Cloud Dynamical Controls on Climate Forcing by Aerosol-Cloud Interactions: New Insights from Observations, High-Resolution Models, and Parameterizations

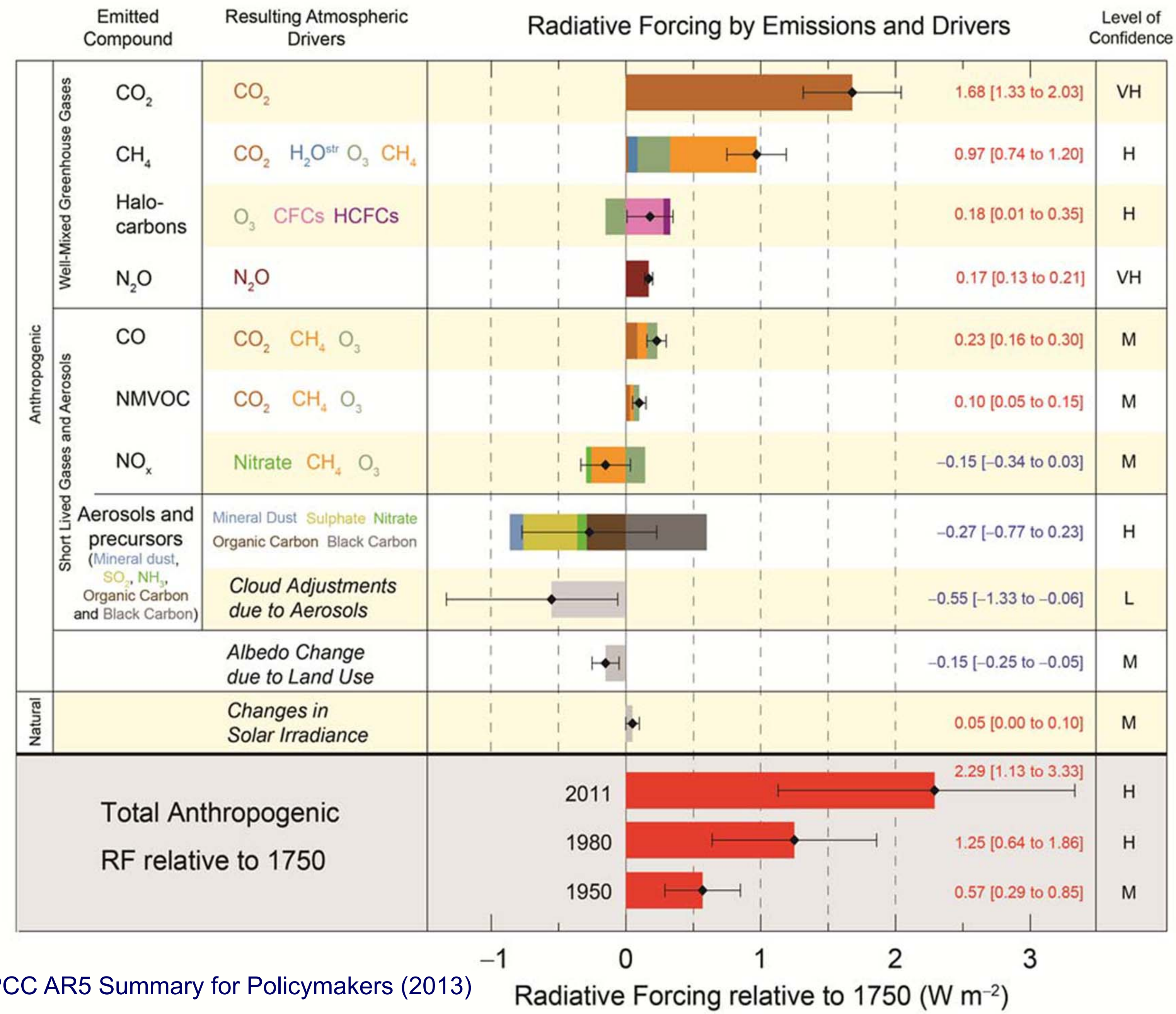
Leo Donner
GFDL/NOAA, Princeton University

EGU, Vienna, 18 April 2016

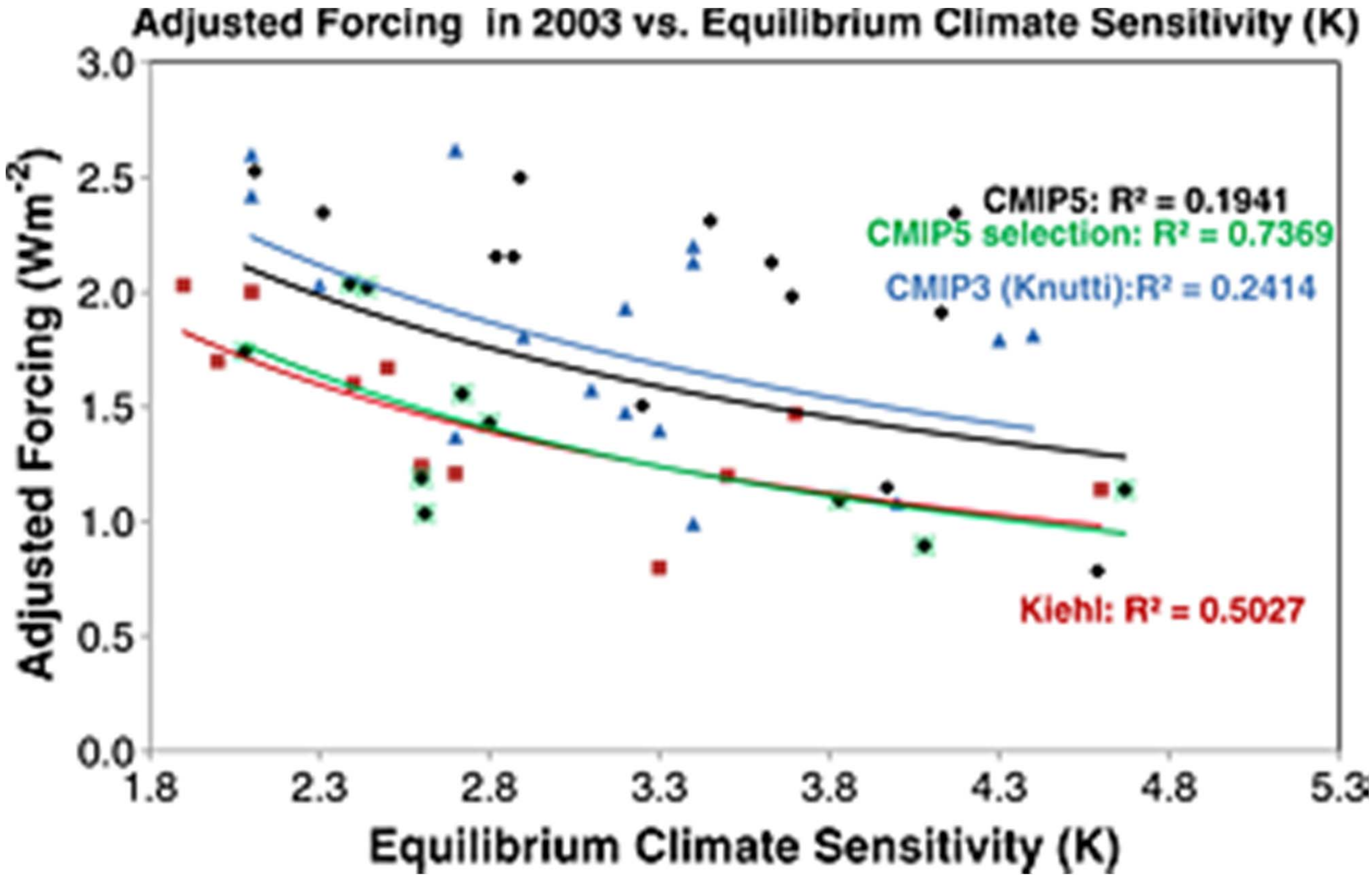
Introduction

- Uncertainties in both climate forcing and sensitivity limit the extent to which climate projections can meet critical societal needs.
- The observed climate transition from pre-industrial to present times depends simultaneously on climate forcing, sensitivity, and variability, precluding determination of any of these from observations alone.

