Course Goals

- Expose students to nitty-gritty of cloud modeling: build a basic, 2D model.
- Learn techniques of model development: Build from simple to complex. Testing.
- Learn theoretical approaches to studying convection: simple models with analytics solutions to 3D CRMs.

- Learn about global (statistical) convection and how it is represented in large-scale models (e.g., cumulus parameterization).

- Learn how the physical processes that are important for deep, moist convection are represented in CRMs.

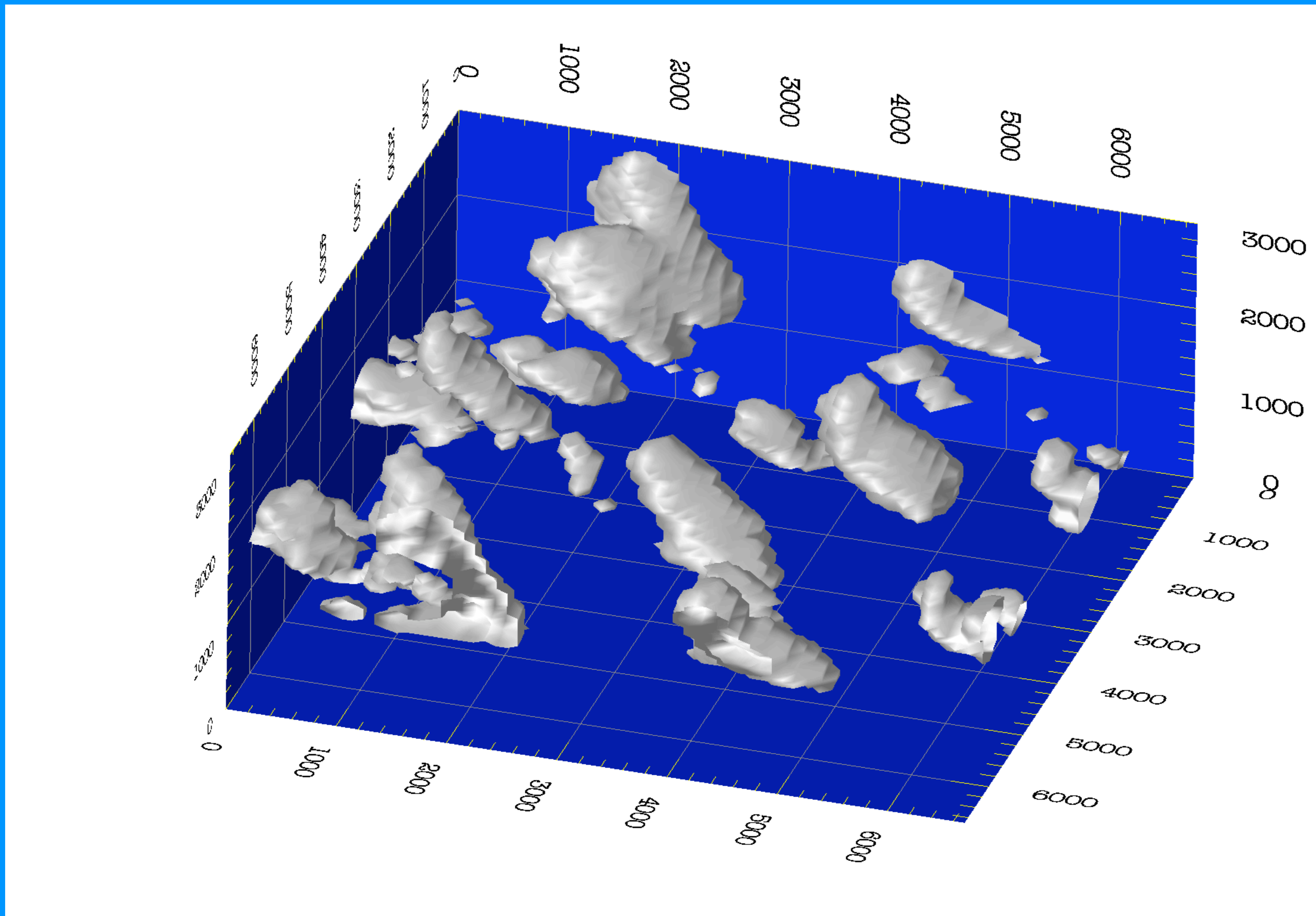
time-lapse movie of cumulus development


Mt Lemmon
09:01:00 Fri Aug 16 2002

Cloud-Resolving Model

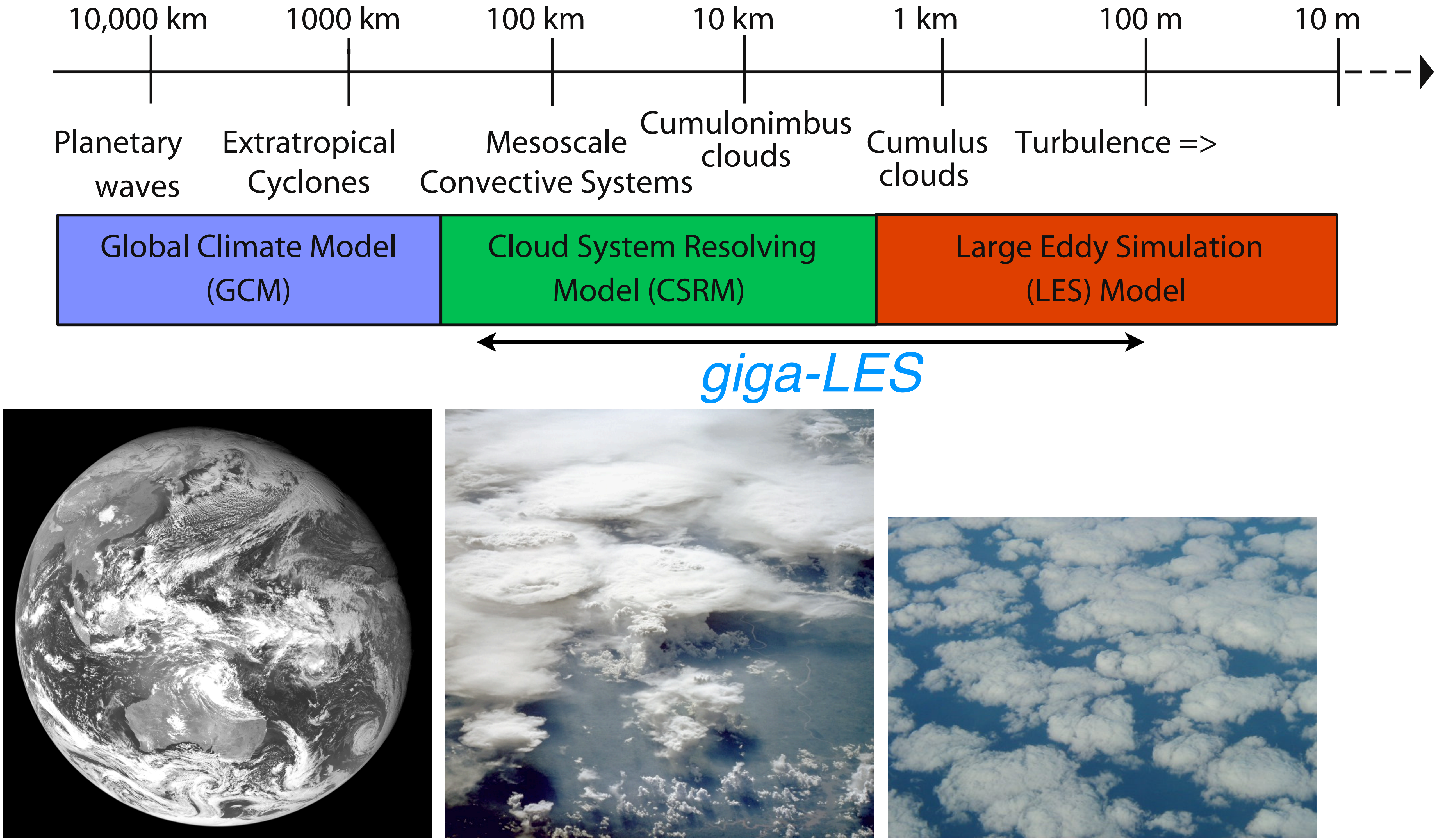
- A 2D or 3D non-hydrostatic numerical model that resolves individual cloud-scale circulations.
- It includes representations of:
  - moist thermodynamics
  - cloud and precipitation microphysics
  - radiative transfer
  - unresolved turbulence
  - surface fluxes

Isosurface of cloud water: 0.001 (g/kg)

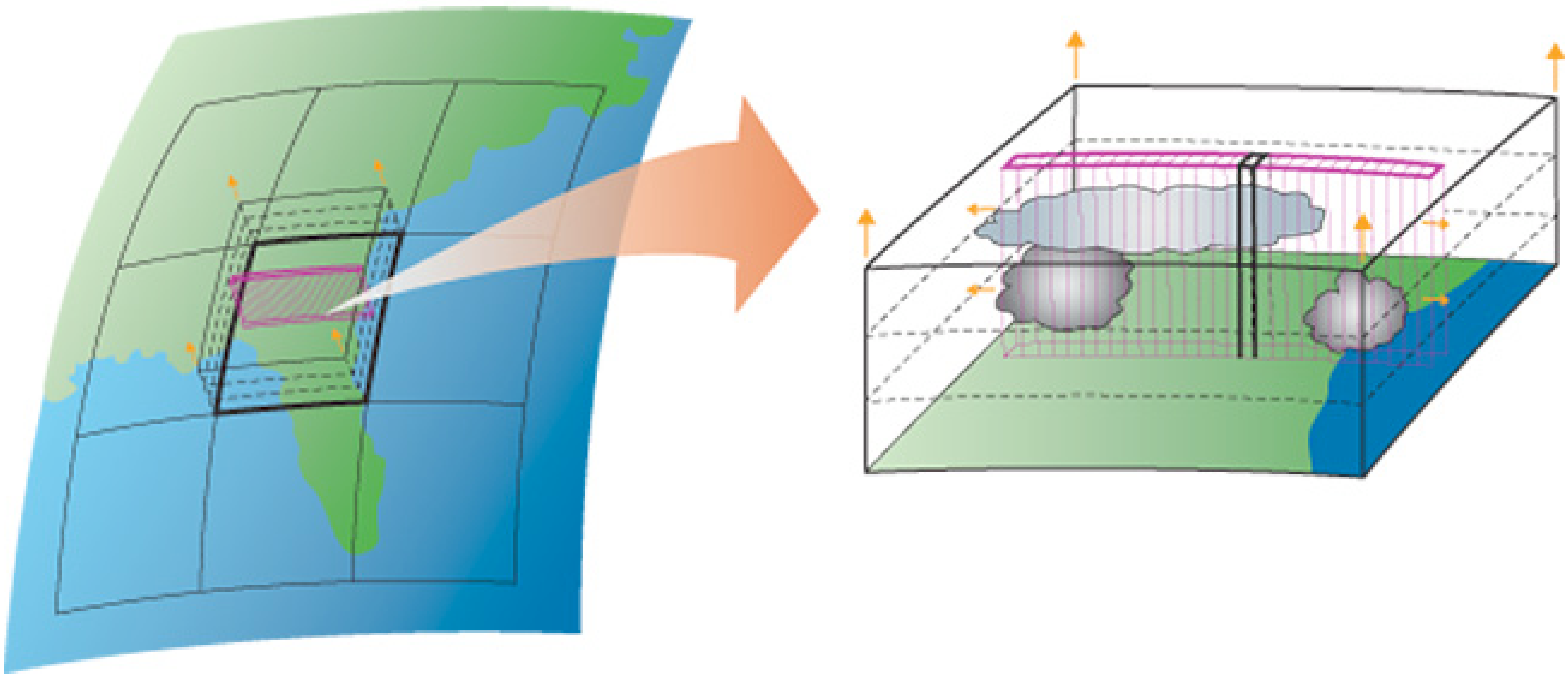


(courtesy of W. R. Cotton & J.-C. Golaz)

Scales of Atmospheric Motion



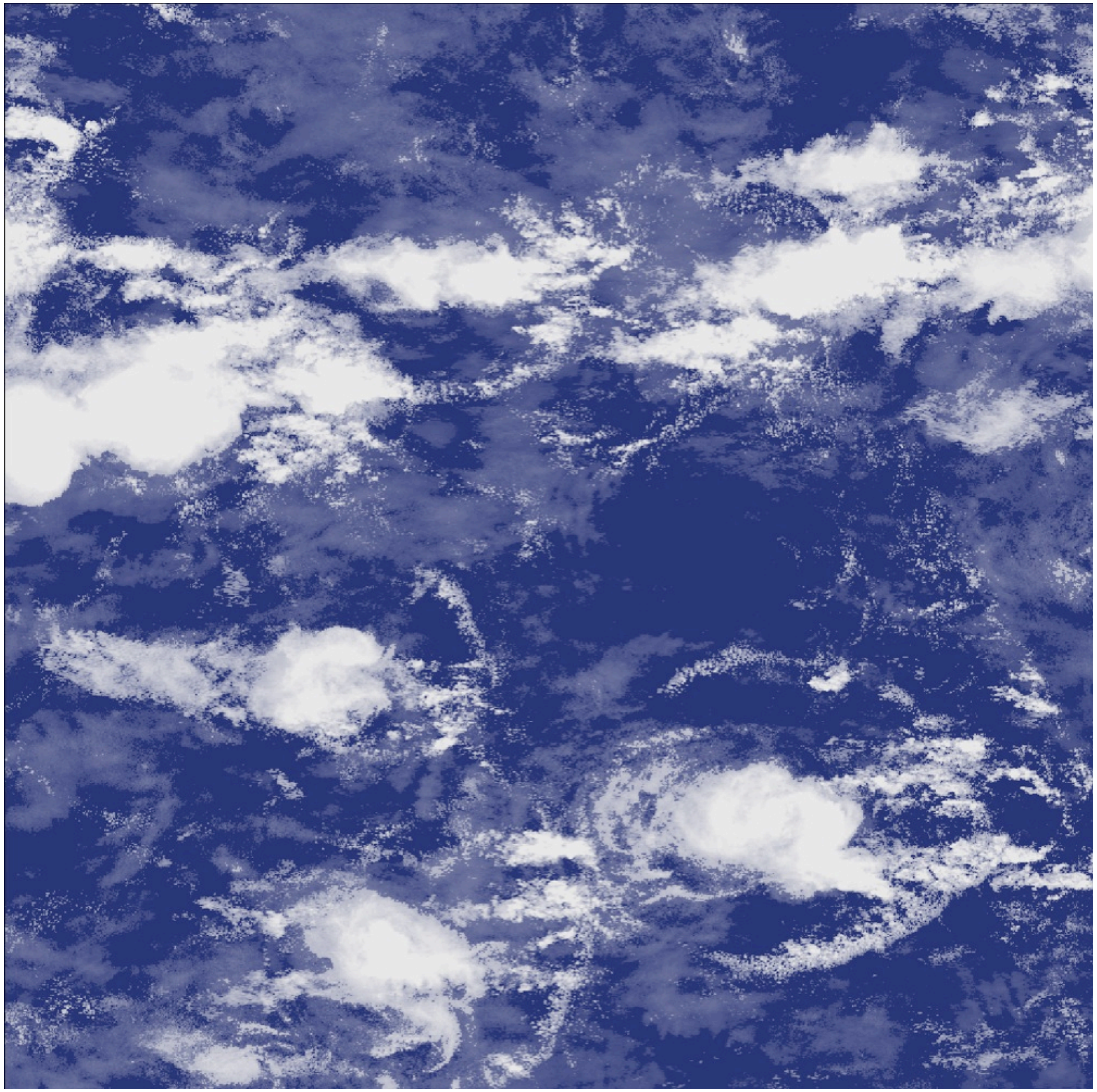
Multiscale Modeling Framework (MMF)

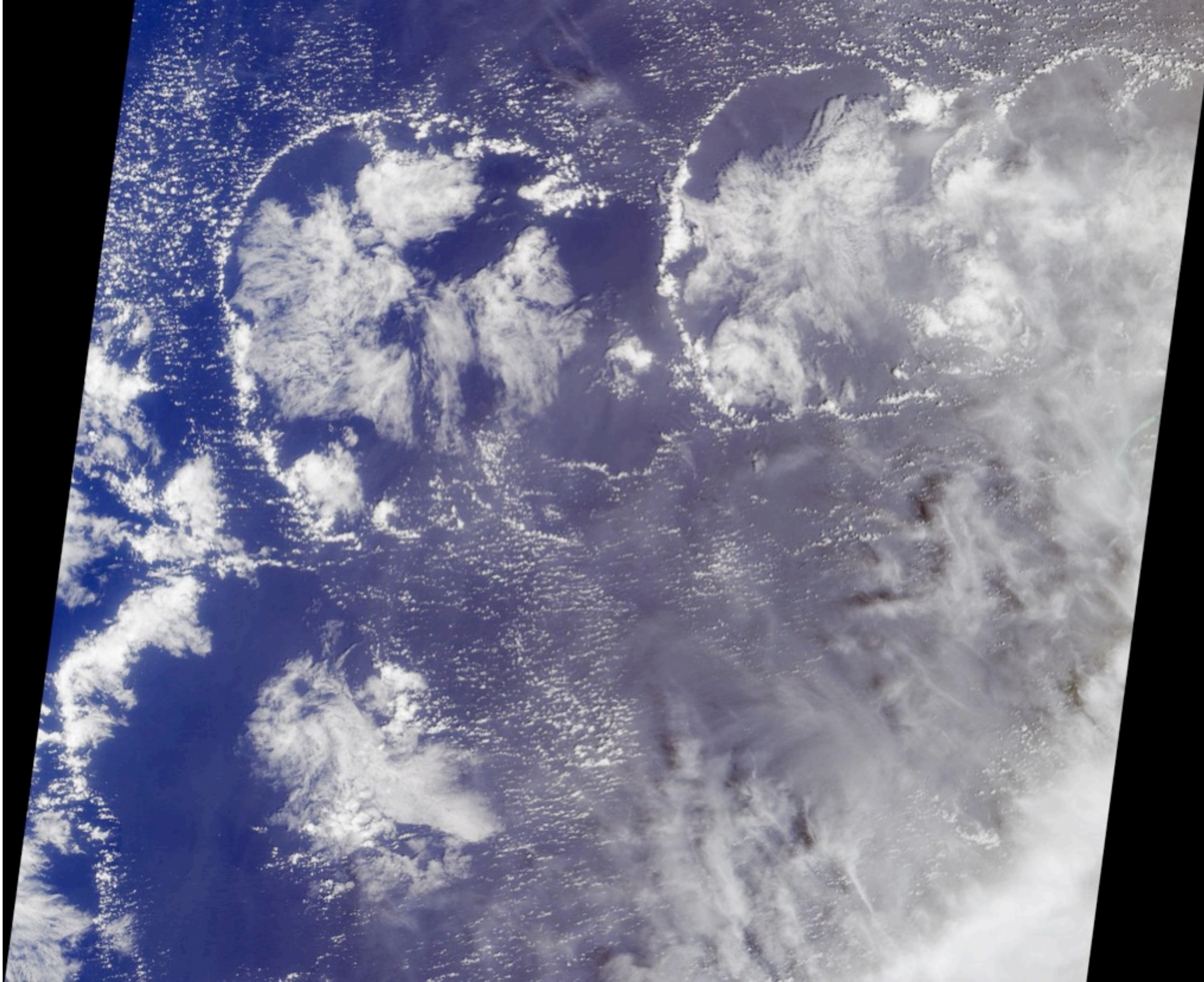


Giga-LES of deep convection

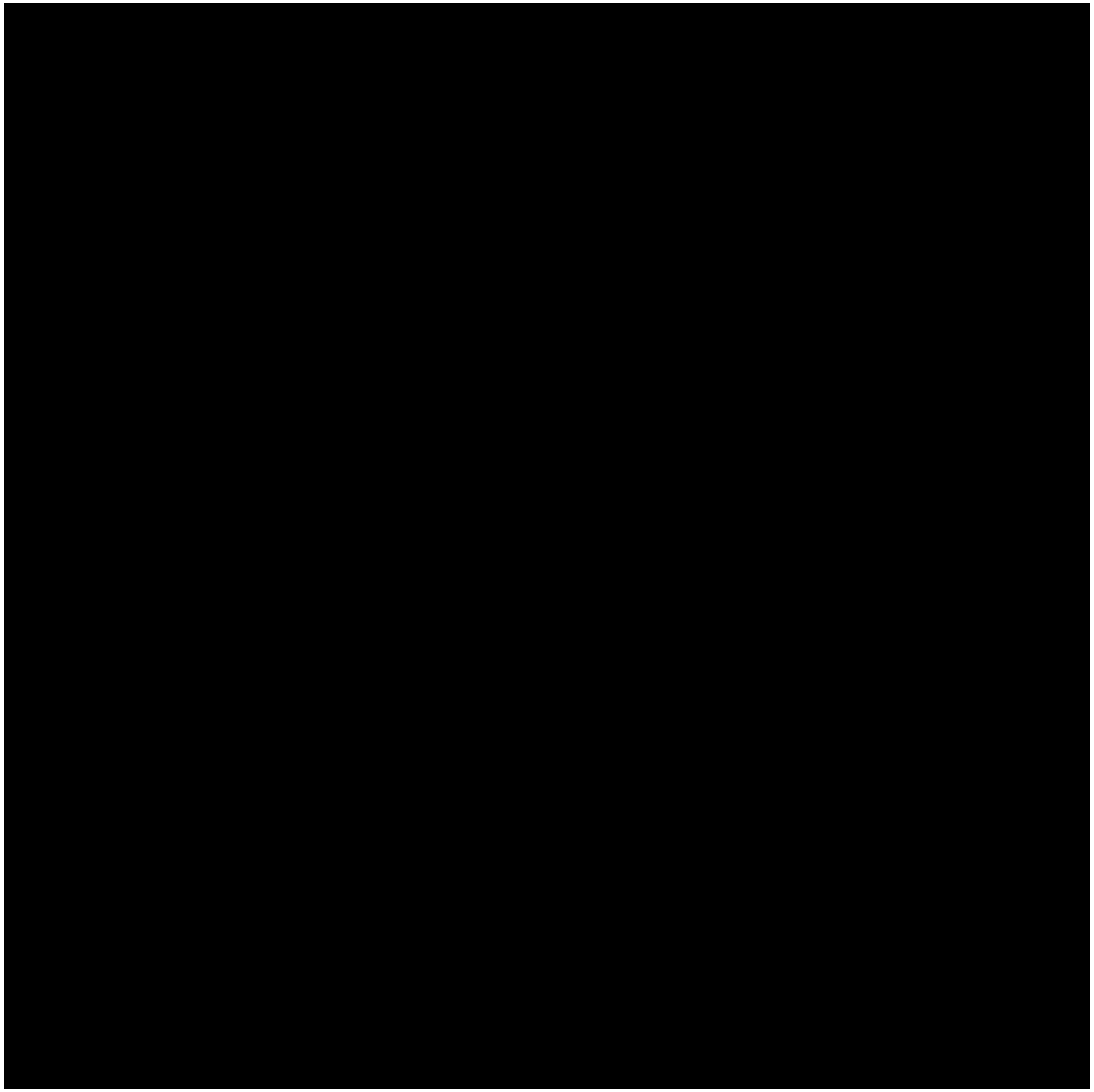
- Goal is to simultaneously simulate boundary layer turbulence, shallow convection, deep convection, and mesoscale convective systems to provide a benchmark for evaluation of coarser-grid simulations.
- Idealized GATE (tropical ocean) simulation with shear.
- Used a CSRM (SAM) with 2048 x 2048 x 256 (10^9) grid points and 100-m grid size for a 24-h LES.
- Equivalent to 1024 6.4-km x 6.4-km LESs.

