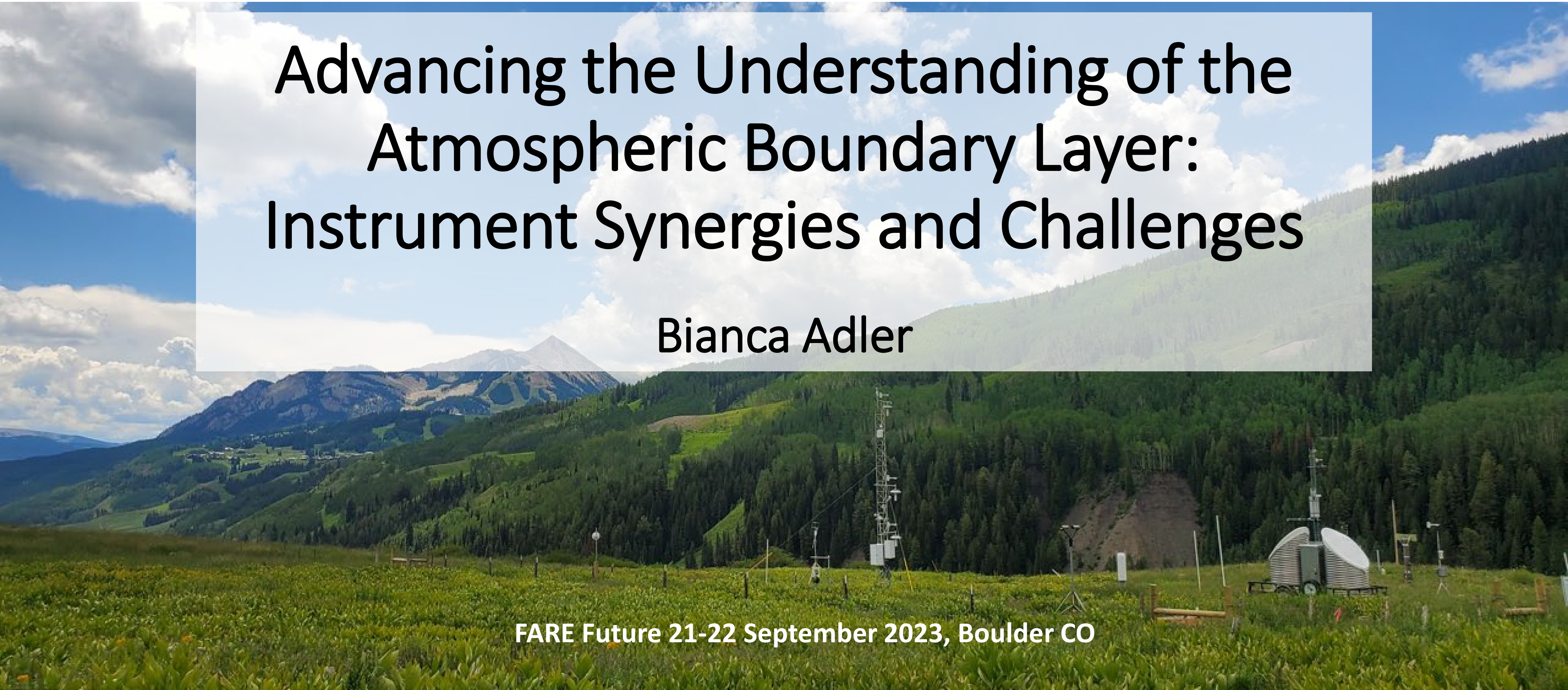
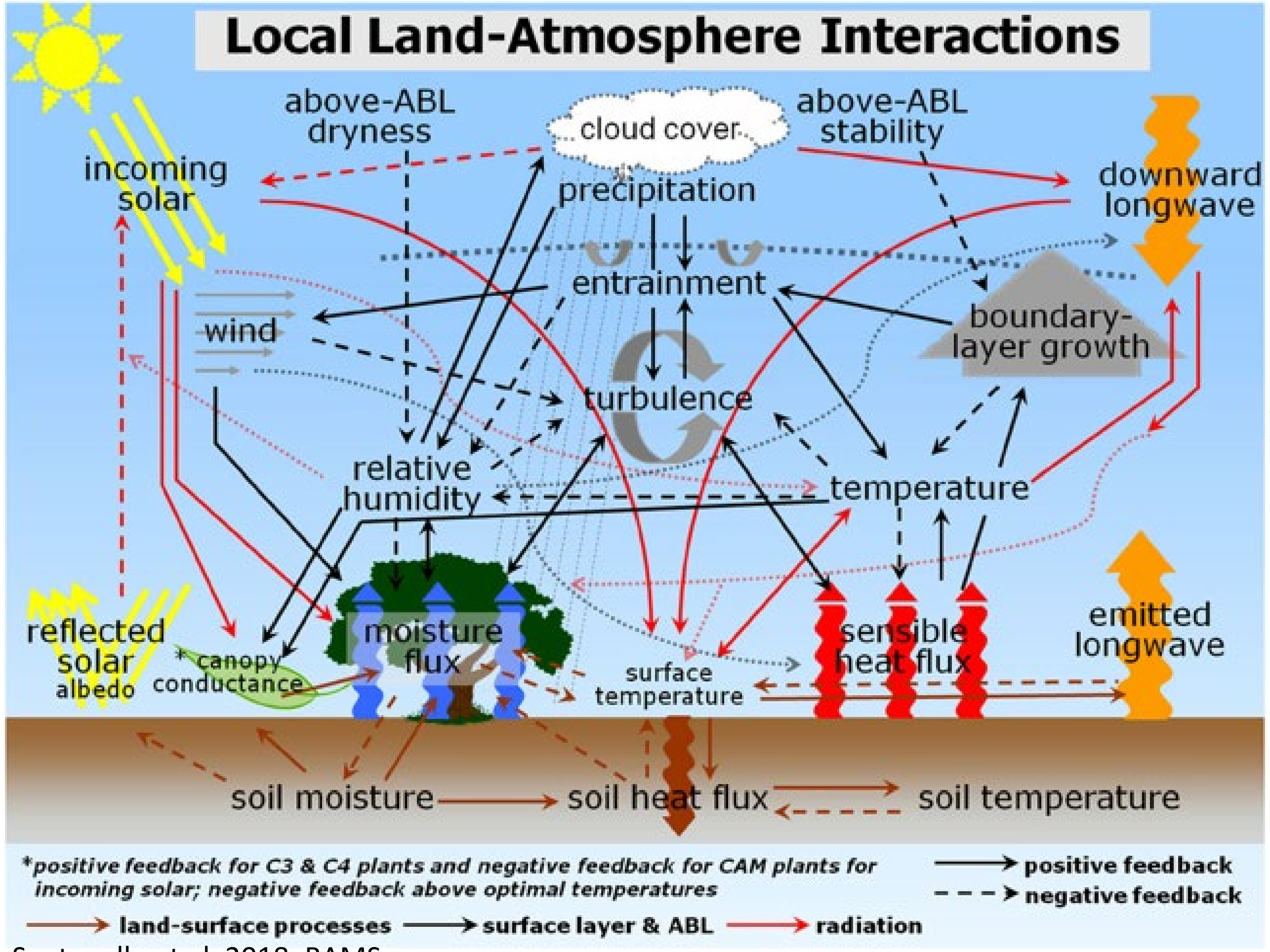
Advancing the Understanding of the Atmospheric Boundary Layer: Instrument Synergies and Challenges

Bianca Adler



FARE Future 21-22 September 2023, Boulder CO

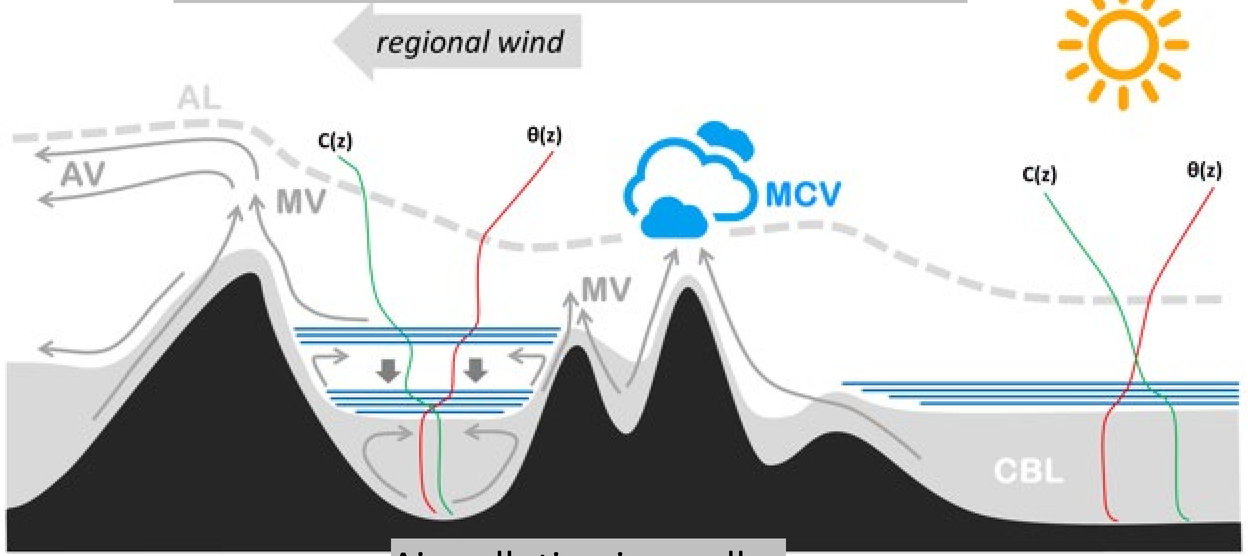
Why is the boundary layer important?



