Introduction to ground-based remote sensing of the urban boundary layer

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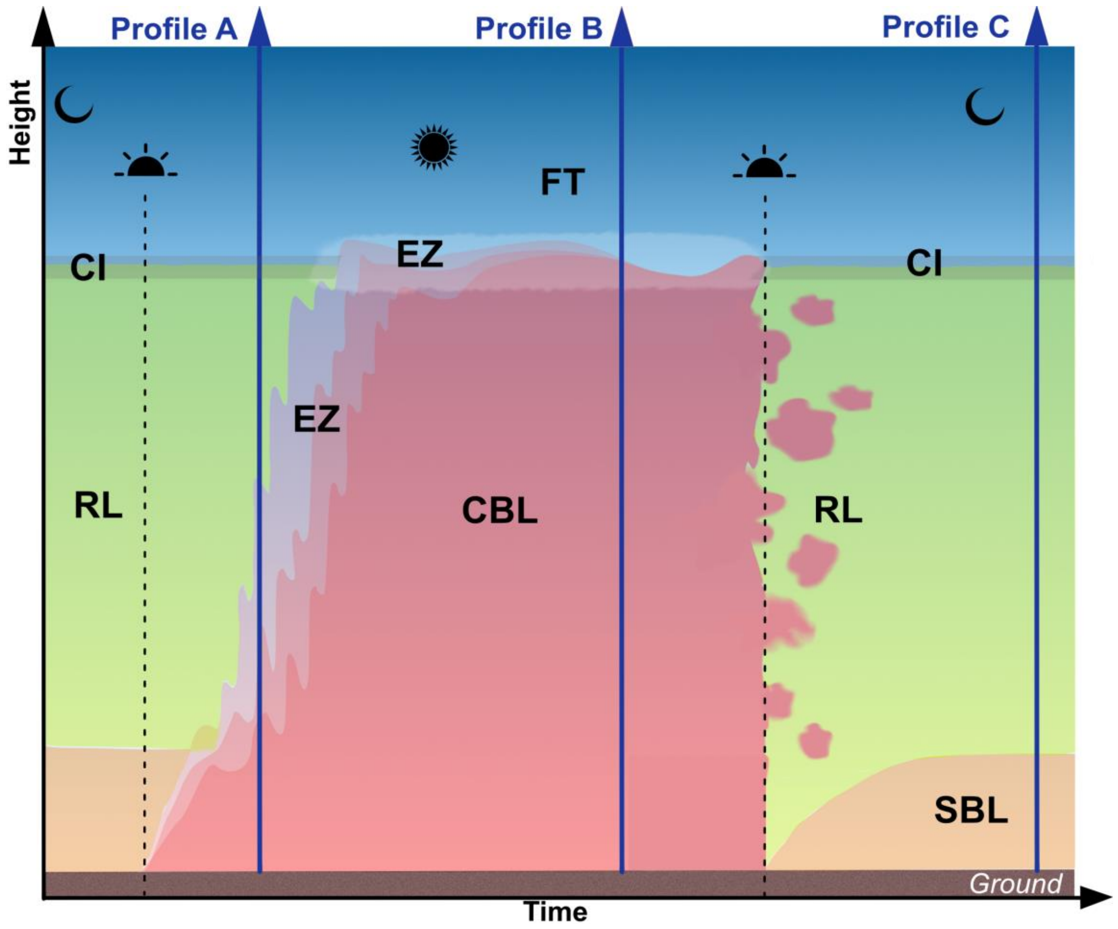
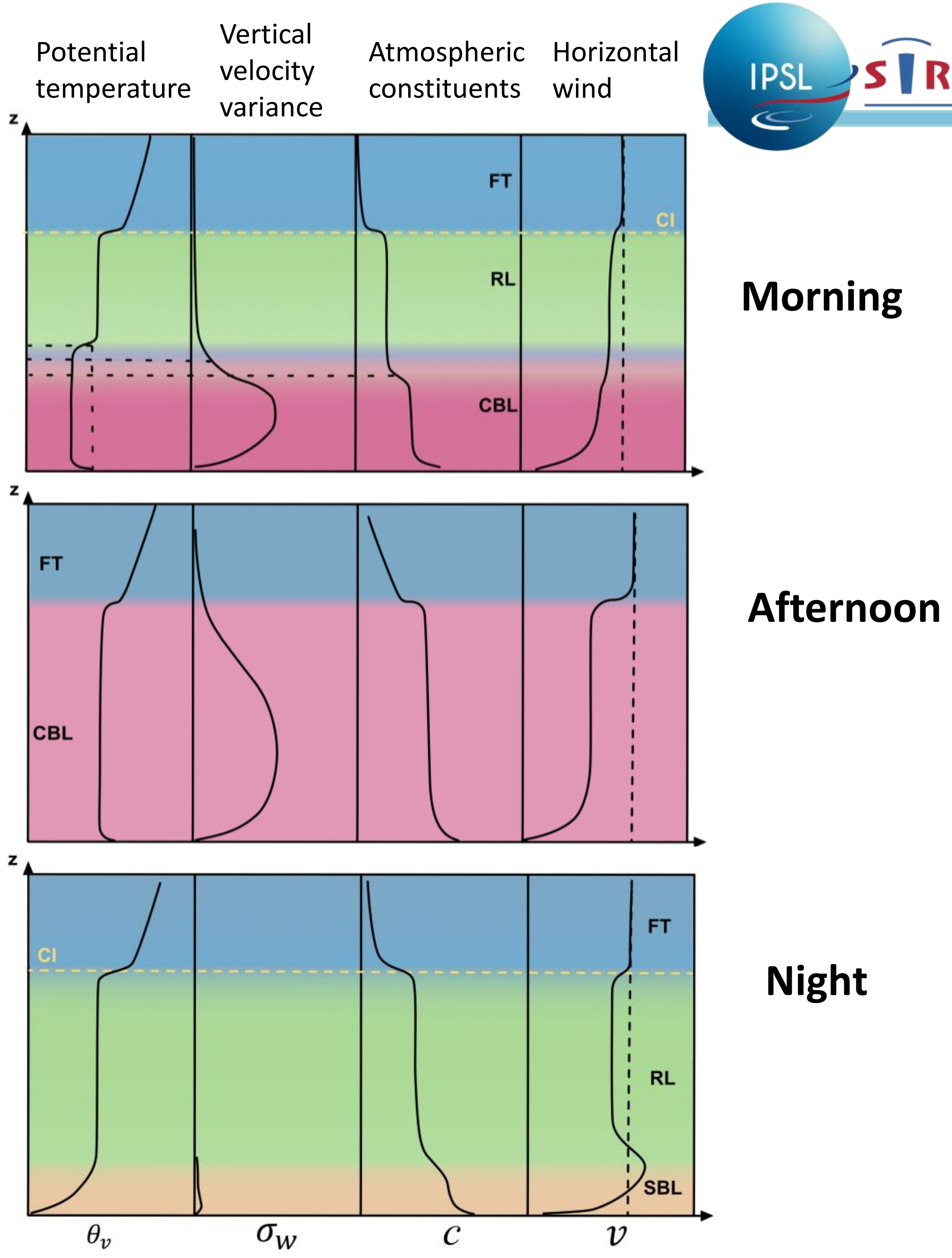
Atmospheric Boundary Layer



