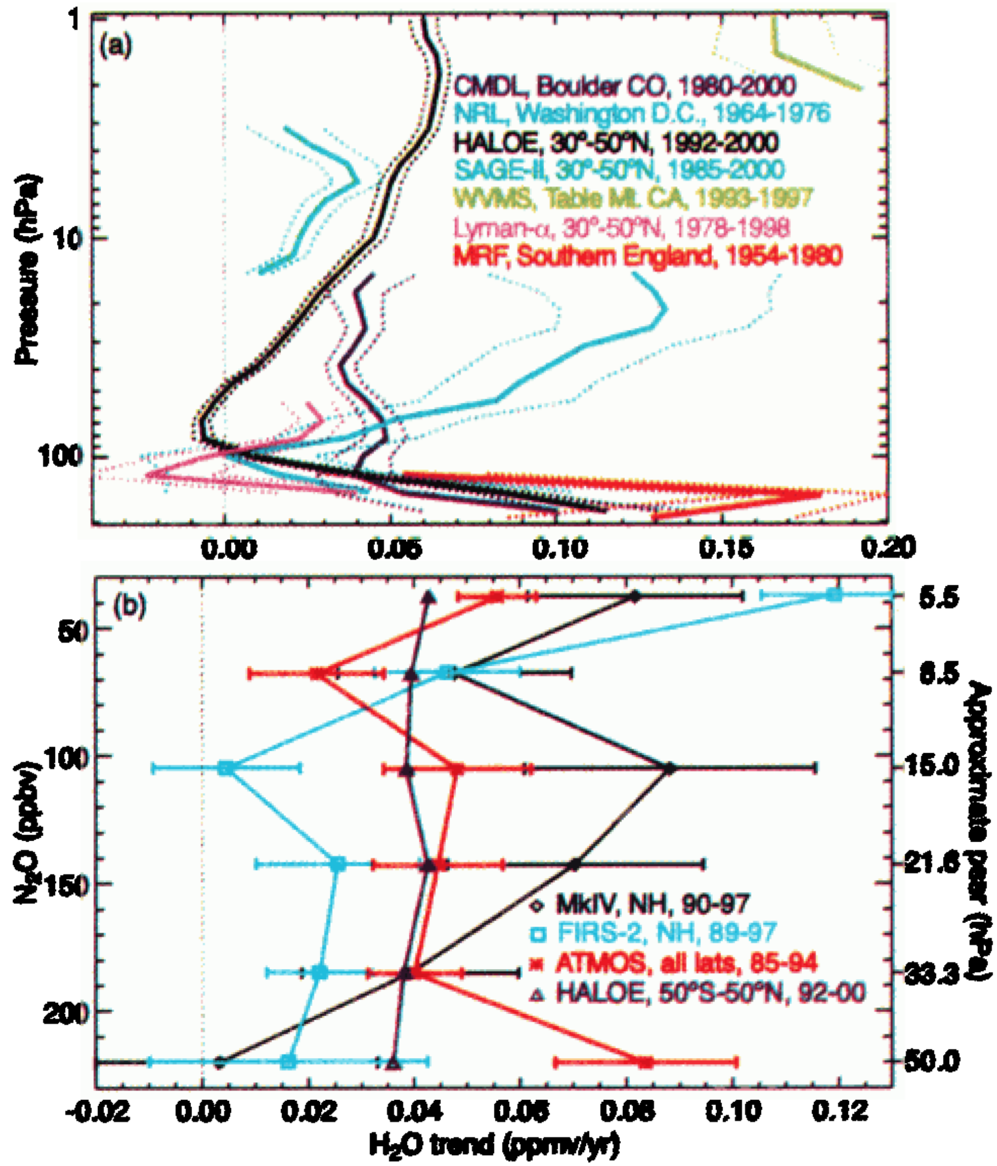
4th SPARC General Assembly, Bologna, 4 September 2008

Presentation Outline

- Water vapor trends: Observations and GCMs
- Stratospheric water vapor: Conceptual models and observational constraints
- Advection and stratospheric water vapor in GCMs
- Convection, cloud macrophysics, and cloud microphysics in GCMs
- Cloud-system-resolving models

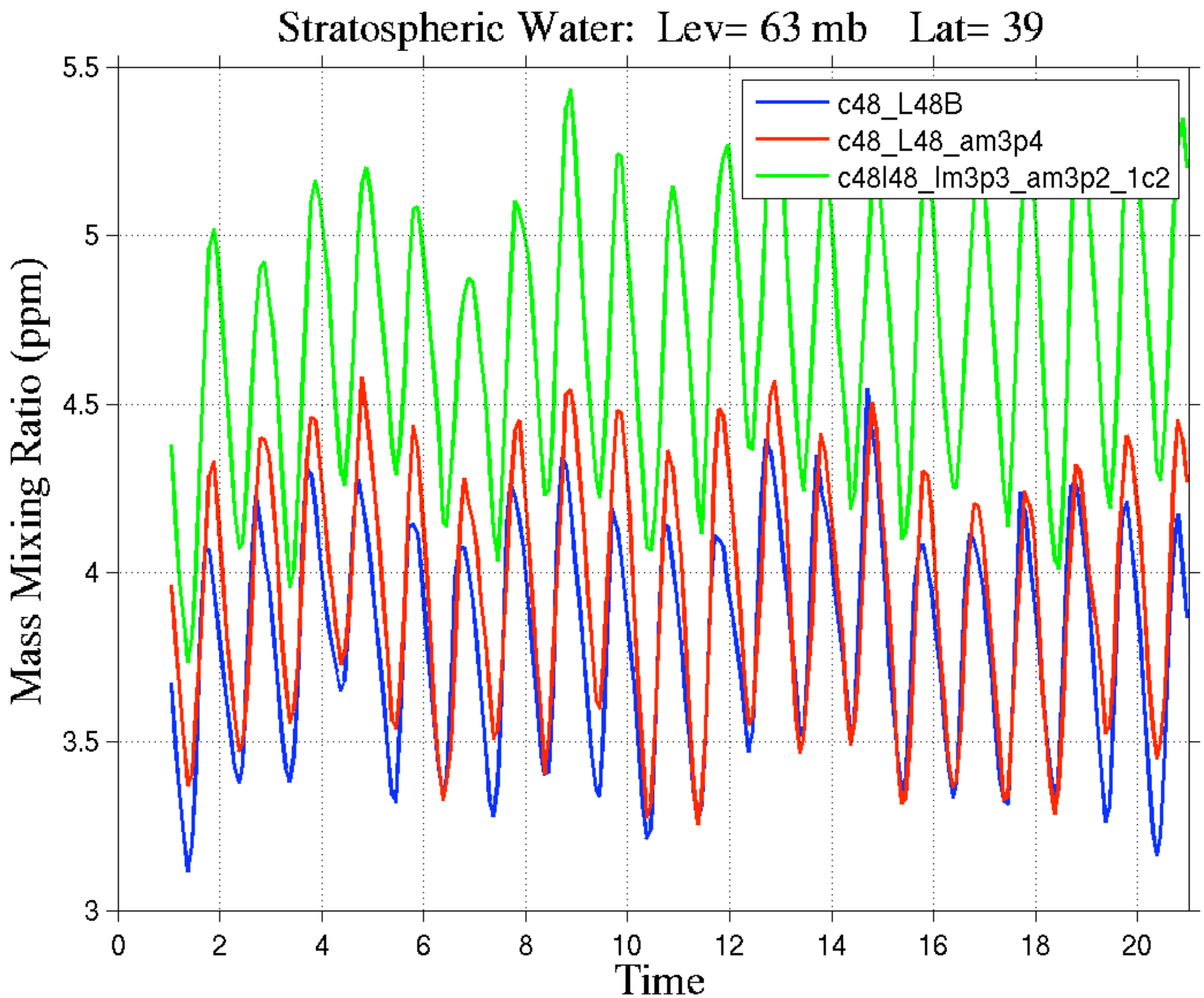
Water Vapor Trends: Observations and General Circulation Models

Water Vapor Increasing about 1% per year, 1950-2000



from Rosenlof et al. (2001, *GRL*)

