Convective invigoration in polluted environments: Fact or fiction?

Wojciech W. Grabowski

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NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

UNIVERSITY CORPORATION FOR ATMOSPHERIC RESEARCH

ASR Atmospheric System Research

U.S. DEPARTMENT OF ENERGY Office of Science

Invigoration: increase of updraft strength due to cloud microphysics.

Science 2004

Smoking Rain Clouds over the Amazon

M. O. Andreae,[1]* D. Rosenfeld,[2]* P. Artaxo,[3] A. A. Costa,[4]
G. P. Frank,[1] K. M. Longo,[5] M. A. F. Silva-Dias[6]

Heavy smoke from forest fires in the Amazon was observed to reduce cloud droplet size and so delay the onset of precipitation from 1.5 kilometers above cloud base in pristine clouds to more than 5 kilometers in polluted clouds and more than 7 kilometers in pyro-clouds. Suppression of low-level rainout and aerosol washout allows transport of water and smoke to upper levels, where the clouds appear "smoking" as they detrain much of the pollution. Elevating the onset of precipitation allows invigoration of the updrafts, causing intense thunderstorms, large hail, and greater likelihood for overshooting cloud tops into the stratosphere. There, detrained pollutants and water vapor would have profound radiative impacts on the climate system. The invigorated storms release the latent heat higher in the atmosphere. This should substantially affect the regional and global circulation systems. Together, these processes affect the water cycle, the pollution burden of the atmosphere, and the dynamics of atmospheric circulation.

Satellite observations of pollution, aircraft observations of the aerosols, no cloud penetrations…

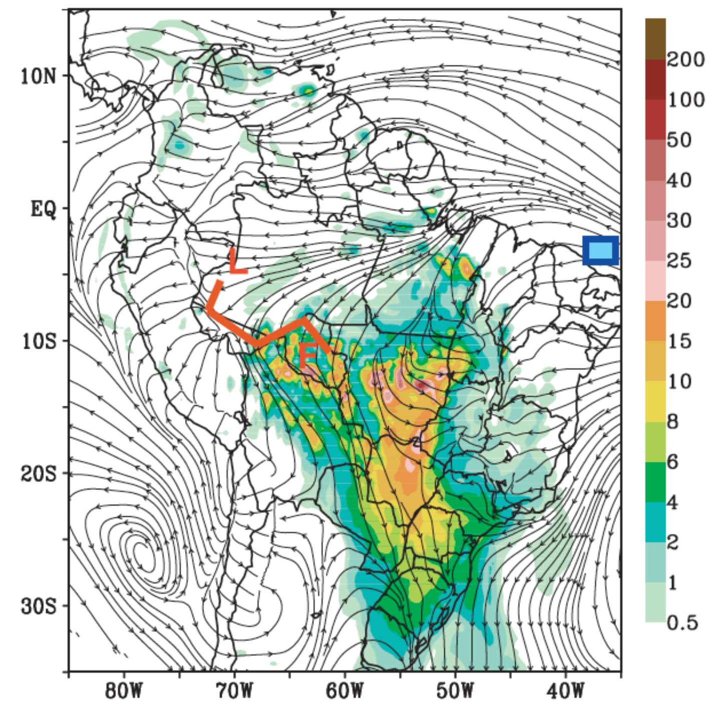
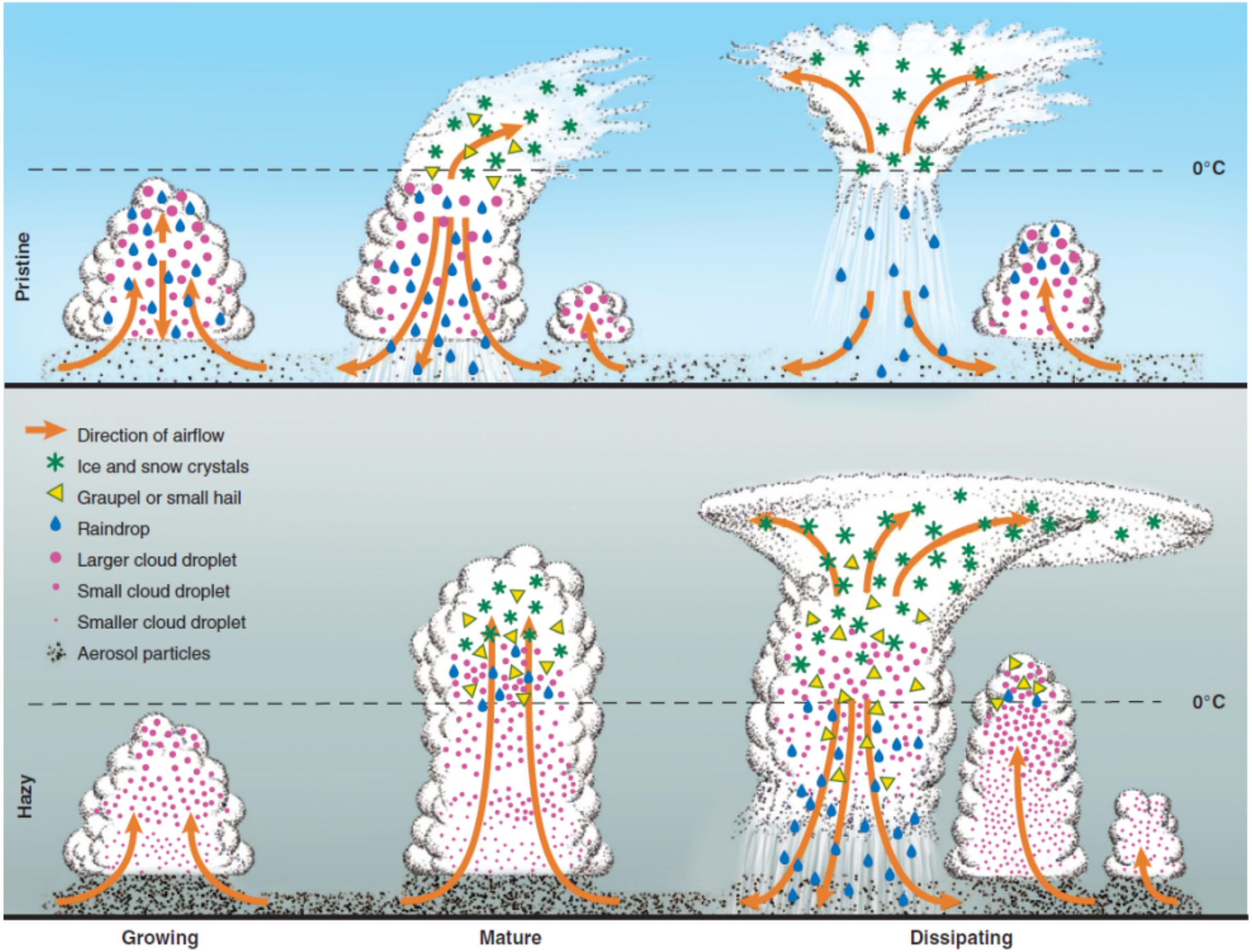


Fig. 1. Smoke aerosol distribution ($D < 2.5$ μm; in μg m^{-2}) and wind field in the BL over South America during the transect flights from Rondonia to the western Amazon. The aerosol distribution was obtained with the use of the Geostationary Operational Environmental Satellites–Automated Biomass Burning Algorithm (GOES ABBA) Fire product to estimate smoke emissions and the RAMS model to simulate their transport and removal (*38*). The flight track is indicated as a red line; the study area off Fortaleza, by a blue rectangle; and letters L and F represent the locations of the LET and FNS sounding sites, respectively (fig. S1).

clean

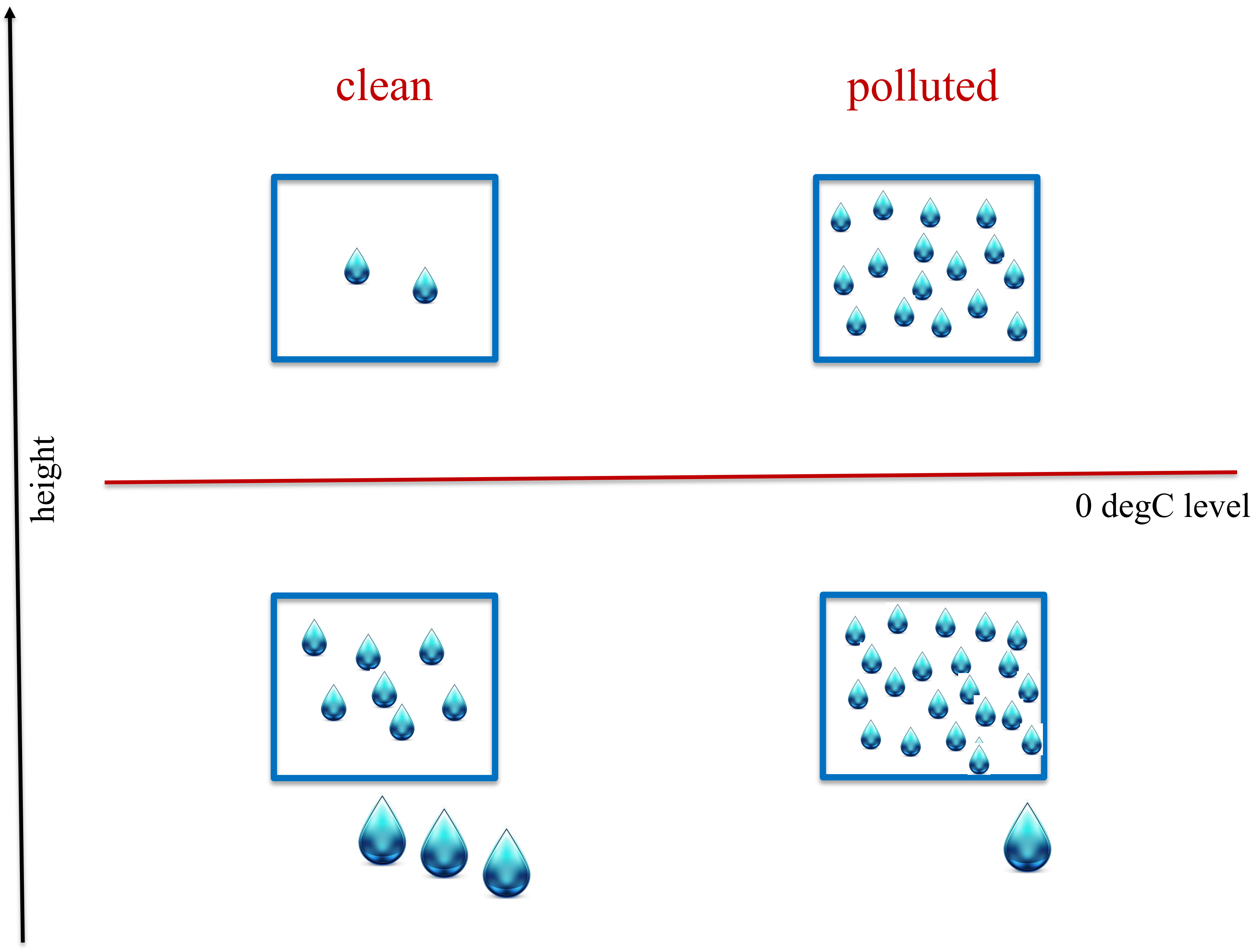
polluted

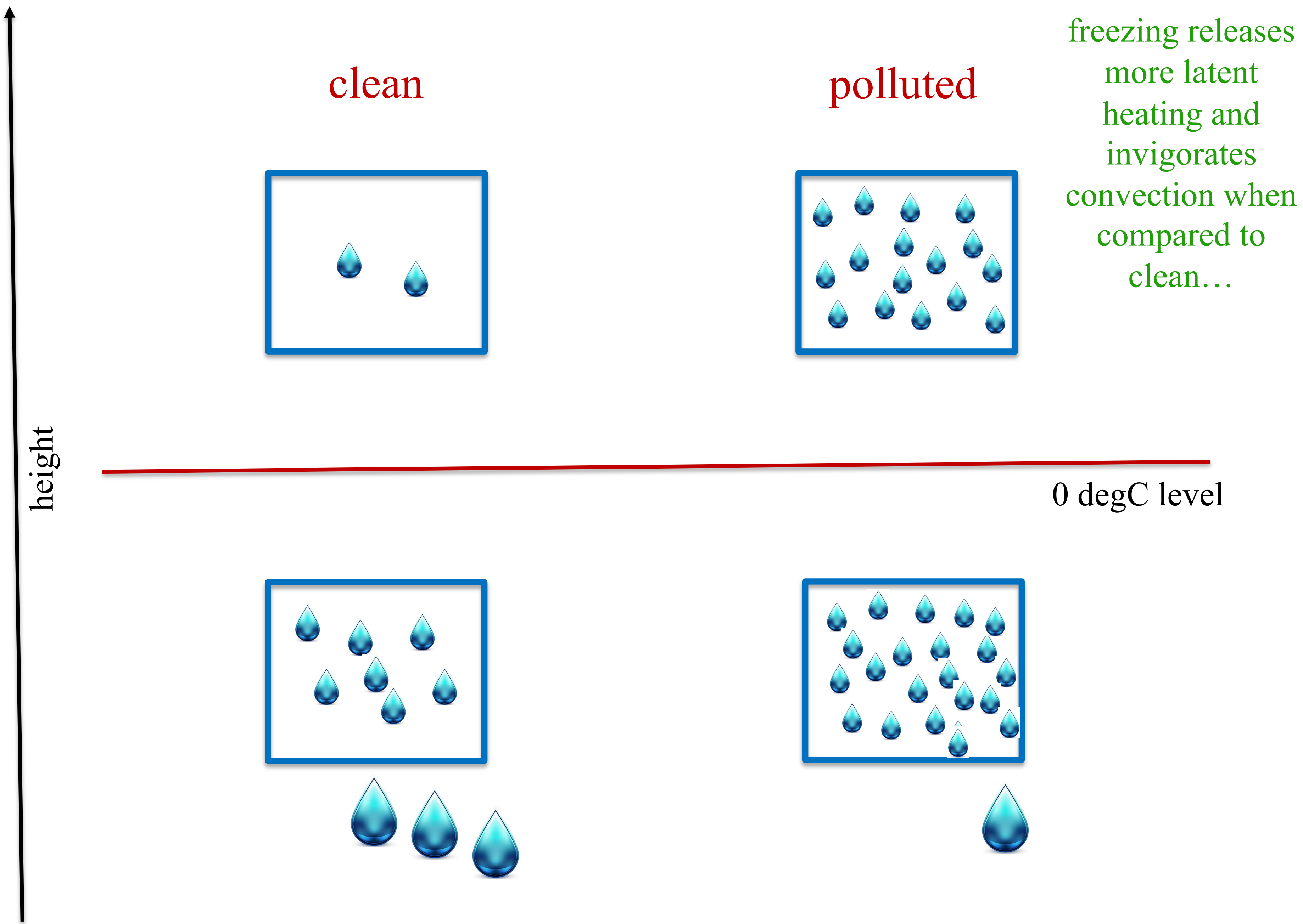


Science, 2008

Flood or Drought: How Do Aerosols Affect Precipitation?

