Using Ground-Based Remote-Sensors to Study Boundary-Layer Vertical Velocity Statistics

Stephen Klein
Program for Climate Model Diagnosis and Intercomparison
Lawrence Livermore National Laboratory

Keck Institute for Space Studies: Climate Feedbacks and Future Remote Sensing Observations
California Institute of Technology
Pasadena, California
Tuesday, September 8, 2009

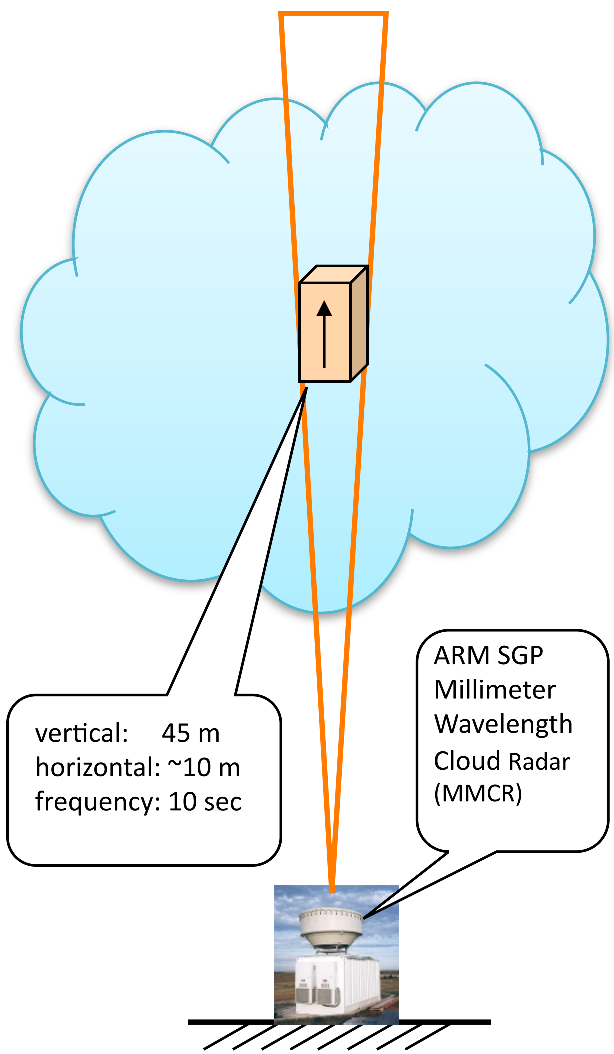
ARM Atmospheric Radiation Measurement

LLNL-PRES-416520

Outline

- Vertical Velocities from Ground-Based Remote -Sensors
- Vertical Velocities in Clear Convective Boundary Layers
- Vertical Velocities in Shallow Cumulus
- Vertical Velocities in Mixed-Phase Stratocumulus
- Additional Possibilities
- Final Remarks

Vertical Velocities From Ground-Based Remote-Sensors



- Doppler millimeter wavelength cloud radars (MMCR) have been operating continuously at a number of sites worldwide (such as ARM) for years
- Millimeter wavelength → Sees cloud particles
- Doppler → measures velocity of the scattering target in the direction of the beam
- Vertically Pointing → the vertical velocity of the scattering target
- Volume → ~10 m x ~10 m x 45 m
- Frequency → Every 10 sec

Vertical Velocities From Ground-Based Remote-Sensors

- In the case of non-precipitating liquid clouds, the scatterers are liquid cloud droplets. Beneath clouds, the scatterers are insects (if present) primarily, and aerosols and other matter secondarily
- You may choose to assume that the velocity of the scatterer is the air vertical motion (ok for small cloud droplets, not as ok for insects who have their own momentum)

