Cloud microphysics and climate: progress and prospects

Wojciech Grabowski

National Center for Atmospheric Research, Boulder, Colorado

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(my biased view)

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Cloud microphysics and climate: my suggestions for CMMAP

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Thanks:

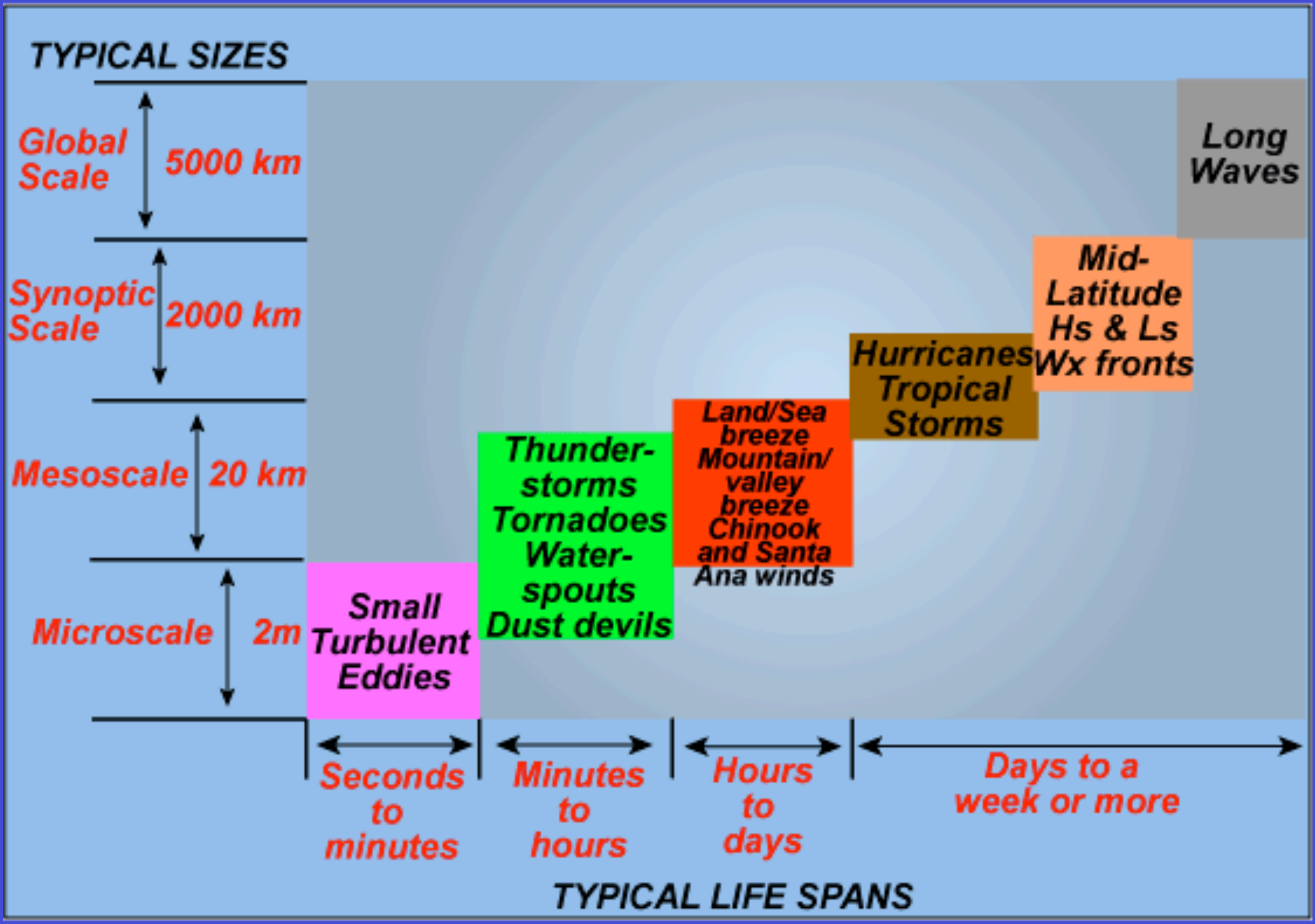
Hugh Morrison (ASP/MMM, NCAR)

Sally McFarlane (PNNL)

Yaping Li and Ed Zipser (U of Utah)

Piotr Rasinski (Warsaw University, Poland)

Why is it so hard to simulate the Earth climate system?



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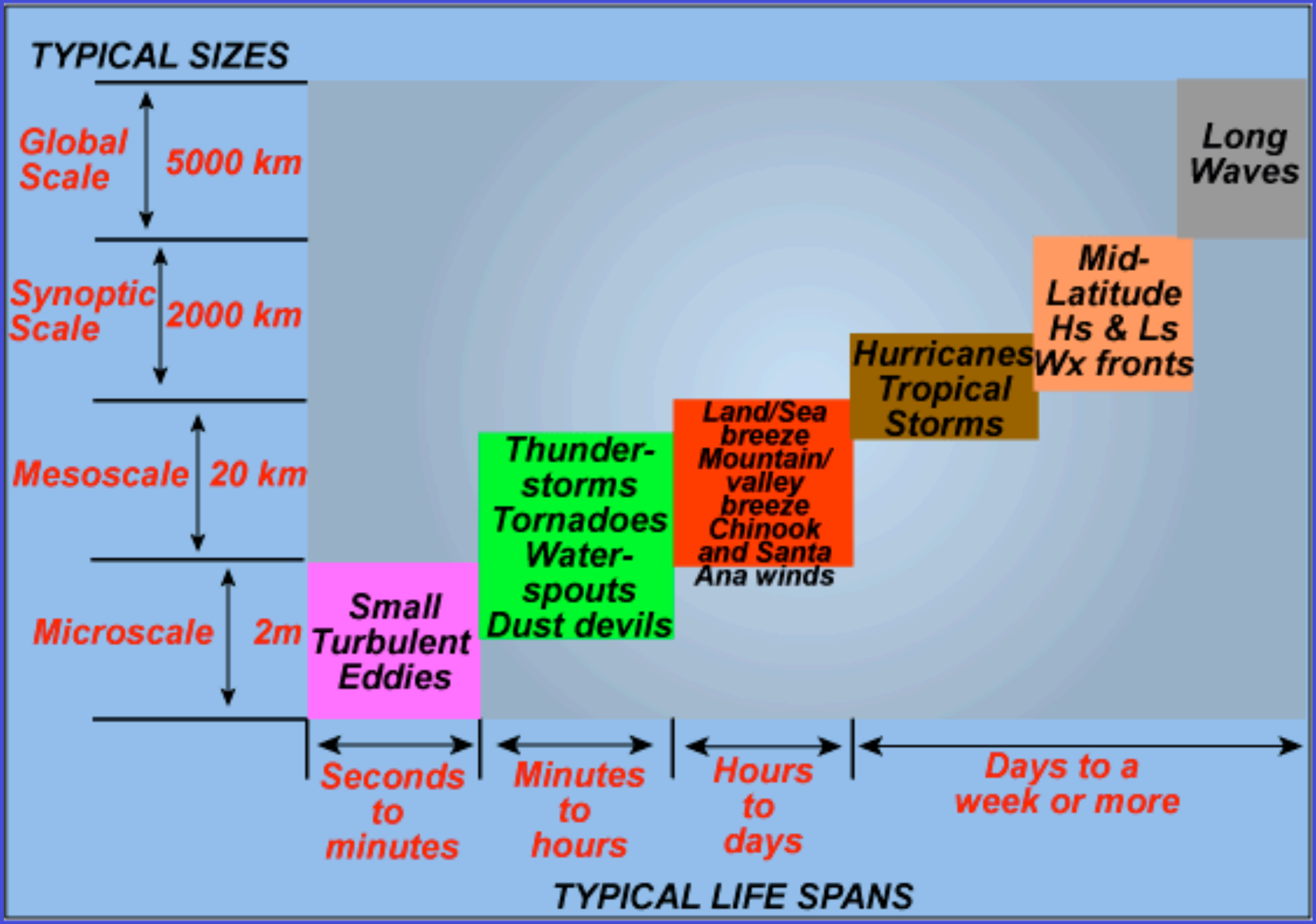

Because some of the key processes are even not on this diagram….

Why does the cloud microphysics matter?

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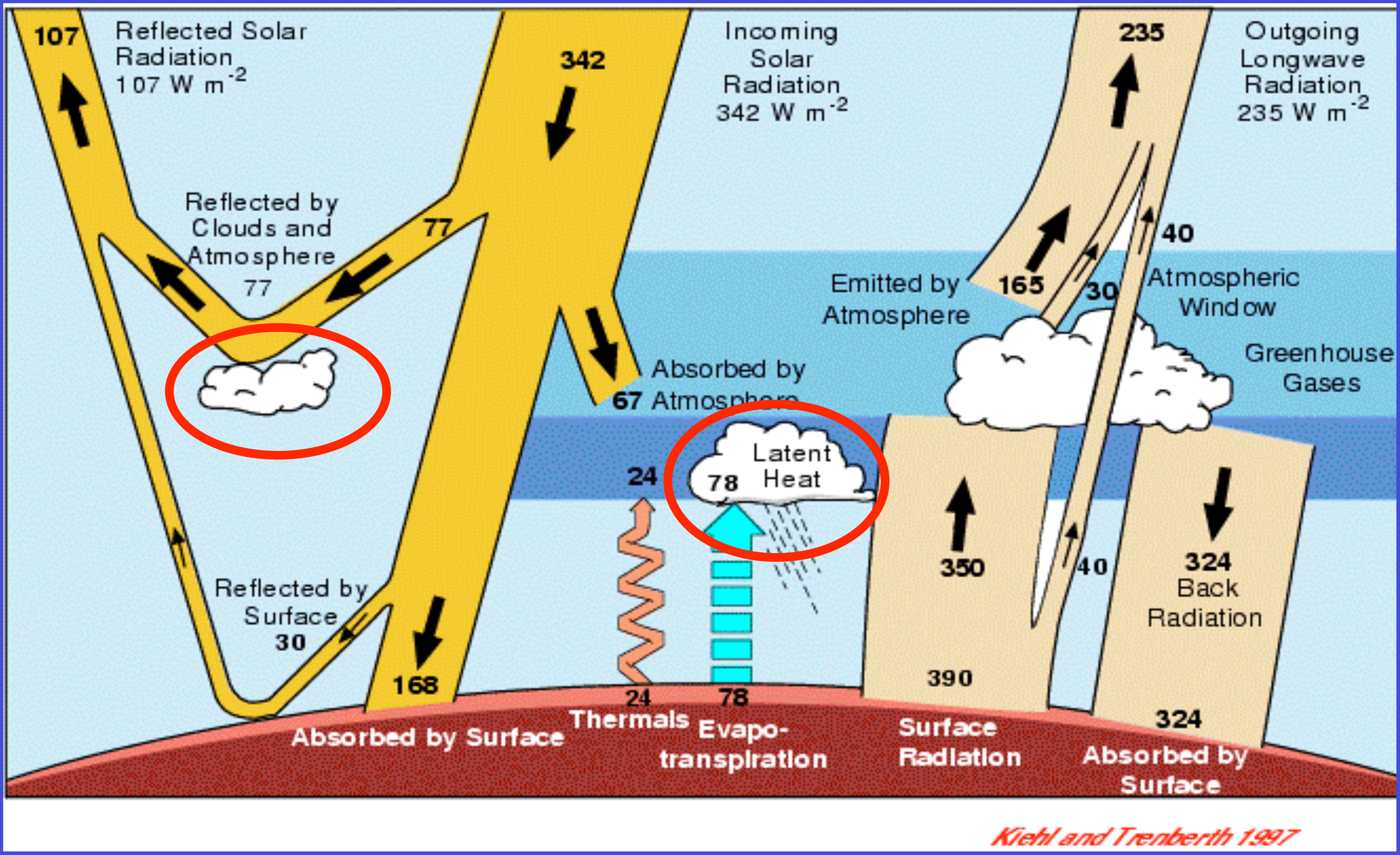
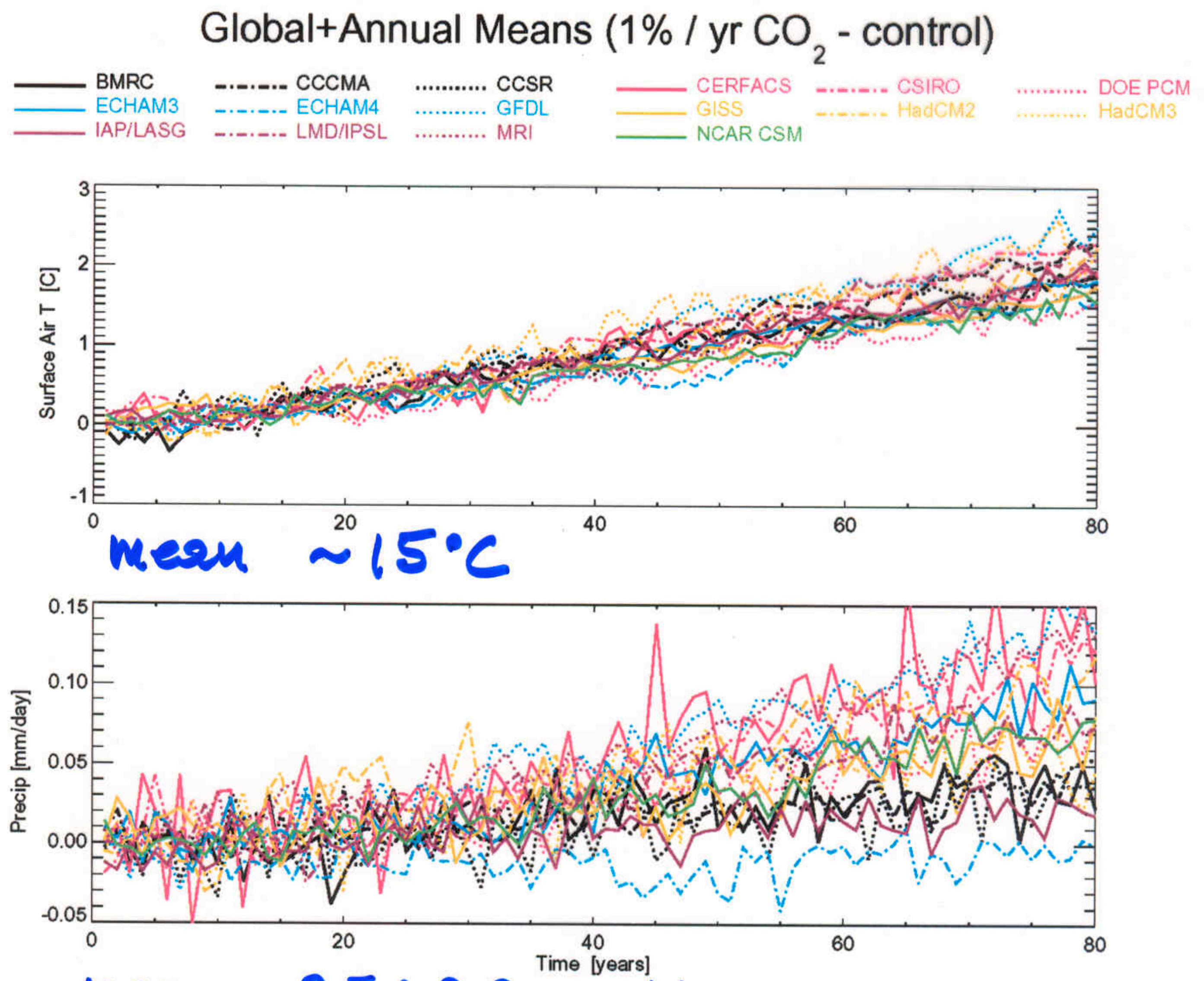
-impact on radiative fluxes

-development of precipitation (hydrologic cycle)



Kiehl and Trenberth 1997

The Earth annual and global mean energy budget



mean ~15°C

mean 2.5÷2.8 mm/day

CMIP results (GEWEX Newsletter, February 2003)

Why does the cloud microphysics matter?

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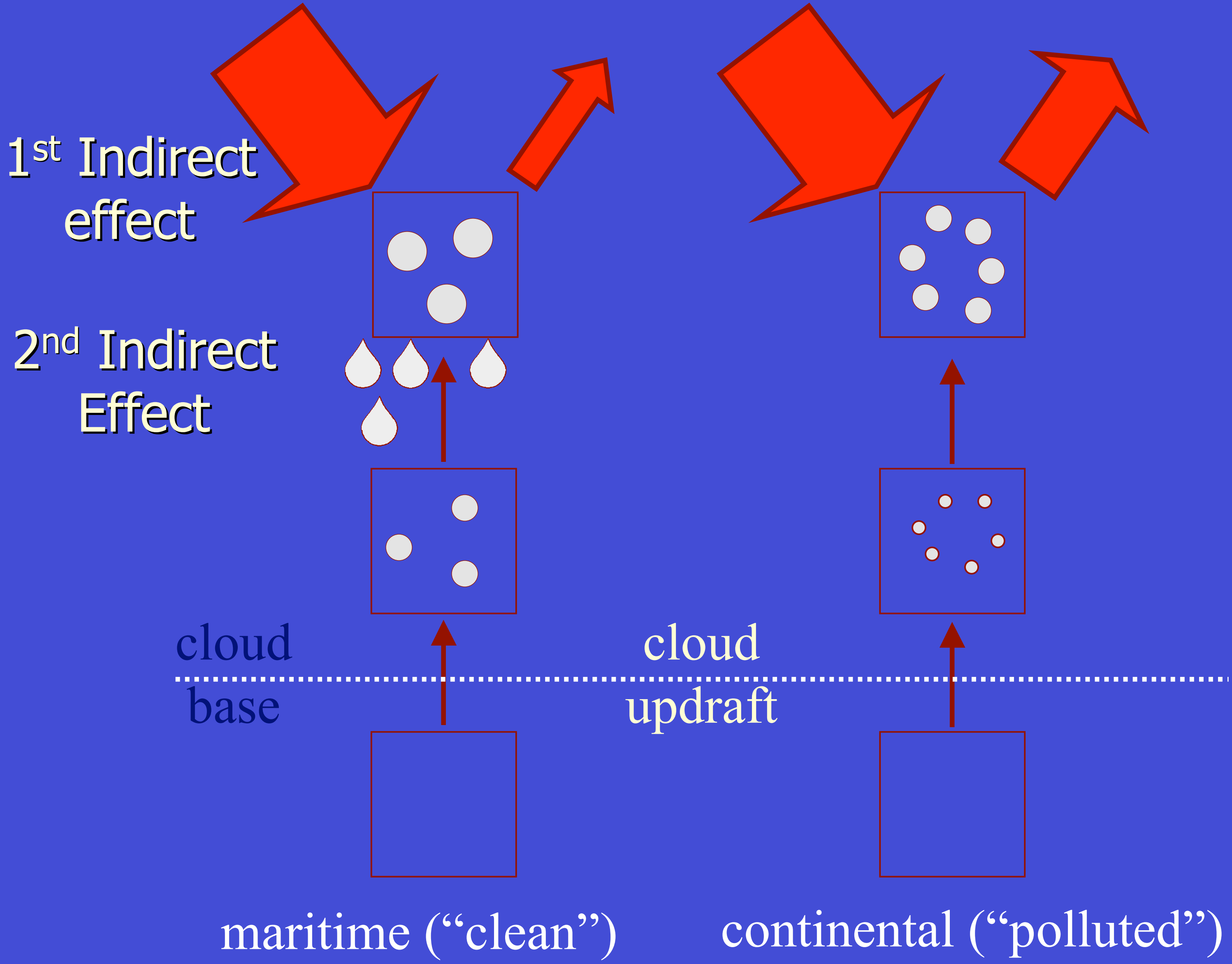
-development of precipitation (hydrologic cycle)

Changes in atmospheric aerosols affect both:
the indirect effect of aerosols on climate

Indirect aerosol effects



1st Indirect effect

2nd Indirect Effect

cloud base

cloud updraft

maritime (“clean”)

continental (“polluted”)

What should be CMMAP goal for the cloud microphysics?

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Develop capabilities to predict cloud microphysical parameters that affect development of precipitation and cloud radiative properties (concentration, phase, shape, etc. of cloud and precipitation particles)

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I would argue that this requires:

-cloud-scale dynamics (hence need for SP and CR-AGCM)

-coupling to the aerosol physics (to predict CCN and IN)

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I would argue that this requires:

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-coupling to the aerosol physics (to predict CCN and IN)

Note: Cloud microphysical parameters are typically used as primary tuning variables in today's AGCMs.

