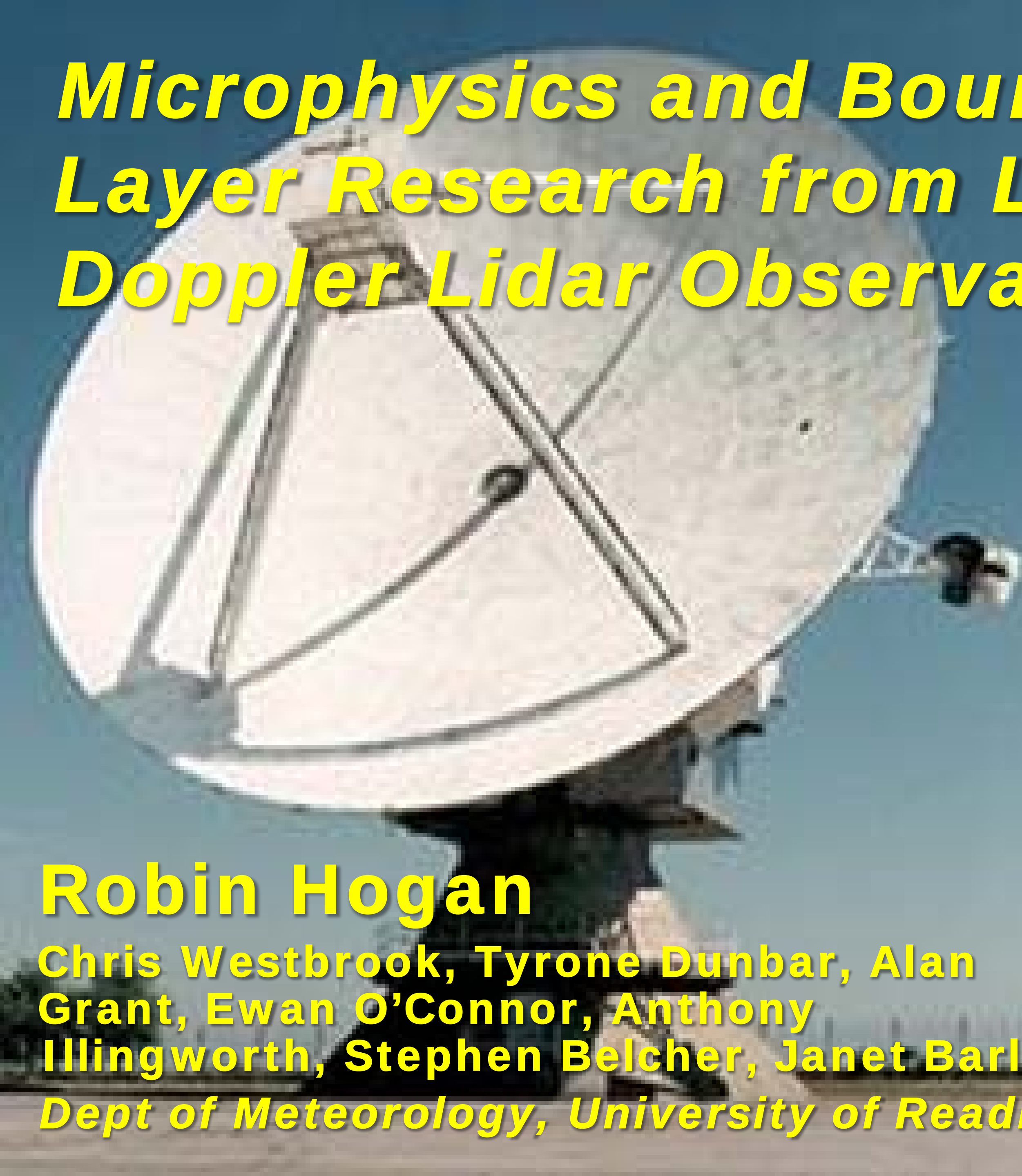


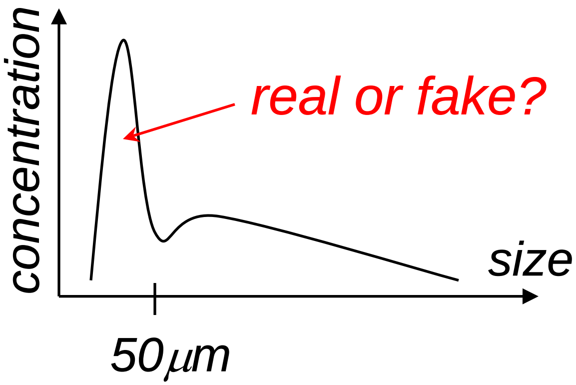
Microphysics and Boundary Layer Research from Long-term Doppler Lidar Observations

Robin Hogan

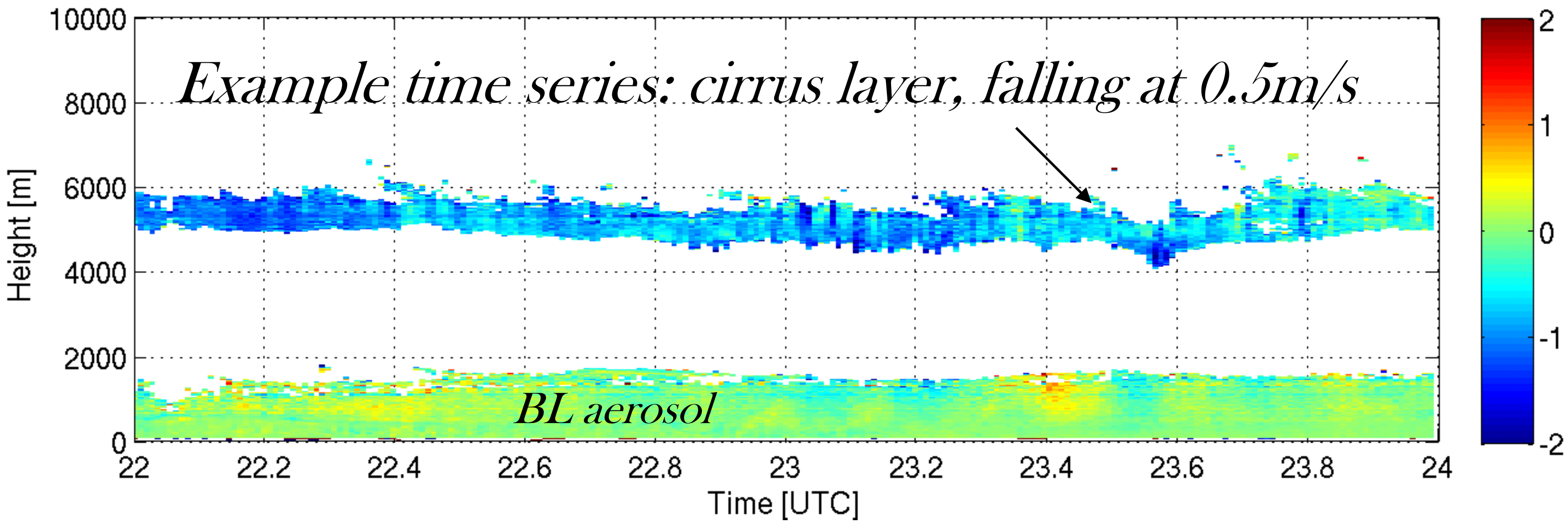
Chris Westbrook, Tyrone Dunbar, Alan Grant, Ewan O'Connor, Anthony Illingworth, Stephen Belcher, Janet Barlow

Dept of Meteorology, University of Reading

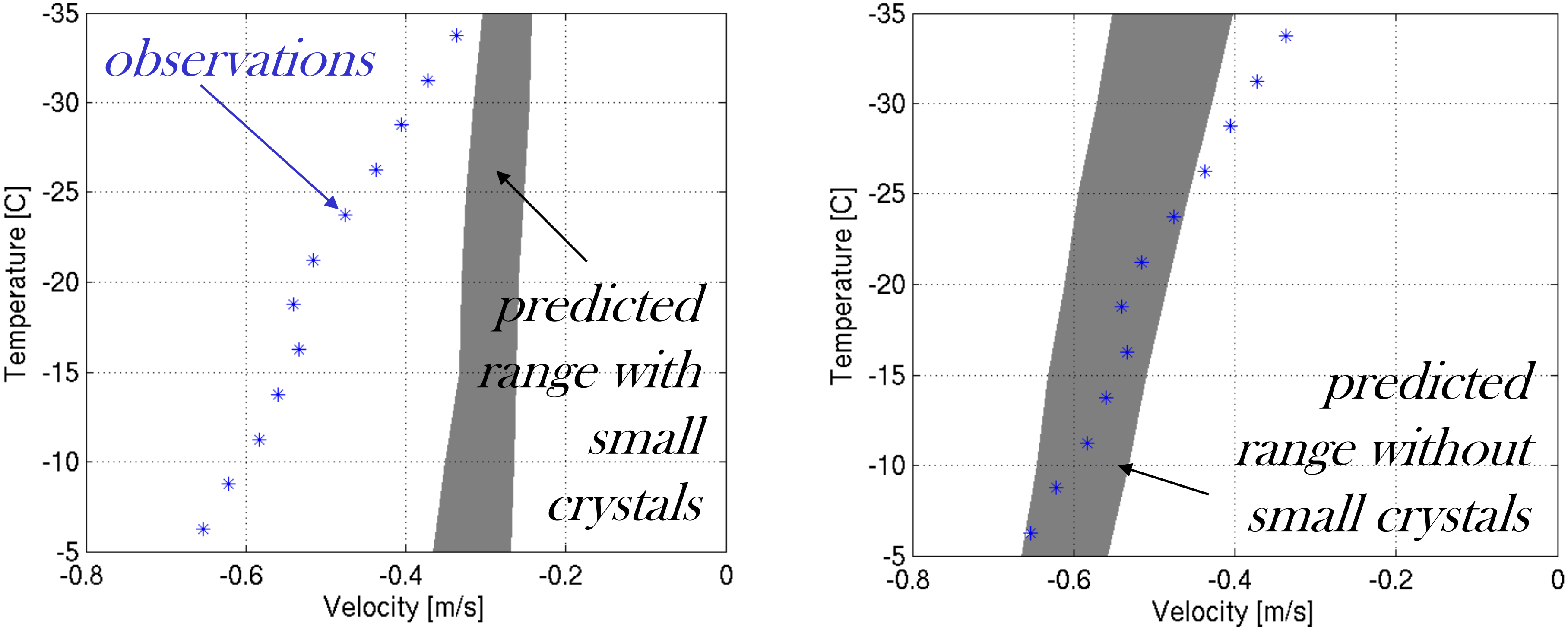
Resolving small-crystal controversy



- Aircraft probe measurements: enormous numbers (1 cm^{-3}) of tiny crystals < 50µm in cirrus
- Cloud physics community is divided: are these real or an artefact due to break-up of larger particles on inlet?
- Mitchell (2008) showed that if included in climate model, cloud albedo doubled