Daniel Rosenfeld,[1*] Ulrike Lohmann,[2] Graciela B. Raga,[3] Colin D. O'Dowd,[4] Markku Kulmala,[5] Sandro Fuzzi,[6] Anni Reissell,[5] Meinrat O. Andreae[7]


clean
polluted
height
0 degC level


clean
polluted
freezing releases more latent heating and invigorates convection when compared to clean…
height
0 degC level

Is that really possible?

Liquid condensate freezing: the impact of latent heating approximately balances loading effect:

$$\Theta_d = \Theta\,(1 + \varepsilon q_v - q_c)$$

δq – change of cloud water mixing ratio

$$\delta\Theta_d \sim \delta\Theta + \Theta\,\delta q$$

$$\delta\Theta \sim L_f/cp\,\delta q \sim 3 \cdot 10^2\,\delta q \qquad L_f \sim 3 \cdot 10^5\ J/kg$$

$$\Theta\,\delta q \sim 3 \cdot 10^2\,\delta q$$

Grabowski and Morrison *JAS* 2020

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So the condensate off-loading is the key…

Substantial convection and precipitation enhancements by ultrafine aerosol particles

Jiwen Fan,[1*] Daniel Rosenfeld,[2] Yuwei Zhang,[1,3] Scott E. Giangrande,[4] Zhanqing Li,[3,5] Luiz A. T. Machado,[6] Scot T. Martin,[7] Yan Yang,[1,8] Jian Wang,[4] Paulo Artaxo,[9] Henrique M. J. Barbosa,[9,10] Ramon C. Braga,[6] Jennifer M. Comstock,[1] Zhe Feng,[1] Wenhua Gao,[1,11] Helber B. Gomes,[12] Fan Mei,[1] Christopher Pöhlker,[13] Mira L. Pöhlker,[13] Ulrich Pöschl,[13,14] Rodrigo A. F. de Souza[15]

Science, 2018

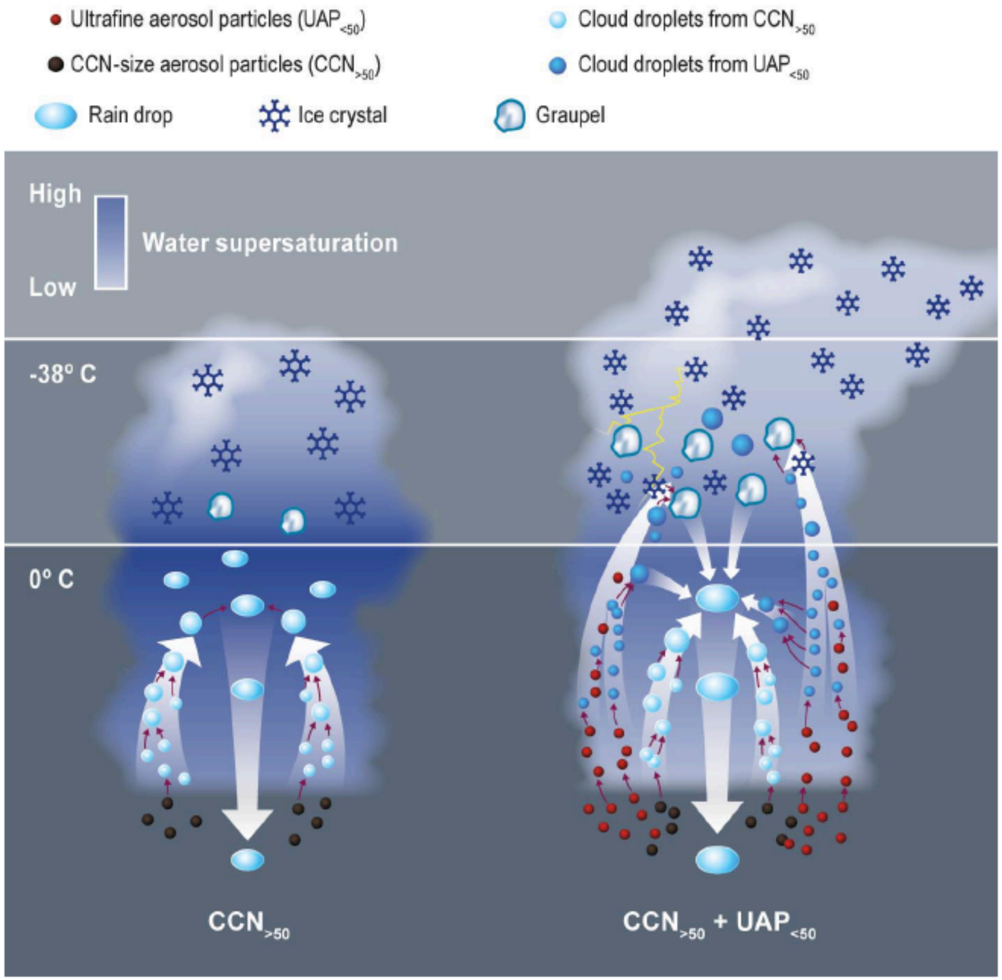

Fig. 1. Illustration of the effect of ultrafine aerosol particles ($UAP_{<50}$) on tropical convective clouds. In clouds that lack $UAP_{<50}$ (left), the clouds are highly supersaturated as a result of fast drop coalescence that forms warm rain and reduces the integrated droplet surface area available for condensation. With added $UAP_{<50}$ (right, red dots), an additional number of cloud droplets are nucleated above cloud base, which lowers supersaturation drastically by enhanced condensation, releasing additional latent heat at low and middle levels, thus intensifying convection. The additional condensate adds to both the warm rain and supercooled cloud water; when freezing occurs aloft, this addition further enhances convection (i.e., a small increase in convection but enhancement of precipitation and storm electrification).

Do Ultrafine Cloud Condensation Nuclei Invigorate Deep Convection?

WOJCIECH W. GRABOWSKI AND HUGH MORRISON

Mesoscale and Microscale Meteorology Laboratory, National Center for Atmospheric Research, Boulder, Colorado

(Manuscript received 11 January 2020, in final form 18 May 2020)

Grabowski and Morrison *JAS* 2020

Convective invigoration by aerosols

Comments on "Do ultrafine cloud condensation nuclei invigorate deep convection?"

Jiwen Fan[1] and Alexander Khain[2]

Convective invigoration: fact or fiction?

Reply to Fan and Khain comments on Grabowski and Morrison 2020 paper "Do ultrafine cloud condensation nuclei invigorate deep convection?"

Wojciech W. Grabowski and Hugh Morrison

exchange in *JAS*...

Invigoration: increase of updraft strength due to cloud microphysics.

One needs to distinguish between "more convection" versus "stronger convection".

J. Atmos. Sci. 1996

Moist Convective Scaling: Some Inferences from Three-Dimensional Cloud Ensemble Simulations

FRANÇOISE R. ROBE AND KERRY A. EMANUEL

Center for Meteorology and Physical Oceanography, Massachusetts Institute of Technology, Cambridge, Massachusetts

(Manuscript received 7 August 1995, in final form 15 April 1996)

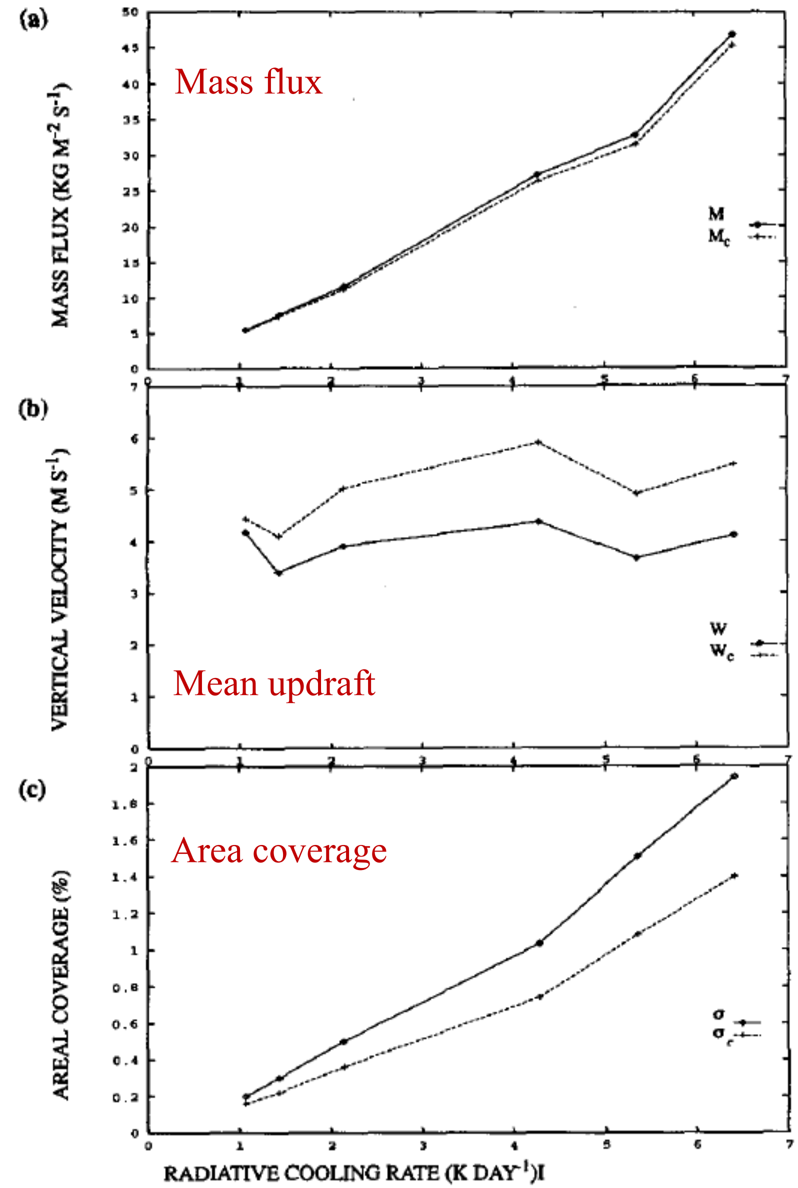

FIG. 7. Time mean of cloud properties at 6.75 km of altitude, plotted as a function of the cooling rate, R, and logarithmic curve fits. (a) Upward cloud mass flux M and convective mass flux M_c. (b) Mean upward velocity $\overline{w}$ and mean convective velocity $\overline{w}_c$ in the clouds. (c) Areal coverage of cloudy updrafts σ and of convective updrafts σ_c (units are in percentages of the total area).

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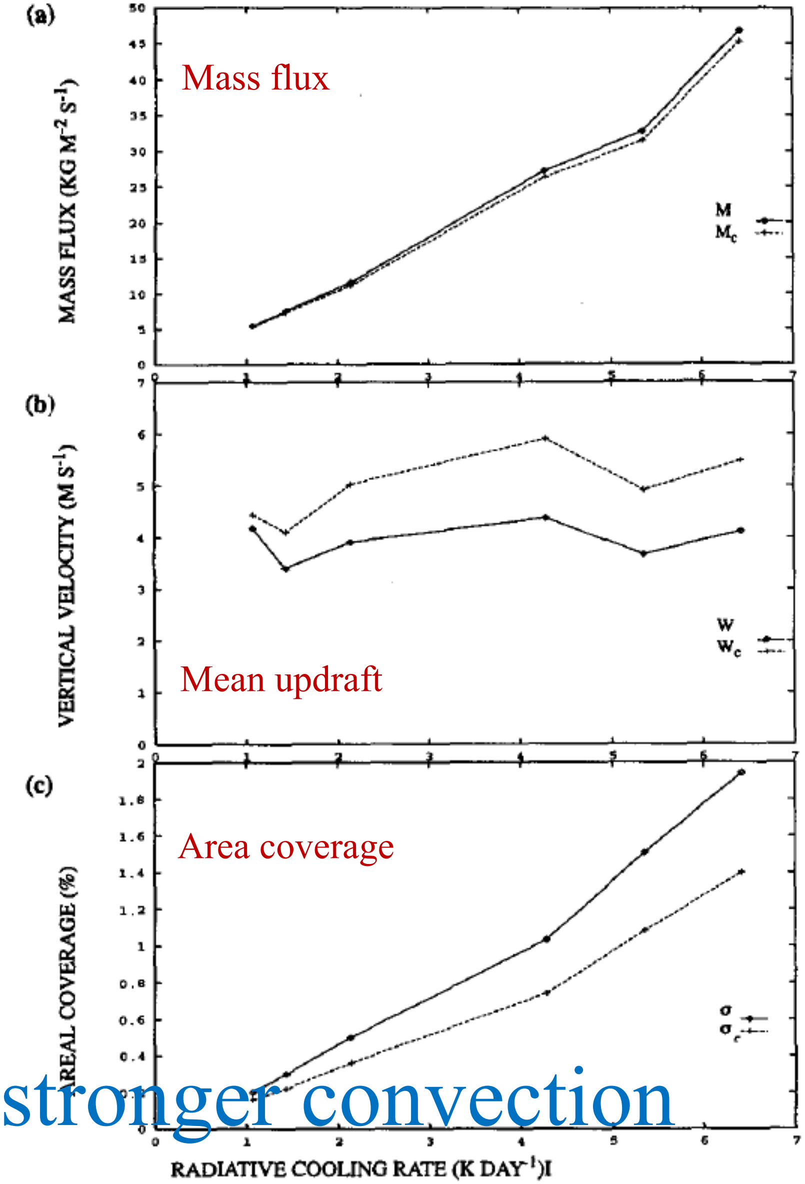

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more convection, NOT stronger convection

One may argue that documenting aerosol effects of deep convections should be relatively simple in observations. In fact, there are several studies that attempted that (examples to follow).

However, there are two key problems:

- Correlations between aerosol and convection do not imply causality: aerosols and meteorology can co-vary.

