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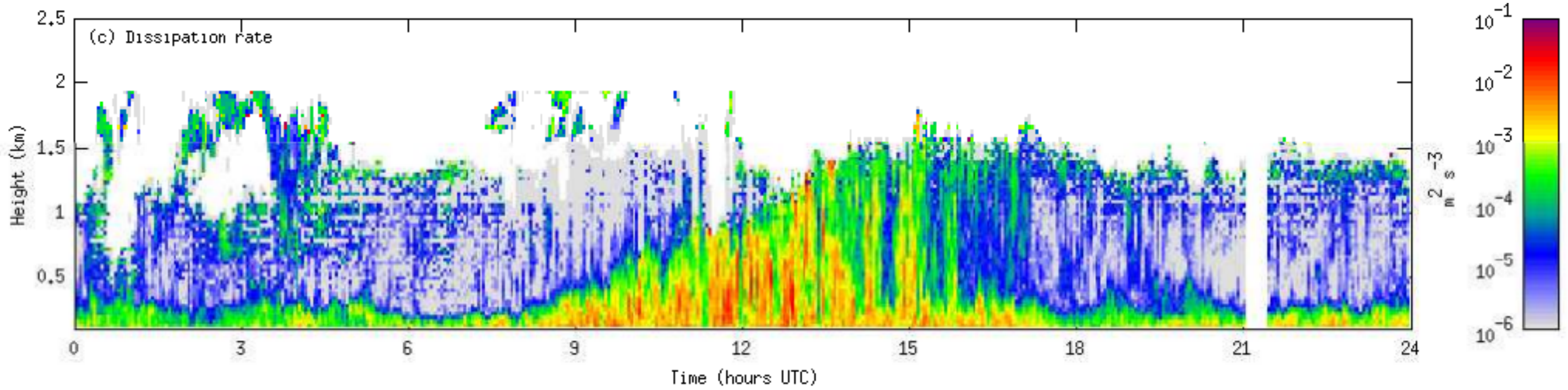
Diagnosing boundary layer properties from remote-sensing observations



Ewan O'Connor

FMI (Finnish Meteorological Institute), Helsinki, Finland

University of Reading, Reading, UK

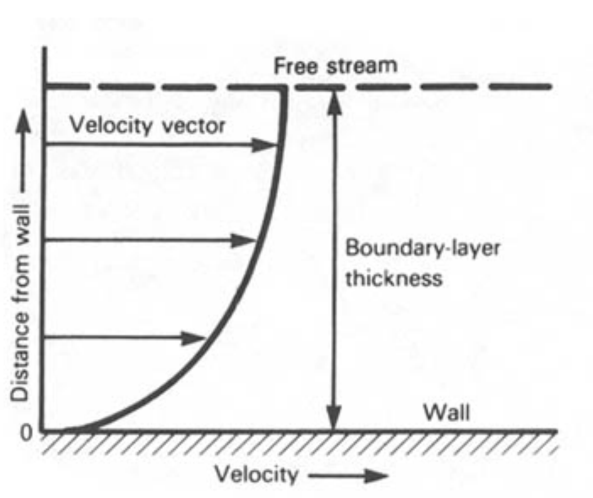
3/15/16

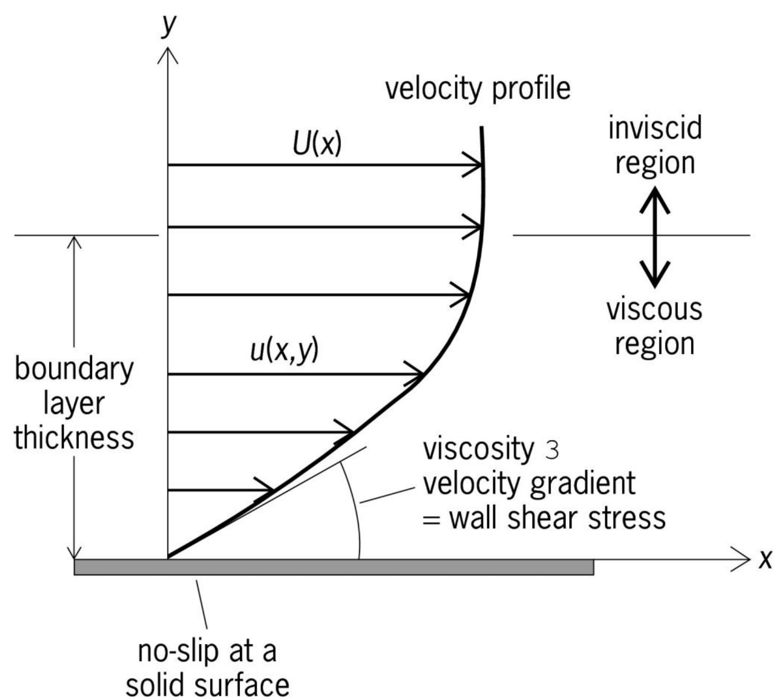
Boundary Layer

- **Friction-only**
  - Classical fluid dynamics
- **Atmospheric stability**
- **Atmospheric**
  - Include convection, cloud
  - Include coast, cities

What is a boundary layer?

- **Classical fluid dynamics:** the layer in a nearly inviscid fluid next to a surface in which frictional drag associated with that surface is significant (Prandtl, 1905), i.e. no slip-boundary (v = 0 at surface),
- Boundary layer can be laminar or turbulent





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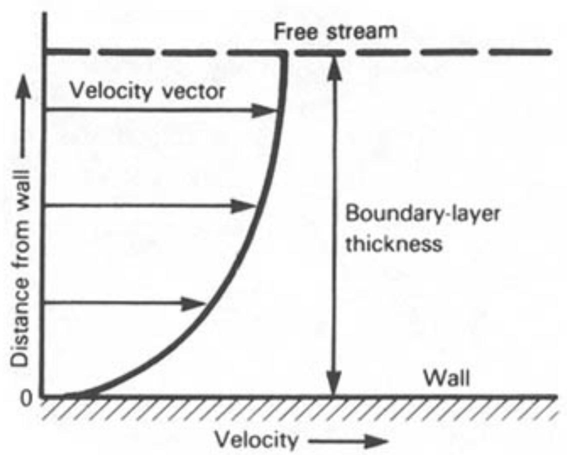

$$u_z = \frac{u_*}{\kappa}\left[\ln\left(\frac{z-d}{z_0}\right)\right]$$

u_* friction velocity, a measure of shear stress
k von Kármán constant (=0.41)
z distance from surface
z_0 surface roughness
d displacement height (for rough surfaces)

Turbulent motions

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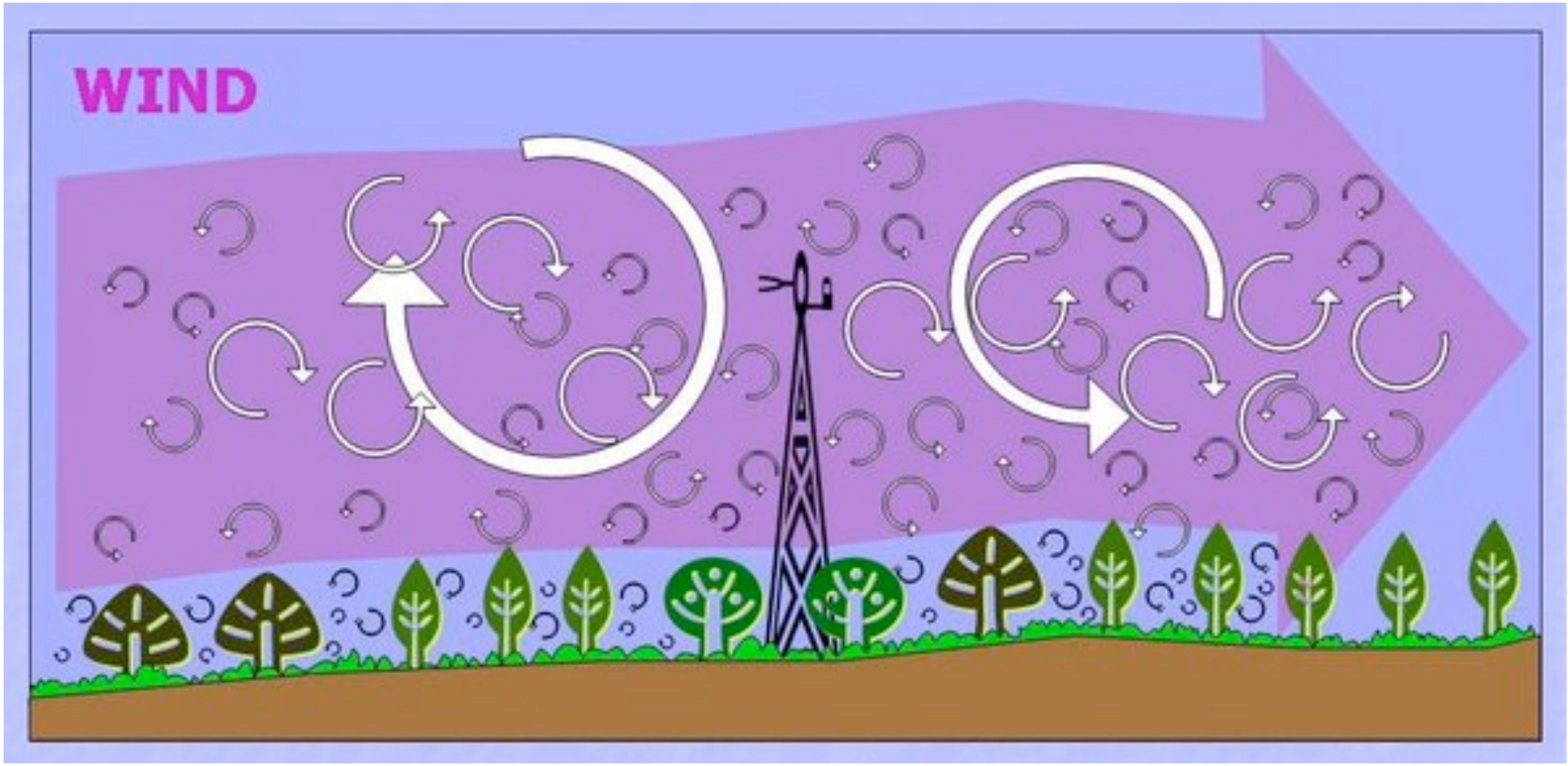
Turbulent motions



Atmospheric Boundary Layer?

- Displacement height is where zero wind speed is achieved as a result of flow obstacles such as trees or buildings.
  - Typical value is 2/3 of the average obstacle height
- Roughness length is between 1/10 and 1/30 of the average height of the roughness elements on the ground:

Surface	Roughness length (m)
flat, open grassland	
cropland	
scrub or forest	
cities with skyscrapers	
ice (smooth to rough)	
smooth open water	

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cropland	
scrub or forest	
cities with skyscrapers	
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smooth open water	

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Surface	Roughness length (m)
flat, open grassland	0.03
cropland	0.1 – 0.25
scrub or forest	
cities with skyscrapers	
ice (smooth to rough)	
smooth open water	

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cropland	0.1 – 0.25
scrub or forest	0.5 - 1
cities with skyscrapers	
ice (smooth to rough)	
smooth open water	

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cropland	0.1 – 0.25
scrub or forest	0.5 - 1
cities with skyscrapers	2
ice (smooth to rough)	
smooth open water	

Atmospheric Boundary Layer?

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ice (smooth to rough)	0.002 – 0.4
smooth open water	

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scrub or forest	0.5 - 1
cities with skyscrapers	2
ice (smooth to rough)	0.002 – 0.4
smooth open water	0.0002

Atmospheric Boundary layer?

- **In addition to friction**:
  - Surface heat exchange (convection)
  - Moisture (and effects on convection)
  - Earth's rotation
  - Complex surface characteristics and topography
- There are significant fluxes of momentum, heat and/or moisture carried by turbulent motions whose horizontal and vertical scales are on the order of the boundary layer depth, and whose circulation timescale is a few hours or less.

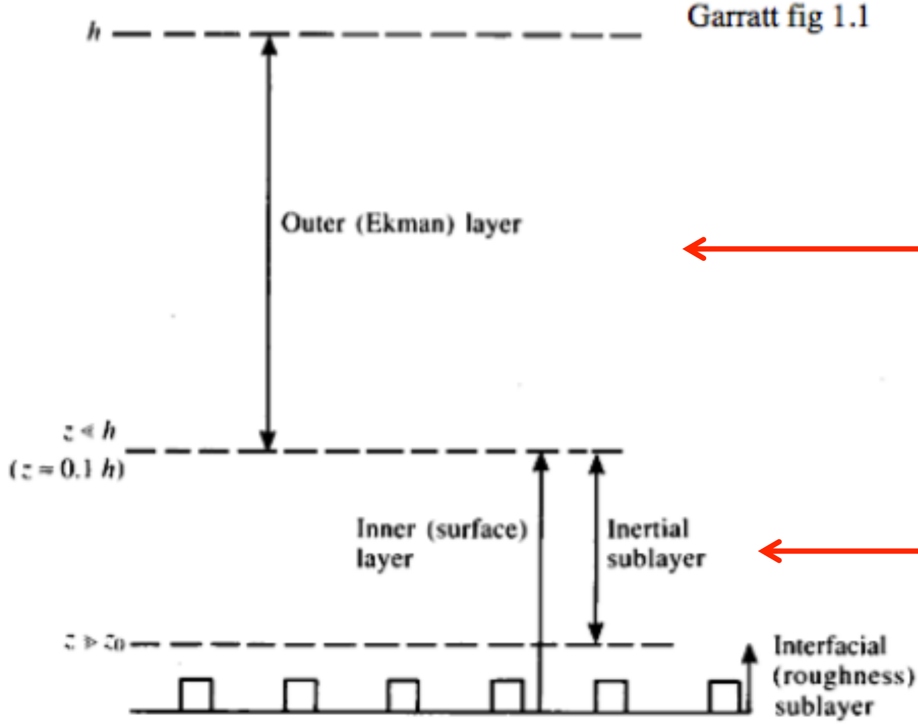
- This is similar for the ocean surface, although with different scaling parameters

Atmospheric boundary layer?

- has multiple components

Free atmosphere

Garratt fig 1.1



Turbulent stress

Log law applies here

Viscous stress

Atmospheric stability – Potential temperature

- **Definition:** θ is the temperature that an air parcel would have if adiabatically brought to a standard reference pressure P_0

$$\theta = T\left(\frac{P_0}{P}\right)^{R/c_p},$$

T current absolute temperature (in K) of the parcel,

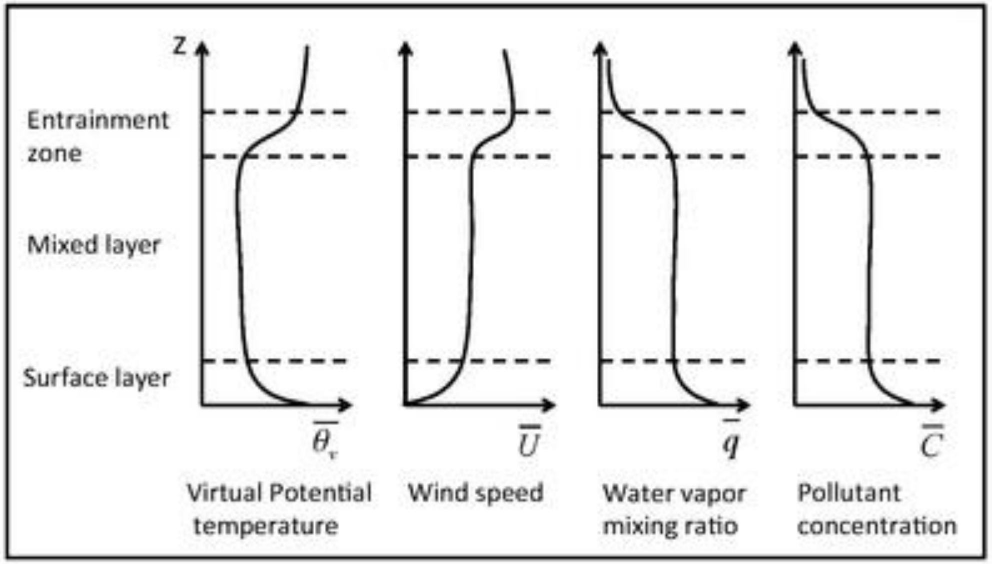
R gas constant for air

c_p specific heat capacity at constant pressure

$R/c_p = 0.286$ in air

Atmospheric stability – Potential temperature

- θ is conserved under dry adiabatic conditions
- potential temperature will not change in the absence of heating, cooling, evaporation, or condensation
- θ_v (virtual θ) is useful approximation to include moist adiabatic processes



Atmospheric stability – Potential temperature

- In equilibrium: BLH determined by competition between
  - static stability, N^2
  - velocity shear, S^2

- Gradient Richardson number

$$\mathrm{Ri} = \frac{N^2}{S^2}$$

Atmospheric stability – Potential temperature

- In equilibrium: BLH determined by competition between
  - static stability, N^2
  - velocity shear, S^2

- Gradient Richardson number

$$\mathrm{Ri} = \frac{N^2}{S^2} \qquad \mathrm{Ri} \equiv \frac{\beta(\partial\theta_v/\partial z)}{(\partial u/\partial z)^2 + (\partial v/\partial z)^2} > \mathrm{Ri}_c = 0.25.$$

$$\beta = g/T_0$$

Atmospheric stability – Potential temperature

- In equilibrium: BLH determined by competition between
  - static stability, N^2
  - velocity shear, S^2

- Bulk Richardson number:

$$\mathrm{Ri} = \frac{N^2}{S^2} \qquad \mathrm{Ri}_B \equiv \frac{\beta \Delta \theta_v h}{U^2}$$

$$U = \sqrt{u^2(h) + v^2(h)},$$

Monin-Obukhov similarity

Obukhov length: characteristic length scale of surface layer turbulence

$$L = -\frac{u_*^3 \bar{\theta}_v}{kg(\overline{w'\theta_v'})_s}$$

u_*	friction velocity, a measure of shear stress
$\bar{\theta}_v$	mean virtual potential temperature
$(\overline{w'\theta_v'})_s$	virtual potential temperature flux (at surface)
k	von Kármán constant (=0.41)

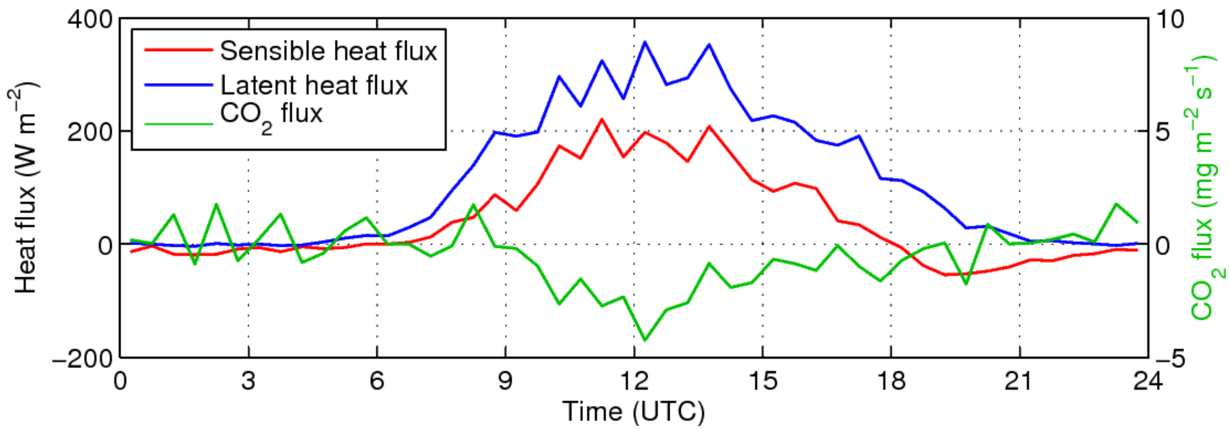
$$\overline{w'\theta_v'} = \overline{w'\theta'} + 0.61\overline{T}\,\overline{w'q'}$$

Sensible and latent heat flux

Monin-Obukhov similarity

Obukhov length

$L =$



$(\overline{w'\theta'_v})_s$

- +ve daytime L < 0
- 0 dawn/dusk L = ∞
- -ve nighttime L > 0

Monin-Obukhov similarity

Obukhov length

$$L = -\frac{u_*^3 \bar{\theta}_v}{kg(\overline{w'\theta_v'})_s}$$

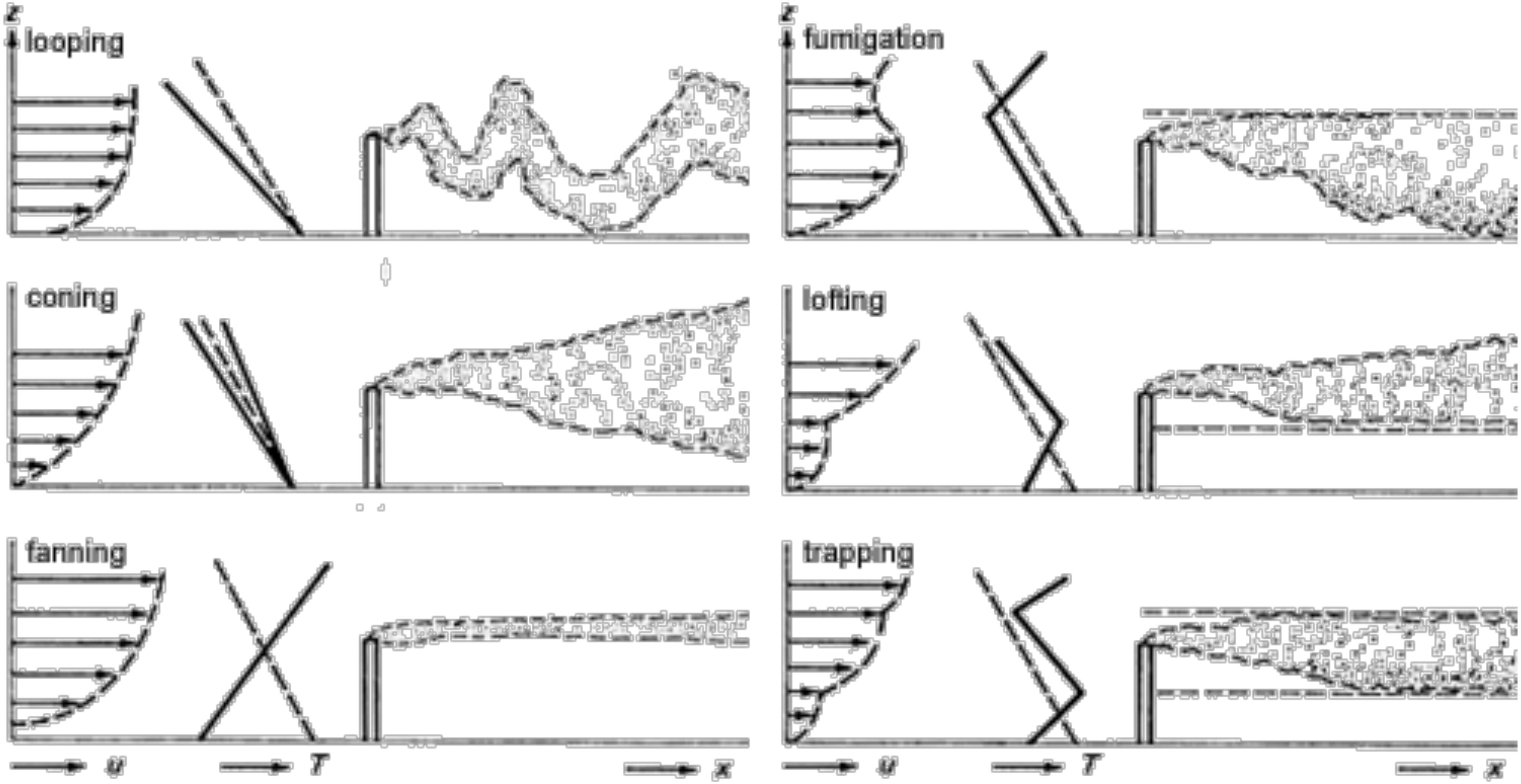
$(\overline{w'\theta_v'})_s$

+ve	daytime	$L < 0$	unstable
0	dawn/dusk	$L = \infty$	neutral
-ve	nighttime	$L > 0$	stable

