# Cloud Updrafts, Climate Forcing, and Climate Sensitivity

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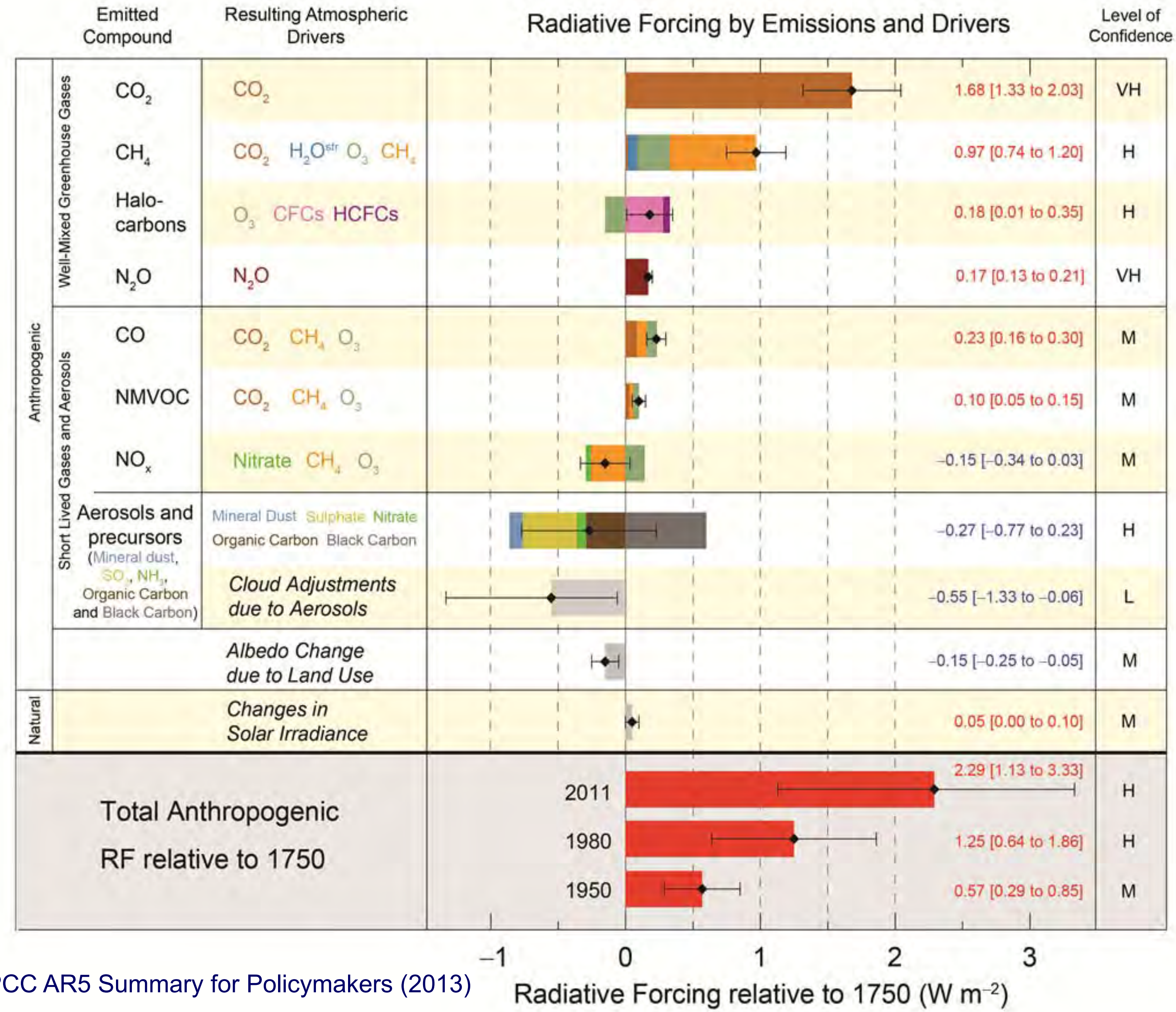
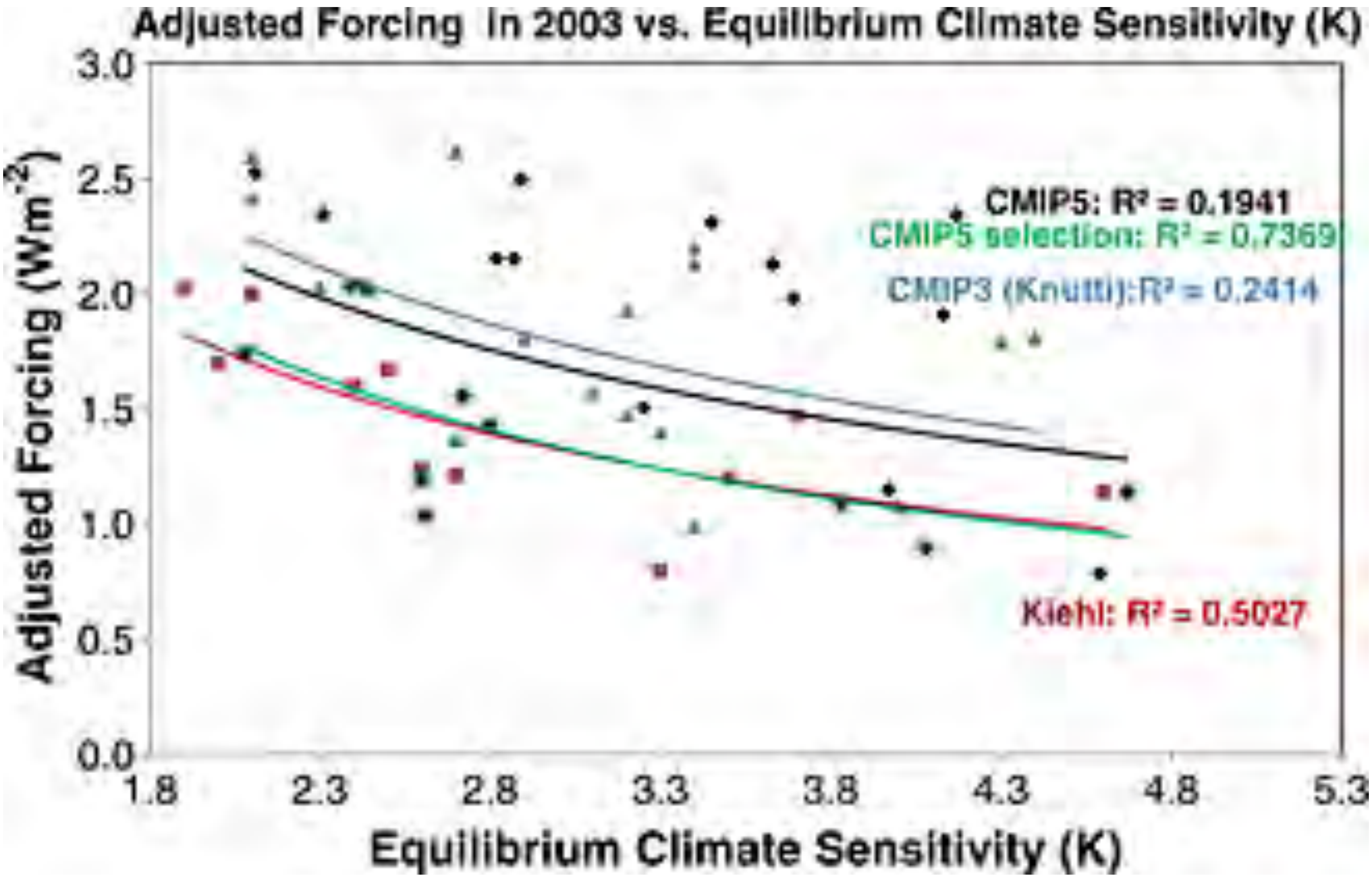
# Introduction