- Atmospheric observations may not be accurate enough to eliminate meteorological factors, see Grabowski (*JAS* 2018).

Observations: correlation does not imply causality!

Couple examples of erroneous interpretation of observations:

Li et al. (*Nature Geo* 2011) show correlation between clouds and aerosols over ARM SGP site; they say in the abstract:

"…precipitation frequency and rain rate are altered by aerosols"

Varble (*JAS* 2018) shows that aerosols and meteorology co-vary at SGP!

Storer et al. (*JGR* 2014) show correlation between aerosol and tropical convection over Atlantic; they say in the abstract:

"These observations suggest that convective invigoration occurs with increased aerosol loading, leading to deeper, stronger storms in polluted environments"

Lightning enhancement over major oceanic shipping lanes

GRL 2017

Joel A. Thornton[1], Katrina S. Virts[2], Robert H. Holzworth[3], and Todd P. Mitchell[4]

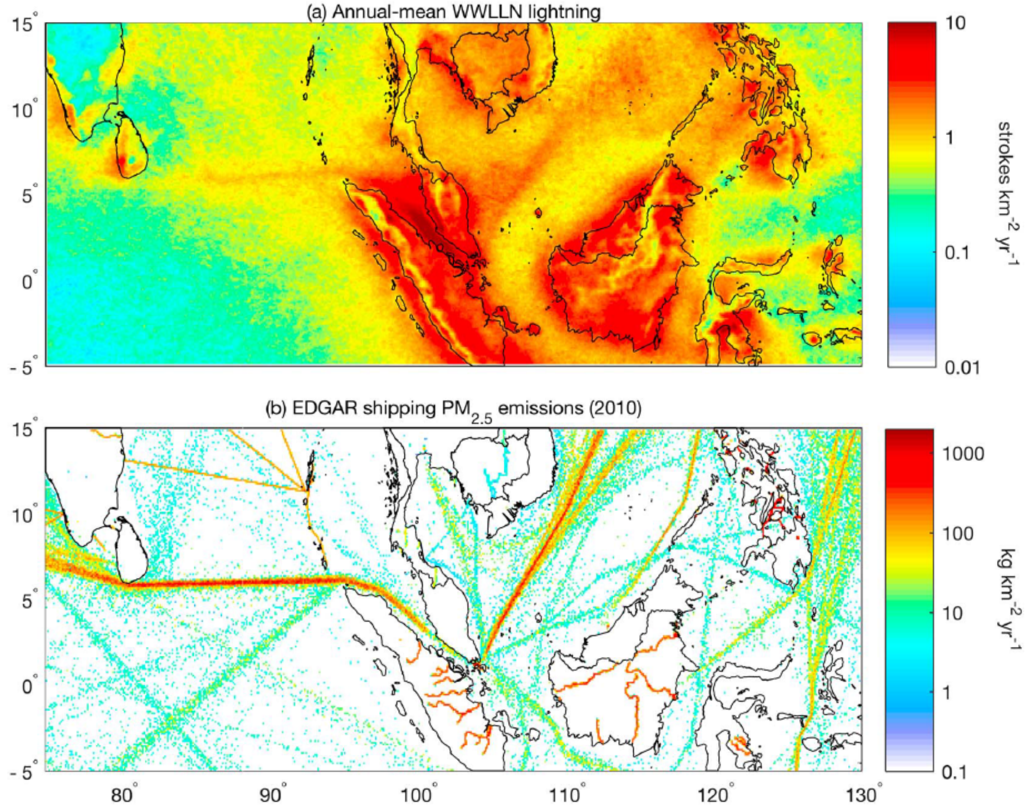

Figure 1. (a) Observed annual-mean WWLLN lightning density for 2005–2016 in the eastern Indian Ocean and the South China Sea. (b) $PM_{2.5}$ shipping emissions estimates from EDGAR database for 2010, both at 0.1° resolution. See text and SI for more details.

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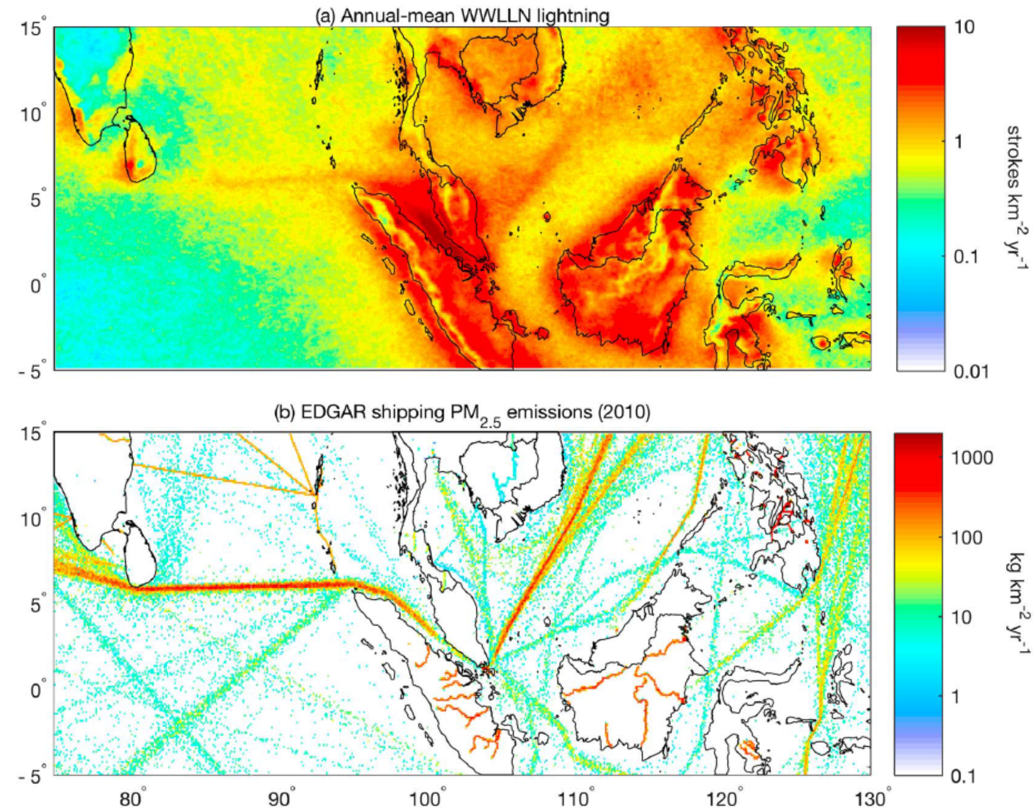

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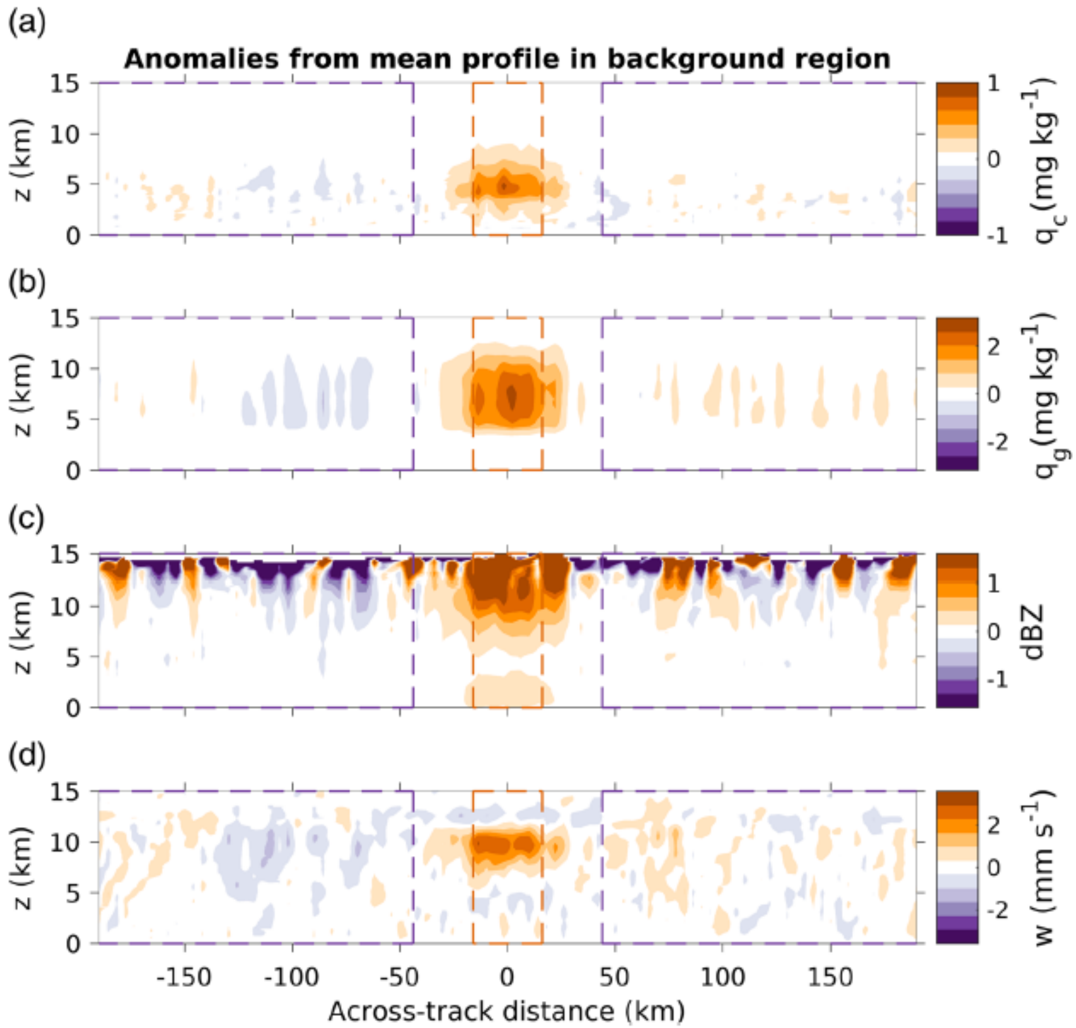
"We conclude that aerosol particles resulting from ship exhaust enhance CCN, which invigorate convection and ice processes above the shipping lanes, leading to enhanced lightning. …"

Locally Enhanced Aerosols Over a Shipping Lane Produce Convective Invigoration but Weak Overall Indirect Effects in Cloud-Resolving Simulations

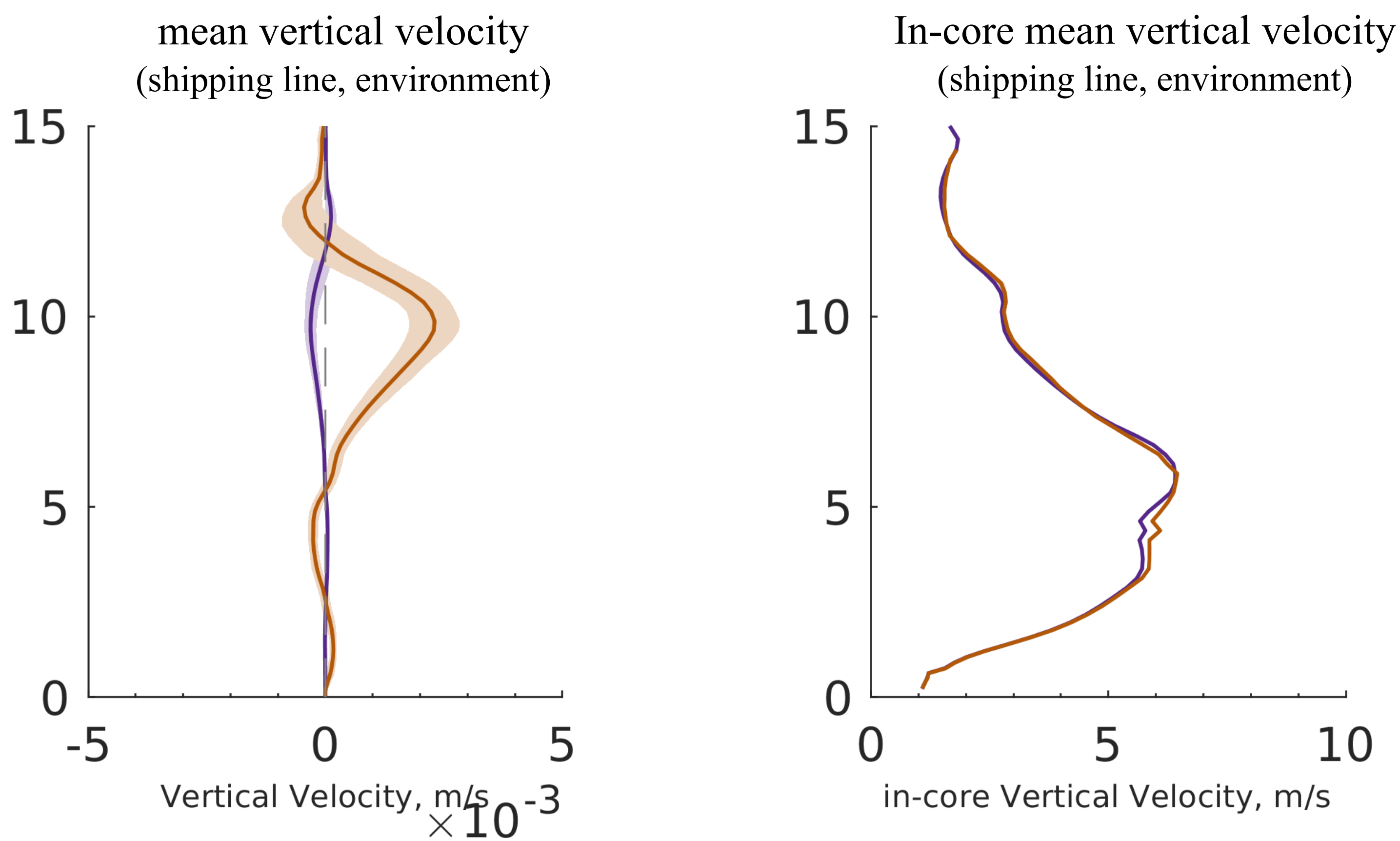
GRL 2018

Peter N. Blossey[1], Christopher S. Bretherton[1,2], Joel A. Thornton[1], and Katrina S. Virts[3]

30-day long 3D simulation over ~(400km)^2 domain with 1 km grid length and shipping lane in the middle, 29 degC SST…



Additional analysis of the simulations dataset (P. Blossey, personal communication; not included in the GRL paper):



