High-Resolution Simulation of Shallow-to-Deep Convection Transition over Land

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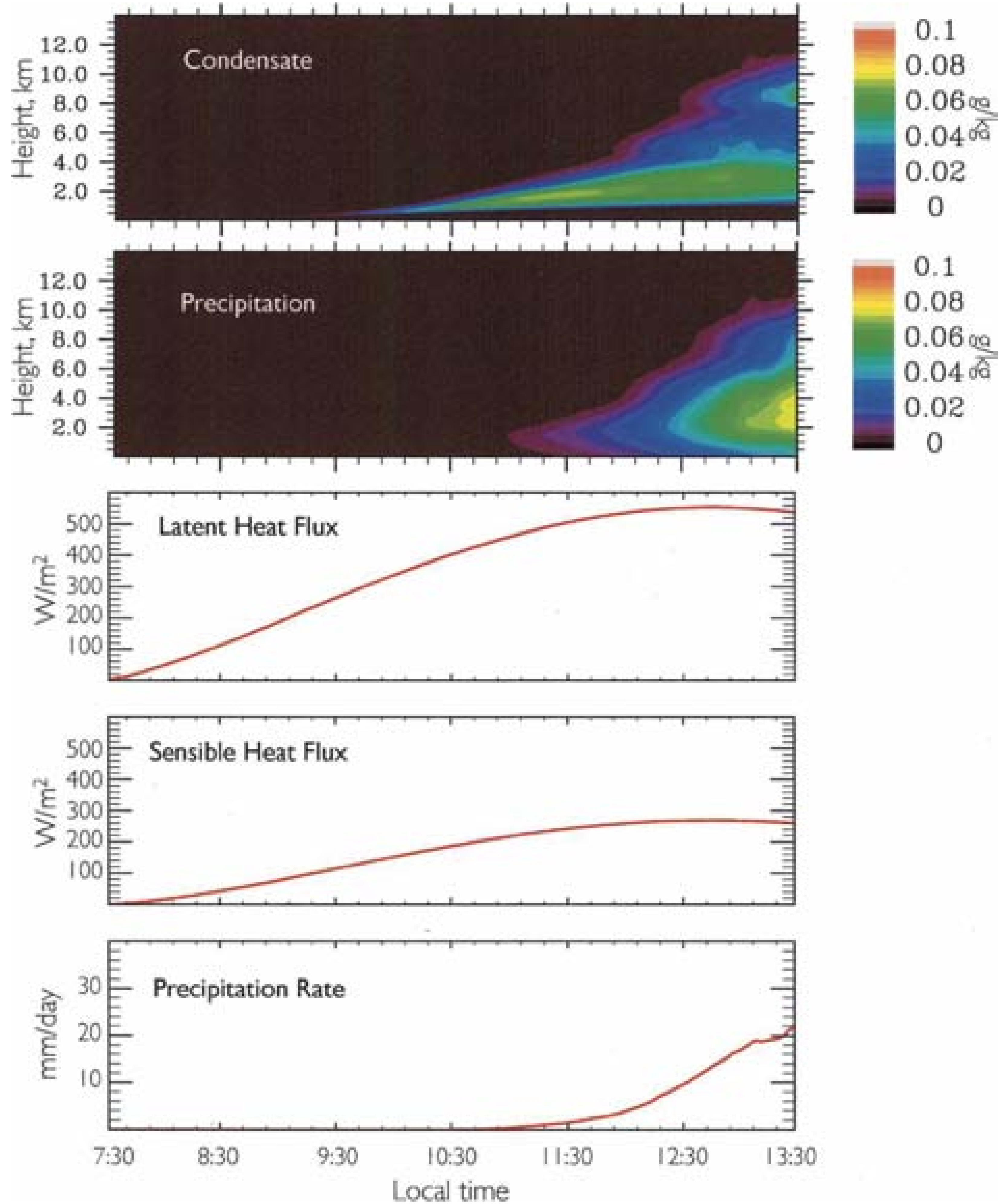
(Manuscript received 7 October 2005, in final form 10 March 2006)

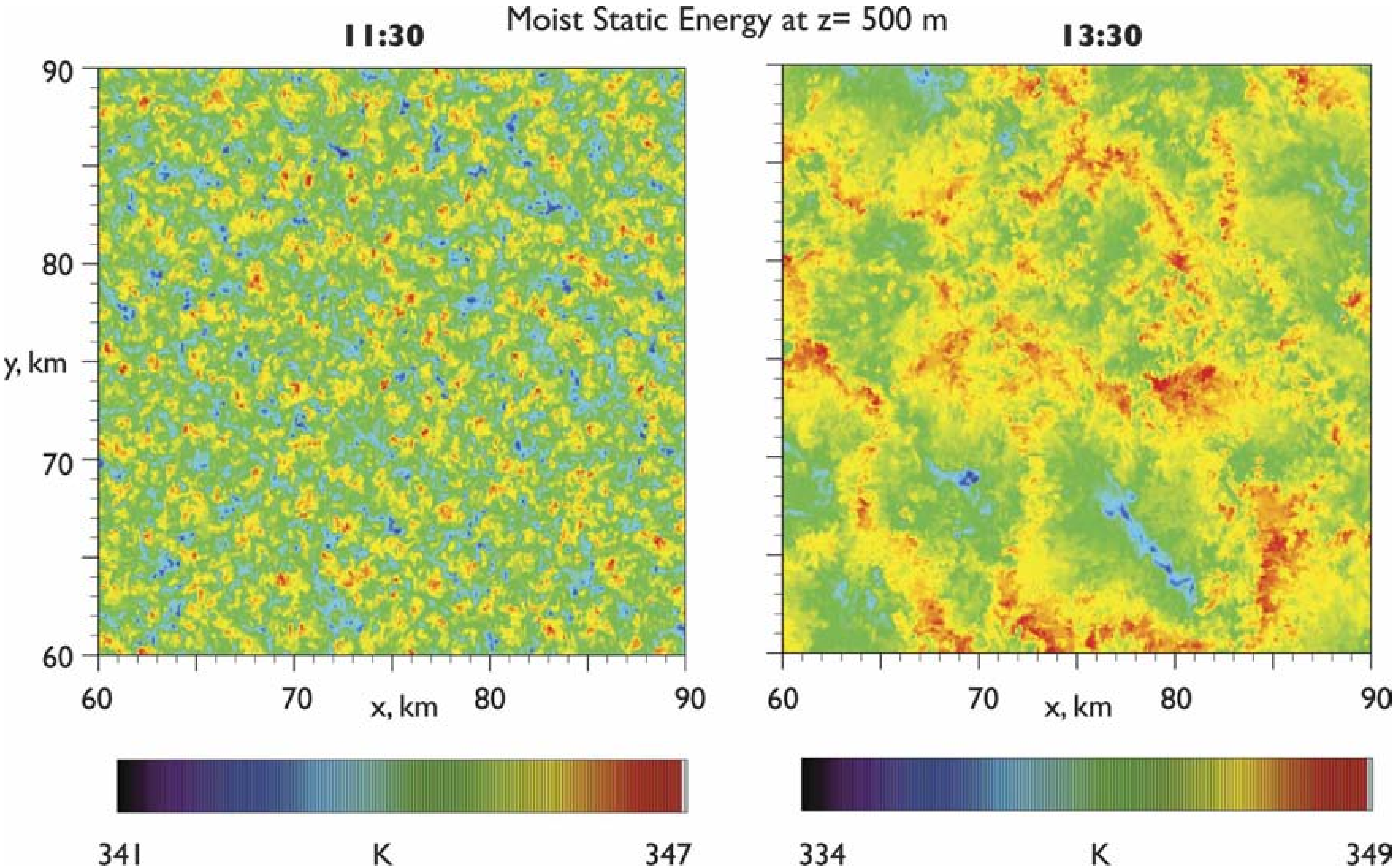
In this paper, we present and discuss the results of a high-resolution three-dimensional simulation of shallow-to-deep convection transition over a relatively large area of about 150 × 150 km^2, using the forcing derived from an idealization of the observations made during the LBA experiment in Amazonia during the TRMM-LBA mission on 23 February 1999. The simulation starts from the early morning sounding at 0730 LT with a uniform initial state forced by prescribed surface latent and sensible heat fluxes that are applied uniformly.



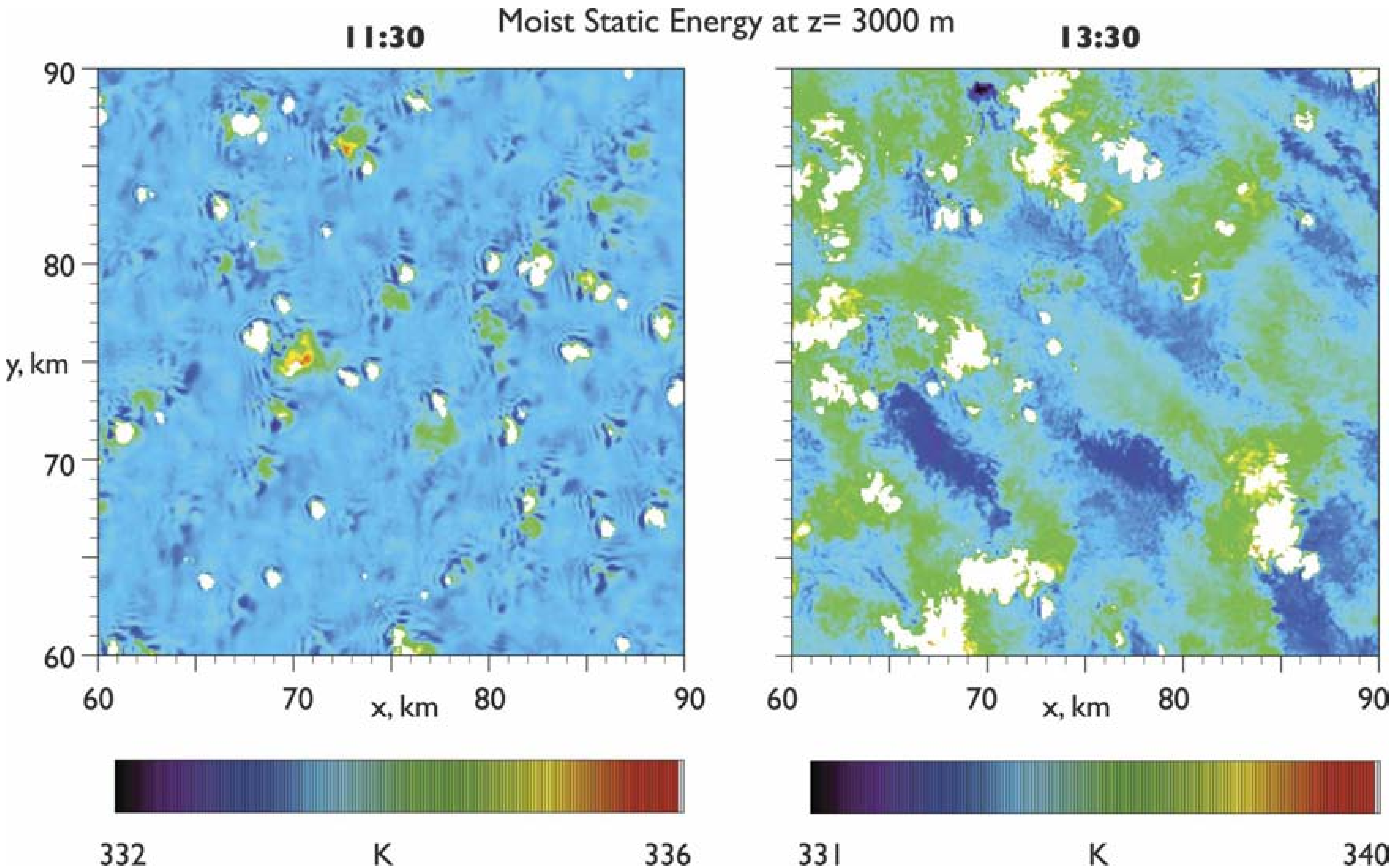
Condensate
Height, km
12.0
10.0
8.0
6.0
4.0
2.0
0.1
0.08
0.06
0.04
0.02
0
g/kg
Precipitation
Height, km
Latent Heat Flux
W/m²
500
400
300
200
100
Sensible Heat Flux
W/m²
Precipitation Rate
mm/day
30
20
10
7:30
8:30
9:30
10:30
11:30
12:30
13:30
Local time

Throughout the simulation, including the initial state, the mean thermodynamic sounding has a rather considerable amount of CAPE, in the range from about 1600 J kg^{-1} in the early morning to 2400 J kg^{-1} at the end of the simulation, with virtually no CIN. Theoretically, clouds could rise as high as 12 km as early as at 0930; however, deep clouds emerge only at about 1230 in the afternoon.

clouds during the shallow and congestus stages have sizes (i.e., horizontal scales) comparable to the sizes of boundary layer eddies, that is, generally less than 1 km, and are fairly quickly diluted by the environmental air through entrainment. This prevents deep clouds from forming. Thus the existence of positive buoyancy through a deep layer is not by itself sufficient to permit deep convection, even in an environment characterized by low convective inhibition; however, such triggering is often allowed in cumulus parameterizations.

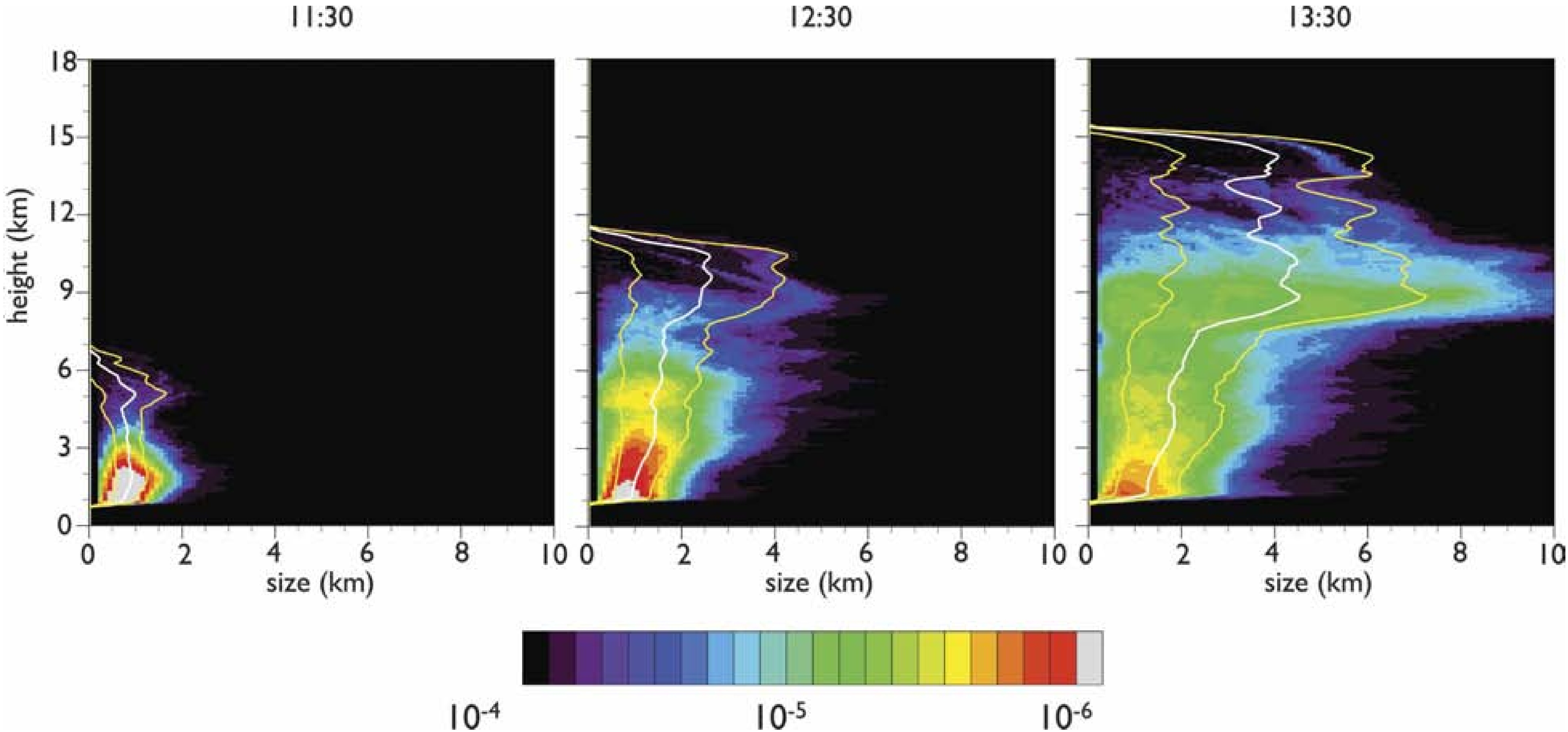


Moist Static Energy at z= 500 m
11:30
13:30
90
80
y, km
70
60
60
70
x, km
80
90
341
K
347
334
K
349