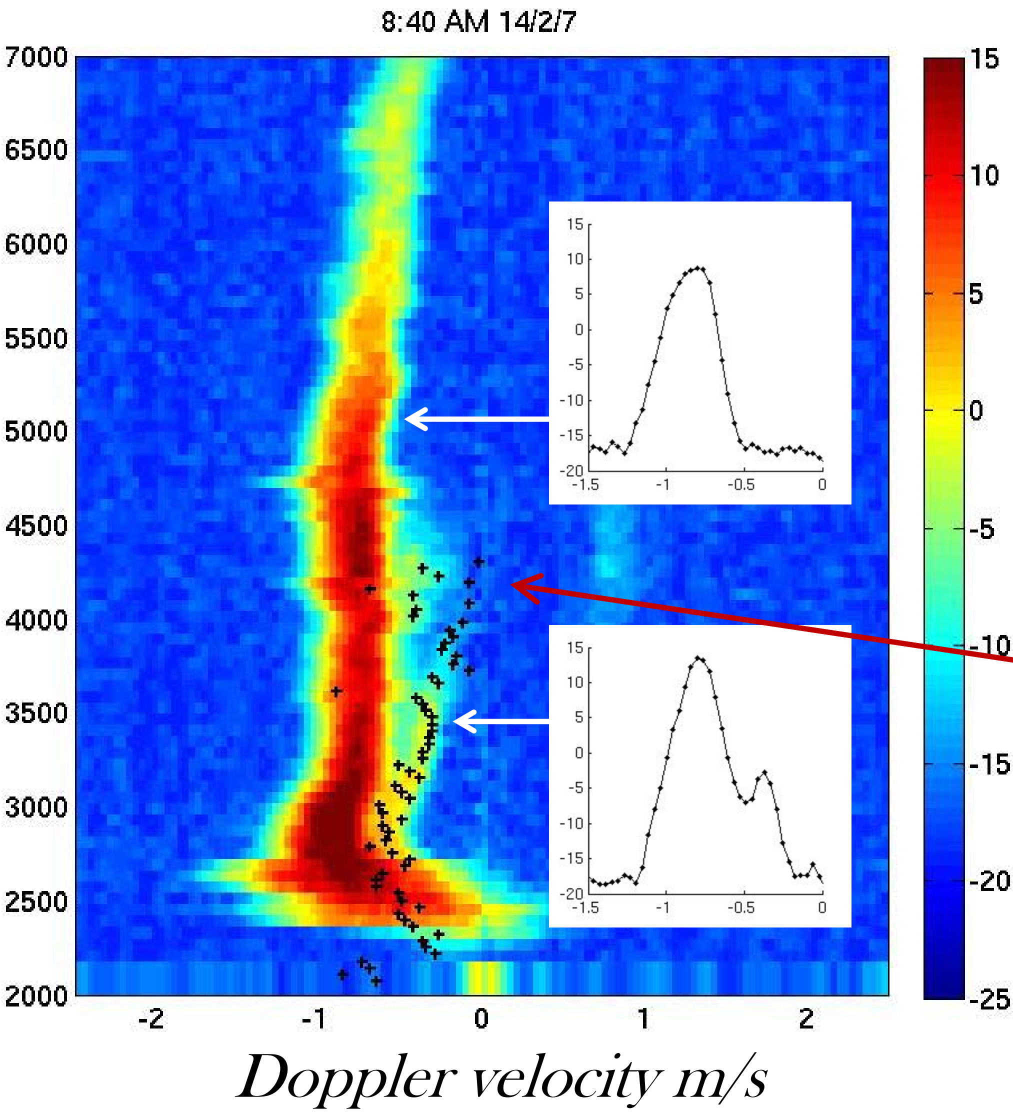


1.5-years of Doppler lidar data



- Much better agreement when small crystals are not included
- Suggests that they are not ubiquitous and are at least partially explained by shattering on aircraft probles
- *Westbrook & Illingworth (Geophys. Res. Lett., 2009)*

Sometimes small-crystals do exist

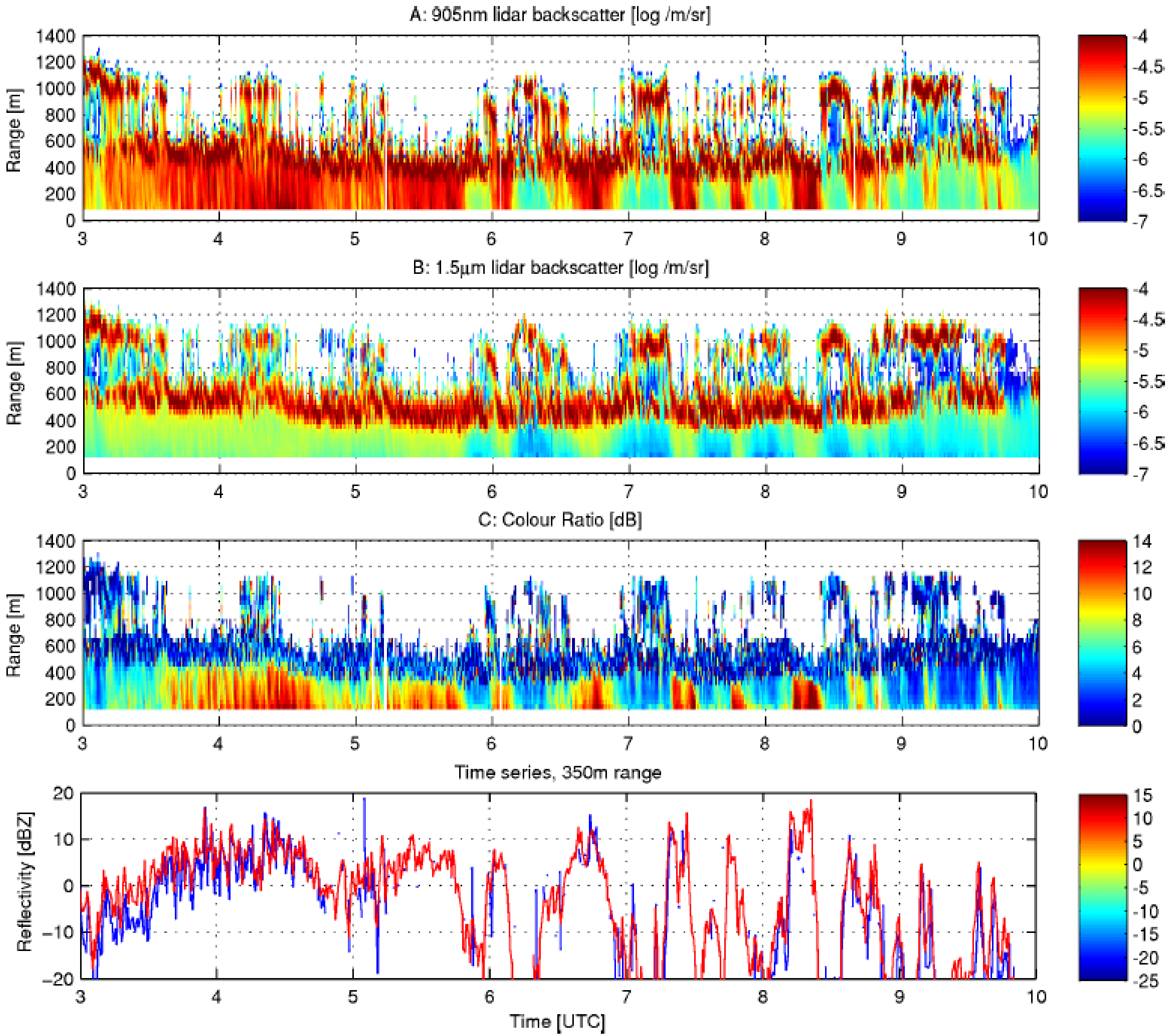


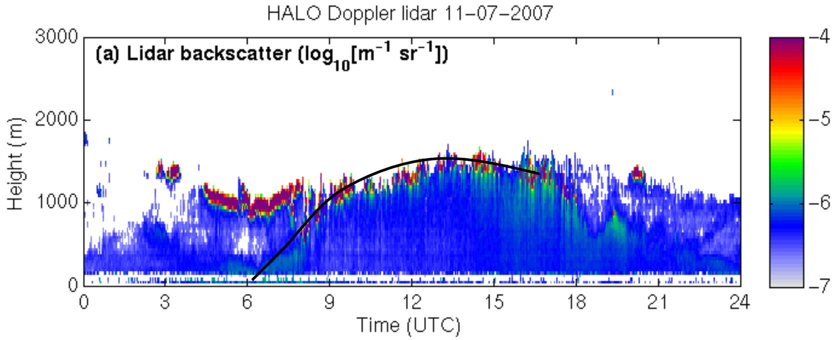
Chilbolton 35-GHz Copernicus radar

- Deep ice cloud
- Single mode at cloud top
- Nucleation at mid-levels
- Bimodal when warmer than -15°C
  - Large aggregates ~1 m/s
  - Small pristine plates ~0.3 m/s
  - Black crosses show Doppler lidar
- Sometimes small ice can be seen to be falling from supercooled liquid layers
- *Westbrook et al. (2010, QJRMS)*