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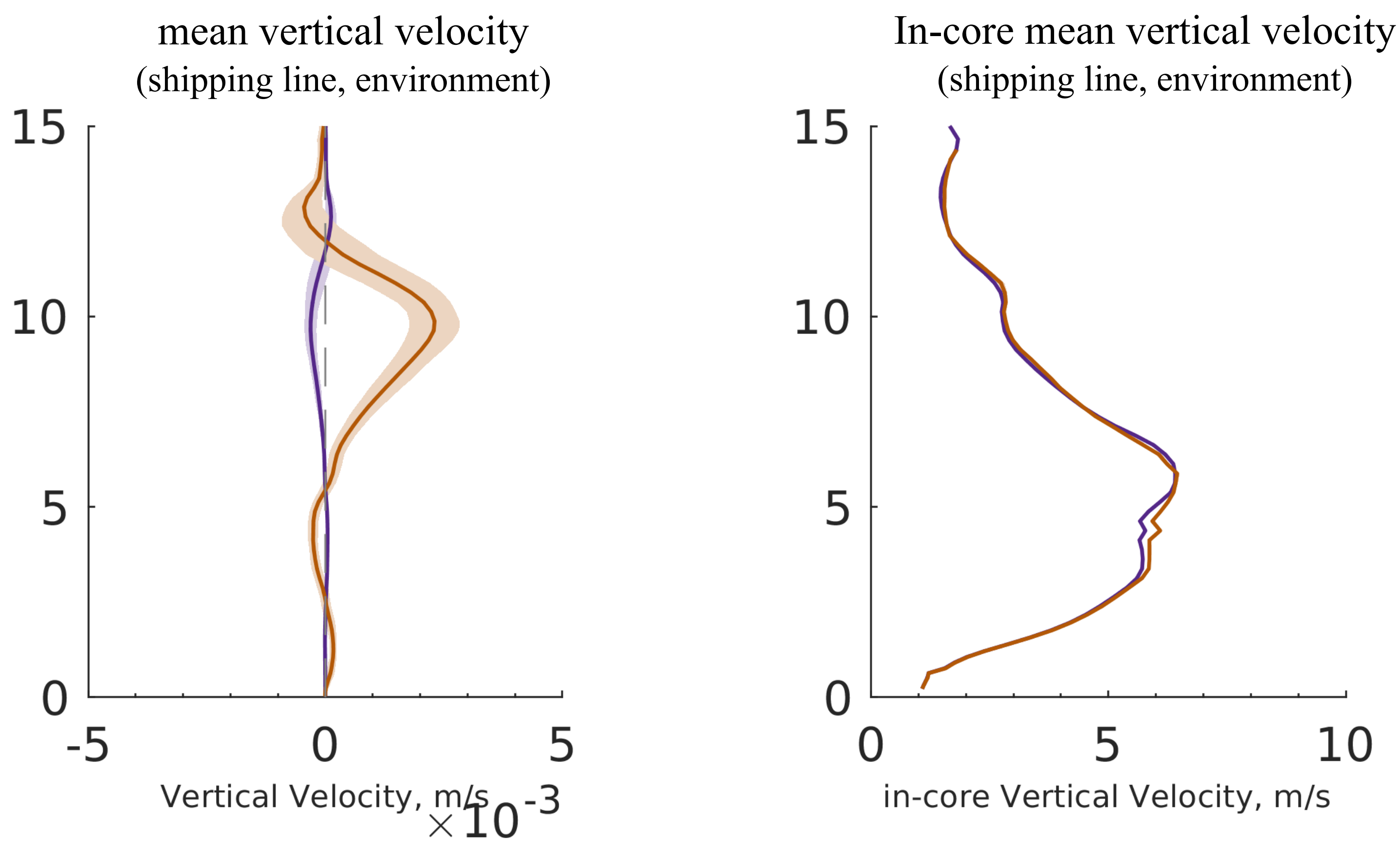

“more convection”, no “stronger convection”…

Grabowski and Morrison *JAS* 2020

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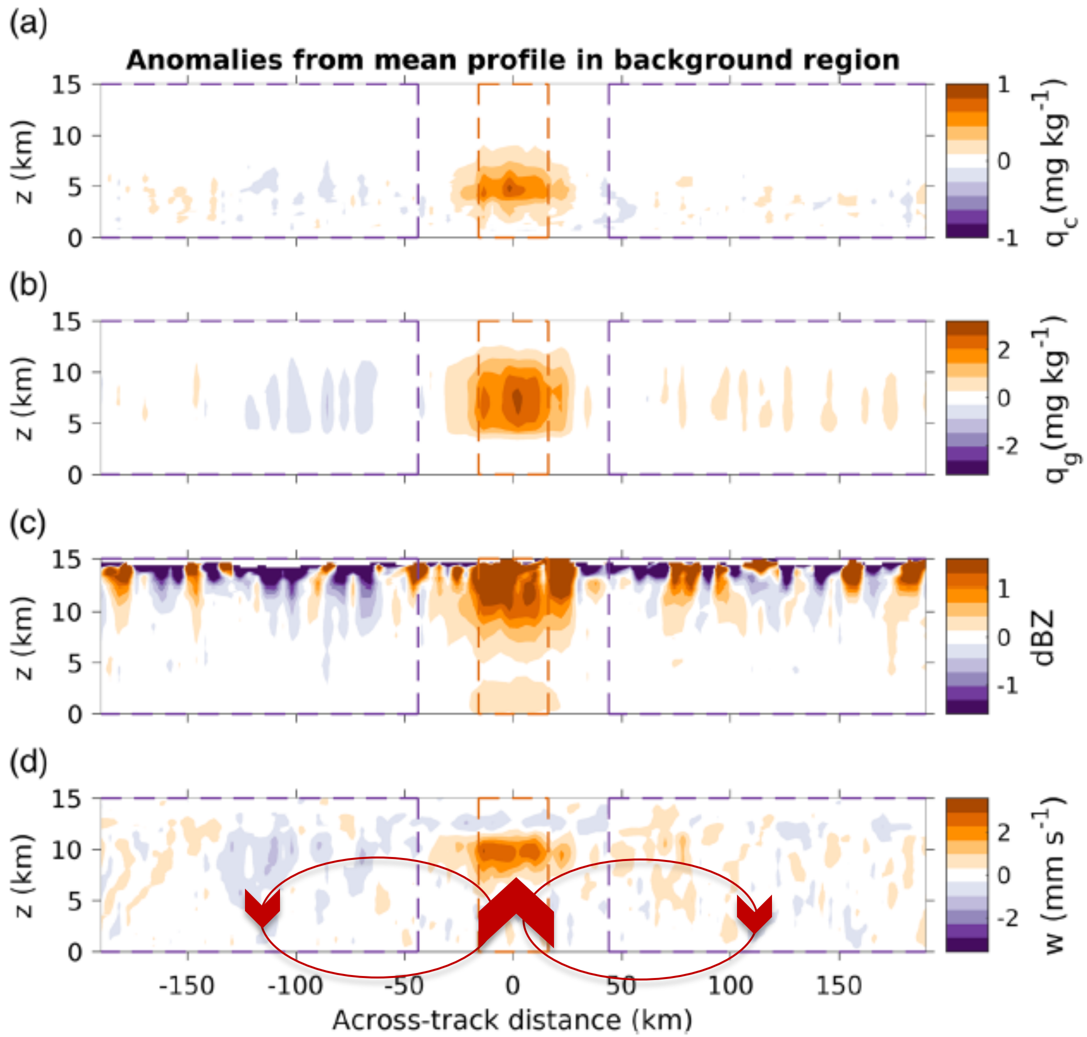


mesoscale circulation!!!

See also Morrison and Grabowski (*ACP* 2011)

Atmos. Chem. Phys., 12, 709–725, 2012
www.atmos-chem-phys.net/12/709/2012/
doi:10.5194/acp-12-709-2012

Atmospheric Chemistry and Physics

Aerosol-cloud-precipitation effects over Germany as simulated by a convective-scale numerical weather prediction model

A. Seifert[1], C. Köhler[1,2], and K. D. Beheng[3]

[1]Deutscher Wetterdienst, Offenbach, Germany
[2]Deutsches Zentrum für Luft- und Raumfahrt, Institut für Physik der Atmosphäre,Oberpfaffenhofen, Germany
[3]Karlsruher Institut für Technologie, Institut für Meteorologie und Klimaforschung, Karlsruhe, Germany

Correspondence to: A. Seifert (axel.seifert@dwd.de)

Received: 6 July 2011 – Published in Atmos. Chem. Phys. Discuss.: 18 July 2011
Revised: 5 December 2011 – Accepted: 8 January 2012 – Published: 16 January 2012

2008, 2009, 2010 summers (JJA) convection-permitting (~3 km grid length) 48-hour hindcasts using COSMO-DE

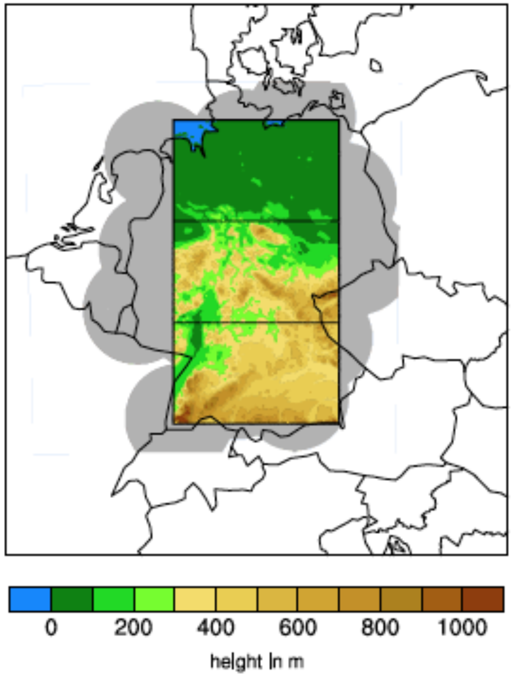


Fig. 1. COSMO-DE model domain, with insertions of coverage of the German radar composite (grey), and the three evaluation sub-domains with the model orography.

Table 3. Experiments performed for this study. The data can be accessed from DWD using the database IDs given here for individual experiments and years.

No.	ID in database 2008	2009	2010	microphysics scheme	CCN	IN
1	7544	7451	7895	two-moment	high	low
2	7545	7452	7899	two-moment	low	low
3	7547	7454	7954	two-moment	high	high
4	7907	7906	7955	two-moment	low	high
5	7546	7453	8013	two-moment	high	very low
6	8056	8055	8026	two-moment	low	very low
7	7483	7450	7897	one-moment	–	–

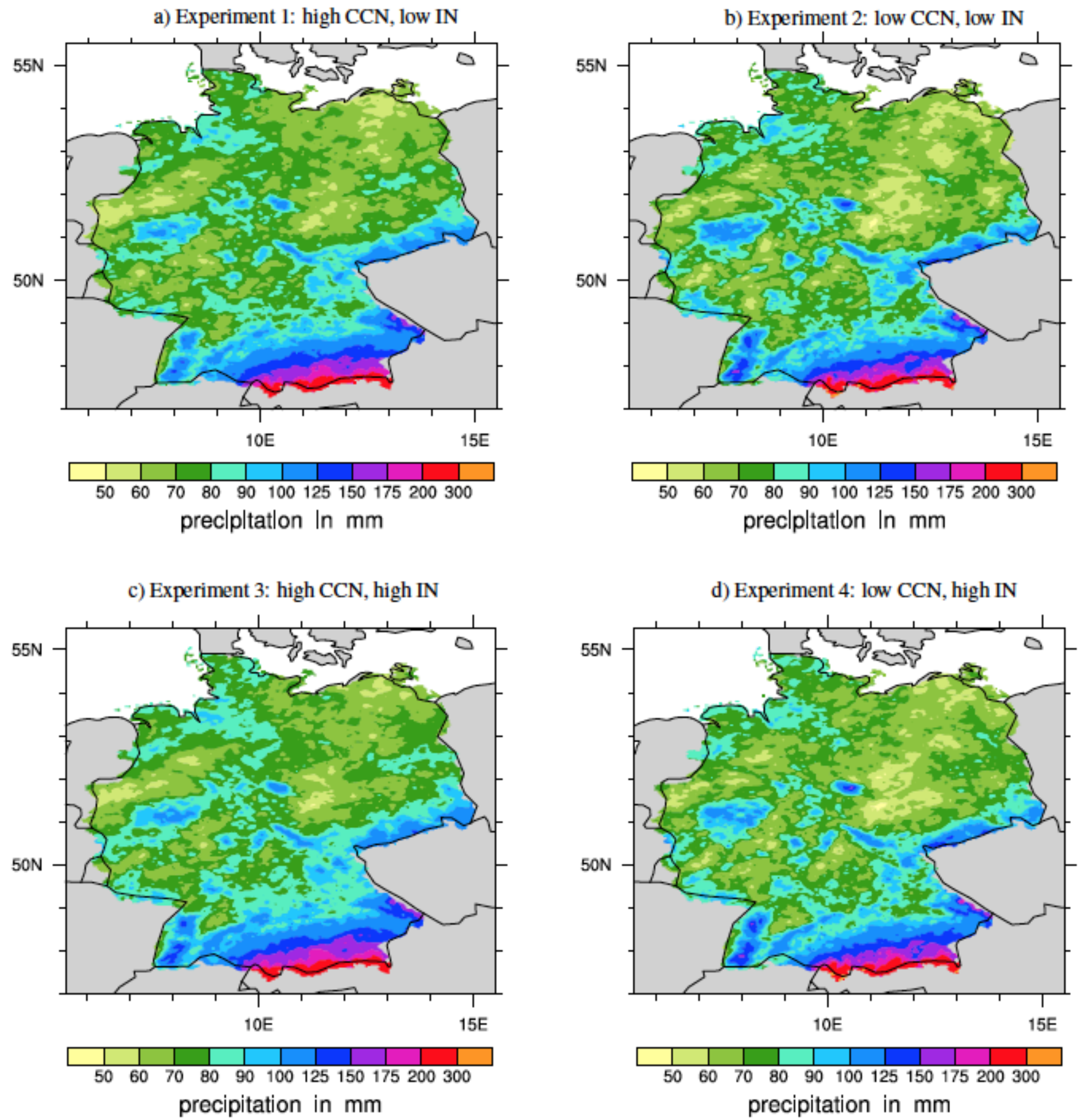


Fig. 5. Monthly mean precipitation amount of JJA 2008–2010 for experiments 1–4 combined from 06:00–18:00 h hindcasts initialized at 00:00 and 12:00 UTC.