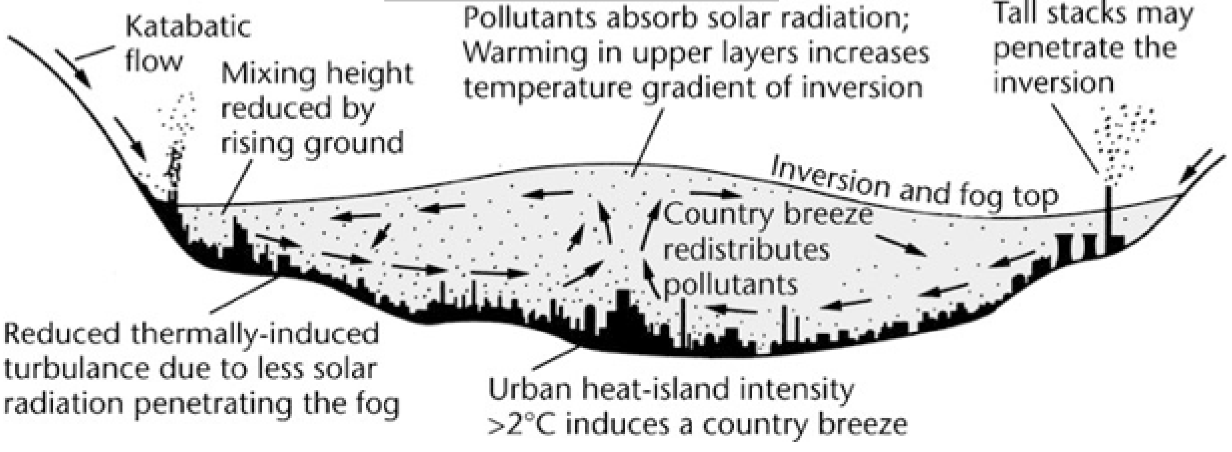
Santanello et al. 2018, BAMS

Serafin et al. 2018, Atmosphere

Exchange processes over mountainous terrain

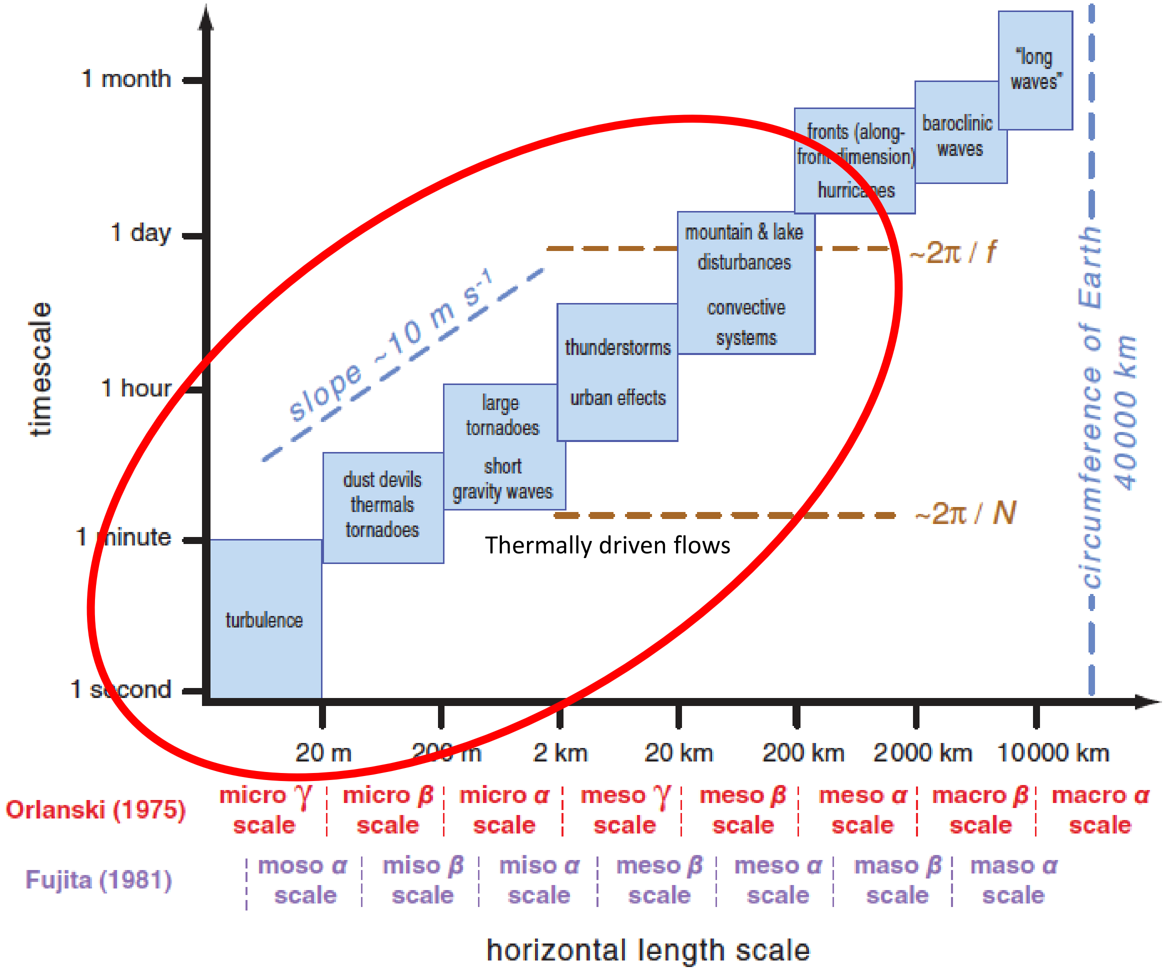


Air pollution in a valley

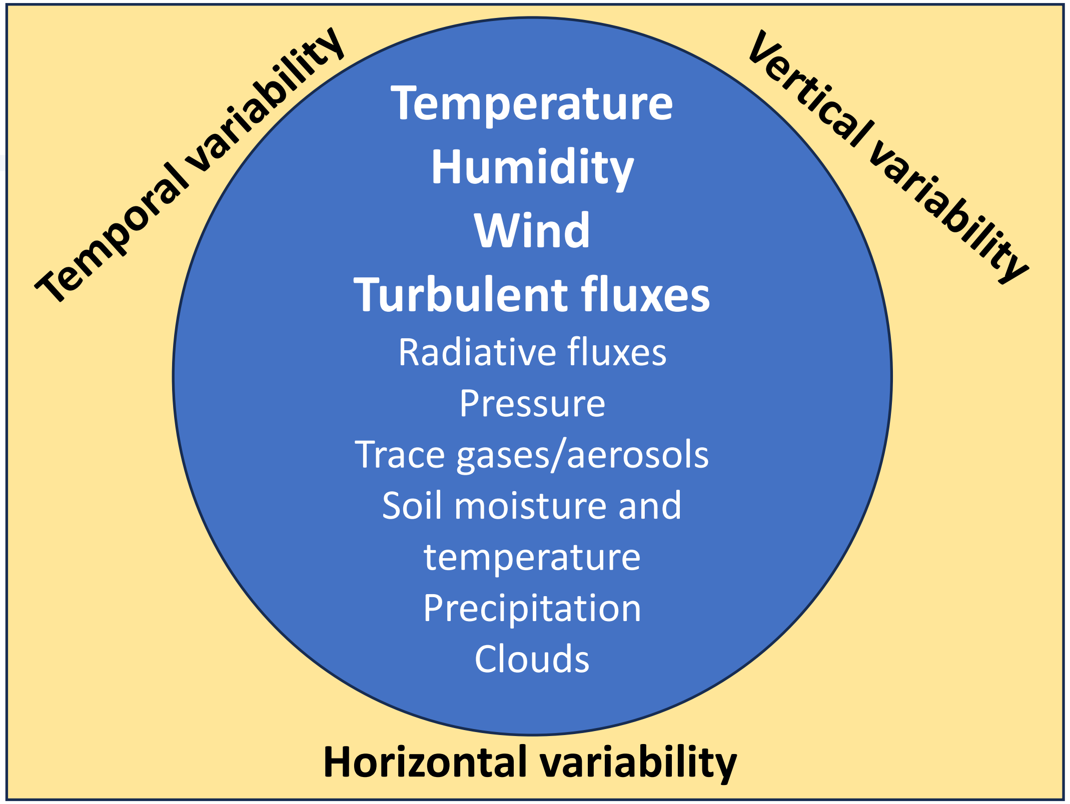


Steyn et al. 2013, Springer Atmospheric Sciences

What do we need to observe?



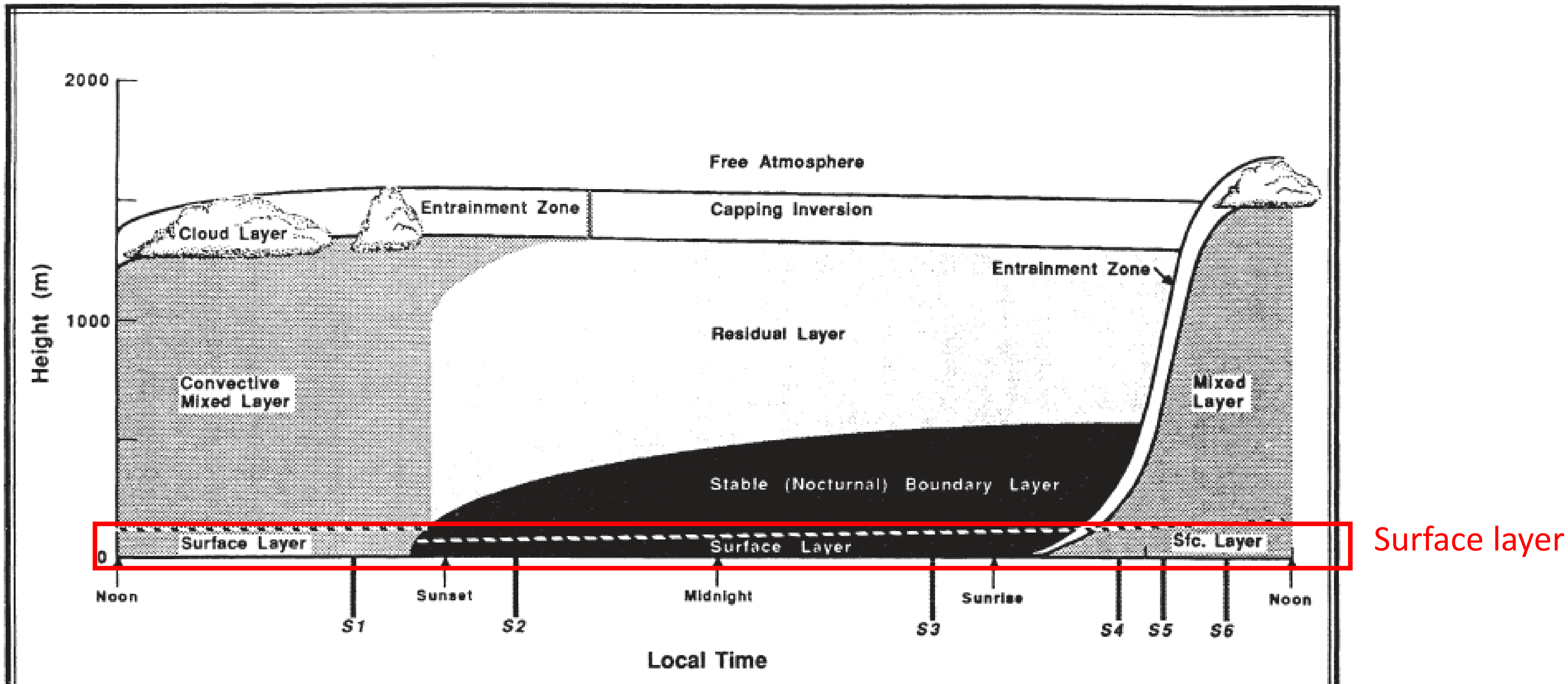
Markowski and Richardson, 2010. Mesoscale Meteorology.



Applications:

- process understanding
- NWP model evaluation
- parameterization development
- data assimilation
- air quality forecasting
- climate assessment

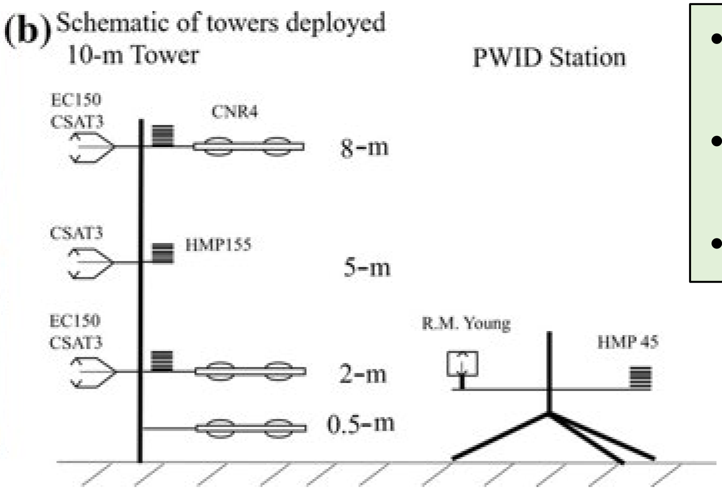
The atmospheric boundary layer



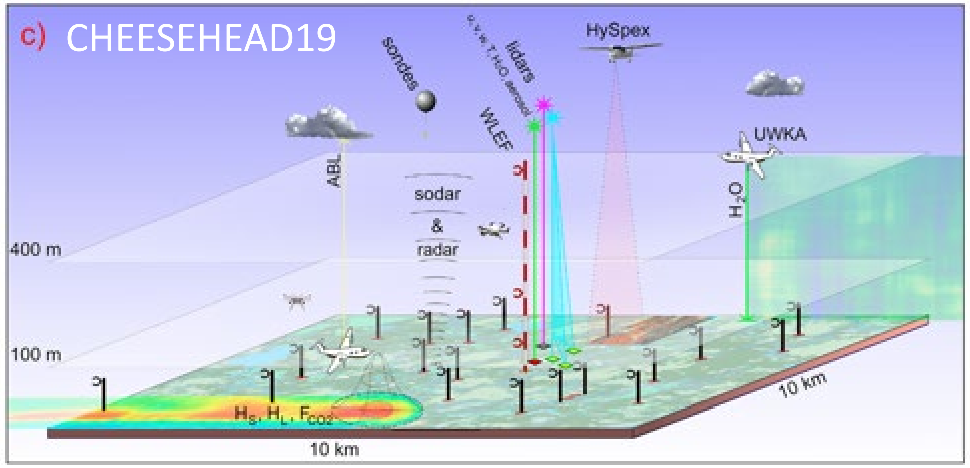
Stull 1988, Boundary Layer Meteorology

Tall towers and tower arrays

Morrison et al. 2021,



- High quality flux measurements
- Well established processing technique
- Reliable and proven