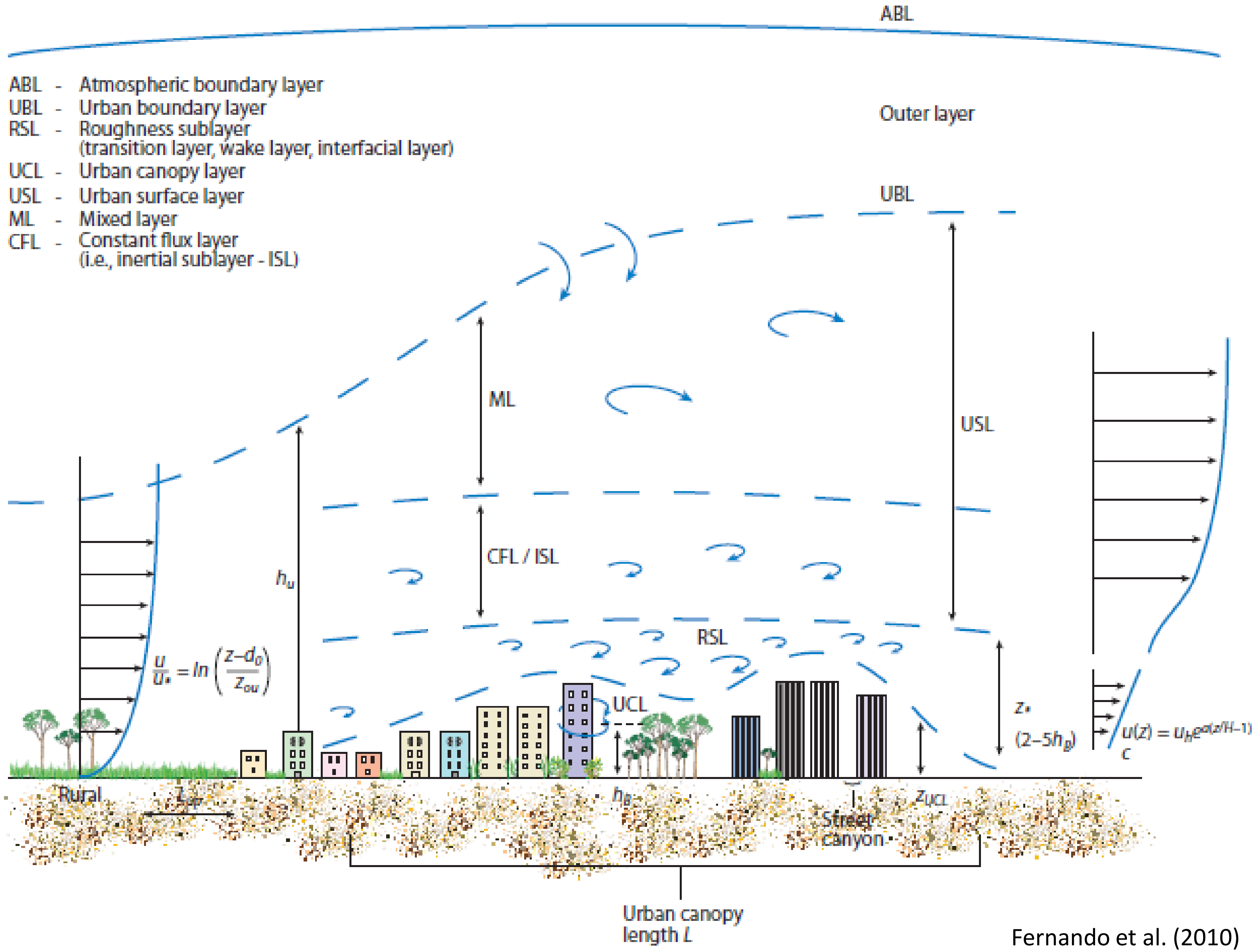


EZ: entrainment zone
CBL: Convective boundary layer

SBL: stable boundary layer
RL: residual layer

CI: capping inversion
FT: free troposphere

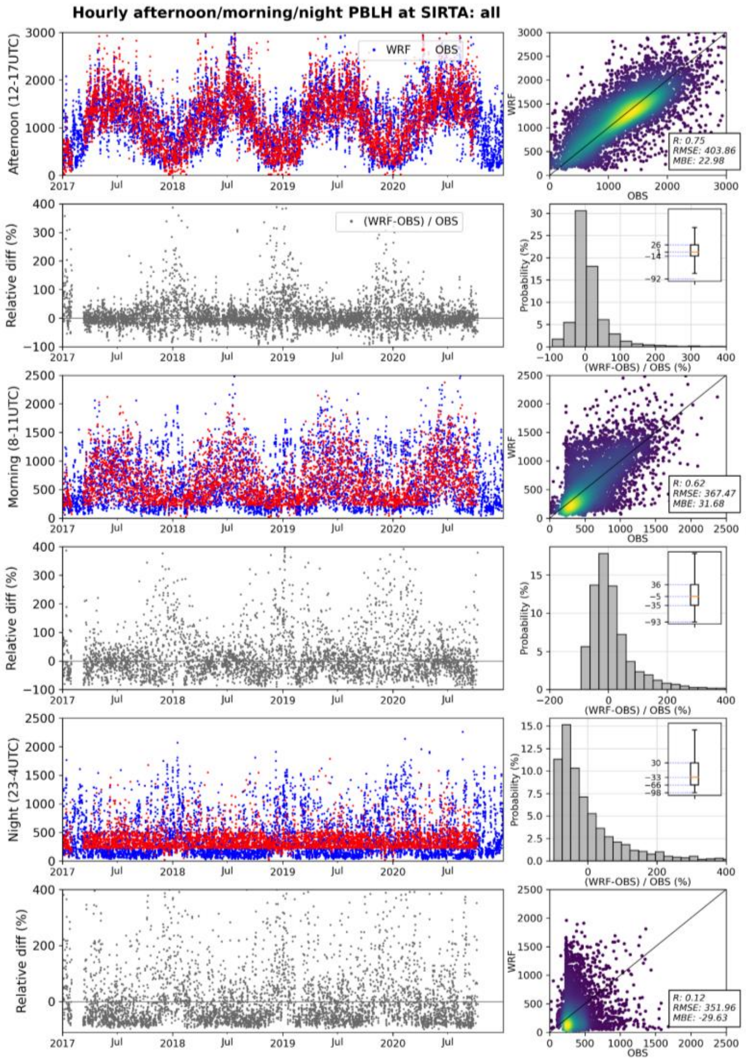
Urban Boundary Layer



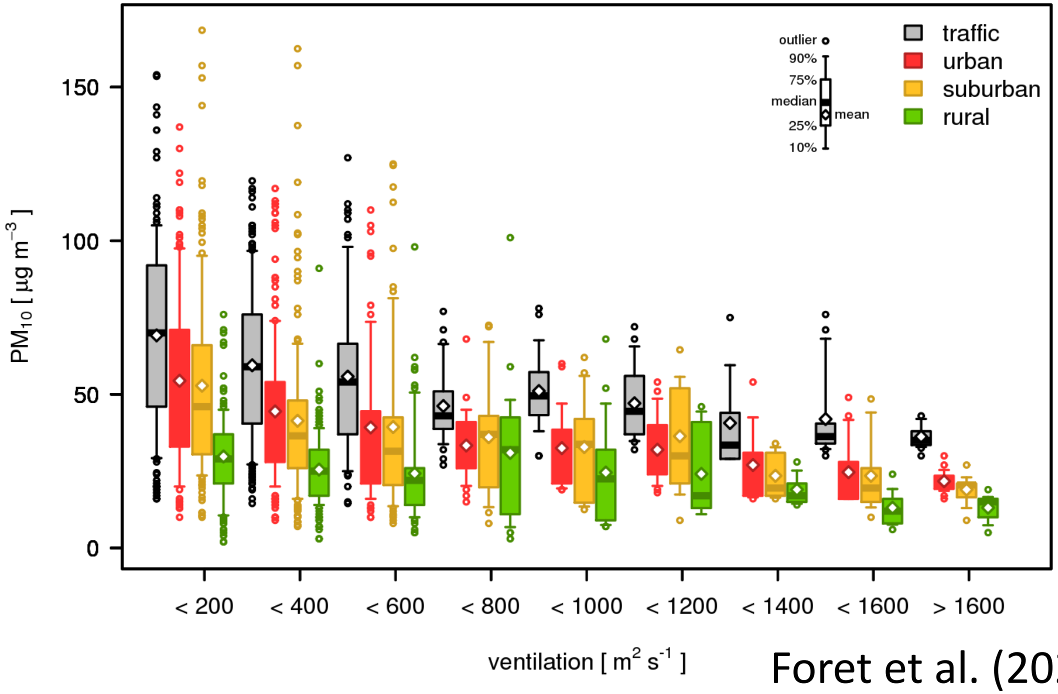
Fernando et al. (2010)

UBL observations required for…

Model evaluation and constraints



Process studies
(urban heat, pollution, clouds, thunderstorms, …)

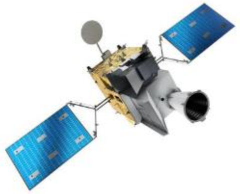


Extreme winter-time surface-level PM_{10} in Paris only observed when ventilation coefficient is low (MLH x wind speed)

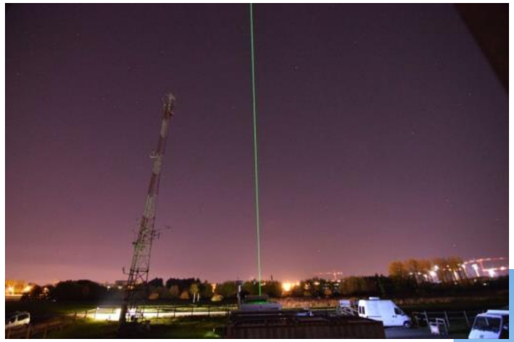
Foret et al. (2022)