LES “visible image” 180 km x 180 km

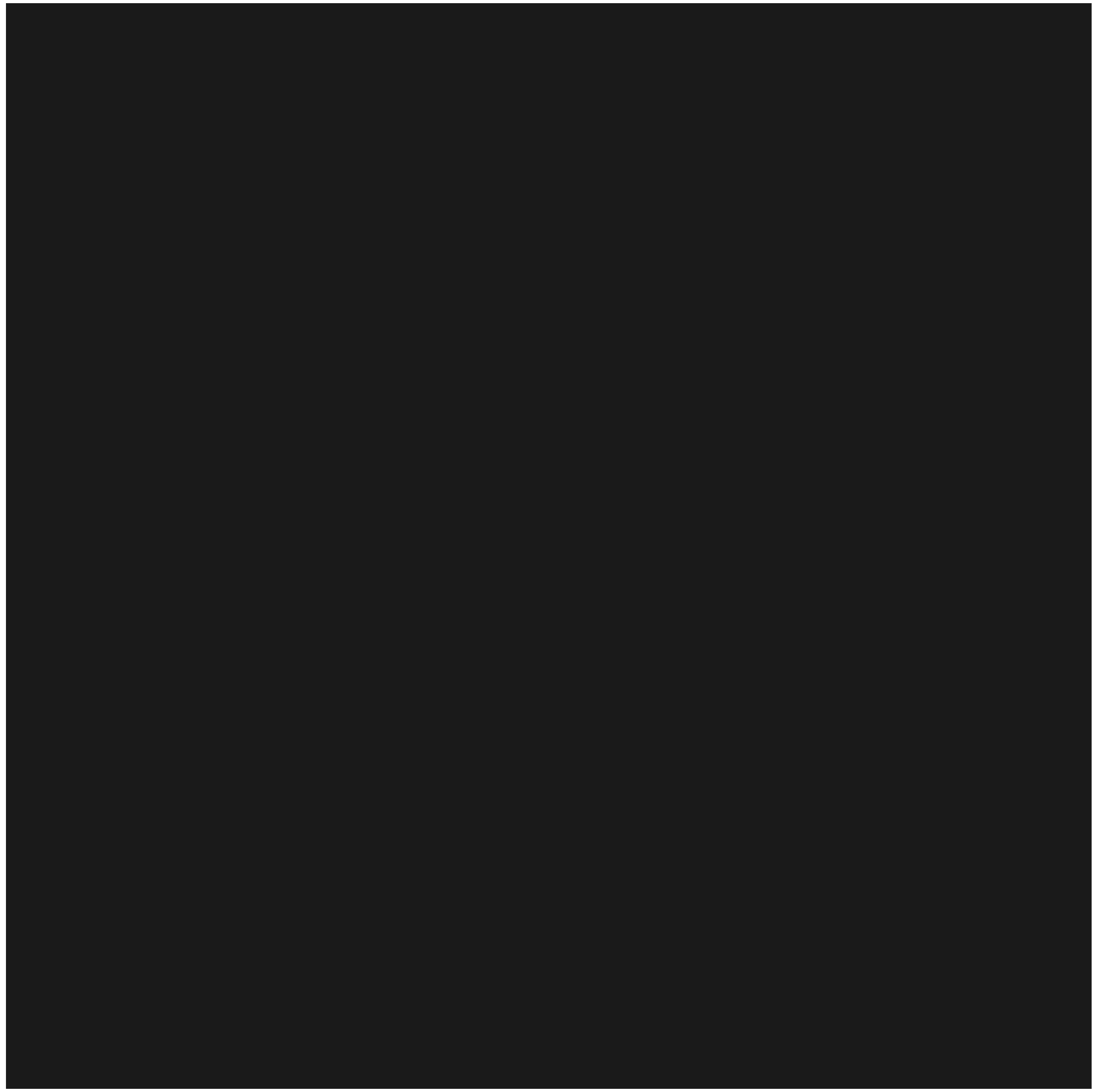




Cloud Water Path (vertical integral)



Ice Water Path (vertical integral)



Water Vapor Mixing Ratio at surface

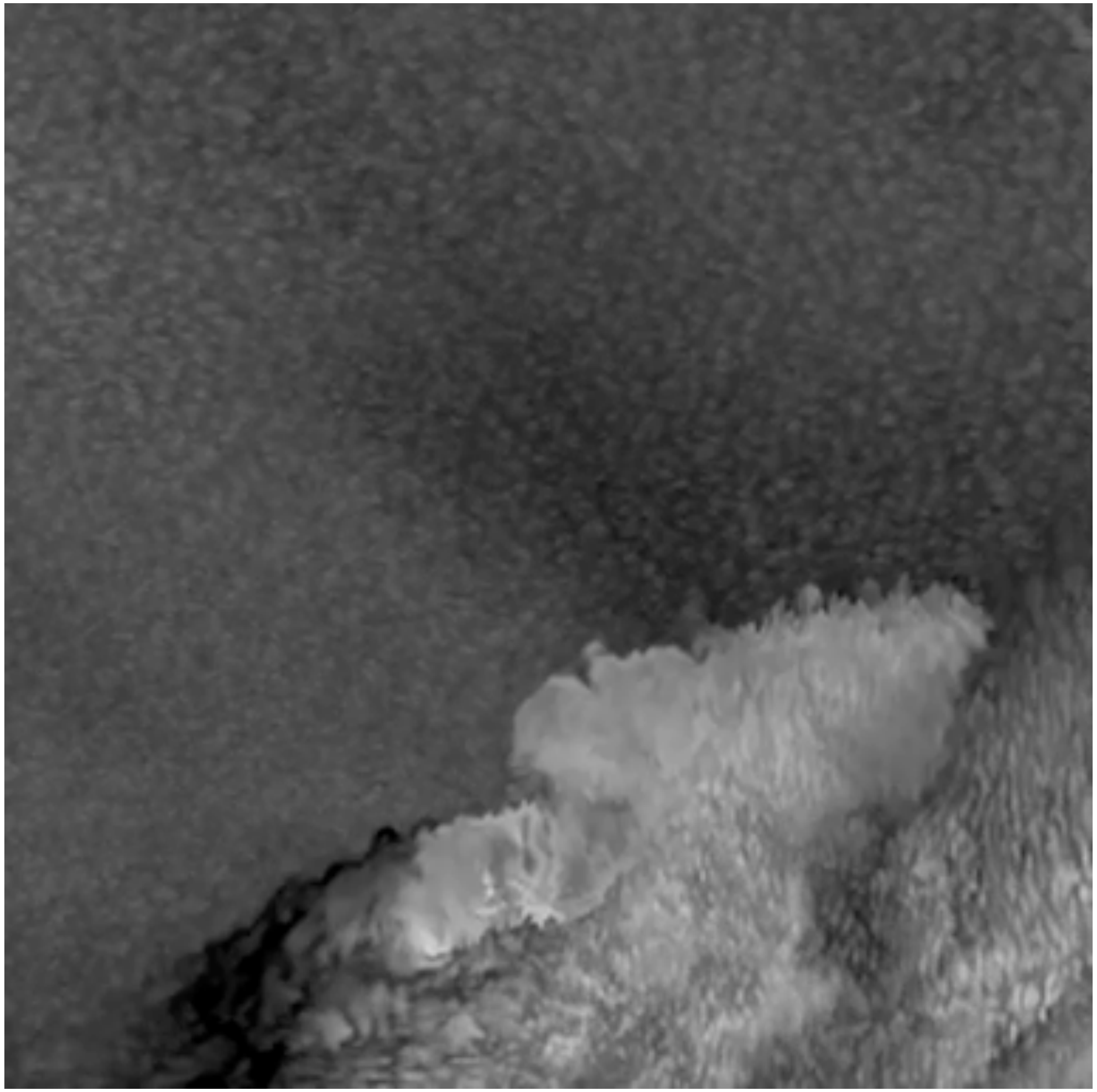
zoom into 50 km by 50 km

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

Waterspouts?

- Several vortices of waterspout strength occurred.
- These vortices would presumably become waterspouts with higher resolution.
- Preferred location is along gust fronts which produce low-level vorticity.
- This vorticity is amplified by stretching due to low-level convergence.

surface water vapor
25.6 x 25.6 km, 50 minutes duration



JOURNAL OF THE ATMOSPHERIC SCIENCES

Cumulonimbus Vertical Velocity Events in GATE. Part I: Diameter, Intensity and Mass Flux

MARGARET A. LEMONE AND EDWARD J. ZIPSER

National Center for Atmospheric Research,[1] *Boulder, CO 80307*

(Manuscript received 21 March 1980, in final form 18 July 1980)

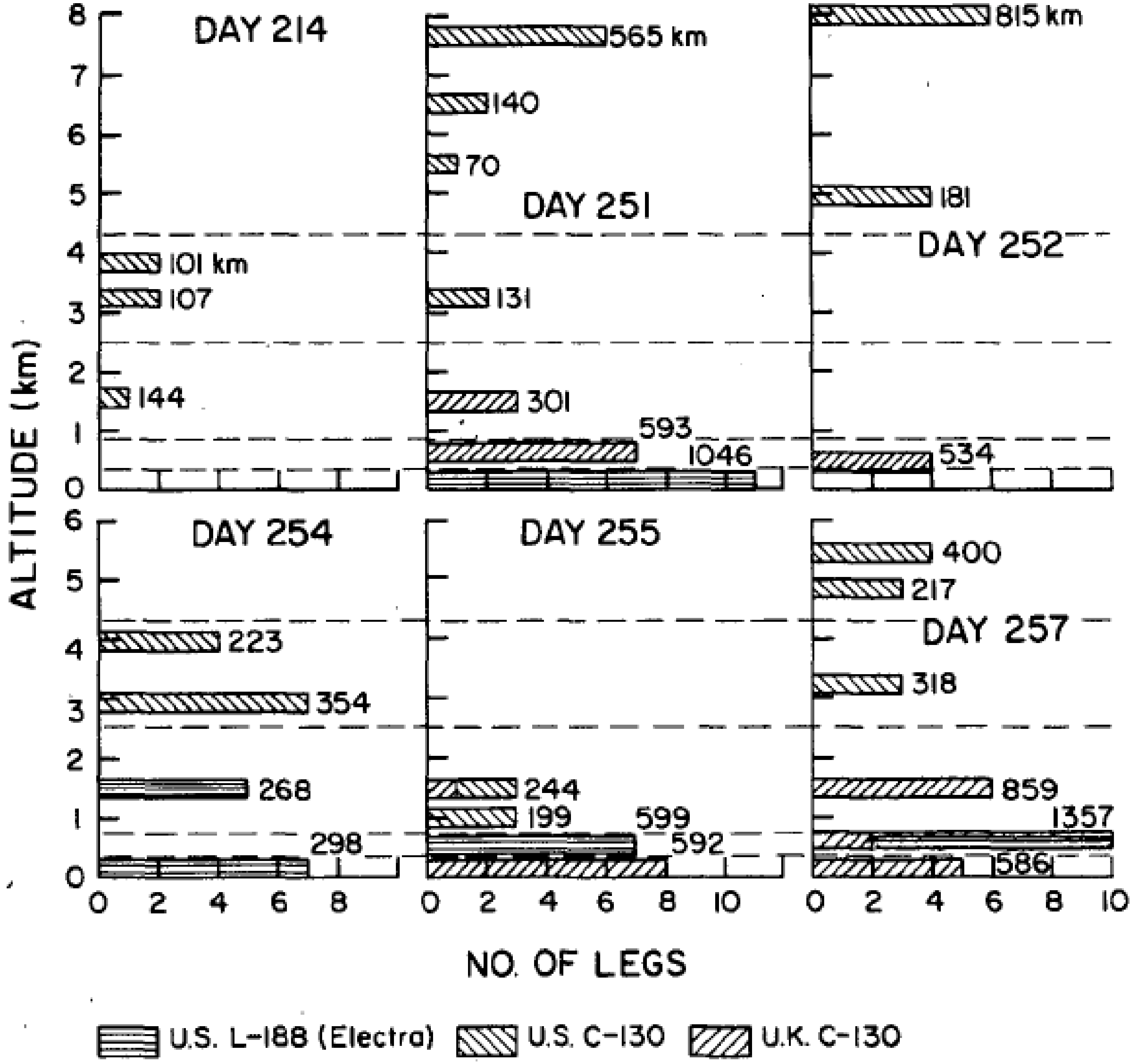


FIG. 1. Summary of aircraft data used in this study. Numbers to the right of bar graphs indicate total length of legs used in kilometers for each day and for each altitude. Dashed lines denote altitude class intervals used in the analysis.

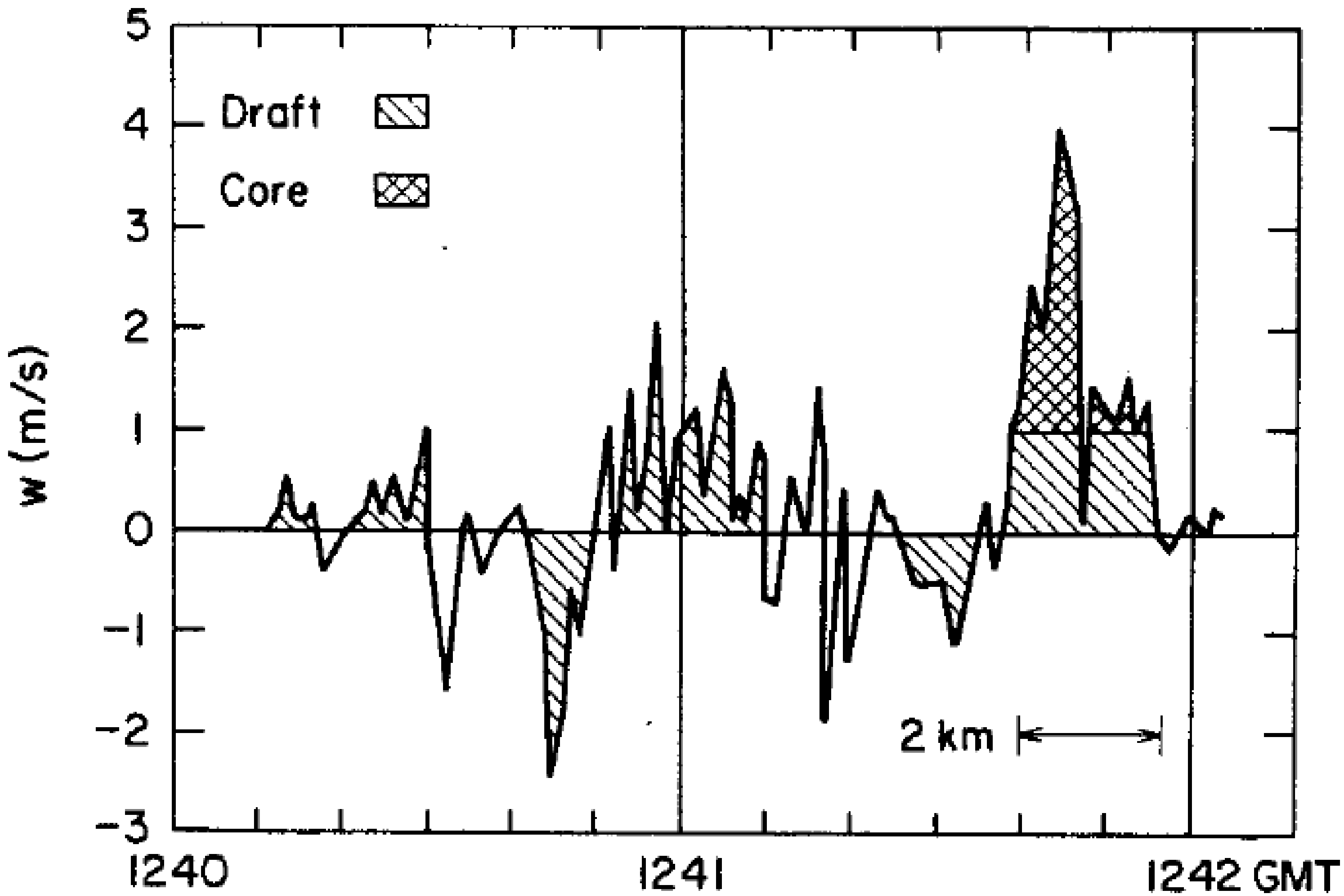
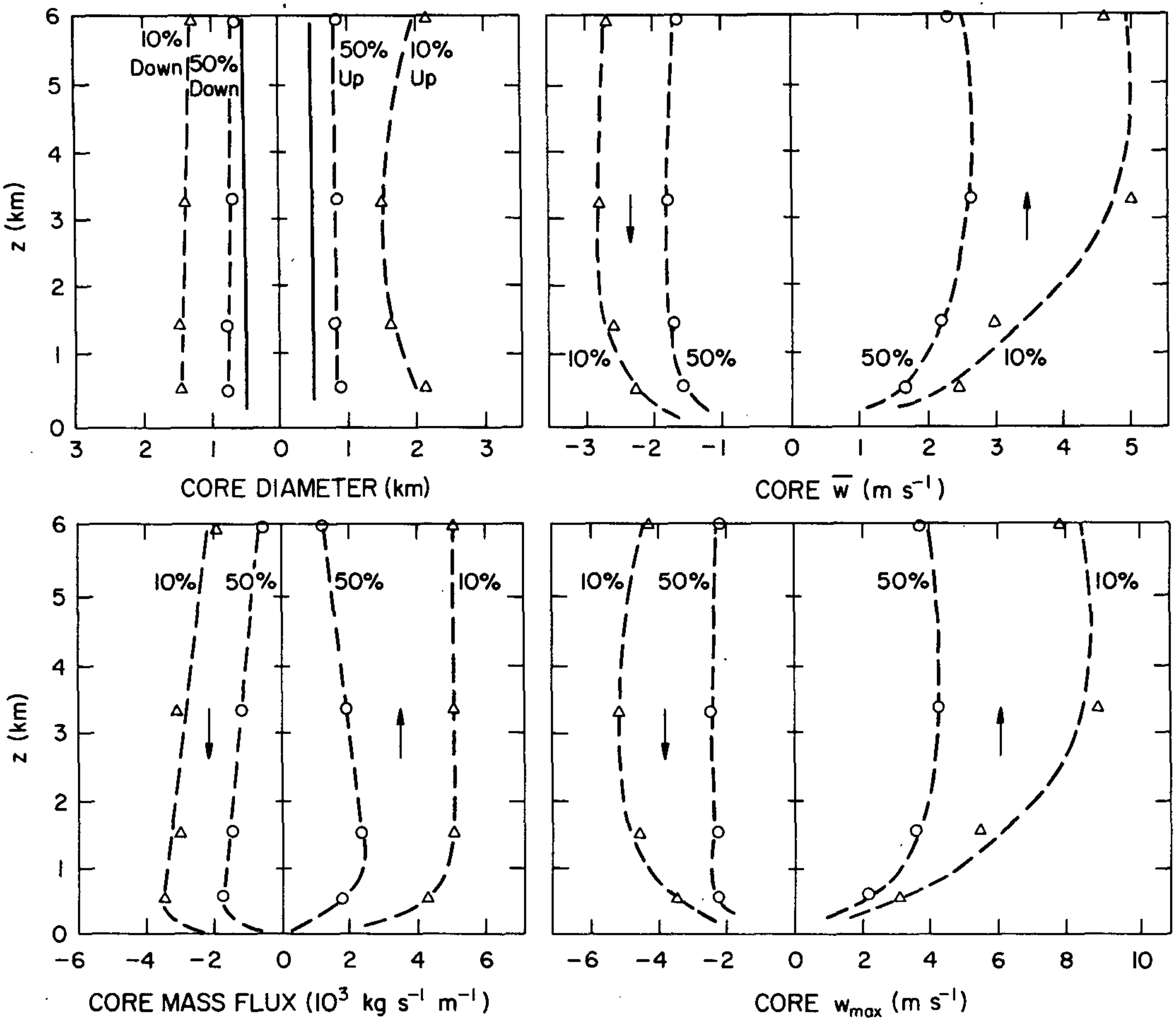


FIG. 2. Time series illustrating definition of drafts and cores, adapted from US C-130 at 5471 m, Day 257. An updraft has to reach 0.5 m s^{-1} and be positive for 0.5 km (~5 s) or more; a core has to have w of at least 1 m s^{-1} for 0.5 km or more. Downdrafts and downdraft cores are defined in the same way. Note that the draft at the right has two cores.

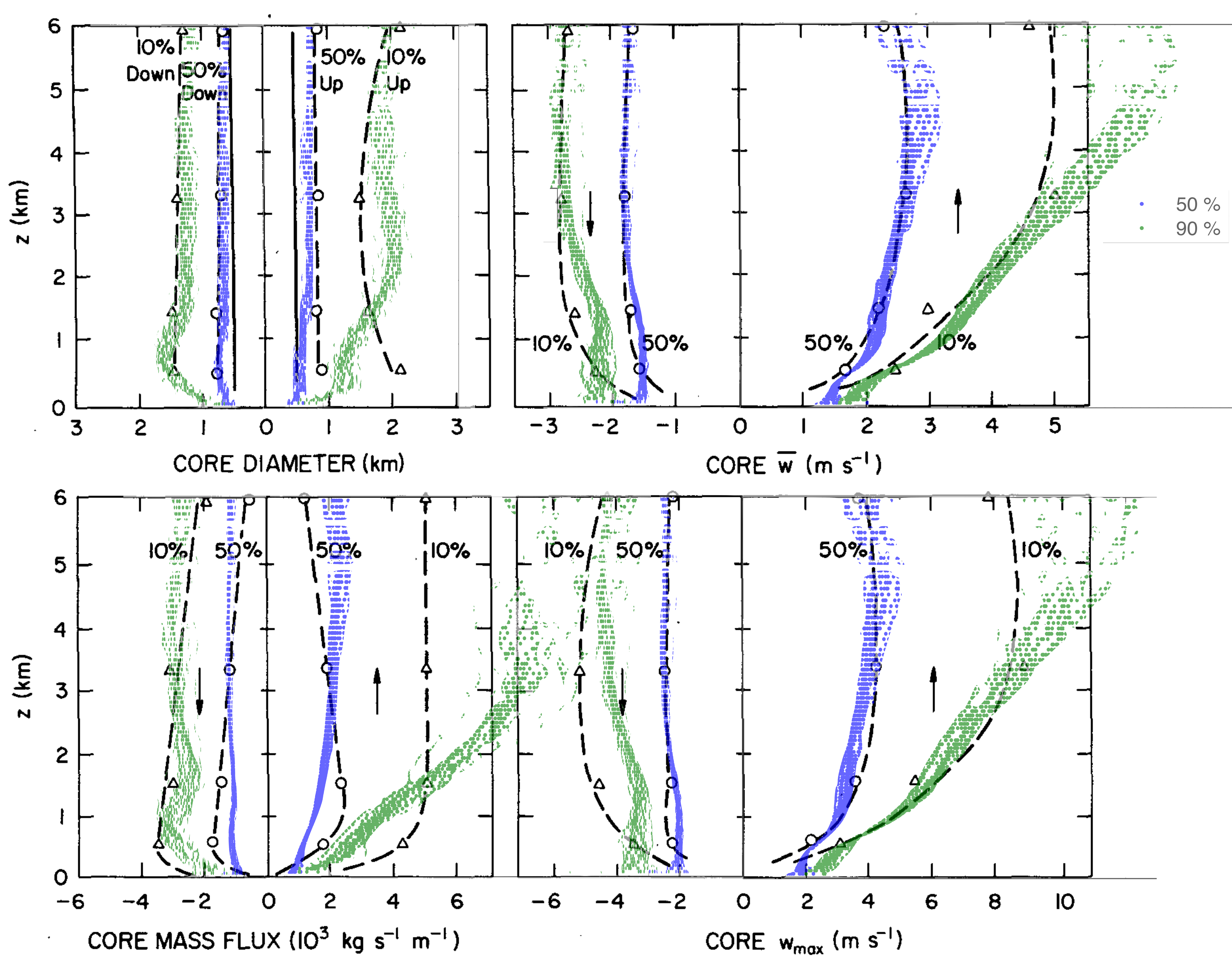


z (km)
10% Down
50% Down
50% Up
10% Up
CORE DIAMETER (km)
10%
50%
CORE $\overline{w}$ (m s^{-1})
CORE MASS FLUX (10^3 kg s^{-1} m^{-1})
CORE w_{max} (m s^{-1})

The following are statistics from the giga-LES for up-cores and down-cores.

