Cumulus Convection, Climate Sensitivity, and Heightened Imperatives for Physically Robust Cumulus Parameterizations in Climate Models

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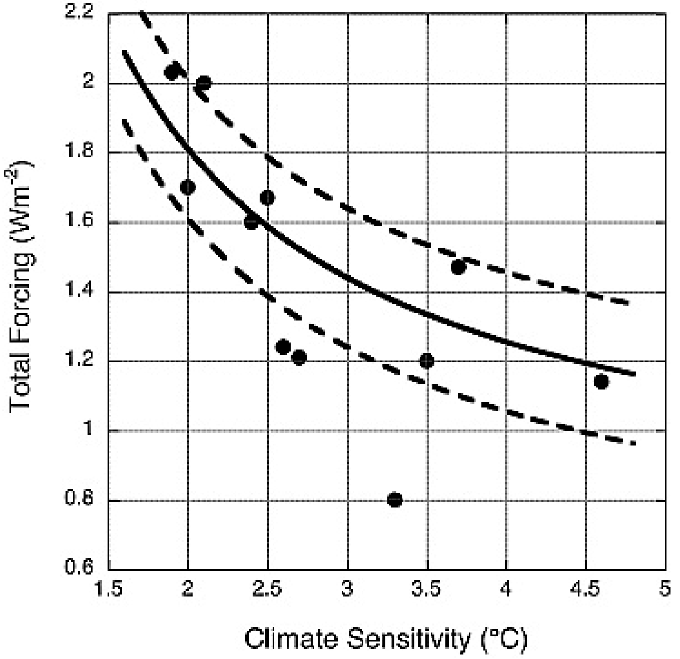
NCAR, 11 February 2014

Key Points

- In climate models with aerosol-cloud interactions, historical simulations depend strongly on model parameter choices, resolution, and emission specifications.
- Parameterized cumulus convection is a key factor determining model climate sensitivity.
- Knowledge of controls on forcing and sensitivity reduces utility of historical simulations as independent test of model realism.
- Increased physical robustness for cumulus and cloud parameterizations essential for reducing uncertainty and increasing model credibility.

In models with aerosol-cloud interactions, historical simulations depend strongly on parameter choices, model resolution, and emission specifications.

Twentieth century climate model response and climate sensitivity

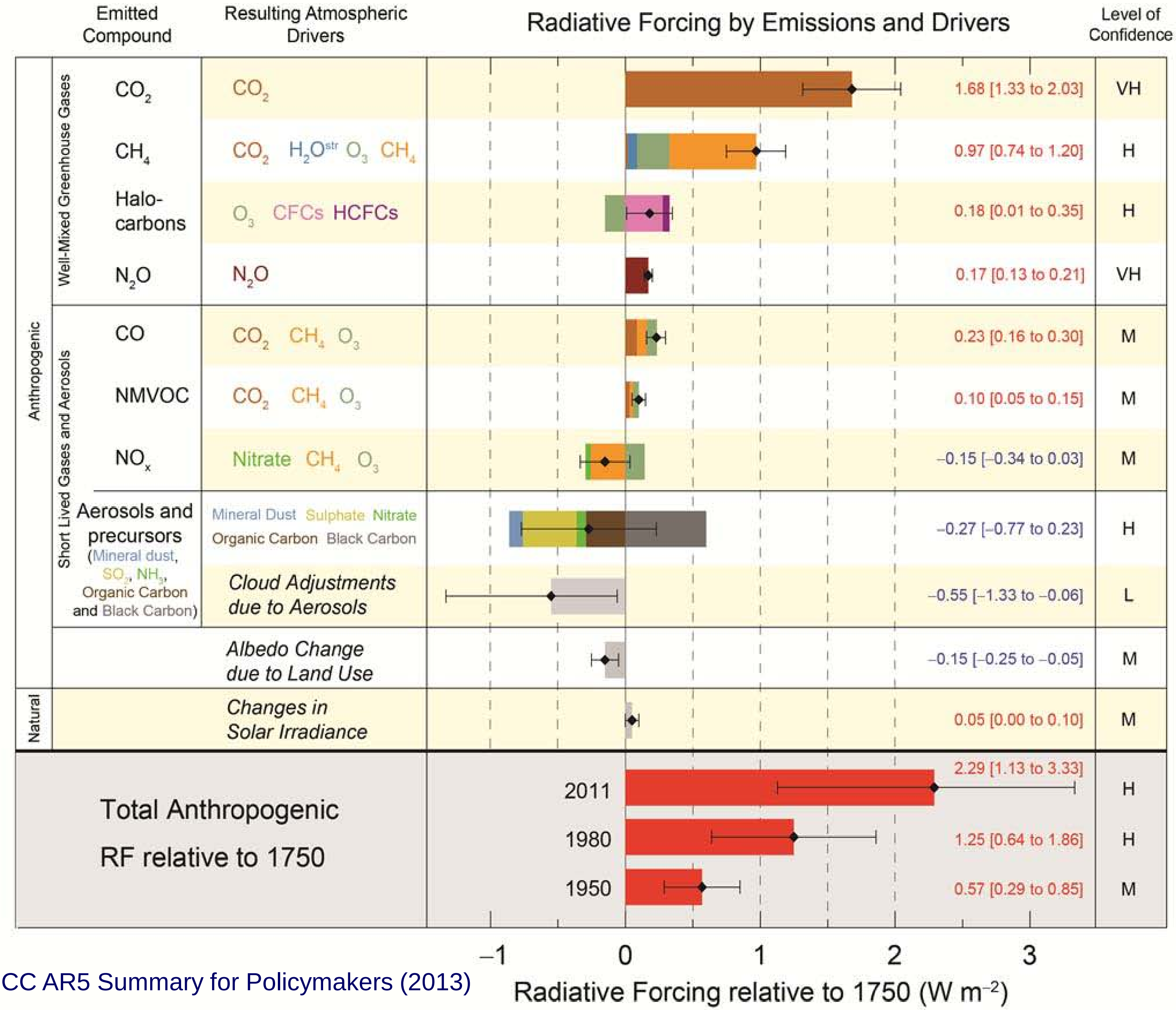


Kiehl (2007)

Most forcing uncertainty related to threefold range in aerosol forcing. For CMIP5 models, Forster *et al.* (2013, *J. Geophys. Res.*) find no significant relationship between “adjusted forcing” and equilibrium climate sensitivity.

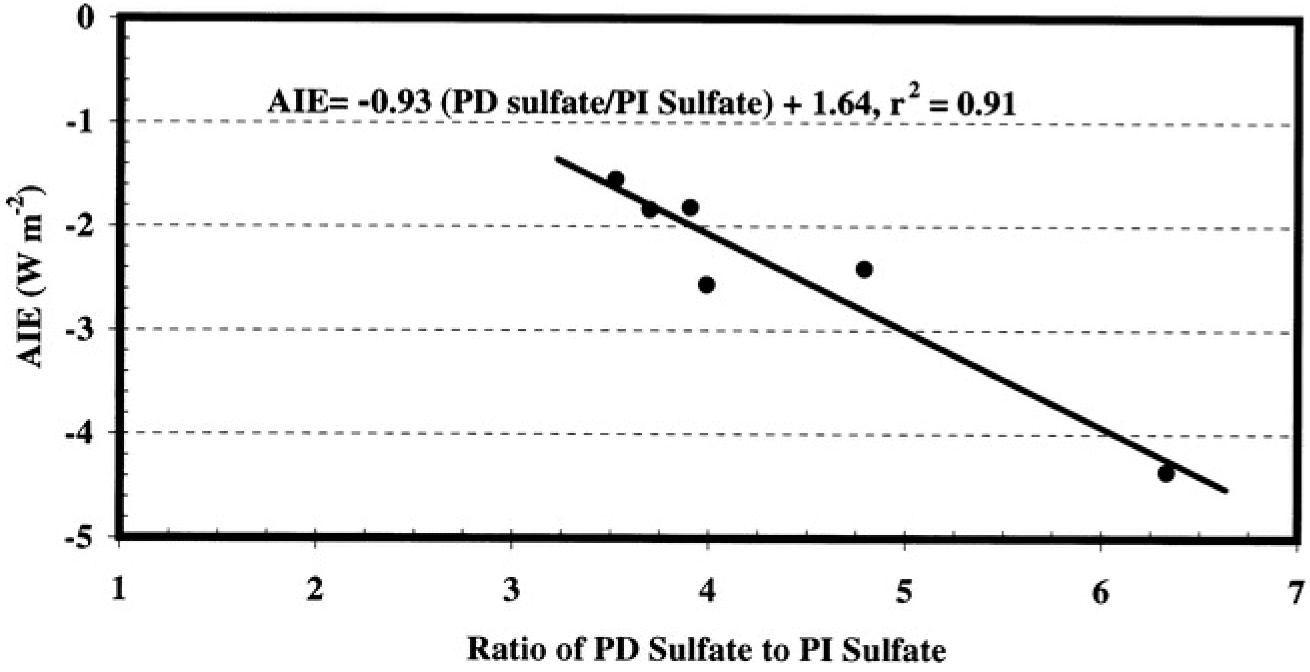
Geophysical Research Letters
Volume 34, Issue 22, L22710, 28 NOV 2007 DOI: 10.1029/2007GL031383
http://onlinelibrary.wiley.com/doi/10.1029/2007GL031383/full#grl23729-fig-0001

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)

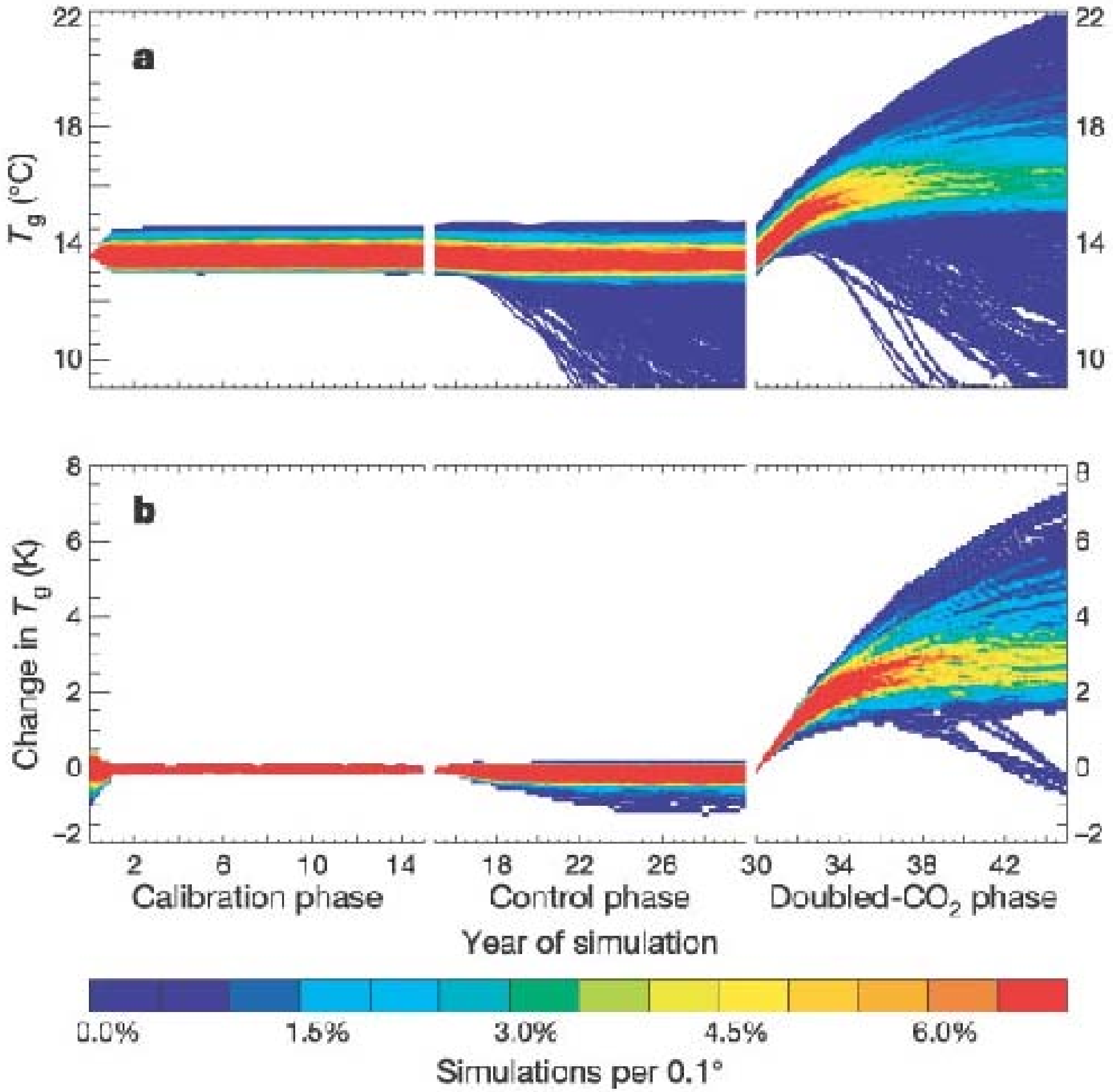
Emissions are major control on historical simulation through aerosol-cloud interactions.



from Menon *et al.* (2002, *J. Atmos. Sci.*)

Strong dependence of radiative forcing by anthropogenic aerosols also discussed by Carslaw *et al.* (2013, *Nature*).

Parameteric Control on Simulations without Cloud-Aerosol Interactions

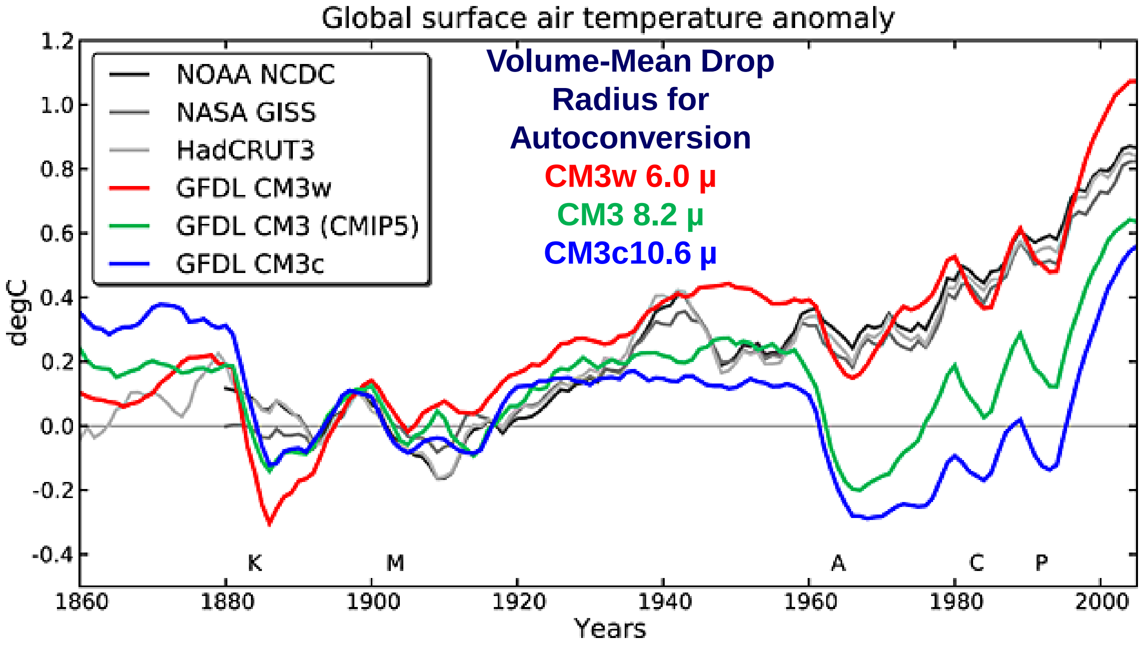


From Stainforth *et al*. (2005, *Nature*)

Parametric Control on Simulations with Aerosol-Cloud Interactions

Cloud tuning in a coupled climate model: Impact on 20th century warming

Aerosol Effective Forcing ranges from -2.3 W m^{-2} for CM3c to -1.0 W m^{-2} for CM3w.
Cess sensitivity ranges only from 0.65 to 0.67 K/(W m^{-2}).



Volume-Mean Drop Radius for Autoconversion
CM3w 6.0 μ
CM3 8.2 μ
CM3c10.6 μ

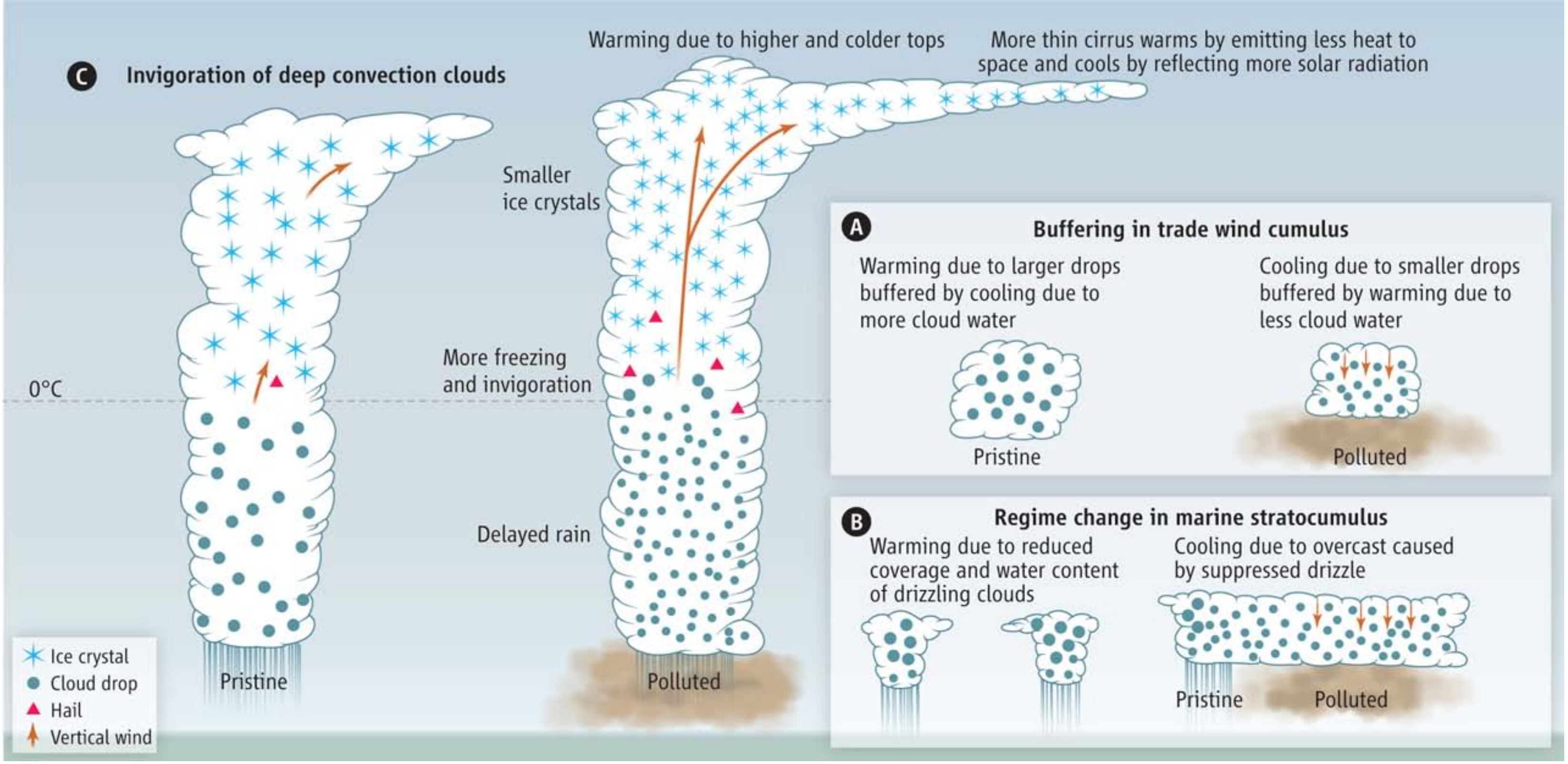
Models tuned for radiation balance using cloud erosion scales and width of SGS vertical velocity PDF.
Strong impact of autoconversion formulation also found by Rotstayn (2000, *J. Geophys. Res.*)

Geophysical Research Letters Golaz *et al.* (2013)
Volume 40, Issue 10, pages 2246-2251, 27 MAR 2013 DOI: 10.1002/grl.50232
http://onlinelibrary.wiley.com/doi/10.1002/grl.50232/full#grl50232-fig-0003

Credible Parameter Choices: VMDR for Precipitation

- Golaz et al. (2013, *GRL*) show choice of VMDR impacts 20th century simulation: 6.0µm yields fairly realistic warming; 10.6µm no warming until after 1990
- CM3 used 8.2µm
- Field experiments show VMDR for precipitation initiation 10-12µm: Gerber (1996, *JAS*), Boers et al. (1998, *QJRMS*), Pawlowska and Brengueir (2003, *JGR*), and Turner (2012, *GMD*)
- CloudSat radiances show VMDR for precipitation 10-15µm (Suzuki et al., 2013, *GRL*)

How aerosols affect the radiative properties of clouds.By nucleating a larger number of smaller cloud drops, aerosols affect cloud radiative forcing in various ways.