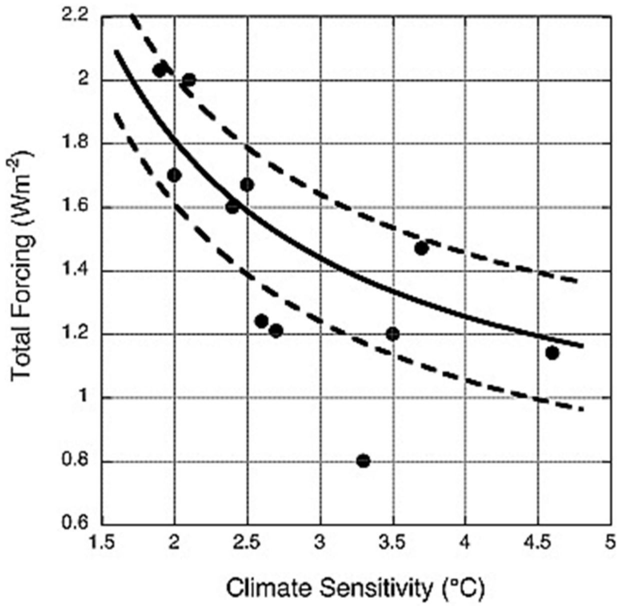
IPCC AR5 estimates total aerosol forcing to be -0.9 [-1.9 to -0.1] W m^{-2}.



from IPCC AR5 Summary for Policymakers (2013)



From Forster et al. in **Journal of Geophysical Research: Atmospheres**
Volume 118, Issue 3, pages 1139-1150, 6 FEB 2013 DOI: 10.1002/jgrd.50174
http://onlinelibrary.wiley.com/doi/10.1002/jgrd.50174/full#jgrd50174-fig-0007



Kiehl (2007, *Geophys. Res. Lett.*)

How did the 20th Century warm? High forcing/low sensitivity or low forcing/high sensitivity? Why is it important?

Future climate change will be driven more by greenhouse gases than aerosols, as aerosols have shorter lifetime than dominant anthropogenic greenhouse gases and aerosols likely to be regulated by air-pollution policy. “Masking” by aerosols will be less. Projecting warming requires knowledge of sensitivity.

Forcing from interactions between clouds and human-produced aerosols is a key uncertainty in current climate models. Cloud dynamics, cloud-scale updraft speeds in particular, are a major control on this forcing.

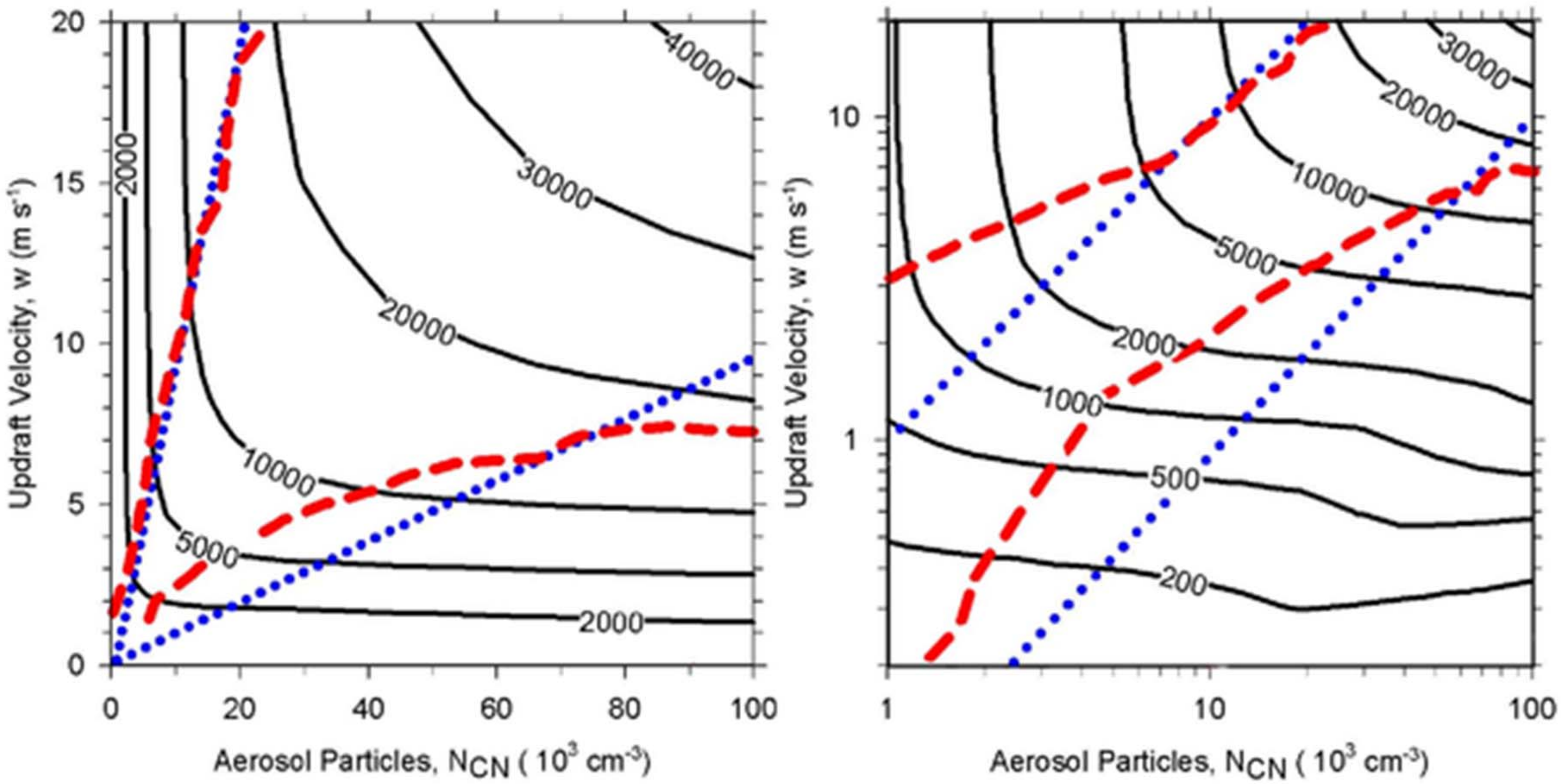
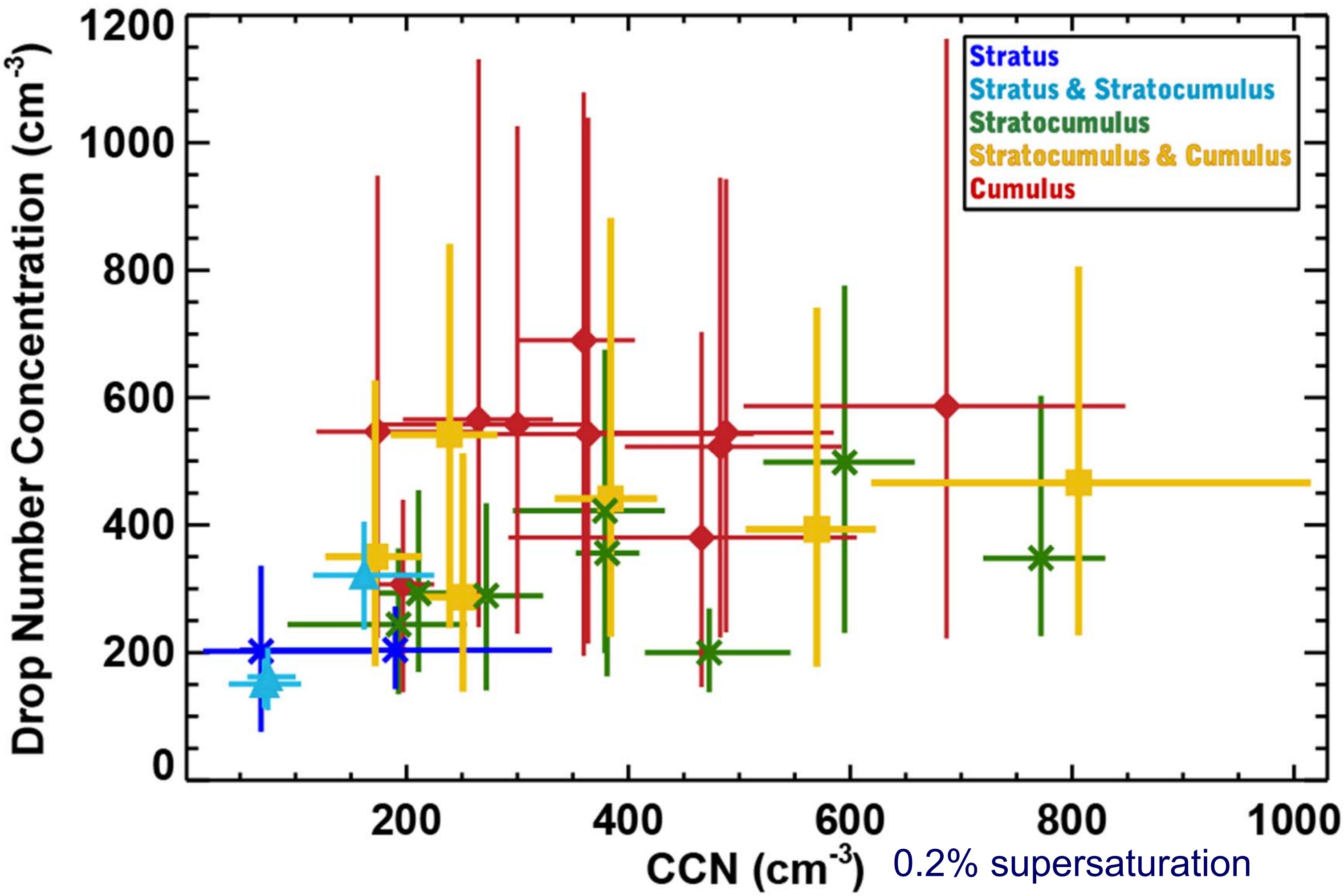