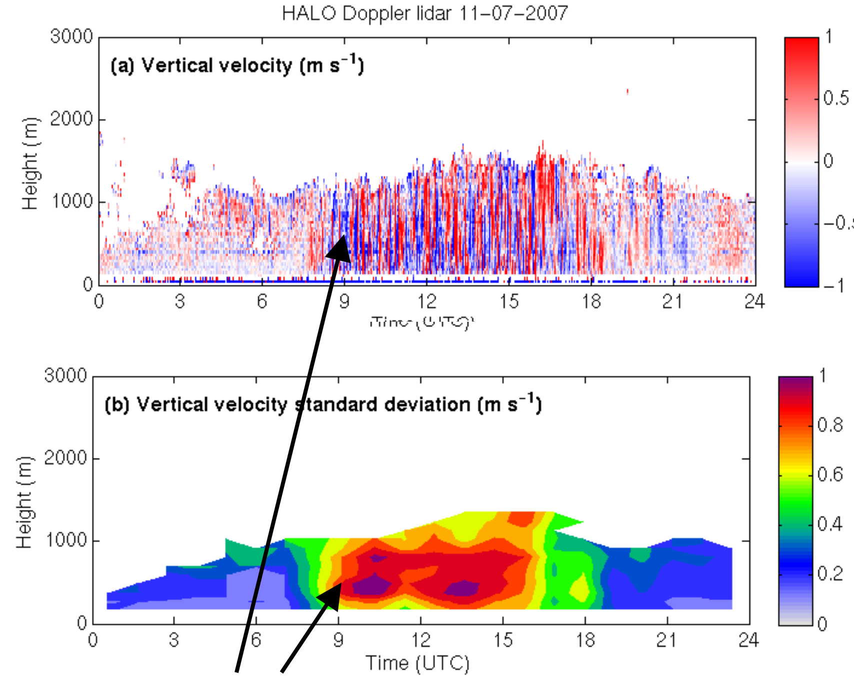
Two-color rain/drizzle sizing

- Refractive index of water at 1.5 μm: 1.32 – 0.000135i
  - Half of energy absorbed over path of 600 μm
- Refractive index of water at 905 nm: 1.33 – 0.000000561i
  - 1% of energy absorbed over path of 600 μm
- Color ratio in rain and drizzle is monotonically related to size
  - Can derive rain rate and any other moment of the distribution
  - In particular, can predict the radar reflectivity for verification
- In principle, could use the Doppler capability to also infer vertical wind
  - Similar to O'Connor et al. (JTECH 2005) for radar/lidar drizzle sizing
- Sizing also possible in ice, although interpretation of the size measurement depends on particle habit
- *Westbrook et al. (2010, Atmos. Meas. Technol.)*


A: 905nm lidar backscatter [log /m/sr]
B: 1.5µm lidar backscatter [log /m/sr]
C: Colour Ratio [dB]
Time series, 350m range
Range [m]
Reflectivity [dBZ]
Time [UTC]



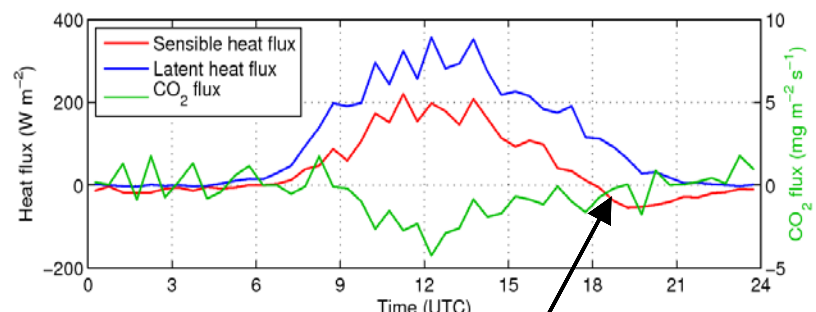
Input of sensible heat "grows" a new cumulus-capped boundary layer during the day (small amount of stratocumulus in early morning)