Moist Static Energy at z= 3000 m
11:30
13:30
90
80
70
60
y, km
60
70
80
90
x, km
332
K
336
331
K
340

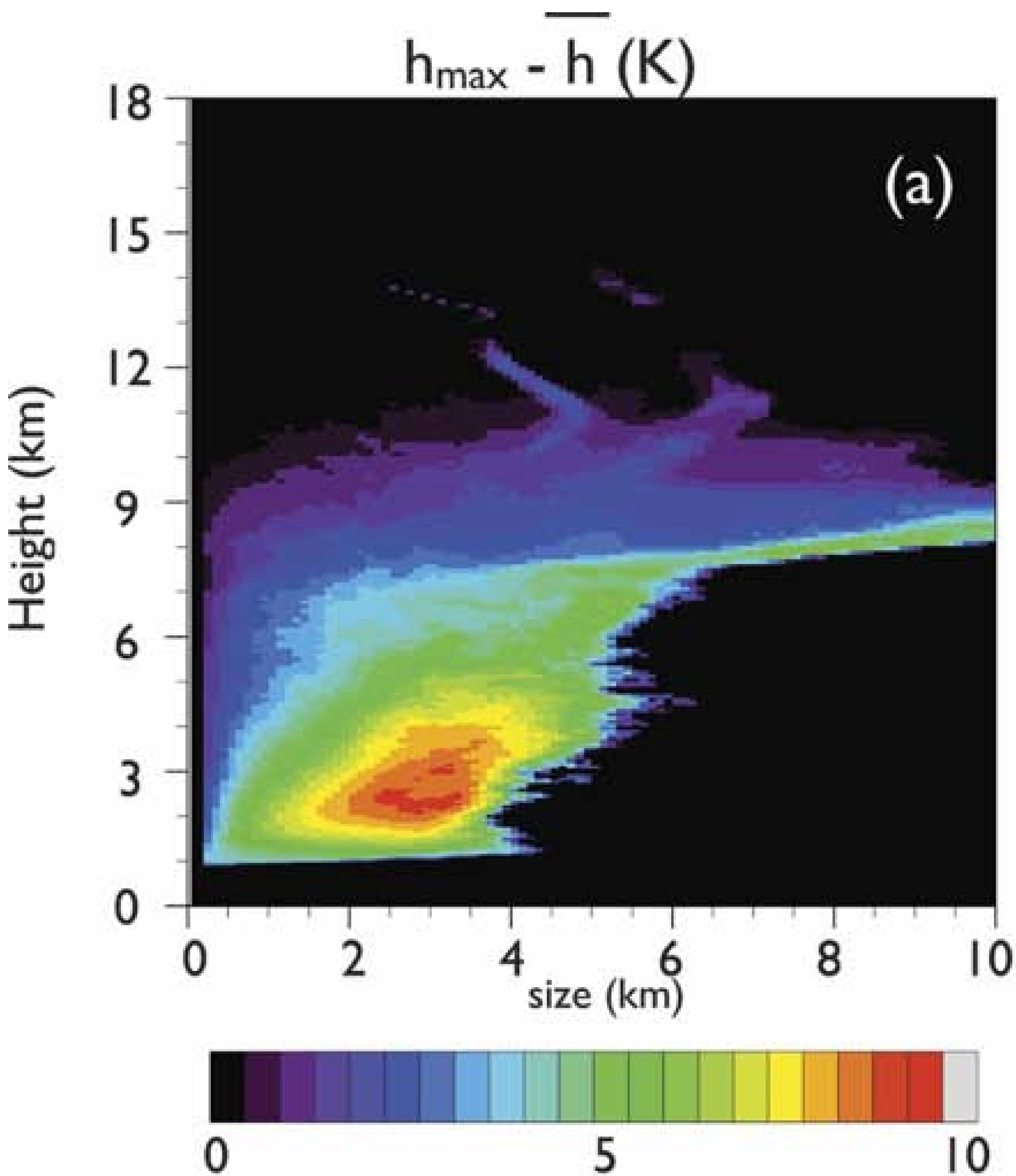
The joint PDFs of cloud size and other in-cloud variables such as total water, moist static energy, and vertical velocity show that the bigger clouds are far less diluted above their bases than their smaller counterparts. As a result, the bigger clouds are more buoyant and, therefore, maintain high in-core vertical velocities, and penetrate deeper into the troposphere.

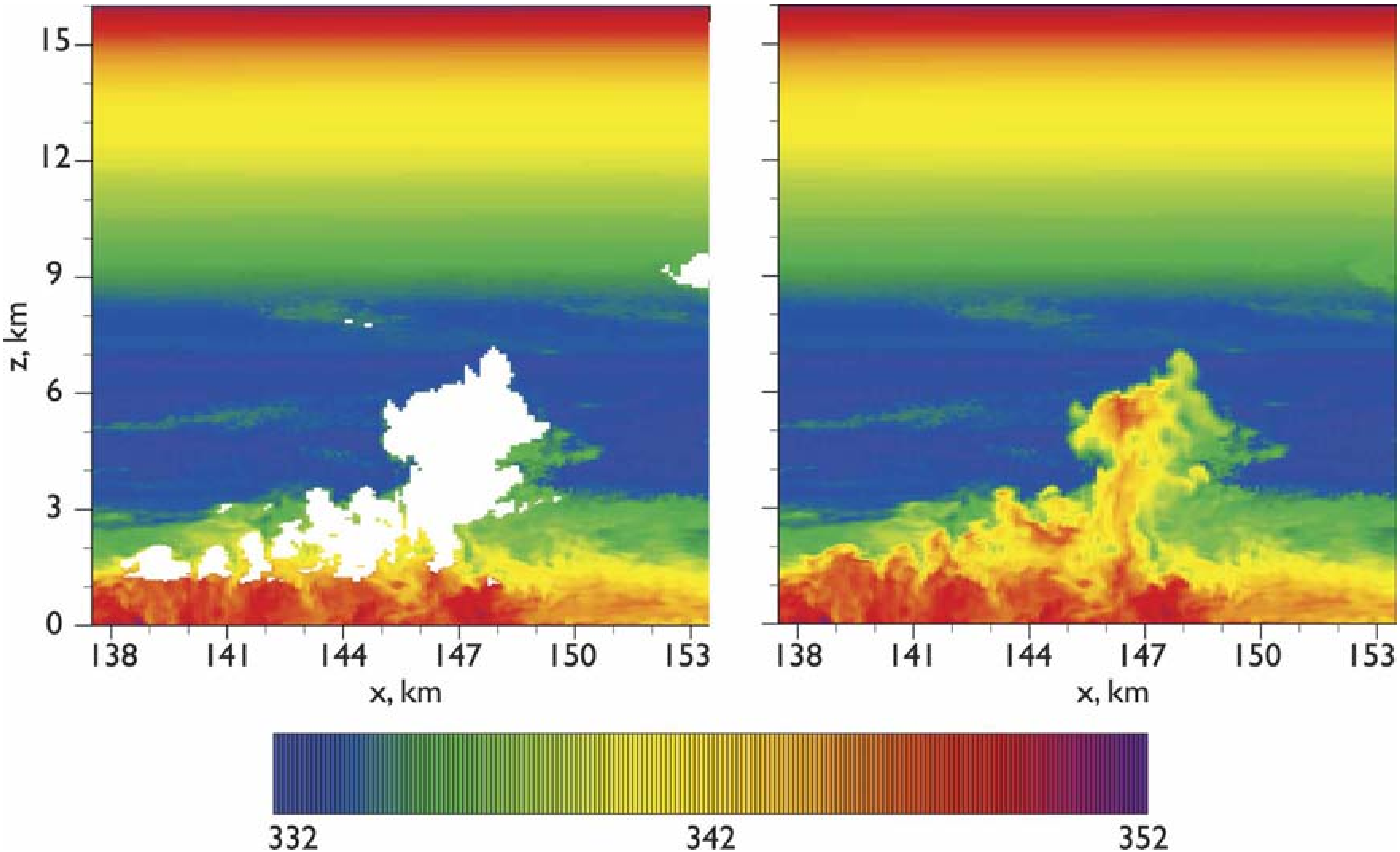
PDF of cloud size



It is remarkable that regardless of cloud size, the thermodynamic properties at cloud bases are nearly identical for all of the simulated clouds, in agreement with the findings of KB05.

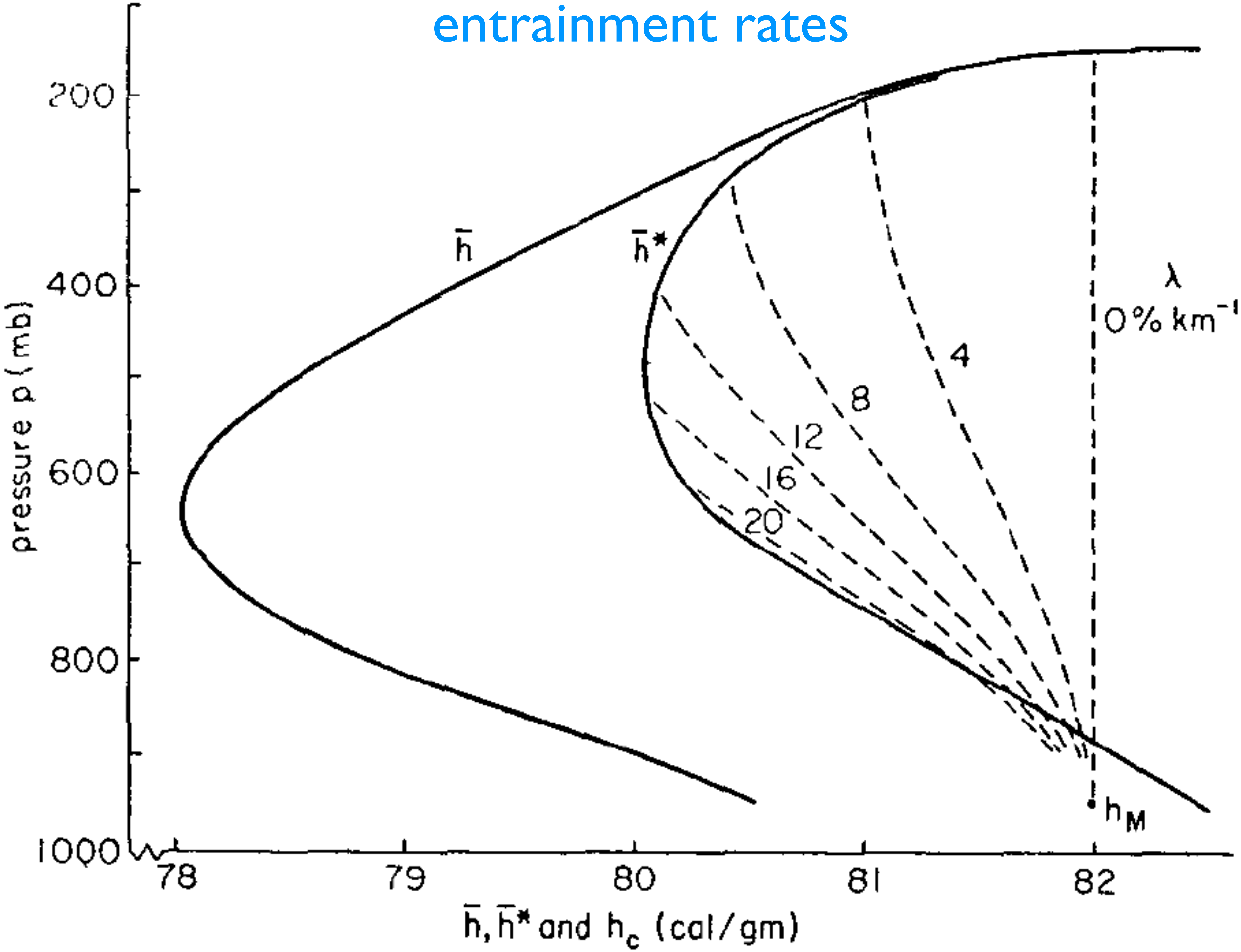
Joint PDF of cloud size and maximum deviation from the mean of moist static energy



