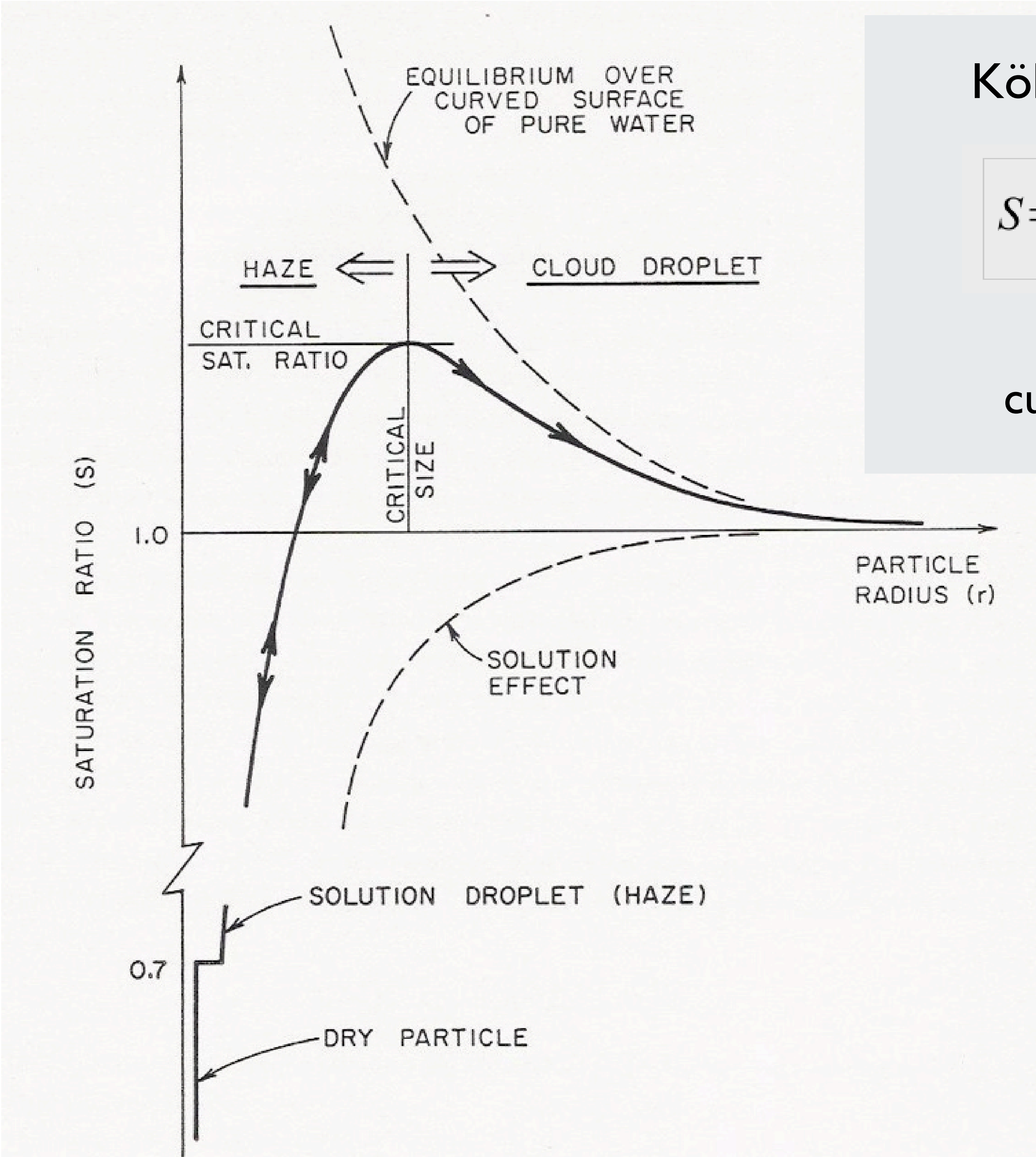
Clouds and precipitation

- quick review of basic ideas
- topics of debate
- impacts of uncertainties in cloud physics

Gabor Vali - University of Wyoming

with many contributions; my own where no other reference given

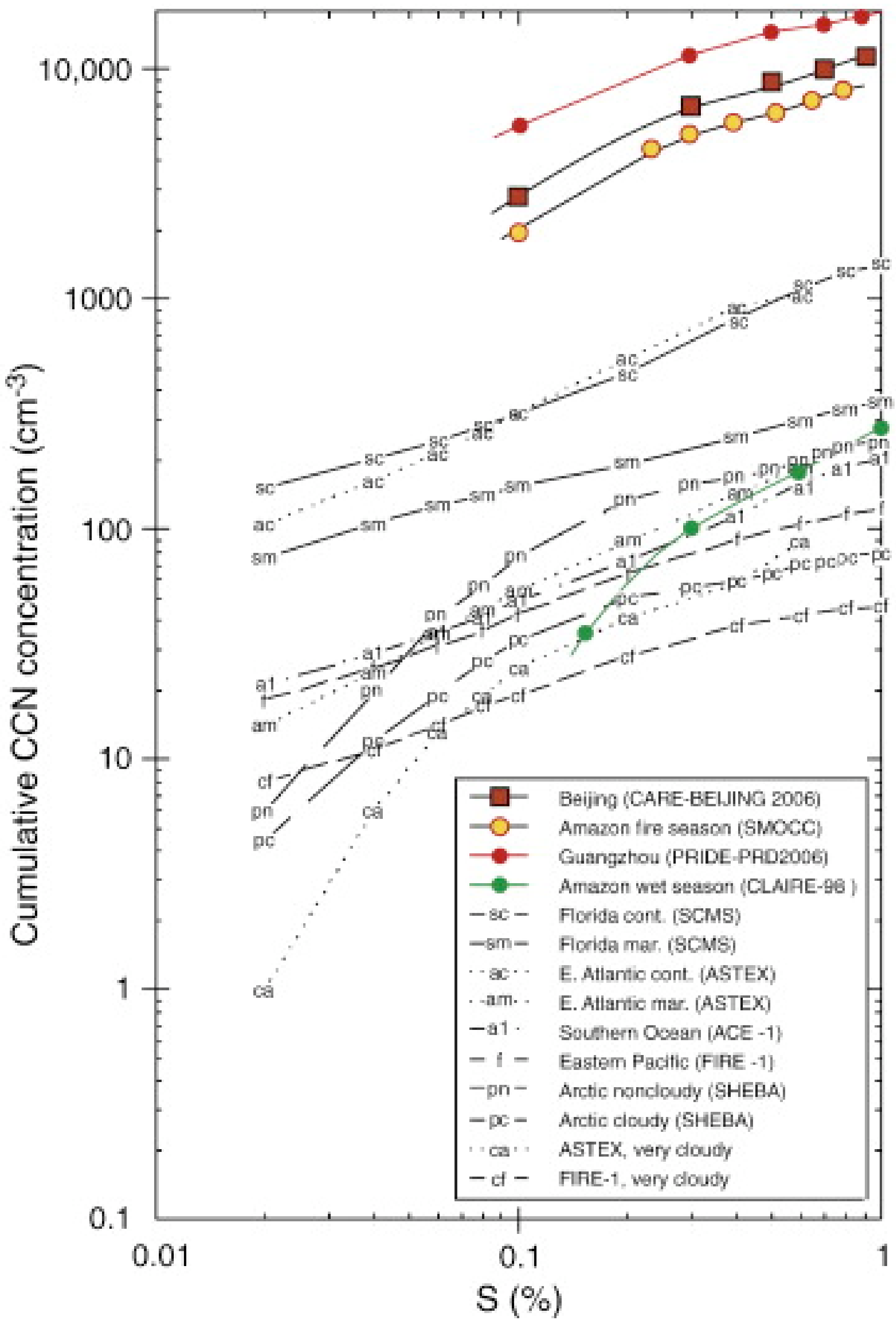
aerosol → cloud droplet



Köhler theory

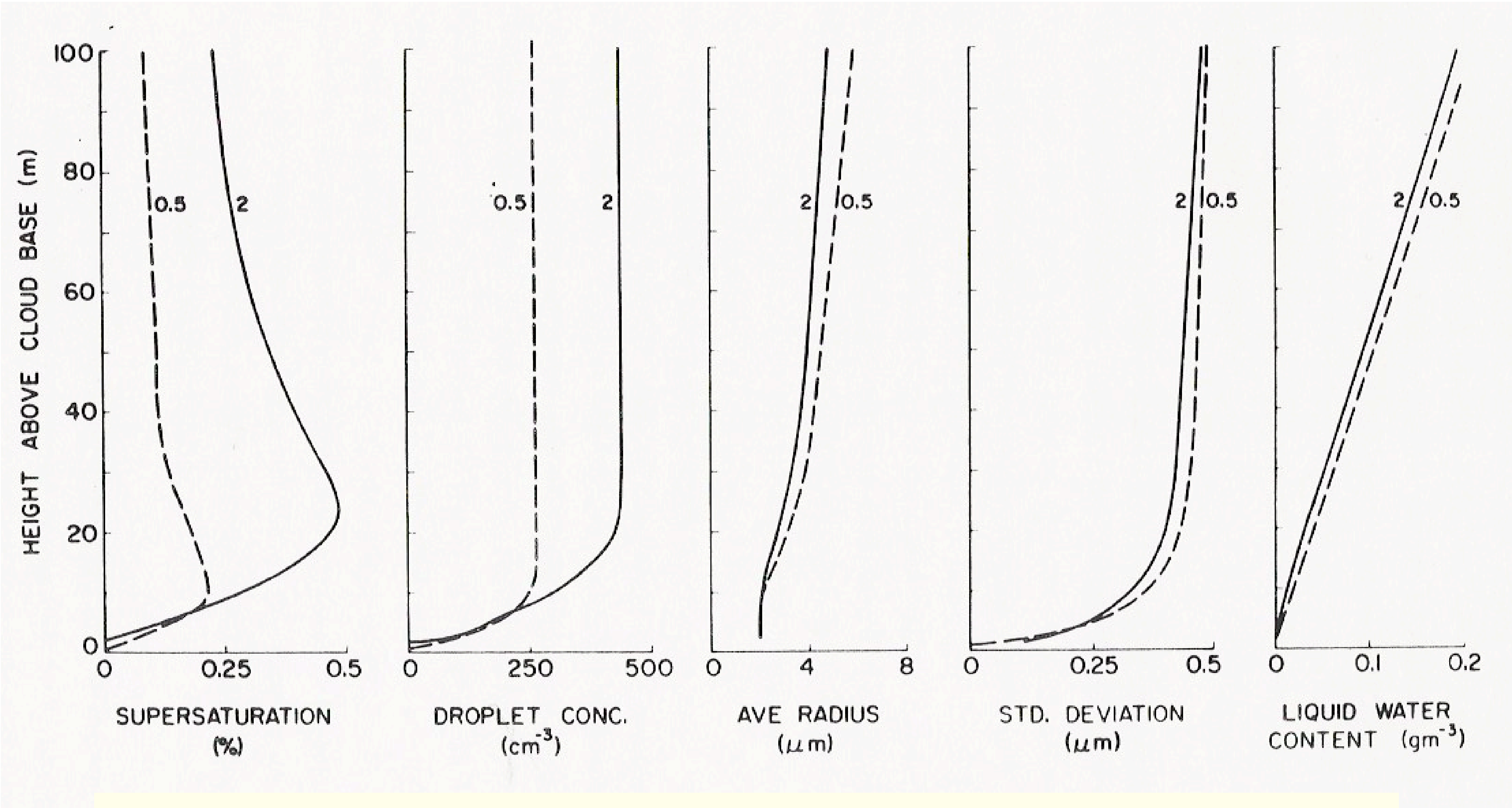
$$S = 1 + \frac{A}{r} - \frac{B}{r^3}$$

curvature　　solution



$$N = C\,S^k$$

Andreae & Rosenfeld, 2008, *Earth Sci. Rev.* **89**, 13-41



Supersaturation due to competition between adiabatic lifting versus uptake of water vapor by a population of cloud condensation nuclei. Supersaturation reaches a maximum close to cloud base at which point the droplet number reaches a stable level.

$$N \approx a\,C^{(2/k+2)}\left[b\,w^{1.5}\right]^{(k/k+2)}$$

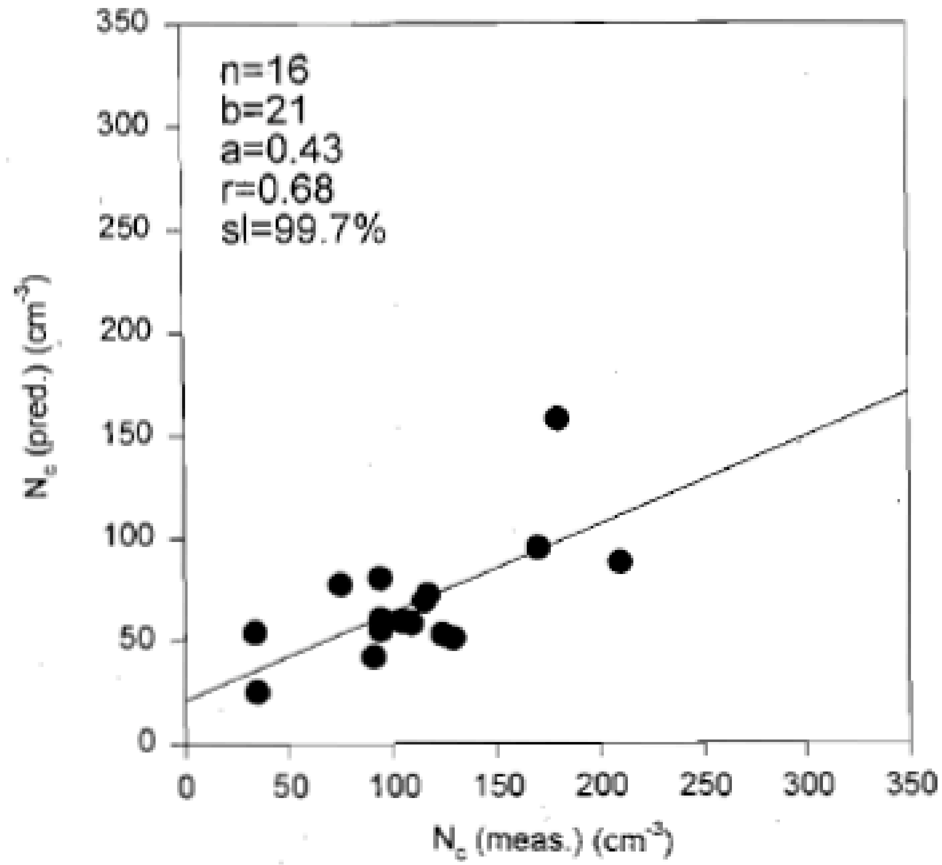


Figure 2. Predictions of N_c for individual cloud parcels based on *Twomey* [1959] (equation 1) are plotted against FSSP measurements of N_c in near-adiabatic cloud parcels. The predictions are based on near-simultaneous CCN spectra just below the same cloud parcels and the average updraft (W) measured within the cloud parcels.

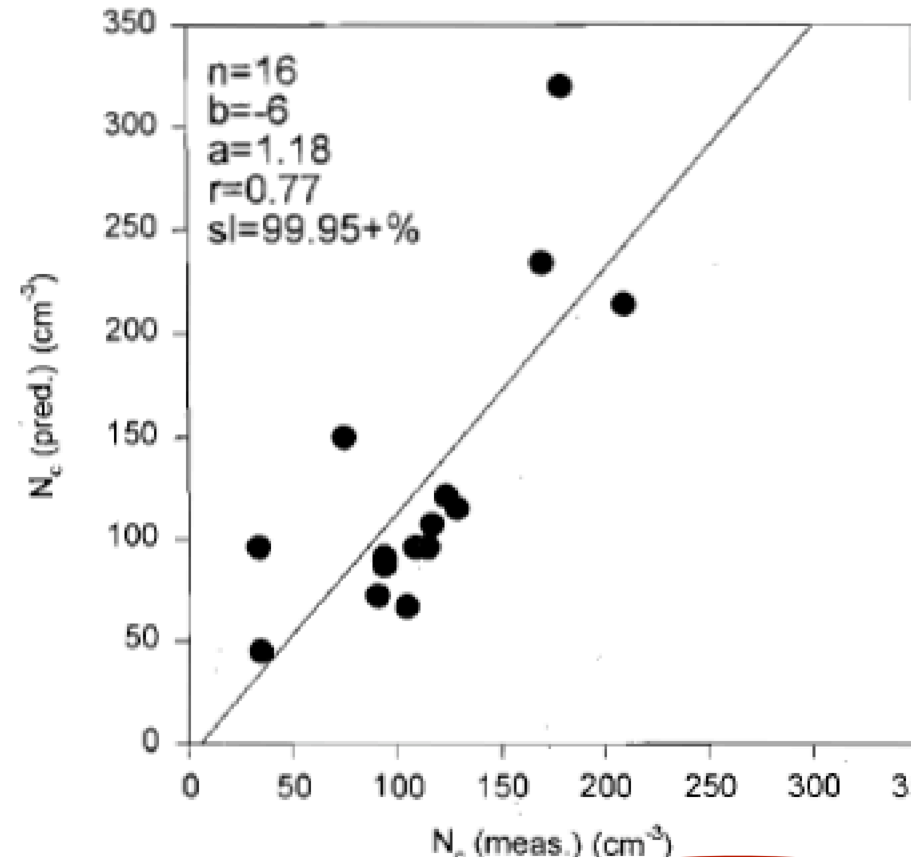
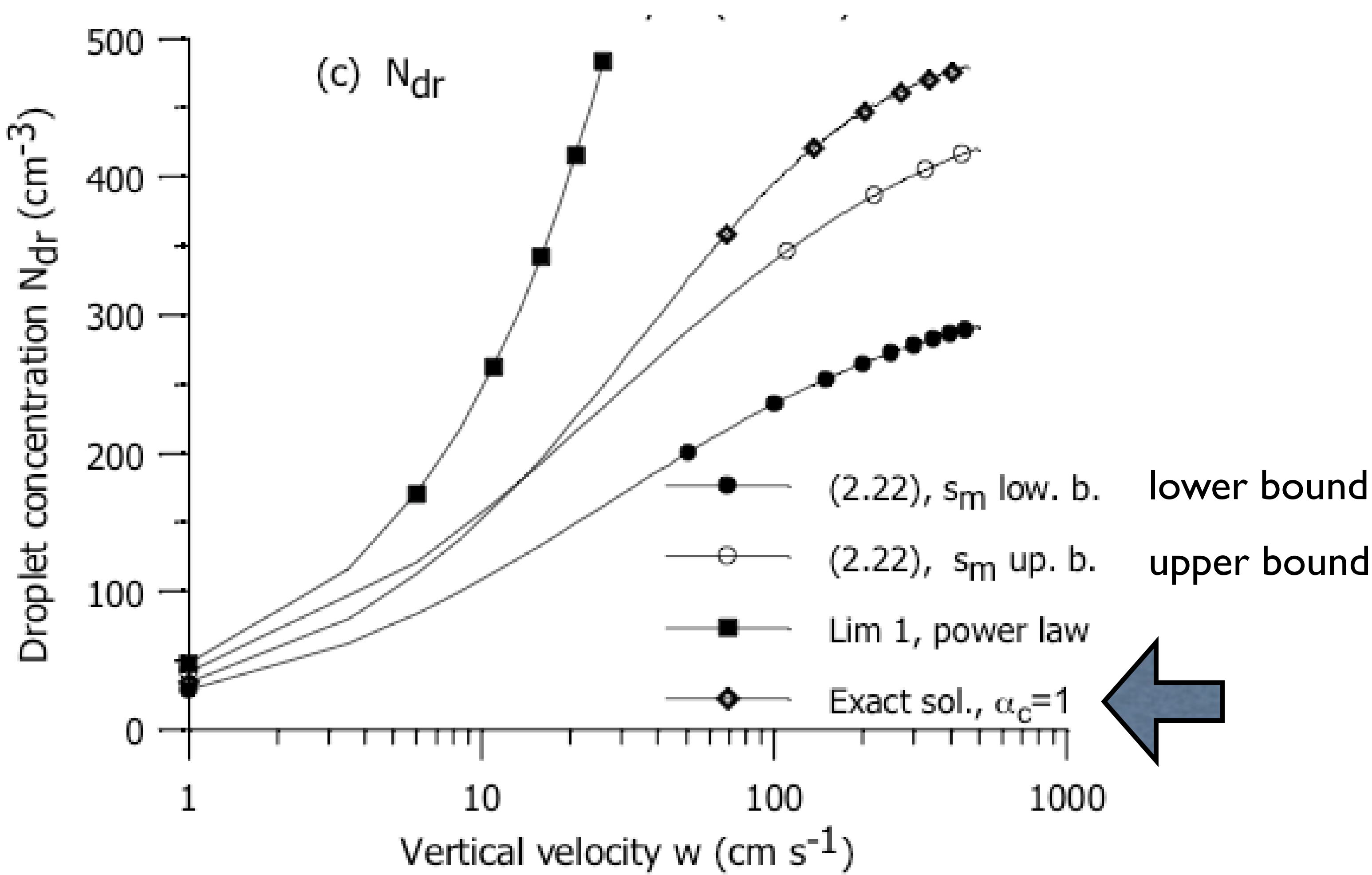


Figure 3. As in Figure 2, but the *Robinson* [1984] model with ß=1 is used for the predictions of N_c.

Yum, Hudson & Xie, 1998, *J. Geophys. Res.* **103**, 16625



Khvorostyanov & Curry, 2009, *J. Atmos. Sci.* (to appear)

cloud droplet populations

diffusional growth: $$\frac{dr}{dt} = \frac{1}{r}\frac{(S-1-\frac{a}{r}+\frac{b}{r^3})}{(Fd+Fk)}$$

initial spread in sizes due to CCN, GCCN, UGCNN

effects of turbulence, mixing, entrainment, ...