GFDL Experimental AM3 1980-2000 Simulation

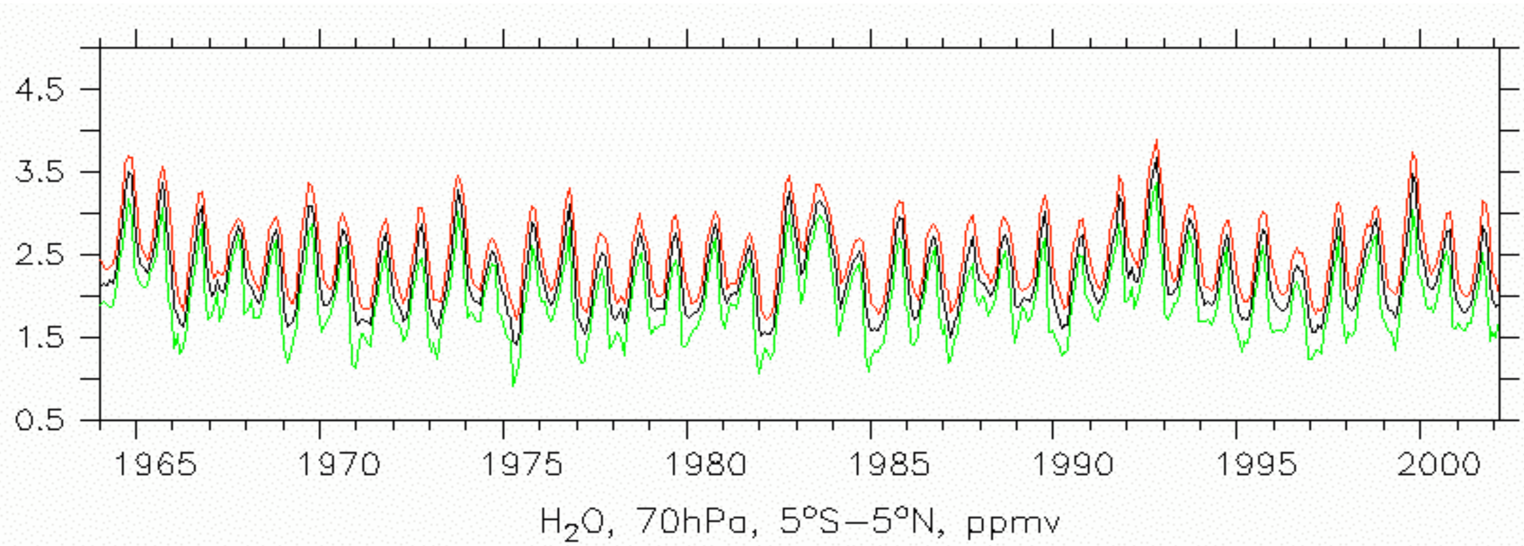


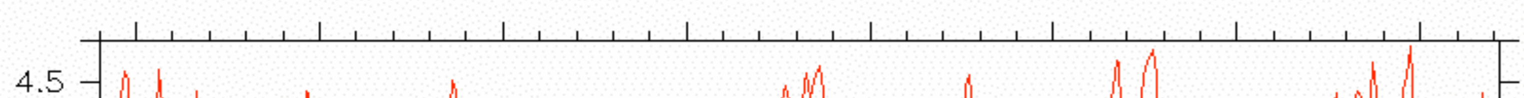
NOTE: Spin-up in early integration

ECHAM5-MESSy, 1964-2002 Simulation

Poster 13, Christoph Bruehl

H2O at 70 hPa, 5N-5S
monthly zonal mean (black)
monthly grid point maximum (red)
monthly grid point minimum (green)





Stratospheric Water Vapor: Conceptual Models and Observational Constraints

Sources and Sinks of Stratospheric Water Vapor

- Advection by large-scale flow
- Transport by convection to LNB, followed by large-scale vertical and horizontal advection
- Transport into UT/LS by overshooting convection
- Detrainment of ice in UT/LS

Advection by Large-Scale Flow

Dessler and Sherwood (2000, *JGR*), modeling tropical UT with only advection and condensation above 100% RH: “We see no evidence to suggest that accurate predictions of the humidity in this region are dependent on accurate simulations of microphysical processes or on transport of ice or liquid water. Our results instead suggest that accurate predictions of the humidity primarily require realistic three-dimensional large-scale (greater than a few hundred kilometers) wind fields.”

Convection to LNB - Advection (Rosenlof, 2003, *Science*)

- Stratosphere contains less water than saturation at average minimum tropical temperature
- Newell and Gould-Stewart “stratospheric fountain:” Convection to LNB and advection s.t. air enters stratosphere only at coldest locations and times (over Indonesia, NH winter)
- Contradicted by satellite observations showing air entering stratosphere throughout year and downward motion in lower stratosphere over Indonesia

Transport into UT/LS by Overshooting Convection

- Air de-hydrates in convective overshoots
- Convective overshoots colder than surroundings. Dilution, rather than condensation, plays important role in overshoots.
- Sherwood and Dessler (2000, *GRL*); Sherwood and Dessler (2003, *JAS*) found realistic lags and amplitudes in lower stratosphere of CO_2-like tracer (rel to surface) and H_2O (rel to tropopause temp)

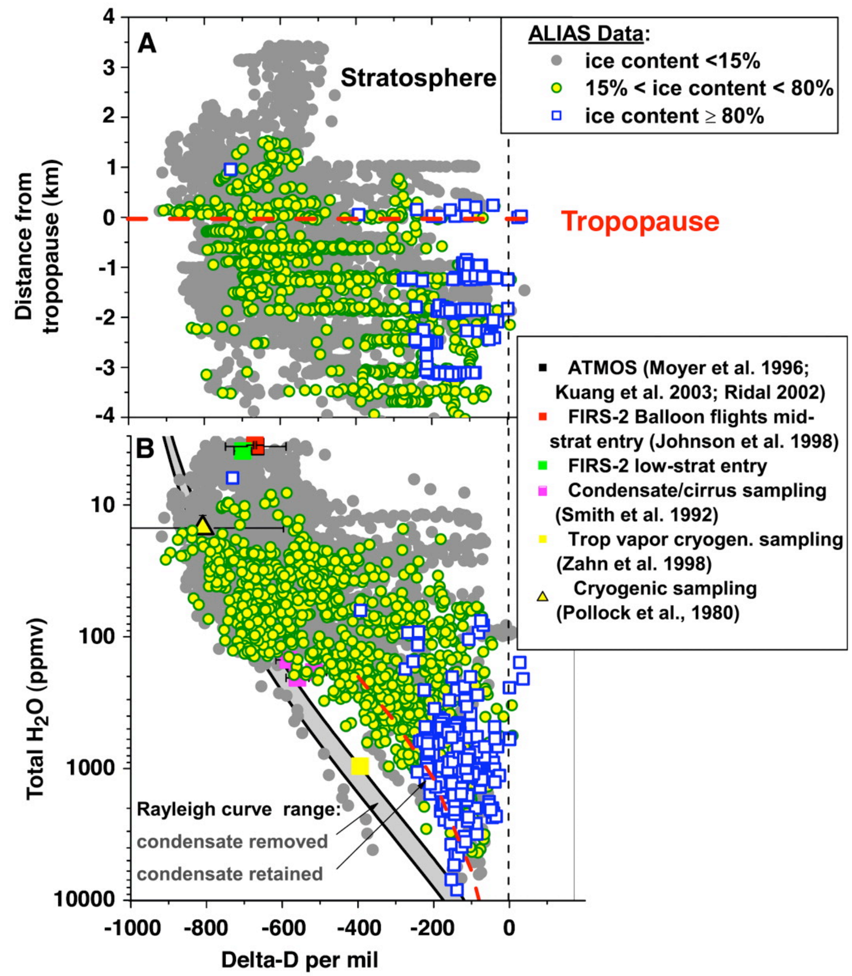
Detrainment of Ice into UT/LS

- Accompanies convective overshooting
- Predicted isotope fractionation (HDO and $H_2^{18}O$ vs. $H_2^{16}O$) linked to water vapor source
- Conceptual models by Moyer et al. (1996, *GRL*), Sherwood and Dessler (2001, *JAS*), Dessler and Sherwood (2003, *ACP*)
- Observational support from ATMOS (Moyer et al, 1996, *GRL*) and UARS/MLS (Wu et al., 2005, *JAS*) showing ice to dominate total water above convective centers

Aircraft Observations: Convective Tropopause Punctures?

- Ridley et al. (2004, *Atmos. Env.*): No evidence of convective transport into lower stratosphere in NASA WB-57F mid-latitude flights
- Hegglin et al. (2004, *APC*) and Ray et al. (2004, *JGR*): Aircraft observations suggest convective transport into stratosphere in Projects SPURT and CRYSTAL-FACE

Fig. 1. {delta}D intercomparison using unfiltered data (20 s averaged) from all nine flights versus distance from the tropopause (A) and versus total water (B)



