Clear-sky and Cloudy Boundary Layers

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Define Boundary Layer

Stull (1988) defined the atmospheric boundary layer as "the part of the troposphere that is directly influenced by the presence of the earth's surface, and responds to surface forcings with a time scale of *about an hour or less*."

Typical Boundary Layer Depths and time-scales

Scenario	Time/Length scale
Clear-air Convective	30 mins/1 km
Cumulus Topped Boundary Layer	30 mins/1 km
Stratocumulus Topped Boundary Layer	1 hour/1-1.5 km
Deep Convection	30-60 min/~10-15 km

Stull (1988)

Sources of Turbulence

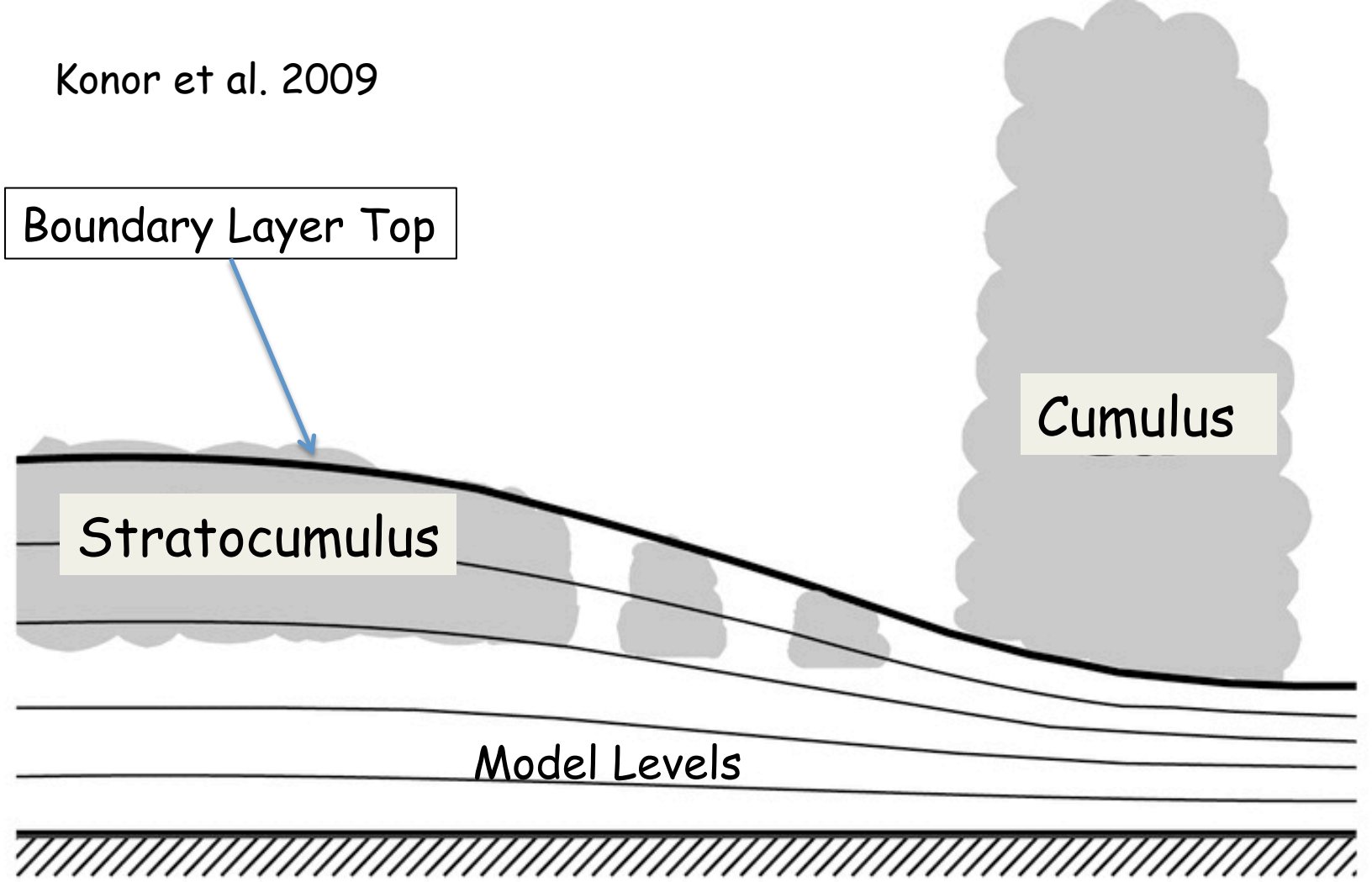
$$\frac{\partial \overline{e}}{\partial t} + \overline{\mathbf{u}} \cdot \nabla \overline{e} = S + B + T + D$$

e = Ensemble Mean Turbulent Kinetic Energy
S = Shear term. Change in winds with height.
Always positive
B = Buoyancy term. e.g. surface heating, evaporation, radiative cooling, latent heating etc. Can be Positive or negative
T = Transport term. e.g. pressure perturbation term. Redistributes turbulence
D = Dissipation term. Always negative

Global Boundary Layer Depth

- NCEP reanalysis long-term (1981-2010) mean.
- 3 hourly values for the entire year in meters.

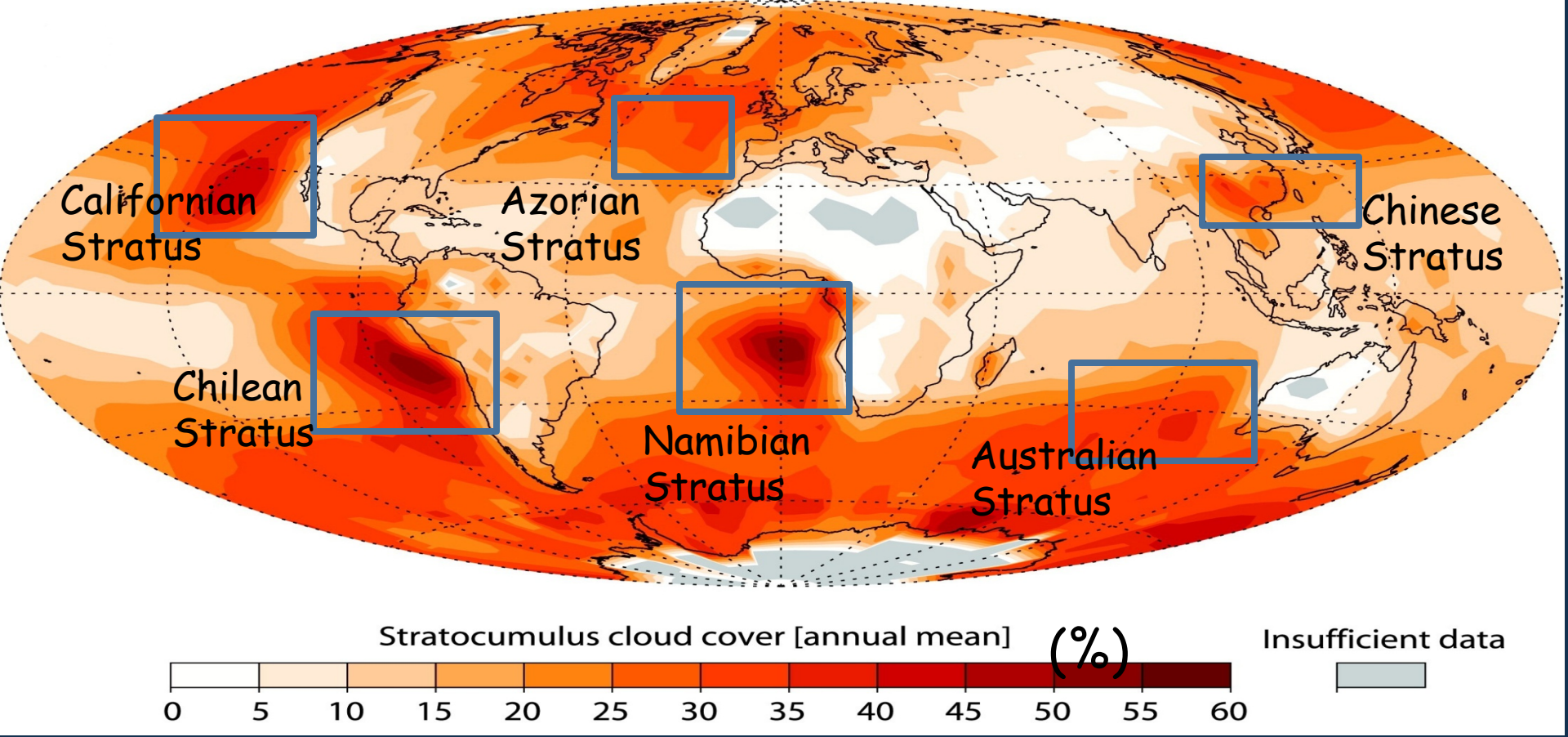
Konor et al. 2009



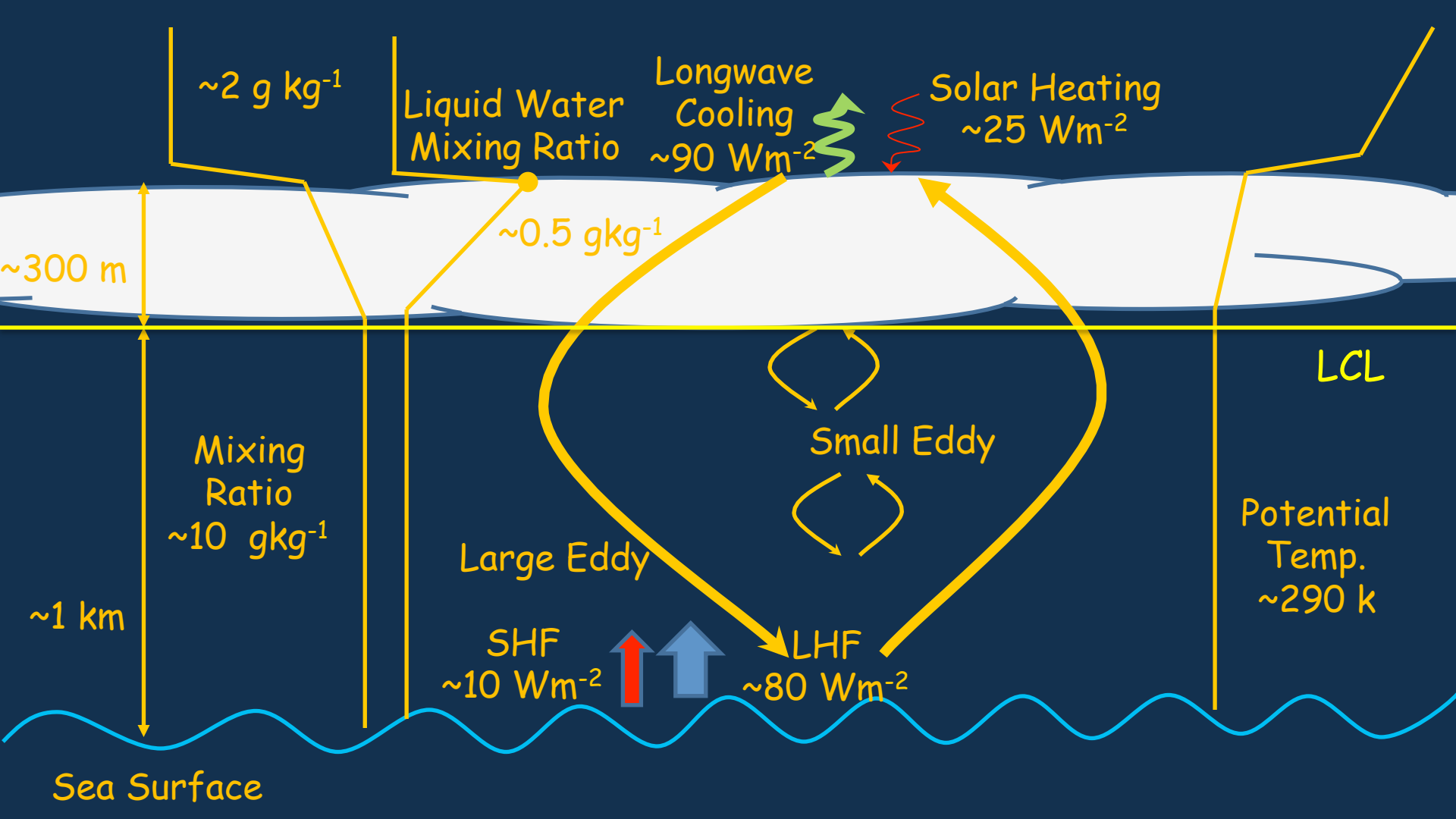
Boundary Layer

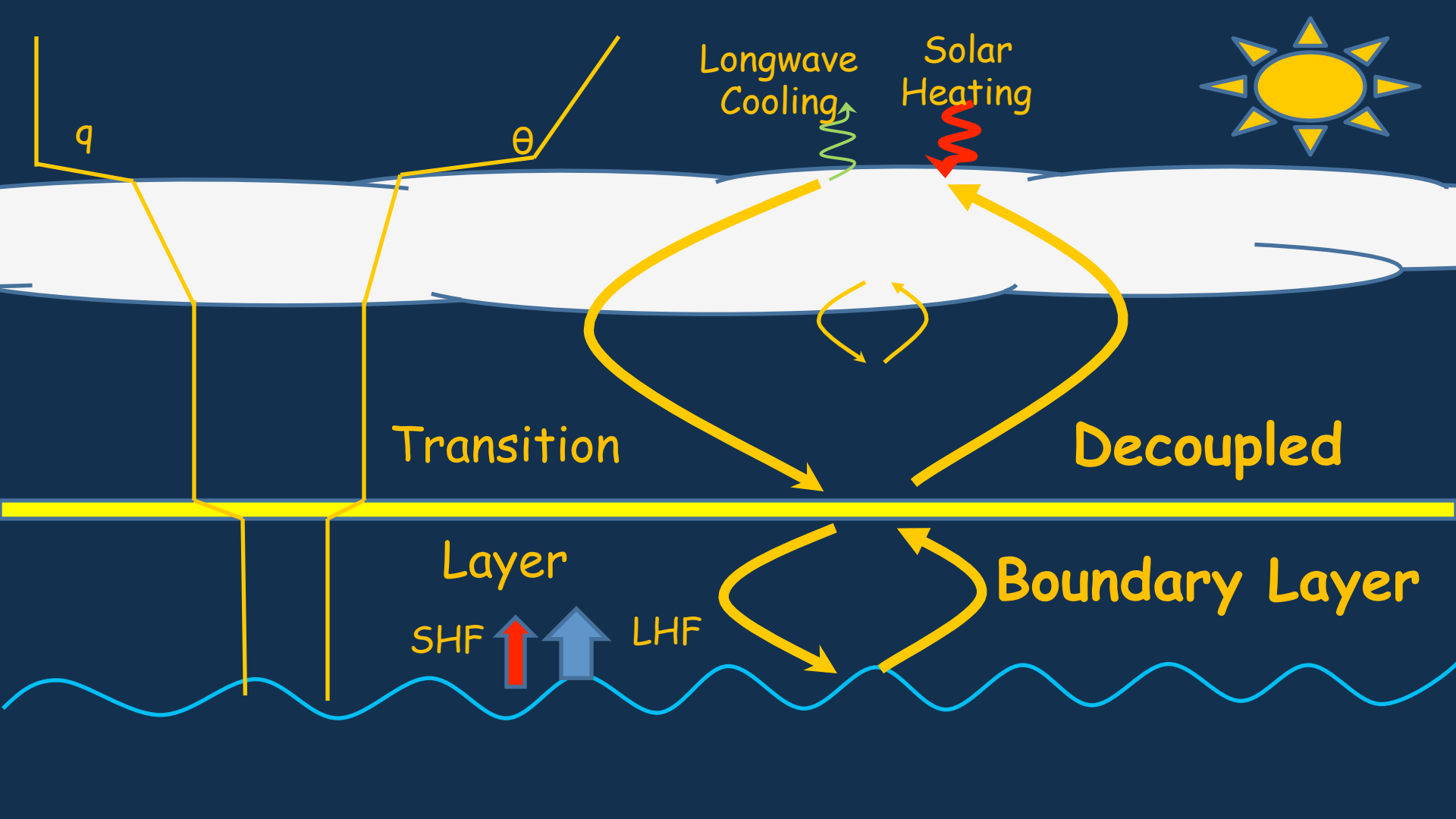
- Stratocumulus Topped Marine Boundary Layers