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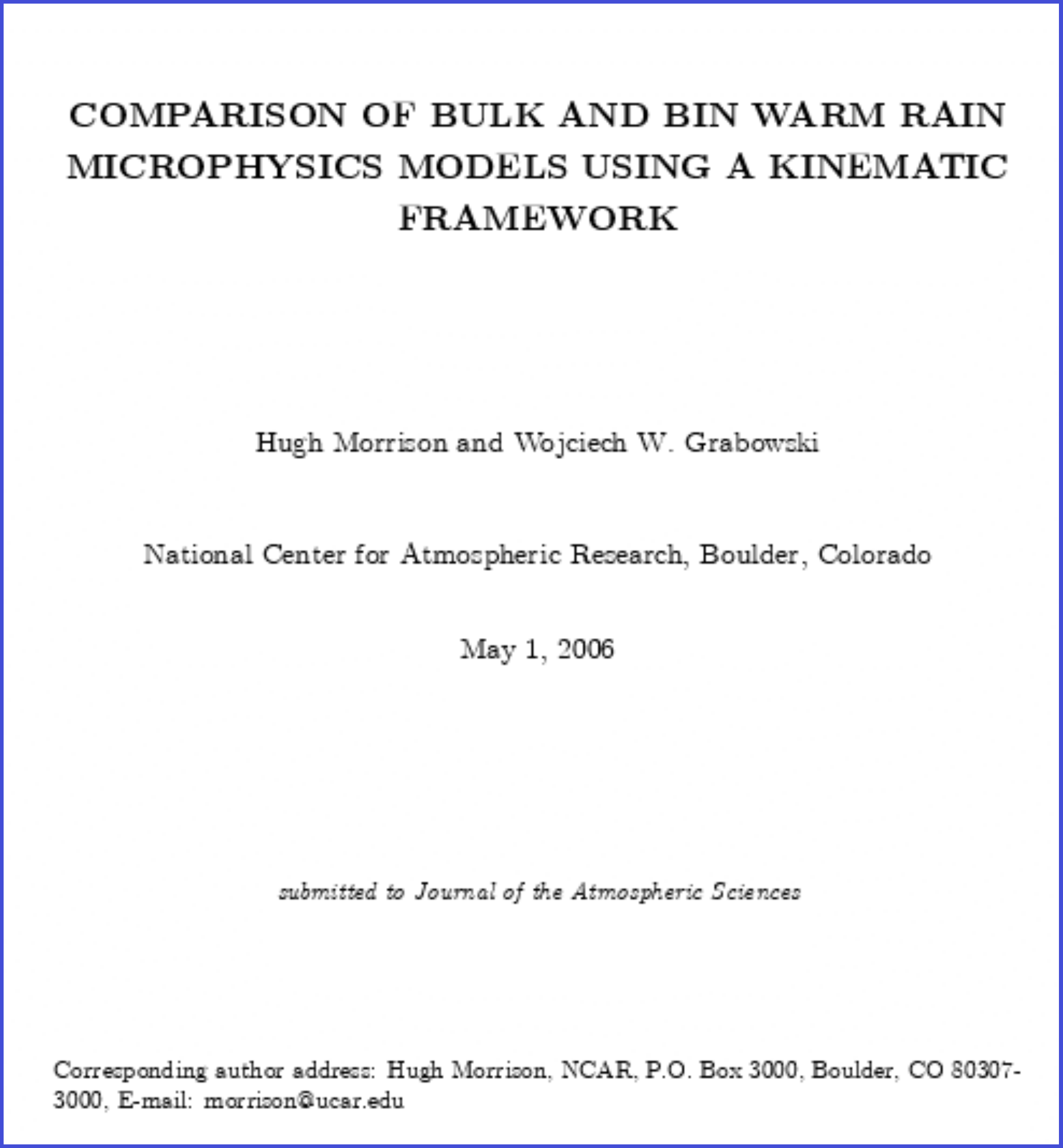


COMPARISON OF BULK AND BIN WARM RAIN MICROPHYSICS MODELS USING A KINEMATIC FRAMEWORK

Hugh Morrison and Wojciech W. Grabowski

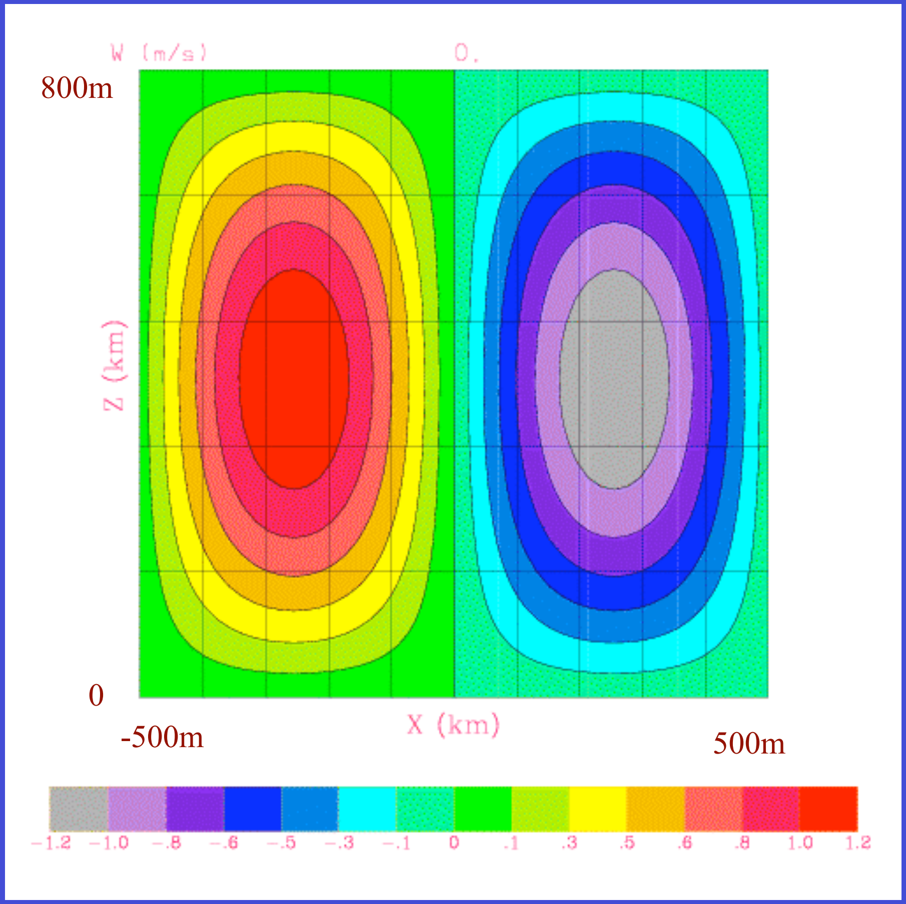
National Center for Atmospheric Research, Boulder, Colorado

May 1, 2006

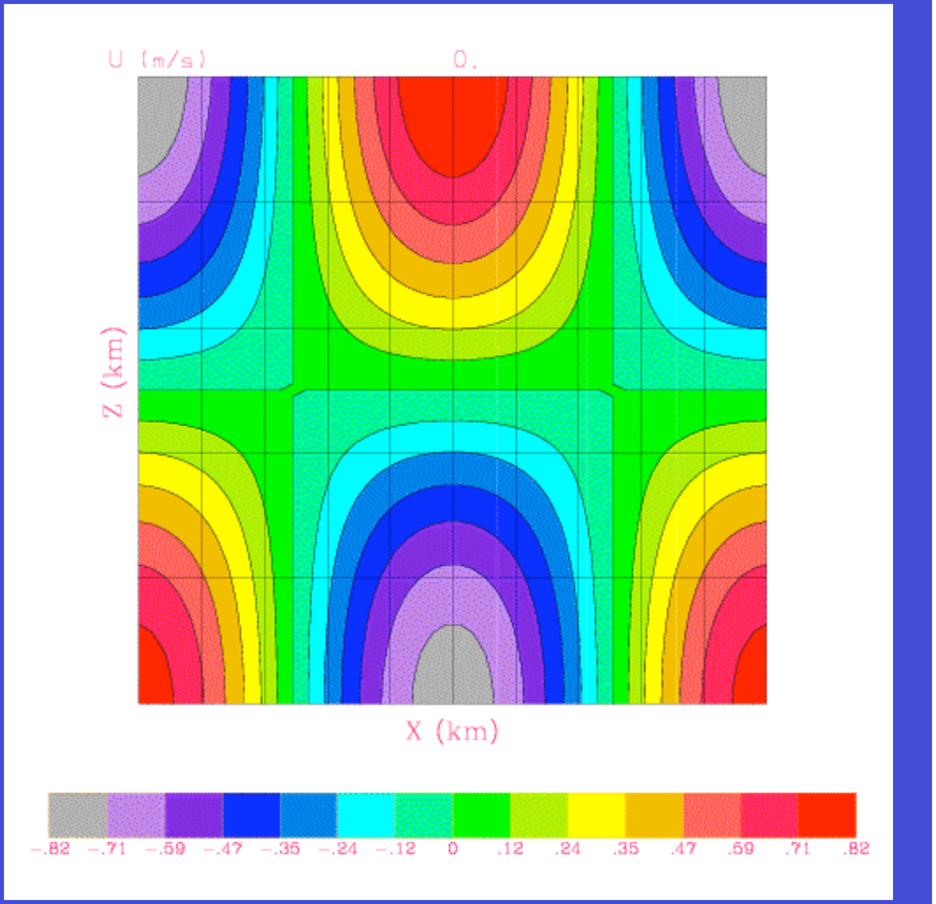
submitted to Journal of the Atmospheric Sciences

Corresponding author address: Hugh Morrison, NCAR, P.O. Box 3000, Boulder, CO 80307-3000, E-mail: morrison@ucar.edu

Kinematic (prescribed-flow) model of microphysical processes in Stratocumulus (2D: x-z)



Vertical velocity



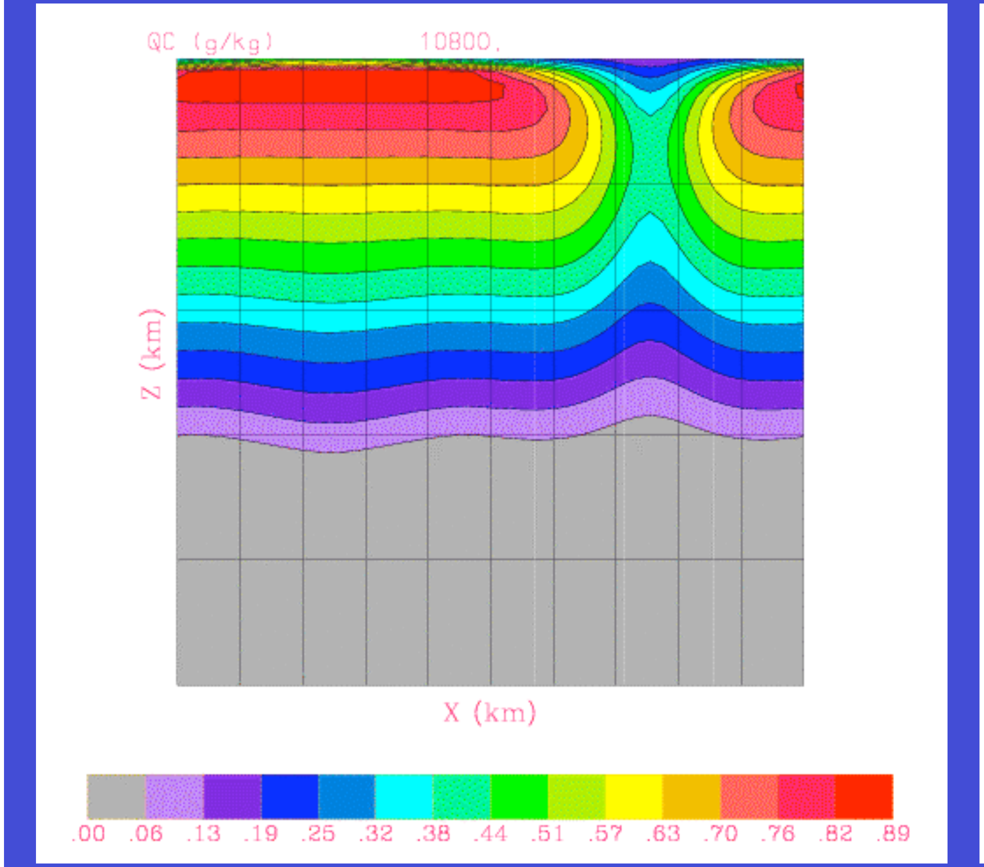
Horizontal velocity

Run up to quasi-steady-state is obtained (typically couple hours)…

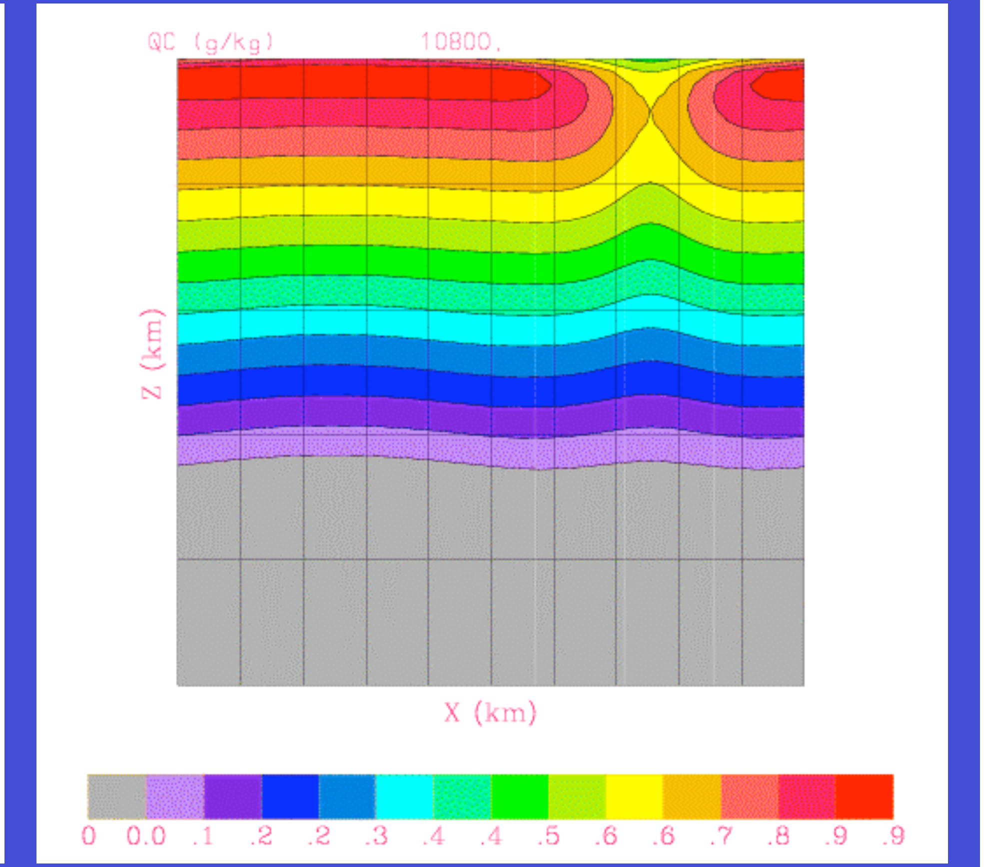
Piotr Rasinski (Warsaw University)

Cloud water (after 3hrs)

Maritime (clean)



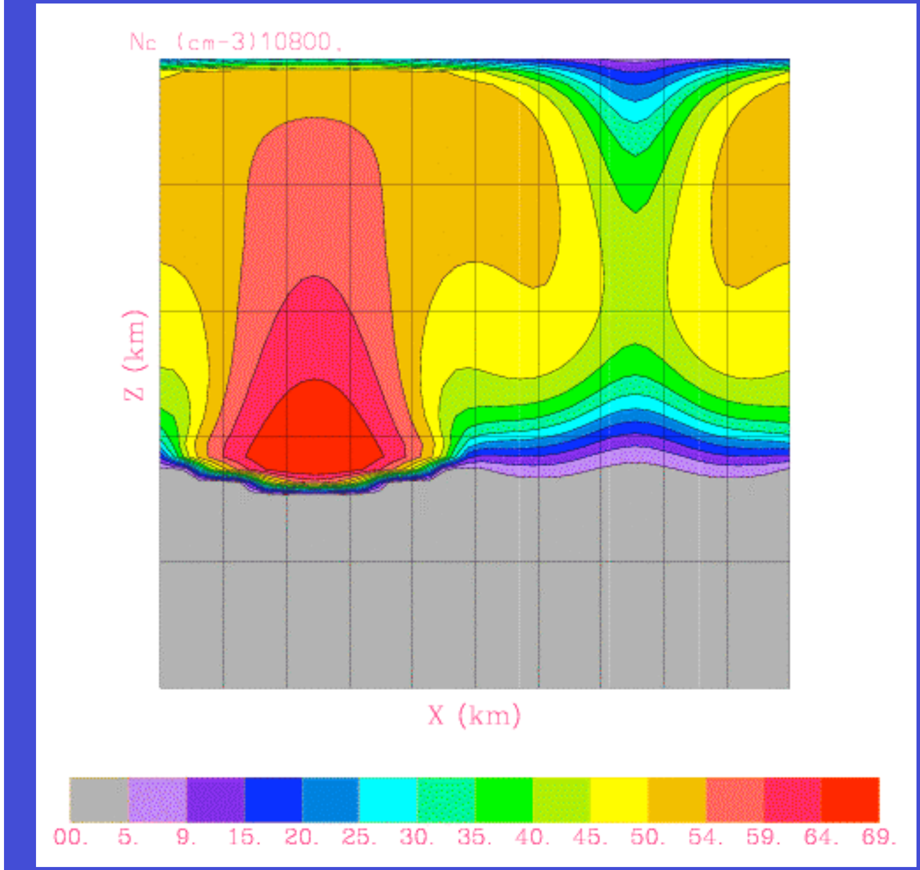
Continental (polluted)



Piotr Rasinski (Warsaw University)

Cloud droplet (r < 20 microns) number concentration

Maritime (clean)



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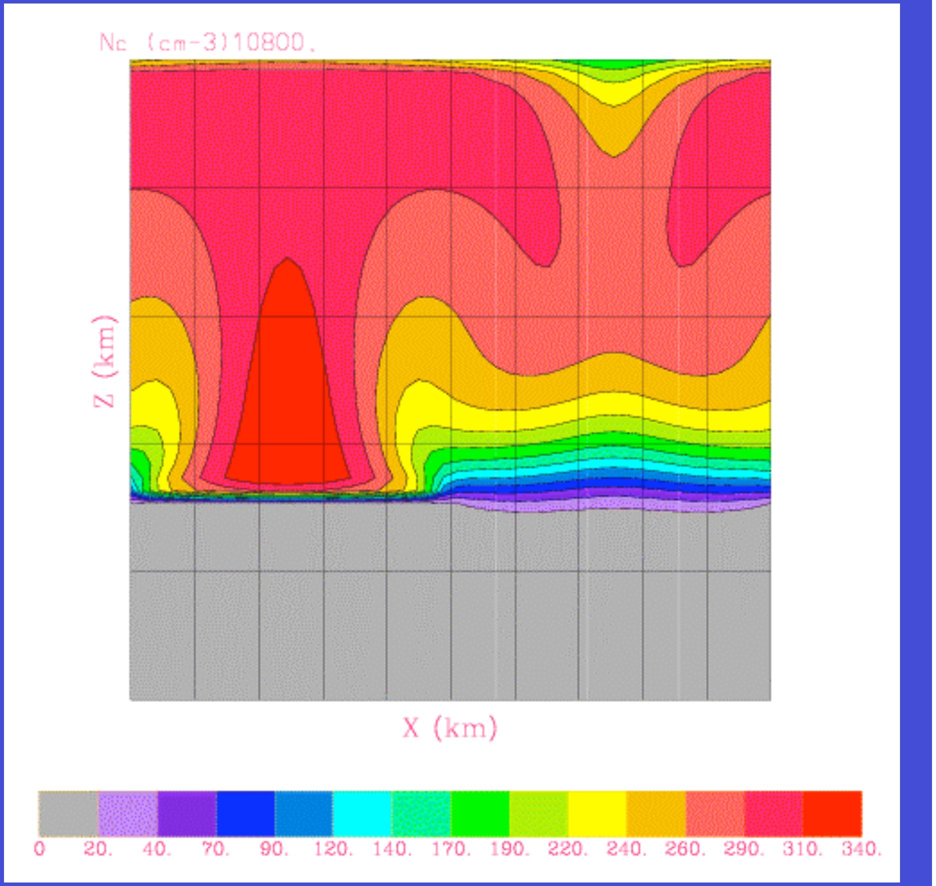
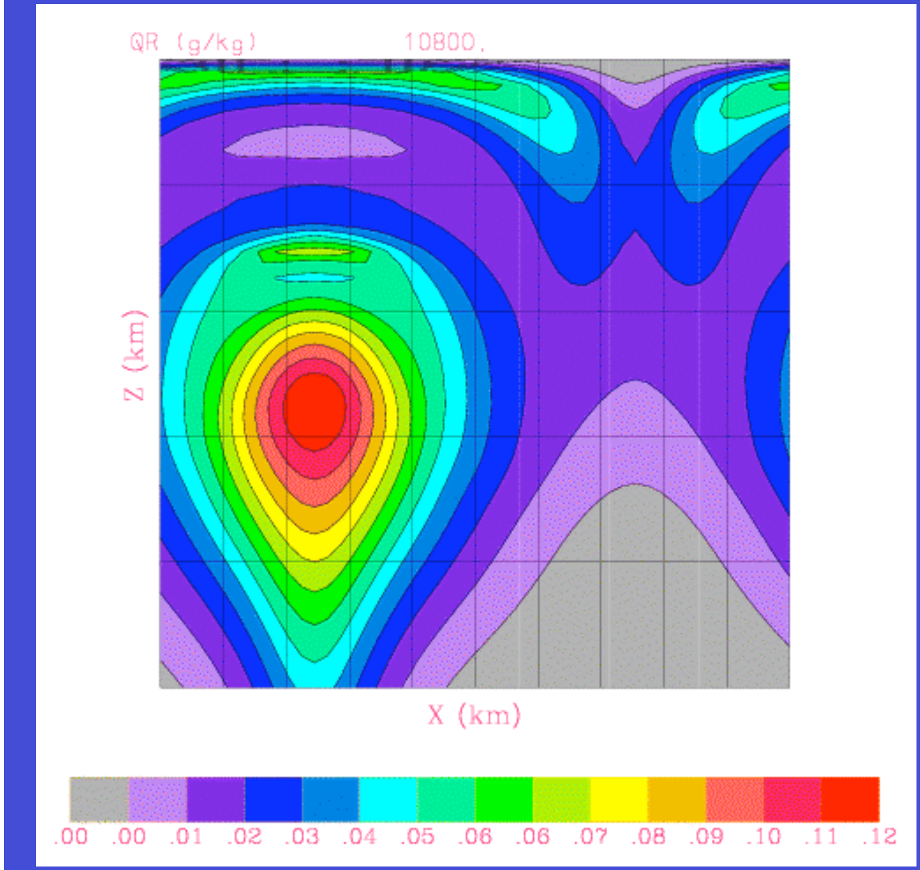