- 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 the historical record 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
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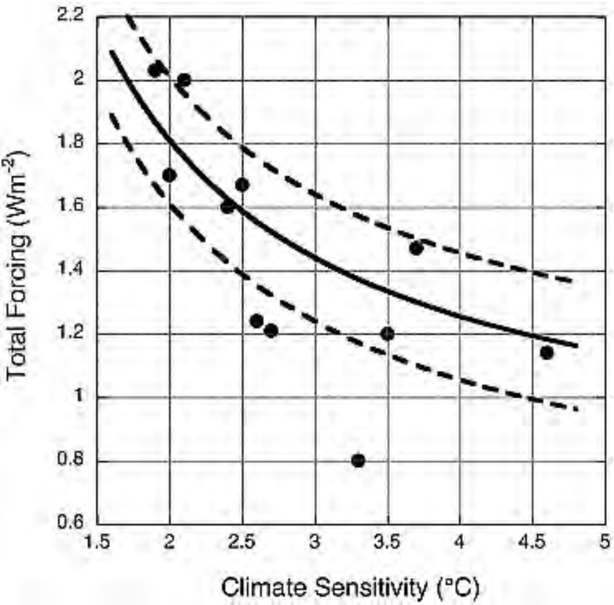


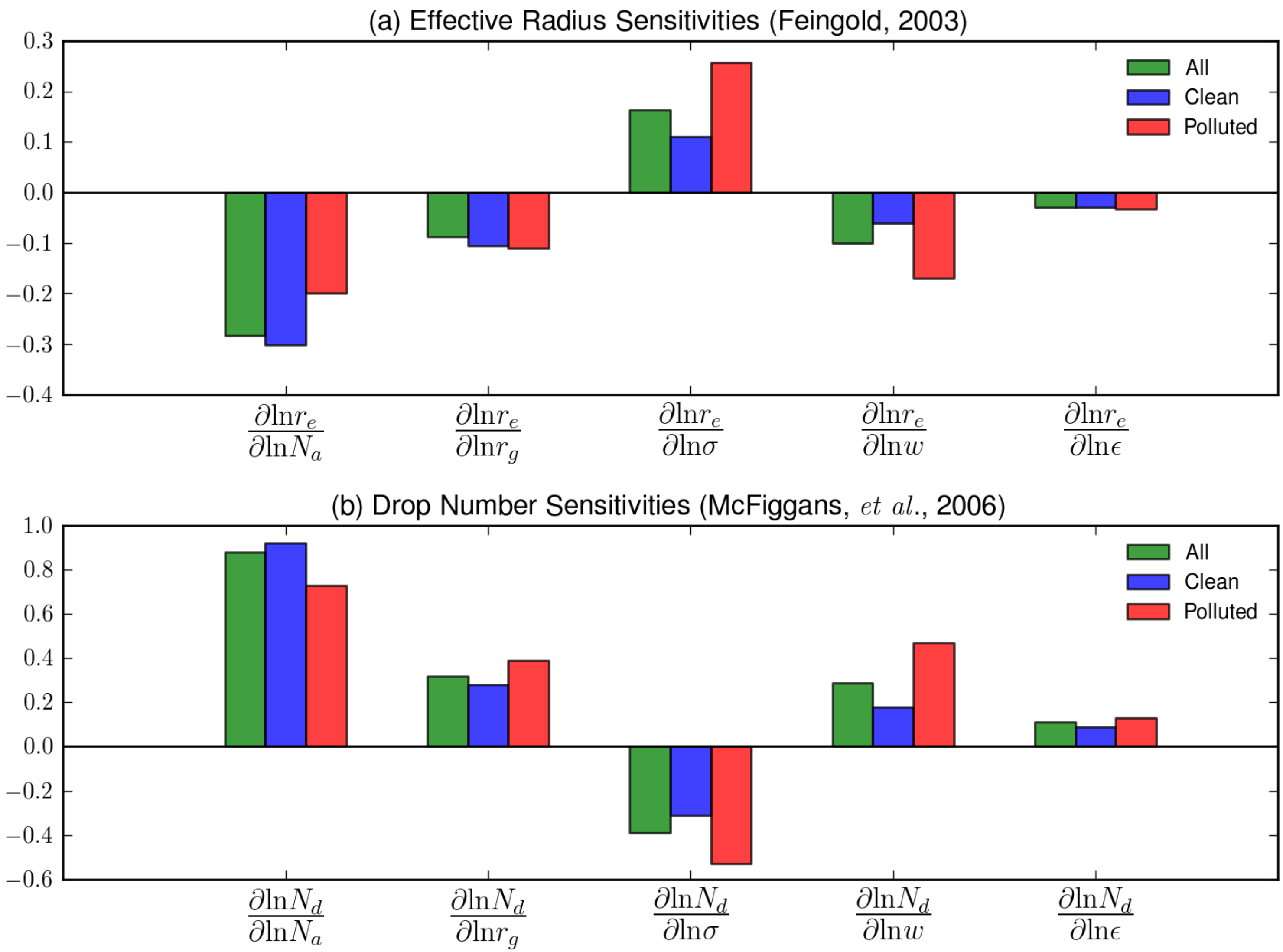

Kiehl (2007, *Geophys. Res. Lett.*)

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.

# Climate Forcing and Cloud Updrafts

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.