C. R. Webster et al., Science 302, 1742 -1745 (2003)

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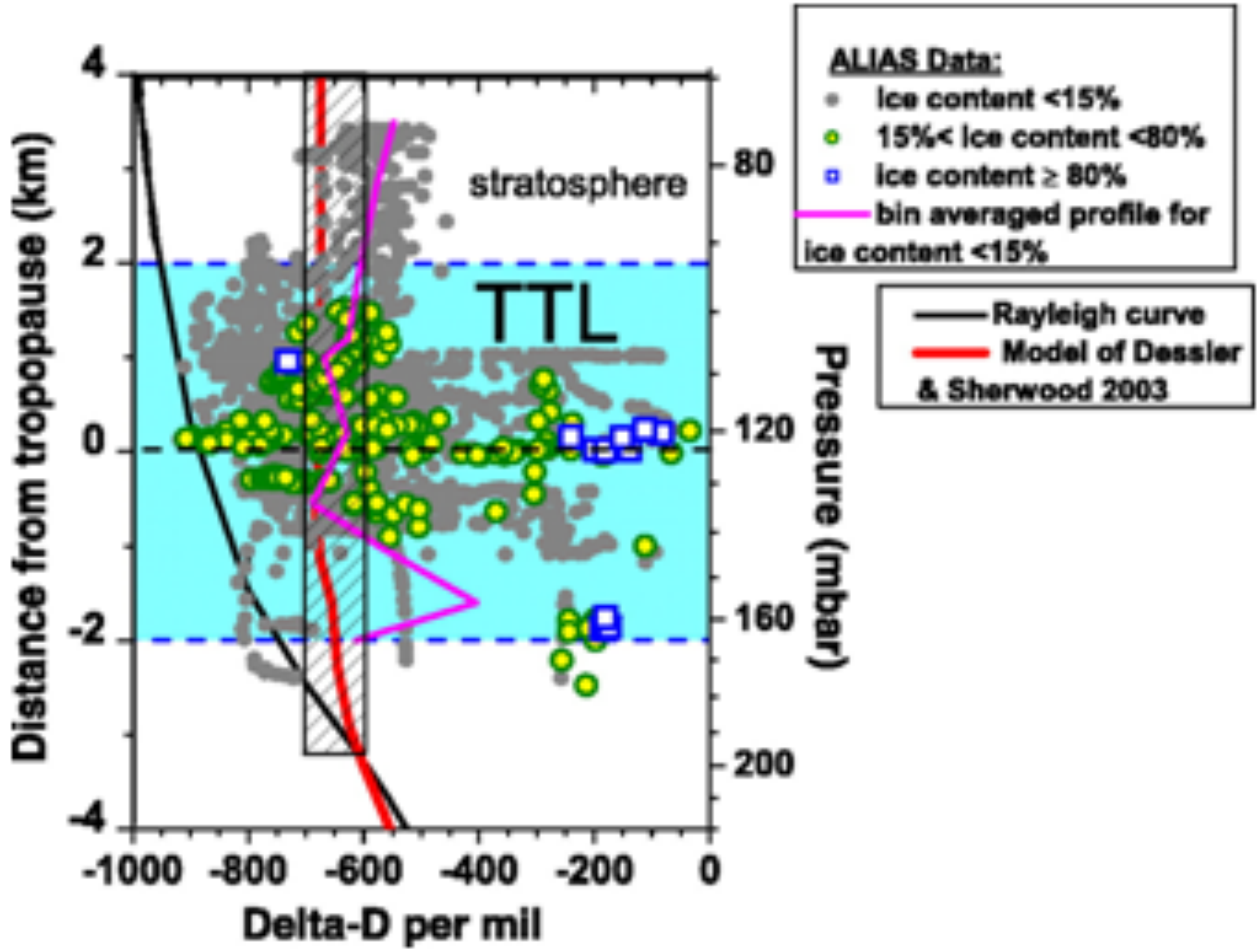
Fig. 2. Observations in the TTL compared with model calculations (41) that used {delta}Dice= -565{per thousand}



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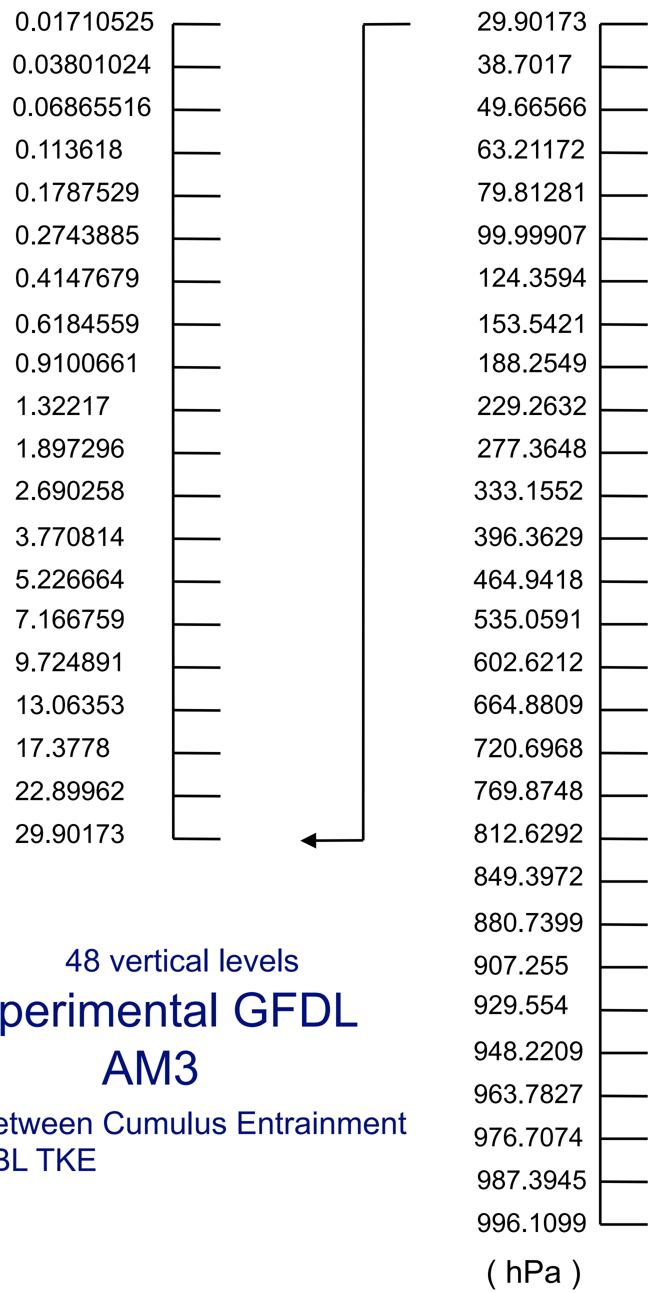
Advection, Convection, Microphysics, and Macrophysics in General Circulation Models

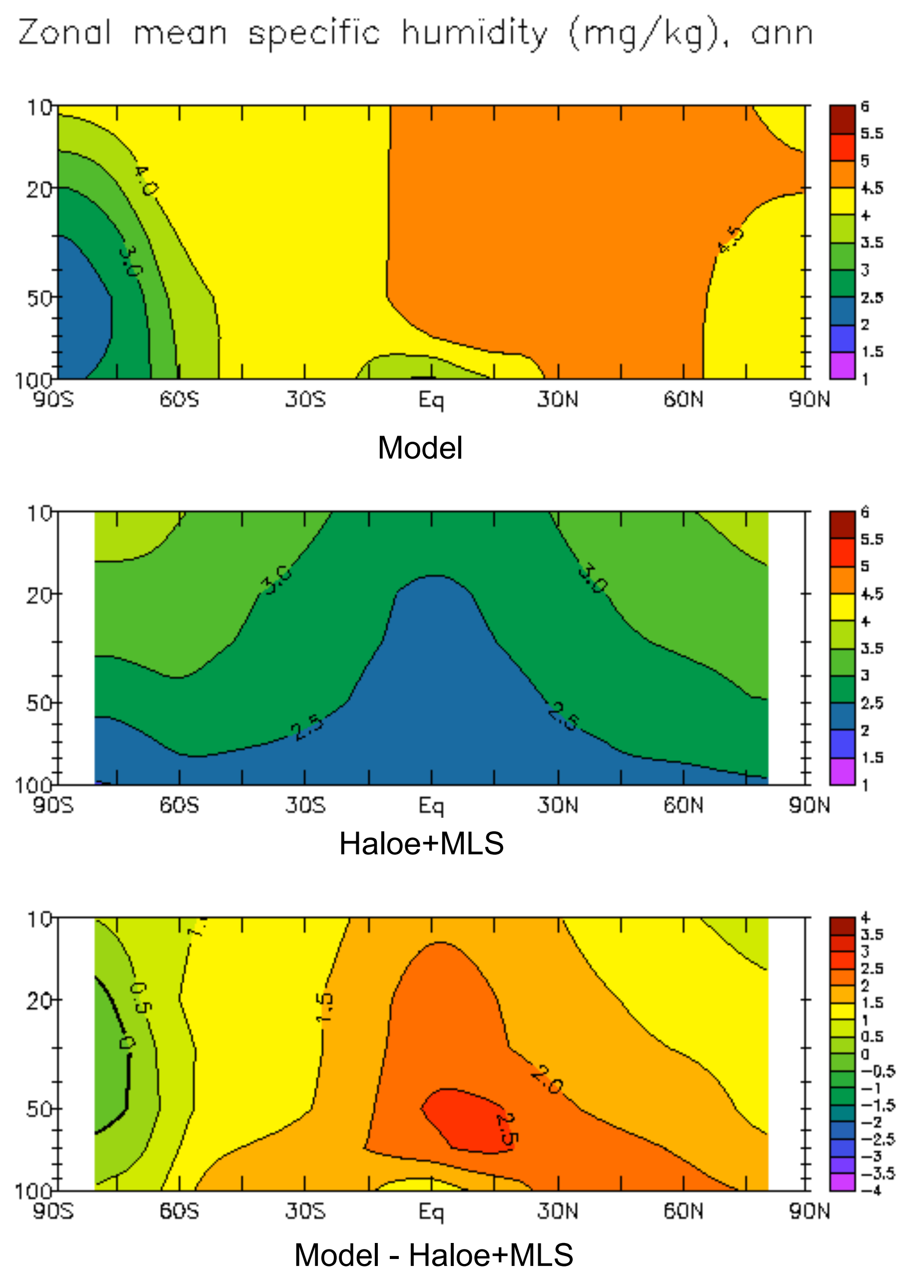
Advection depends strongly on vertical resolution and numerical method in general circulation models.