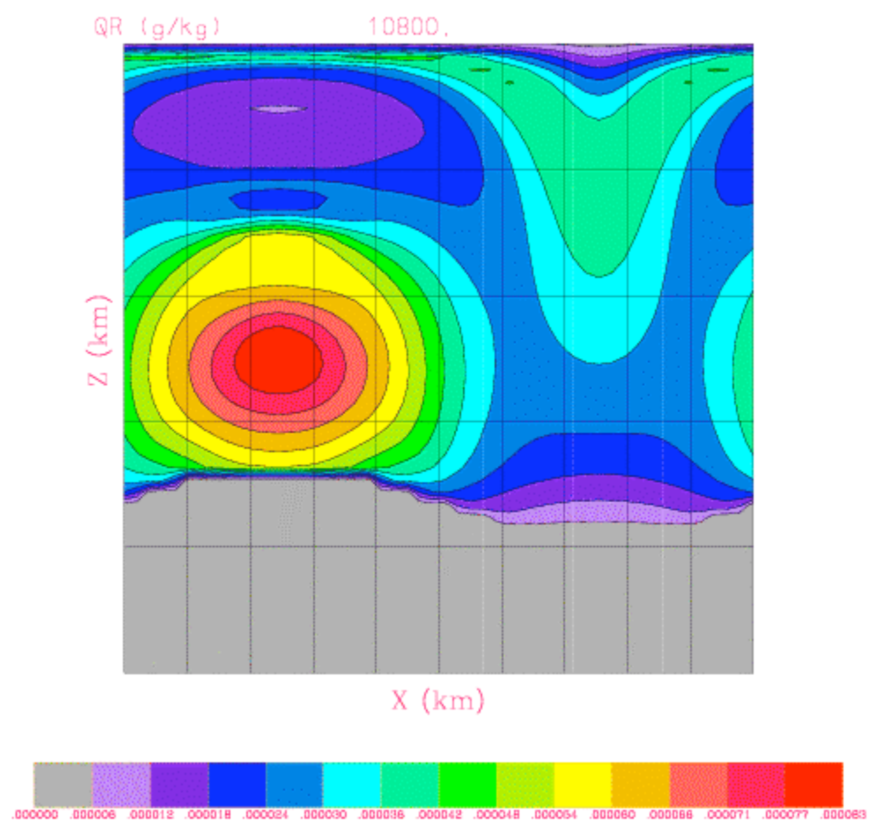
Piotr Rasinski (Warsaw University)

Drizzle (r > 25 microns) mixing ratio

Maritime (clean)



Continental (polluted)



Piotr Rasinski (Warsaw University)

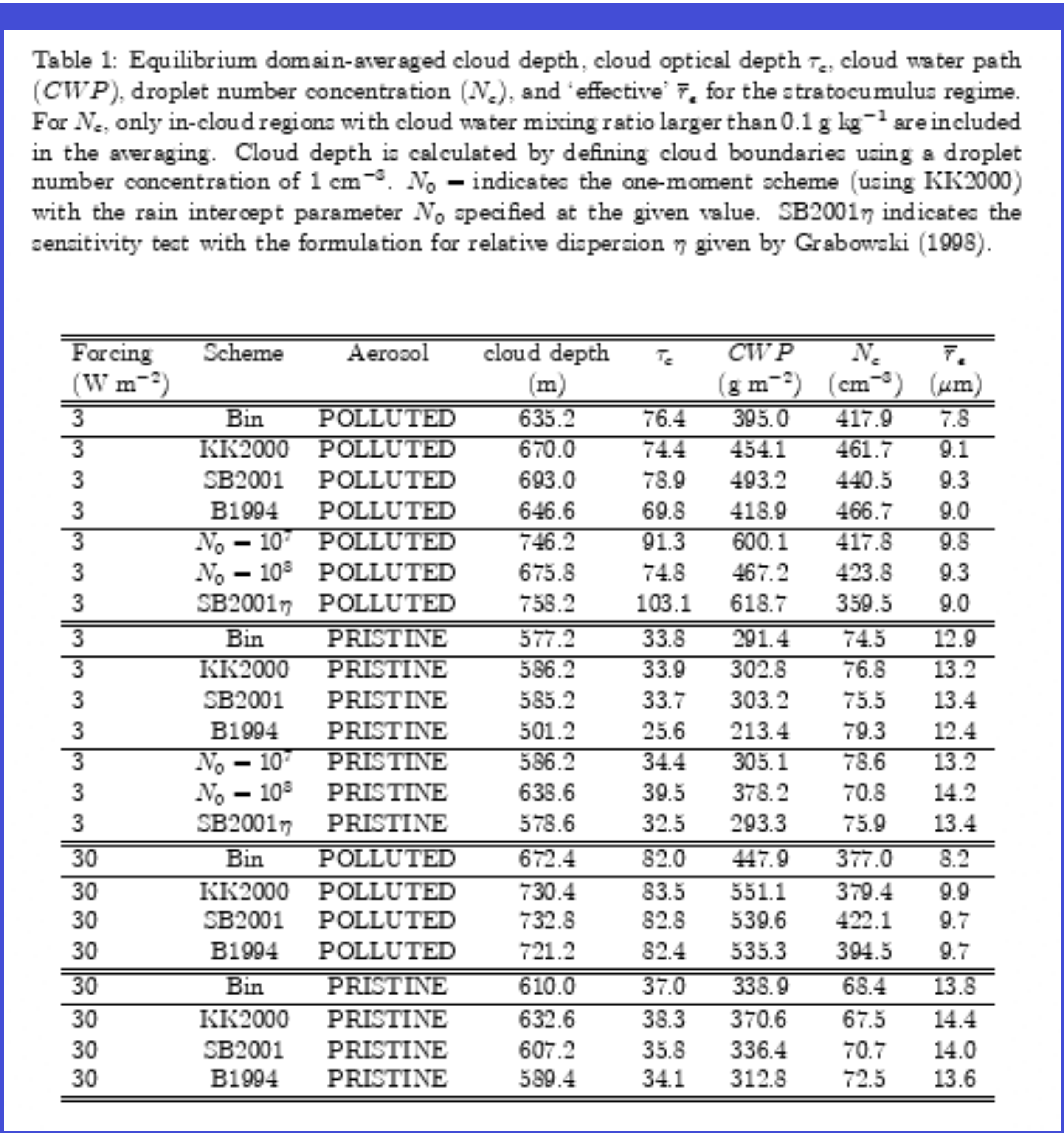
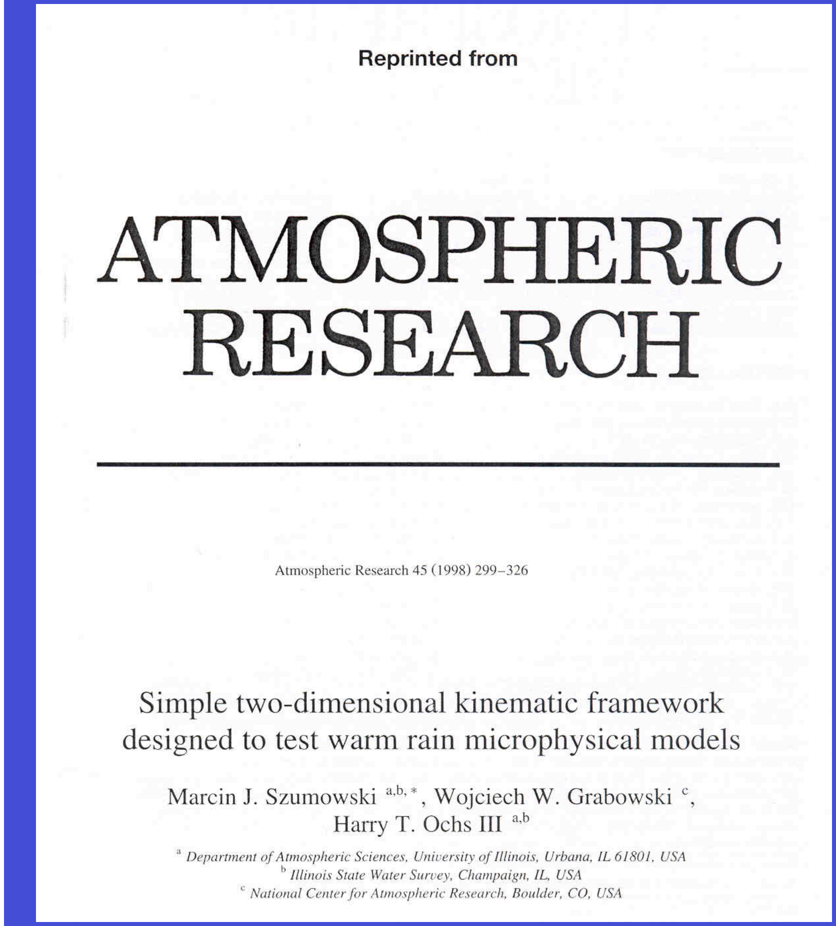


Table 1: Equilibrium domain-averaged cloud depth, cloud optical depth τ_c, cloud water path (CWP), droplet number concentration (N_c), and 'effective' $\overline{r}_e$ for the stratocumulus regime. For N_c, only in-cloud regions with cloud water mixing ratio larger than 0.1 g kg^{-1} are included in the averaging. Cloud depth is calculated by defining cloud boundaries using a droplet number concentration of 1 cm^{-3}. N_0 = indicates the one-moment scheme (using KK2000) with the rain intercept parameter N_0 specified at the given value. SB2001η indicates the sensitivity test with the formulation for relative dispersion η given by Grabowski (1998).

Forcing (W m^{-2})	Scheme	Aerosol	cloud depth (m)	τ_c	CWP (g m^{-2})	N_c (cm^{-3})	$\overline{r}_e$ (μm)
3	Bin	POLLUTED	635.2	76.4	395.0	417.9	7.8
3	KK2000	POLLUTED	670.0	74.4	454.1	461.7	9.1
3	SB2001	POLLUTED	693.0	78.9	493.2	440.5	9.3
3	B1994	POLLUTED	646.6	69.8	418.9	466.7	9.0
3	$N_0 = 10^7$	POLLUTED	746.2	91.3	600.1	417.8	9.8
3	$N_0 = 10^8$	POLLUTED	675.8	74.8	467.2	423.8	9.3
3	SB2001η	POLLUTED	758.2	103.1	618.7	359.5	9.0
3	Bin	PRISTINE	577.2	33.8	291.4	74.5	12.9
3	KK2000	PRISTINE	586.2	33.9	302.8	76.8	13.2
3	SB2001	PRISTINE	585.2	33.7	303.2	75.5	13.4
3	B1994	PRISTINE	501.2	25.6	213.4	79.3	12.4
3	$N_0 = 10^7$	PRISTINE	586.2	34.4	305.1	78.6	13.2
3	$N_0 = 10^8$	PRISTINE	638.6	39.5	378.2	70.8	14.2
3	SB2001η	PRISTINE	578.6	32.5	293.3	75.9	13.4
30	Bin	POLLUTED	672.4	82.0	447.9	377.0	8.2
30	KK2000	POLLUTED	730.4	83.5	551.1	379.4	9.9
30	SB2001	POLLUTED	732.8	82.8	539.6	422.1	9.7
30	B1994	POLLUTED	721.2	82.4	535.3	394.5	9.7
30	Bin	PRISTINE	610.0	37.0	338.9	68.4	13.8
30	KK2000	PRISTINE	632.6	38.3	370.6	67.5	14.4
30	SB2001	PRISTINE	607.2	35.8	336.4	70.7	14.0
30	B1994	PRISTINE	589.4	34.1	312.8	72.5	13.6

Morrison and Grabowski, JAS, 2006 (in review)



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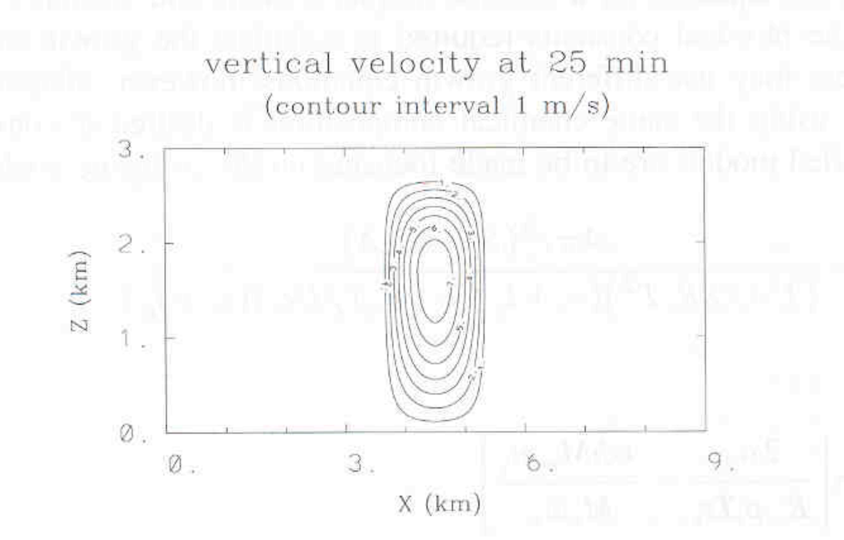
ATMOSPHERIC RESEARCH

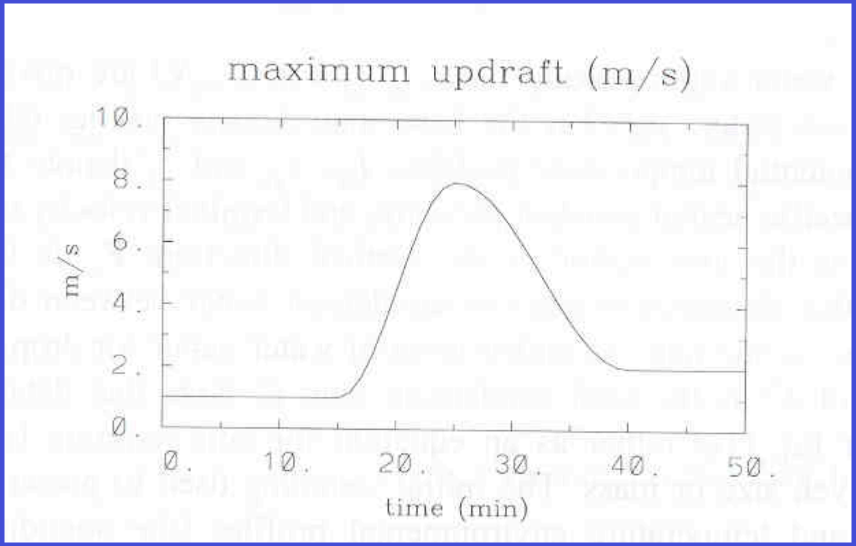
Atmospheric Research 45 (1998) 299–326

Simple two-dimensional kinematic framework designed to test warm rain microphysical models

Marcin J. Szumowski [a,b,*], Wojciech W. Grabowski [c],
Harry T. Ochs III [a,b]

[a] *Department of Atmospheric Sciences, University of Illinois, Urbana, IL 61801, USA*
[b] *Illinois State Water Survey, Champaign, IL, USA*
[c] *National Center for Atmospheric Research, Boulder, CO, USA*


vertical velocity at 25 min
(contour interval 1 m/s)


maximum updraft (m/s)

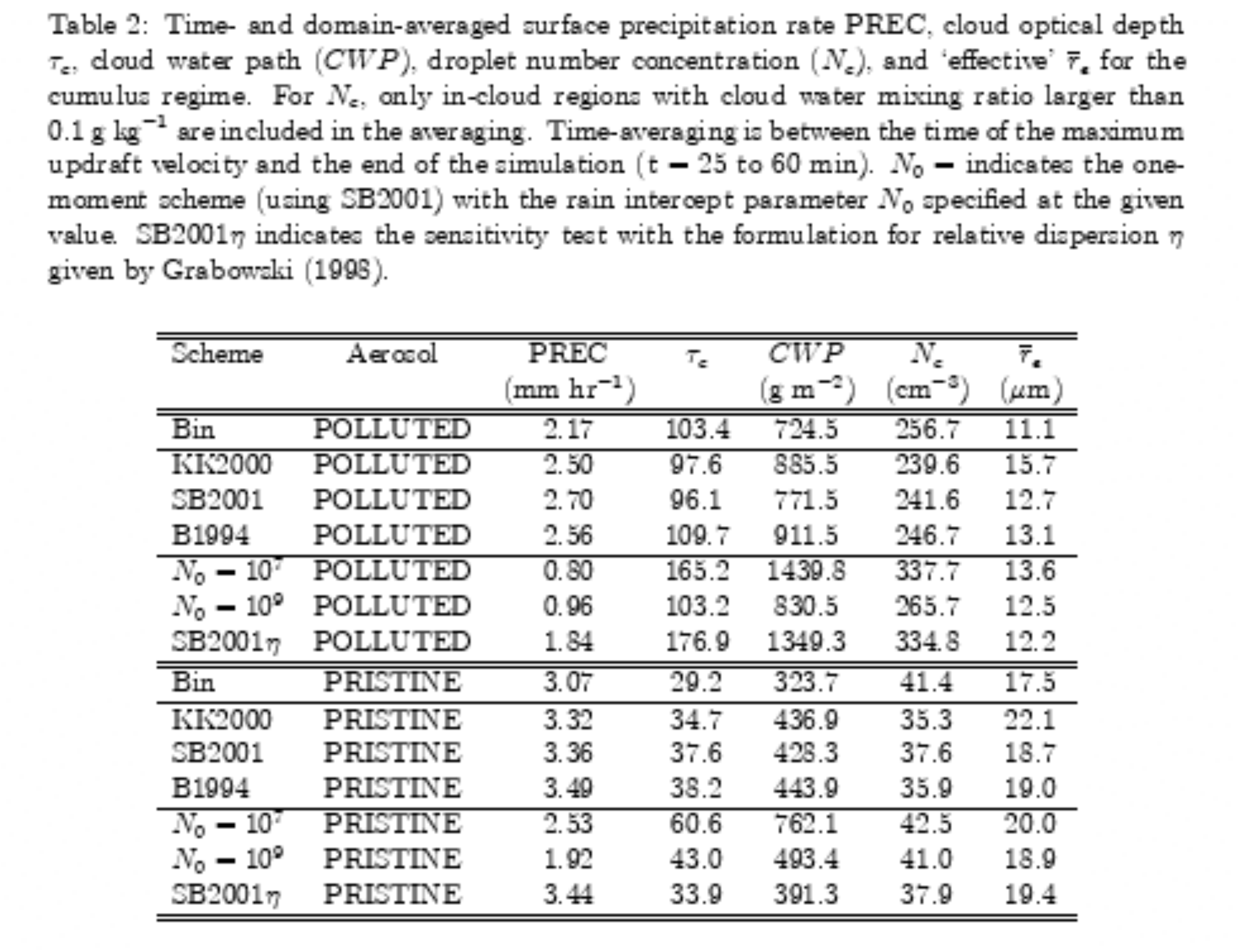


Table 2: Time- and domain-averaged surface precipitation rate PREC, cloud optical depth τ_c, cloud water path (CWP), droplet number concentration (N_c), and 'effective' $\overline{r}_e$ for the cumulus regime. For N_c, only in-cloud regions with cloud water mixing ratio larger than 0.1 g kg^{-1} are included in the averaging. Time-averaging is between the time of the maximum updraft velocity and the end of the simulation ($t = 25$ to 60 min). $N_0 =$ indicates the one-moment scheme (using SB2001) with the rain intercept parameter N_0 specified at the given value. SB2001η indicates the sensitivity test with the formulation for relative dispersion η given by Grabowski (1998).