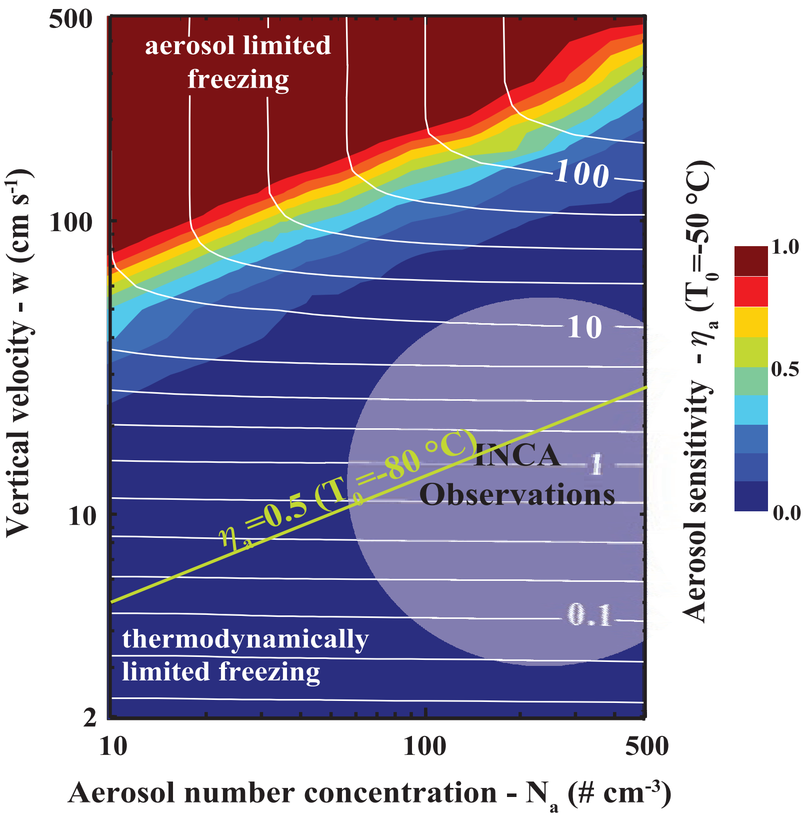


(a) Effective Radius Sensitivities (Feingold, 2003)
0.3
0.2
0.1
0.0
−0.1
−0.2
−0.3
−0.4
All
Clean
Polluted
$\frac{\partial \ln r_e}{\partial \ln N_a}$
$\frac{\partial \ln r_e}{\partial \ln r_g}$
$\frac{\partial \ln r_e}{\partial \ln \sigma}$
$\frac{\partial \ln r_e}{\partial \ln w}$
$\frac{\partial \ln r_e}{\partial \ln \epsilon}$
(b) Drop Number Sensitivities (McFiggans, *et al.*, 2006)
1.0
0.8
0.6
0.4
0.2
0.0
−0.2
−0.4
−0.6
All
Clean
Polluted
$\frac{\partial \ln N_d}{\partial \ln N_a}$
$\frac{\partial \ln N_d}{\partial \ln r_g}$
$\frac{\partial \ln N_d}{\partial \ln \sigma}$
$\frac{\partial \ln N_d}{\partial \ln w}$
$\frac{\partial \ln N_d}{\partial \ln \epsilon}$

# 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 ($\eta_\alpha$) 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 ($\eta_\alpha$).

**$r_{a\_dry}$= 0.2 μm (mono-disperse)**
$\alpha_i$ (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

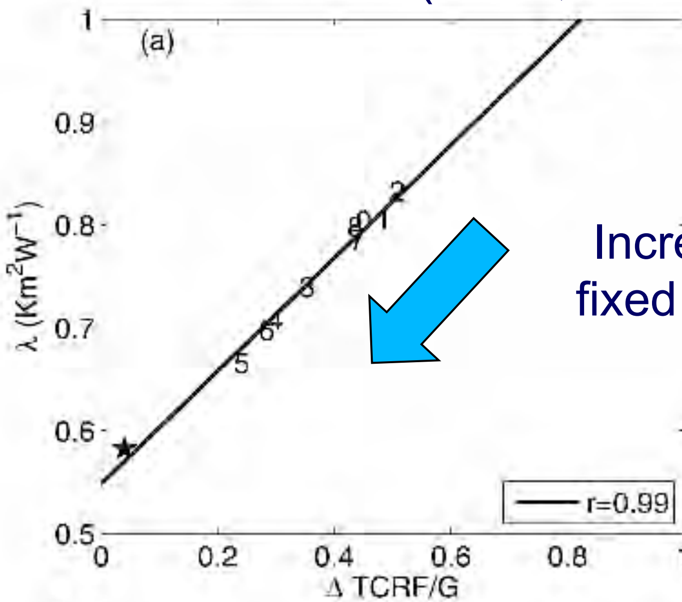
# Climate Forcing and Cloud Updrafts

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.

# Dependence of Climate Sensitivity on Convective Entrainment (Zhao, 2014, *J. Climate*)

GFDL model

Climate Sensitivity

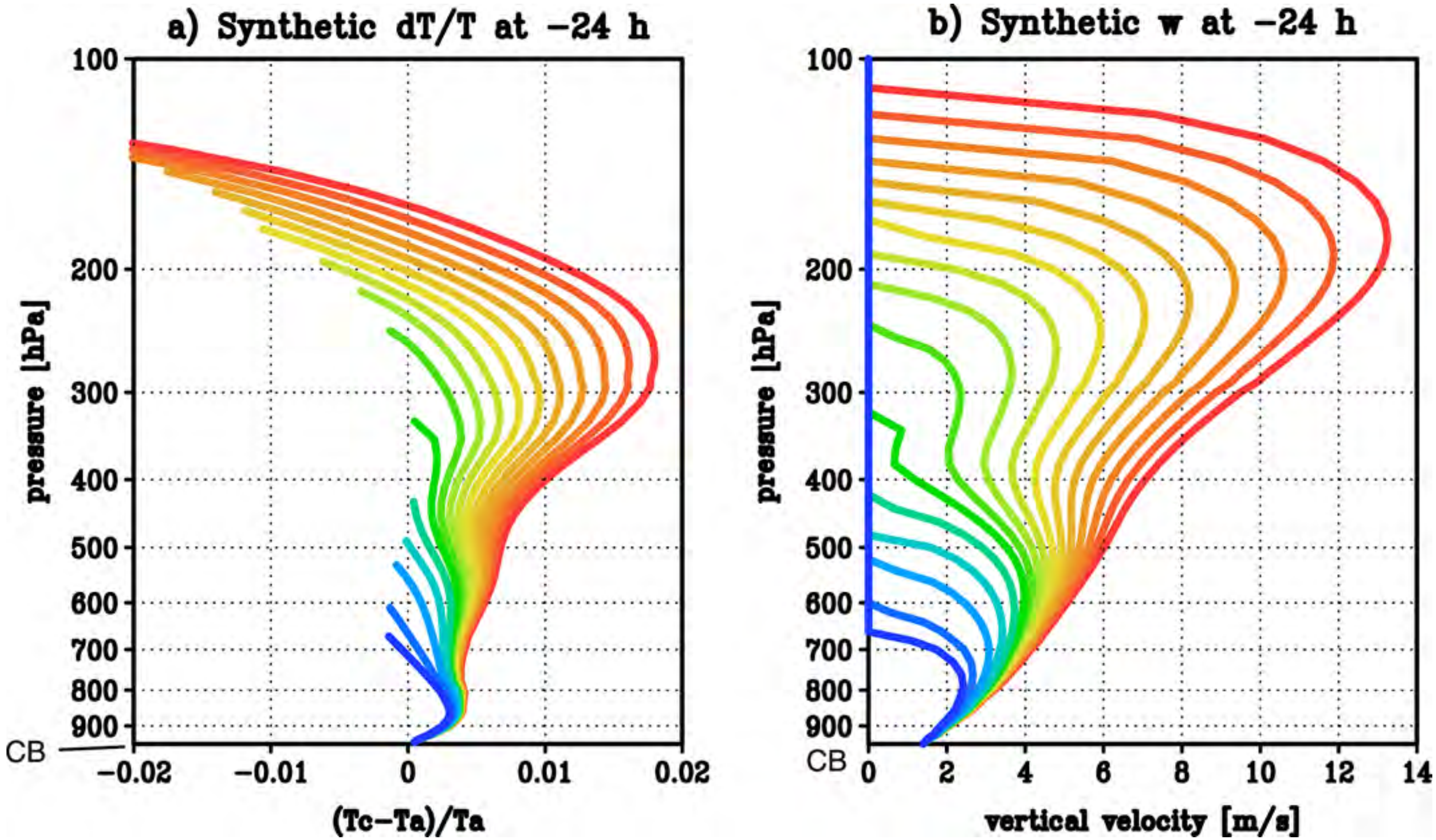



Increasing Entrainment for fixed precipitation threshold, except for Exp. 2

Change in Cloud-Radiative Effect, Normalized by Energy-Balance Change

Climate sensitivity dependence on entrainment also shown by Stainforth *et al.* (2005, *Nature*), Sanderson *et al.* (2010, *Clim. Dyn.*), and for shallow but not deep convection, Klocke *et al.* (2011, *J. Climate*).