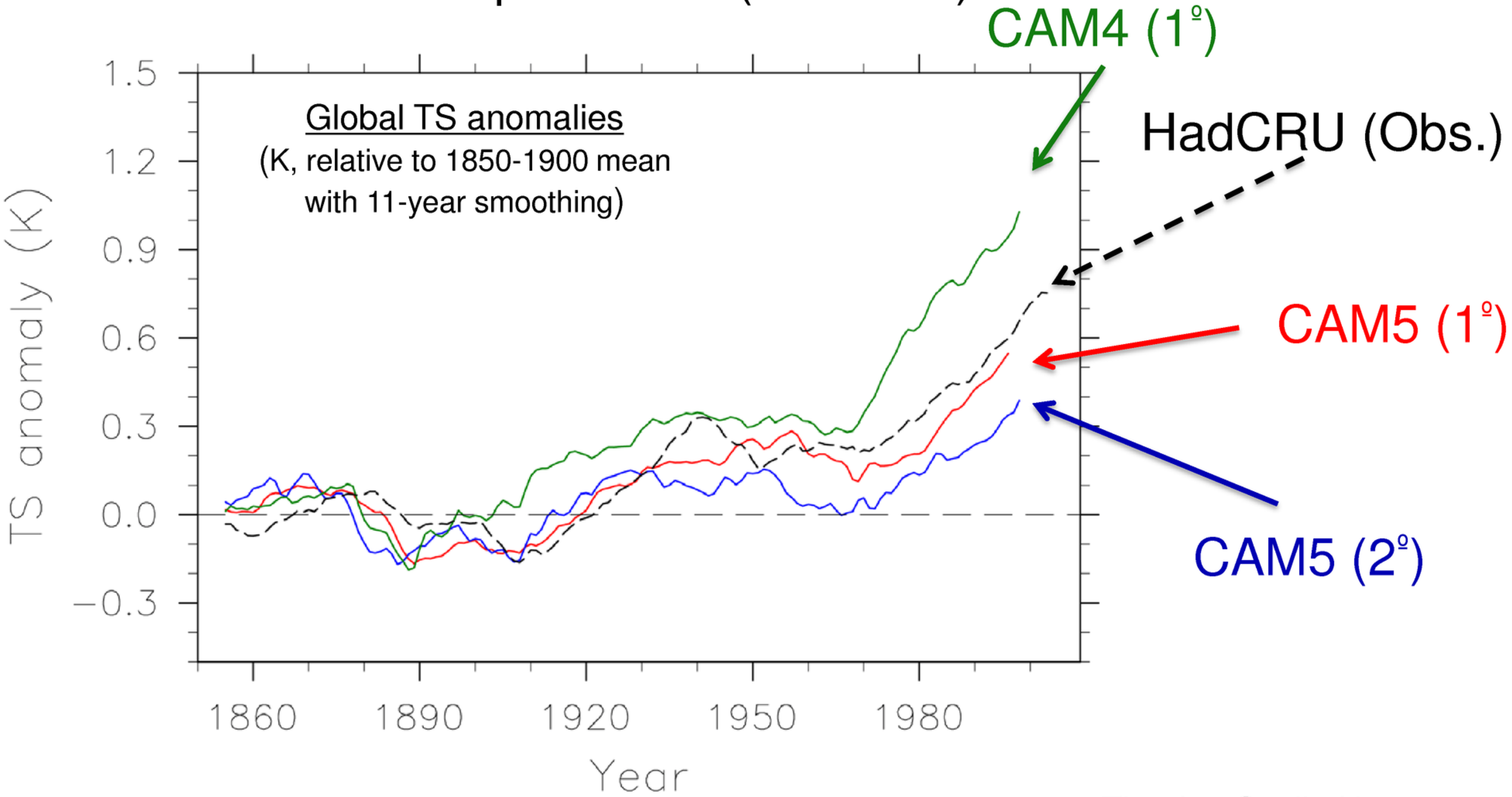


D Rosenfeld et al. Science 2014;343:379-380

Published by AAAS

Dependence of Historical Simulations on Resolution

20th Century Coupled Experiments (1° ocean)



Global TS anomalies

(K, relative to 1850-1900 mean with 11-year smoothing)

CAM4 (1°)

HadCRU (Obs.)

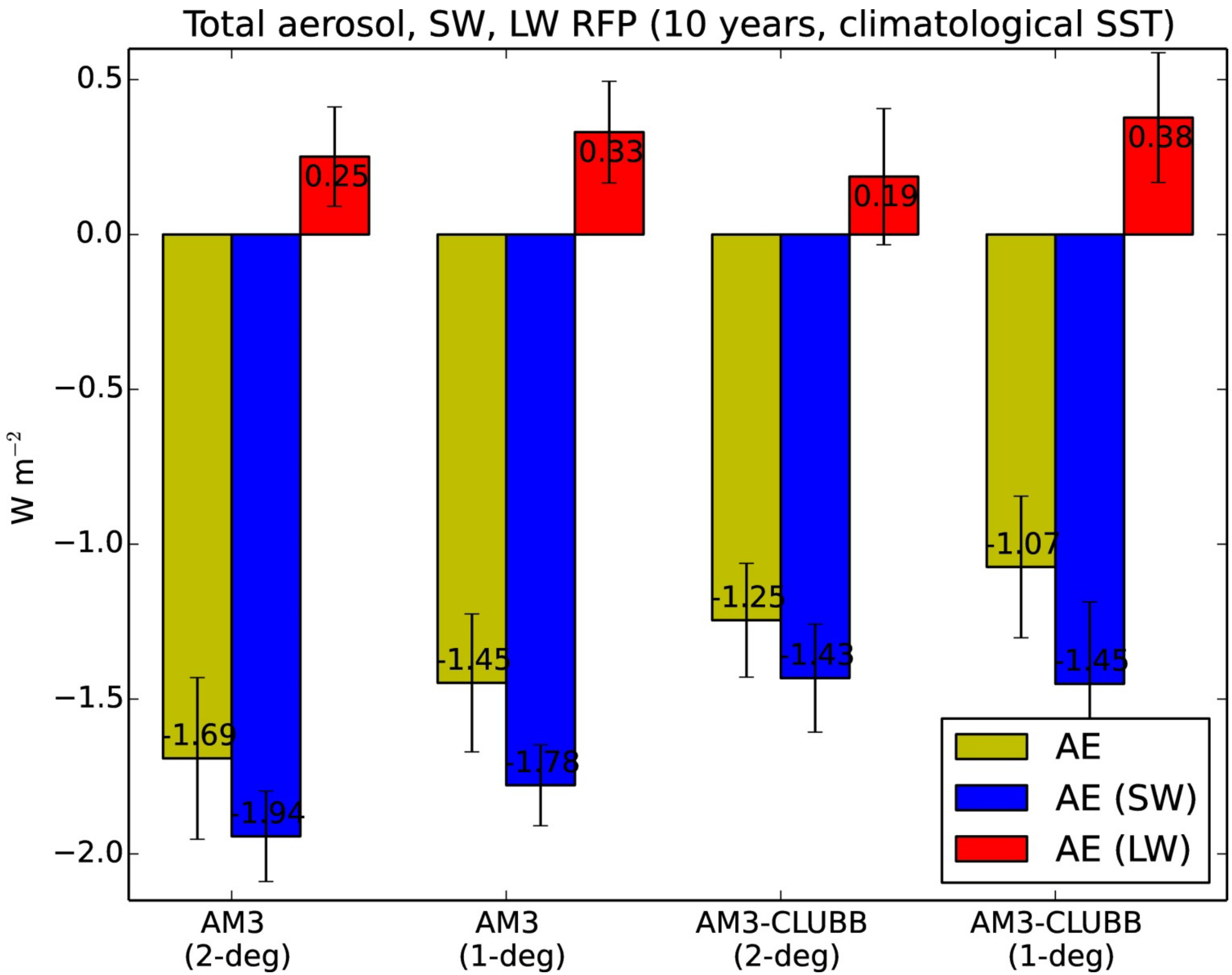
CAM5 (1°)

CAM5 (2°)

Thanks: Cecile Hannay

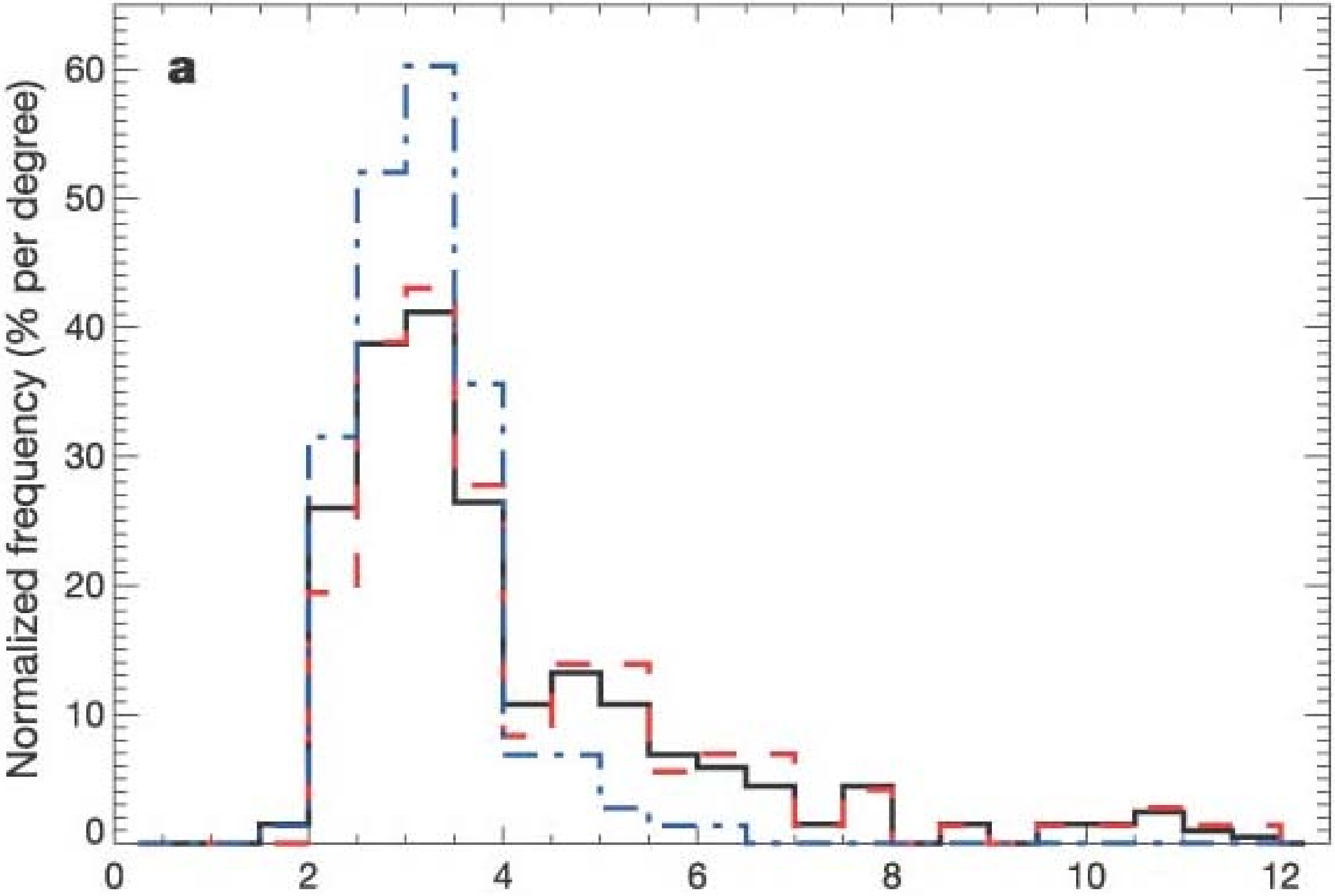
from Rich Neale, AMWG, Feb 2011

Dependence of Aerosol Forcing on Resolution



from Huan Guo, GFDL

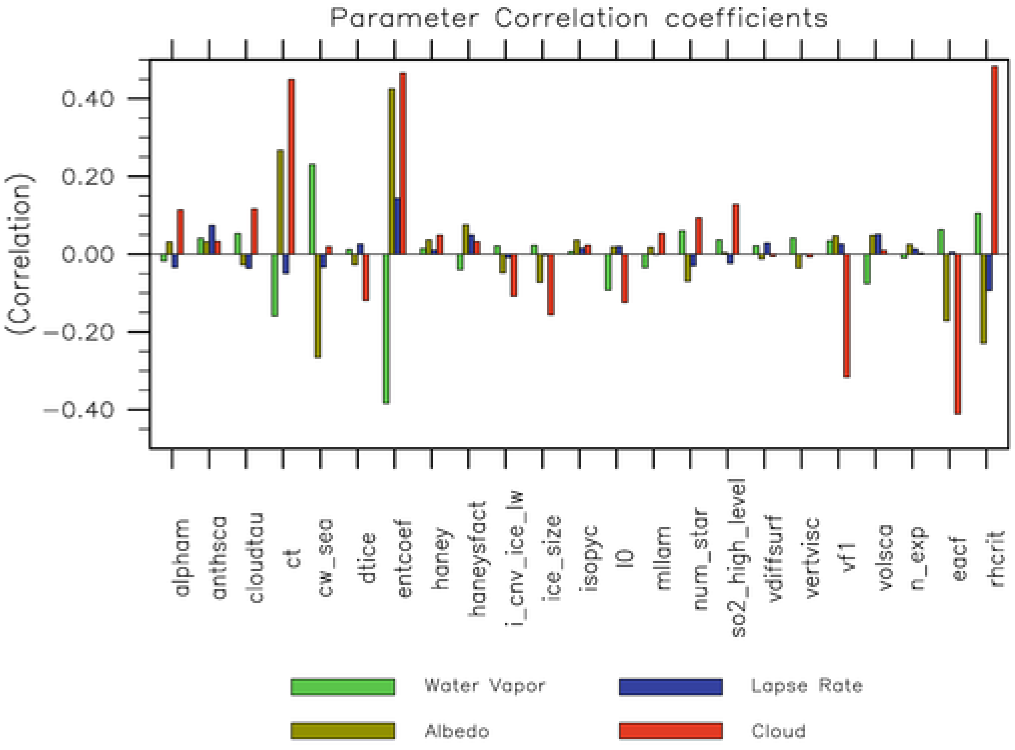
Parameterized cumulus convection is a key factor determining model climate sensitivity.



Global-mean temperature increase due to CO_2 doubling

from Stainforth *et al*. (2005, *Nature*) Blue: No Entrainment Variation
Red: No Autoconversion Variation

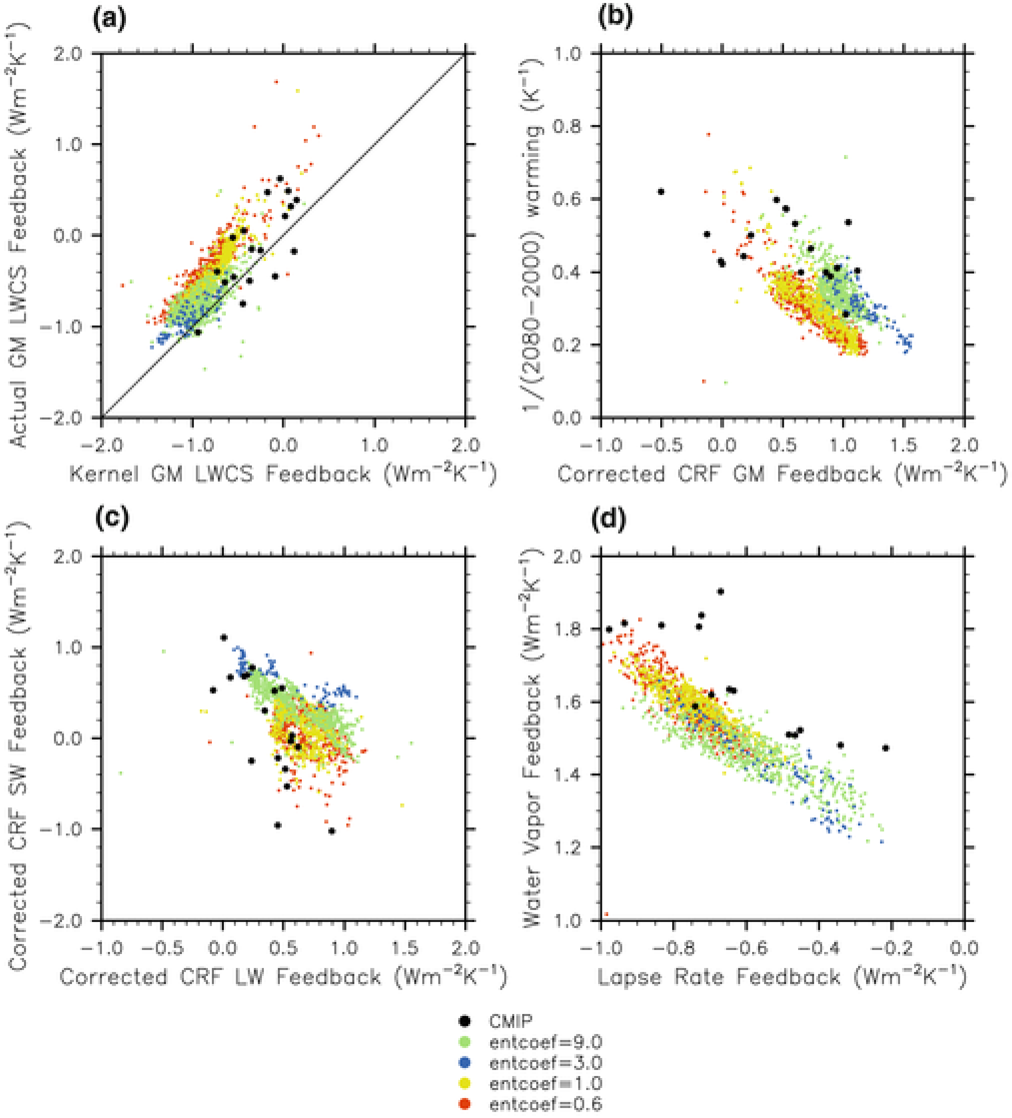
Fig. 5 Correlation coefficients between perturbed parameter values in climate*prediction*.net and various kernel-derived global mean feedbacks