- Cumulus Topped Boundary Layer

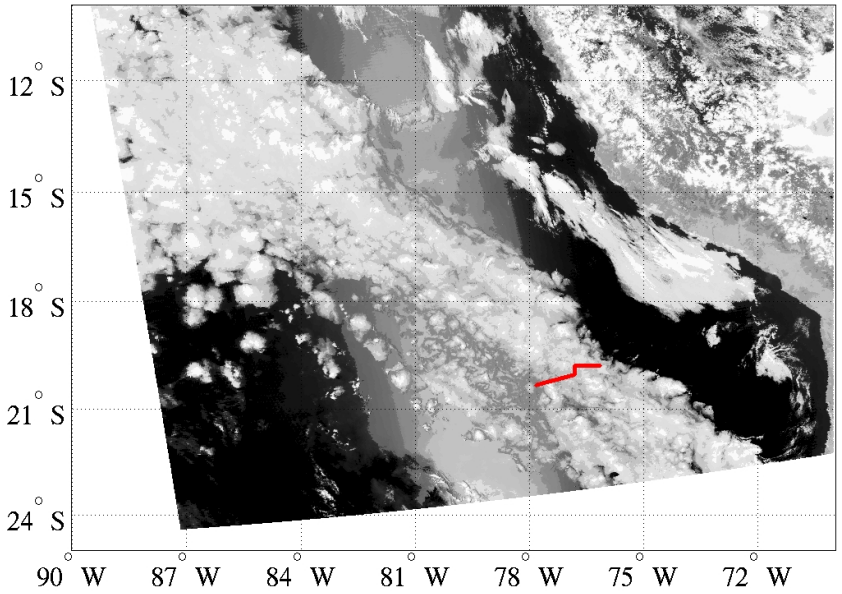


Hahn and Warren, 2007; Wood, 2012


~2 g kg-1
Liquid Water Mixing Ratio
~0.5 gkg-1
Longwave Cooling ~90 Wm-2
Solar Heating ~25 Wm-2
~300 m
LCL
Small Eddy
Large Eddy
Mixing Ratio ~10 gkg-1
Potential Temp. ~290 k
~1 km
SHF ~10 Wm-2
LHF ~80 Wm-2
Sea Surface

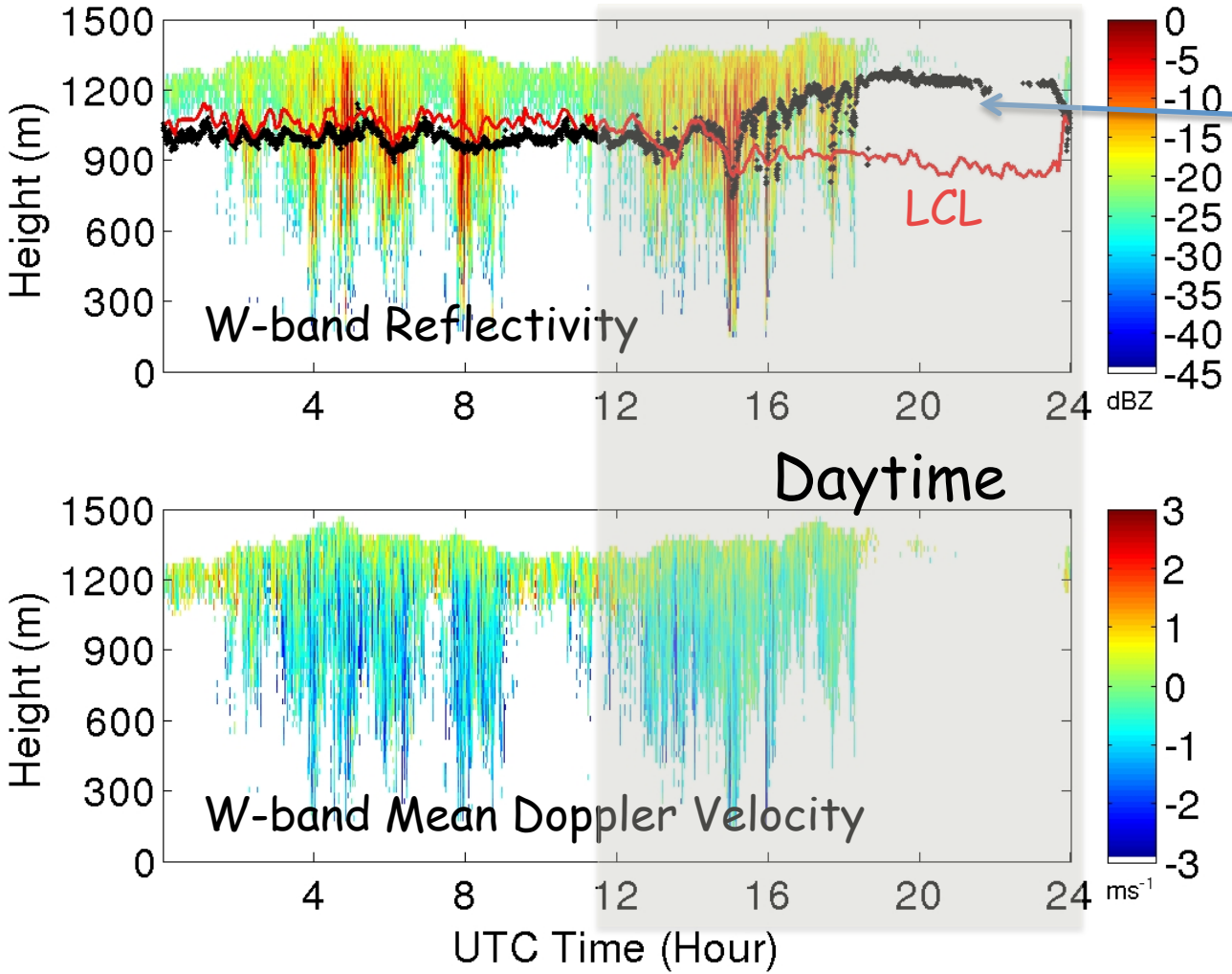

q
θ
Longwave Cooling
Solar Heating
Transition Layer
Decoupled Boundary Layer
SHF
LHF

VOCALS Field Campaign, 2008

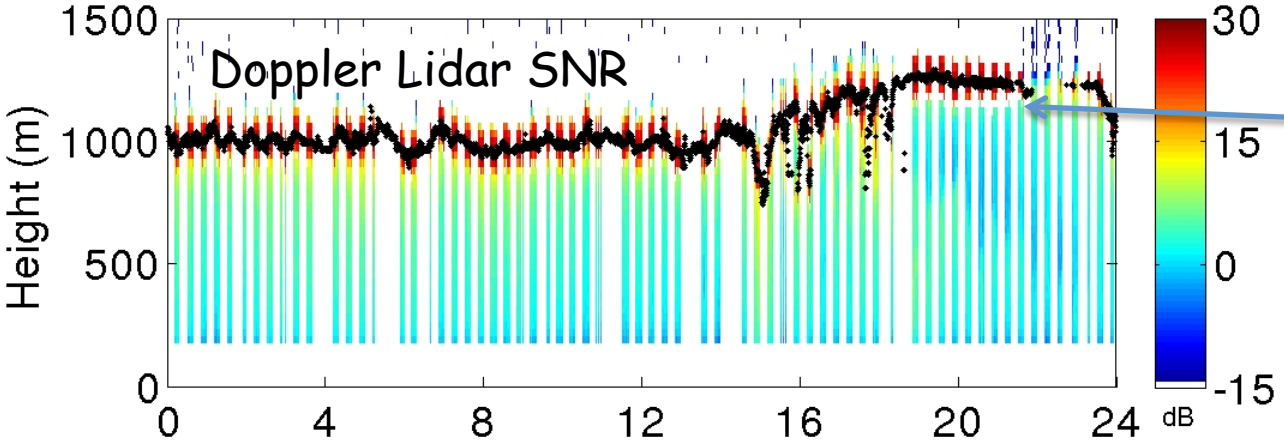


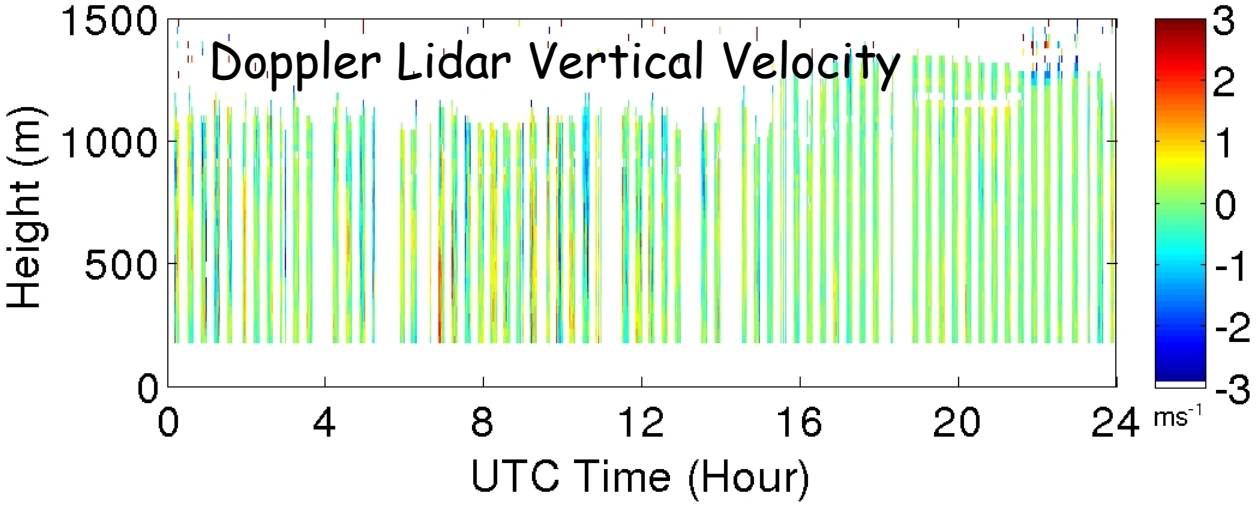
- VAMOS Ocean-Cloud-Atmosphere-Land Study (VOCALS)
- Use observations made onboard R/V Ronald H. Brown

- Characterize the dynamical structure of the entire stratocumulus topped boundary layer.
- Contrast Coupled Vs Decoupled Conditions