## Convective and large-scale mass flux profiles over tropical oceans determined from synergistic analysis of a suite of satellite observations

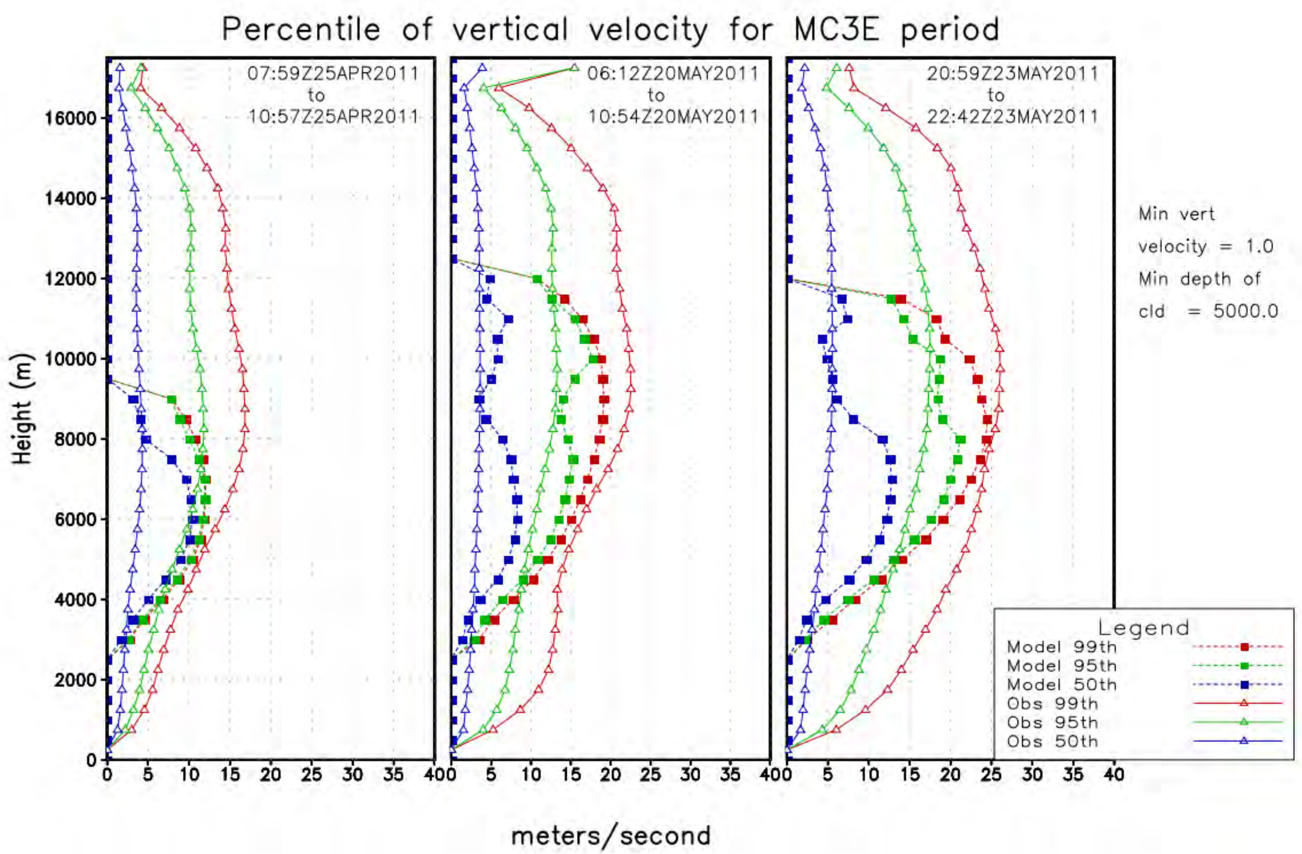



Plume entrainment rates from 0 to 0.4 km$^{-1}$ as red goes to blue.

**Journal of Geophysical Research: Atmospheres**
Volume 121, Issue 13, pages 7958-7974, 12 JUL 2016 DOI: 10.1002/2016JD024753
http://onlinelibrary.wiley.com/doi/10.1002/2016JD024753/full#jgrd53104-fig-0002

from Masunaga and Luo (2016, *JGR*)

# 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.

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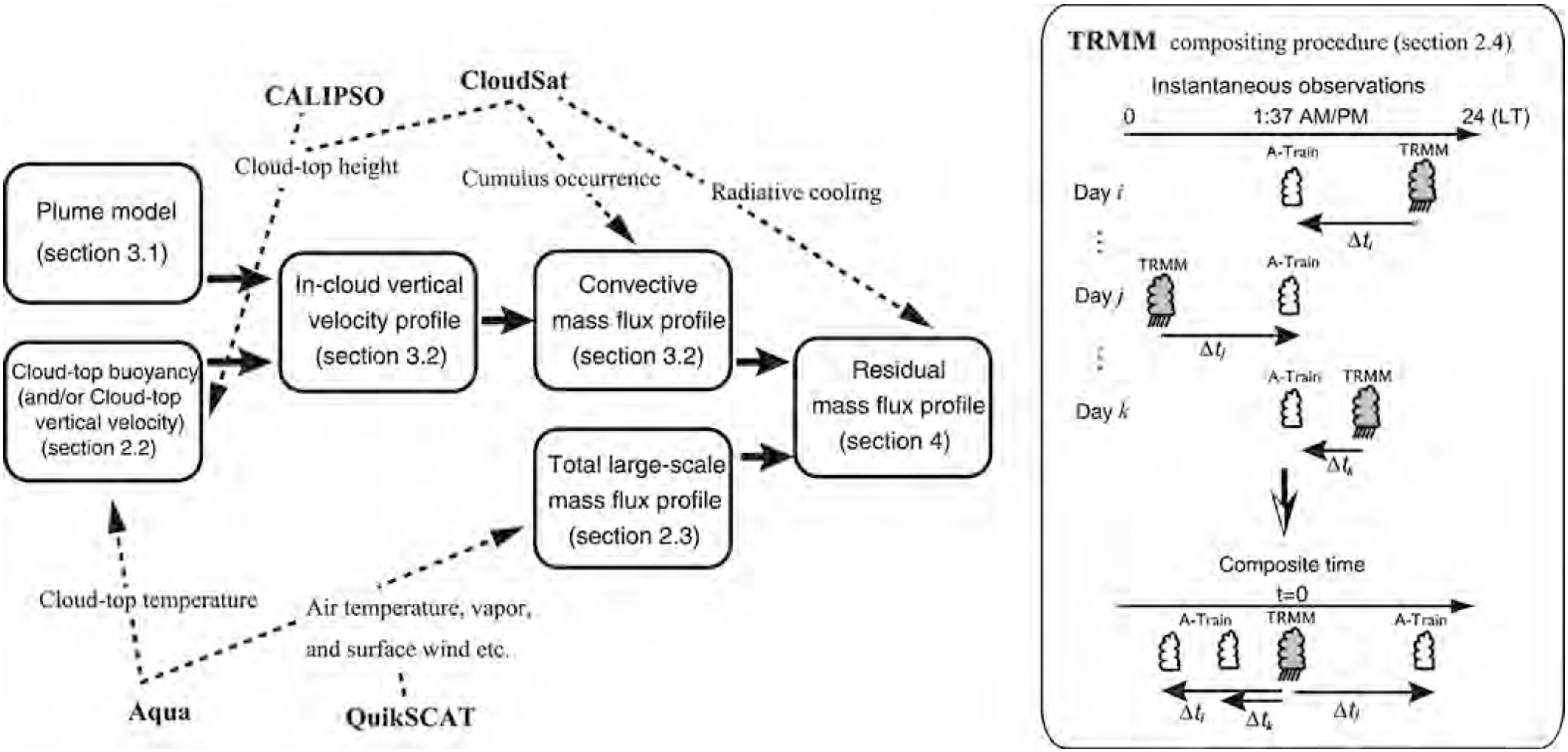