Springer

Source: Sanderson et al. (2010, Climate Dynamics, pp. 1219-1236)

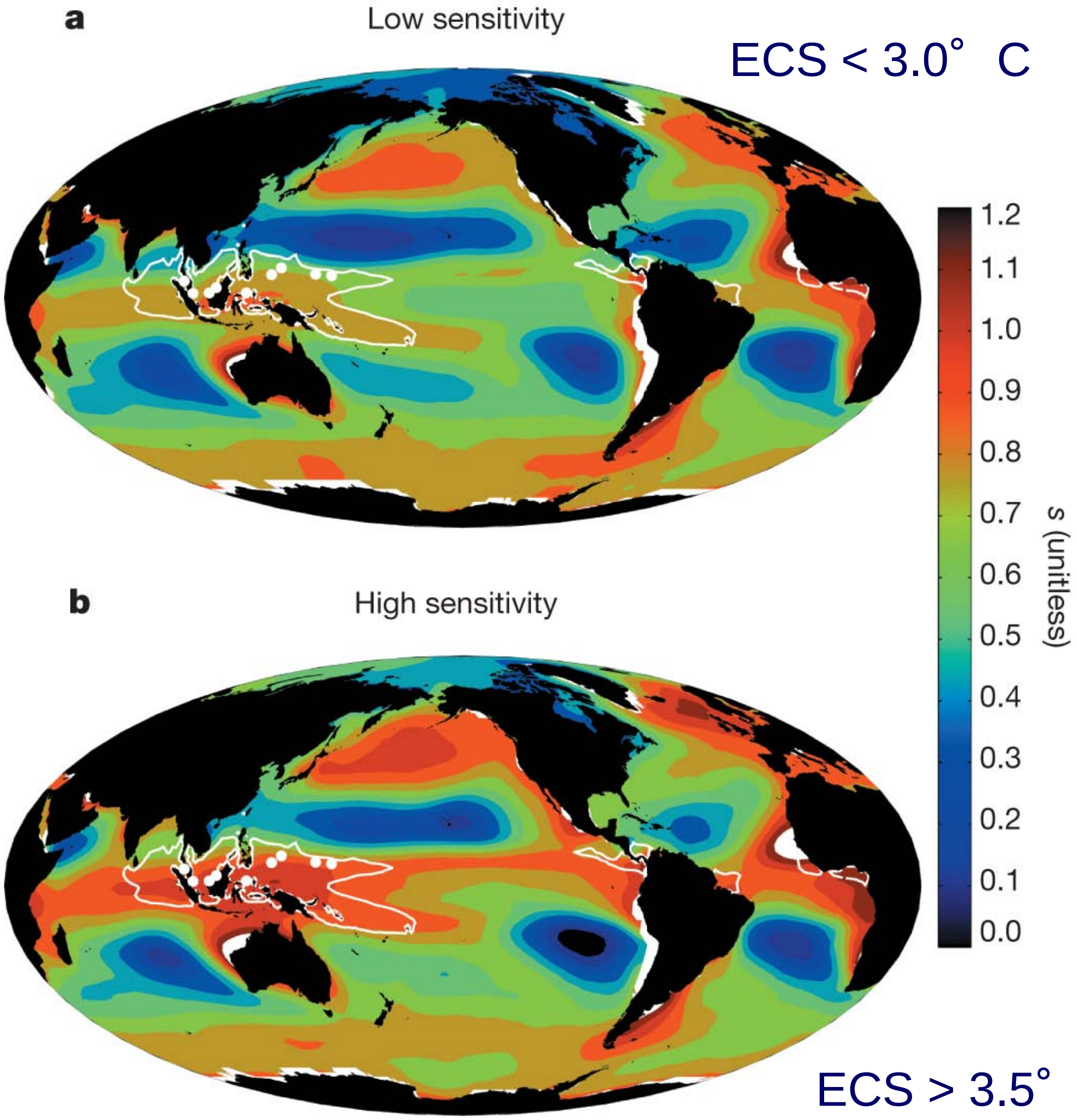
Fig. 3 Scatter plots showing the relationship between various global mean feedback quantities in both climate*prediction*.net and the CMIP-3 ensemble. *Black points* represent members of the CMIP-3 ensemble, while *colored points* are members of the climate*prediction*.net ensemble. Coloring is indicative of the value of the 'Entrainment Coefficient' parameter in the climate*prediction*.net parameter sampling scheme. 'GM' refers to global mean values, while 'CRF' refers to cloud radiative forcing



Springer

Source: Sanderson et al. (2010, Climate Dynamics, pp. 1219-1236)

Multi-model mean local stratification parameter



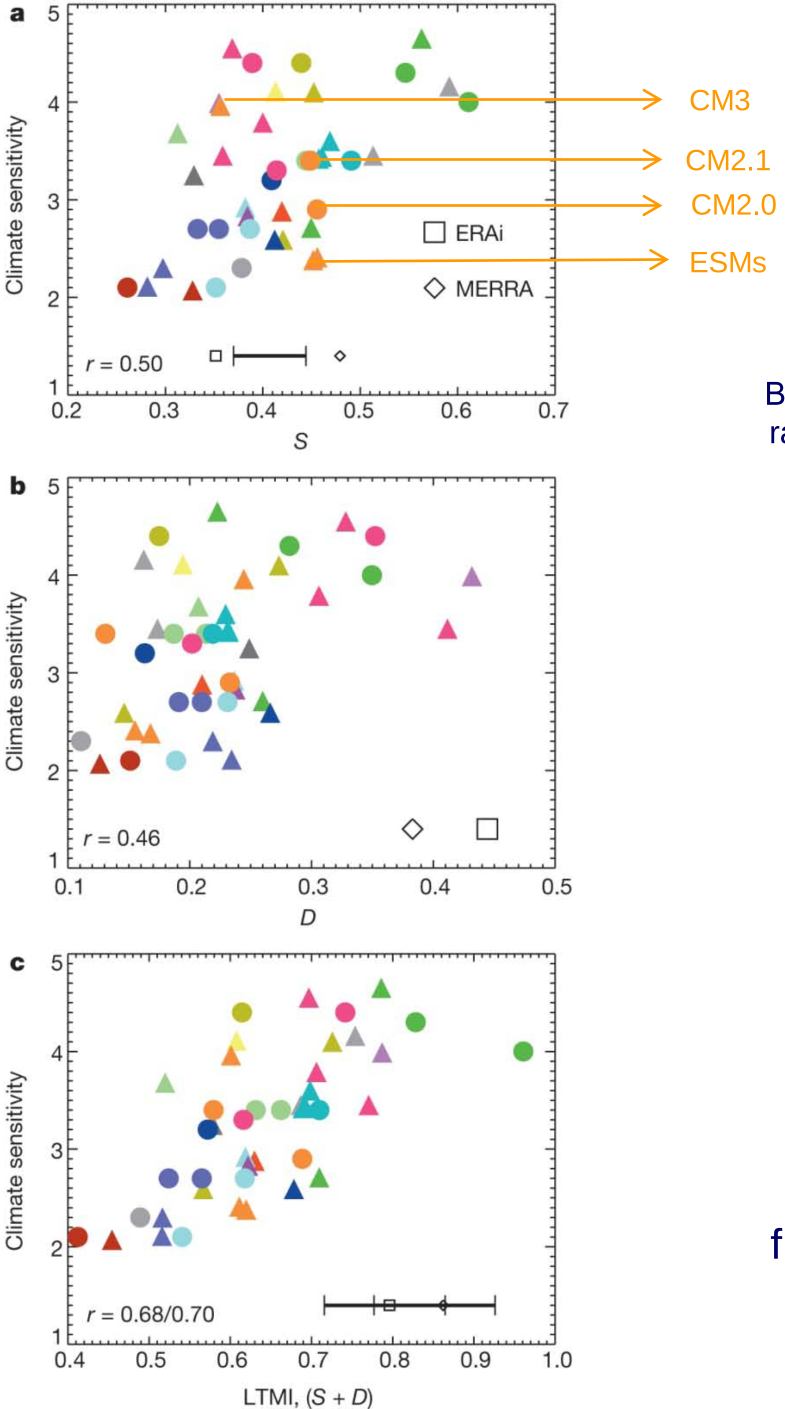
ECS < 3.0° C

ECS > 3.5° C

Global stratification parameter *S* defined within white contours. Radiosondes at white squares.

from Sherwood *et al.* (2014, *Nature*)

Relation of lower-tropospheric mixing indices to ECS

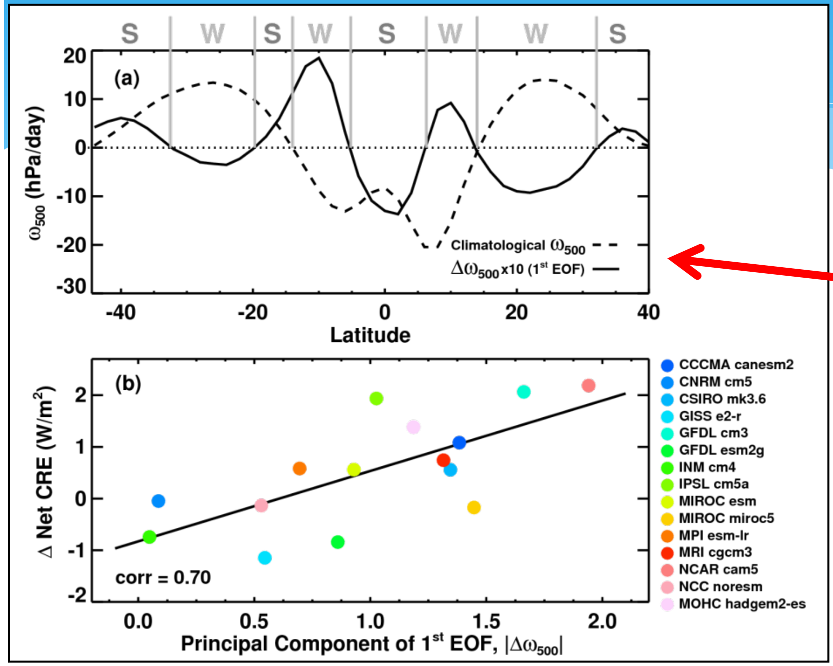


Bar indicates 2σ range of radiosonde observations

LTMI explains about 50% of ECS variance

from Sherwood *et al.* (2014, *Nature*)

Quantifying the Model Differences in Circulation and Relation with Cloud Radiative Effect Changes

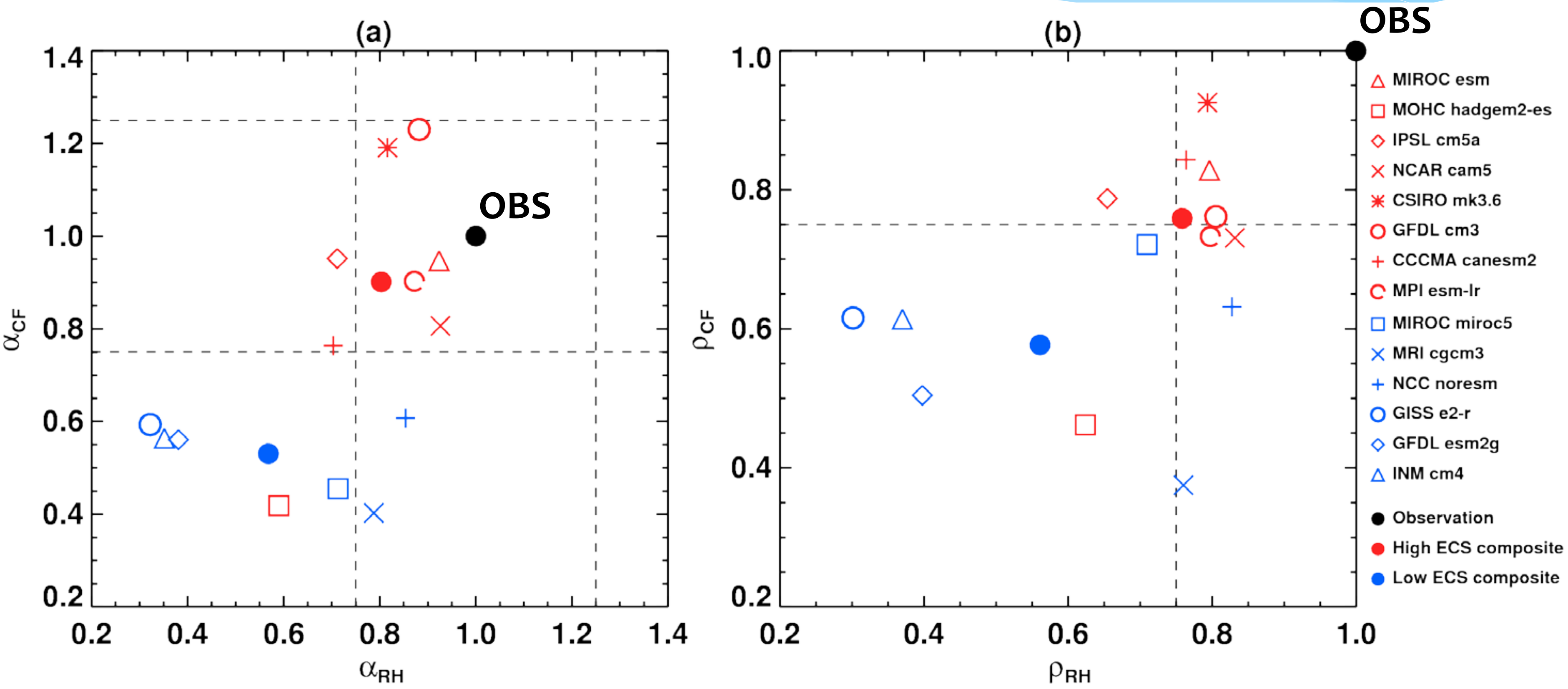


The explained variance by the 1st EOF is **57%**

- **Area-weighted CRE changes for the weakening and strengthening segments account for 54% and 46% of the total CRE change within the HC.**
- **The amplitudes of the 1st EOF mode differ by two orders of magnitude in models.**
- **Model differences in the HC change explains ~50% of model spread in CRE change.**

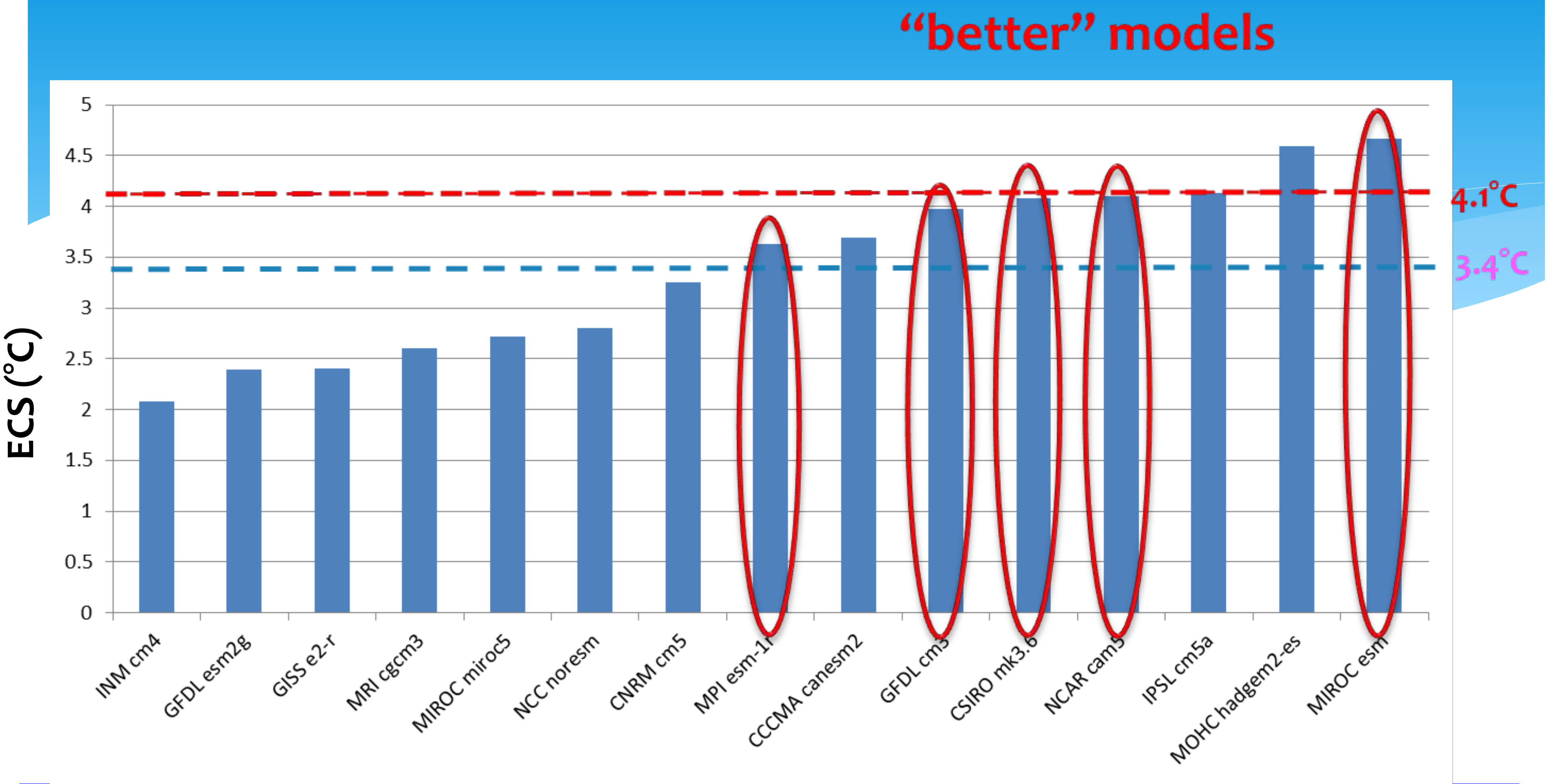
cf., Su *et al.* (2014, in review)

Quantitative Model Performance Metrics to Represent the Hadley Circulation Structure



cf., Su *et al.* (2014, in review)

Satellite-based “Best Estimates” of ECS



The best estimates of ECS range from 3.6 to 4.7°C, with a mean of **4.1**°C and a standard deviation of **0.4**°C, compared to the multi-model-mean of **3.4**°C and a standard deviation of **0.9**°C.

cf., Su *et al.* (2014, in review)

Implications of “Convective Controls” on Climate Sensitivity

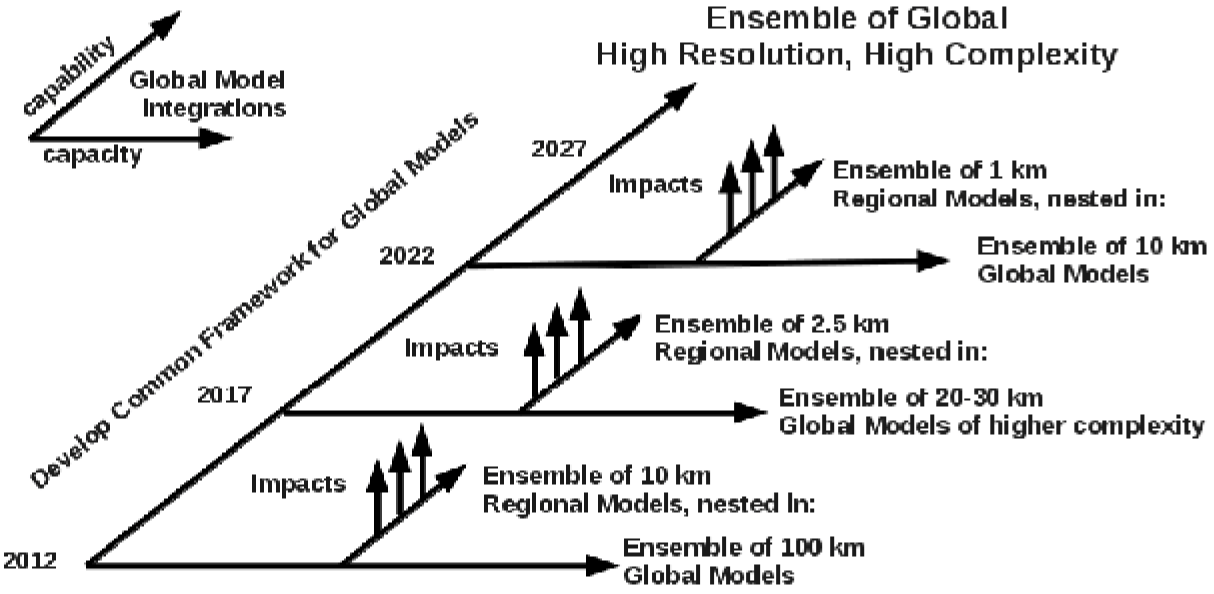
- If 20th-century trends optimized, physical robustness of model components determining trend essential.
- Stainforth et al. (2005, *Nature*) and Sanderson et al. (2010, *Clim. Dyn.*), and Zhao (2013, *JCL*) have found entrainment coefficient in deep convection to be major control on climate sensitivity => Especially important cumulus parameterization be validated outside climate model.
- GFDL AM3 cumulus parameterizations extensively tested outside AM3: Deep vertical velocities and vertical structures for heating and drying in Donner (1993, *JAS*), closures in Donner and Phillips (2003, *JGR*), forecast mode in Lin et al. (2012, *JGR*). Shallow using BOMEX observations and LES by Bretherton et al. (2004, *MWR*)
- Important to evaluate physical robustness of cumulus parameterizations outside of GCM environment

Recent Developments and Opportunities in Cumulus Parameterization (Holloway *et al.*, *Atmos. Sci. Lett.*, 2014, submitted)

To What Extent Can Improved Resolution Supplant Cumulus Parameterization over the Next 5-10 Years in Climate Models?