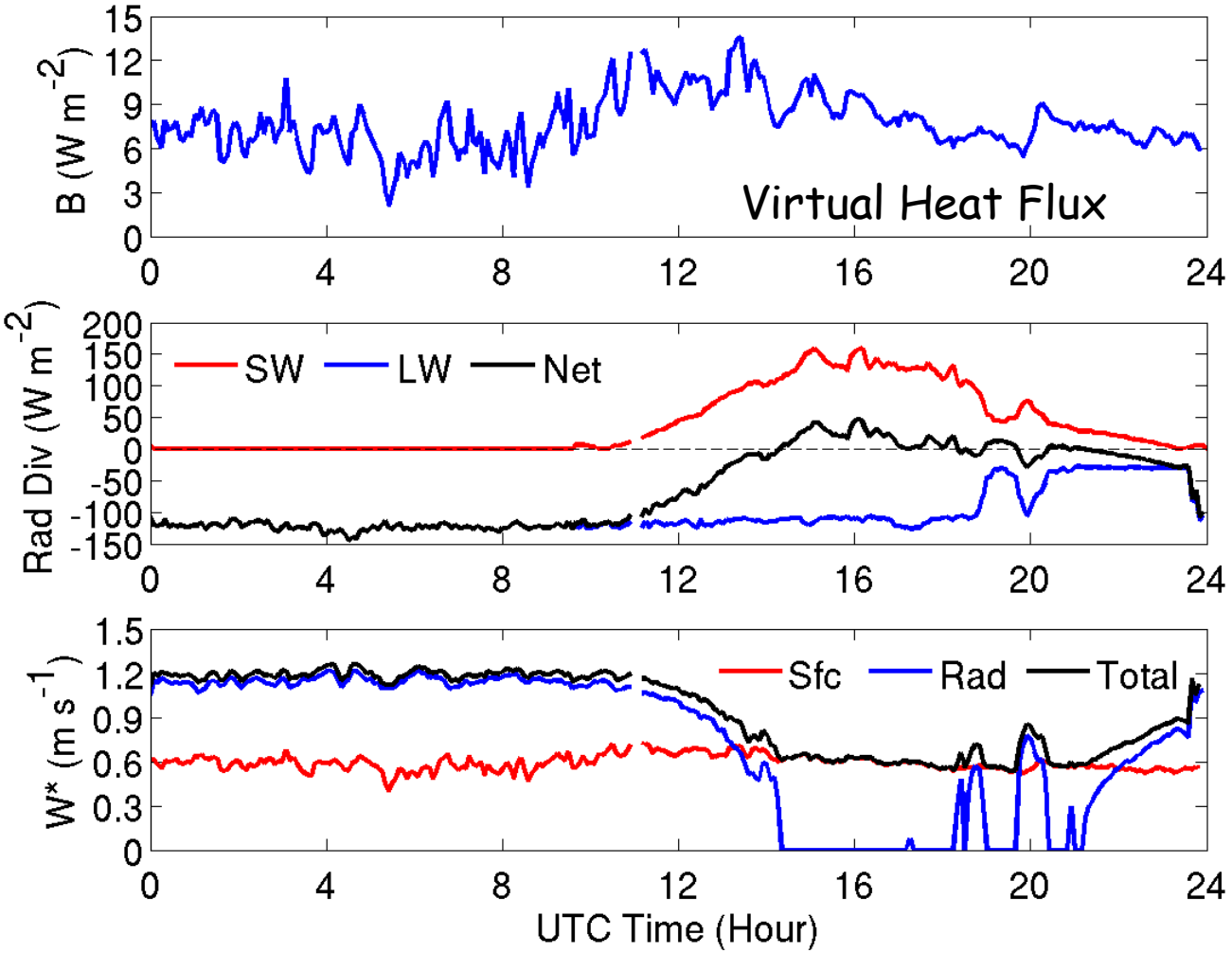


Ceilometer Cloud Base



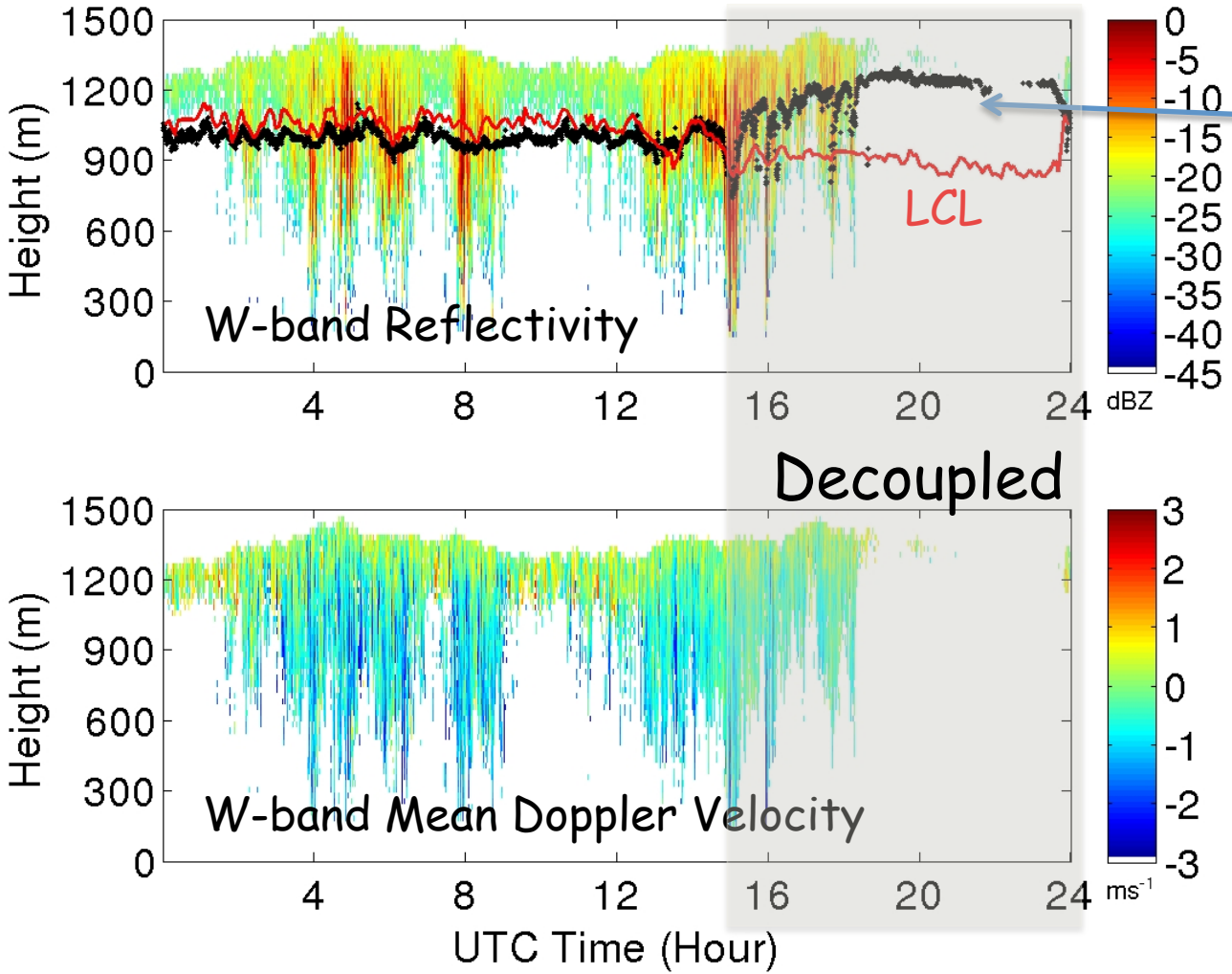


Ceilometer Cloud Base

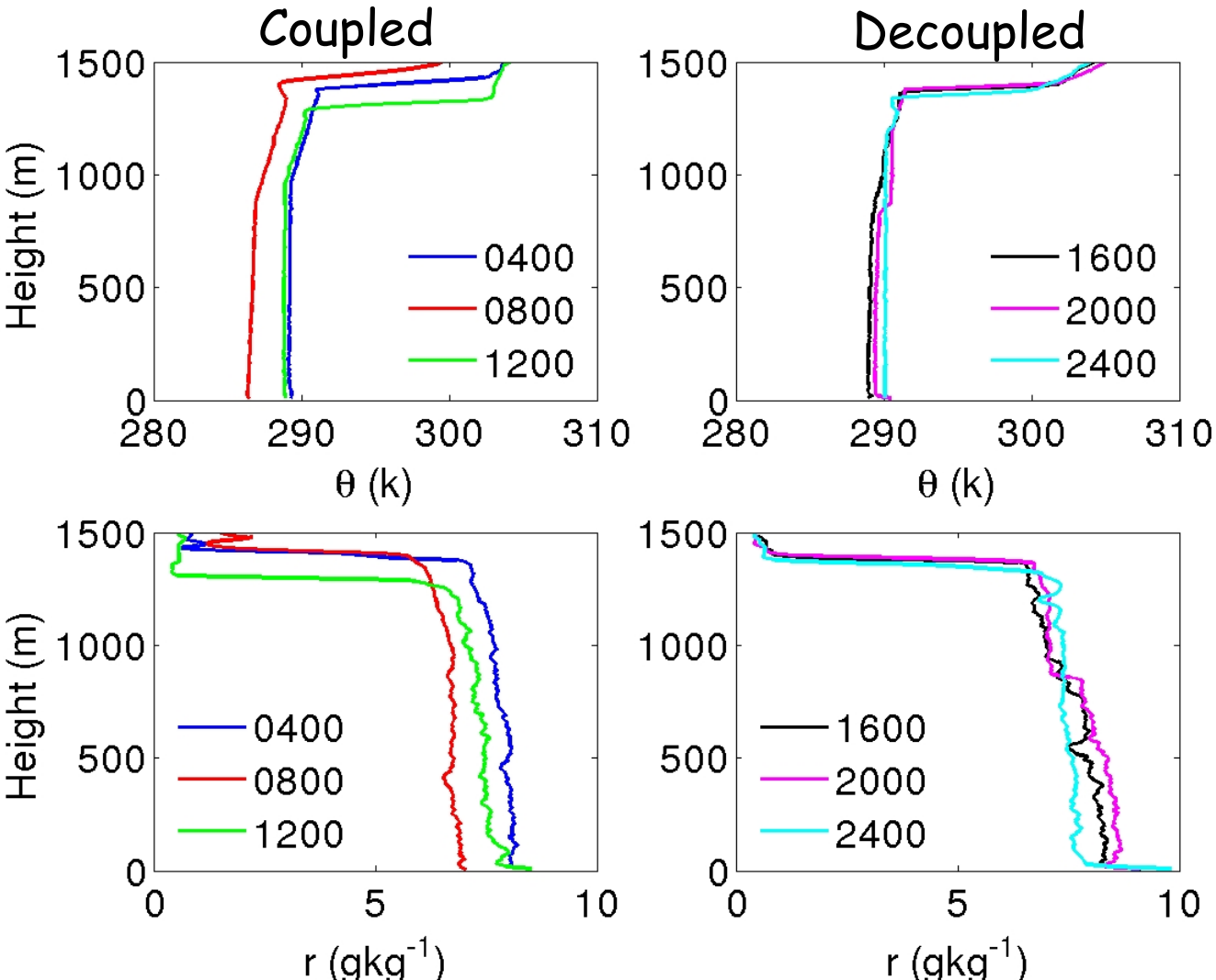


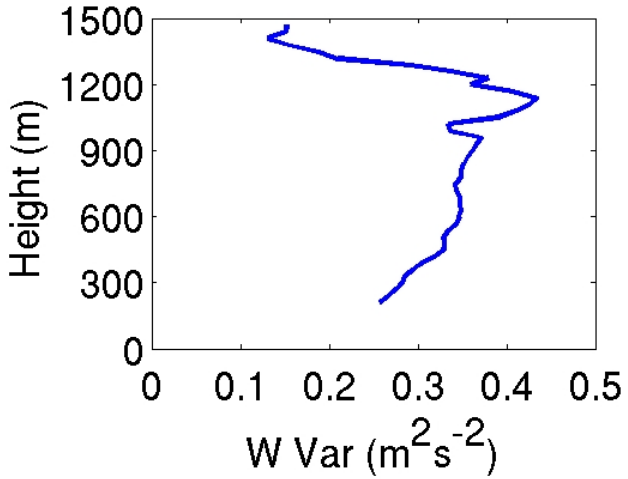
Surface Buoyancy

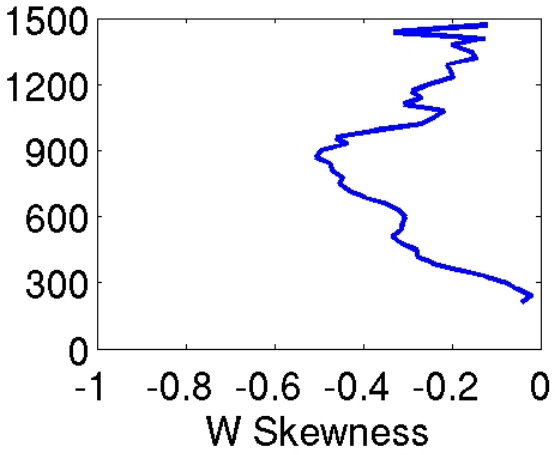
Cloud Top Buoyancy



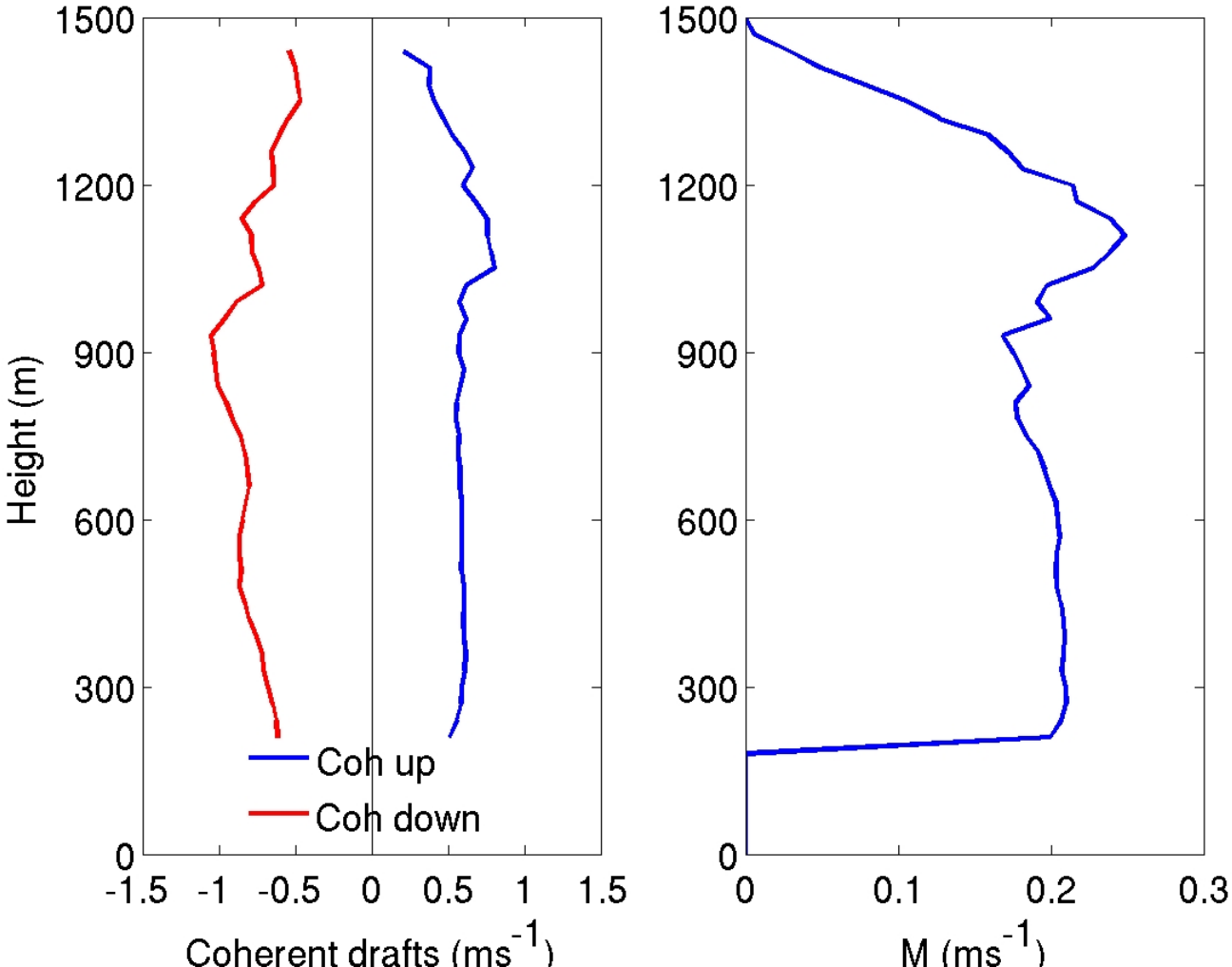
Ceilometer Cloud Base

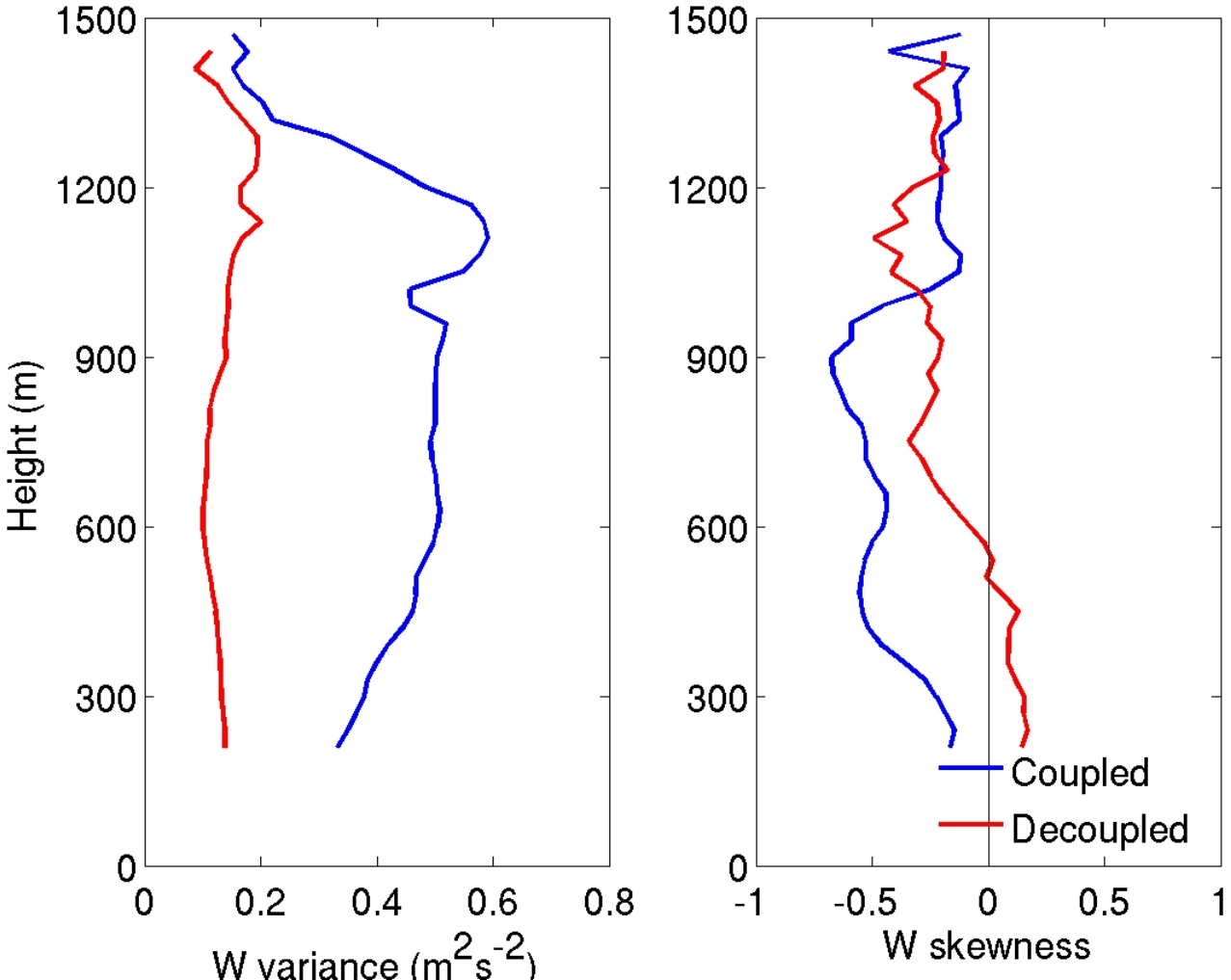

Coupled
Decoupled
Height (m)
1500
1000
500
0
280
290
300
310
θ (k)
0400
0800
1200
1600
2000
2400
0
5
10
r (gkg-1)