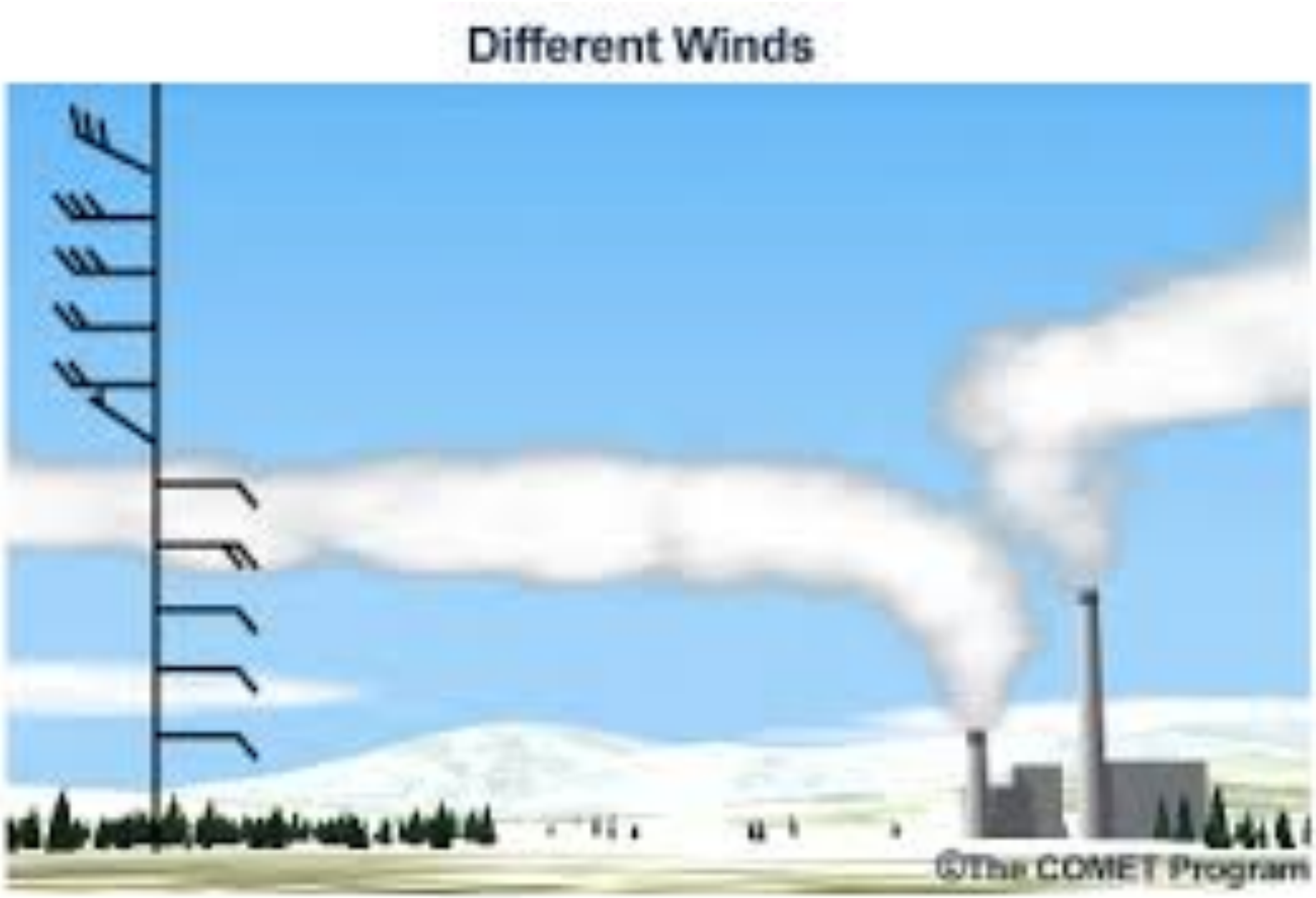
|L| determines whether buoyancy dominates shear

Why is BL height important?

Plume model


z
looping
coning
fanning
z
fumigation
lofting
trapping
u
T
x
u
T
x

Plume model



Plume observations - Kuopio

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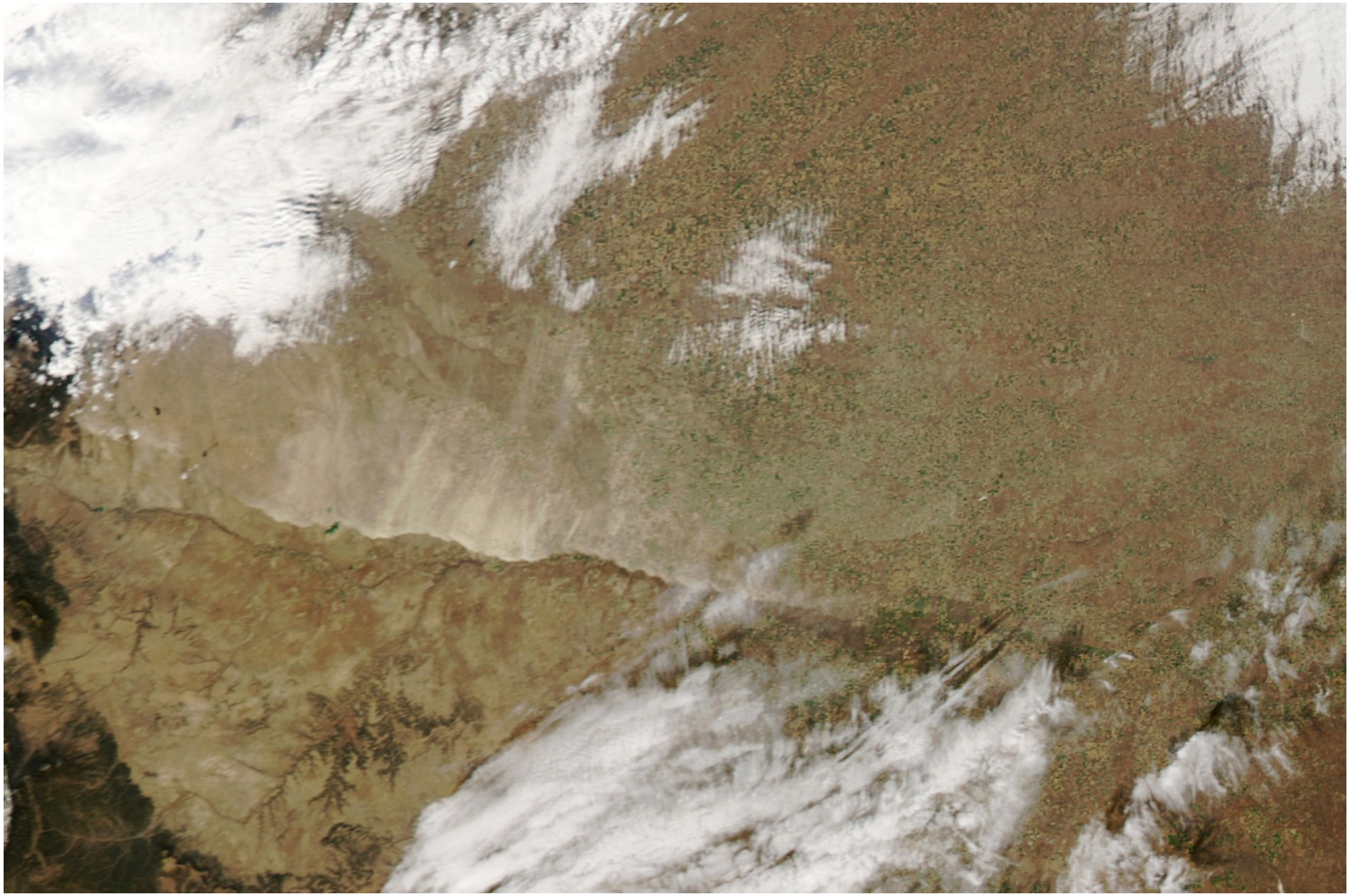
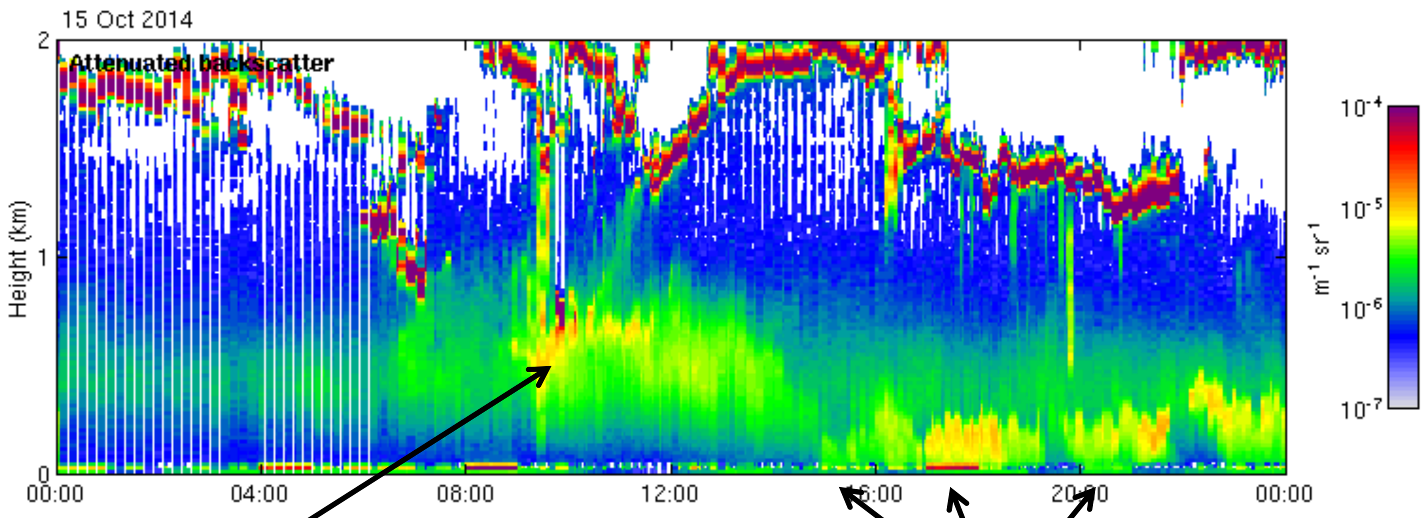
Plume observations - Kuopio

Synoptic scale – dust lofted by front



Example from aircraft

Re-suspended ash/dust – NCAS DL at Hatun (Iceland)



Elevated dust

Local dust being lofted

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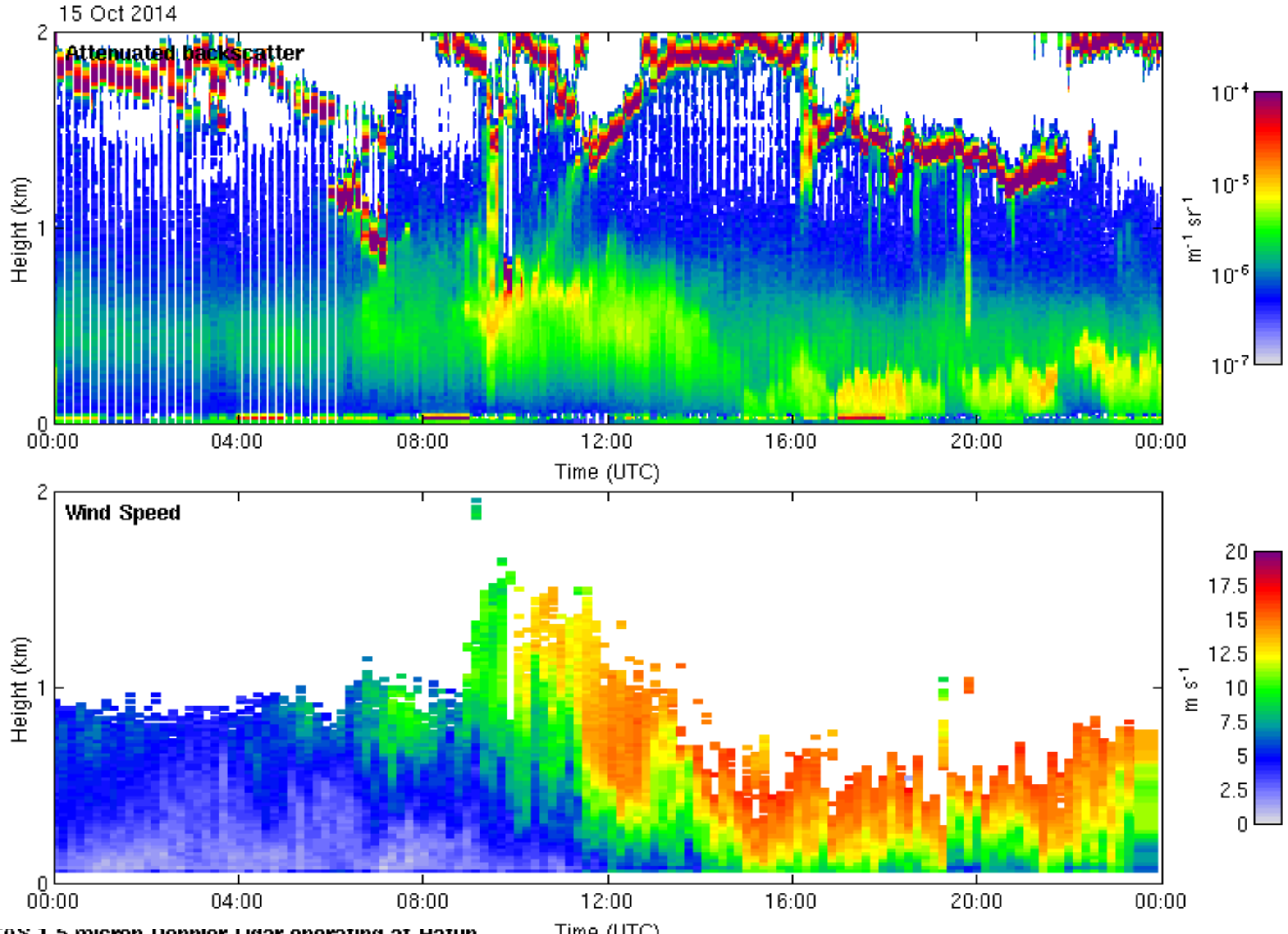
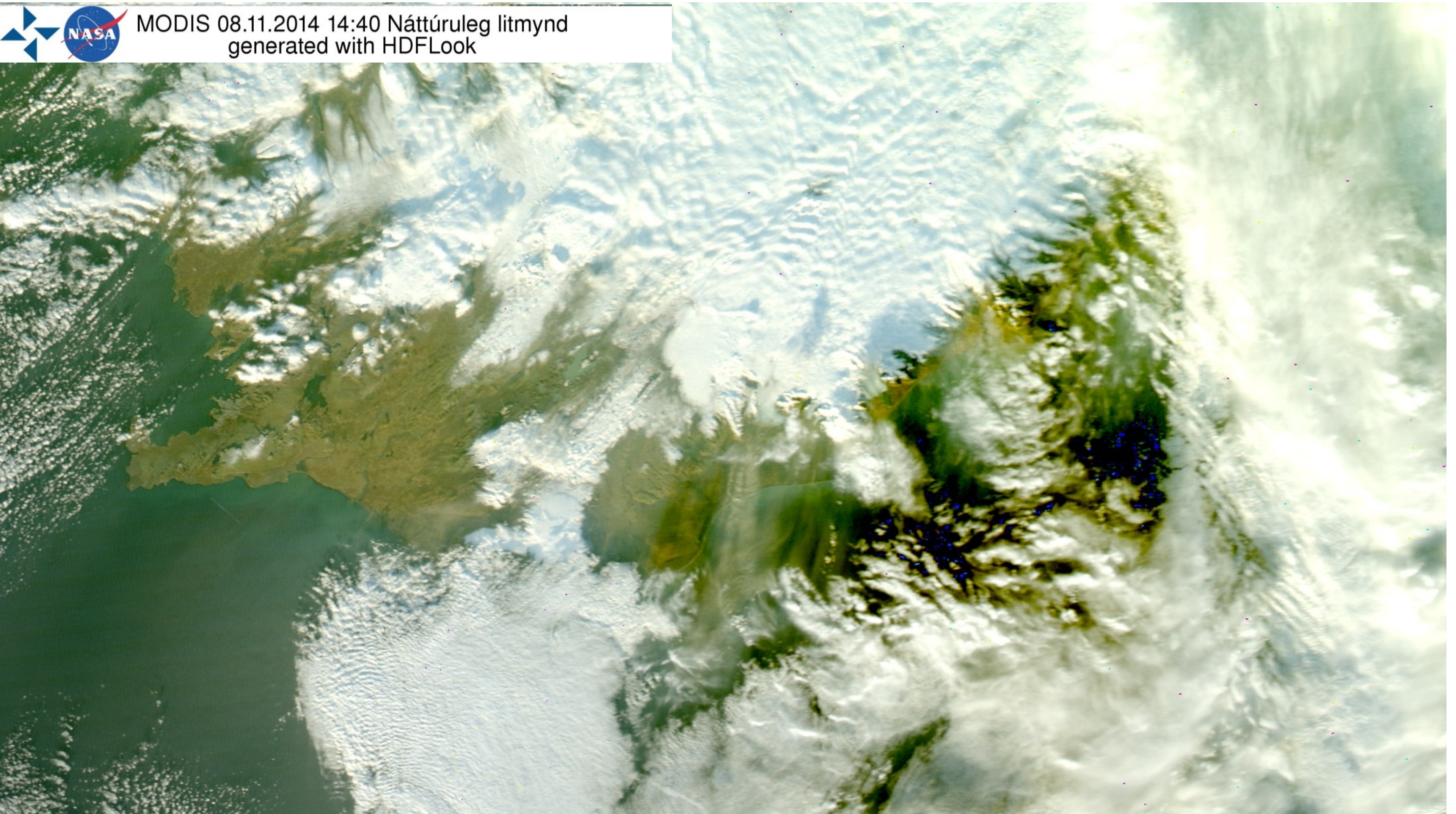
Re-suspended ash/dust – NCAS DL at Hatun (Iceland)