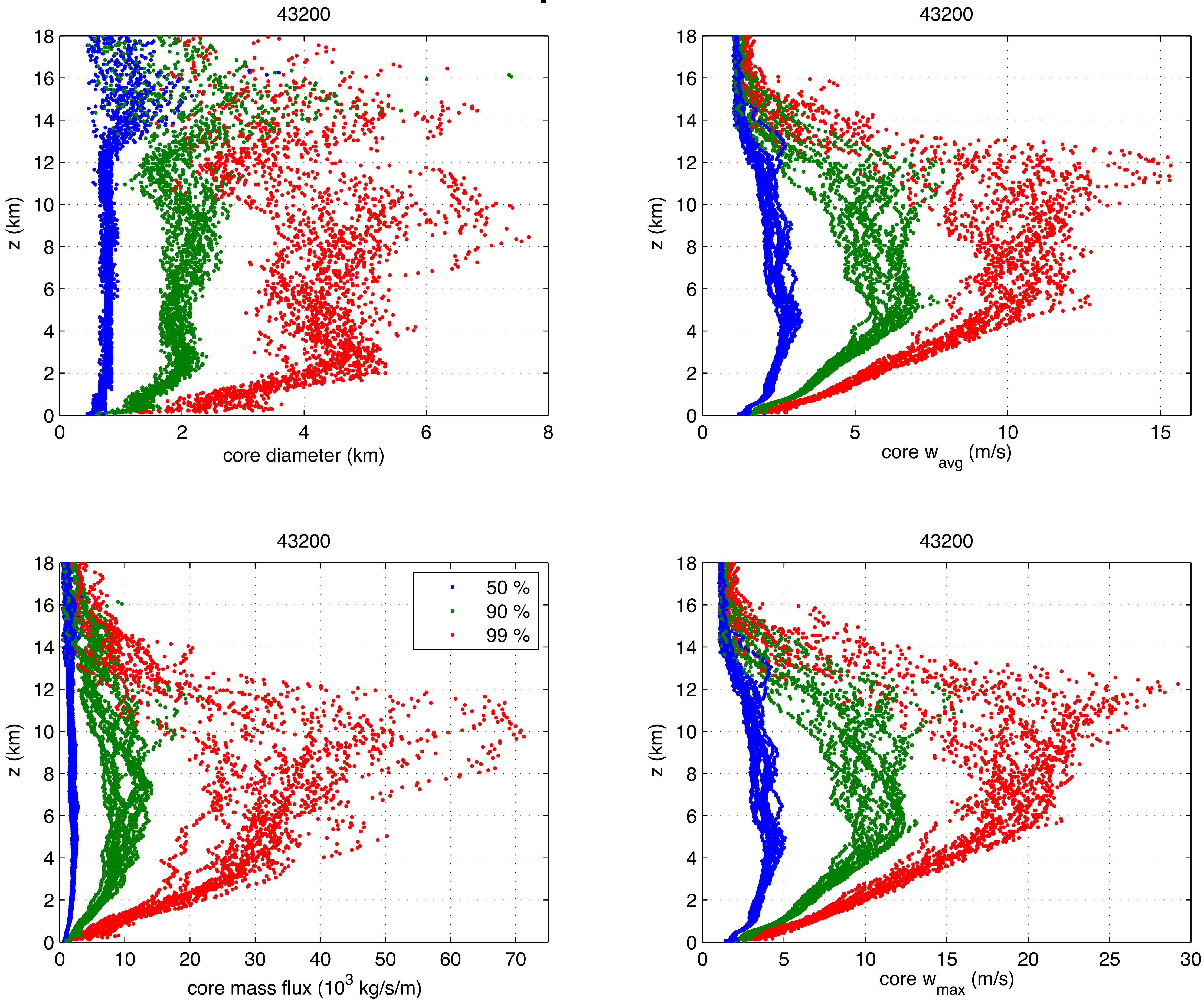
Each plotted point represents one level at one time. Hourly results for the last 12 hours are plotted.

The first plot is a comparison to LeMone & Zipser's results. The second and third plots include results to 18 km and the 99th percentile.



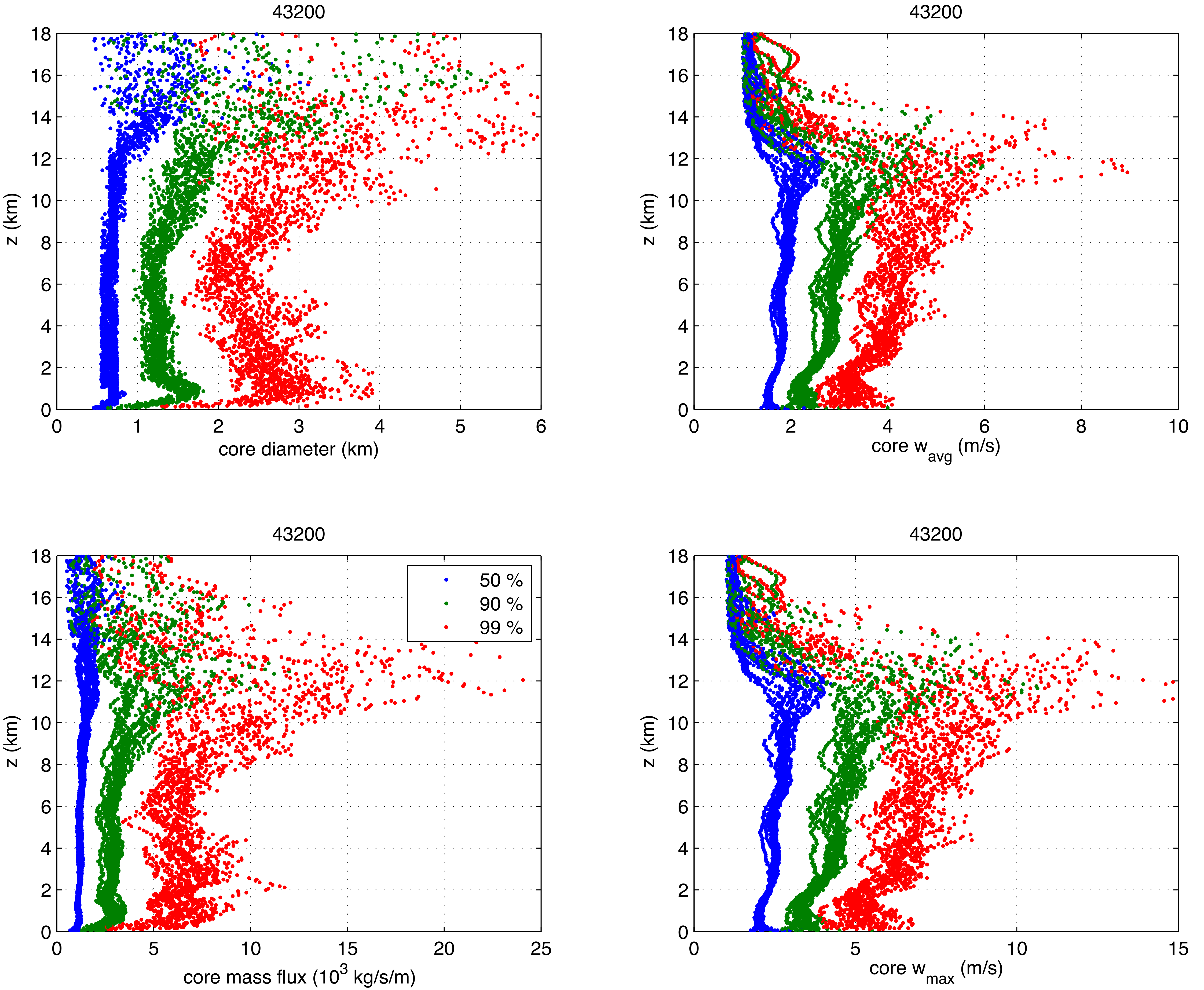
10% Down
50% Down
50% Up
10% Up
z (km)
CORE DIAMETER (km)
10%
50%
CORE $\overline{w}$ (m s^{-1})
50 %
90 %
CORE MASS FLUX (10^3 kg s^{-1} m^{-1})
CORE w_{max} (m s^{-1})

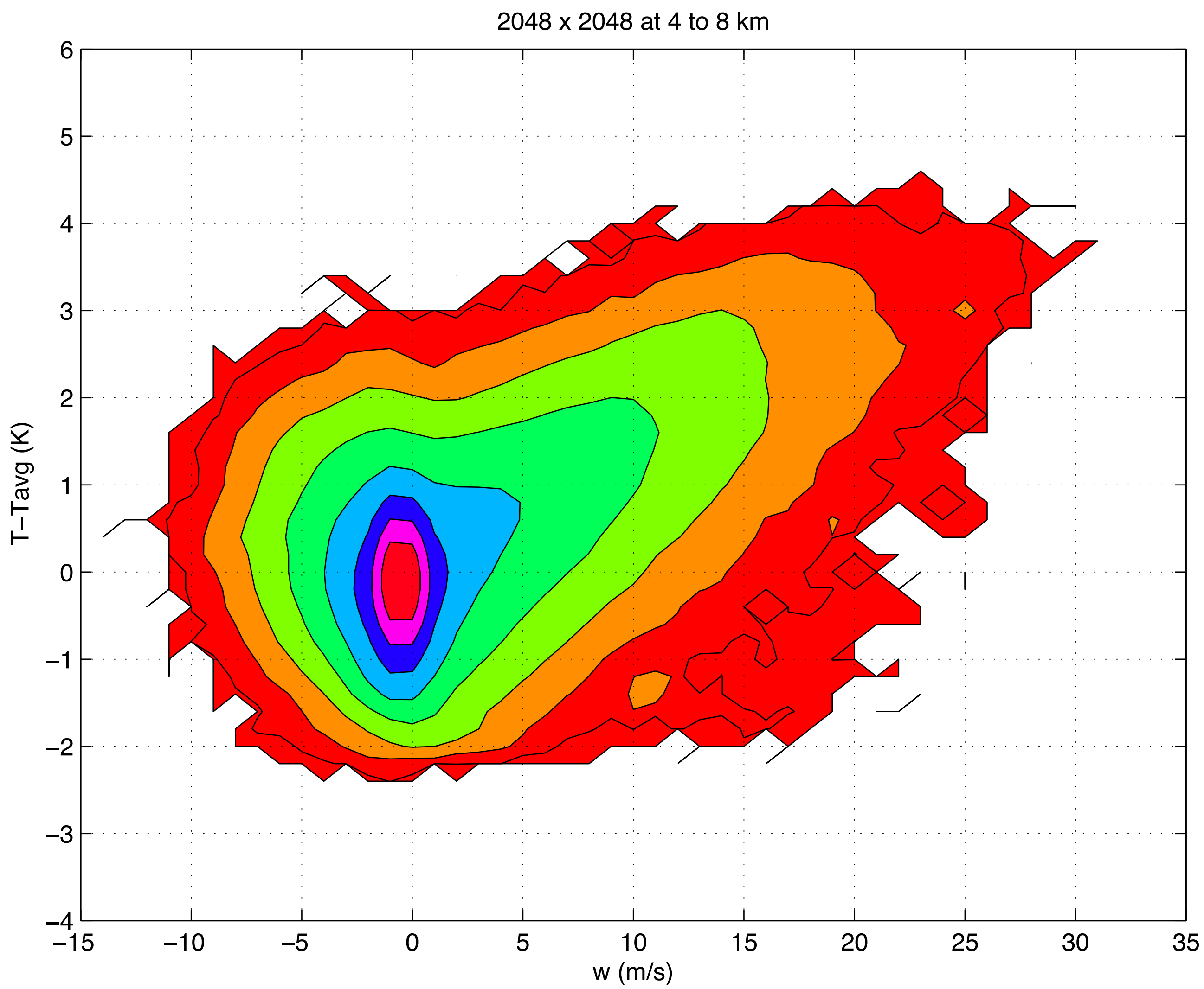
Updrafts

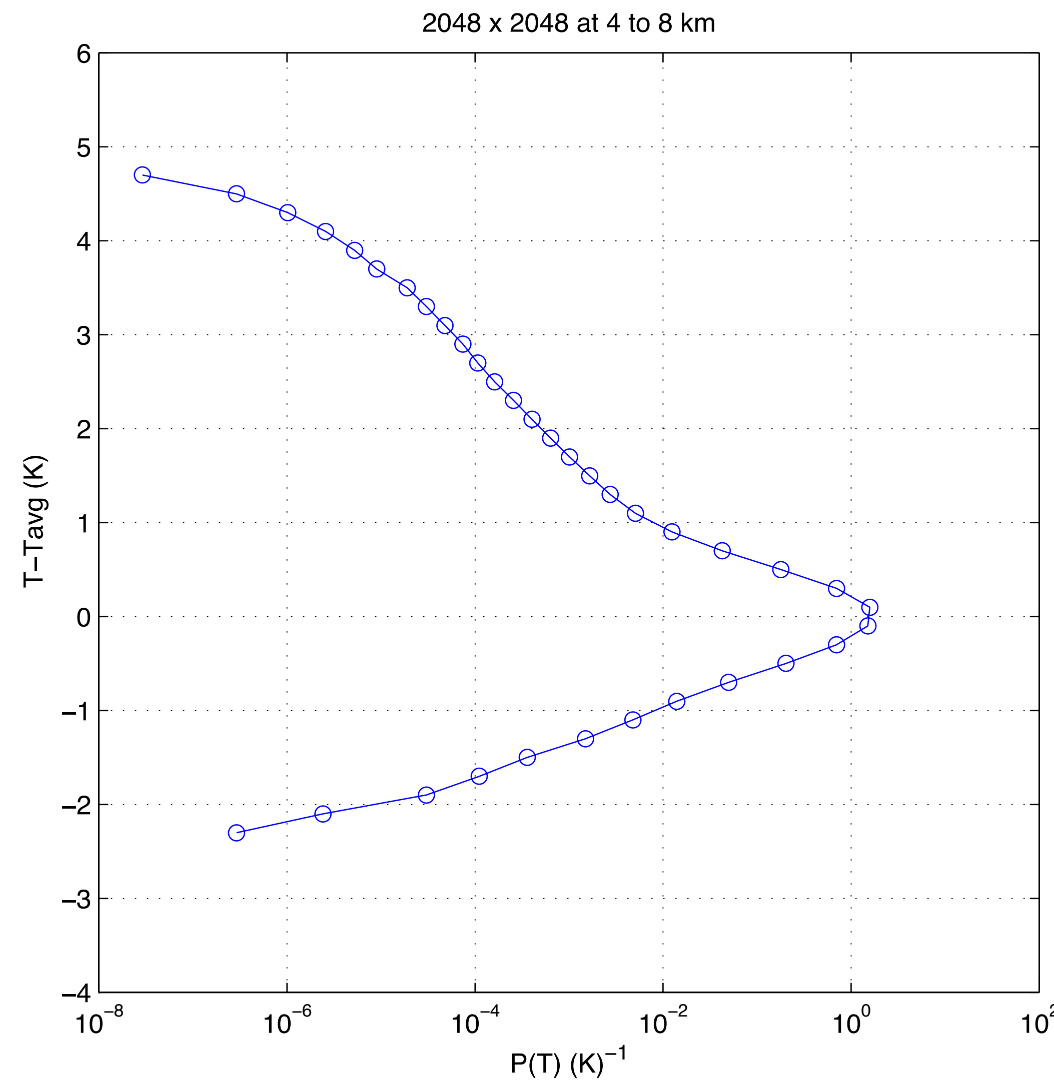


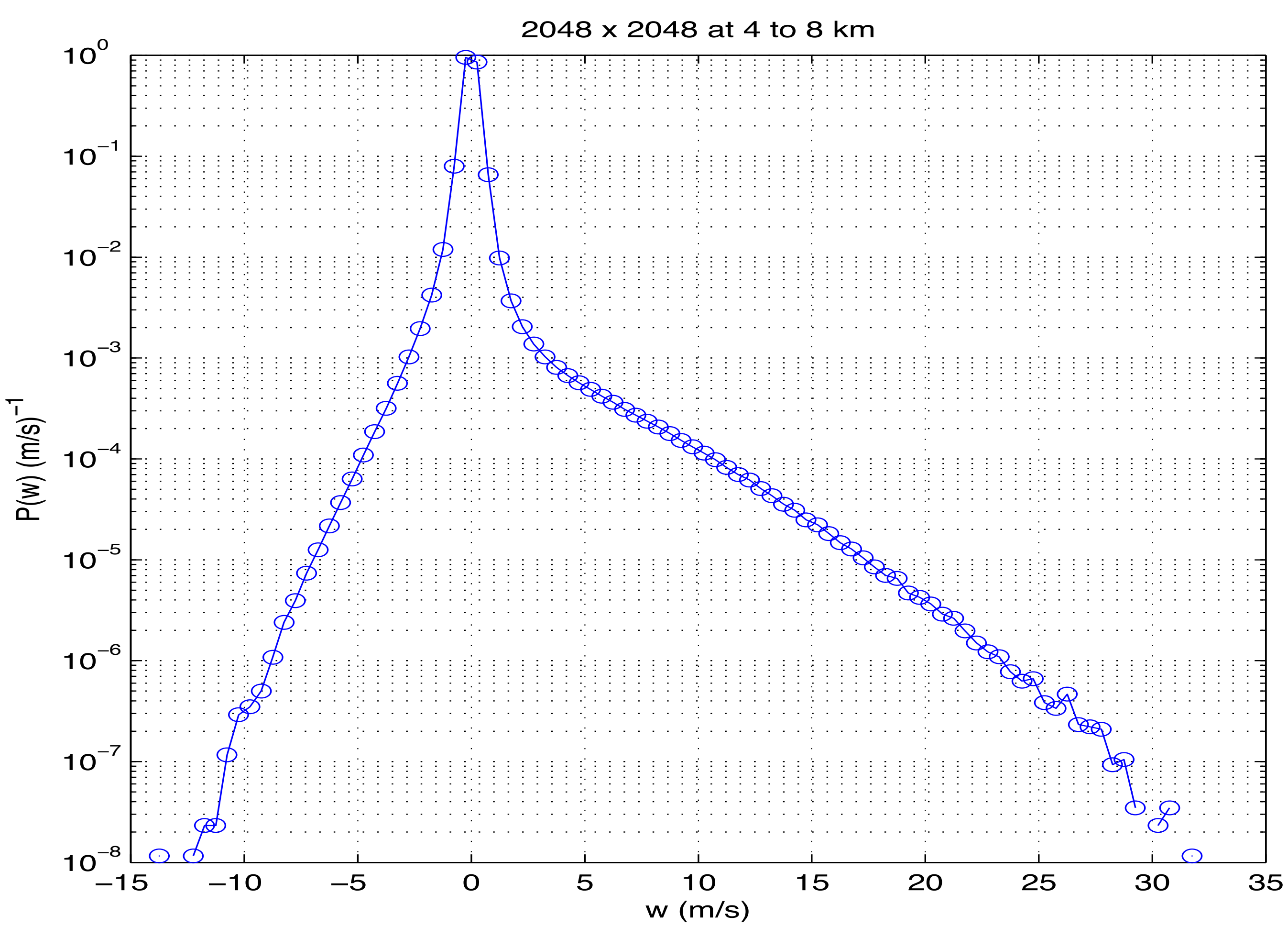
43200
18
16
14
12
10
8
6
4
2
0
z (km)
0
2
4
6
8
core diameter (km)
43200
z (km)
0
5
10
15
core w_{avg} (m/s)
43200
z (km)
0
10
20
30
40
50
60
70
core mass flux (10^3 kg/s/m)
50 %
90 %
99 %
43200
z (km)
0
5
10
15
20
25
30
core w_{max} (m/s)

Downdrafts

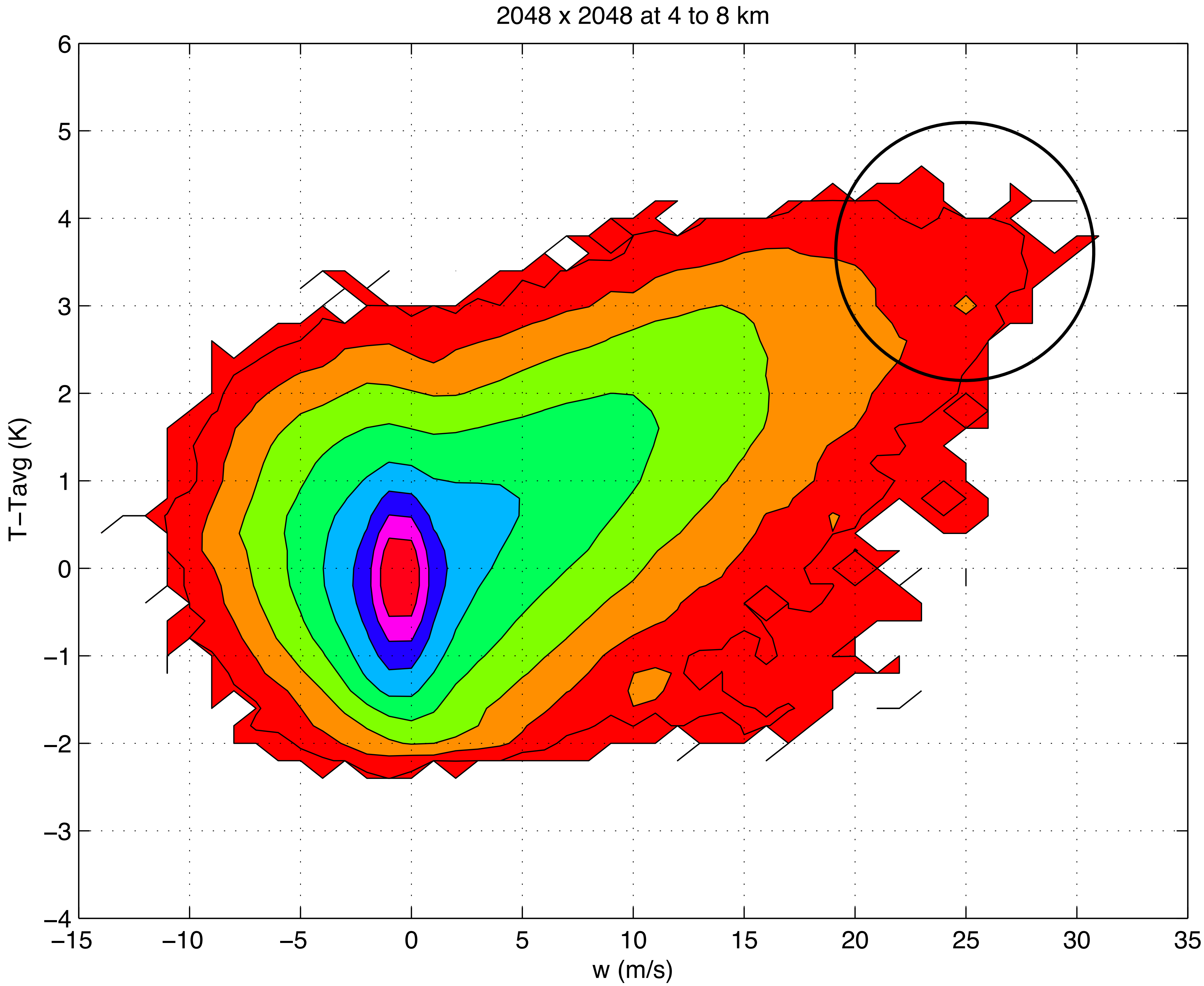

43200
z (km)
core diameter (km)
43200
z (km)
core w_{avg} (m/s)
43200
z (km)
core mass flux (10^3 kg/s/m)
50 %
90 %
99 %
43200
z (km)
core w_{max} (m/s)