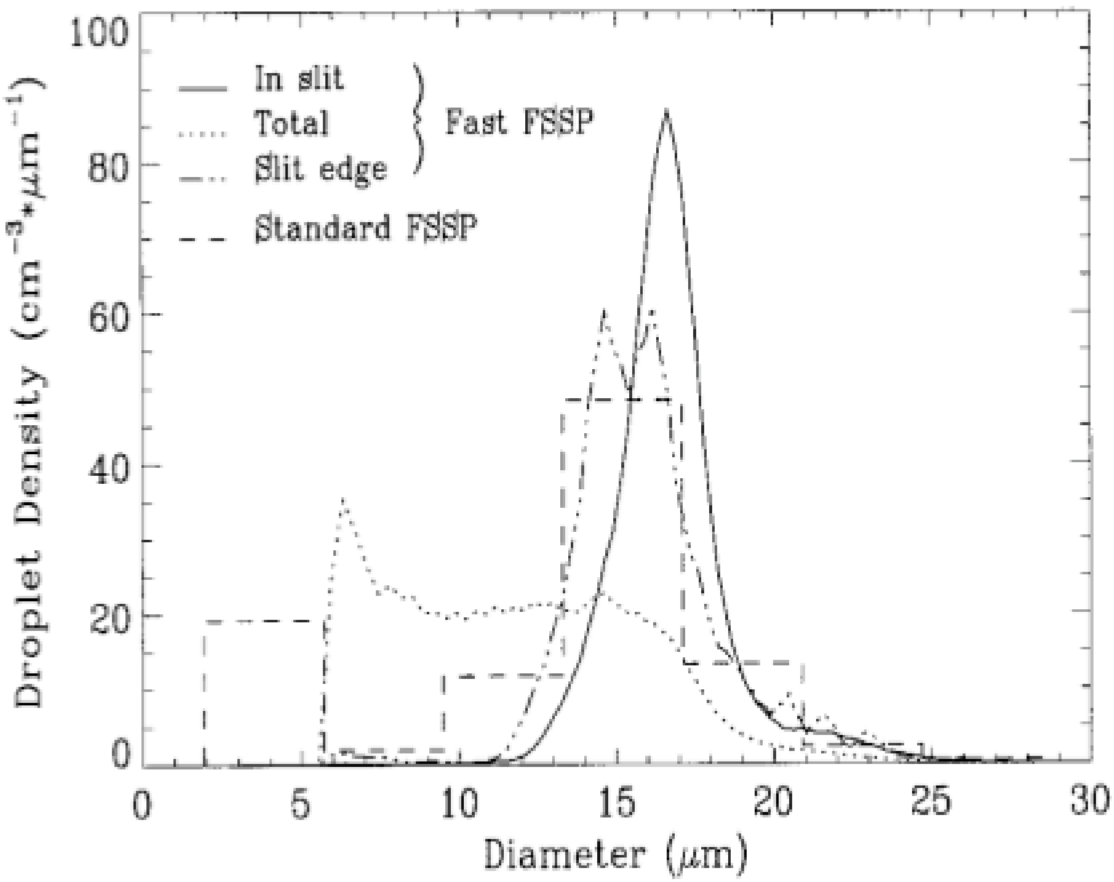
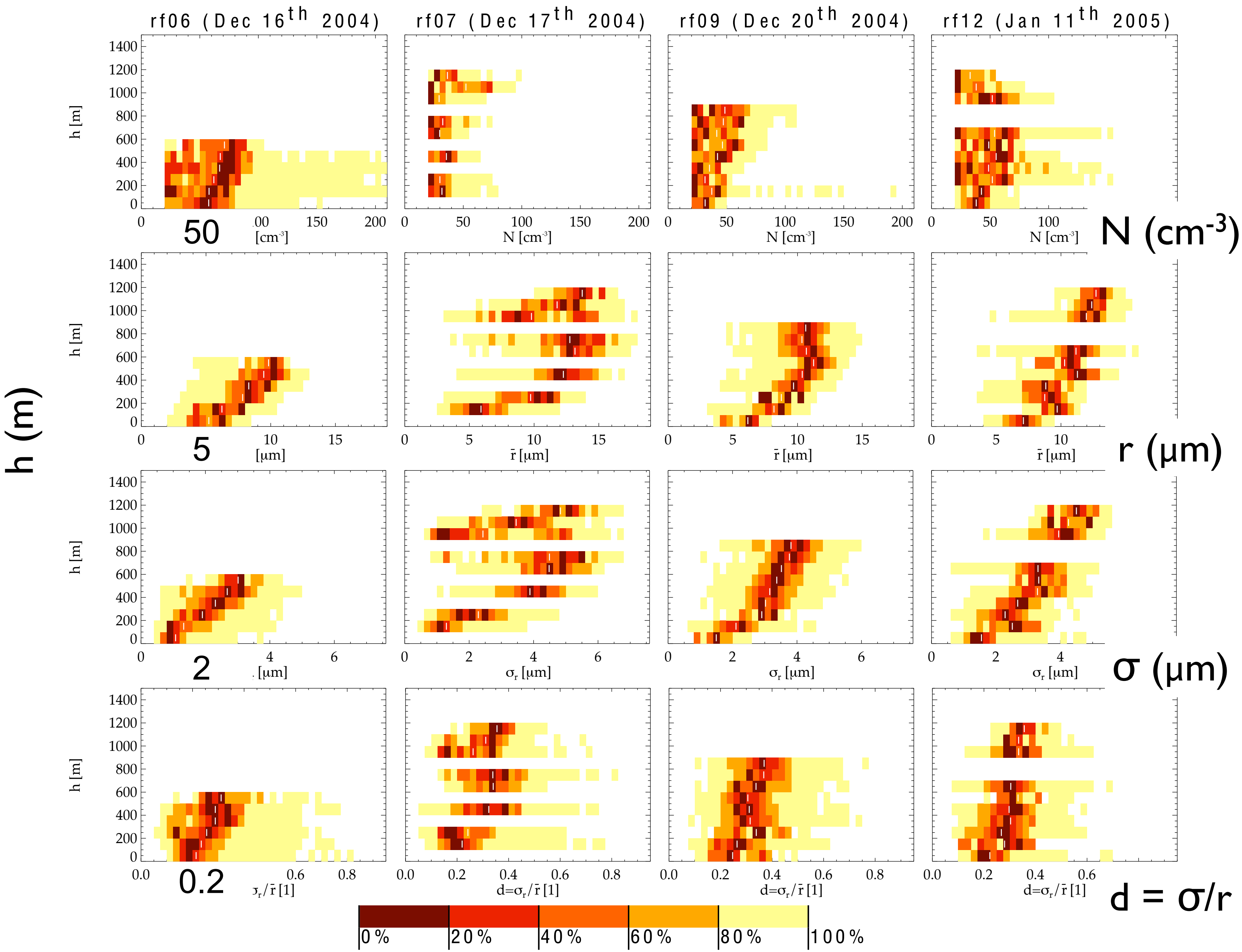


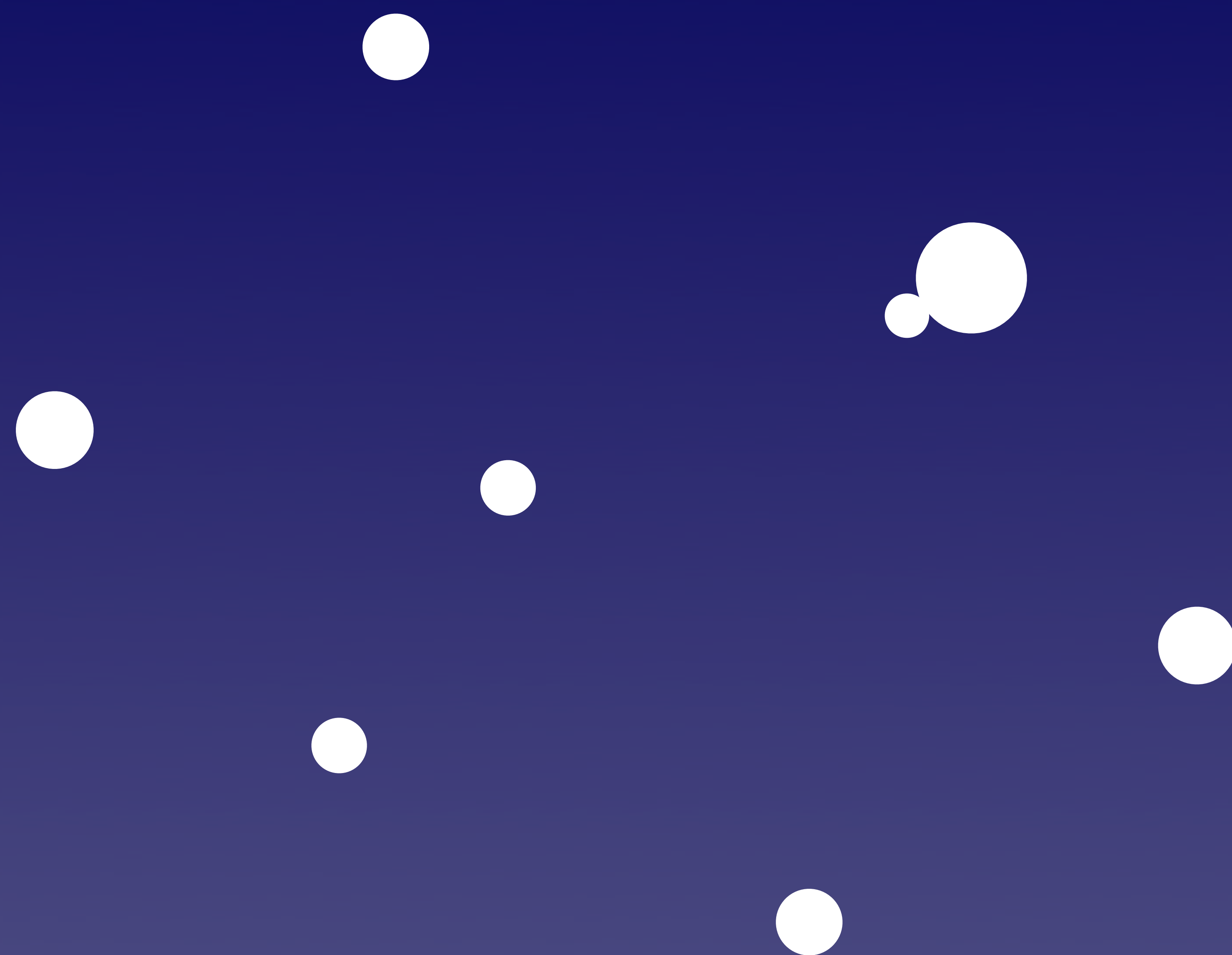
FIG. 8. Droplet size distribution measured in an adiabatic core during the SCMS-95 experiment Merlin flight 95-11, 1631:40–1631:44 UTC 10 August. Solid line: Fast-FSSP DOF-accepted counts. Dotted line: Fast-FSSP total counts. Dashed–dotted line: Fast-FSSP counts selected at the limit of the DOF. Dashed line: Standard FSSP DOF and beam edge selected counts. (The counts in the first class are an instrumental artifact due to the use of the delay mode in the FSSP.)

Brenguier et al., 1998, *J. Atmos. Ocean. Techn.* **15**, 1077



Arabas, Pawlowska & Grabowski, 2009
Geophys. Res. Lett. (to appear)

cloud droplets ➜ rain drops



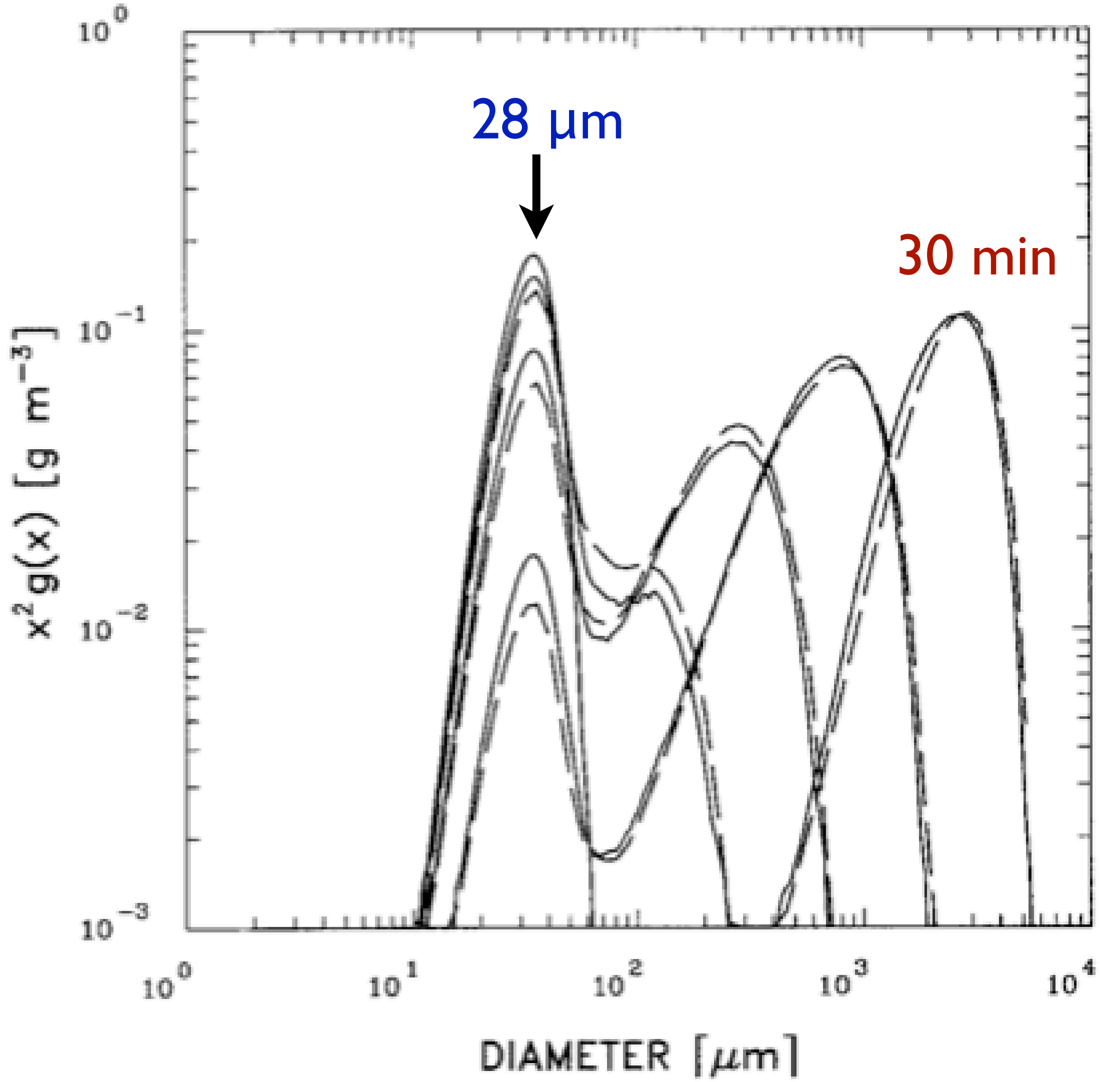
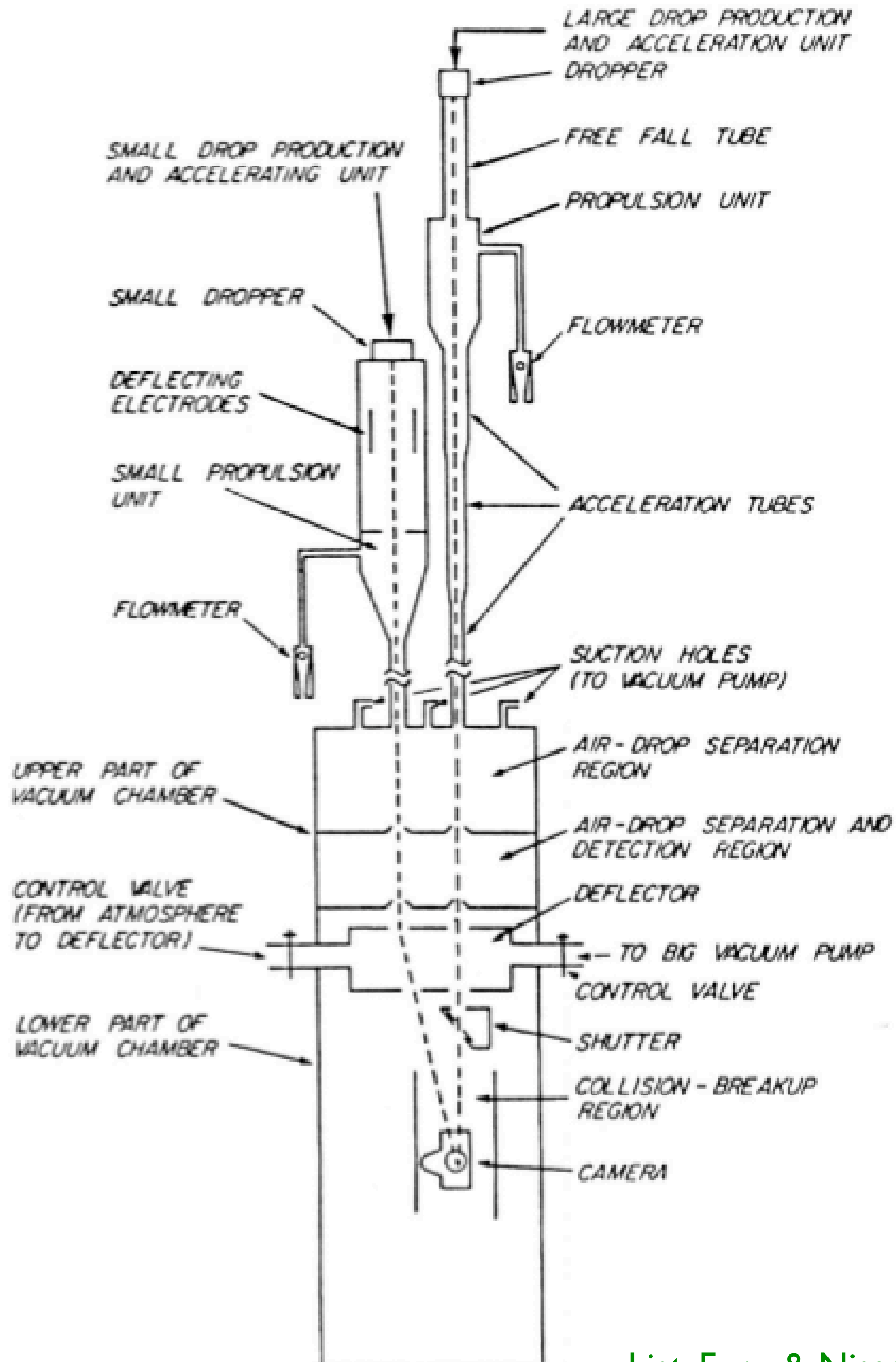


FIG. C3. Mass distribution functions, as in Fig. 4, comparing results obtained using the method described in this paper (solid lines) to those obtained using the method of Berry and Rinehardt (1974a; dashed lines). The initial size spectrum was a gamma distribution function with mean diameter of 28 µm.

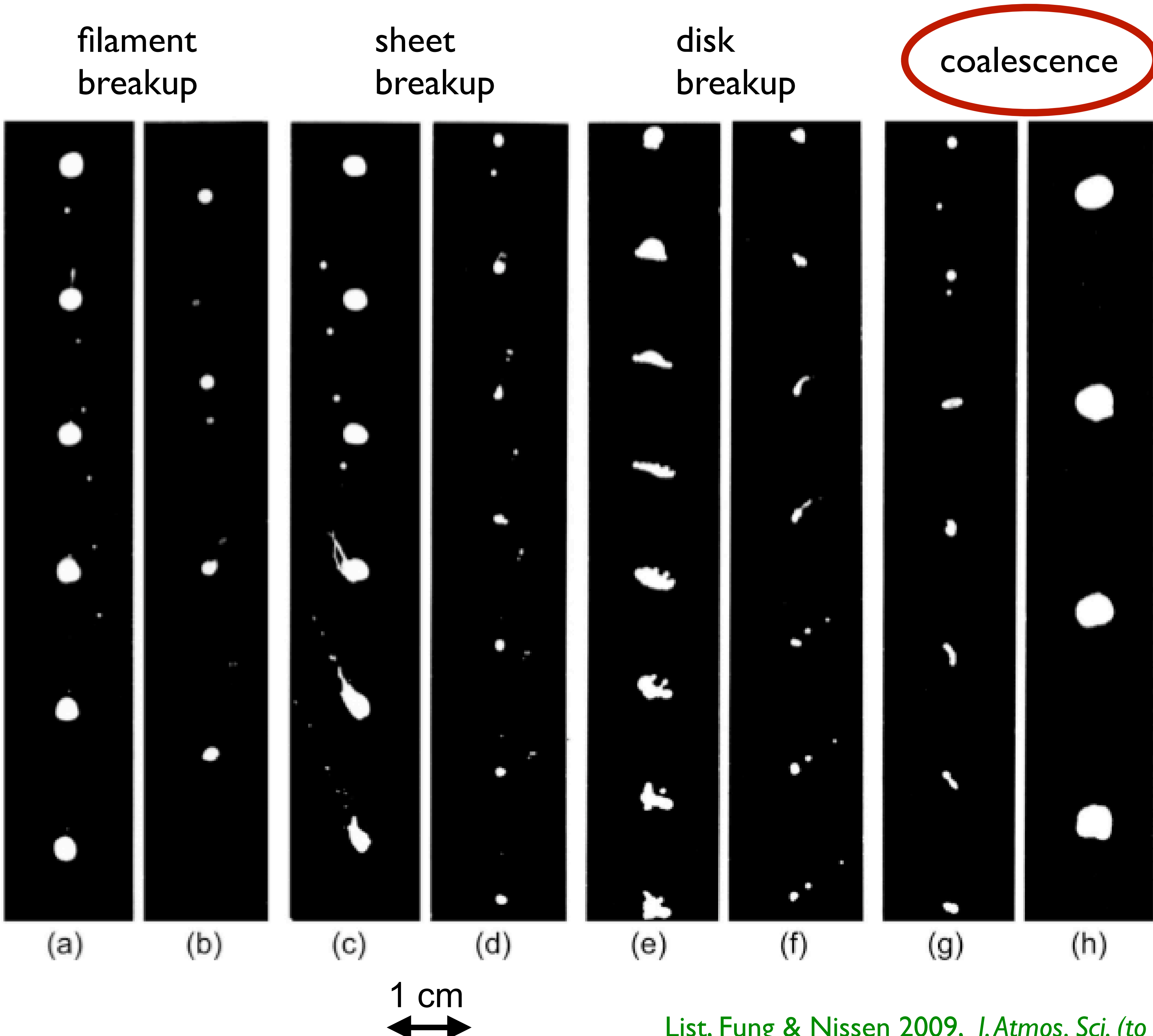
<u>stochastic coalescence equation</u>

key inputs:
- collision efficiency
- coalescence efficiency

Cooper, Bruintjes & Mather 1997, *J. Appl. Meteor.* **36**, 1449



List, Fung & Nissen 2009, *J. Atmos. Sci. (to appear)*



List, Fung & Nissen 2009, *J. Atmos. Sci. (to appear)*

rain drop size distributions, N(D)