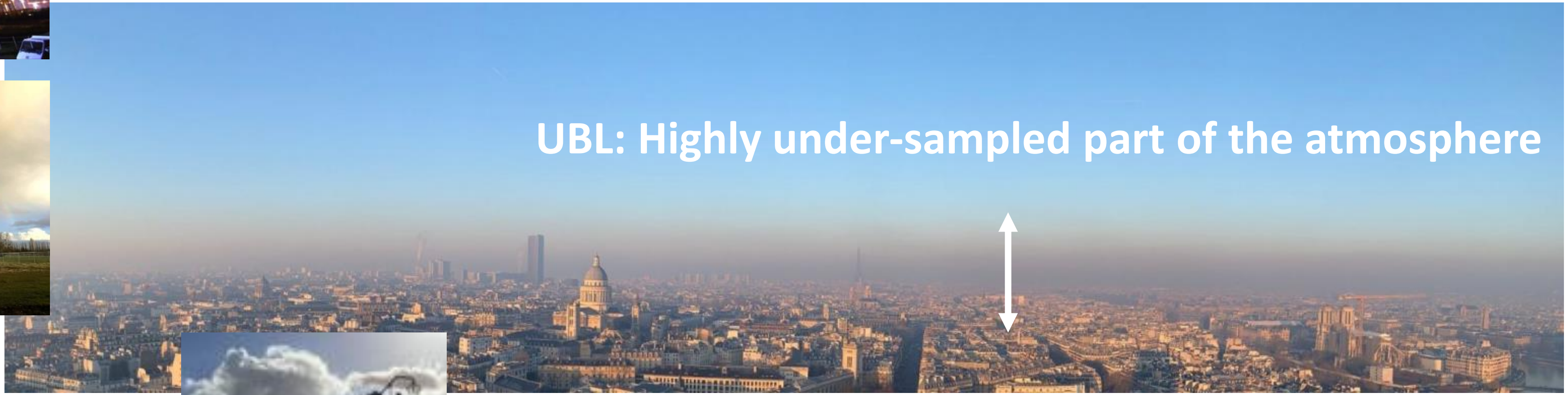
Carbon inverse modelling for Paris: Lian et al. (2022)

Urban boundary layer



Upper atmosphere: increasingly monitored from space
(ABL region of maximum uncertainty)





Research stations with profiling capabilities often in rural/suburban settings

Surface stations and local-scale flux towers increasingly monitor the UCL and CFL, respectively

Surface stations networks: historically aim to avoid “urban influence”

In-situ profiling

light-weight options are becoming available as tested this summer in Paris, Berlin, Houston, …

Radiosondes

- measure temperature & humidity at high vertical resolution, wind speed, wind direction and pressure derived from GPS
- Expensive, labour intensive, horizontal drift
- Traditional radiosondes not in urban settings
- Limited Temporal resolution

Tall towers

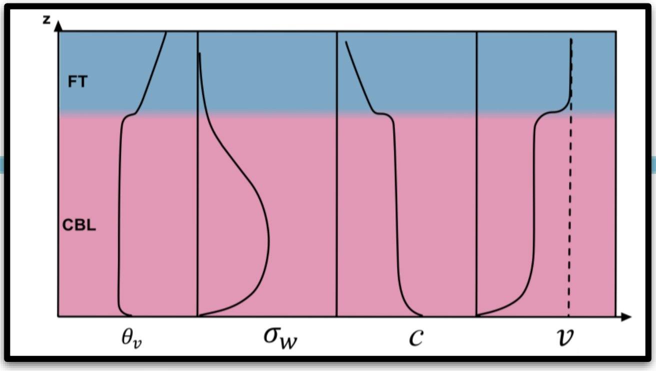
- Continuous observations of many variables at high temporal resolution (very valuable e.g. for turbulent flux observations)
- Very rare installations, limited vertical range

Atmospheric profile remote-sensing

Active			Passive	
SODAR *acoustic signal*	LIDAR *light signal*	RADAR *radio signal*	*Microwave* radiometers	*Infrared* spectrometers
	•Doppler wind lidar •Aerosol lidar •Raman lidar •Differential absorption lidar	•Cloud radar •Rain radar •Radar wind profiler		

Radio-acoustic sounding system (RASS): synergy of e.g. radar wind profiler + SODAR

Profiling the ABL



Temperature humidity/trace gases	Wind and turbulence	Aerosol

Microwave radiometer
Infrared spectrometer
Raman lidar
Differential absorption lidar
	Sodar
	Doppler wind lidar
	Radar wind profiler
	Cloud radar
		Aerosol lidar
		• High-power lidar
		  • Elastic backscatter lidar
		  • Raman lidar
		• Automatic lidars and ceilometers (ALC)
		Doppler lidar (after focal correction)

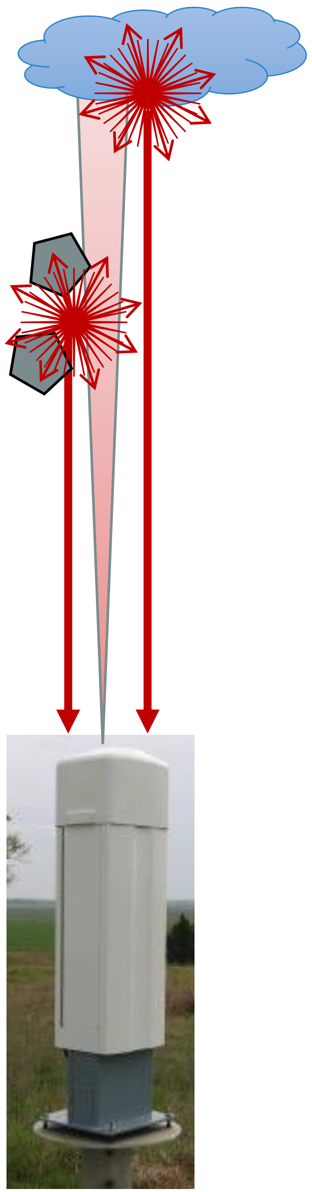
Urban operations:

- Compact installations
- Eye-safe lasers, no sound disturbance

Network applications:

- Mature technology, low maintenance, automatic operations
- Relatively low cost

Atmospheric **profile** remote-sensing

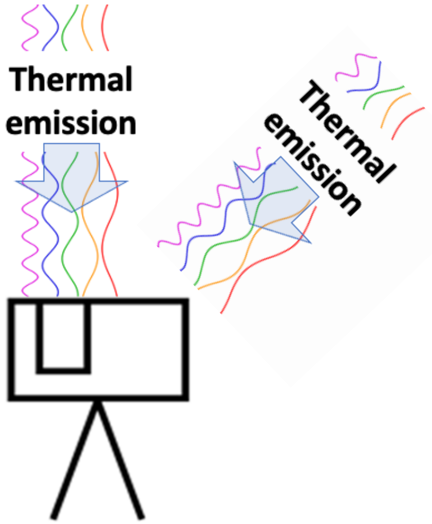


Active *ranging* systems

- Range = Distance to sensor
- Most instruments send out pulsed signal
- Range is estimated from round-trip time

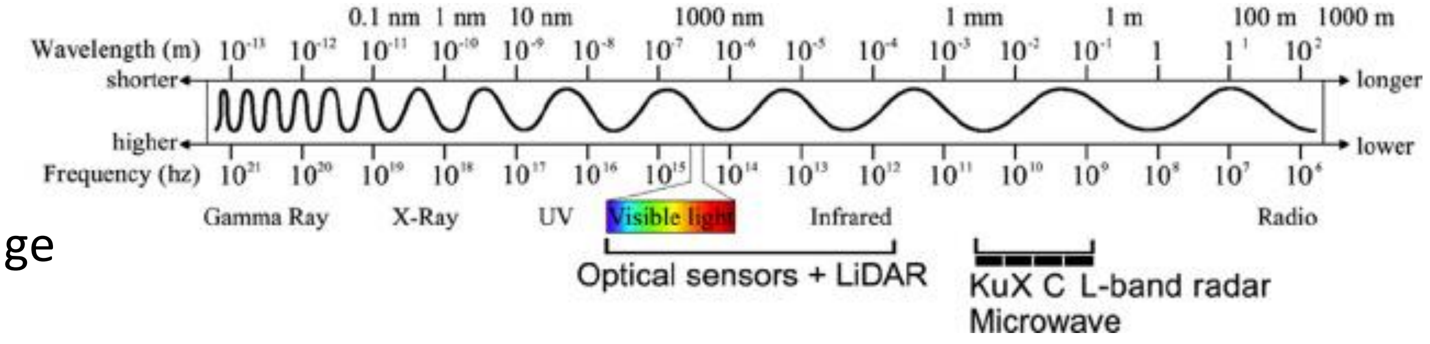
Passive *scanning* systems

- Passive radiometers measure integrated quantities
- Profiling achieved by combining scans along different elevation angles



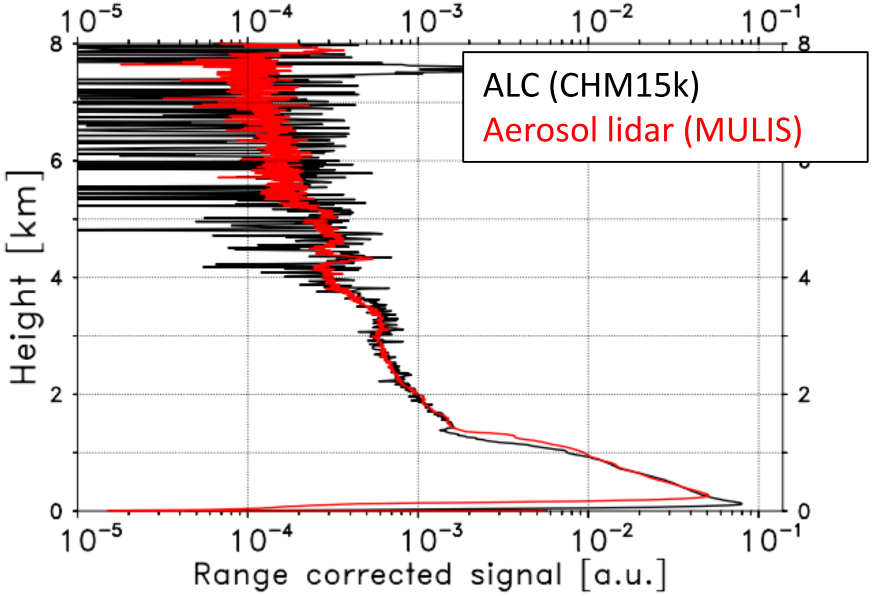
LIDAR general characteristics

- Laser beam at wavelength UV-IR
- Monochromatic or multiple wavelength
- Measurement quality depends on
  a) signal-to-noise ratio (**SNR**) in upper range
  b) incomplete **optical overlap** between transmitter and receiver in near range