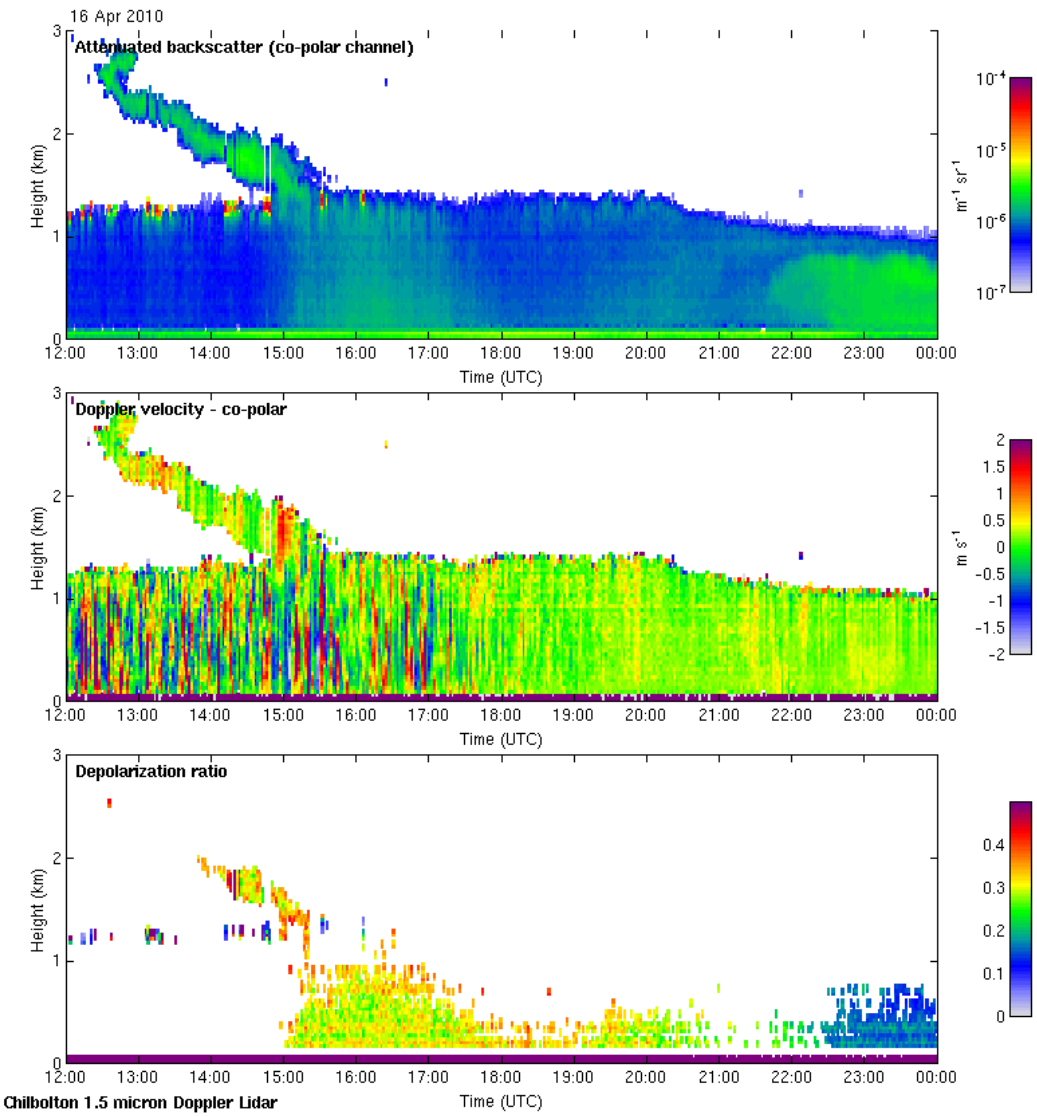


Re-suspended ash/dust

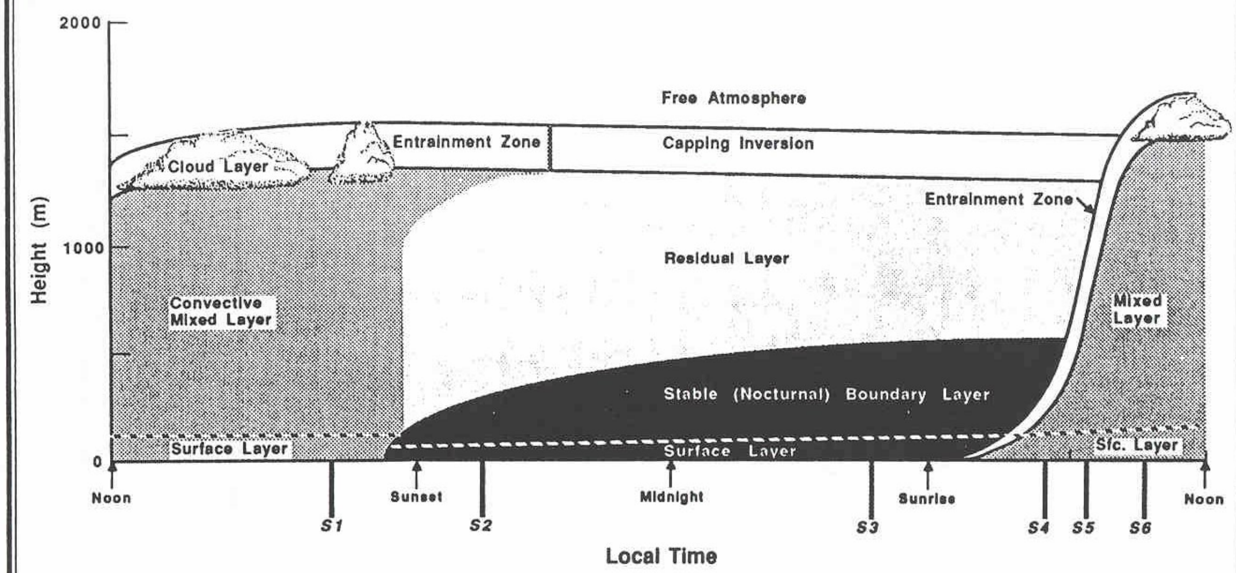


Volcanic ash plume from Eyjafjallajökull

Plume over UK 16th April 2010



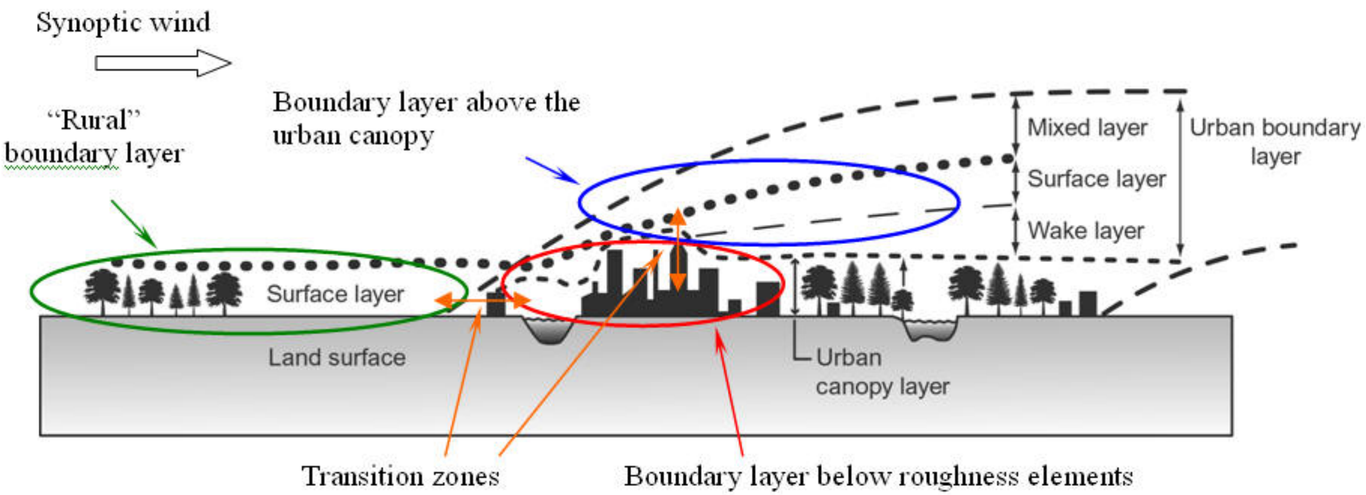
Atmospheric boundary layer



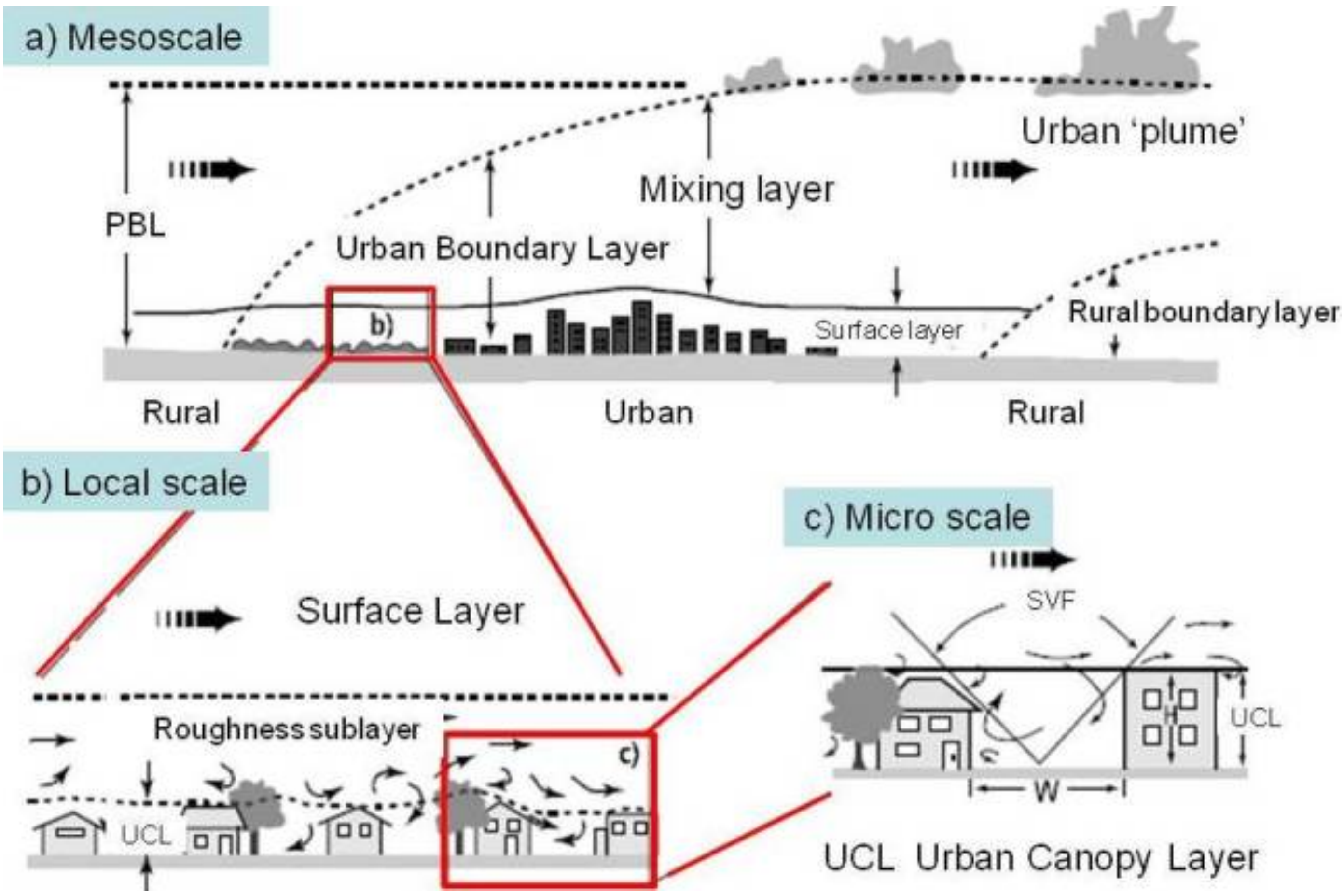
The boundary layer in high pressure regions over land consists of three major parts: a very turbulent mixed layer; a less-turbulent residual layer containing former mixed-layer air; and a nocturnal stable boundary layer of sporadic turbulence. The mixed layer can be subdivided into a cloud layer and a subcloud layer.

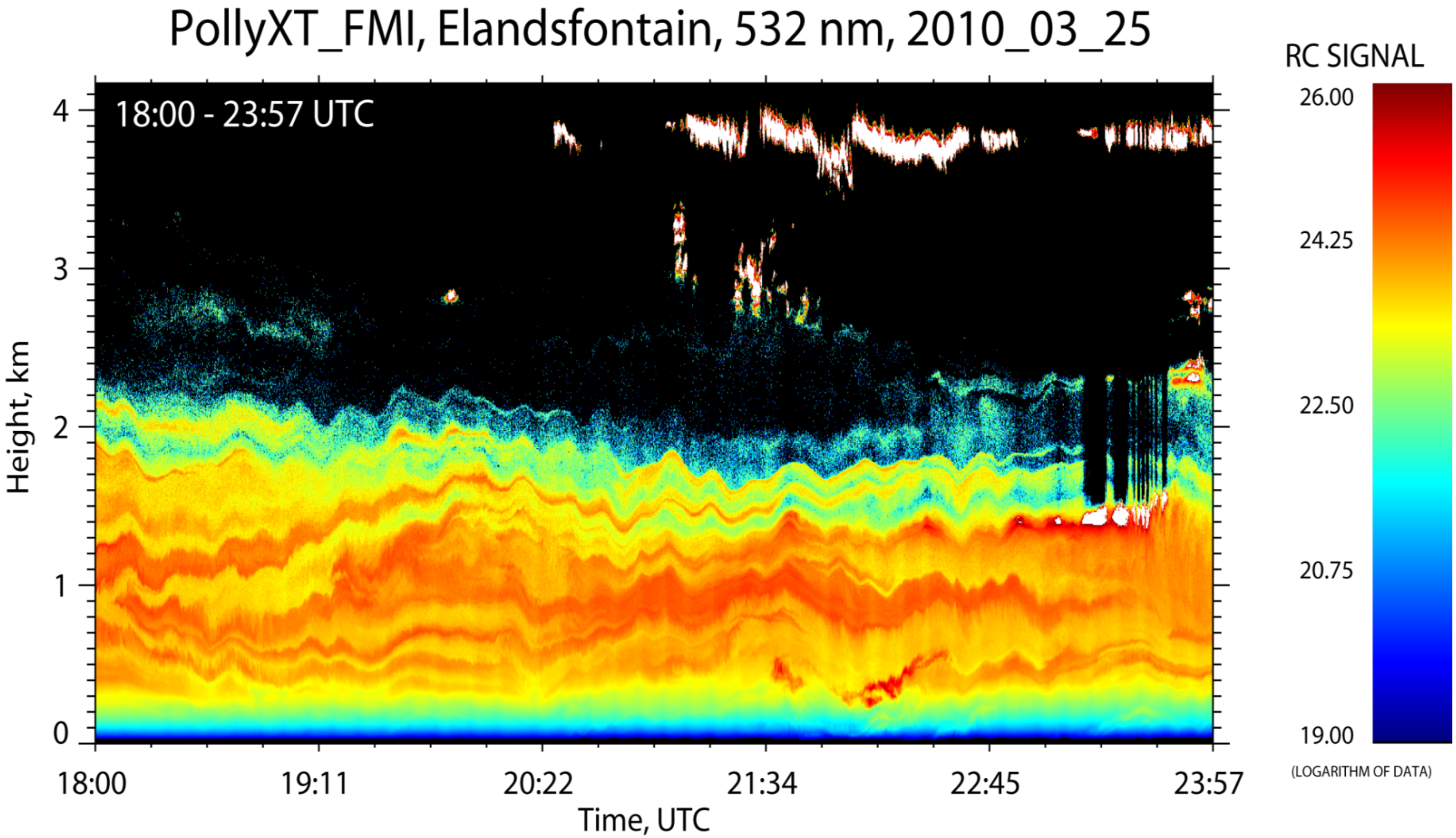
FIGURE 3 (Taken from Stull, 1988)

Over cities


Synoptic wind
"Rural" boundary layer
Boundary layer above the urban canopy
Mixed layer
Surface layer
Wake layer
Urban boundary layer
Surface layer
Land surface
Urban canopy layer
Transition zones
Boundary layer below roughness elements

Over cities


a) Mesoscale
Urban 'plume'
Mixing layer
PBL
Urban Boundary Layer
b)
Surface layer
Rural boundary layer
Rural
Urban
Rural
b) Local scale
Surface Layer
Roughness sublayer
c)
UCL
c) Micro scale
SVF
UCL
H
W
UCL Urban Canopy Layer


PollyXT_FMI, Elandsfontain, 532 nm, 2010_03_25
18:00 - 23:57 UTC
Height, km
0
1
2
3
4
18:00
19:11
20:22
21:34
22:45
23:57
Time, UTC
RC SIGNAL
26.00
24.25
22.50
20.75
19.00
(LOGARITHM OF DATA)

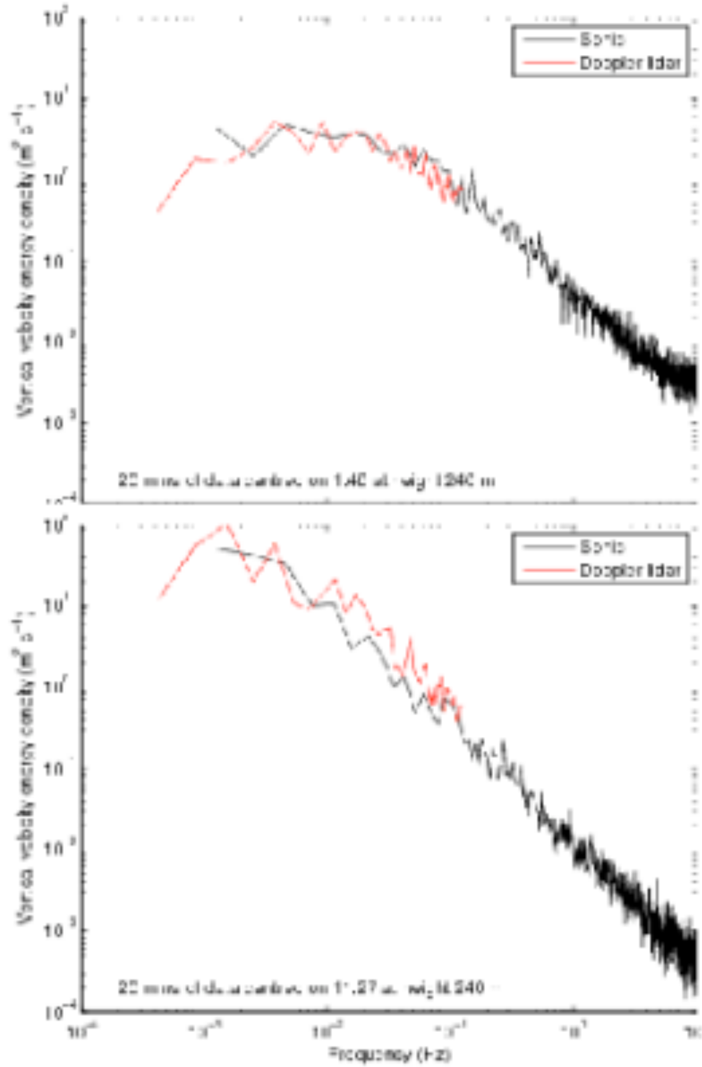
How can we diagnose boundary layer properties from remote sensing?

How can we diagnose boundary layer properties from remote sensing?

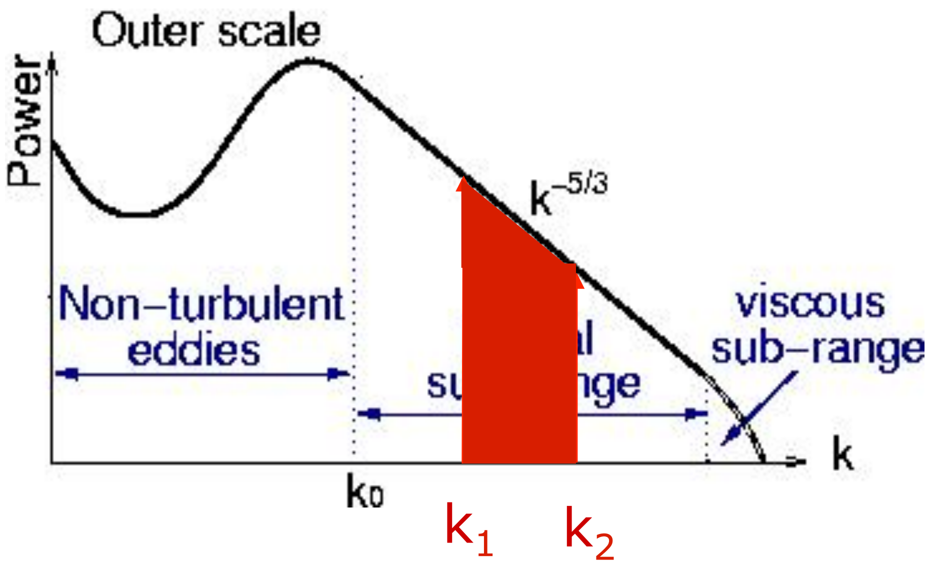
- Possible tracers for turbulent mixing:
  - Velocity variance
  - Temperature
  - Humidity
  - Aerosol
  - Trace gases

Doppler lidar velocity spectra have the expected shape

(if high SNR!)



TKE dissipation rate ε



In the inertial sub-range (Kolmogorov)

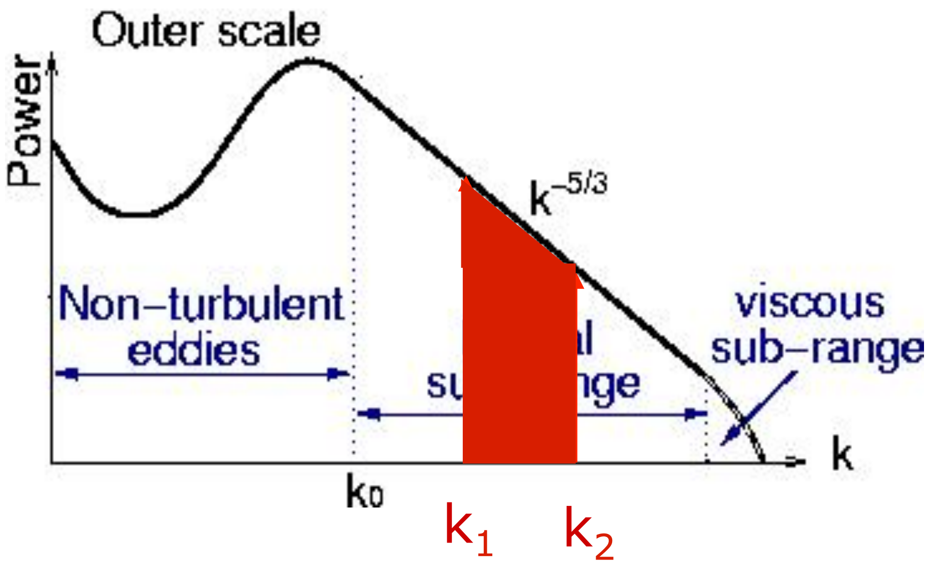
$$S(k) = a\varepsilon^{2/3}k^{-5/3}$$

k_1 is min horizontal wavenumber sampled over 300 s (use model winds)
k_2 is max horizontal wavenumber due to beamwidth of lidar

Part of TKE spectrum can be interpreted in terms of the variance of the mean Doppler velocity:

$$\sigma_{\bar{v}}^2 = \int_{k_1}^{k_2} S(k)\,dk$$

TKE dissipation rate ε



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$$S(k) = a\varepsilon^{2/3}k^{-5/3}$$

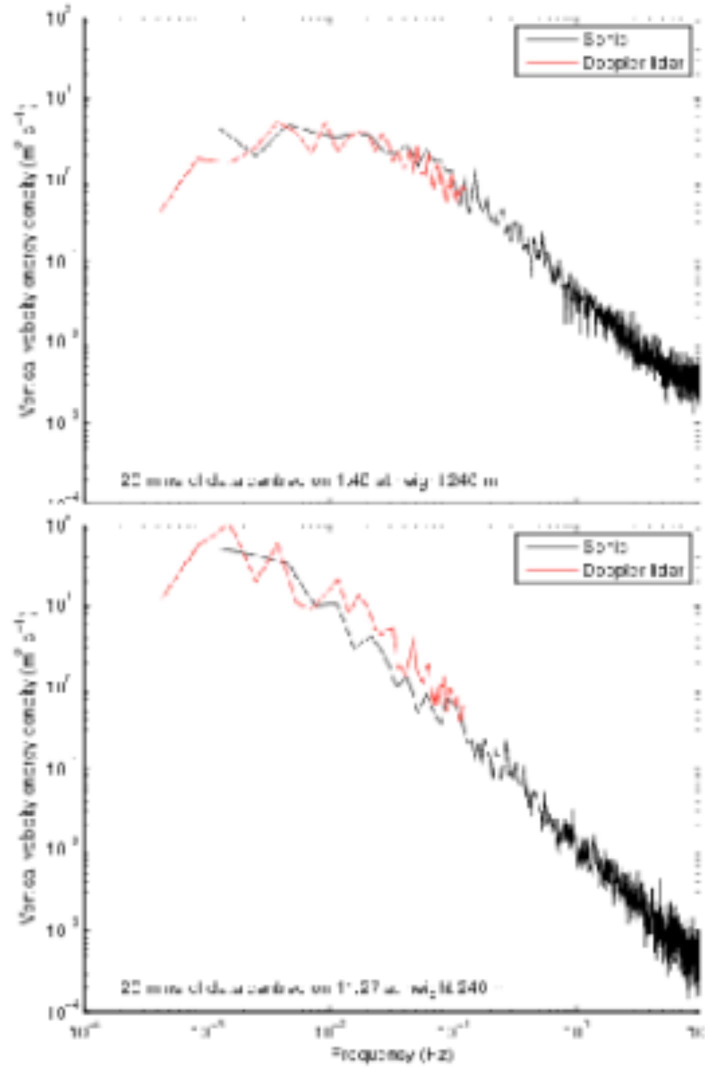
k_1 is min horizontal wavenumber sampled over 300 s (use model winds)
k_2 is max horizontal wavenumber due to beamwidth of lidar

$$\sigma_{\bar{v}}^2 = \frac{3a}{2}\varepsilon^{2/3}\left(k_2^{-2/3} - k_1^{-2/3}\right)$$

$$\varepsilon = \left(\frac{2}{3a}\right)^{3/2}\sigma_{\bar{v}}^{\;3}\left(k_1^{-2/3} - k_2^{-2/3}\right)^{3/2}$$

Doppler lidar velocity spectra have the expected shape

(if high SNR!)