exponential, gamma, etc. pdf

sub-cloud evaporation

drizzle and rain observations

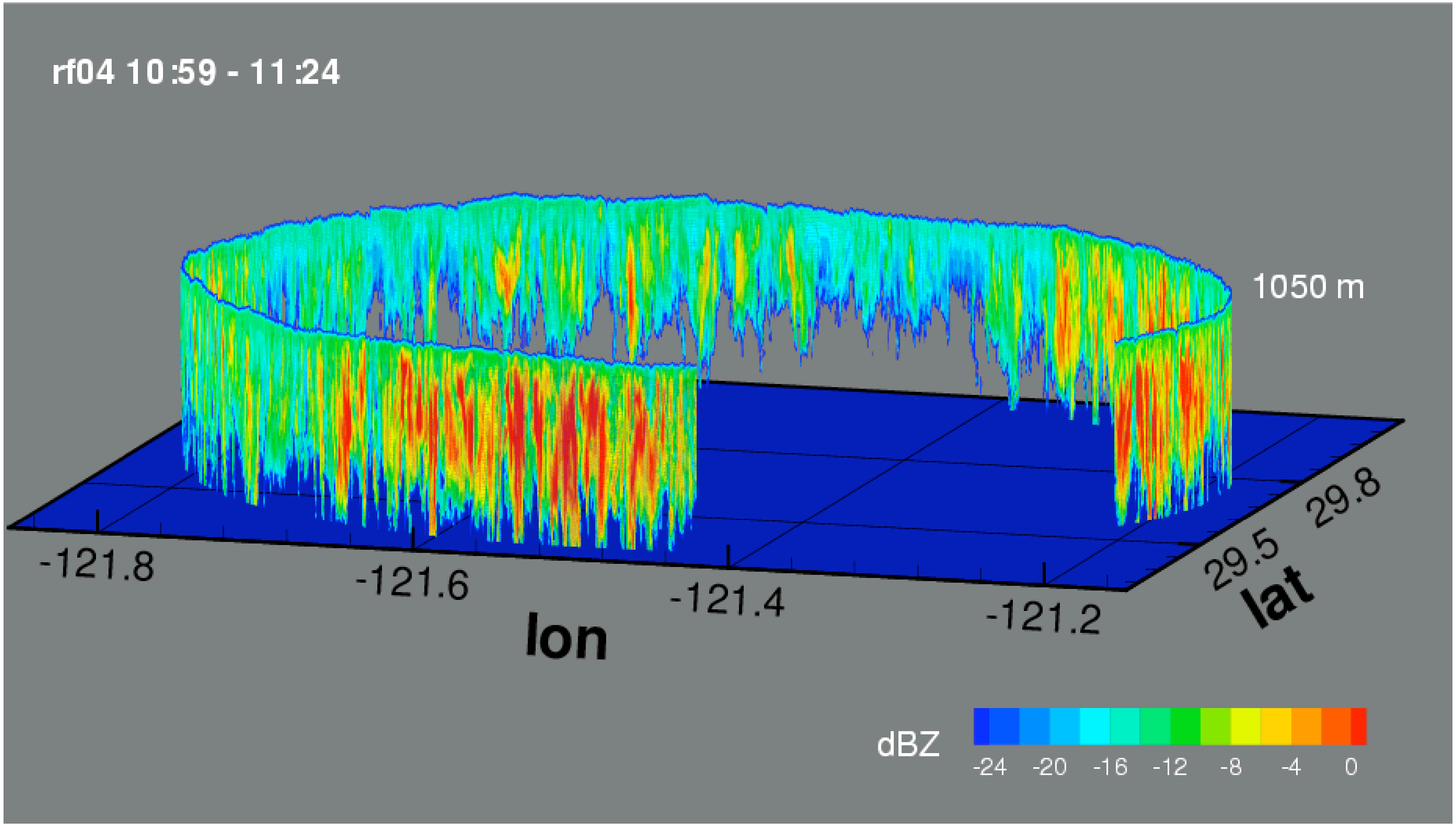
radar reflectivity:

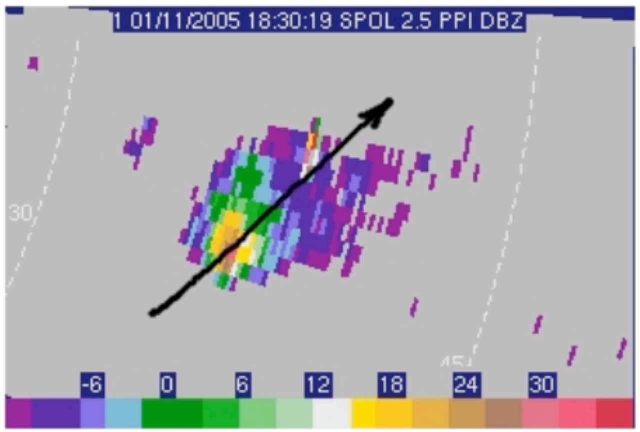
$$Z \approx const \int N(D)\, D^6$$

$$dBZ = 10 \log\left(\frac{Z}{Z_0}\right)$$

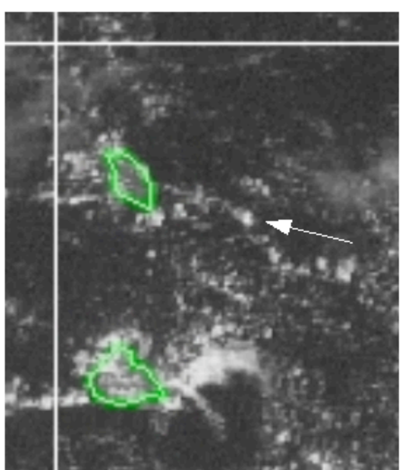
Doppler velocity:

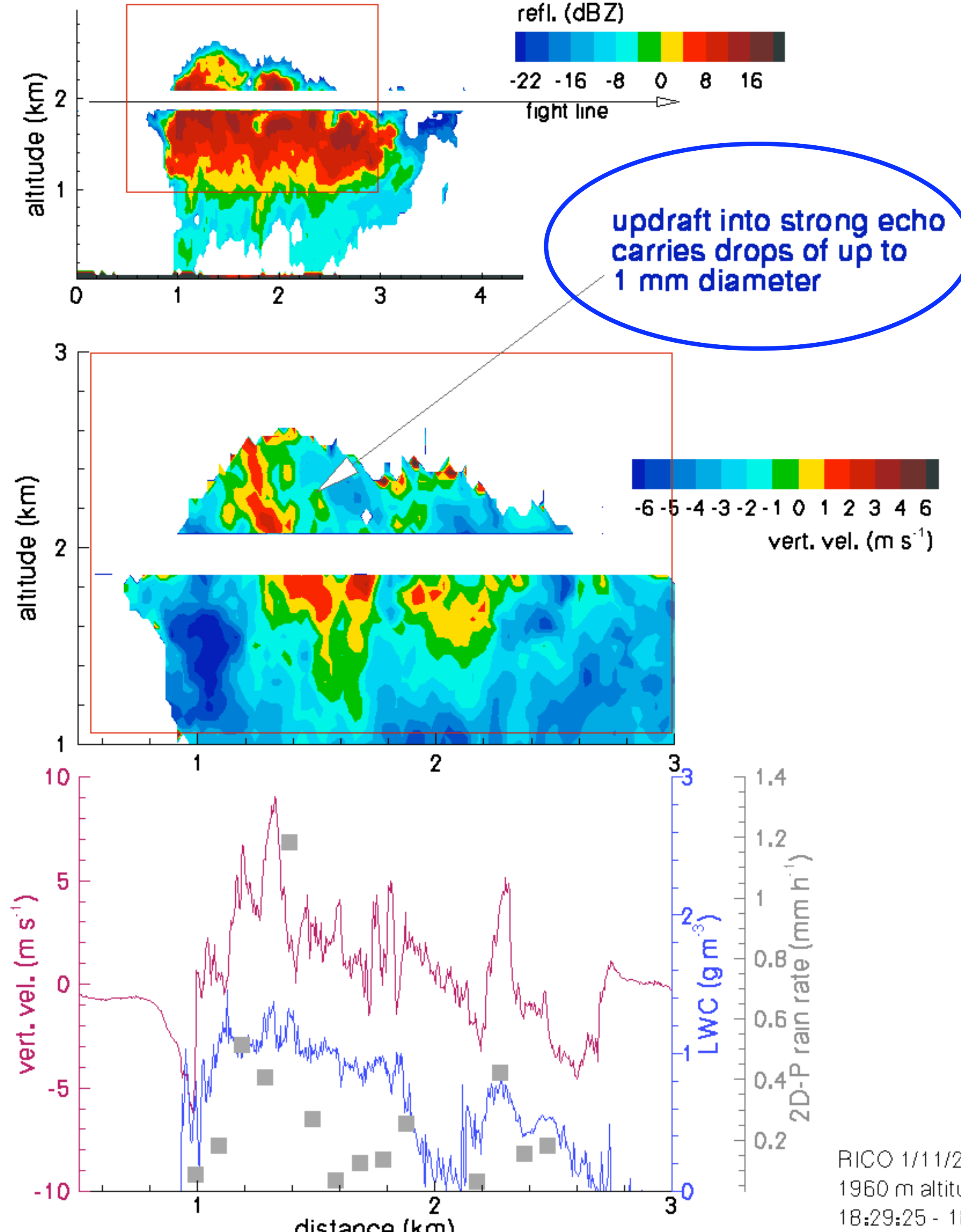
$$(particle\ velocity + air\ velocity) \cdot \boldsymbol{i}$$


rf04 10:59 - 11:24
1050 m
-121.8
-121.6
-121.4
-121.2
lon
29.5
29.8
lat
dBZ
-24
-20
-16
-12
-8
-4
0



cell tracked from
17:29 till 18:52

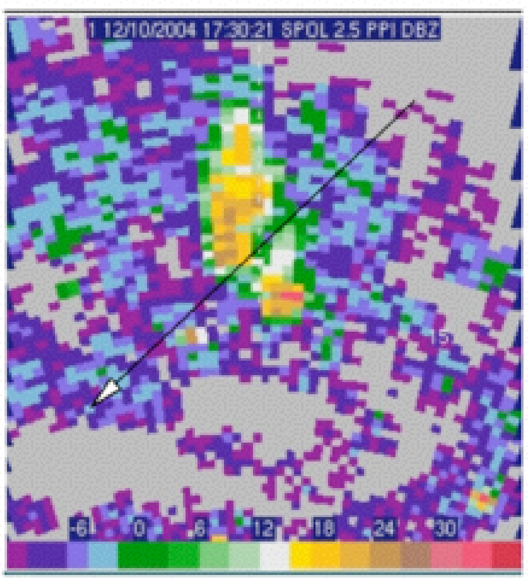




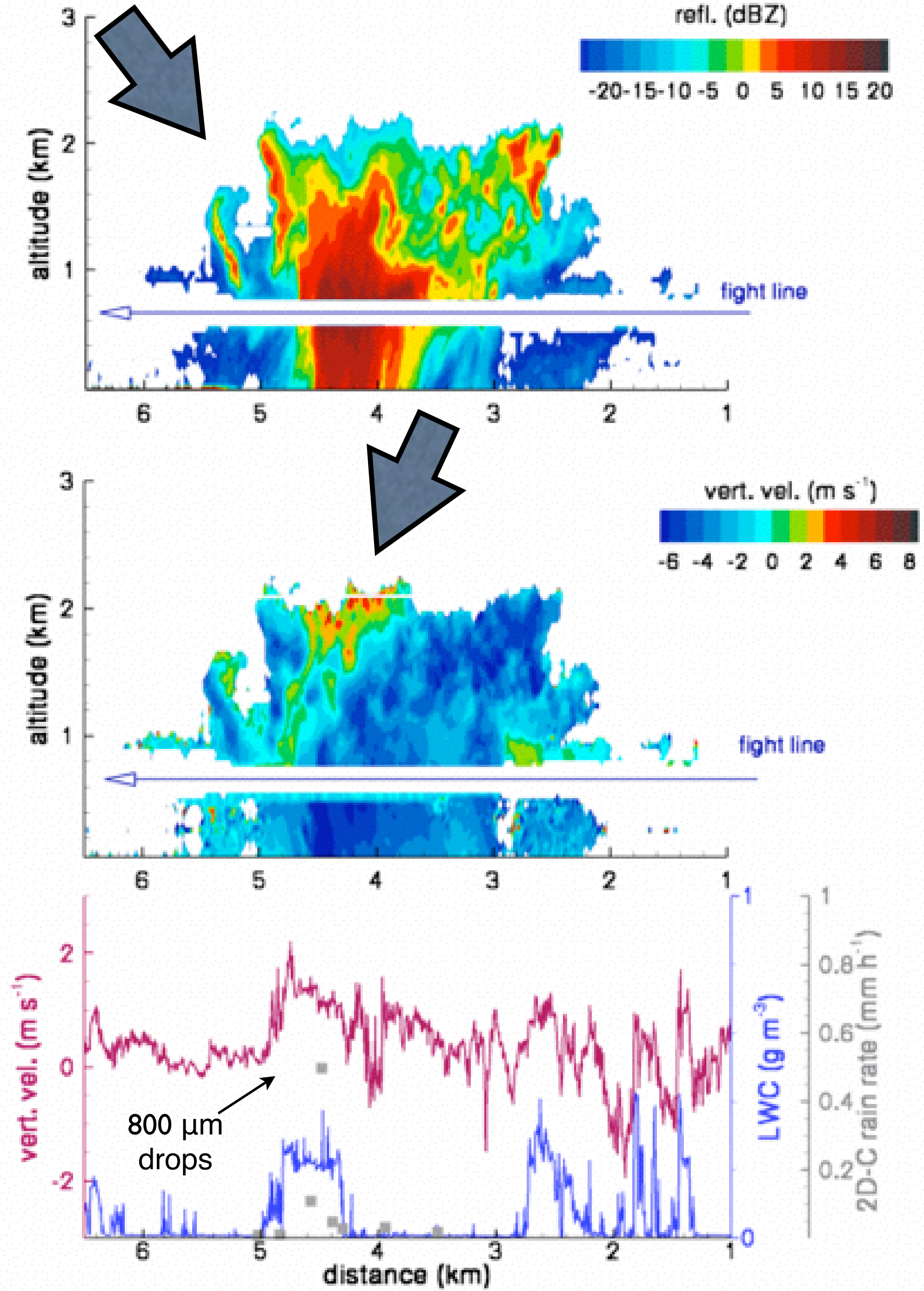
RICO 1/11/2005
1960 m altitude
18:29:25 - 18:30:10
Pass along 043° heading

Source: G. Vali, unpublished

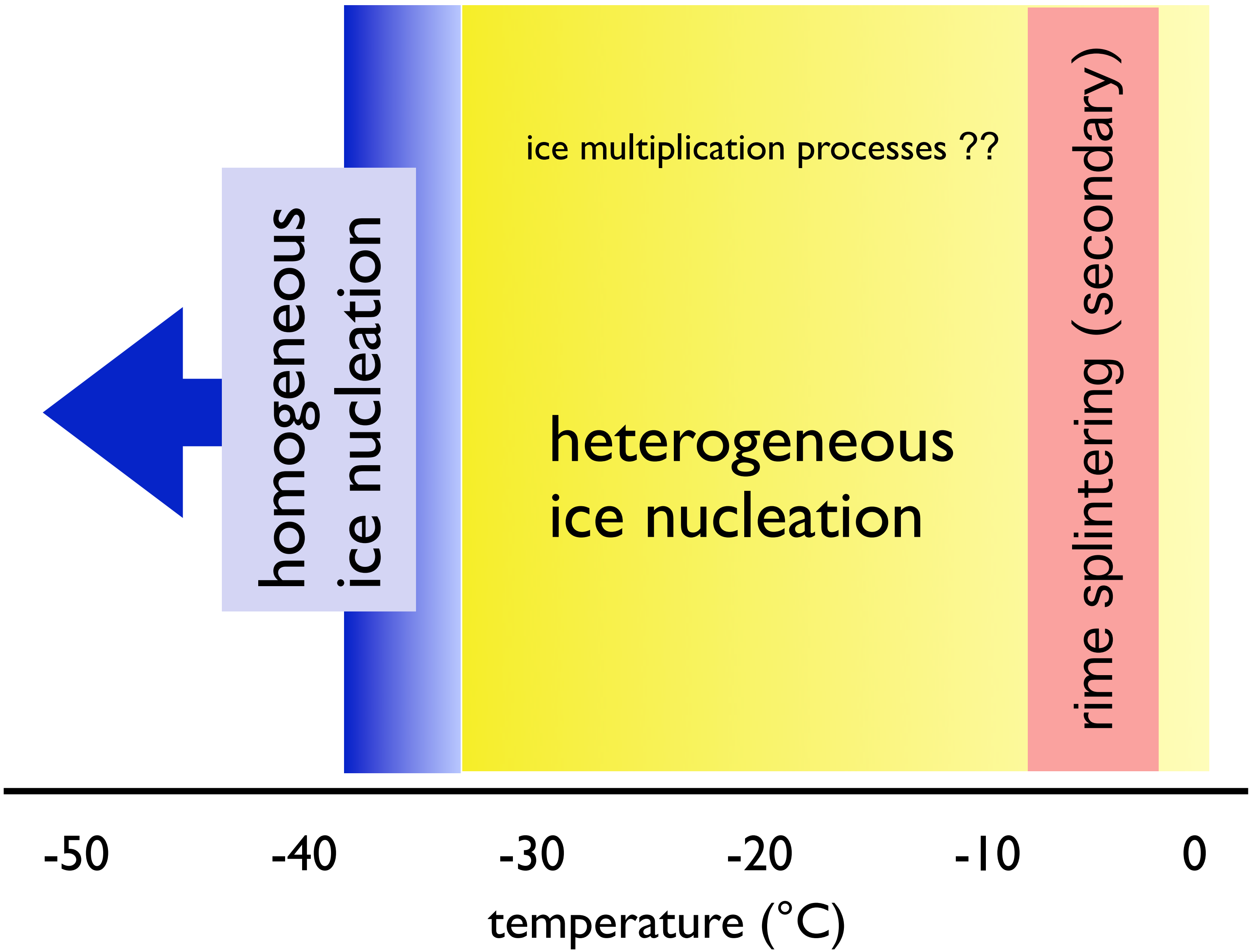
RICO 20051210   17:28:26 - 17:29:52
656 m altitude
Pass along 245° heading.

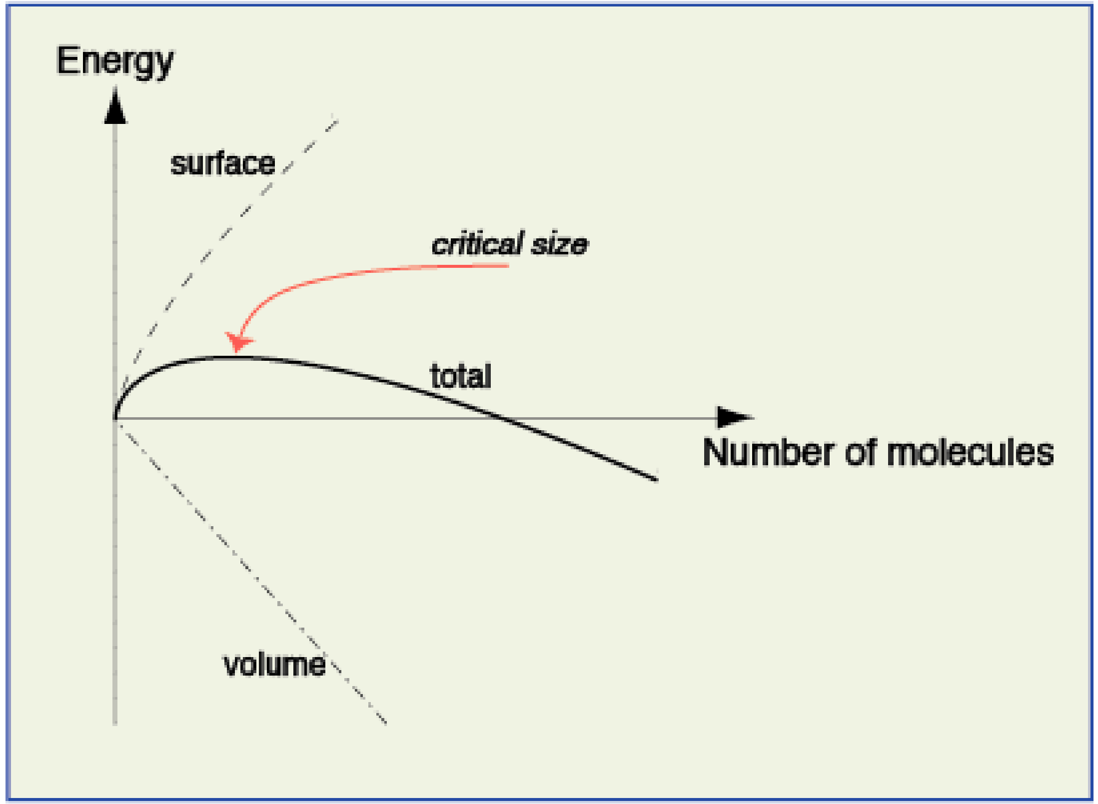


SPol 17:30:35   2.5°   ~ 0.7 km



aerosol → ice particle


ice multiplication processes ??
homogeneous ice nucleation
heterogeneous ice nucleation
rime splintering (secondary)
-50
-40
-30
-20
-10
0
temperature (°C)



Homogeneous ice nucleation in pure water

Homogeneous ice nucleation in haze droplet

Heterogeneous ice nucleation on solid particle

Size distribution of germs : $N(n) = N_o\ e^{-\Delta G(n)/kT}$

Nucleation rate : $J = A\ e^{-\Delta G^*/kT}$

Deposition : $$J = A\ exp\left[- B\ \frac{\sigma^3}{T^3}\ \frac{1}{(\ln S)^2}\right]$$

Freezing : $$J = A_f\,\sigma_{i/w}^{1/2}\ exp\left[- B_f\ \frac{\sigma_{i/w}^3}{kT}\ \frac{1}{\{\ln[T_0/T]\}^2}\right]$$

-38°C

-35°C

Benz et al. 2005 (J. Photochem. Photobiol.)

Cloud chamber observation of rate of homogeneous freezing nucleation.