Scheme	Aerosol	PREC (mm hr^{-1})	τ_c	CWP (g m^{-2})	N_c (cm^{-3})	$\overline{r}_e$ (μm)
Bin	POLLUTED	2.17	103.4	724.5	256.7	11.1
KK2000	POLLUTED	2.50	97.6	885.5	239.6	15.7
SB2001	POLLUTED	2.70	96.1	771.5	241.6	12.7
B1994	POLLUTED	2.56	109.7	911.5	246.7	13.1
$N_0 = 10^7$	POLLUTED	0.80	165.2	1439.8	337.7	13.6
$N_0 = 10^9$	POLLUTED	0.96	103.2	830.5	265.7	12.5
SB2001η	POLLUTED	1.84	176.9	1349.3	334.8	12.2
Bin	PRISTINE	3.07	29.2	323.7	41.4	17.5
KK2000	PRISTINE	3.32	34.7	436.9	35.3	22.1
SB2001	PRISTINE	3.36	37.6	428.3	37.6	18.7
B1994	PRISTINE	3.49	38.2	443.9	35.9	19.0
$N_0 = 10^7$	PRISTINE	2.53	60.6	762.1	42.5	20.0
$N_0 = 10^9$	PRISTINE	1.92	43.0	493.4	41.0	18.9
SB2001η	PRISTINE	3.44	33.9	391.3	37.9	19.4

Morrison and Grabowski, JAS, 2006 (in review)

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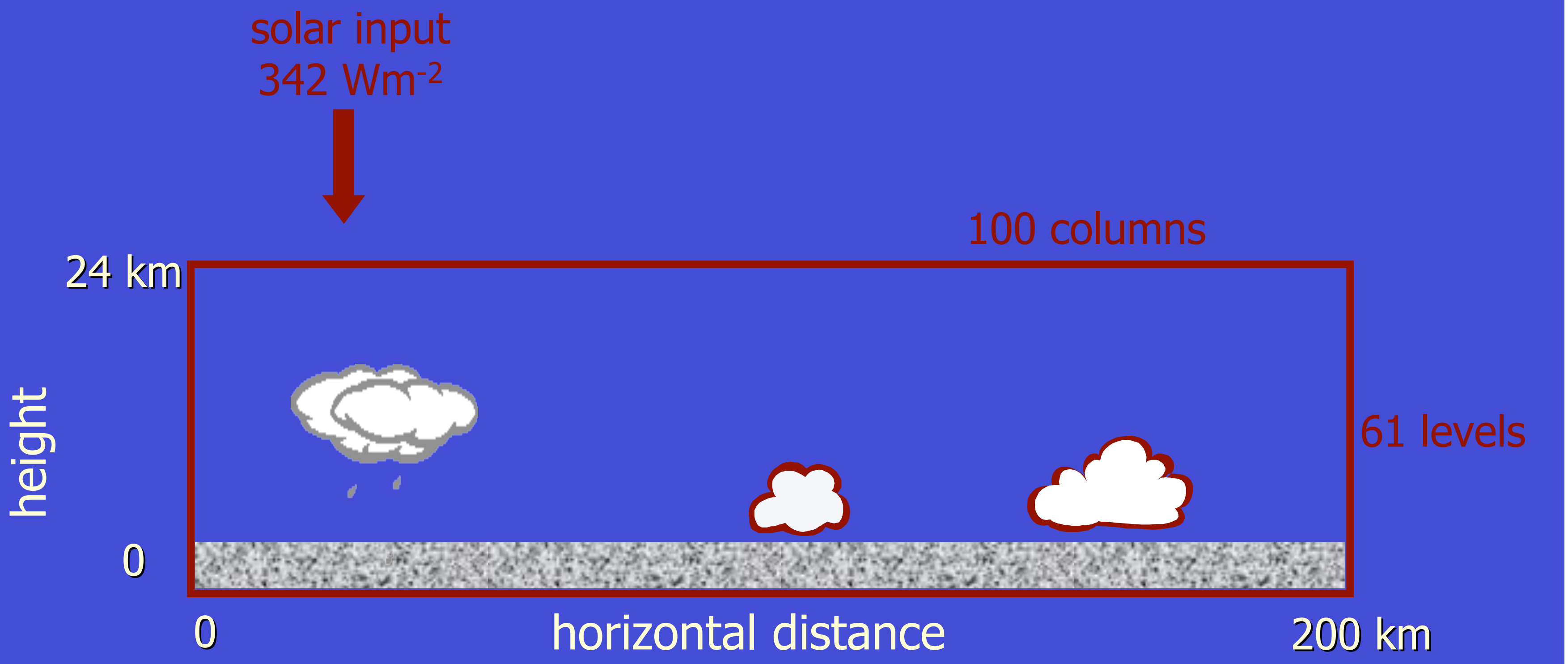
Ice microphysics:

- major overhaul needed!

Radiative-convective quasi-equilibrium mimicking planetary energy budget using a cloud-resolving model



Surface temperature = 15° C
Surface relative humidity = 80%
Surface albedo = 0.15

Grabowski, J. Climate (in press)

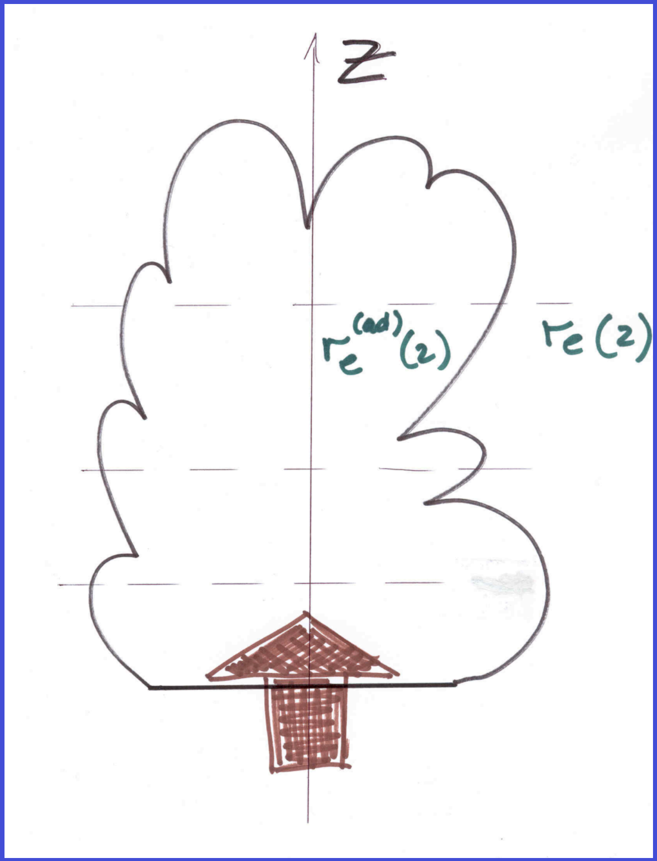
Conclusions:

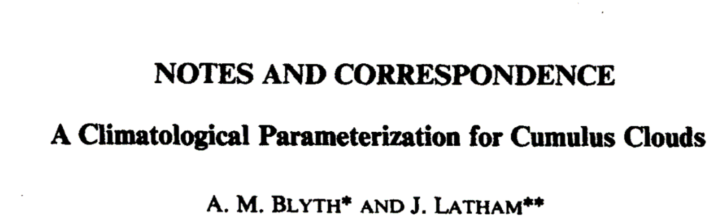
- ***An idealized convective-radiative quasi-equilibrium mimics observed mean energy and water fluxes across Earth's atmosphere to within 10 W m^{-2}.***

- ***Indirect aerosol effect is dominated by the 1st effect:***
  - ***mean cloud optical depth of water clouds changes by factor of 3: 2 comes from mean effective radius; 1.5 from mean LWP.***

- ***No impact on the hydrologic cycle:***
  - ***highlights the difference between "single cloud" and "cloud ensemble" approaches to investigate the indirect effects of aerosols on climate.***

- ***Assumptions about microphysical transformations during entrainment and mixing for shallow Cu are critical for the 1st indirect effect:***
  - ***the same TOA albedo and surface net solar flux in PRISTINE with homogeneous mixing as in POLLUTED with extremely inhomogeneous mixing.***

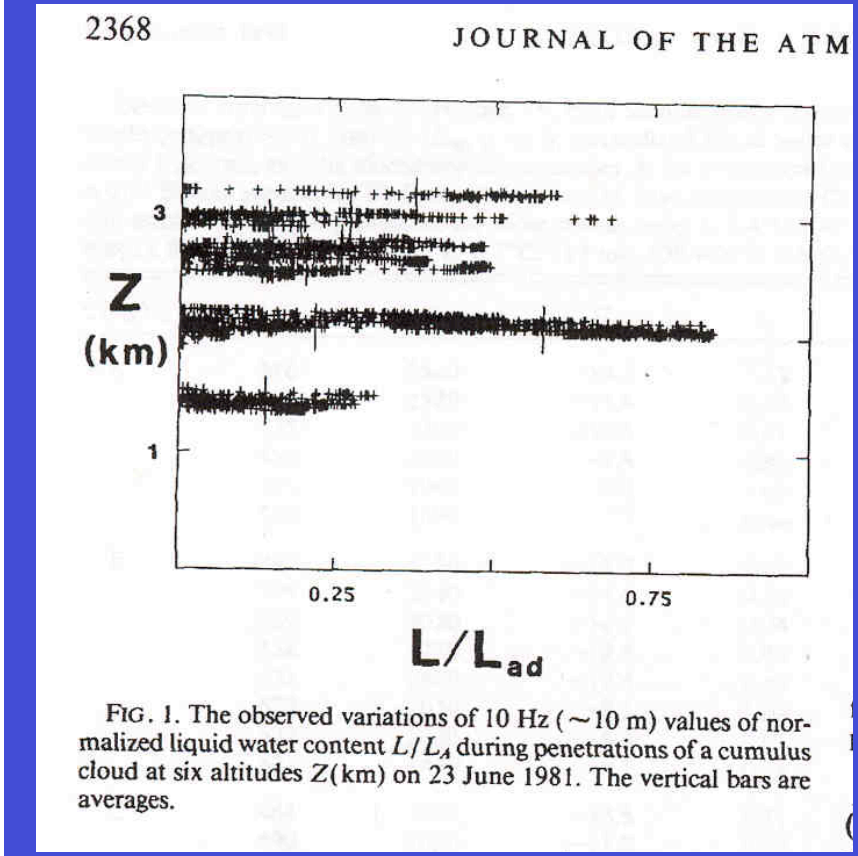

Z
$r_e^{(ad)}(z)$
$r_e(z)$



NOTES AND CORRESPONDENCE

A Climatological Parameterization for Cumulus Clouds

A. M. BLYTH* AND J. LATHAM**



2368 JOURNAL OF THE ATM

FIG. 1. The observed variations of 10 Hz (~10 m) values of normalized liquid water content L/L_A during penetrations of a cumulus cloud at six altitudes Z(km) on 23 June 1981. The vertical bars are averages.

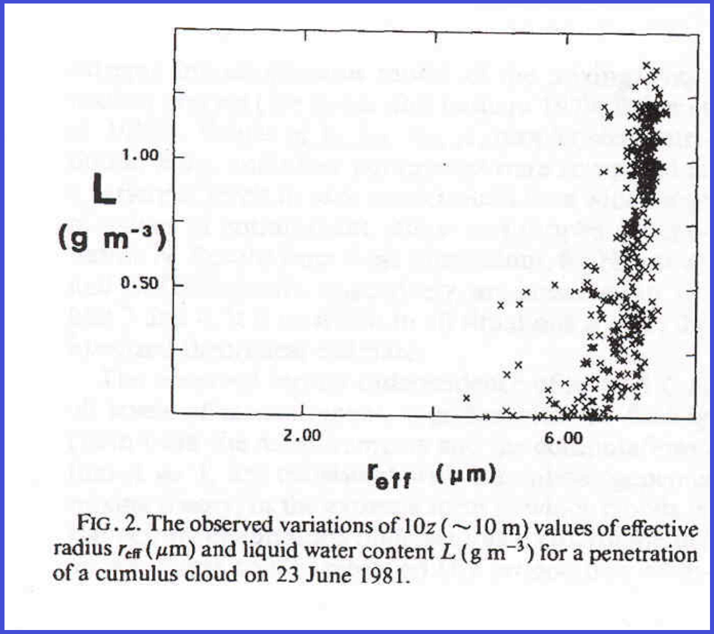


FIG. 2. The observed variations of $10z$ (~10 m) values of effective radius $r_{\rm eff}$ (μm) and liquid water content L (g m^{-3}) for a penetration of a cumulus cloud on 23 June 1981.

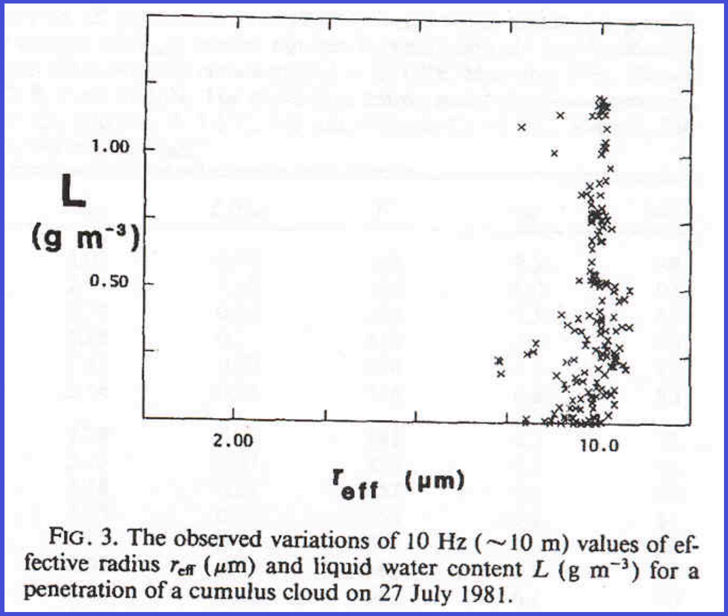


FIG. 3. The observed variations of 10 Hz (~10 m) values of effective radius $r_{\rm eff}$ (μm) and liquid water content L (g m^{-3}) for a penetration of a cumulus cloud on 27 July 1981.

Blyth and Latham JAS 1991

ENTRAINMENT, MIXING, AND MICROPHYSICS IN RICO CUMULUS

H. Gerber
Gerber Scientific Inc., Reston, VA, U.S.A.

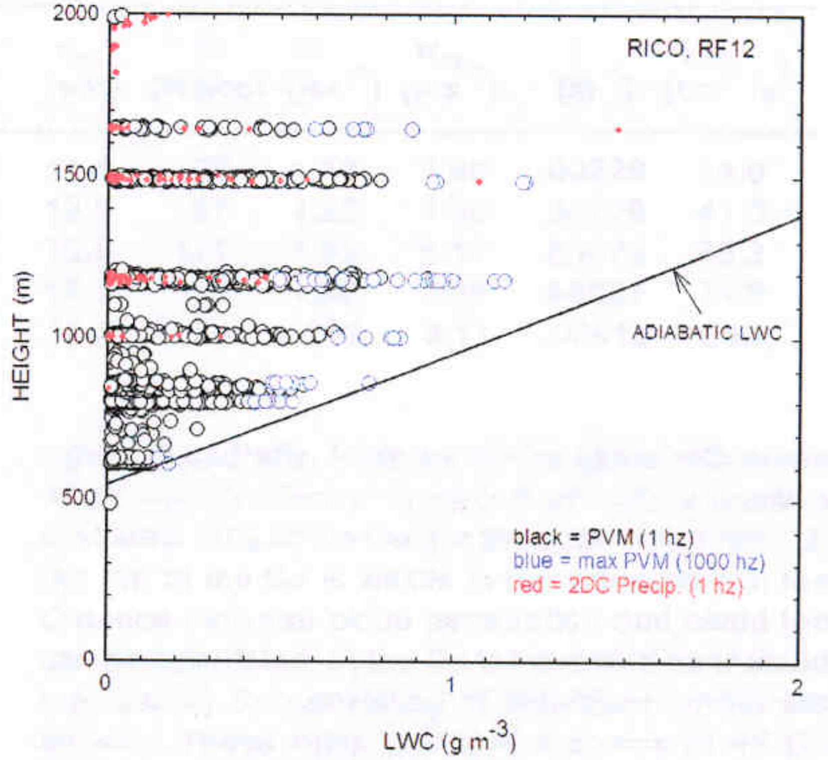


Figure 1 - 100-m resolution (1Hz), maximum 10-cm resolution (1000 Hz),and 2DC LWC for all ~ 200 Cu aircraft passes for flight RF12.

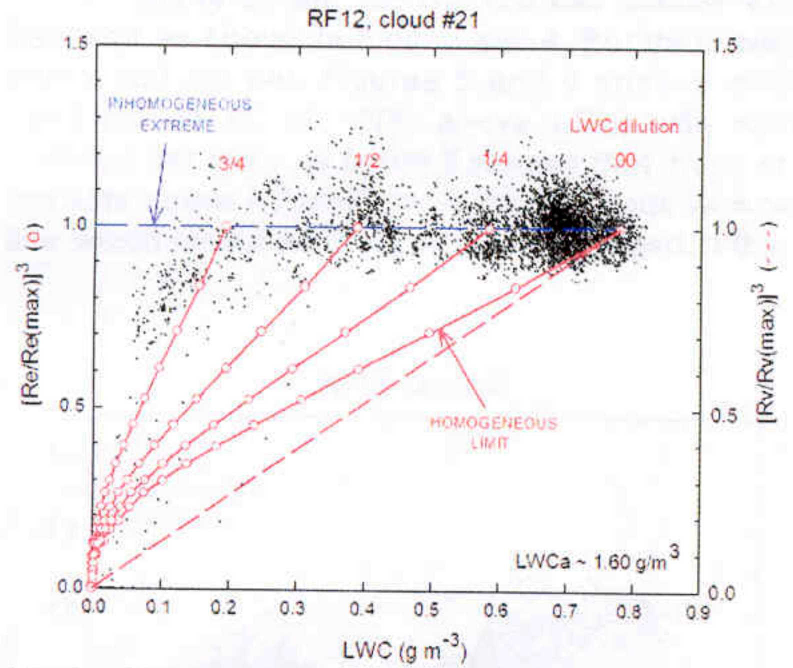


Fig.3 - Normalized effective radius (Re) to maximum Re in Cu pass for cloud #21 as a function of high data-rate LWC.