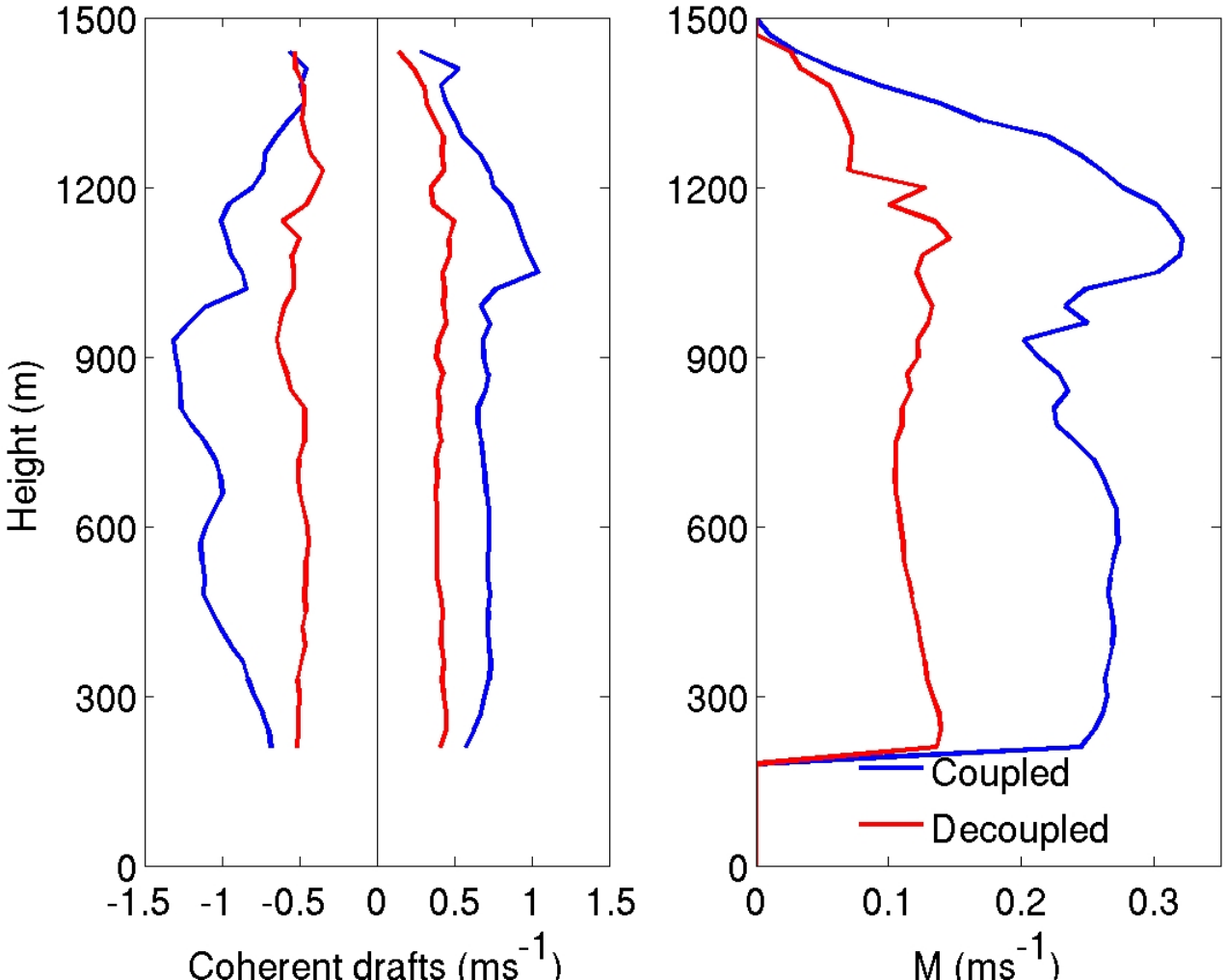




- Variance of Vertical Velocity peaks near cloud base.
- Skewness of vertical velocity is negative in the entire boundary layer … downdrafts stronger than updrafts.

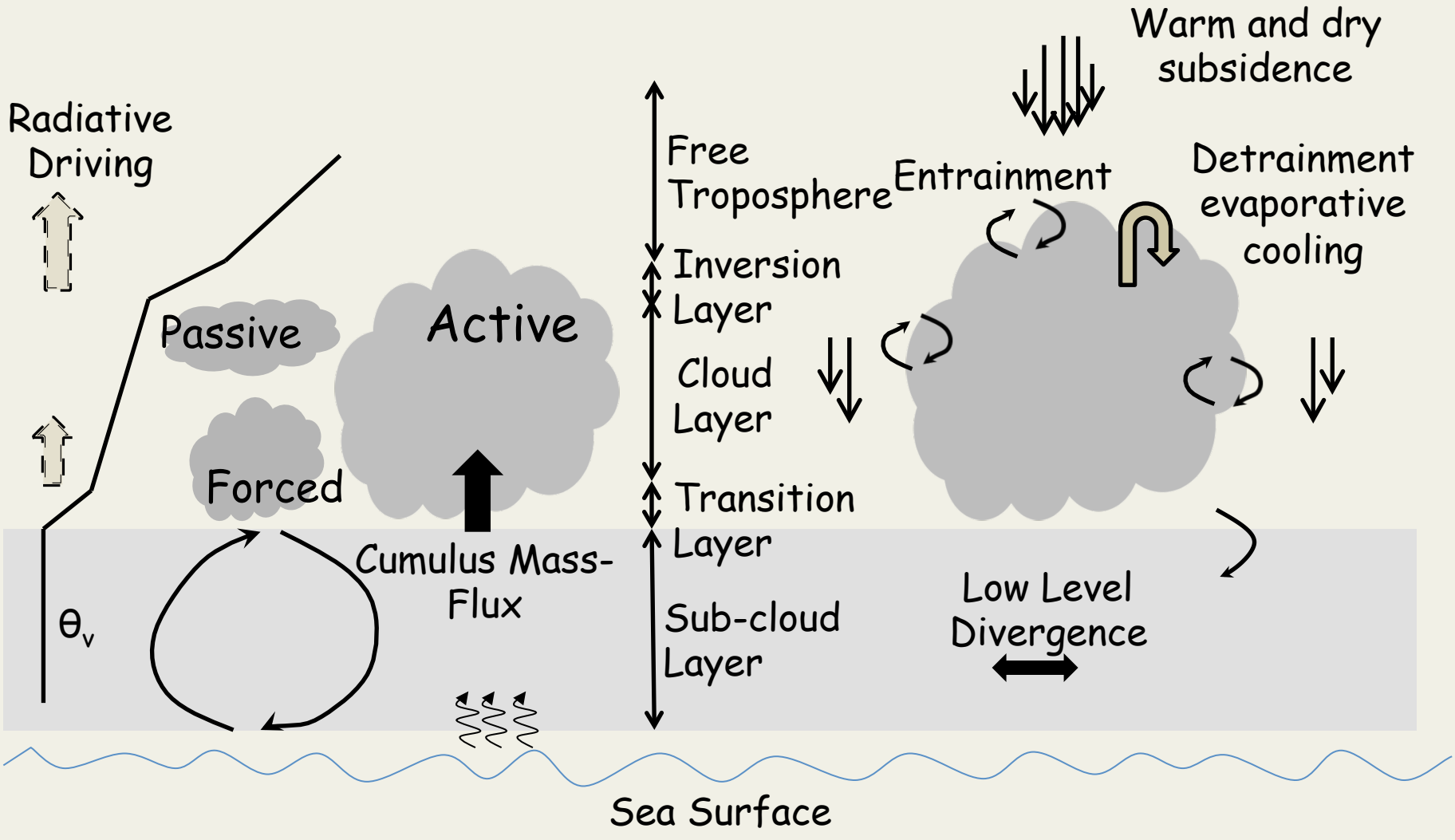

1500
1200
900
600
300
0
Height (m)
-1.5
-1
-0.5
0
0.5
1
1.5
Coherent drafts (ms-1)
Coh up
Coh down
0
0.1
0.2
0.3
M (ms-1)


1500
1200
900
600
300
0
Height (m)
0
0.2
0.4
0.6
0.8
W variance (m2s-2)
-1
-0.5
0
0.5
1
W skewness
Coupled
Decoupled


1500
1200
900
600
300
0
Height (m)
-1.5
-1
-0.5
0
0.5
1
1.5
Coherent drafts (ms-1)
0
0.1
0.2
0.3
M (ms-1)
Coupled
Decoupled

Few Conclusions

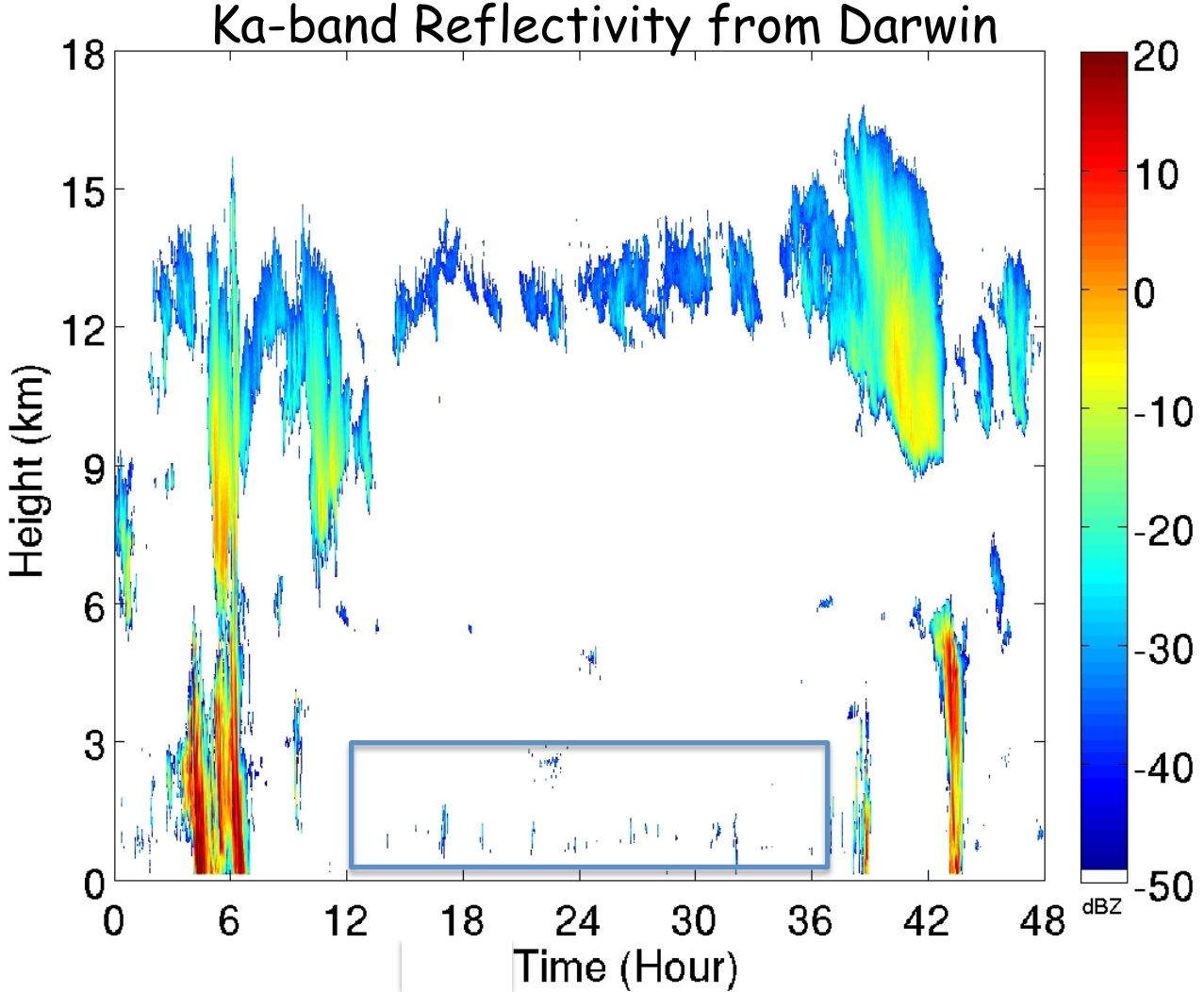
- Coherent updraft and downdrafts spanning through entire BL were observed during both coupled and decoupled conditions.
- Skewness of vertical velocity was positive in the lower third of BL during decoupled conditions.

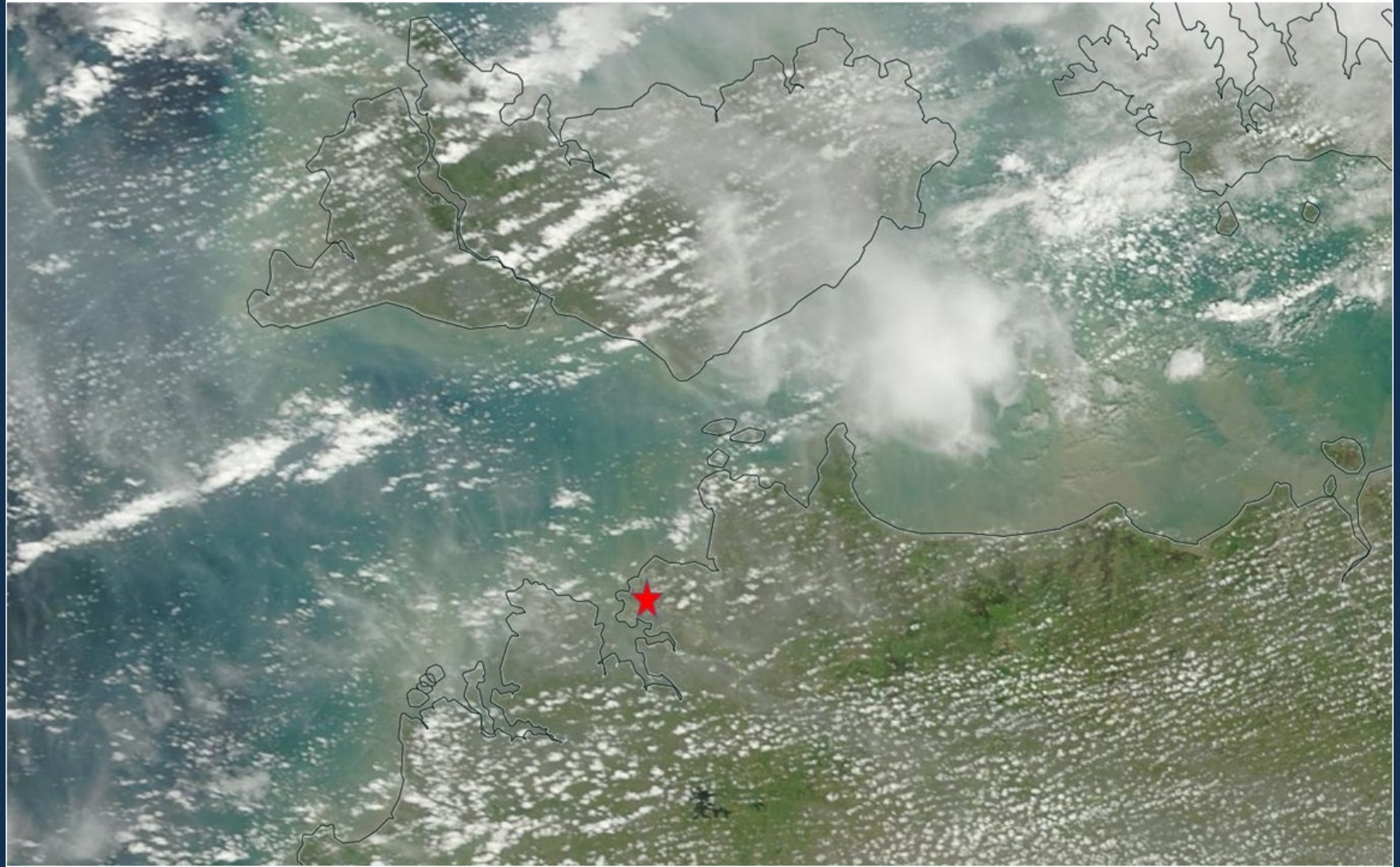

Warm and dry subsidence
Radiative Driving
Free Troposphere
Entrainment
Detrainment evaporative cooling
Inversion Layer
Passive
Active
Cloud Layer
Forced
Transition Layer
Cumulus Mass-Flux
θ_v
Sub-cloud Layer
Low Level Divergence
Sea Surface