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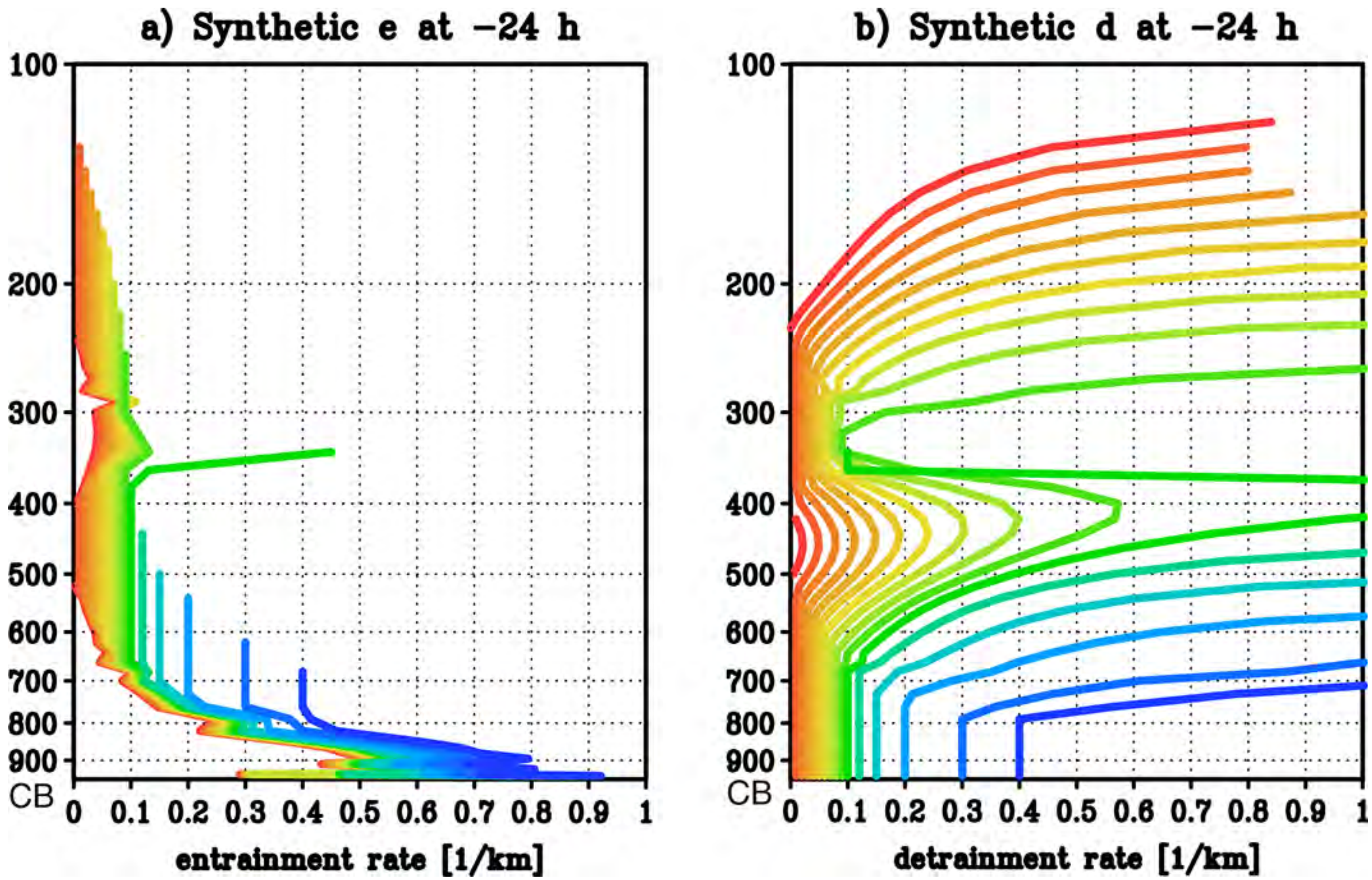


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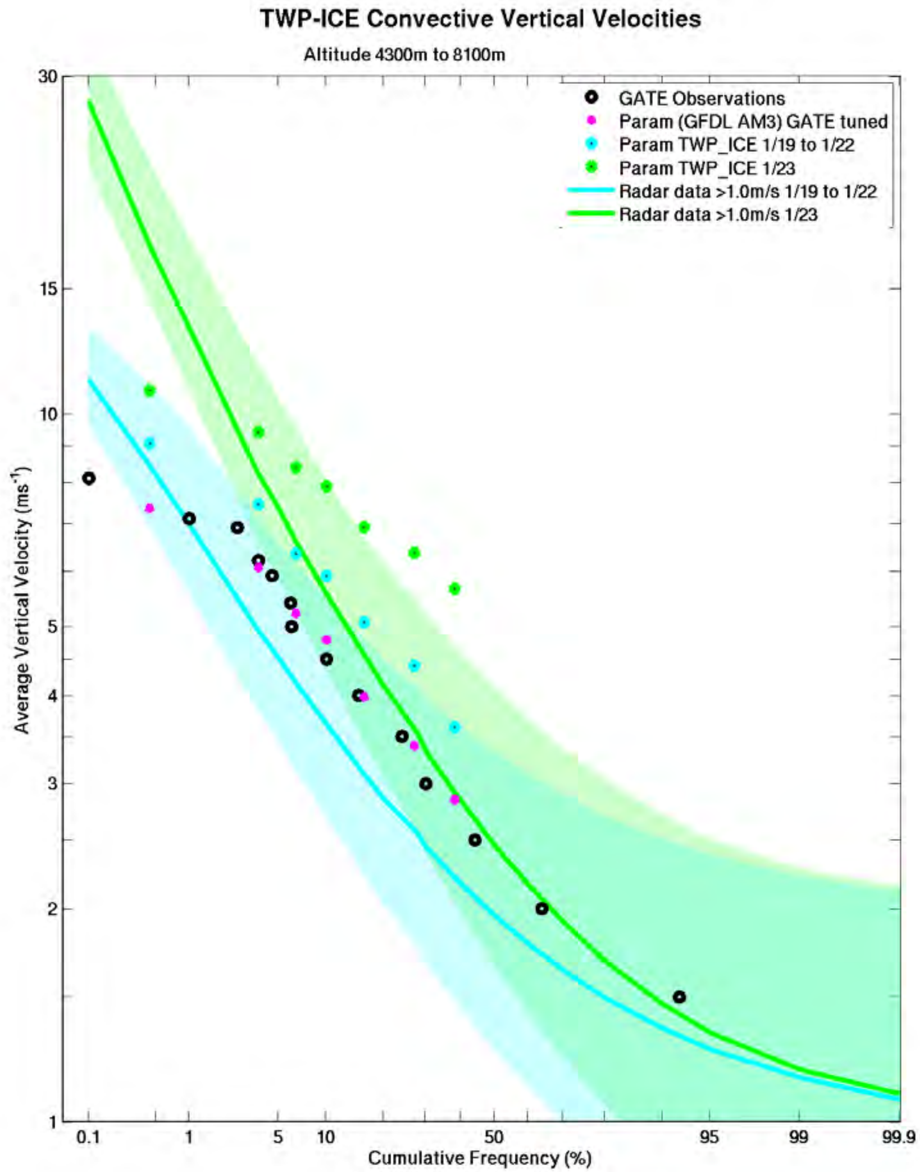
from Masunaga and Luo (2016, *JGR*)

# Conclusions

- 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 satellite observations and parameterizations offer prospects for this improved modeling.