Doppler lidar velocity uncertainty

$$\sigma_e = \left(\frac{\Delta v^2 \sqrt{2}}{\alpha N_p} (1 + 1.6\alpha + 0.4\alpha^2) \right)^{1/2},$$

Δv signal spectral width

B receiver bandwidth

α Ratio of detector photon count to speckle count

$$\alpha = \frac{\mathrm{SNR}}{(2\pi)^{1/2}(\Delta v / B)},$$

N_p Accumulated photon count

$$N_p = \mathrm{SNR}\ n\ M,$$

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Doppler lidar velocity uncertainty

Heterodyne detection

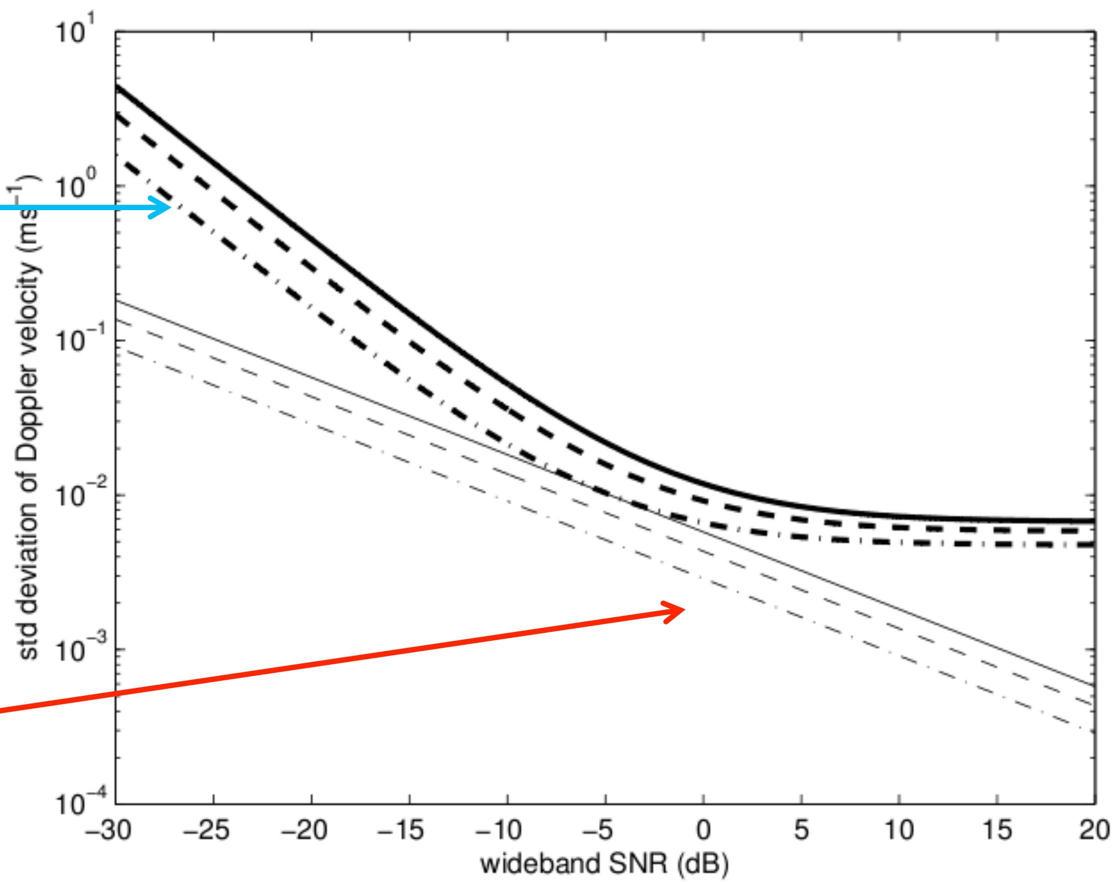
Lines indicate choice of

Δv

(signal spectral width)

Direct detection

$$\sigma_e = \Delta v/(N_p{}^{0.5}),$$



Measurements

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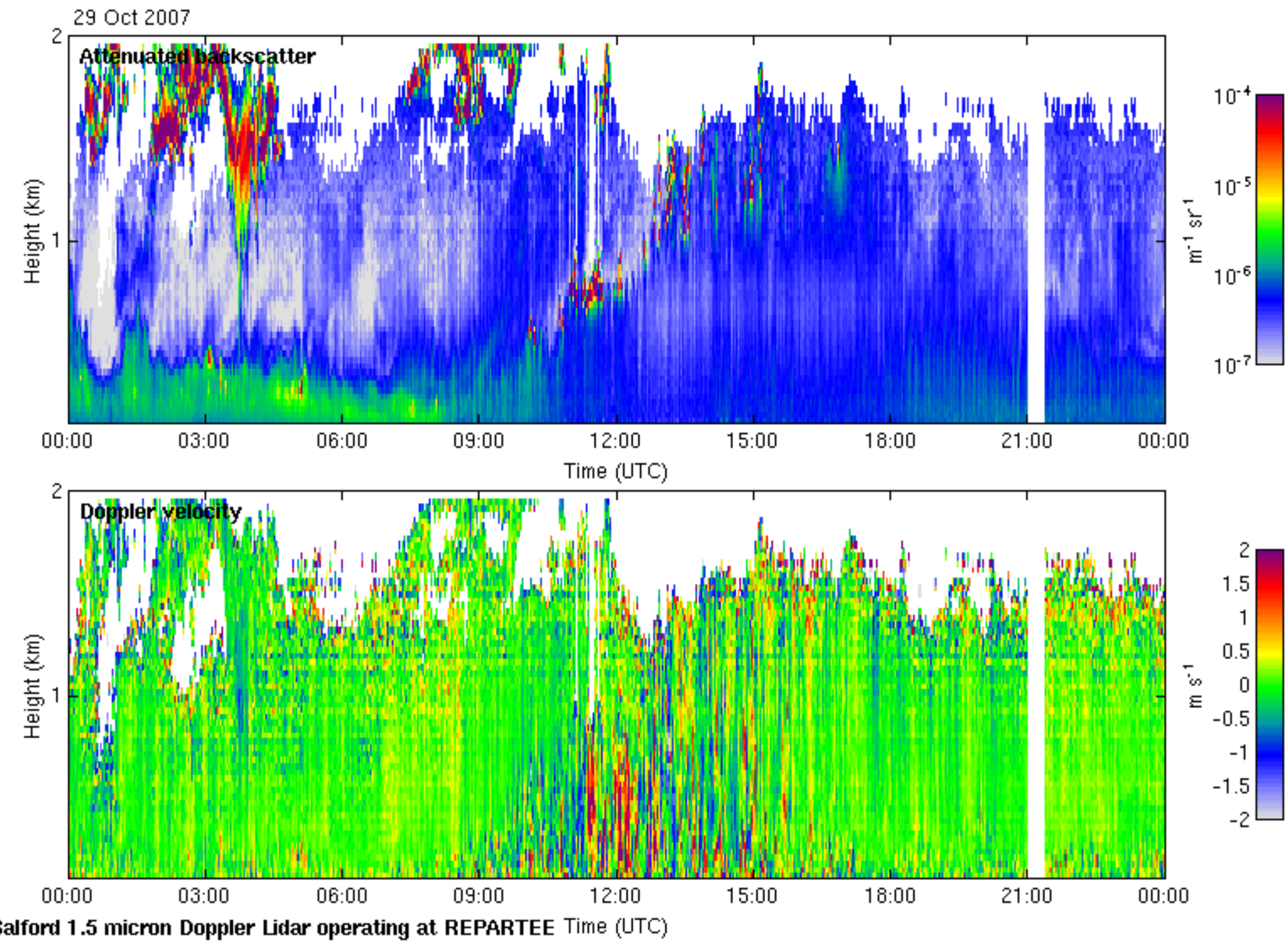

Salford 1.5 micron Doppler Lidar operating at REPARTEE

Measurements

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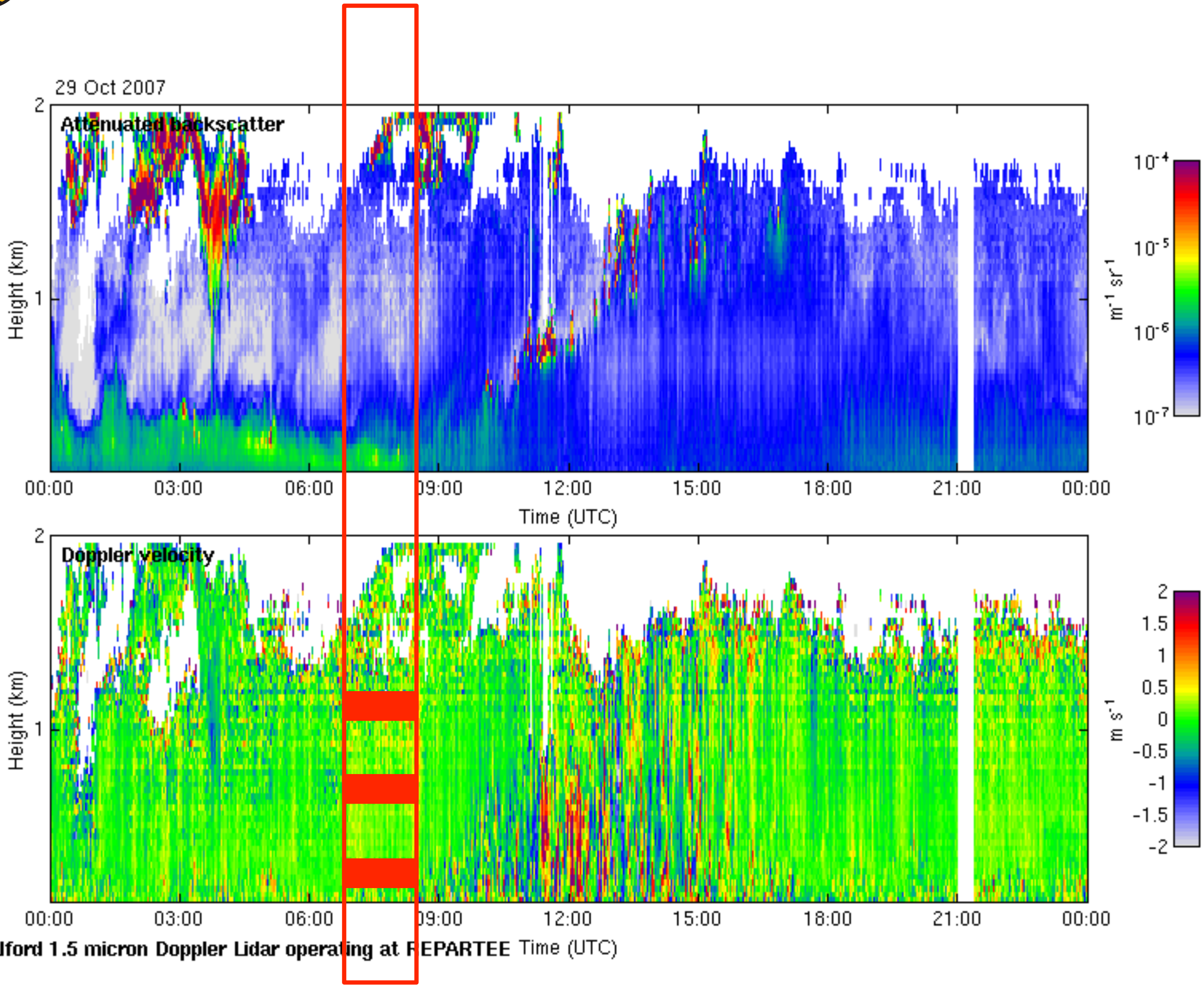

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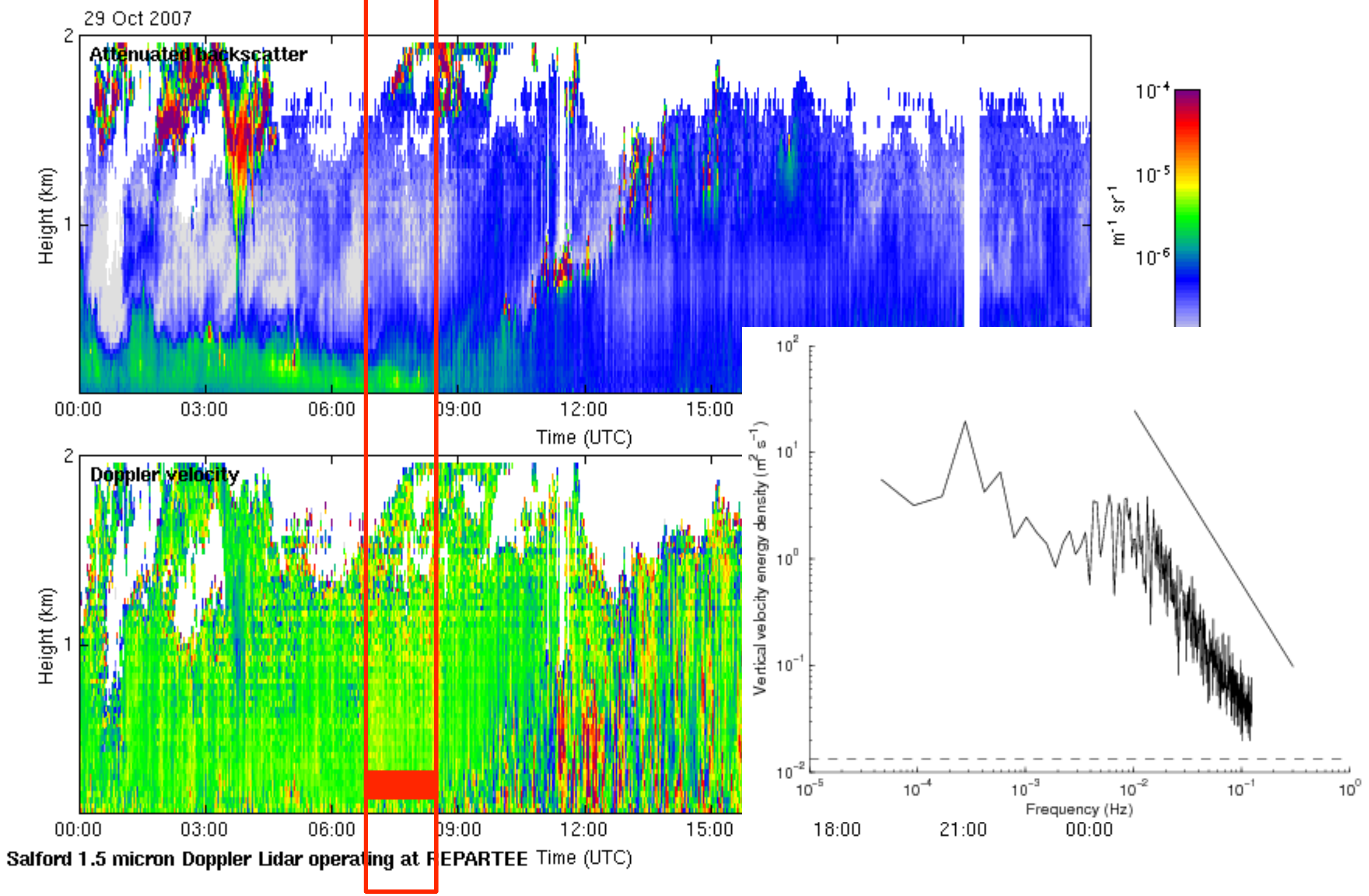

Measurements

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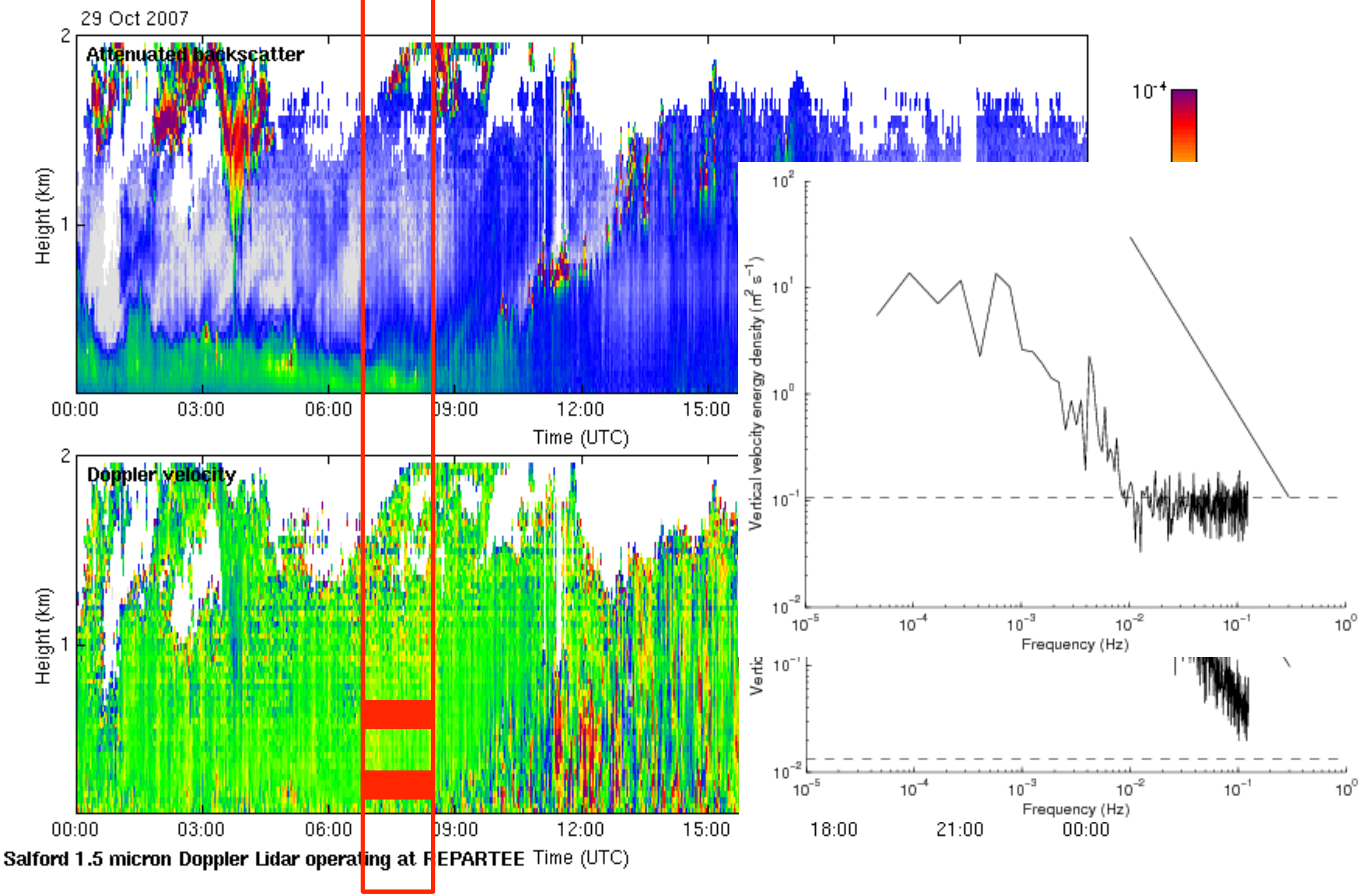

Measurements

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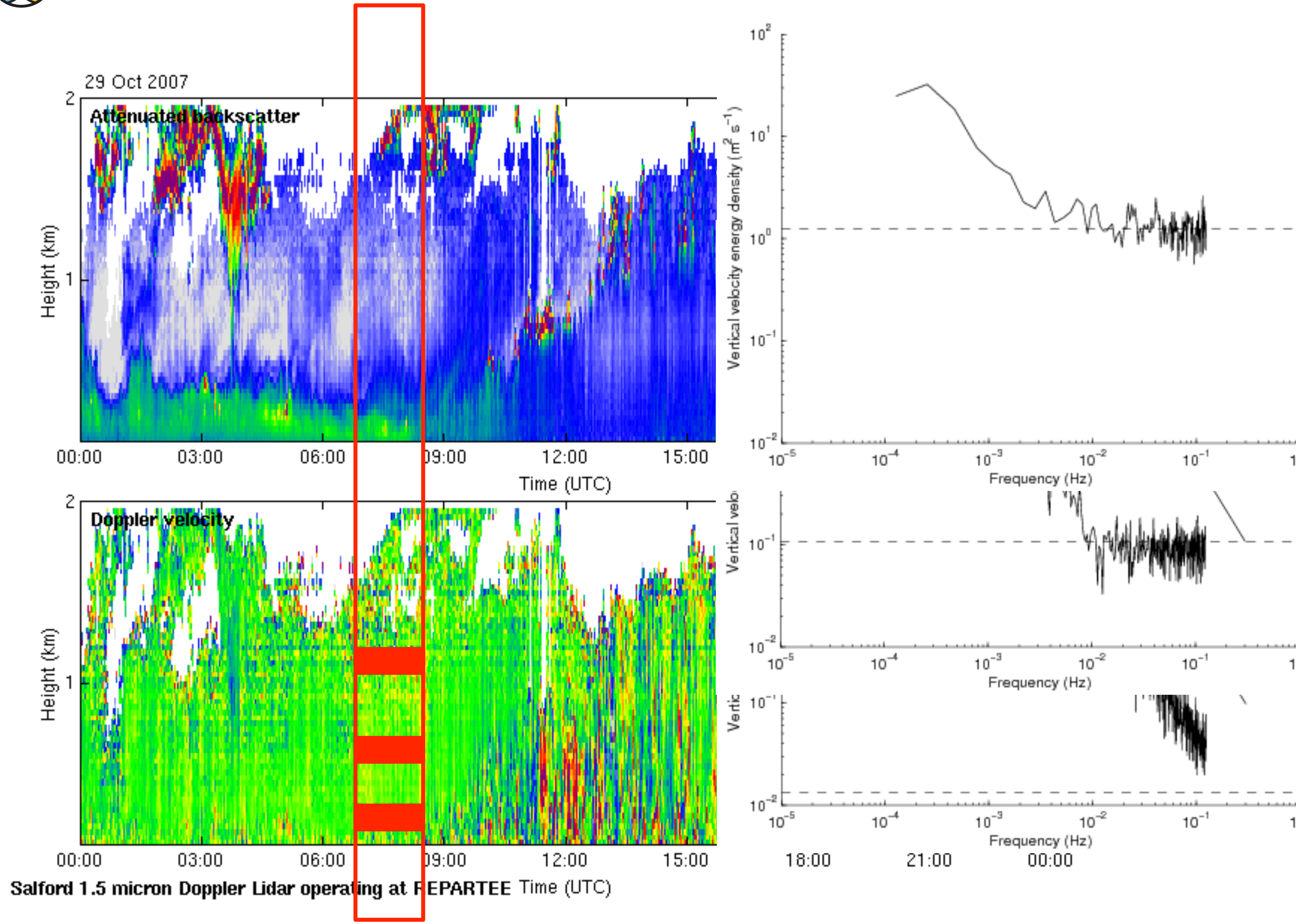

Calculate dissipation rate (after correcting variance)

$$\sigma_{\bar{v}}{}^2 = \sigma_{\bar{w}}{}^2 + \sigma_e{}^2 + \sigma_d{}^2,$$

Observed variance

Droplet fall speed distribution

Turbulent term

Measurement uncertainty

$$\Delta\sigma_{\bar{w}}{}^2 \approx \sigma_{\bar{w}}{}^2 \sqrt{\frac{4}{N}\frac{\sigma_e{}^2}{\sigma_{\bar{w}}{}^2}},$$

Uncertainty in variance

Fractional error in epsilon

$$\frac{\Delta\epsilon}{\epsilon} = \frac{3\Delta\sigma_{\bar{w}}}{\sigma_{\bar{w}}} + \frac{\Delta L}{L}.$$

$$L = Ut + 2z\sin\left(\frac{\theta}{2}\right),$$

Uncertainty in length scales derived from horizontal winds

$$\Delta{\sigma_{\bar{w}}}^2 \approx {\sigma_{\bar{w}}}^2\sqrt{\frac{4}{N}\frac{{\sigma_e}^2}{{\sigma_{\bar{w}}}^2}},$$