Infrastructure Strategy Roadmap

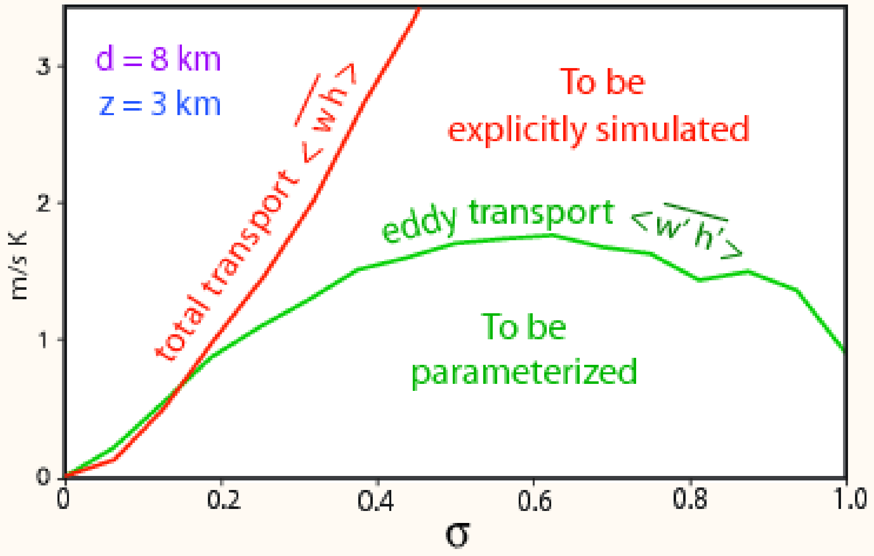
A grand Challenge :
towards 1 km scale
global climate model



from *Infrastructure Strategy for the European Earth System Modelling Community 2012-2022*

Horizontal resolutions in GCMs for climate simulation are moving toward deep convective scales (*e.g.,* Noda *et al.,*2012, *J. Clim.,* 7 km). At what resolutions is physically sound NOT to parameterize deep convection?

DIAGNOSED VERTICAL TRANSPORT OF MOIST STATIC ENERGY



Fractional area covered by updrafts

– a measure of cloud population in the grid cell –

h : Deviation of moist static energy from a reference state

$\overline{(\ )}$: Average over all CRM grid points in the sub-domain

< > : Ensemble average over cloud-containing (σ > 0) sub-domains during the analysis period (12 hr)

$(\ )' : (\ ) - \overline{(\ )}$

Parameterization must not overdo its job

so that explicitly-simulated transport is not over-stabilized .

from Akio Arakawa, UCLA

Convective Organization and Cumulus Parameterizations on Single Grid Columns: Mesoscale Structures, Vertical Velocities, and Entrainment

Observational View of Convective Organization (Leary and Houze, 1980)

JOURNAL OF THE ATMOSPHERIC SCIENCES

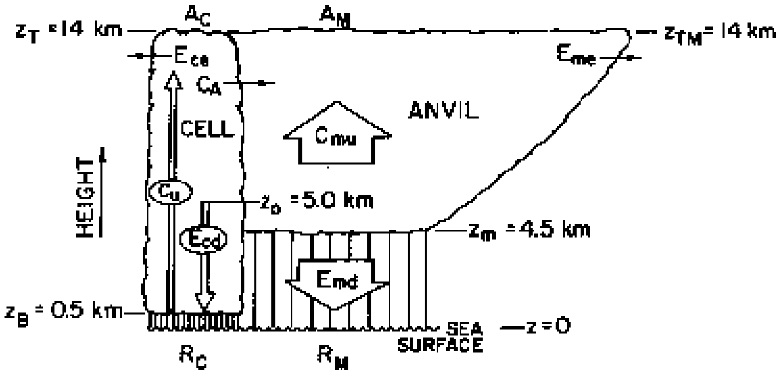
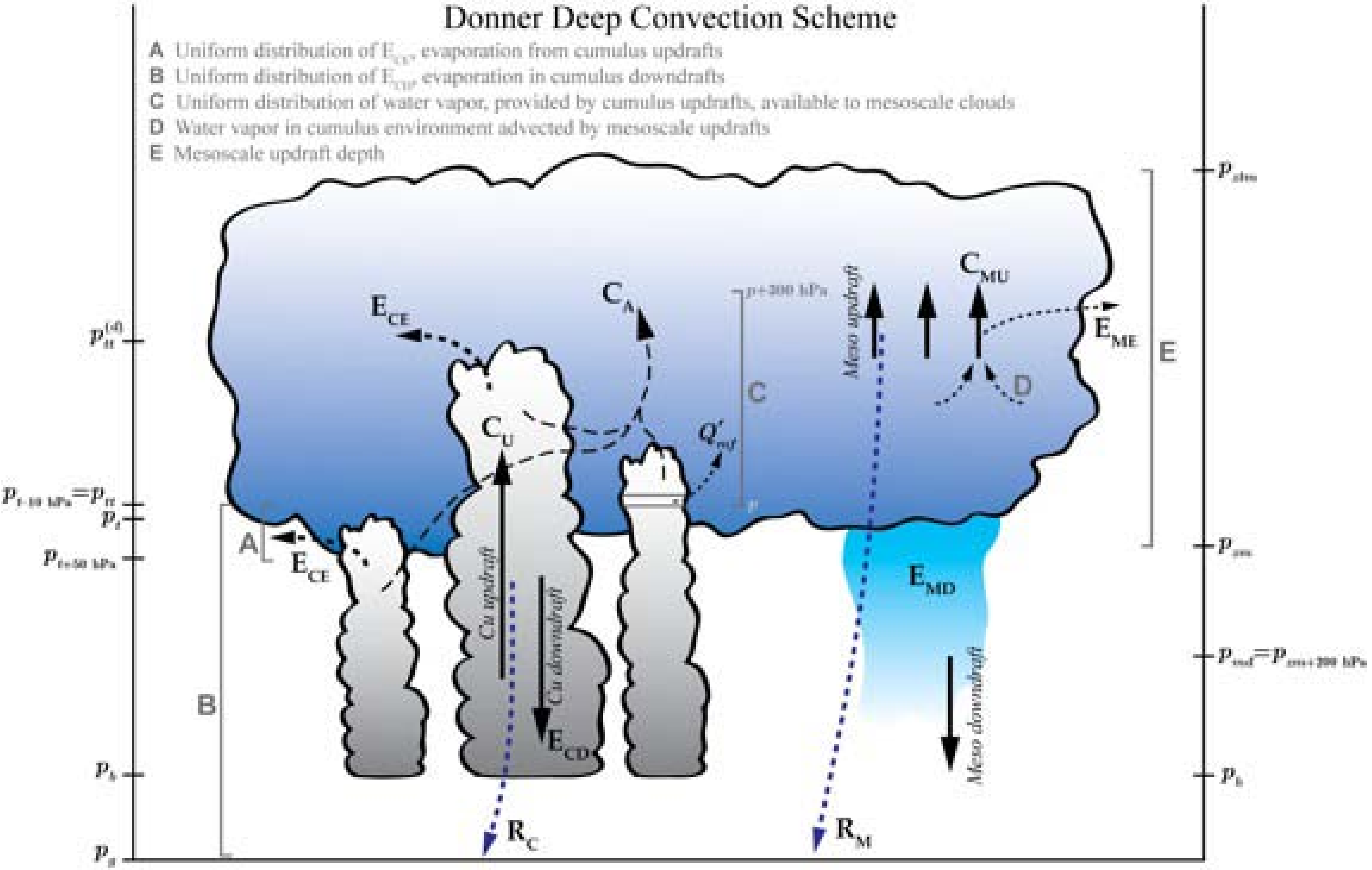
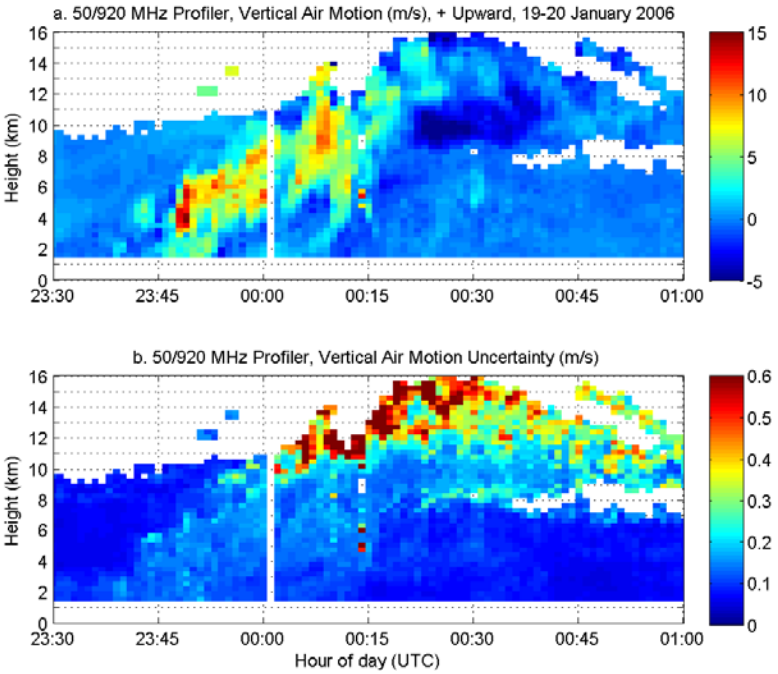


FIG. 2. Schematic vertical cross section of the idealized mesoscale system showing sources and sinks of condensed water. Symbols are defined in Section 2 of the text.



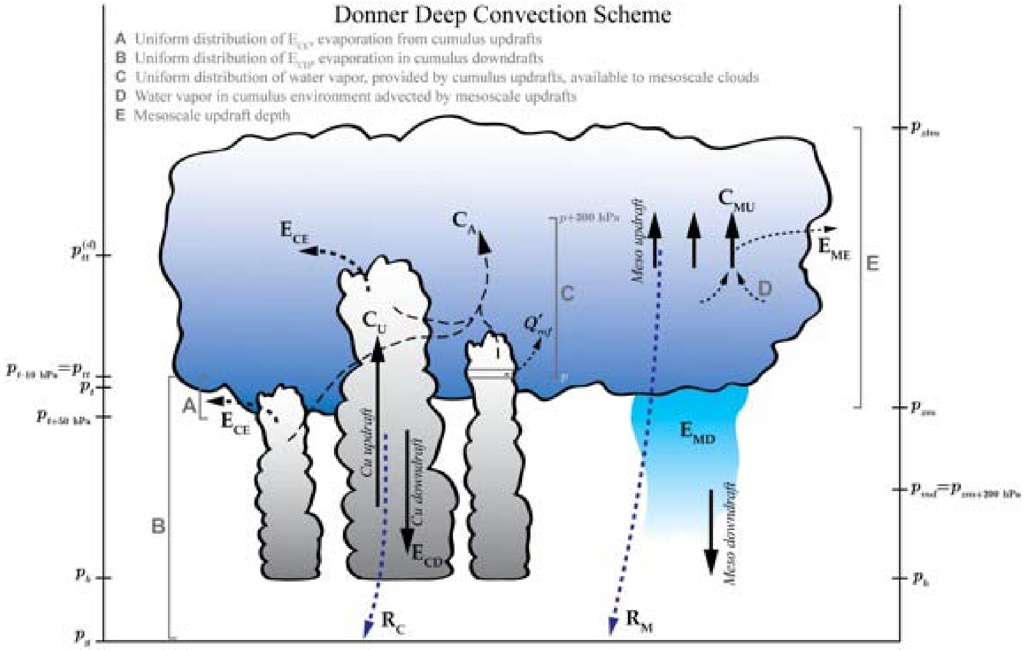
from Benedict *et al.* (2013, *J. Climate*)



fom Collis *et al.* (2013, *J. Appl. Meteor. Climatol.*)

Convective vertical velocities from radar show general structural agreement with AM3 deep convection parameterization (multiple deep updrafts with large vertical velocities, mesoscale updraft with lower vertical velocities, mesoscale downdraft).

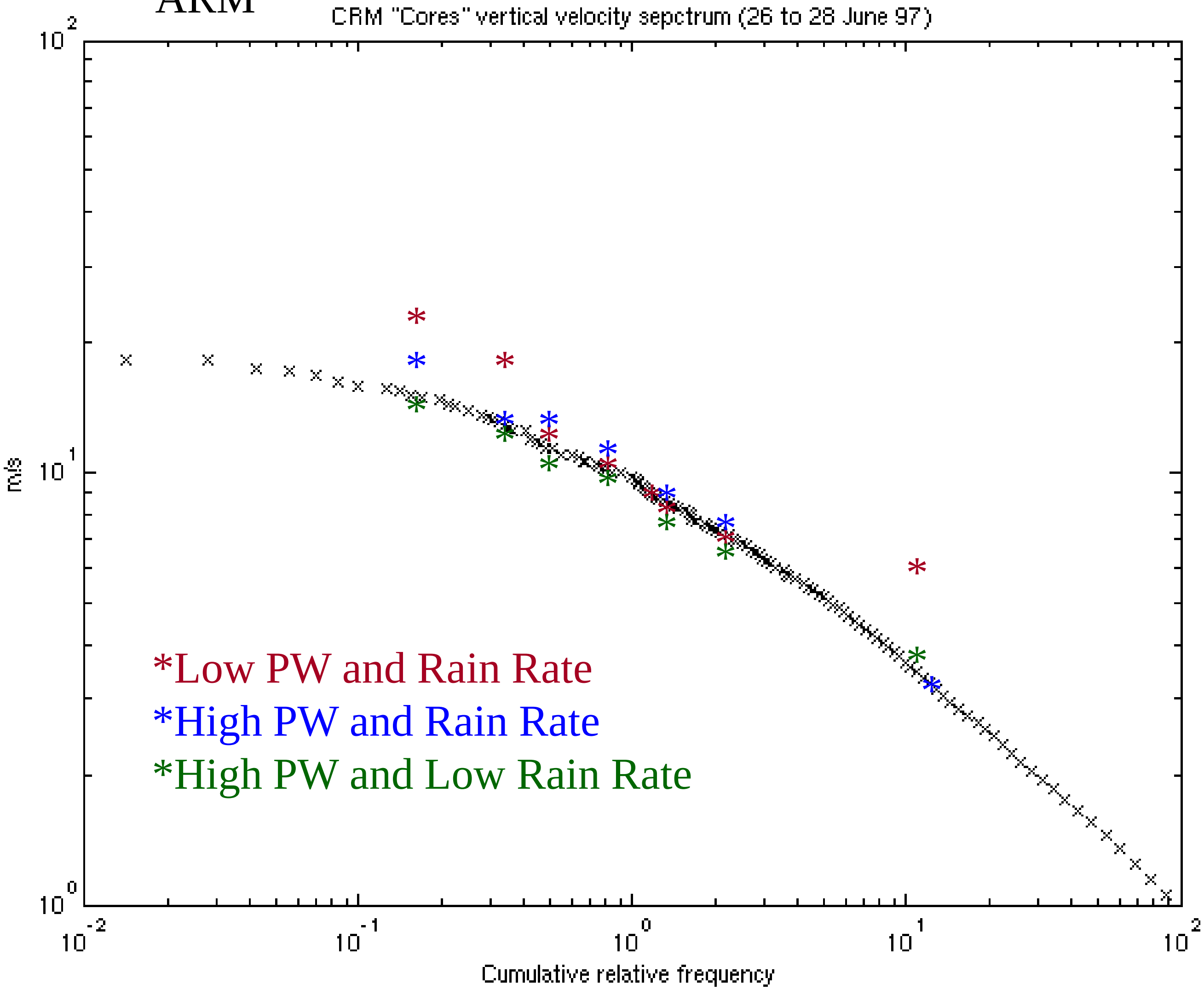
Quantitative assessment of parameterized vertical velocity PDFs using radar observations is an urgent priority.



from Benedict *et al.* (2013, *J. Climate*)