Fig. 4. Cloud droplet number concentrations (N_{CD}, cm^{-3}; isolines) calculated as a function of updraft velocity (w, $\mathrm{m\,s}^{-1}$) and initial aerosol particle number concentration (N_{CN}, cm^{-3}). **(a)** linear scale; **(b)** log-log scale. Red dashed lines indicate the borders between different regimes defined by (∂ ln NCD/ ∂ ln w)/(∂ ln N_{CD}/∂ ln N_{CN})=4 or 1/4, respectively. Blue dotted lines indicate approximate borders determined by w/N_{CN}.

Source: Reutter et al. (2009), Atmos. Chem. Phys, doi:10.5194/acp-9-7067-2009

CCN and Drop Number Observations from RACORO* Aircraft Campaign in US Southern Great Plains



provided by Andy Vogelmann, Brookhaven National Lab

*Routine AAF CLOWD Optical Radiative Observations

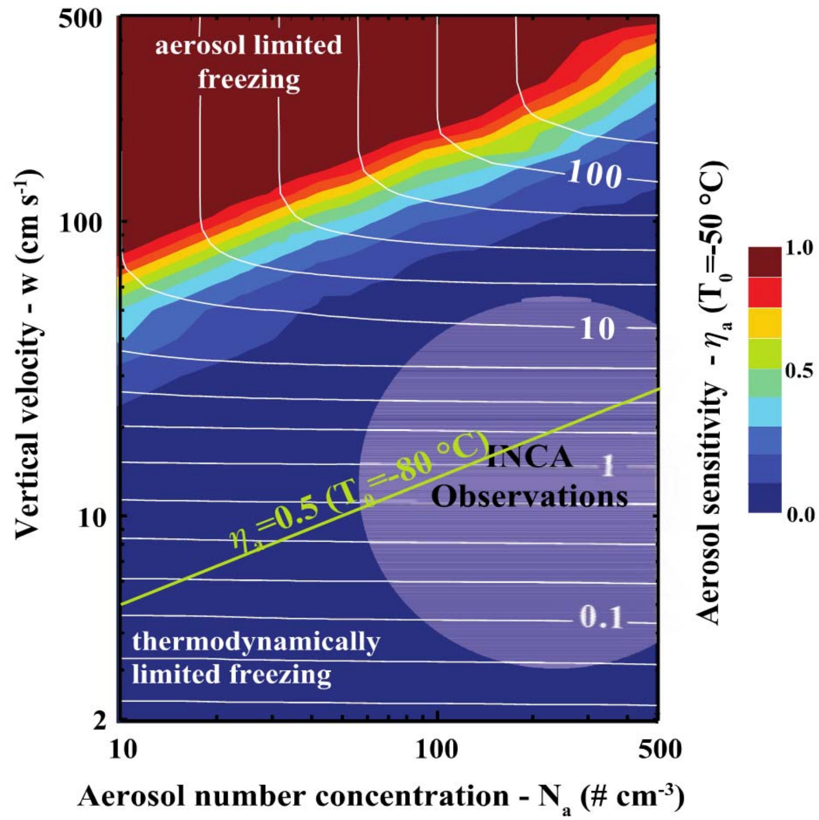
Aerosol Sensitivity

In order to study the sensitivity of ice number density (N_i) resulting from **homogeneous freezing** to aerosol concentration (N_a), an aerosol sensitivity parameter (η_α) was defined, following Kay and Wood 2008.

$$\eta_a \equiv \frac{d(\ln\ N_i)}{d\ \ln(N_a)}$$

N_i (cm^{-3}) contoured as a function of updraft velocity (V) and aerosol concentration (N_a).
Colors indicate the aerosol sensitivity parameter (η_α).

r_{a_dry}= 0.2 μm (mono-disperse)
α_i (deposition coefficient)=0.1;
T_0= -50°C, P_0=250 hPa;



Kay and Wood (2008, *Geophys. Res. Lett.*)

Slide courtesy of Xiaohong Liu, U. Wyoming

- Vertical velocities at both resolved and unresolved scales have received little attention in the development of climate models.

- Accurately simulated vertical velocities in climate models and appropriate treatment of their scaling properties when using them to drive cloud and aerosol processes could narrow uncertainty in climate forcing. New observations and parameterizations offer prospects for this improved modeling.

CHO AND LINDBORG: HORIZONTAL VELOCITY STRUCTURE FUNCTIONS

Aircraft Observations

Structure Function measures change in horizontal wind speed as function of distance *r* between two points (components transverse and longitudinal to flight direction)