SNR

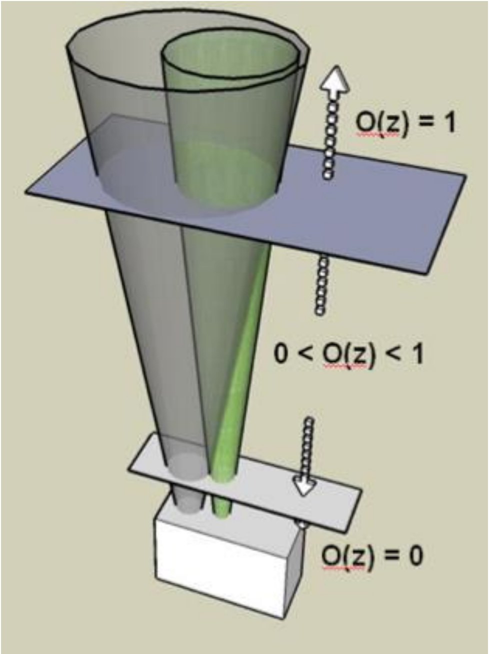
- Signal strength decreases exponentially with range
- SNR increases with aerosol load and laser pulse energy



Wiegner et al. (2020)

Optical overlap

- Optical overlap can be partly corrected but there is always a certain blind zone in the near range
- Blind zone increases with decreasing range resolution (increasing laser pule energy)



Profiling the ABL

Temperature
humidity/trace gases

Microwave radiometers
Infrared spectrometer
Raman lidar
Differential absorption lidar

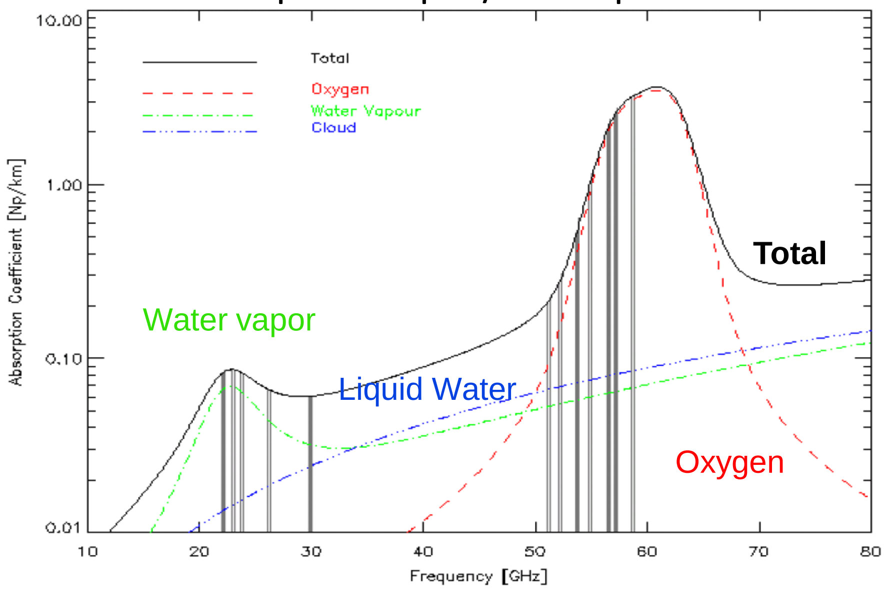
- All temperature profilers still rarely deployed in cities
- MWR network operations advance in Europe (MWRnet)
- IRS used e.g. in USA
- Technological development of compact DIAL systems advancing

Microwave radiometers (MWR)

- Passive ground-based remote sensing systems collecting atmospheric natural thermal radiation
- Observed thermal radiation comes primarily from atmospheric gases (oxygen, water vapor) and hydrometeors (mainly liquid water)
- Measured quantity (radiance) converted into **brightness temperature** T_B (K)
- Depending on the number and frequency of channels, temperature and/or humidity can be inferred

(typical spectral range: 20-60 GHz or 1.5 cm – 0.05 cm)