AMS Cloud Physics Conference, Madison, July 2006

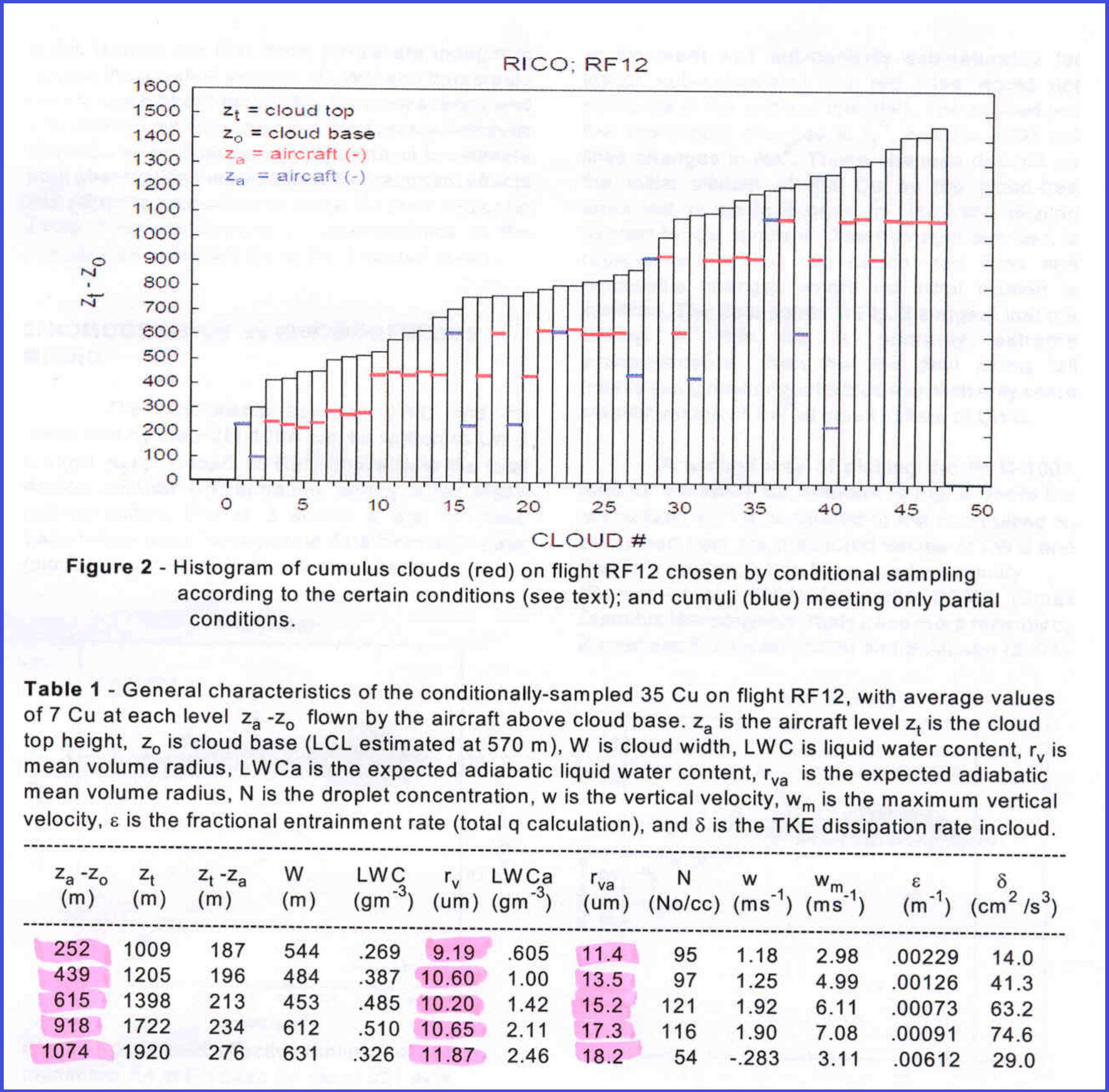
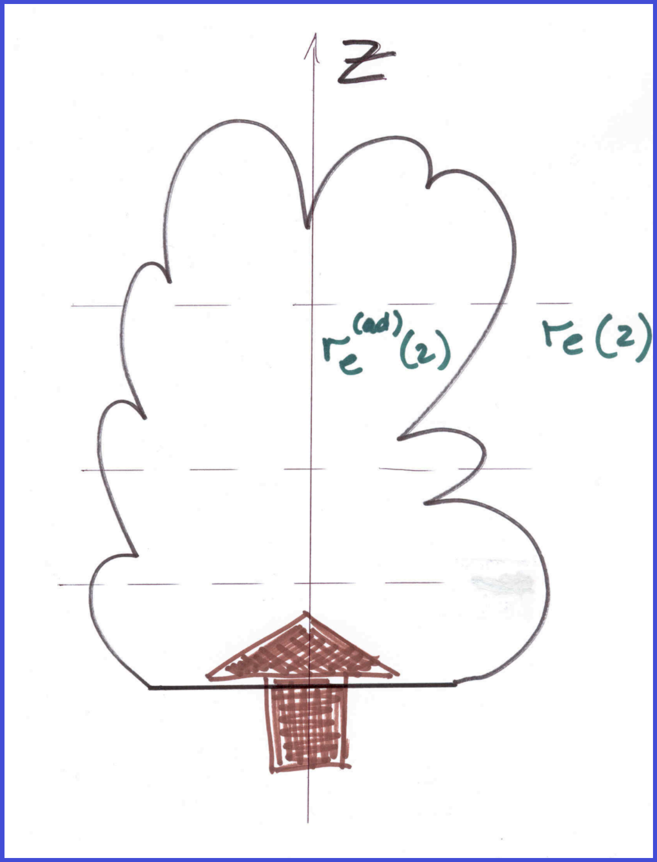


Figure 2 - Histogram of cumulus clouds (red) on flight RF12 chosen by conditional sampling according to the certain conditions (see text); and cumuli (blue) meeting only partial conditions.

Table 1 - General characteristics of the conditionally-sampled 35 Cu on flight RF12, with average values of 7 Cu at each level $z_a - z_o$ flown by the aircraft above cloud base. z_a is the aircraft level z_t is the cloud top height, z_o is cloud base (LCL estimated at 570 m), W is cloud width, LWC is liquid water content, r_v is mean volume radius, LWCa is the expected adiabatic liquid water content, r_{va} is the expected adiabatic mean volume radius, N is the droplet concentration, w is the vertical velocity, w_m is the maximum vertical velocity, ε is the fractional entrainment rate (total q calculation), and δ is the TKE dissipation rate incloud.

$z_a - z_o$ (m)	z_t (m)	$z_t - z_a$ (m)	W (m)	LWC (gm^{-3})	r_v (um)	LWCa (gm^{-3})	r_{va} (um)	N (No/cc)	w (ms^{-1})	w_m (ms^{-1})	ε (m^{-1})	δ (cm^2/s^3)
252	1009	187	544	.269	9.19	.605	11.4	95	1.18	2.98	.00229	14.0
439	1205	196	484	.387	10.60	1.00	13.5	97	1.25	4.99	.00126	41.3
615	1398	213	453	.485	10.20	1.42	15.2	121	1.92	6.11	.00073	63.2
918	1722	234	612	.510	10.65	2.11	17.3	116	1.90	7.08	.00091	74.6
1074	1920	276	631	.326	11.87	2.46	18.2	54	-.283	3.11	.00612	29.0

?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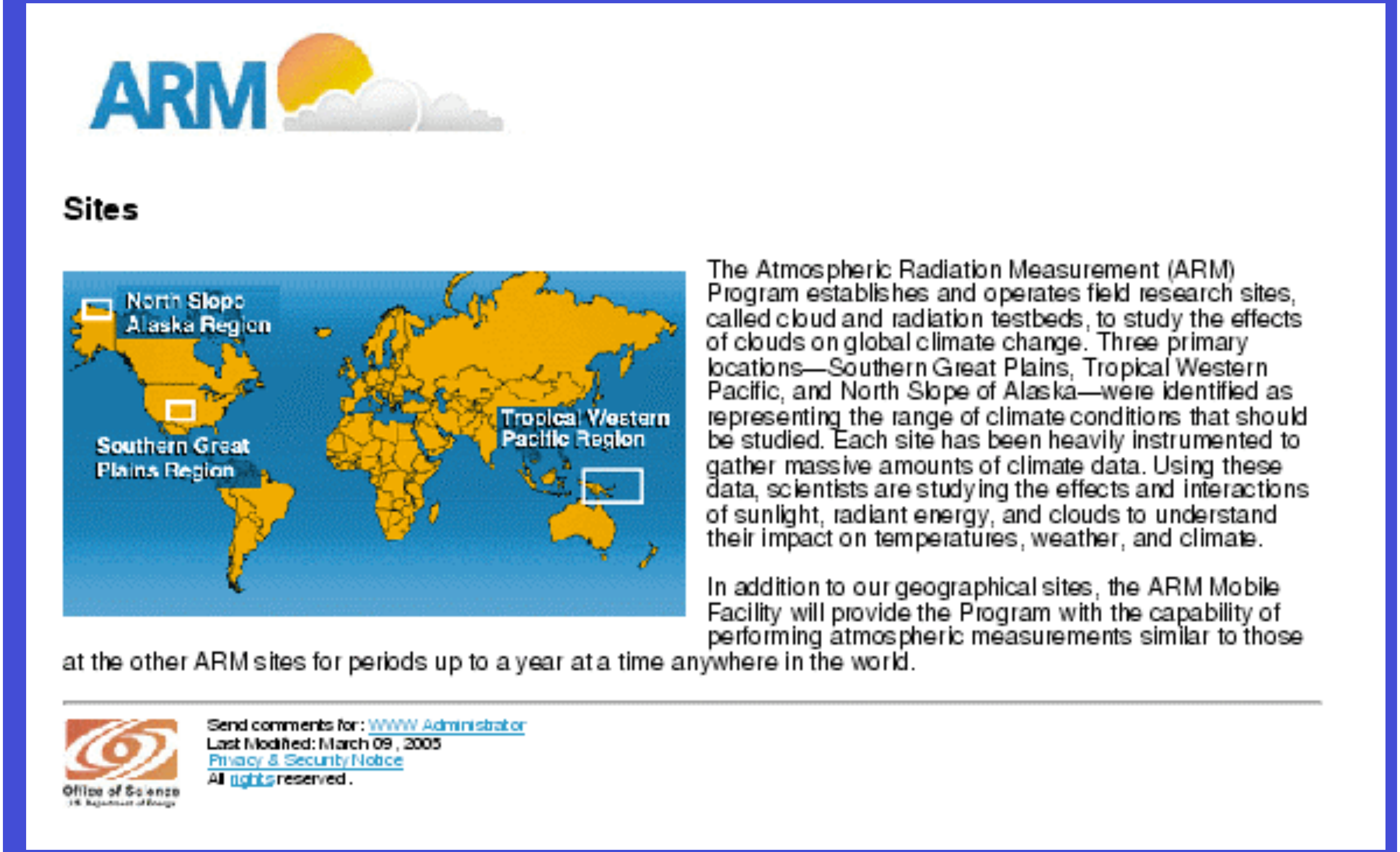

Sites

The Atmospheric Radiation Measurement (ARM) Program establishes and operates field research sites, called cloud and radiation testbeds, to study the effects of clouds on global climate change. Three primary locations—Southern Great Plains, Tropical Western Pacific, and North Slope of Alaska—were identified as representing the range of climate conditions that should be studied. Each site has been heavily instrumented to gather massive amounts of climate data. Using these data, scientists are studying the effects and interactions of sunlight, radiant energy, and clouds to understand their impact on temperatures, weather, and climate.

In addition to our geographical sites, the ARM Mobile Facility will provide the Program with the capability of performing atmospheric measurements similar to those at the other ARM sites for periods up to a year at a time anywhere in the world.

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McFarlane et al., JGR D, 2002

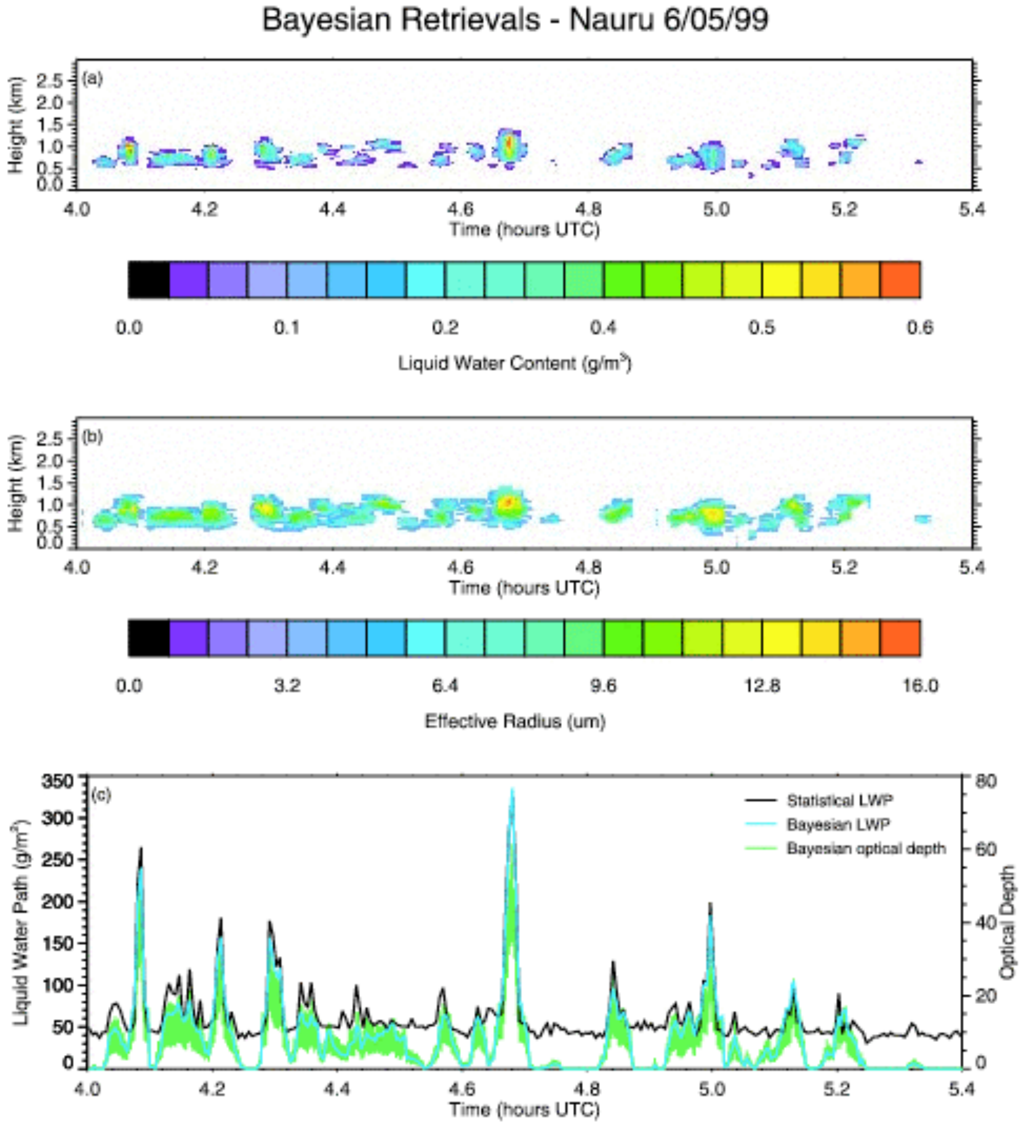
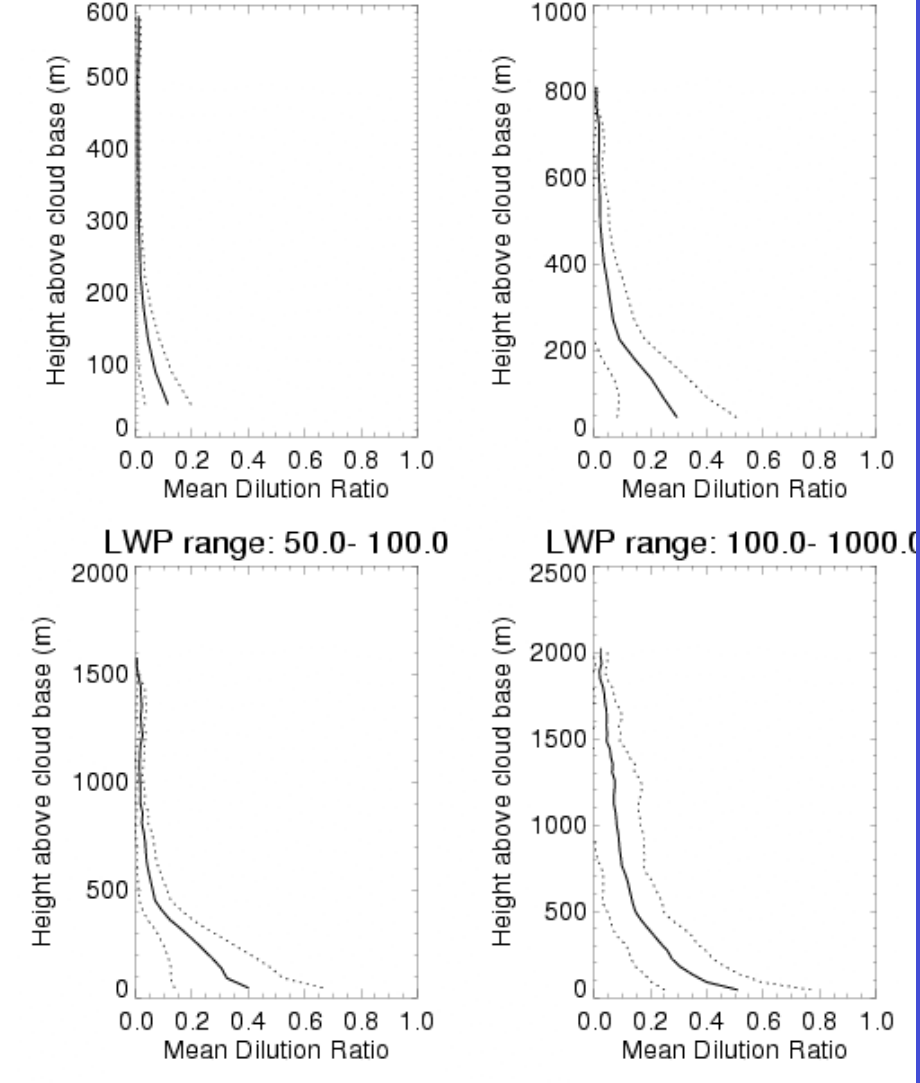
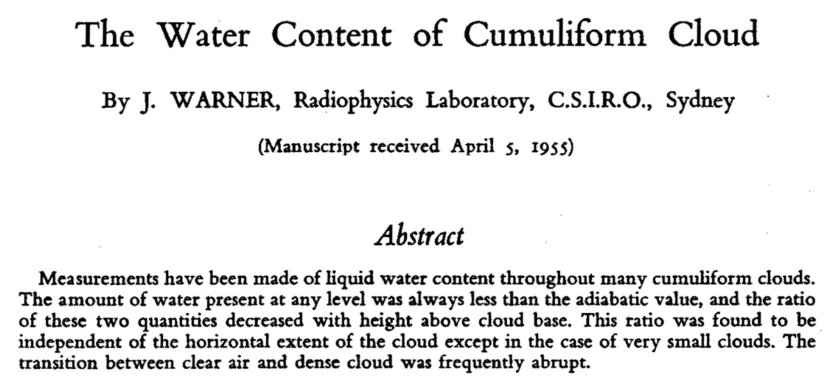


Figure 12. Examples of Bayesian retrievals at Nauru on 5 June 1999. Time–height cross sections of (a) retrieved liquid water content and (b) effective radius. (c) Time series of retrieved liquid water path and optical depth at Nauru. The black line is the ARM retrieved statistical liquid water path during this time. The blue line is the Bayesian retrieved liquid water path, and the green line is the Bayesian optical depth plus error bars.



Remotely sensed data from ARM Tropical Western Pacific Nauru site (1 month of data; S. McFarlane, PNL)



The Water Content of Cumuliform Cloud

By J. WARNER, Radiophysics Laboratory, C.S.I.R.O., Sydney

(Manuscript received April 5, 1955)

Abstract

Measurements have been made of liquid water content throughout many cumuliform clouds. The amount of water present at any level was always less than the adiabatic value, and the ratio of these two quantities decreased with height above cloud base. This ratio was found to be independent of the horizontal extent of the cloud except in the case of very small clouds. The transition between clear air and dense cloud was frequently abrupt.

J. WARNER

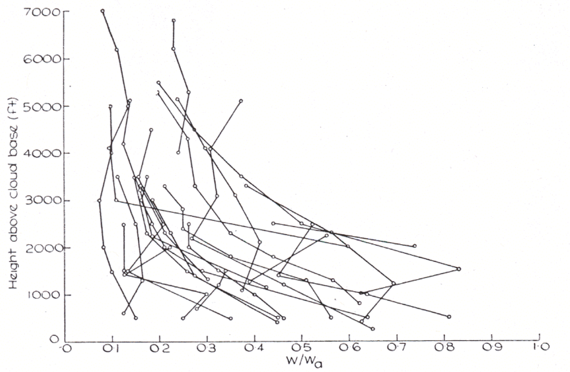


Fig. 7. Ratio of observed liquid water content to adiabatic value versus height above base.