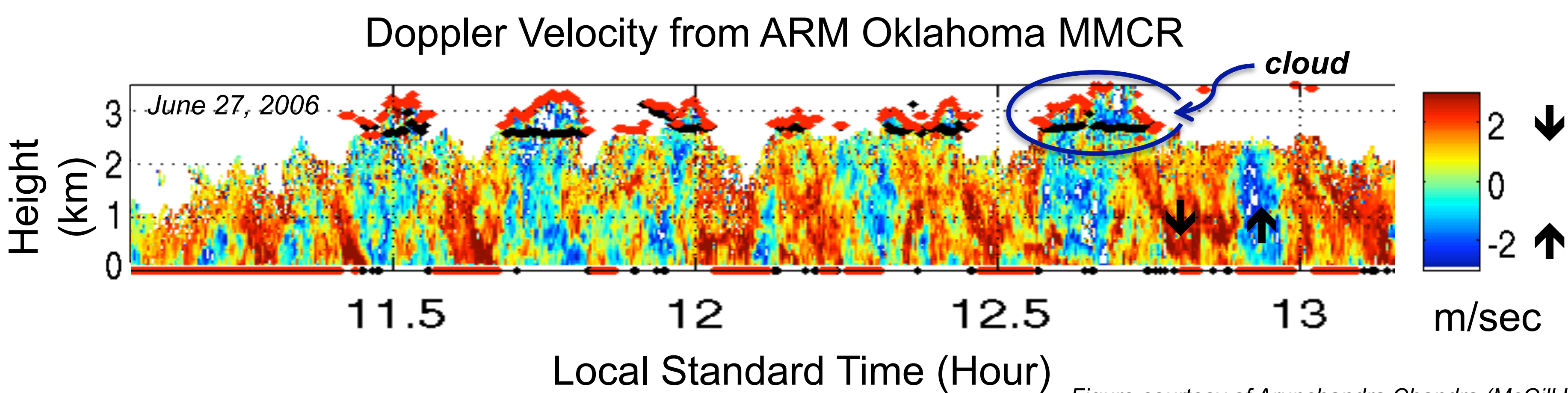
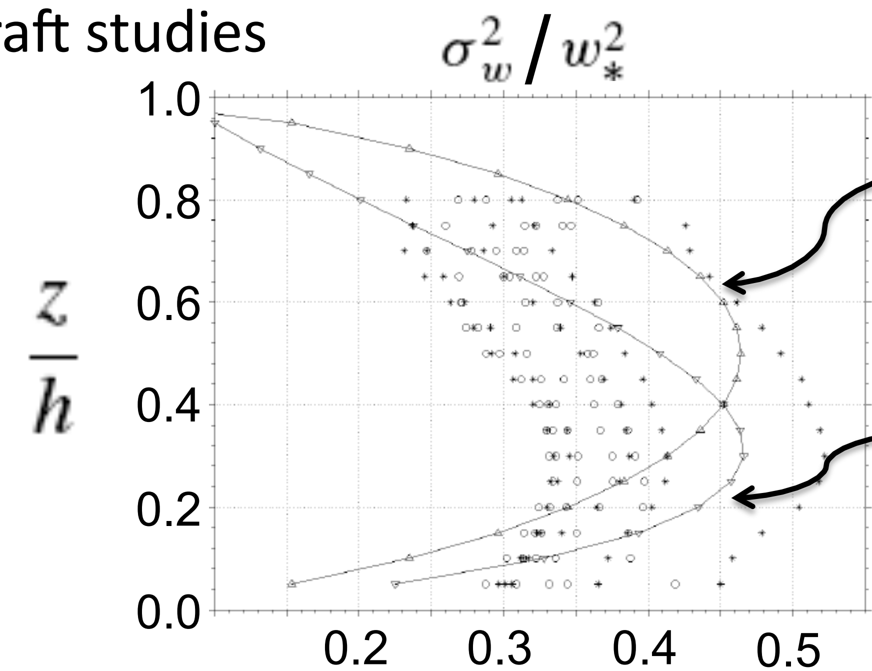


Figure courtesy of Arunchandra Chandra (McGill U.)

