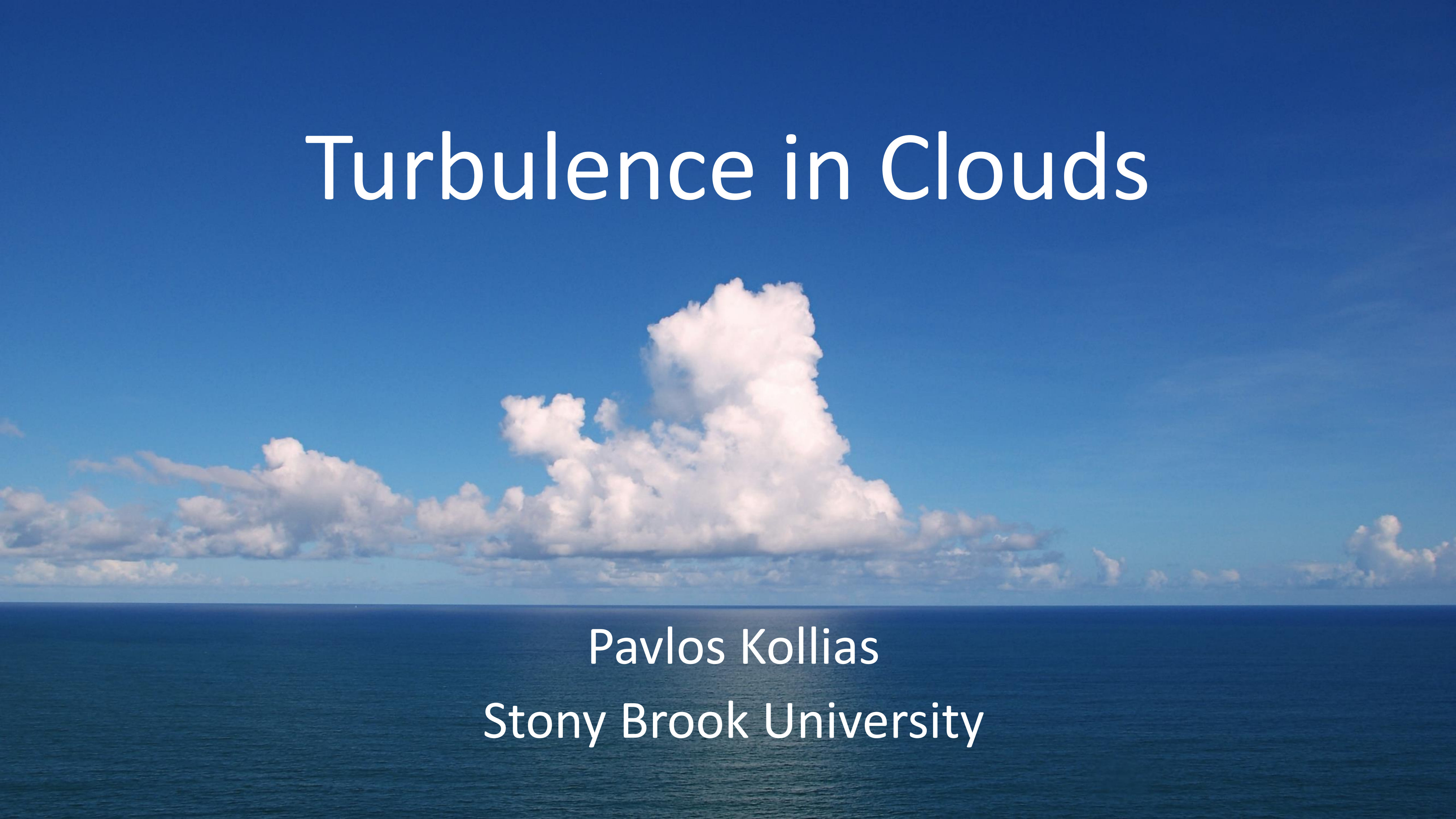
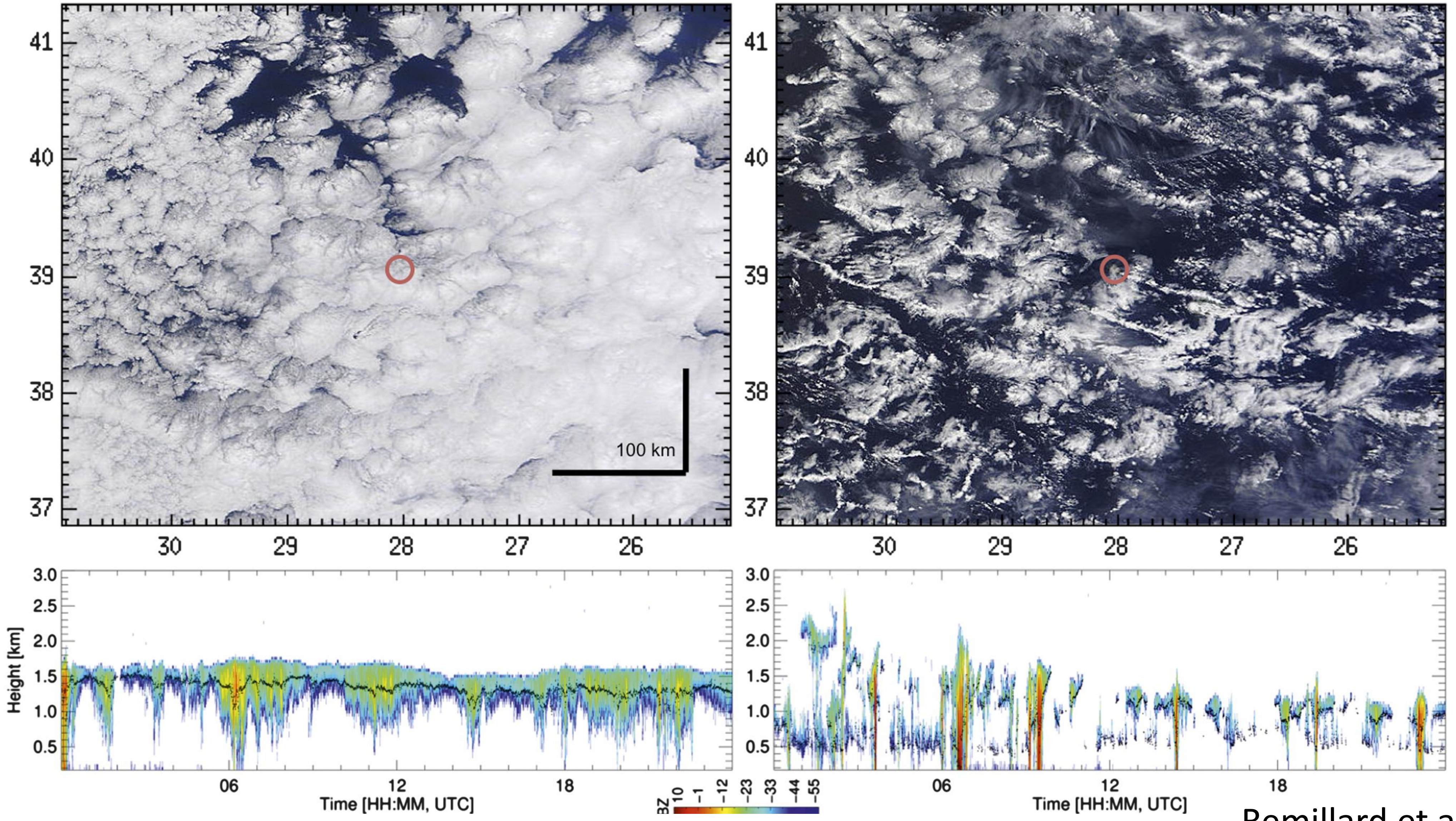


Turbulence in Clouds

Pavlos Kollias
Stony Brook University

Focus in cloud-scale turbulence and do not consider the interaction of large-scale meteorology with cloud-scale



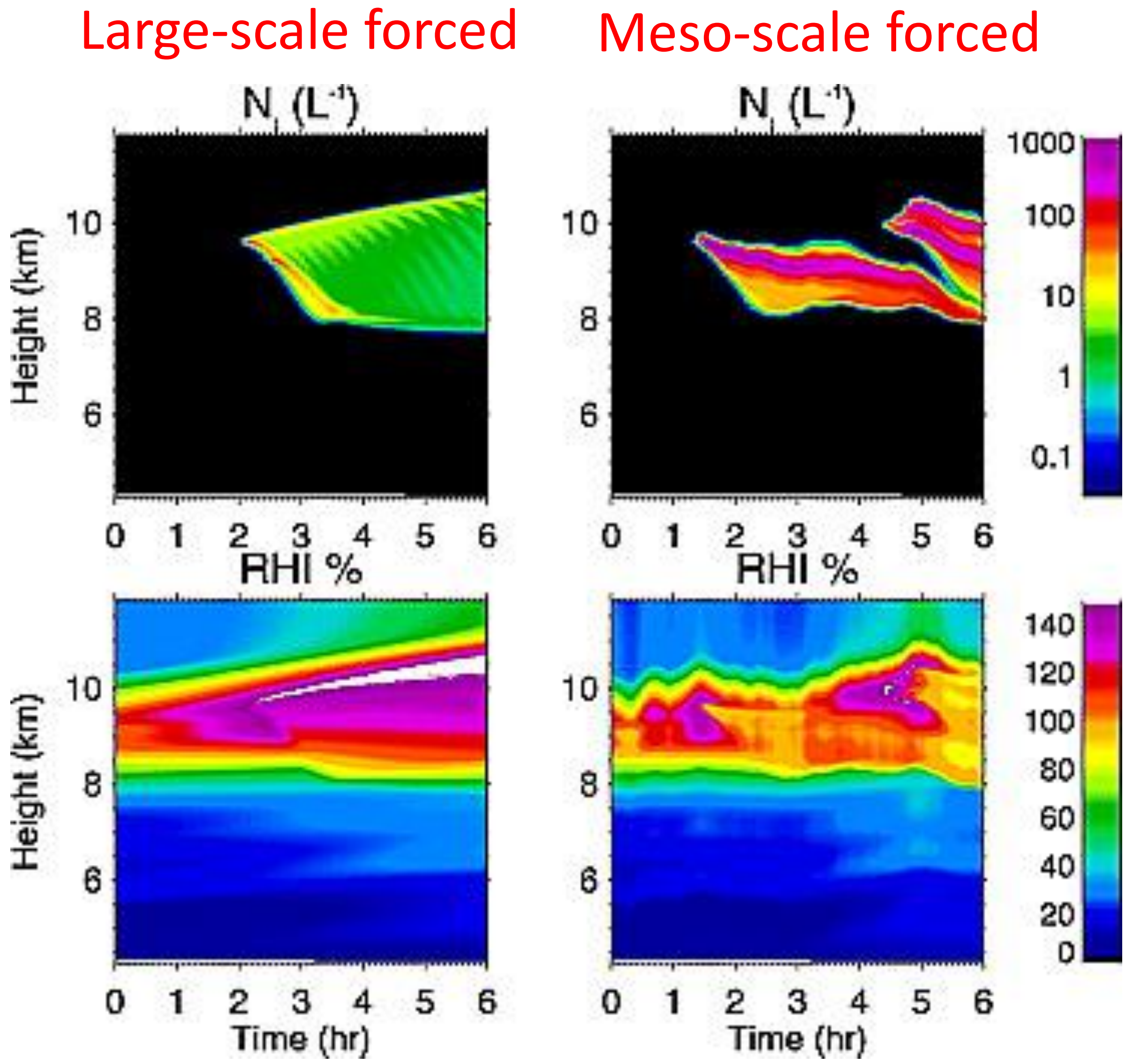
Remillard et al., 2013

Science Frontiers

- Warm boundary layer clouds
  - Entrainment – mixing
  - 3D turbulence
  - Vertical transport
  - Condensational growth and turbulence
  - Collisions, coalescence and turbulence
- Mixed-phase clouds
  - Cloud-forced turbulent mixed-layer
- Ice clouds
  - Role of cirrus clouds dynamics in ice nucleation processes
  - Role of cloud-top generating cells in ice microphysics
- Role of complex terrain generated turbulence in cloud processes