Measurements

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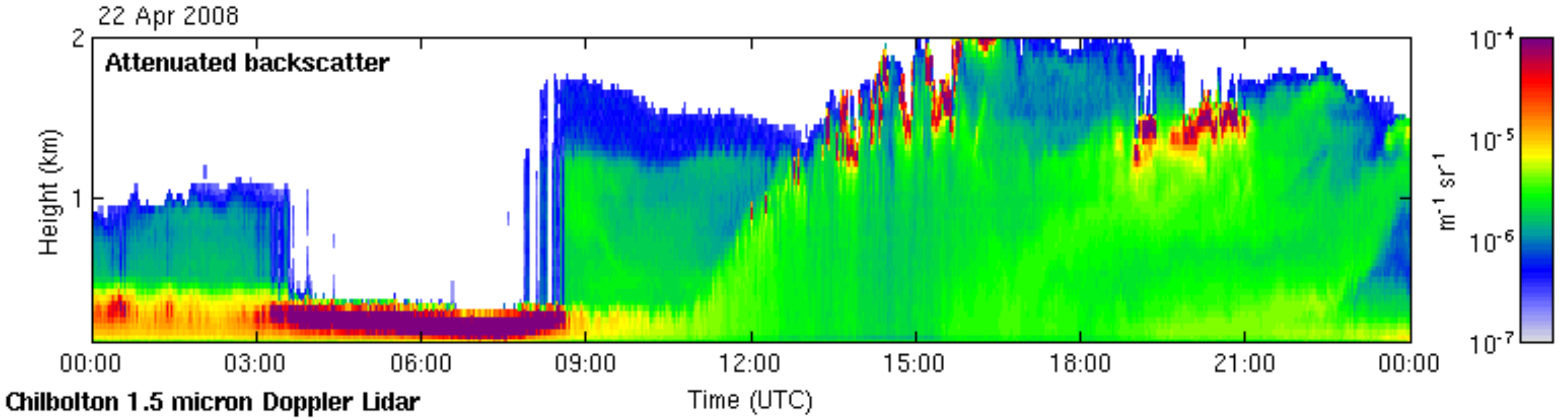
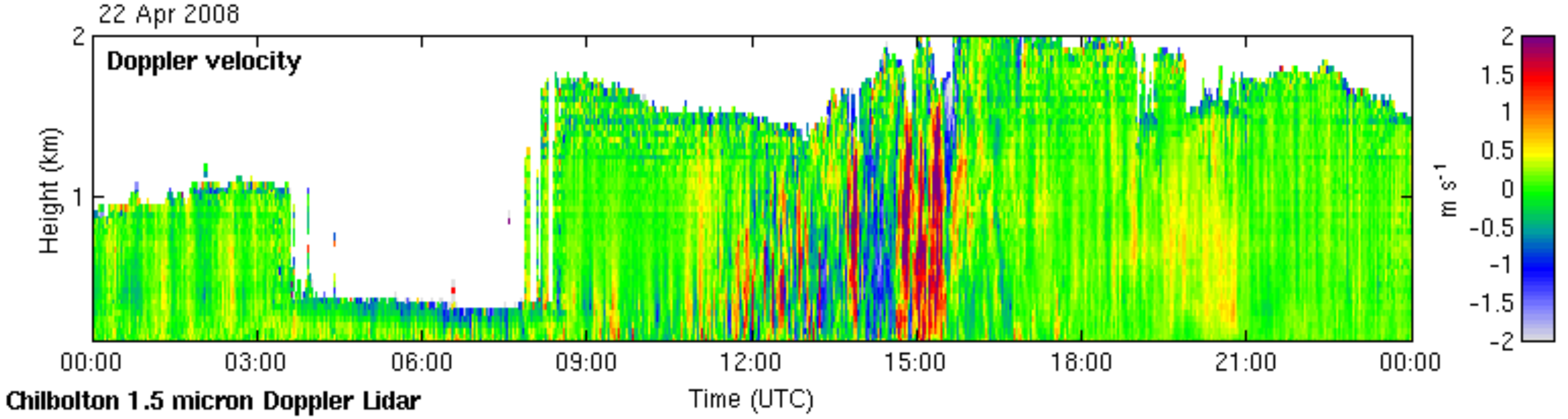
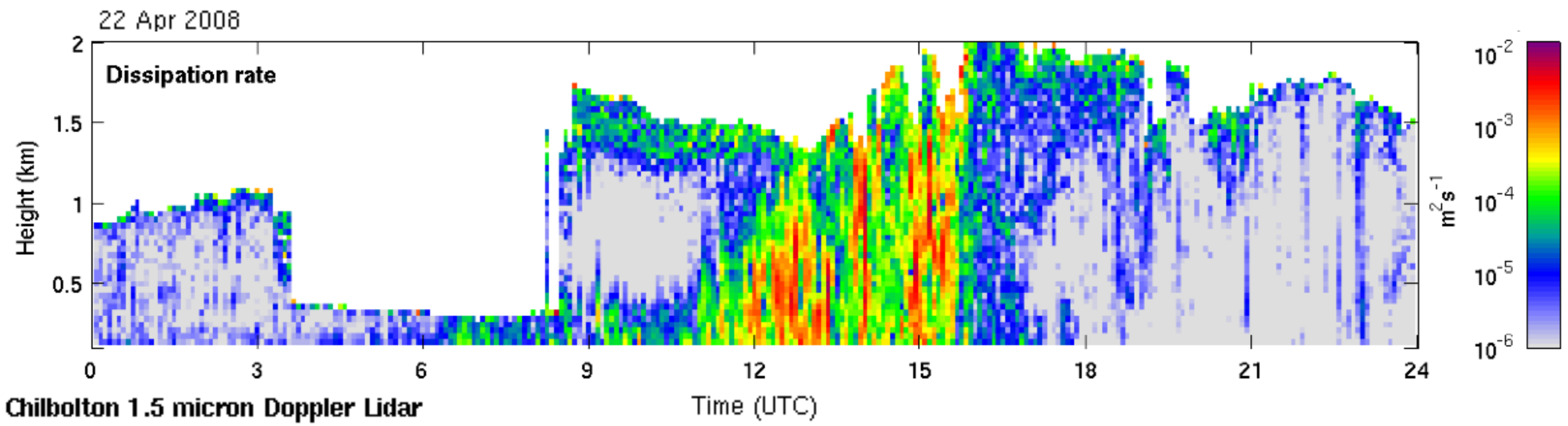
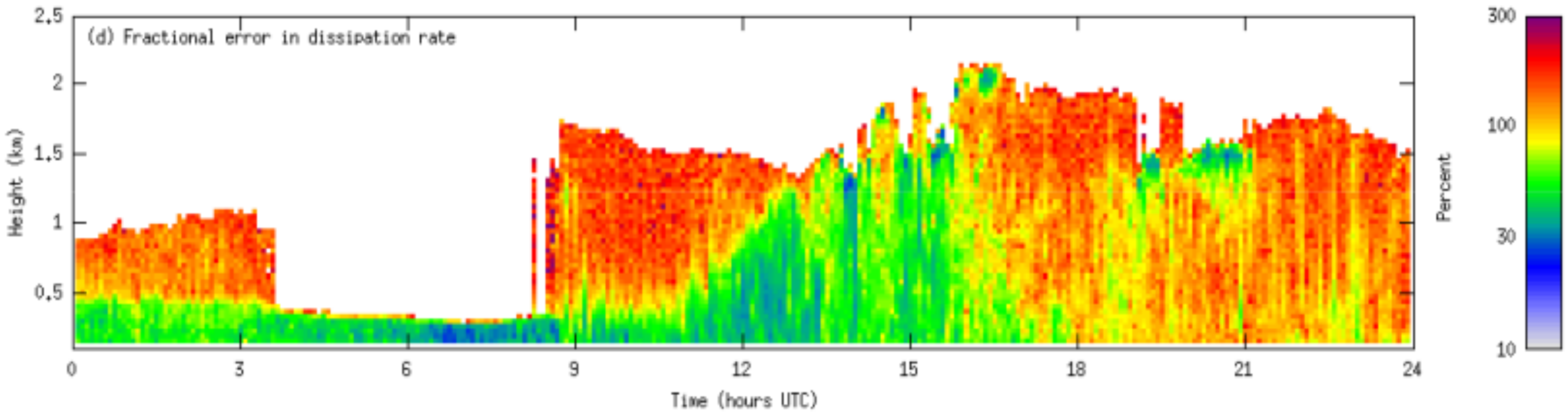
Doppler Lidar data for 22 April 2008



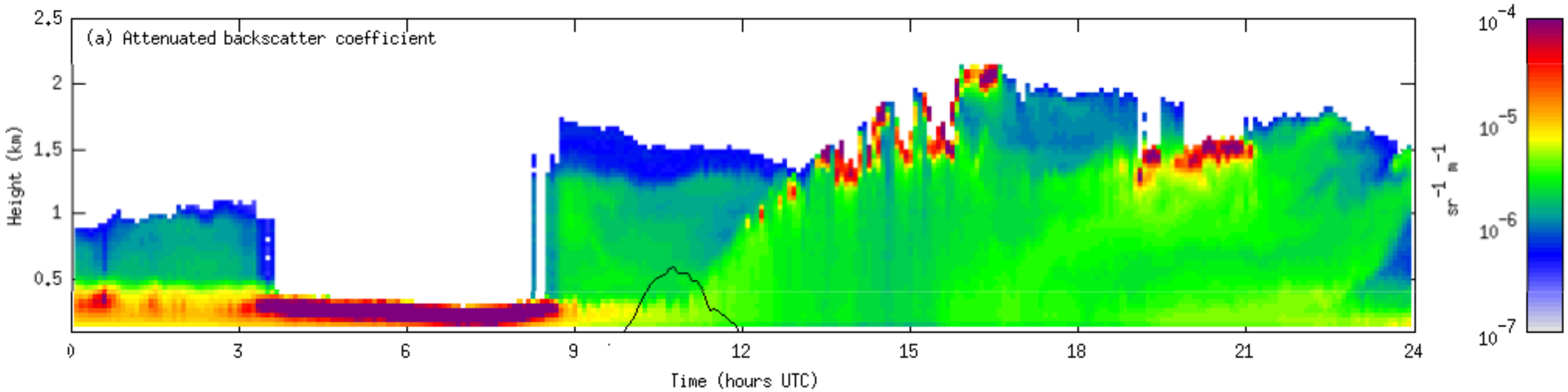


Turbulence

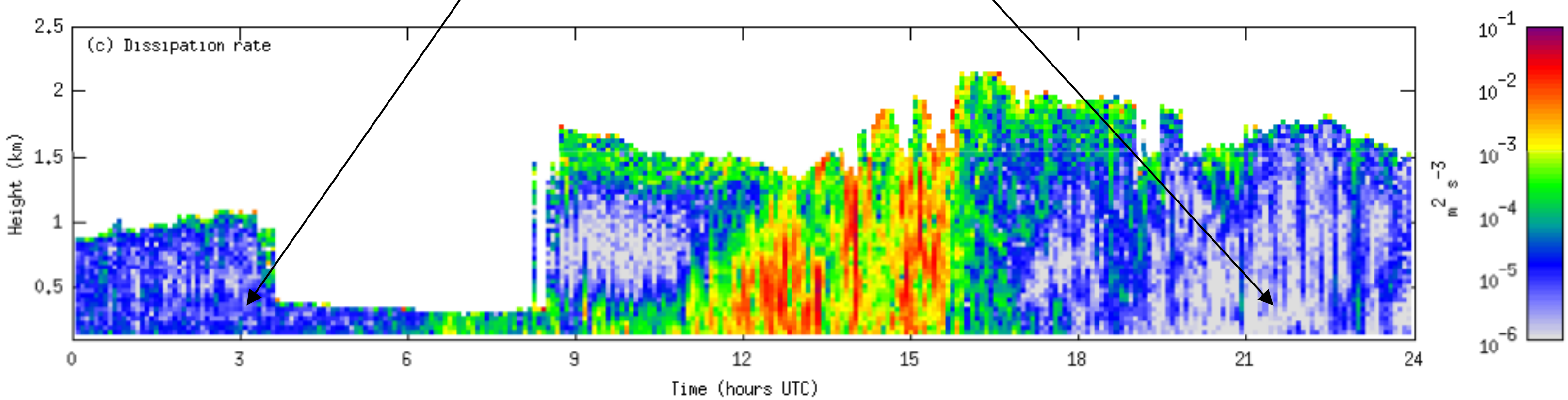

22 Apr 2008
Dissipation rate
Height (km)
2
1.5
1
0.5
0
3
6
9
12
15
18
21
24
Time (UTC)
Chilbolton 1.5 micron Doppler Lidar
$m^2 s^{-1}$
10^{-2}
10^{-3}
10^{-4}
10^{-5}
10^{-6}


(d) Fractional error in dissipation rate
Height (km)
2.5
2
1.5
1
0.5
0
3
6
9
12
15
18
21
24
Time (hours UTC)
Percent
300
100
30
10

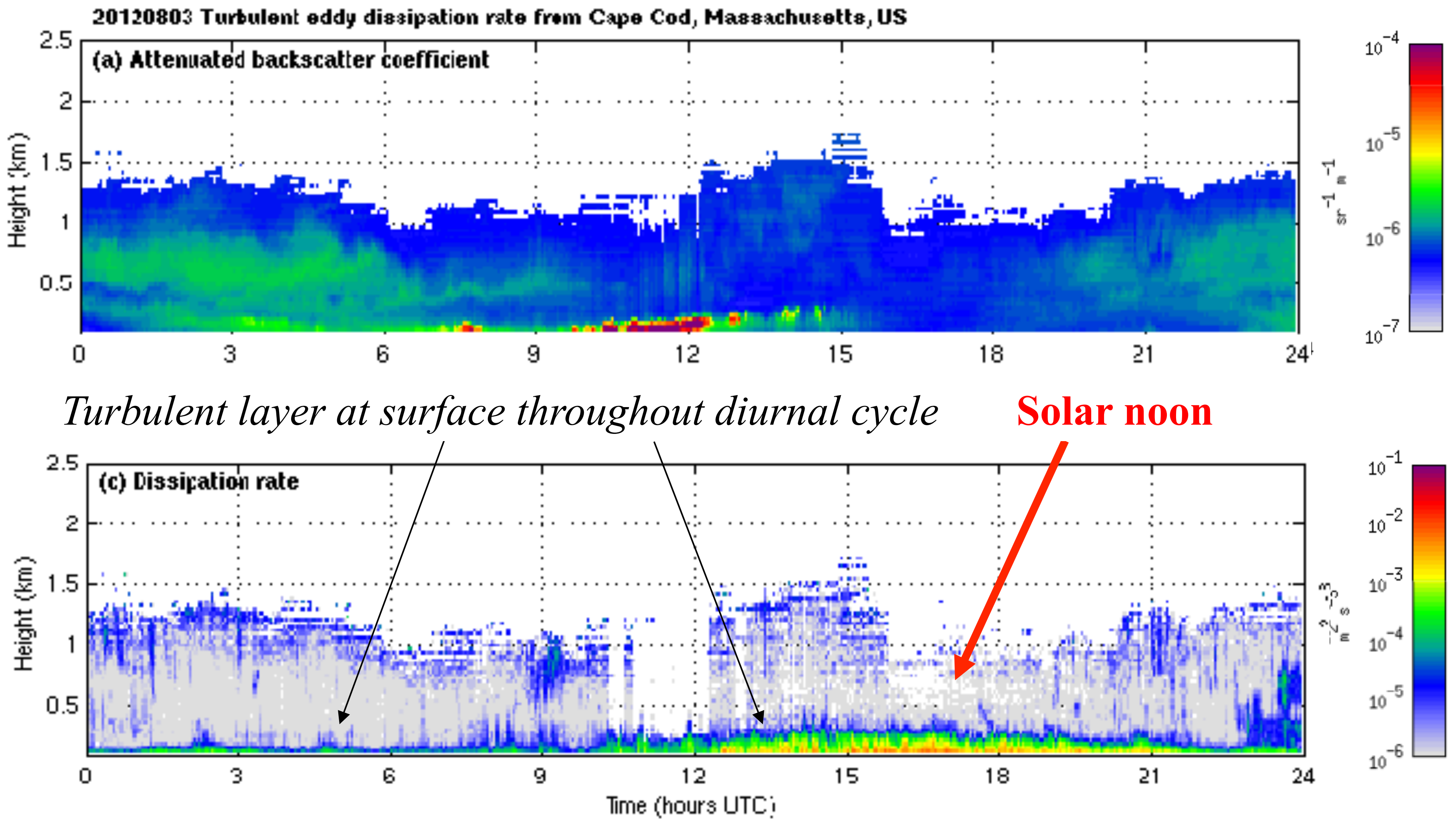
Chilbolton (Rural): 20080422



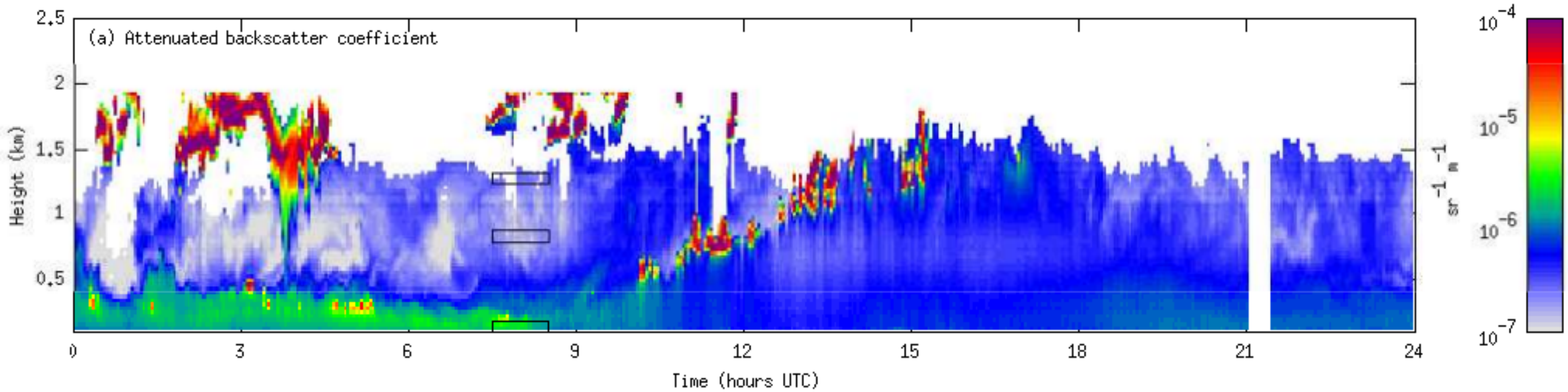
No turbulent layer at night



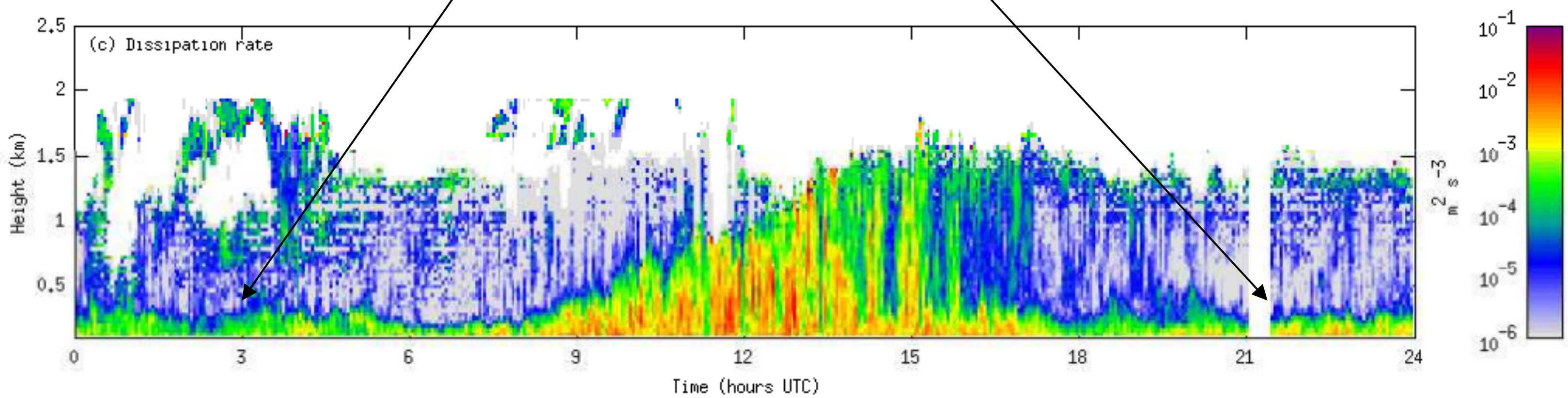
Cape Cod (Marine): 20120803



London (Urban): 20071029



Turbulent layer at surface throughout diurnal cycle



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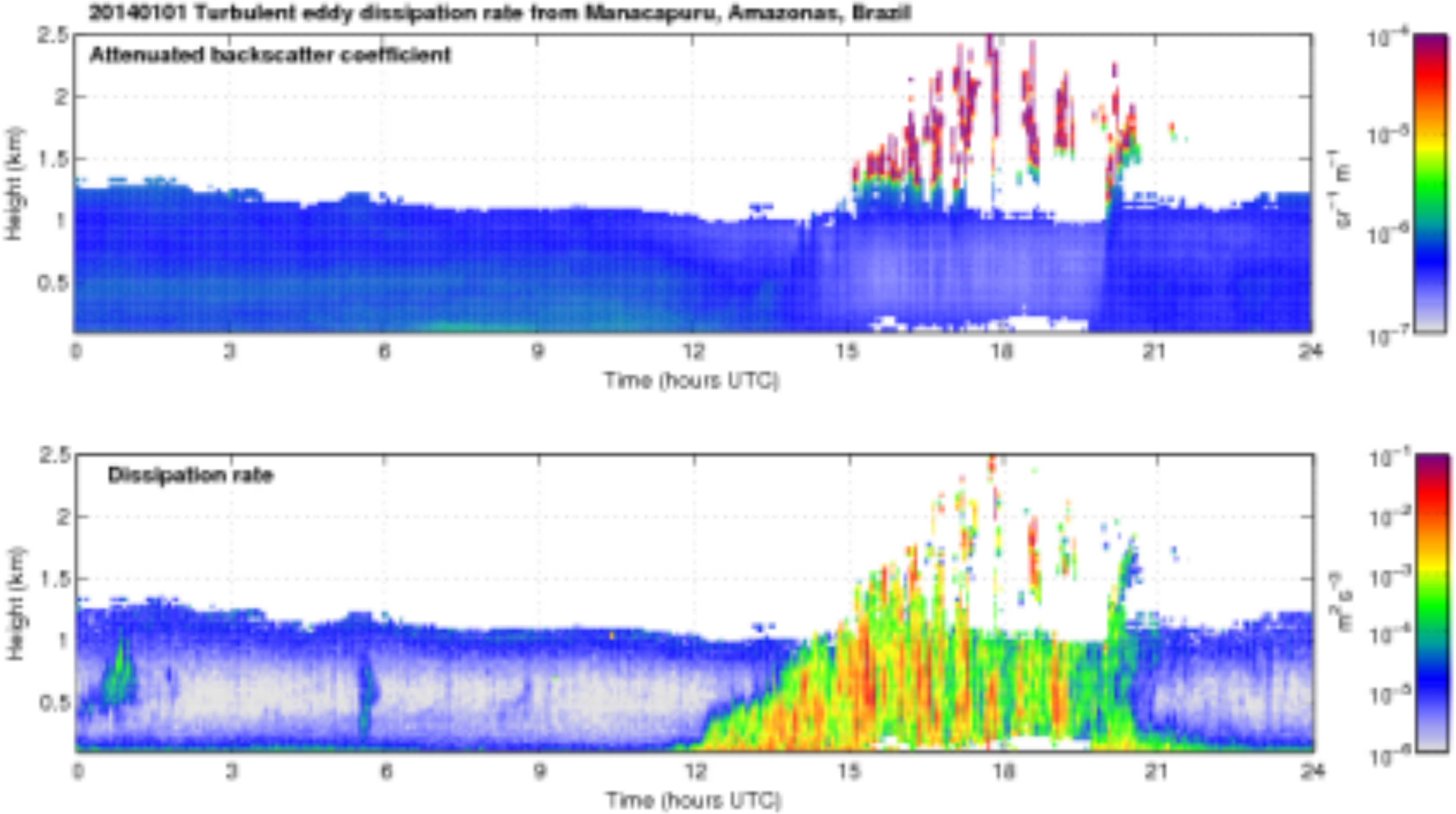
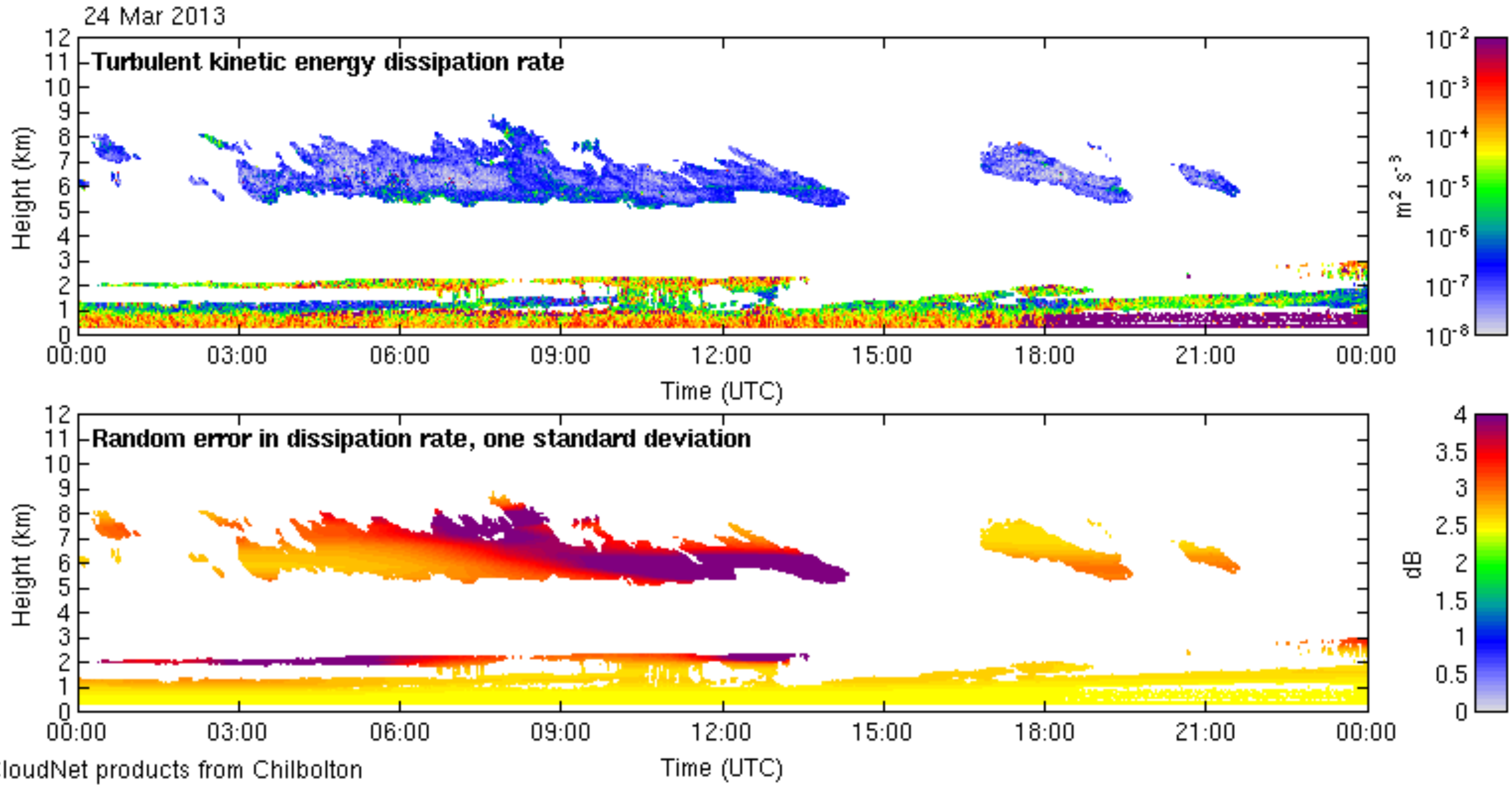
Amazon (rainforest): 20140101