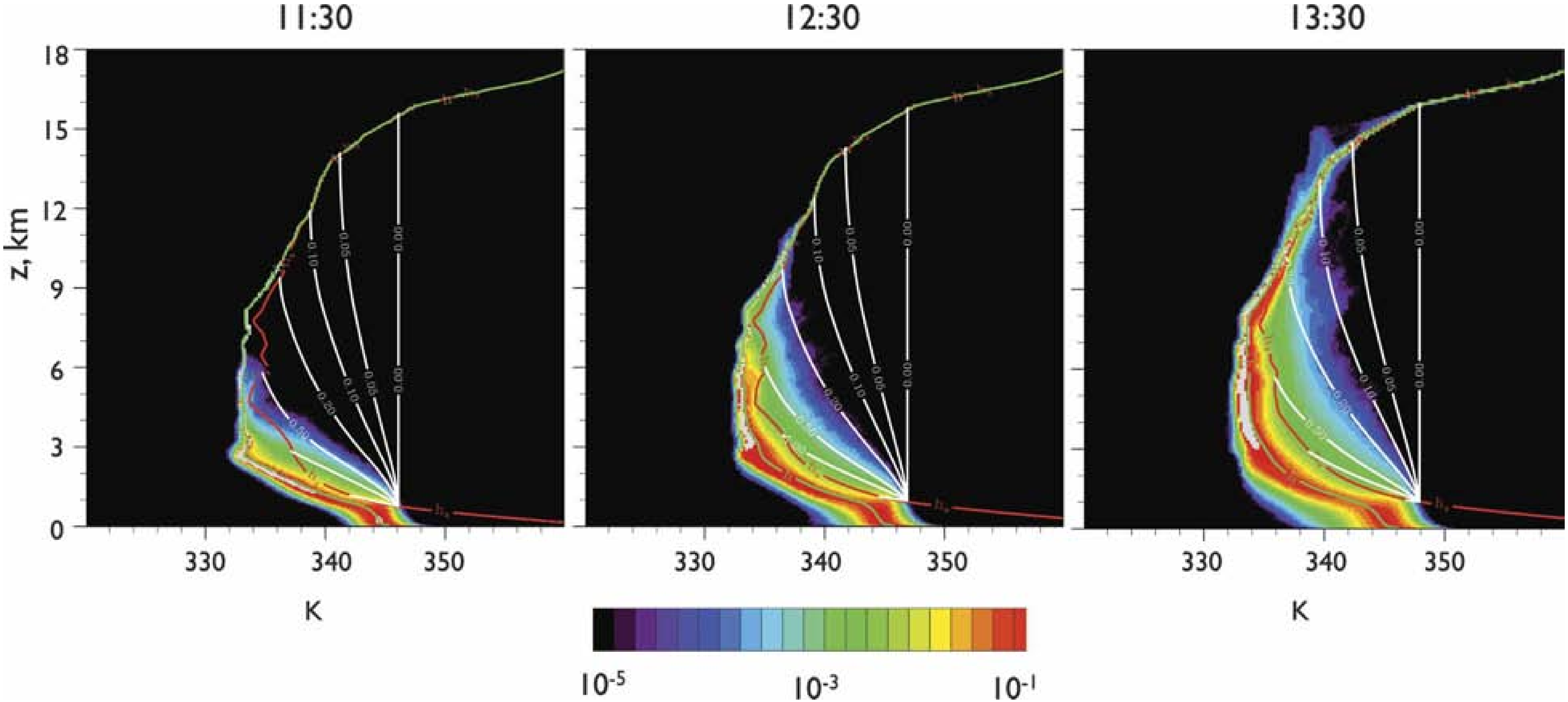


z, km
0
3
6
9
12
15
138
141
144
147
150
153
x, km
x, km
332
342
352

Moist static energy profiles for different fractional entrainment rates



PDF of moist static energy



PDF of moist static energy for w > 5 m/s

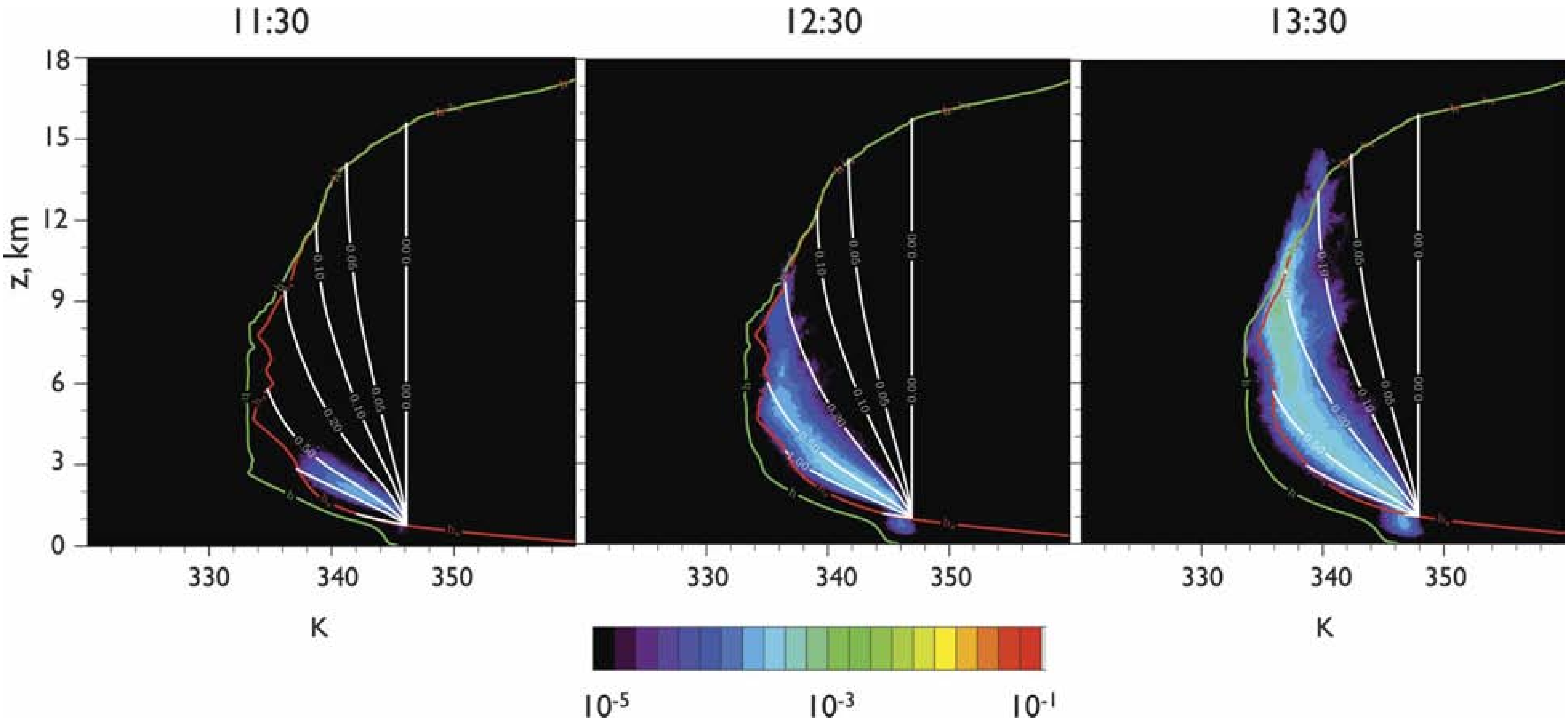
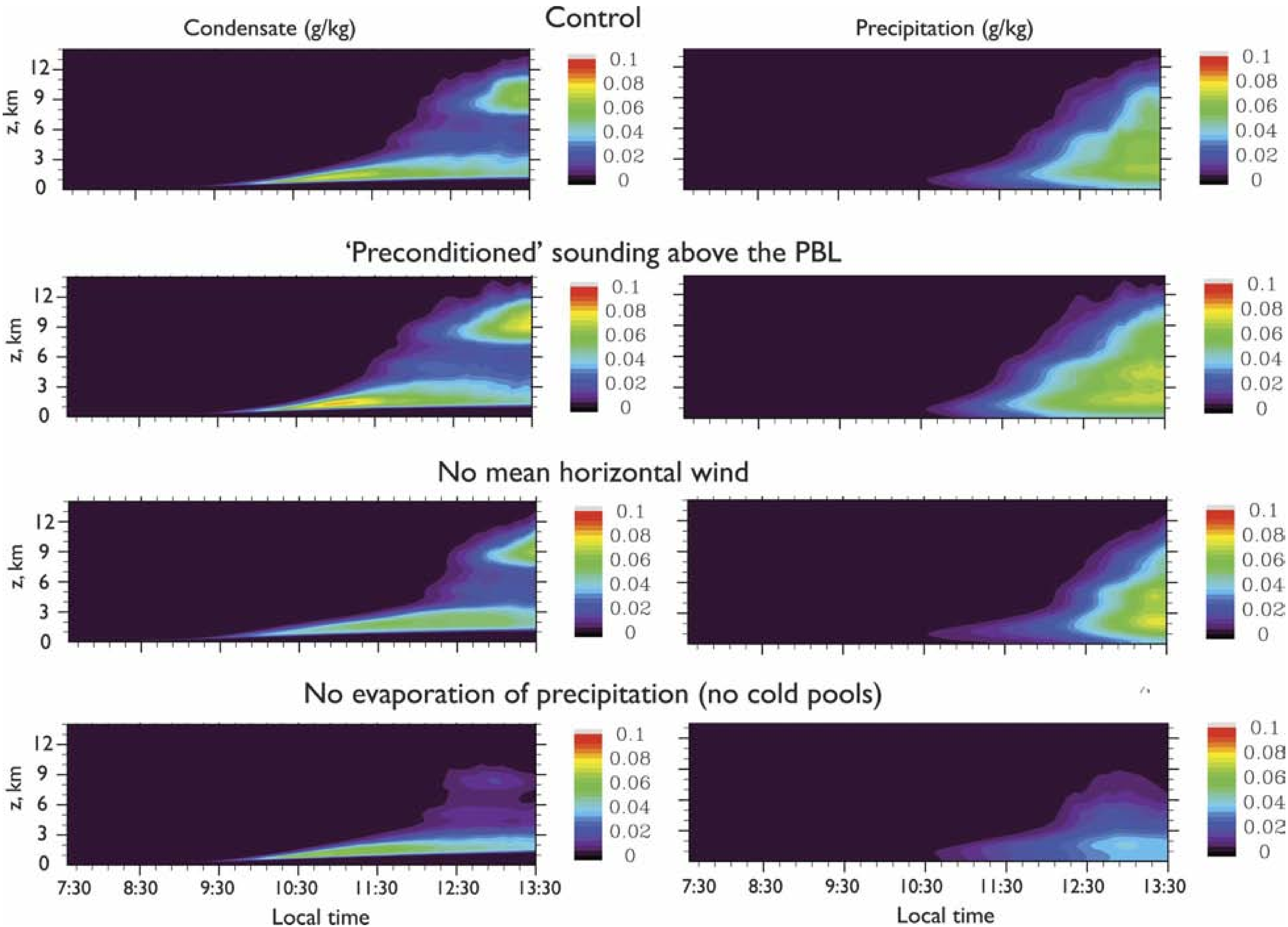


FIG. 12. As in Fig. 11 except for the updraft cores defined by the vertical velocity being in excess of 5 m s^{-1}.

It is demonstrated that the transition of convection from shallow to deep is strongly favored by a positive feedback involving evaporating precipitation. Larger clouds precipitate more heavily and, thus, through the cold pool dynamics, tend to produce larger boundary layer thermals that may grow into even larger precipitating clouds. This feedback, first discussed by KB05, is eliminated in a sensitivity experiment by artificially switching off the evaporation of precipitation.

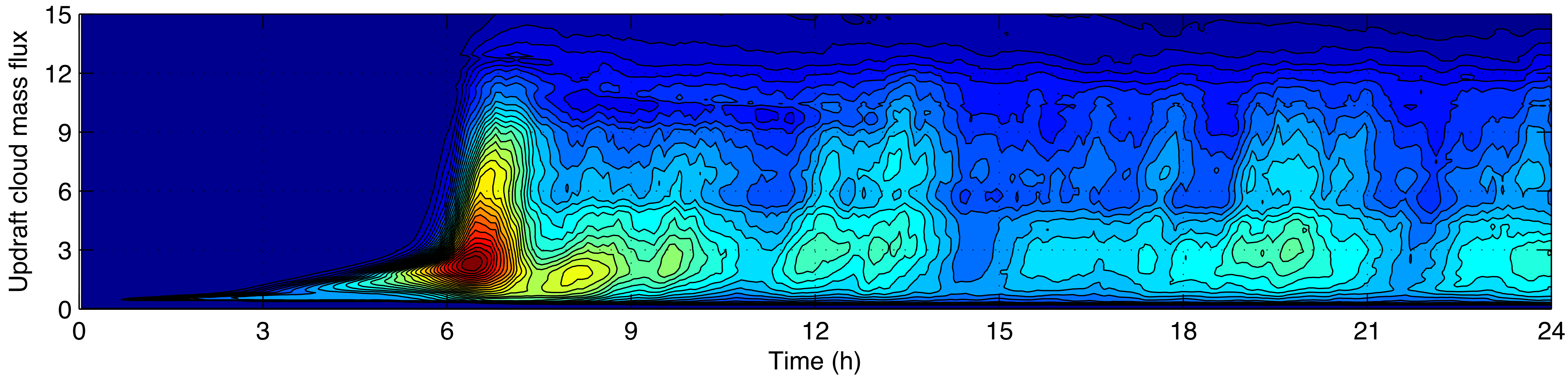

Control
Condensate (g/kg)
Precipitation (g/kg)
'Preconditioned' sounding above the PBL
No mean horizontal wind
No evaporation of precipitation (no cold pools)
z, km
0
3
6
9
12
0
0.02
0.04
0.06
0.08
0.1
7:30
8:30
9:30
10:30
11:30
12:30
13:30
Local time

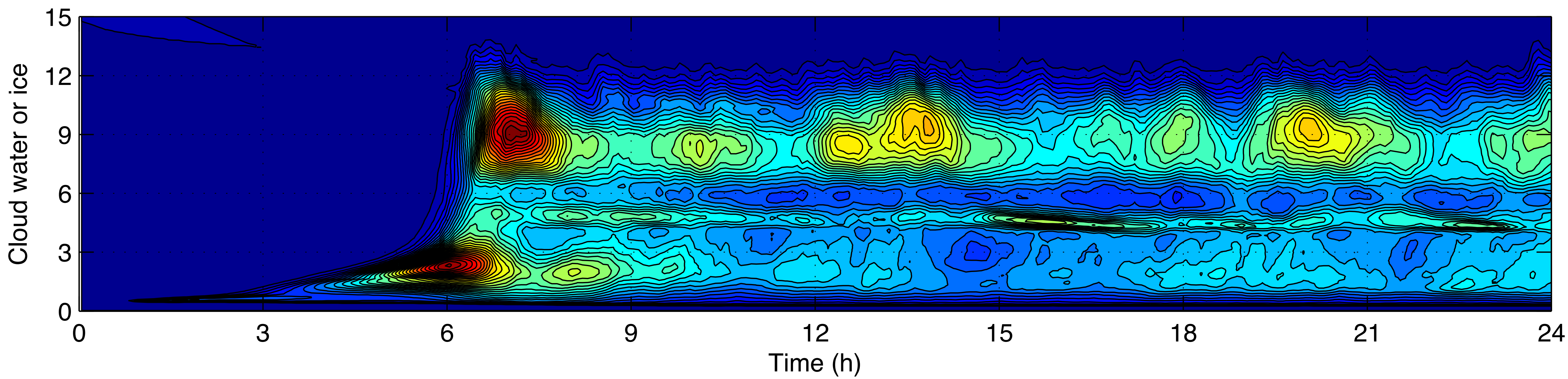
Giga-LES of deep convection

- Goal is to simultaneously simulate boundary layer turbulence, shallow convection, deep convection, and mesoscale convective systems.
- Idealized GATE (tropical ocean) simulation with shear.
- Used a CRM (SAM) with 2048 x 2048 x 256 (10^9) grid points and 100-m grid size for a 24-h LES.

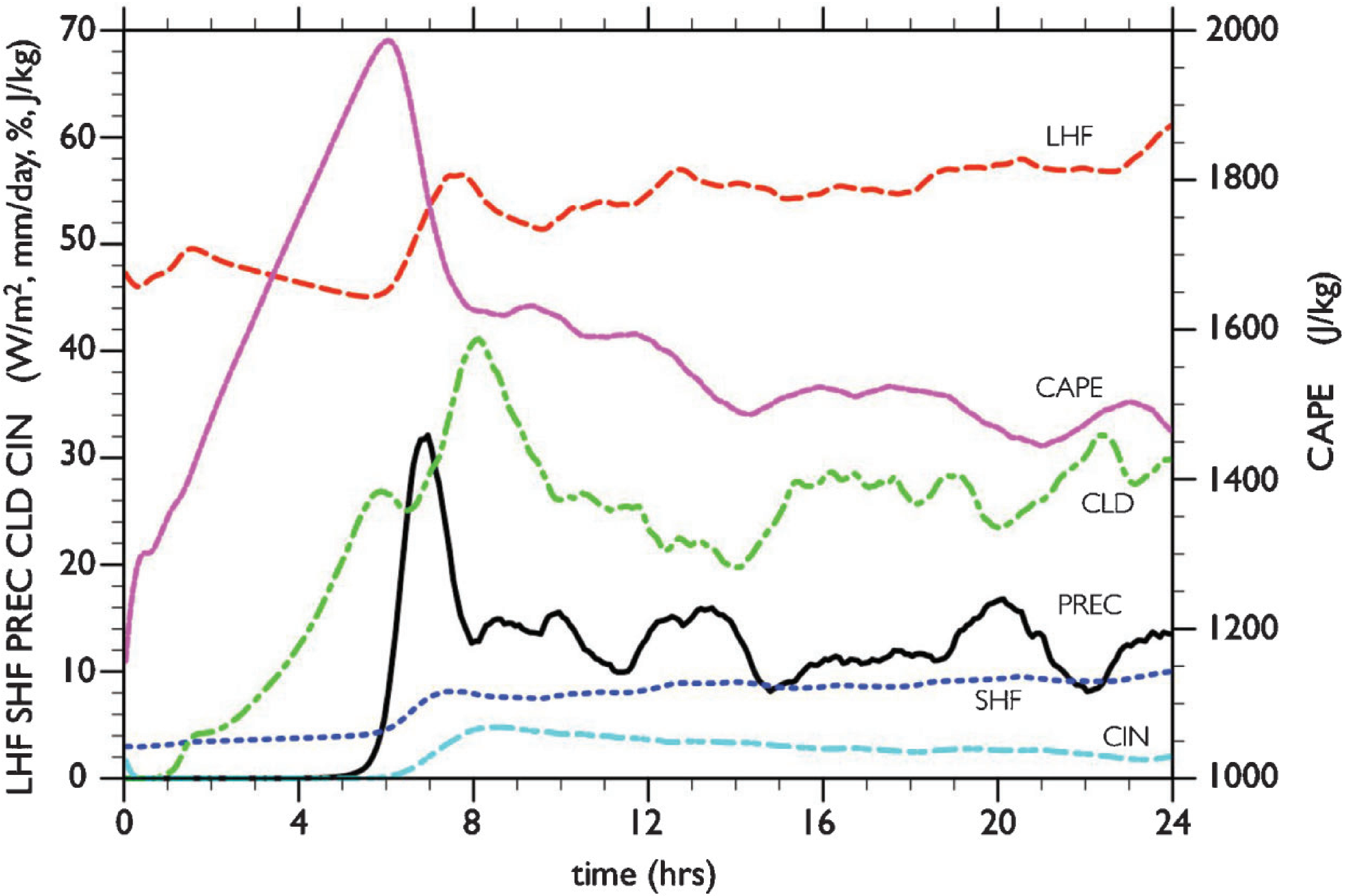
Khairoutdinov, M. F. , S. K. Krueger, C.-H. Moeng, P. A. Bogenschutz, and D. A. Randall, 2009: Large-eddy simulation of maritime deep tropical convection. *J. Adv. Model. Earth Syst.,* **1,** Art. #15, 13 pp., doi:10.3894/JAMES 2009.1.15.