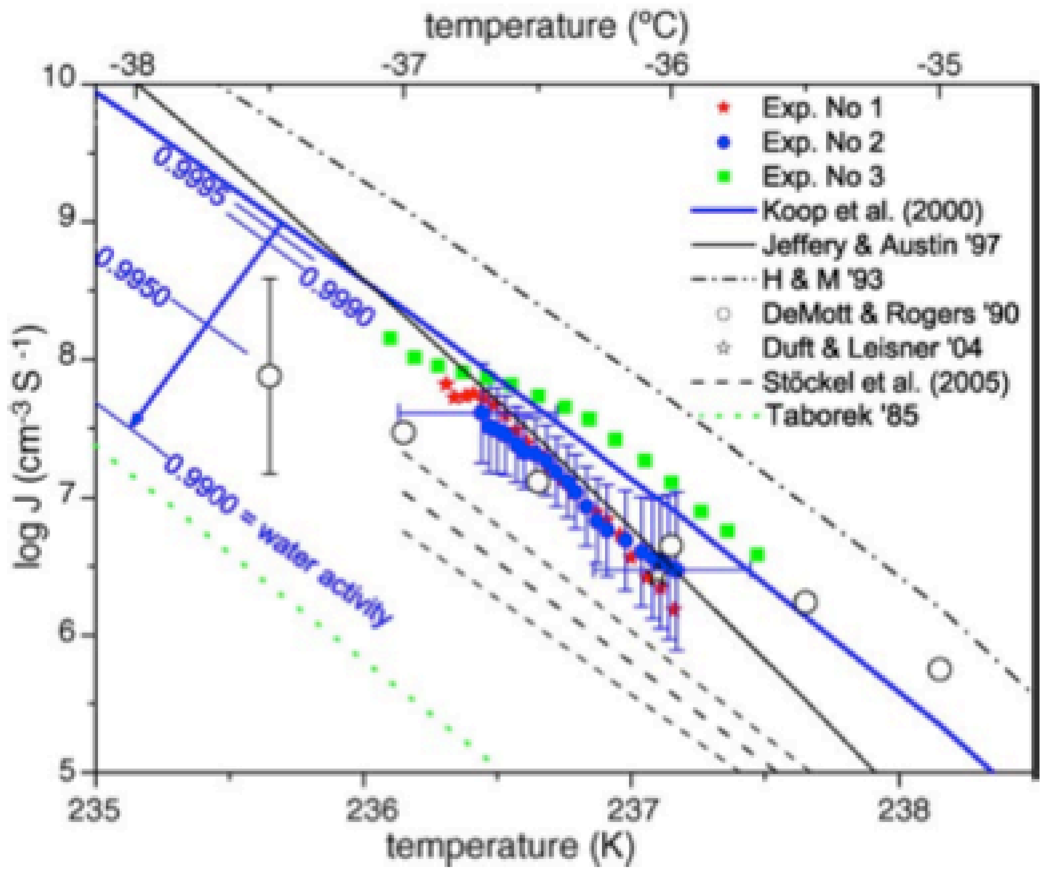
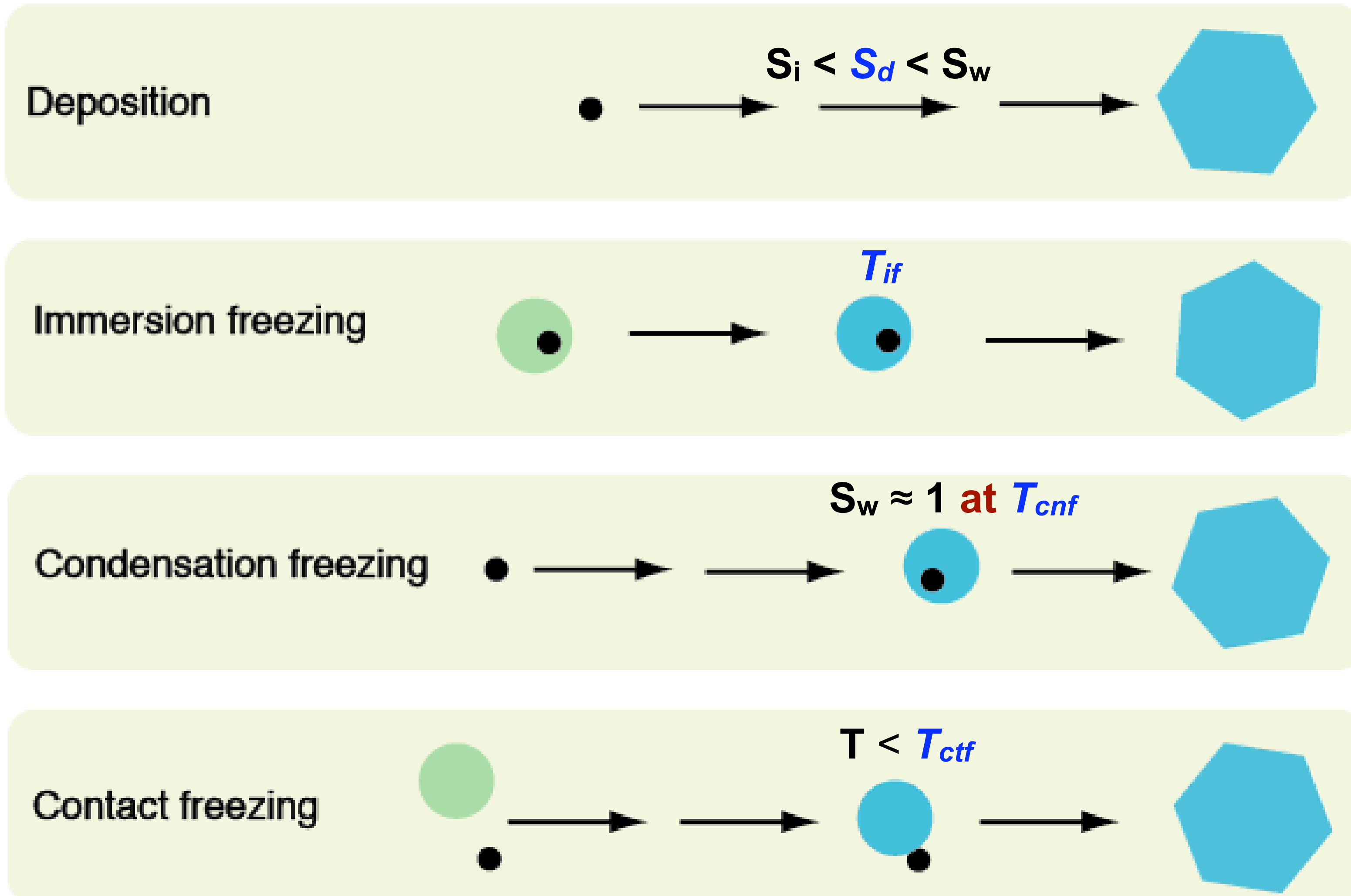
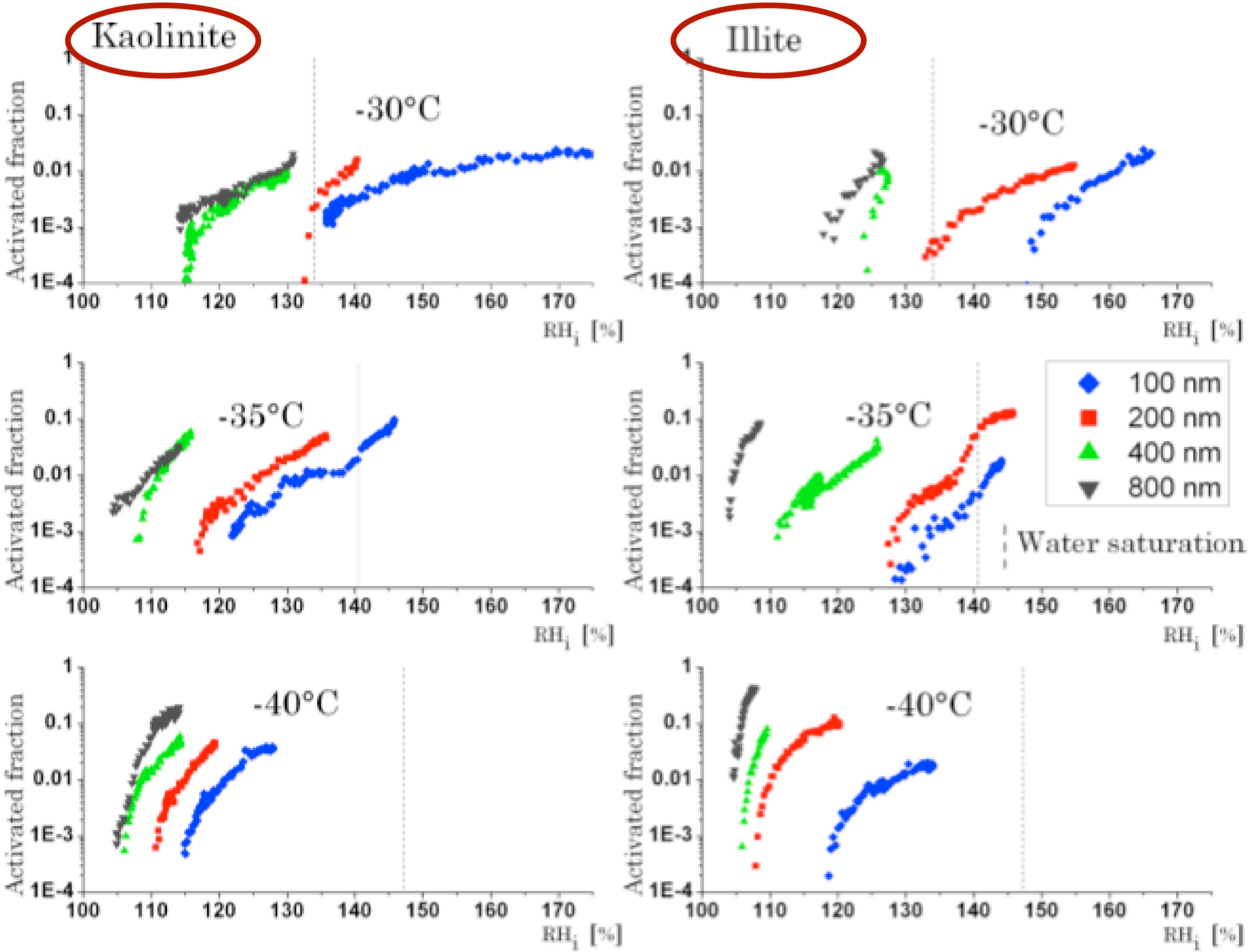


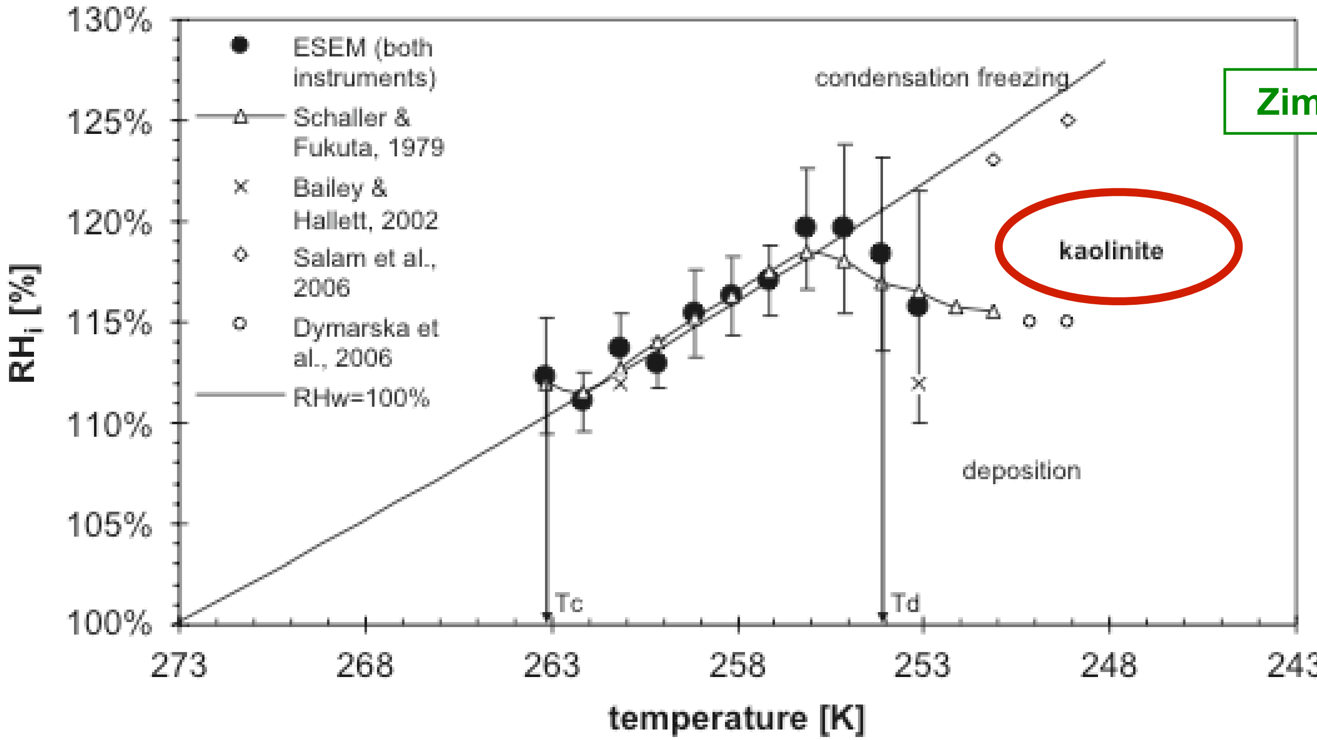
Fig. 8. Filled symbols: nucleation rates $J(T)$, this work, including corrections for all *known* systematic uncertainties, error bars shown for one experiment only. Thick solid line: parameterisation of the nucleation rate by Pruppacher [10] and adopted by Koop et al. [35] in their parameterisation of $J(T,a)$, as explained in text; thin solid line: parameterisation proposed by Jeffery and Austin [13]; dash-dotted line: parameterisation based on measurements in clouds by Heymsfield and Miloshevich (H & M) [26]; large open circles: cloud chamber study by DeMott and Rogers [19]; dashed line with error range (thin dashed lines): levitated droplet measurements by Stöckel et al. [36]; open star: levitated droplet measurement by Duft and Leisner [18]. Short dashed line in lower left corner: emulsified droplet measurements of Taborek [37].


Deposition
$S_i < S_d < S_w$
Immersion freezing
T_{if}
Condensation freezing
$S_w \approx 1$ at T_{cnf}
Contact freezing
$T < T_{ctf}$

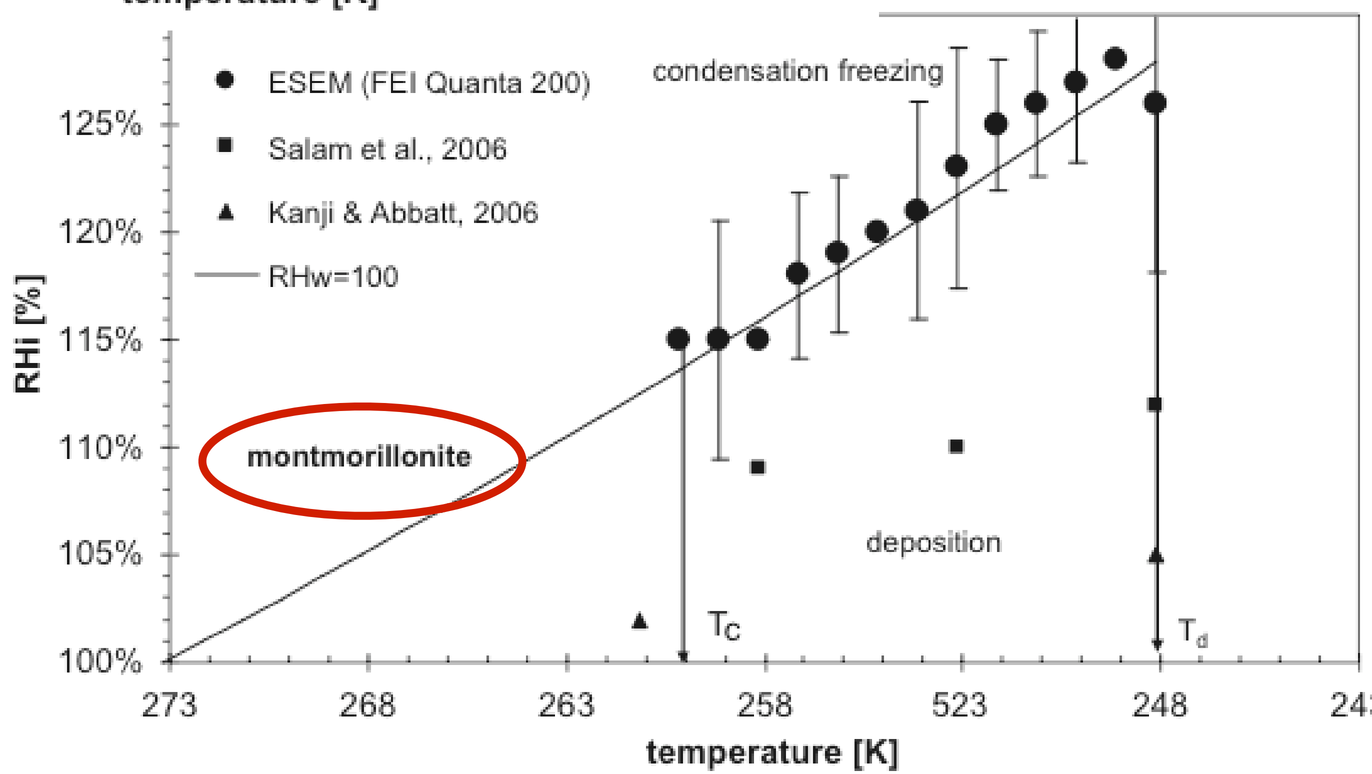
ZINC - Zurich Ice Nucleation Chamber: continuous flow, parallel plate diffusion chamber

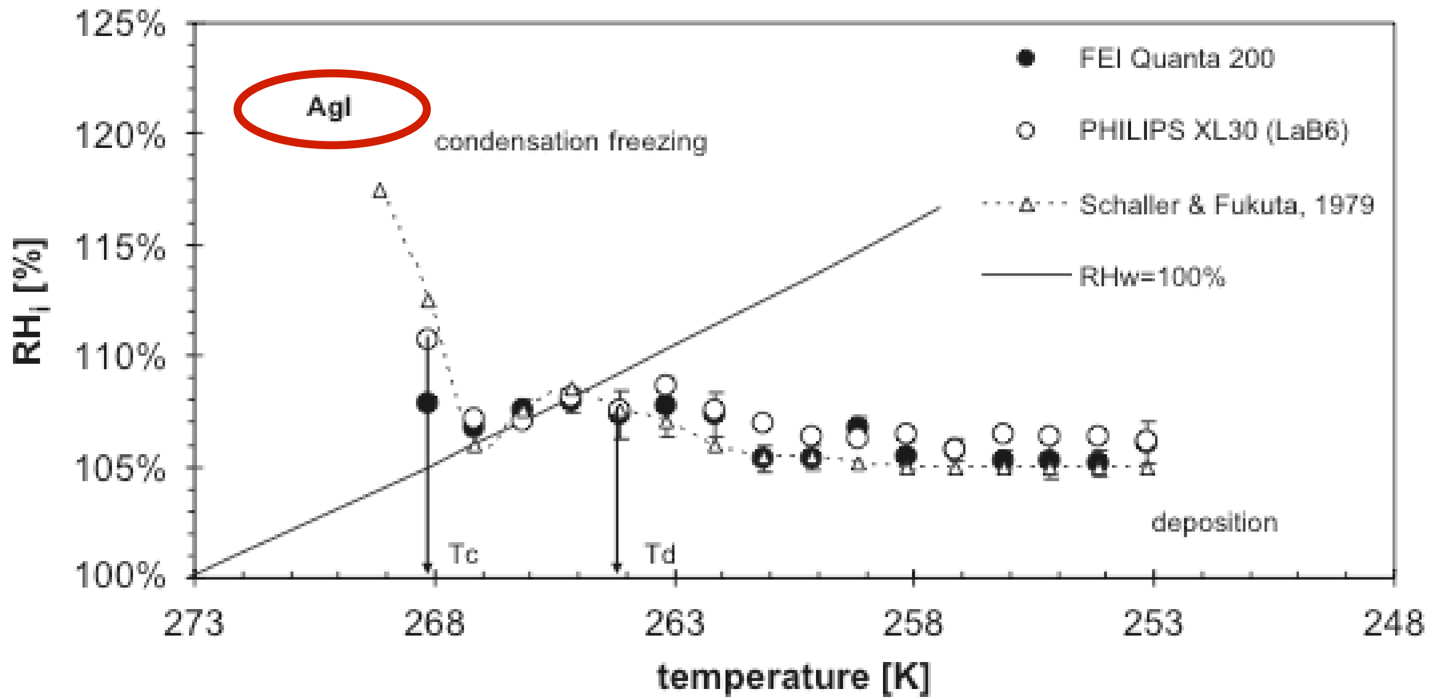


Welti et al., 2009, *Atmos. Phys. Chem. Disc.*, **9**, 6829-6955.



Zimmermann et al., 2007 Atmos. Environm.