Similar technique for cloud radar



CloudNet products from Chilbolton

SoDAR (Sonic Detection and Ranging)

- **Sodar operating principles**
  - Sound propagation
  - Pulse type
- **Sodar measures turbulence**
- **Sodar measures radial velocity**
  - How do we get horizontal wind?
    - DBS scans
  - Instrument type
    - Multi-beam
    - Phased-array

Operating principles – sound propagation

- **Sodar emits a pulse of sound**
- Energy is scattered by localised fluctuations in refractive index for acoustic waves (in all directions)
  - Fluctuations may be in temperature, humidity, velocity
- Backscattered energy from the transmitted pulse measured
  - Signal strength gives measure of turbulence
  - Doppler shift in signal gives radial velocity

  - For monostatic sodar system, backscattered energy is caused by thermally-induced turbulence only

Operating principles – sound propagation

Backscatter at arbitrary angle (θ)

$$\sigma(\theta) = 0.03k^{1/3}\cos^2\theta\left[\sin\left(\frac{\theta}{2}\right)\right]^{-11/3}\left[\frac{C_V^2}{c^2}\cos^2\left(\frac{\theta}{2}\right) + 0.13\frac{C_T^2}{T^2}\right]$$

$k = 2\pi/\lambda$,

T is temperature in k,

C_v = structure function constant for velocity,

C_T = structure function constant for temperature

Operating principles – sound propagation

Backscatter at 180 degrees

$$\sigma(\pi) = (0.03k^{1/3})\left(0.13\frac{C_T^2}{T^2}\right) = 0.0039k^{1/3}\frac{C_T^2}{T^2}$$

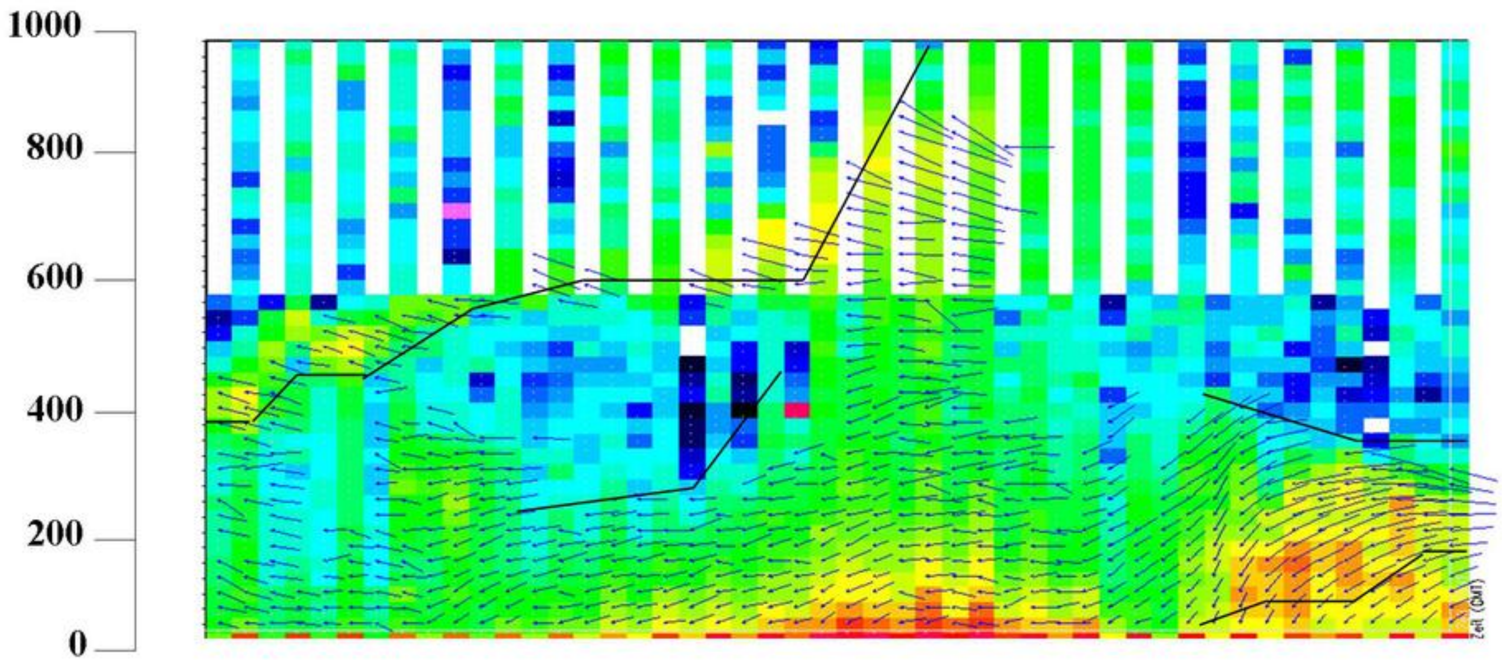
$k = 2\pi/\lambda$,

T is temperature in k,

C_T = structure function constant for temperature

Operating principles – sound propagation

Backscatter is a measure of turbulence



Courtesy: Stefan Emeis

Operating principles – velocity

The speed of sound in an ideal gas is

$$v_{sound} = \sqrt{\frac{\gamma RT}{M}}$$

where

γ = adiabatic constant
R = gas constant
M = molecular mass of gas
T = absolute temperature

For air, γ = 1.4 and average M (DRY) = 28.95 gm/mol.

$$v_{sound} = \sqrt{\frac{1.4(8.314 J/mol \cdot K)}{.02895 kg/mol}} \sqrt{T} = 20.05 \sqrt{T} \quad m/s$$

At T = 273 K, v_{sound} ~330 m s^{-1} in dry air.

- **Consider a target at a range, R, from a sodar**
- **Total distance the pulse travels is 2R**
- **Corresponding to:**
  - $2R/\lambda$ wavelengths, or
  - $4\pi R/\lambda$ radians of phase

- **Consider a target at range R, moving with velocity v, towards the sodar**
- **Change in phase due to the motion of the target between returned signals is**

$$\phi_2 - \phi_1 = \frac{4\pi R_2}{\lambda} - \frac{4\pi R_1}{\lambda}$$

- The rate of change in phase detected at sodar

$$\frac{d\phi}{dt} = \frac{4\pi v}{\lambda}$$

- This can be described as a frequency shift since

$$\frac{d\phi}{dt} = 2\pi\nu$$

- The Doppler frequency shift

$$\nu_D = \frac{2v}{\lambda}$$

- Doppler frequency shift tells us the speed that the target is moving
- For a given wavelength the frequency shift is dependent only on the velocity of the target

- **Since λ = c/f, the Doppler frequency shift**

$$v_D = 2fV/c$$

- **For a wind of 15 m s^{-1}**
  - Operating frequency = 1500 Hz
    - v_D = 135 Hz
  - Operating frequency 5 kHz
    - v_D = 455 Hz

Time between pulses?

Require no signal from 1st pulse contaminating 2nd pulse

$R = ct/2$,

Choice depends on sensitivity:

assume 6 s

gives R ~990 m

Range resolution?

Typical operating pulse lengths are about 0.01 s

Potential resolution is therefore 6.6 m

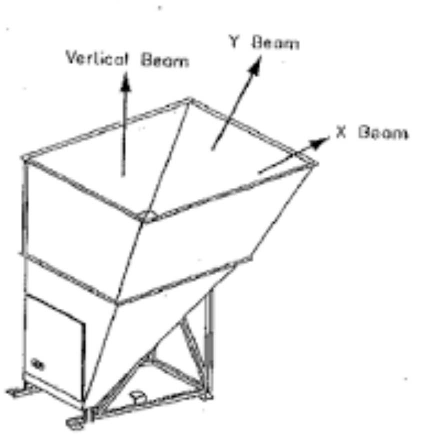
However, may use a coded pulse to improve sensitivity:

If this is 16 bits, pulse length = 0.16 s

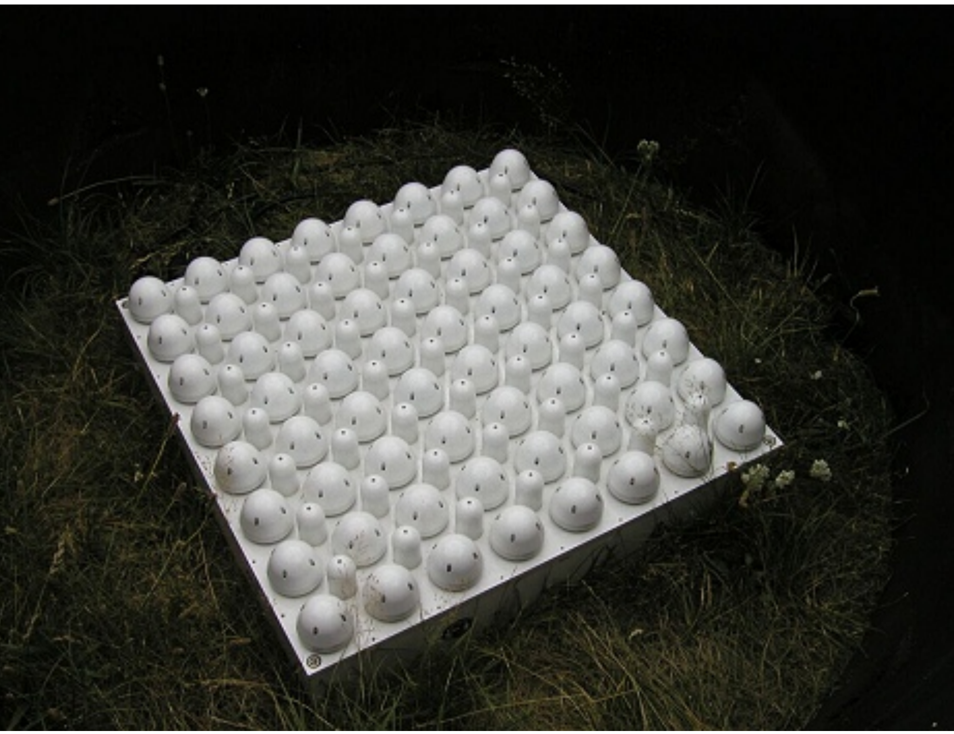
First gate is >100 m

Resolution is theoretically similar to above but in practice smoother

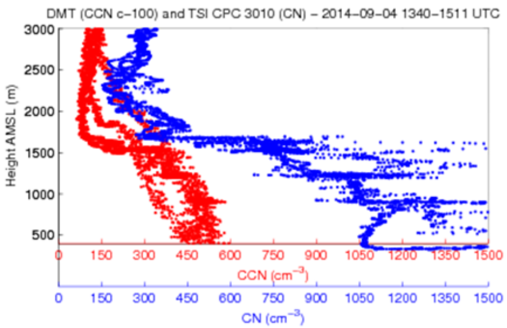
Instrument configurations – 3 beam

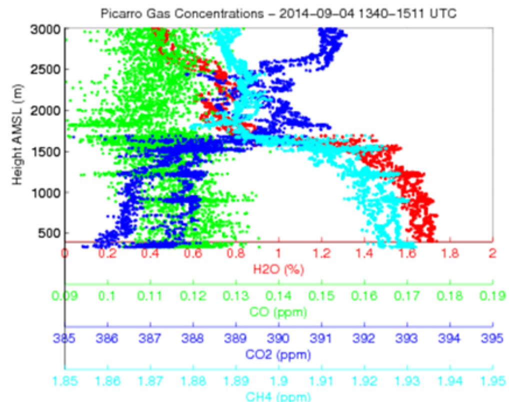


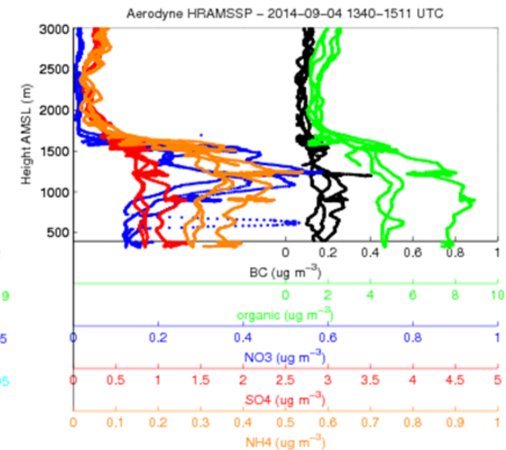
Instrument configurations – Phased array

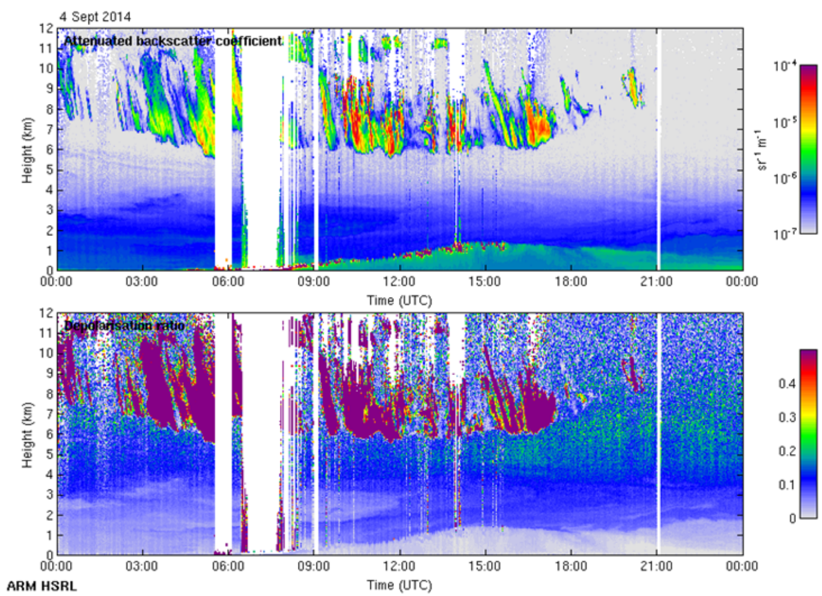


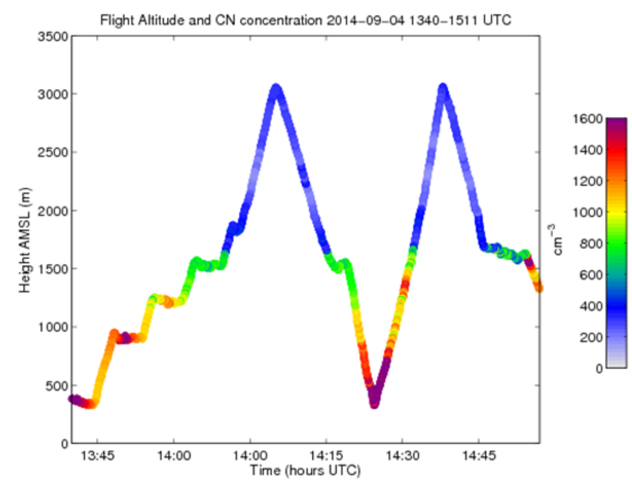
Aerosol and trace gases











Aerosol as a tracer

- **mixing layer height (MLH) is important for many applications**
- **Most of current Retrievals are based on proxies:**
  - Potential Temperature determines how far up a parcel may rise
    - but starting temperature is often not well defined
    - t
  - Trace
    - s
    - b
  - Aeros
    - Is a tracer with strongest source at the surface (see above)
    - But is also influenced by relative humidity
- **Mixing itself is vertical movement of air**
  - => vertical staring Doppler lidar measures mixing directly and instantenously

Idea:
aerosol backscatter (gradient) is a proxy
vertical wind is direct measure of mixing
=> Compare to validate MLH(aerosol)

Jan Schween (Köln, Germany)

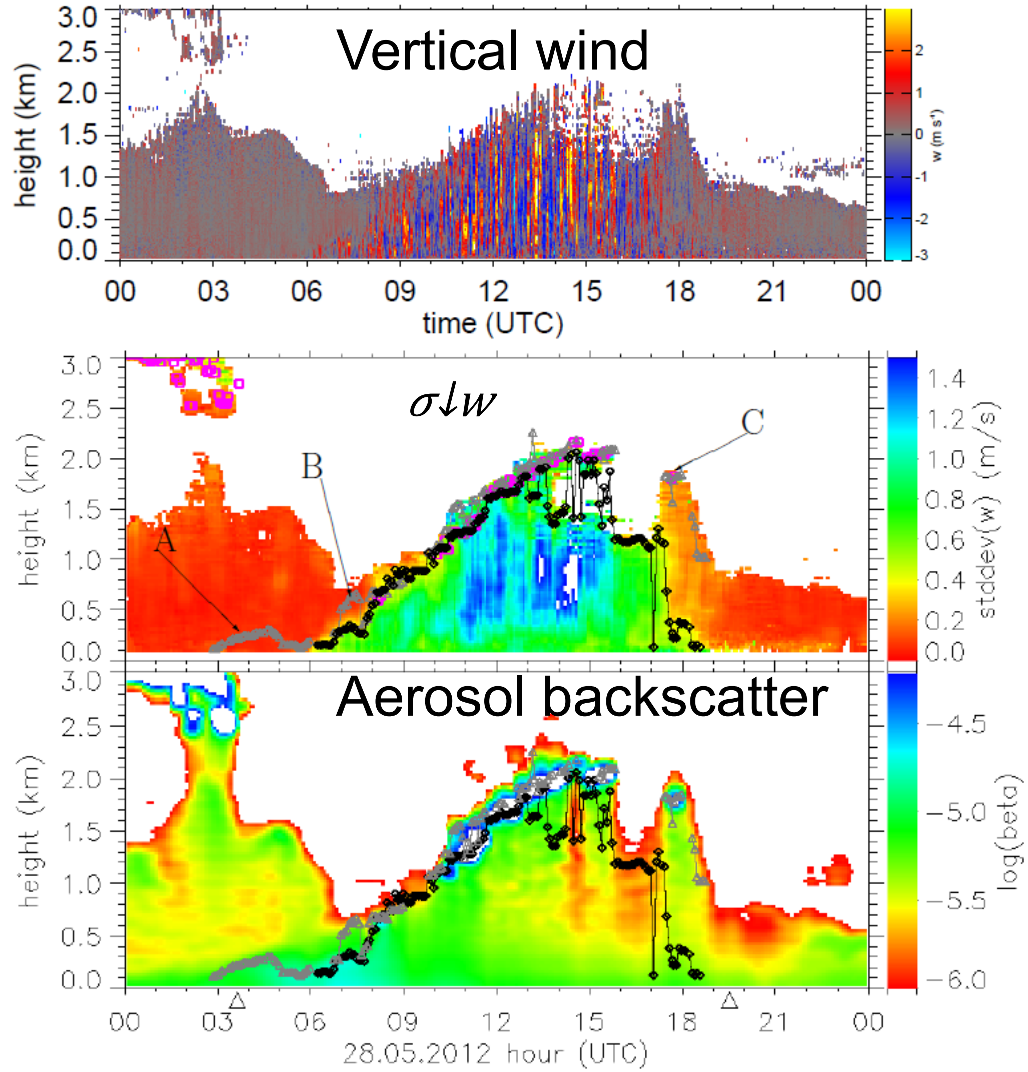
Compare in case study

- **MLH_{wind} from σ_w in black**
- **MLH_{aero} from aerosol in gray**
- **General good agreement – but three periods where they disagree:**

  A: late night: strong inversion, strong aerosol gradient due to high Rel.Humidity

  B: morning: growth of MLH into RL with no clear gradient in aerosol backscatter between both layers

  C: late afternoon decay of turbulence, aerosol reflects history but not current state of ML



Jan Schween (Köln, Germany)

More complicated situations

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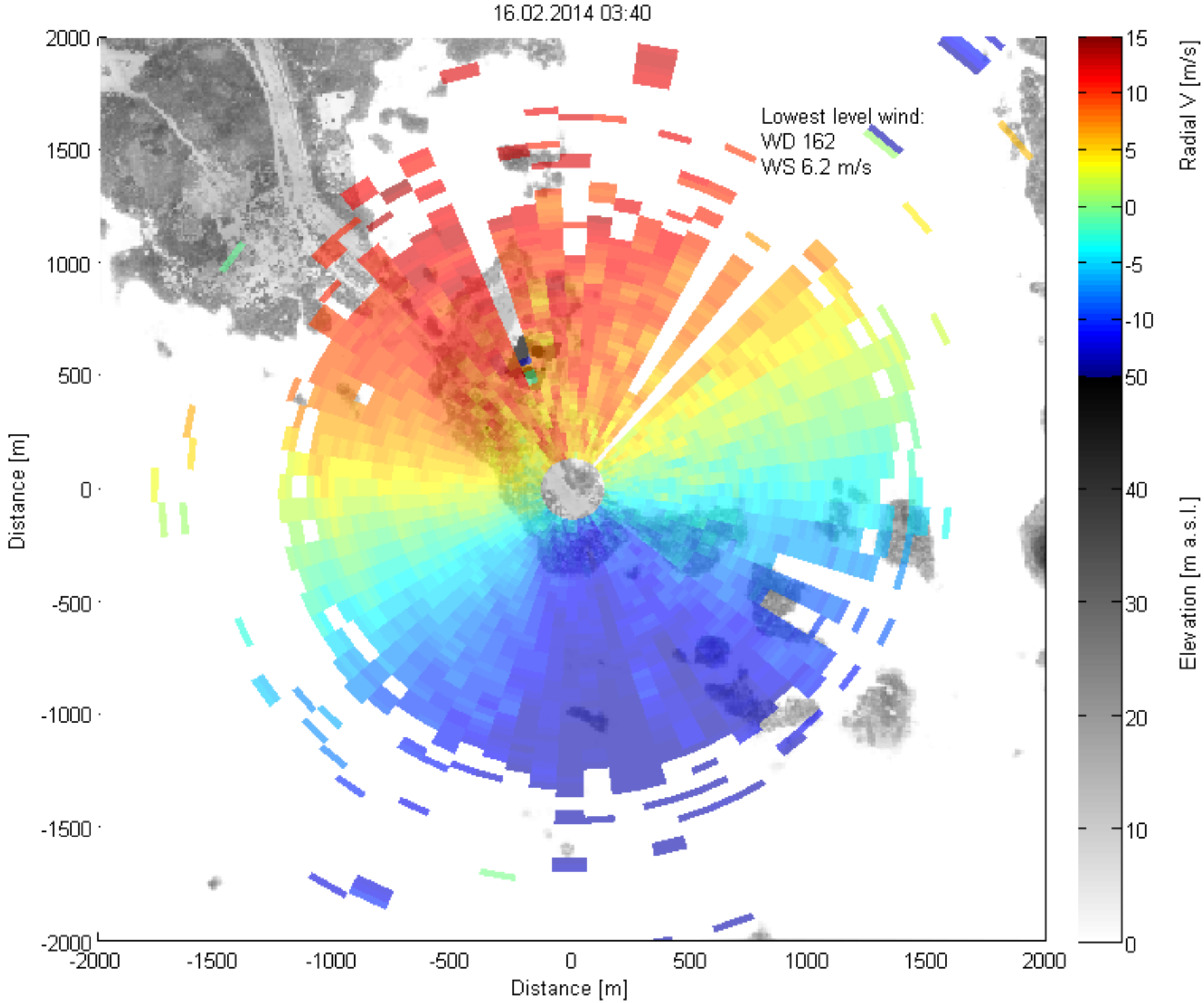