Vertical Velocities in Clear Convective Boundary Layers

Pavlos Kollias, Arunchandra Chandra, and Scott Giagrande (McGill U.), Steve Klein (LLNL)

- Relying on the insects to tell us the vertical motion of the air in the clear convective boundary layer, one can examine the vertical profile of vertical velocity variance and skewness
- Radar observations from ~300 days at the ARM Oklahoma site are broadly consistent with parameterizations based on old aircraft studies



$$\frac{\sigma_w^2}{w_*^2} = 1.17\left[\frac{z}{h}\left(1-\frac{z}{h}\right)\right]^{2/3}$$

Sorbjan (1989)

$$\frac{\sigma_w^2}{w_*^2} = 1.8\left(\frac{z}{h}\right)^{2/3}\left(1-0.8\frac{z}{h}\right)^2$$

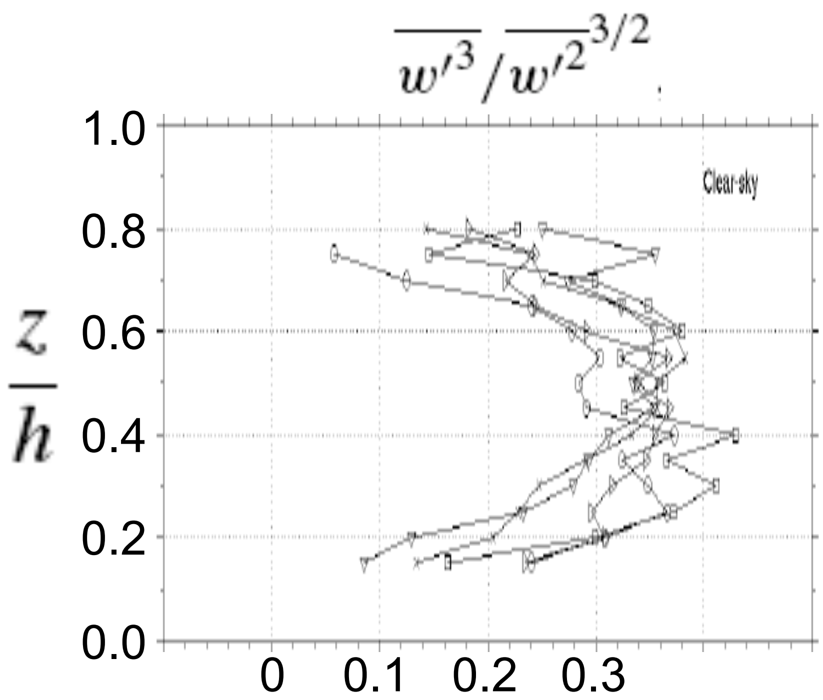
Lenschow et al. (JAS 1980)

Chandra et al. (J. Clim. 2009, submitted)

Vertical Velocities in Clear Convective Boundary Layers

Pavlos Kollias, Arunchandra Chandra, and Scott Giagrande (McGill U.), Steve Klein (LLNL)

- Convective boundary layers have positive skewness (as expected) due to heating from below
- Chandra et al. (2009) also compute convective mass-fluxes and show that over 80% majority of the mass-flux transport is contributed by coherent vertical structures
- The observations could be used to assess eddy-diffusive mass-flux boundary layer parameterizations *(Siebesma et al. JAS 2007)*