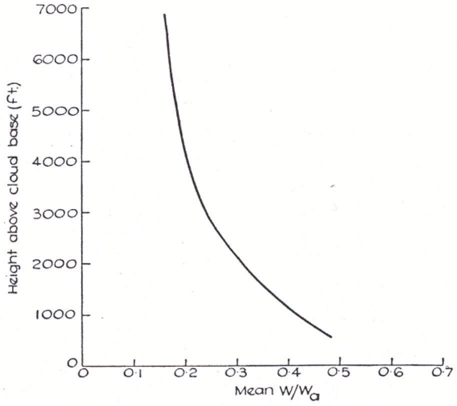
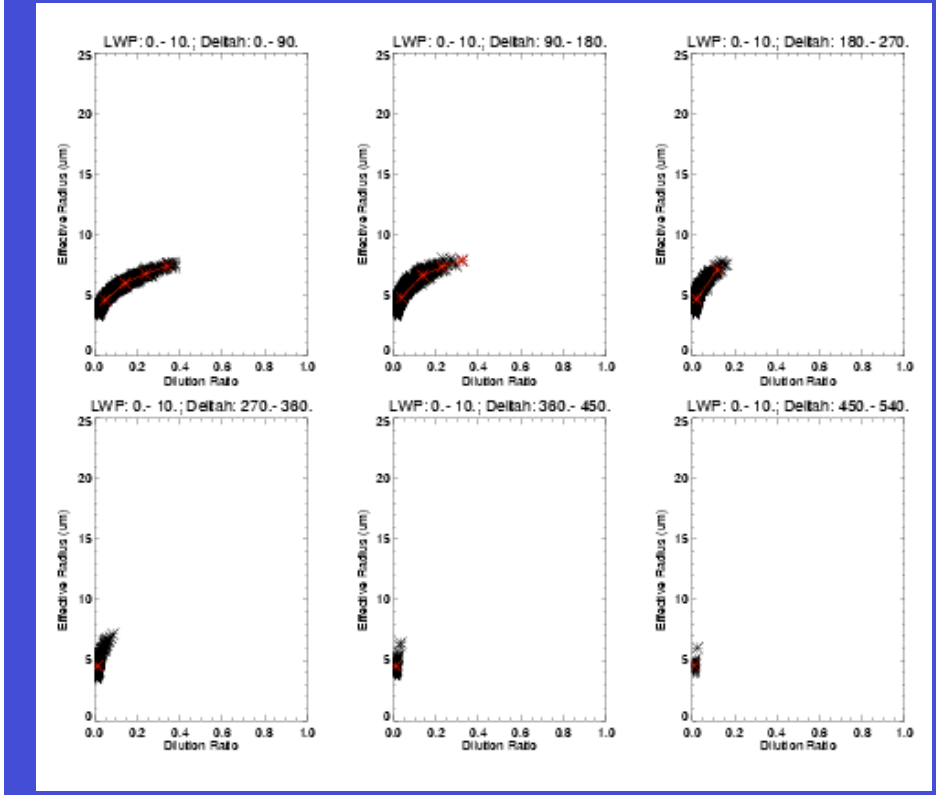


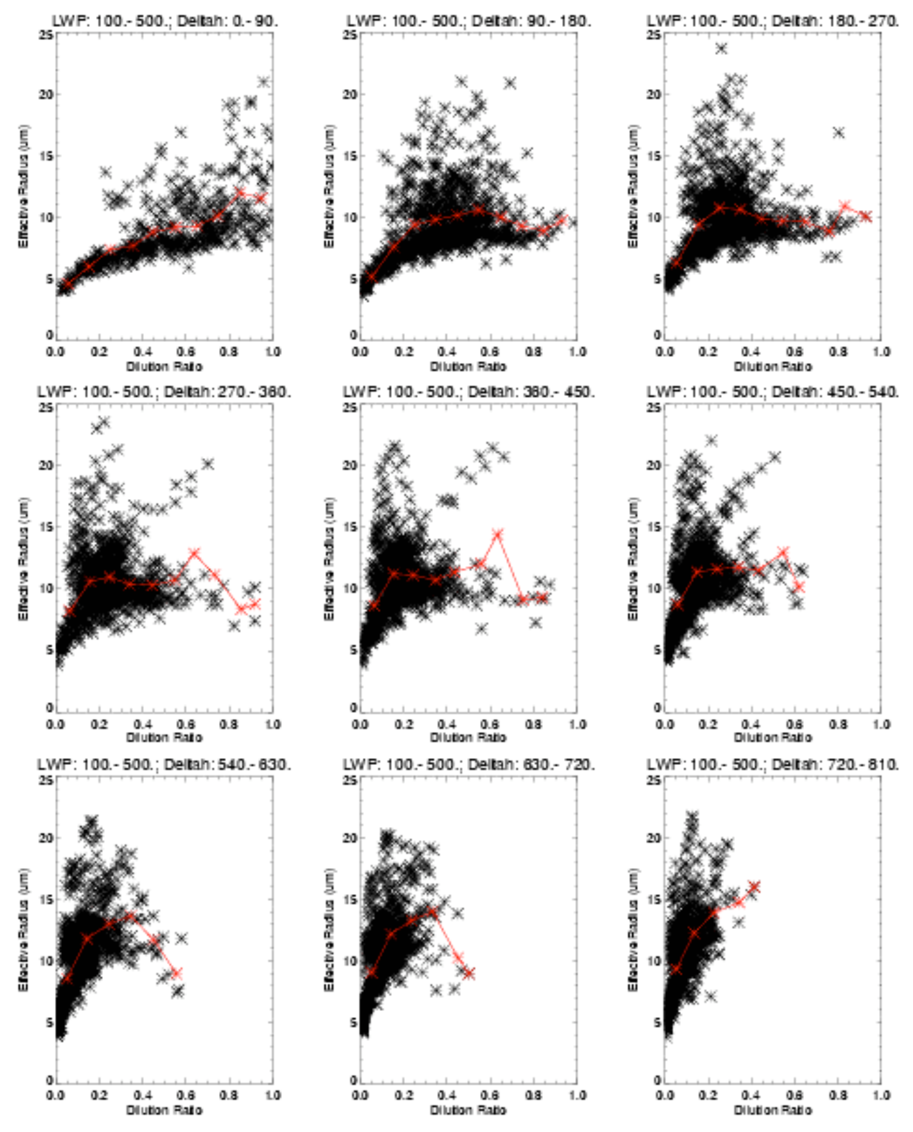
Fig. 8. Mean ratio W/W_a versus height above base.

Fig

Shallow clouds

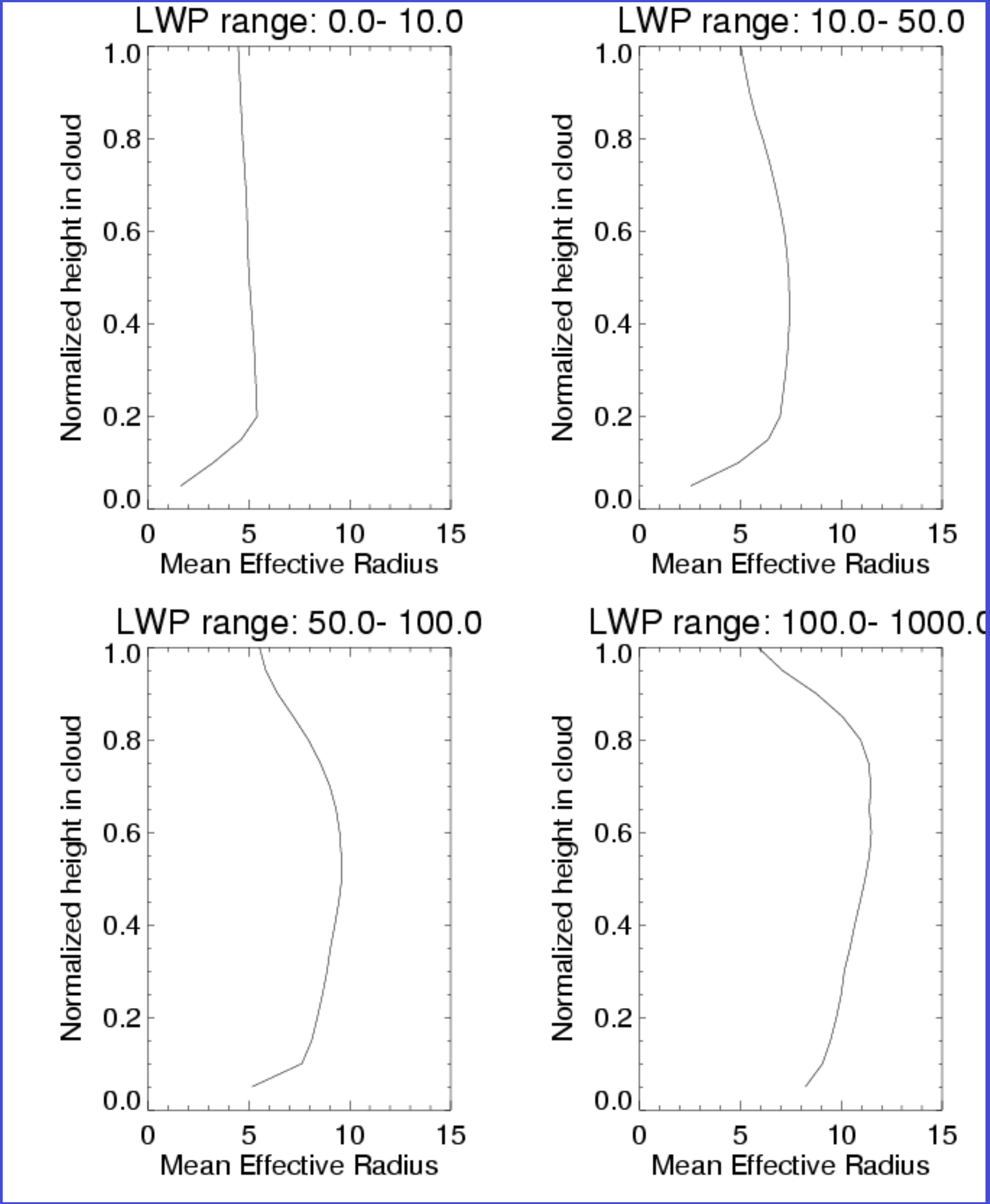


Deeper clouds



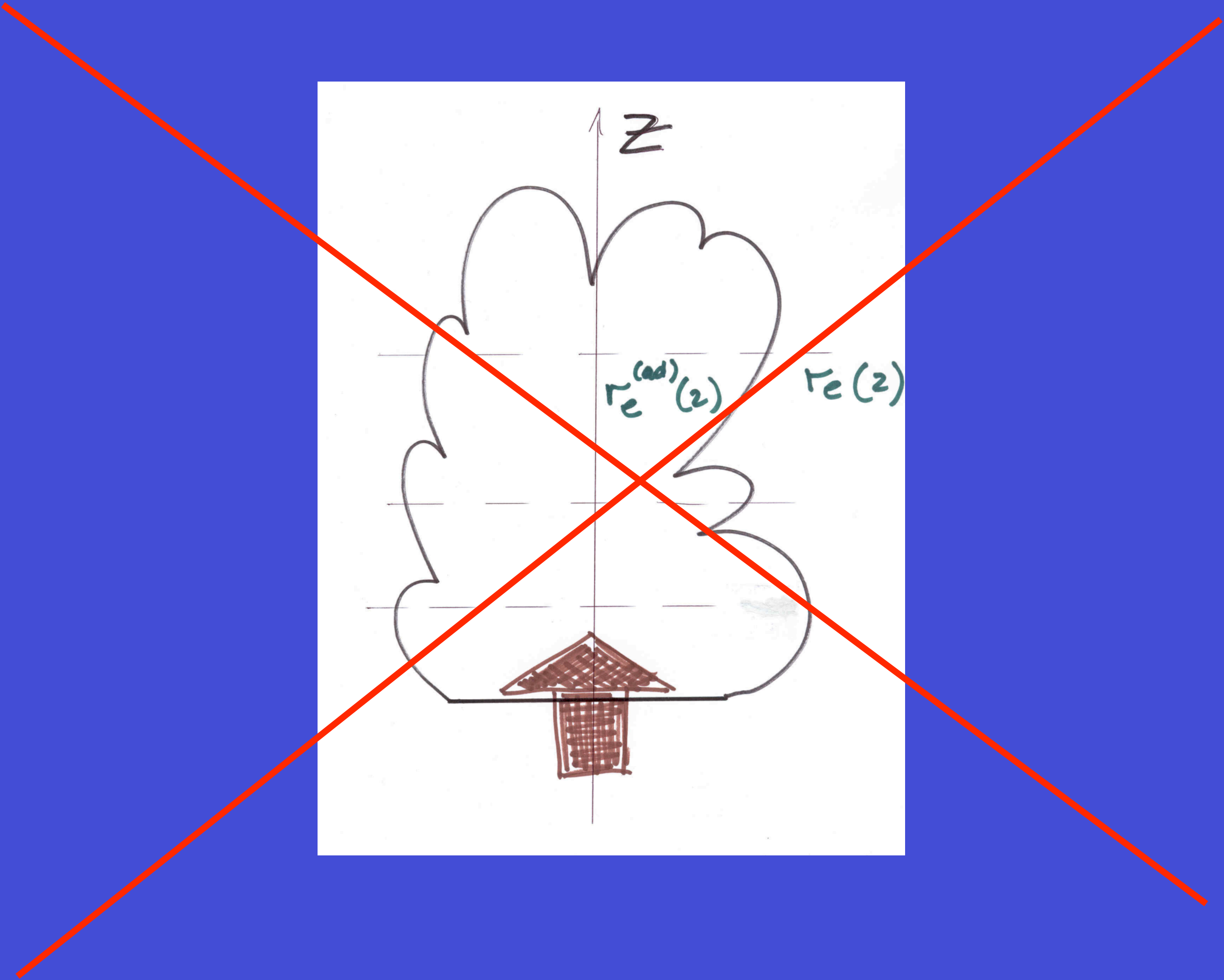
Remotely sensed data from ARM Tropical Western Pacific Nauru site (1 month of data; S. McFarlane, PNL)

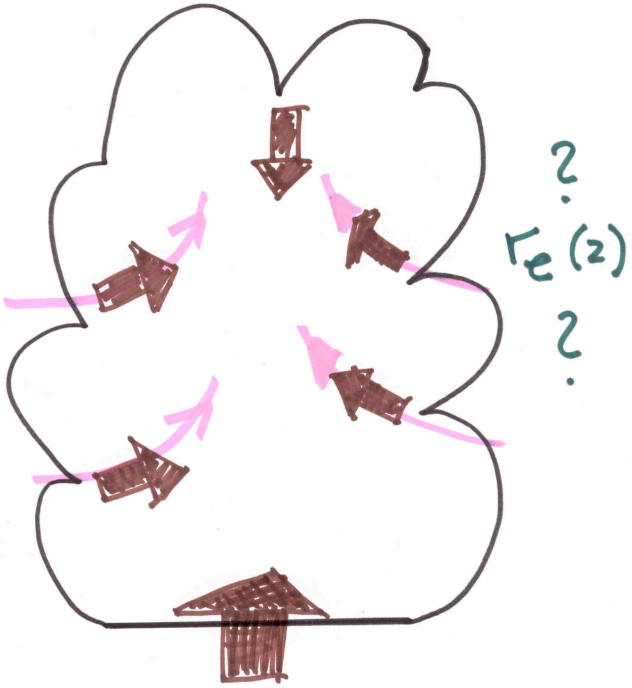
Remotely sensed data from ARM Tropical Western Pacific Nauru site (1 month of data; S. McFarlane, PNL)



Effective radius does not change much with height

Deeper clouds have larger effective radius


Z
$r_e^{(ad)}(z)$
$r_e(z)$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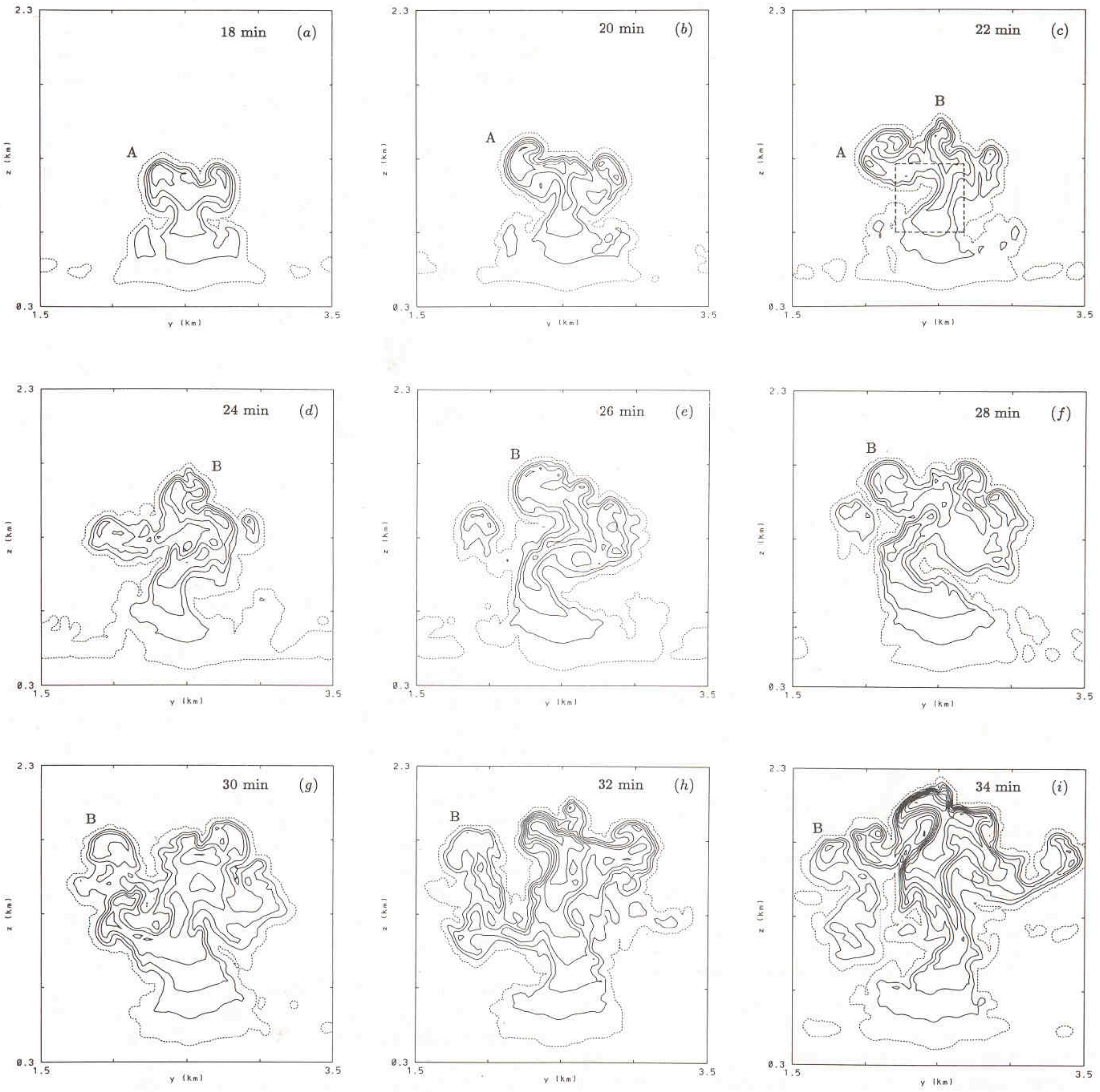
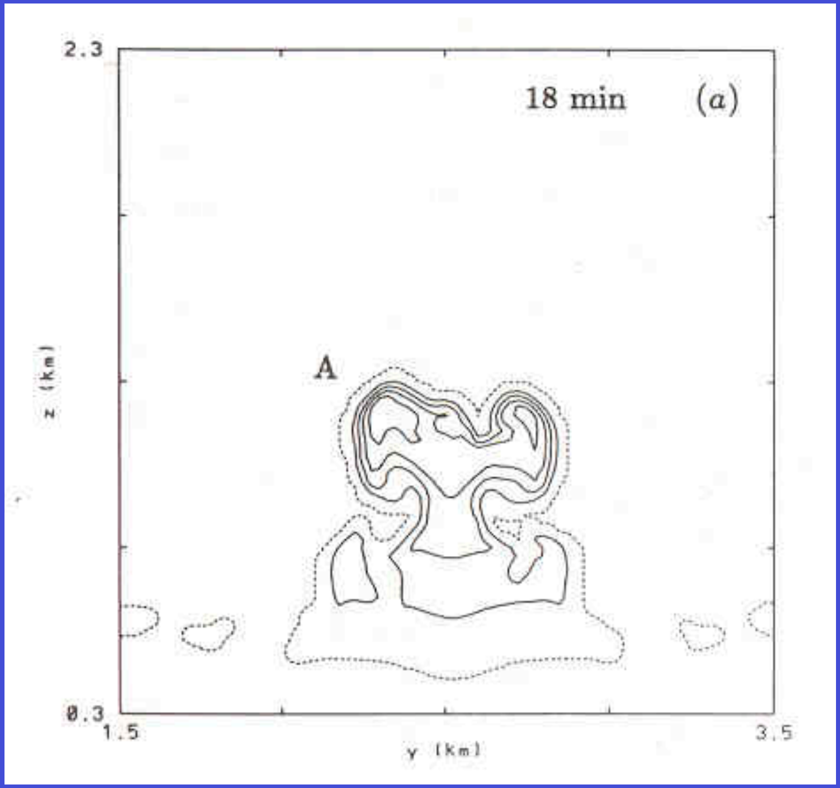
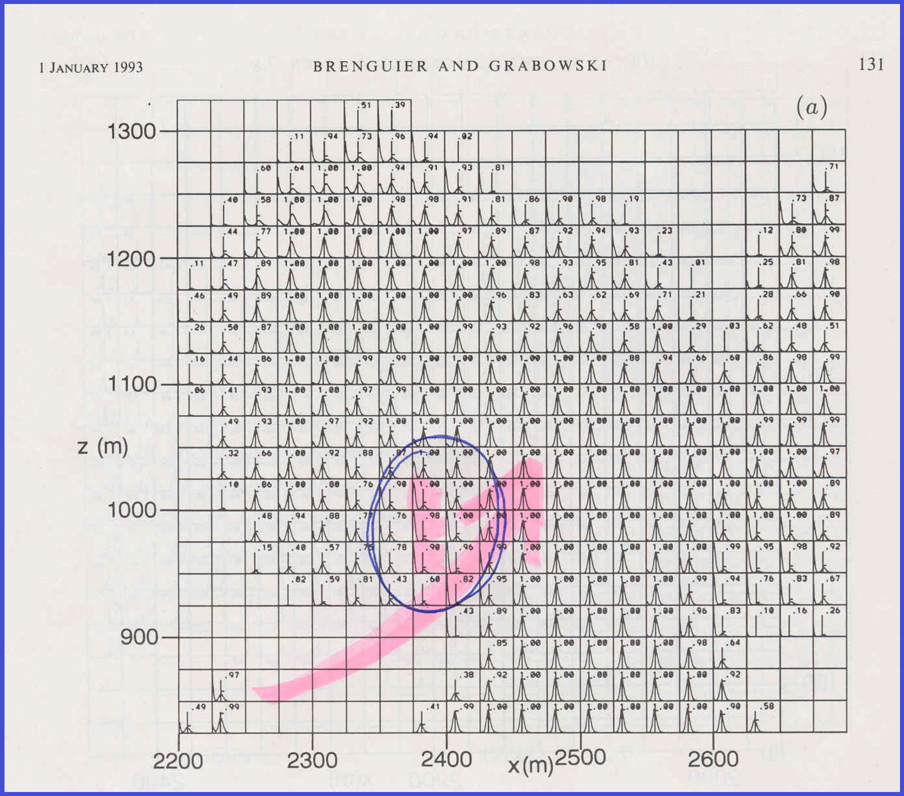


FIG. 3. Cloud water mixing ratio in the inner domain for t = 18 min (a) through t = 34 min (i). Contour interval of 0.4 g kg^{-1}. Dashed line is for mixing ratio of 0.01 g kg^{-1}. Position of the domain shown in Fig. 9 is indicated in (c).