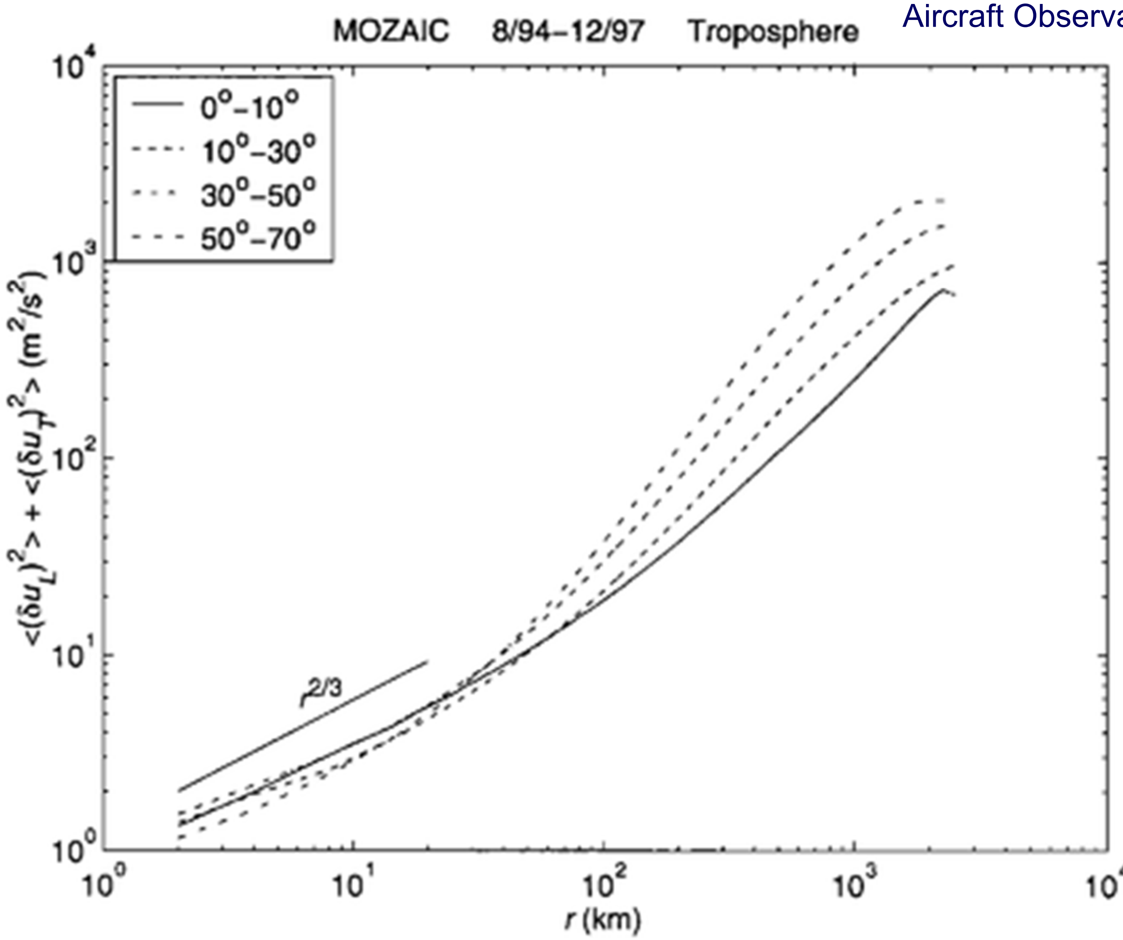
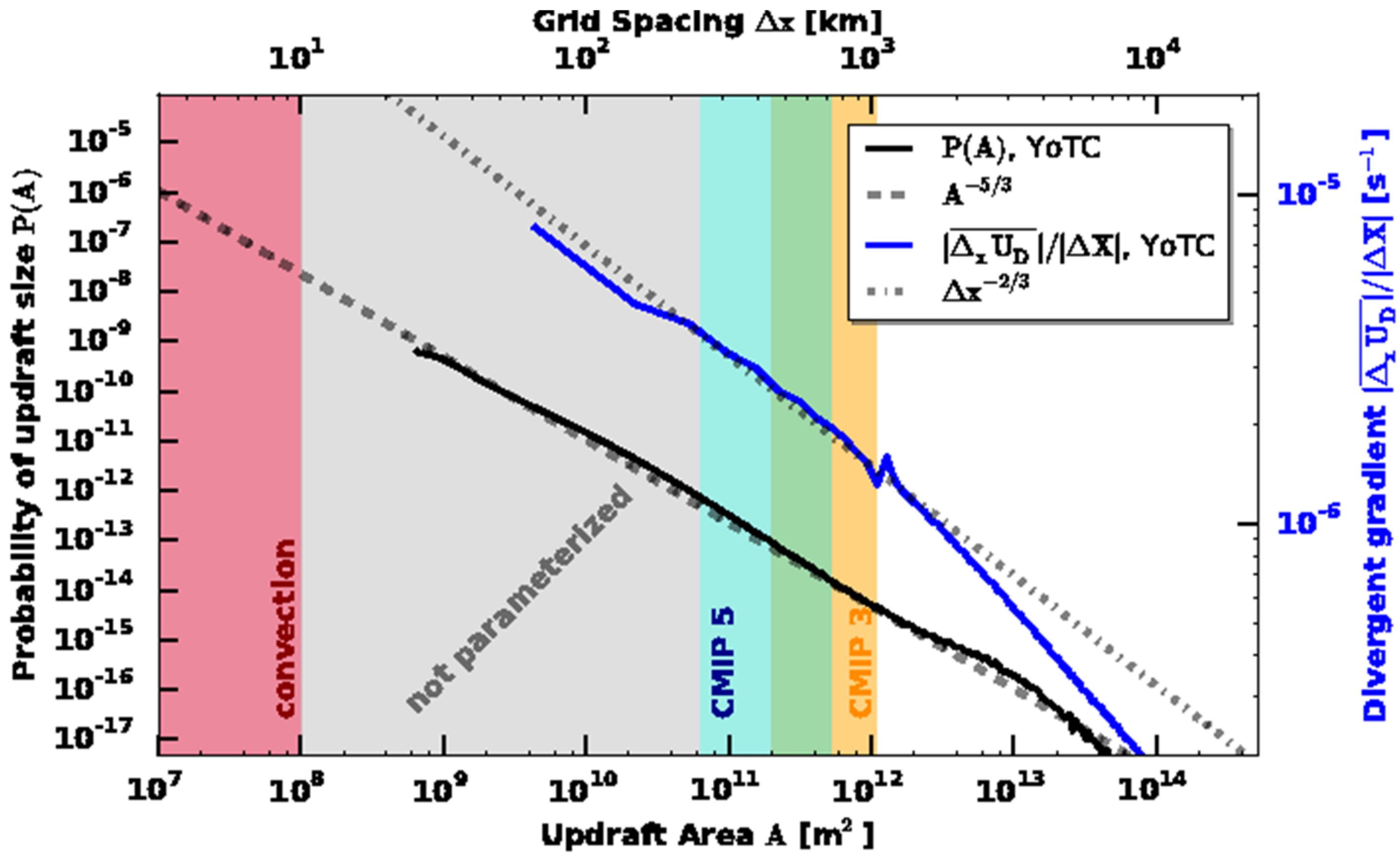


Figure 2. Sum of the tropospheric longitudinal and transverse second-order horizontal velocity structure functions versus latitude. Latitudes are absolute values.

Structure function measures change of horizontal velocity with distance. Related to vertical velocity by mass continuity. NOTE SCALE DEPENDENCE!

Source: Cho and Lindborg (2001), JGR-Atmos, doi:10.1029/2000JD900814

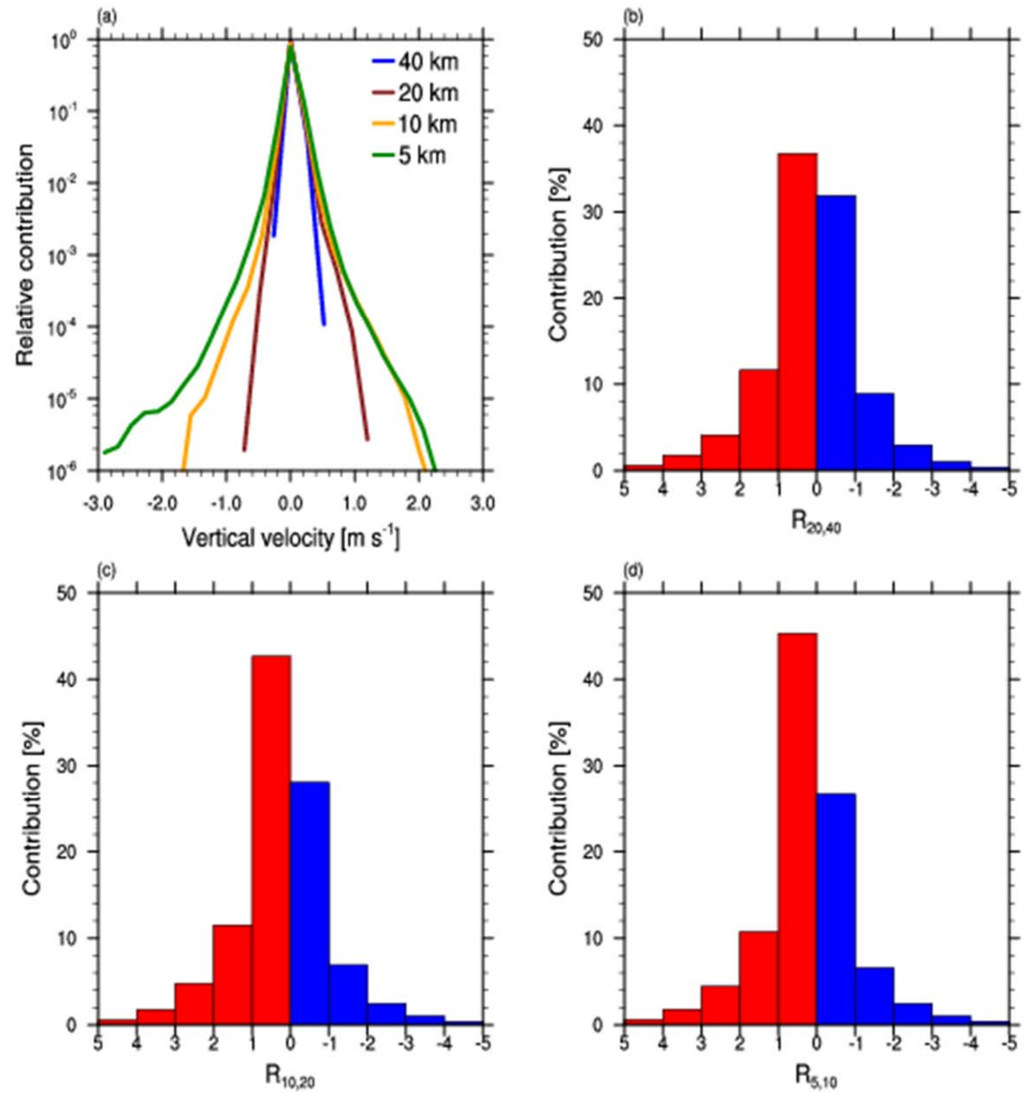
500-hPa divergent gradient and vertical velocity scale *nonlinearly* with grid size in ECMWF T799 forecasts, but cloud processes depend intrinsically on vertical velocity



Cho and Lindborg (2001, *J. Geophys. Res.*) observed similar structure functions in MOZAIC aircraft observations