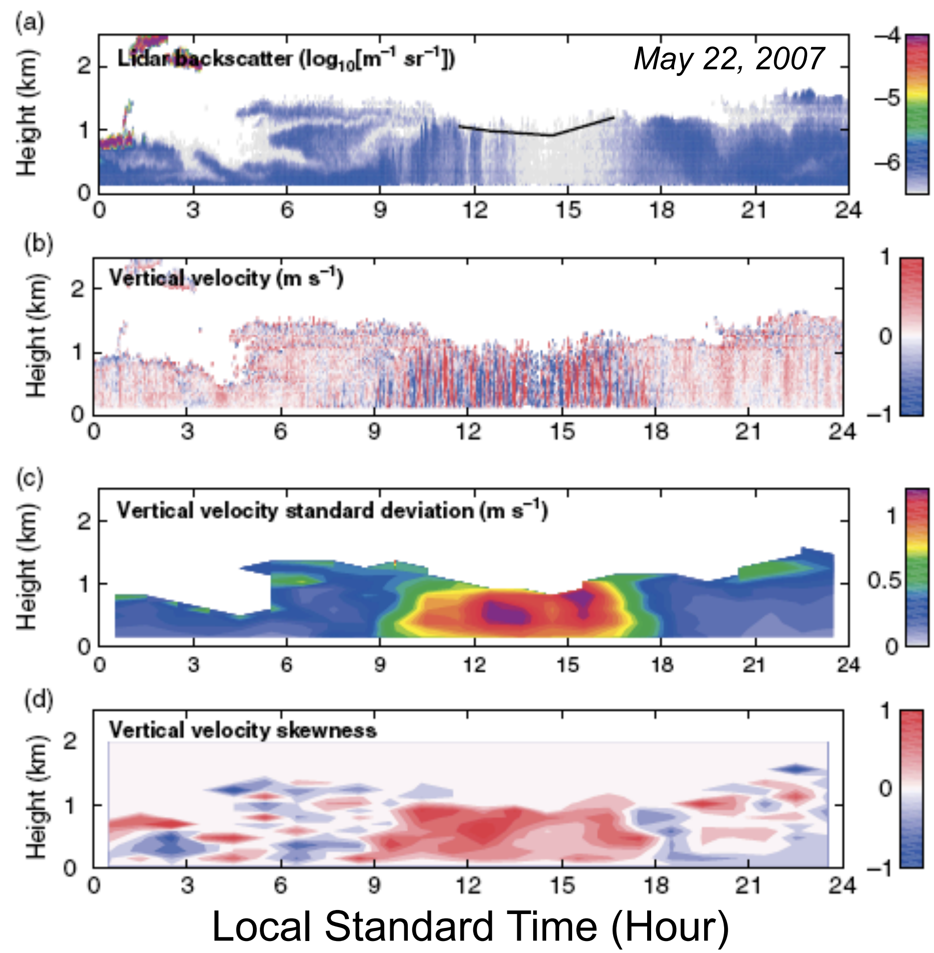


Chandra et al. (J. Clim. 2009, submitted)

Vertical Velocities in Clear Convective Boundary Layers

Robin Hogan (U. Reading)

- If you don't like insects, you can use a doppler lidar, which by using a wavelength in the near infrared (λ= 1.5 μm) is more sensitive to the smaller particles such as aerosols, to tell you about the vertical velocity in the clear-convective boundary layer

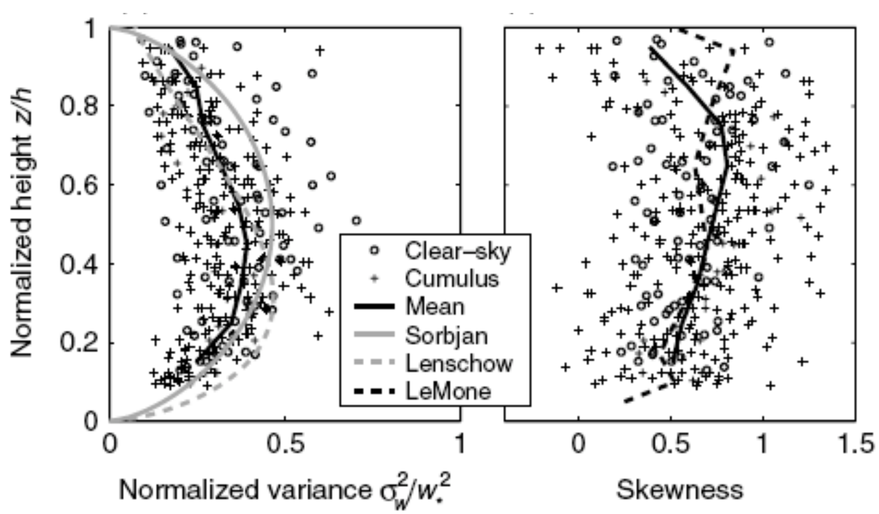


Hogan et al. (Quart. J. Roy. Met. 2009)

Vertical Velocities in Clear Convective Boundary Layers

Robin Hogan (U. Reading)