Updraft cloud mass flux

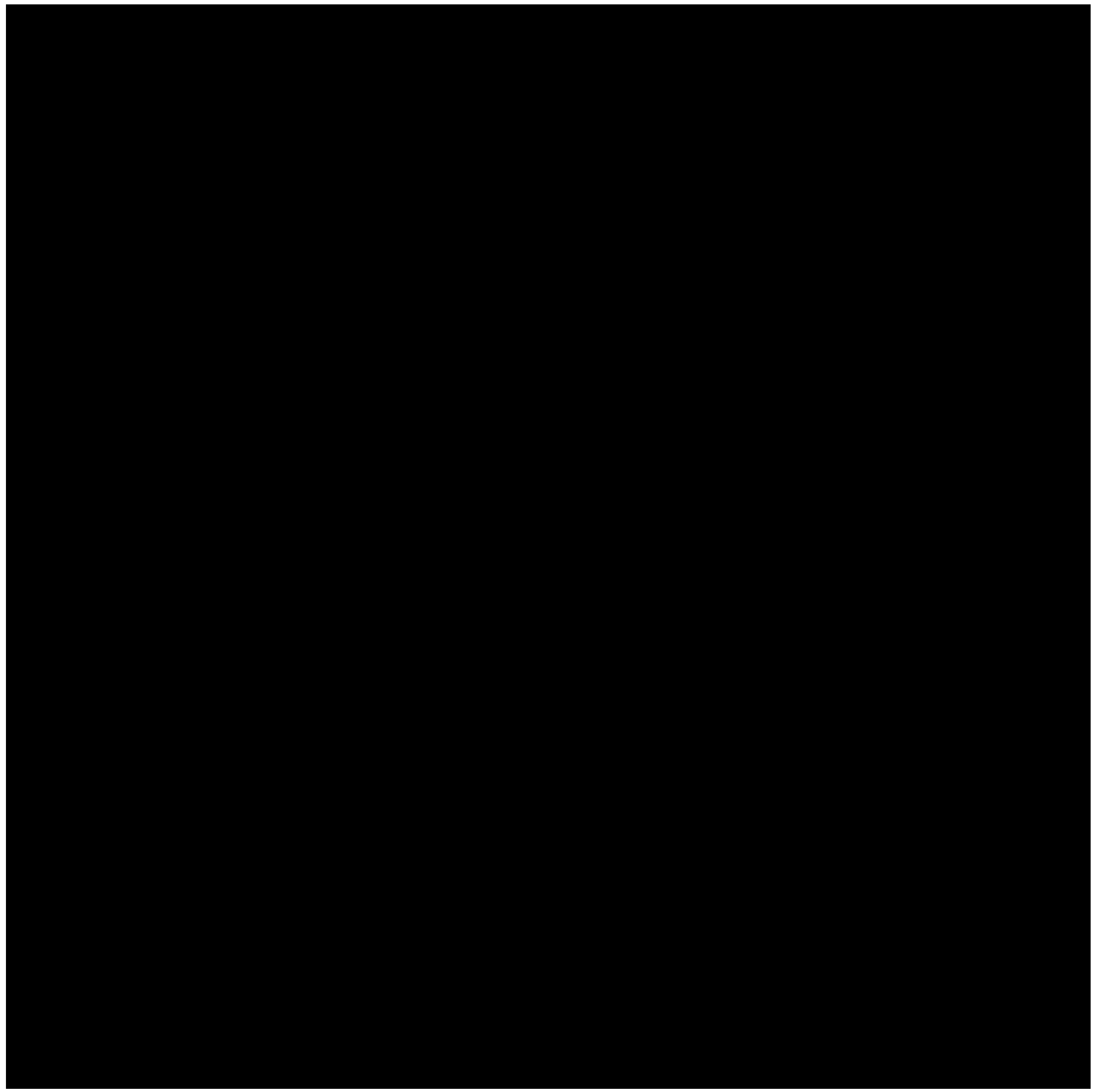




Cloud water or ice


LHF
CAPE
CLD
PREC
SHF
CIN
LHF SHF PREC CLD CIN (W/m², mm/day, %, J/kg)
CAPE (J/kg)
time (hrs)
0
4
8
12
16
20
24
0
10
20
30
40
50
60
70
1000
1200
1400
1600
1800
2000

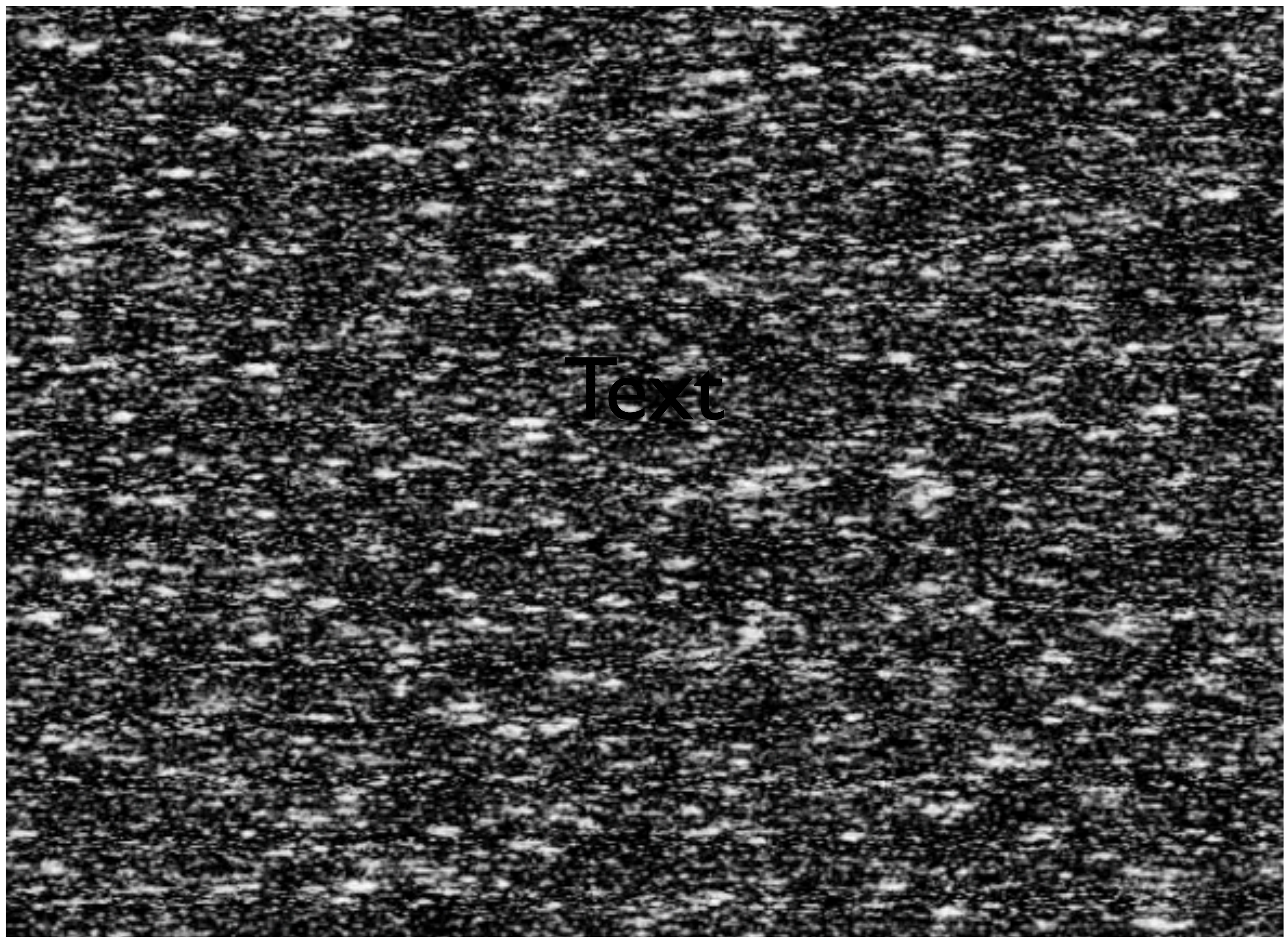
Cloud Liquid Water Path (vertical integral)
(shows low and middle clouds)



zoom into 50 km by 50 km (shows all clouds)

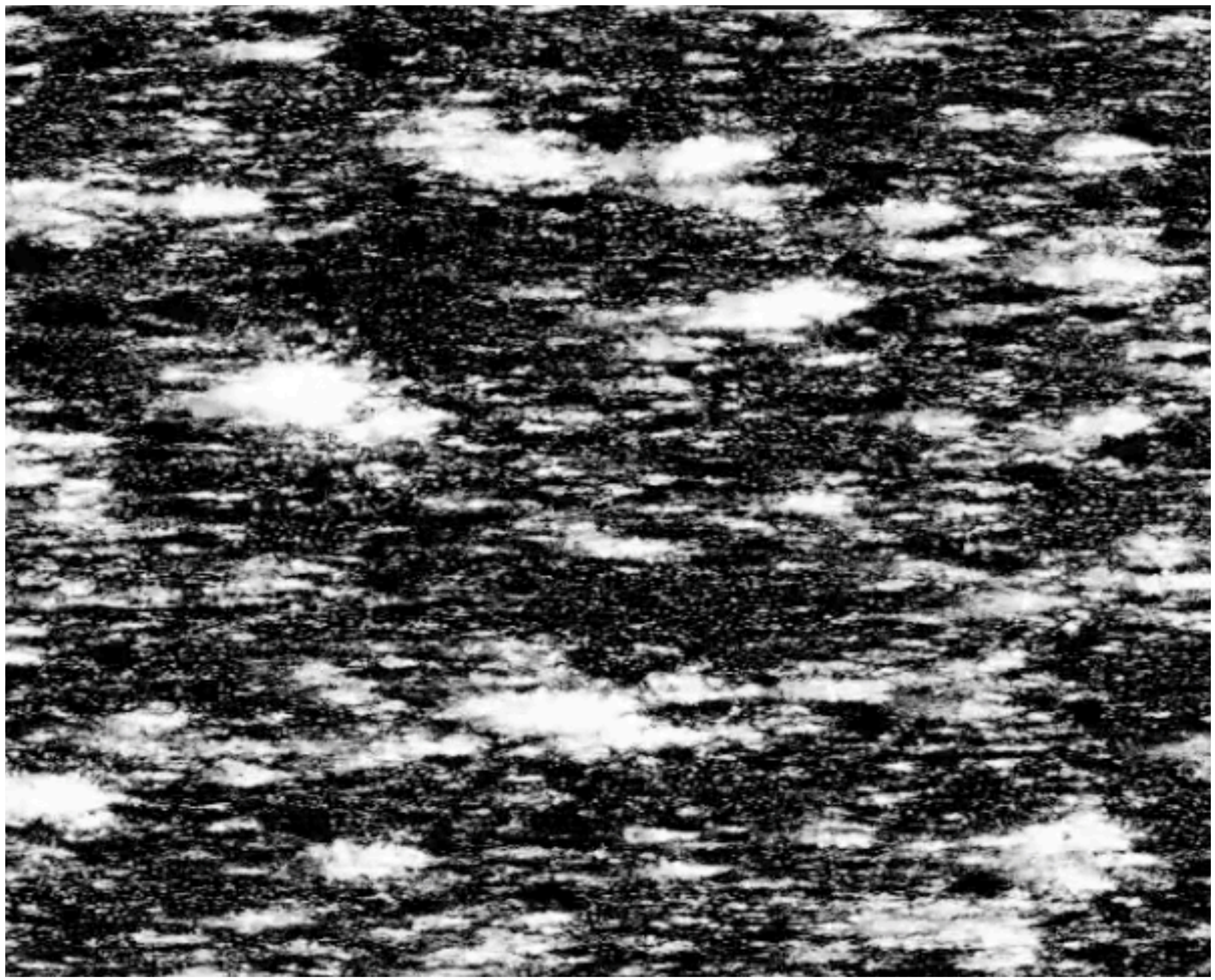
QuickTime™ and a
decompressor
are needed to see this picture.