Atmospheric absorption/emission spectrum

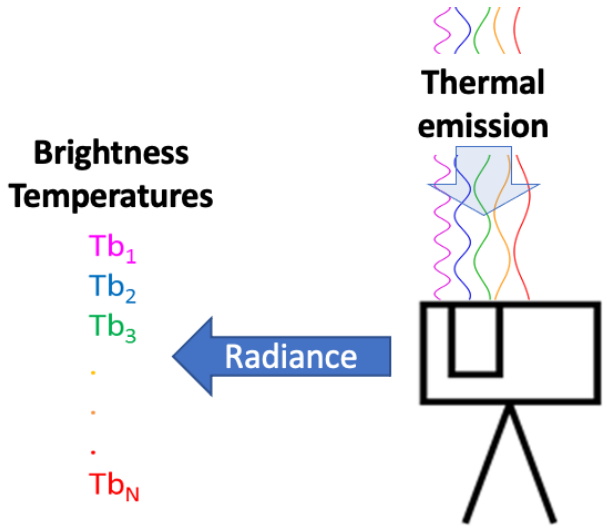


WV-LW channels

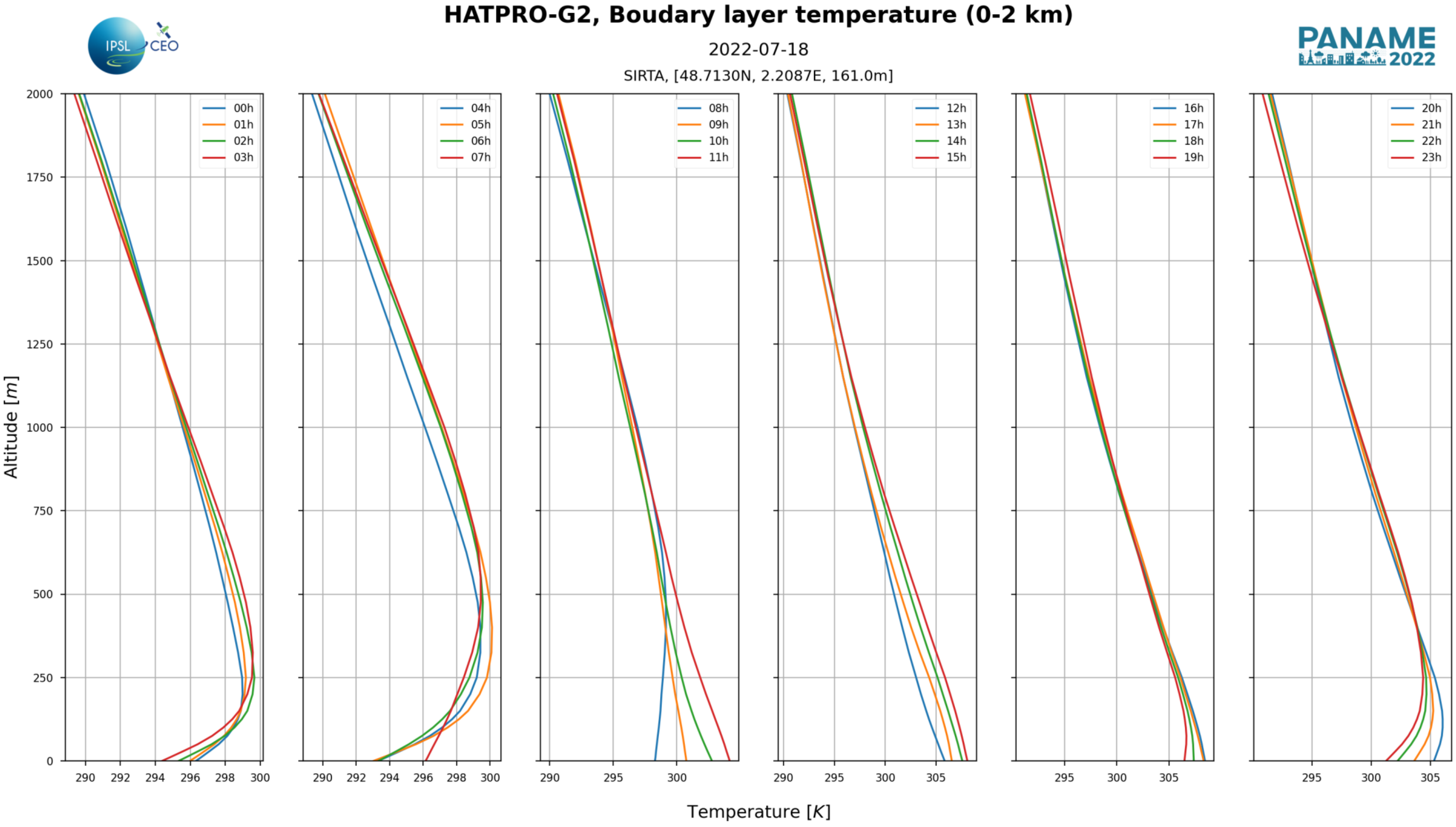
T channels

- Channels have height-dependant weighting functions
- Differential absorption between channels: profile retrieval
- Also integrated water vapour (IWV), liquid water path (LWP)
- Typical inversion methods:

  Statistical regression, Neural networks, Physical (optimal estimation)



MWR temperature profile



- MWR: smoother than temperatures from radiosondes
- Continuous Characterisation of SBL
- Diurnal evolution of atmospheric stability
- Thermodynamic estimation of CBLH

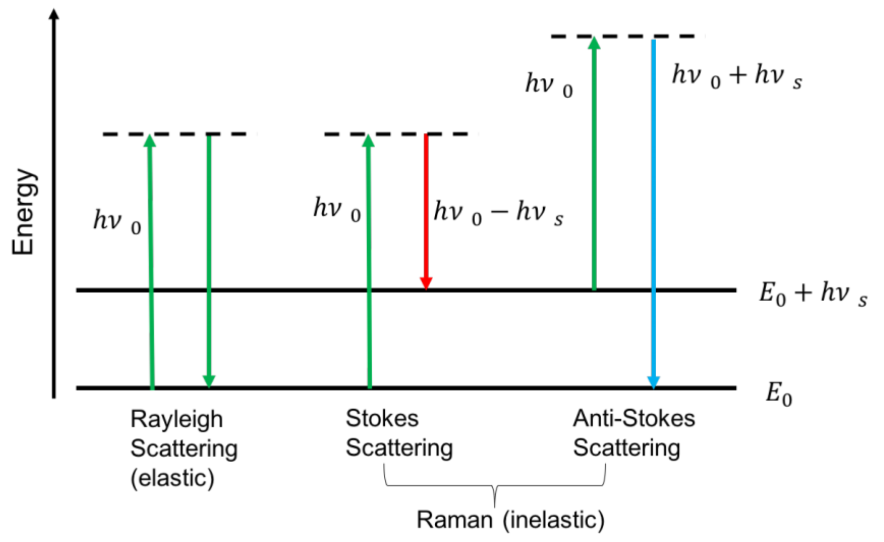
Infrared spectrometer

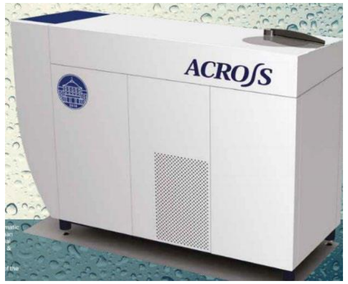
- High spectral resolution radiances measured in the thermal infrared spectrum (3000-520 cm^{-1} wavenumber; 3.3–19 µm)
- Temperature, water vapor profiles, trace gases in cloud-free air
- IRS data have greater information content than MWR

  → higher vertical resolution in ABL for temperature and humidity profiles
- Signal disturbed by rain and clouds