- These doppler lidar observations confirm the millimeter wavelength cloud radar results for variance and skewness
- For nocturnal boundary layer clouds, negative skewness is found beneath cloud base → this is characteristic of turbulence driven from cloud-top radiative cooling
- Lidars are not as helpful for boundary layer clouds because they can't penetrate beyond an optical depth of 3

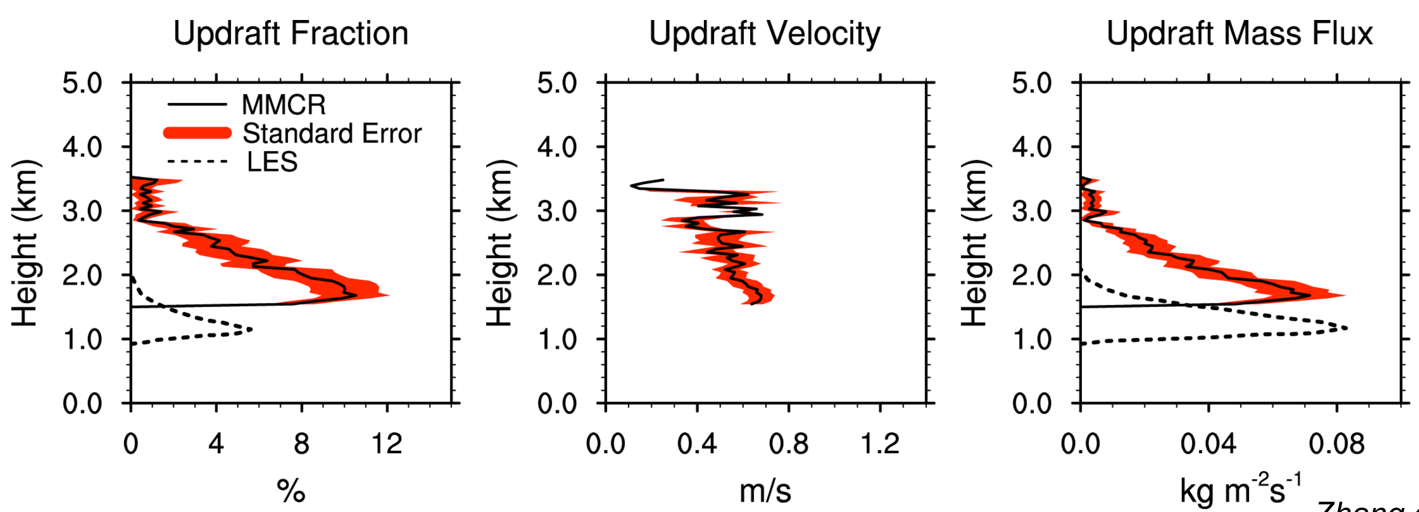


Hogan et al. (Quart. J. Roy. Met. 2009)

Vertical Velocities in Shallow Cumulus

Pavlos Kollias (McGill U.)
Yunyan Zhang and Steve Klein (LLNL)

- From MMCR data at the ARM Oklahoma site, composites are made of daytime shallow cumulus cloud fractions, and the areas and vertical velocities in updrafts and downdrafts
- Vertical profile shape with decreasing cloud fraction above cloud base; most clouds are shallow, fewer go deeper
- Vertical velocity decreases with height above cloud base, consistent with negative buoyancy in the cloud layer