48 vertical levels

Experimental GFDL AM3

Link between Cumulus Entrainment and PBL TKE



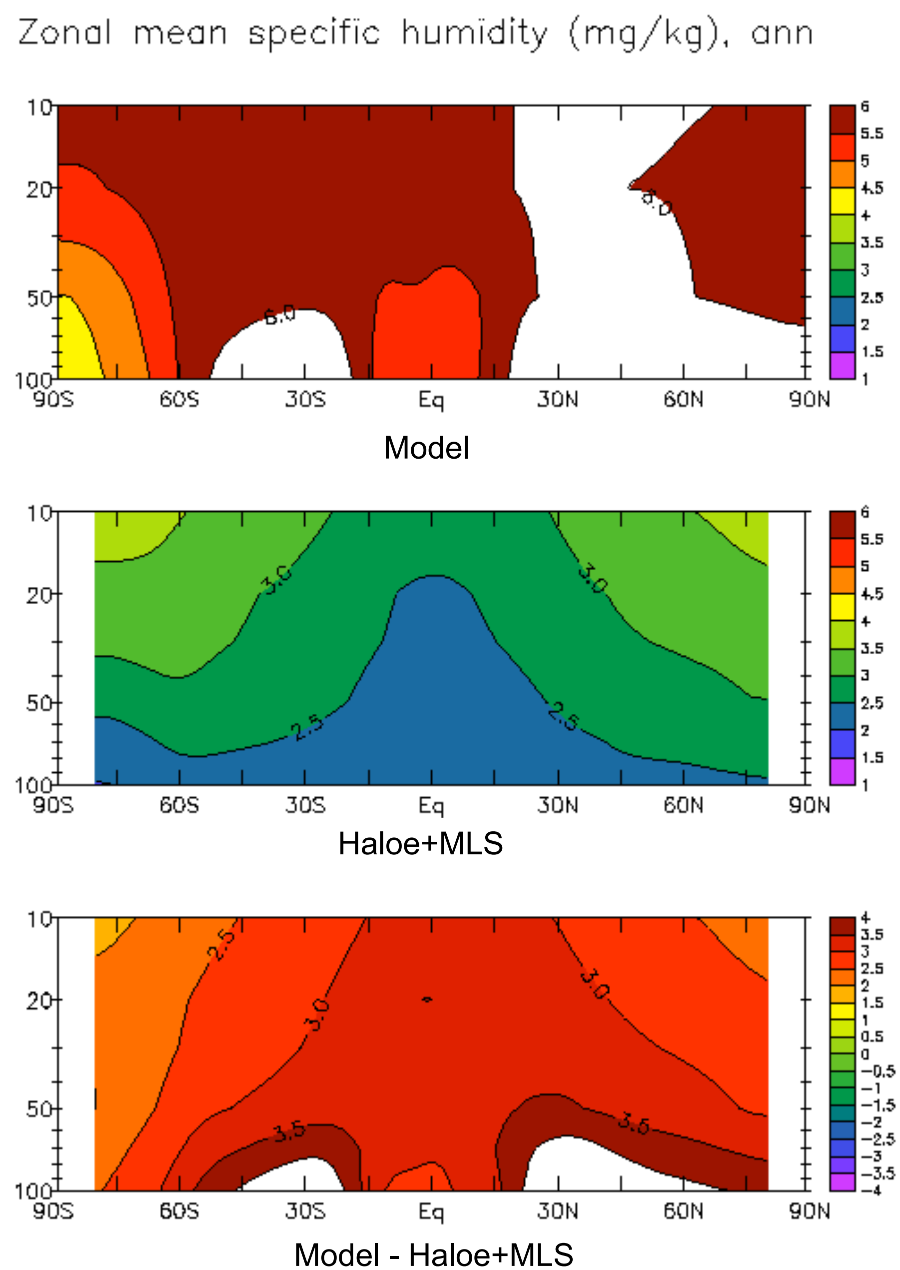
24 vertical levels

Experimental GFDL AM3

Link between Cumulus Entrainment and PBL TKE

3.650293
19.0884
52.34019
99.12992
157.381
224.7492
298.9444
378.0866
458.3251
533.7864
601.7172
662.5931
716.8593
764.9444
807.2677
844.2424
876.2772
903.7783
927.1495
946.7935
963.1113
976.5034
987.3693
996.1084

(hPa)



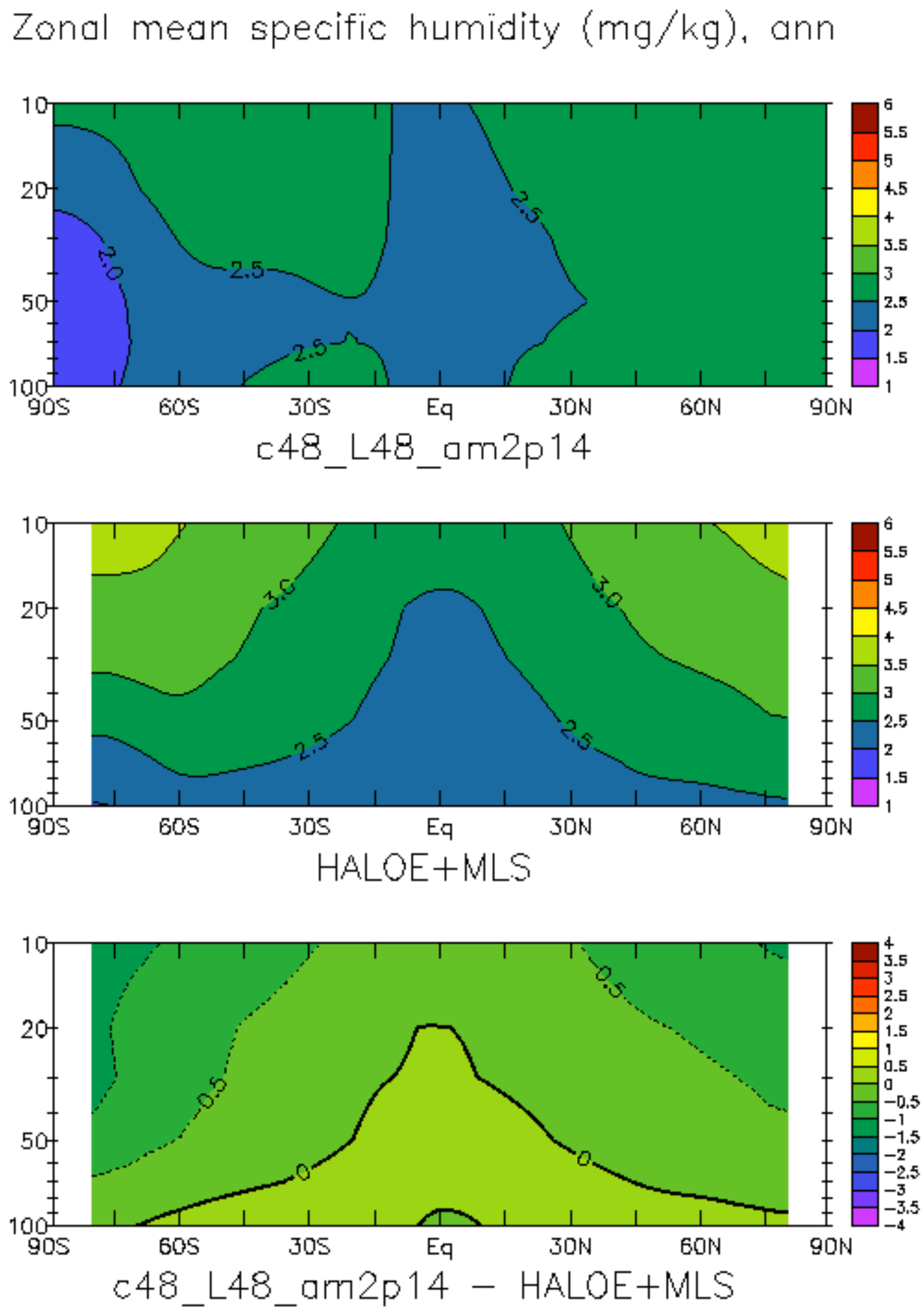
Mass-Flux Cumulus Parameterizations

- Most GCMs use mass-flux cumulus parameterizations
- No convective overshooting
- Cloud top at level of neutral buoyancy (LNB) where $T_{grid\text{-}mean} = T_c$

$$\frac{d}{dz}(MassFlux) = f_1(Entrainment)$$

$$\frac{d}{dz}T_c = f_2(T_{grid-mean}, Entrainment)$$

GCM *without* convective overshoots can simulate reasonable stratospheric water vapor. Not consistent with Webster and Heymsfield (2003).



GFDL AM2 48 levels cubed-sphere (GFDL GAMDT, 2004, *JCL*)

GCMs with convective overshooting under development. Mass fluxes, water vapor, ice lofting, and tracer transport differ from GCMs without convective overshooting.