Cirrus clouds: Role of cloud dynamics in ice nucleation processes

- By determining temperature and cooling rates dynamical processes affect cirrus macrophysical and microphysical properties (Lynch et al., 2002, Comstock et al., 2008)

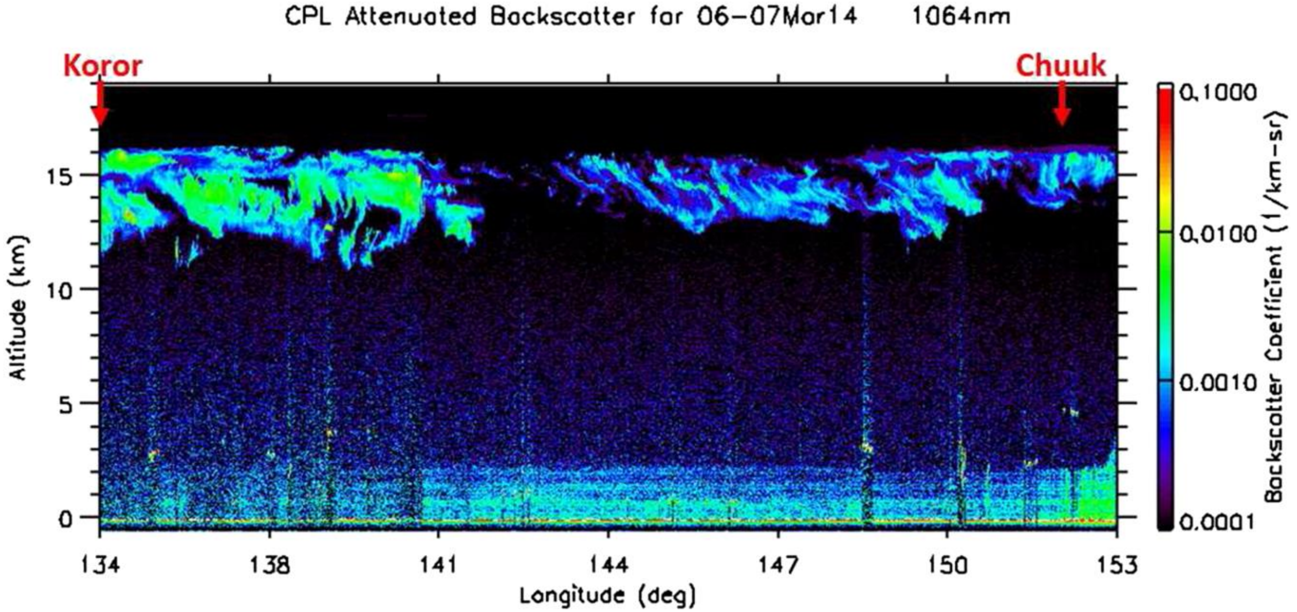


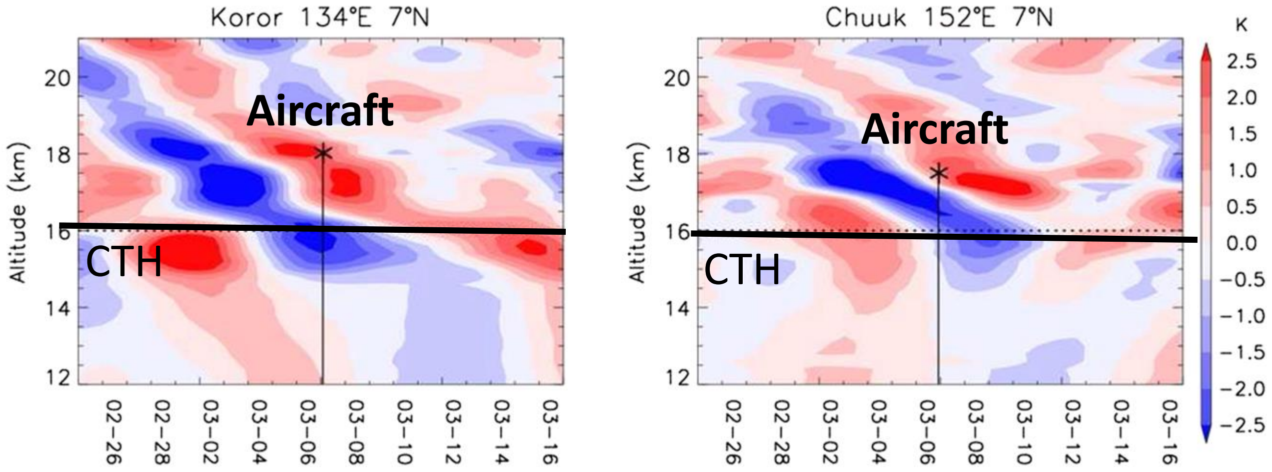
TTL cirrus formation and dehydration process

Airborne Tropical Tropopause Experiment (ATTREX)

Investigate how planetary waves affect the TTL cirrus formation and dehydration processes

λ ~ 8000 km





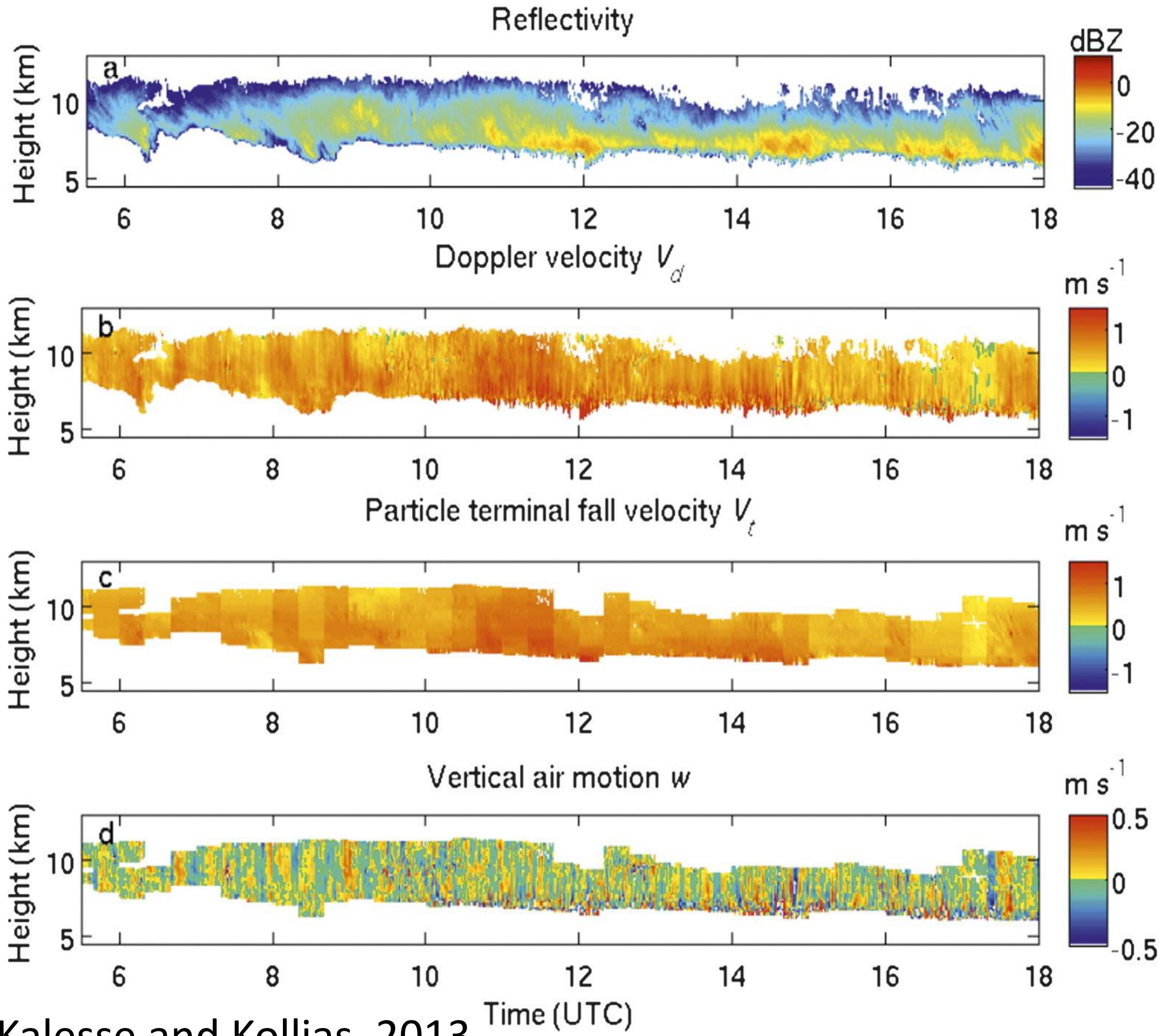
Jensen et al, 2017

Cirrus clouds dynamics from profiling cloud radars

25-years of profiling cloud radar observations at a mid-latitude (Oklahoma) and tropical site (Manus)

Decomposition of the mean Doppler velocity to dynamical and microphysical component

The presence of gravity waves was found to have substantial influences on high cloud properties at both sites.