Surface heating leads to convectively generated turbulence

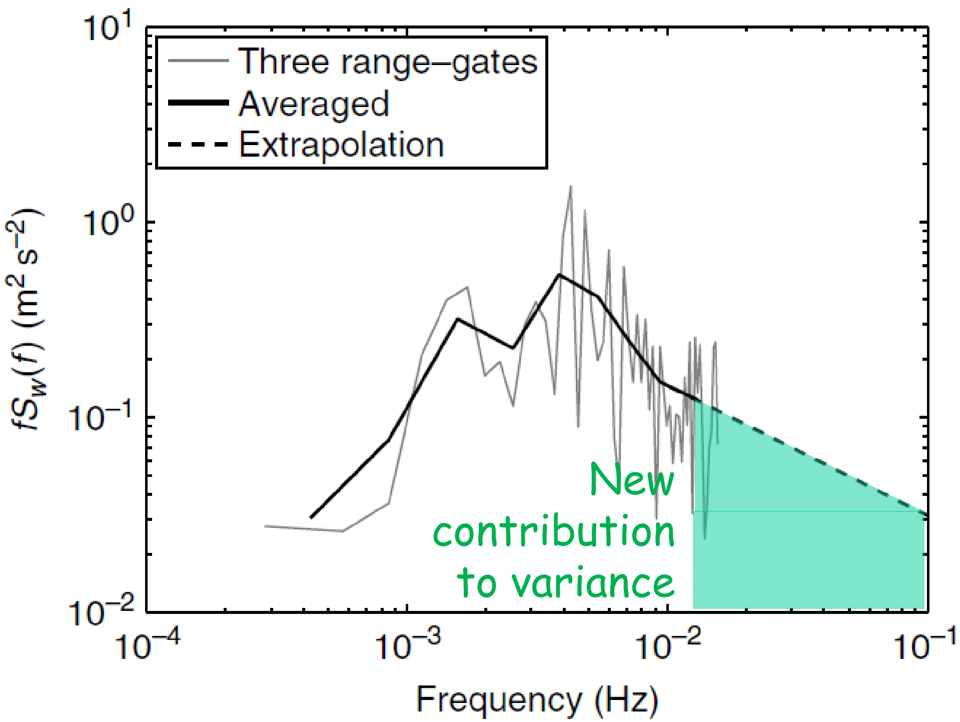
Boundary layer dynamics

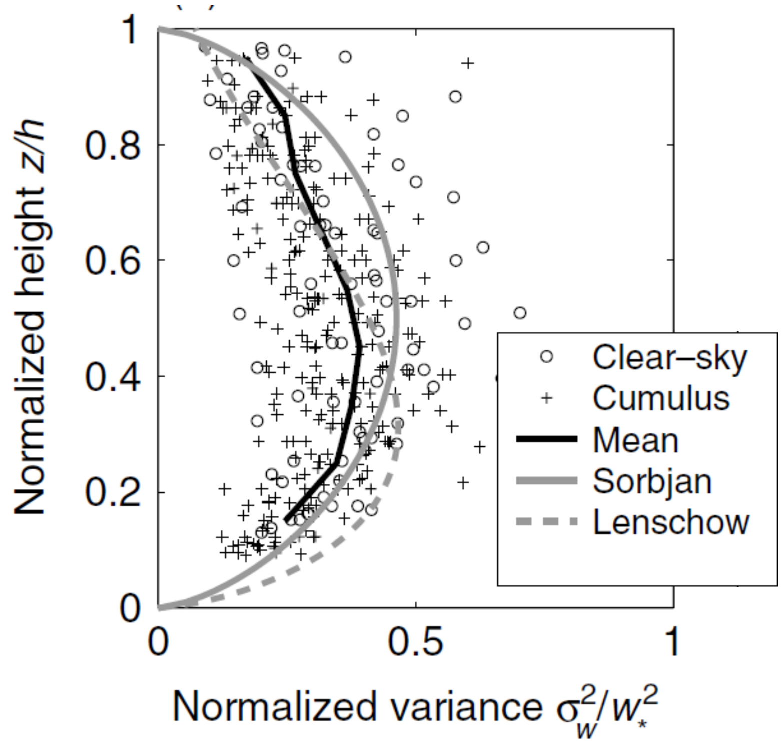
- *Hogan et al. (QJRMS 2009)*



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

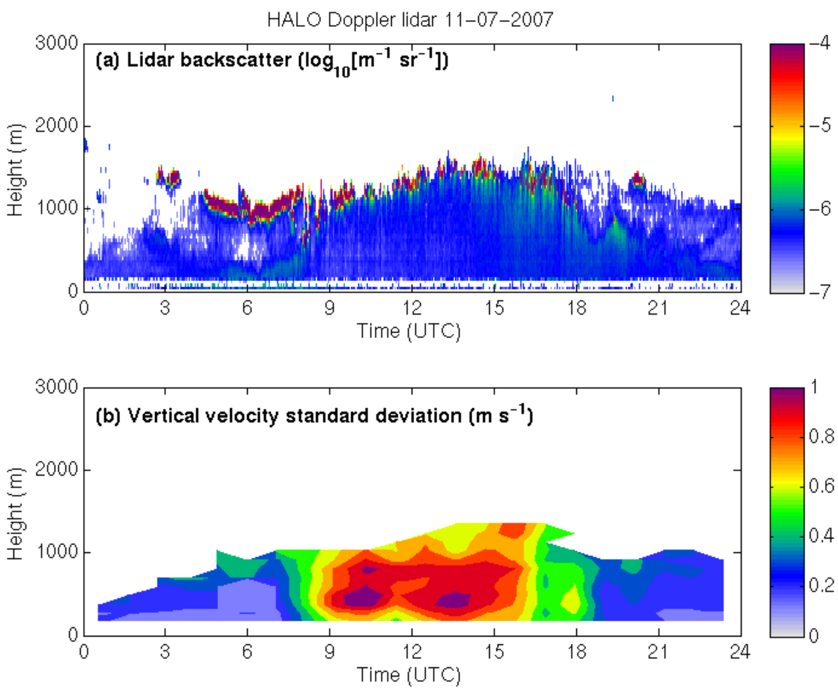
Comparing variance to previous studies

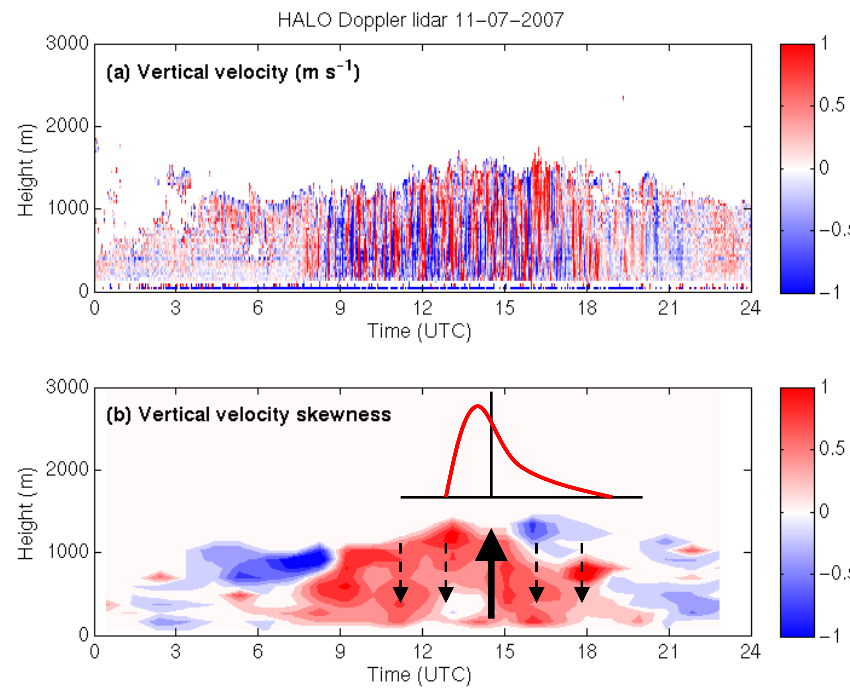




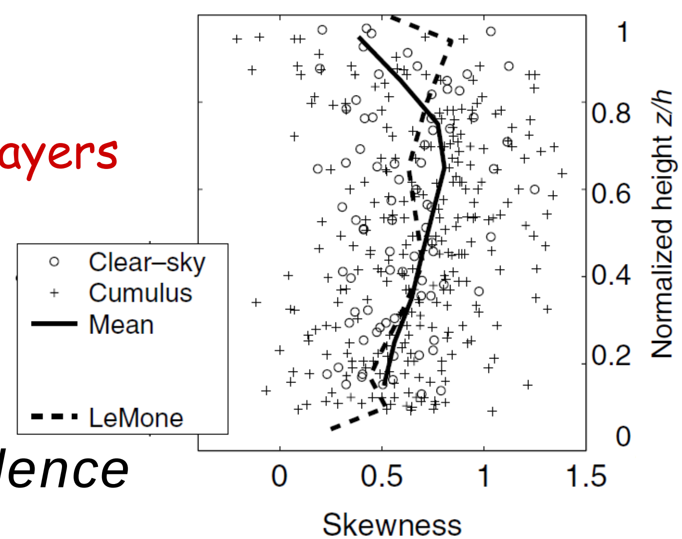
- Lidar temporal resolution of ~30 s
  - *Smallest eddies not detected, so add them using -5/3 law*
  - *Only valid in convective boundary layers where part of the inertial subrange is detected*
- Normalize variance by convective velocity scale $$w_* = \left(\frac{g}{\overline{T}_{\rm v}}\overline{w'T_{\rm v}'}\,h\right)^{1/3}$$
  - *Reasonable agreement with Sorbjan (1980) and Lenschow et al. (1989)*

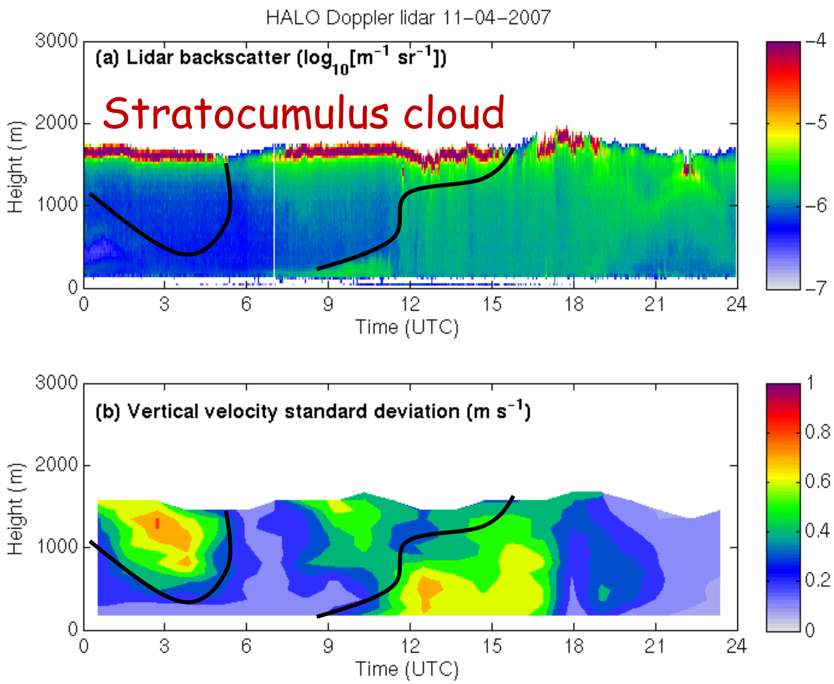
Skewness

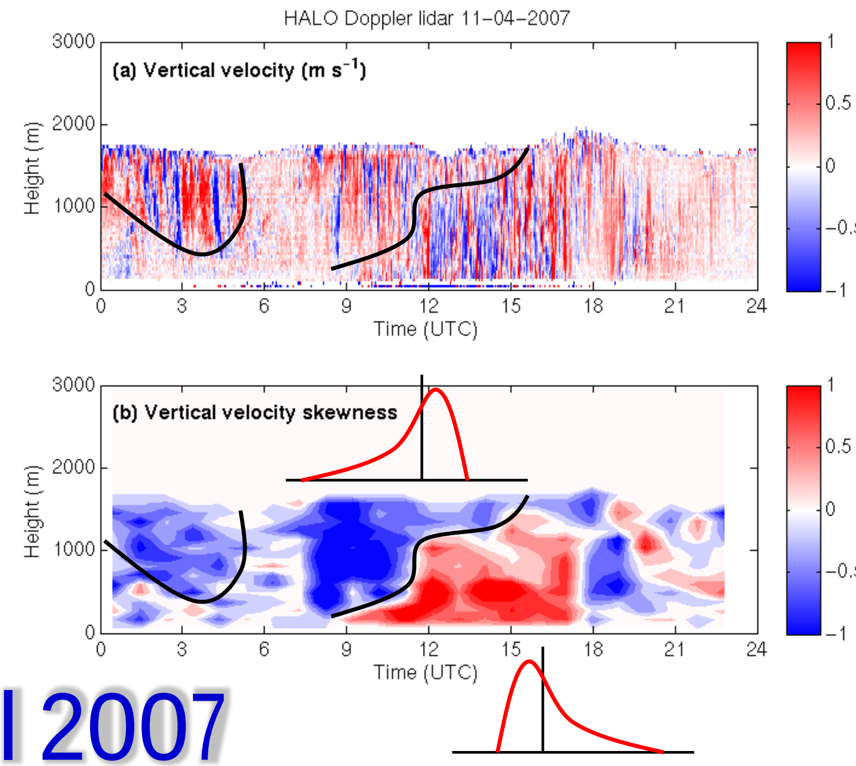




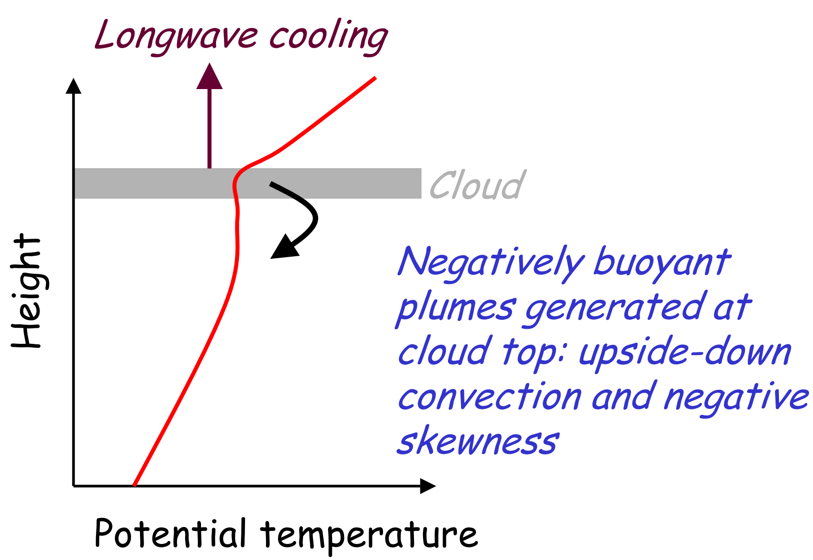
- Skewness defined as $s = \overline{w'^3} / \overline{w'^2}^{3/2}$
  - Positive in convective daytime boundary layers
  - Agrees with aircraft observations of LeMone (1990) when plotted versus the fraction of distance into the boundary layer
- *Useful for diagnosing source of turbulence*

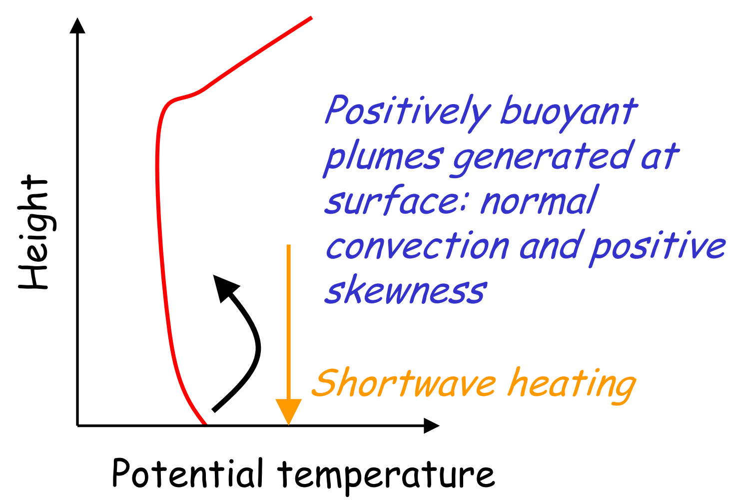






11 April 2007

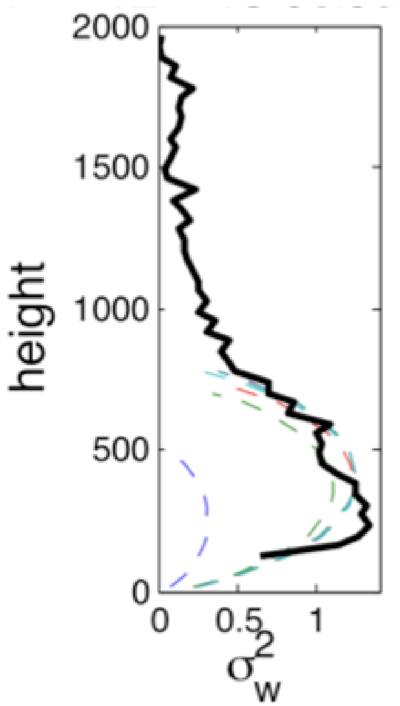


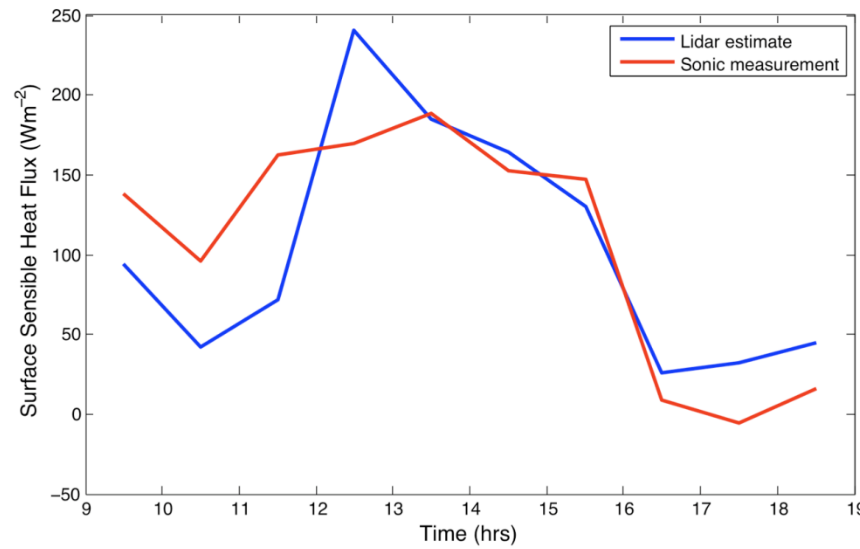


Inferring sensible heat flux

- Vertical wind variance matches what would be predicted from measured surface sensible heat flux *H* (via *w**)
- Over urban areas it is impossible to measure a representative *H* using eddy correlation
- Tyrone Dunbar, Stephen Belcher and Janet Barlow are developing a technique to infer *H* from variance of vertical wind