Shallow Convection



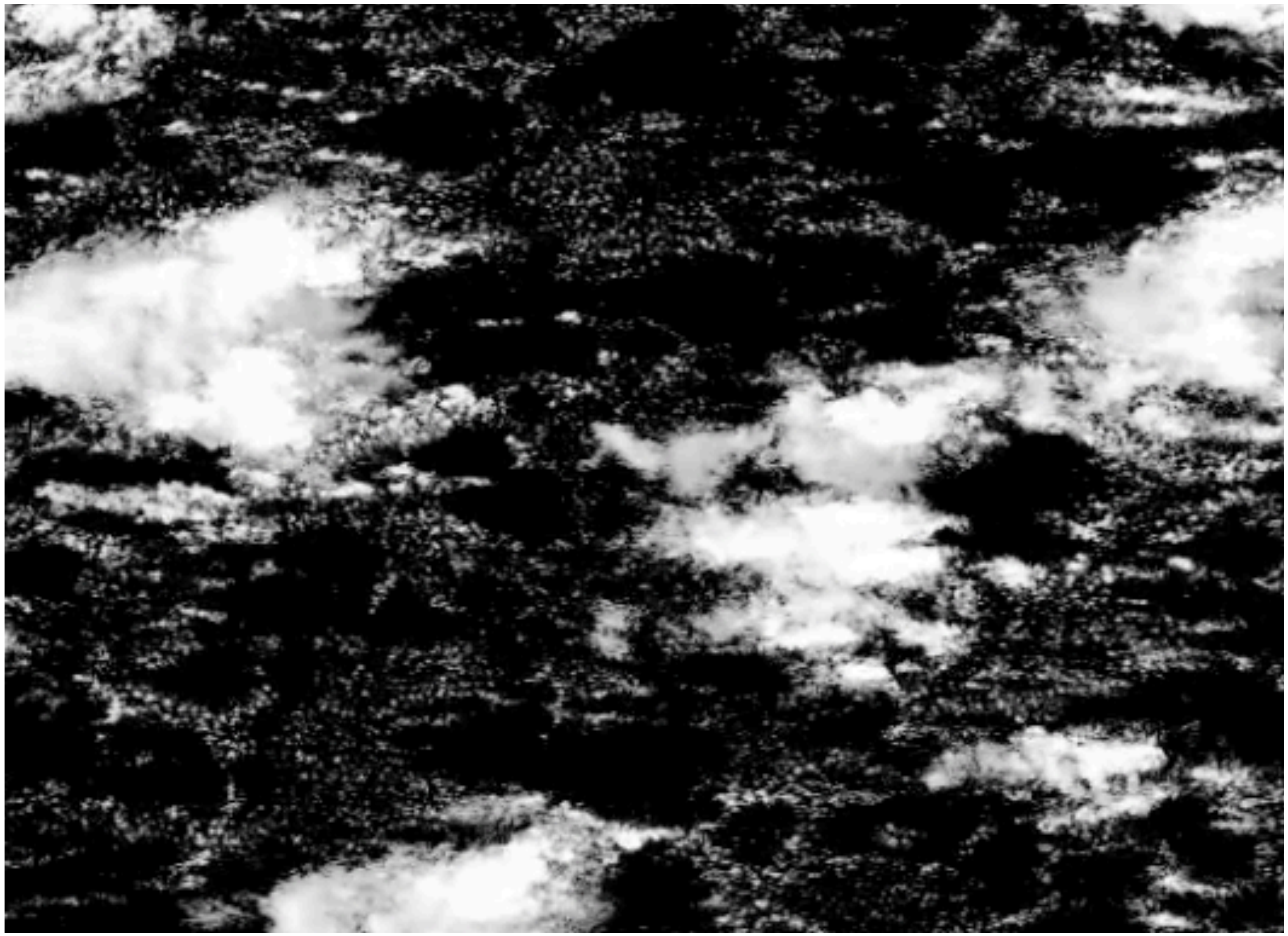
Cloud Water Path at t = 4 hours

Congestus



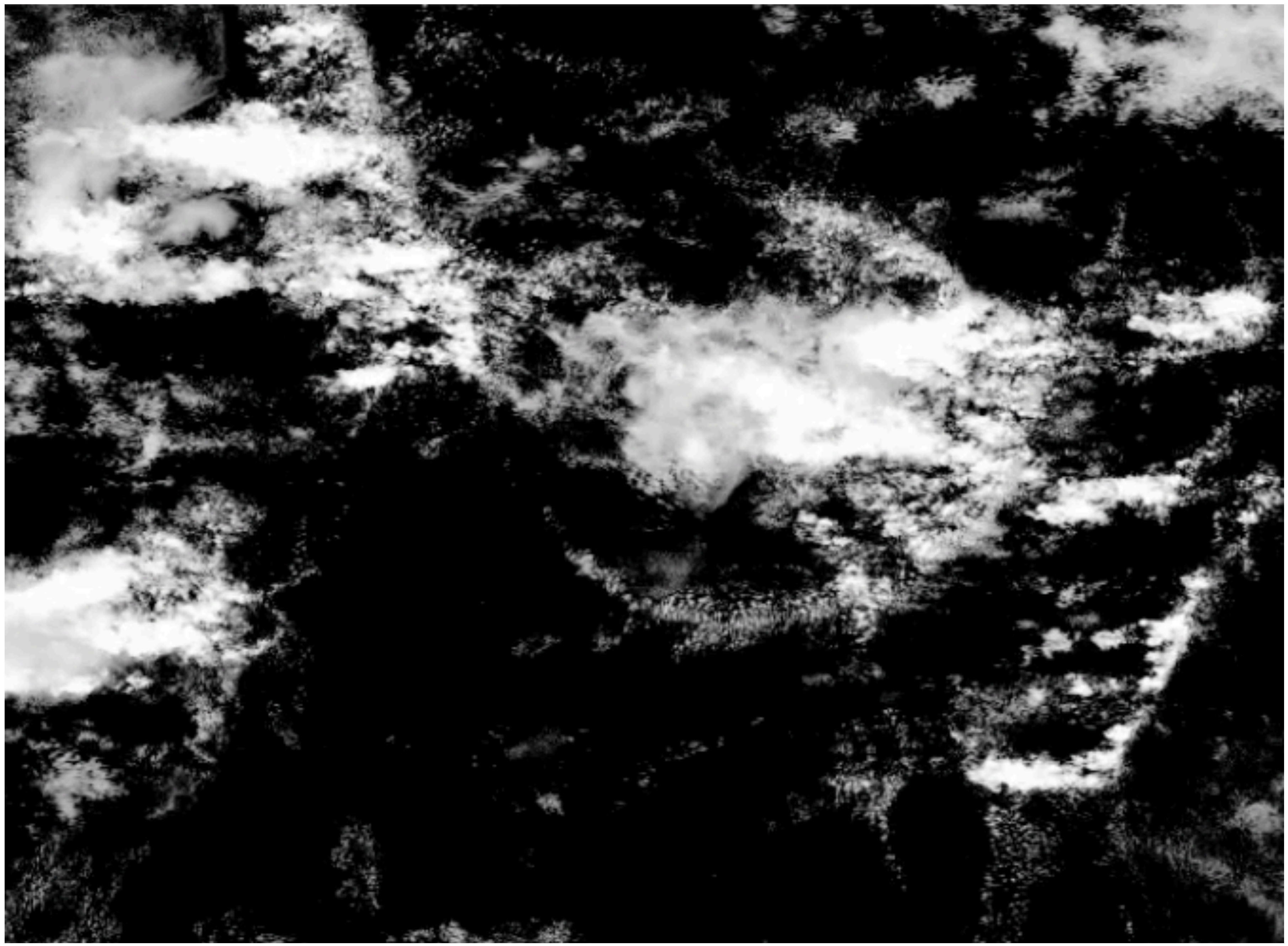
CWP at t = 5.75 hours

Transition

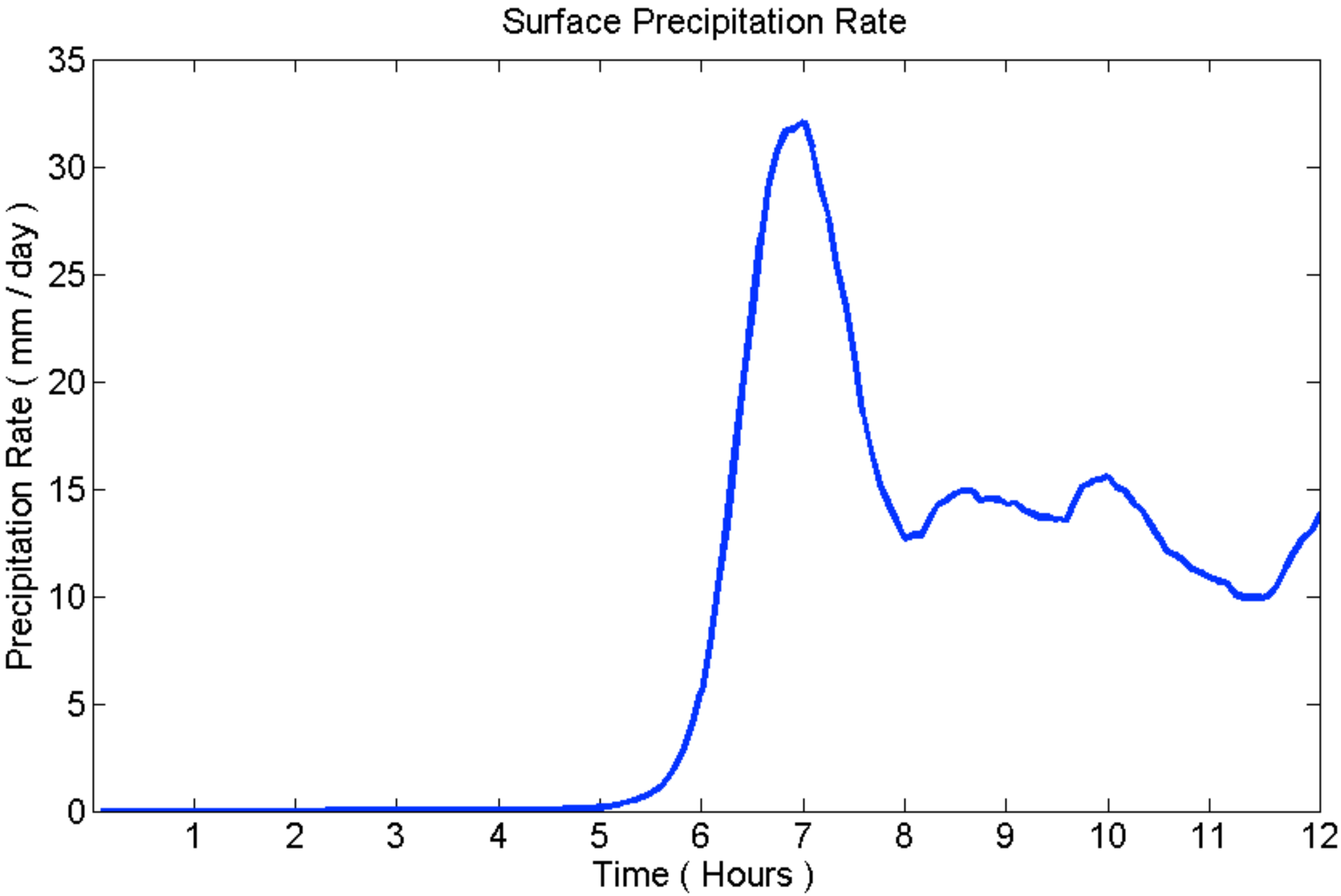


CWP at t = 7 hours

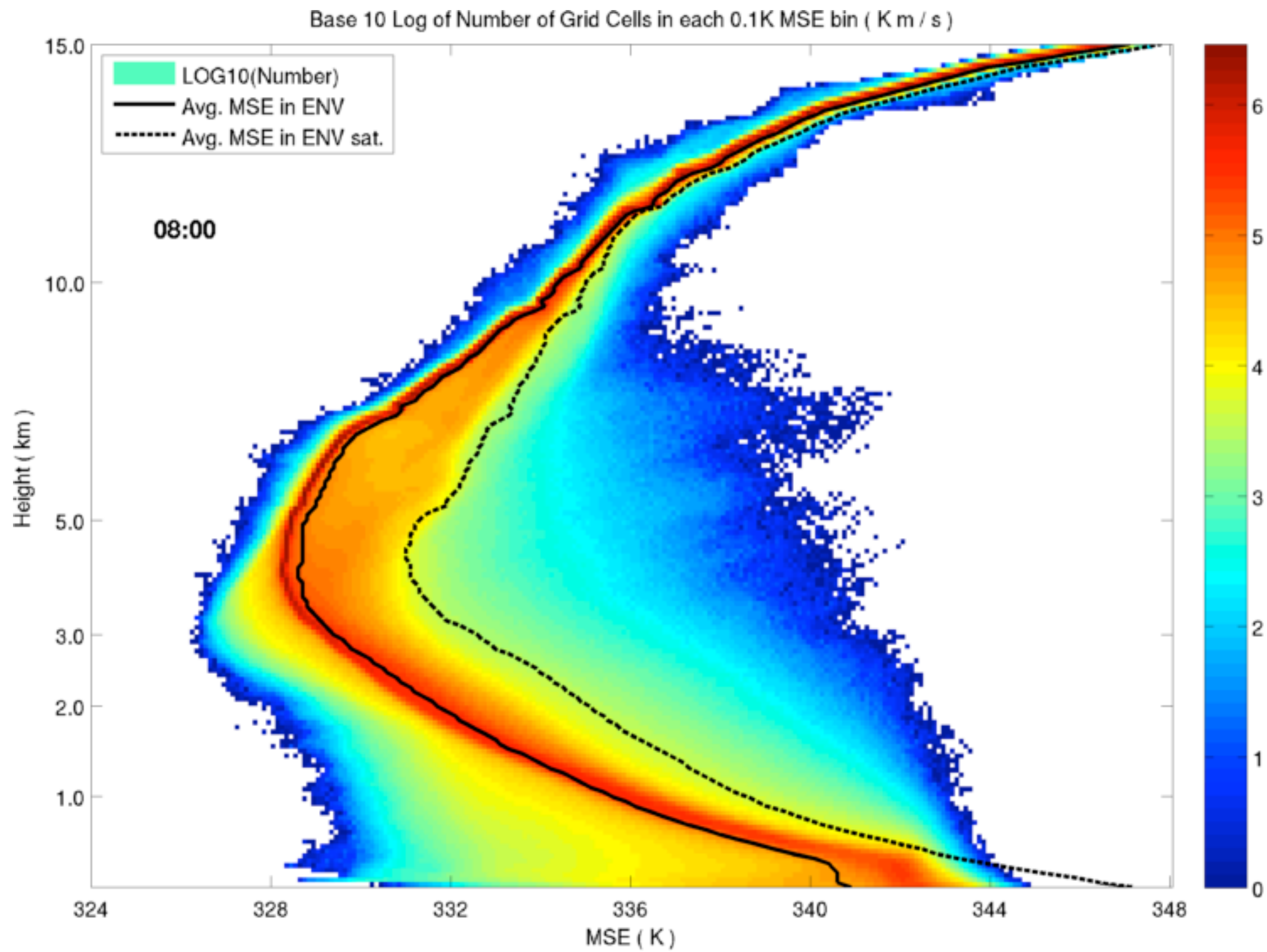
Deep Convection



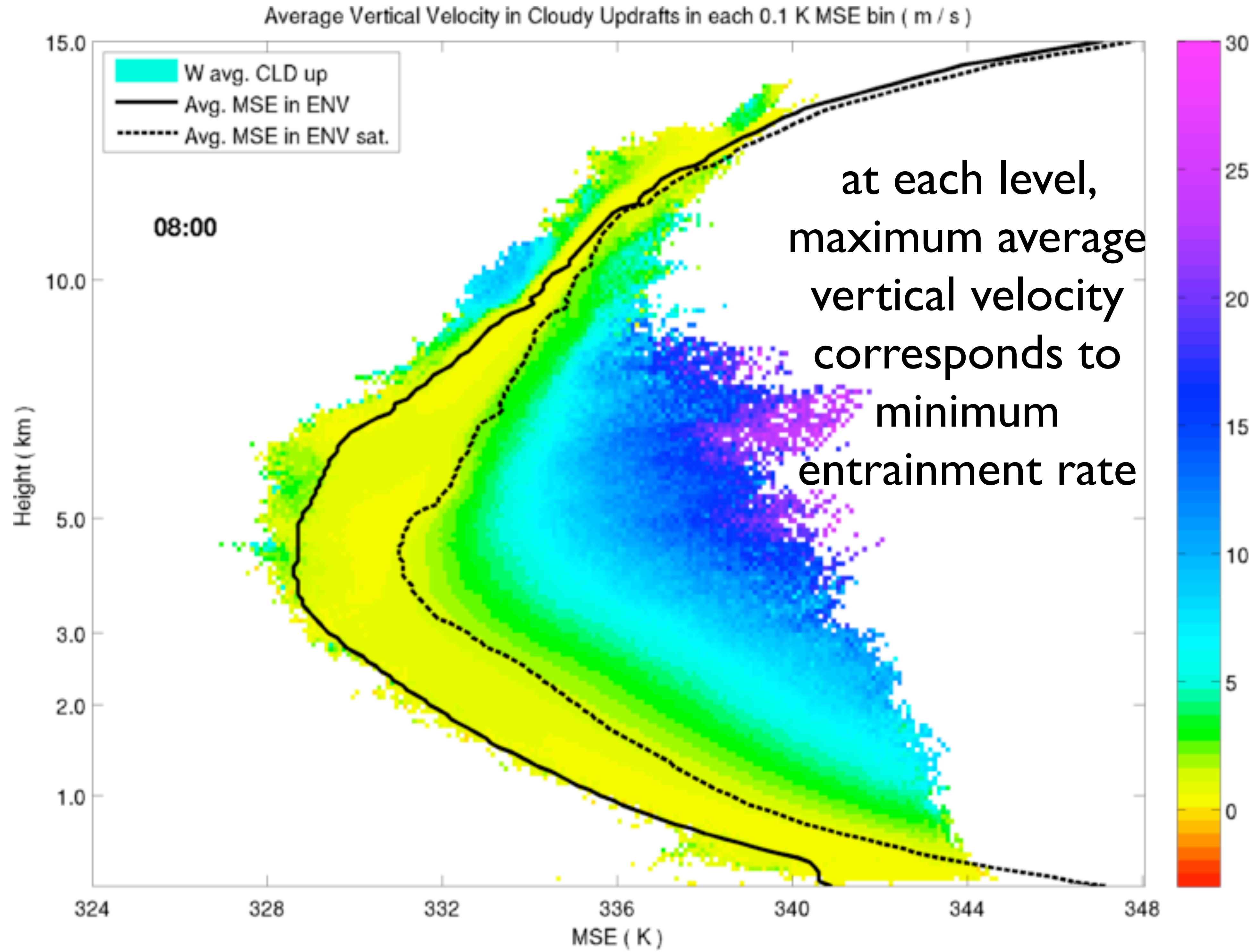
CWP at t = 12 hours


Surface Precipitation Rate
Precipitation Rate (mm / day)
35
30
25
20
15
10
5
0
1
2
3
4
5
6
7
8
9
10
11
12
Time (Hours)