Analysis by Travis O'Brien, LBNL

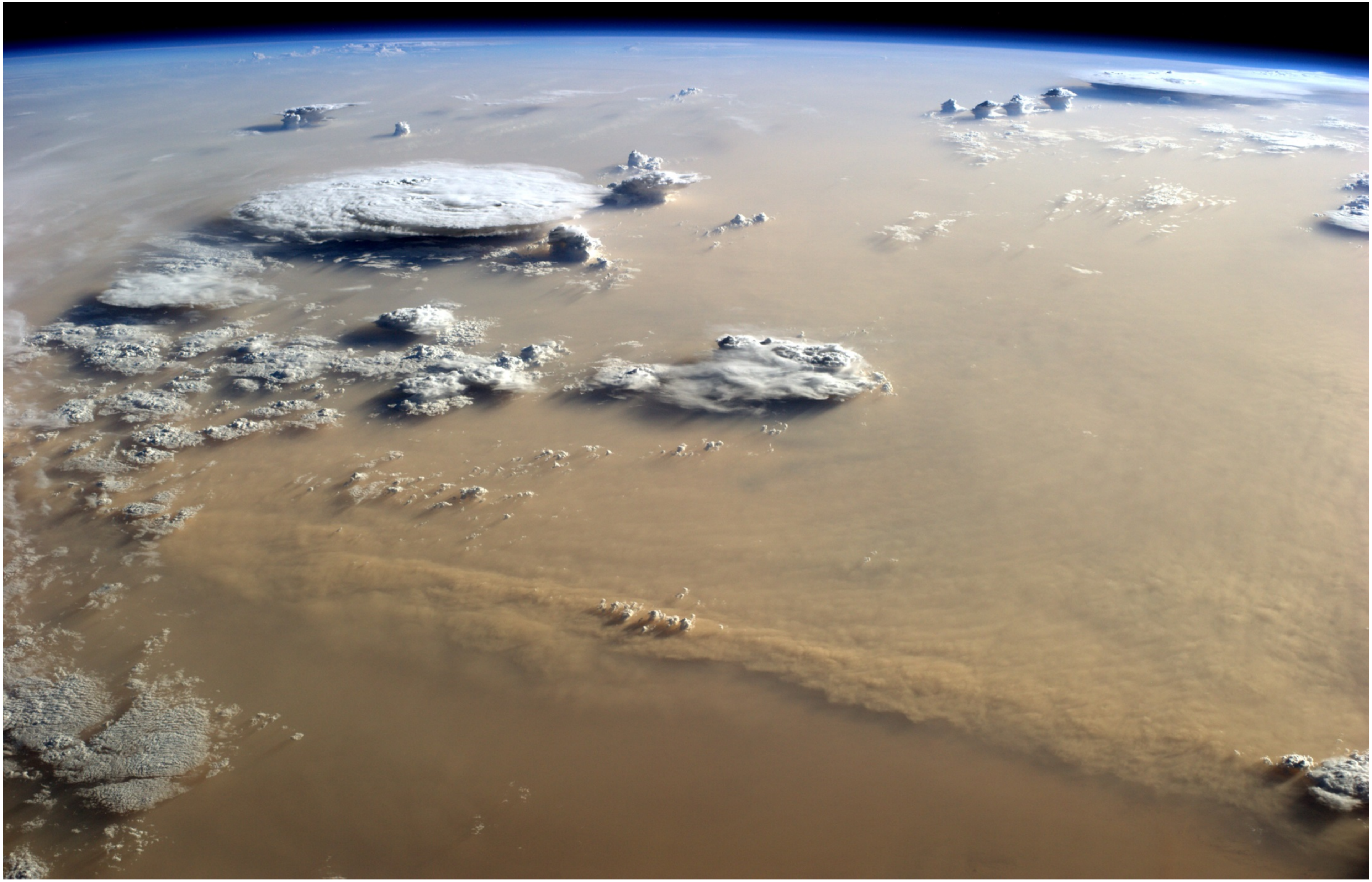
Heterogeneous Freezing in ICON-ART model shows (a) vertical velocity at which freezing occurs depends on resolution and (b)-(d) tends to occur more frequently at finer resolutions.



$R_{2,1}$= log($\bar{n}_2/n_1$)
n_1: number of particles frozen at coarse resolution
$\bar{n}_2$: mean number of particles frozen in corresponding space at fine resolution

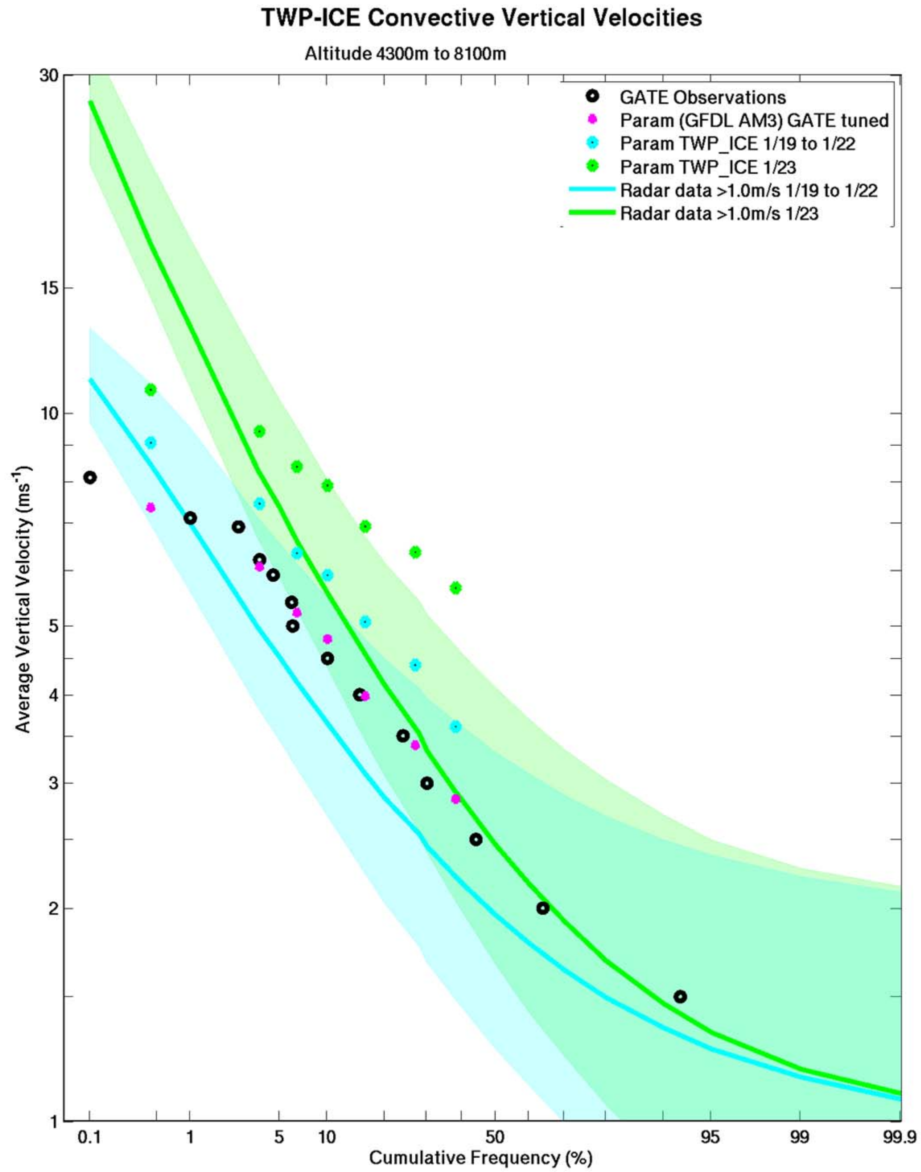
Analysis by Daniel Rieger and Bernhard Vogel, Karlsruhe Institute of Technology

Ma *et al.* (2015, *Geophys. Res. Lett.*) found aerosol indirect forcing decreased 15% globally in CAM5 as grid spacing decreased from 2° to 0.25°



Multi-Scale Convection: ISS over Libya, 8 September 2014, photo by Alex Gerst

Convective Vertical Velocities from GFDL AM3 (Donner *et al.*, 2011) and TWP ICE dual-Doppler (Collis *et al.*, 2013, *J. Appl. Meteor. Climatol.*)