Optimal estimation technique to find H and h that best fit $\sigma_w^2(z)$

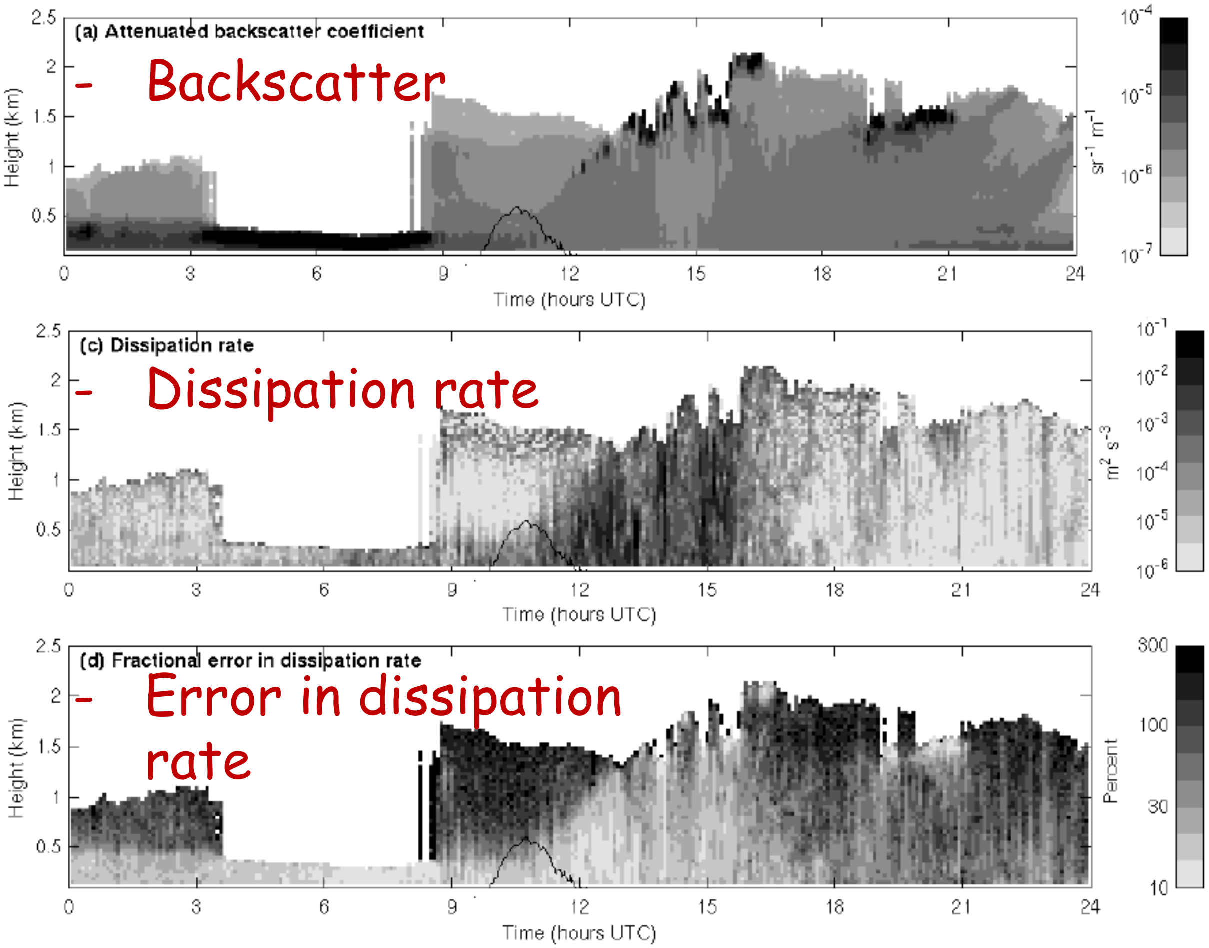




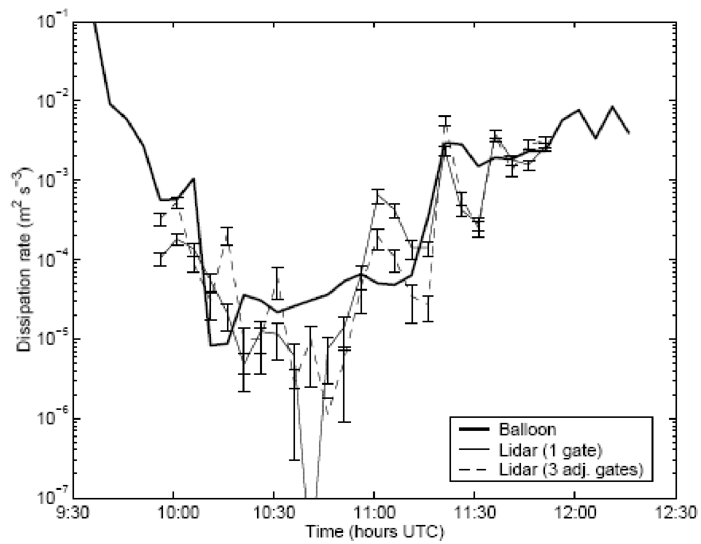
Reasonable fit to sonic over Chilbolton

Estimating TKE dissipation rate

- Can estimate ε from variance in vertical velocity over ~1 min, and horizontal wind-speed
- *O'Connor et al. (2010, submitted to JTECH)*



- In-situ validation from tethered balloon

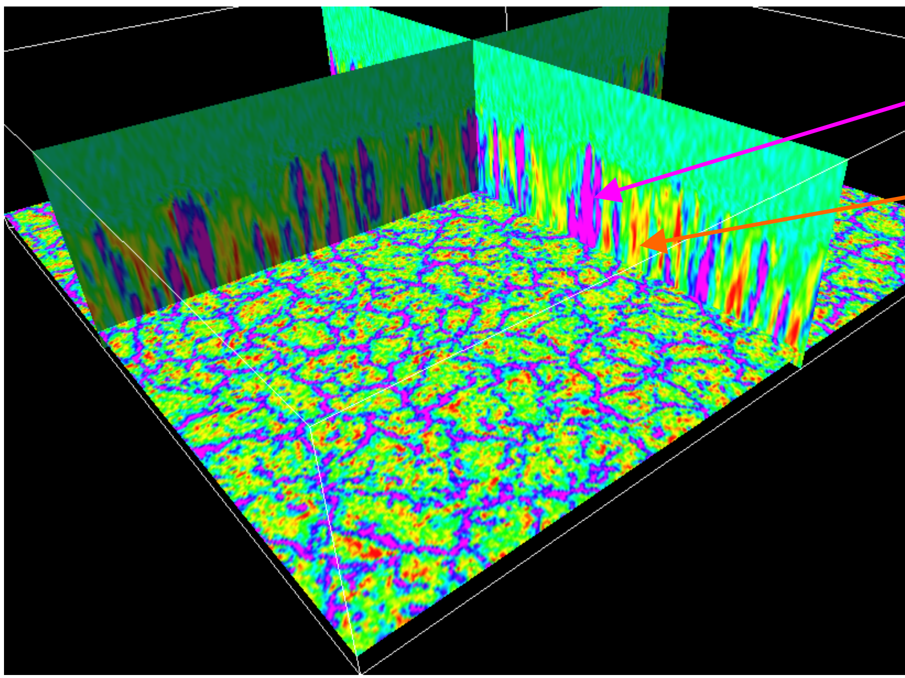


Lots of uses for 1.5-μm Doppler lidar

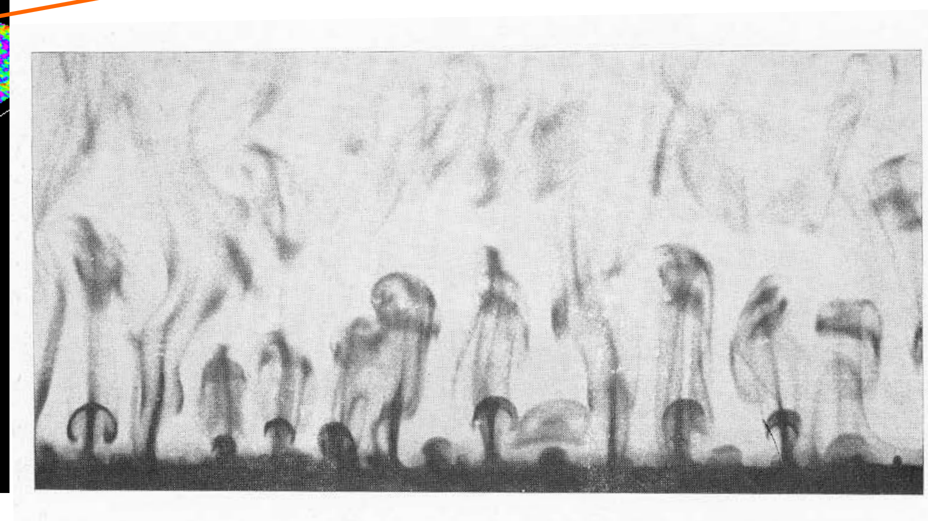
- Properties of small crystals
- Microphysics of mixed-phase clouds
- Size of raindrops and large ice particles (with two lidars)
- Vertical wind at liquid cloud base for activation of CCN
- TKE dissipation rate – evaluation of large-eddy models
- Inferring sensible heat flux over urban areas
- Determining source of turbulence (top-down or bottom-up)
- Evaluating boundary layer parameterizations in GCMs/NWP
- Evaluating vertical velocity representation in dispersion models