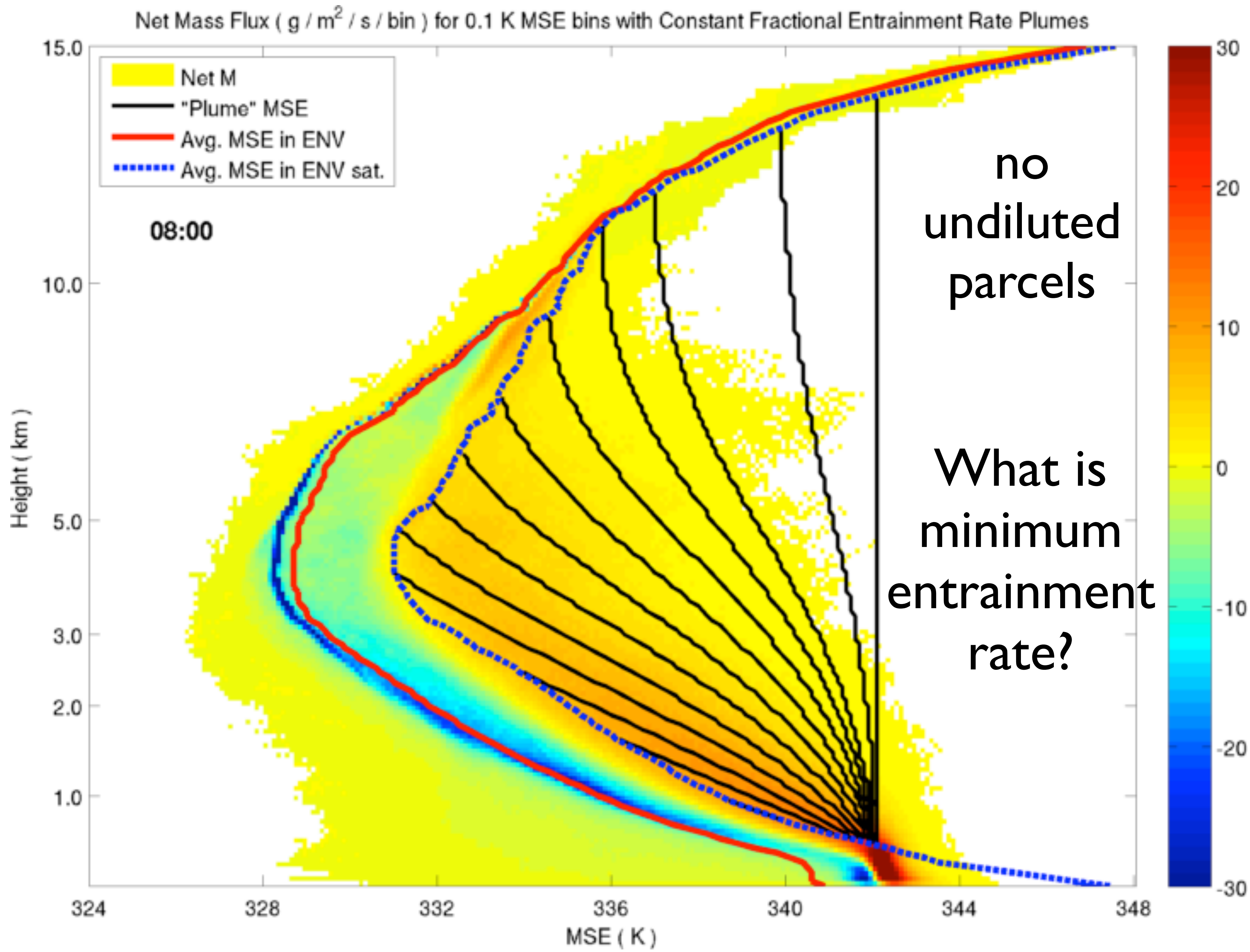
MSE Histogram



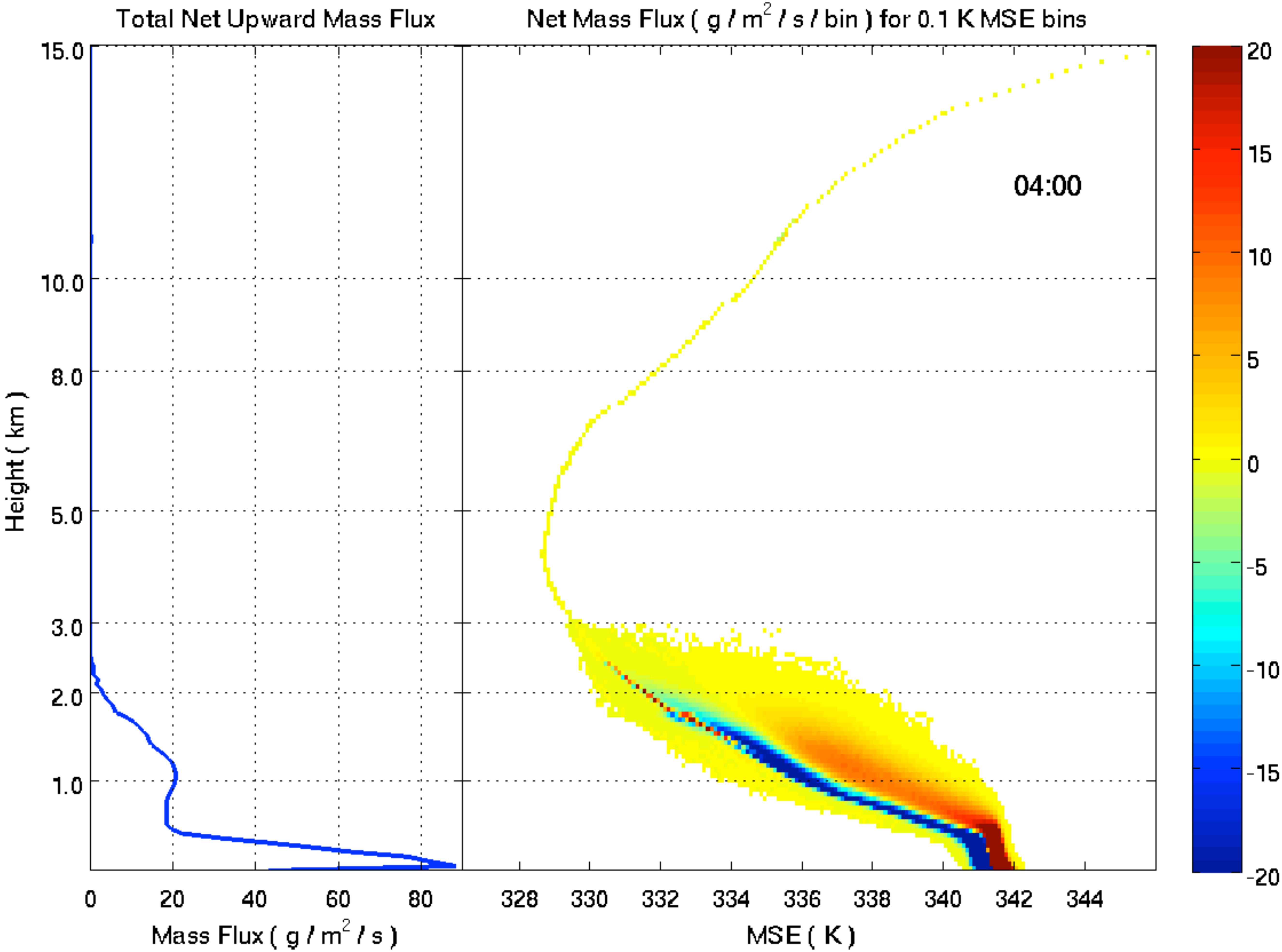
Average Vertical Velocity in Cloudy Updrafts



Mass Flux Spectrum

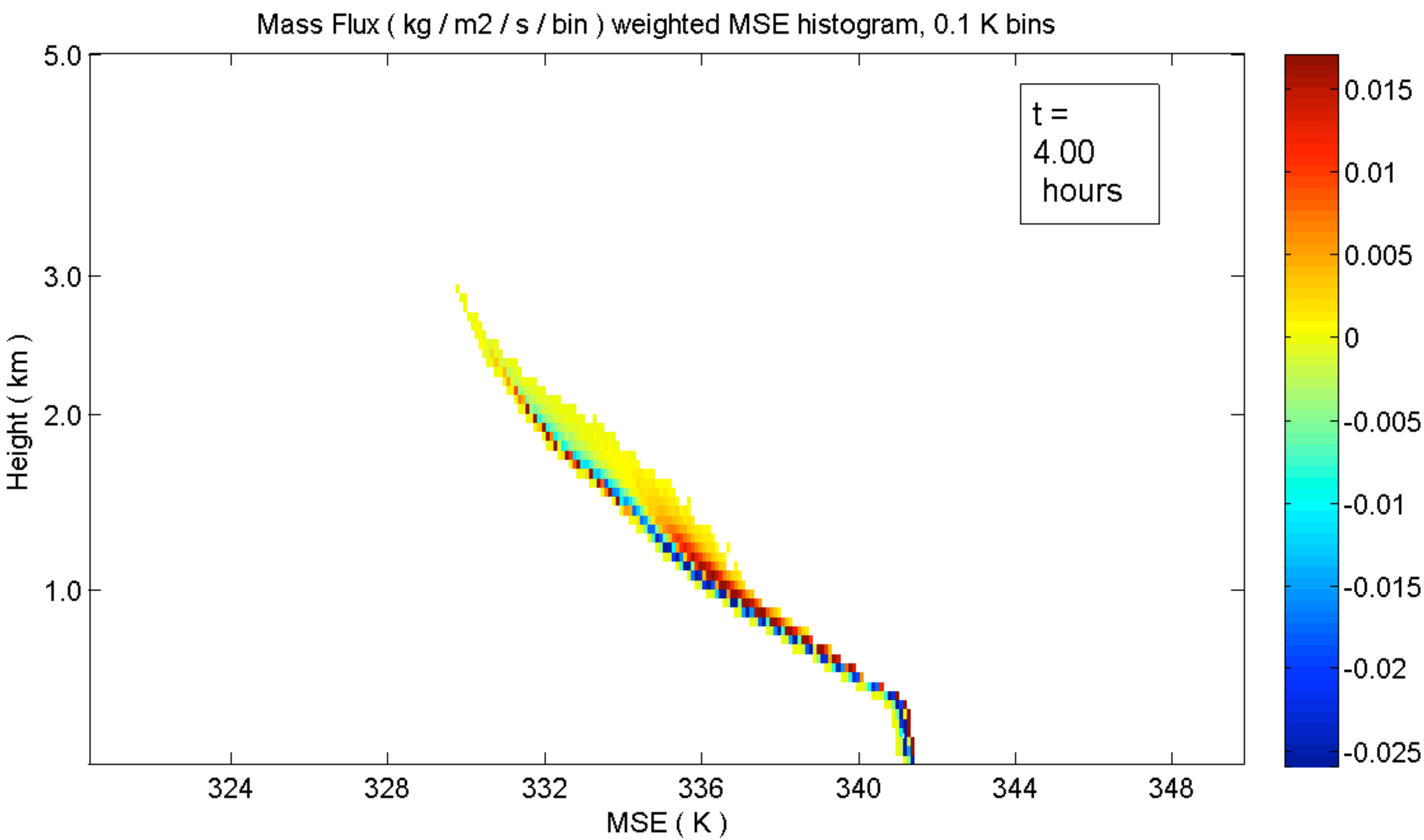


with MSE profiles for several fractional entrainment rates

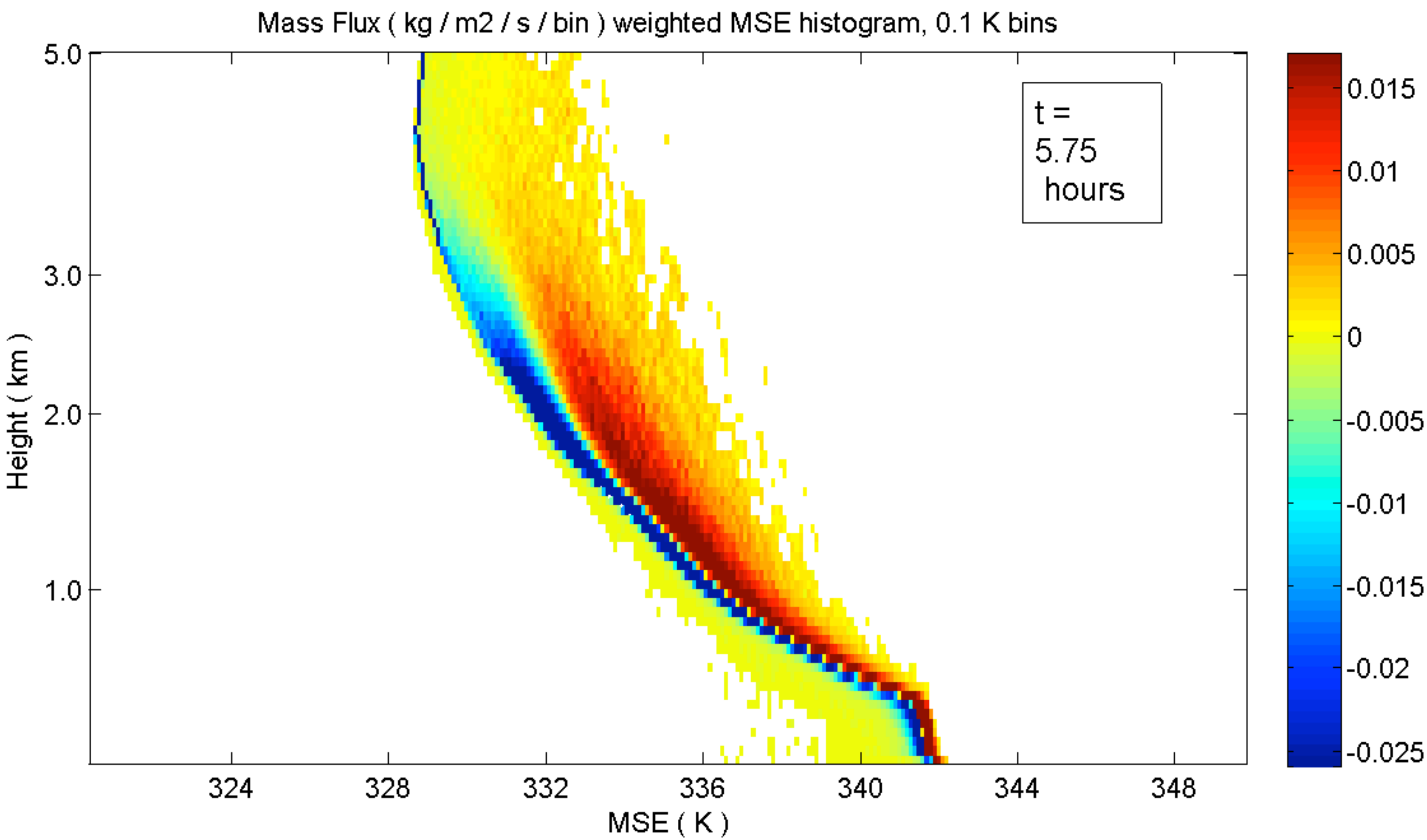


Total Net Upward Mass Flux
Net Mass Flux (g / m² / s / bin) for 0.1 K MSE bins
Height (km)
15.0
10.0
8.0
5.0
3.0
2.0
1.0
0
20
40
60
80
Mass Flux (g / m² / s)
328
330
332
334
336
338
340
342
344
MSE (K)
04:00
20
15
10
5
0
-5
-10
-15
-20