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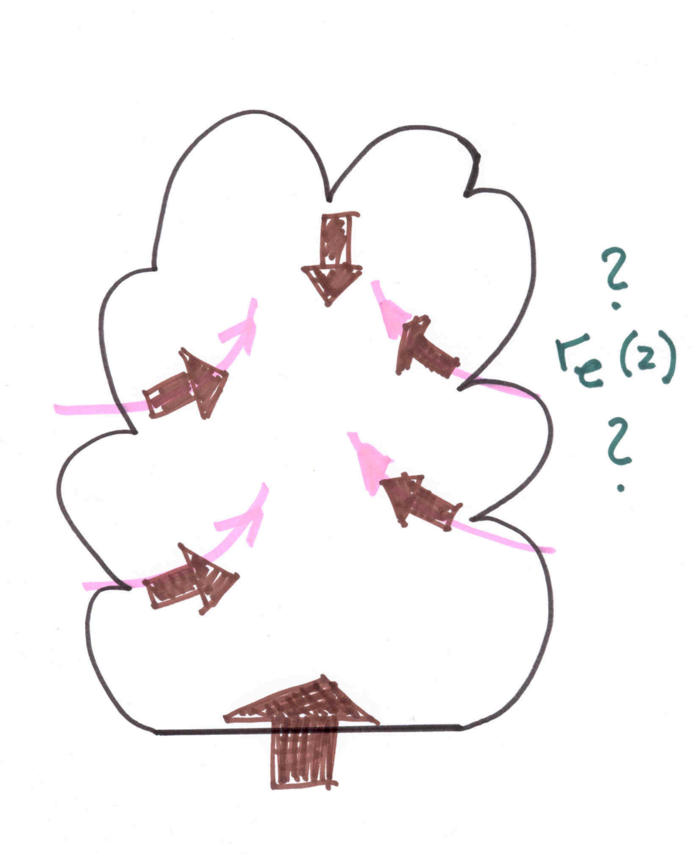


Fresh nucleation during entrainment and mixing is a significant source of new droplets

This is the only way one can explain the much slower increase with height of the mean volume radius (and thus the effective radius) of cloud droplets compared to the adiabatic one in cumulus clouds

This has important implications for the representation of the effective radius in traditional parameterizations…

Detailed microphysics is out of the question (it is just to expensive).

Detailed microphysics should be used as a benchmark for less computationally-intensive approaches.

The two-moment bulk microphysics schemes (i.e., schemes that predict mass and number of various cloud and precipitation particles) is a reasonable compromise.

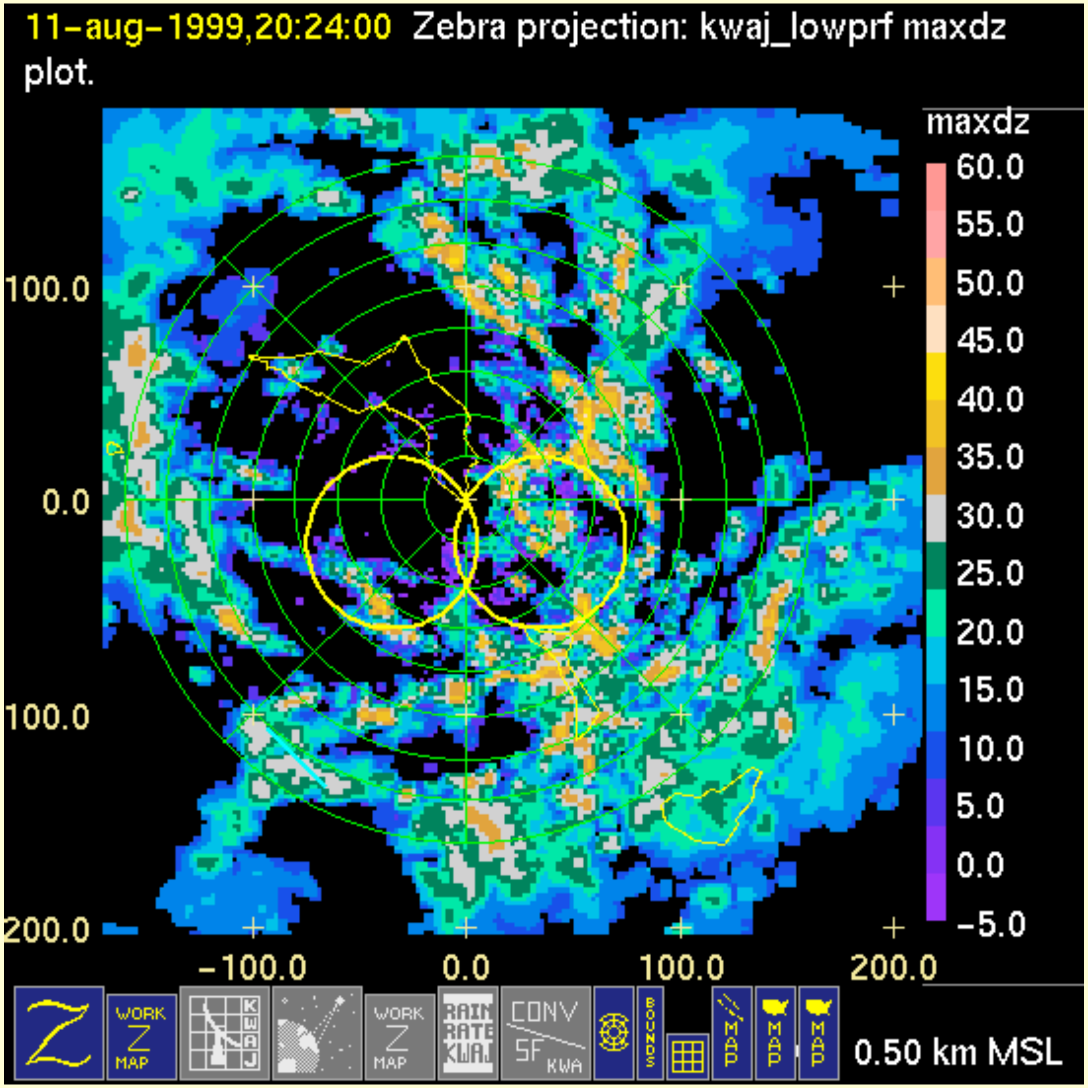
Warm-rain microphysics:

- validation of a two-moment scheme with detailed microphysics;
- formulation of the effective radius in warm convective clouds.

Ice microphysics:

- major overhaul needed!

11-12 August 1999 KWAJEX
Mesoscale Convective System (MCS)



11-aug-1999,20:24:00 Zebra projection: kwaj_lowprf maxdz plot.

0.50 km MSL

The **KWAJEX** *(Kwajalein Experiment)* took place over the ***central tropical Pacific Ocean*** during 23 July-15 Sept. 1999

Large system with good radar observations

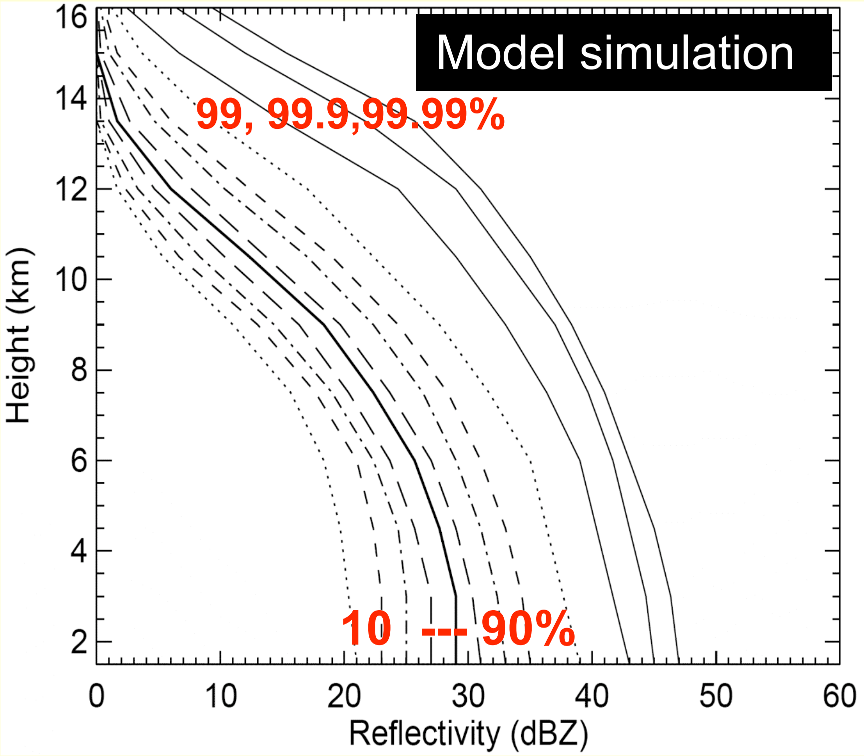
2024 Z 11 Aug. - 0624 Z 12 Aug.

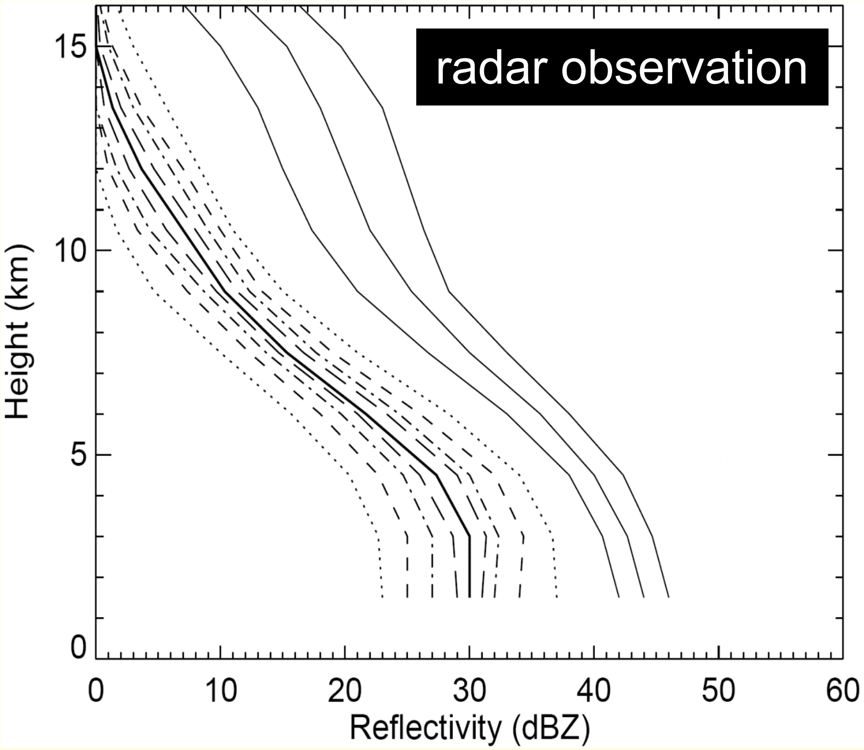
Evolved from a highly ***convective* state** (2030UCT) to ***stratiform* state** (0230 UTC)

Li, Zipser, Krueger, and Zulauf; AMS Cloud Physics Conference, Madison, 2006

CCFAD of simulated and observed radar reflectivity

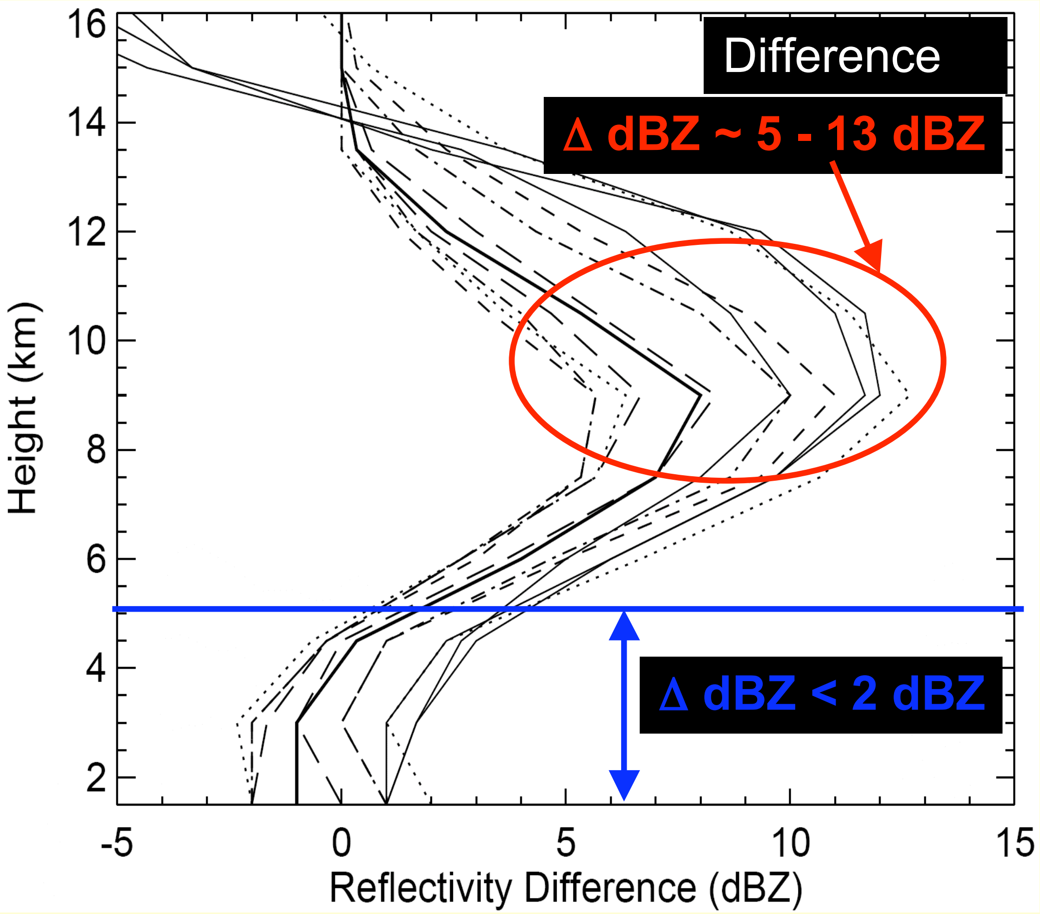
Contoured cumulative frequency by altitude diagram (CCFAD)
of model simulated reflecitivity





Li, Zipser, Krueger, and Zulauf; AMS Cloud Physics Conference, Madison, 2006

Differences between simulated and observed radar reflectivity



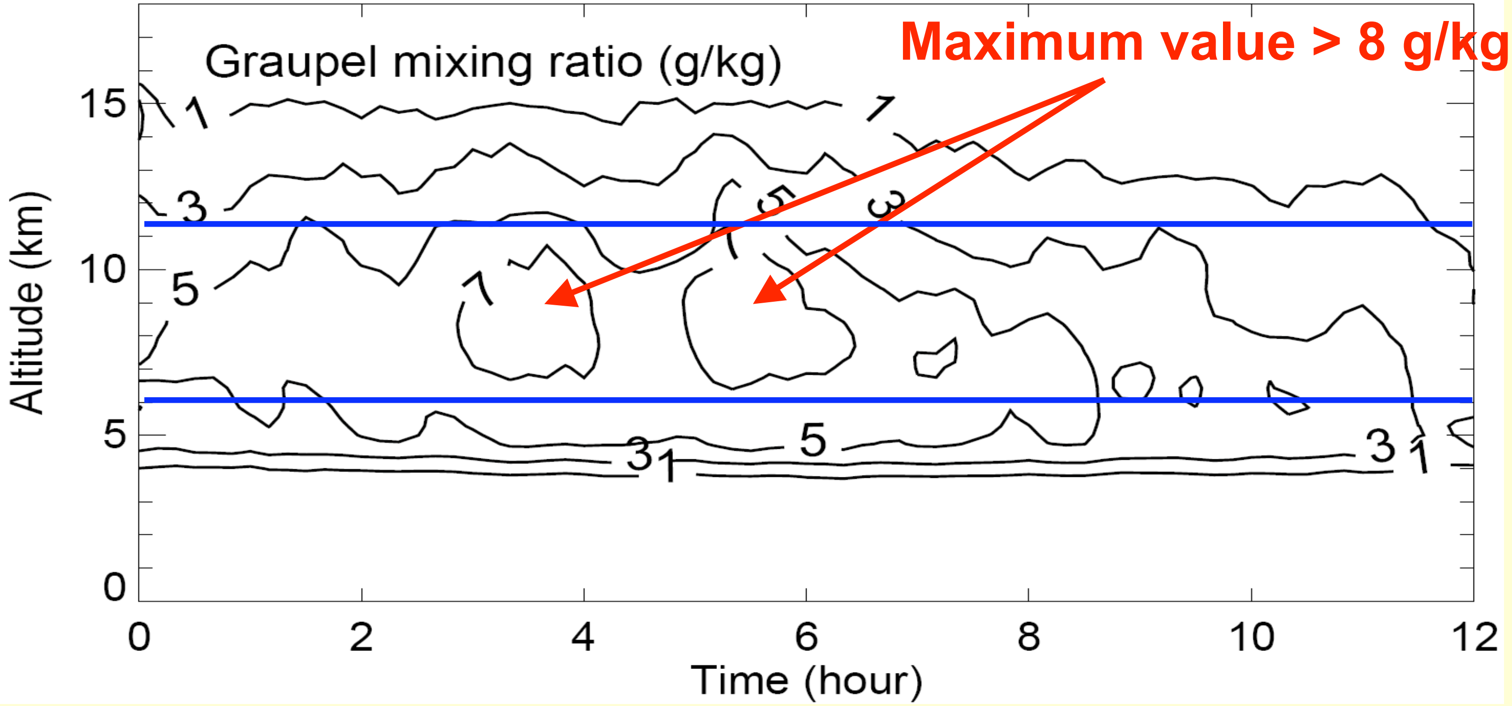
Δ dBZ ~ 5 - 13 dBZ

Δ dBZ < 2 dBZ

What causes such a big difference?