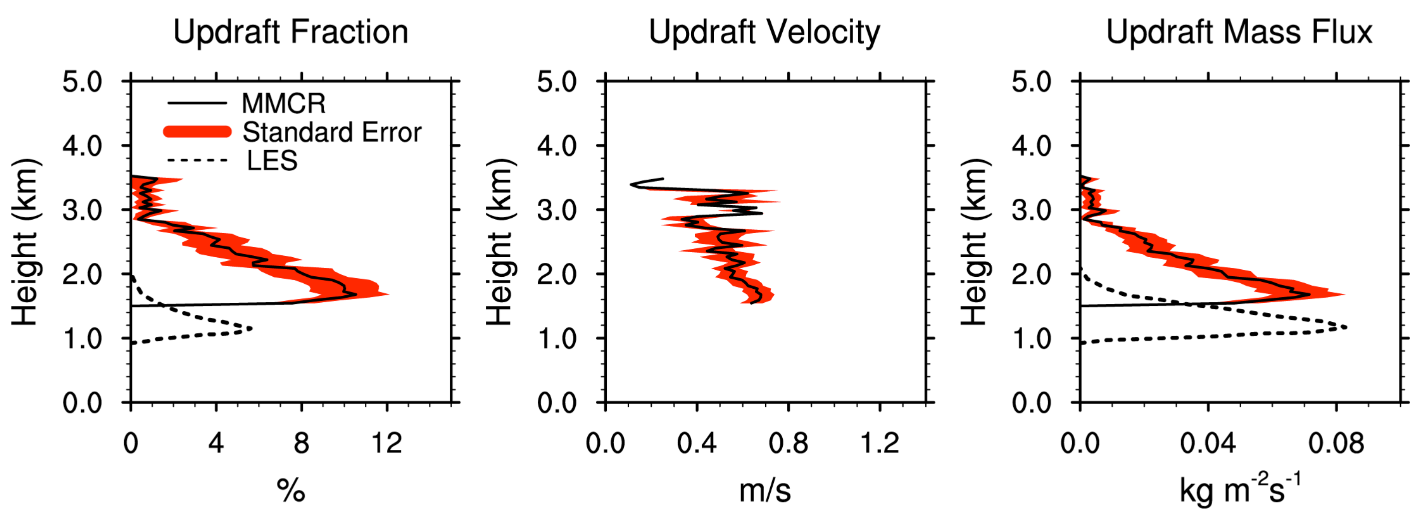


Zhang et al. (in preparation)

Vertical Velocities in Shallow Cumulus

Pavlos Kollias (McGill U.)
Yunyan Zhang and Steve Klein (LLNL)

- Cumulus mass flux (~ updraft area * updraft velocity) is a fundamental variable in the analysis of convection; it is central to convection parameterizations
- Cloud cover and mass-flux is comparable to LES composite simulation from a LES-intercomparison study of land shallow convection (GCSS "ARM Shallow Cu" day)

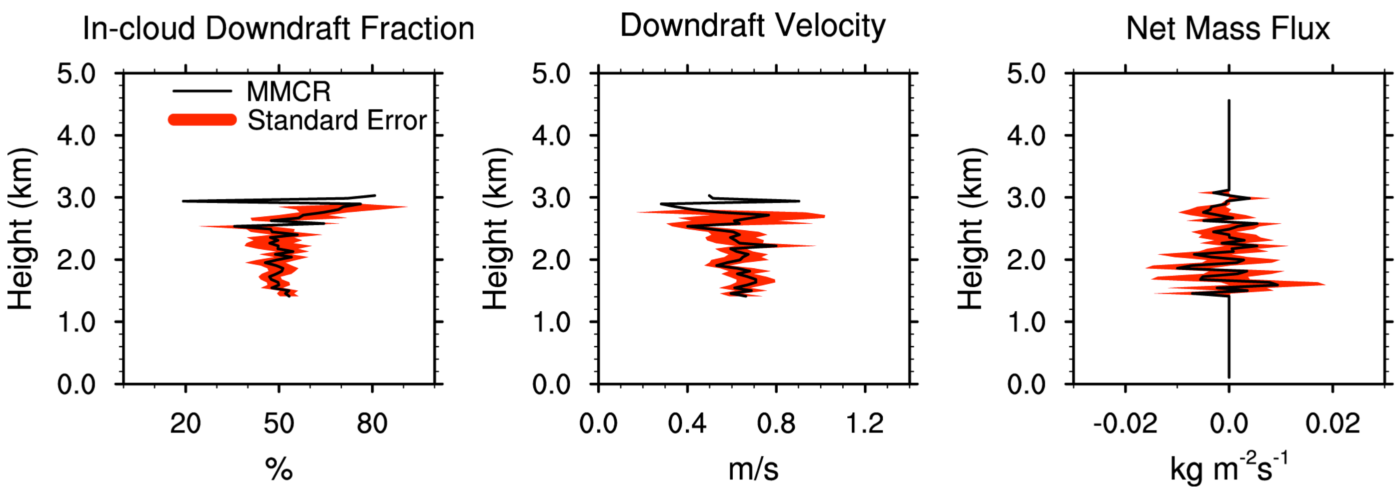


Zhang et al. (in preparation)