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

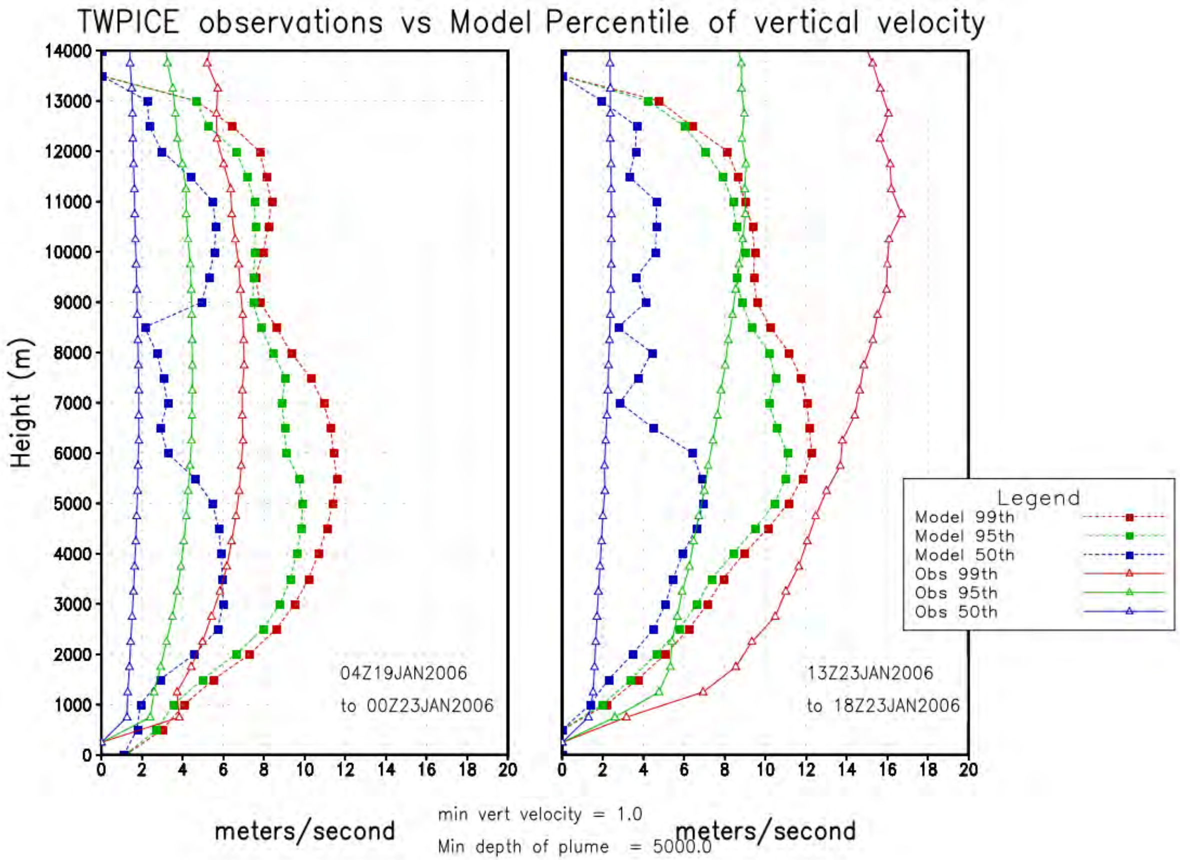



Shading shows ranges of radar observations with lower cut-off from 0.5 to 2.0 m $s^{-1}$ over 5-km layer. 95$^{th}$ percentile by extrapolating AM3 ensembles ~ 1 m $s^{-1}$ for GATE, 1.5 m $s^{-1}$ for TWP ICE 1/19-22, and 2.0 m $s^{-1}$ for TWP ICE 1.23.

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.*)

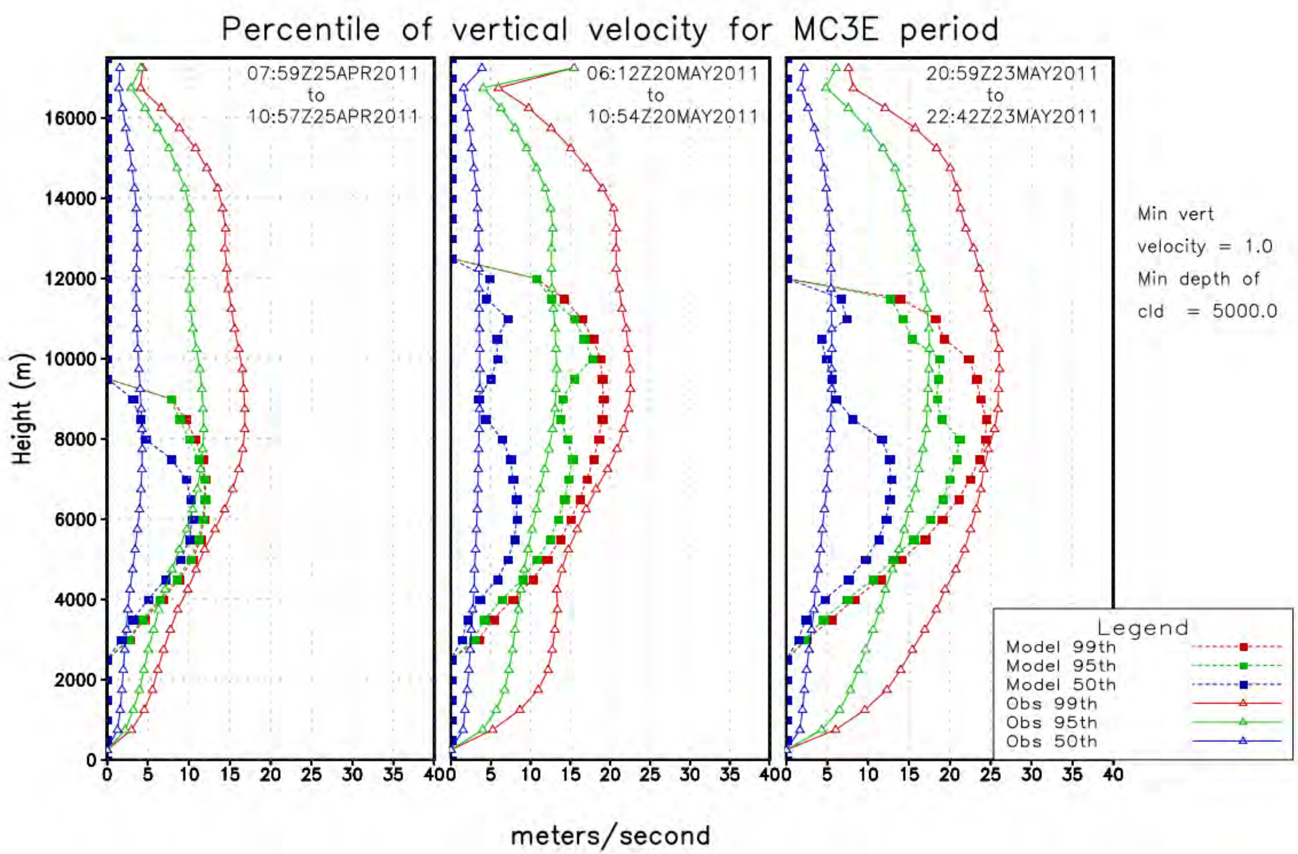
Analysis by Will Cooke, GFDL; GATE observations provided by Ian Glenn, U. Utah.