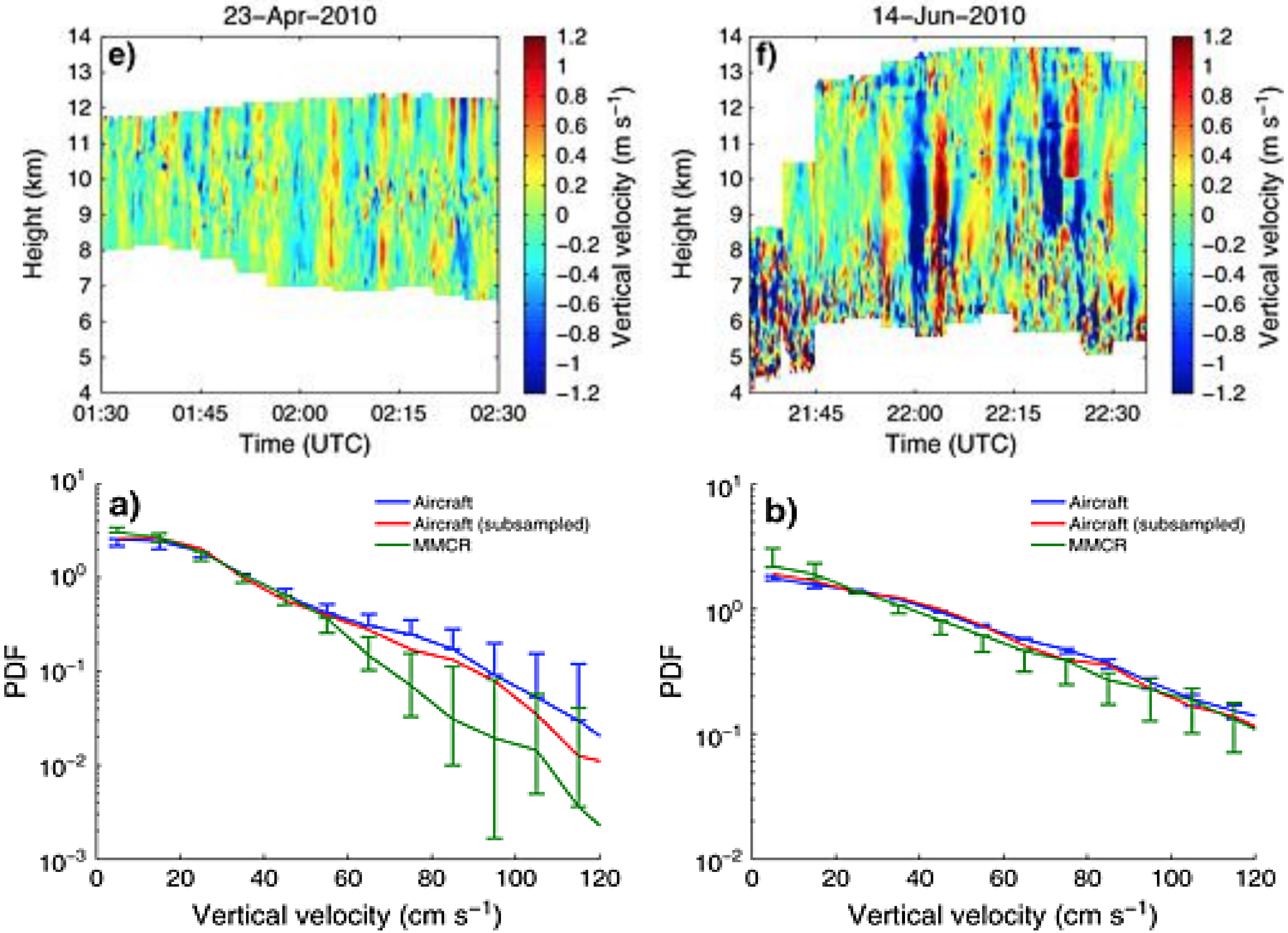


Kalesse and Kollias, 2013

Aircraft observations of gravity waves in cirrus clouds

Gultepe and Starr (1995) reported waves with wavelengths between 0.8 – 11 km, mesoscale waves (50-150 km) and intermitten turbulence

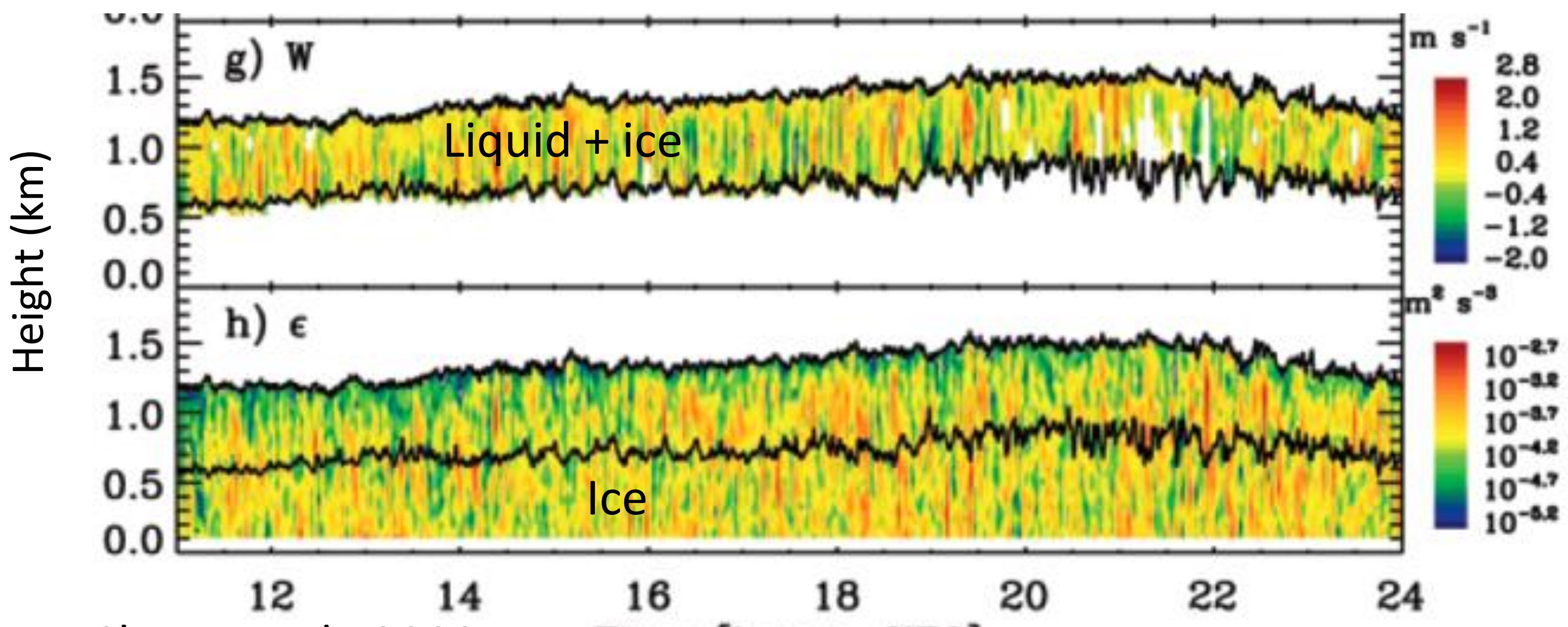
Muhlbauer et al., 2014 compared ground-based and aircraft-based vertical air motion measurements



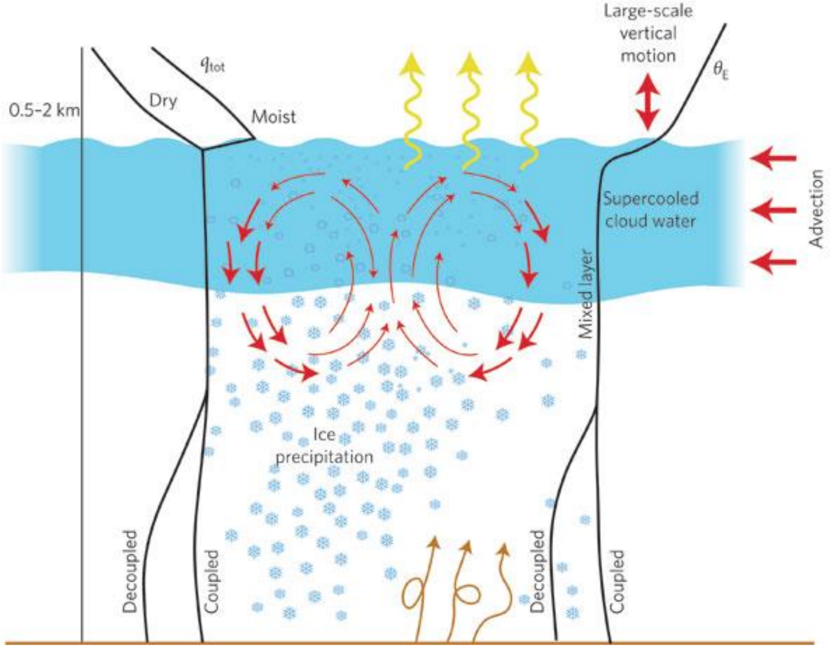
Science Frontier: Role of cirrus clouds dynamics in ice nucleation processes

Key measurement requirement(s) (e.g. physical parameter)	**Instrument requirement(s)**	**Challenges (technological, cost, resolution, coverage**
Amplitude and frequency of gravity waves	Ground-based or airborne cloud Doppler radar	Need coincident measurements ice microphysics and dynamics
Profiles of water vapor pressure (supersaturation)	Ground-based or airborne profiling backscatter & Raman Lidar	Humidity profiles are difficult issues for remote sensing
Profiles of temperature (buoyancy)	Radiosondes	Supersaturation wrt ice difficult to estimate at low T
Ice particles properties	In situ aircraft	

Mixed-phase clouds



Shupe et al., 2008



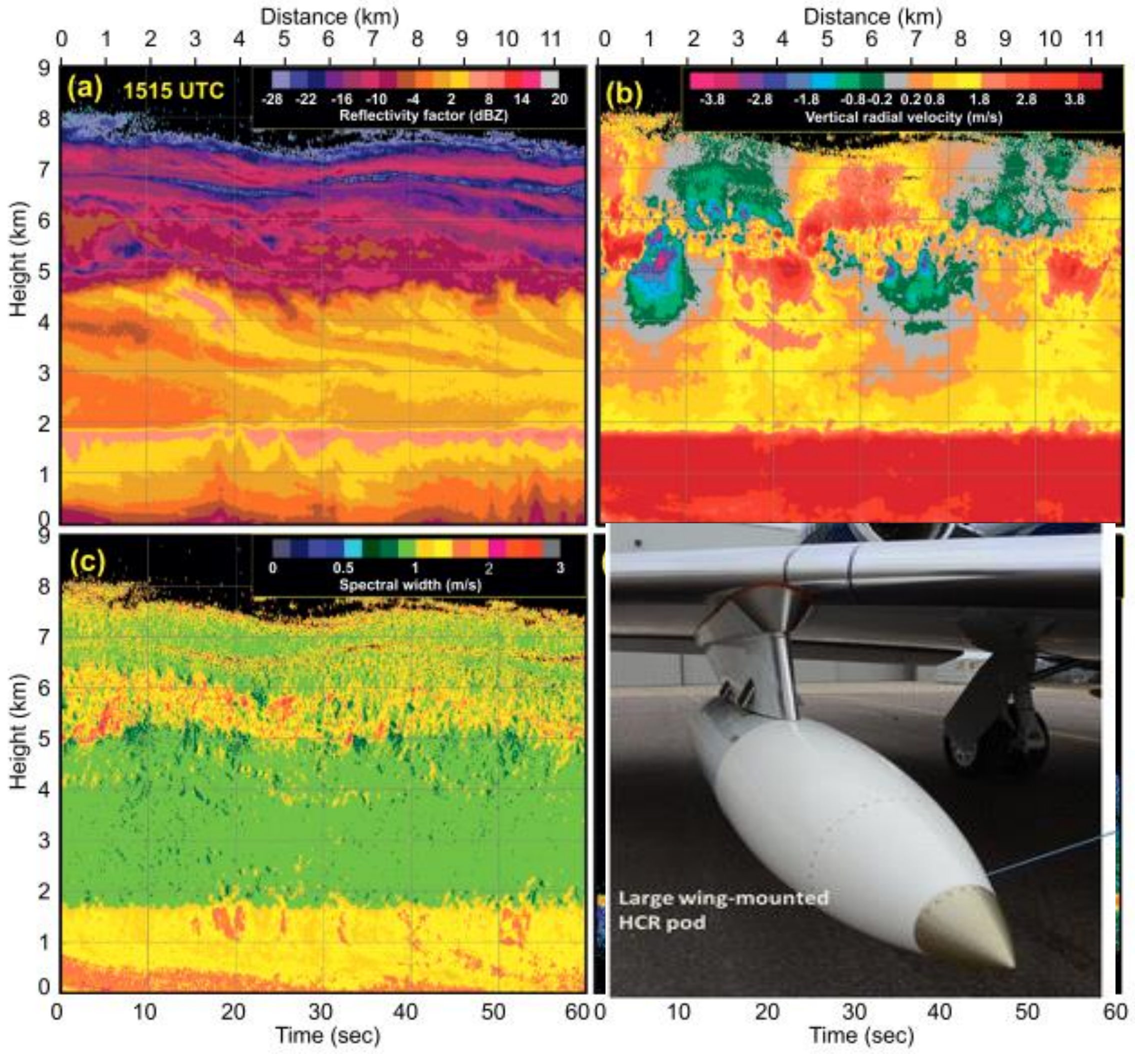
Morrison et al., 2012

The combination of profiling Doppler radars and lidars enables the high resolution mapping of BL dynamics (Δr ~ 15-45 m, Δt ~ 1-2 sec)

Frontal systems – Role of cloud top generating cells on ice microphysics

Finescale structural features present within a major Northeast United States snowstorm as viewed with the new HIAPER Cloud Radar aboard the NCAR GV aircraft.