Vertical Velocities in Shallow Cumulus

Pavlos Kollias (McGill U.)
Yunyan Zhang and Steve Klein (LLNL)

- Clouds are equal part updrafts and downdrafts
- Downdrafts are strongest at cloud-base
- Net mass flux is near zero
- The similarity of updrafts to downdrafts would be consistent with parcel overshoots of the mixed-layer



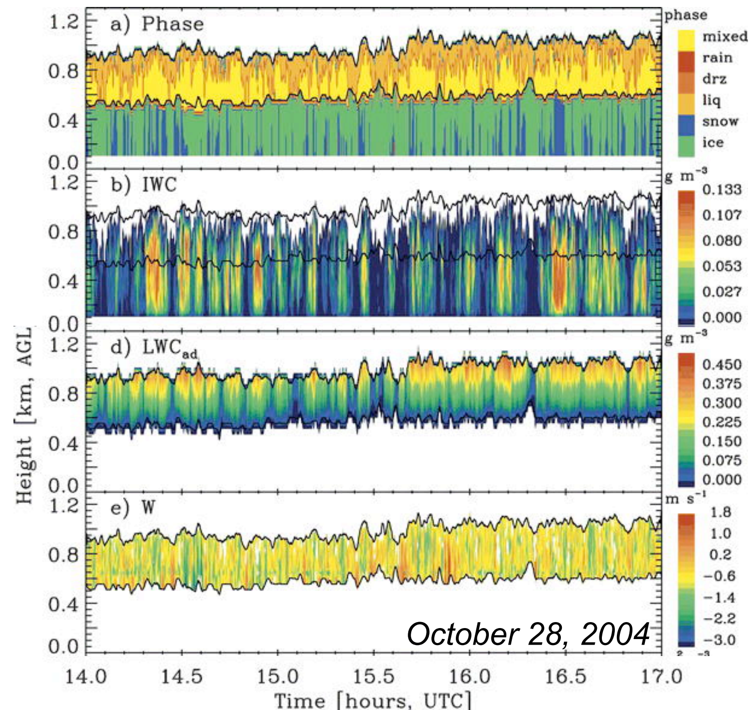
Zhang et al. (in preparation)

Vertical Velocities in Mixed-Phase Stratocumulus

Matthew Shupe (NOAA CIRES)

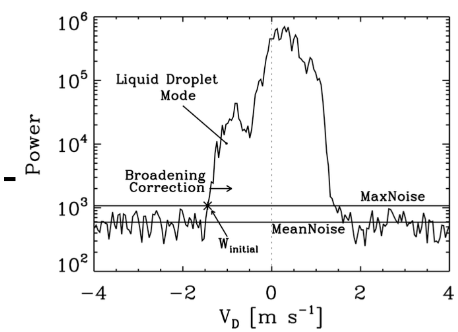
- In more complicated situations such as co-existing liquid droplets and large ice crystals, you can retrieve the vertical air motion by considering the radar spectra (= radar power as a function of the velocity of the scatterer)
- This should work for drizzling stratocumulus (so says Matt)

ARM Barrow, Alaska



Shupe et al. (JAS 2008)