Butterworth et al. 2021, BAMS

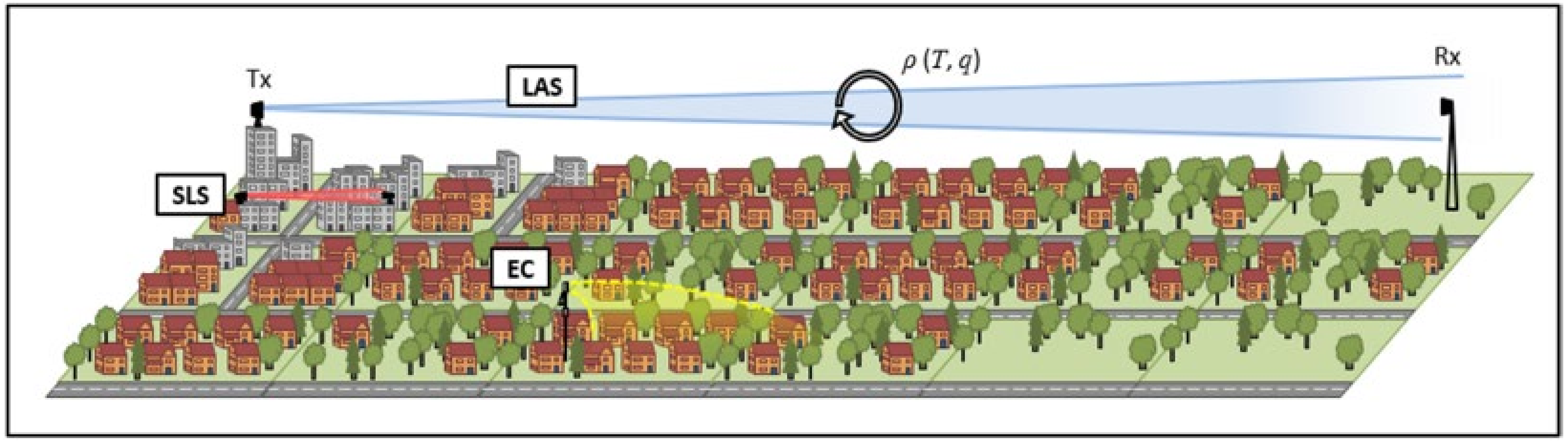
Some challenges:

- Surface energy balance closure
- Representativeness of single-point flux measurements
- Scaling similarity theory over heterogeneous terrain

Wolfe and Lataitis 2018, BAMS

Scintillometers for spatially averaged surface heat fluxes

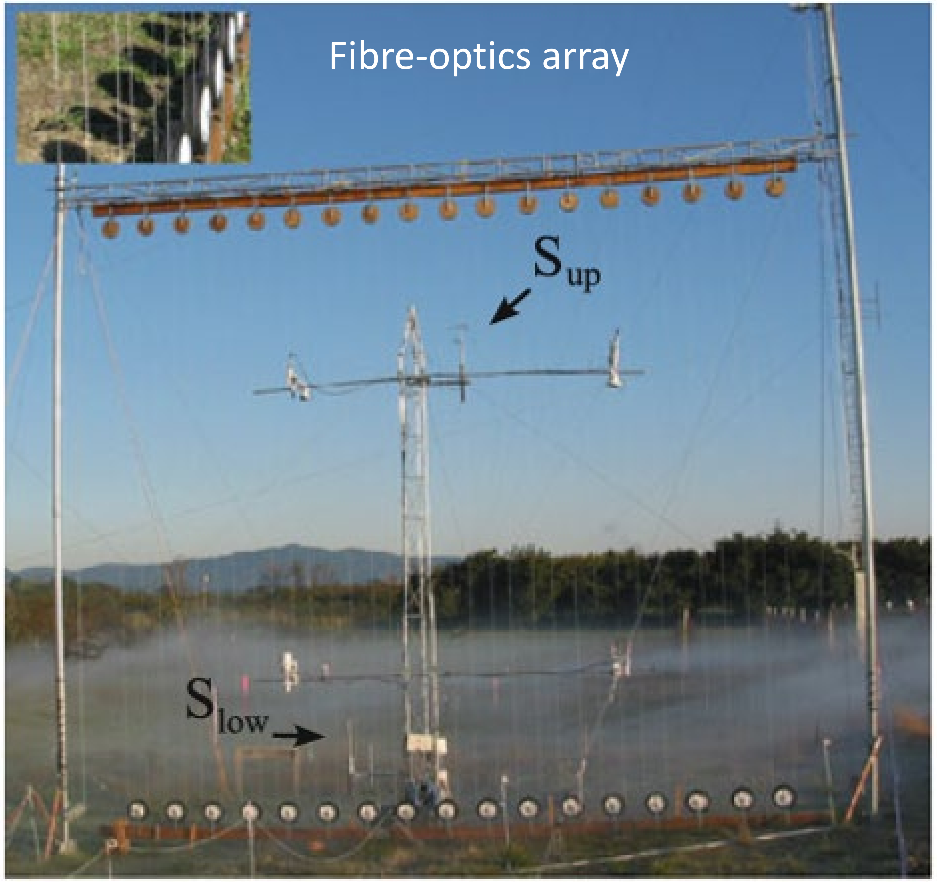
- Area-averaged fluxes
- Comparable to model grid box
- Inaccessible areas above cities and across valleys



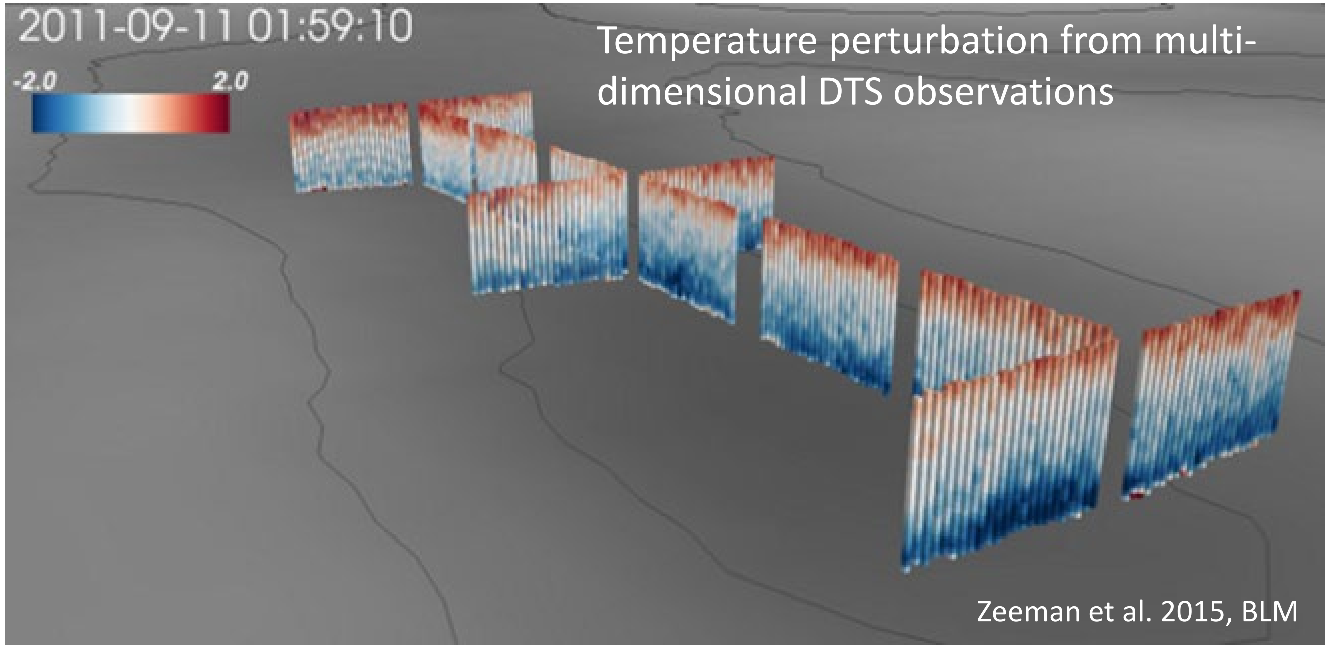
Ward 2017, Meas. Sci. Technol.

Some challenges:
- Assumptions for processing
- Requires Monin-Obukhov similarity theory to retrieve fluxes
- Interpretation over complex environments

Distributed temperature sensing (DTS)



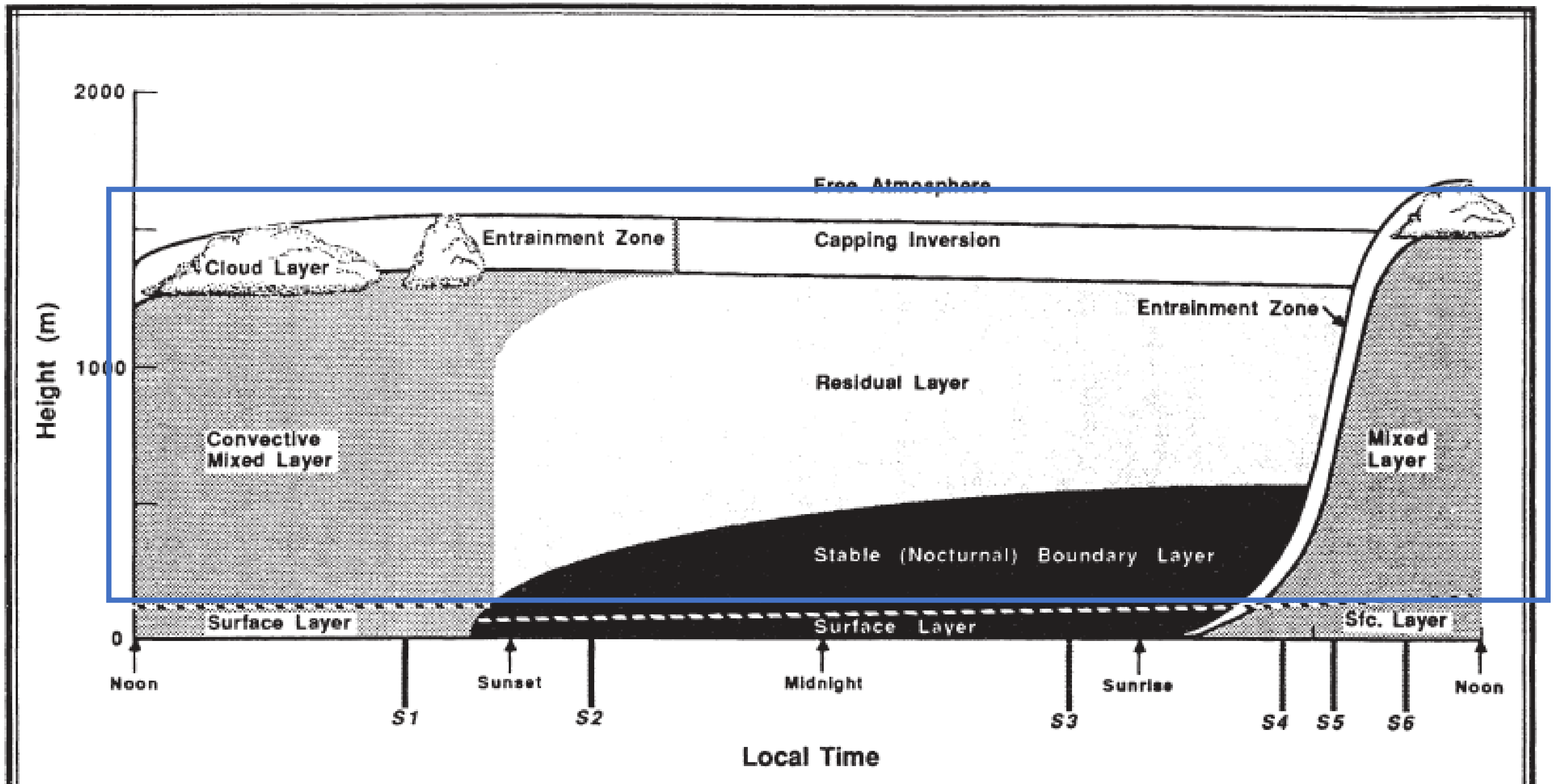
Thomas et al. 2012, BLM



- Dense spatial information on temperature variability in 3 dimensions
- Intermittent turbulence and non-stationary conditions

Some challenges:
- Non-trivial installation
- Horizontal and vertical coverage limited