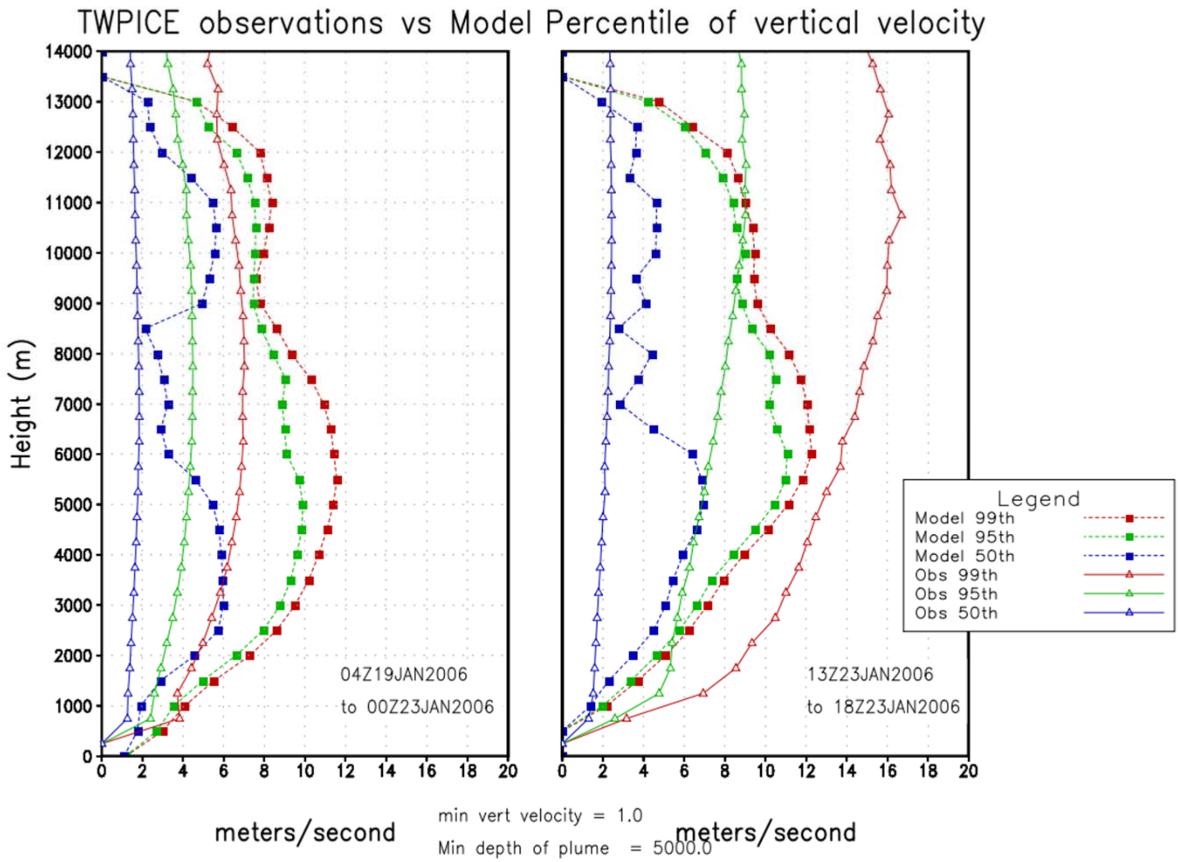


Shading shows ranges of radar observations with lower cut-off from 0.5 to 2.0 m s^{-1} over 5-km layer. 95th percentile by extrapolating AM3 ensembles ~ 1 m s^{-1} for GATE, 1.5 m s^{-1} for TWP ICE 1/19-22, and 2.0 m s^{-1} for TWP ICE 1.23.

TWP-ICE results suggest more entrainment at lower vertical velocities (de Rooy *et al.*, *QJRMS;* Zhang *et al.*, 2015, *Clim. Dyn.;* Lu *et al.*, 2016, *J. Atmos. Sci.*)

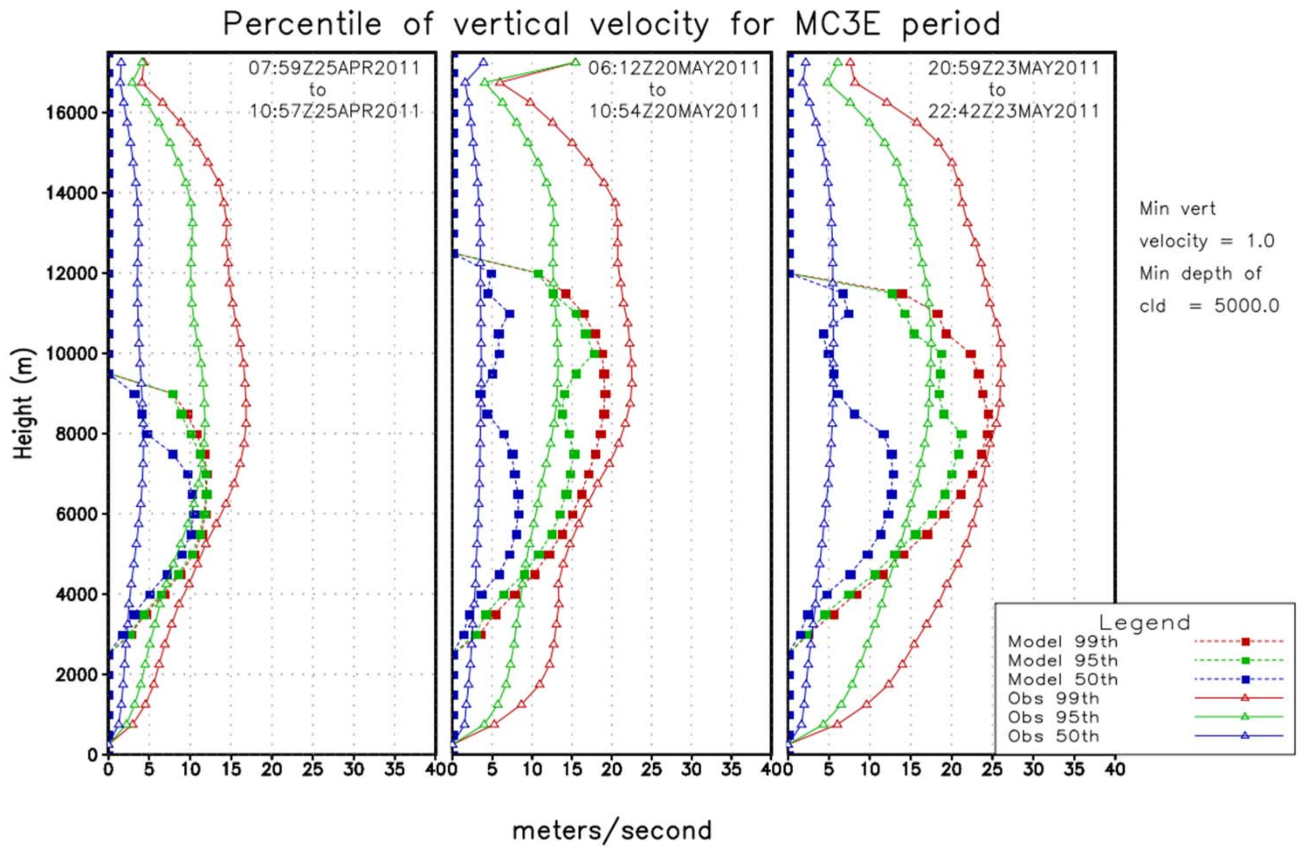
Analysis by Will Cooke, GFDL; GATE observations provided by Ian Glenn, U. Utah.

TWP-ICE PDFs of Cumulus Vertical Velocity in GFDL AM3 and Radar Observations: Prospects for Sub-Grid Parameterization



PDFs of cumulus vertical velocities at TWP-ICE from GFDL AM3 (Donner *et al.* (2011, *J. Climate*) and dual-Doppler radar (Collis *et al.,* 2013, *J. Appl. Meteor. Climatol.*) show AM3 vertical velocity values often, but not always, larger than observed. Analysis by Will Cooke, GFDL.

MC3E PDFs of Cumulus Vertical Velocity in GFDL AM3 and Radar Observations



PDFs of cumulus vertical velocities at MC3E from GFDL AM3 (Donner *et al.* (2011, *J. Climate*) and dual-Doppler radar (Collis *et al.,* 2013, *J. Appl. Meteor. Climatol.*) show AM3 vertical velocity values often, but not always, larger than observed. Analysis by Will Cooke, GFDL.