Radar Spectra for Mixed-Phase Volume

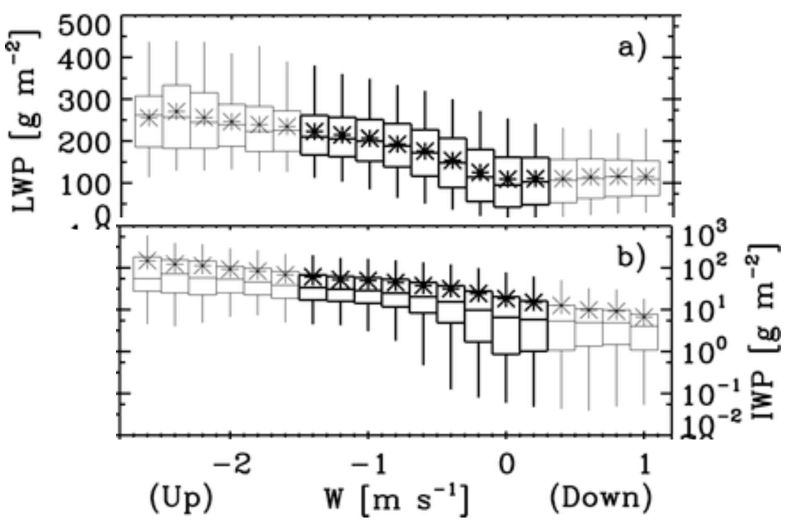


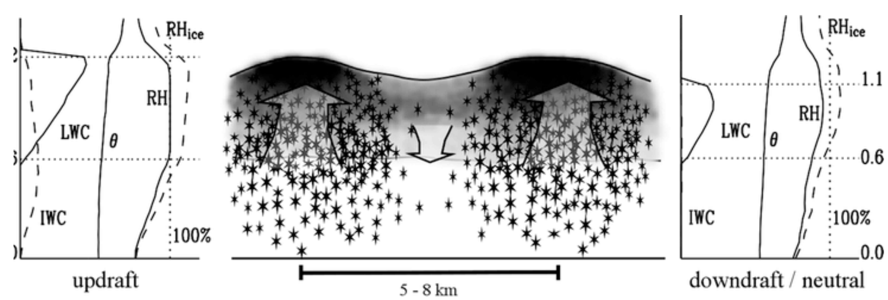
Shupe et al. (JAOT 2008)

Vertical Velocities in Mixed-Phase Stratocumulus

Matthew Shupe (NOAA CIRES)

- Data show that in mixed-phase stratocumulus there is both more liquid and more ice in cloudy updrafts than in cloudy downdrafts → Ice is formed in high water content regions
- The lack of ice in the downdrafts tells you that the fallout time of ice (ΔZ_{cloud} / V_{fall} ~ 10 min) is shorter than the large-eddy turnover time scale (ΔZ_{layer} / w* ~ > 30 min)





Shupe et al. (JAS 2008)

Additional Possibilities

- With assumptions made on the nature of the ice size distribution and particle fall speeds, Jay Mace and Ming Deng have retrieved a multi-year record of radar sample volume vertical velocity in cirrus clouds *(Deng and Mace, J. Appl. Met. Clim. 2006, 2008)*
- It is also possible to retrieve the vertical velocity in stratiform rain and potentially convective updrafts in precipitating convection from wind profilers
- If you horizontally scan, you see horizontal motion out to ~5 km
  - Lidar → the horizontal structure of the clear-boundary layer or the sub-cloud layer
  - Cloud radar → Overturning eddies for boundary layer cloud

Efforts are underway to more routinely do horizontal scans

Final Remarks

- New possibilities for modelers or observationalists to dive into remotely sensed multi-year records of cloud-scale vertical motions. This potentially allows one to:
  - Improve the understanding of the connection between cloud properties and small-scale cloud dynamics
  - Provide observational targets for Large-eddy simulations and aspects of large-scale model parameterizations

Final Remarks

- What is new about this? How did we measure vertical velocity before?
  - Dual-doppler precipitation radars were limited to deriving air motions in deep convective cloud systems at larger scales
  - Aircraft data has been the preferred way to measure small-scale vertical motions, but with limited sampling

Thus what is new is availability of cloud-scale (~20 m) vertical motions for long periods of time in non-precipitating cloud-systems

Final Remarks

- What about the potential of measuring cloud-scale vertical velocity from space?
  - I had heard that a Doppler radar planned for Earthcare – but spatial volumes it will see would be larger (~1 km?) – not cloud-scale (~10s of meters)?