Evidence for elevated convection, cloud-top generating cells, wave motions and layers of turbulence where local fluctuations in vertical radial velocity occurred on the order of 1–2 m s^{-1}.

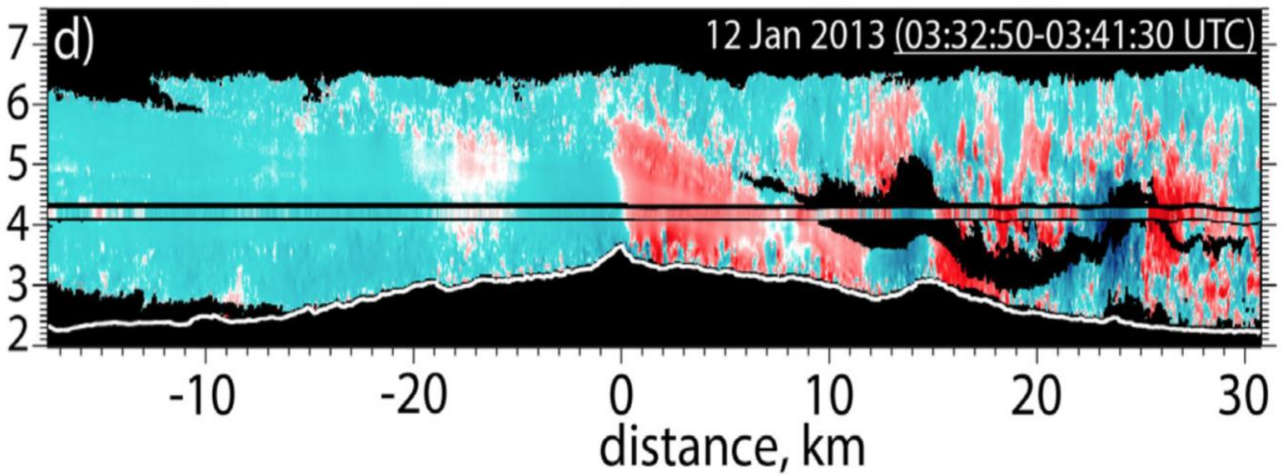


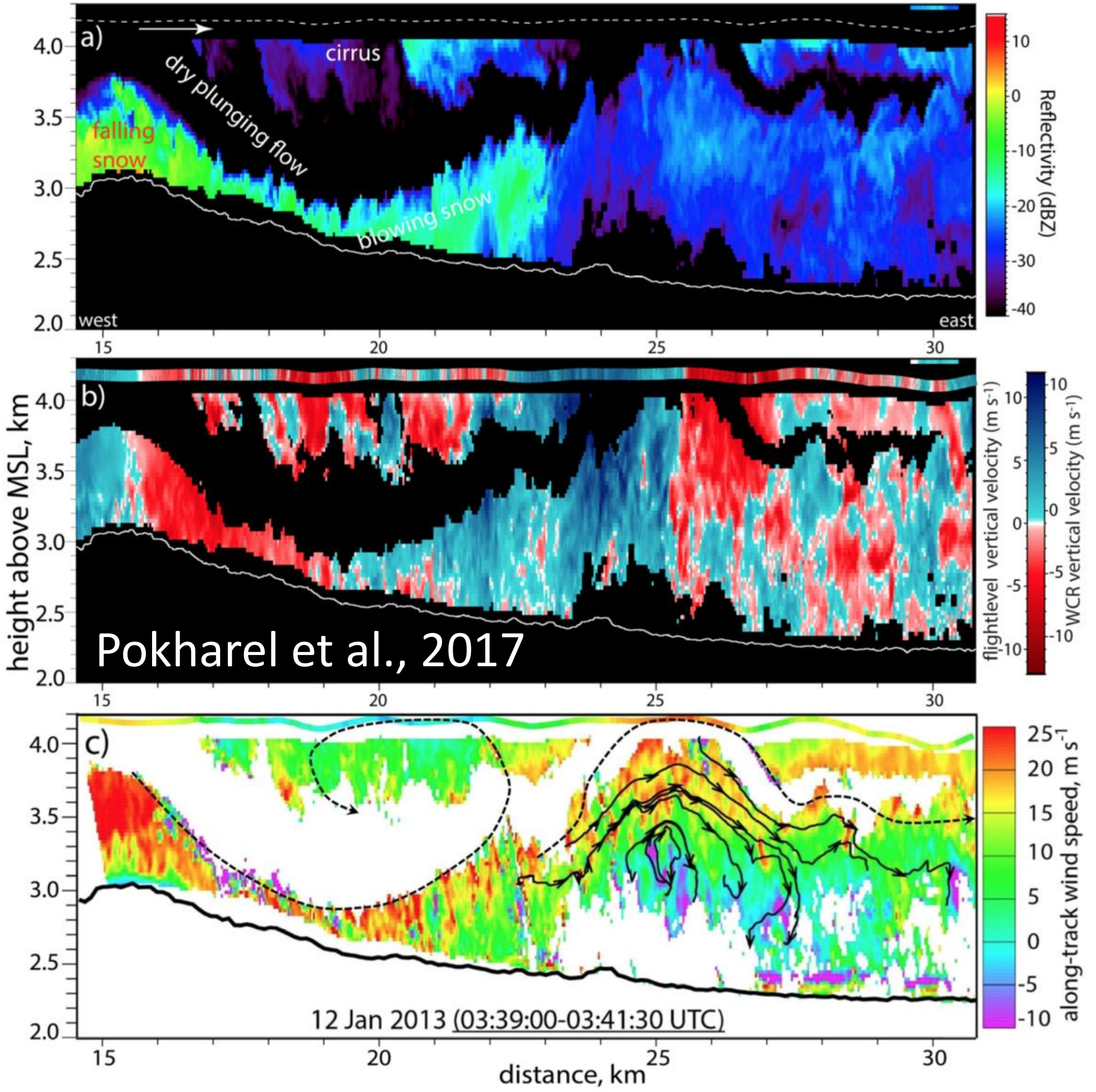
Rauber et al., 2016

Complex terrain – Role of mountain generated waves on cloud microphysics

The predictability of downslope windstorms based on coincident upstream conditions alone is poor

Moderate to severe turbulence in the vicinity of the plunging jet and the wave breaking area