Shallow Convection

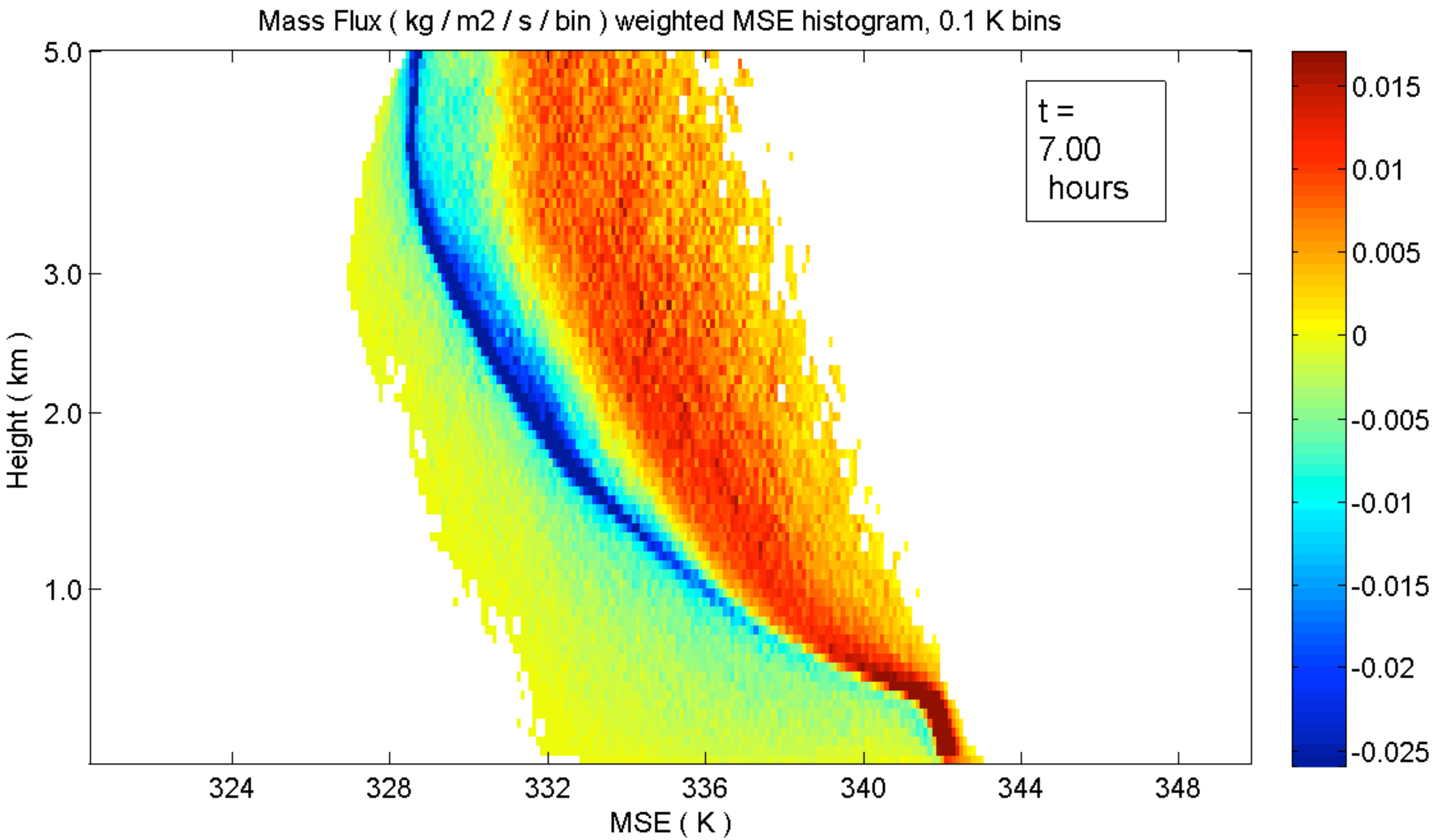


Congestus

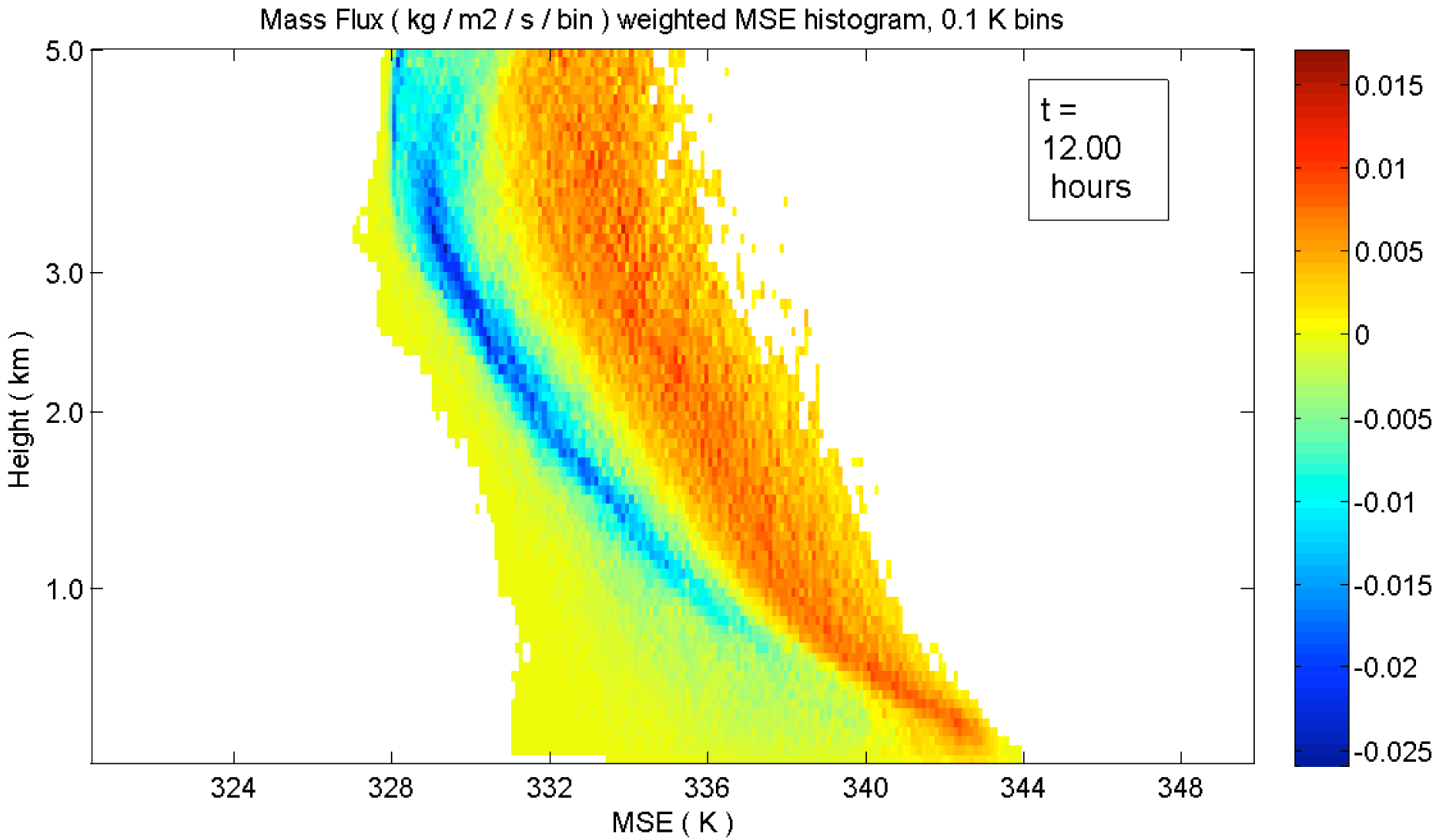


Mass Flux (kg / m2 / s / bin) weighted MSE histogram, 0.1 K bins
t =
5.75
hours
Height (km)
5.0
3.0
2.0
1.0
324
328
332
336
340
344
348
MSE (K)
0.015
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025