CRM results provide independent evaluation of entrainment PDF

ARM



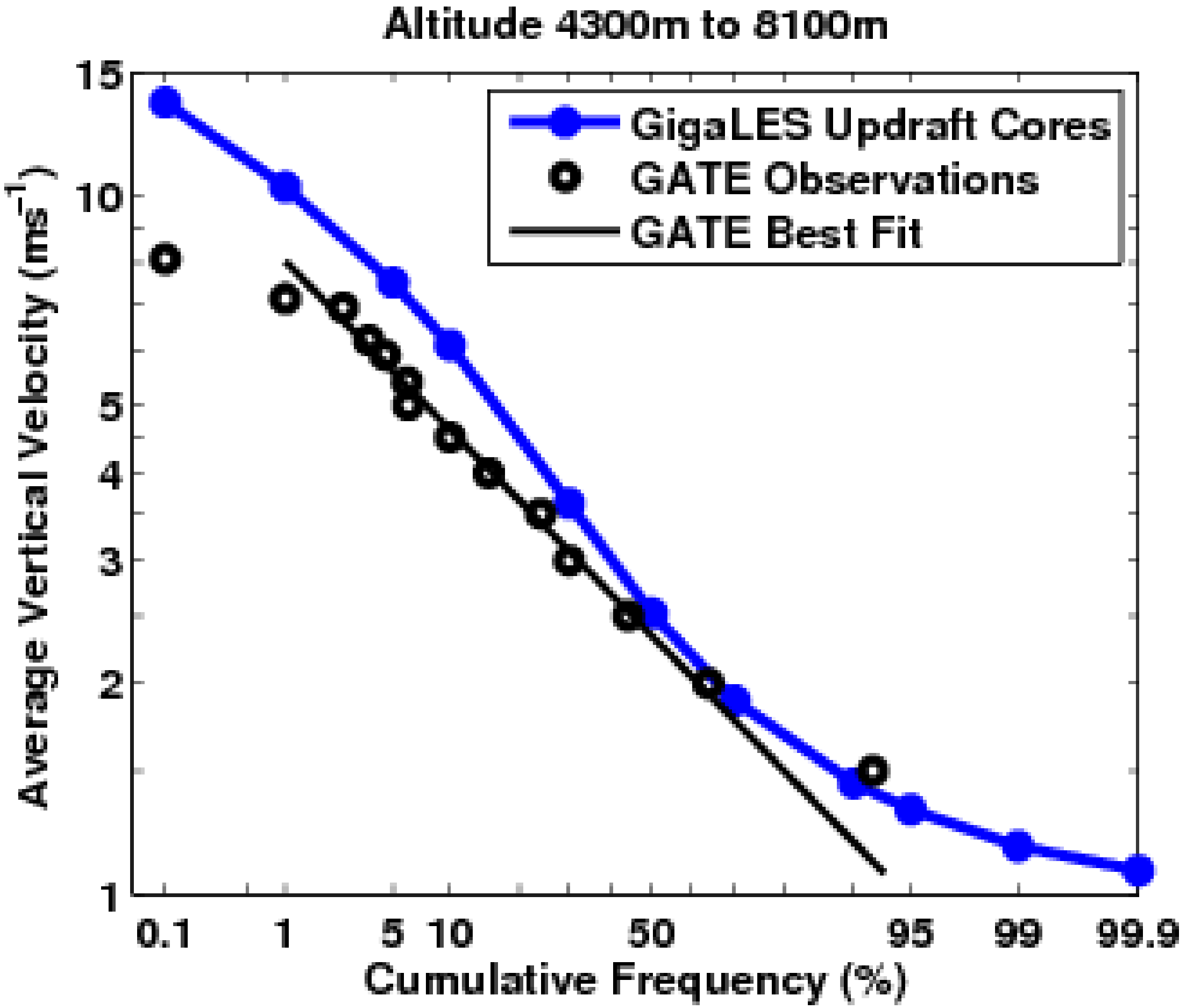
*Low PW and Rain Rate

*High PW and Rain Rate

*High PW and Low Rain Rate

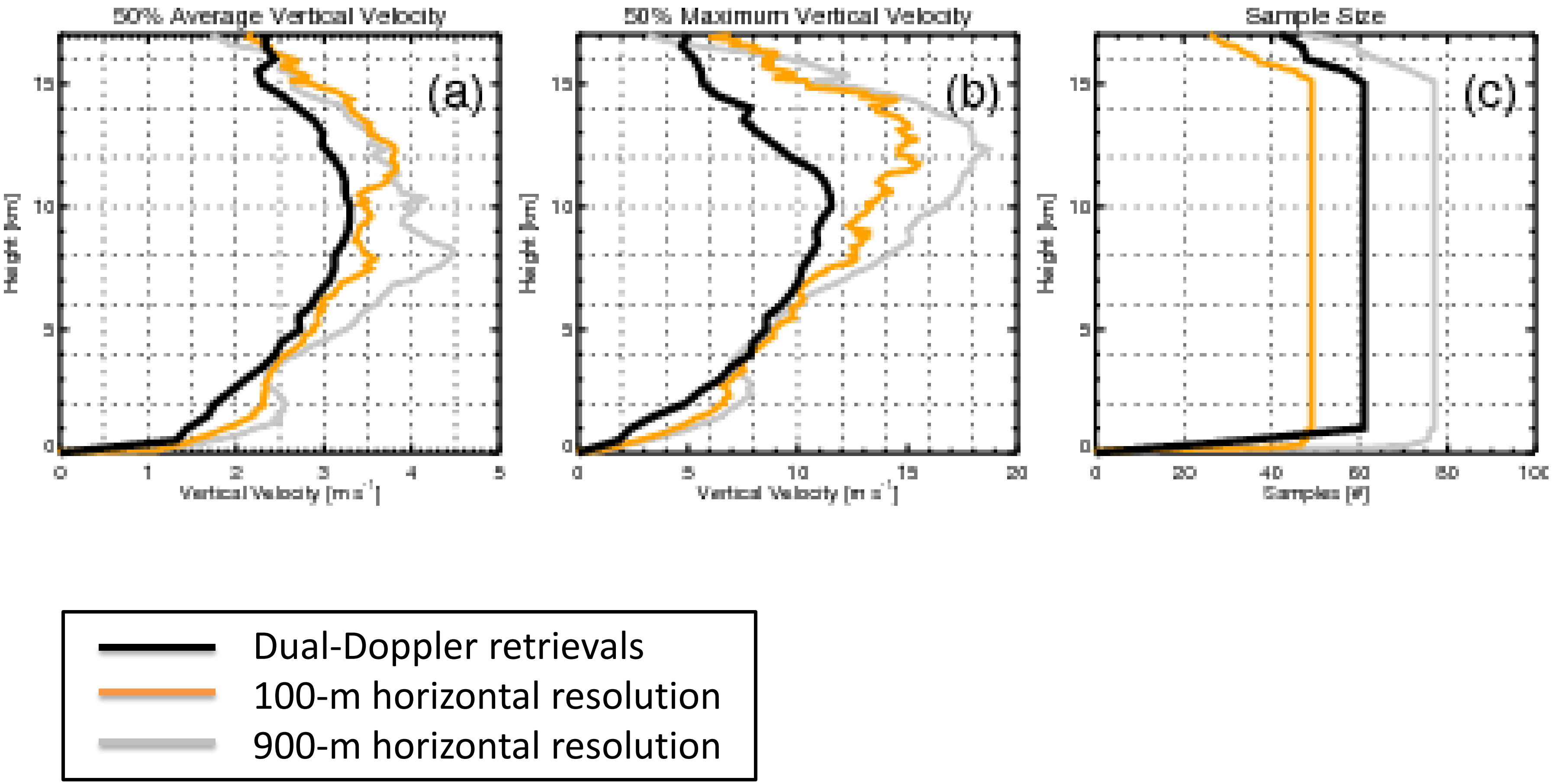
CRM results from Cris Batstone, CDC; *,*,* from Donner (1993, *JAS*) entrainment PDF

100-m horizontal resolution *w* PDFs from giga-LES agree reasonably well with observations.



Analysis by Ian Glenn and Steve Krueger, University of Utah

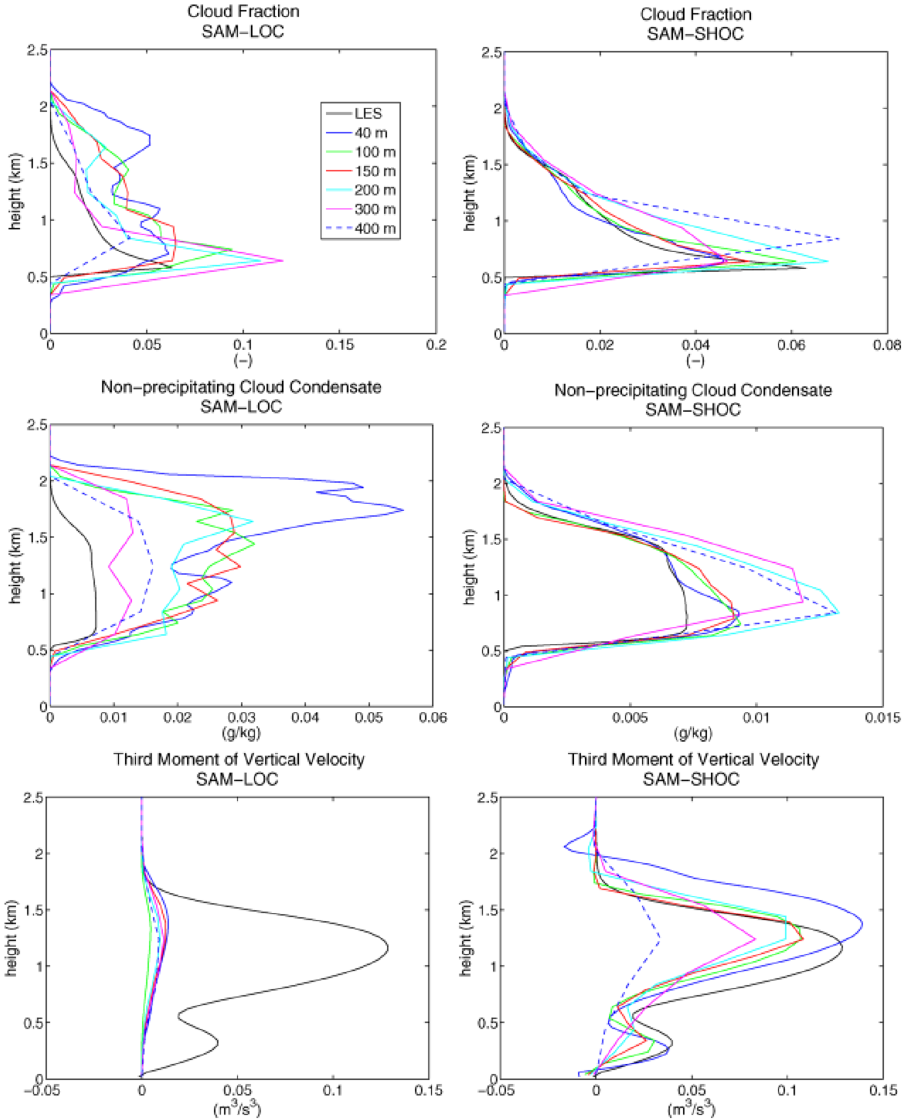
TWP-ICE, 23 January 2006: Vertical Velocities from DHARMA CRM with Double-Moment Microphysics



▬ Dual-Doppler retrievals
▬ 100-m horizontal resolution
▬ 900-m horizontal resolution

DHARMA integrations by Ann Fridlind, NASA GISS
Analysis by Adam Varble, University of Utah

A simplified PDF parameterization of subgrid-scale clouds and turbulence for cloud-resolving models



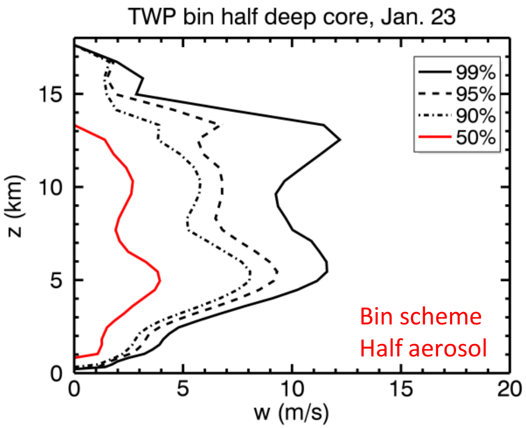
Journal of Advances in Modeling Earth Systems

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

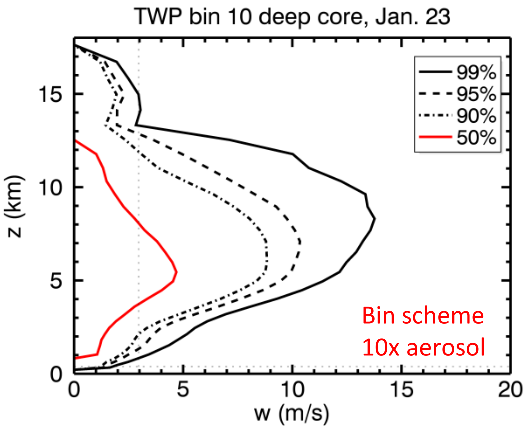
Bogenschutz and Krueger (2013)

Vertical Velocity in Convective Cores: Sensitivities to Aerosol and Microphysics

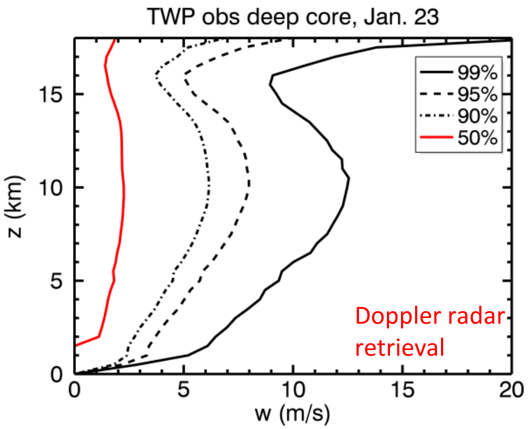
TWP-ICE case study


TWP bin half deep core, Jan. 23

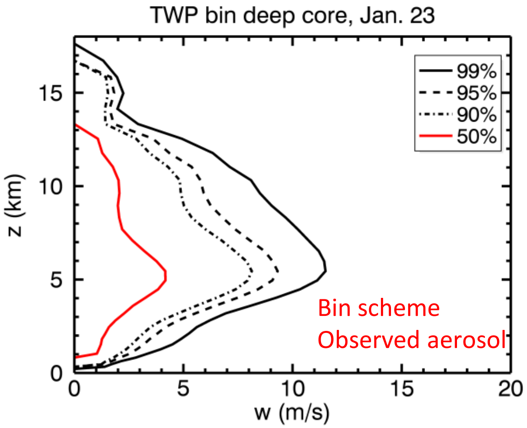
Bin scheme
Half aerosol


TWP bin 10 deep core, Jan. 23

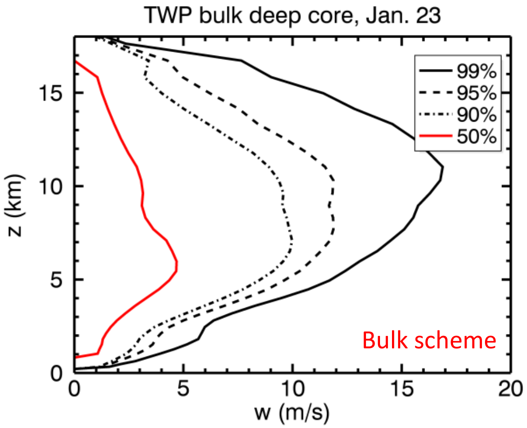
Bin scheme
10x aerosol


TWP obs deep core, Jan. 23

Doppler radar
retrieval


TWP bin deep core, Jan. 23

Bin scheme
Observed aerosol


TWP bulk deep core, Jan. 23

Bulk scheme

A convective core is defined as a column where w exceeds 1m/s for at least 4 km continuously.