Skewness in convective BLs

- Both model simulations and laboratory visualisation show convective boundary layers heated from below to have *narrow, intense updrafts* and *weak, broad downdrafts,* i.e. positive skewness

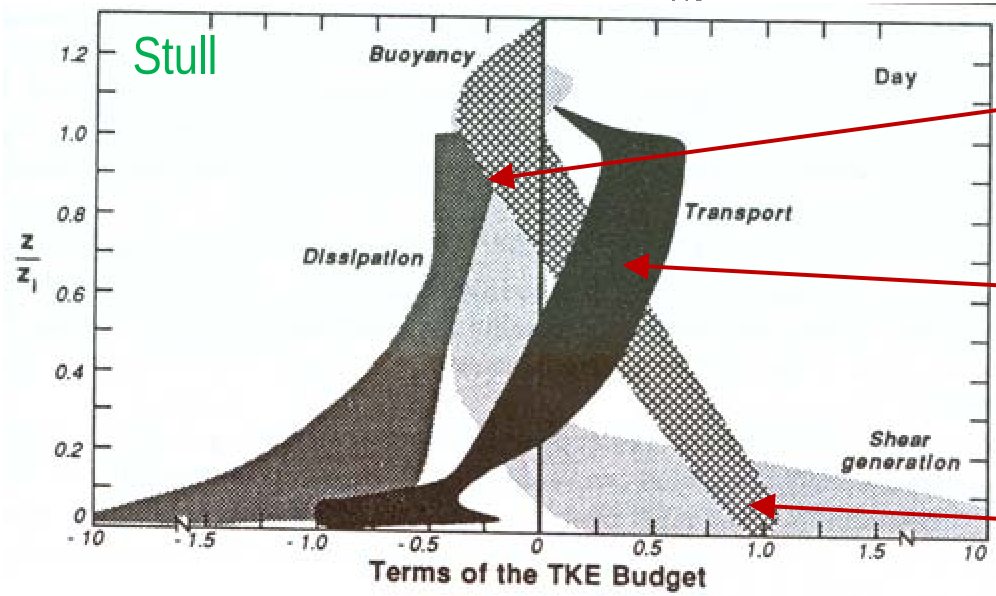


Courtesy Peter Sullivan NCAR



Why is skewness positive?

- Consider TKE budget: $\frac{TKE}{m} = \bar{e} = 0.5\left(\overline{u'^2} + \overline{v'^2} + \overline{w'^2}\right)$



TKE destroyed by dissipation & buoyancy suppression at BL top

TKE transported upwards by turbulence

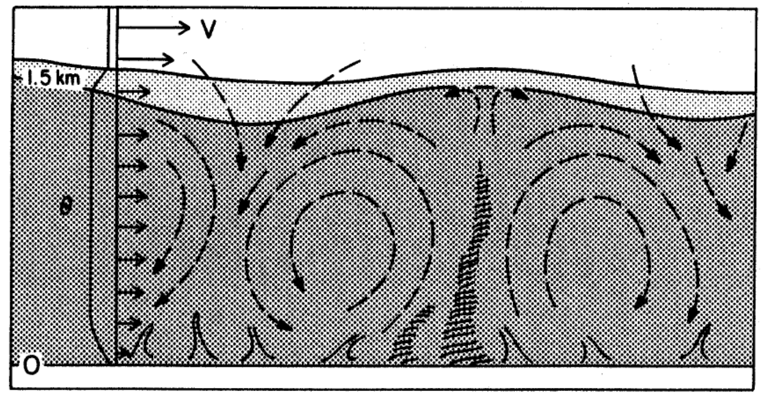
TKE generated by shear and buoyancy in lower BL

$$\frac{\partial \bar{e}}{\partial t} = -\bar{U}\frac{\partial \bar{e}}{\partial x} + \frac{g}{\bar{\theta}_v}\left(\overline{w'\theta_v'}\right) - \overline{u'w'}\frac{\partial \bar{U}}{\partial z} - \frac{\partial\left(\overline{w'e}\right)}{\partial z} - \frac{1}{\bar{\rho}}\frac{\partial\left(\overline{w'p'}\right)}{\partial z} - \varepsilon$$

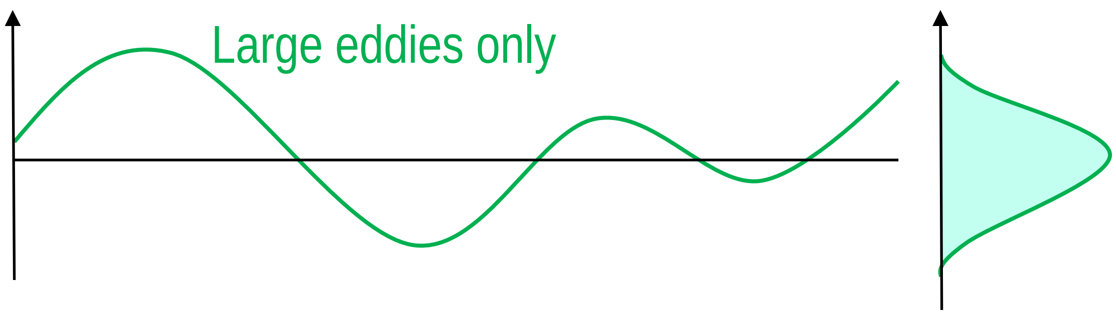
Transport

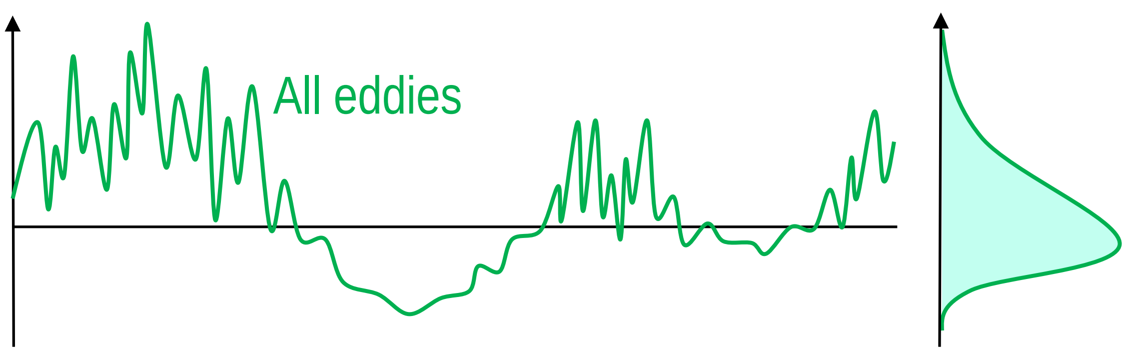
- Vertical flux of TKE is $\overline{w'e} = \left(\overline{w'u'^2} + \overline{w'v'^2} + \overline{w'^3}\right)/2$
  - *So skewness positive when TKE transported upwards by turbulence*

...a alternative related explanation

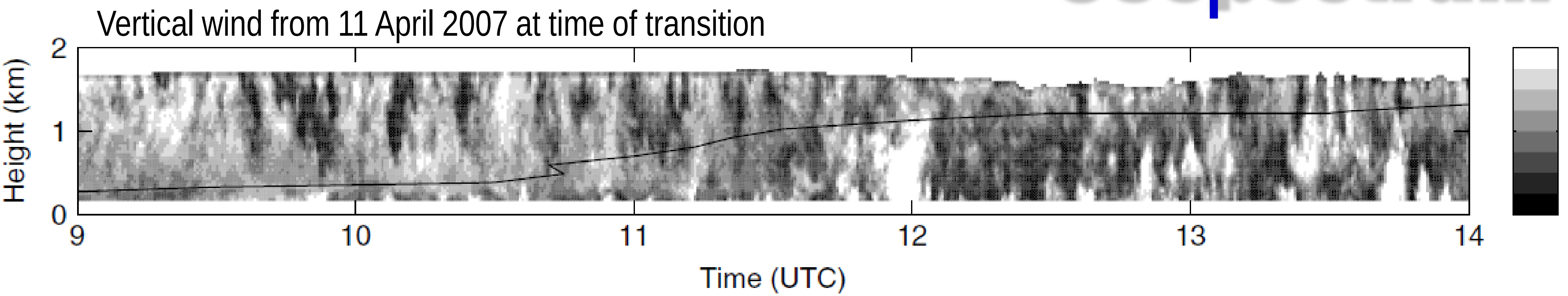


- Updraft regions of large eddies have more intense small-scale turbulence than the downdraft regions
- This leads to an asymmetric velocity distribution
- *Will test this later…*