The atmospheric boundary layer



Stull 1988, Boundary Layer Meteorology

Above the surface layer

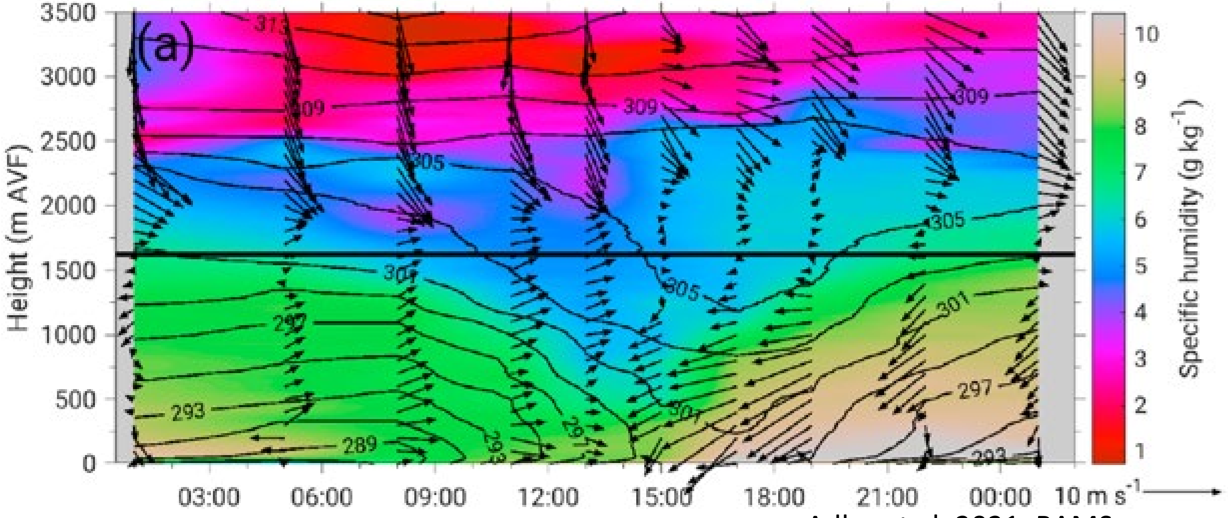
In situ profile measurements

Radiosonde

Tethersonde

- 'gold standard'
- Profiles throughout the troposphere with high vertical resolution
- Penetrate through clouds

Boundary layer evolution in an Alpine valley



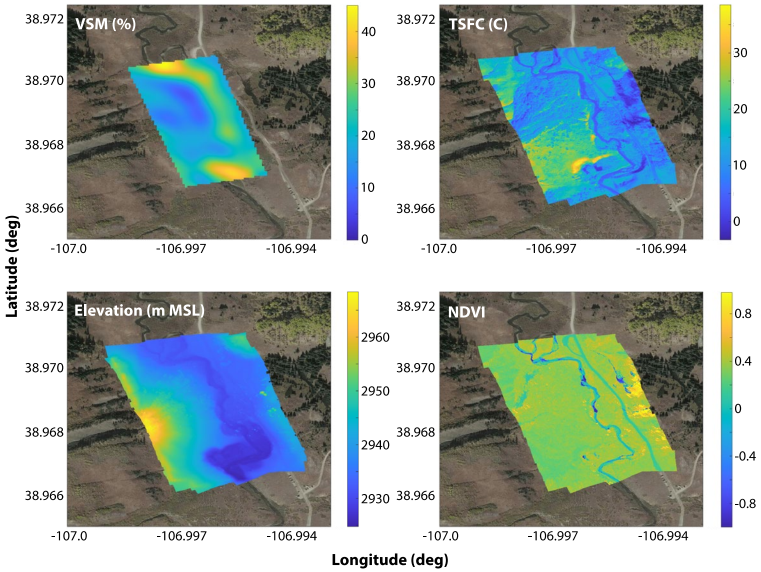
Adler et al. 2021, BAMS

Some challenges:
- Snapshot only
- Labor intensive (unless automatic launchers)
- Helium shortage !

UAS for boundary layer profiling and surface characterization

de Boer et al., 2022 ESSD

University of Colorado RAAVEN UAS

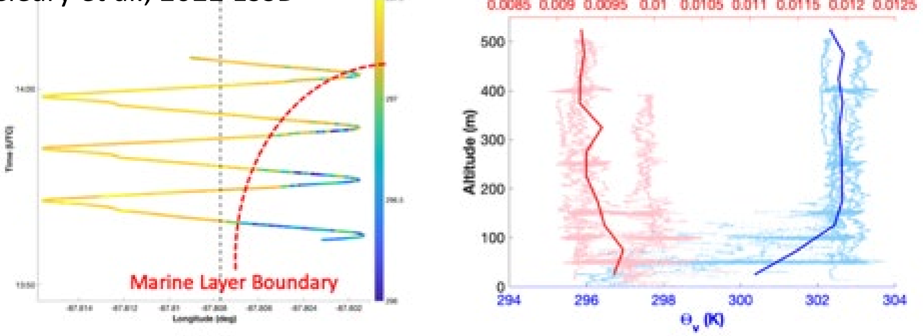


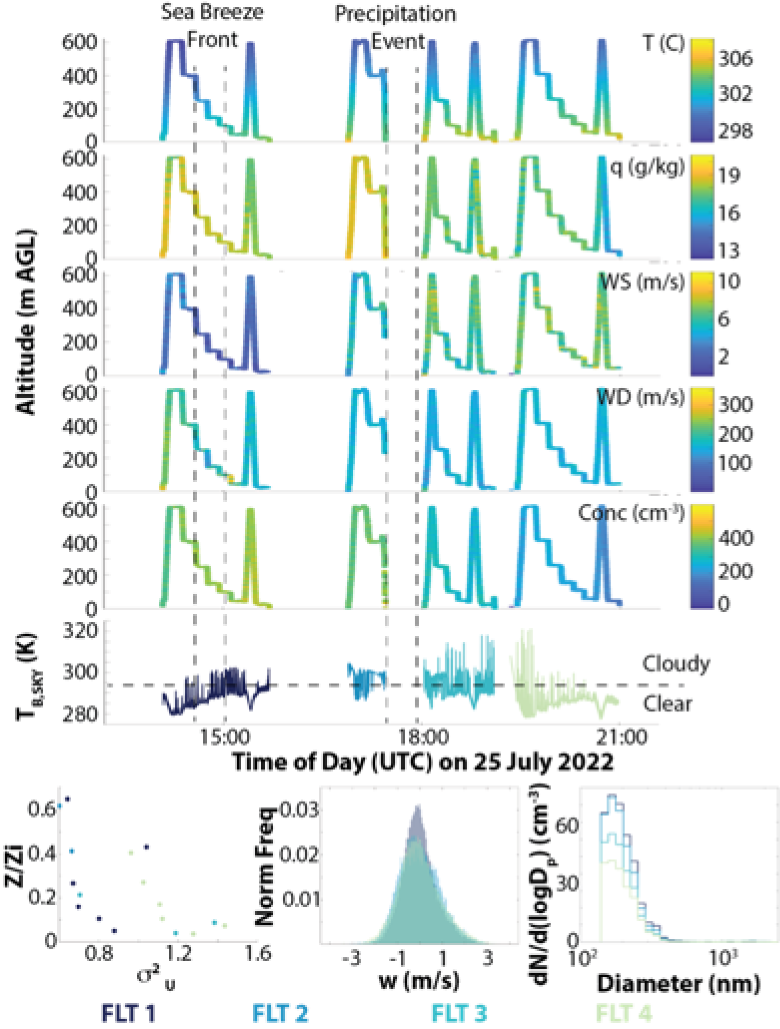
- Very high temporal and spatial resolution
- Ability to collect in-situ observations, (e.g., aerosol concentrations, turbulent fluxes)
- Highly mobile for targeting features of interest
- Can be operated over a variety of surface types and boundaries (e.g., ocean, coastal, forested, dangerous)

Some challenges:

- Flight permissions can be challenging
- More challenging to operate
- Requires multi-person crew ($)
- Limited instrument payload

Cleary et al., 2022 ESSD





Ground-based remote sensing of wind profiles

Pulsed and continuous wave Doppler lidars

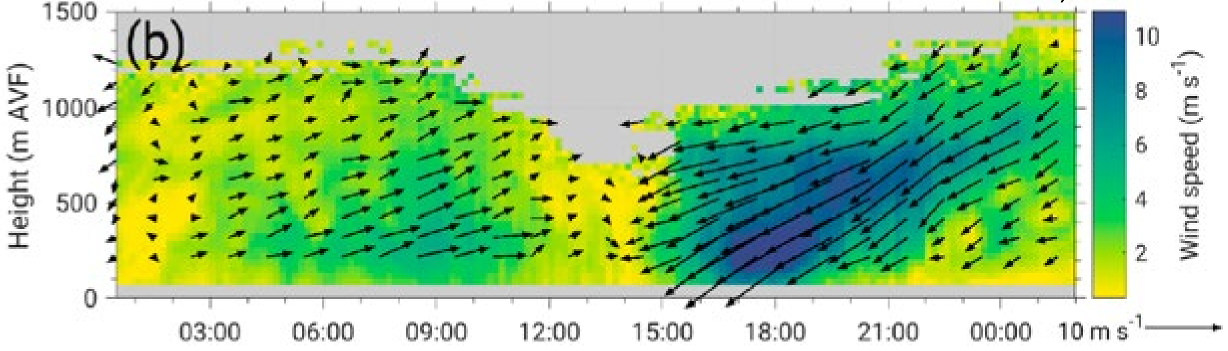
Adler et al. 2021, BAMS

- high temporal and vertical resolution
- continuous and reliable automated operation

Some challenges:
- Limited vertical range
- Cannot penetrate clouds (lidar)
- Relatively high first range gate
- Assumption of horizontal homogeneity for VAD

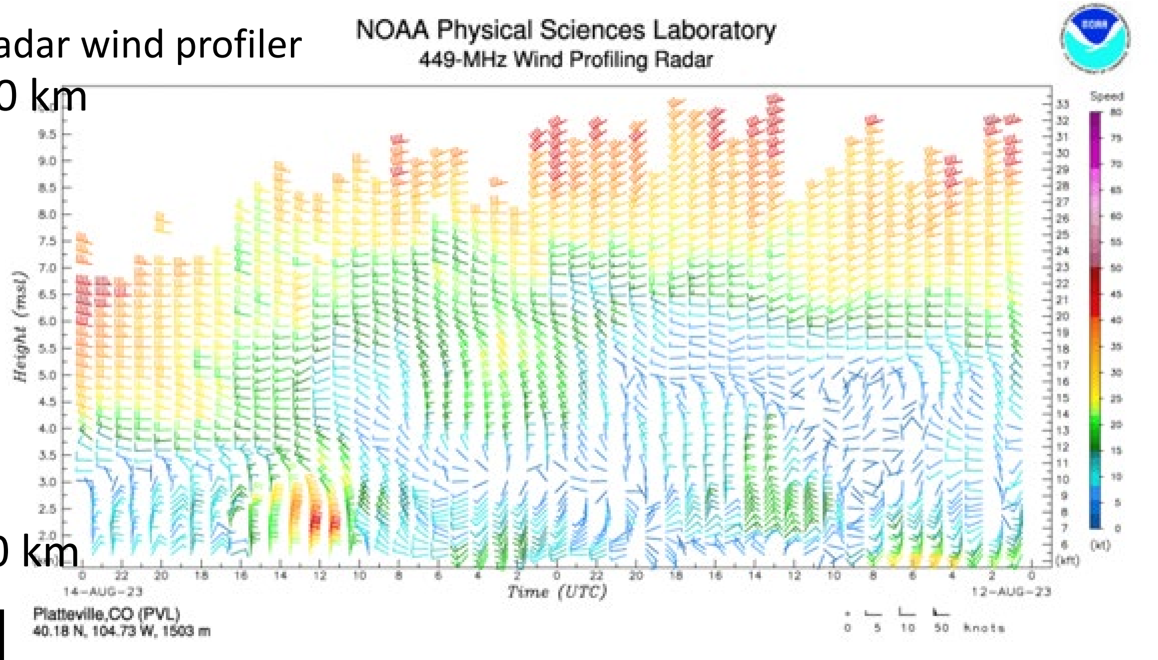
Doppler lidar

Adler et al. 2021, BAMS



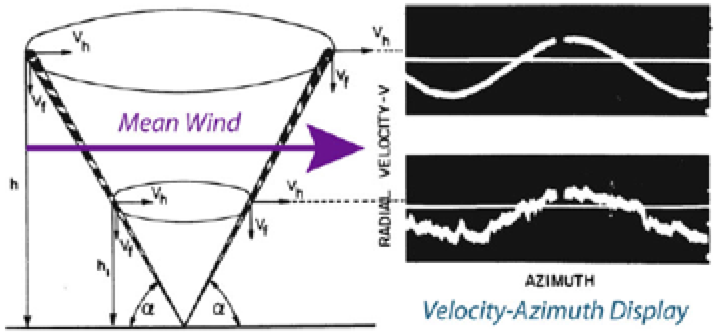
Radar wind profiler

10 km



0 km

Radar wind profiler with RASS



Wilson and Miller 1972

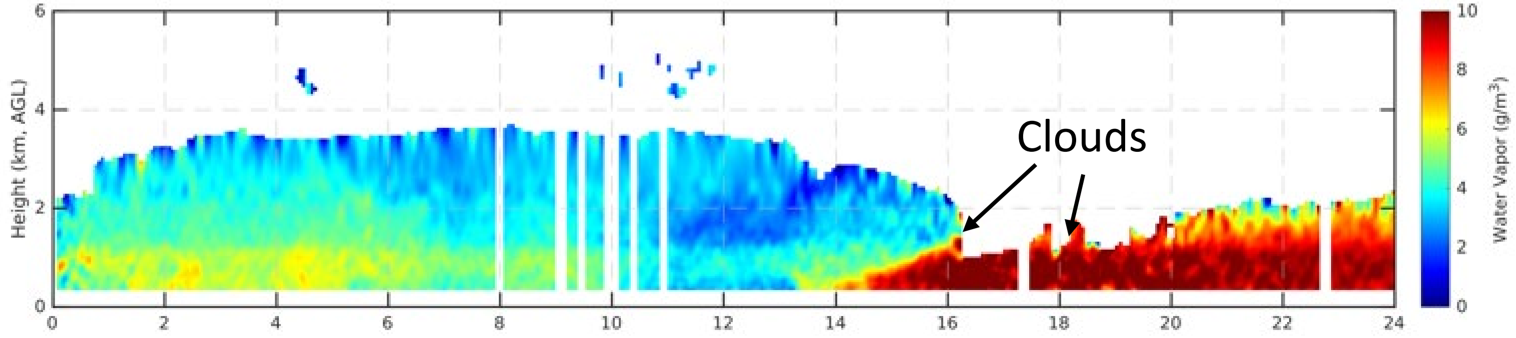
Ground-based thermodynamic profiling – active sensors