By Xiaowen Li and Wei-Kuo Tao,
NASA GSFC

ENSEMBLE-AVERAGE VERTICAL EDDY TRANSPORT

— THE EFFECT OF MULTIPLE STRUCTURE OF CLOUDS —

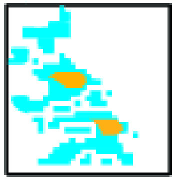
single

0.5 m/s < w

double

2 m/s < w

0.5 m/s < w < 2 m/s

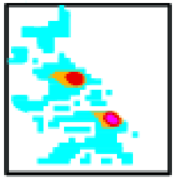


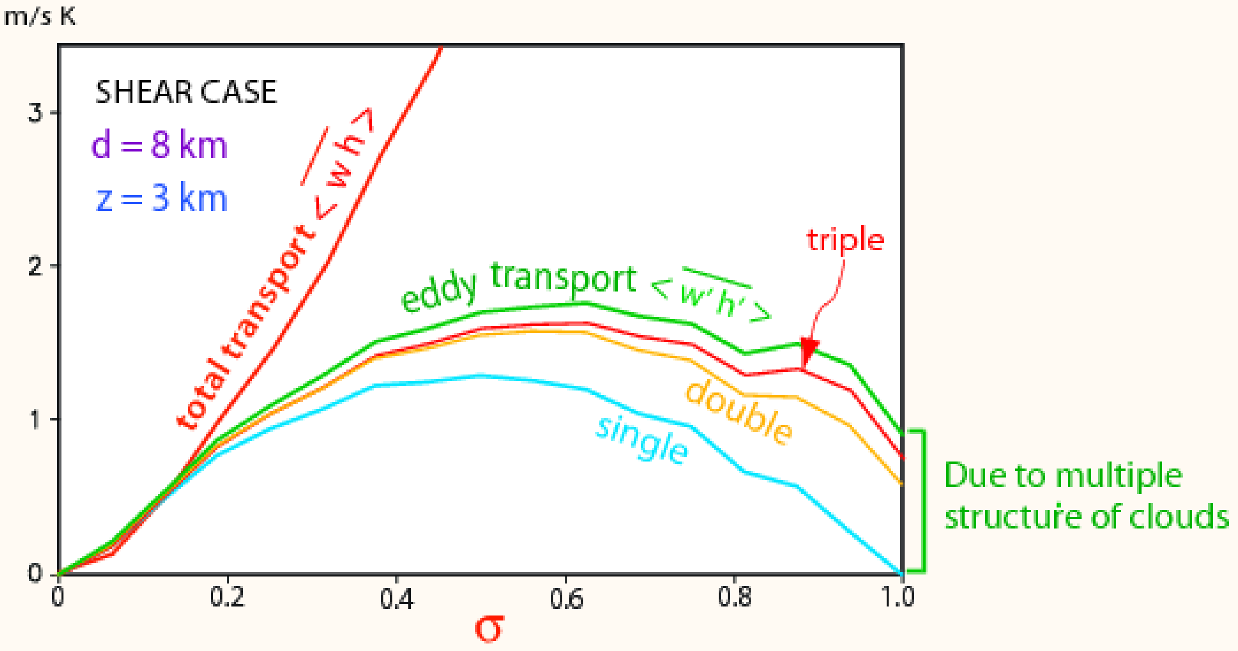
triple

4 m/s < w

2 m/s < w < 4 m/s

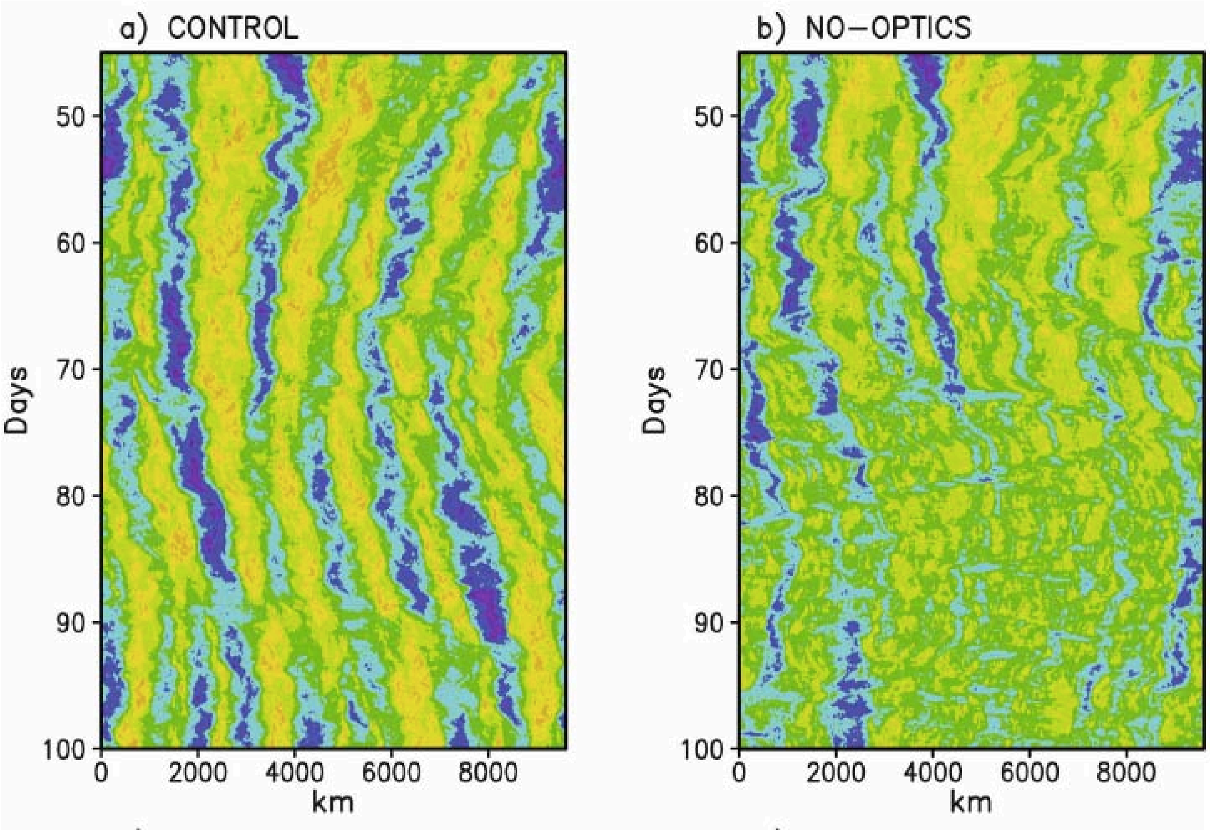
0.5 m/s < w < 2 m/s





from Akio Arakawa, UCLA

Radiative Influences

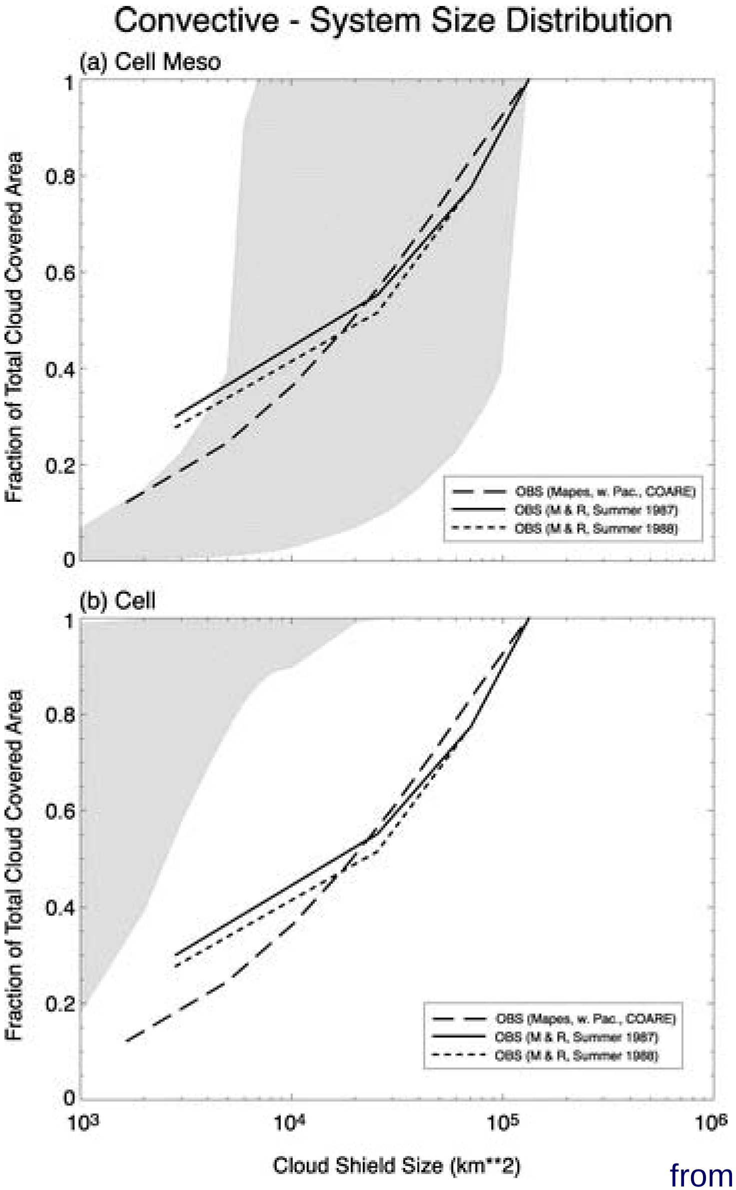


Time series of precipitable water (mm) for fully interactive radiation scheme (left) and interactive radiation without contributions by clouds and precipitation (after Stephens, van den Heever and Pakula, 2008)

- Breakdown of banded organization
- Effects of clouds on radiative heating and feedbacks to convective organization important

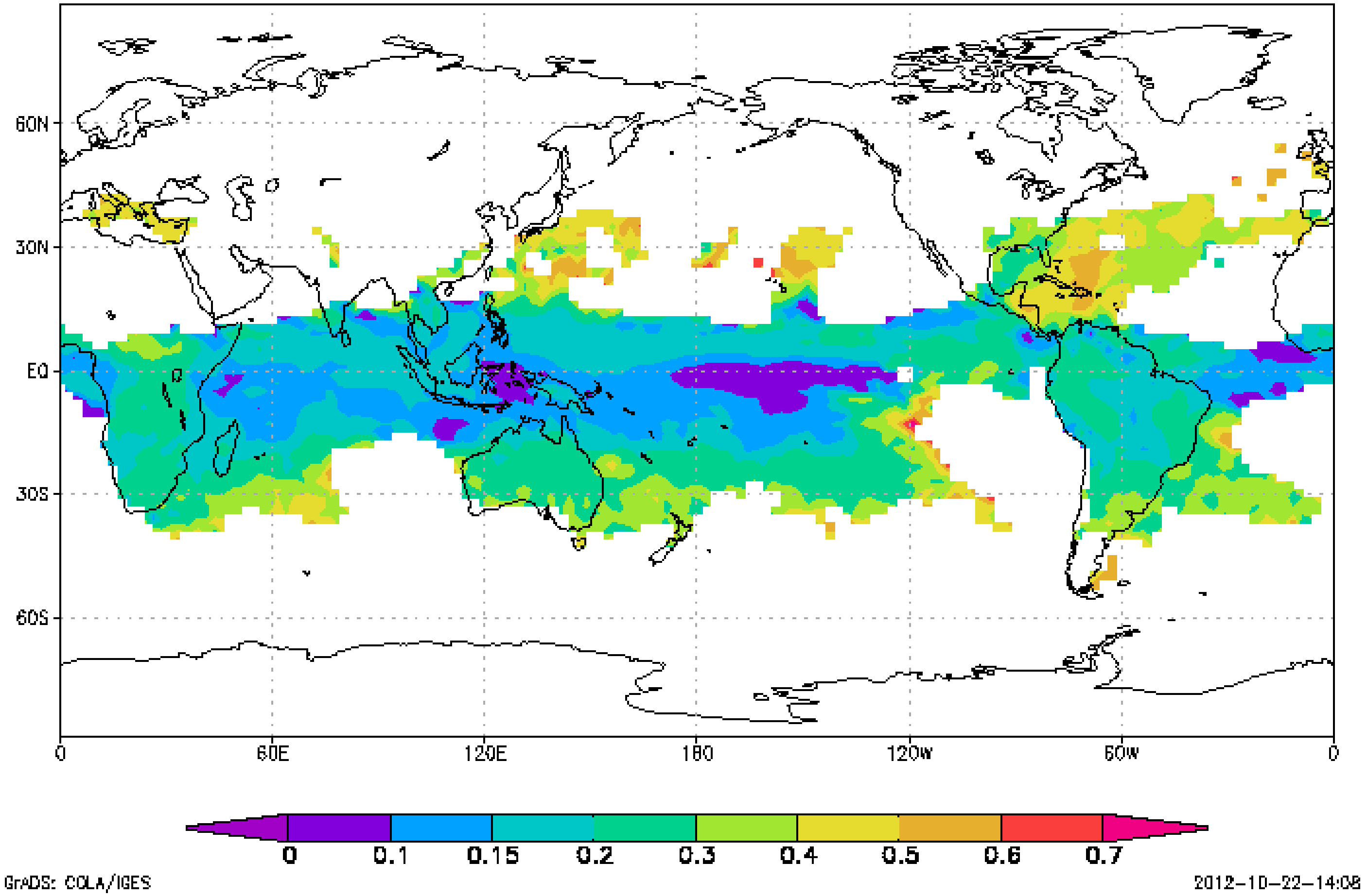
from Sue Van Den Heever, CSU

Sizes of Convective Systems in GFDL AGCM



from Donner *et al.* (2001, *J. Climate*)

AM3 50km Mesoscale Precipitation Fraction (DJF)



Until recently, cumulus closures have mostly been based on a grid-mean view of interactions between cumulus plumes and their environment, *e.g.*, quasi-equilibrium.

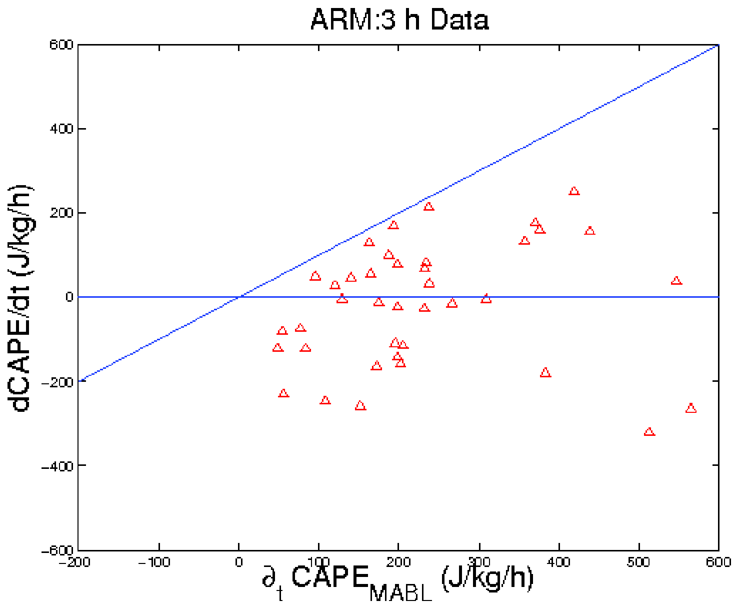
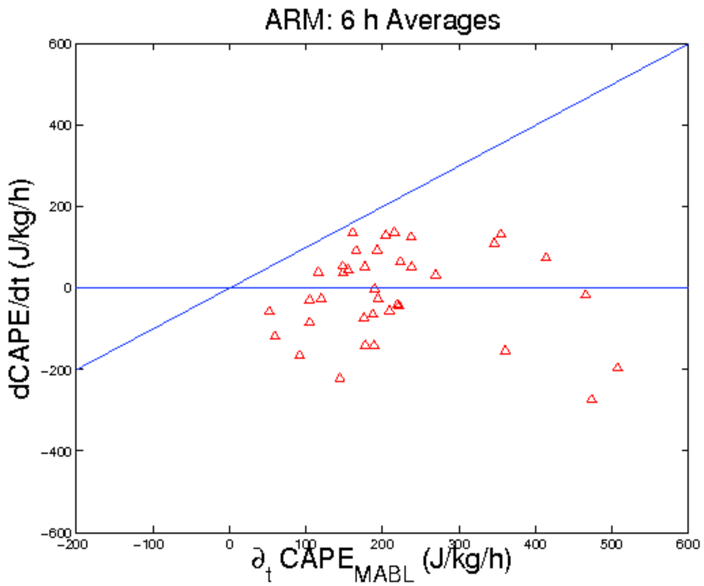

ARM:3 h Data

Fig. 4b


ARM: 6 h Averages

from Donner and Phillips (2003, *J. Geophys. Res.*)

Fig. 4c

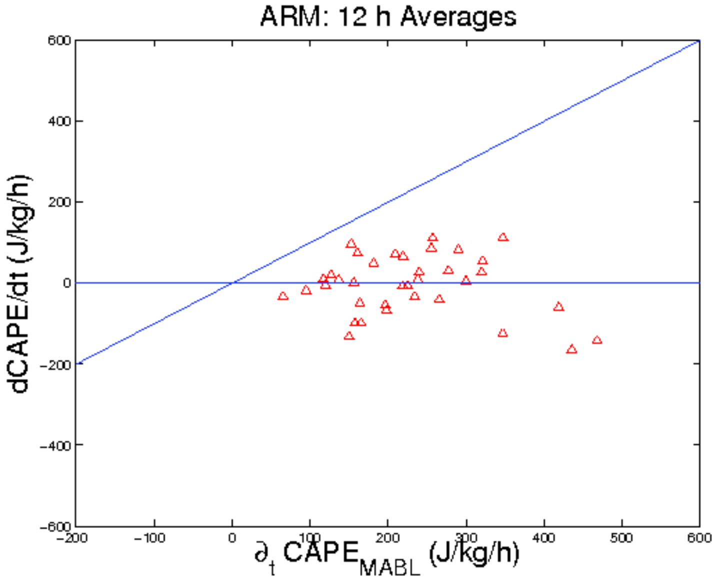
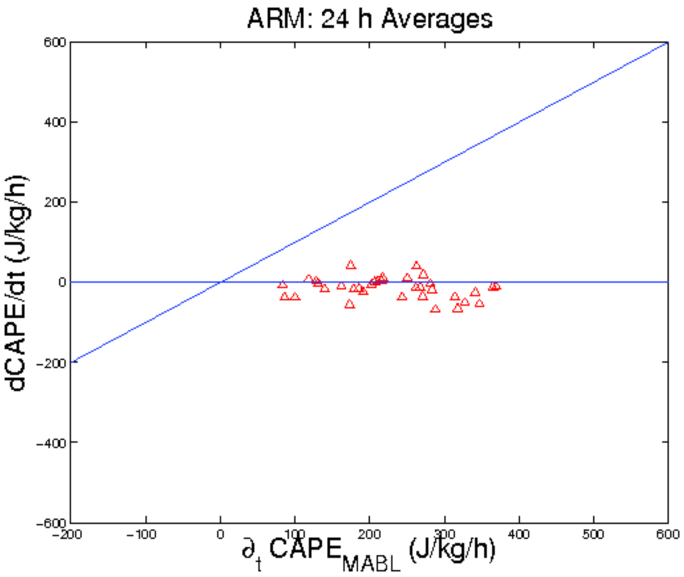
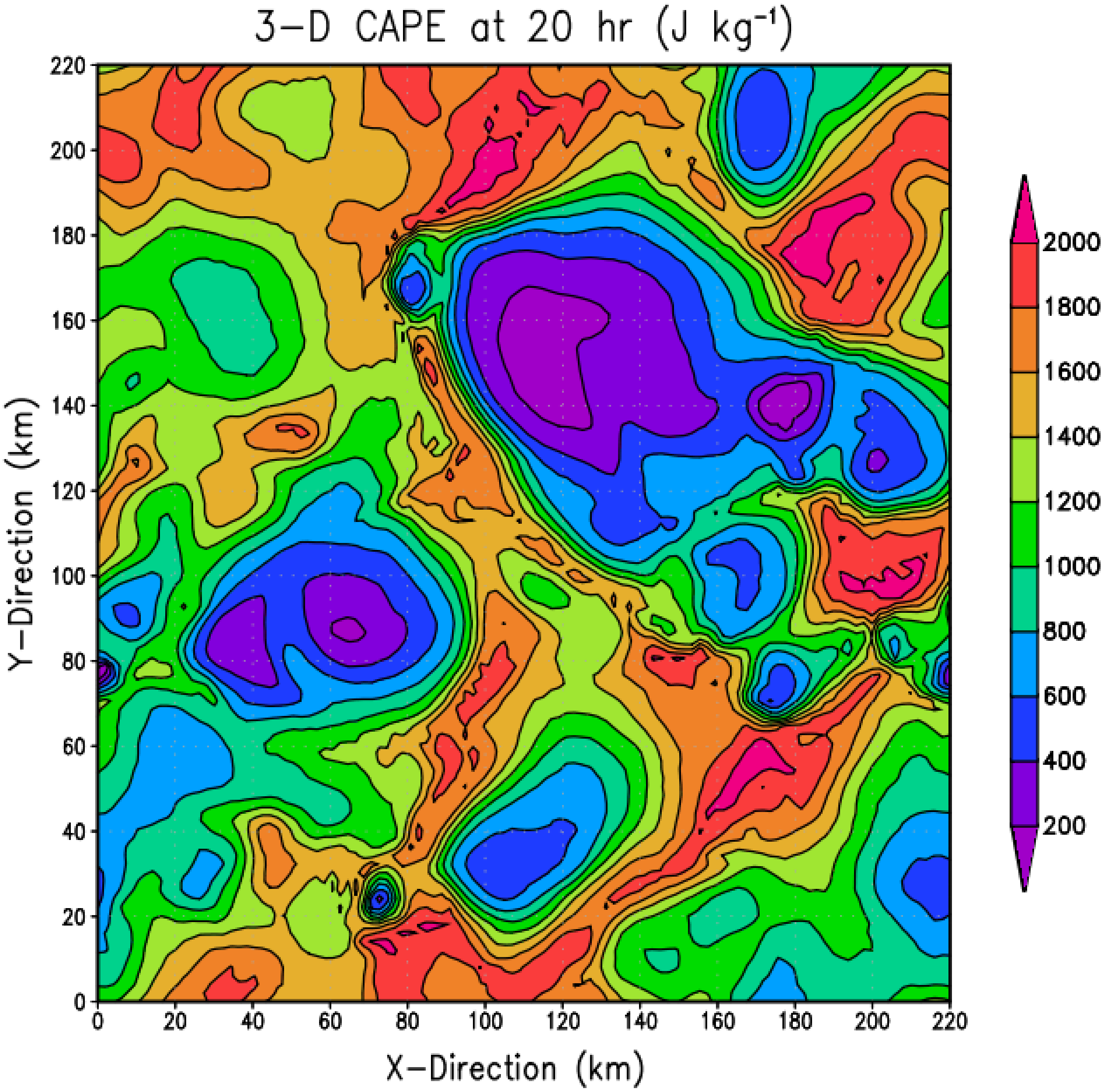

ARM: 12 h Averages

Fig. 4d


ARM: 24 h Averages

Cloud-resolving models suggest few cumulus plumes “see” grid-mean properties. Sub-grid variability in cloud environments is more relevant.