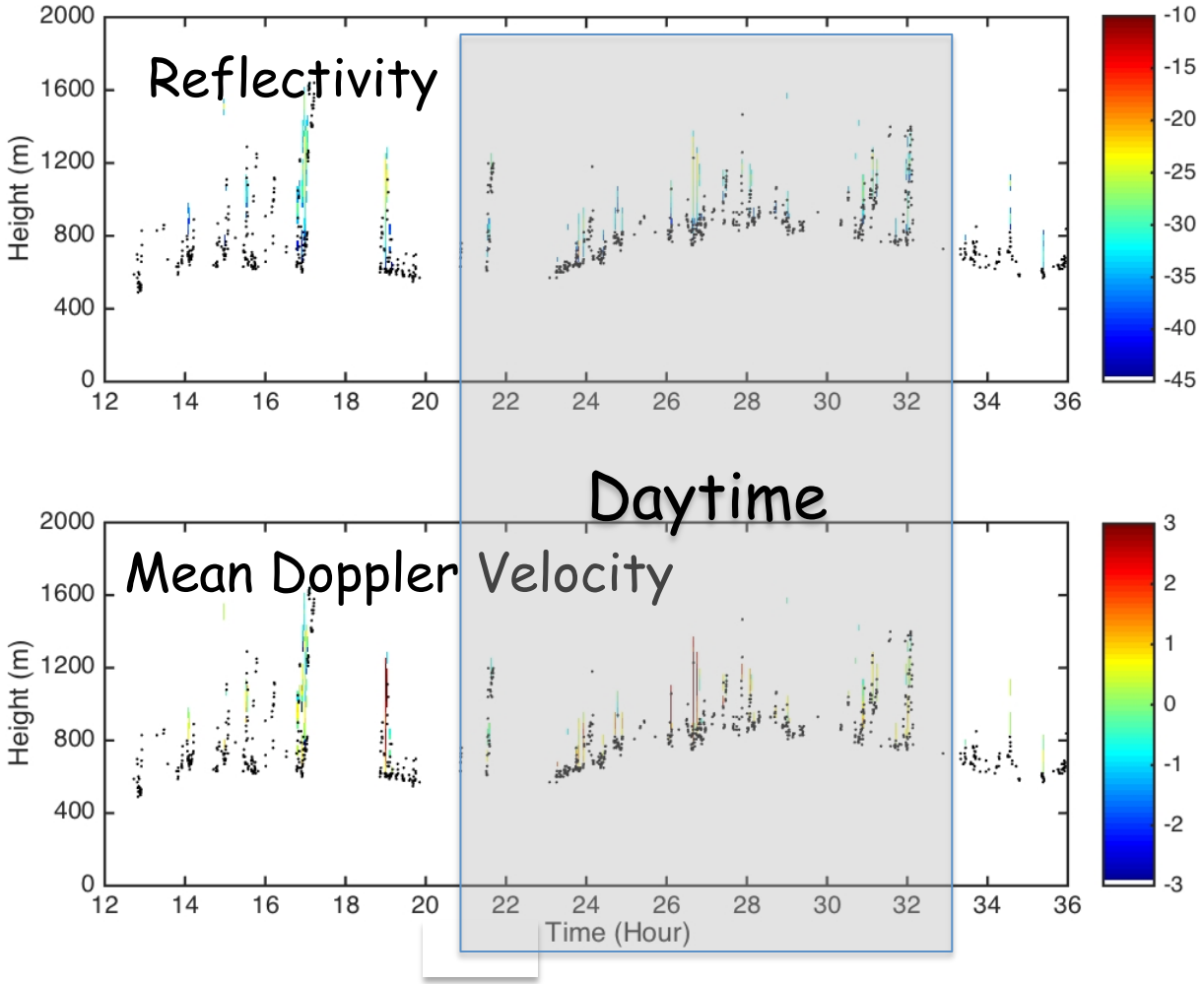
Cumulus Topped Boundary Layer

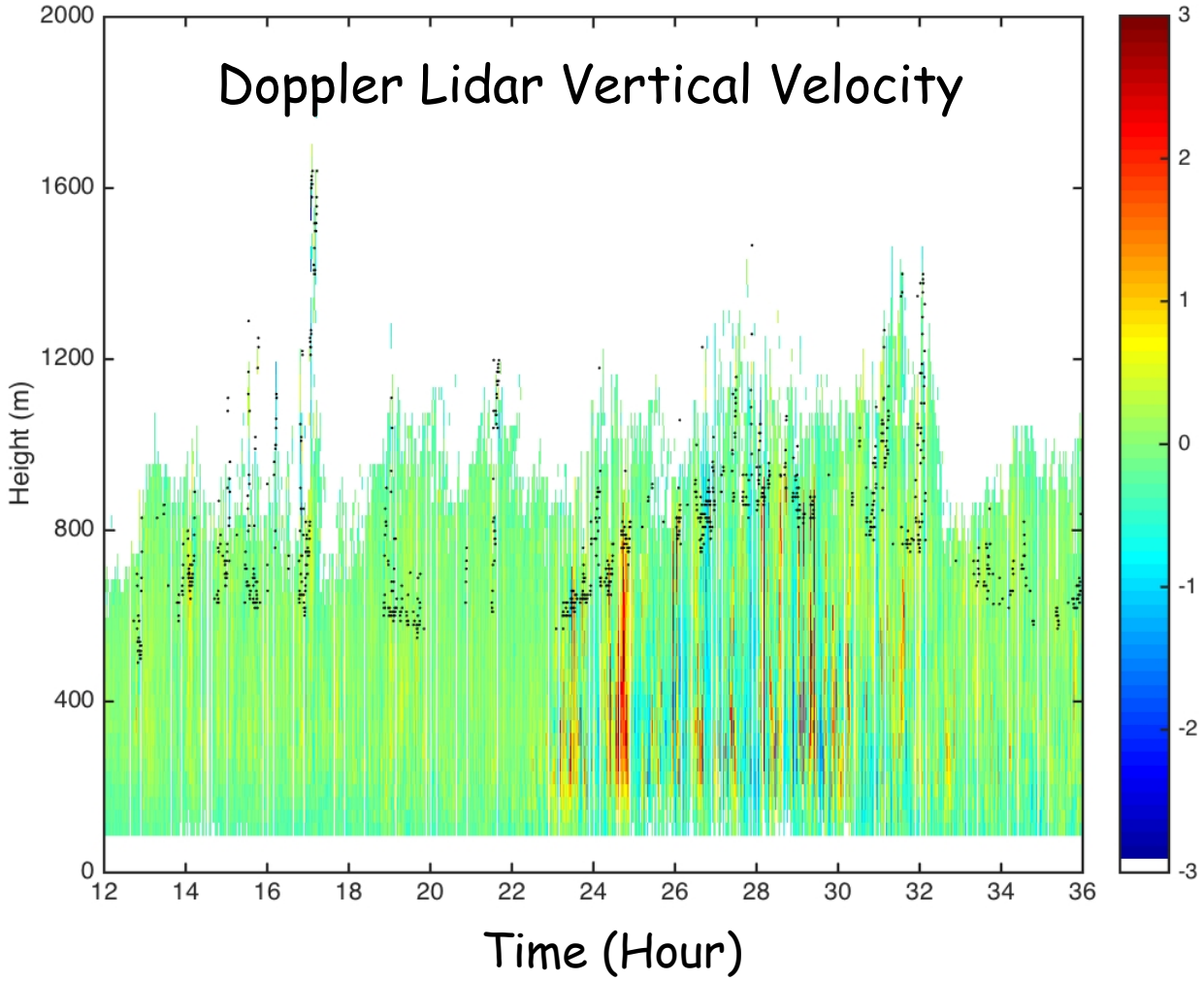
- Characterize the dynamical structure of the boundary layer.

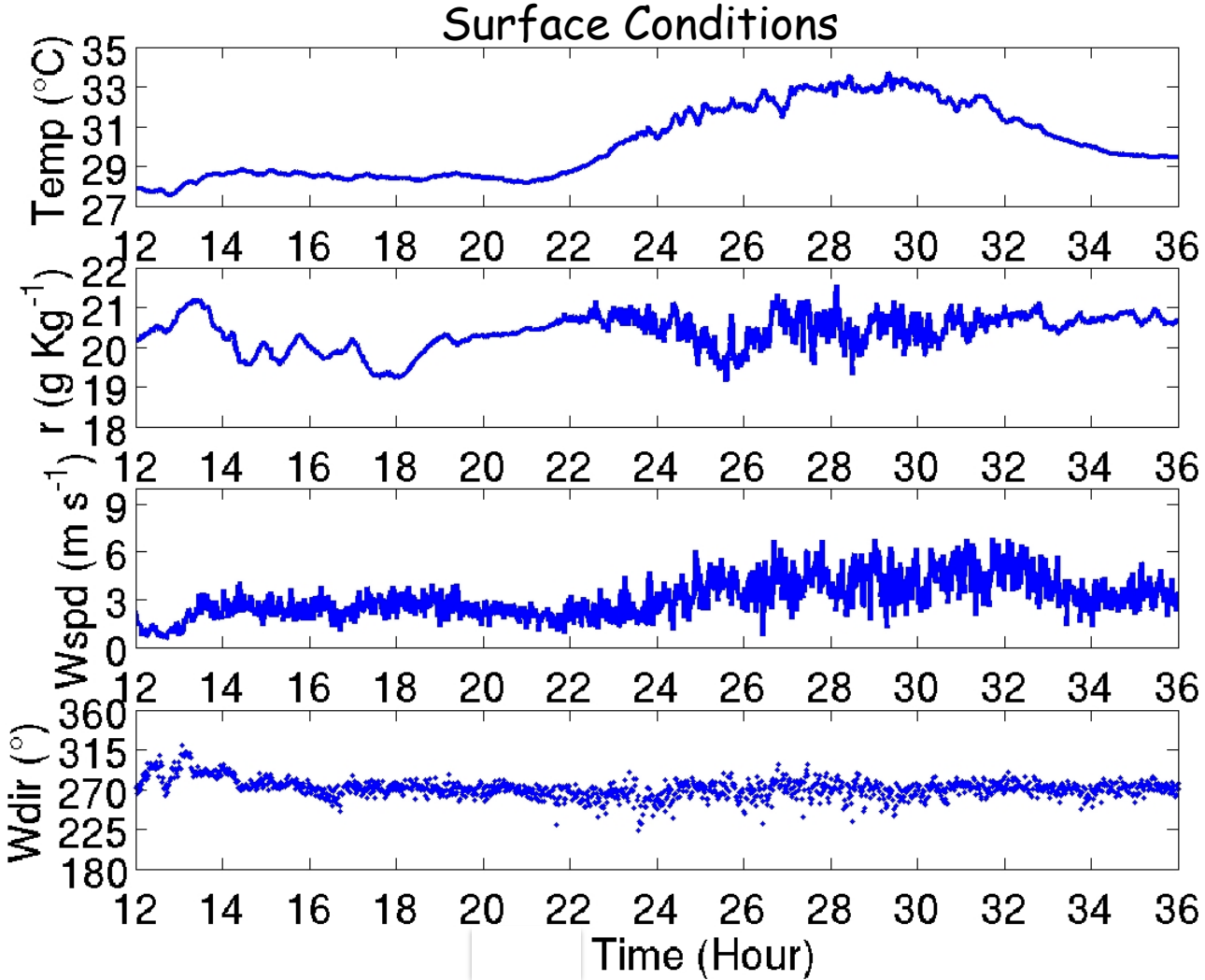
- Understand the changes in the boundary layer with forcing.

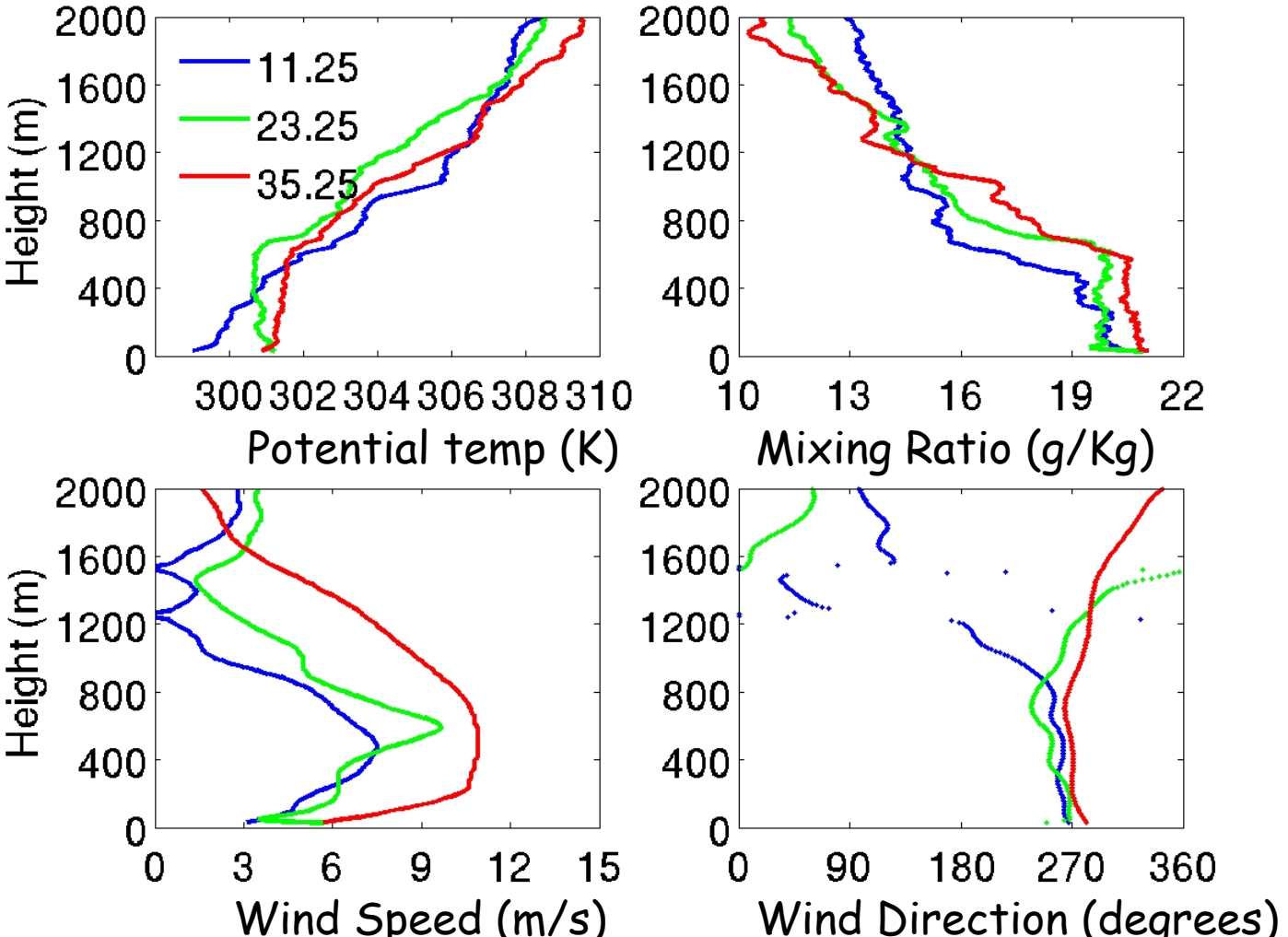

Ka-band Reflectivity from Darwin
Height (km)
0
3
6
9
12
15
18
0
6
12
18
24
30
36
42
48
Time (Hour)
20
10
0
-10
-20
-30
-40
-50
dBZ