# 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

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

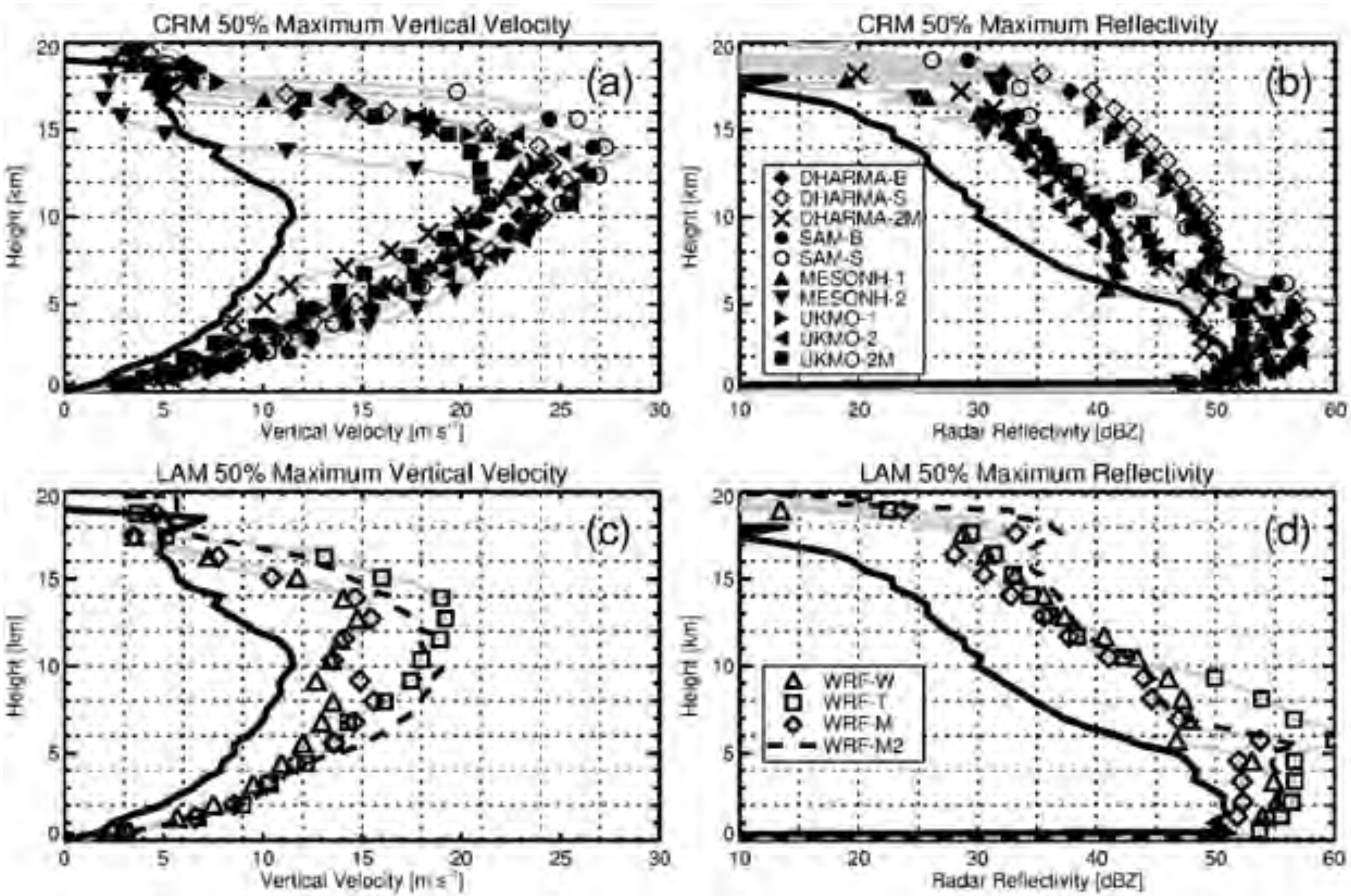
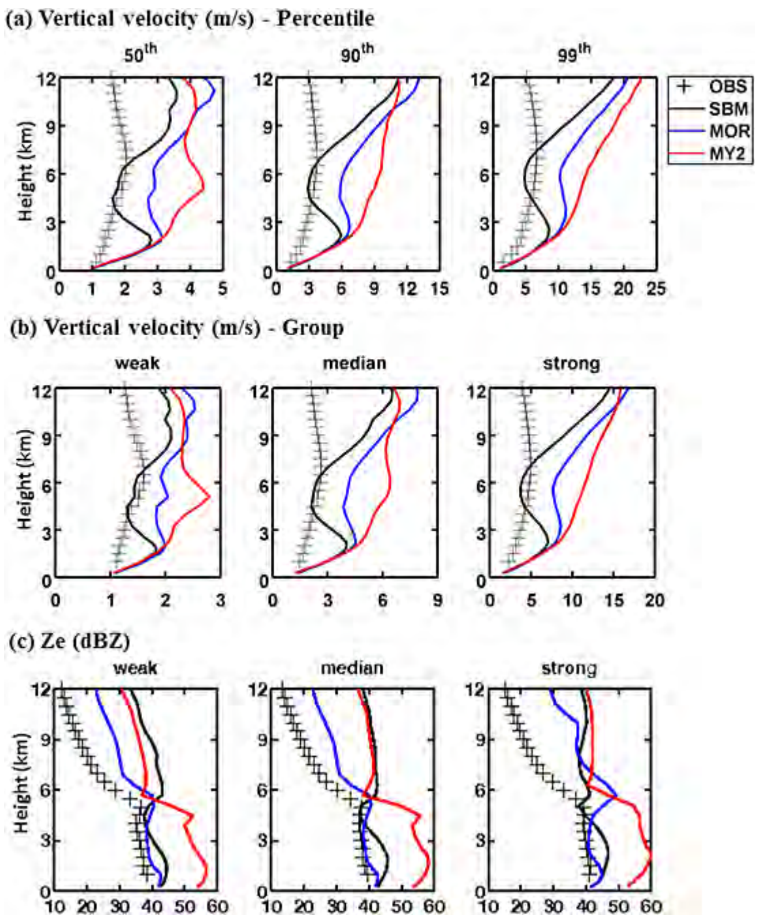