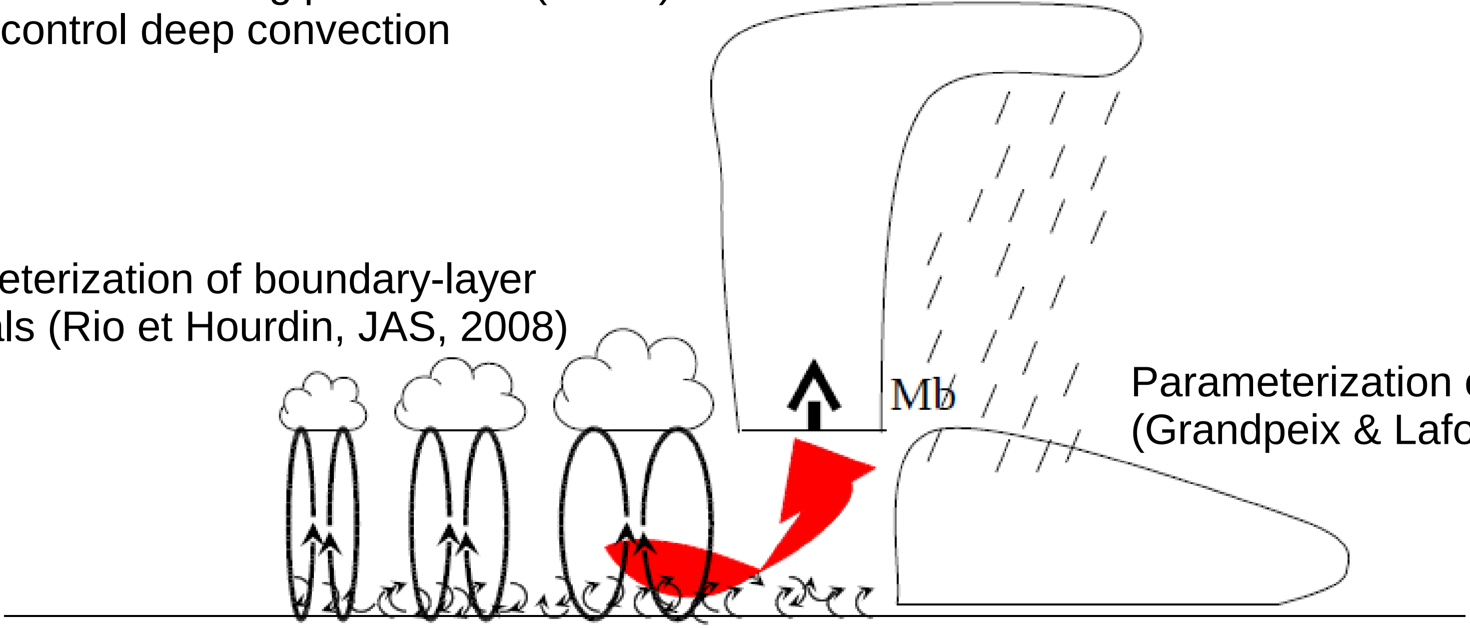
from Donner *et al.* (2001, *J. Atmos. Sci.*)

Control of deep convection by sub-cloud lifting processes: The ALP closure in the LMDZ5B general circulation model

Rio et al., *Clim. Dyn., 2012*

Sub-cloud lifting processes, boundary-layer thermals (th) and cold pools (wk), provide:
> an available lifting energy: ALE (J/kg) and
> an available lifting power: ALP (W/m2)
that control deep convection

Parameterization of boundary-layer thermals (Rio et Hourdin, JAS, 2008)



Parameterization of cold pools (Grandpeix & Lafore, JAS, 2011)

Triggering:

MAX(ALEth, ALEwk) > |CIN|

Closure:

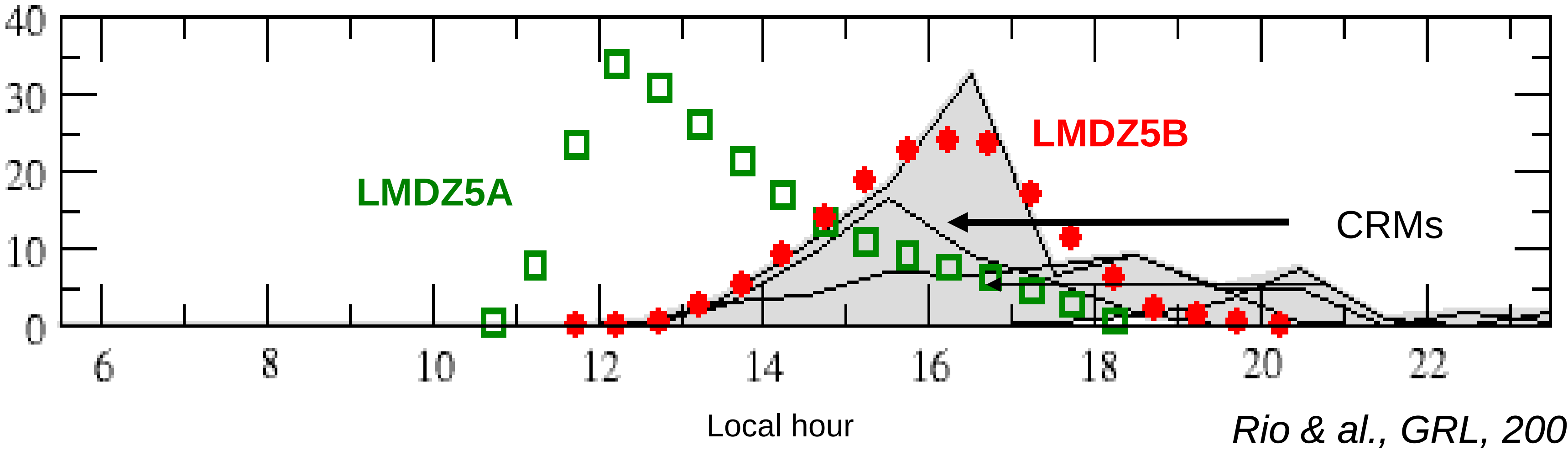
$$M_b = \frac{ALP}{[|CIN| + 2{w_b}^2]}$$

ALP = ALPth+ALPwk ~ w'3

wb=f(PLFC)

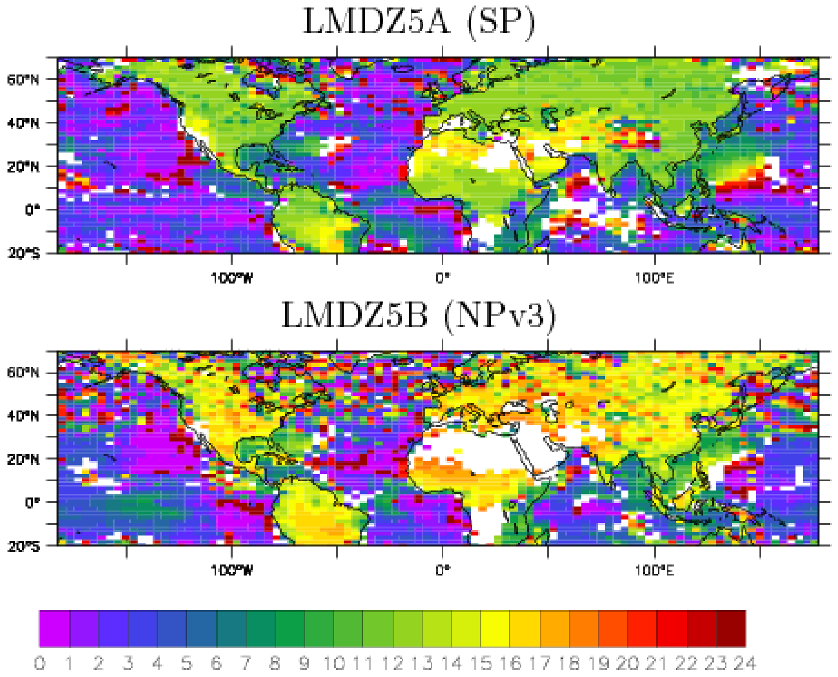
Diurnal cycle of convection over land: From 1D to global simulations

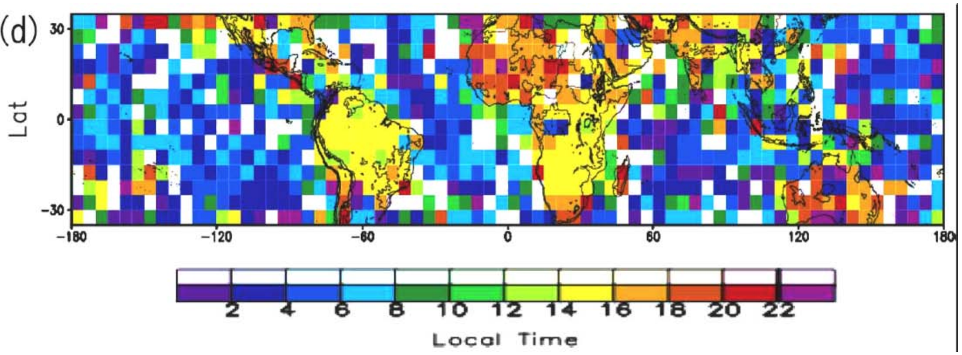
Diurnal cycle of precipitation (mm/day) the 27 of June 1997 in Oklahoma (EUROCS case)



Rio & al., GRL, 2009

Shift of the local hour of maximum rainfall in 1D and 3D simulations





Observations (TRMM, from Hirose et al., 2008)

LMDZ5A: CAPE Closure LMDZ5B: ALP Closure

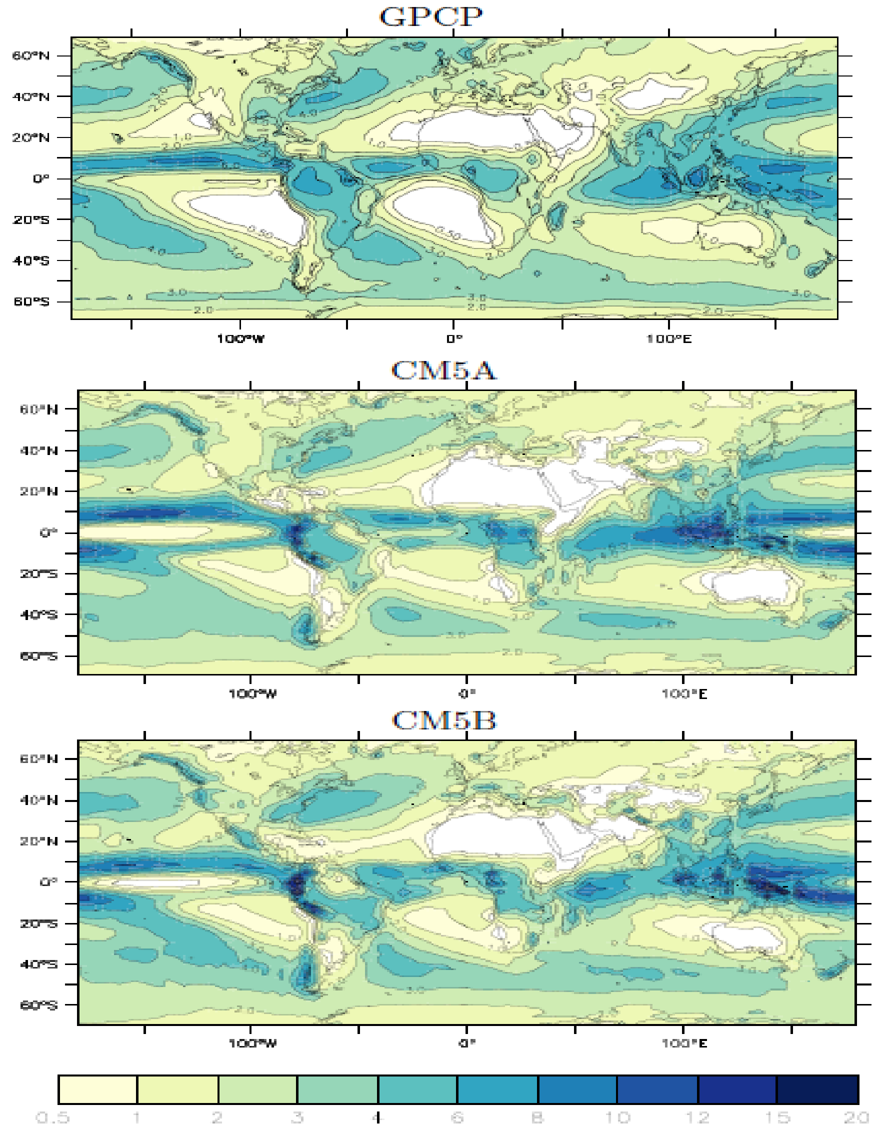
Rio & al., 2012

Impact on precipitation mean and variability

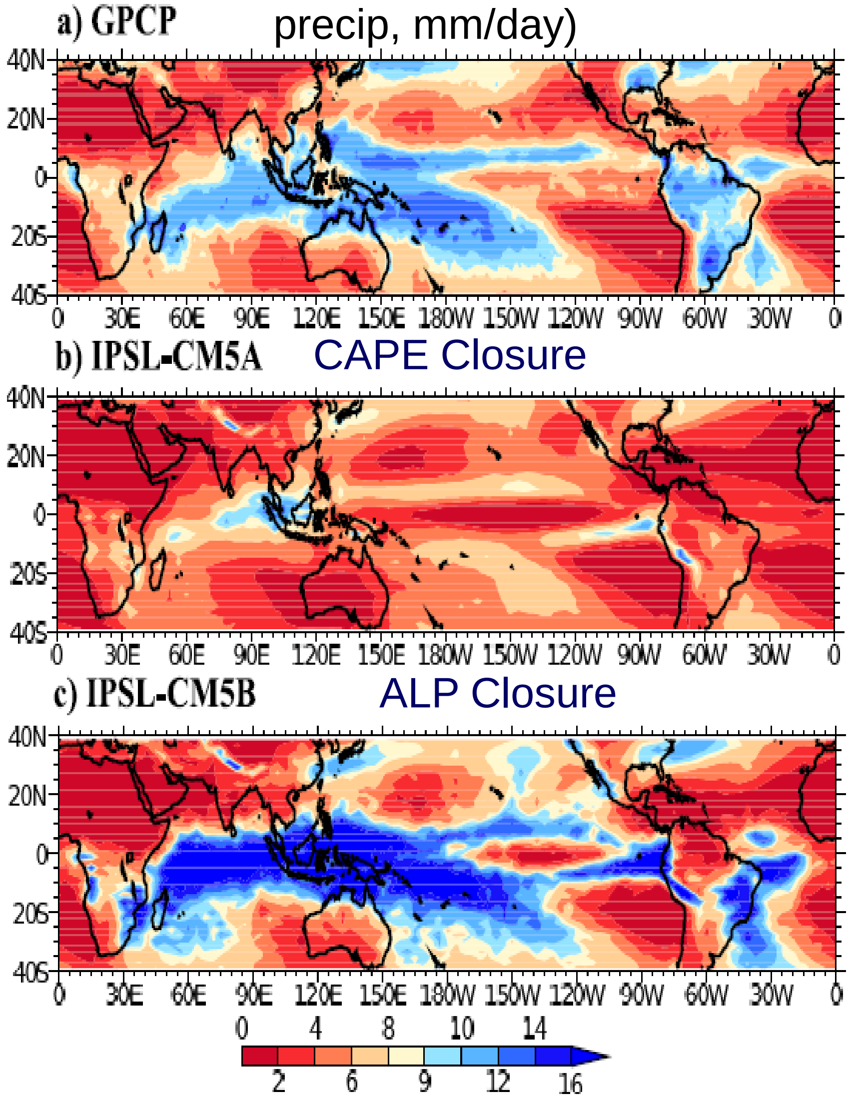
Hourdin et al., Clim. Dyn. 2012

IPSL-CM5A/CM5B: 10 years of coupled pre-industrial simulations

Mean precipitation (mm/day)



Intra-seasonal variability of precipitation (SD daily precip, mm/day)



CAPE Closure

ALP Closure

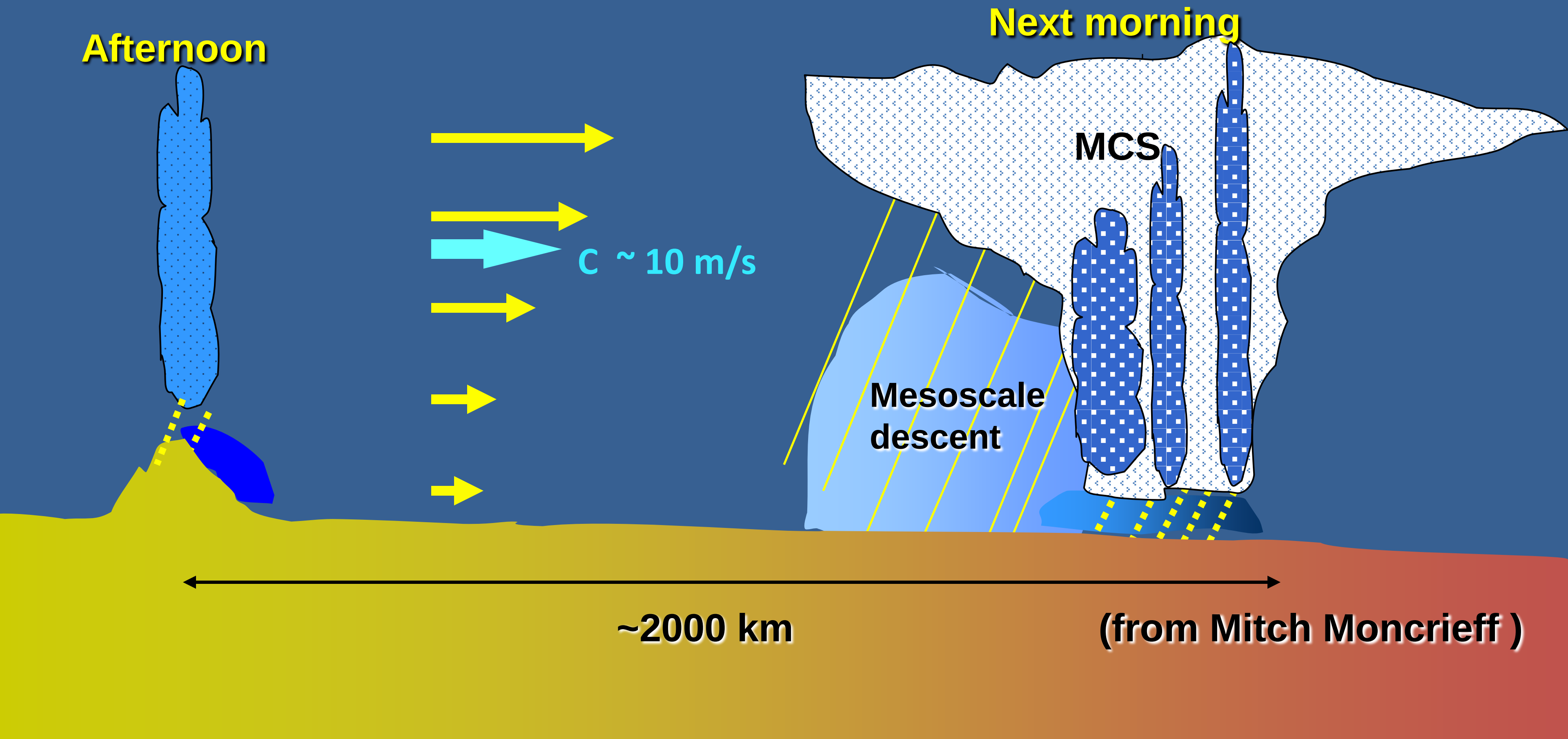
Some impact on precipitation annual mean

Strong impact on intra-seasonal variability

Some types of organized convection have such large space and time scales that they are most easily modeled explicitly in high-resolution models.