Cumulus Parameterizations: Mass Fluxes & Vertical Velocities

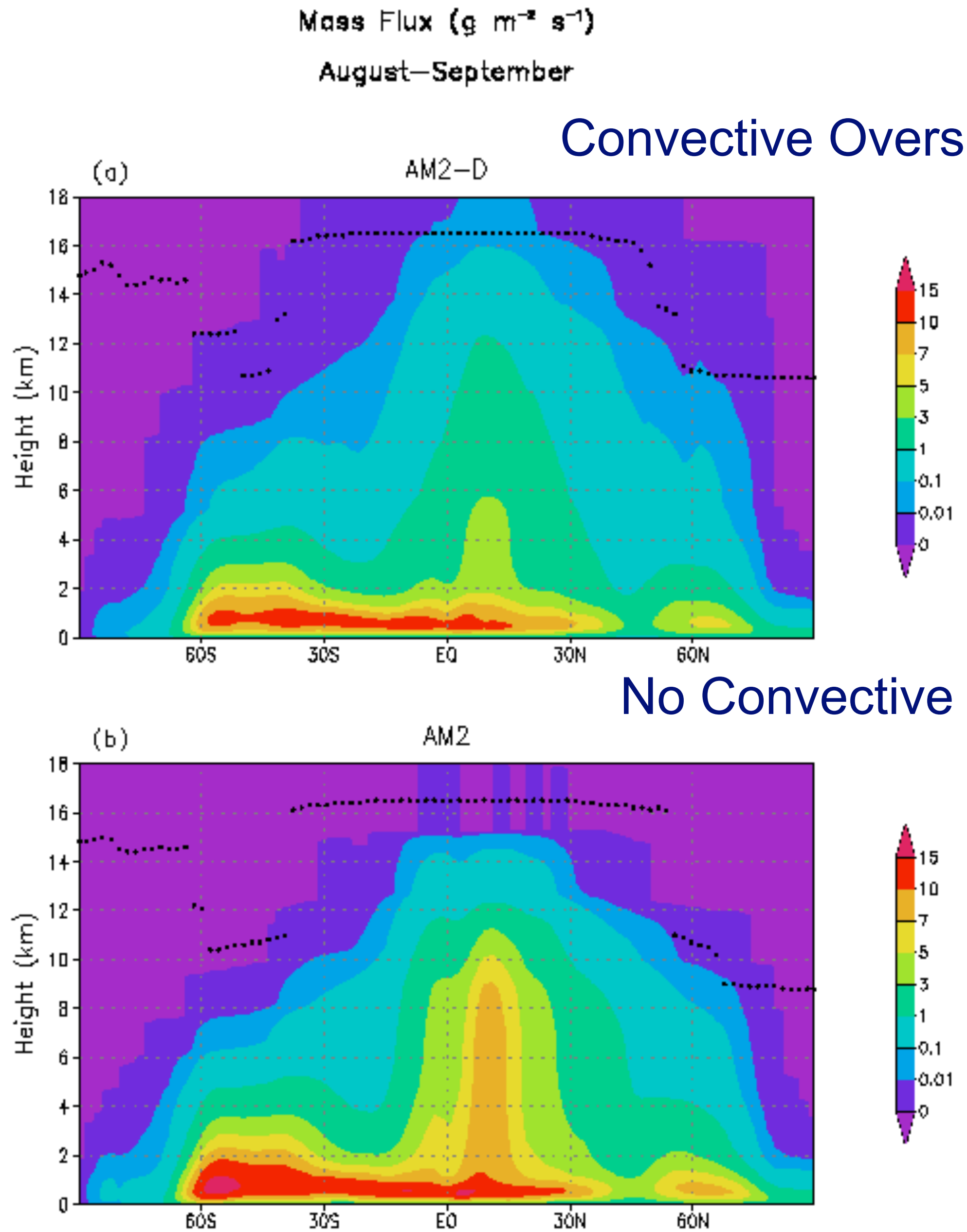
- Convective overshooting
- Cloud top where w_c=0
- Cloud tops above or below LNB

$$\frac{d}{dz}(Mass\,Flux) = f_1(Entrainment)$$

$$\frac{d}{dz}T_c = f_2(T_{grid\,mean}, Entrainment)$$

$$\frac{d}{dz}w_c = f_3(T_{grid\,mean}, Entrainment, Microphysics)$$

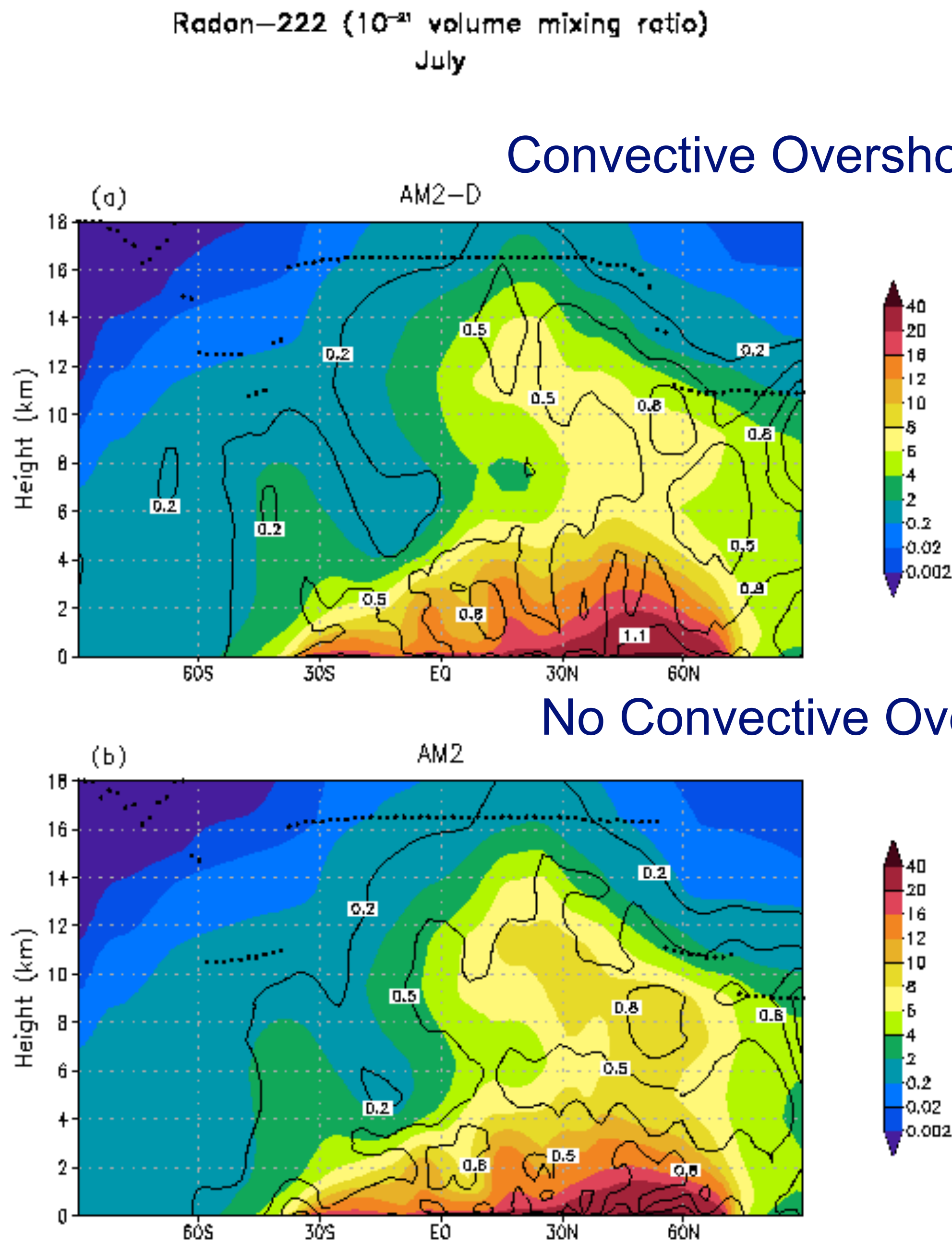
$$\frac{d}{dz}(Microphysics) = f_4(w_c, T_{grid\,mean}, Entrainment)$$



Convective Overshooting

No Convective Overshooting

from Donner et al. (2007, *JGR*)



Convective Overshooting

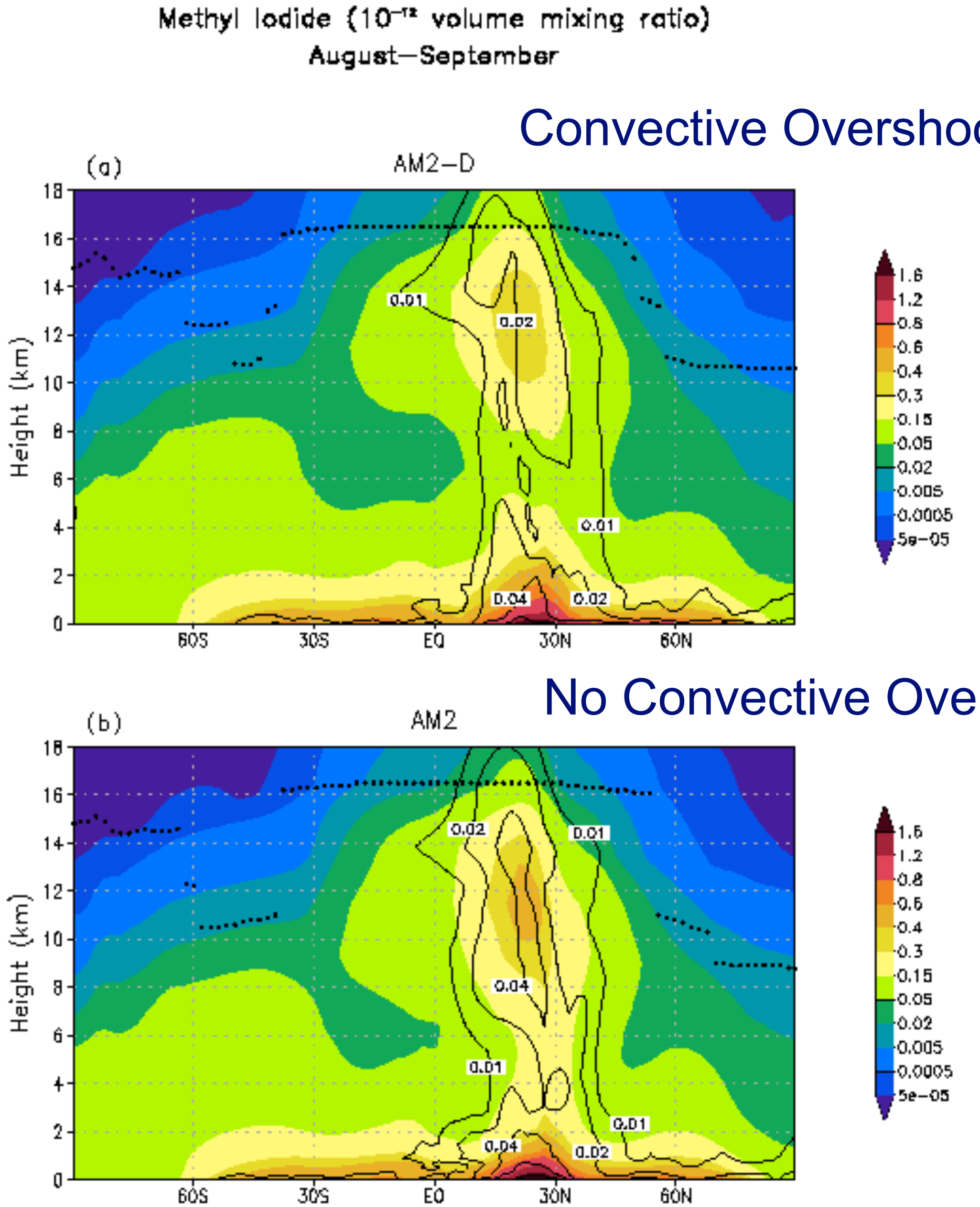
No Convective Overshooting

Solid lines indicate standard deviations.