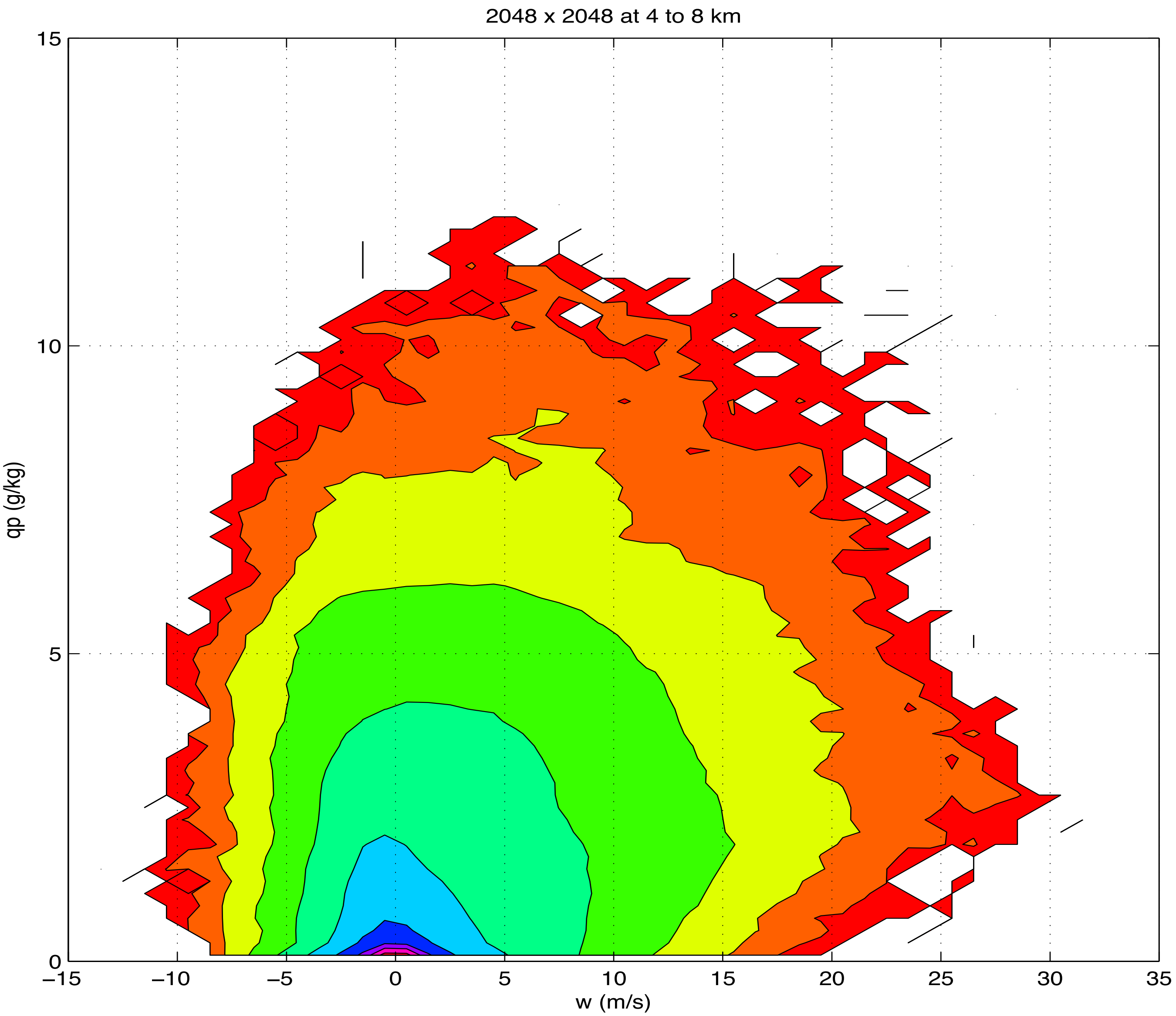


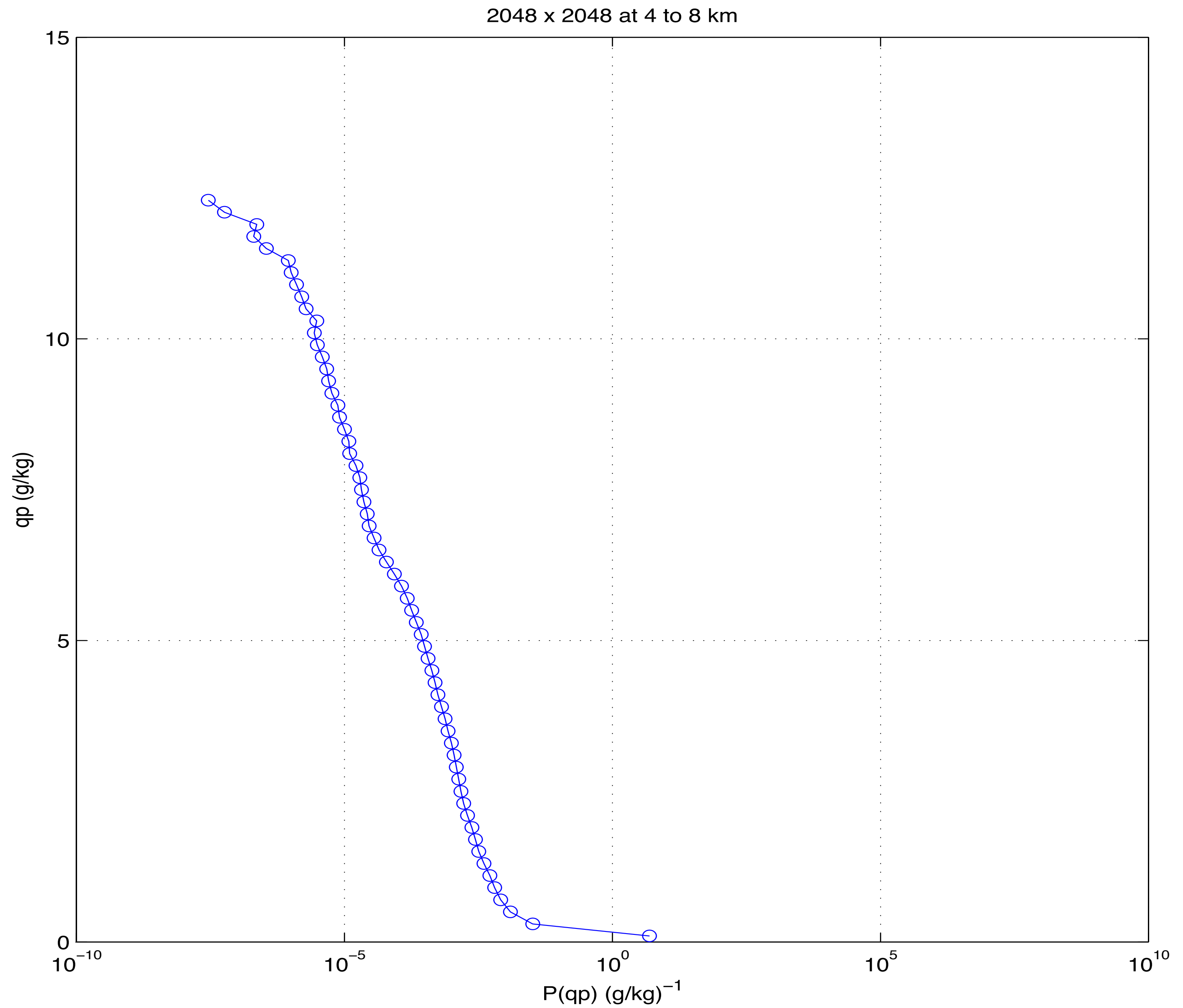


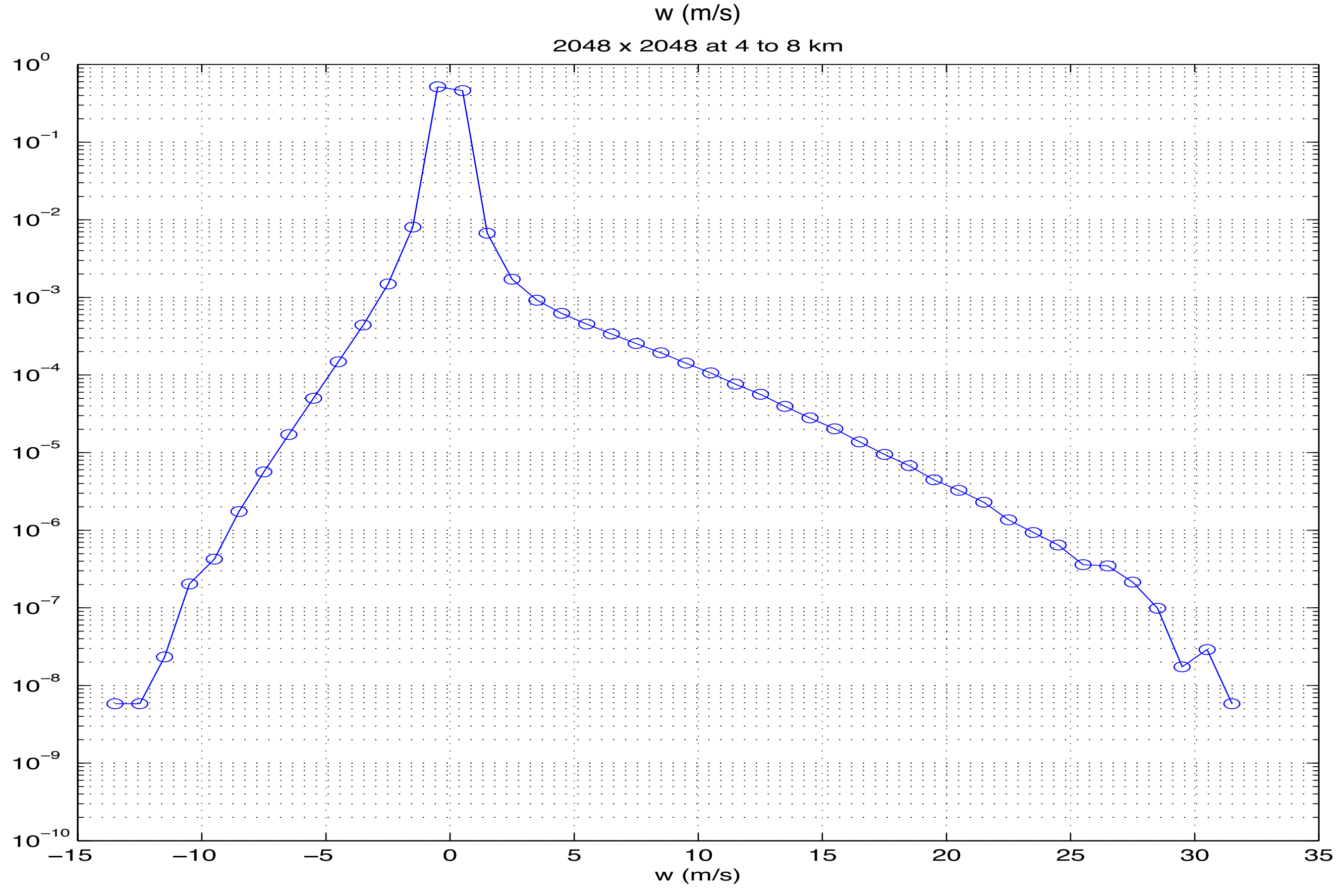


w-T pdfs for 4-8 km (buoyancy)


2048 x 2048 at 4 to 8 km
T−Tavg (K)
w (m/s)
6
5
4
3
2
1
0
−1
−2
−3
−4
−15
−10
−5
0
5
10
15
20
25
30
35

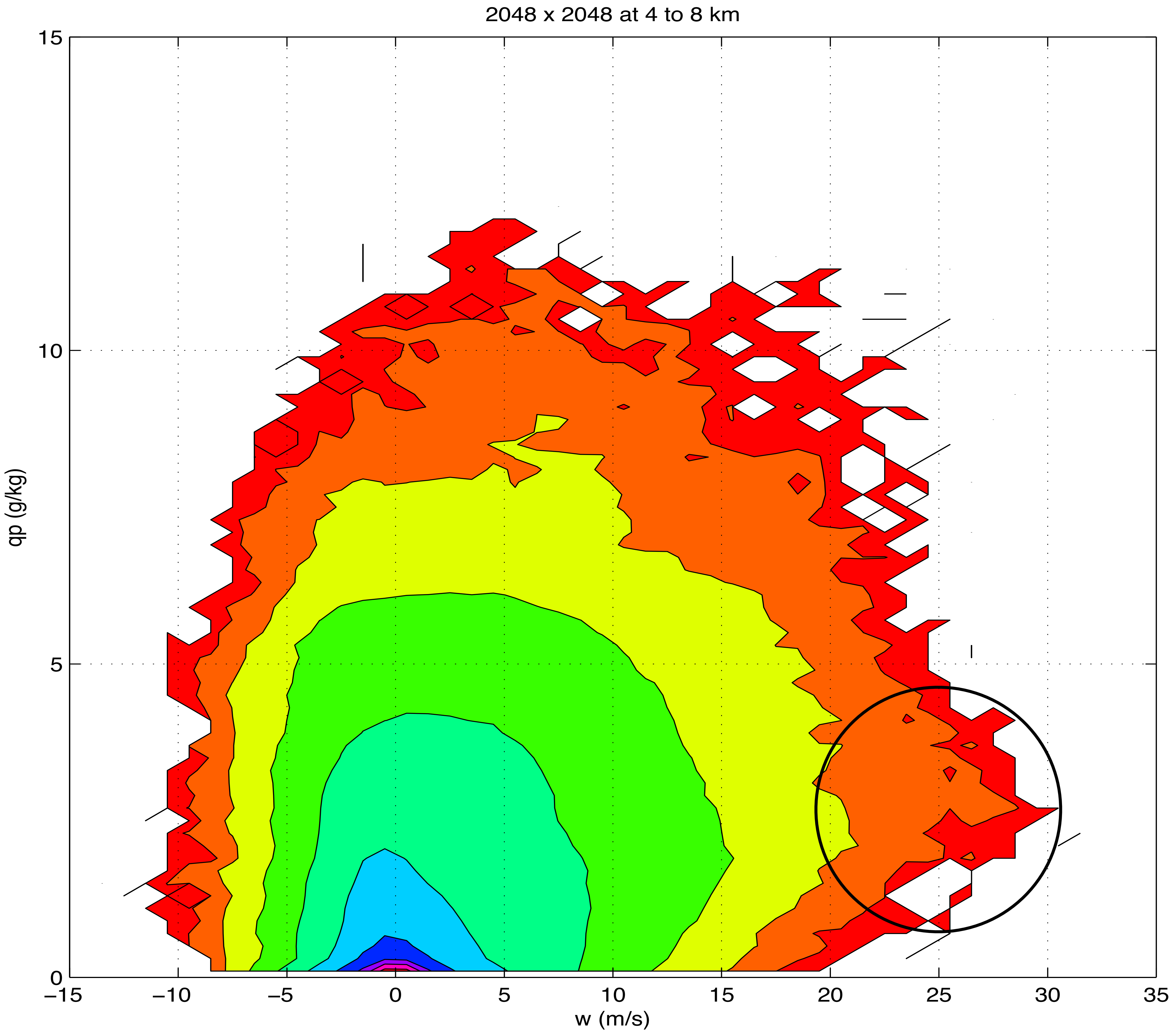






w-precip pdfs

(drag)



2048 x 2048 at 4 to 8 km
qp (g/kg)
w (m/s)
15
10
5
0
−15
−10
−5
0
5
10
15
20
25
30
35

Giga-LES statistics

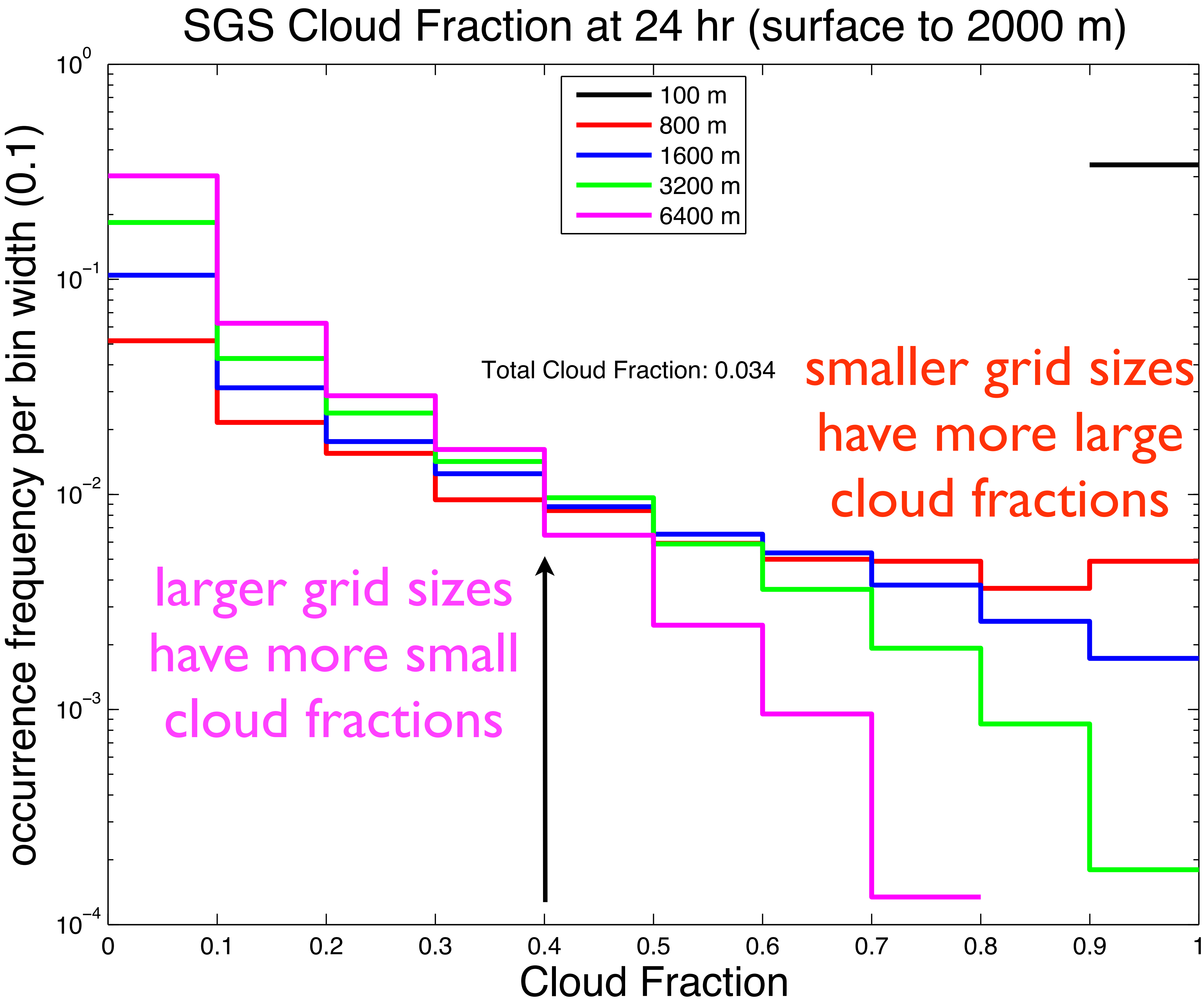
- Giga-LES core statistics compare well to LZ GATE observations.
- Joint pdfs of buoyancy and drag show that strongest updrafts have large buoyancy and small drag.
- Co-located observations of w and precip could be used to study dynamics of deep convection.

Boundary layer clouds in cloud-system-resolving models (CSRMs)

- CSRMs may have horizontal grid sizes of 4 km or more.
- Such CSRMs are used in MMF, GCRMs (global CSRMs), and tropical cyclone models.
- In MMF and GCRMs, CSRMs are expected to represent all types of cloud systems.
- However, many cloud-scale circulations are not resolved by CSRMs.
- Representations of SGS (subgrid-scale) circulations currently used in CSRMs can be improved.

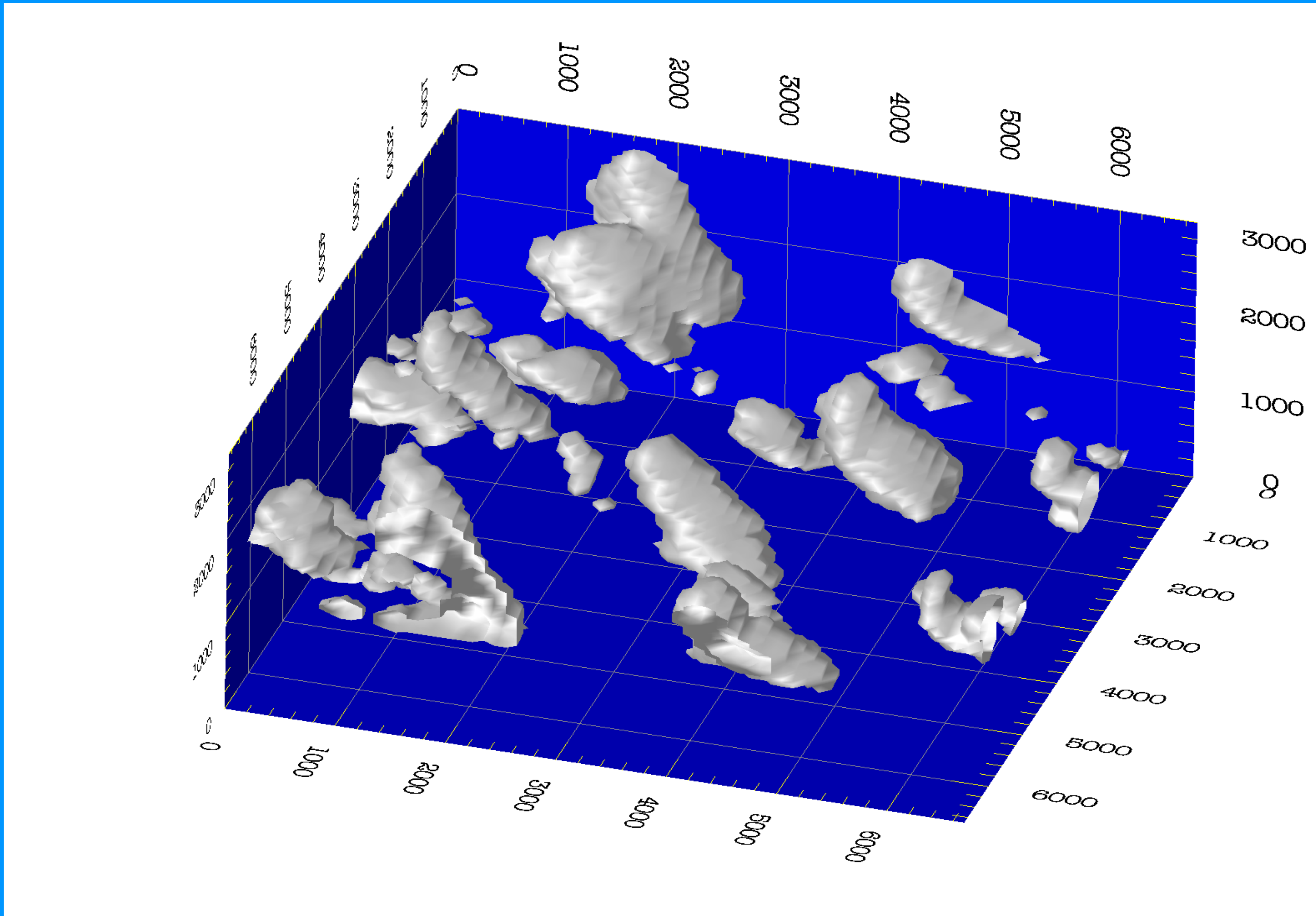
Use results from the giga-LES to test the assumed PDF method

- Collected statistics for calculating the moments needed to specify assumed PDFs for grid sizes of 800 m x 800 m x 100 m and multiples thereof.
- The statistics also include cloud fraction, liquid water mixing ratio, and its vertical flux, that can be compared to those obtained from the PDF.


