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

Bianca Adler
Why is the boundary layer important?

Santanello et al. 2018, BAMS

Serafin et al. 2018, Atmosphere

Steyn et al. 2013, Springer Atmospheric Sciences
What do we need to observe?

Thermally driven flows

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

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

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

Morrison et al. 2021,

Butterworth et al. 2021, BAMS

Wolfe and Lataitis 2018, BAMS
Scintillometers for spatially averaged surface heat fluxes

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

https://www.scintec.com/catalogs/laser-scintillometers/


- Area-averaged fluxes
- Comparable to model grid box
- Inaccessible areas above cities and across valleys
Distributed temperature sensing (DTS)

- 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

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

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

Vaisala AS41 Autosonde system

Adler et al. 2021, BAMS

Boundary layer evolution in an Alpine valley

Madonna et al. 2020, AMT
UAS for boundary layer profiling and surface characterization

- 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

Credit: Gijs de Boer, CIRES/IRISS/NOAA PSL
Ground-based remote sensing of wind profiles

Pulsed and continuous wave Doppler lidars

- 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

Wilson and Miller 1972

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UNIVERSITY OF COLORADO BOULDER and NOAA

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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)

RASS temperature measurements

NOAA Physical Sciences Laboratory
449 MHz Wind Profiling Radar

Water vapor mixing ratio from Raman lidar at SGP

© Catherine Bunn

www.arm.gov
Ground-based thermodynamic profiling – passive sensors

Radiance spectra observed by IRS

- 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

Water vapor profiles retrieved from IRS radiances

Temperature profiles retrieved from IRS radiances
Boundary layer height detection

- 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

- 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

2-d flow field across a valley

Boundary layer height across a valley

Adler et al. 2021, BAMS

Babić et al. 2023, under review
**Airborne and truck mounted remote sensing**

Mixing ratio profiles from airborne DIAL

![Graph showing mixing ratio profiles](image1)

Carroll et al. 2021, MWR

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

Detailed spatial information on boundary layer conditions

Vertical velocity and horizontal wind profiles from truck mounted mobile lidar

![Graph showing vertical velocity and horizontal wind profiles](image2)

Brewer et al. 2022, Coherent Laser Radar Conference
Heat and moisture budgets – Mixing diagrams

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

**NET**  **HADV**  **VADV**  **dQdz**  **dHdz**  **SQ**.

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

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

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

Coevolution of heat and moisture in the daytime boundary layer

Wakefield et al. 2023, JAMC
Estimation of heat and moisture advection from profiler arrays

Array of 5 profiler sites at SGP

- Method agrees well when evaluated for model output

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

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

<table>
<thead>
<tr>
<th>Platform</th>
<th>Temporal Availability</th>
<th>Horizontal Coverage</th>
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<tbody>
<tr>
<td>Radiosonde</td>
<td>1 day</td>
<td>Point</td>
</tr>
<tr>
<td>Tethersonde, Sodar</td>
<td>1 h</td>
<td>1 km</td>
</tr>
<tr>
<td>Profiling lidar, Infrared spectrometer, Microwave radiometer</td>
<td>1 s</td>
<td>100 m</td>
</tr>
<tr>
<td>Tower</td>
<td></td>
<td>100 km</td>
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<tr>
<td>Aircraft</td>
<td></td>
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<td>Truck or trailer mounted</td>
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<tr>
<td>UAS</td>
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<tr>
<td>Scanning Doppler lidar</td>
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<tr>
<td>Scintillometer</td>
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<td>DTS</td>
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- Troposphere
- Boundary Layer
- Surface Layer
References