Observed (Solid Black) & CRM Vertical Velocities (Varble *et al.*, 2014, *JGR*)

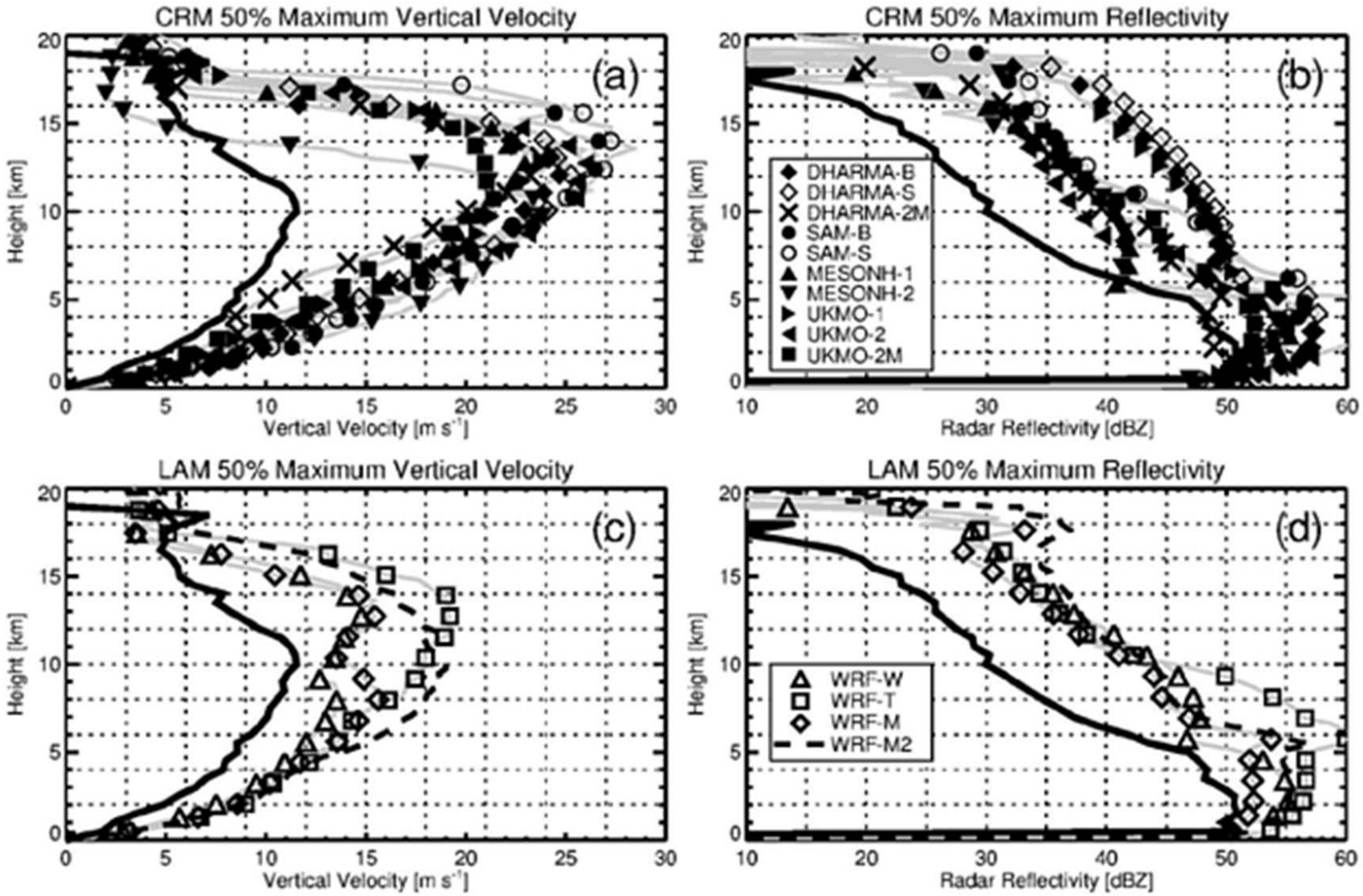
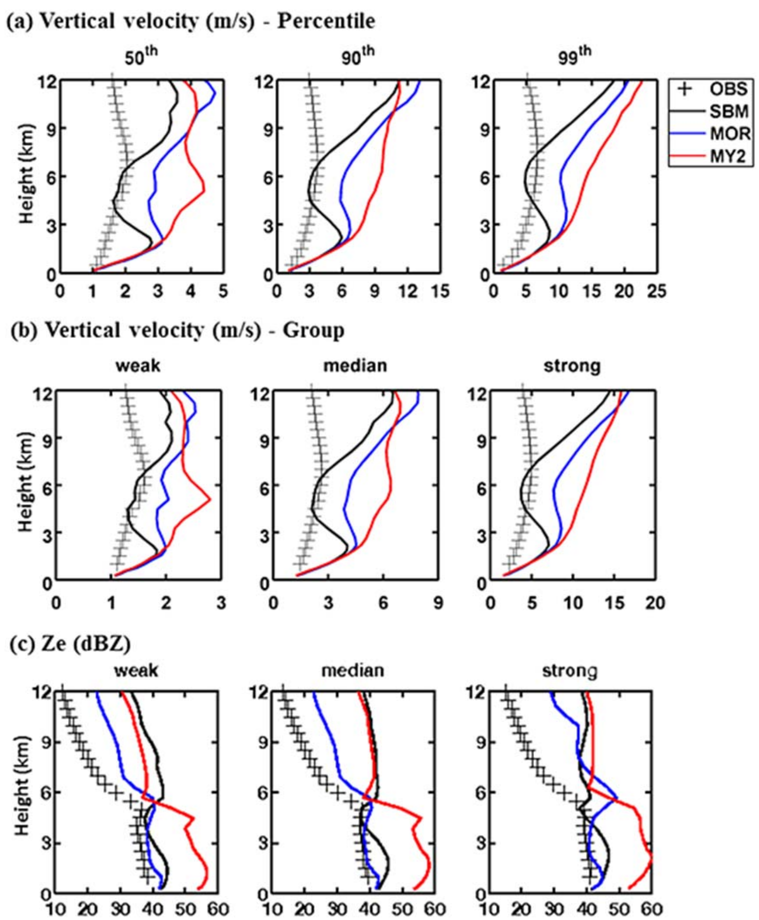


Figure 9: Median profiles of maximum vertical velocity (a,c) and radar reflectivity (b,d) for three-dimensionally defined convective updrafts beginning below 1 km and ending above 15 km for the period of 1310Z to 1750Z on 23 January 2006. CRM statistics are shown in (a-b) and LAM statistics are shown in (c-d). Gray lines with symbols and the dashed black lines represent simulations. Observations are represented by solid black lines.

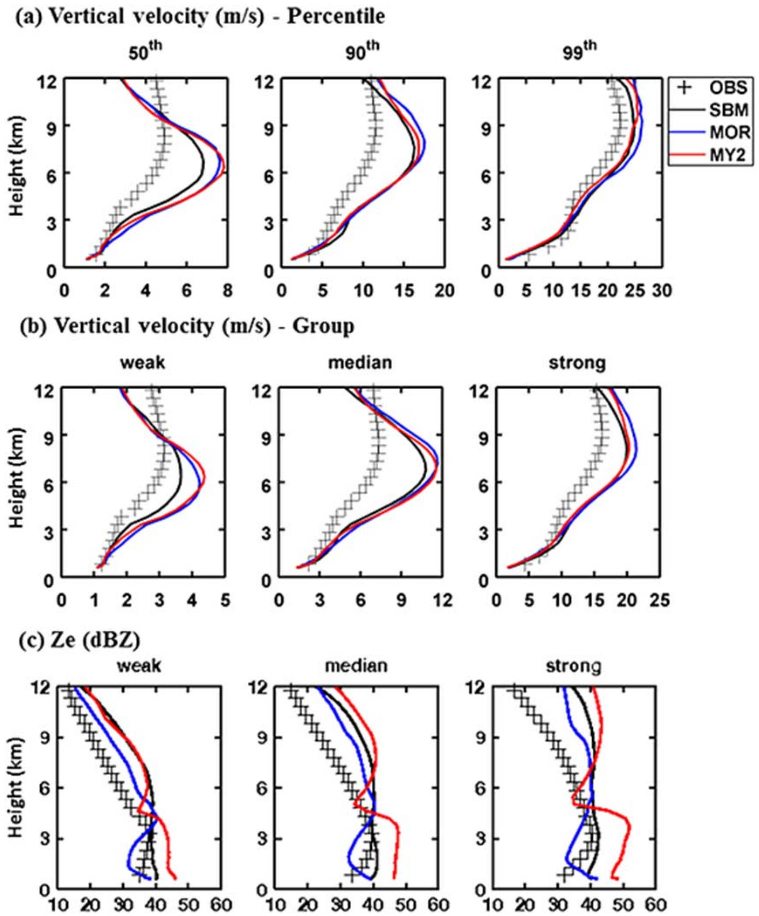
Improving representation of convective transport for scale-aware parameterization: 1. Convection and cloud properties simulated with spectral bin and bulk microphysics