Figure 9: Median profiles of maximum vertical velocity (a,c) and radar reflectivity (b,d) for three-dimensionally defined convective updrafts beginning below 1 km and ending above 15 km for the period of 1310Z to 1750Z on 23 January 2006. CRM statistics are shown in (a-b) and LAM statistics are shown 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.*)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2014JD022142, 29 APR 2015 DOI: 10.1002/2014JD022142
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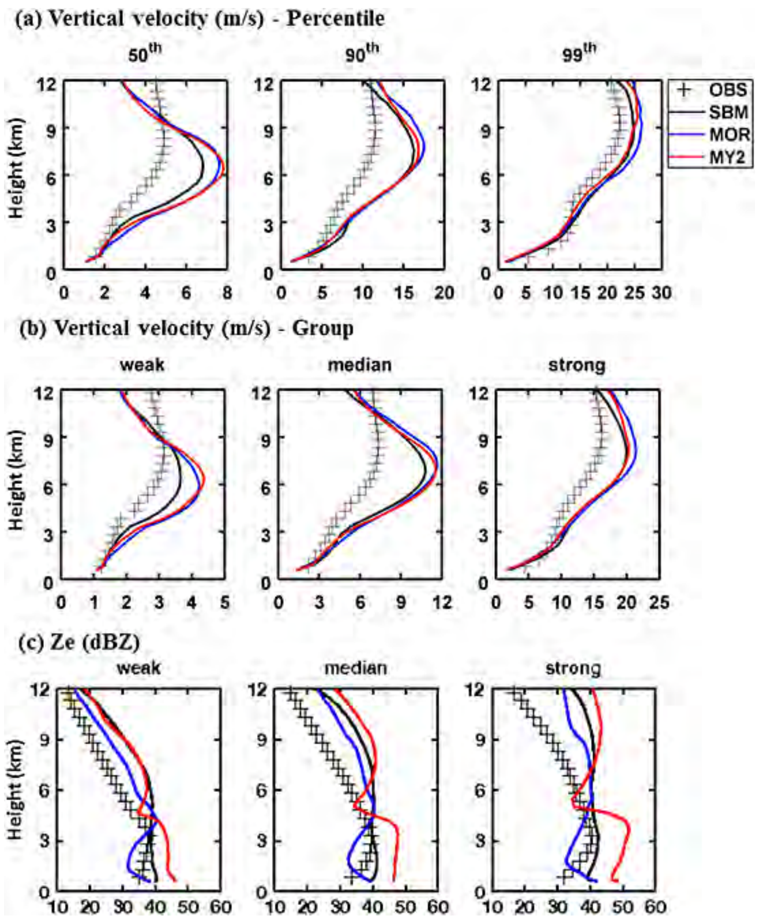


MC3E, 20 May 2011
SBM: spectral microphysics; MOR, MY2: bulk microphysics (from Fan *et al.*, 2015, *JGR-Atmos.*)

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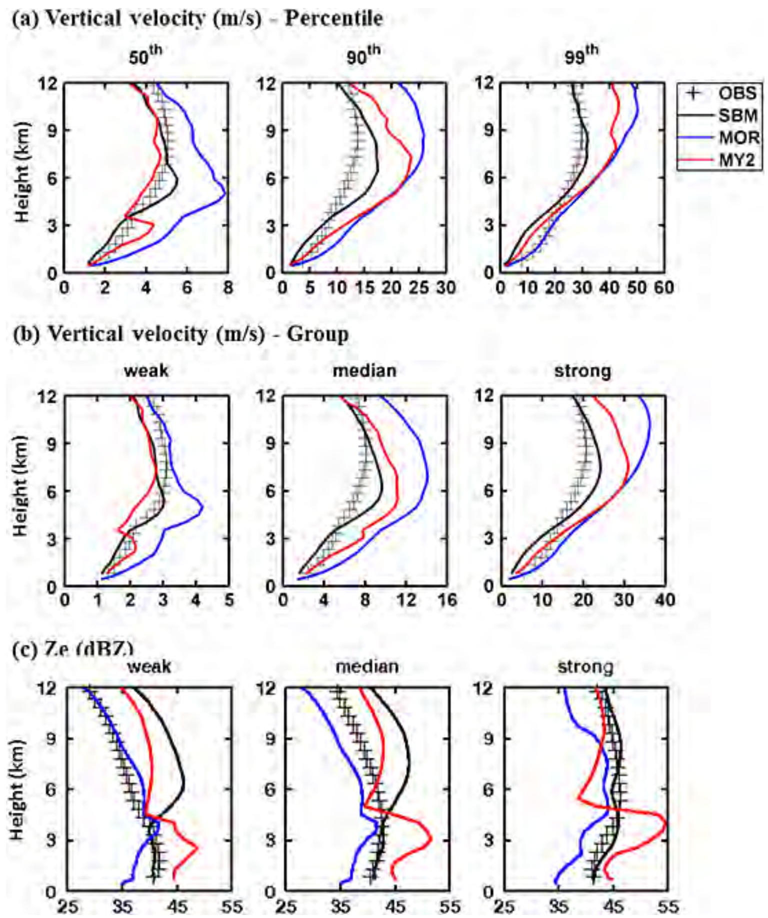


MC3E, 23 May 2011, SBM: spectral bin microphysics; MOR and MY2: bulk microphysics, from Fan *et al.* (2015, *JGR-Atmos.*)


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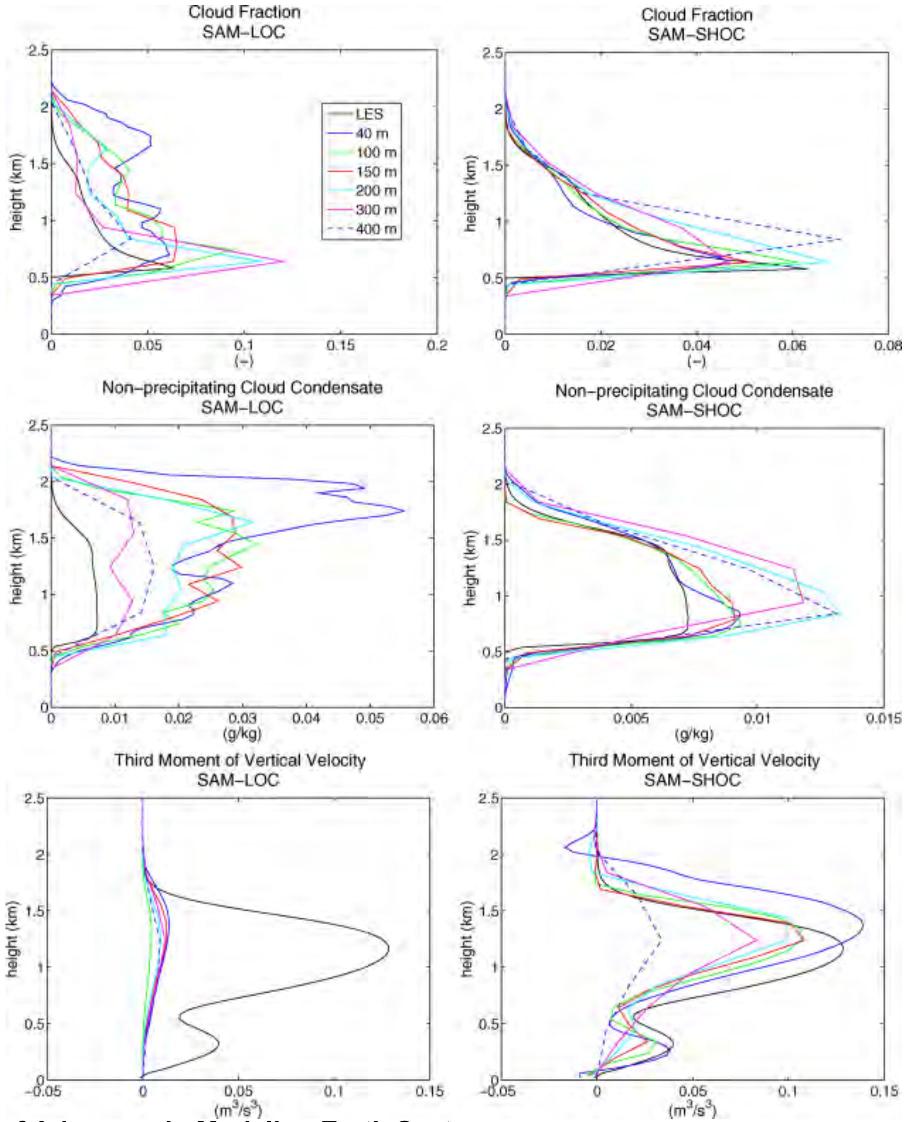
# A simplified PDF parameterization of subgrid-scale clouds and turbulence for cloud-resolving models (horizontal resolution 3.2 km)

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)