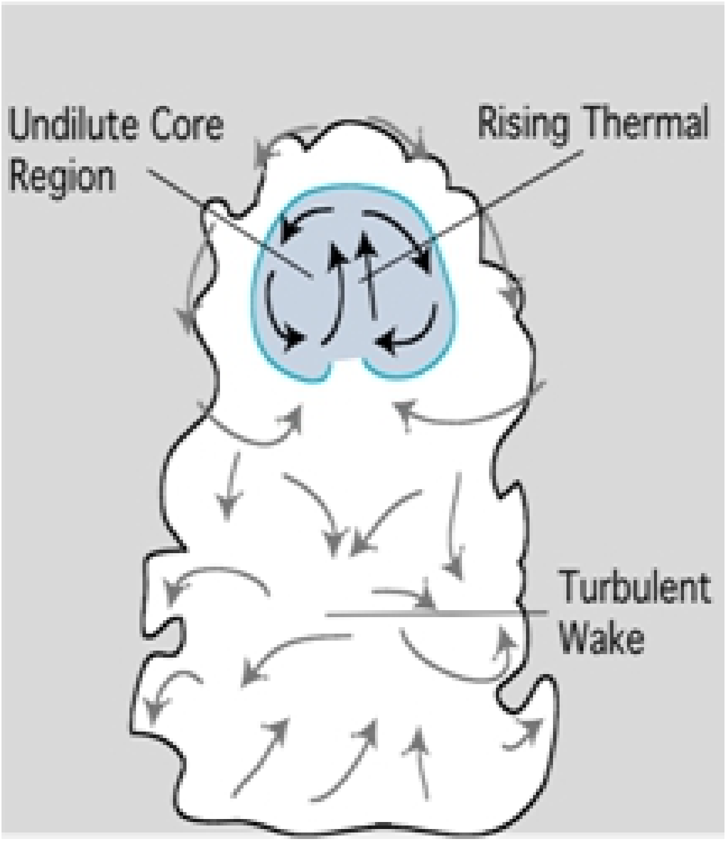


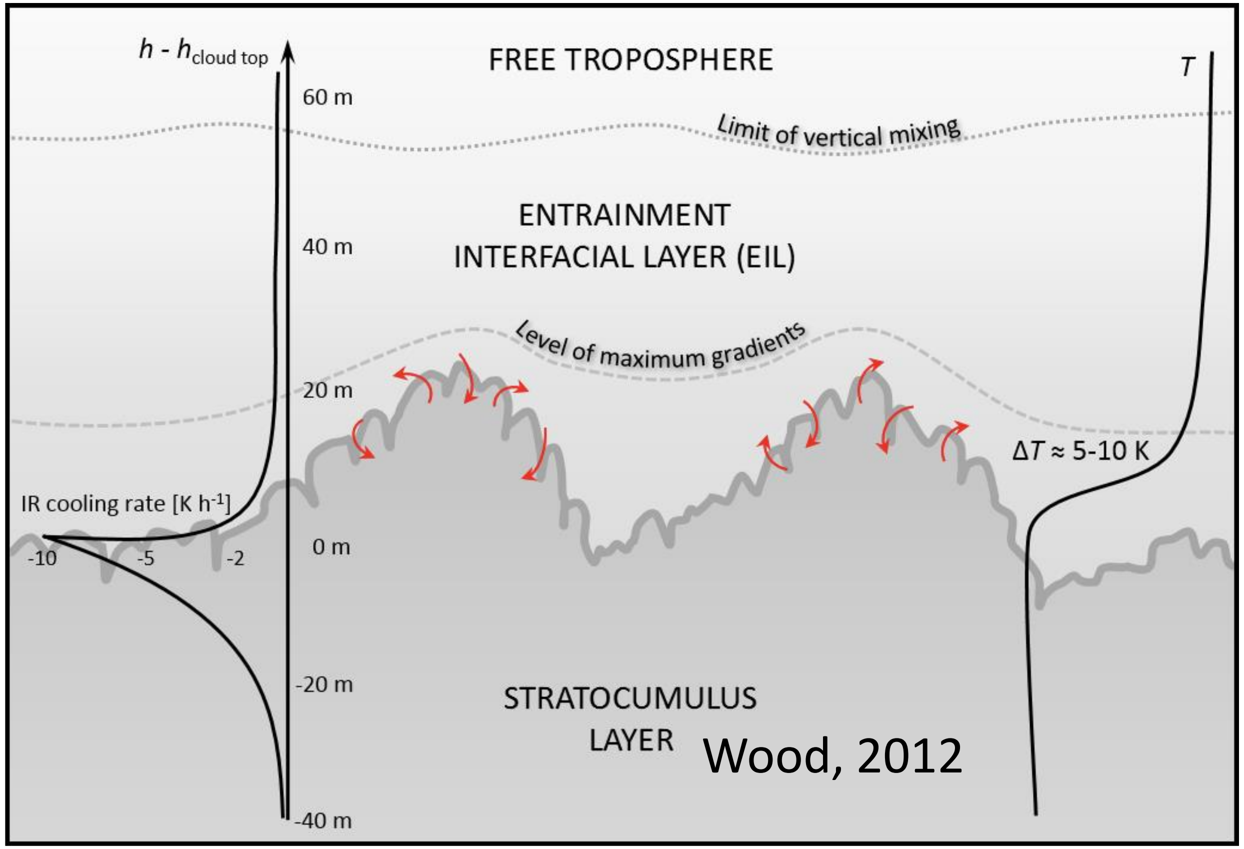
Pokharel et al., 2017

Science Frontiers: Role of turbulence in mixed-phase clouds
Role of cloud-top generating cells in ice microphysics
Role of terrain-generated turbulence in cloud microphysics

Key measurement requirement(s) (e.g. physical parameter)	**Instrument requirement(s)**	**Challenges (technological, cost, resolution, coverage**
Cloud-scale vertical velocity and EDR Profiles of water vapor pressure (supersaturation) Profiles of temperature (buoyancy) Ice particles properties	Ground-based or airborne cloud Doppler radar Profiling backscatter, Doppler & Raman Lidar Microwave radiometer Radiosondes Aircraft aerosol and microphysics	Need coincident measurements ice microphysics and dynamics Humidity profiles are difficult issues for remote sensing

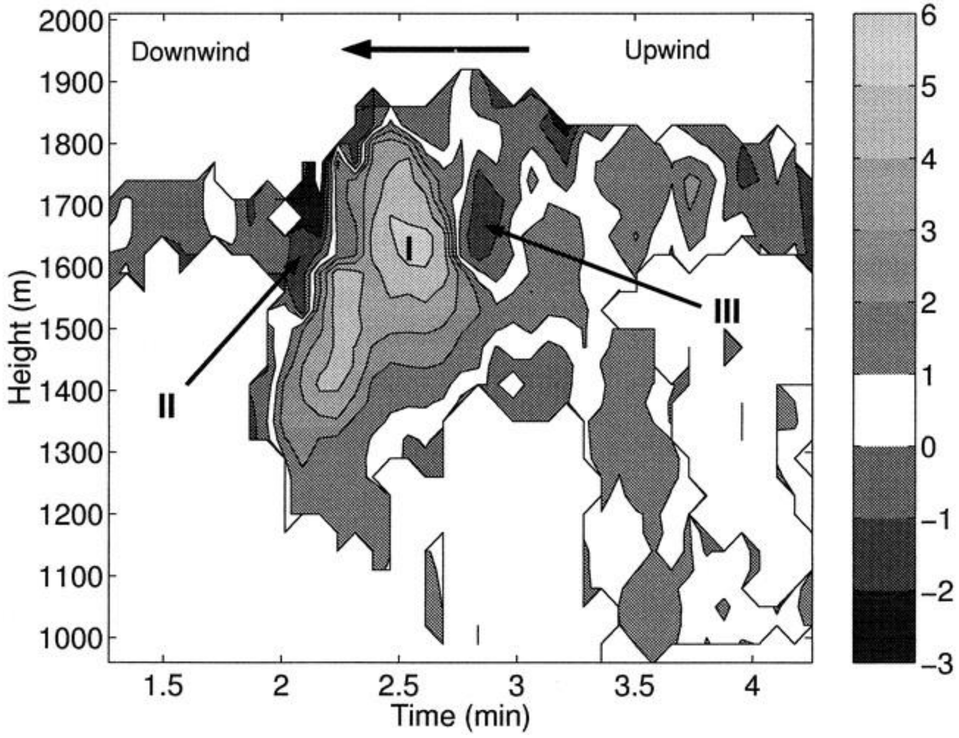
Cloud-scale and small-scale turbulence
Entrainment and Mixing

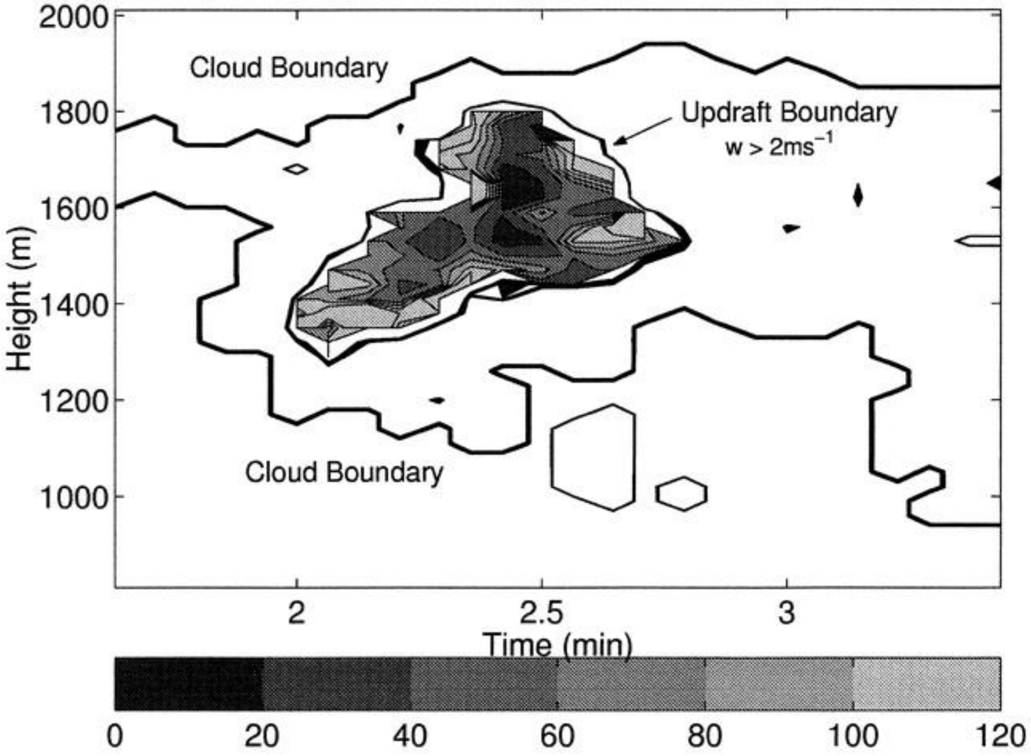




Wood, 2012

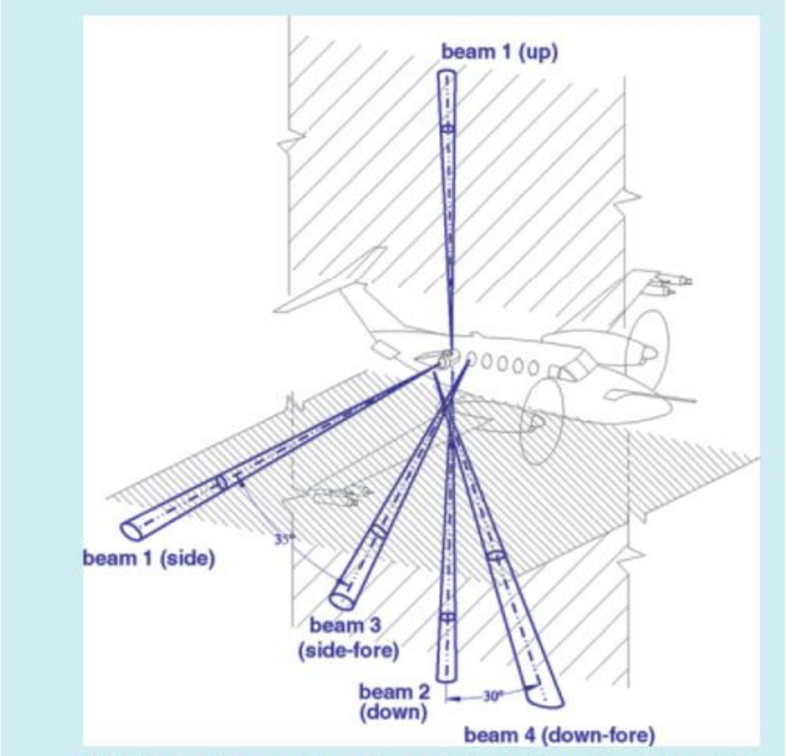
Updrafts and downdrafts in shallow cumulus