from Donner et al. (2007, *JGR*)

Convective Overshooting

No Convective Overshooting



Solid lines indicate standard deviations.

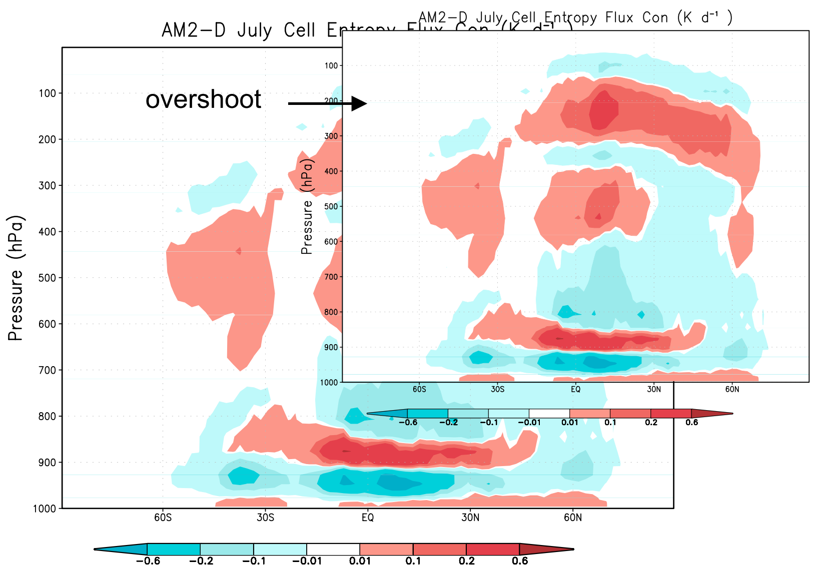
from Donner et al. (2007, *JGR*)

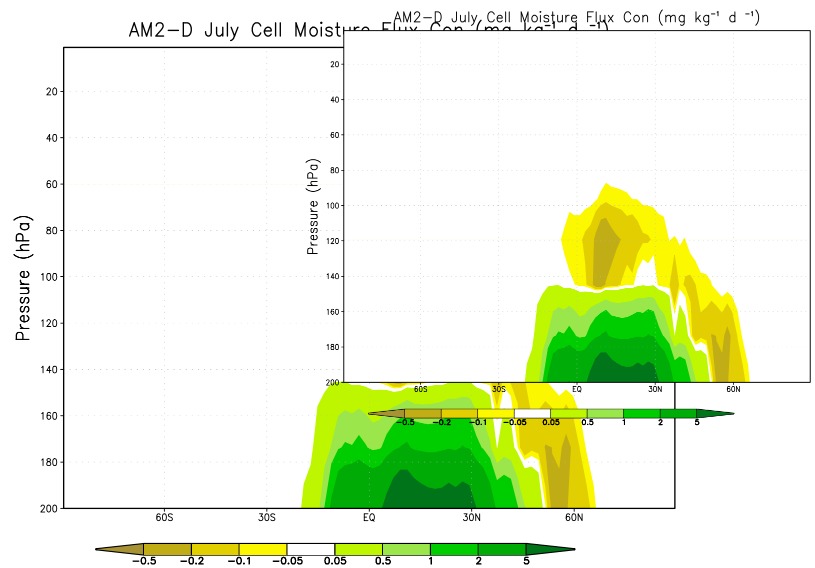
Methyl Iodide “Convective Index”

	Bell et al. (2002, JGR) OBS	*AM2-D Overshoot*	*AM2 No Overshoot*
N. Pac.	.22	.21	.37
Hawaii	.20	.19	.38
Christmas I.	.24	.28	.43
Fiji	.16	.18	.25
Tahiti	.23	.21	.26

Convective index is ratio of concentrations in layer 8-12 km to layer 0-2.5 km.

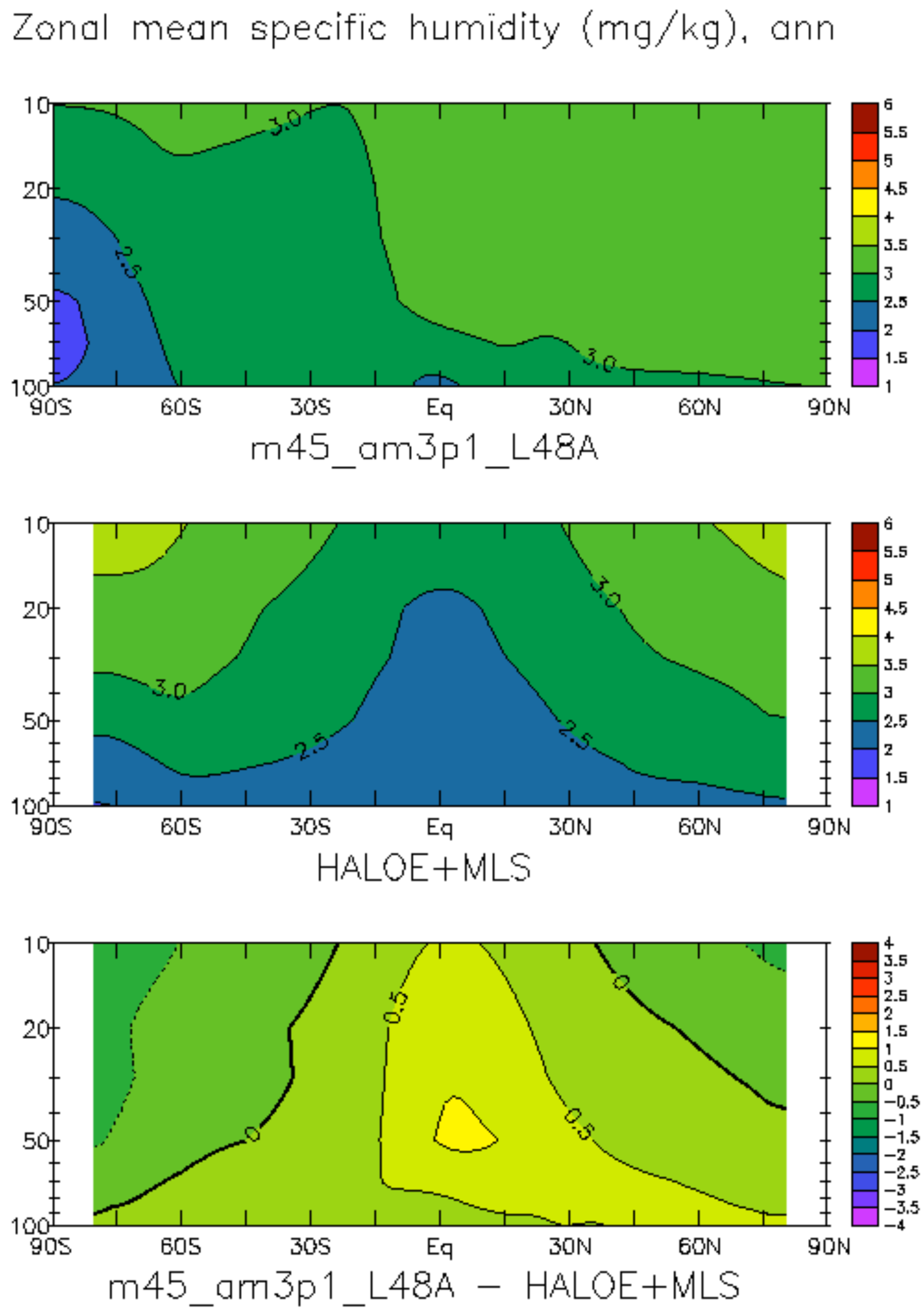
Dehydration in Convective Overshoots in GFDL AM2-D