A rather insignificant impact of aerosols (CCN and IN) on mean rain accumulation!

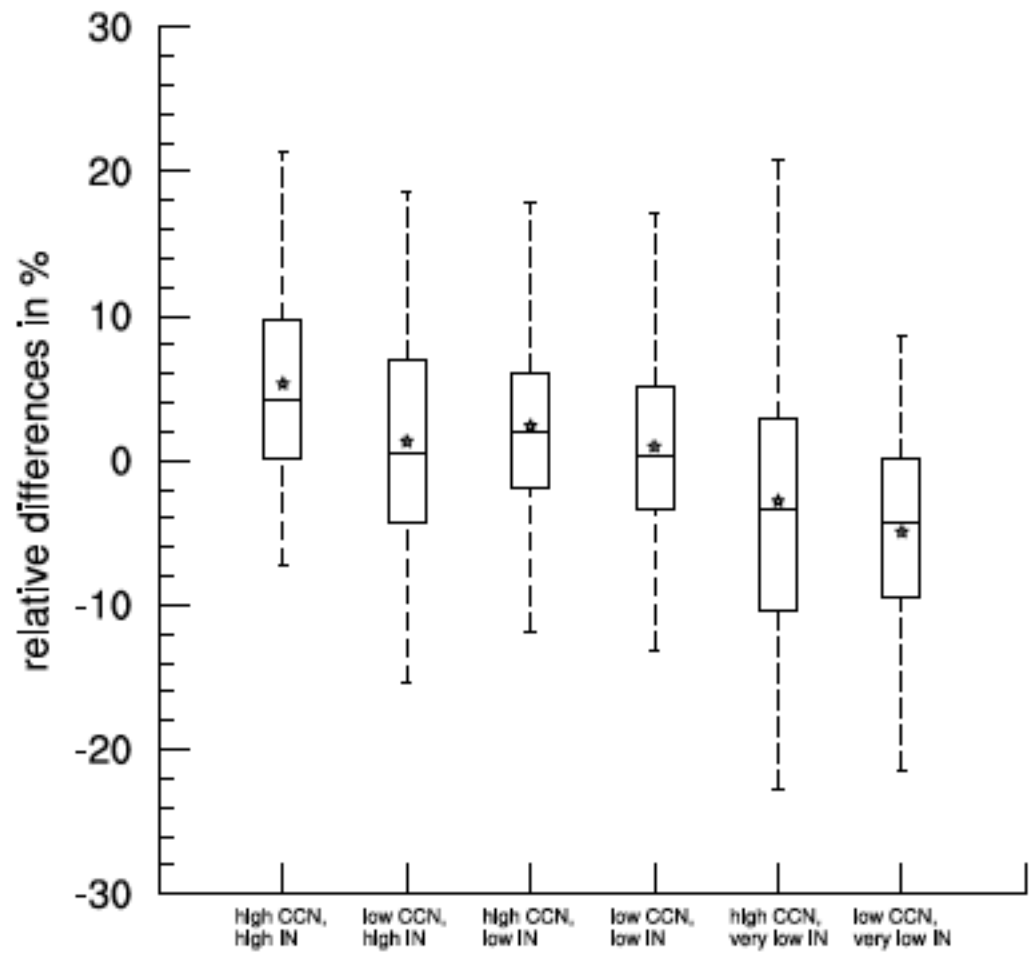
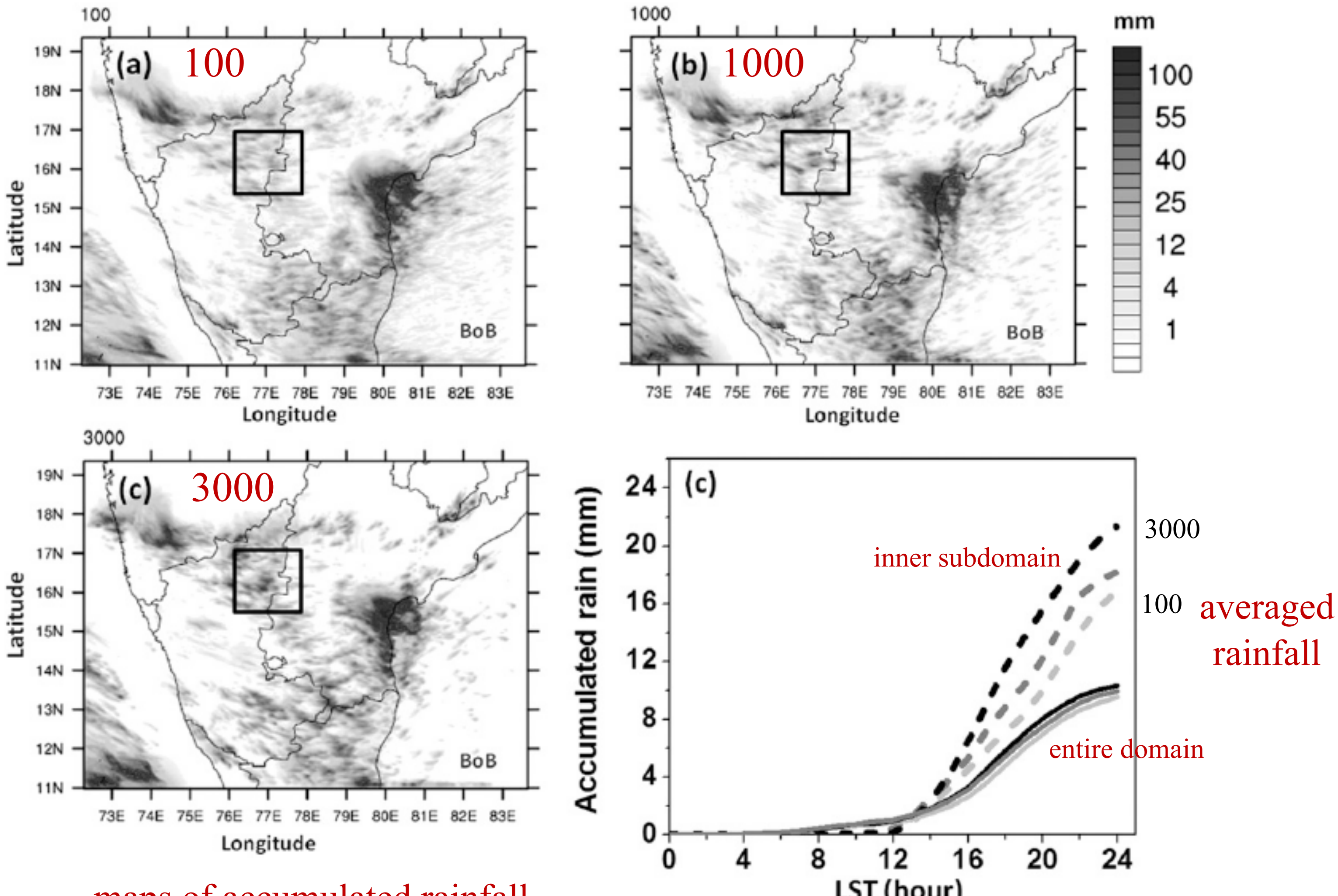


Fig. 9. Box-whisker plot of relative change of 12-h accumulated area-averaged precipitation of JJA 2008–2010. Shown are anomalies relative to the mean of Exps. 1–6. The precipitation data has been averaged over either one of the three subdomains. The bottom and top of the boxes are the lower and upper quartiles, the line near the middle of the boxes is the median, whiskers are the 5th and 95th percentiles and the stars represent the mean value.

Separation of physical impacts from different flow realizations: three 24-hr simulations with CCN of 100, 1000, and 3000 per cc

Aerosol–Cloud Interaction in Deep Convective Clouds over the Indian Peninsula Using Spectral (Bin) Microphysics

Gayatri et al. *JAS* 2017



maps of accumulated rainfall

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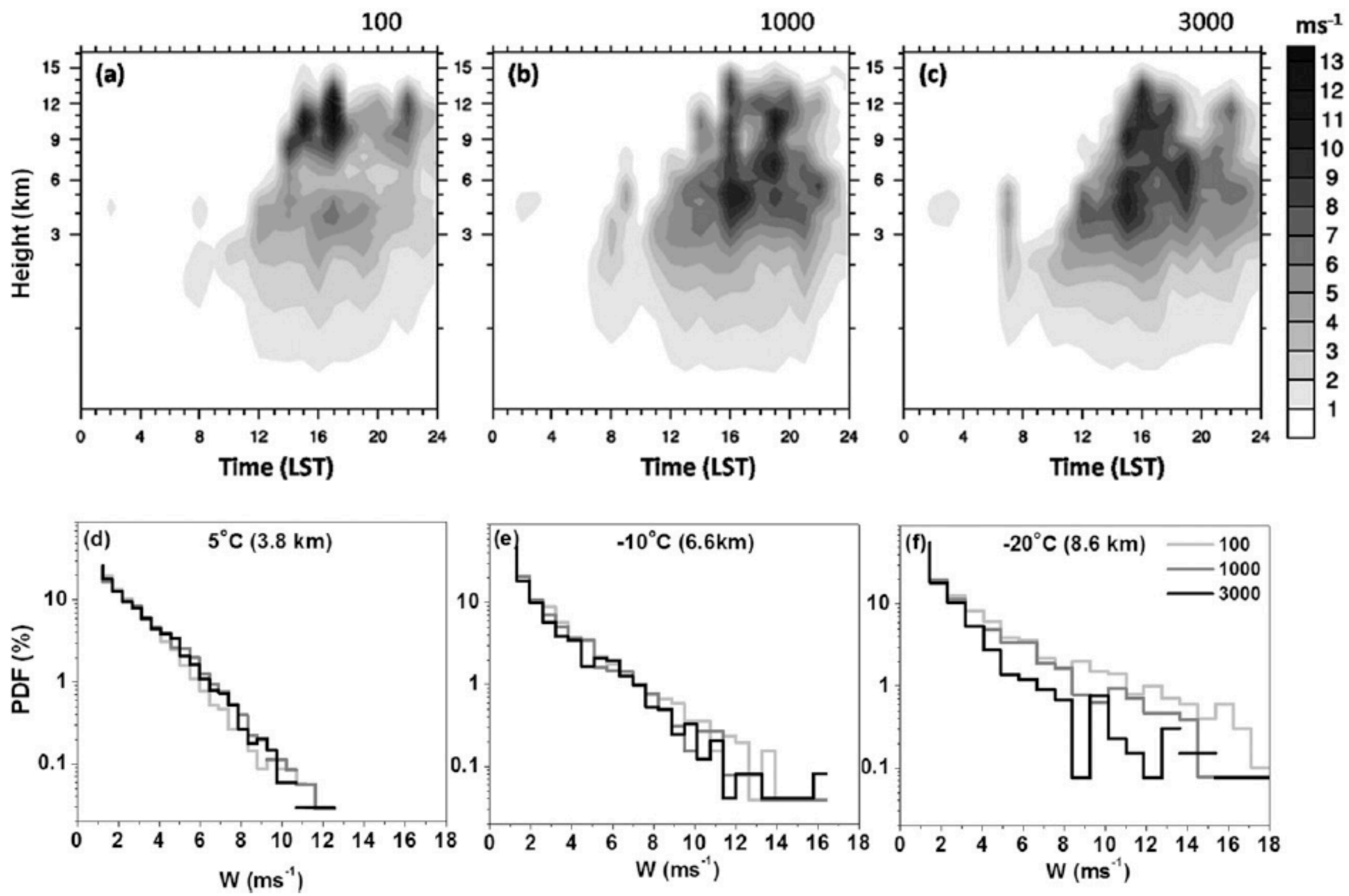

FIG. 11. (top) Time evolution of vertical profiles of simulated maximum updraft in the selected study region for CCN concentrations of (a) 100, (b) 1000, and (c) 3000 cm^{-3} where updrafts are greater than 1 $m\,s^{-1}$. (bottom) PDFs (%) over the whole domain at (d) 5°, (e) −10°, and (f) −20°C during 1500–1800 LST are also shown.

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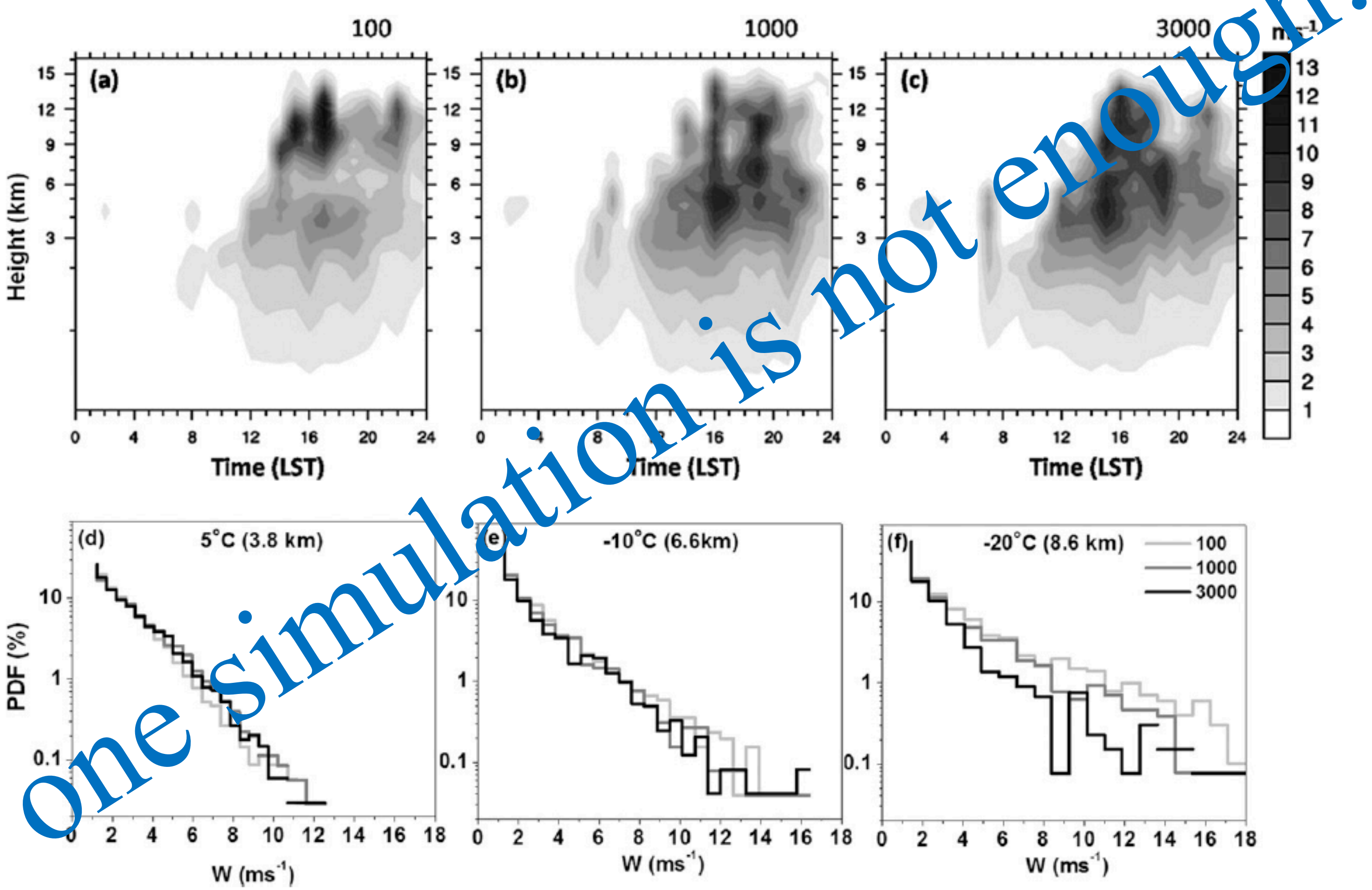