SGS Cloud Fraction at 24 hr (surface to 2000 m)
occurrence frequency per bin width (0.1)
Cloud Fraction
10^0
10^{-1}
10^{-2}
10^{-3}
10^{-4}
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
100 m
800 m
1600 m
3200 m
6400 m
Total Cloud Fraction: 0.034
smaller grid sizes have more large cloud fractions
larger grid sizes have more small cloud fractions

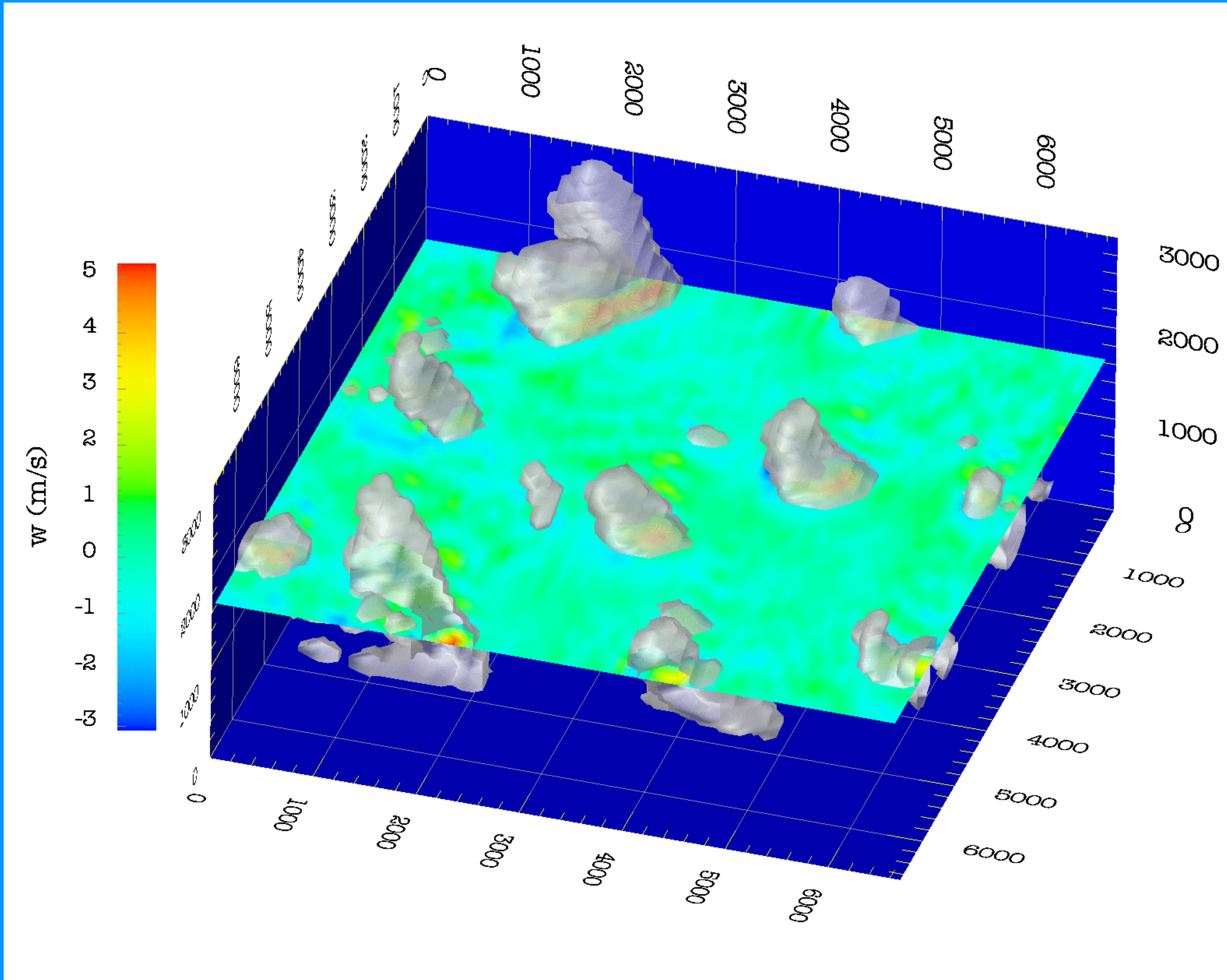
PDFs of cumulus clouds

Isosurface of cloud water: 0.001 (g/kg)



(courtesy of W. R. Cotton & J.-C. Golaz)

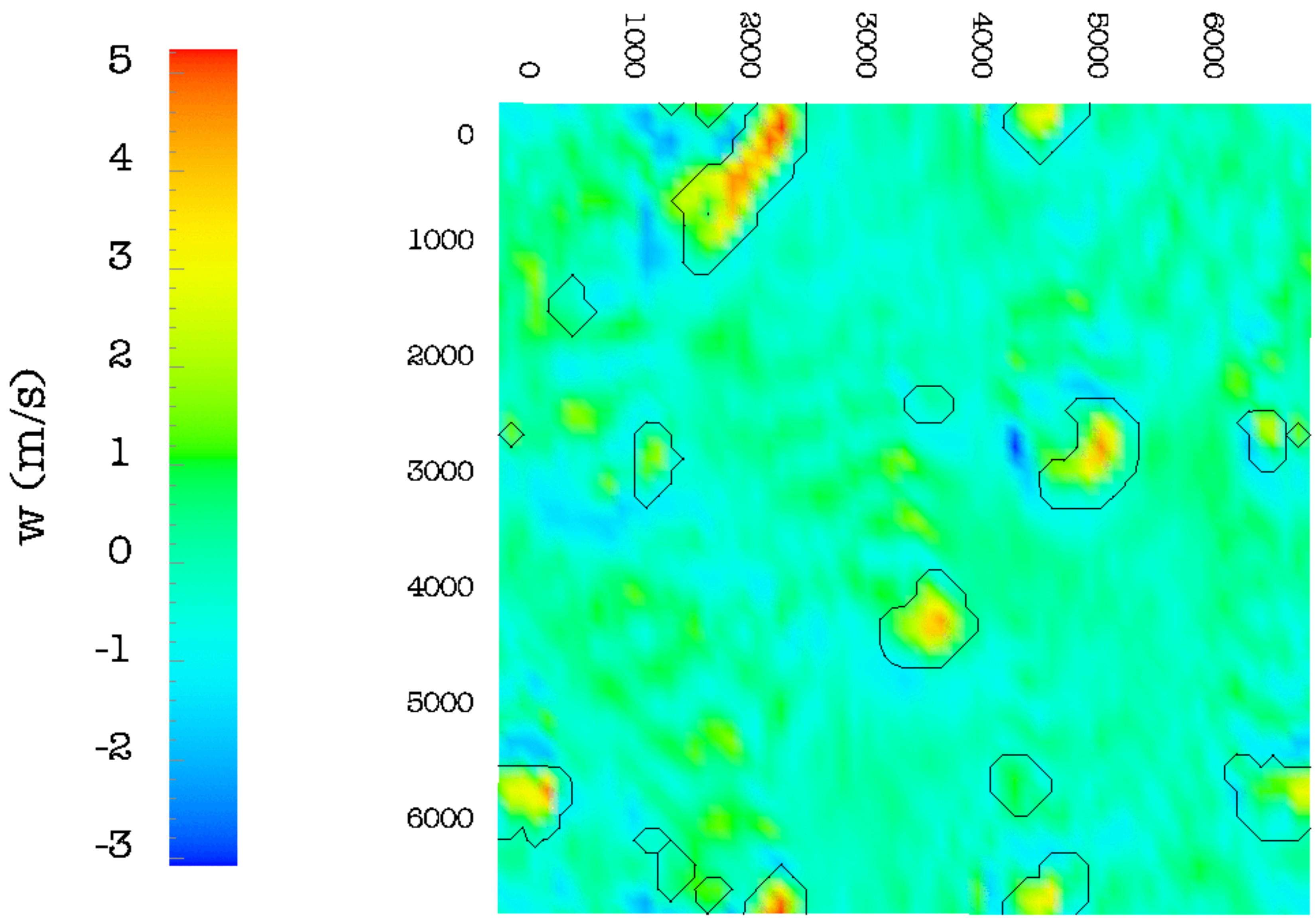
PDFs of cumulus clouds



(courtesy of W. R. Cotton & J.-C. Golaz)

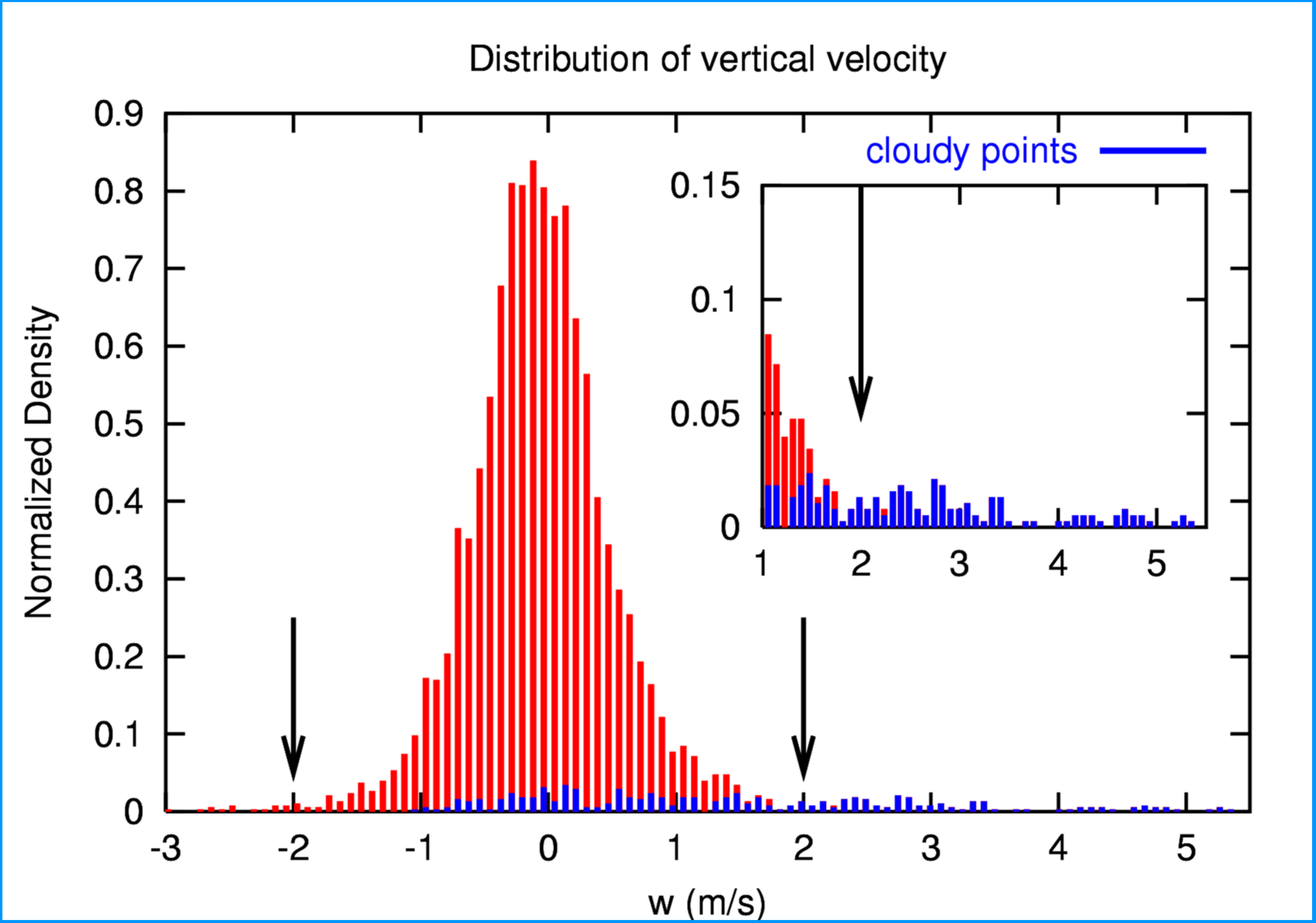
PDFs of cumulus clouds

Horizontal cross section of vertical velocity; z=1680(m)



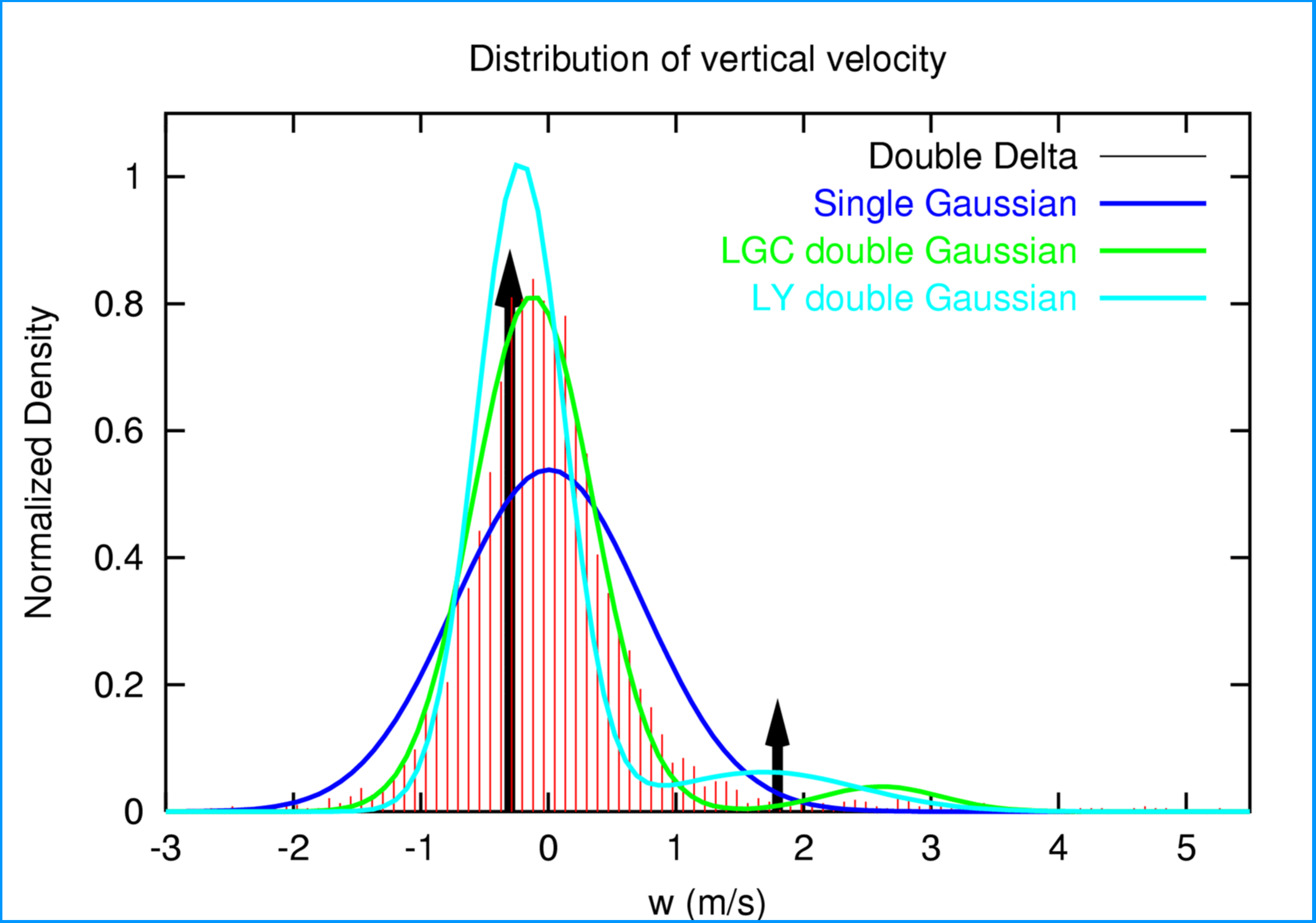
(courtesy of W. R. Cotton & J.-C. Golaz)

PDFs of cumulus clouds



(courtesy of W. R. Cotton & J.-C. Golaz)

Example of a PDF fit



(courtesy of W. R. Cotton & J.-C. Golaz)

Evaluations of the PDFs

- To get a better idea of the performance of the four families of PDFs, use Giga-LES results.
- Compute
  - Cloud fraction
  - Cloud water
  - Liquid water flux

for various grid sizes, from the Giga-LES.

Pete recently presented these results.

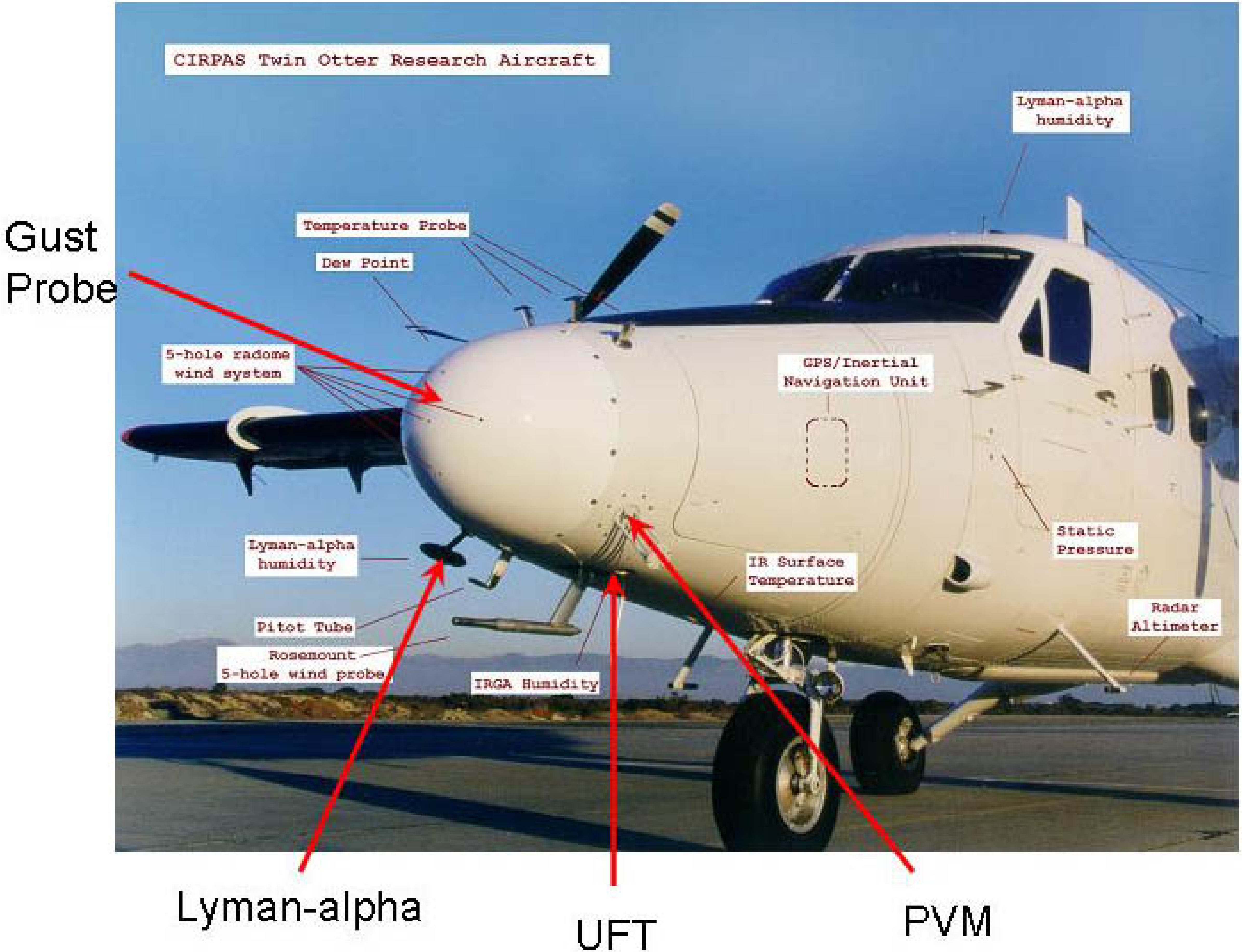
Giga-LES & Assumed PDF Method

- We are using the “benchmark” results from a large-domain LES of deep convection to test the assumed PDF method for various horizontal grid sizes.
- We will also use the “benchmark” results to evaluate coarse-grid CSRMs with various configurations (SGS parameterization, grid size, domain size, and dimensionality).
- Large-domain LES of deep convection can be used to study many multiscale phenomena, such as triggering of new convection, entrainment, cold pools, gust fronts, and even waterspouts.

POST (Physics of Stratocumulus Top)

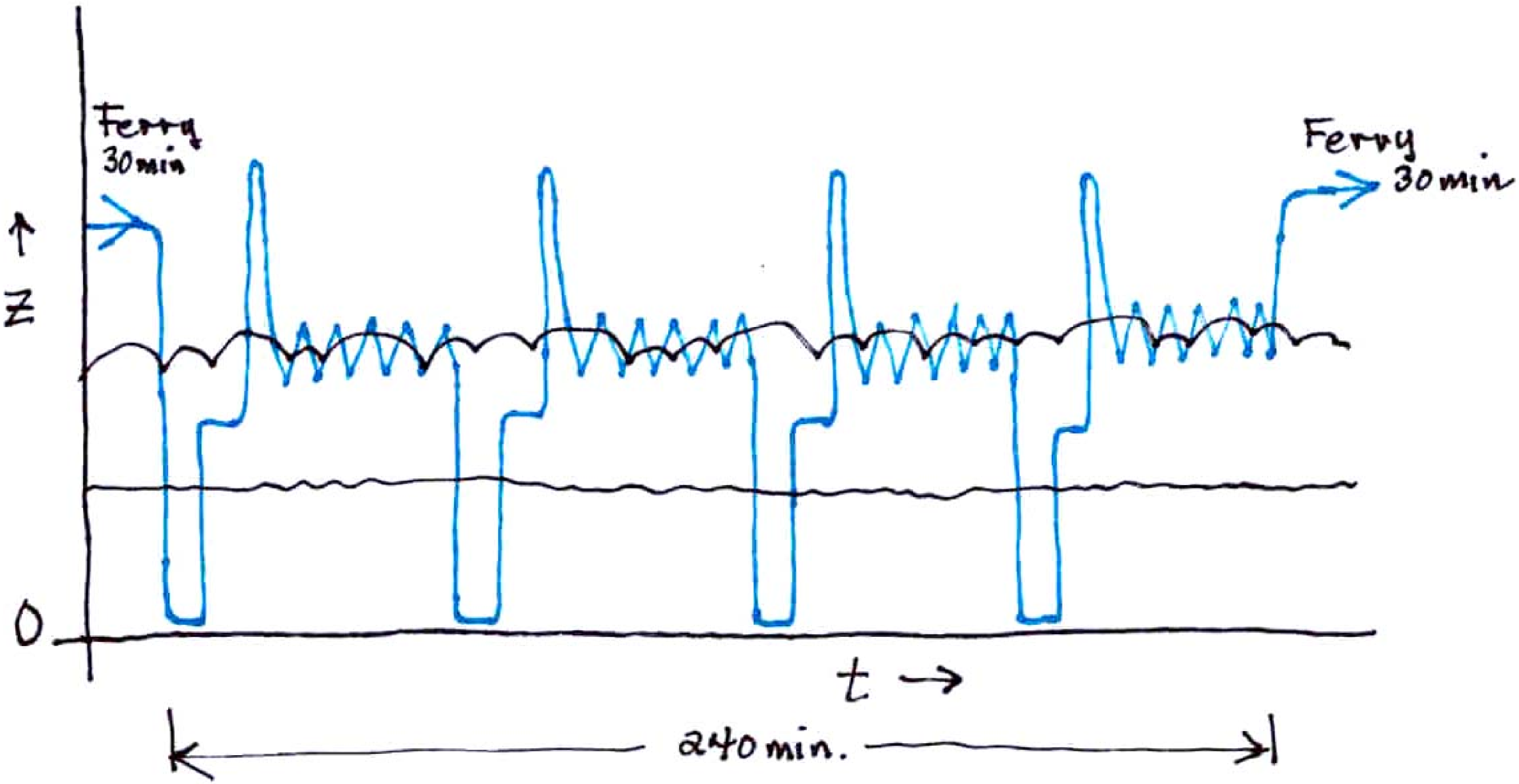
- A collaborative NSF project that involves 19 scientists from 11 institutions who are studying the stratocumulus-topped boundary layer off the west coast of California using a combination of aircraft measurements and modeling.
- The CIRPAS Twin Otter research aircraft was deployed out of Monterey, California, for 17 flights during July and August 2008.
- The experiment will provide unprecedented high-resolution (0.5 m) co-located measurements of temperature and cloud water content.