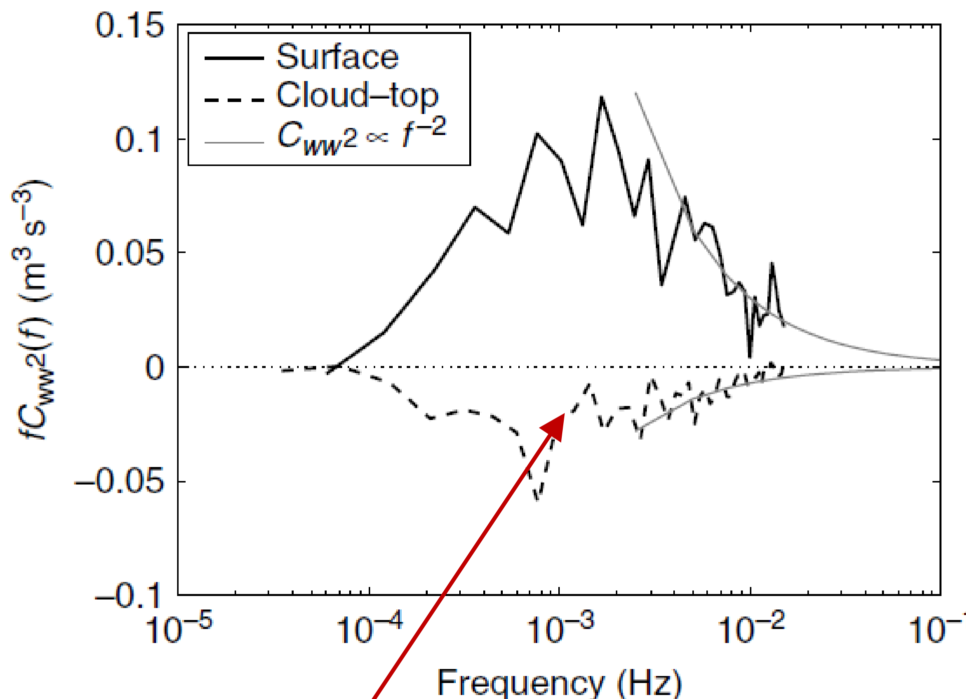
Cospectrum



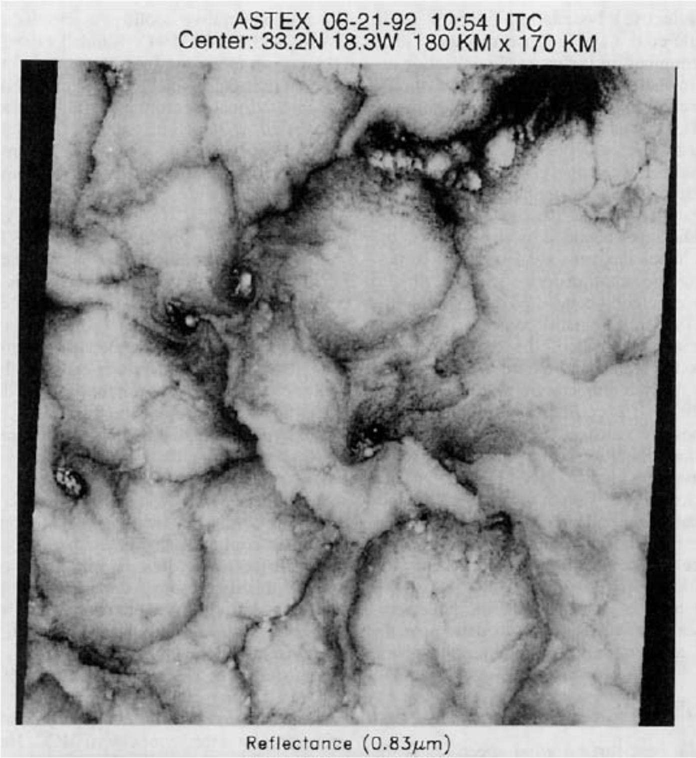
- The cospectrum, C_{ww2}:
  - *Defined as the complex conjugate of FFT of w' multiplied by FFT of w'^2*
- Can be thought of as a spectral decomposition of the third moment:

$$\overline{w'^3} = \int_0^\infty C_{ww^2}(f)\,\mathrm{d}f$$

- Hunt et al. (1988) showed that it goes as freq^{-2} in intertial subrange



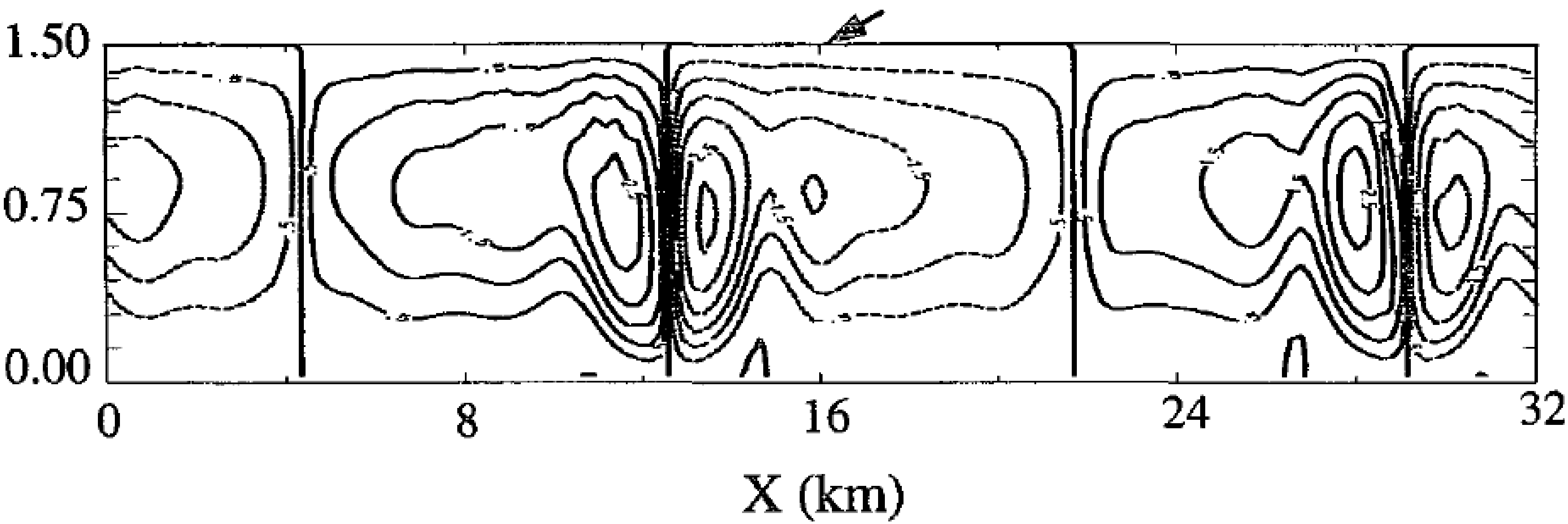
Skewness dominated by larger (20 minute timescale) eddies



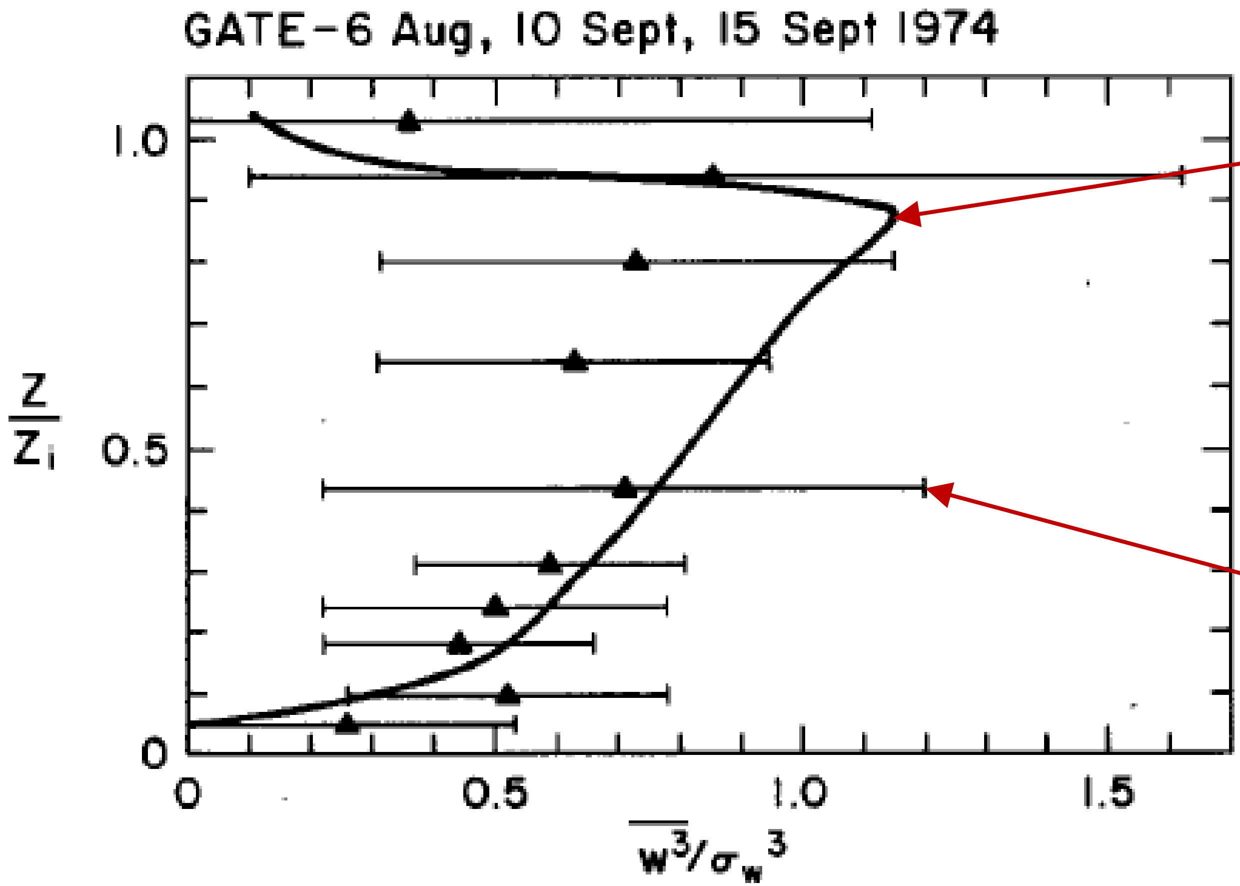
Closed-cell stratocu.

- Previous studies have shown updraft/downdraft asymmetry in stratocumulus at the largest scales
- Puzzle as to why aspect ratio of cells is as much as 30:1

Shao & Randall (JAS 1996)



Aircraft vs LES



LES: Moeng and Wyngaard (1988)

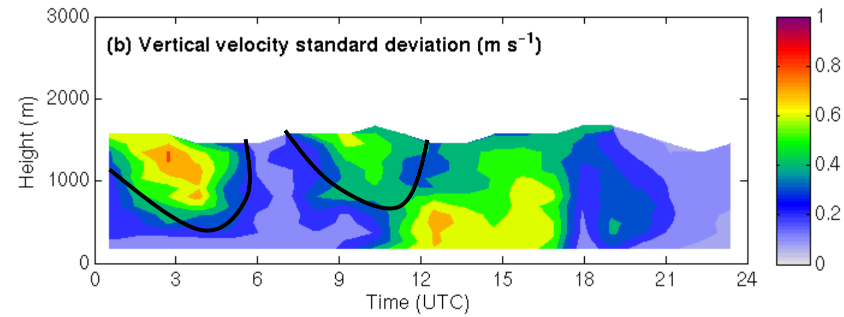
Aircraft observations: LeMone (1990)