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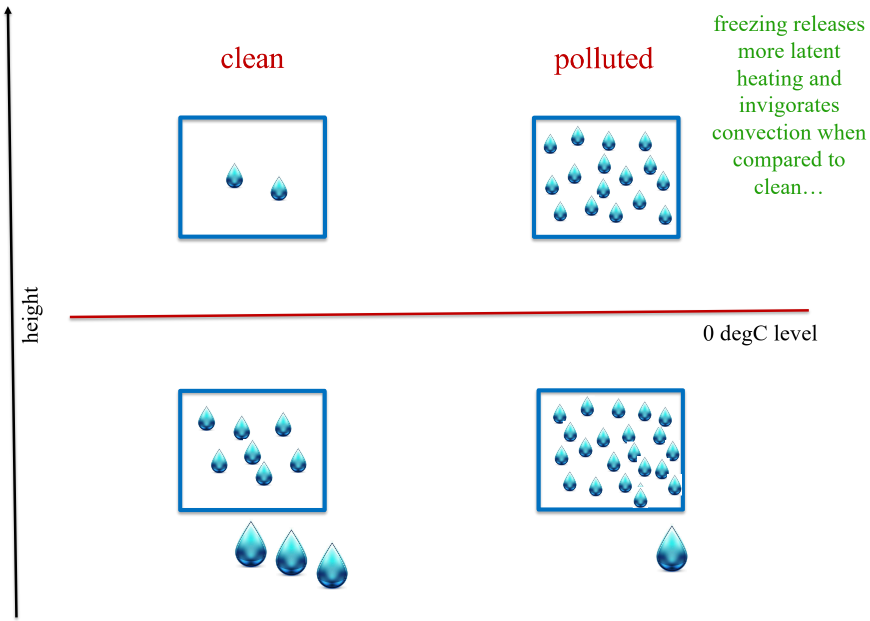
Is that really possible?



Liquid condensate freezing: the impact of latent heating approximately balances loading effect:

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δq – change of cloud water mixing ratio

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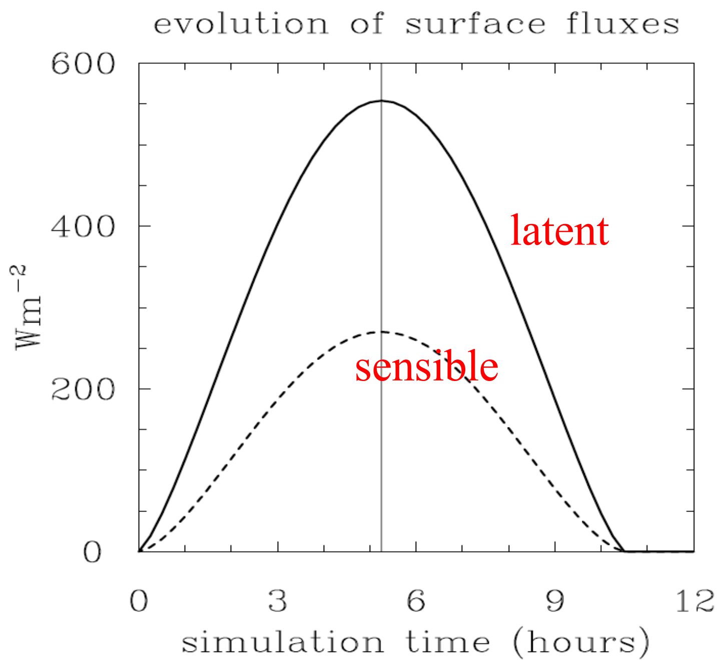
If the mechanism works, it should be seen even in simulations with simple warm-rain microphysics…

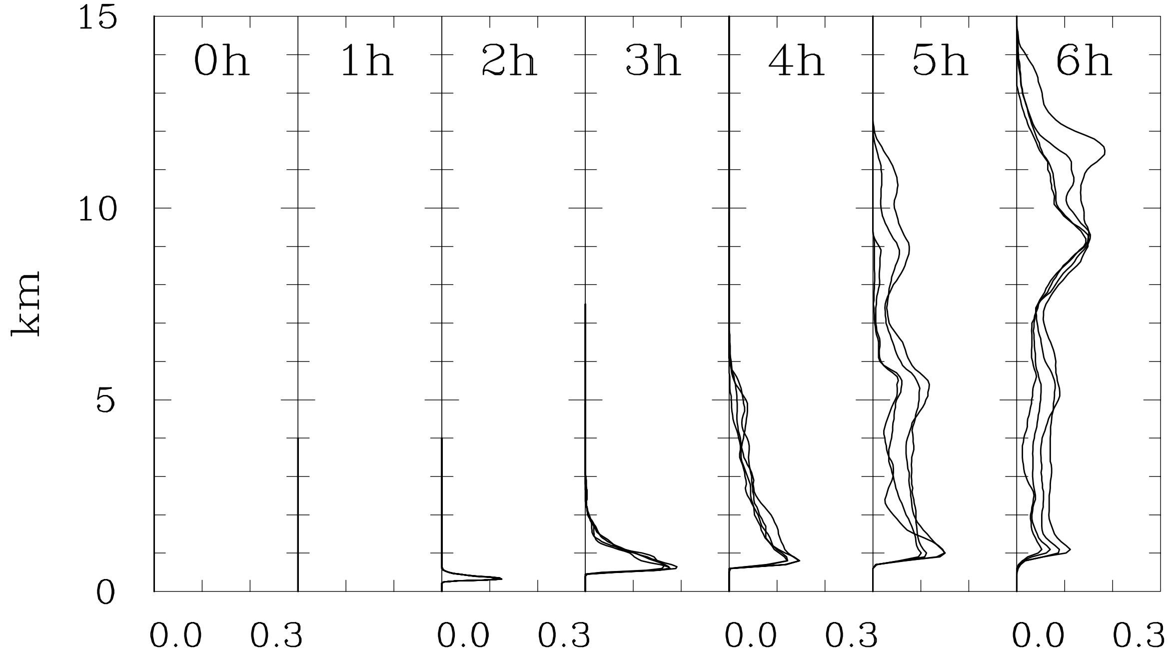
Q. J. R. Meteorol. Soc. (2006), **132**, pp. 317–344 doi: 10.1256/qj.04.147

Daytime convective development over land: A model intercomparison based on LBA observations

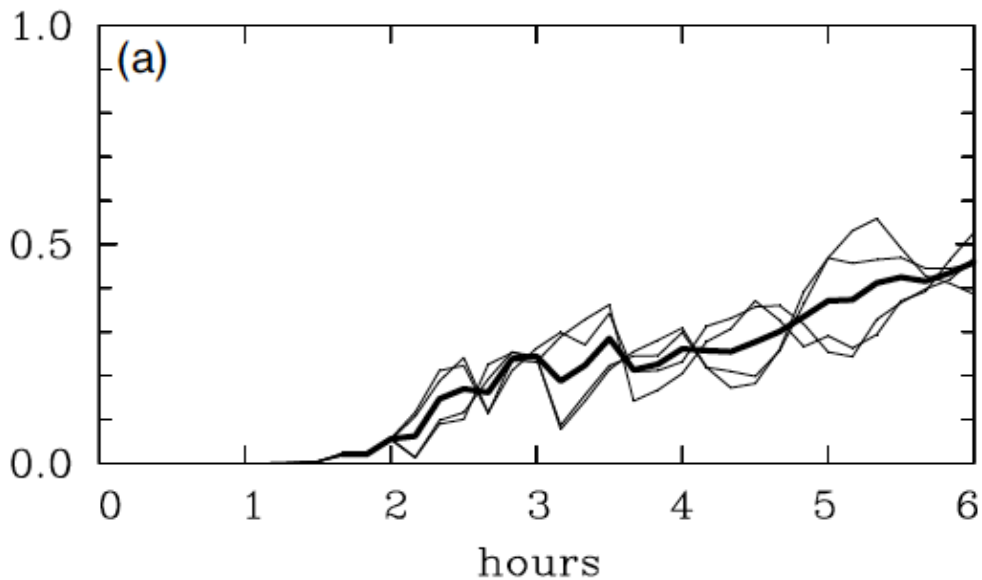
By W. W. GRABOWSKI[1]*, P. BECHTOLD[2], A. CHENG[3], R. FORBES[4], C. HALLIWELL[4], M. KHAIROUTDINOV[5], S. LANG[6], T. NASUNO[7], J. PETCH[8], W.-K. TAO[6], R. WONG[8], X. WU[9] and K.-M. XU[3]



Daytime development of deep convection based on observations in Amazonia…



evolution of cloud fraction profiles



evolution of cloud cover

Grabowski et al. (QJ 2006)

Cloud-resolving simulations of LBA shallow to deep convection transition with 1-moment bulk (Grabowski *AR* 1999) and 2-moment bulk (Morrison and Grabowski *JAS* 2008, 2009) microphysics:

- 50 x 50 x 24 km^3 domain;

- 400 m horizontal gridlength;

- stretched grid in the vertical: 81 levels, ~50 m near the surface, ~300 m in the middle troposphere, ~600 m near the upper boundary;

- run for 12 hours, 3D fields saved every 6 min, time-averaged surface rain rate saved every 3 min.

Grabowski (*JAS* 2015), Grabowski and Morrison (*JAS* 2016, 2020)

1-moment warm-rain and ice scheme (IAB):

Grabowski (*AR* 1999) applied in Grabowski (2015)

saturation adjustment; prescribed droplet concentrations (100 vs 1000 per cc; affects drizzle/rain formation; ice properties only weakly linked to droplet concentration; PRI vs POL

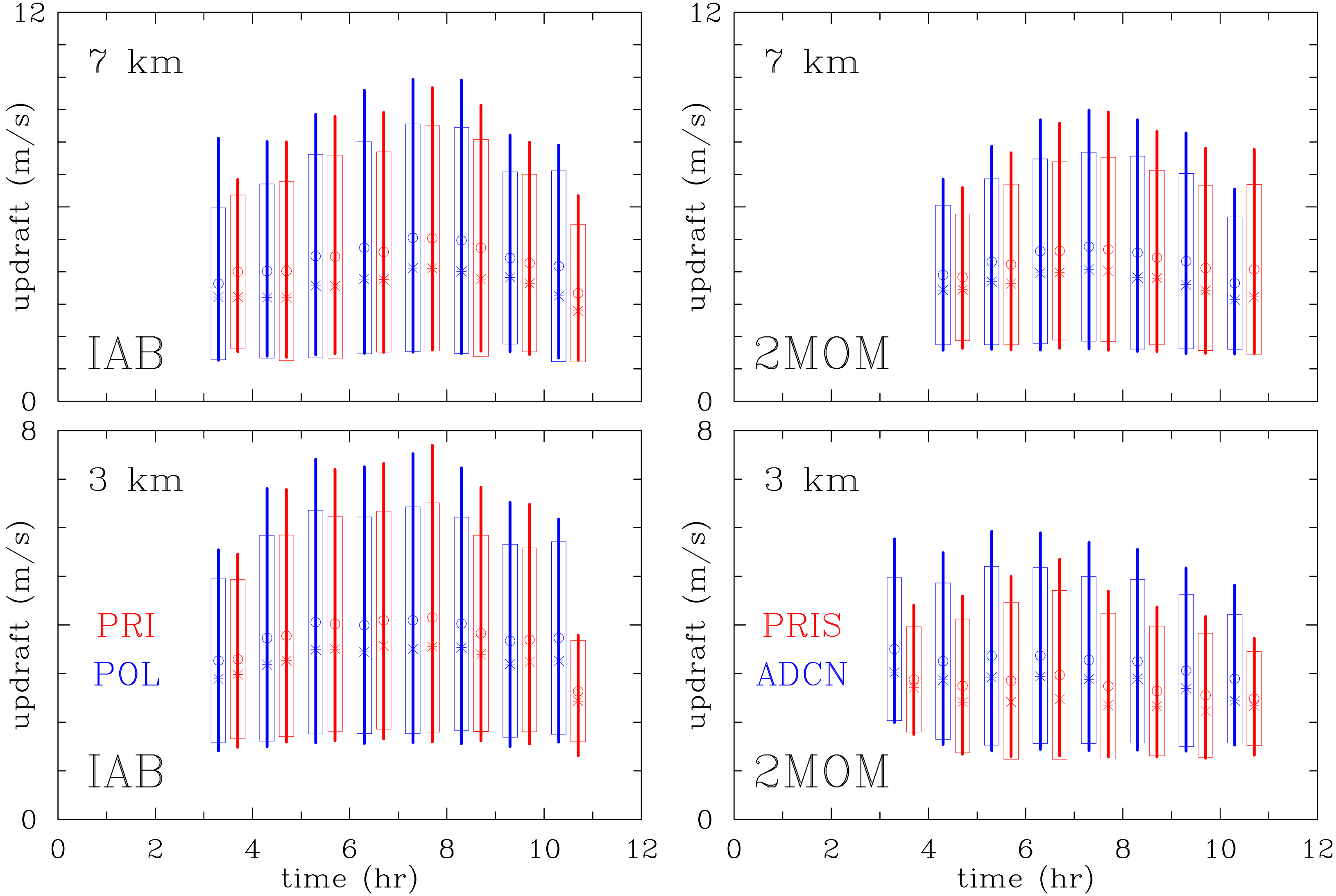
2-moment bulk warm-rain and ice scheme (2MOM):