- high temporal and vertical resolution
- Water vapor and temperature profiles in the boundary layer

Some challenges:

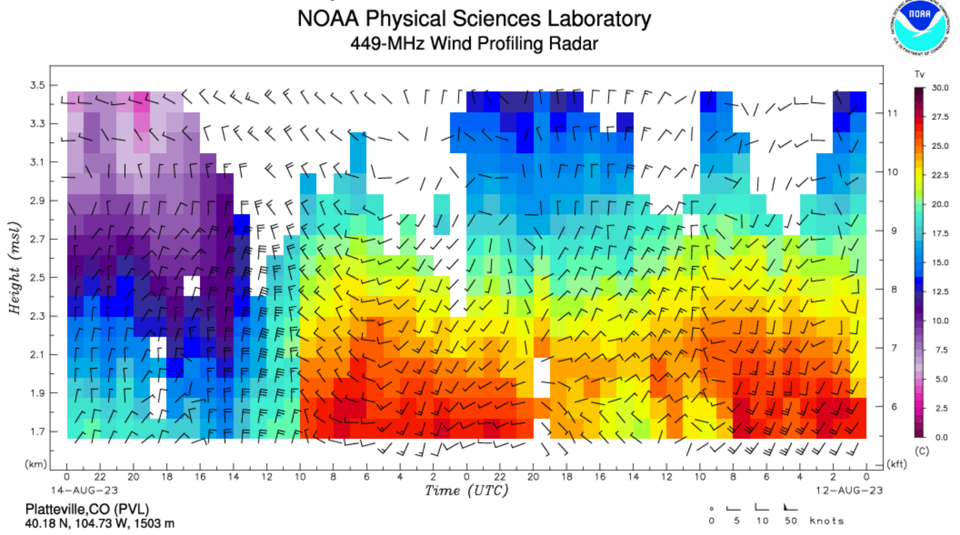
- Limited vertical range
- Cannot penetrate clouds (lidar)
- Site selection (RASS)

Water vapor mixing ratio from Micro Pulse Differential Absorption Lidar (MPD)

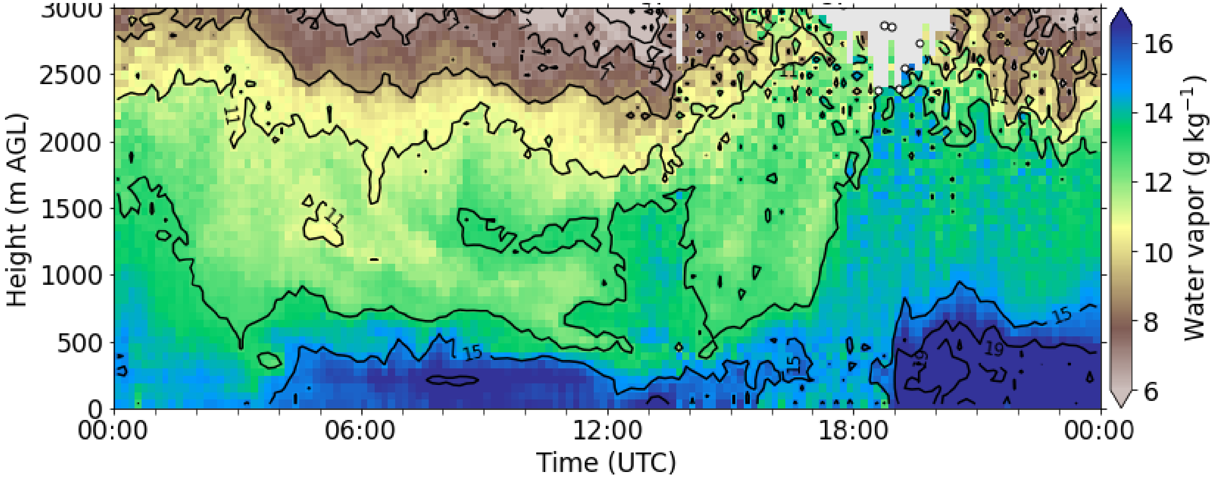


http://catalog.eol.ucar.edu/operations/lidar/

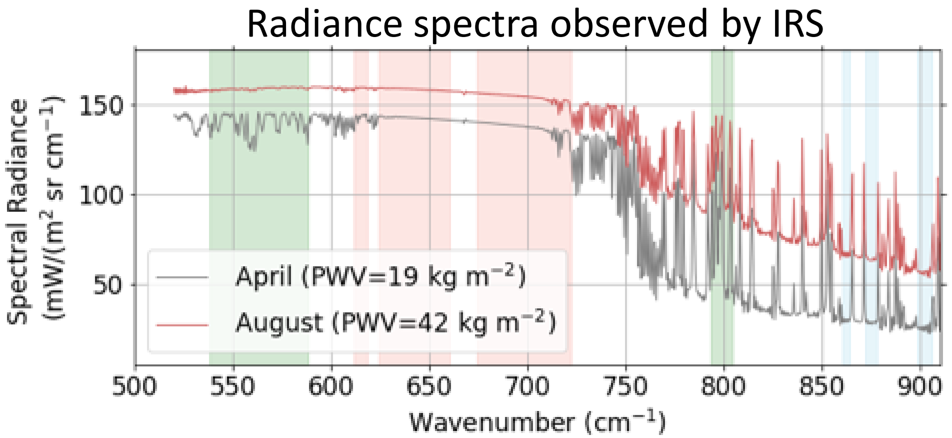
RASS temperature measurements

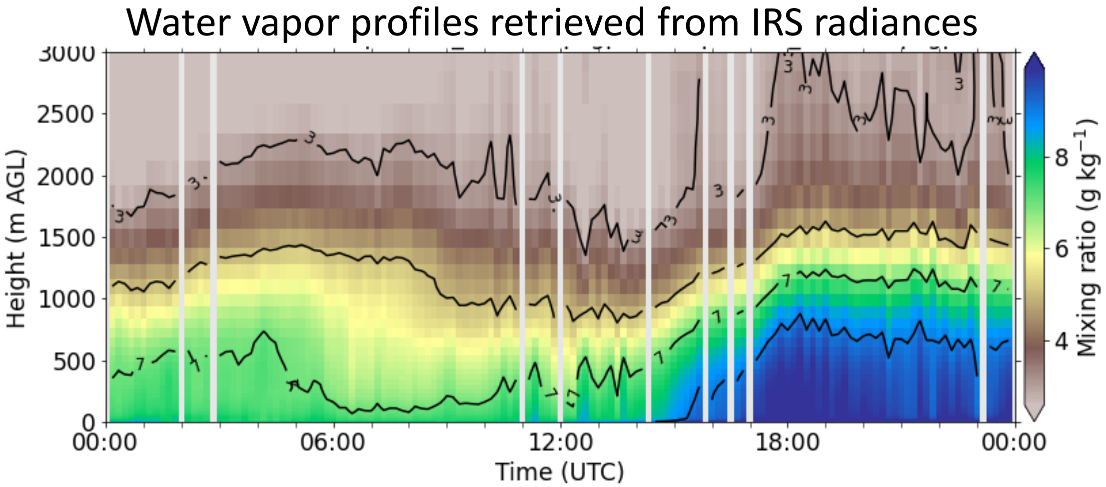


Water vapor mixing ratio from Raman lidar at SGP



Ground-based thermodynamic profiling – passive sensors

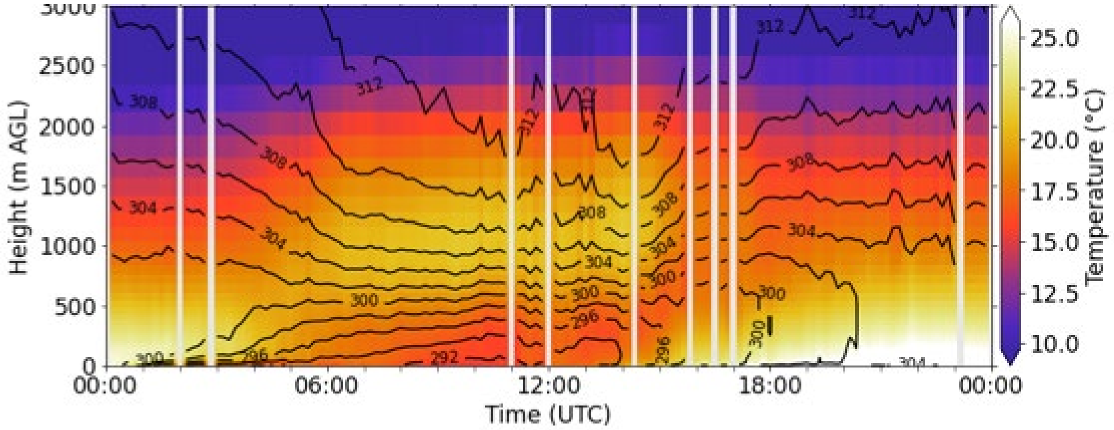




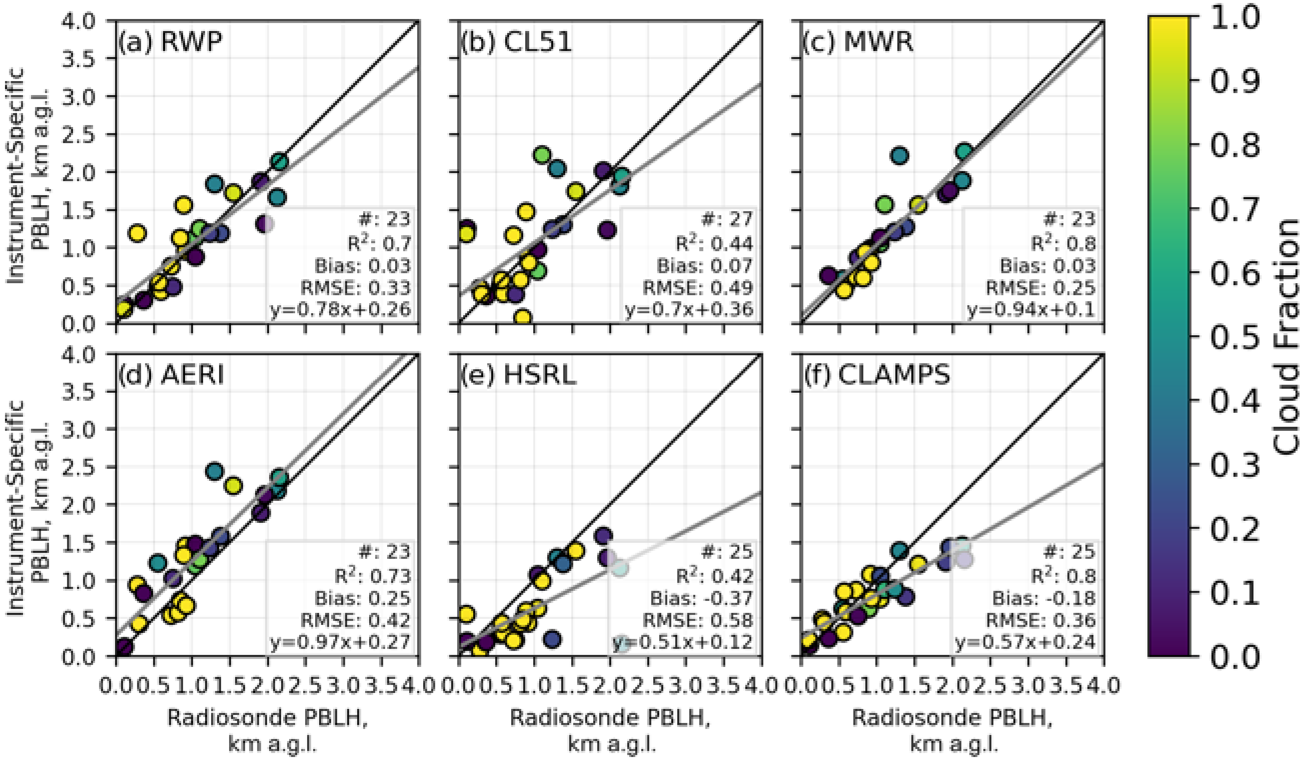
- High temporal resolution
- Can penetrate clouds (MWR)
- Continuous and reliable automated operation