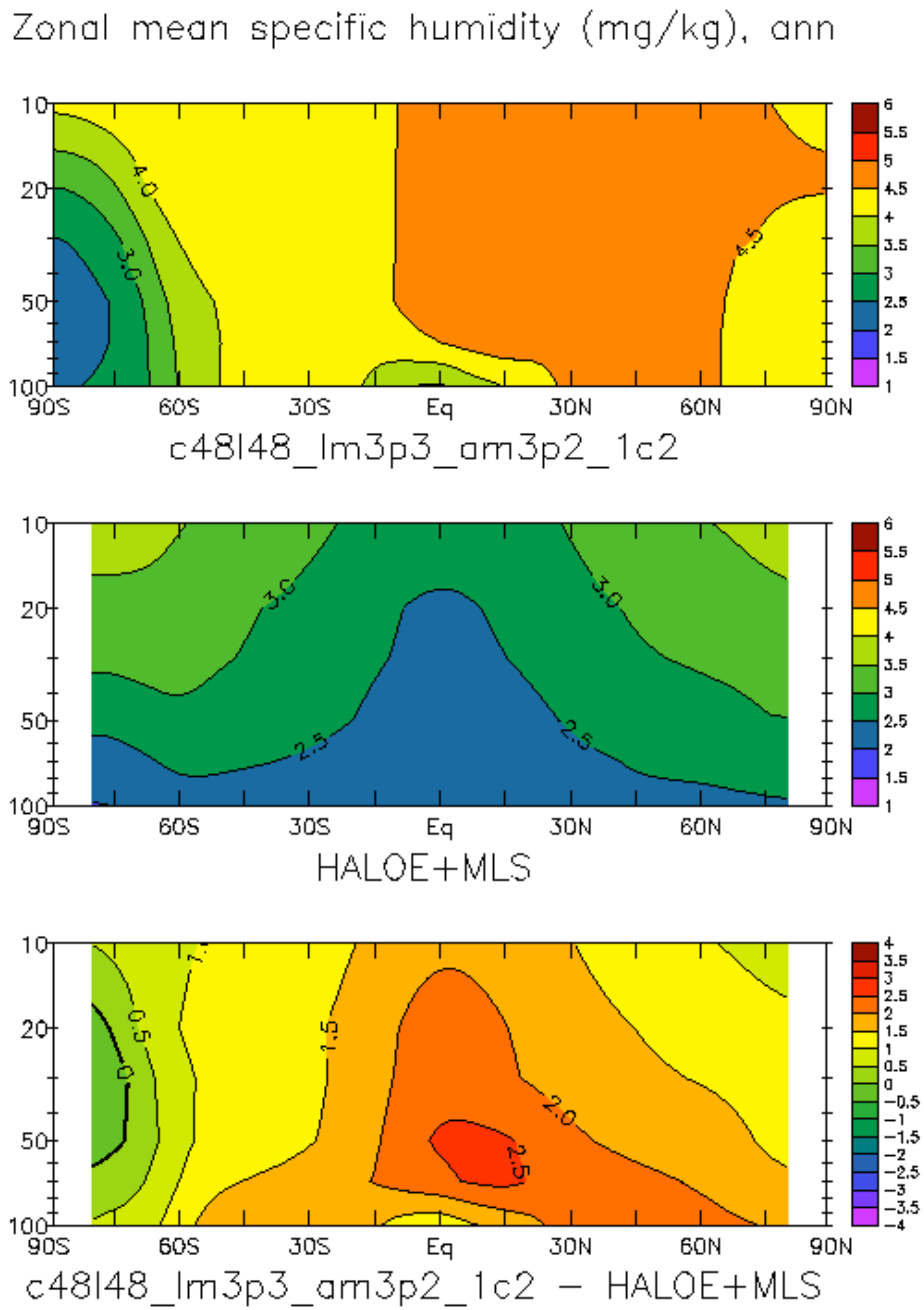
Extent of convective overshooting depends strongly on details of formulation of cumulus parameterization

No Link between PBL TKE and Cumulus Entrainment



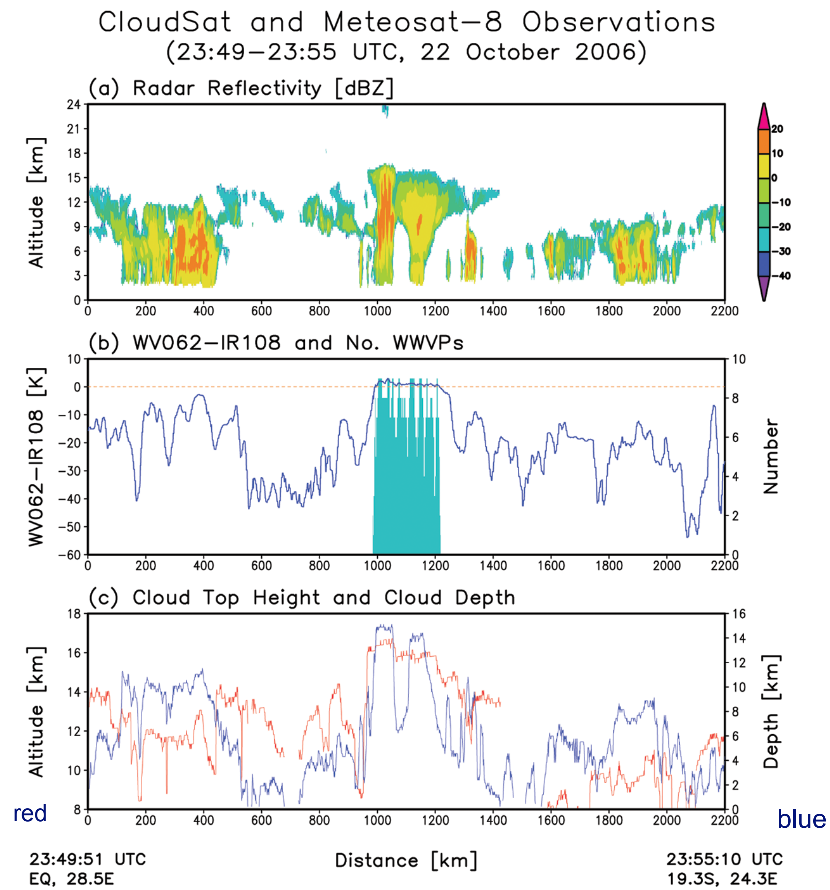
Experimental GFDL AM3

Link between PBL TKE and Cumulus Entrainment



Evaluating Overshooting in GCMs: Isotope and Satellite Analysis

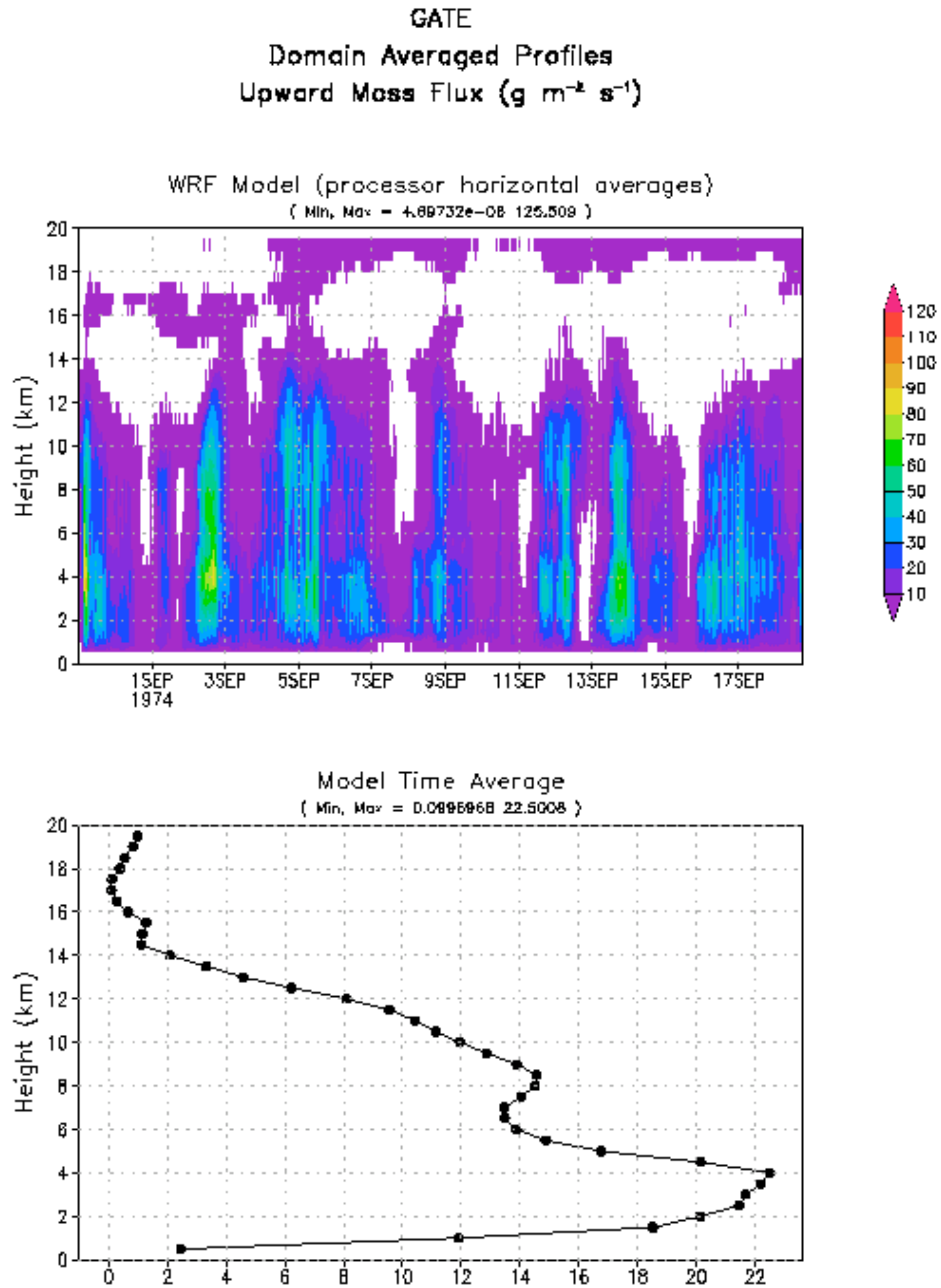
Brightness temperature Difference (water vapor-IR window channel) related to overshoot extent (e.g., Schmetz et al., 1997, *Adv. Space Res.*)



from Chung et al. (2008, *GRL*)