Morrison and Grabowski (*JAS* 2008, 2009) applied in Grabowski and Morrison (2016, 2020)

supersaturation predicted; droplet concentration predicted from assumed CCN (pristine PRIS vs additional CCN ADCN) and local conditions; 3-variable ice scheme (concentration + 2 mixing ratios) directly linked to droplet concentrations

updraft statistics at 3km (10 degC) and 7 km (-12 degC) for w > 1m/s, q > 1 g/kg

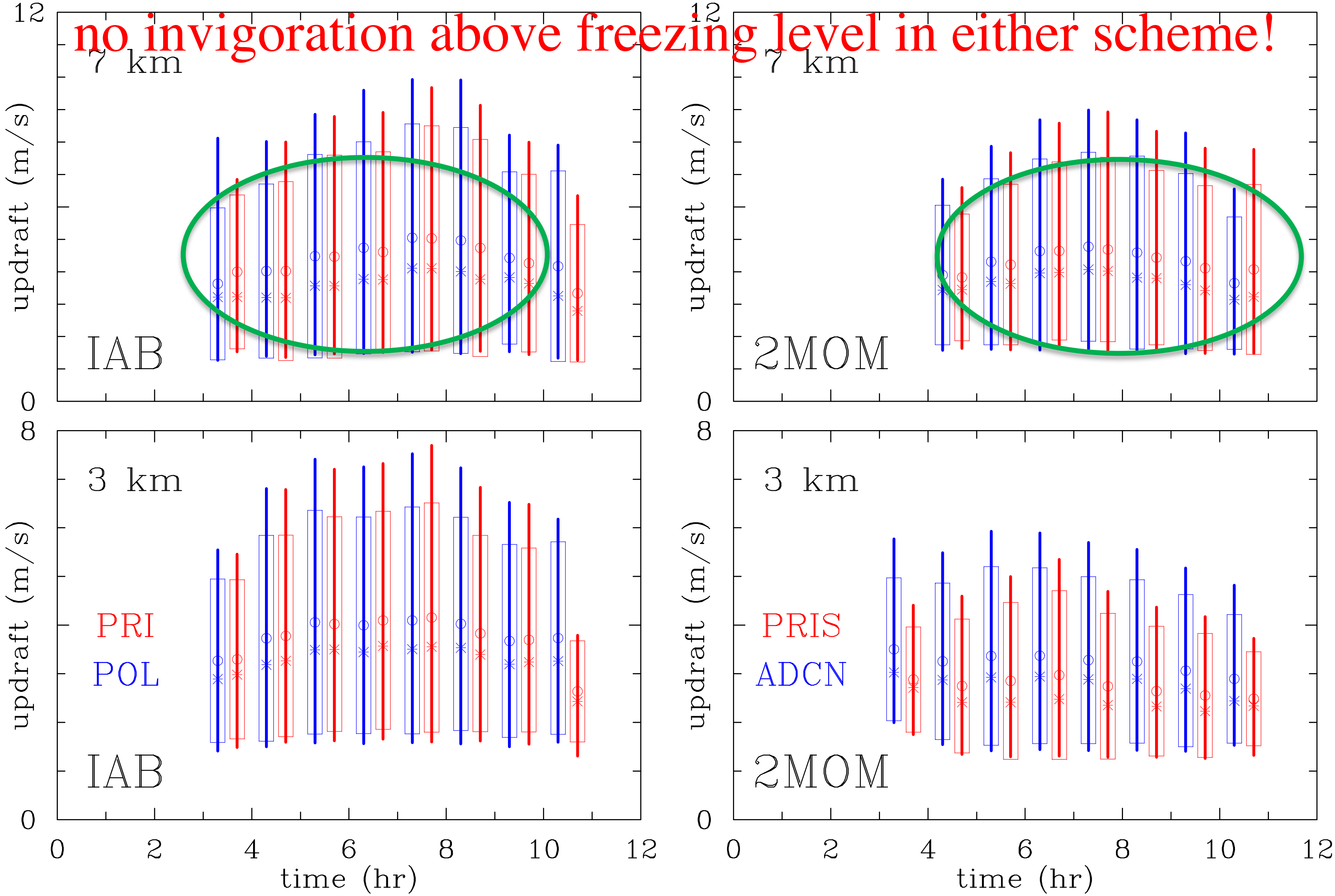
median and mean
lines: 10^{th}-90^{th} percentile;
boxes: mean ± st. dev.



Grabowski (2015)

Grabowski and Morrison (2020)

updraft statistics at 3km (10 degC) and 7 km (-12 degC) for w > 1m/s, q > 1 g/kg



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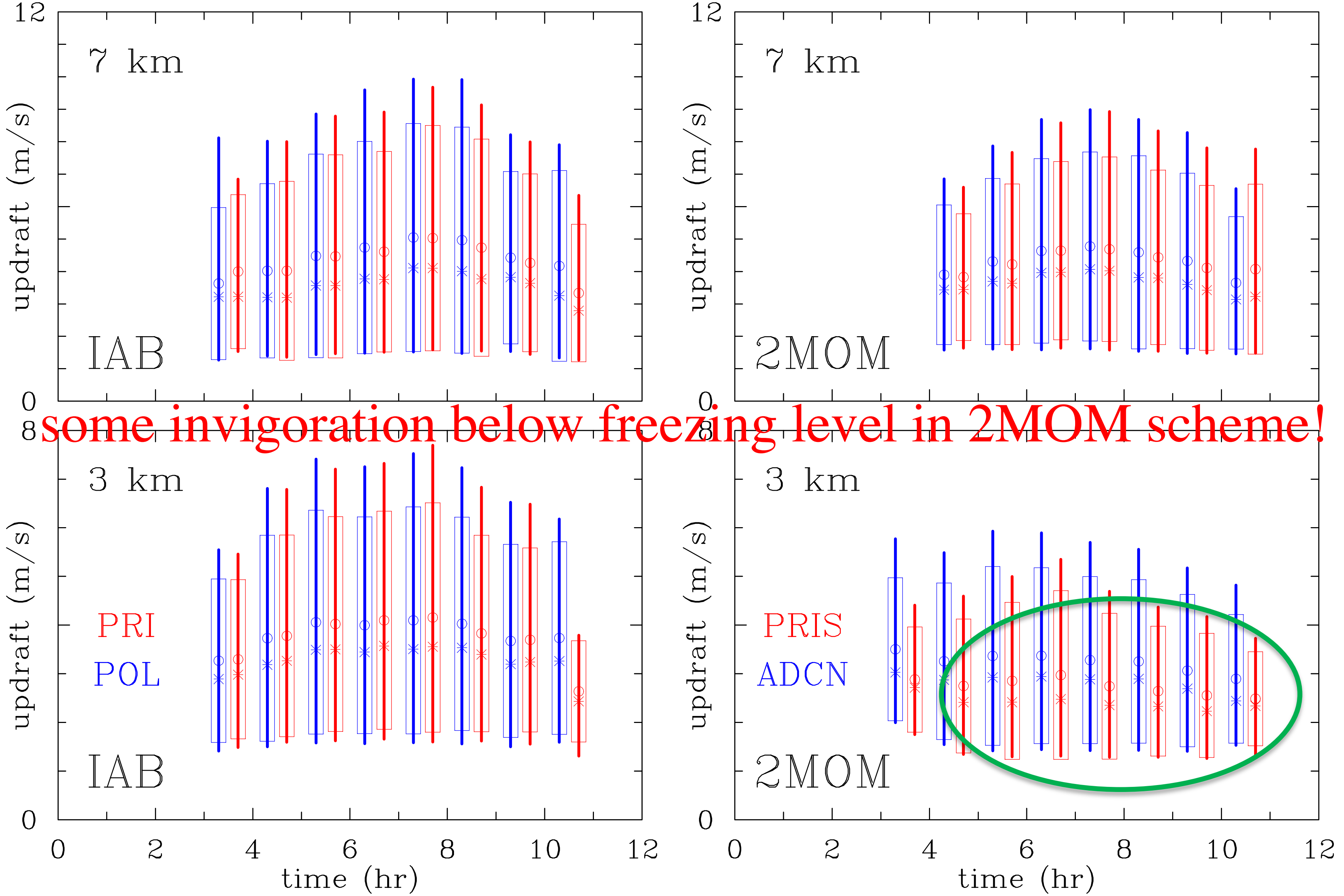
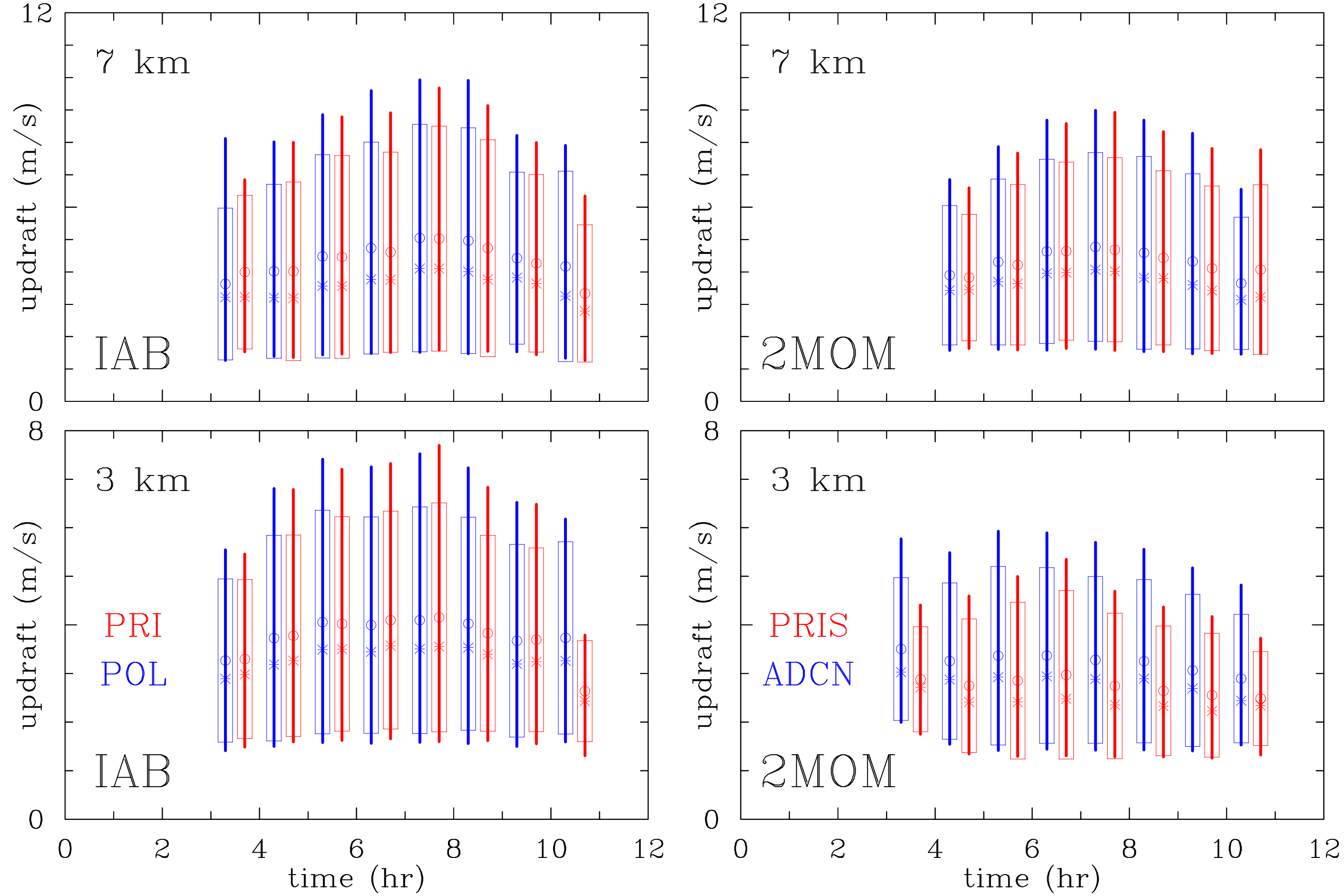


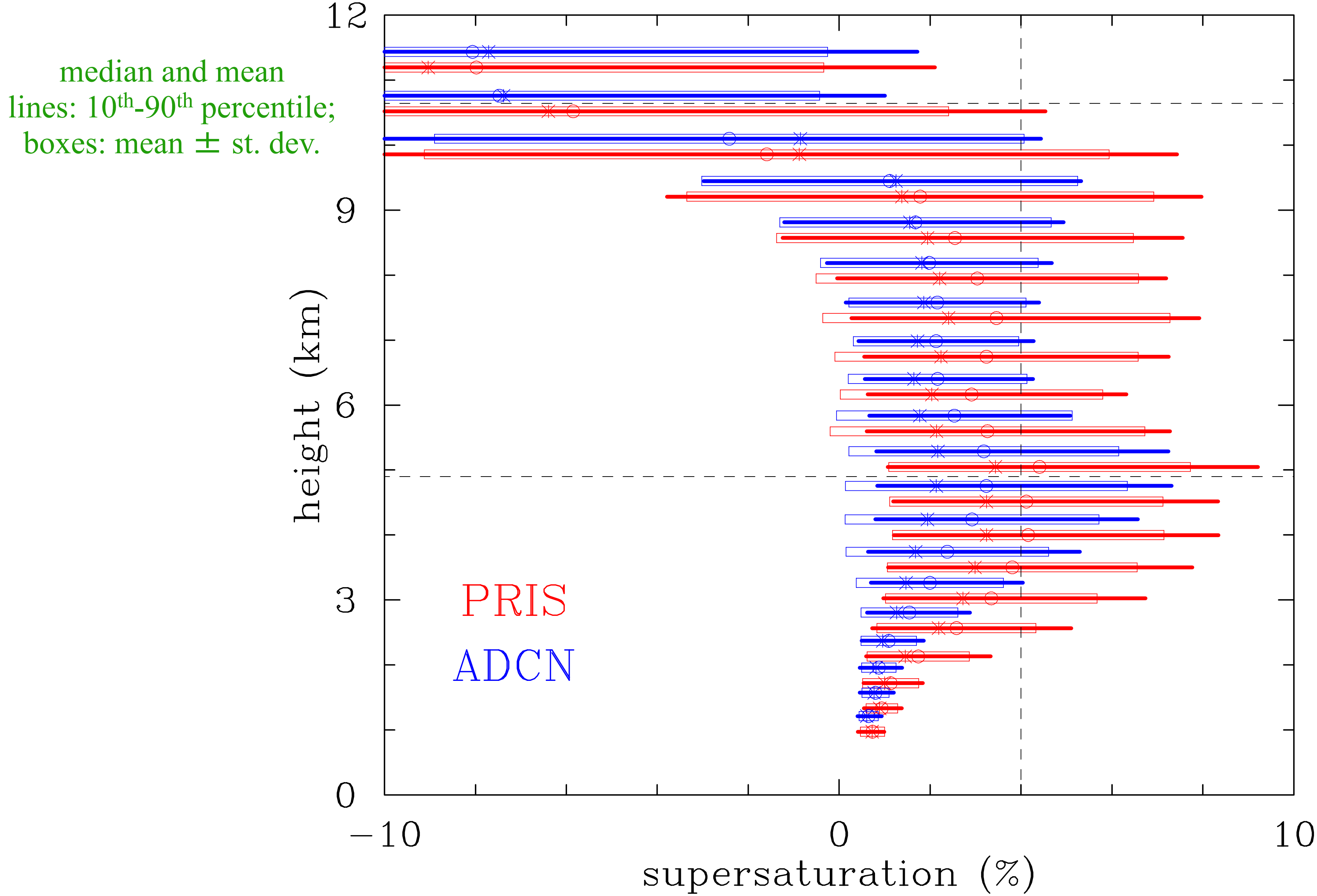
some invigoration below freezing level in 2MOM scheme!

updraft statistics at 3km (10 degC) and 7 km (-12 degC) for w > 1m/s, q > 1 g/kg



microphysics parameterization does matter!