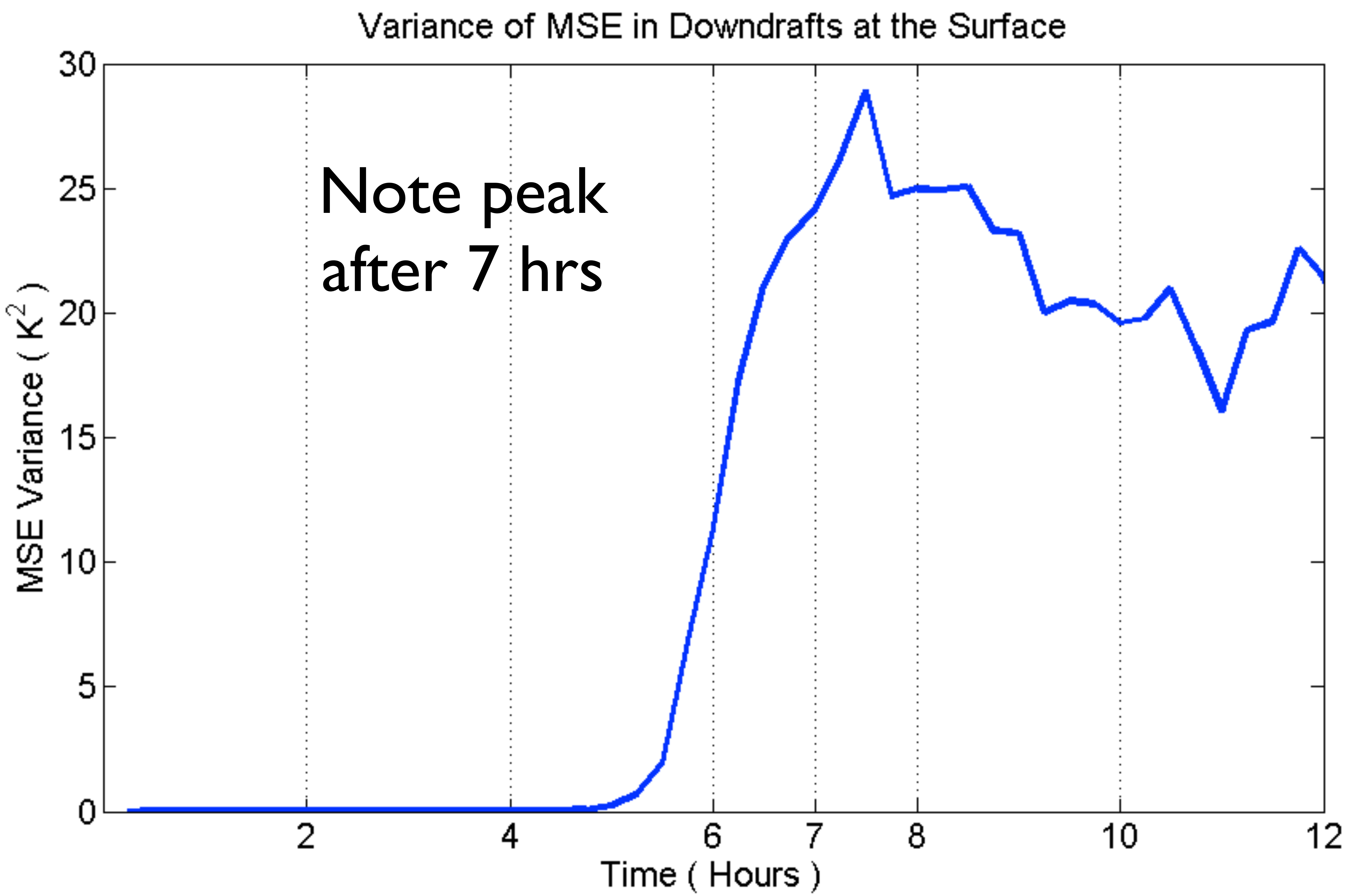
Vigorous Transition



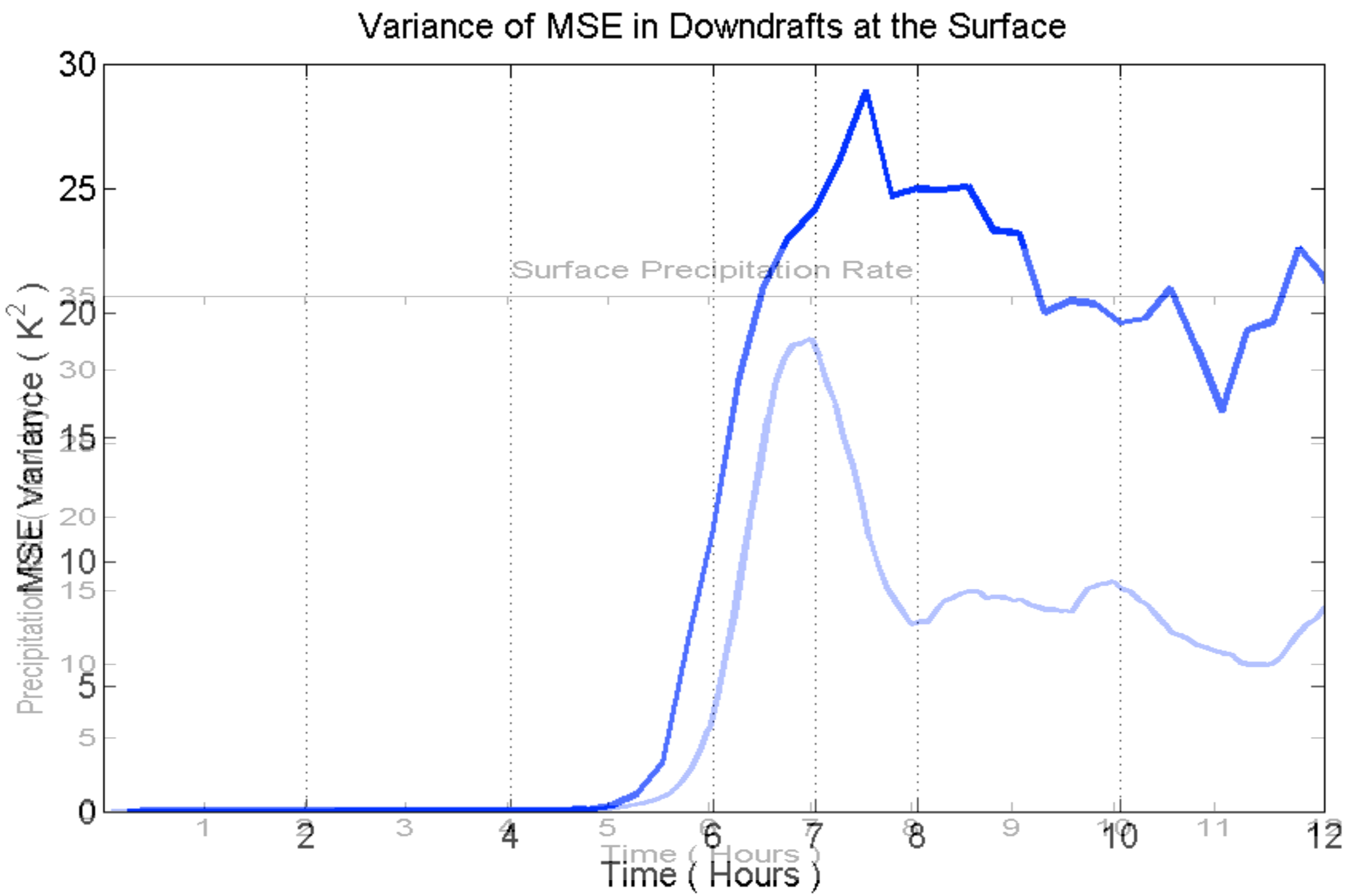
Deep Convection



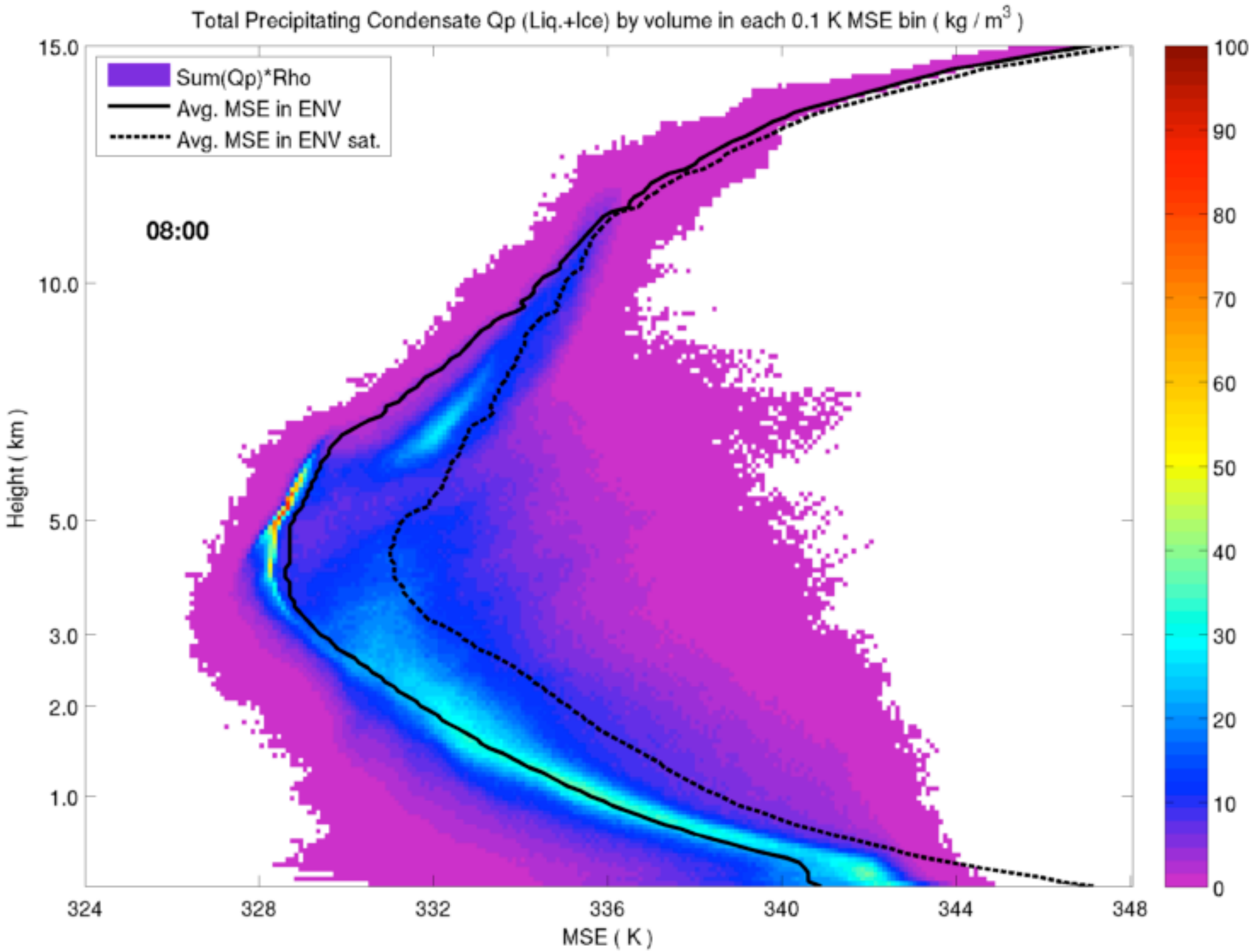
Downdraft MSE Variance at SFC

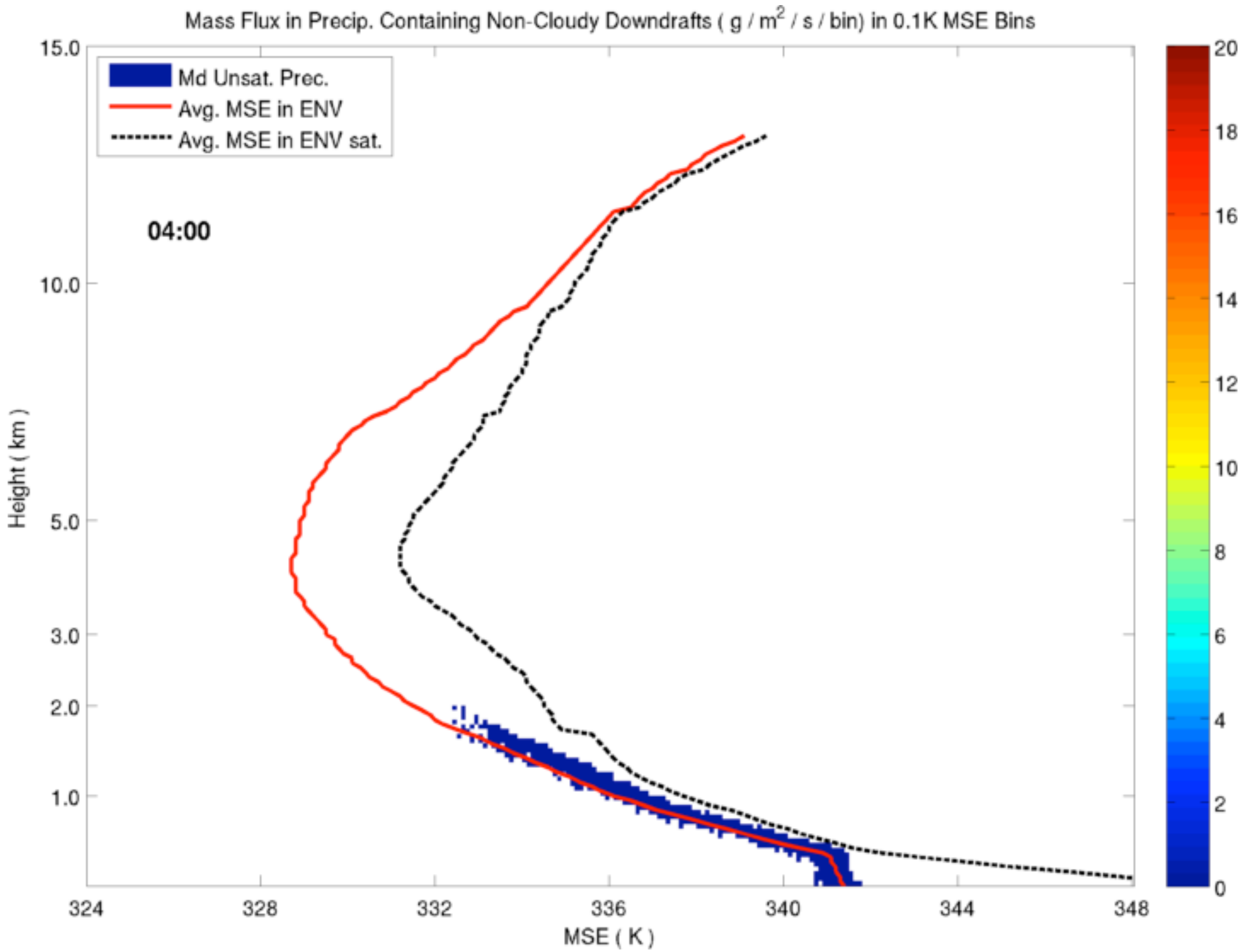


MSE variance (downdrafts) leads precip by ~20 min



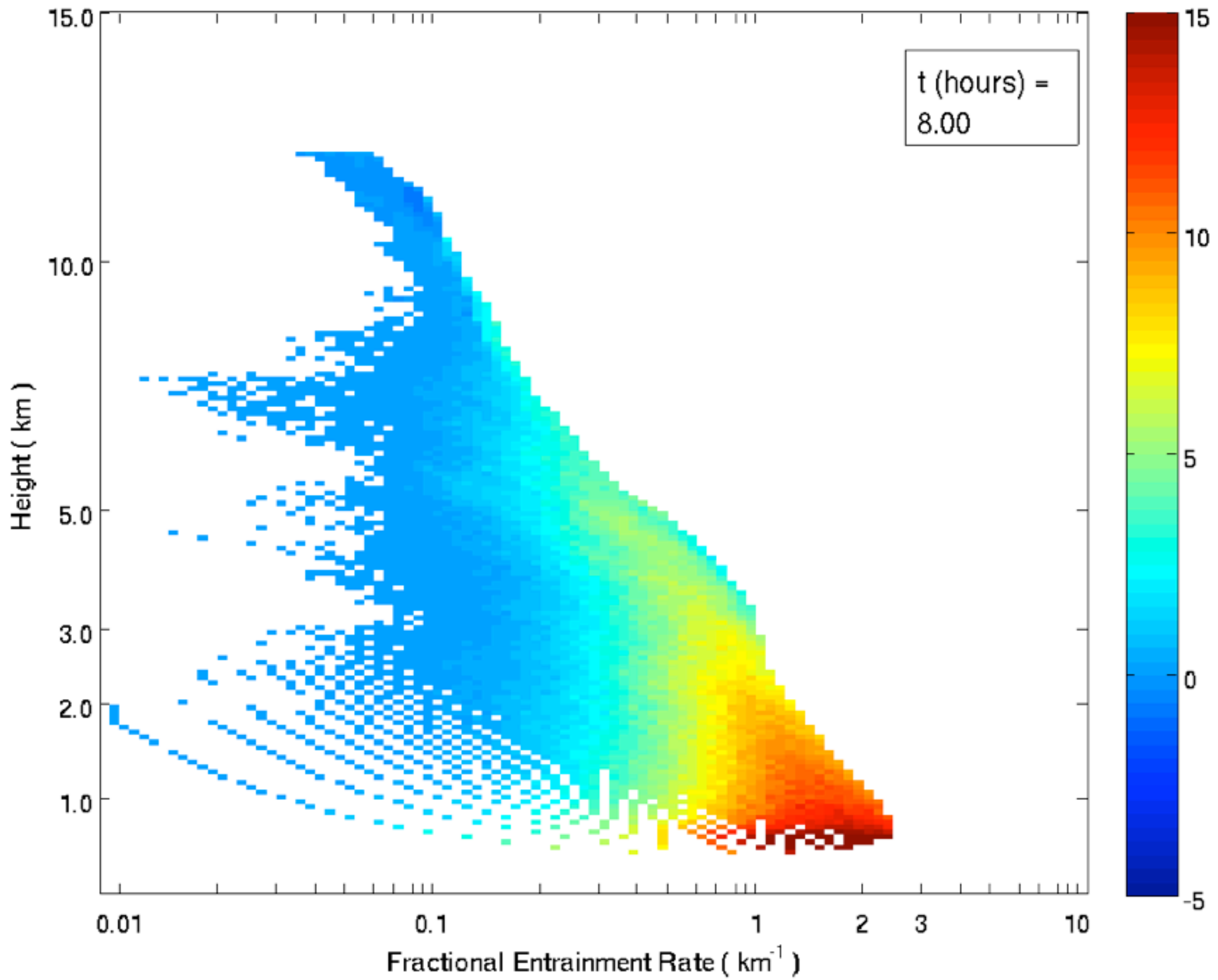
Precipitating Condensate Spectrum

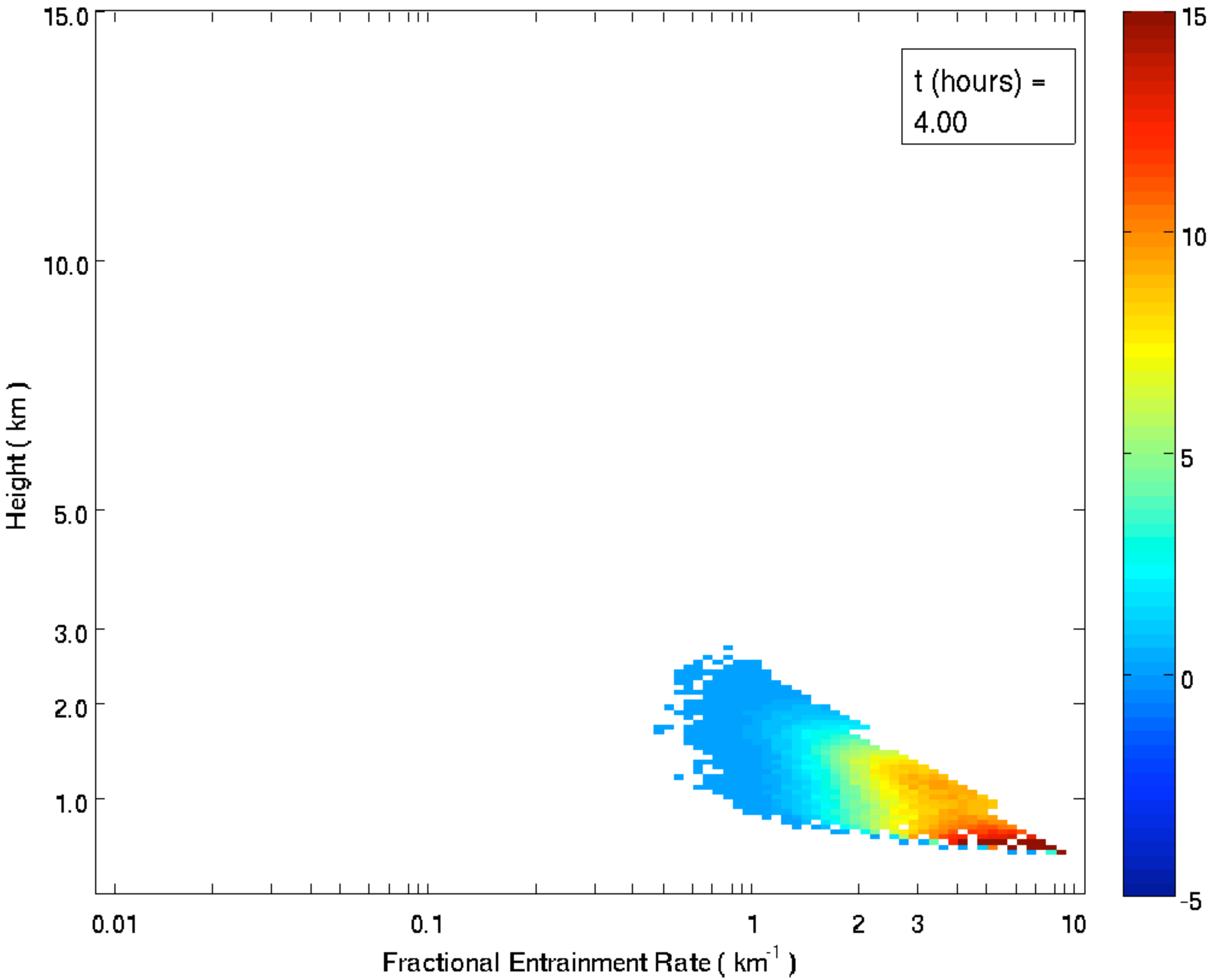




Mass Flux in Precip. Containing Non-Cloudy Downdrafts (g / m2 / s / bin) in 0.1K MSE Bins
Md Unsat. Prec.
Avg. MSE in ENV
Avg. MSE in ENV sat.
04:00
Height (km)
15.0
10.0
5.0
3.0
2.0
1.0
324
328
332
336
340
344
348
MSE (K)
20
18
16
14
12
10
8
6
4
2
0

Mass Flux Spectrum vs Fractional Entrainment Rate





t (hours) =
4.00
Height (km)
15.0
10.0
5.0
3.0
2.0
1.0
0.01
0.1
1
2
3
10
Fractional Entrainment Rate (km^{-1})
15
10
5
0
-5

Important Physical Processes

- Boundary layer turbulence
- Shallow cumulus convection
- Precipitation formation
- Entrainment in cumulus clouds
- Downdrafts and cold pools

Implications for Modeling

- Requires large-eddy simulations of deep convection:
  - High-resolution (~ 100 m grid size)
  - Large domain
- These are very expensive simulations.
- They are also challenging to analyze due to the volume of output.

Implications for Modeling

- CMMAP will perform a new Giga-LES of continental convection based on ARM data.
- CMMAP will make the results immediately available to the ASR community.