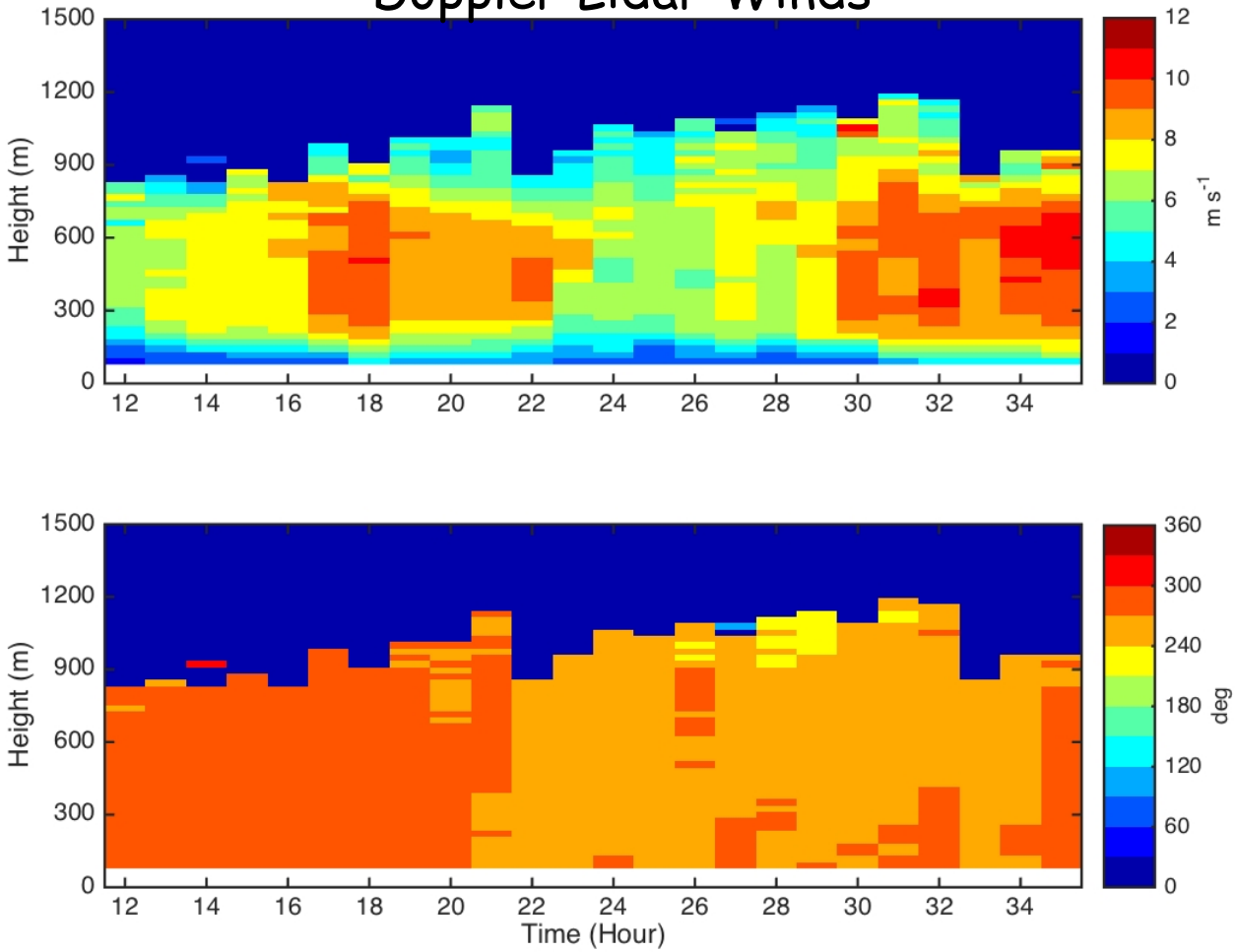

Reflectivity
Daytime
Mean Doppler Velocity
Height (m)
Time (Hour)
2000
1600
1200
800
400
0
12
14
16
18
20
22
24
26
28
30
32
34
36
-10
-15
-20
-25
-30
-35
-40
-45
3
2
1
0
-1
-2
-3

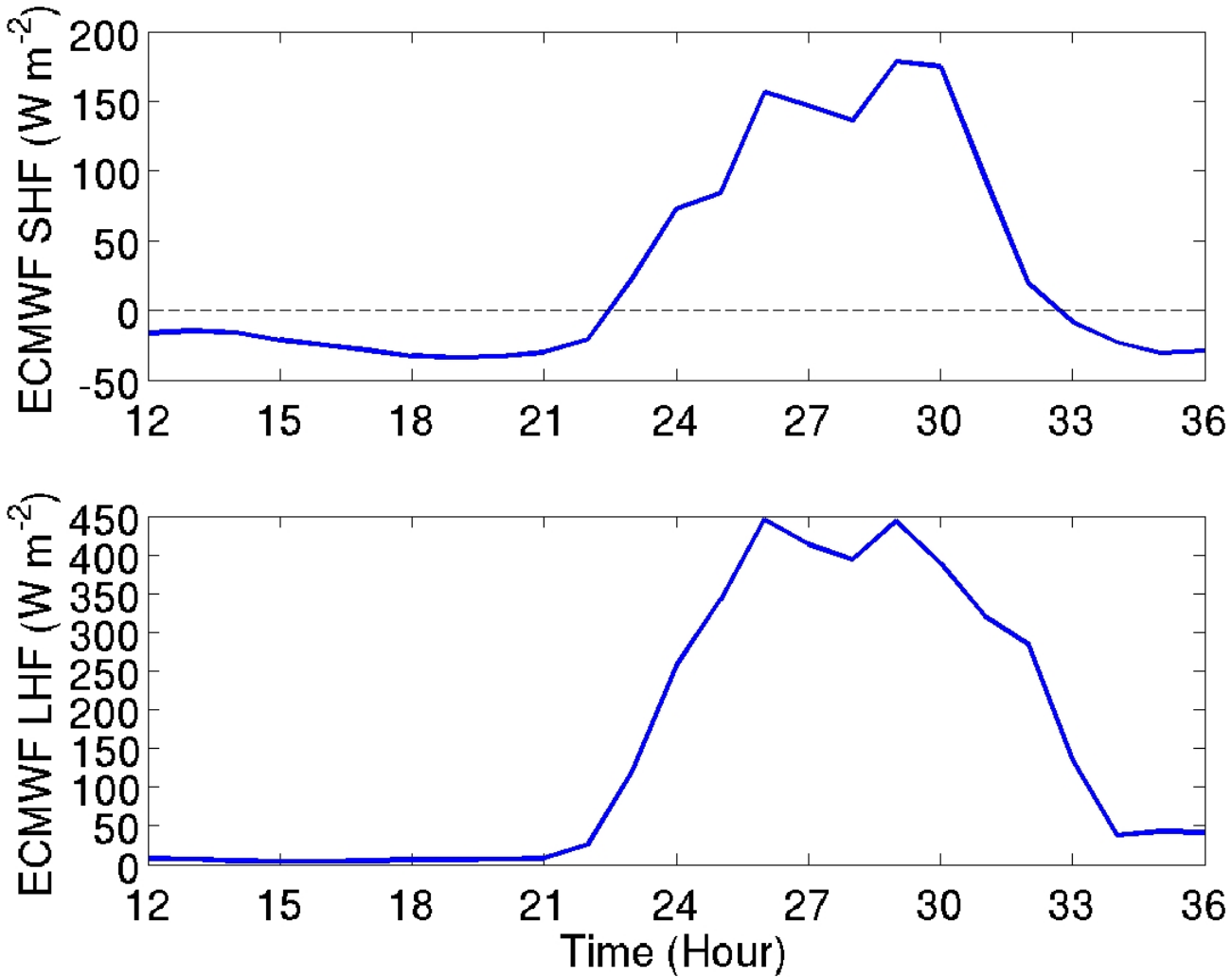

Doppler Lidar Vertical Velocity
Height (m)
2000
1600
1200
800
400
0
12
14
16
18
20
22
24
26
28
30
32
34
36
Time (Hour)
3
2
1
0
-1
-2
-3

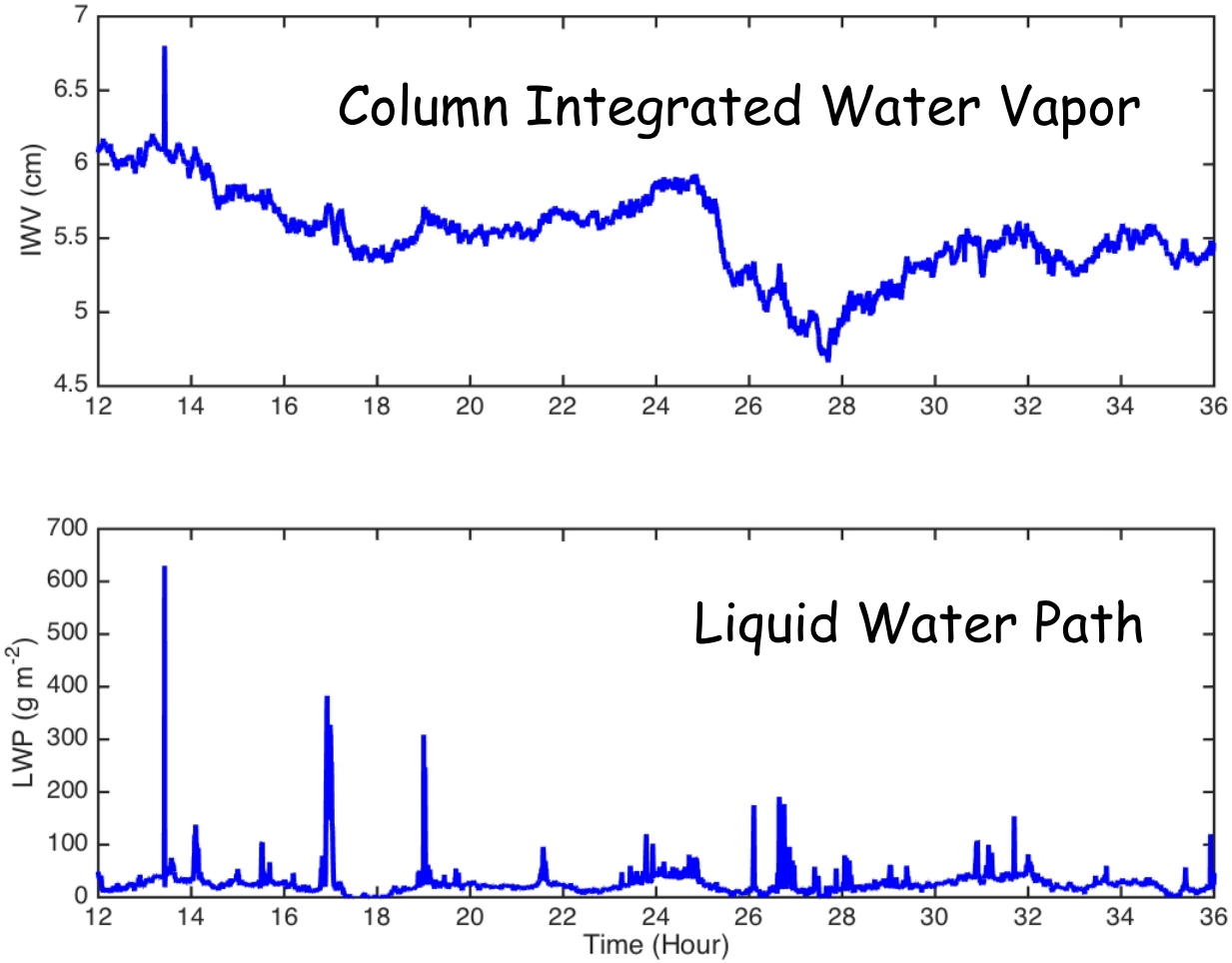

Surface Conditions
Temp (°C)
35
33
31
29
27
r (g Kg-1)
22
21
20
19
18
Wspd (m s-1)
9
6
3
0
Wdir (°)
360
315
270
225
180
12 14 16 18 20 22 24 26 28 30 32 34 36
Time (Hour)

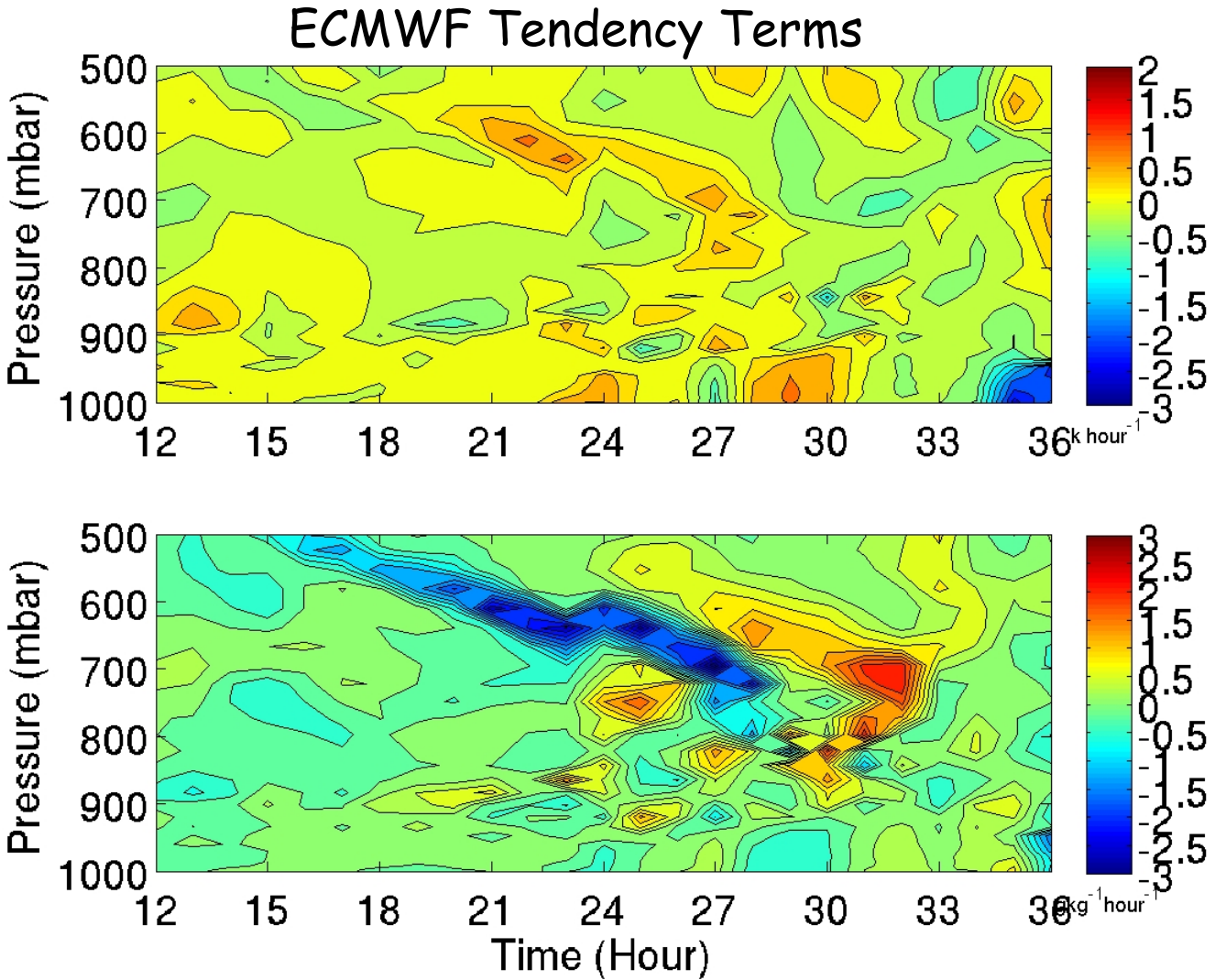

11.25
23.25
35.25
Height (m)
2000
1600
1200
800
400
0
300 302 304 306 308 310
Potential temp (K)
10 13 16 19 22
Mixing Ratio (g/Kg)
0 3 6 9 12 15
Wind Speed (m/s)
0 90 180 270 360
Wind Direction (degrees)