Supersaturation statistics for all updraft points; hours 6 and 7 (strongest convection)



Grabowski and Morrison (2020)

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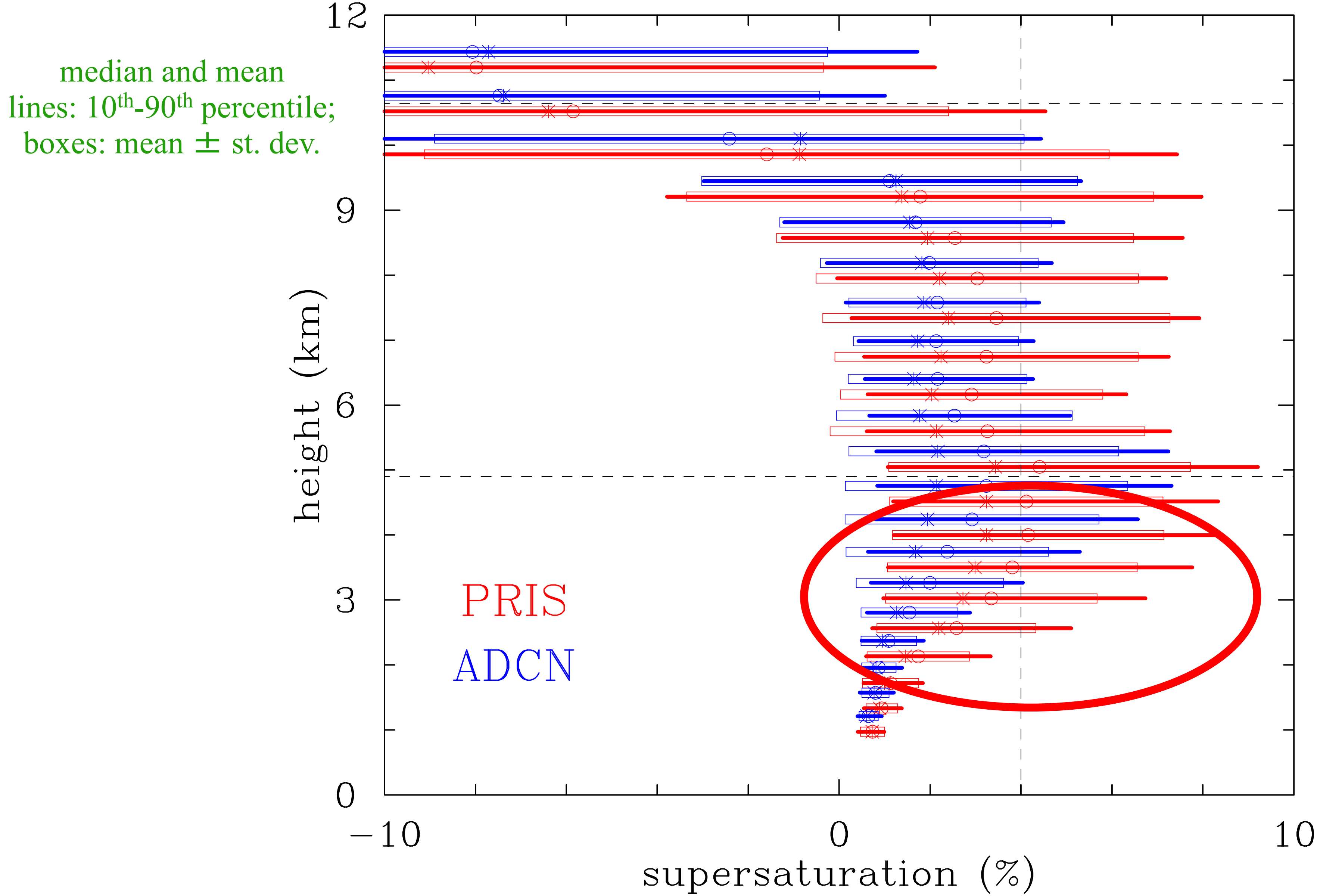
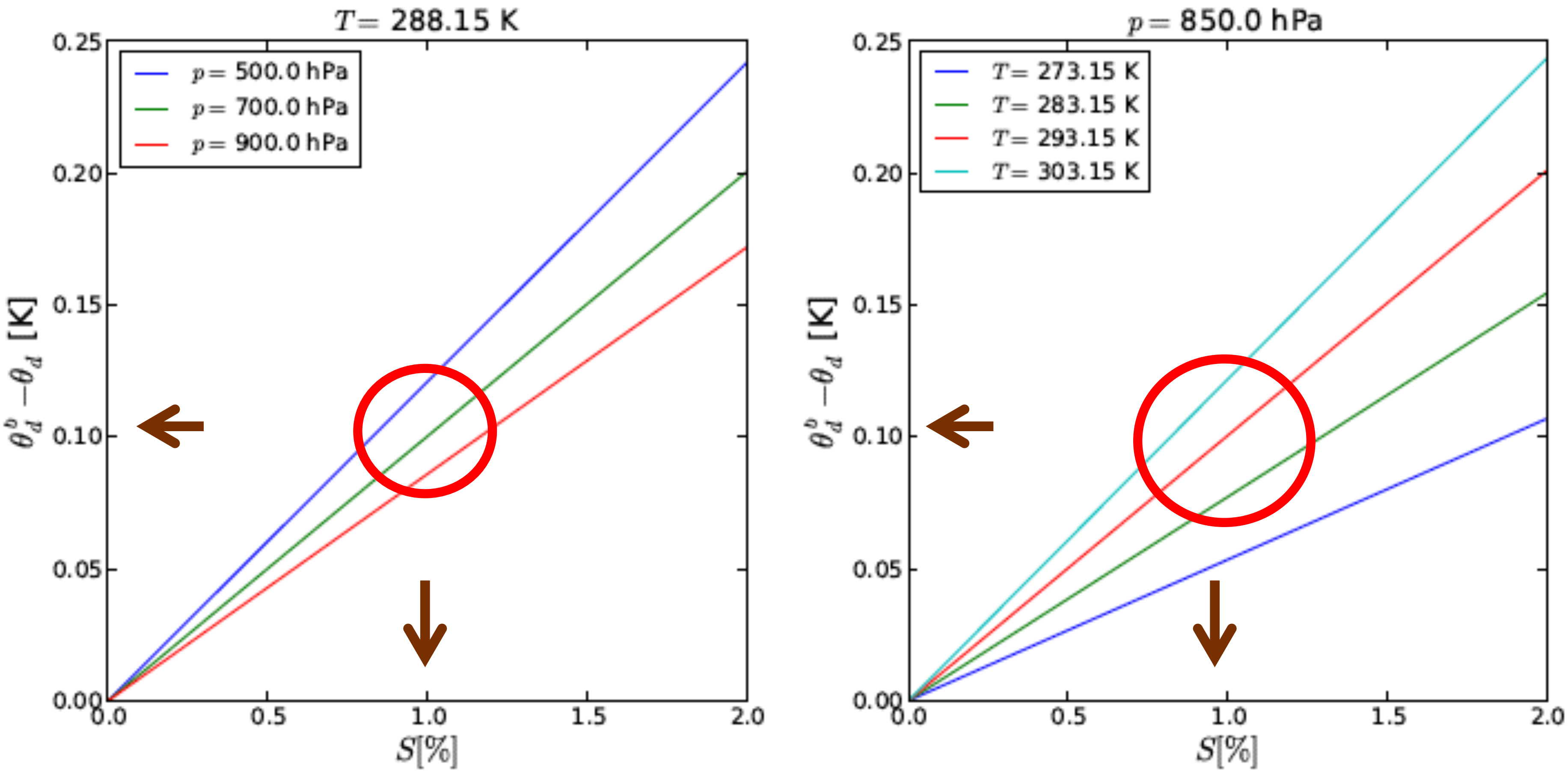


Grabowski and Morrison (2020)

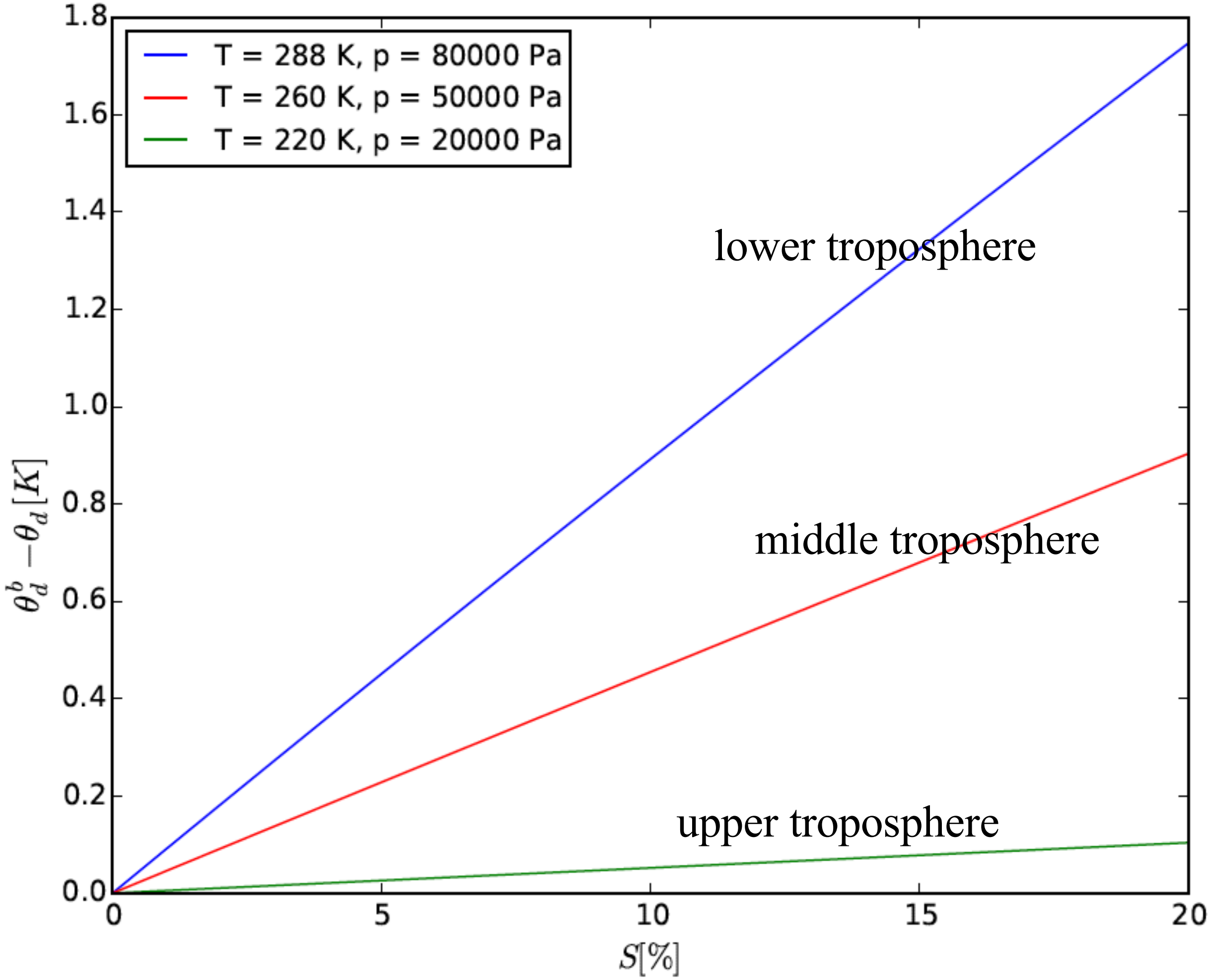
Comparing Θ_d with finite supersaturation with Θ_d at S=0, Θ_d^b



1% supersaturation ≈ 0.1 K density temperature reduction

Grabowski and Jarecka (*JAS*, 2015)

Comparing Θ_d with finite supersaturation with Θ_d at S=0, Θ_d^b



10% supersaturation ~ 0.5 K density temperature reduction

Grabowski and Morrison (*JAS*, 2017)

Summary:

PRI versus POL simulations in Grabowski and Morrison (*JAS* 2016) and PRIS vs ADCN in Grabowski and Morrison (*JAS* 2020) with 2-moment bulk scheme:

- **small modification of the cloud dynamics in the warm-rain zone due to differences in the supersaturation field;**
- **no invigoration above the freezing level;**
- **significant *microphysical* impact on convective anvils: higher droplet concentrations leading to higher ice concentrations, small ice terminal velocities and longer anvil life times.**

In summary, I strongly believe that the convection invigoration is a myth, at least in the way it is presented in papers by Danny Rosenfeld and his colleagues (e.g., Rosenfeld et al. *Science* 2008, Fan et al. *Science* 2018).