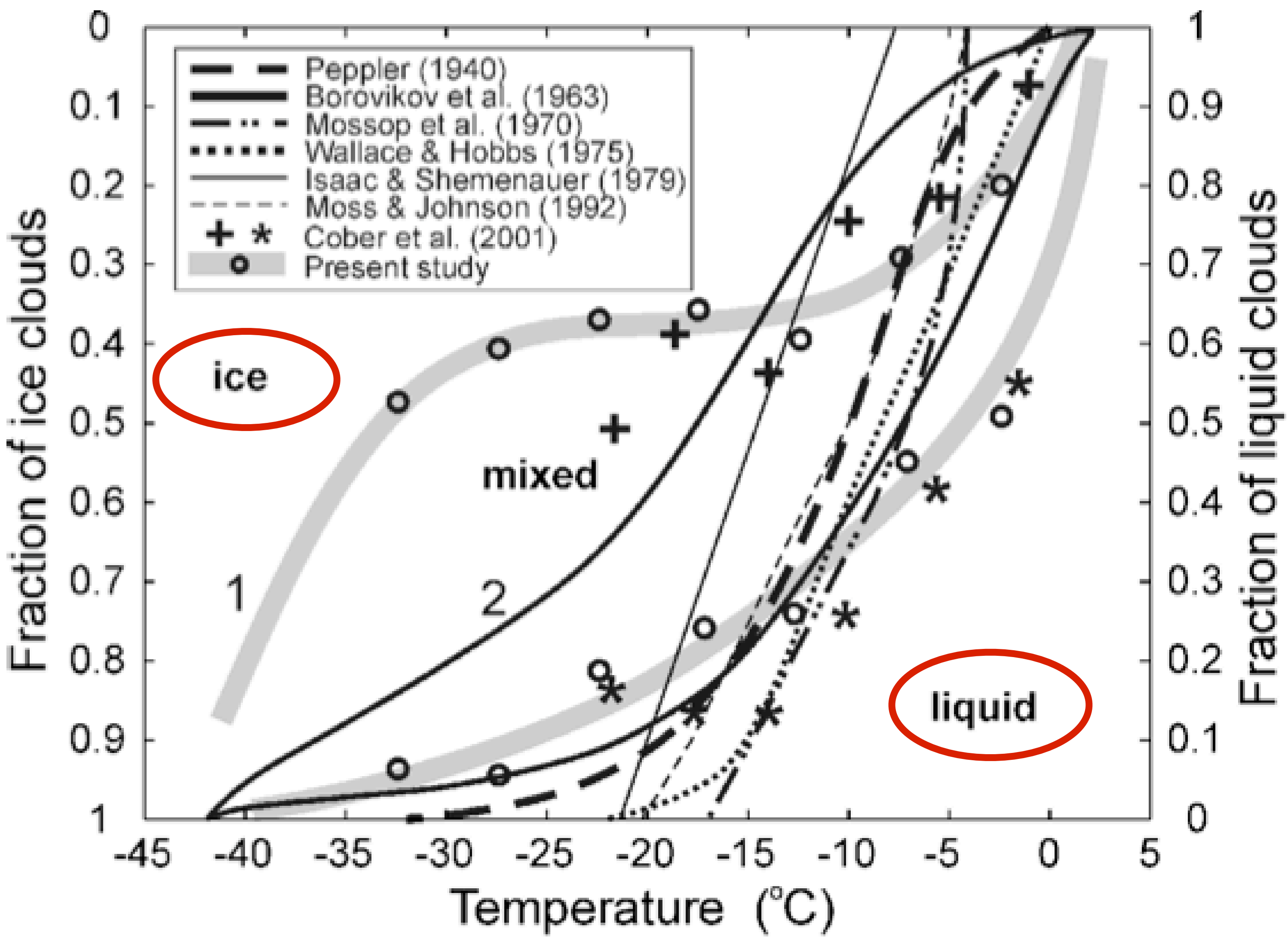




Zimmermann et al., 2007 Atmos. Environm.

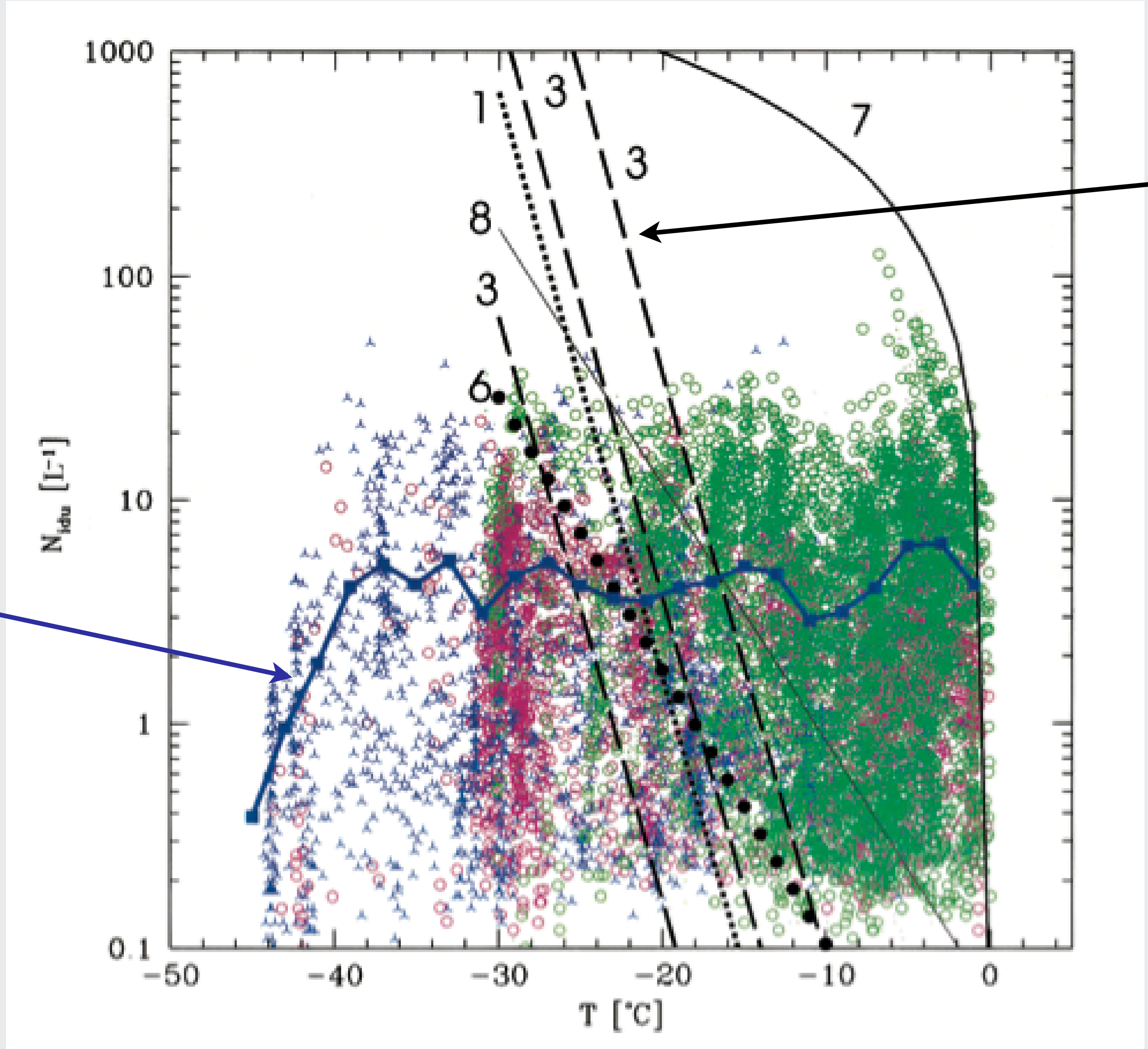
ice nuclei and ice particles in clouds

Source: Korolev et al., 2003 (Quart. J. Roy. Meteor. Soc.)

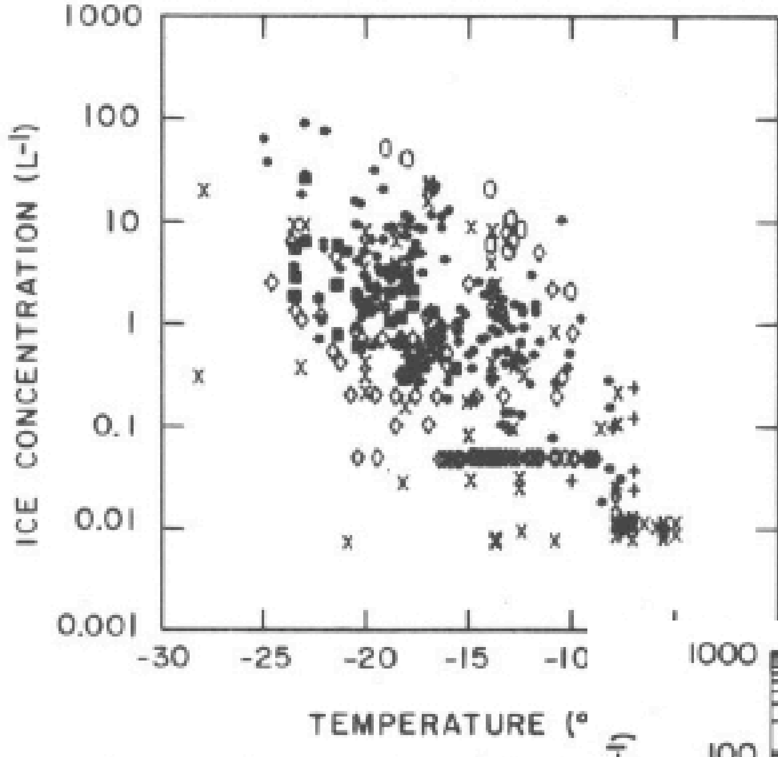


Zones of ice and liquid clouds by temperature.

Source: Gultepe et al., 2001(Int'l J. Climat.)

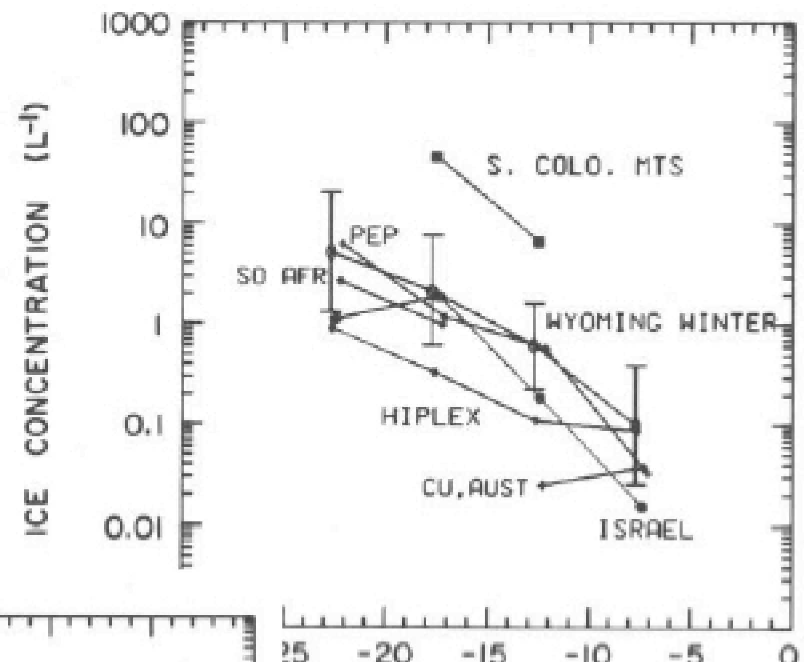


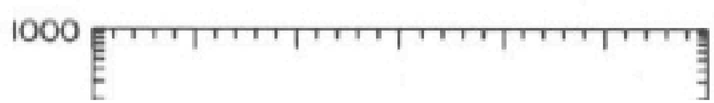
Ice particle concentrations from aircraft measurements (2D-C probe) in various projects



Cooper,1986

for cases where ice concentration can be attributed to nucleation





Letter abstract
Nature Geoscience
Published online: 17 May 2009 | doi:10.1038/ngeo521

In situ detection of biological particles in cloud ice-crystals

Kerri A. Pratt1, Paul J. DeMott2, Jeffrey R. French3, Zhien Wang3, Douglas L. Westphal4, Andrew J. Heymsfield5, Cynthia H. Twohy6, Anthony J. Prenni2 & Kimberly A. Prather1,7

The impact of aerosol particles on the formation and properties of clouds is one of the largest remaining sources of uncertainty in climate change projections1. Certain aerosol particles, known as ice nuclei, initiate ice-crystal formation in clouds, thereby affecting precipitation and the global hydrological cycle2. Laboratory studies suggest that some mineral dusts and primary biological particles—such as bacteria, pollen and fungi—can act as ice nuclei3. Here we use aircraft-aerosol time-of-flight spectrometry to directly measure the chemistry of individual cloud ice-crystal residues (obtained after evaporation of the ice), which were sampled at high altitude over Wyoming. We show that biological particles and mineral dust comprised most of the ice-crystal residues: mineral dust accounted for ~50% of the residues and biological particles for ~33%. Along with concurrent measurements of cloud ice-crystal and ice-nuclei concentrations, these observations suggest that certain biological and dust particles initiated ice formation in the sampled clouds. Finally, we use a global aerosol model to show long-range transport of desert dust, suggesting that biological particles can enhance the impact of desert dust storms on the formation of cloud ice.

1. Department of Chemistry and Biochemistry, University of California, San Diego, La Jolla, California 92093, USA
2. Department of Atmospheric Science, Colorado State University, Fort Collins, Colorado 80523, USA
3. Department of Atmospheric Science, University of Wyoming, Laramie, Wyoming 82071, USA
4. Marine Meteorology Division, Naval Research Laboratory, Monterey, California 93943, USA
5. Mesoscale and Microscale Meteorology Division, National Center for Atmospheric Research, Boulder, Colorado 80305, USA
6. Department of Oceanic and Atmospheric Sciences, Oregon State University, Corvallis, Oregon 97331, USA
7. Scripps Institution of Oceanography, University of California, San Diego, La Jolla, California 92093, USA

Correspondence to: Paul J. DeMott2 e-mail: pdemott@lamar.colostate.edu

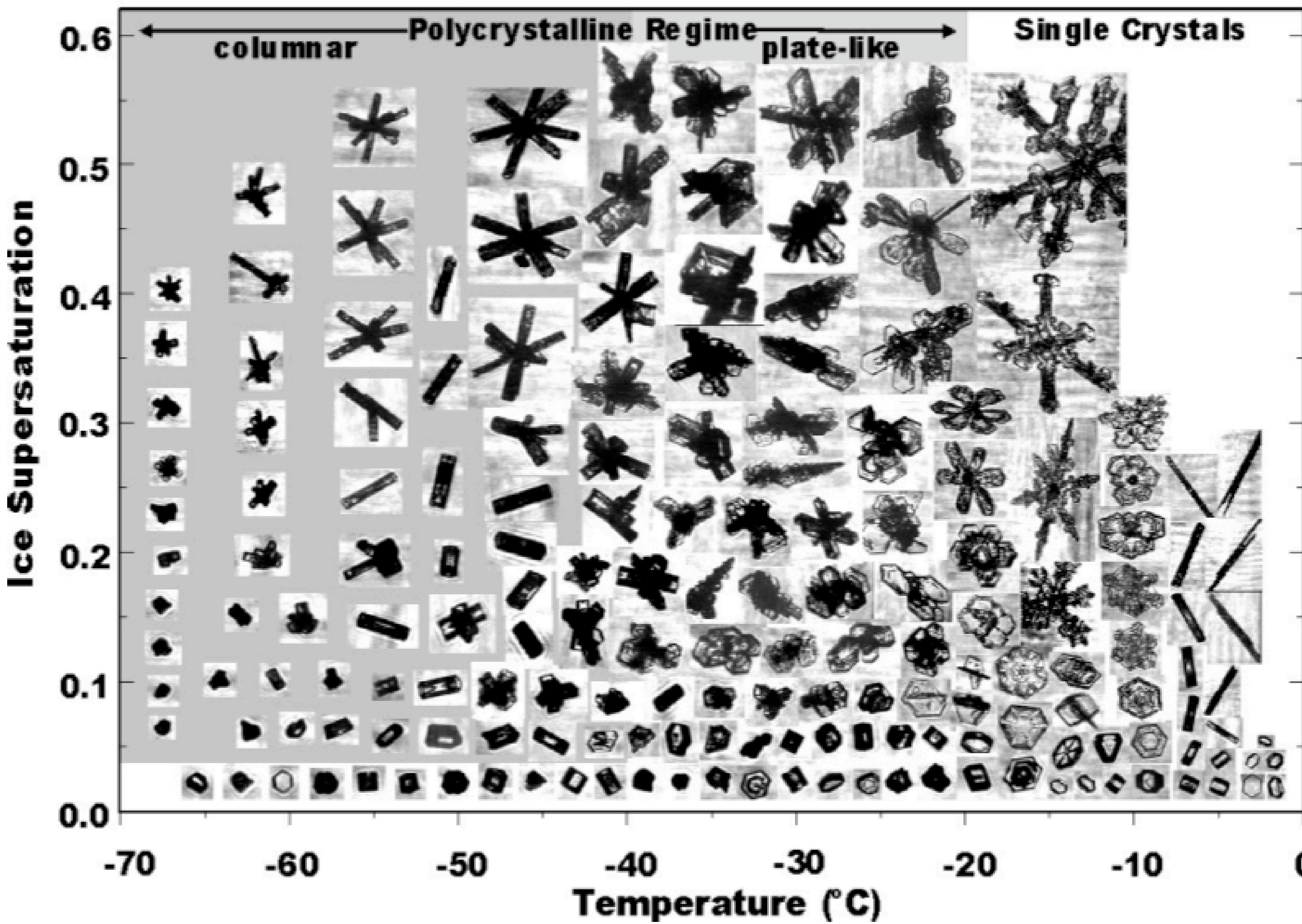
Correspondence to: Kimberly A. Prather1,7 e-mail: kprather@ucsd.edu

ice crystal growth from the vapor

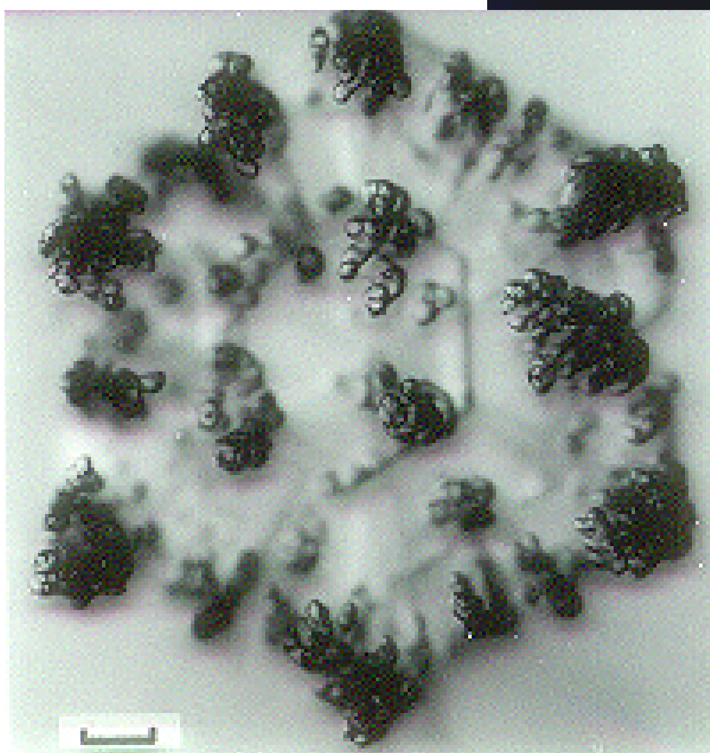
ice crystal riming

ice crystal aggregation

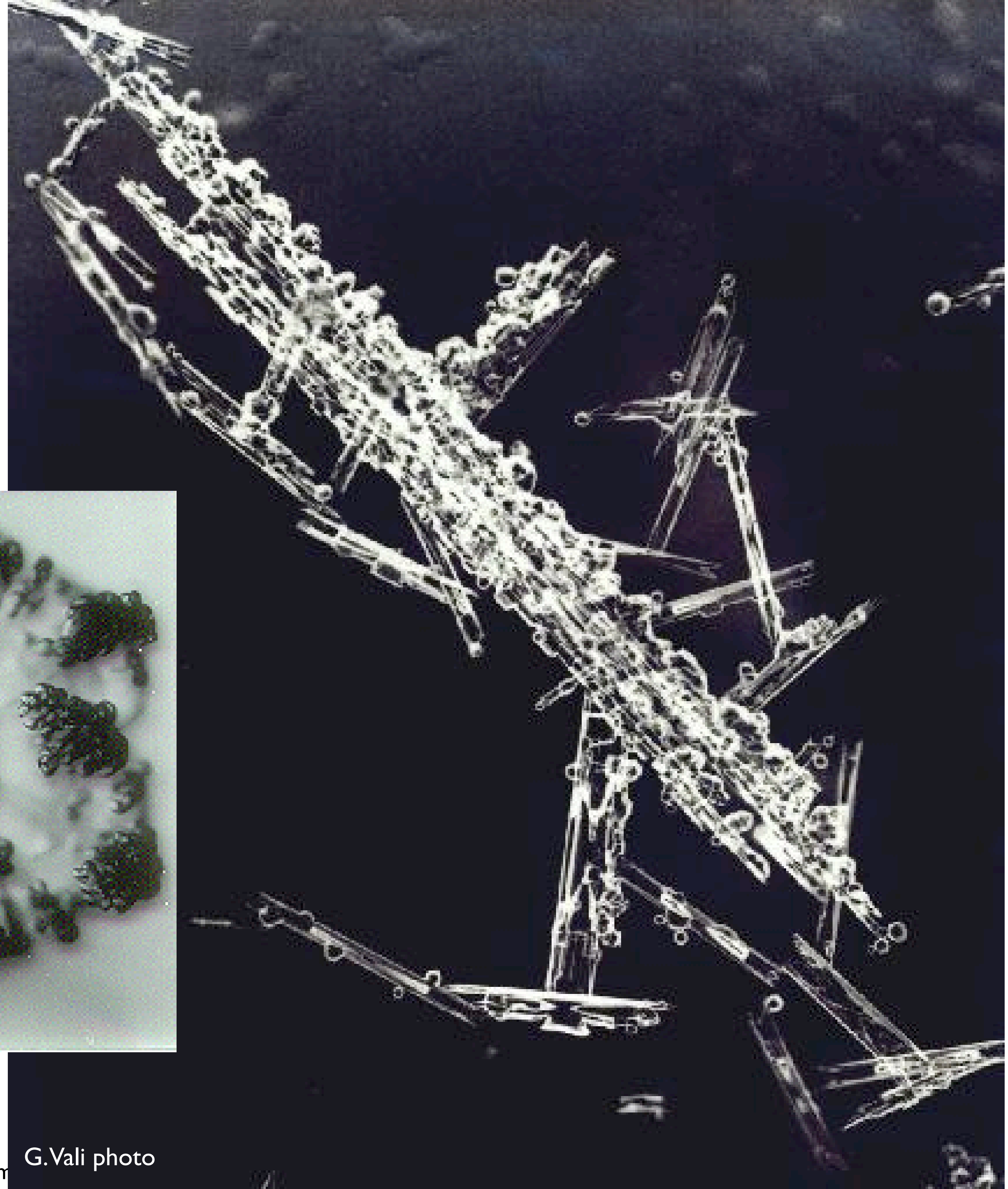
secondary ice origins



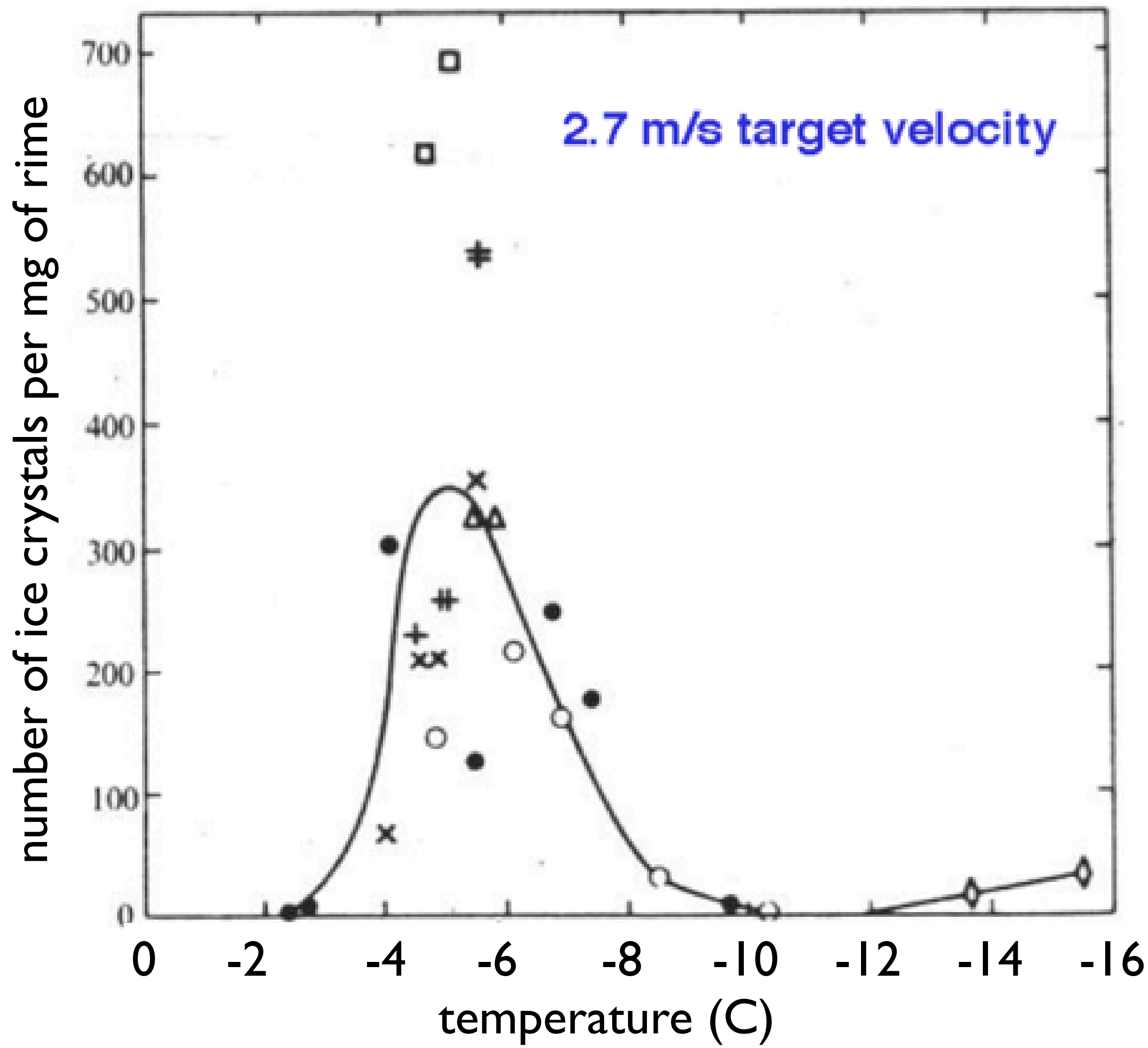
Bailey & Hallett, 2009, to appear *J. Atmos. Sci.*