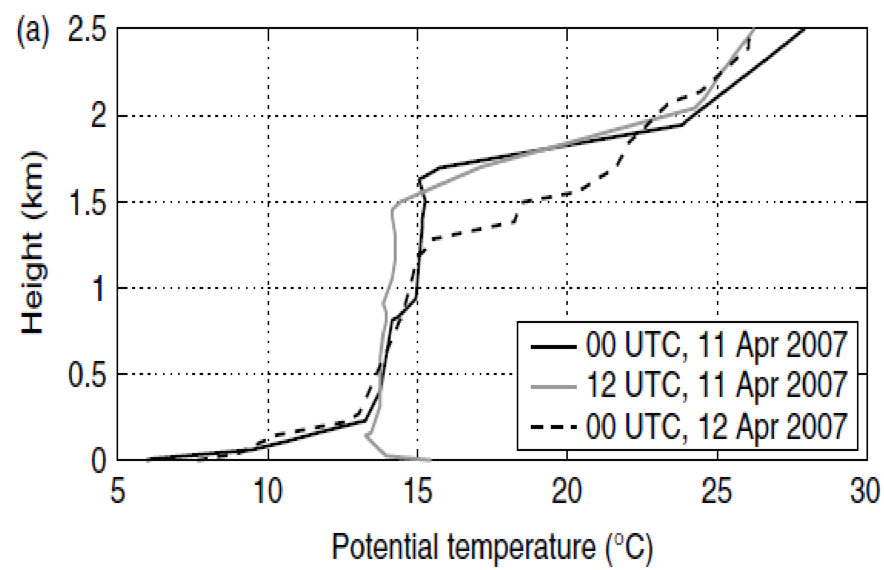
Upside-down Carson's model

- If all the physics is the same but inverted, we can apply Carson's model to predict the growth of the cloud-top-cooling driven mixed layer

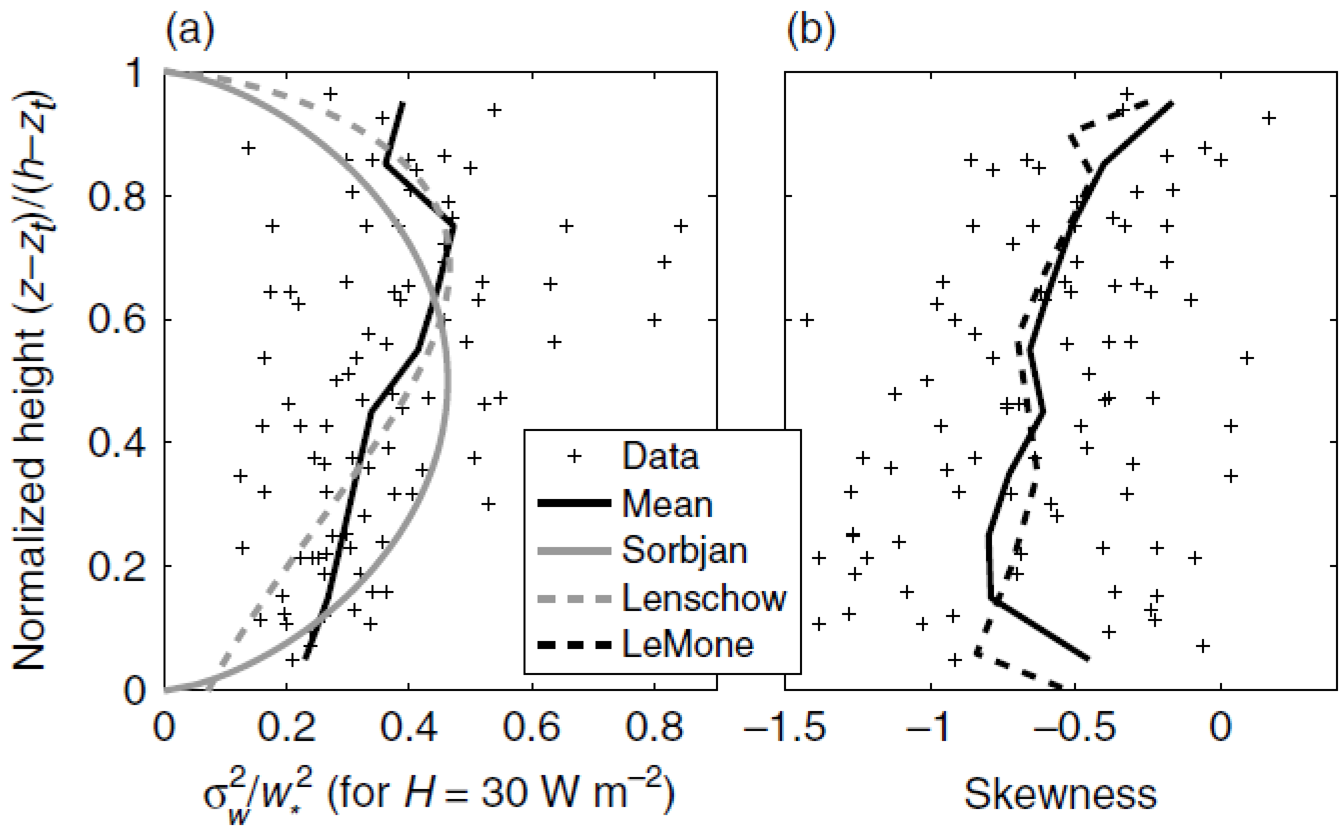
$$h(t) = 1.4\left(\frac{2\overline{w'\theta'_{\mathrm{v}0}}}{\gamma}t\right)^{1/2}$$

- With longwave cooling rate of H = 30 W m^{-2} and lapse rate of γ = 1 K km^{-1}, we estimate growth of 1.1 km in 3 hours, approximately the same as observed

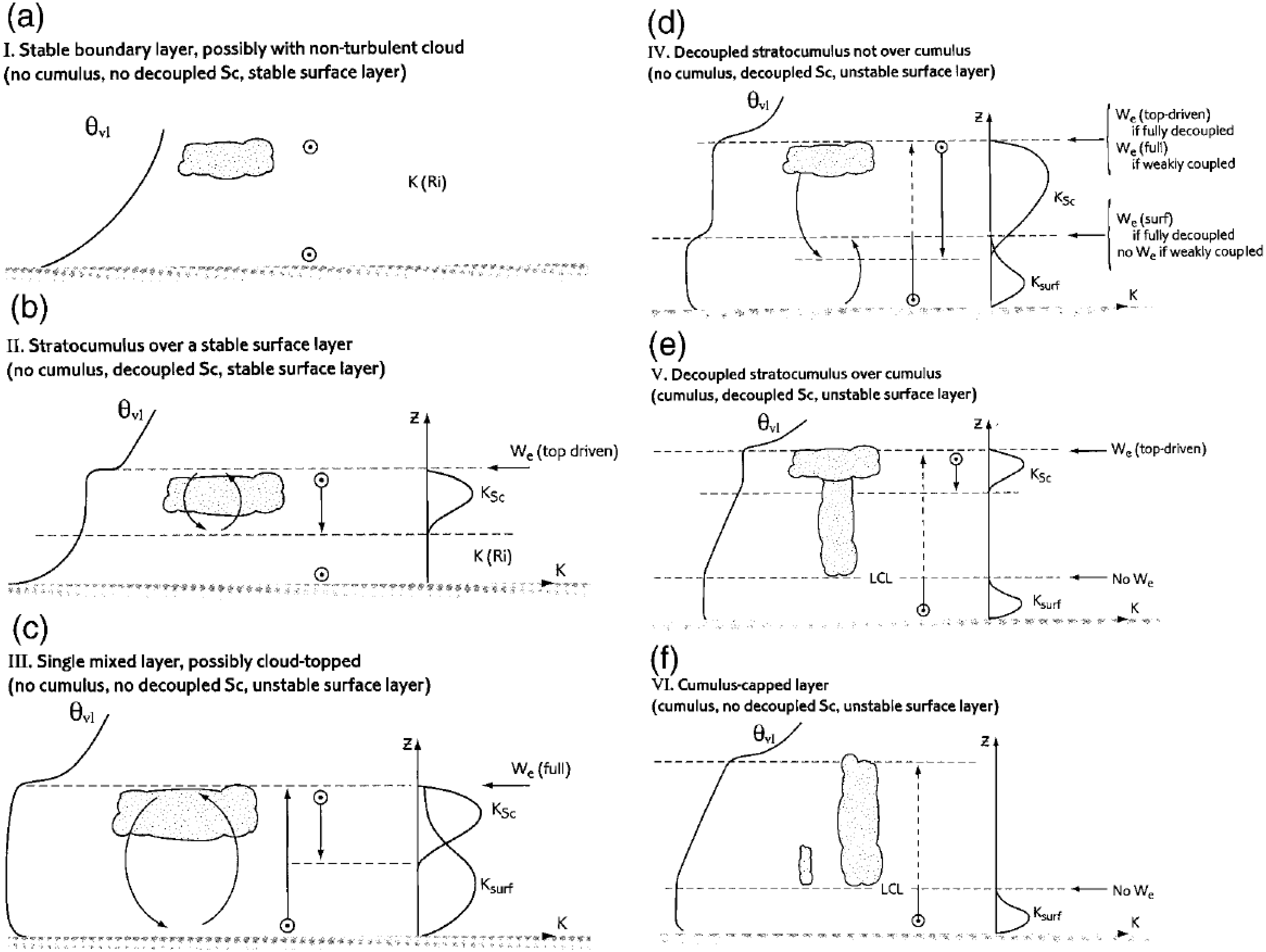




Comparison of top-down and bottom-up



- Variance of vertical wind
  - Good agreement with previous studies if H = 30 W m^{-2}
  - Variance peaks in upper third of BL: agrees with Lenschow et al.'s fit *provided theirs is inverted in height*
- Skewness
  - Very good agreement with the fit of LeMone (1990) to aircraft data *provided hers is inverted in sign and height*
- *Hogan et al. (QJRMS 2009)*


(a)
I. Stable boundary layer, possibly with non-turbulent cloud
(no cumulus, no decoupled Sc, stable surface layer)
θvl
K (Ri)
(b)
II. Stratocumulus over a stable surface layer
(no cumulus, decoupled Sc, stable surface layer)
θvl
z
We (top driven)
KSc
K (Ri)
K
(c)
III. Single mixed layer, possibly cloud-topped
(no cumulus, no decoupled Sc, unstable surface layer)
θvl
z
We (full)
KSc
Ksurf
K
(d)
IV. Decoupled stratocumulus not over cumulus
(no cumulus, decoupled Sc, unstable surface layer)
θvl
z
We (top-driven)
if fully decoupled
We (full)
if weakly coupled
KSc
We (surf)
if fully decoupled
no We if weakly coupled
Ksurf
K
(e)
V. Decoupled stratocumulus over cumulus
(cumulus, decoupled Sc, unstable surface layer)
θvl
z
We (top-driven)
KSc
LCL
No We
Ksurf
K
(f)
VI. Cumulus-capped layer
(cumulus, no decoupled Sc, unstable surface layer)
θvl
z
LCL
No We
Ksurf
K