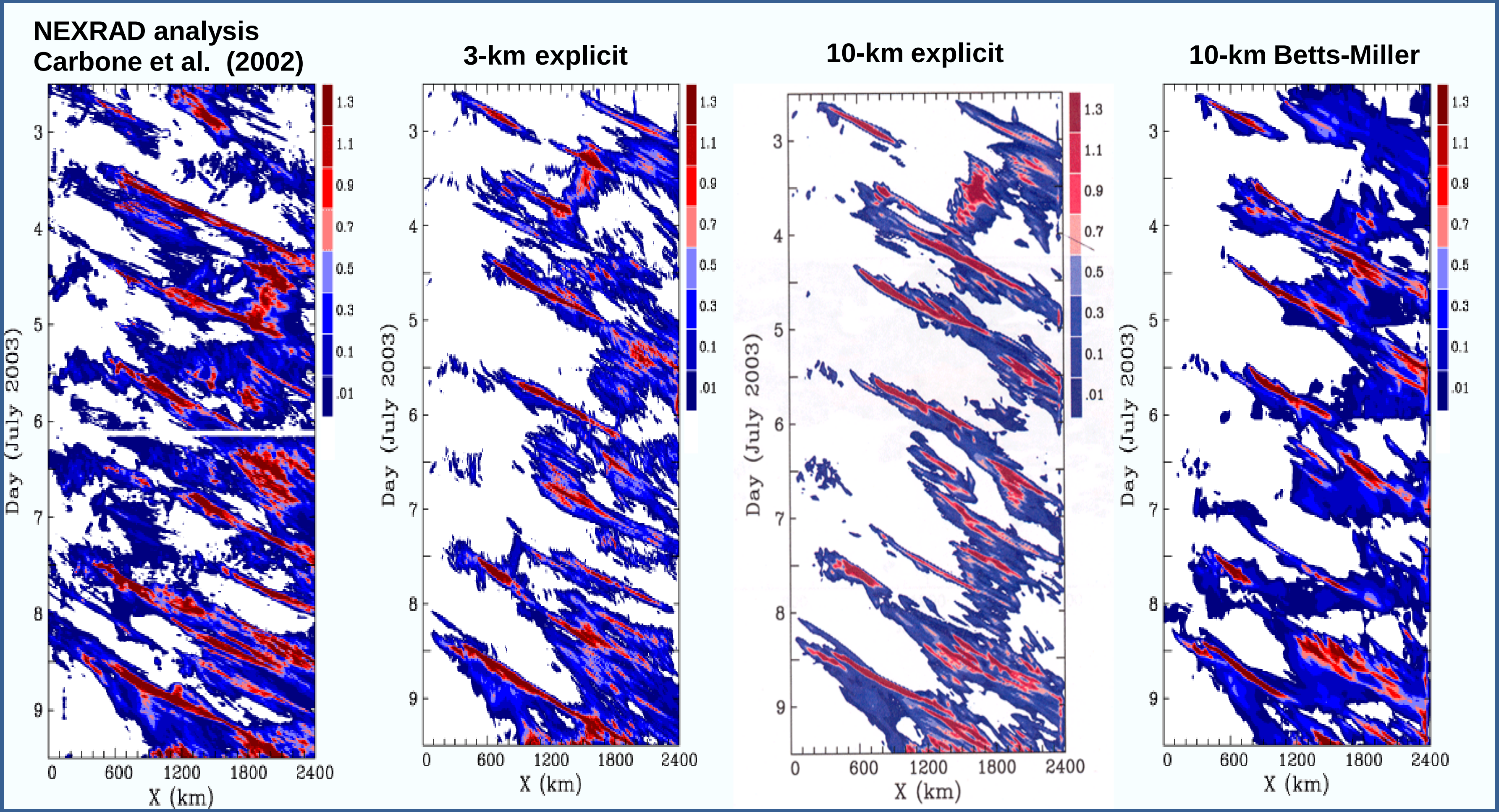
Orogenic MCS and the diurnal cycle of precipitation

Vertical shear organizes sequences of cumulonimbus into long-lasting mesoscale convective systems (MCS), which propagate across continents, efficiently transporting heat, moisture and momentum



(from Mitch Moncrieff)

Propagating MCS over U.S. continent



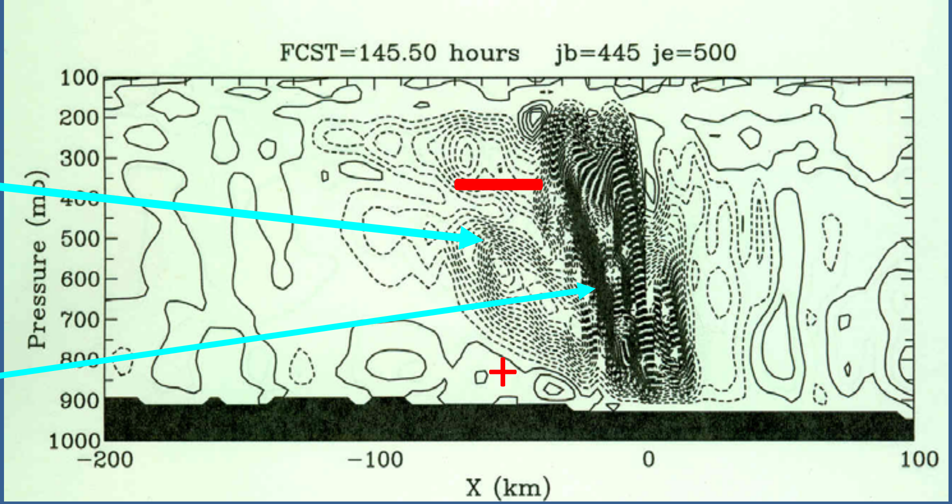
Moncrieff & Liu (2006)

Effect of resolution on CMT:

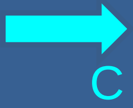
Negative for 3 km & 10 km grids, positive (incorrect) for 30 km grid

Mesoscale circulation

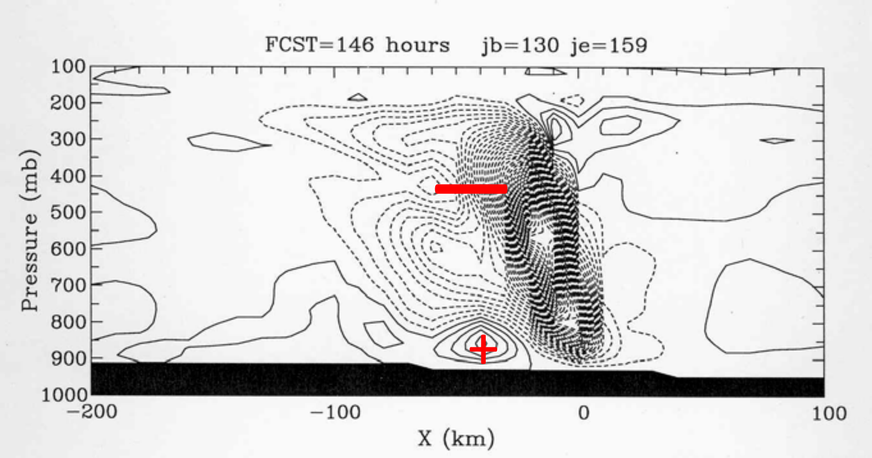
Cumulonimbus family



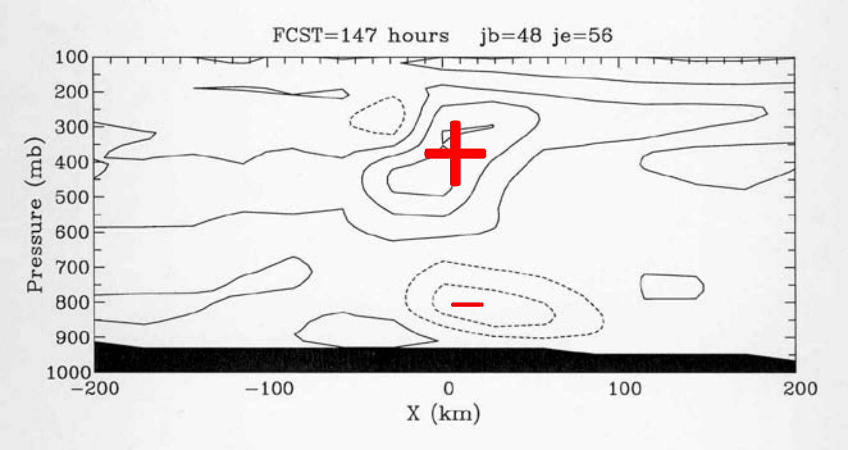
$\Delta = 3\,\mathrm{km}$



Sign of CMT is <u>negative</u> -- opposite to propagation vector (C) -- due to rearward-tilted airflow



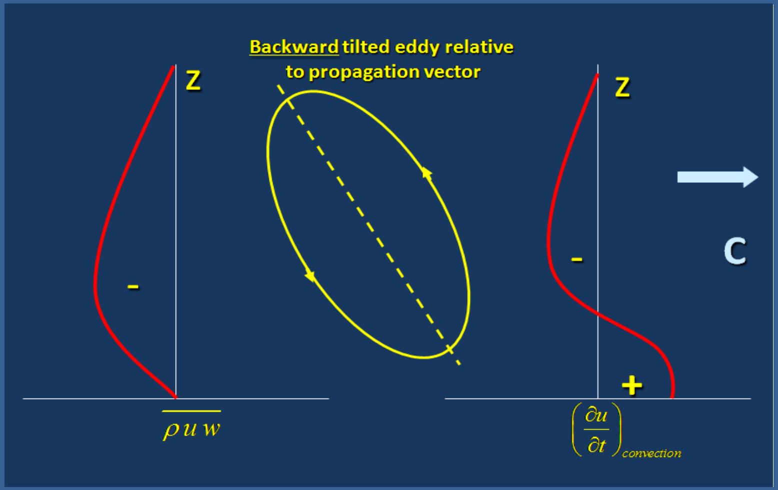
$\Delta = 10\,\mathrm{km}$



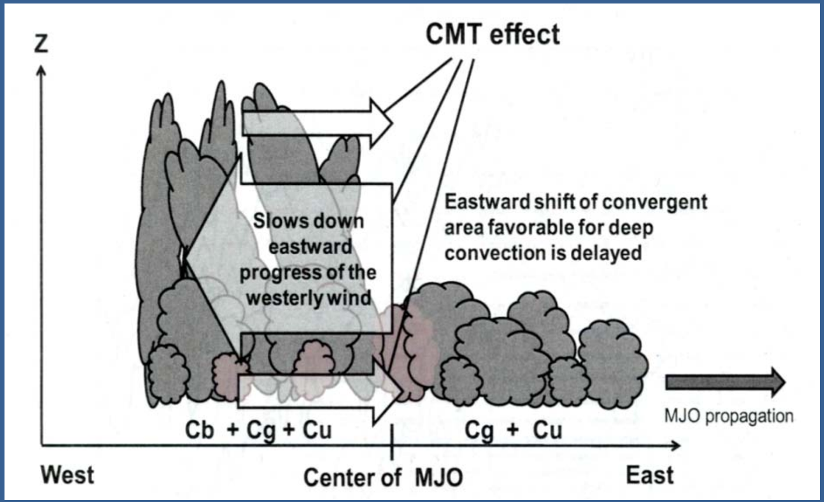
$\Delta = 30\,\mathrm{km}$

from Mitch Moncrieff

Convective momentum transport by MCS in MJOs simulated by a global cloud-system resolving model (NICAM)



$$\frac{\partial \overline{u}}{\partial t} + \dots\dots\dots\dots = -\frac{\partial}{\partial z}\left(\overline{u_m w_m}\right) = \left(\frac{\delta u}{\delta t}\right)_{convection}$$

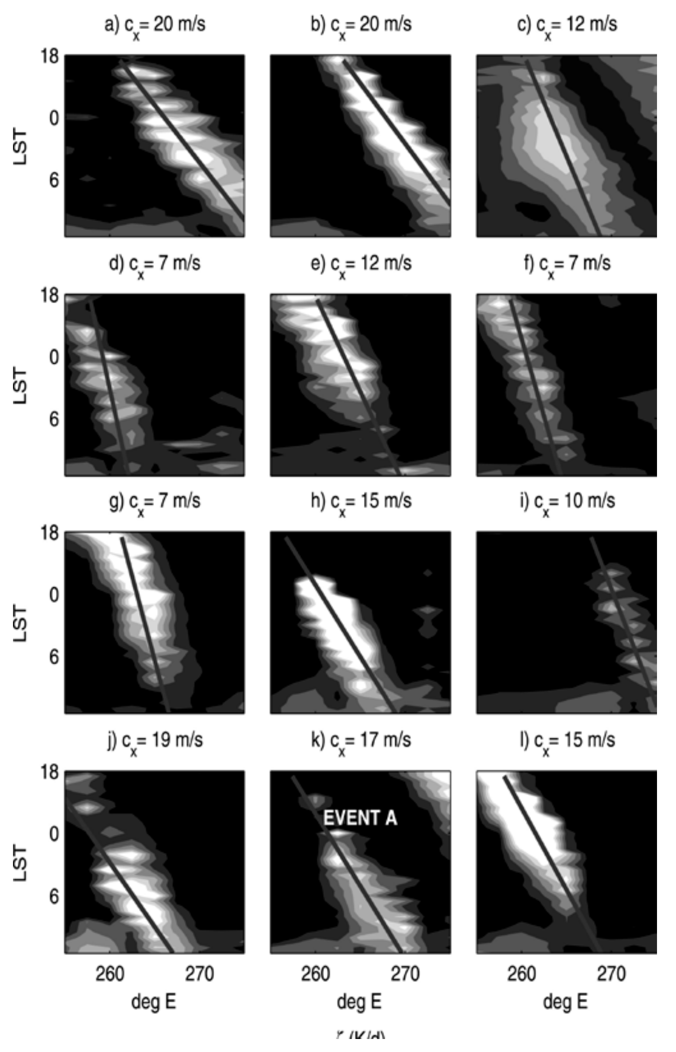


Miyakawa et al. (2011)

Even convective organization with large space and time scales can be simulated to some extent using appropriately cumulus parameterizations.

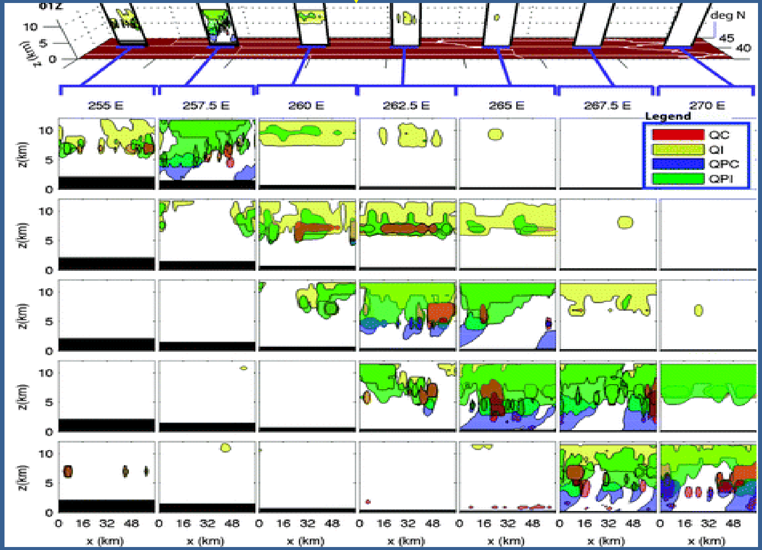
Orogenic MCS over U.S. continent

Superparameterized Community Atmospheric Model (SPCAM)

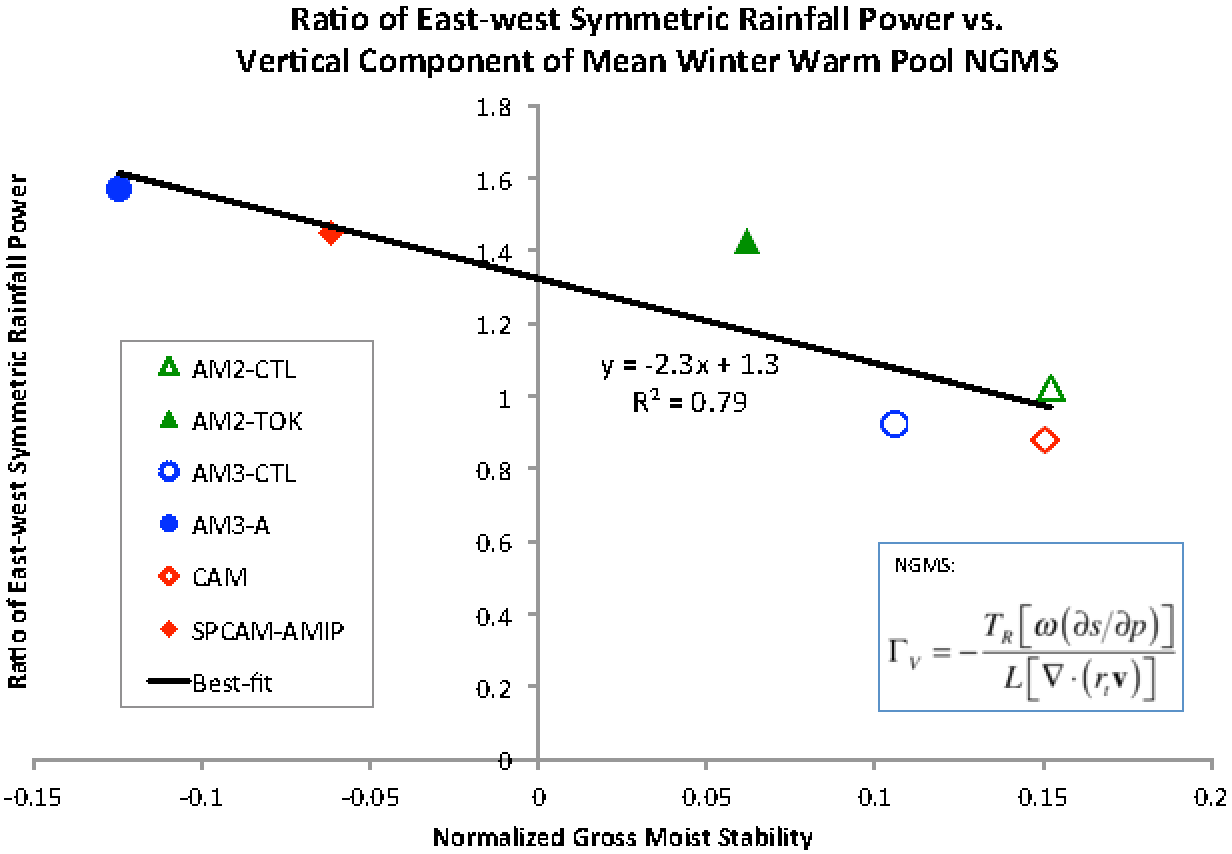


CAM: standard convection parameterization – No MCS

SPCAM: convective heating generated on 2-D CRM grid is organized by large-scale shear into propagating MCS on the climate model grid



Pritchard, Moncrieff & Somerville (2011)



AM3-CTL and AM3-A differ in their deep convective closures and triggers.

from Jim Benedict

Summary

- Parameter sensitivities and “emergent constraints” link convection to climate sensitivity.
- Vertical velocities, entrainment central elements-new observations available for process-level evaluation of parameterizations.
- Non-equilibrium, prognostic closures and sub-grid variability elements of recently developed cumulus parameterizations.
- Limited representation of convective organization, for coarse-resolution model.
- Scale-aware formulation can be used to deal with variable grid and convective system sizes.