C. Knight photo

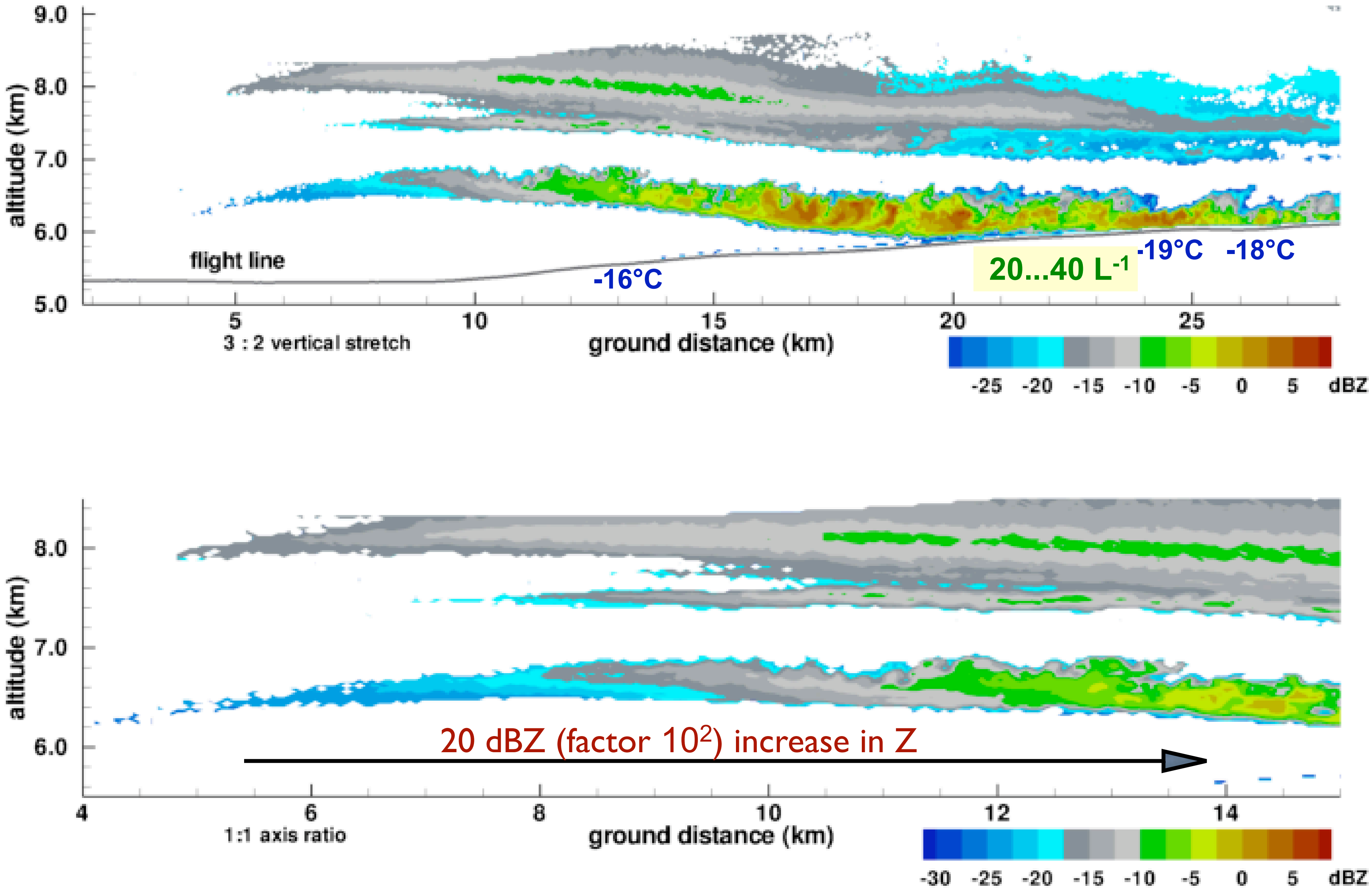


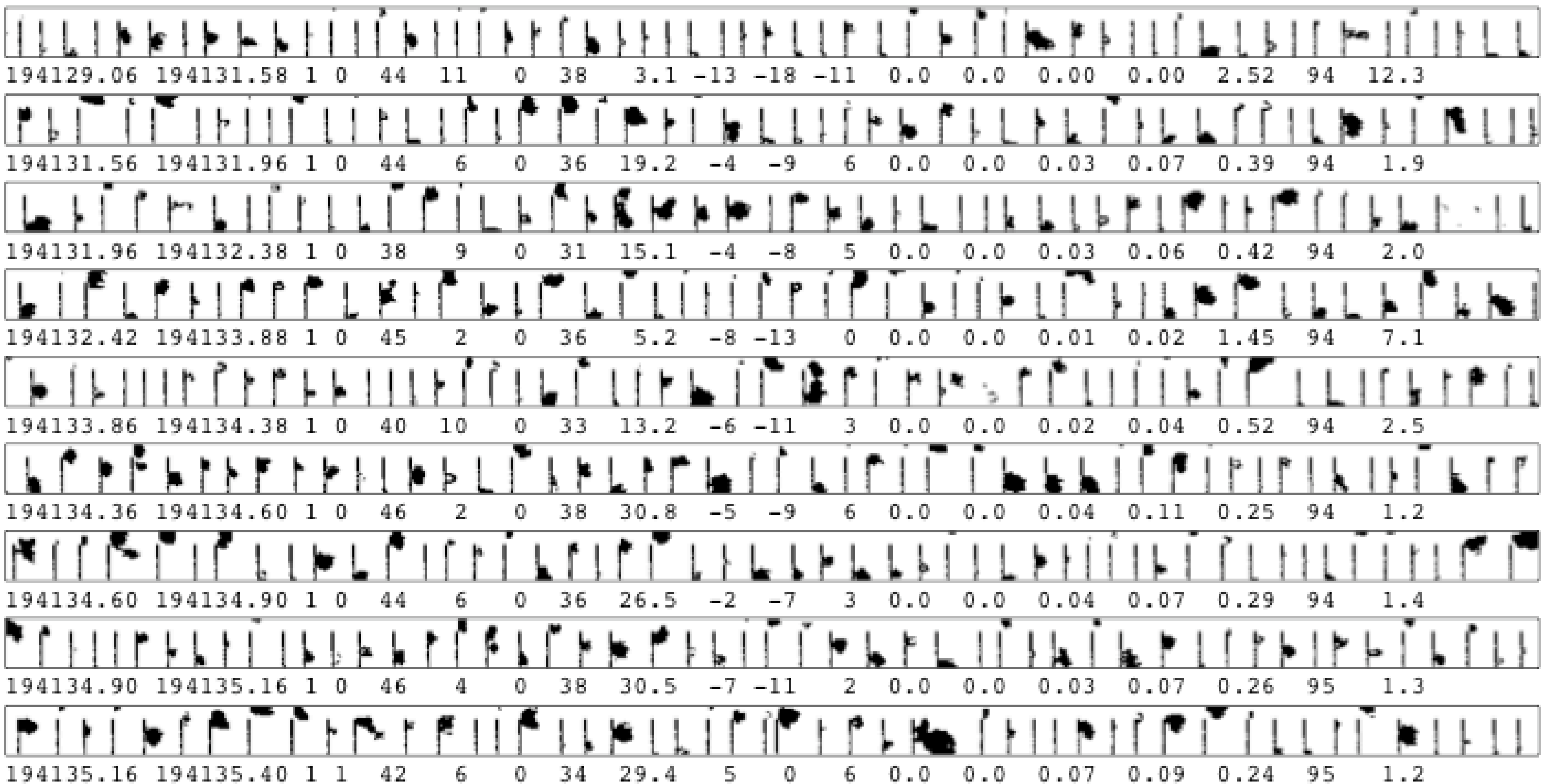
G. Vali photo

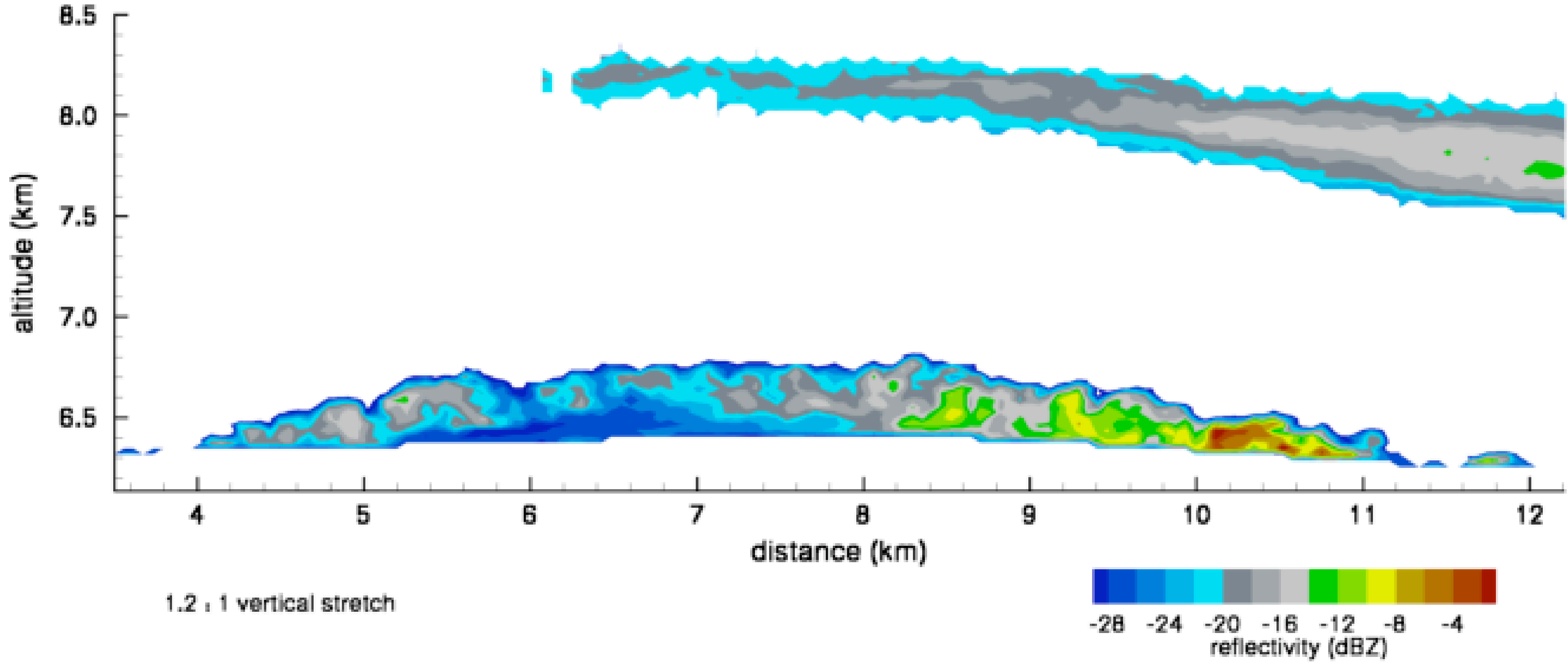


Hallett and Mossop, 1974

Leading edge of stack of clouds looking roughly N at 6400m altitude; 45 km E, 75 km N of LAR at 19:50 UTC, may 9, 2000

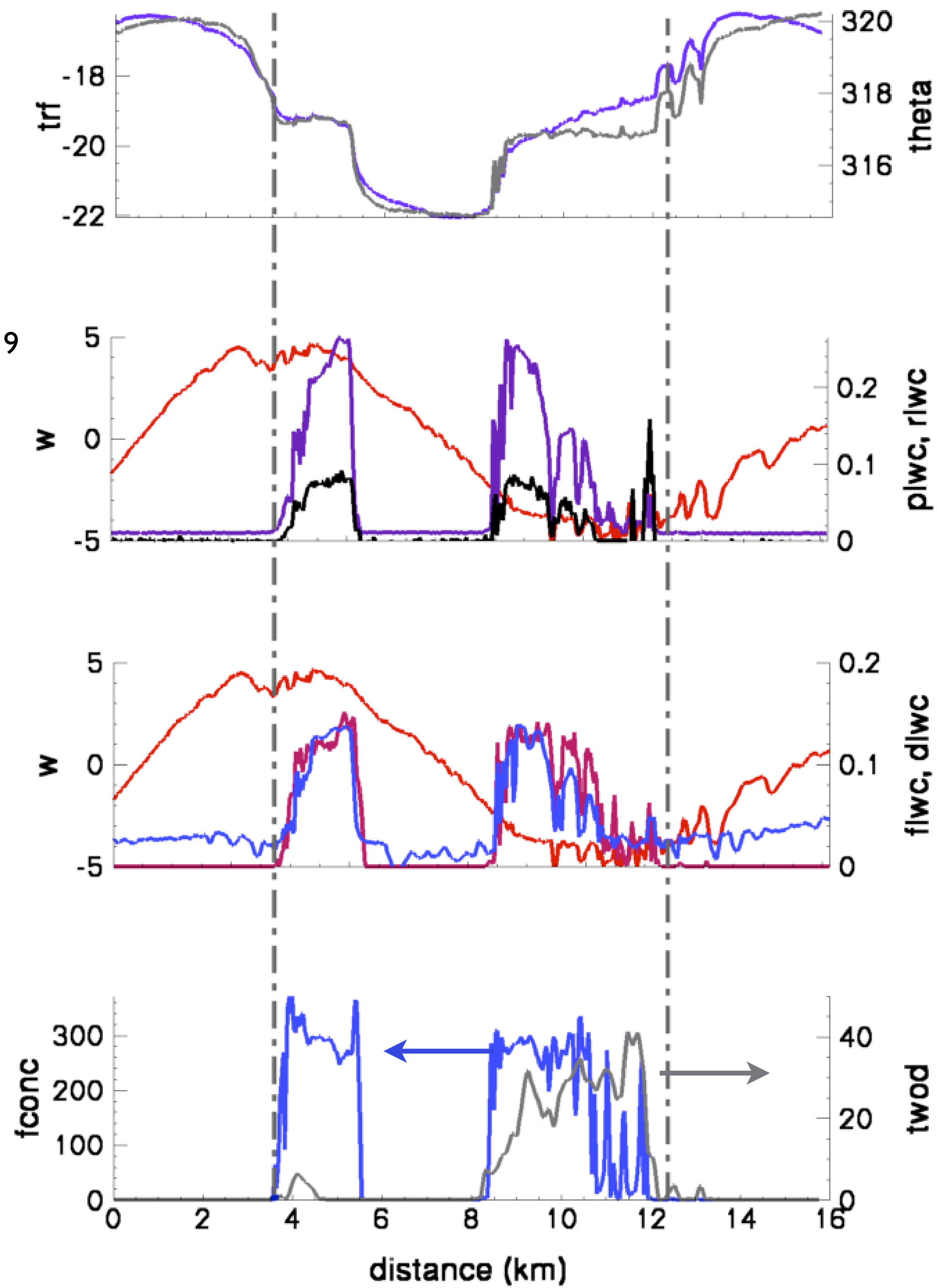

9.0
8.0
7.0
6.0
5.0
altitude (km)
flight line
-16°C
20...40 L^{-1}
-19°C
-18°C
5
10
15
20
25
3 : 2 vertical stretch
ground distance (km)
-25 -20 -15 -10 -5 0 5 dBZ
8.0
7.0
6.0
altitude (km)
20 dBZ (factor 10^2) increase in Z
4
6
8
10
12
14
1:1 axis ratio
ground distance (km)
-30 -25 -20 -15 -10 -5 0 5 dBZ

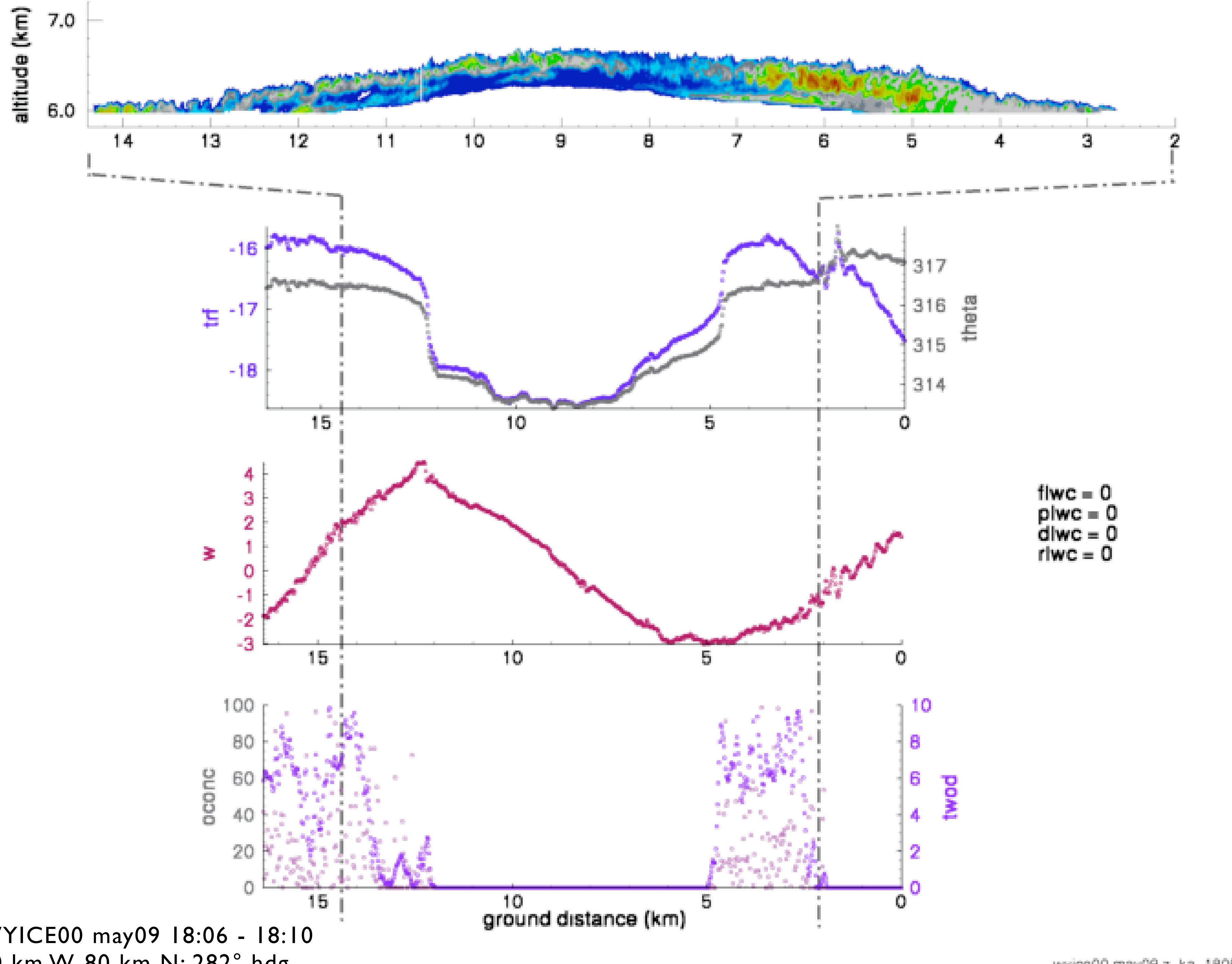

194129.06 194131.58 1 0 44 11 0 38 3.1 -13 -18 -11 0.0 0.0 0.00 0.00 2.52 94 12.3
194131.56 194131.96 1 0 44 6 0 36 19.2 -4 -9 6 0.0 0.0 0.03 0.07 0.39 94 1.9
194131.96 194132.38 1 0 38 9 0 31 15.1 -4 -8 5 0.0 0.0 0.03 0.06 0.42 94 2.0
194132.42 194133.88 1 0 45 2 0 36 5.2 -8 -13 0 0.0 0.0 0.01 0.02 1.45 94 7.1
194133.86 194134.38 1 0 40 10 0 33 13.2 -6 -11 3 0.0 0.0 0.02 0.04 0.52 94 2.5
194134.36 194134.60 1 0 46 2 0 38 30.8 -5 -9 6 0.0 0.0 0.04 0.11 0.25 94 1.2
194134.60 194134.90 1 0 44 6 0 36 26.5 -2 -7 3 0.0 0.0 0.04 0.07 0.29 94 1.4
194134.90 194135.16 1 0 46 4 0 38 30.5 -7 -11 2 0.0 0.0 0.03 0.07 0.26 95 1.3
194135.16 194135.40 1 1 42 6 0 34 29.4 5 0 6 0.0 0.0 0.07 0.09 0.24 95 1.2