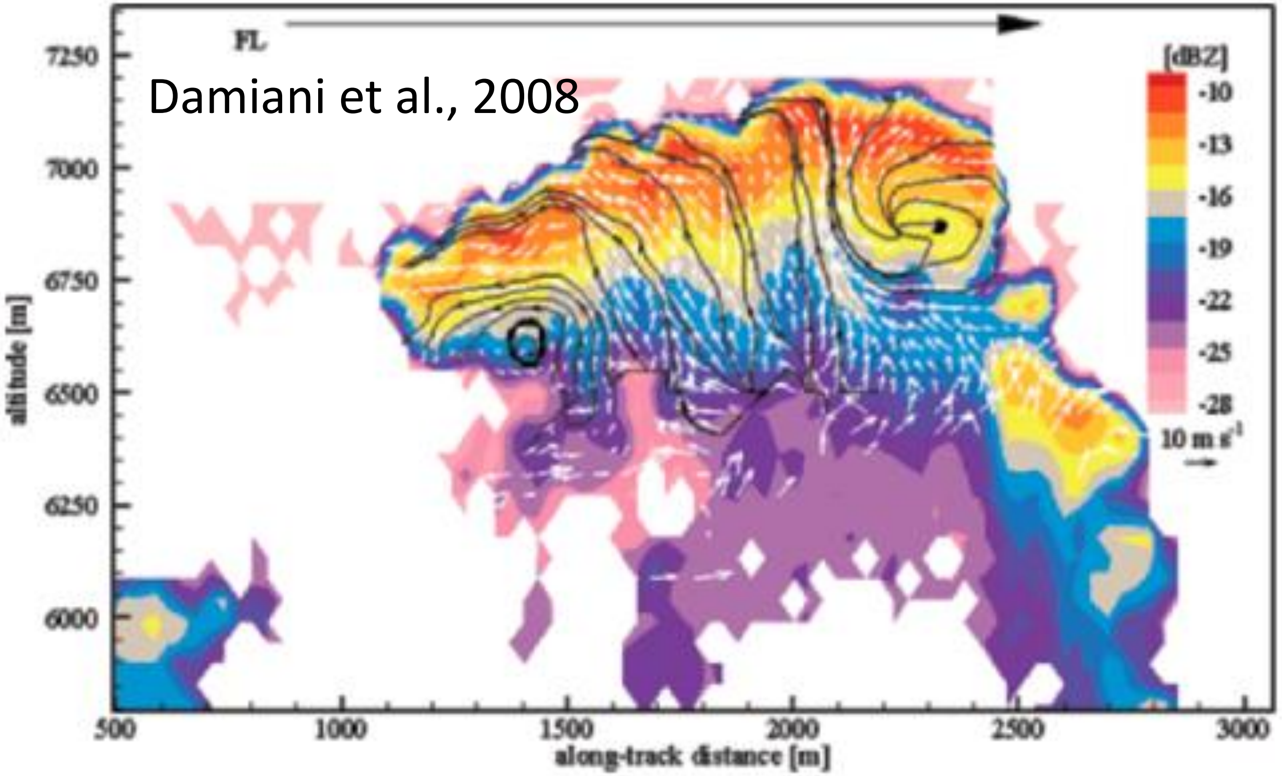


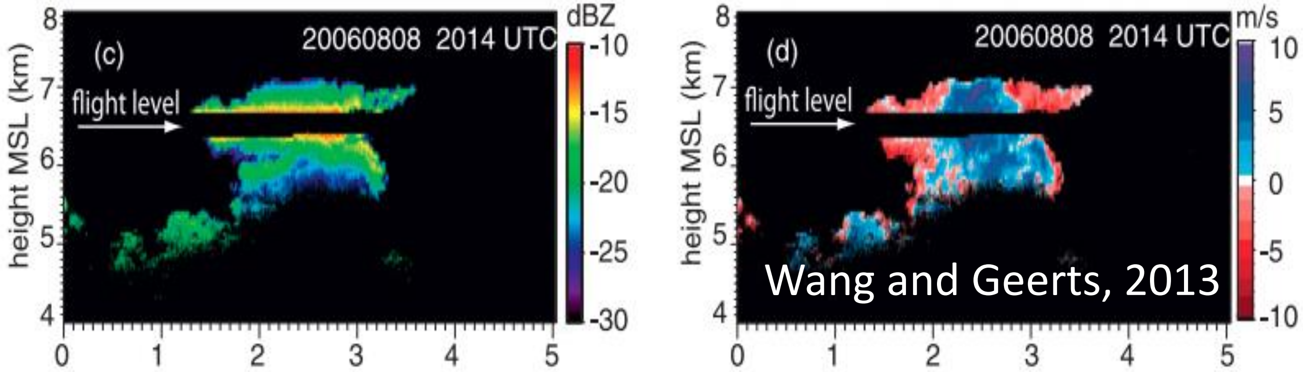
Kollias et al., 2001

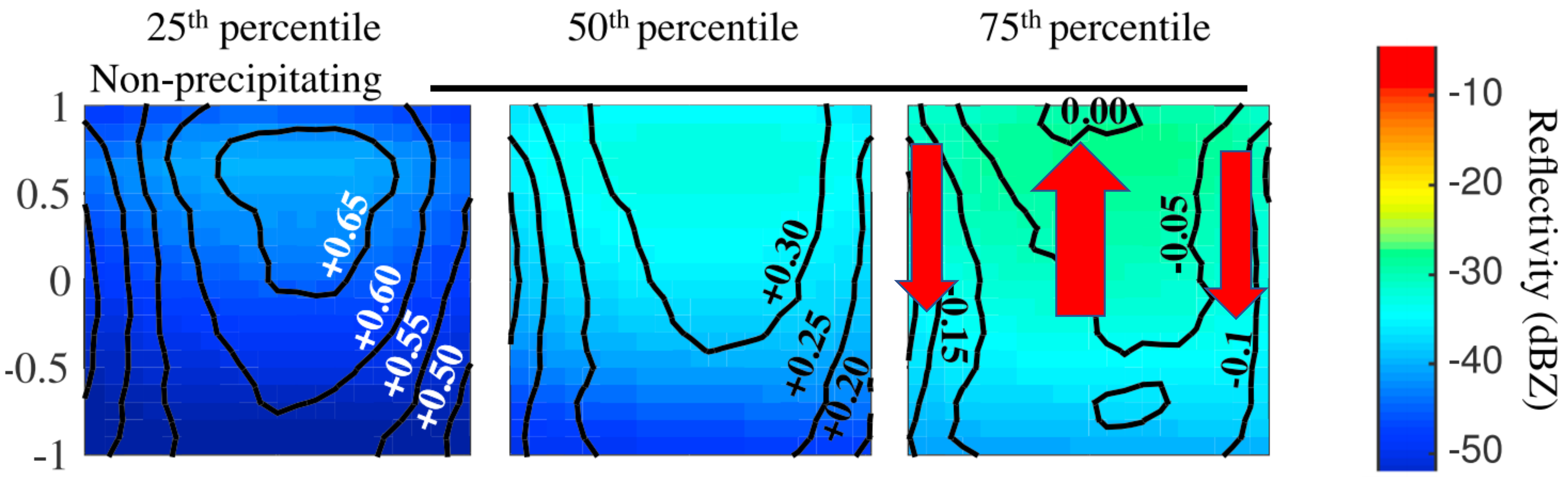
Airborne observations of cumulus dynamics