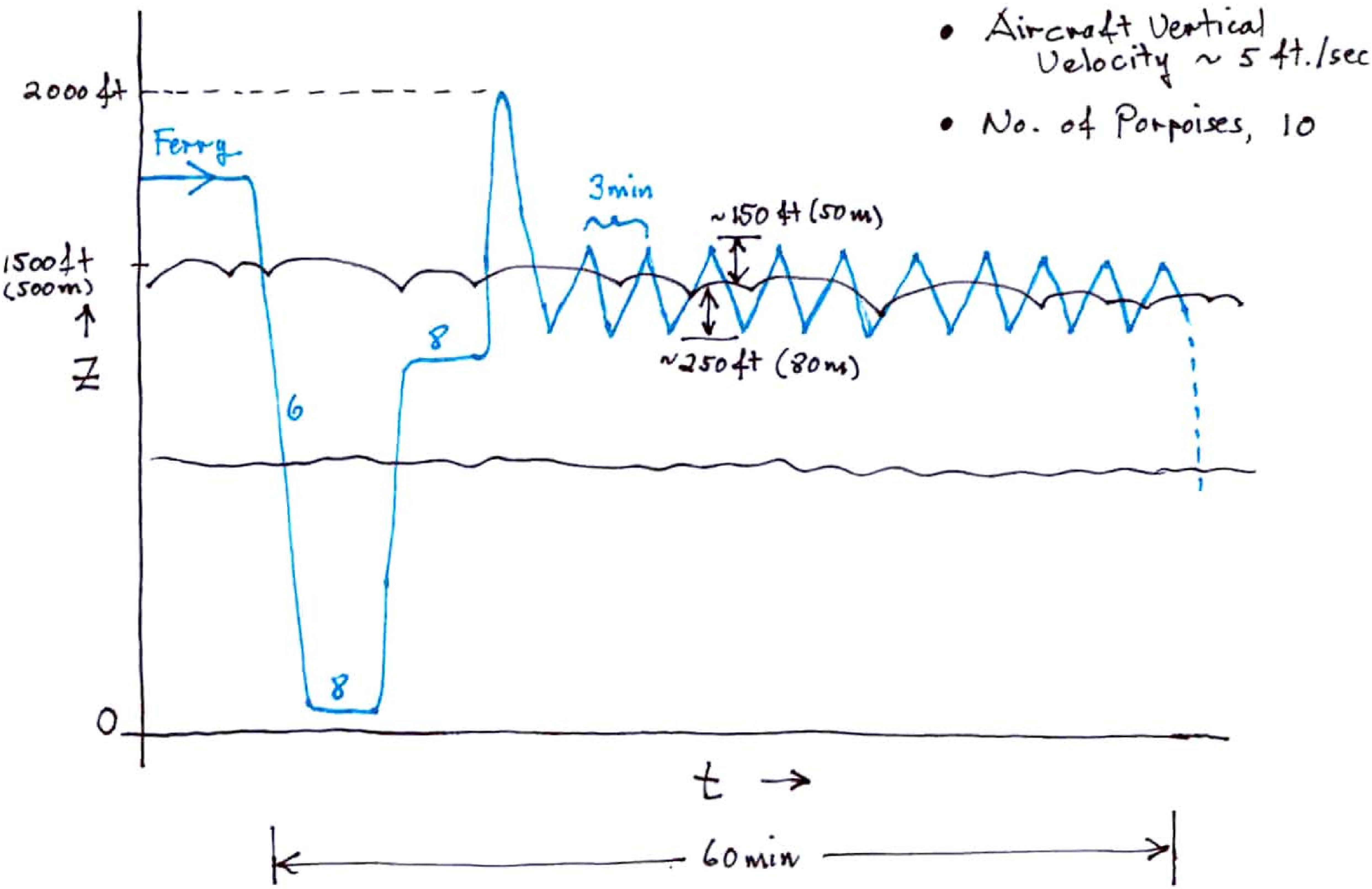

N83NX


CIRPAS Twin Otter Research Aircraft
Lyman-alpha humidity
Temperature Probe
Dew Point
Gust Probe
5-hole radome wind system
GPS/Inertial Navigation Unit
Static Pressure
Lyman-alpha humidity
IR Surface Temperature
Radar Altimeter
Pitot Tube
Rosemount 5-hole wind probe
IRGA Humidity
Lyman-alpha
UFT
PVM

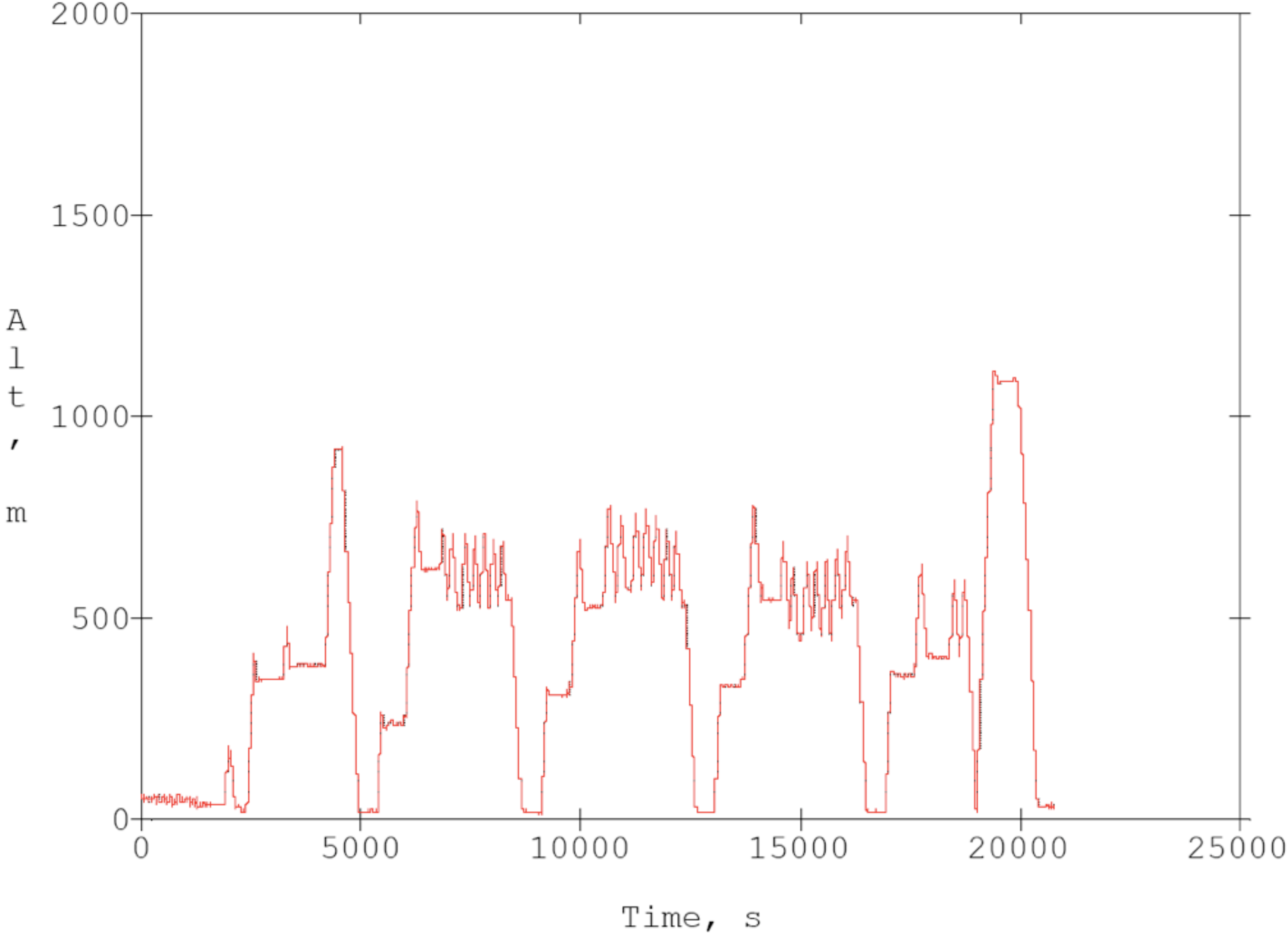
Two high-rate probes (UFT and PVM) were mounted less than 0.5 m apart on the CIRPAS Twin Otter aircraft during POST.

POST Flight Plan

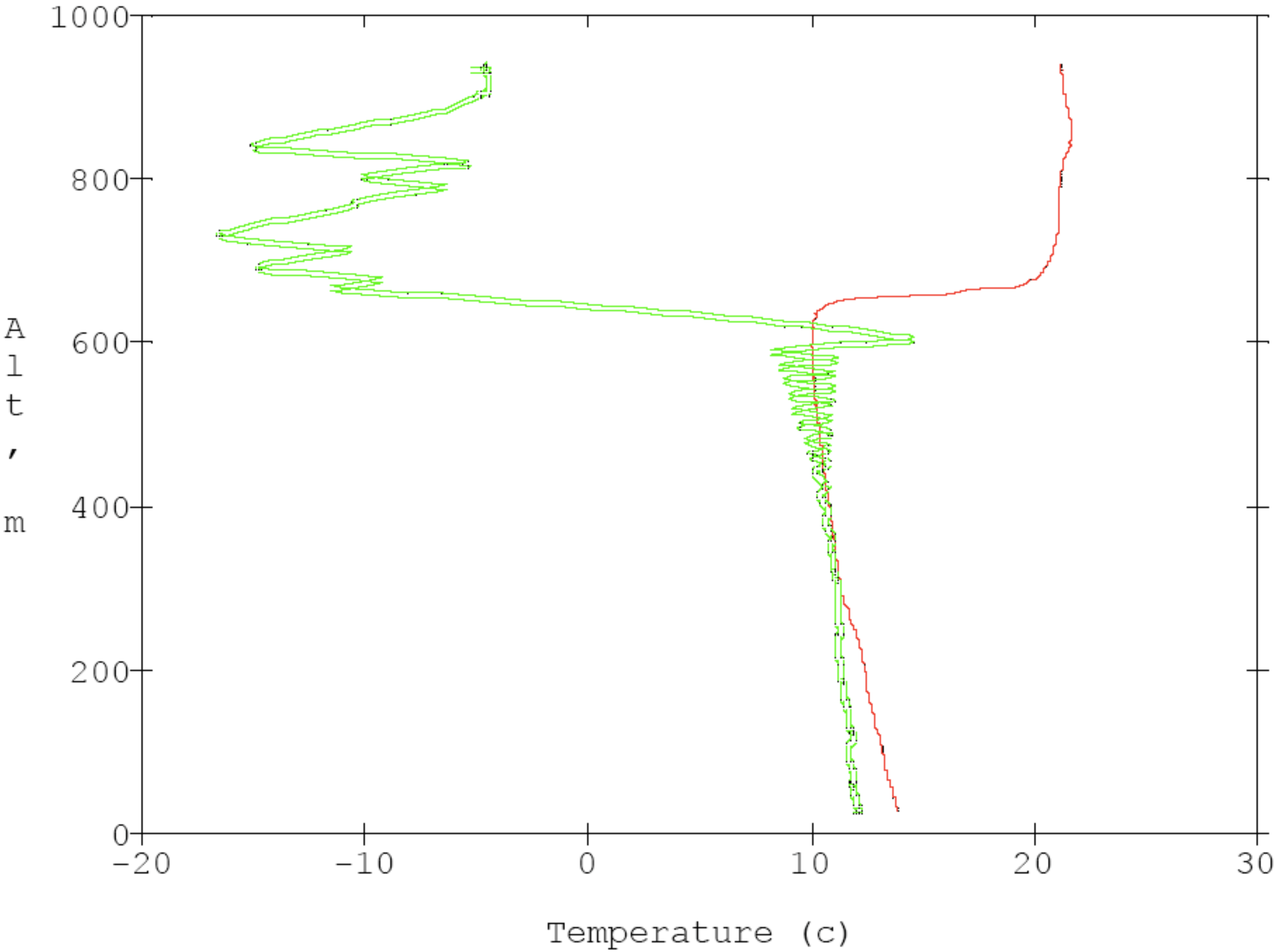




• Aircraft Vertical Velocity ~ 5 ft./sec
• No. of Porpoises, 10
2000 ft
1500 ft (500m)
Z
0
Ferry
6
8
8
3min
~150 ft (50m)
~250 ft (80m)
t
60 min



2000
1500
1000
500
0
Alt, m
0
5000
10000
15000
20000
25000
Time, s



1000
800
600
400
200
0
Alt, m
-20
-10
0
10
20
30
Temperature (c)

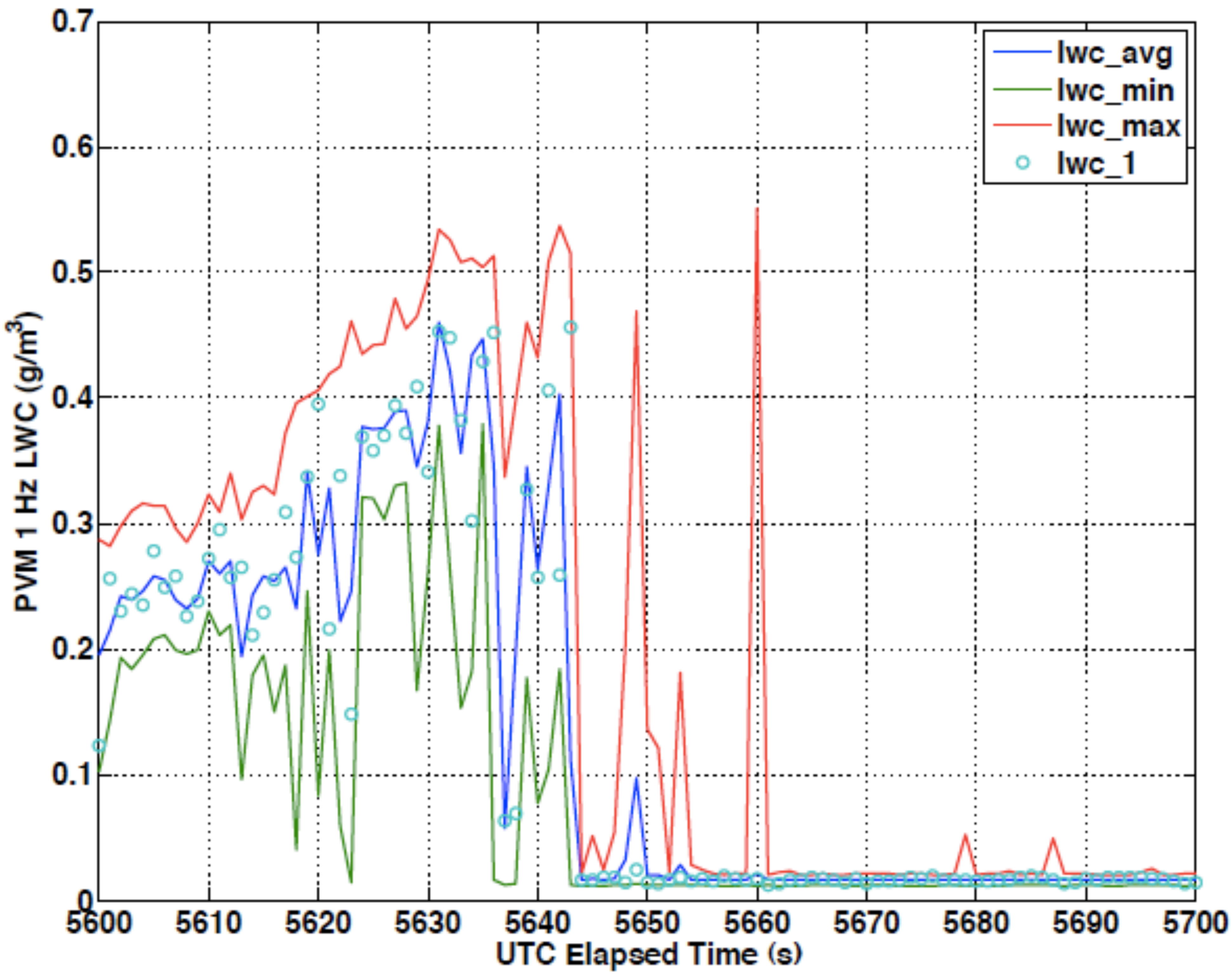
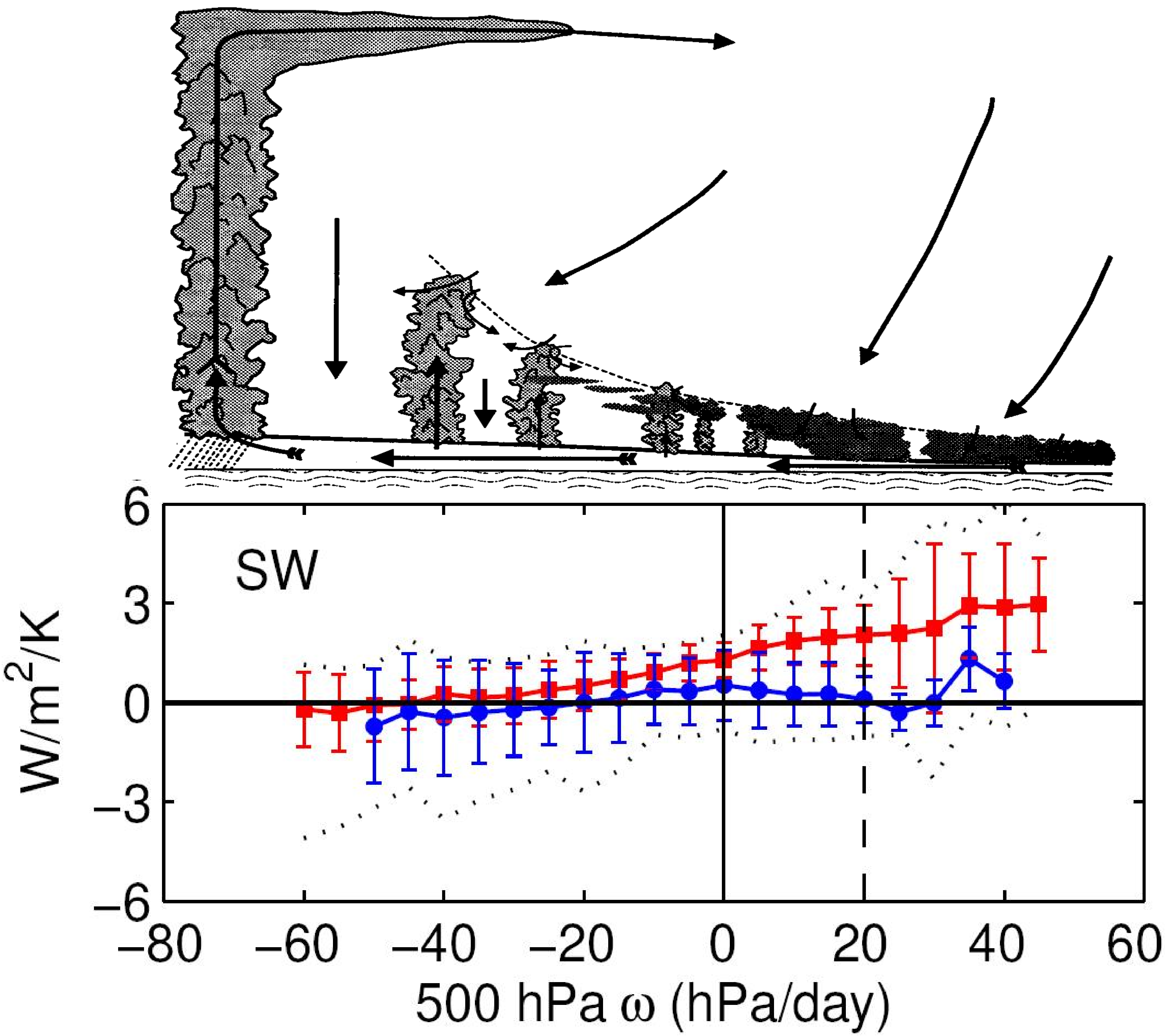


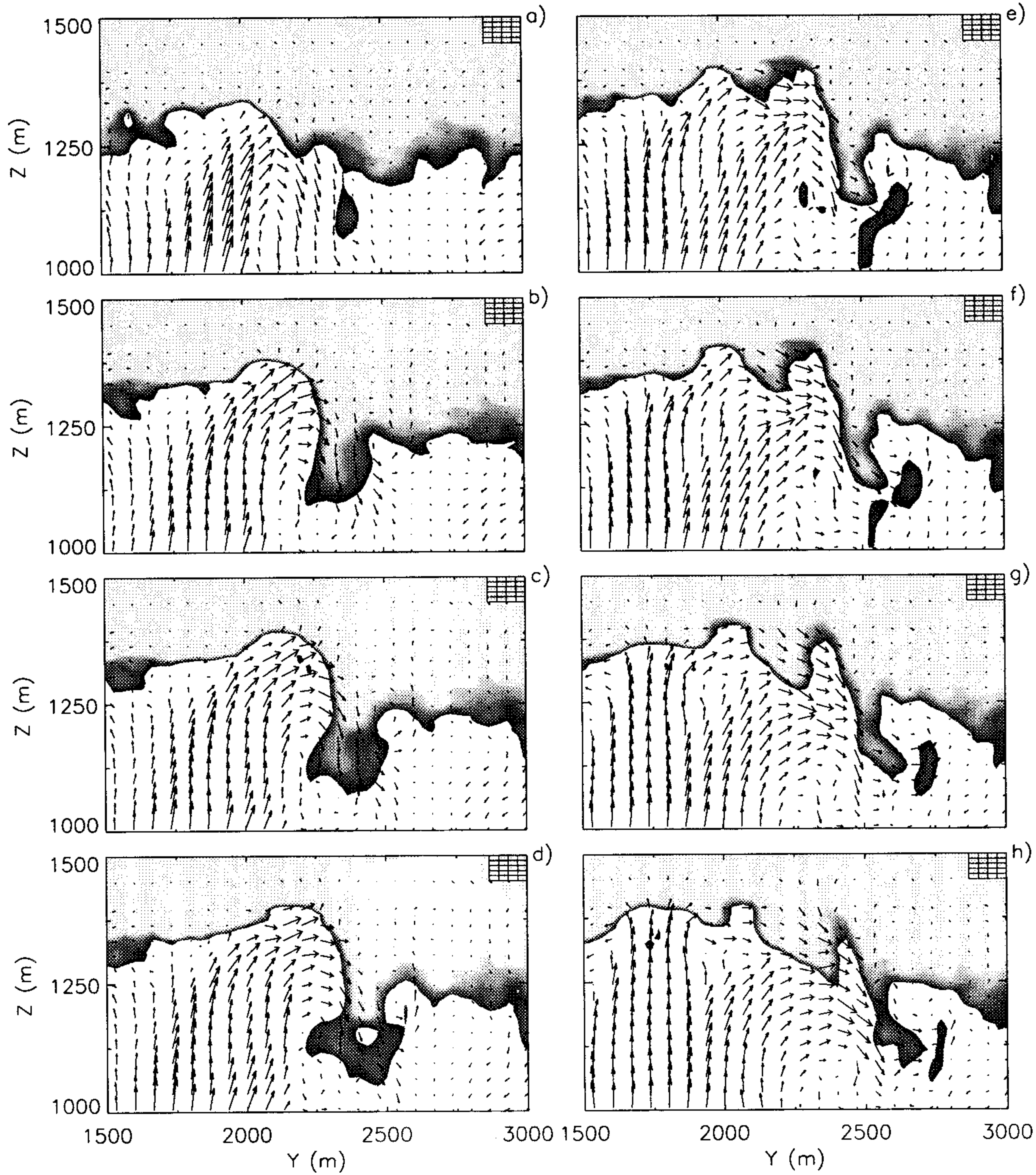
Figure 1: Average, maximum, and minimum LWC from 1-kHz PVM data within each 50-m segment during a 100-s (5-km) long flight segment during RF03 as the aircraft penetrated the EIL from below. The LWC has not been adjusted to remove its zero offset.

Why are stratocumulus clouds important?

Figure 2: Sensitivity of shortwave cloud radiative forcing changes in response to long term SST changes predicted in 1% CO_2 scenarios from 15 CMIP3/AR4 AOGCMs, separated into dynamical regimes. Dotted lines show the maximum and minimum values. The red squares and lines show the mean and standard deviation of the 8 higher sensitivity versions. The 7 lower sensitivity versions are shown in blue. From Bony and Dufresne (2005).