WYICE00 may09 18:17 - 18:19
30 km W, 83 km N; 103° hdg

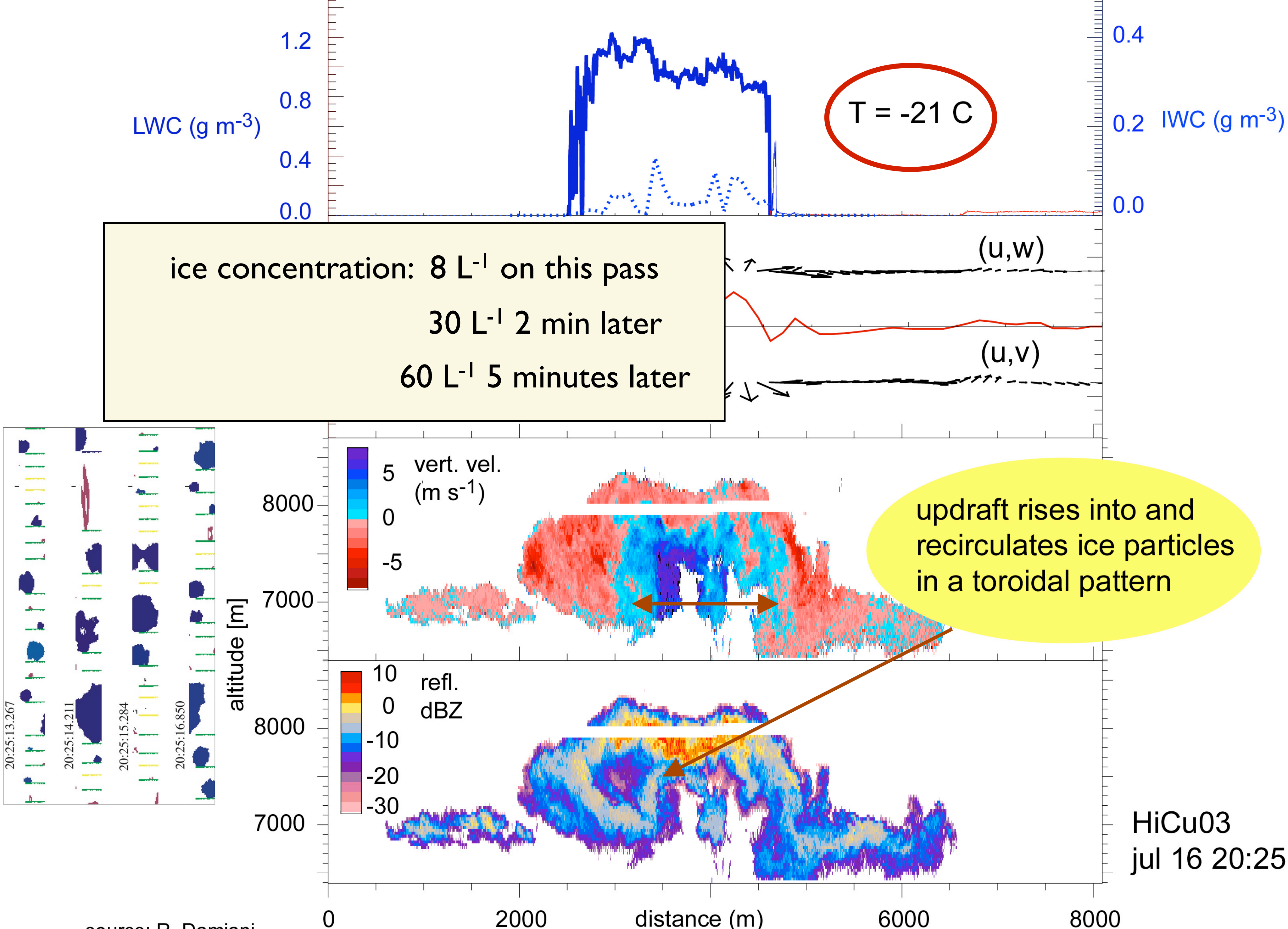
WYICE00 may09 18:17 - 18:19
30 km W, 83 km N; 103° hdg





WYICE00 may09 18:06 - 18:10
30 km W, 80 km N; 282° hdg

Damiani, Vali & Haimov, 2006, *J. Atmos. Sci.*, 63, 1432.



ice concentration: 8 L^{-1} on this pass

30 L^{-1} 2 min later

60 L^{-1} 5 minutes later

source: R. Damiani

Damiani, Vali & Haimov, 2006, *J. Atmos. Sci.*, 63, 1432.

cloud physics frontiers

Outstanding issues in microphysics:

Prediction of cloud characteristics from aerosols.

Large droplets at the tail of the distribution.

Origins of ice particles.

Turbulence and entrainment effects.

How to formulate relevant dynamical conditions ?

How to deal with variability on many scales ?

Areas of intense research activity:

Radiative properties of ice clouds, broken cloud fields, droplets with black carbon, ...

Quantitative precipitation forecasts.

Cloud seeding effectiveness.

Pollution effects on clouds and precipitation.

Incorporation of cloud microphysics in models.

Interpretation of remote sensing data.

cloud physics → applications

WRF-ARW model for CA atmospheric river events

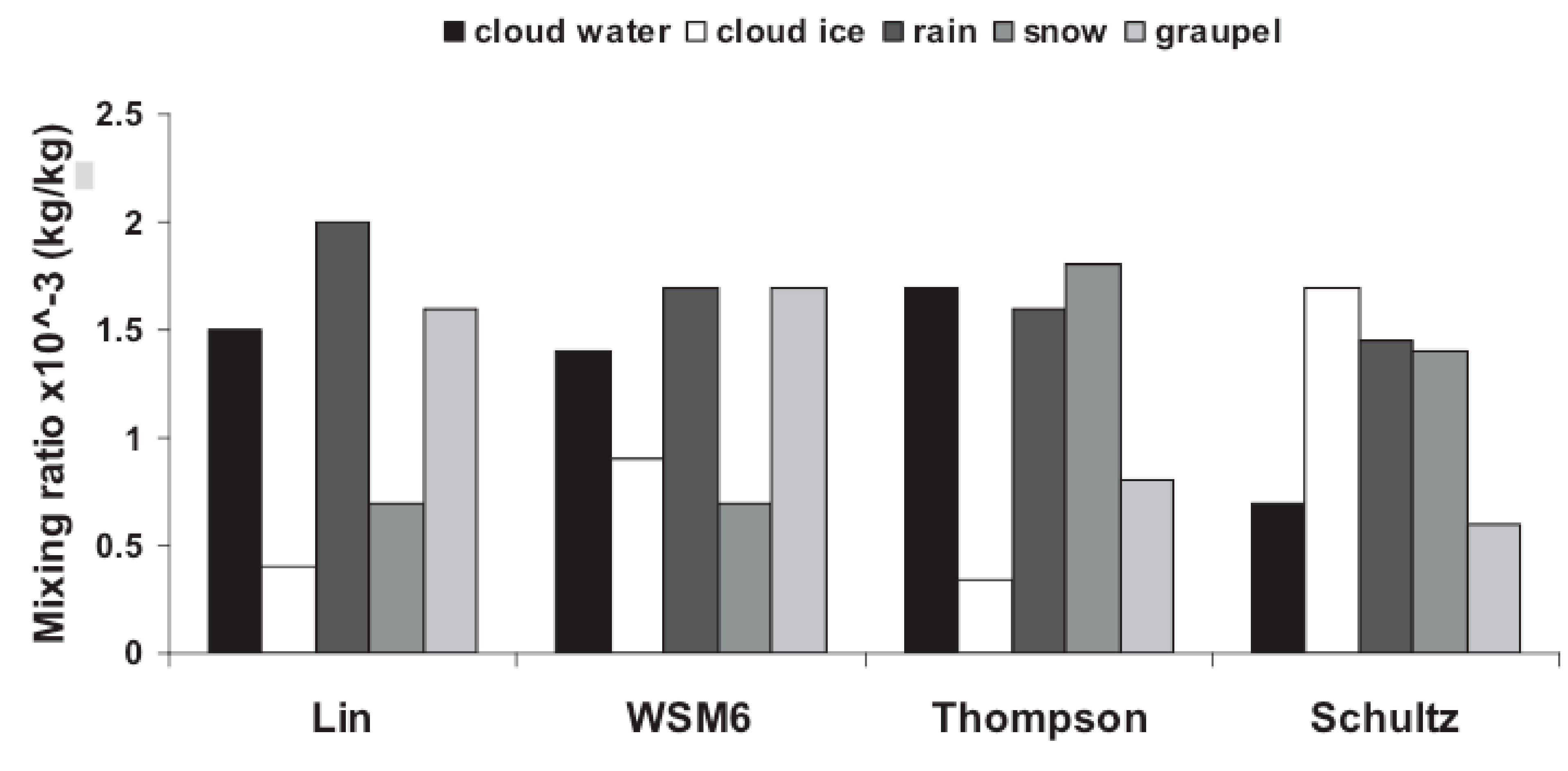


Figure 4. Cloud water, cloud ice, rain, snow and graupel mixing ratios (×10^{-3} kg/kg) averaged over five cases and over the American River Basin for four different microphysics schemes.

Jankov et al., 2009 JHM (to appear)

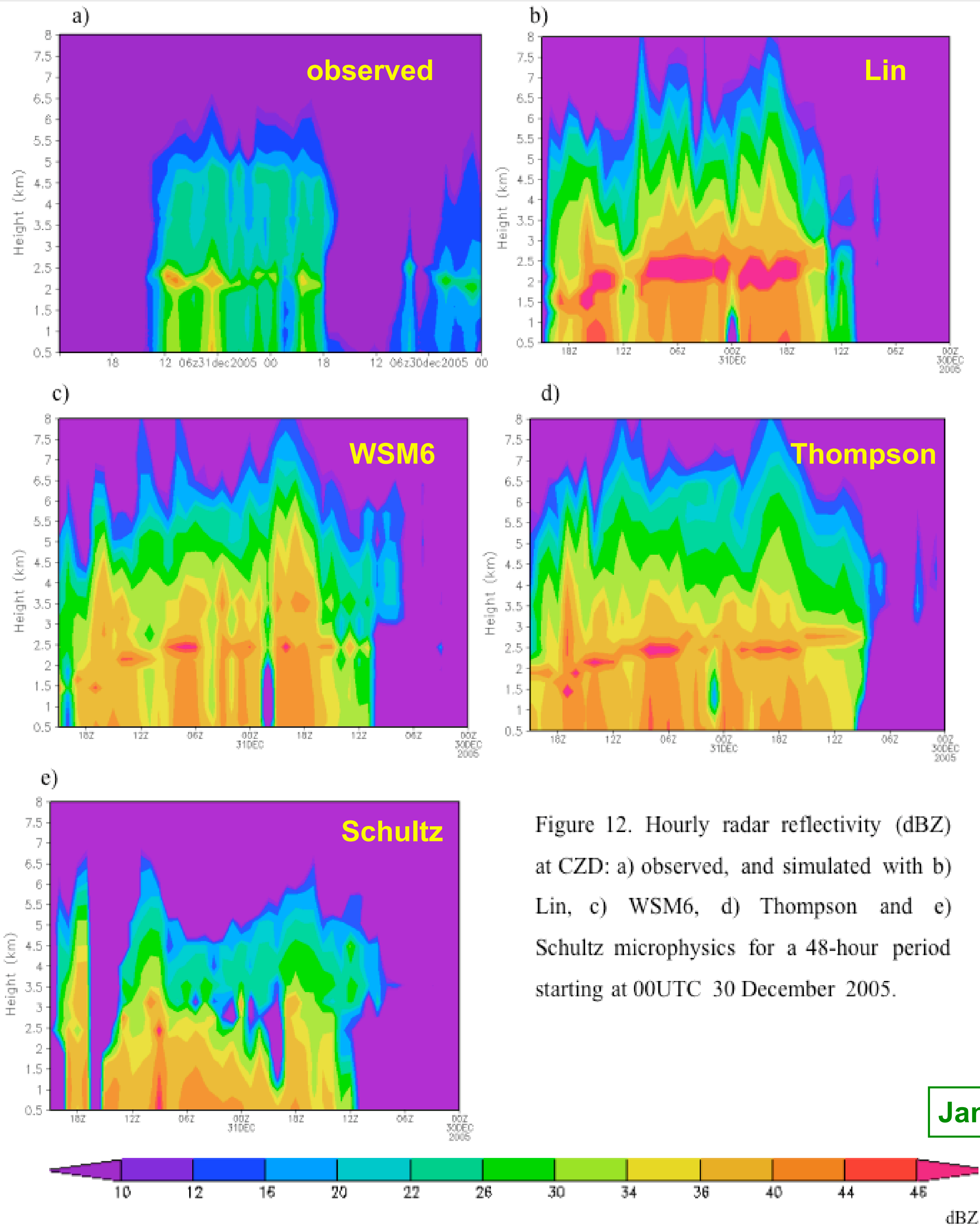
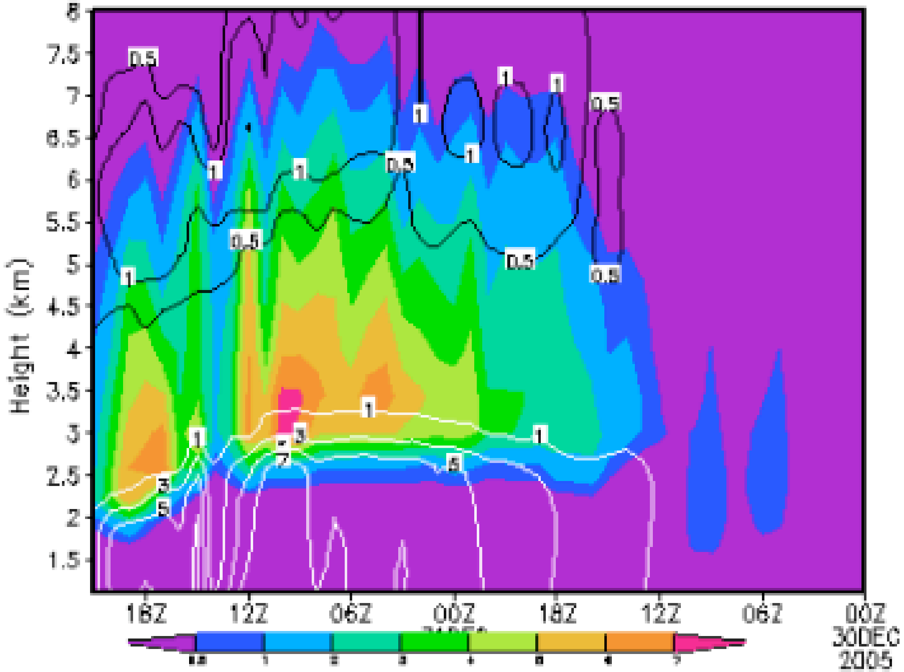


Figure 12. Hourly radar reflectivity (dBZ) at CZD: a) observed, and simulated with b) Lin, c) WSM6, d) Thompson and e) Schultz microphysics for a 48-hour period starting at 00UTC 30 December 2005.

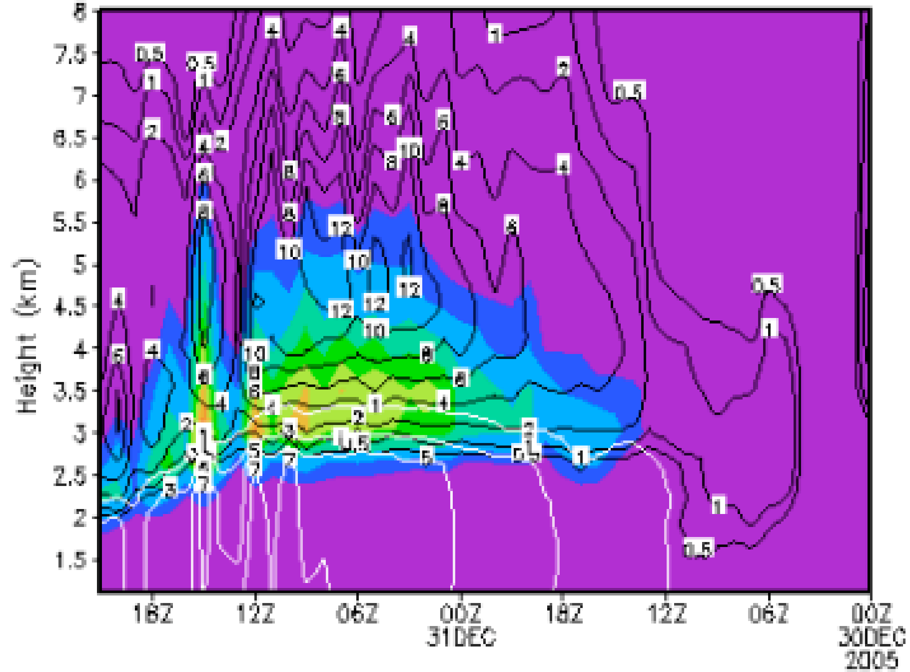
Hourly average reflectivity over 48 hours.

Jankov et al., 2009 JHM (to appear)

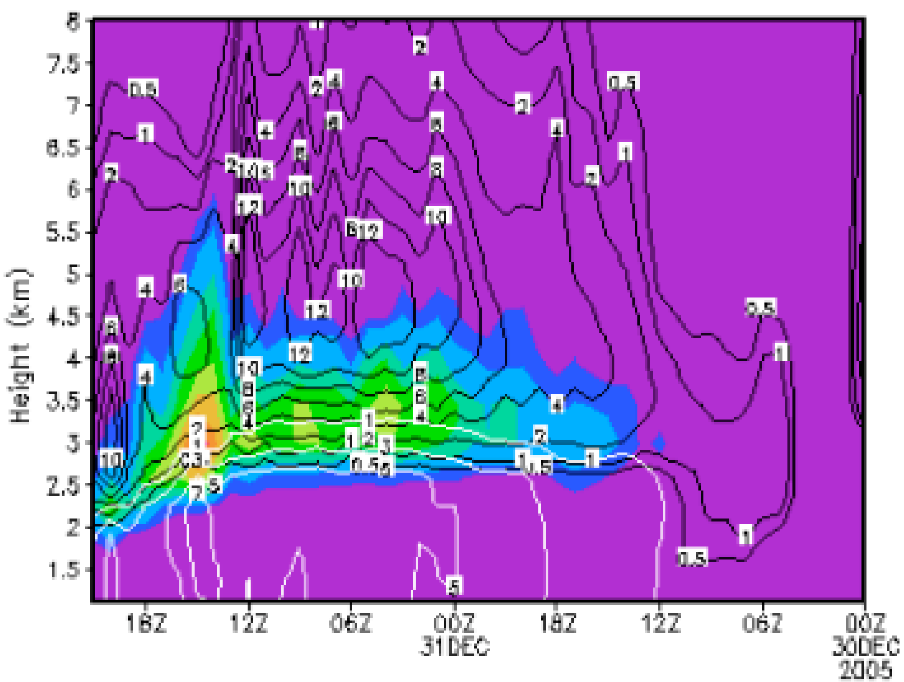
a) Lin scheme

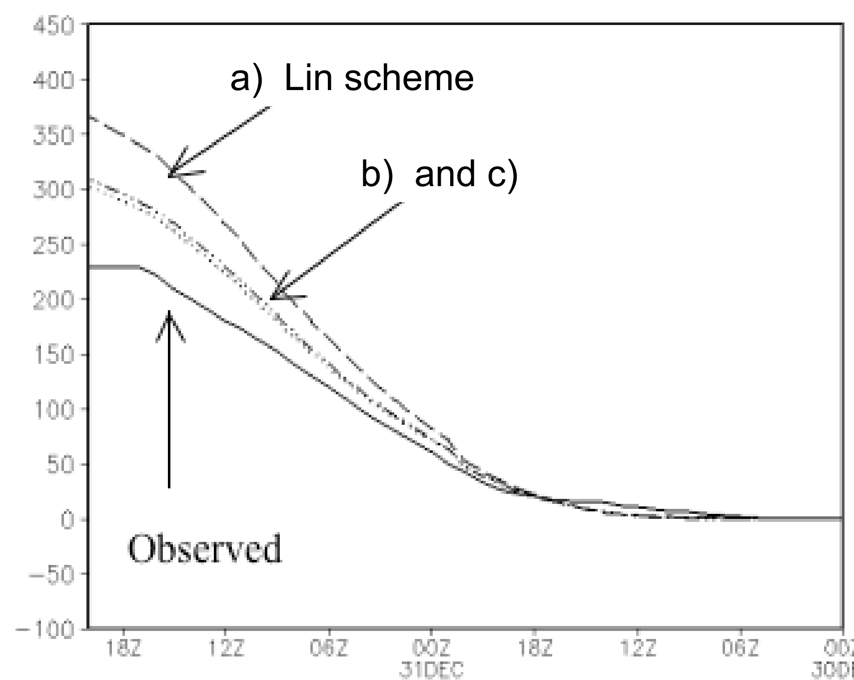


b) w/o snow accretion by graupel



c) w/o snow accretion by graupel and lower autoconversion

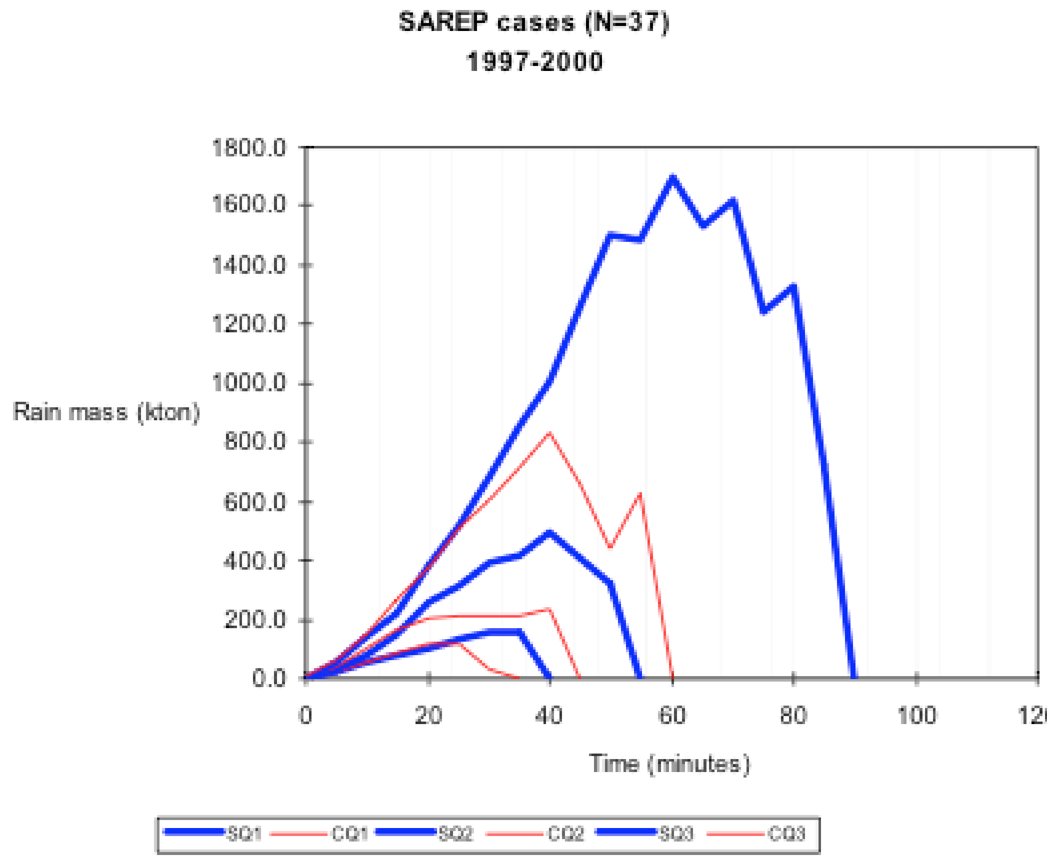




Jankov et al., 2009 JHM (to appear)