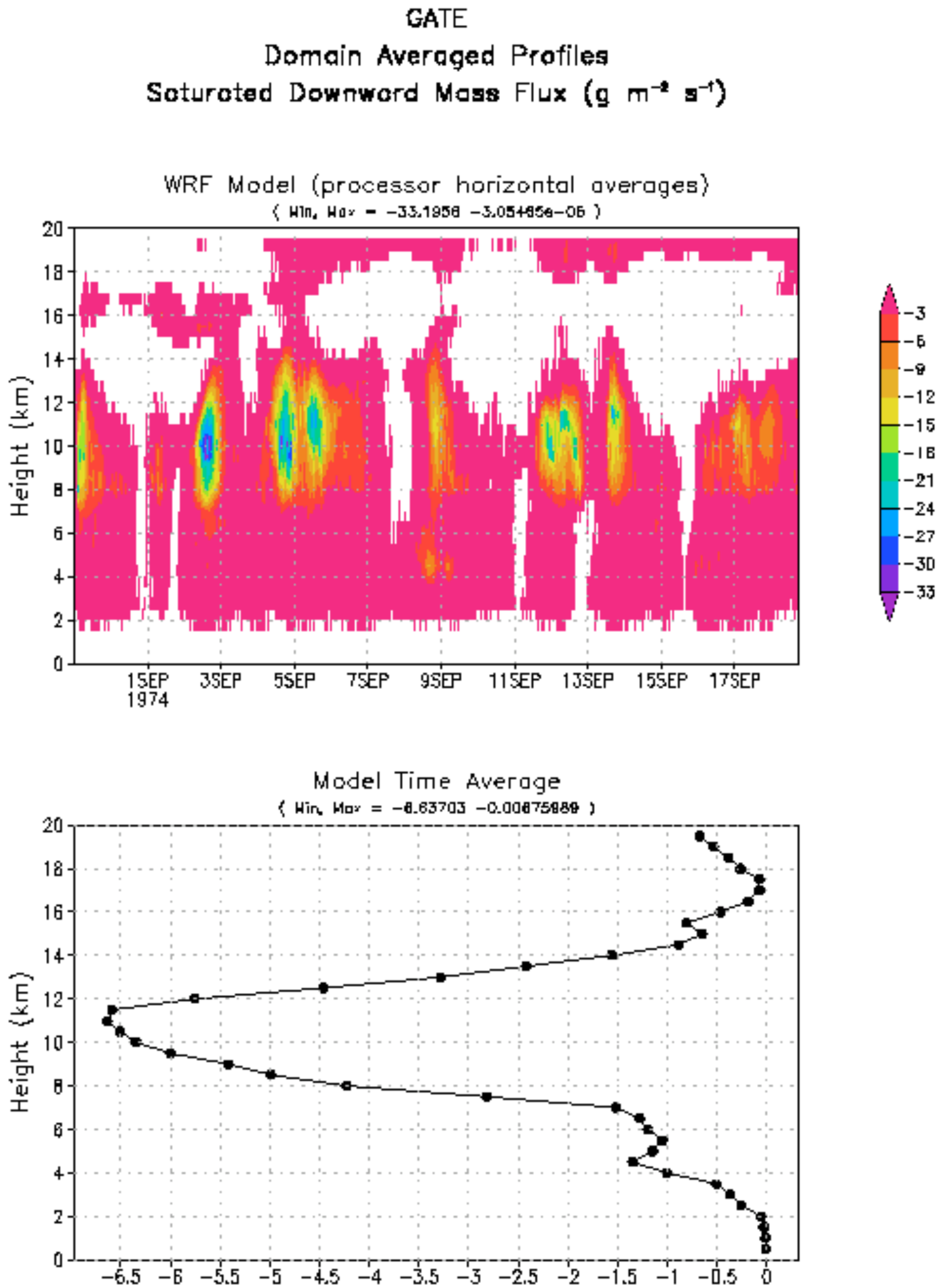
Cloud-System-Resolving Models

- Lu et al. (2000, *JGR*): 5-day GATE simulation exhibited stratosphere-troposphere exchange
- Mullendore et al. (2005, *JGR*): STEPS simulation shows boundary-layer tracer 1 km above tropopause, diluted to 26% of original concentration

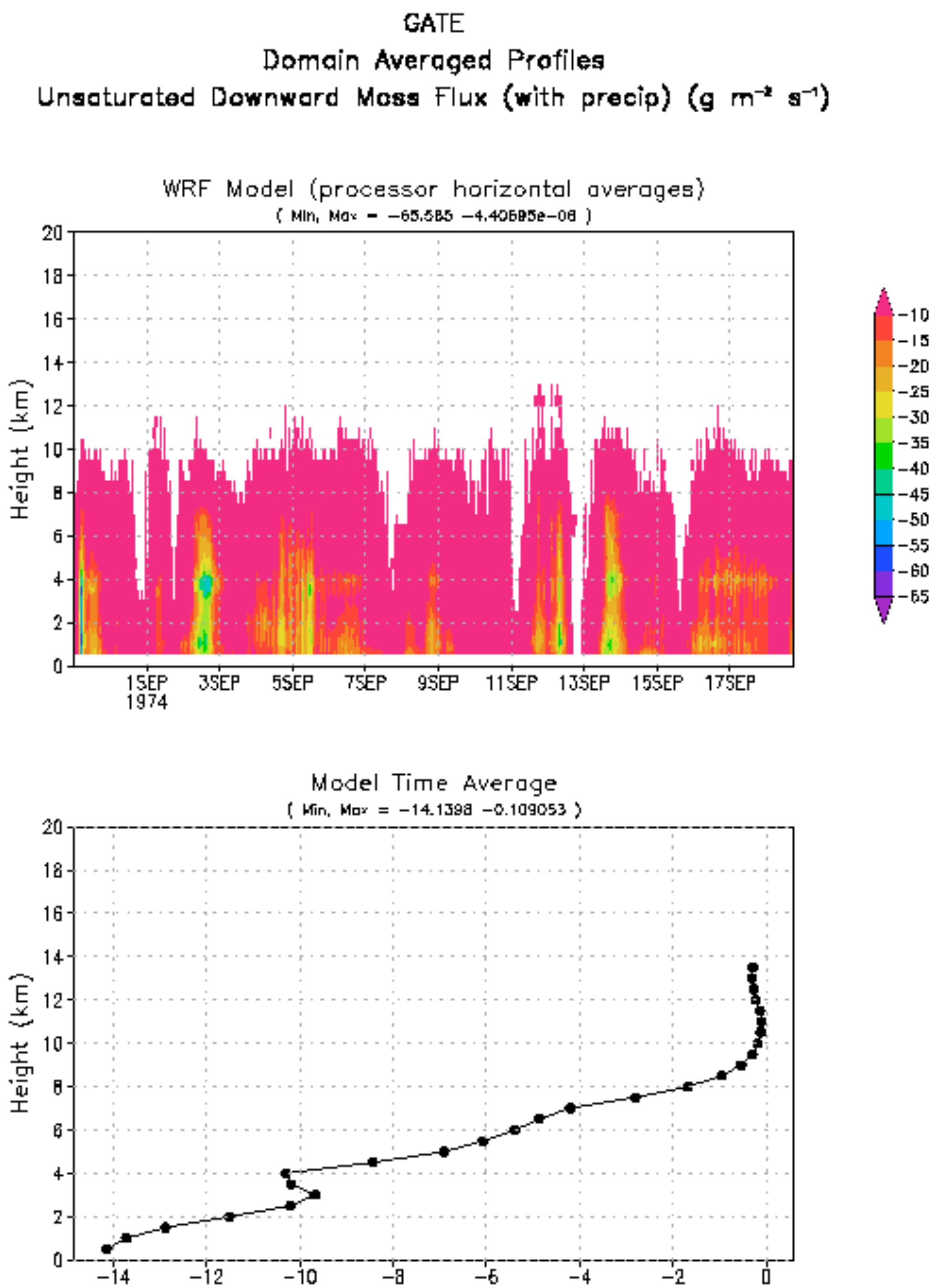


3-D CSRM
84 x 84 x 20 km
2 km hor res
500 m vert res

3-D CSRM
84 x84 x 20 km
2 km hor res
500m ver res



3-D CSRM
84 x 84 x 20 km
2 km hor res
500m ver res



Conclusions

- Observed stratospheric water vapor trends not successfully modeled by GFDL AM presently, due to problematic sub-grid physical processes and possible uncertainty of advection representation. GCM mean water vapor simulations agreeing with observations likely are not physically robust.
- Field experiments with isotopic measurements strongly indicate overshooting convection, advection, and microphysics all crucial to stratosphere water budget.
- GCM overshooting cumulus parameterizations have been developed and are being implemented but require substantial evaluation.
- CSRMs are a strong candidate for bridging field programs and GCM development. CSRMs should be evaluated using isotope observations.