Li, Zipser, Krueger, and Zulauf; AMS Cloud Physics Conference, Madison, 2006

Time-height maximum simulated graupel mixing ratio



The extreme graupel mixing ratio is quite possibly the reason for the extremely high simulated radar reflectivity

Li, Zipser, Krueger, and Zulauf; AMS Cloud Physics Conference, Madison, 2006

NB: Similar conclusion in Blossey et al. (JAS, submitted)

Rutledge and Hobbs, JAS 1984

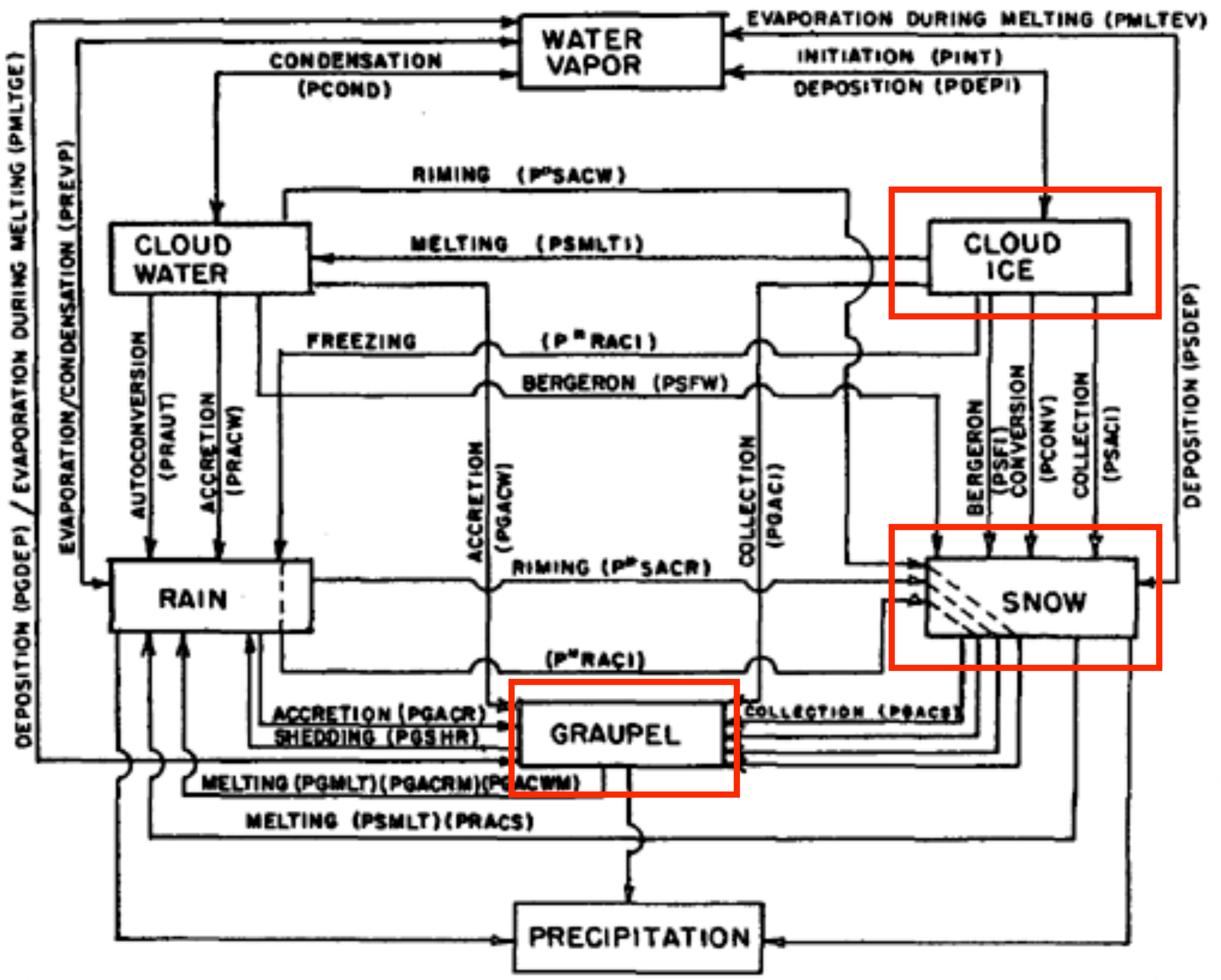


FIG. 1. Schematic depicting the cloud and precipitation processes included in the model for the study of narrow cold-frontal rainbands.

Most schemes used today include the logic of “cloud ice-snow-graupel-hail” to represent ice processes.

Such a logic follows approaches proposed 20+ years ago (Rutledge and Hobbs, Lin et al.) that transplanted ideas from warm-rain microphysics into ice physics. Does it make sense?

Most schemes used today include the logic of “cloud ice-snow-graupel-hail” to represent ice processes.

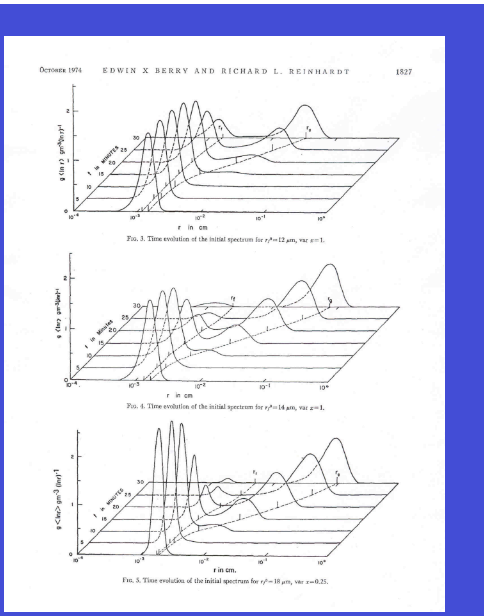
Such a logic follows approaches proposed 20+ years ago (Rutledge and Hobbs, Lin et al.) that transplanted ideas from warm-rain microphysics into ice physics. Does it make sense?

Not really!

-For warm rain, clear separation does exist between cloud water and drizzle/rain; for ice, the boundaries are not obvious and usually gradual transitions from one category to another take place.

-For warm rain, cloud water grows by diffusion of water vapor, drizzle/rain forms through collision/coalescence; for ice, both diffusional and accretional growth contribute to the growth; partitioning between the two mechanisms sets up key microphysical parameters (particle density, sedimentation velocity, etc).

-The ice scheme should produce various types of ice (cloud ice, snow, graupel) just by the physics of particle growth; partitioning ice particles a priori into separate categories introduces unphysical “conversion rates” and involves “threshold behavior” for various parameters (e.g., sedimentation velocity).



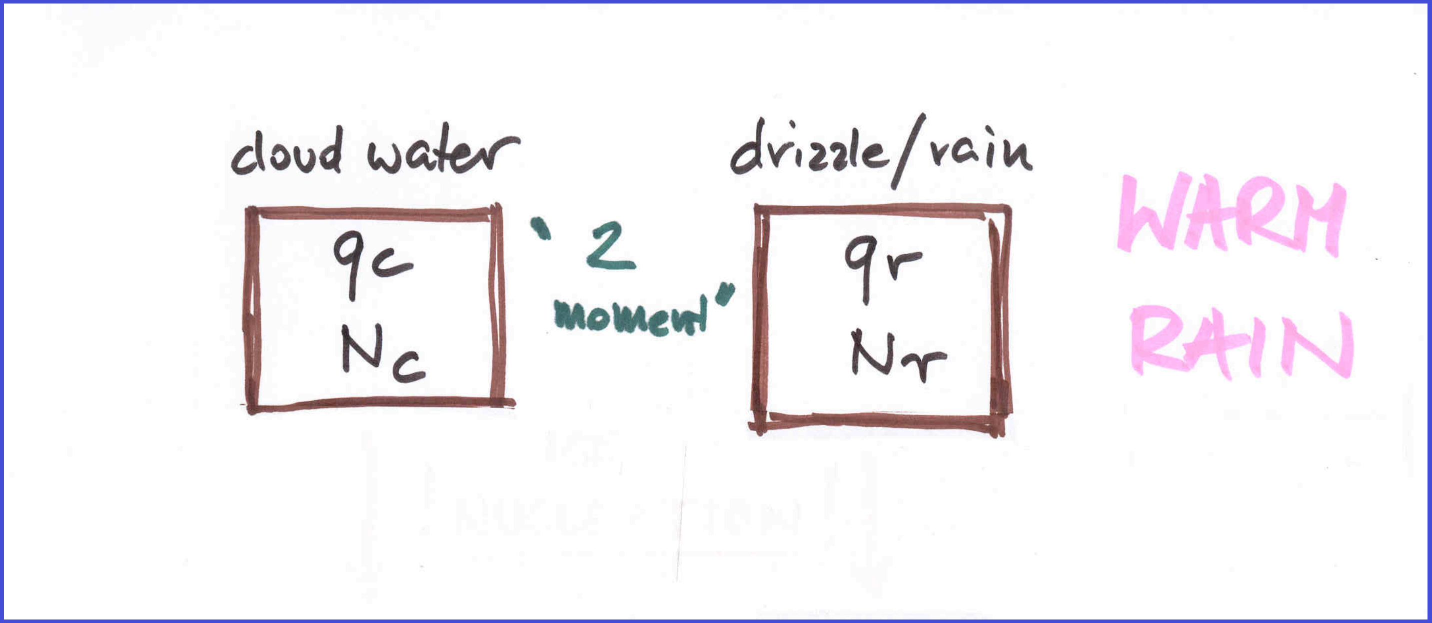
October 1974 EDWIN X BERRY AND RICHARD L. REINHARDT 1827

Fig. 3. Time evolution of the initial spectrum for $r_f{}^0 = 12$ μm, var $x = 1$.

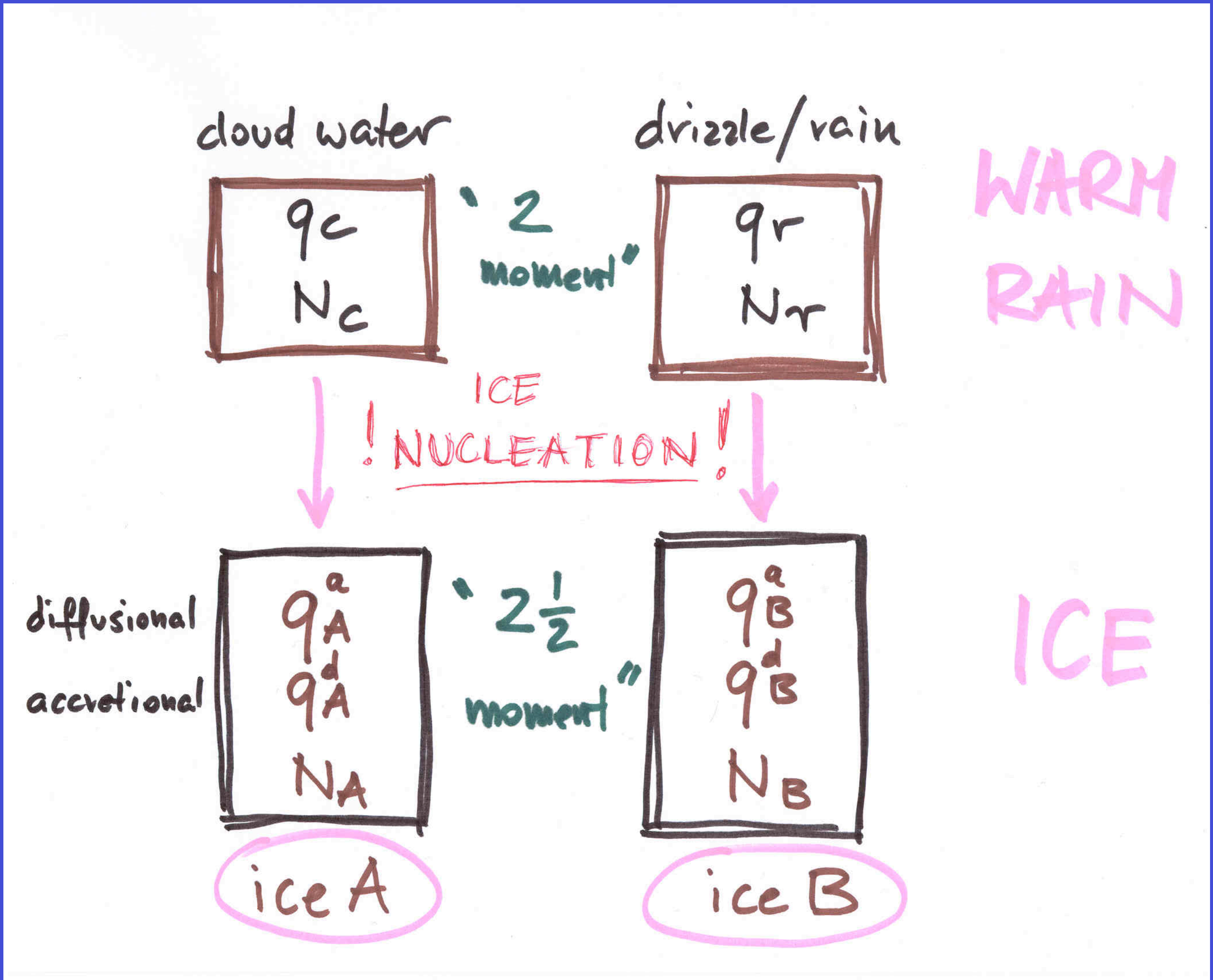
Fig. 4. Time evolution of the initial spectrum for $r_f{}^0 = 14$ μm, var $x = 1$.

Fig. 5. Time evolution of the initial spectrum for $r_f{}^0 = 18$ μm, var $x = 0.25$.

Two-momonet warm rain scheme:



Two-momonet warm rain scheme combined with two-and-a-half moment ice scheme:



Key features:

The scheme tracks the two growth mechanisms: by diffusion and by accretion (riming) which change q for a given N. Partitioning ice particle mass between that acquired by diffusion and by accretion is the key feature, absent from all schemes available today.

Growth by aggregation is directly included (changes of N, but not q).

Sedimentation velocity varies gradually depending on particle mass $[(q^a+q^d)/N]$ and partitioning between diffusional (q^d) and accretional (q^a) growth.

Physics is the same for ice A and ice B (i. e., equations of growth, formulation of the sedimentation velocity, etc).

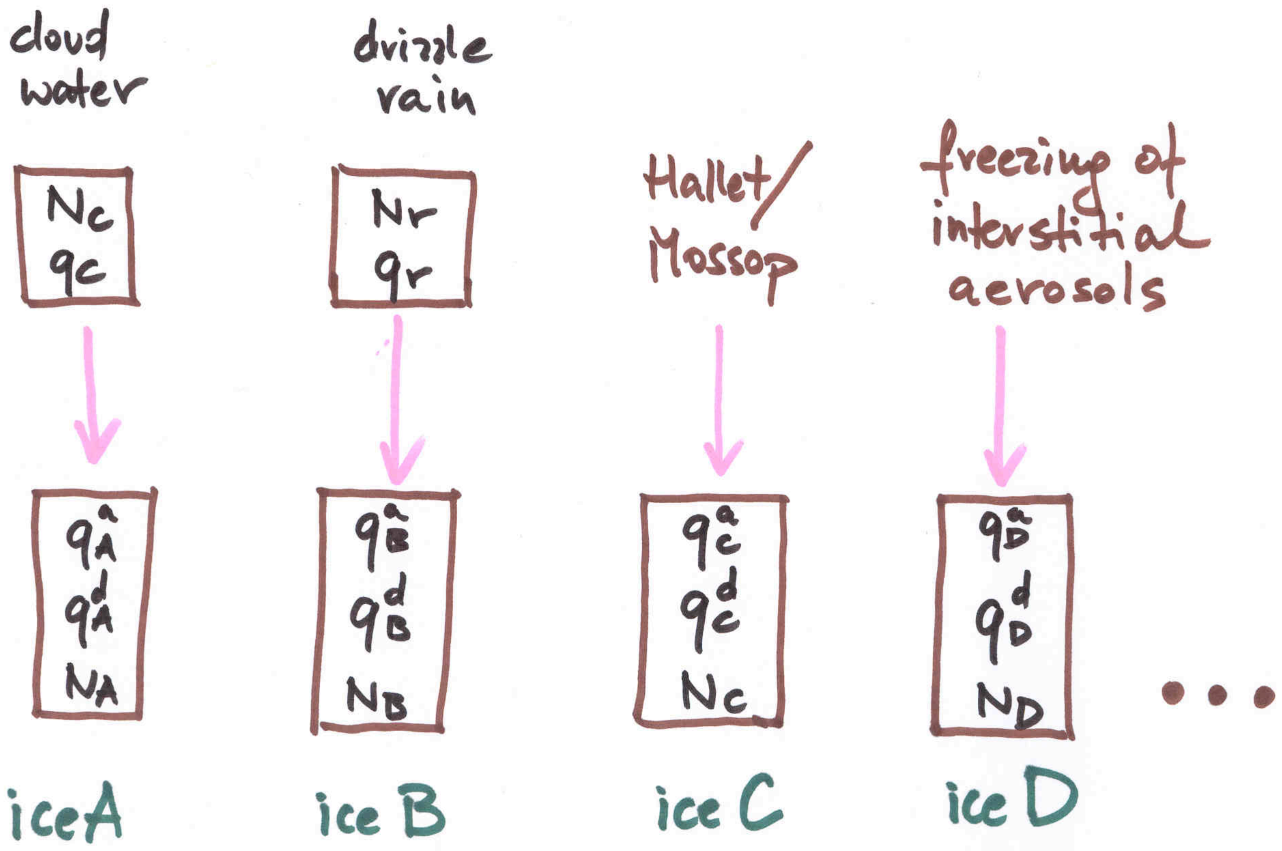
Various ice classes (“cloud ice”, “snow”, “graupel”, “hail”) can be defined from the model output. For instance, “cloud ice”- small ice crystals grown by diffusion; “snow” – large ice crystals with limited riming; “graupel” – large ice crystals with a lot of riming.

Important practical advantages:

The scheme highlights ice nucleation mechanisms, a very uncertain aspect of ice physics, as an essential feature of the model;

Optical properties of various forms of ice (e.g., effective radius; the asymmetry factor) can be better represented for the radiative transfer.

MORE NUCLEATION MECHANISMS ?



Conclusions:

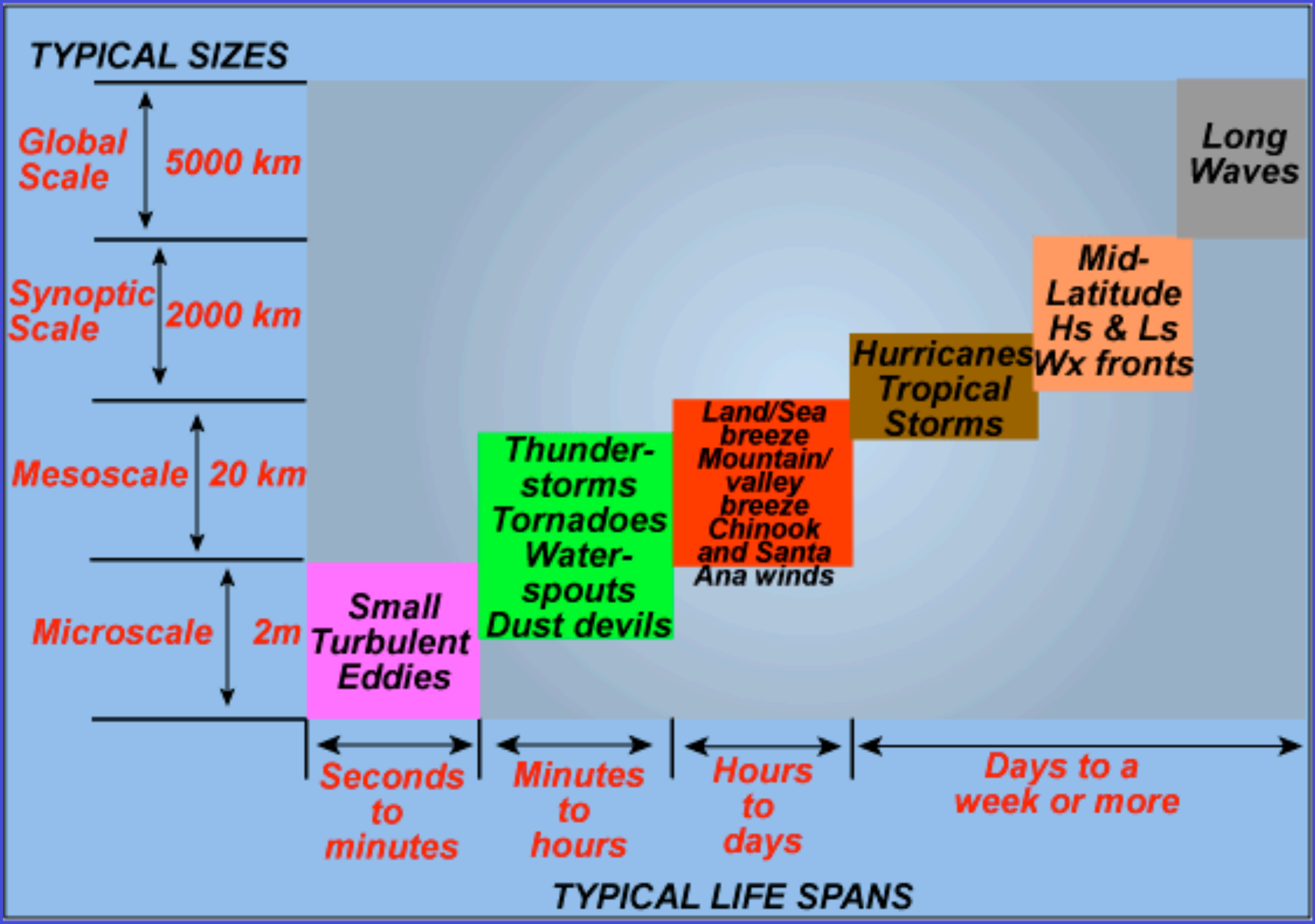
Two-moment cloud microphysics scheme (i.e., the scheme predicting mass and concentration of various cloud and hydrometeor particles) is a promising approach for CRMs, SP-AGCMs, and CR-AGCMs.

Warm-rain two-moment scheme seems to mimic a detailed microphysics when applied to Sc and shallow Cu.

Formulation of the effective radius for warm convective clouds is still uncertain. Robust parameterizations are needed.

Current parameterizations of ice microphysics are questionable, especially when applied to assess indirect effects. A concept of a new physically-based two-moment three-variable approach (“a two-and-a half moment scheme”) is proposed.

Why is it so hard to simulate the Earth climate system?



Because some of the key processes are even not on this diagram….