Some challenges:

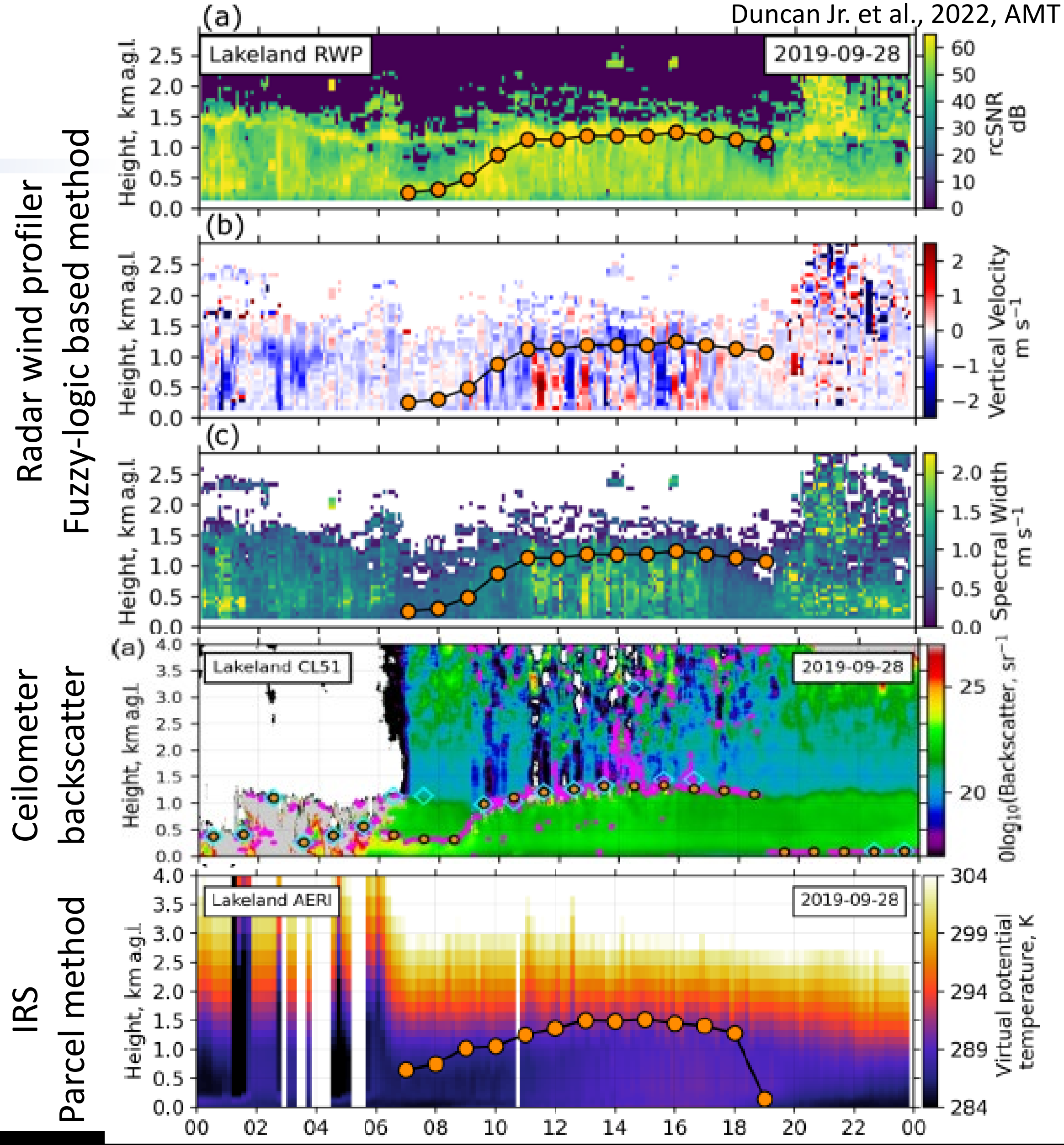
- Limited vertical resolution
- Limited measurements during precipitation
- Calibration sensitive (MWR)
- Retrievals



Boundary layer height detection



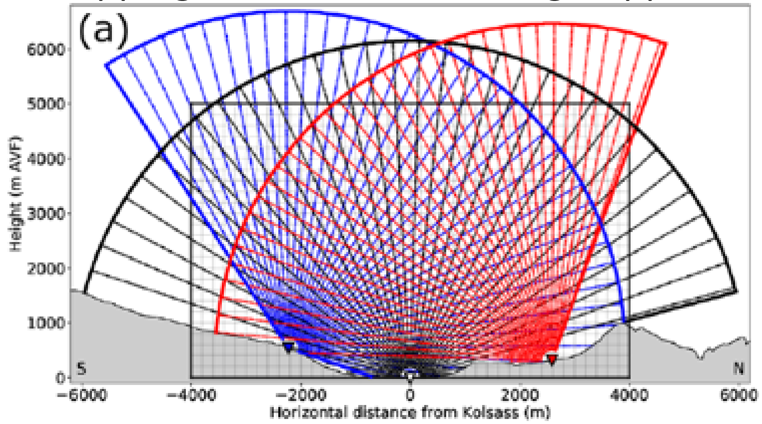
Duncan Jr. et al., 2022, AMT



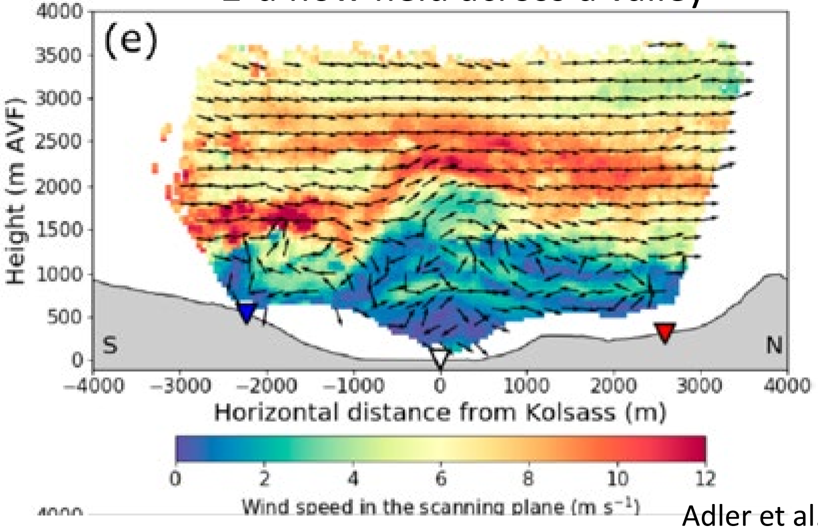
- Overall good agreement between sensors and methods
- Weaknesses under certain conditions (e.g. clouds, very deep boundary layer heights)

Multi-Doppler lidar retrievals for spatial boundary layer characteristics

Overlapping area from 3 scanning Doppler lidars



2-d flow field across a valley

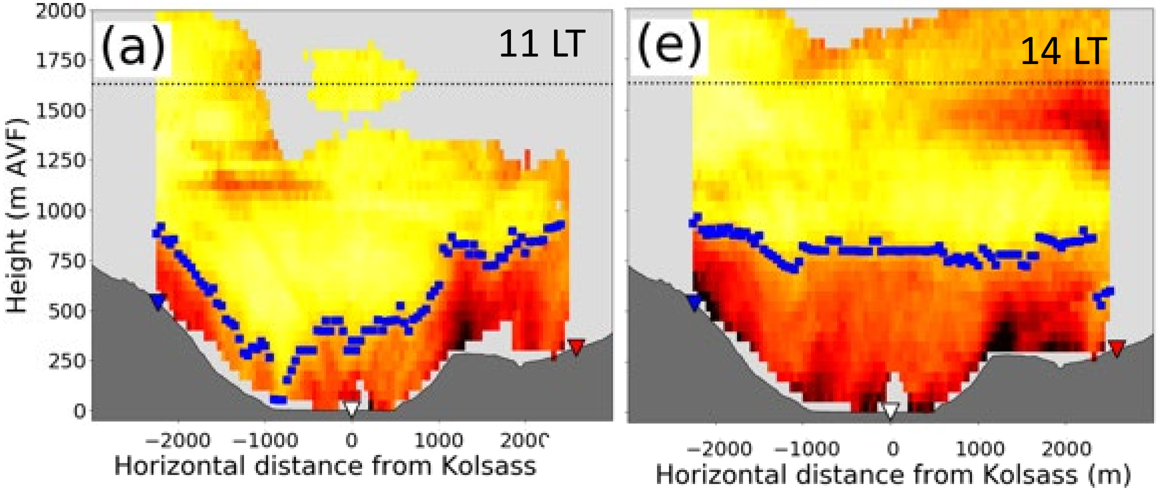


Adler et al. 2021, BAMS

- Spatial information on flow field and boundary layer structure with high temporal resolution

- Precise siting and high degree of synchronization
- Terrain/vegetation blocking
- Measurement range