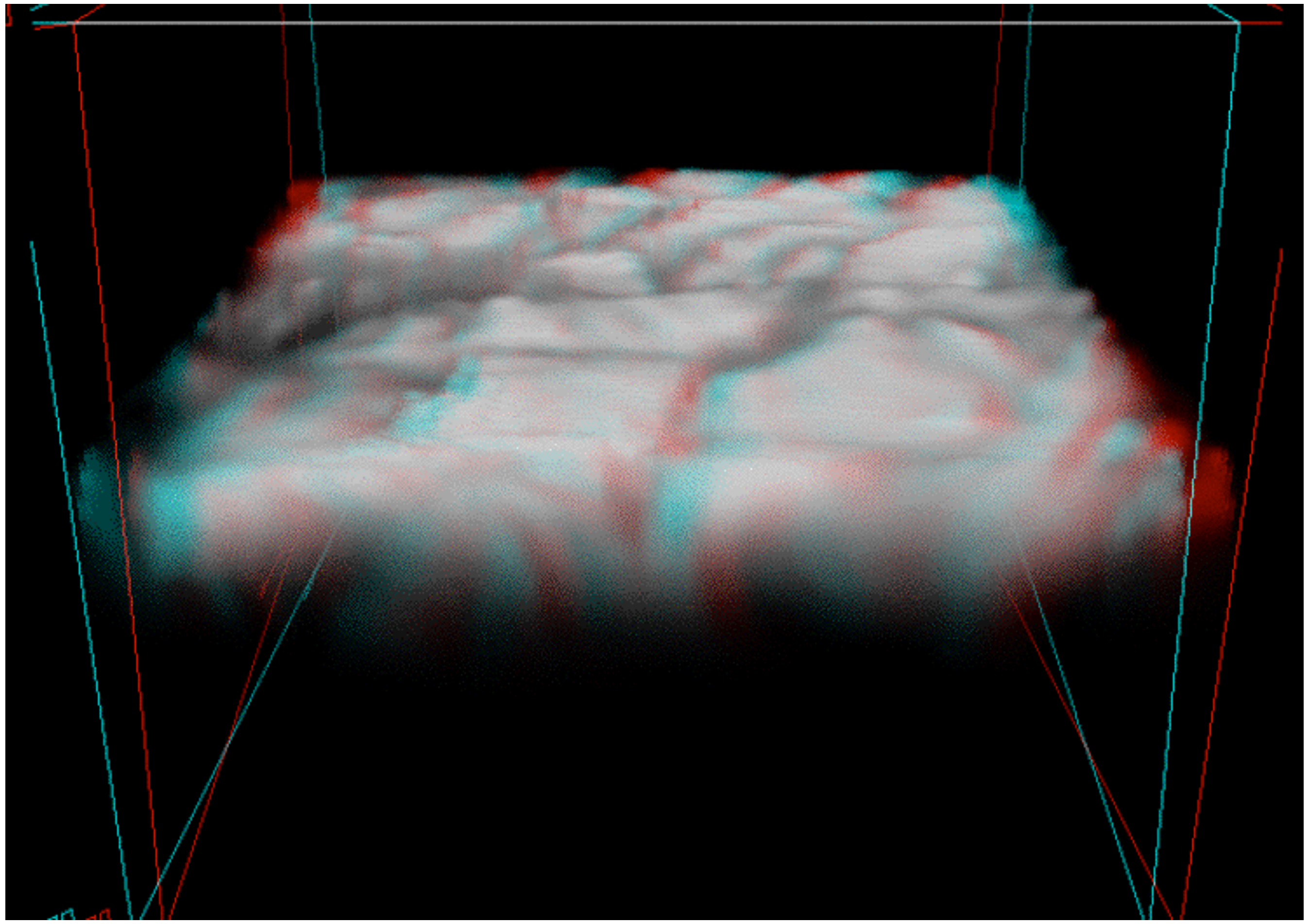


Entrainment at top of a clear convective boundary layer in a LES.

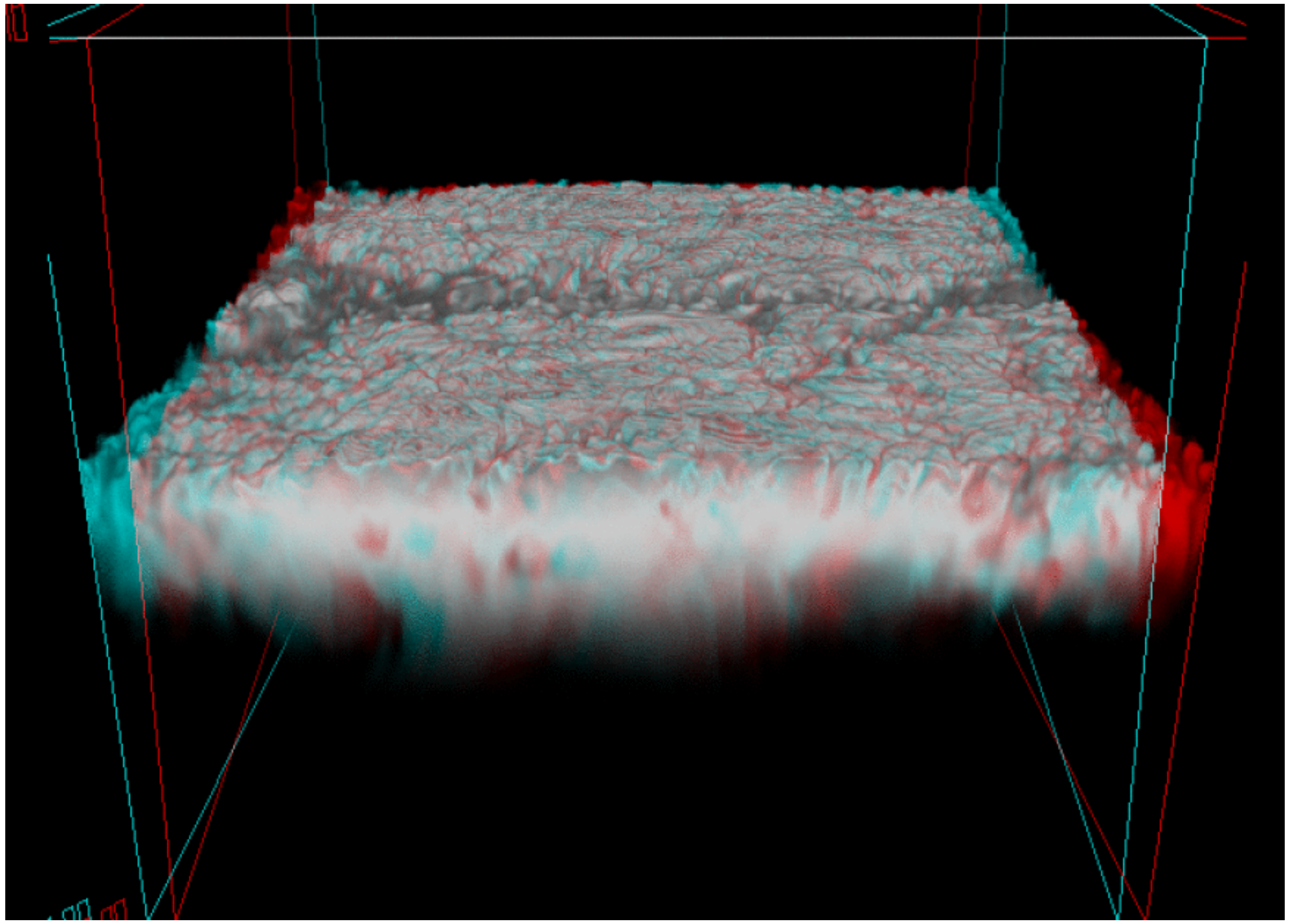


(Moeng & Sullivan 1994)

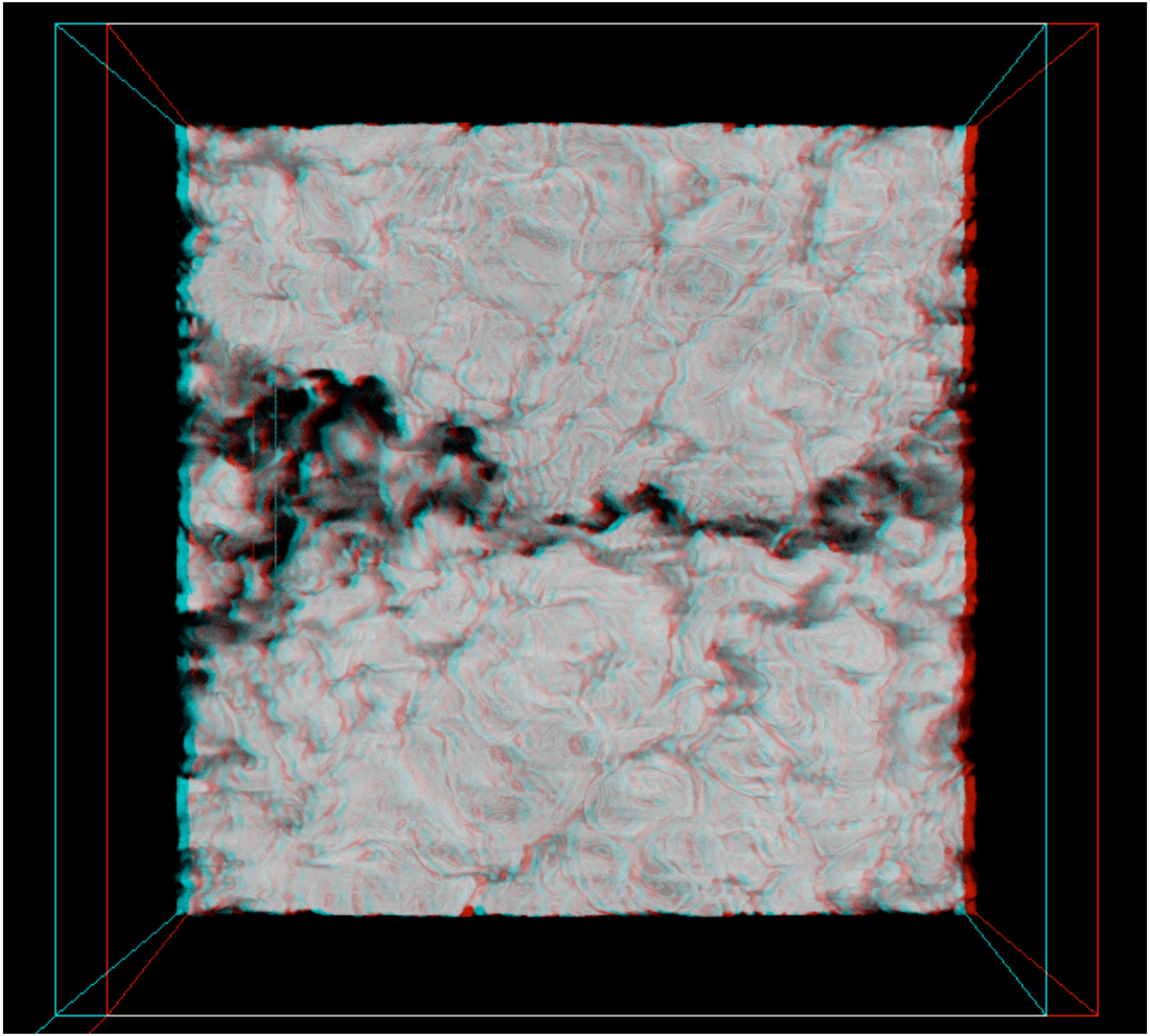
Stratocumulus cloud-top entrainment in the UU LES.



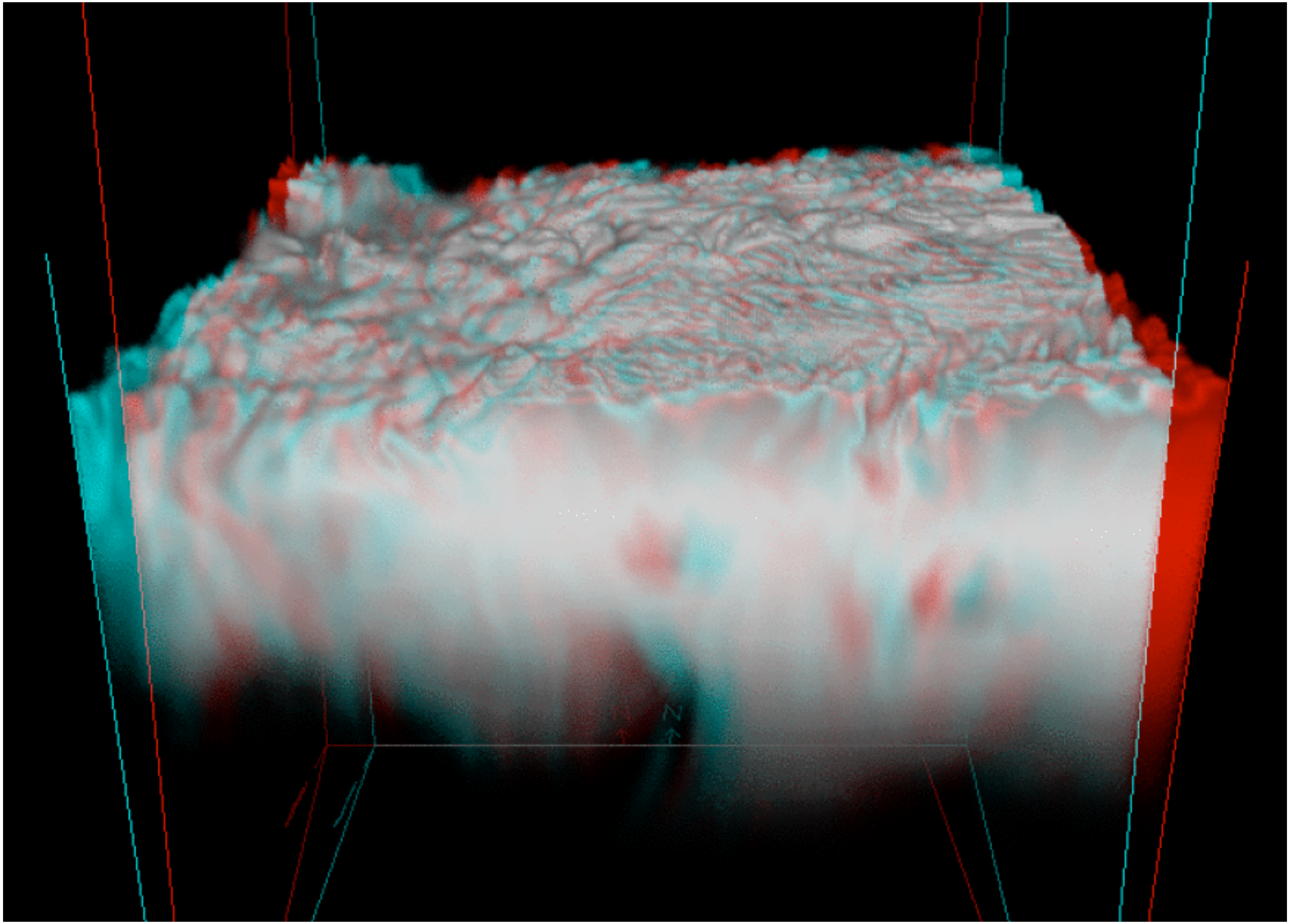
grid size = 50 m



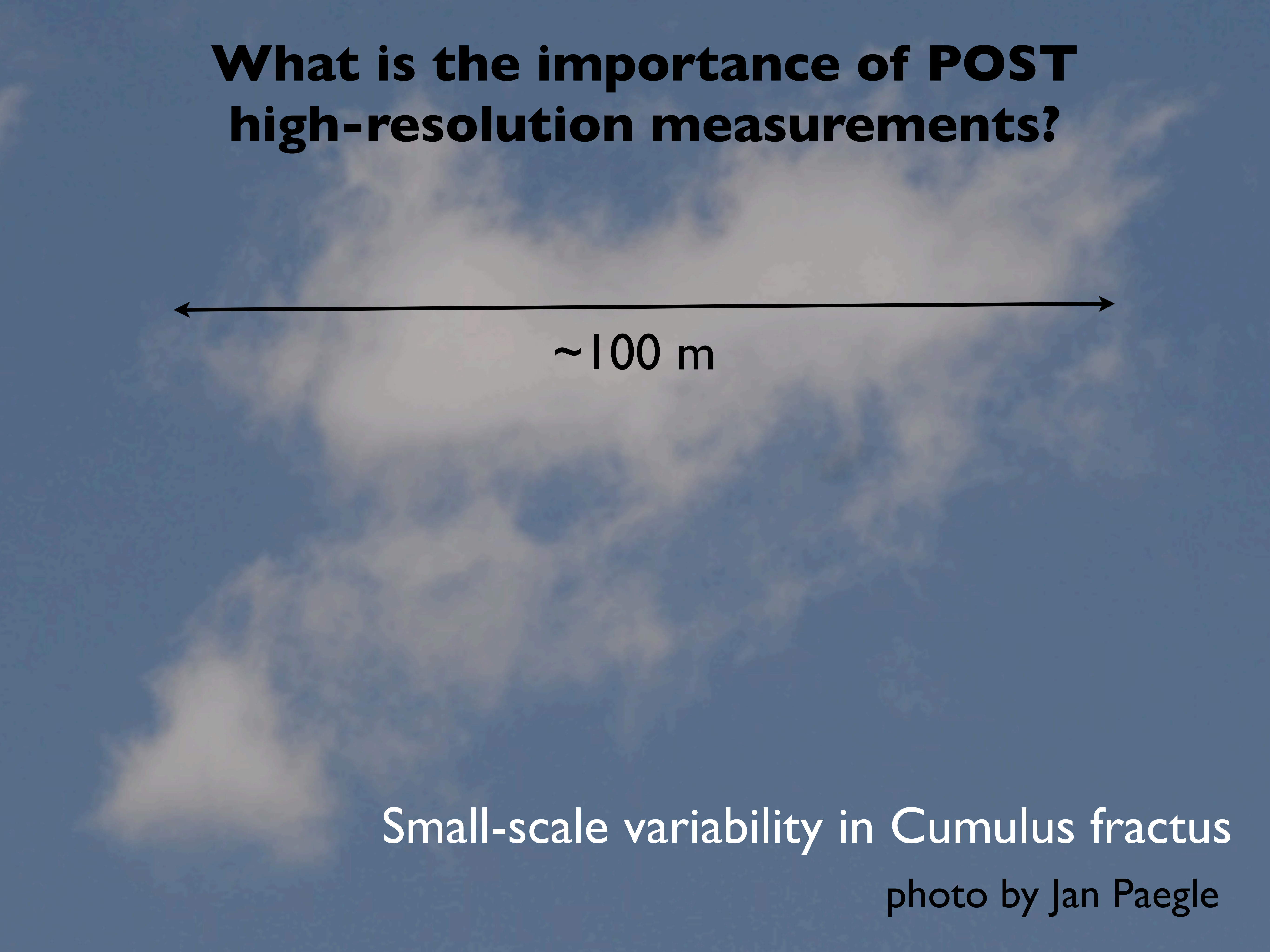
grid size = 6 m



a quarter of the domain



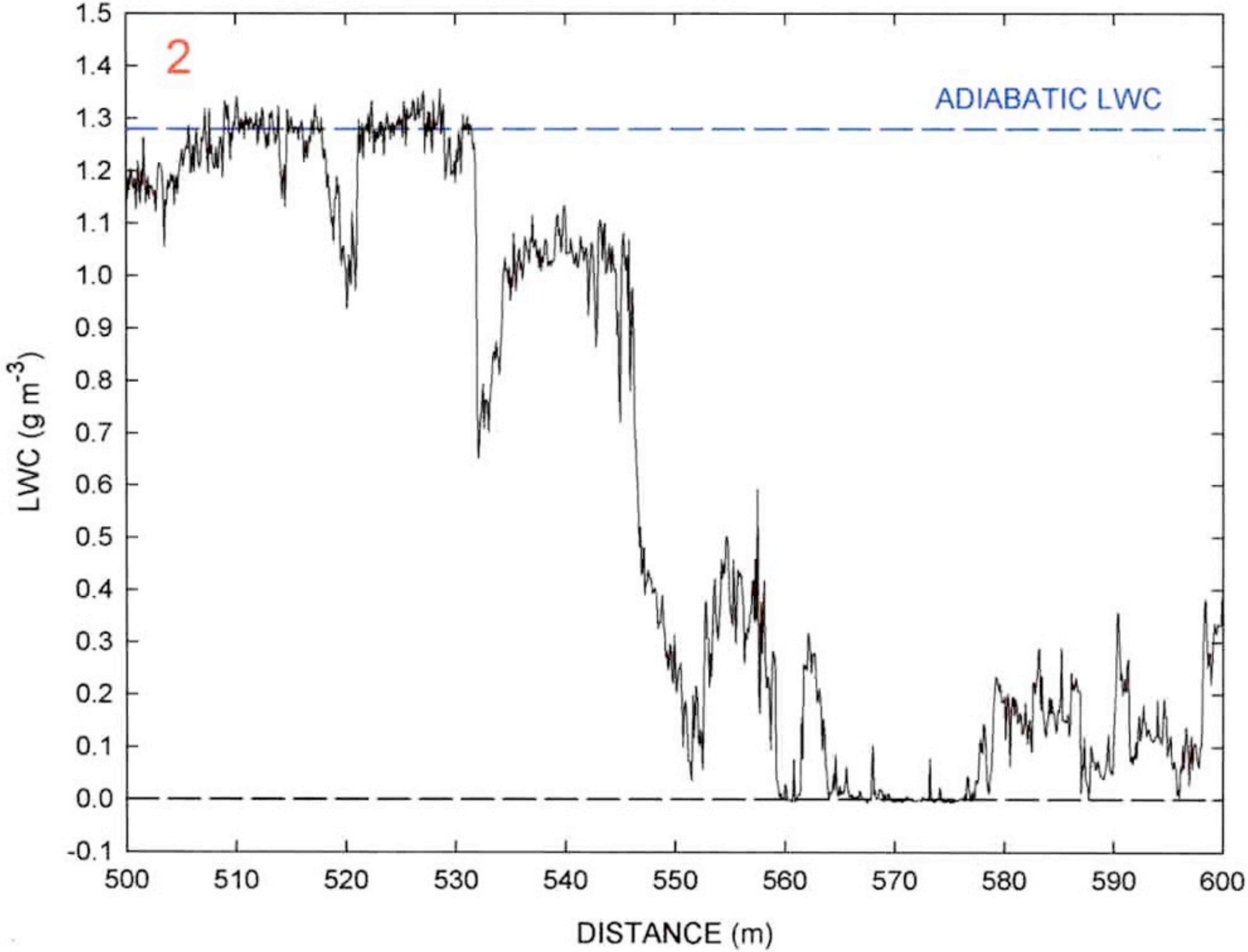
What is the importance of POST high-resolution measurements?