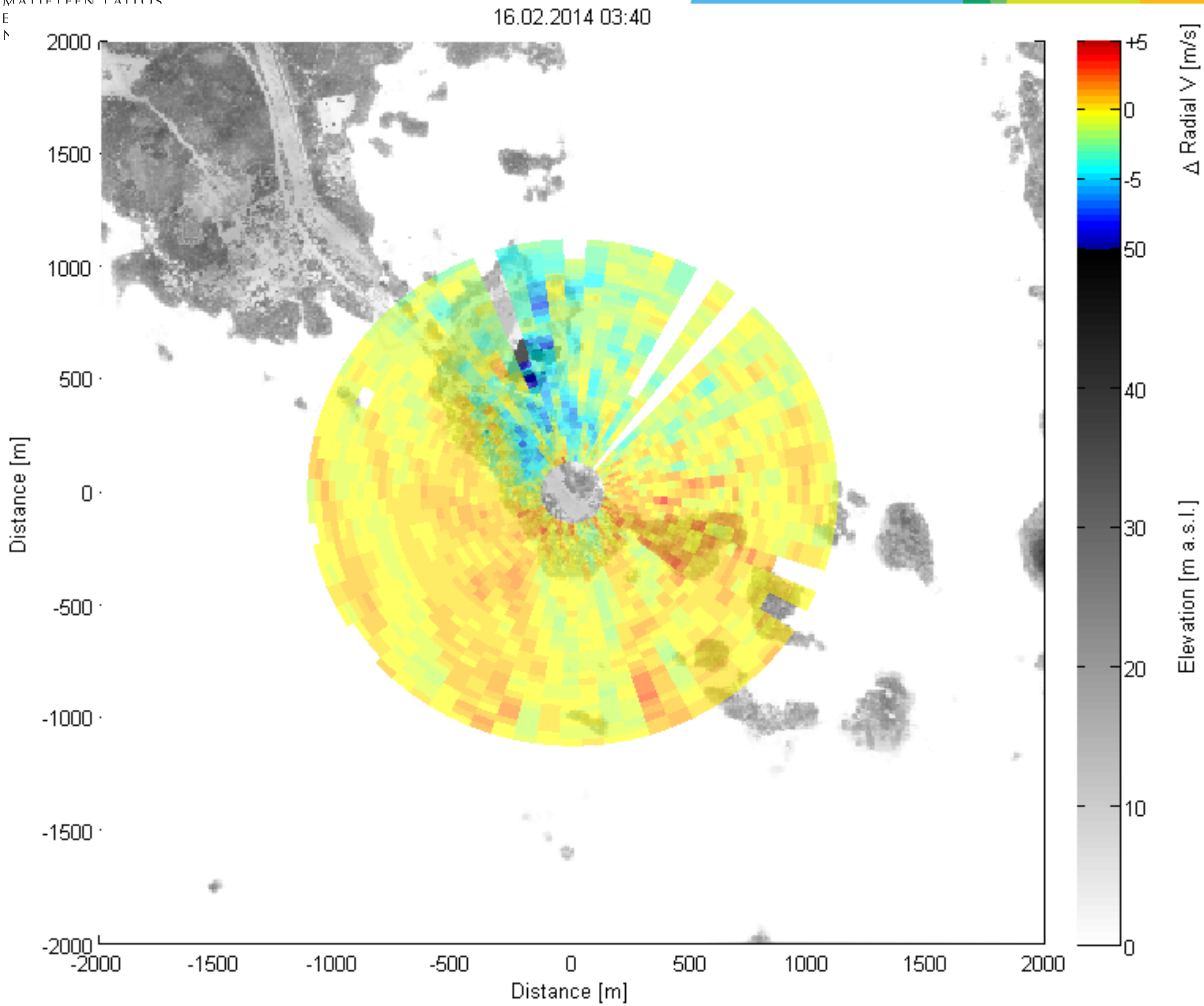

16.02.2014 03:40
2000
1500
1000
500
0
-500
-1000
-1500
-2000
-2000
-1500
-1000
-500
0
500
1000
1500
2000
Distance [m]
Distance [m]
+5
0
-5
50
40
30
20
10
0
Δ Radial V [m/s]
Elevation [m a.s.l.]

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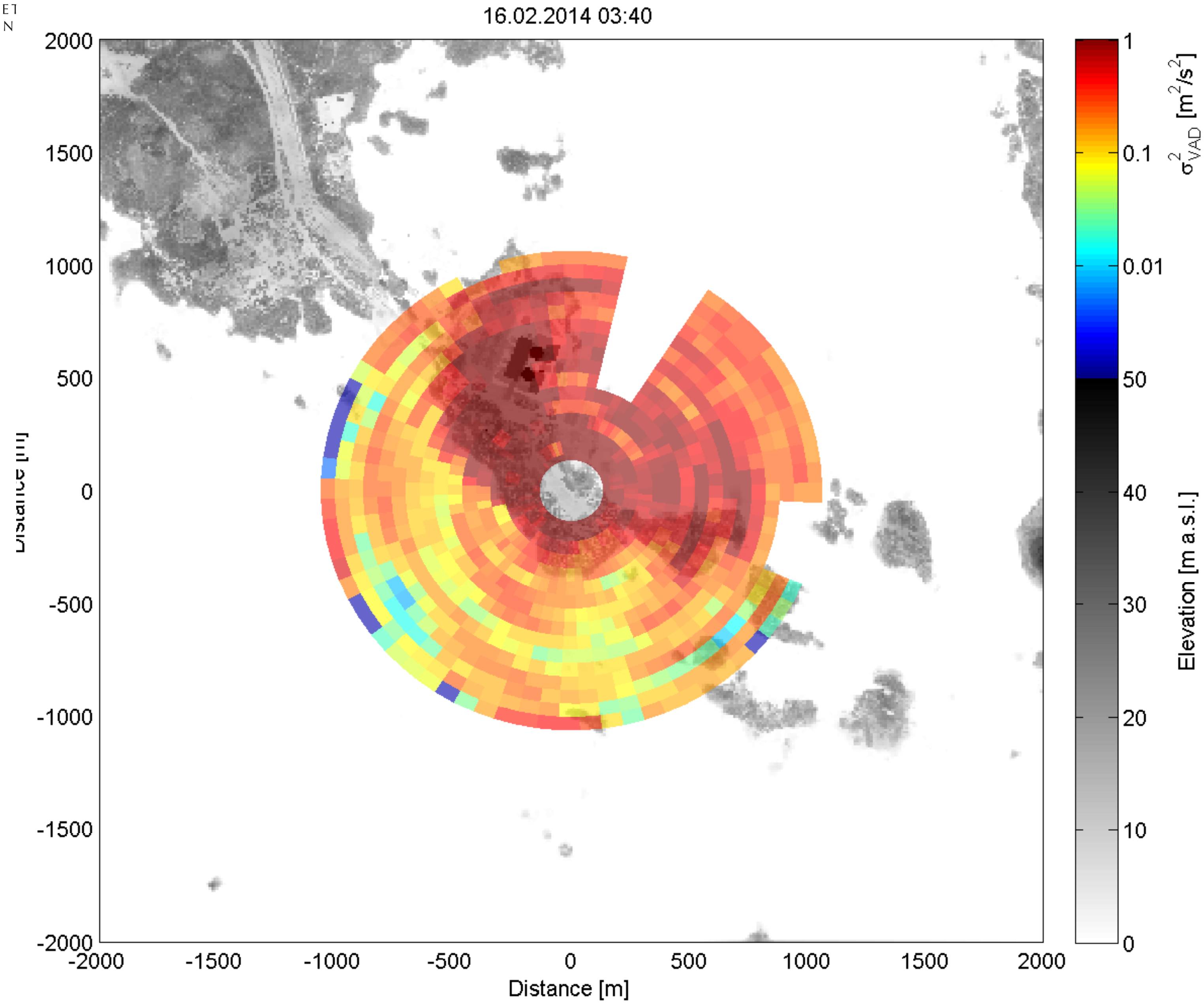
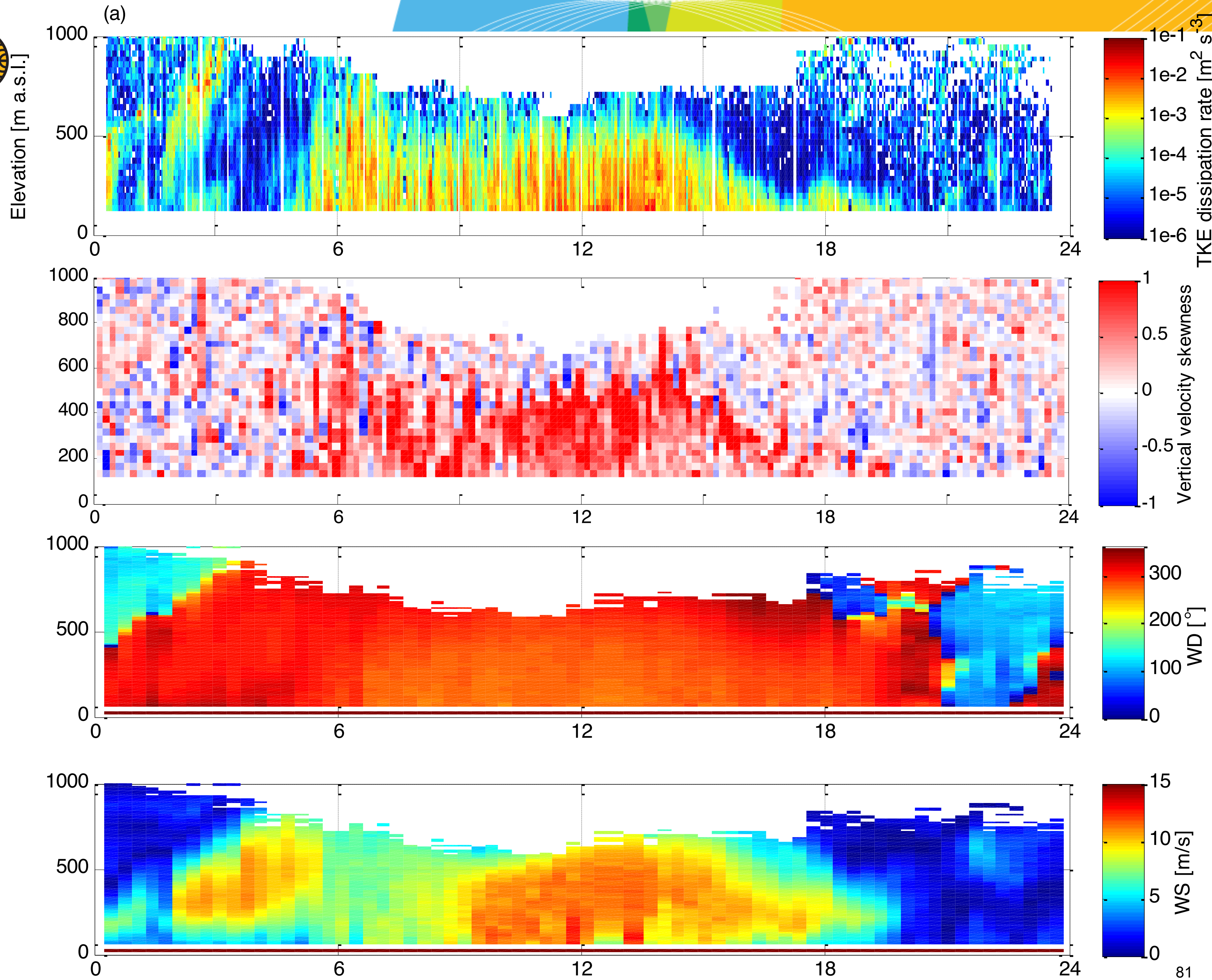
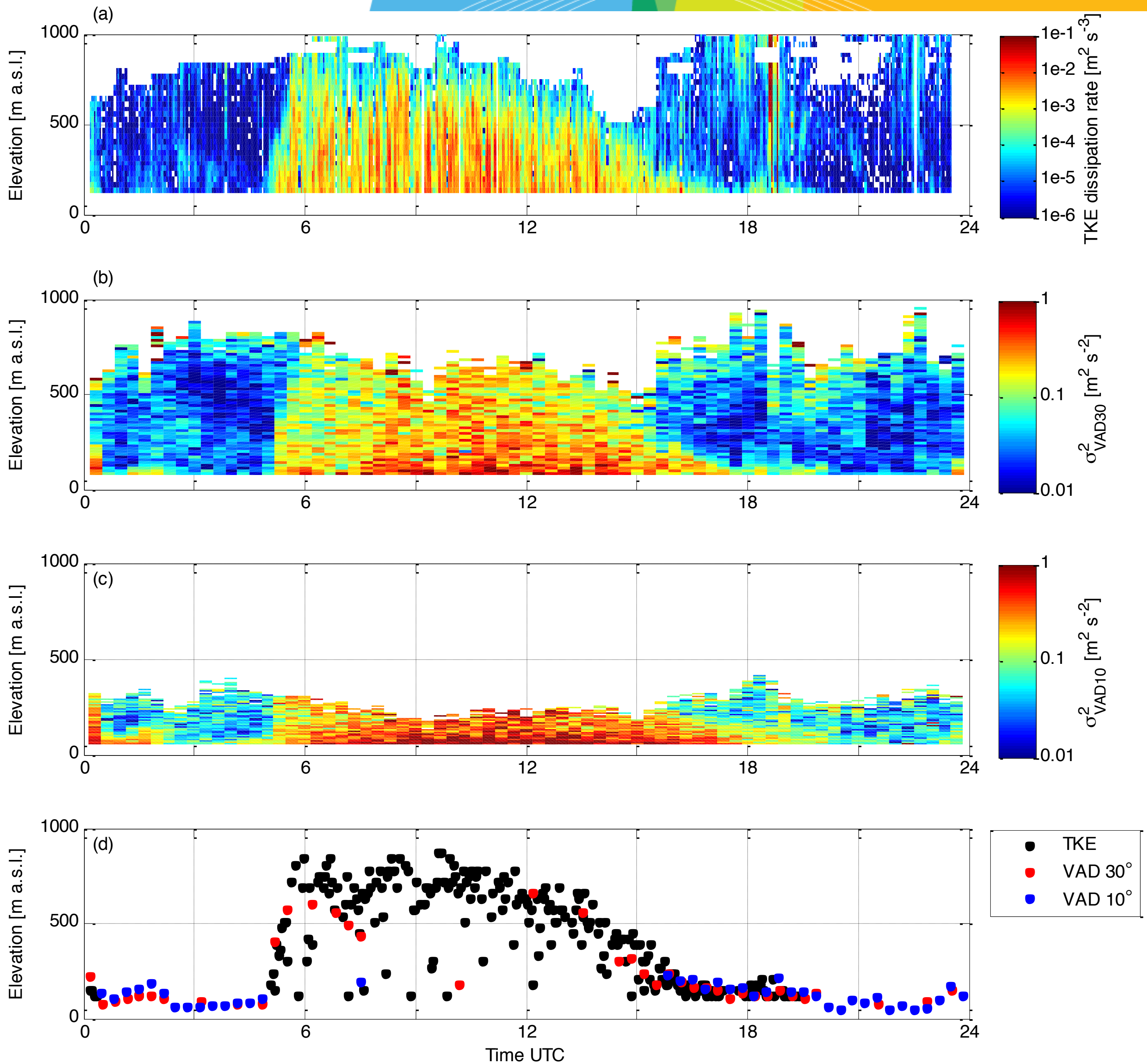
FIN




(a)
Elevation [m a.s.l.]
1000
500
0
0
6
12
18
24
1e-1
1e-2
1e-3
1e-4
1e-5
1e-6
TKE dissipation rate [m^2 s^{-3}]
1000
800
600
400
200
0
1
0.5
0
-0.5
-1
Vertical velocity skewness
300
200
100
0
WD [°]
15
10
5
0
WS [m/s]



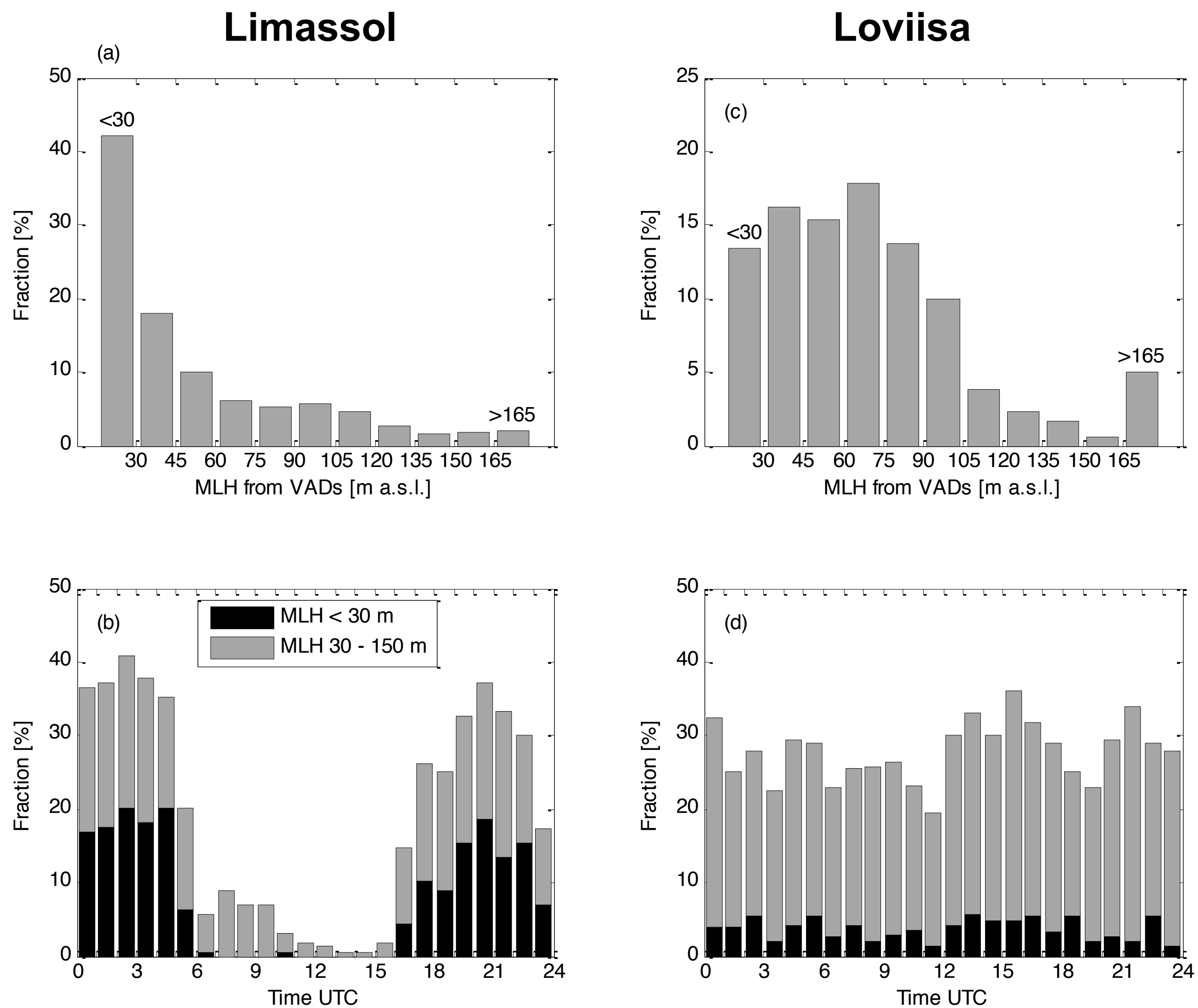
MLH

TKE 1e-4

VADs 0.05

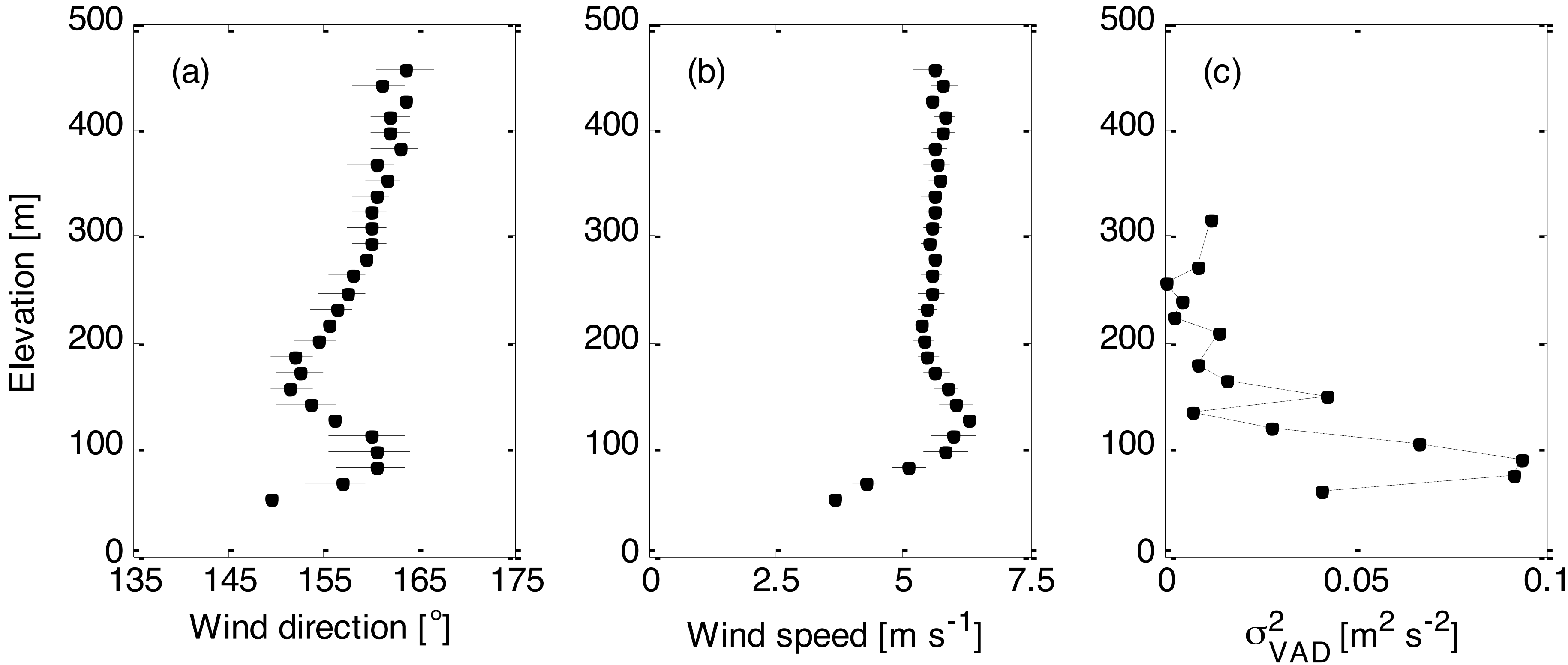
VADs identify frequently low MLH

No mixing in vertically-pointing:

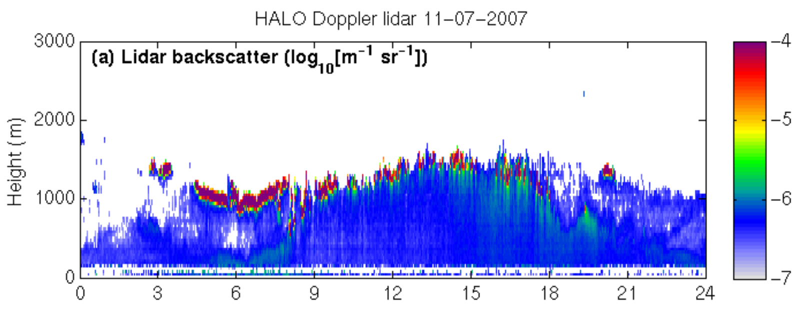


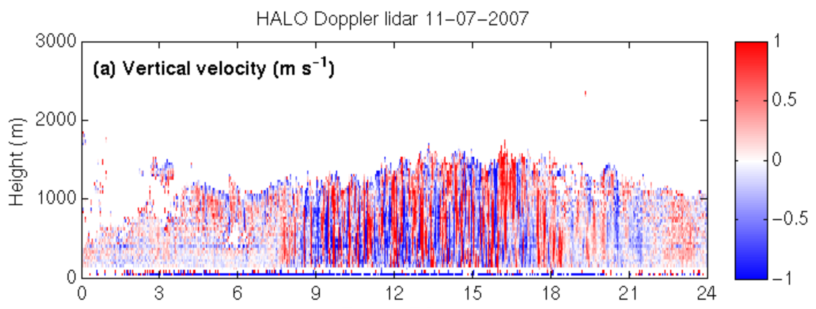
Hyytiälä, Finland, 3 August 2014 at 04:00 UTC

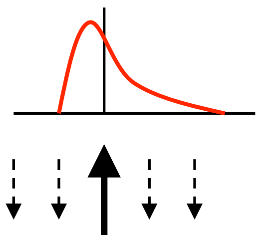
- "Continental" boreal forest
- Night-time turbulent mixing by a low level jet
  - Observed on 70% of nights in August 2014
  - 30° VAD



Vertical velocities



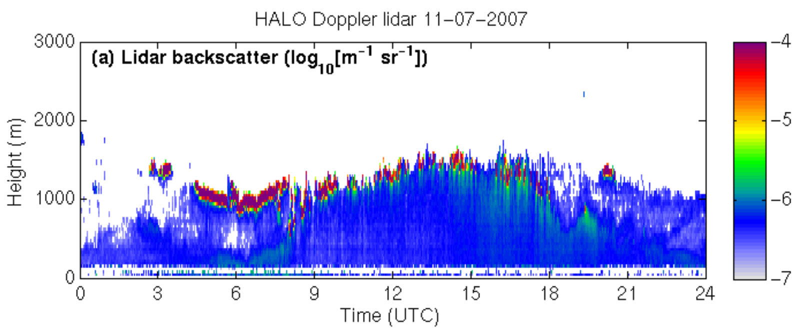


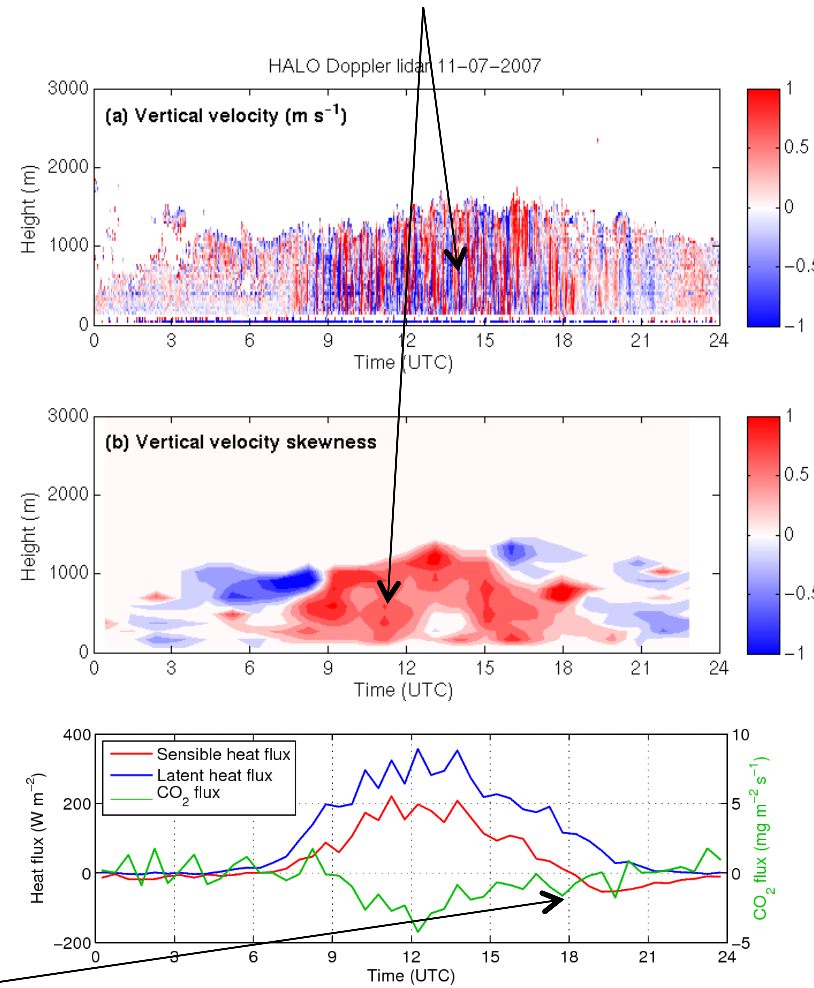


- Skewness defined as $s = \overline{w'^3} / \overline{w'^2}^{3/2}$
  - Positive in convective daytime boundary layers
  - Agrees with aircraft observations of LeMone (1990) when plotted versus the fraction of distance into the boundary layer
- Useful for diagnosing source of turbulence

Surface heating leads to convectively generated turbulence

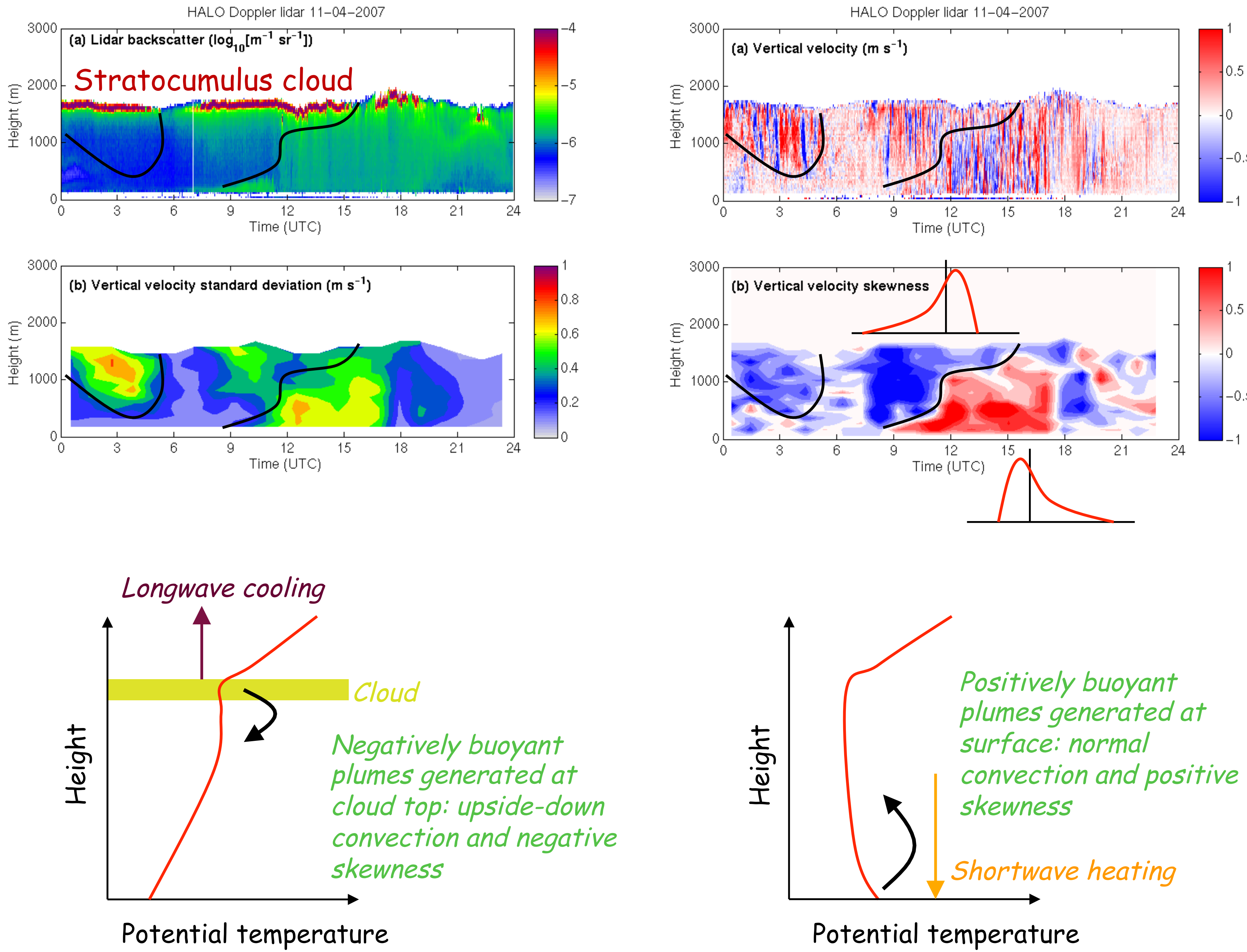
Vertical velocities





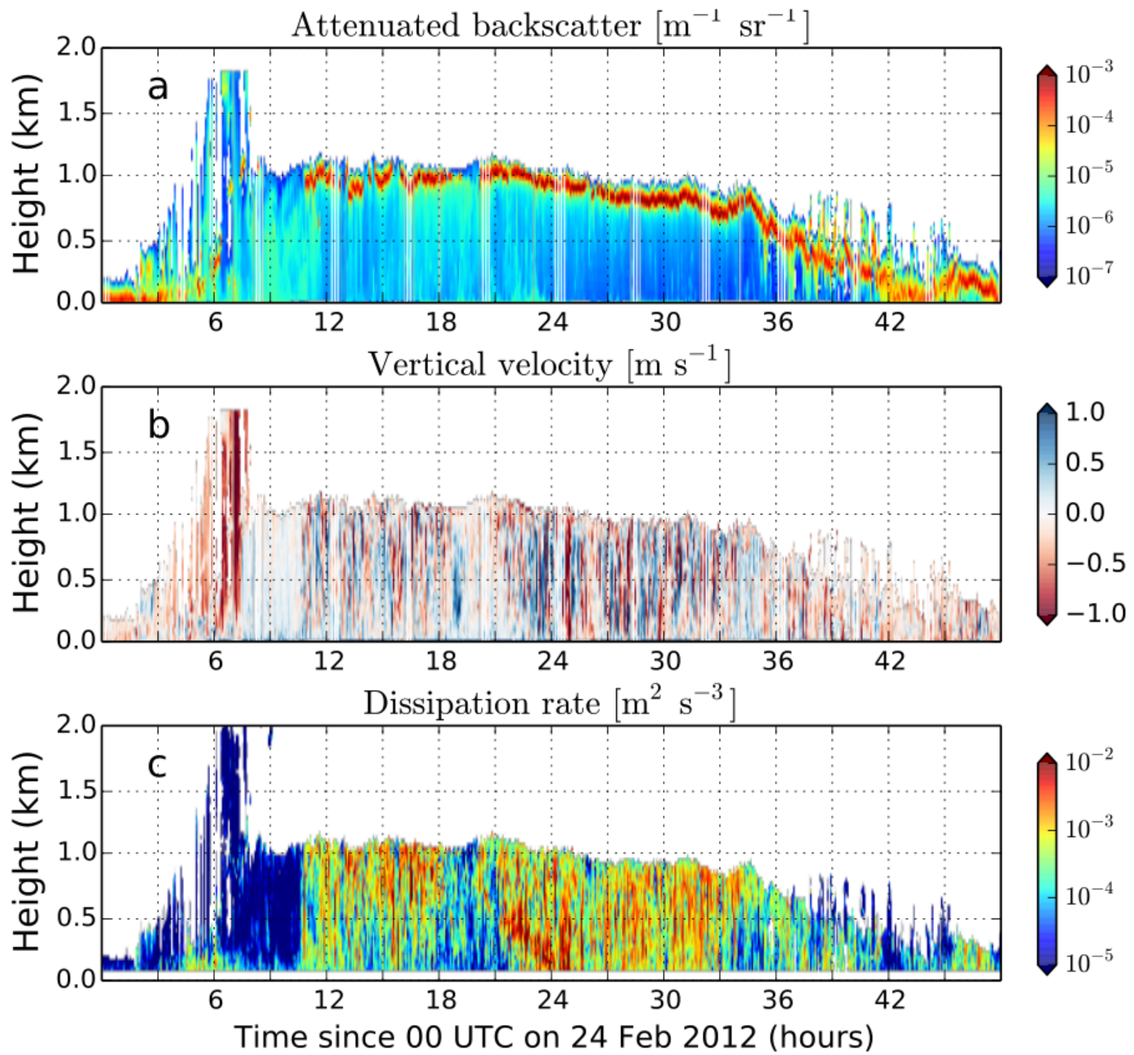
Input of sensible heat "grows" a new cumulus-capped boundary layer during the day (small amount of stratocumulus in early morning)

Convection is "switched off" when sensible heat flux goes negative at 1800

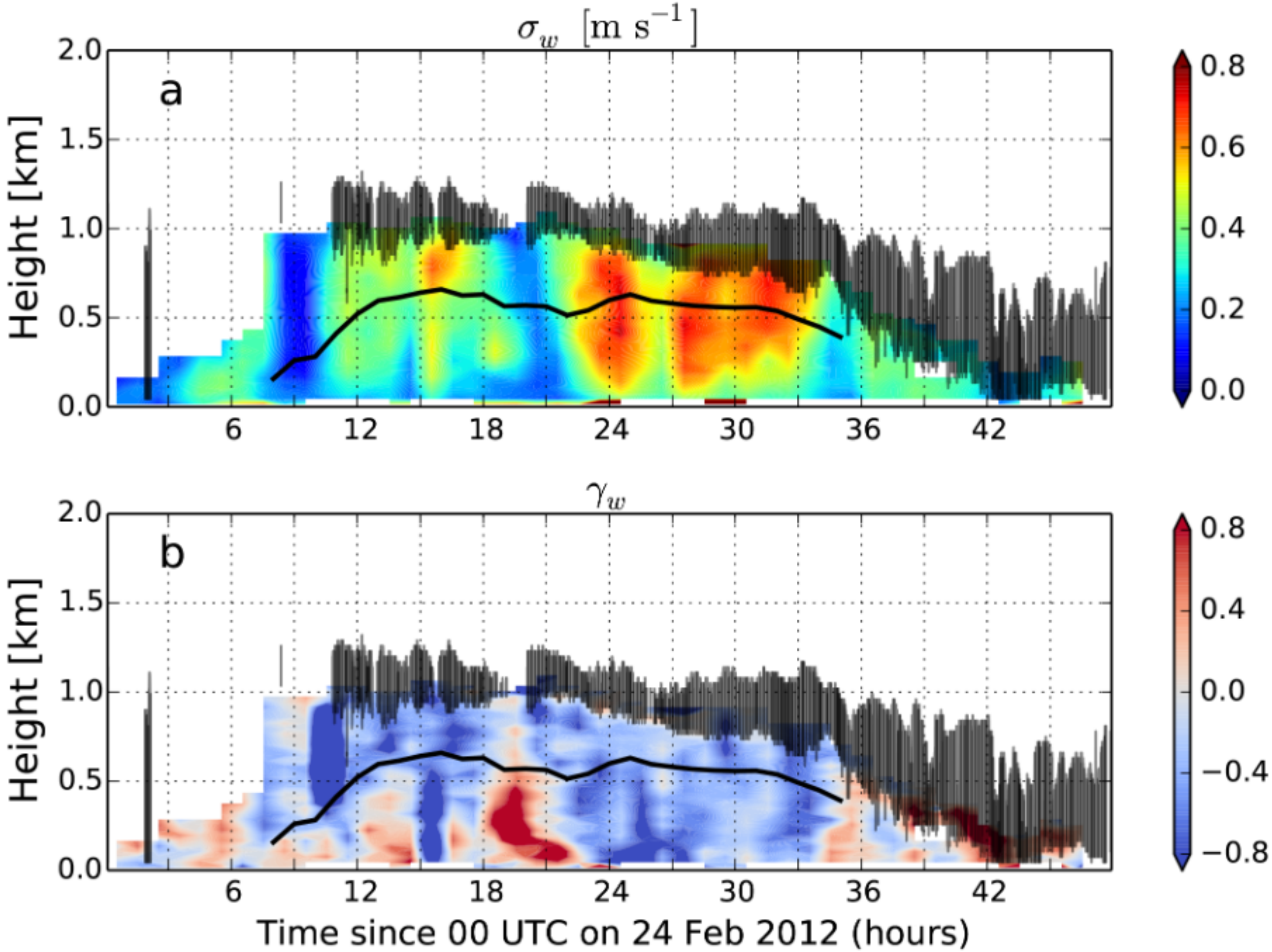


HALO Doppler lidar 11–04–2007
(a) Lidar backscatter (log10[m−1 sr−1])
Stratocumulus cloud
Height (m)
Time (UTC)
(b) Vertical velocity standard deviation (m s−1)
HALO Doppler lidar 11–04–2007
(a) Vertical velocity (m s−1)
(b) Vertical velocity skewness
Longwave cooling
Cloud
Height
Potential temperature
Negatively buoyant plumes generated at cloud top: upside-down convection and negative skewness
Positively buoyant plumes generated at surface: normal convection and positive skewness
Shortwave heating

Marine Stratocumulus



Marine Stratocumulus



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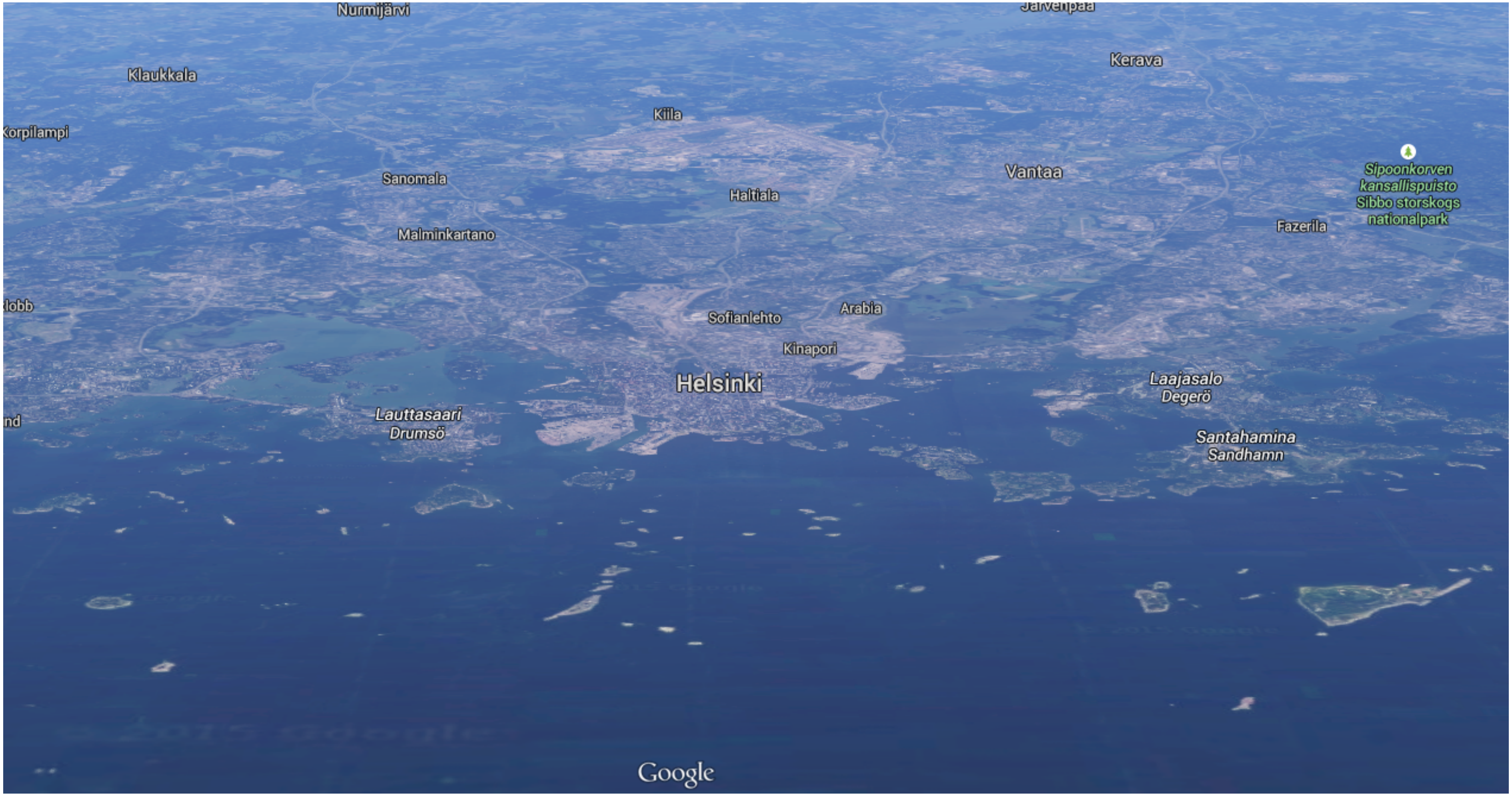
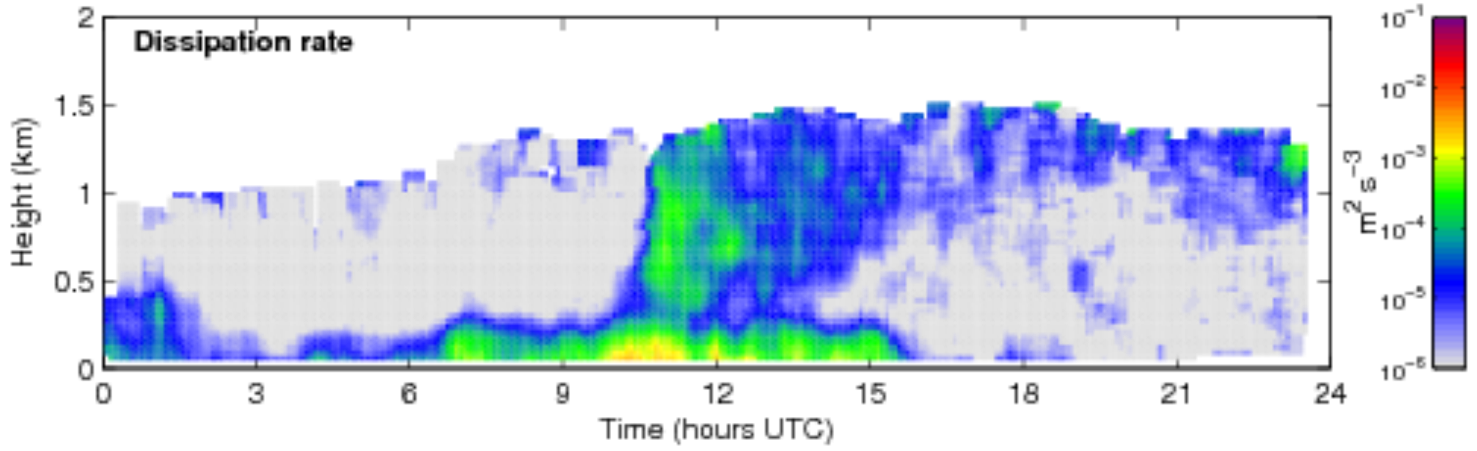
Advection of mixed layers in coastal regions
Example from Helsinki



Advection of mixed layers in coastal regions Example from Helsinki



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Advection of mixed layers in coastal regions Example from Helsinki