WCR Configuration aboard the Wyoming King Air

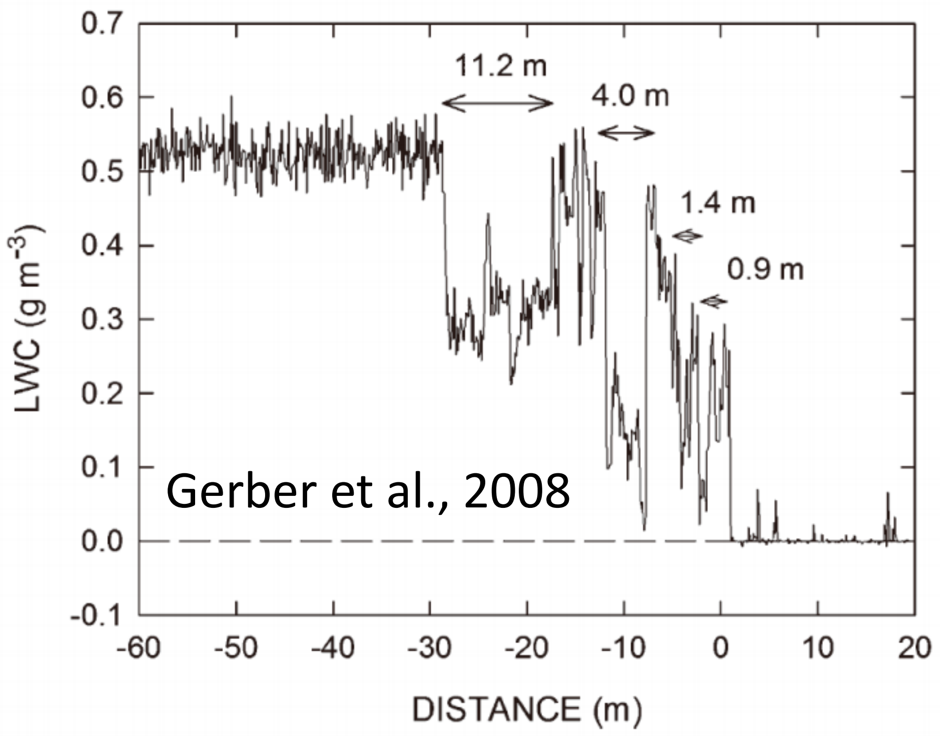






$$\frac{\partial M}{\partial z} = (\varepsilon - \delta)M$$

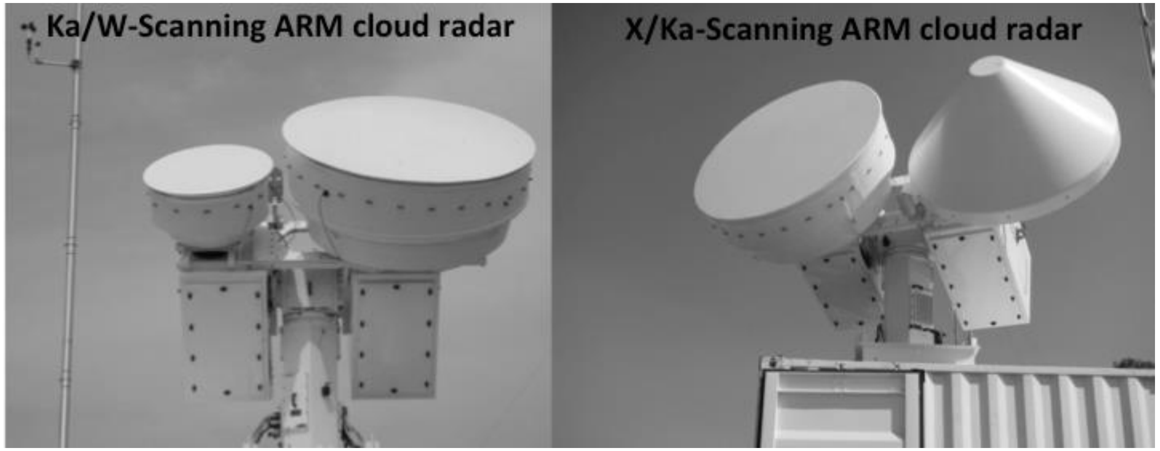
Lamer et al., 2015

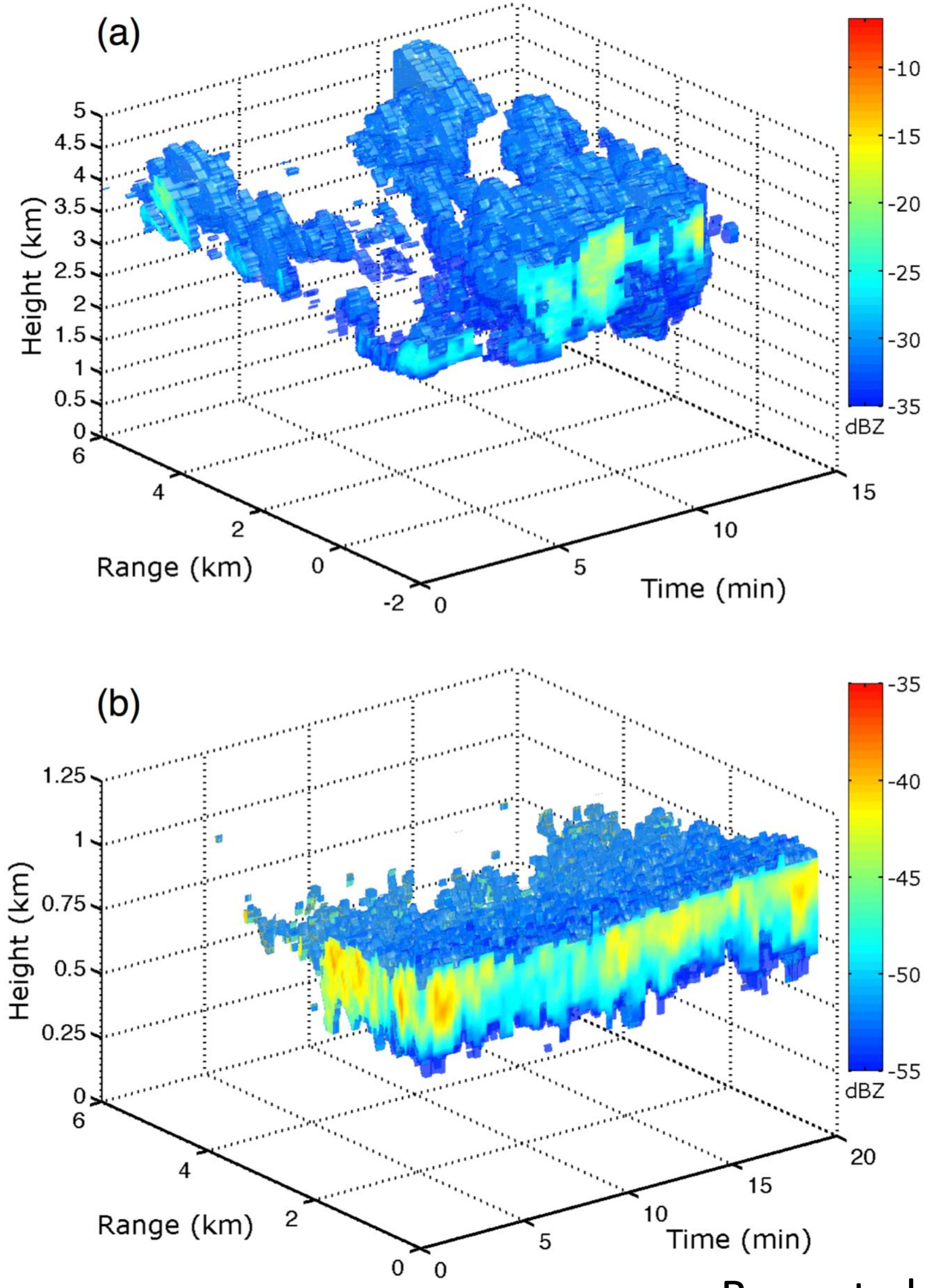


The negative mass flux generated by the subsiding shell is significant. This suggests an important role for lateral mixing throughout the entire cloud layer.

Small scale at boundaries - what is the mechanism for air exchange across boundaries?

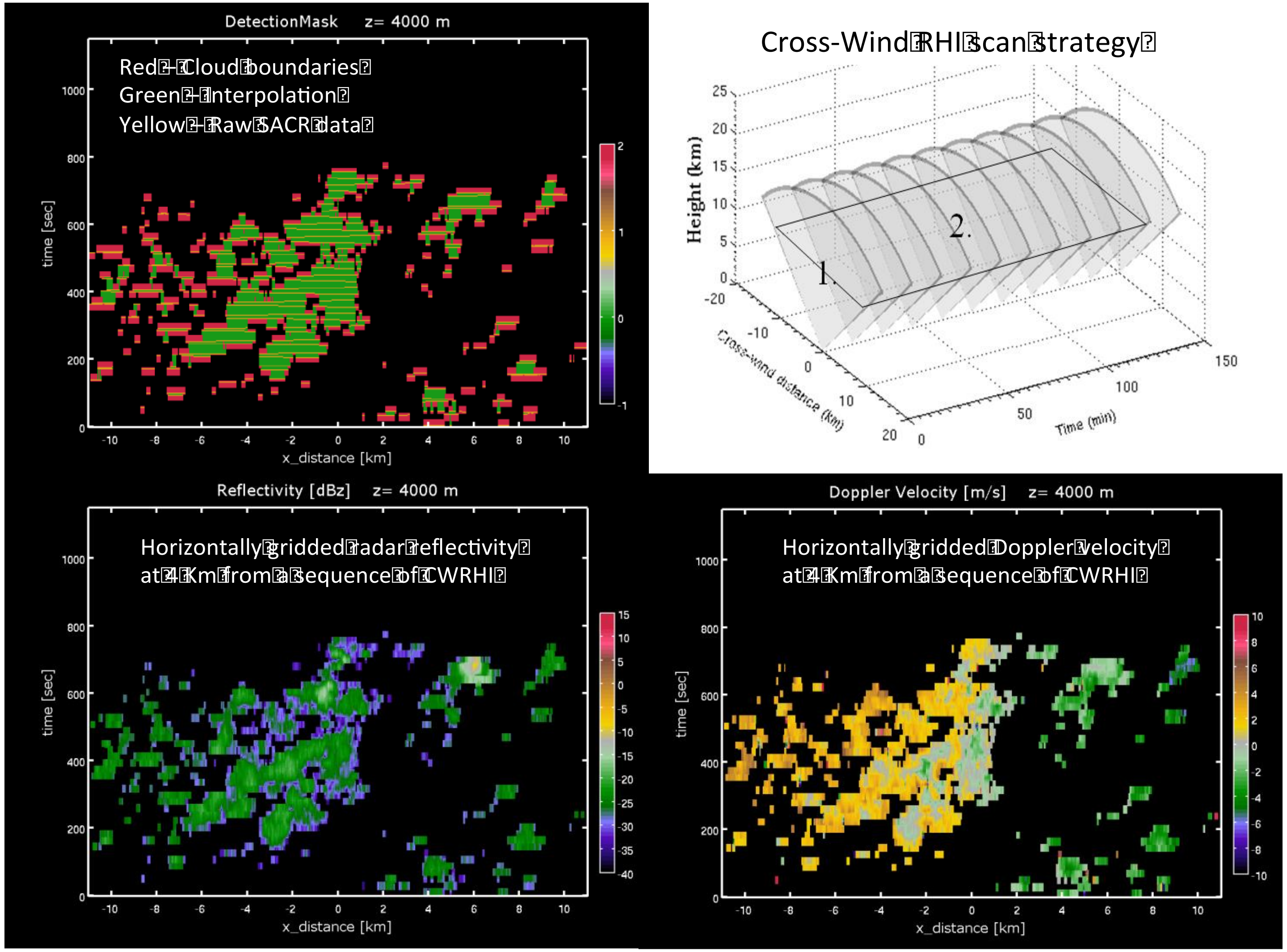
3-D observations of the kinematical structure in cloud can provide insights on the scales and organization of cloud-scale eddies that are responsible for the turbulent transport of condensate, vapor and heat within the cloud and its interaction with the environmental air





Berg et al., 2016

Example of gridded SACR observations from a CW-RHI scan strategy (top right) during the AMF1 deployment at TCAP. The top left panel shows the source of the observations (raw SACR data, interpolated, cloud boundaries) at a fixed height (4 km) and +/-10 km range from the radar and for a sequence of CW-RHI scans.



Science Frontier: Small-scale, entrainment and mixing

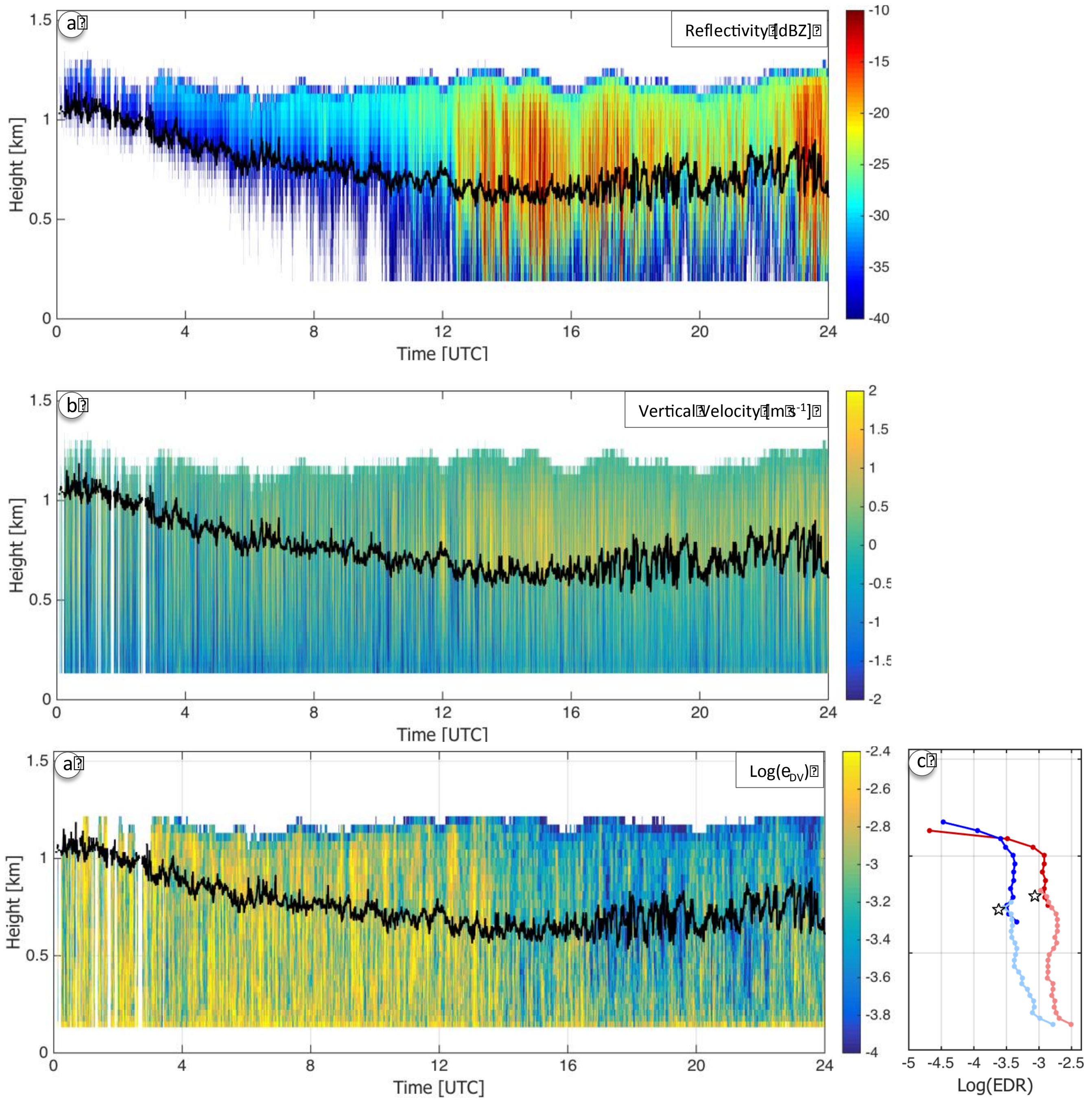
Key measurement requirement(s) (e.g. physical parameter)	Instrument requirement(s)	Challenges (technological, cost, resolution, coverage
Structure, depth, and intensity of cloud-scale and small scale eddies near cloud boundaries Vertical mass fluxes, water content and thermodynamic properties across the clear/cloudy interface Cloud microphysics (number concentration and particle size distribution)	Airborne Doppler cloud radar Vertically pointing Doppler cloud and precipitation radars (X band, W band, K band) Measurement of cloud water and ice particle types and concentrations plus hydrometeors	Need higher radar sampling (2-5 m). Airborne radars cannot provide enough time resolution. Lagrangian studies of cloud lifetime Need coordination between airborne and ground-based facilities.