Boundary layer height across a valley



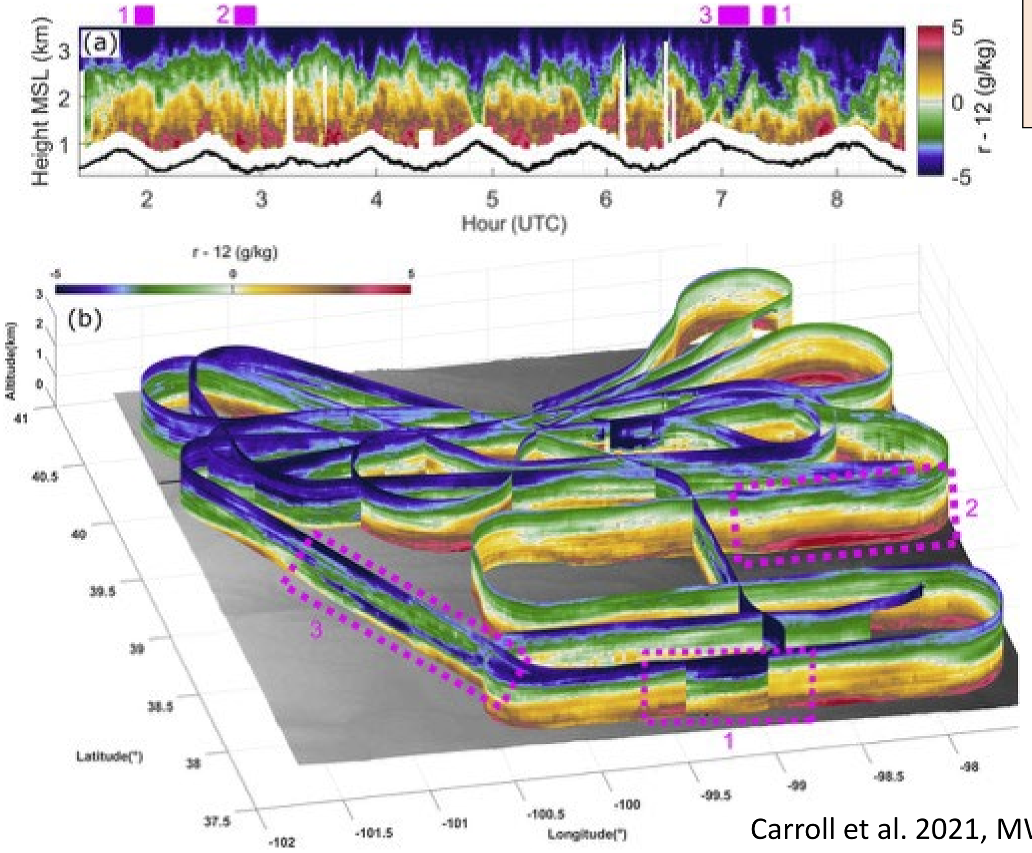
Babić et al. 2023, under review

Airborne and truck mounted remote sensing

- Detailed spatial information on boundary layer conditions

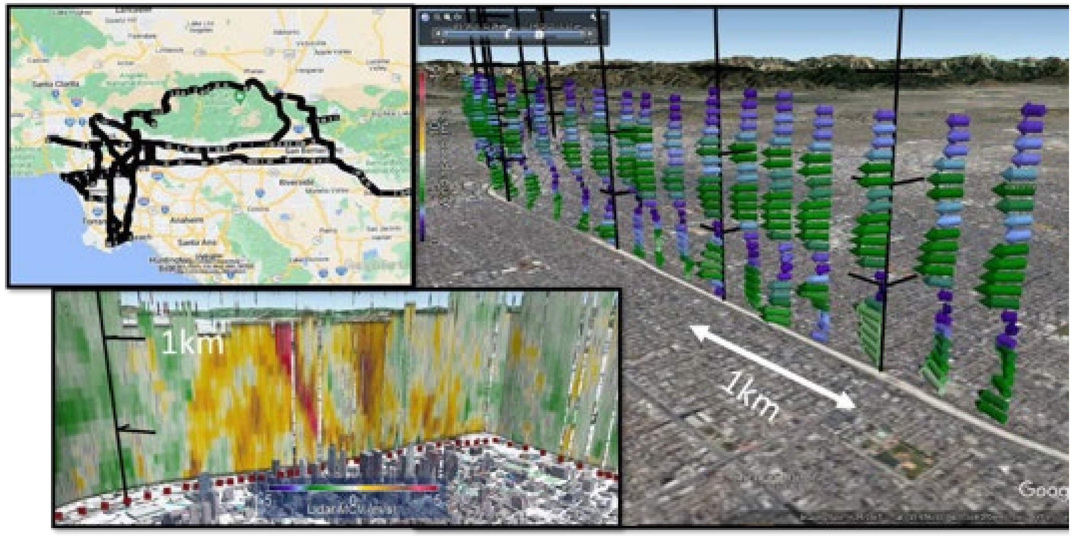
Some challenges:
- ’snapshot’
- Non-stationary conditions
- Labor intensive
- Expensive

Mixing ratio profiles from airborne DIAL



Carroll et al. 2021, MWR

Vertical velocity and horizontal wind profiles from truck mounted mobile lidar



Brewer et al. 2022, Coherent Laser Radar Conference

Heat and moisture budgets – Mixing diagrams

$$\frac{\partial \Theta}{\partial t} = -u\frac{\partial \Theta}{\partial x} - v\frac{\partial \Theta}{\partial y} - w\frac{\partial \Theta}{\partial z} + \frac{1}{\rho c_p}\frac{\partial Q}{\partial z} - \frac{1}{\rho c_p}\frac{\partial H}{\partial z} - \frac{LM}{\rho c_p}$$

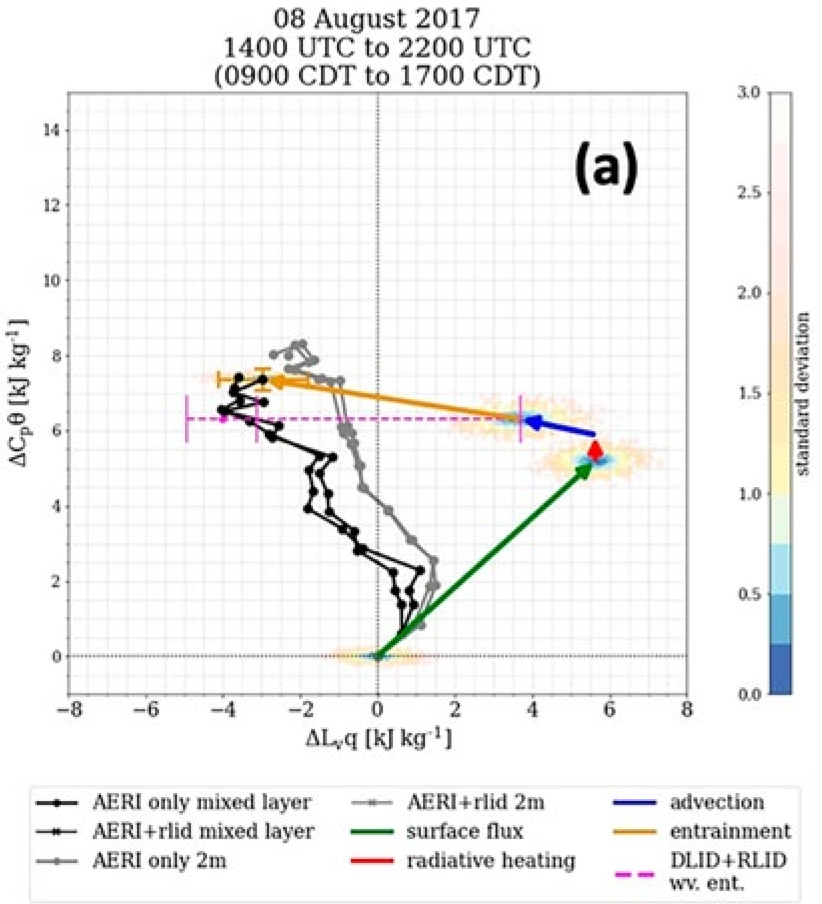
NET *HADV* *VADV* *dQDZ* *dHDz* *SQ*.

NET: local net change
HADV: horizontal advection
VADV: vertical advection
dQdz: divergence of net radiation
dHdz: divergene of sensible heat flux
SQ: phase changes

- Knowledge about individual terms of heat and moisture budgets
- Tool for model evaluation

Some challenges:
- Advection estimated from irregular spaced observations
- Entrainment is residual

Coevolution of heat and moisture in the daytime boundary layer



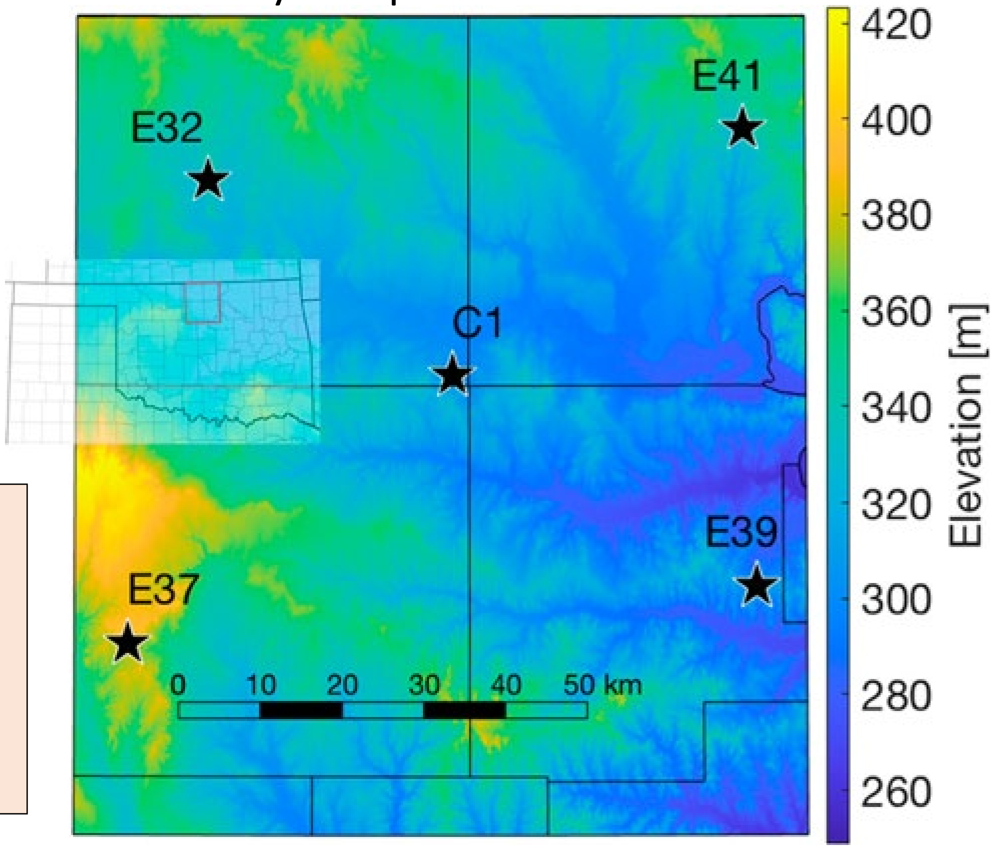
Wakefield et al. 2023, JAMC

Estimation of heat and moisture advection from profiler arrays

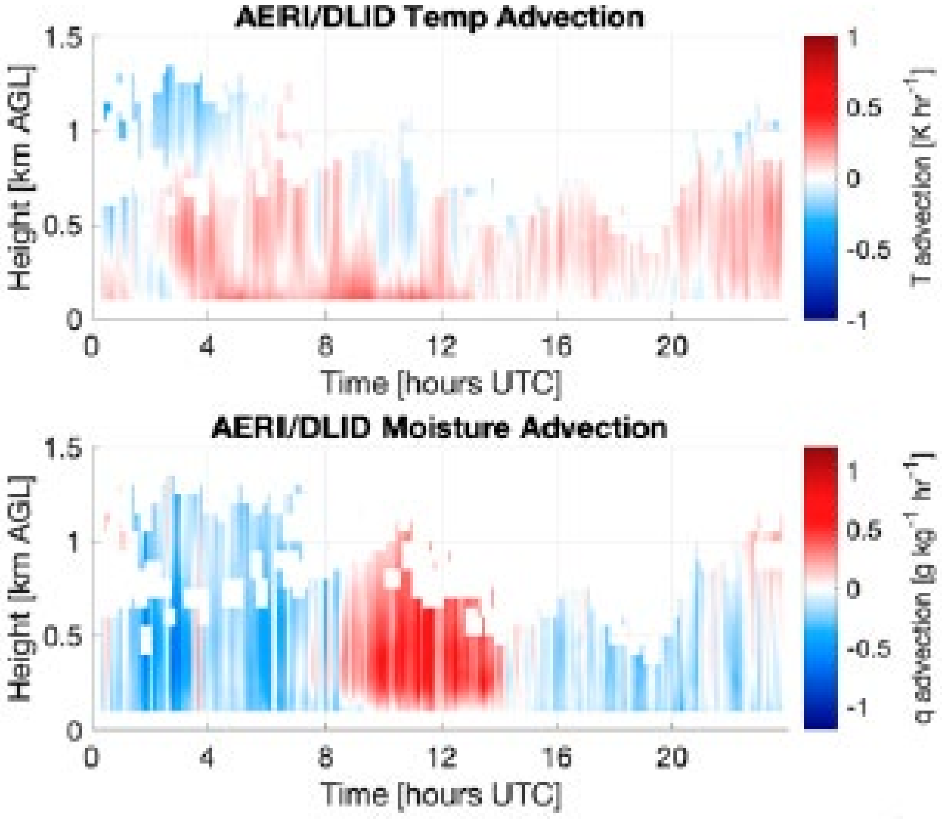
- Method agrees well when evaluated for model output

Some challenges:
- Sensitive to site spacing and selection
- Applicability in complex terrain