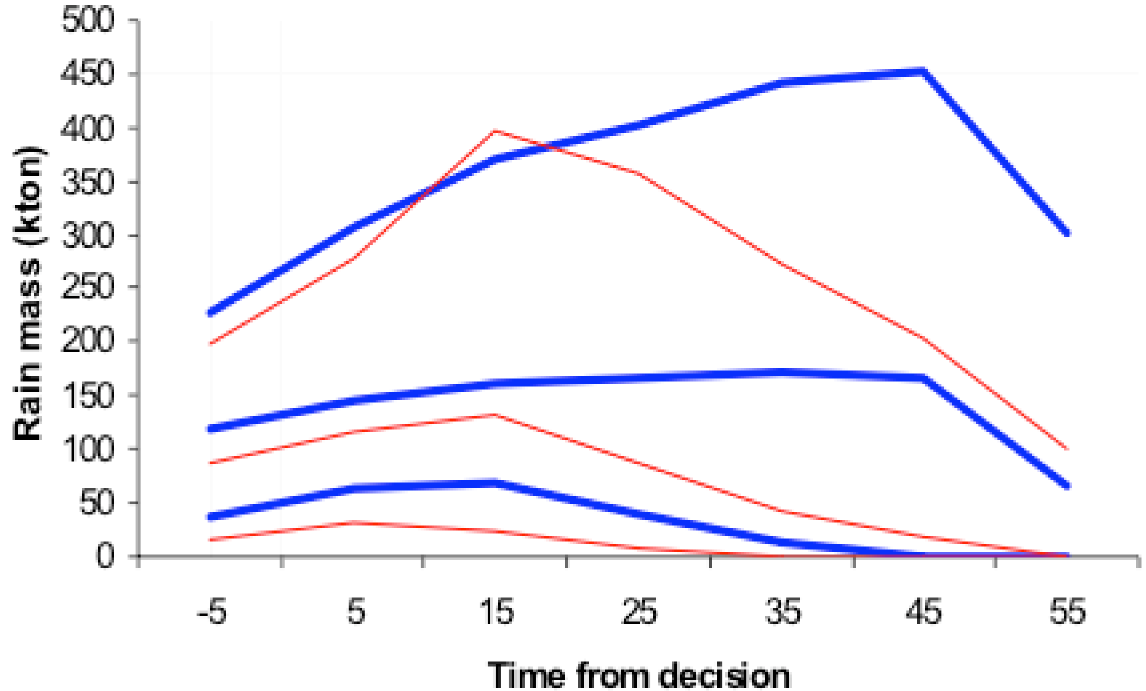
STATISTICAL STUDIES

- An average doubling in rain mass on storm scale
- For the 37 storms analyzed it amounts to about 296 X 10^6 m^3 of additional rainfall
- a cost of R0.04 per m^3

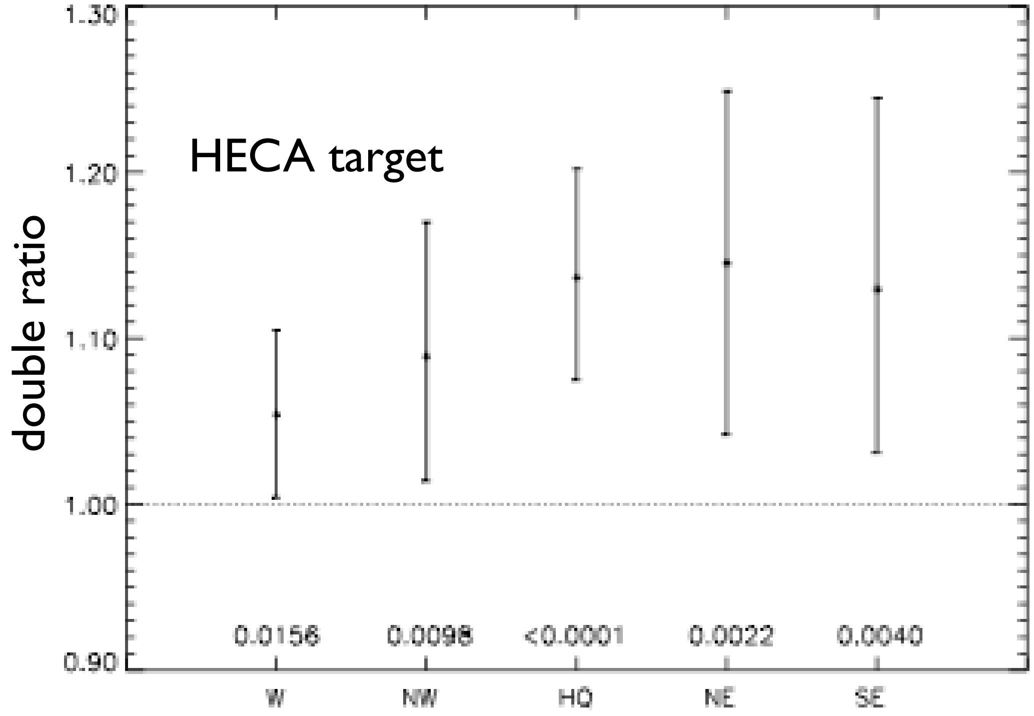


SAREP, Water SA, 2005

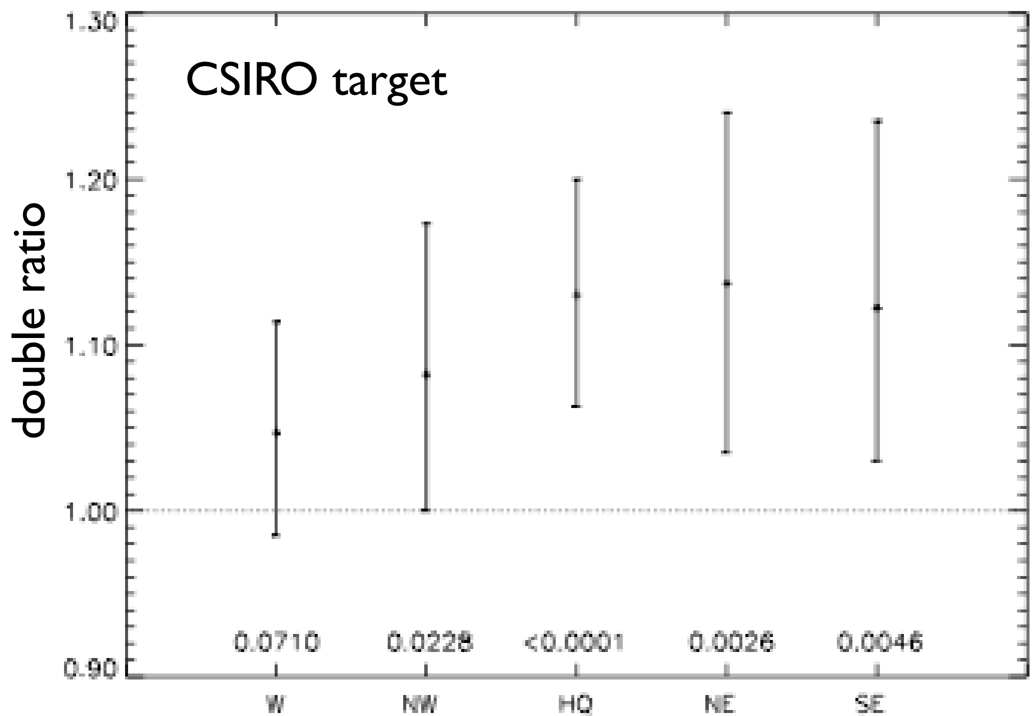
STATISTICAL STUDIES



South African randomized experiment, Journal Applied Meteorology 1997



(a) Results for the pooled 276 month data set for the HECA target.



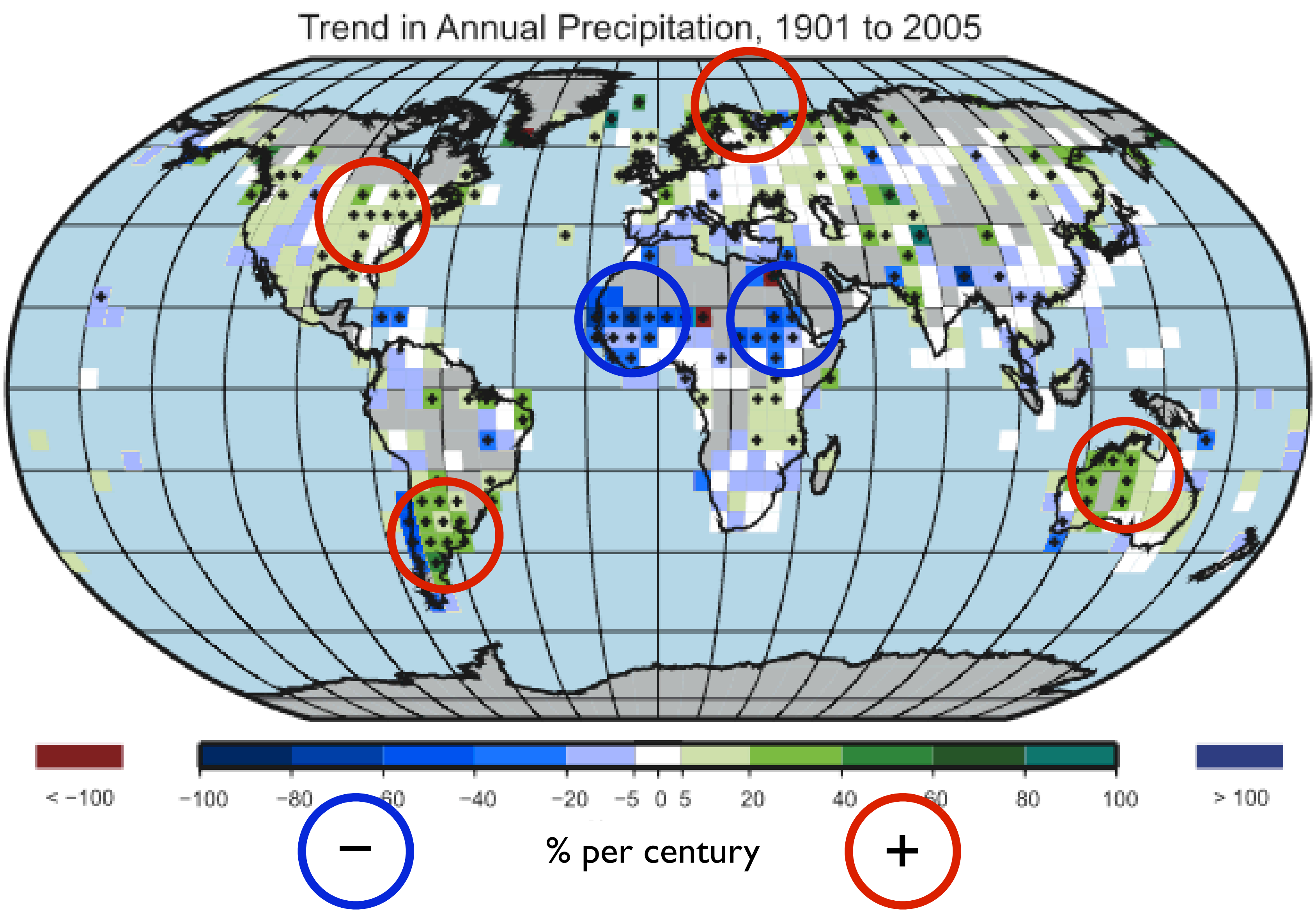
(b) Results for the pooled 276 month data set for the CSIRO target.

Tasmania silver iodide seeding

Pooled 276 months of data.

Double ratios and confidence intervals for the HECA & CSIRO targets vs. the west (W), northwest (NW), high quality (HQ), northeast (NE) and southeast (SE) controls. The bootstrap probabilities for obtaining a double ratio higher than the actual is shown above the horizontal axis.

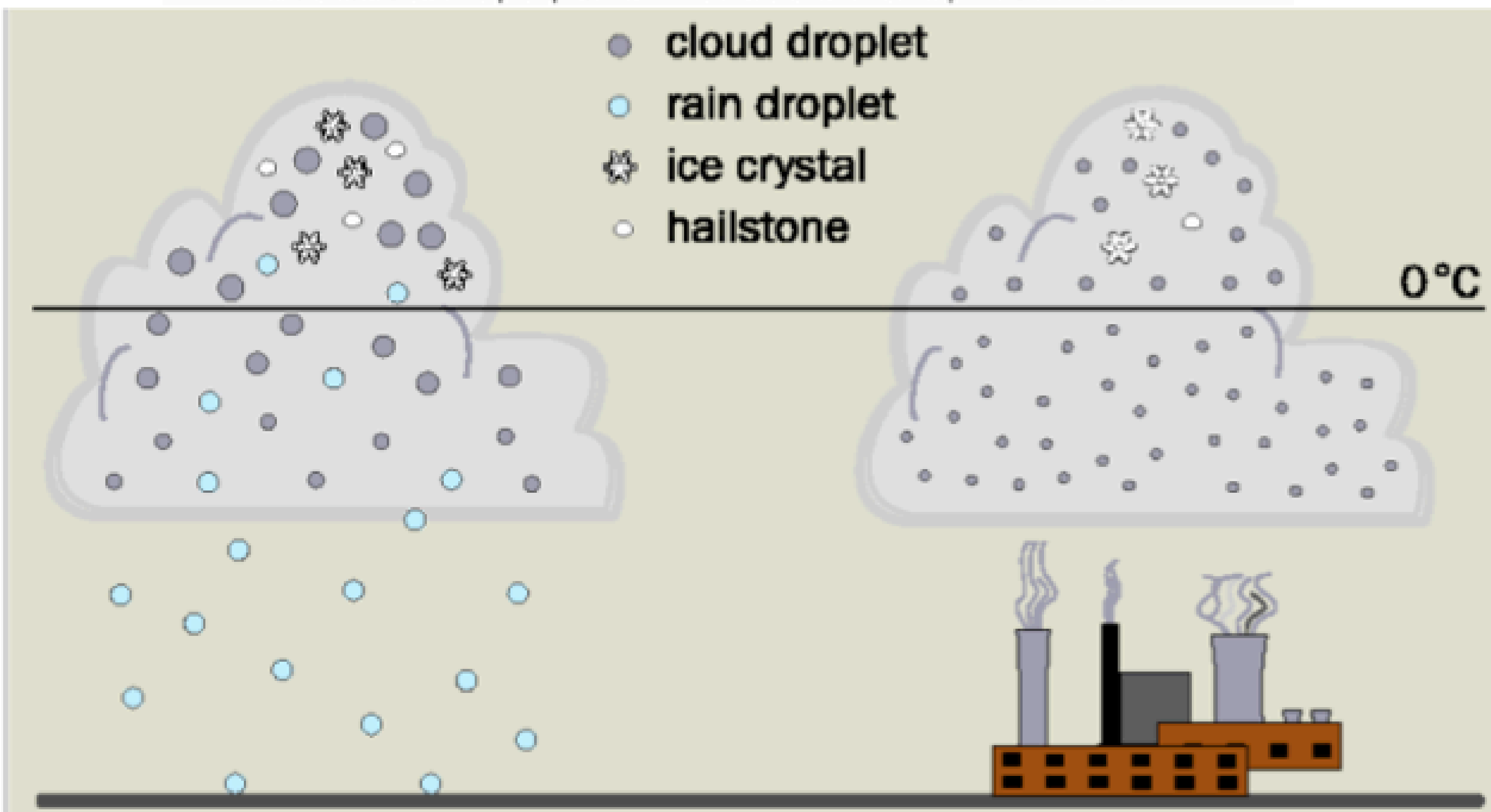
Morrison et al., 2009 JAMC (to appear)


Trend in Annual Precipitation, 1901 to 2005
< −100
−100
−80
−60
−40
−20
−5
0
5
20
40
60
80
100
> 100
−
% per century
+

Suppression of Rain and Snow by Urban and Industrial Air Pollution

Daniel Rosenfeld

Direct evidence demonstrates that urban and industrial air pollution can completely shut off precipitation from clouds that have temperatures at their tops of about −10°C over large areas. Satellite data reveal plumes of reduced cloud particle size and suppressed precipitation originating from major urban areas and from industrial facilities such as power plants. Measurements obtained by the Tropical Rainfall Measuring Mission satellite reveal that both cloud droplet coalescence and ice precipitation formation are inhibited in polluted clouds.

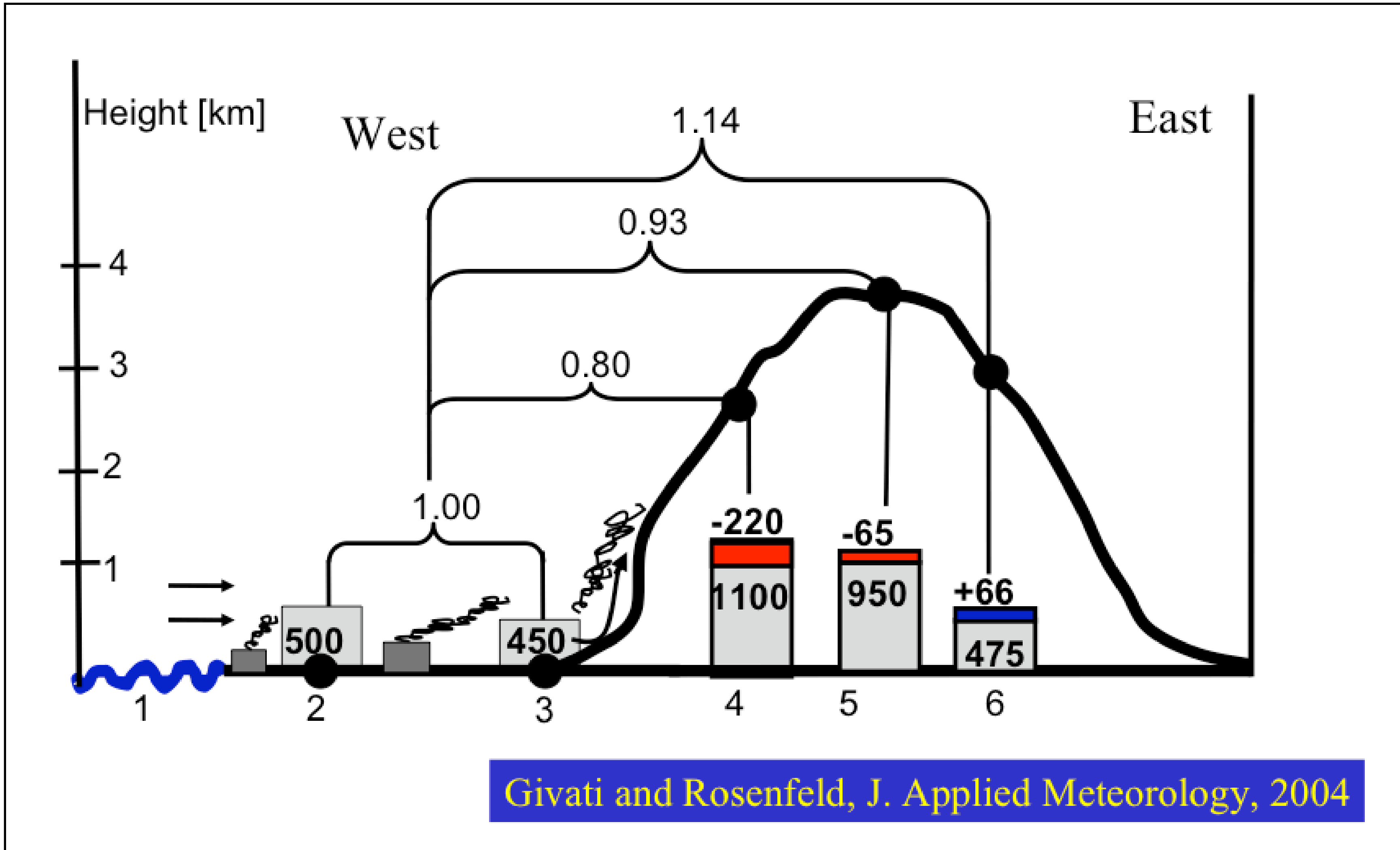


sciencemag.org SCIENCE VOL 287 10 MARCH 2000 1793

Pollution effect:

upslope decrease

downslope increase



Look for upcoming exchange of Alpert, Halfon & Levin vs. Givati & Rosenfeld in JAMC (based on statistics).