Unified turbulence retrievals in cloudy boundary layers using Doppler radar and Doppler lidar (Borque et al., 2016)

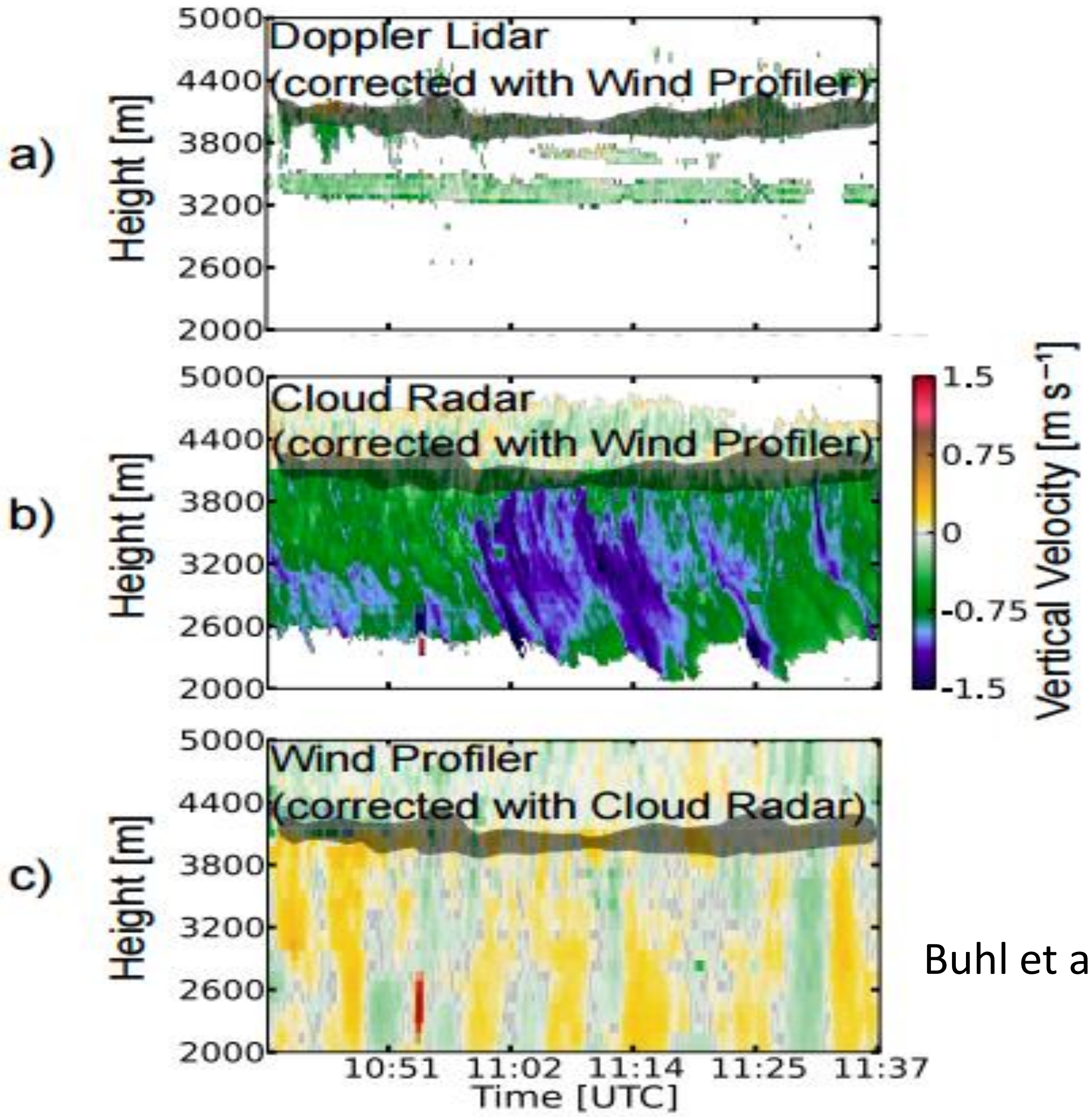
- Influence of precipitation negligible
- Temporal resolution 1-2 sec
- Vertical resolution 20-30 m

- Decomposition of radar Doppler spectrum width to microphysical and dynamical components

Borque et al., 2016

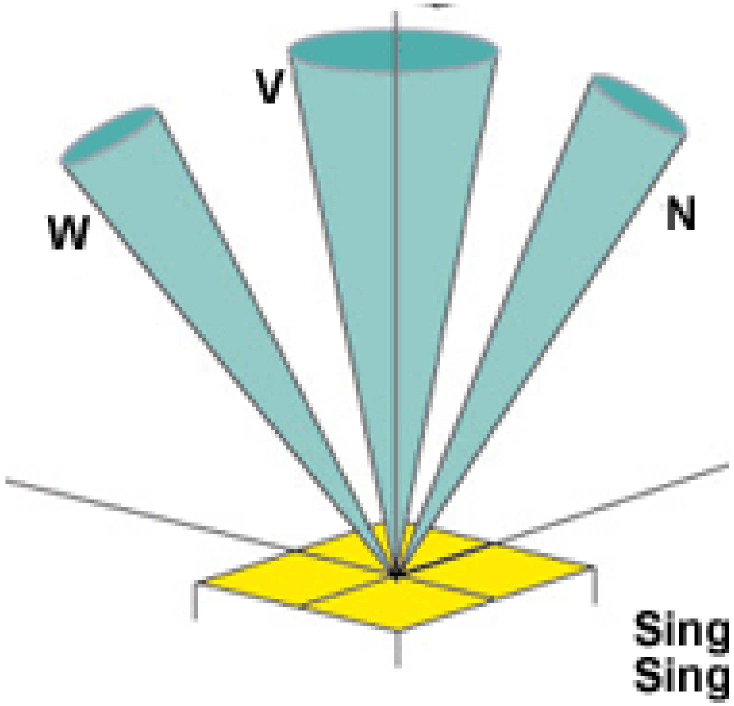


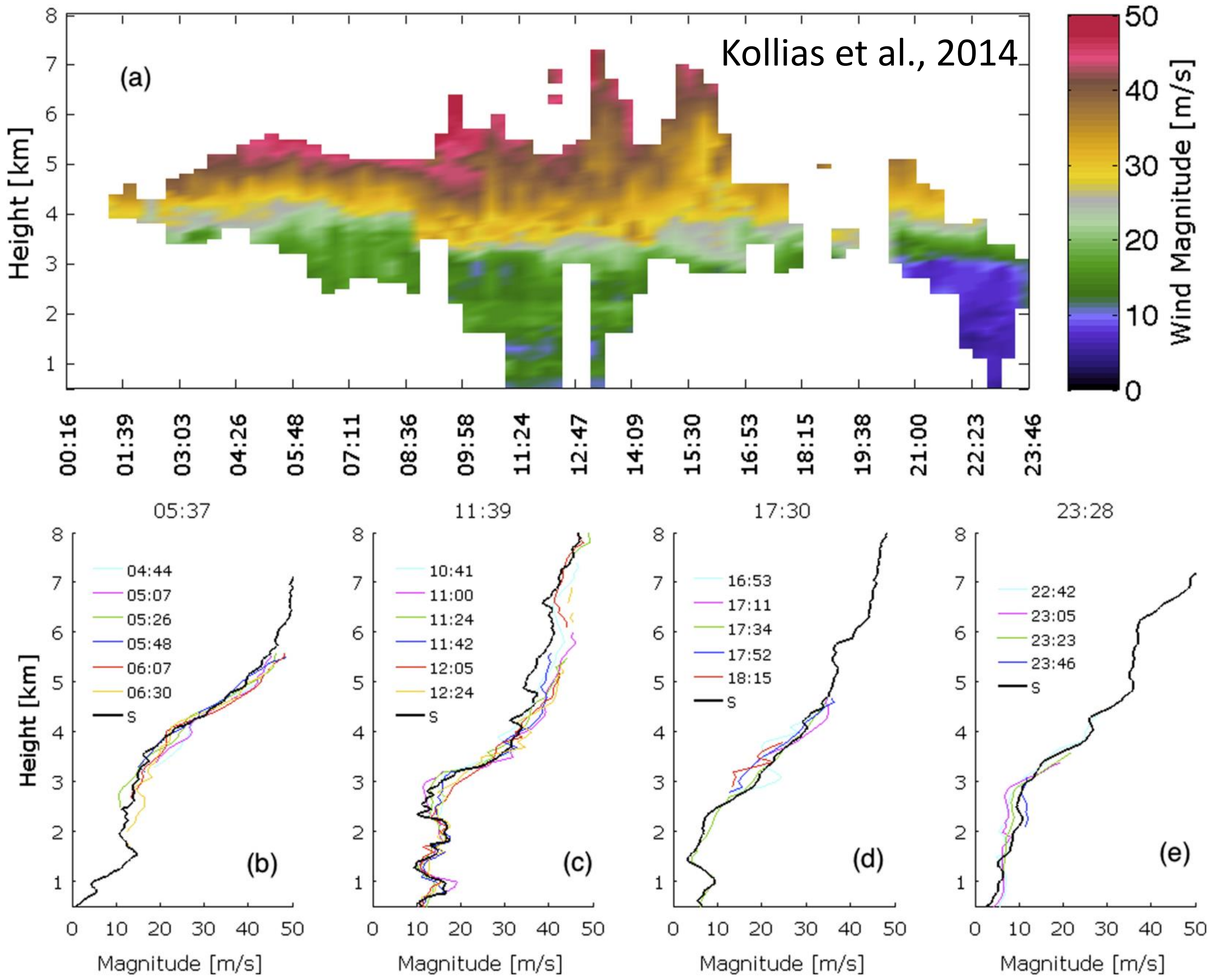
Multi-frequency, multi-sensor ground-based facilities have the potential to provide unified, high temporal and spatial resolution vertical velocity measurements using a combination of scattering mechanisms



Buhl et al., 2015

In-cloud horizontal wind profiling





Science Frontier: Impact of in-cloud turbulence to warm clouds macroscopic structure and precipitation processes

Key measurement requirement(s) (e.g. physical parameter)	**Instrument requirement(s)**	**Challenges (technological, cost, resolution, coverage**
Cloud-scale measurements of vertical air motion, eddy dissipation rate Cloud liquid water content, precipitation rate, particle size Subcloud layer turbulence measurements	Profiling cloud radar, Doppler lidar, ceilometer microwave radiometer Aircraft observations of cloud microphysics and dynamics Radiosondes	In warm clouds, remote sensing can provide high quality turbulence and microphysics. High frequency thermodynamical measurements are desirable. Aircraft observations of number concentration and aerosols are improtant

Summary

The study of turbulence in cloud systems and its role in their macroscopic and microphysical properties requires the use of the following sensors/technologies:

- Doppler cloud radars (airborne/ground-based)
- Backscatter, Doppler and Raman lidars,
- Microwaver radiometers, radiosondes
- Aircraft microphysical and turbulence measurements

Challenges:

- Improve our ability to sample the cloudy-clear air interface
- Integrate RPAS and slower (helicopter) moving platforms with ground-based observations
- Move from 1-D to 3-D cloud turbulence measurements
- Measure aerosol properties from the surface to the cloud layer
- Develop forward operators to link Doppler measurements to model dynamics