Array of 5 profiler sites at SGP



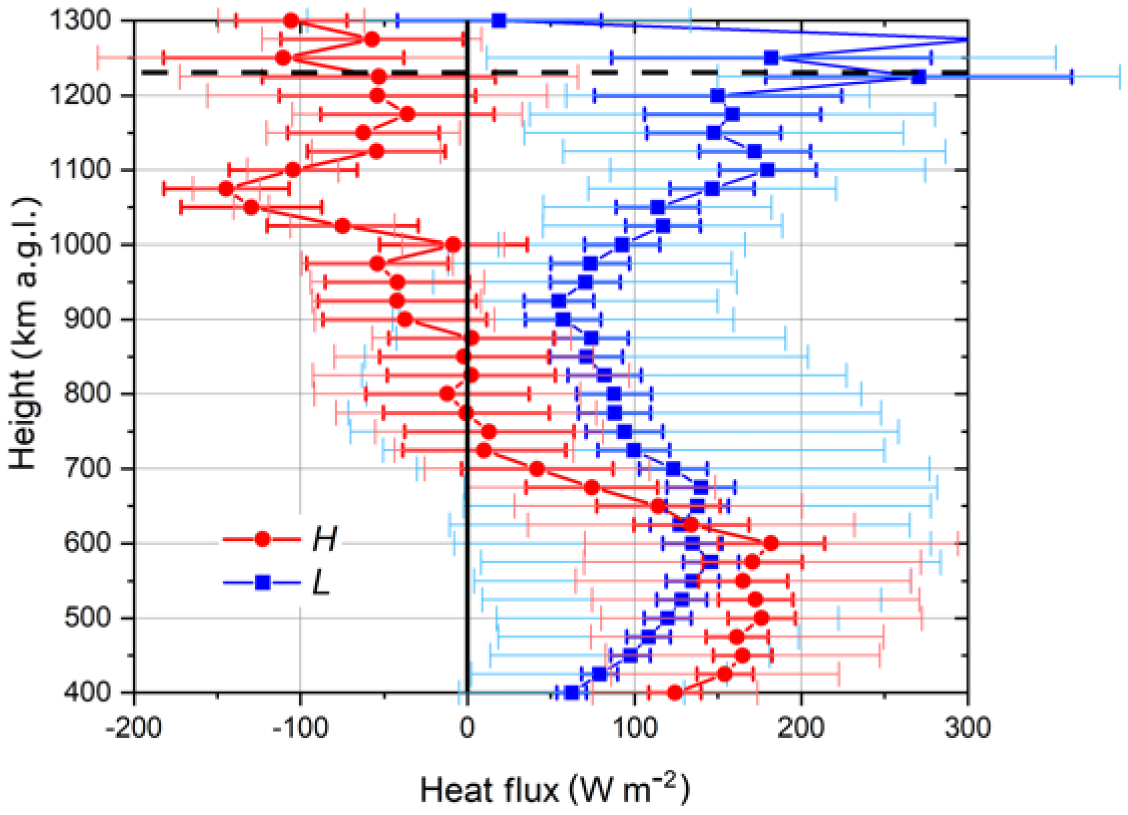
Estimated temperature and moisture advection



Wagner et al. 2022, JAOT

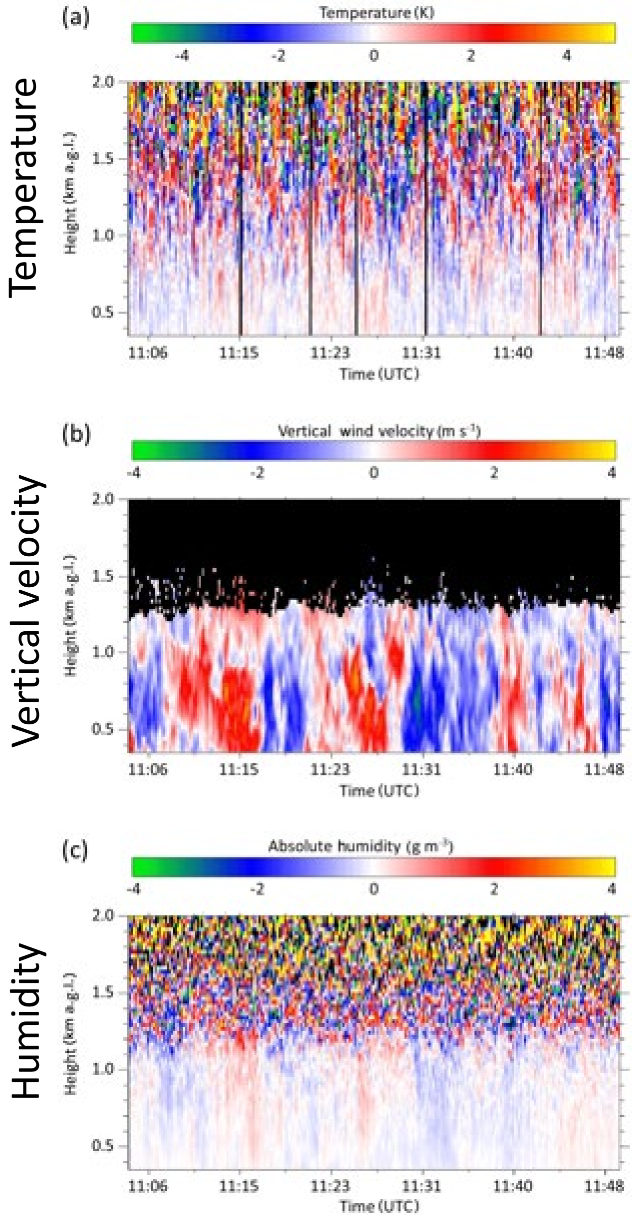
Sensible and latent heat flux profiles

Flux profiles estimated from combinations of Raman lidar, Doppler lidar, and DIAL



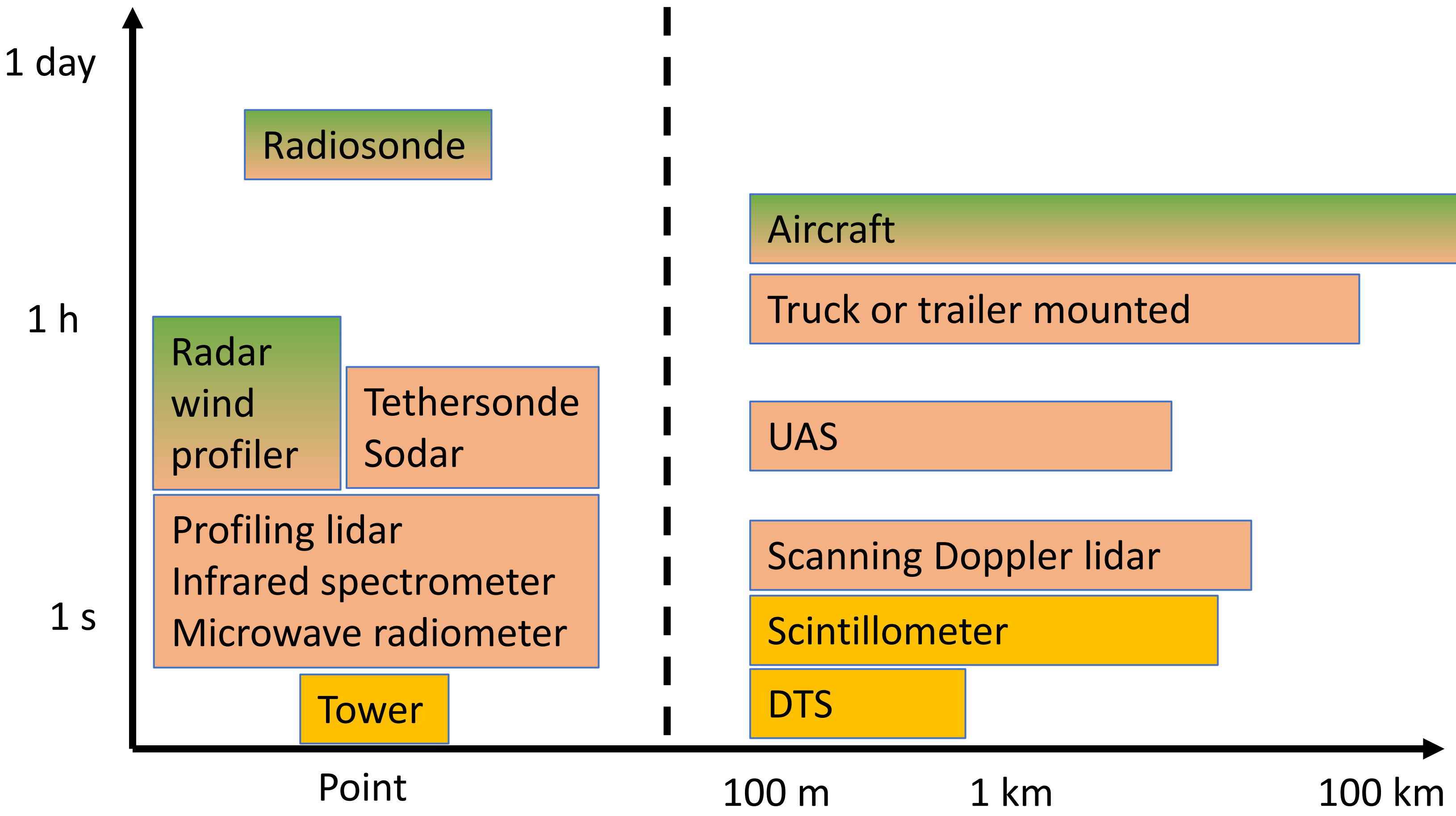
- Estimation of entrainment flux

Some challenges:
- Large error bars (instrument and sampling)
- Few case studies only



Behrendt et al. 2020, AMT

Typical temporal availability and horizontal coverage of platforms and sensors



- Every system has strengths and weaknesses
- Instrument synergies are key to enhance understanding of the atmospheric boundary layer

References

- Adler, Bianca, et al. "CROSSINN: a field experiment to study the three-dimensional flow structure in the Inn valley, Austria." *Bulletin of the American Meteorological Society* 102.1 (2021): E38-E60.
- Babić, Nevio, et al. "Exploring the daytime boundary layer evolution based on Doppler spectrum width from multiple coplanar wind lidars during CROSSINN" *Weather and Climate Dynamics.* Under review.
- Behrendt, Andreas, et al. "Observation of sensible and latent heat flux profiles with lidar." *Atmospheric Measurement Techniques* 13.6 (2020): 3221-3233.
- Brewer, Alan, et al. "Development and Application of NOAA's Ground Based Mobile Doppler Lidar to Study Regional Wind Fields in the Los Angeles Basin During SUNVEx 2021." 21st Coherent Laser Radar Conference.
- Butterworth, Brian J., et al. "Connecting land–atmosphere interactions to surface heterogeneity in CHEESEHEAD19." *Bulletin of the American Meteorological Society* 102.2 (2021): E421-E445.
- Carroll, Brian J., et al. "Lidar observations of a mesoscale moisture transport event impacting convection and comparison to Rapid Refresh model analysis." *Monthly Weather Review* 149.2 (2021): 463-477.
- Duncan Jr, James B., et al. "Evaluating convective planetary boundary layer height estimations resolved by both active and passive remote sensing instruments during the CHEESEHEAD19 field campaign." *Atmospheric Measurement Techniques* 15.8 (2022): 2479-2502.
- Madonna, Fabio, et al. "Use of automatic radiosonde launchers to measure temperature and humidity profiles from the GRUAN perspective." *Atmospheric Measurement Techniques* 13.7 (2020): 3621-3649.
- Markowski, Paul, and Yvette Richardson. *Mesoscale meteorology in midlatitudes*. John Wiley & Sons, 2011.
- Morrison, Travis, et al. "The impact of surface temperature heterogeneity on near-surface heat transport." *Boundary-Layer Meteorology* 180.2 (2021): 247-272.
- Santanello Jr, Joseph A., et al. "Land–atmosphere interactions: The LoCo perspective." *Bulletin of the American Meteorological Society* 99.6 (2018): 1253-1272.
- Serafin, Stefano, et al. "Exchange processes in the atmospheric boundary layer over mountainous terrain." *Atmosphere* 9.3 (2018): 102.
- Steyn, Douw G., et al. "Boundary layers and air quality in mountainous terrain." *Mountain weather research and forecasting: recent progress and current challenges* (2013): 261-289.
- Stull, Roland B. *An introduction to boundary layer meteorology*. Vol. 13. Springer Science & Business Media, 1988.
- Ward, Helen C. "Scintillometry in urban and complex environments: a review." *Measurement Science and Technology* 28.6 (2017): 064005.
- Wilson, D.A., and L.J. Miller, 1972: Atmospheric motion by Doppler radar. Ch. 13 in Remote Sensing of the Troposphere, Ed. V.E. Derr, U.S. Dept. of Commerce Report.
- Wolfe, Daniel E., and R. J. Lataitis. "Boulder Atmospheric Observatory: 1977–2016: The end of an era and lessons learned." *Bulletin of the American Meteorological Society* 99.7 (2018): 1345-1358.
- Wakefield, R. A., et al. "A methodology for estimating the energy and moisture budget of the convective boundary layer using continuous ground-based infrared spectrometer observations." *Journal of Applied Meteorology and Climatology* (2023).
- Wagner, Timothy J., et al. "Observing profiles of derived kinematic field quantities using a network of profiling sites." *Journal of Atmospheric and Oceanic Technology* 39.3 (2022): 335-351.
- Zeeman, Matthias J., John S. Selker, and Christoph K. Thomas. "Near-surface motion in the nocturnal, stable boundary layer observed with fibre-optic distributed temperature sensing." Boundary-layer meteorology 154 (2015): 189-205.