Doppler Lidar Winds



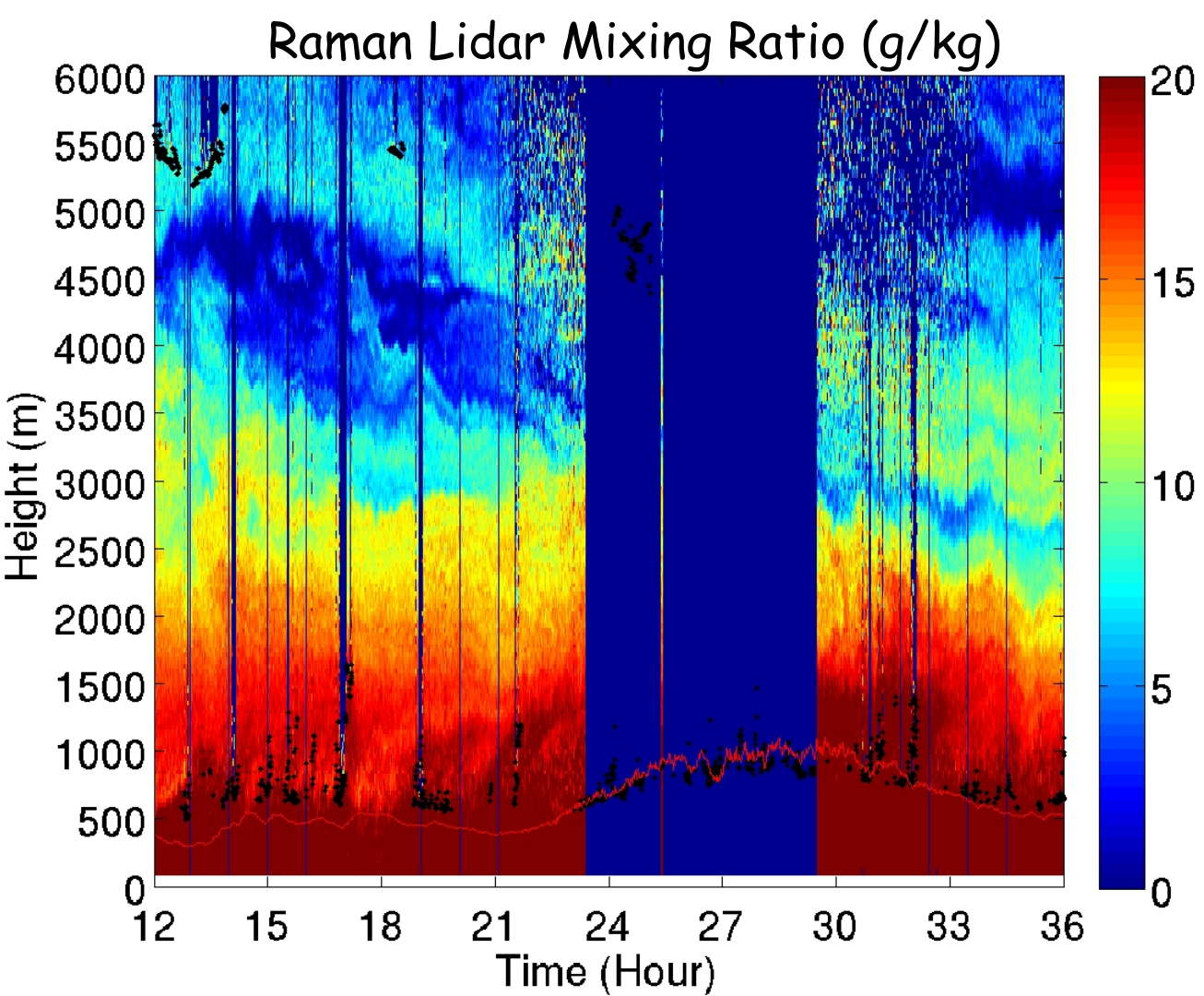

ECMWF SHF (W m-2)
200
150
100
50
0
-50
12
15
18
21
24
27
30
33
36
ECMWF LHF (W m-2)
450
400
350
300
250
200
150
100
50
0
12
15
18
21
24
27
30
33
36
Time (Hour)

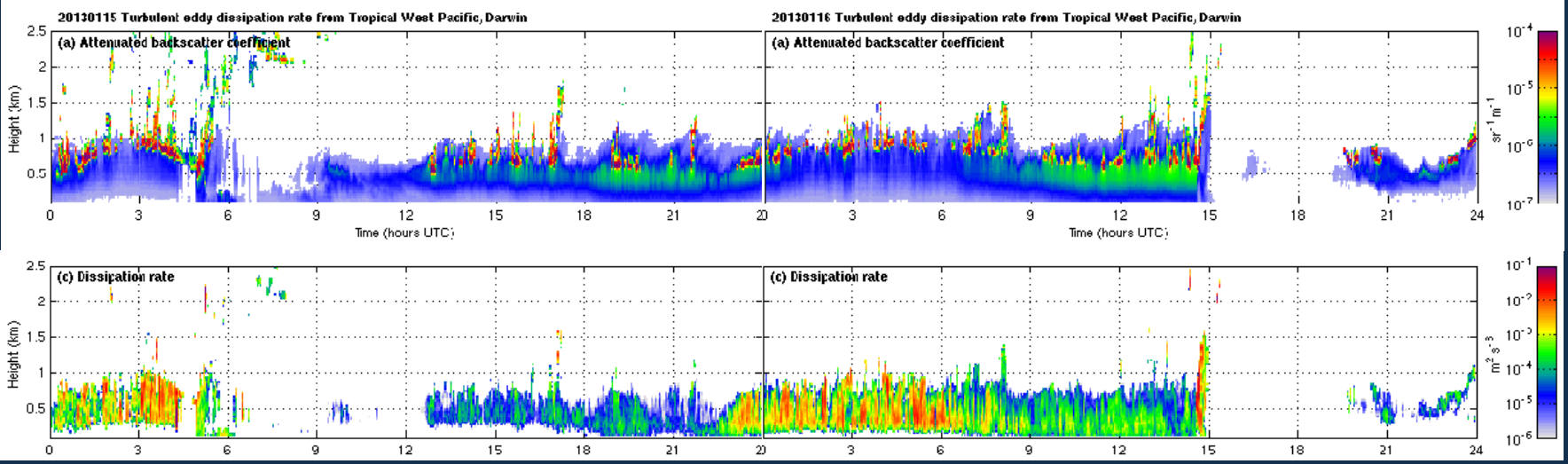

Column Integrated Water Vapor
IWV (cm)
7
6.5
6
5.5
5
4.5
12
14
16
18
20
22
24
26
28
30
32
34
36
Liquid Water Path
LWP (g m-2)
700
600
500
400
300
200
100
0
Time (Hour)

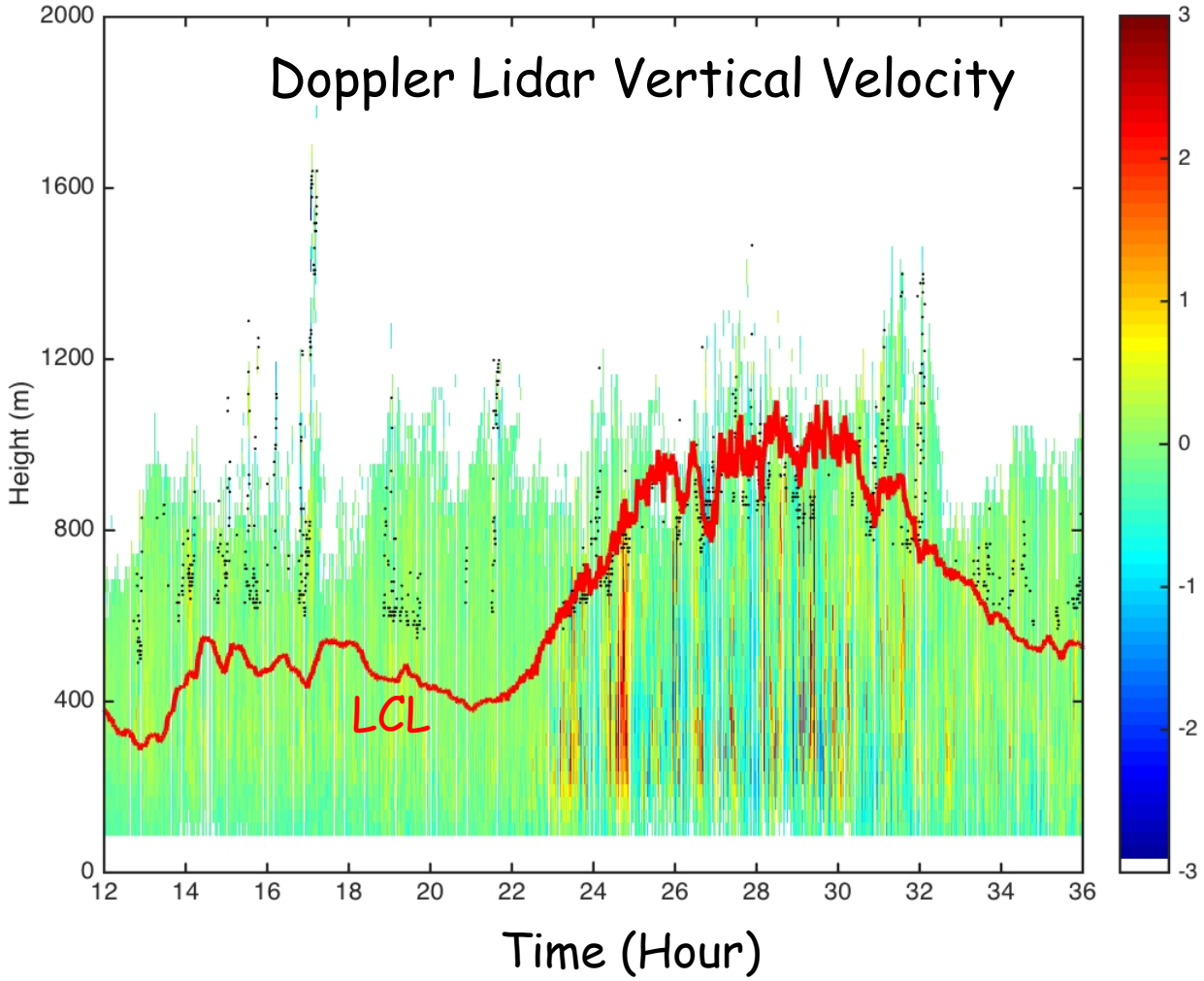


Temperature Tendency (k/hour)

Moisture Tendency (g/kg/hour)


Raman Lidar Mixing Ratio (g/kg)
Height (m)
6000
5500
5000
4500
4000
3500
3000
2500
2000
1500
1000
500
0
12
15
18
21
24
27
30
33
36
Time (Hour)
20
15
10
5
0

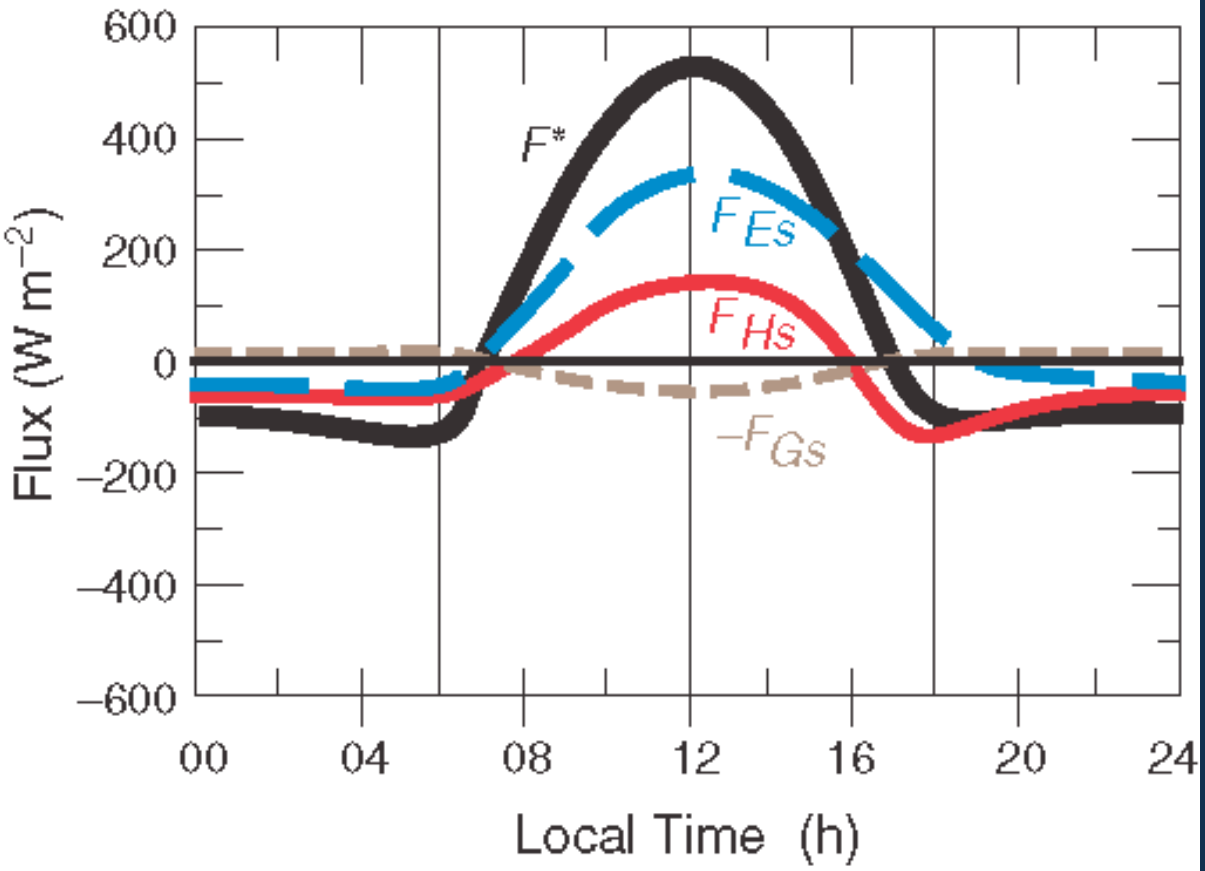

20130115 Turbulent eddy dissipation rate from Tropical West Pacific, Darwin
(a) Attenuated backscatter coefficient
Height (km)
Time (hours UTC)
20130116 Turbulent eddy dissipation rate from Tropical West Pacific, Darwin
(a) Attenuated backscatter coefficient
Time (hours UTC)
sr-1 m-1
(c) Dissipation rate
Height (km)
(c) Dissipation rate
m2 s-3


Doppler Lidar Vertical Velocity
Height (m)
2000
1600
1200
800
400
0
LCL
12
14
16
18
20
22
24
26
28
30
32
34
36
Time (Hour)
3
2
1
0
-1
-2
-3

Question

- Why is the LCL lower than the cloud base height during the nighttime (12-21) and comparable to the cloud base during the daytime (22-33)?

THE END



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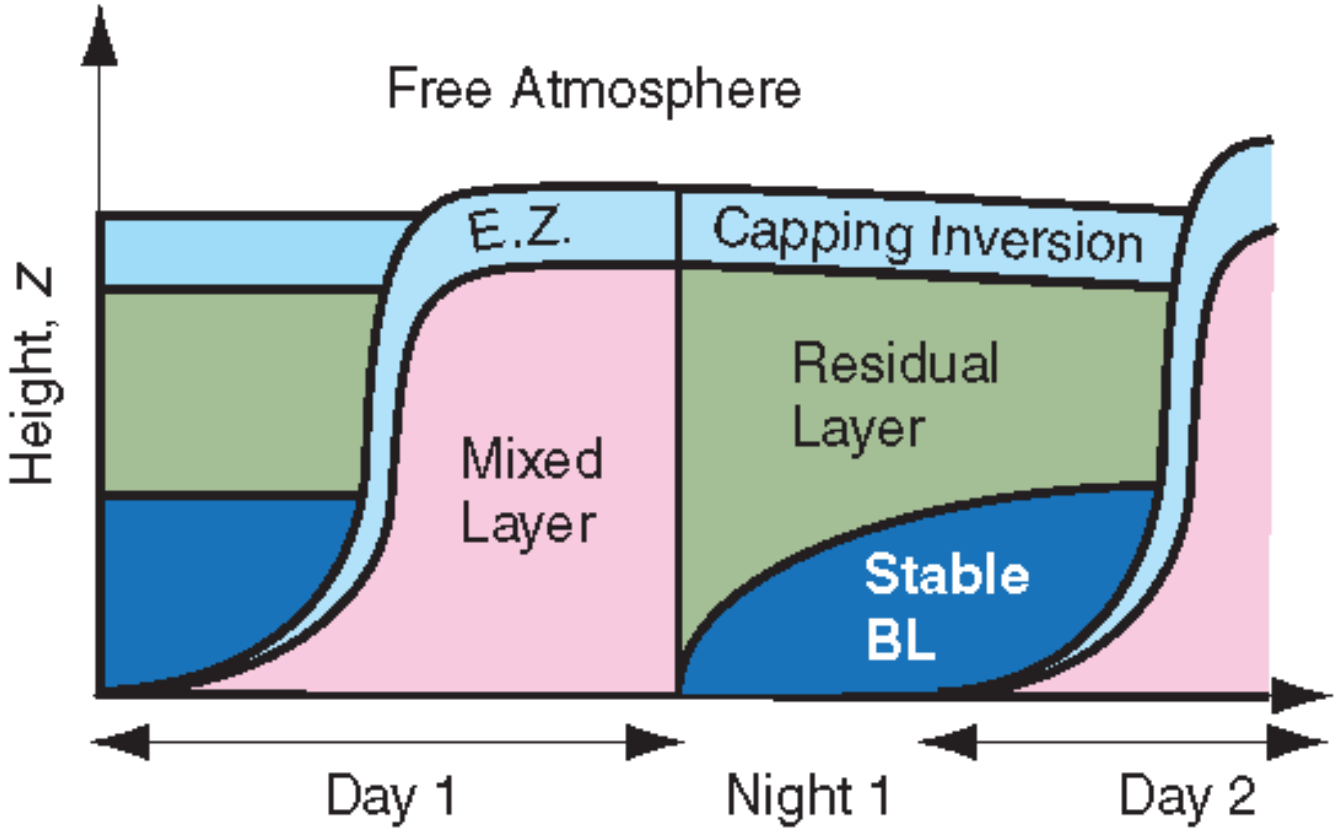