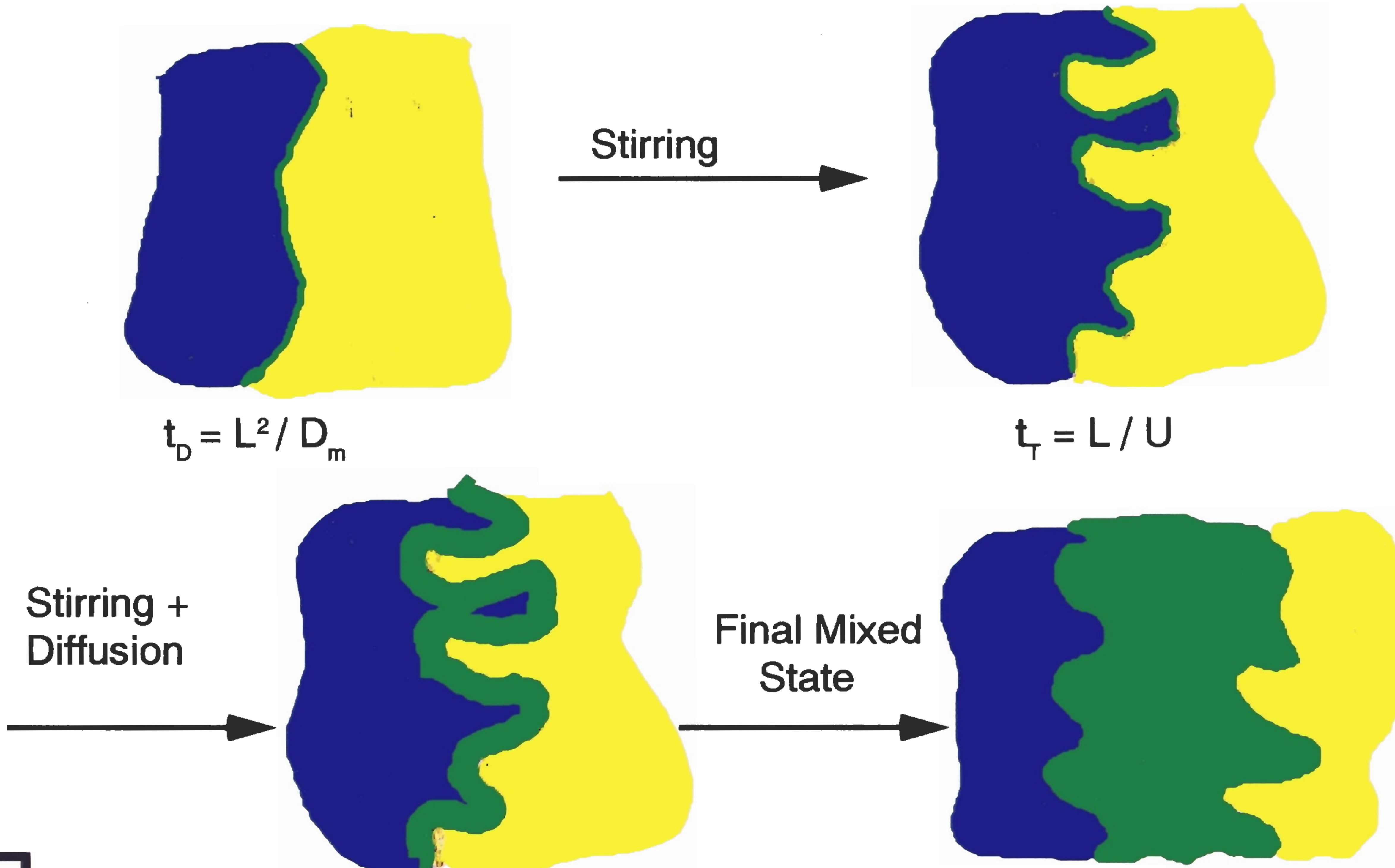
Small-scale variability in Cumulus fractus

photo by Jan Paegle

Aircraft Measurements of Liquid Water Content

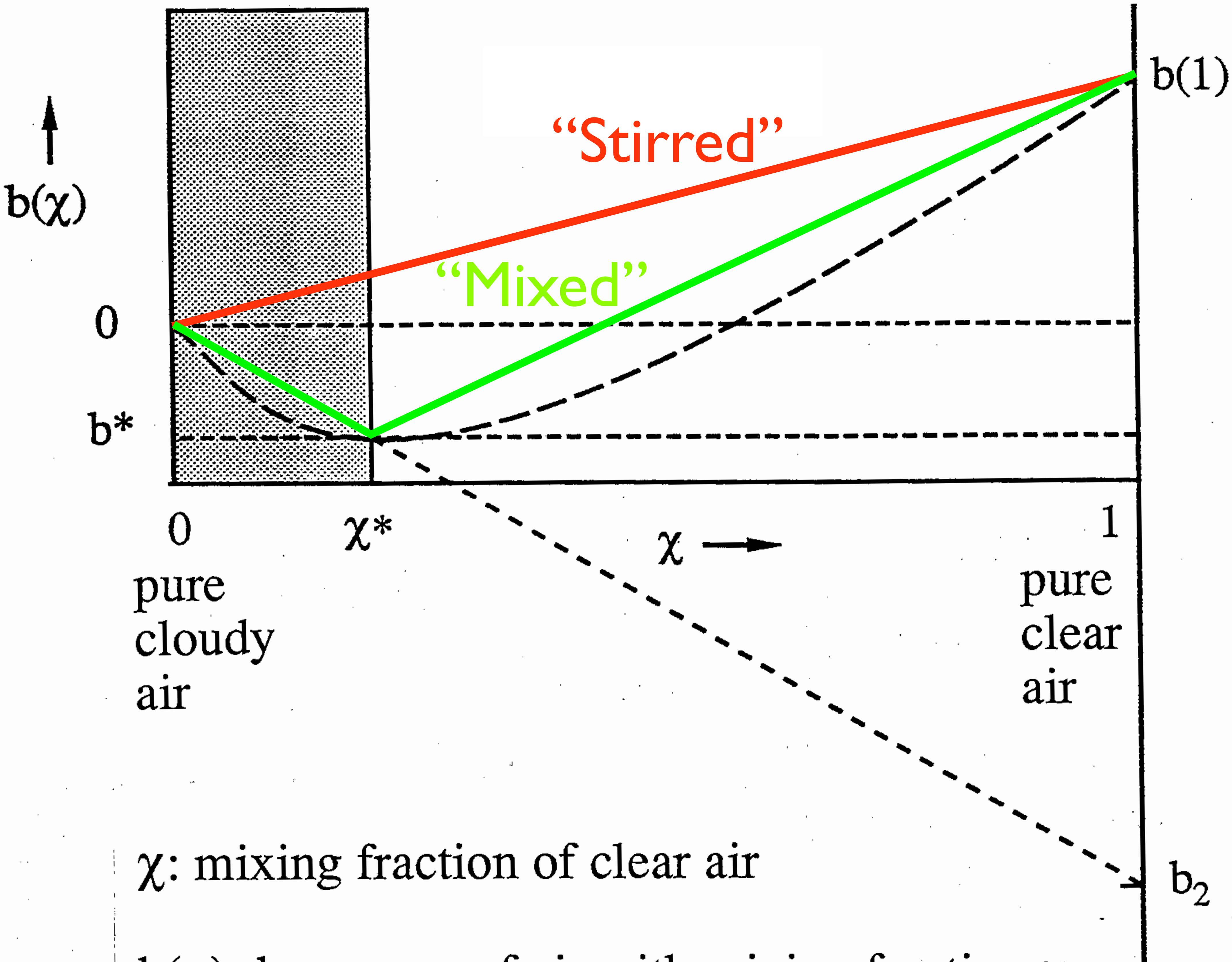


Turbulent Mixing: Process by which a fluid with two initially segregated scalar properties mix at the molecular level



LES of passive scalar in a convective boundary layer (grid size = 20 m)

Buoyancy vs Mixture Fraction



χ: mixing fraction of clear air

b(χ): buoyancy of air with mixing fraction χ

How small does the grid size need to be to *adequately* resolve Sc cloud-top entrainment and mixing?

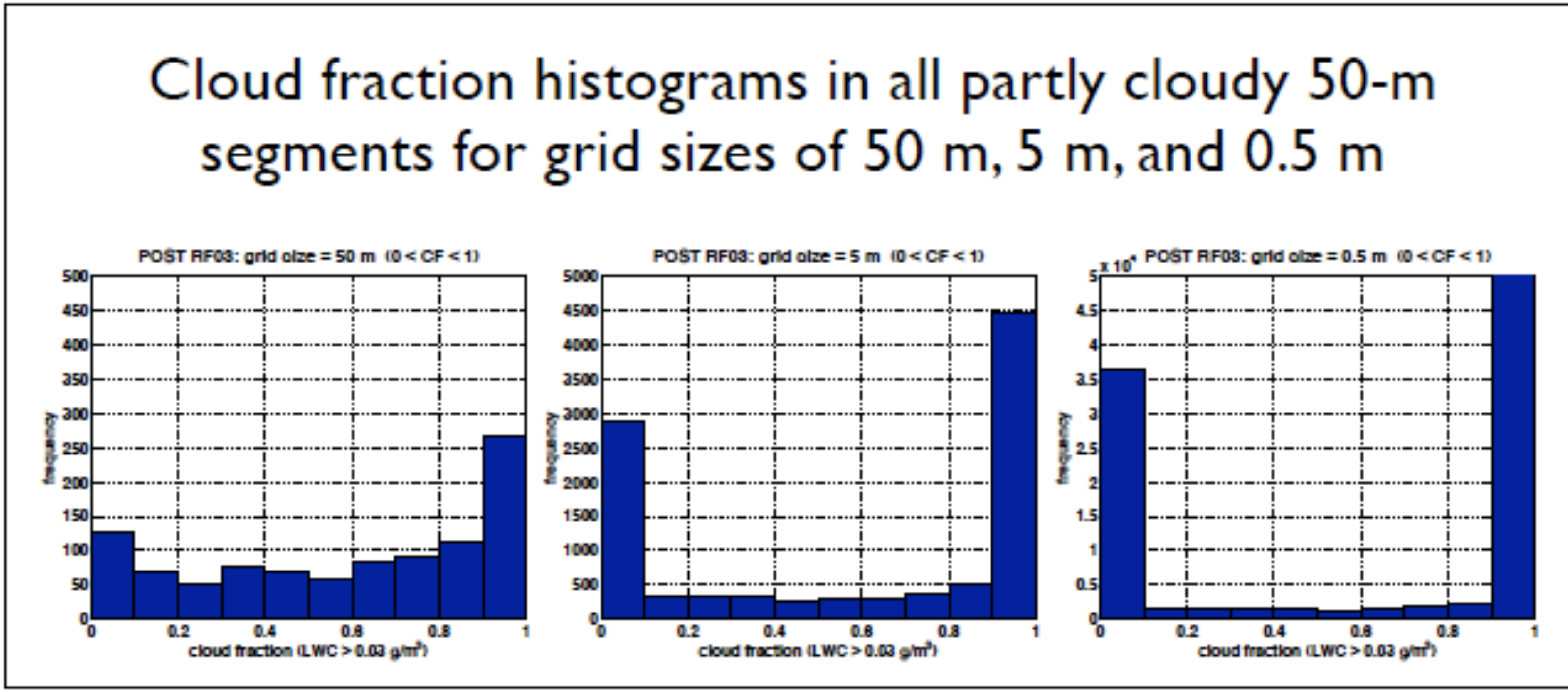
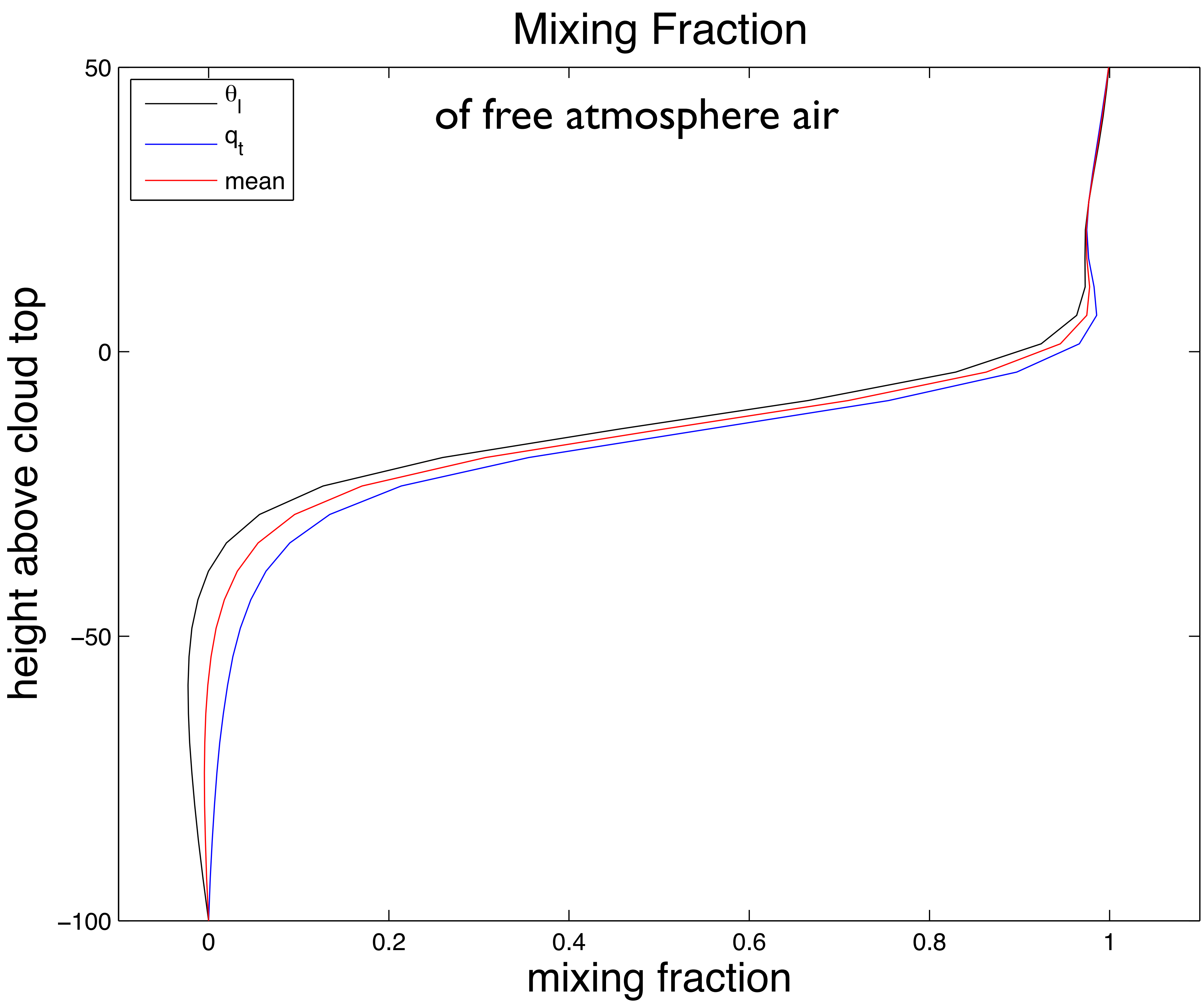


Figure 2: Cloud fraction histograms in all partly cloudy 50-m segments for grid sizes of 50 m, 5 m, and 0.5 m.

POST analysis plans

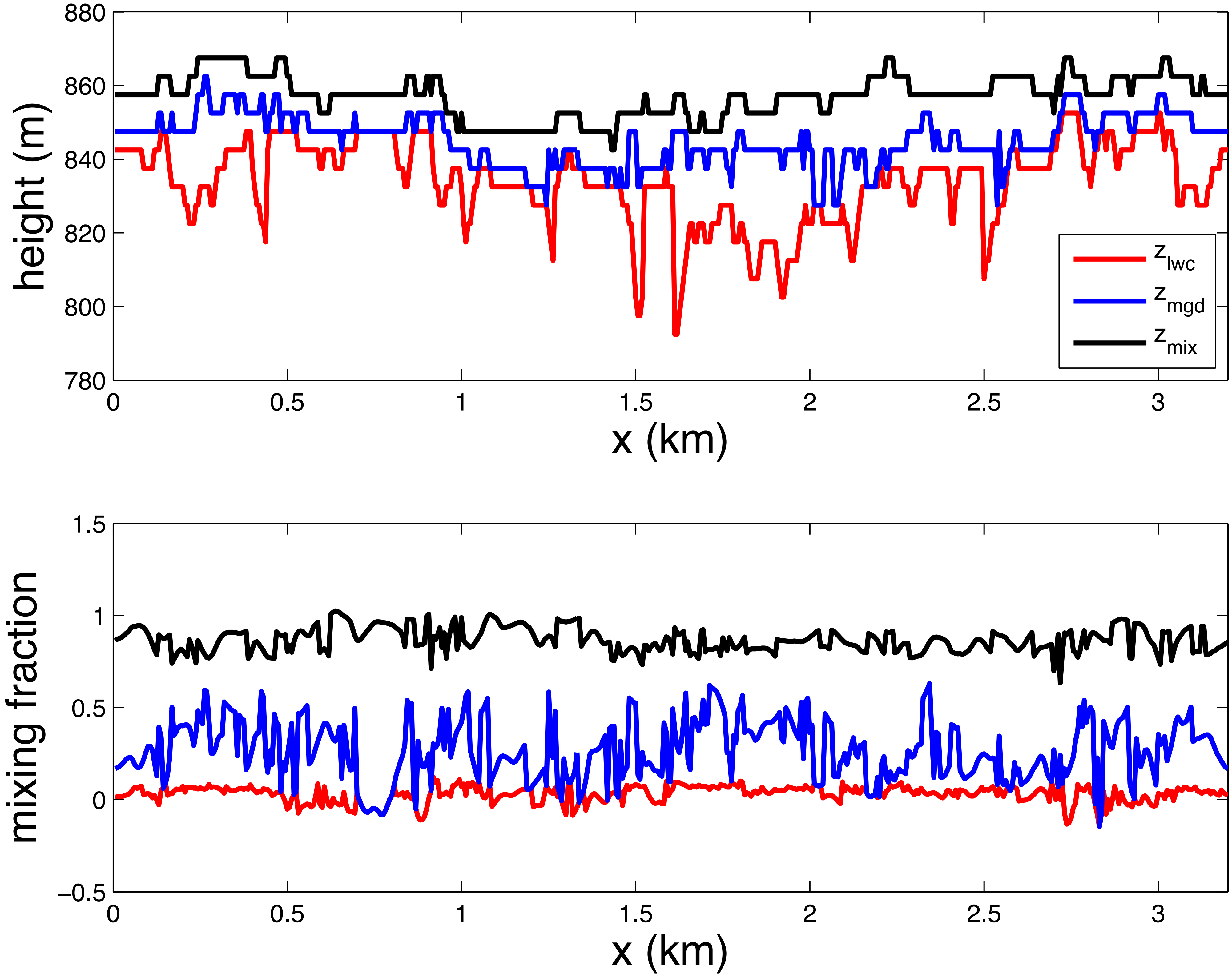
(prototyped using high-resolution LES results)

from LES

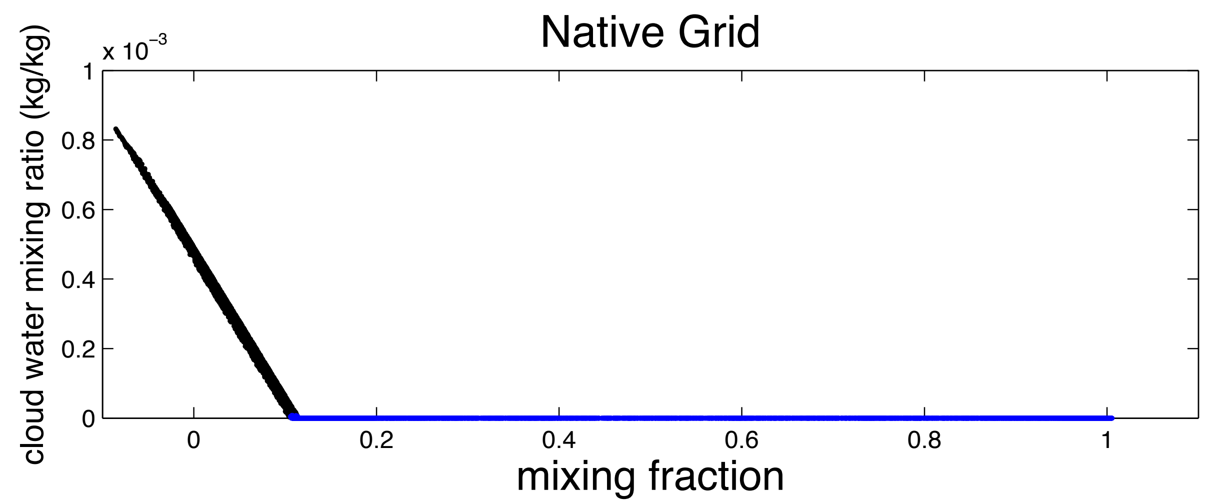

Mixing Fraction
of free atmosphere air
θl
qt
mean
height above cloud top
mixing fraction
50
0
−50
−100
0
0.2
0.4
0.6
0.8
1

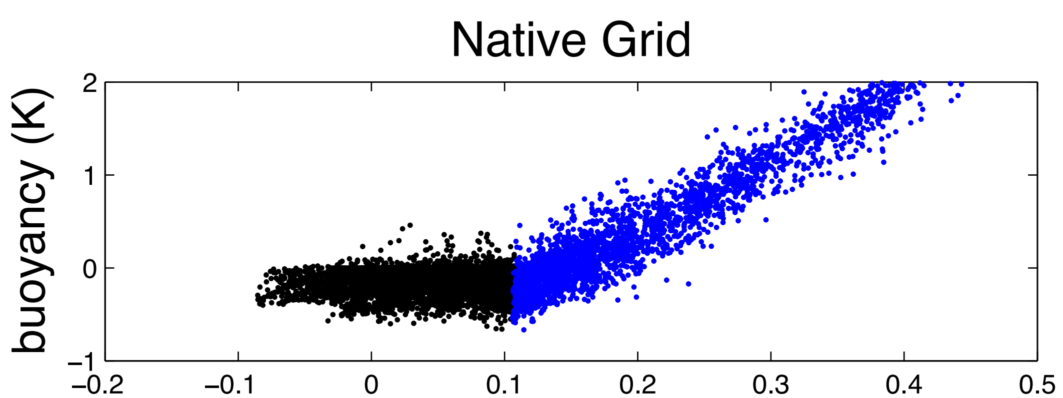
Interface heights from LES

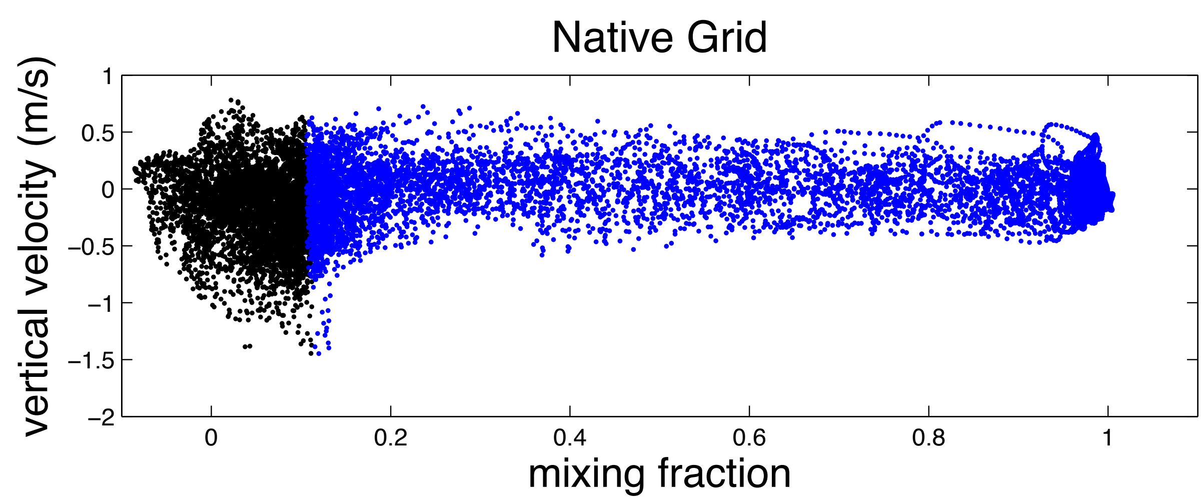
- mixing top
- maximum gradient level
- cloud top

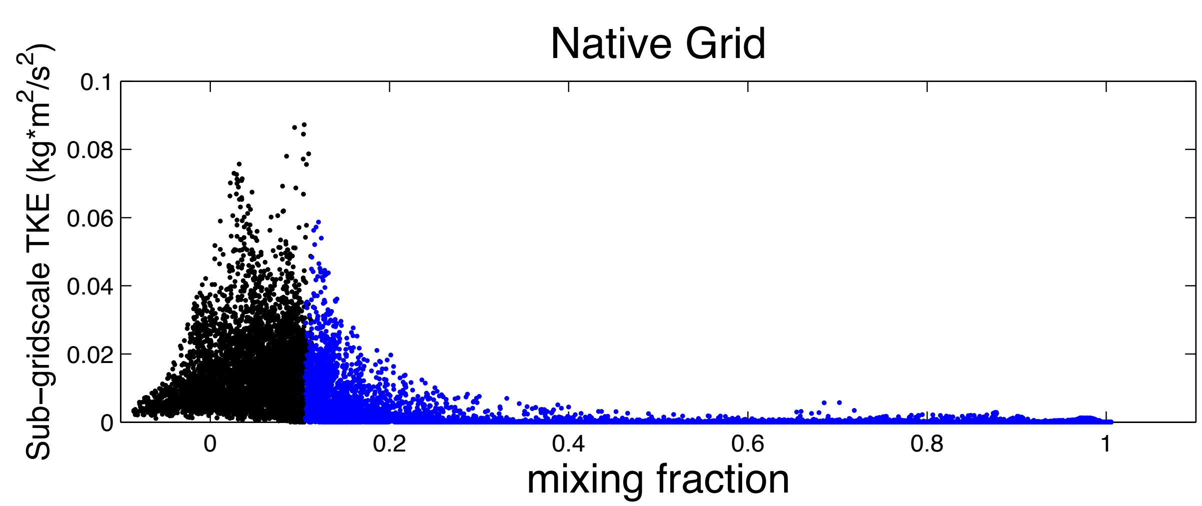


EIL (entrainment interface layer) properties vs mixing fraction from LES









POST summary

- Almost all instruments performed as hoped for most of the flights.
- Main disappointment is lack of high-rate water vapor measurements.
- Co-located high-rate liquid water and temperature measurements will allow unprecedented analyses of mixing process at Sc cloud tops.