TWP-ICE, 22 Jan 2006
SBM: spectral microphysics
MOR, MY2: bulk microphysics (from Fan *et al.*, 2015, *JGR-Atmos.*)

Journal of Geophysical Research: Atmospheres
2014JD022142, 29 APR 2015 DOI: 10.1002/2014JD022142
http://onlinelibrary.wiley.com/doi/10.1002/2014JD022142/full#jgrd52099-fig-0009

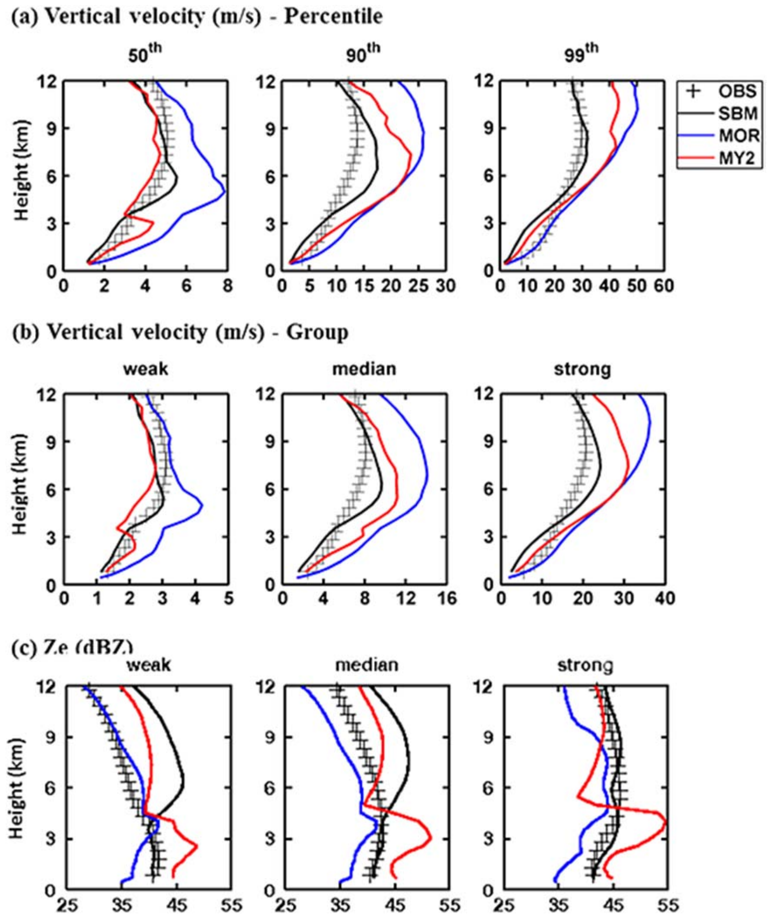
Improving representation of convective transport for scale-aware parameterization: 1. Convection and cloud properties simulated with spectral bin and bulk microphysics



MC3E, 20 May 2011 SBM: spectral microphysics; MOR, MY2: bulk microphysics (from Fan *et al.*, 2015, *JGR-Atmos.*)

Journal of Geophysical Research: Atmospheres
2014JD022142, 29 APR 2015 DOI: 10.1002/2014JD022142
http://onlinelibrary.wiley.com/doi/10.1002/2014JD022142/full#jgrd52099-fig-0008

Improving representation of convective transport for scale-aware parameterization: 1. Convection and cloud properties simulated with spectral bin and bulk microphysics

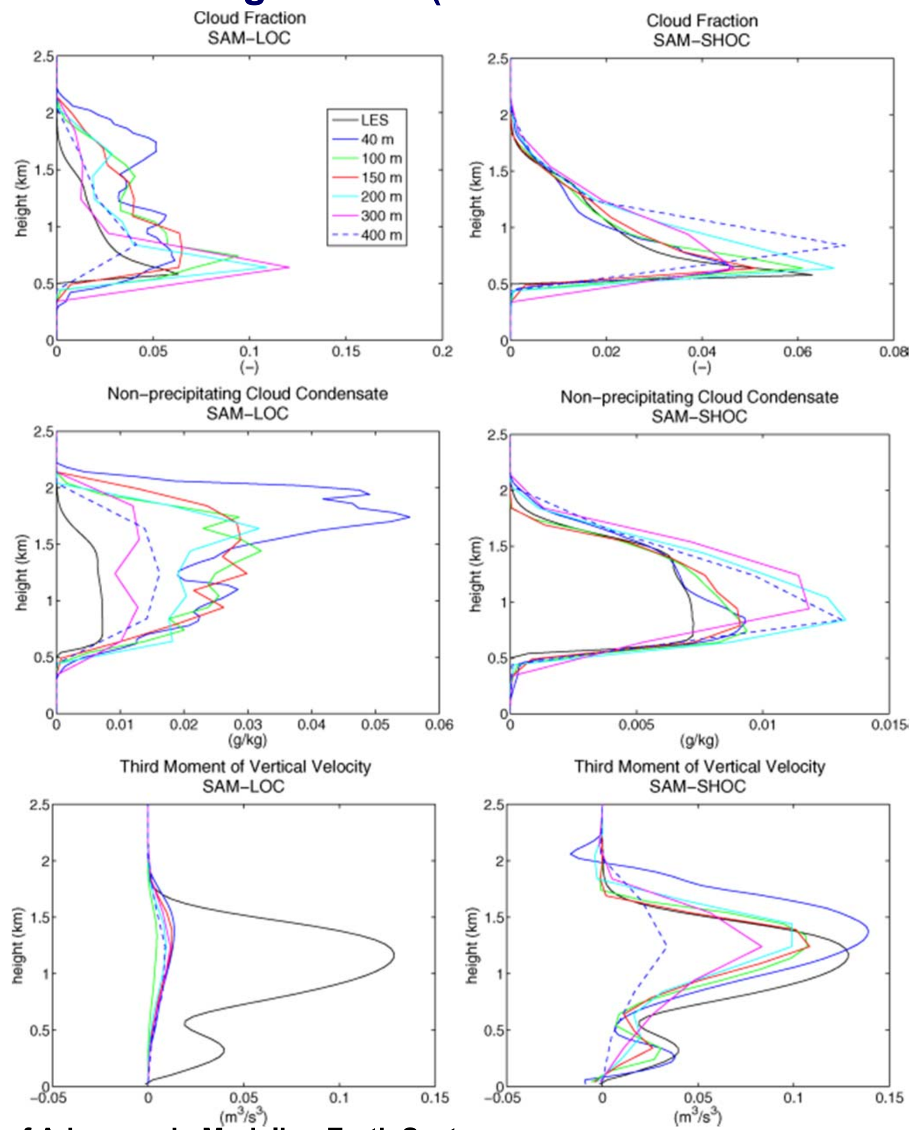


MC3E, 23 May 2011, SBM: spectral bin microphysics; MOR and MY2: bulk microphysics, from Fan *et al.* (2015, *JGR-Atmos.*)

Journal of Geophysical Research: Atmospheres
2014JD022142, 29 APR 2015 DOI: 10.1002/2014JD022142
http://onlinelibrary.wiley.com/doi/10.1002/2014JD022142/full#jgrd52099-fig-0007

A simplified PDF parameterization of subgrid-scale clouds and turbulence for cloud-resolving models (horizontal resolution 3.2 km)

BOMEX



LES
Horizontal resolution: 100m
Vertical resolution: 40m

Local turbulence unsuccessful even at 40m vertical resolution.

Higher-order, assumed distribution turbulence approaches LES even at 200m vertical resolution.

Journal of Advances in Modeling Earth Systems
Volume 5, Issue 2, pages 195-211, 18 APR 2013 DOI: 10.1002/jame.20018
http://onlinelibrary.wiley.com/doi/10.1002/jame.20018/full#jame20018-fig-0003

Bogenschutz and Krueger (2013)

Conclusions

- Observed climate transition from pre-industrial to present times depends simultaneously on climate forcing, sensitivity, and variability, precluding precise determination of any of these from observations alone.
- Interactions between clouds and human-produced aerosols are a key source of uncertainty in current climate models. Cloud-scale updraft speeds are a major control on this forcing.
- Vertical velocities at both resolved and parameterized scales in climate models have received limited attention in climate-model development.
- Accurately simulated vertical velocities and appropriate treatment of their scaling properties when using them to drive aerosol and cloud processes could narrow uncertainty in climate forcing.
- More possibilities: Dynamics related to cloud entrainment appear to be important for climate sensitivity, too!