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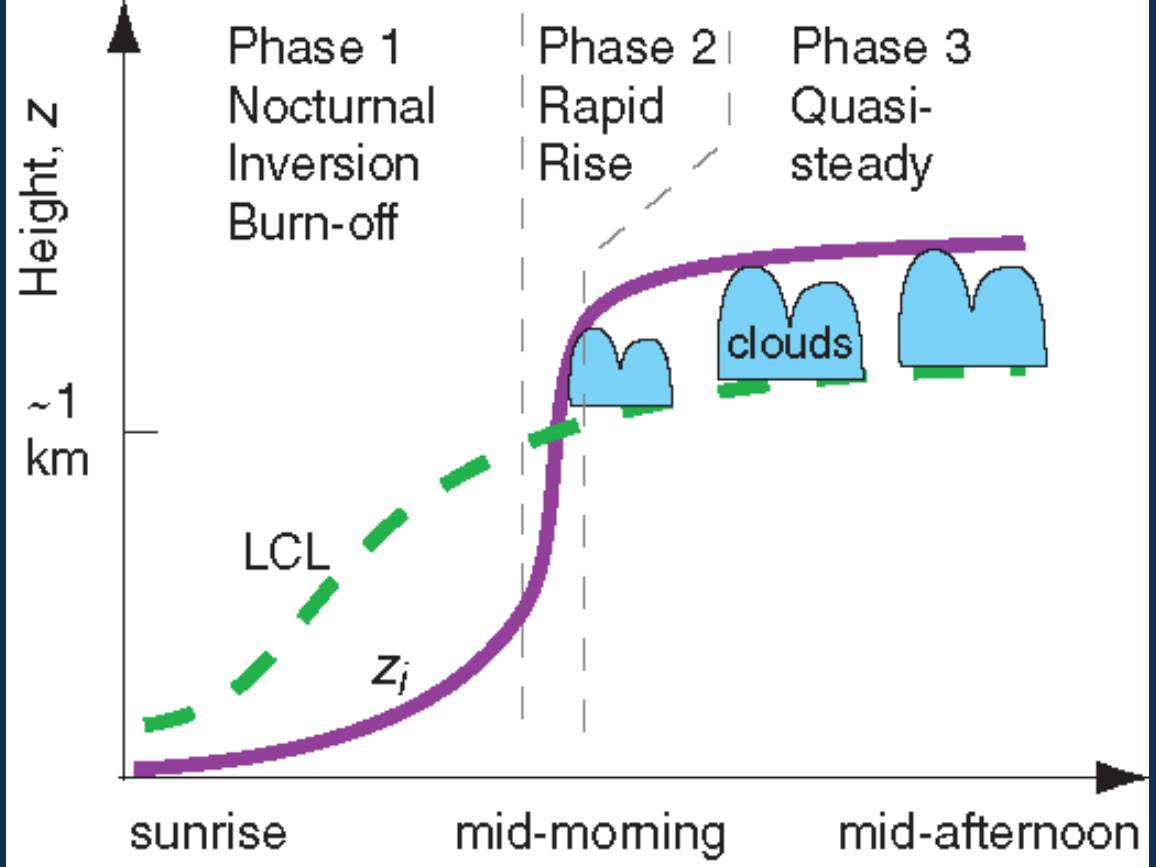
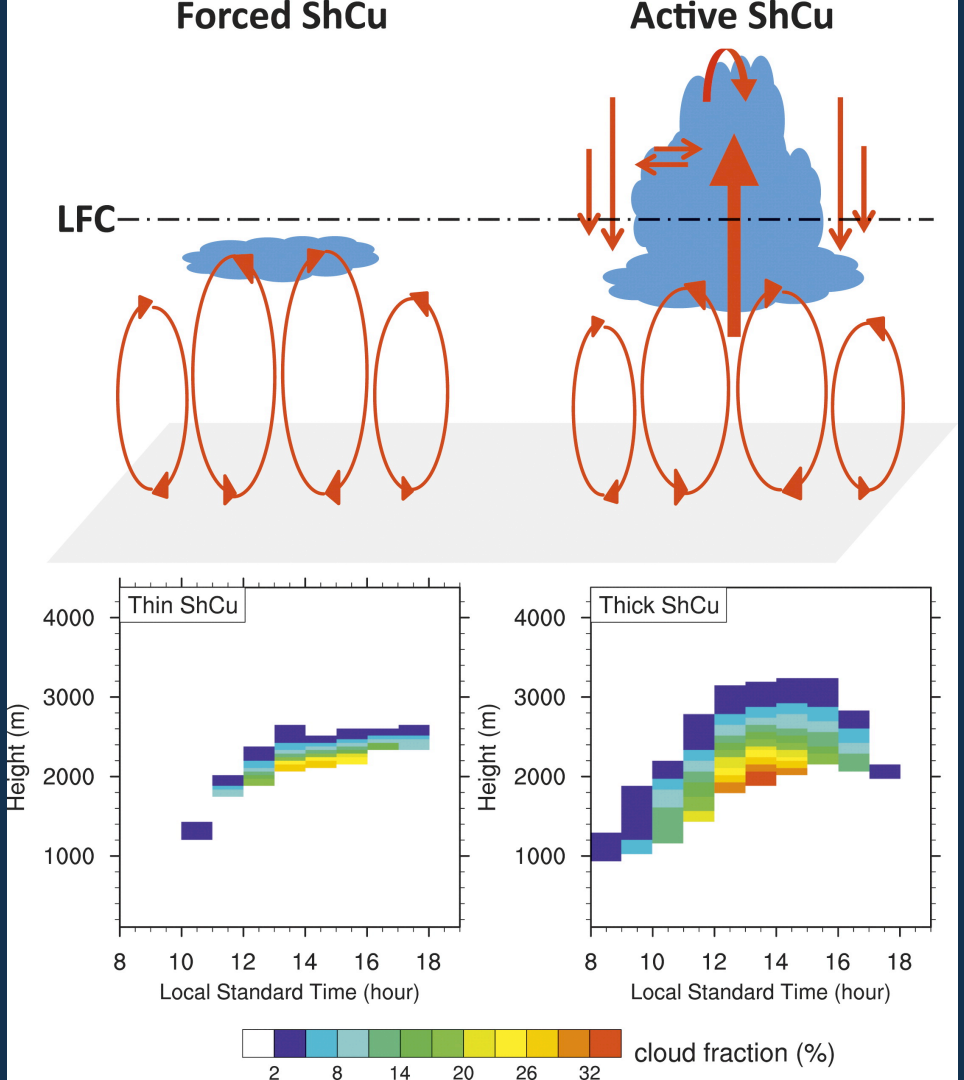


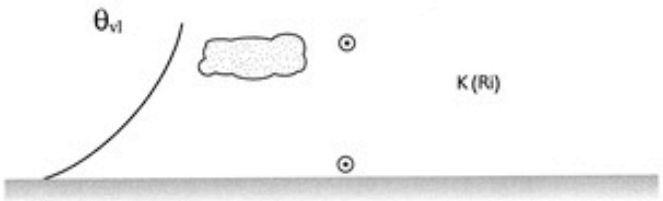
Adapted from R. B. Stull, An *Introduction to Boundary Layer Meteorology*, Kluwer Academic Publishers, Dordrecht, The Netherlands, 1988, Fig. 11.10, p. 452, and Fig. 13.12, p. 564, Copyright 1988 Kluwer Academic Publishers, with kind permission of Springer Science and Business Media.



- Active Cumuli penetrate above the Level of Free Convection (LFC).
- The onset of "Thick Cumuli" is a bit earlier than the "thin Cumuli".
- The vertical extent depend on large-scale upper-level humidity.

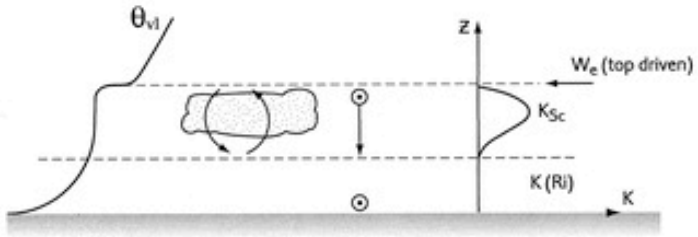
(a)

I. Stable boundary layer, possibly with non-turbulent cloud
(no cumulus, no decoupled Sc, stable surface layer)



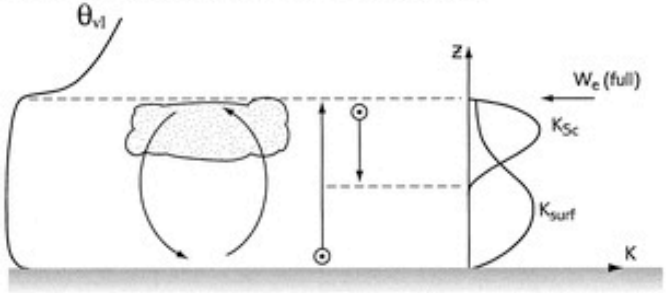
(b)

II. Stratocumulus over a stable surface layer
(no cumulus, decoupled Sc, stable surface layer)



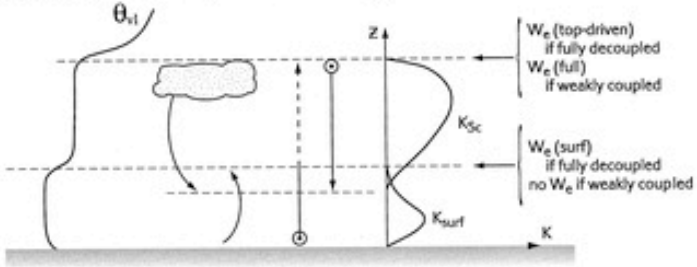
(c)

III. Single mixed layer, possibly cloud-topped
(no cumulus, no decoupled Sc, unstable surface layer)



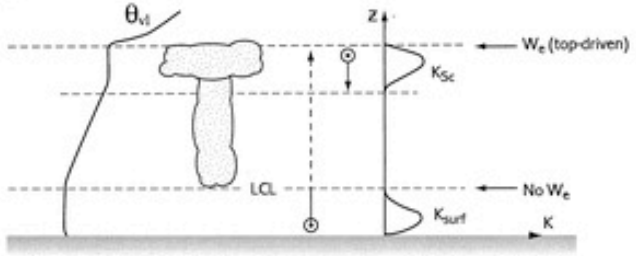
(d)

IV. Decoupled stratocumulus not over cumulus
(no cumulus, decoupled Sc, unstable surface layer)



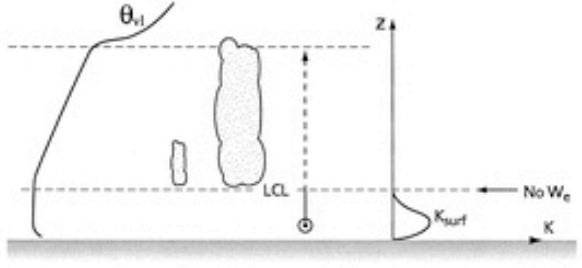
(e)

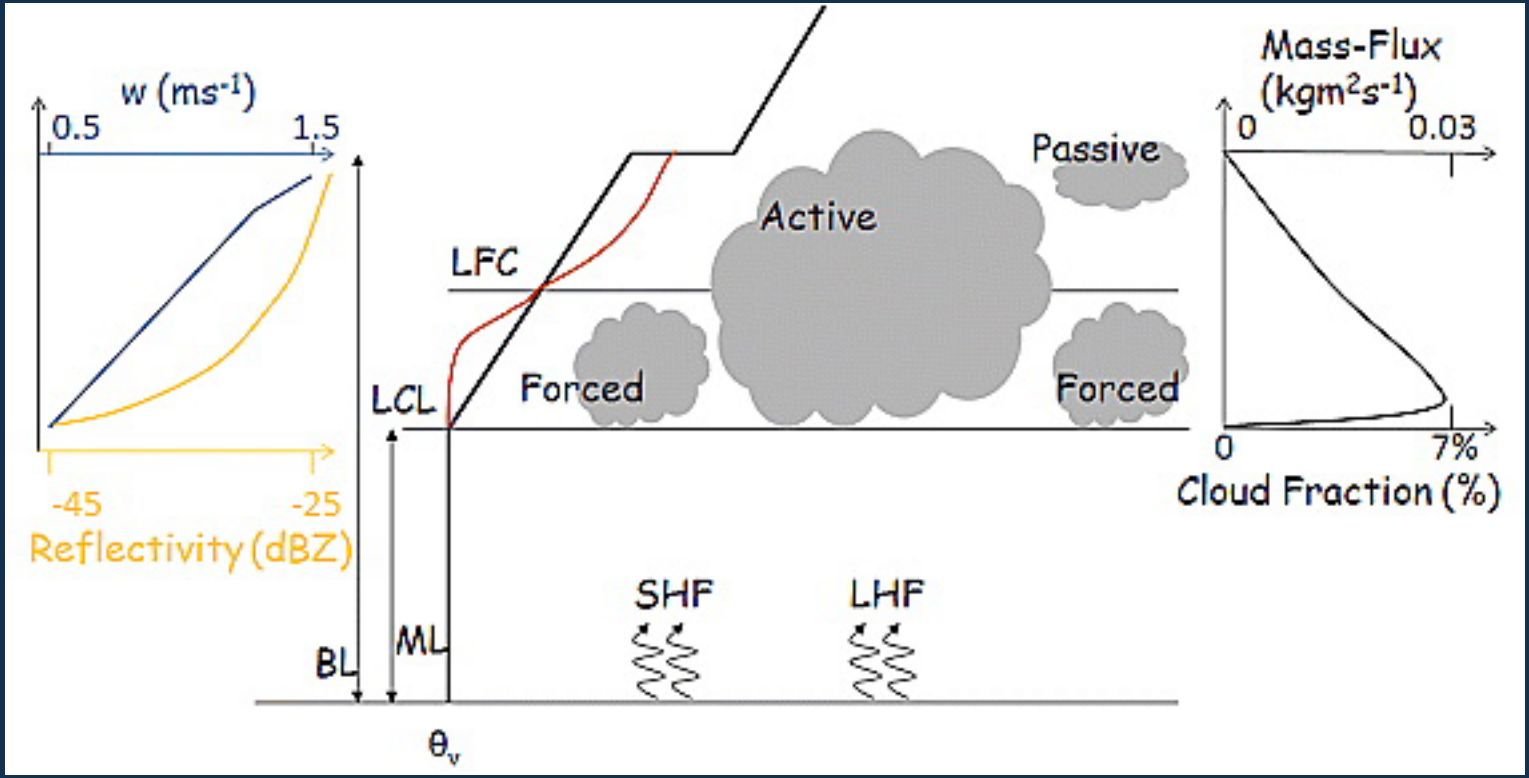
V. Decoupled stratocumulus over cumulus
(cumulus, decoupled Sc, unstable surface layer)



(f)

VI. Cumulus-capped layer
(cumulus, no decoupled Sc, unstable surface layer)




w (ms-1)
0.5
1.5
-45
-25
Reflectivity (dBZ)
LFC
LCL
Forced
Active
Passive
Forced
BL
ML
SHF
LHF
θv
Mass-Flux
(kgm2s-1)
0
0.03
0
7%
Cloud Fraction (%)