Raman lidar

- High-power aerosol lidar that capture Raman (inelastic) scattering at times when background light is low (night)
  → Air temperature/humidity profiles
- Fundamental wavelengths (1064 nm) + second (532 nm) and third (355 nm) harmonics
- Laser not eye-safe (extremely high pulse energy)
- Often large blind zone, operation rather expensive
- Generally not operated continuously but rather with focus on specific events, e.g. to monitor elevated layers & long-range transport (smoke, dust, ash)
- Usually at rural/suburban research institutions

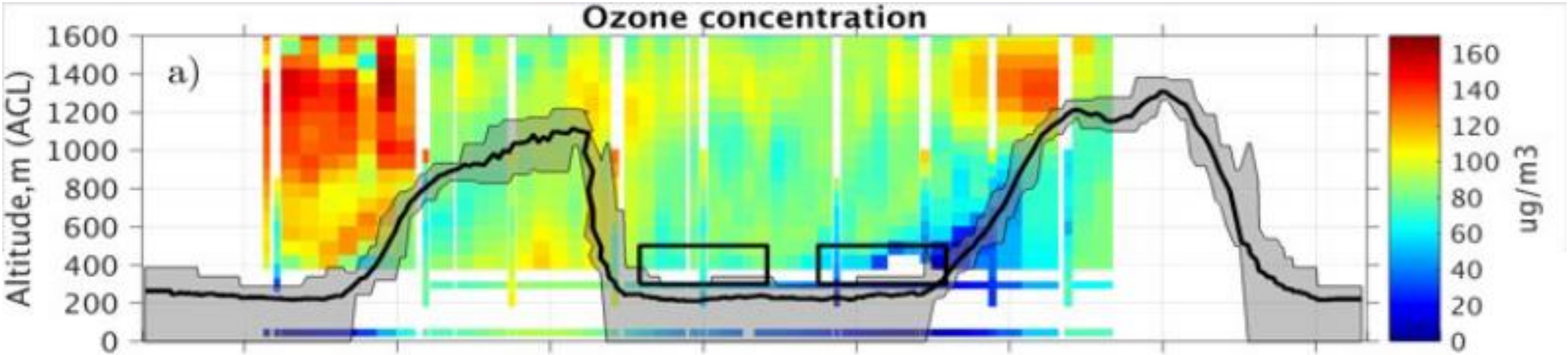




Compact Raman lidars

Differential absorption lidar (DIAL)

- Emitting laser at two near-by wavelengths, exploiting differential attenuation:
  - *online* wavelength at absorption line
  - *offline* wavelength at nearby region with weak/no absorption
- Wavelengths depends on absorption spectrum of water vapour or trace gas (e.g. ozone, CO2, CH4, NO2)
- Compact DIAL systems that can be operated continuously with low maintenance are becoming increasingly available and deployed in urban settings
- Vertical distribution of gas concentrations in UBL, entrainment and dilution are important to understand variations in surface-level concentrations



Residual layer ozone: regional scale photochemical production of previous day

LLJ: advection of air with low ozone concentrations

Ancellet et al (2020)

Profiling the ABL

Wind and turbulence

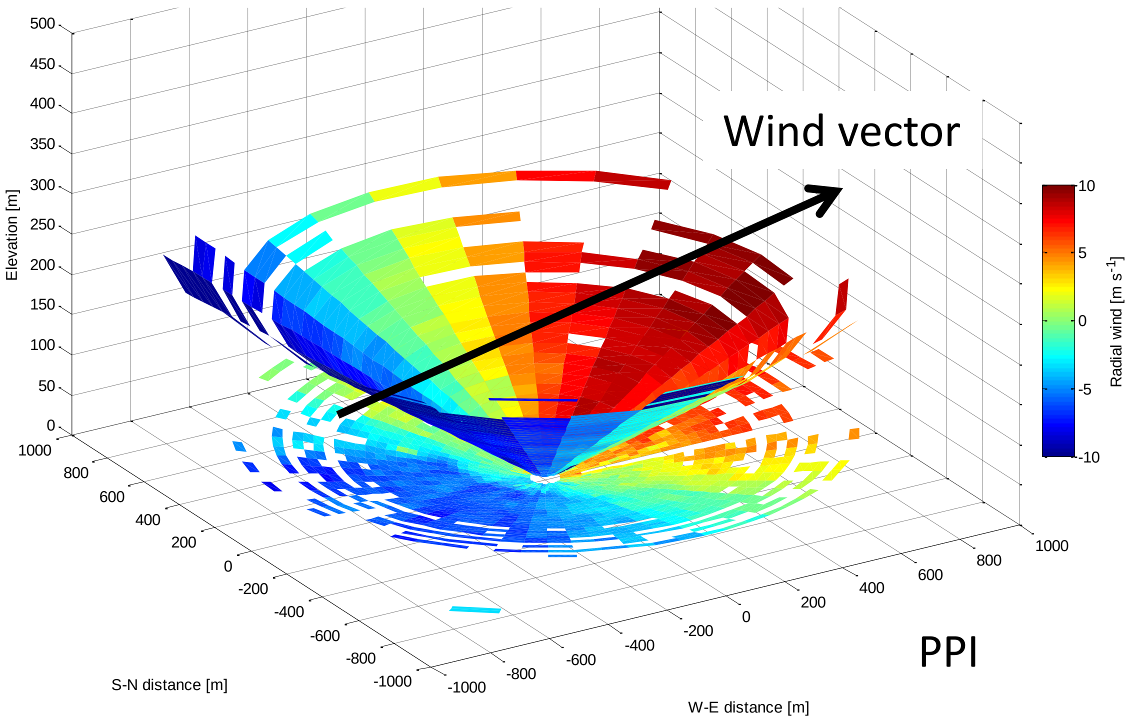
Sodar
Doppler wind lidar
Radar wind profiler
Cloud radar

Monitoring wind and turbulence

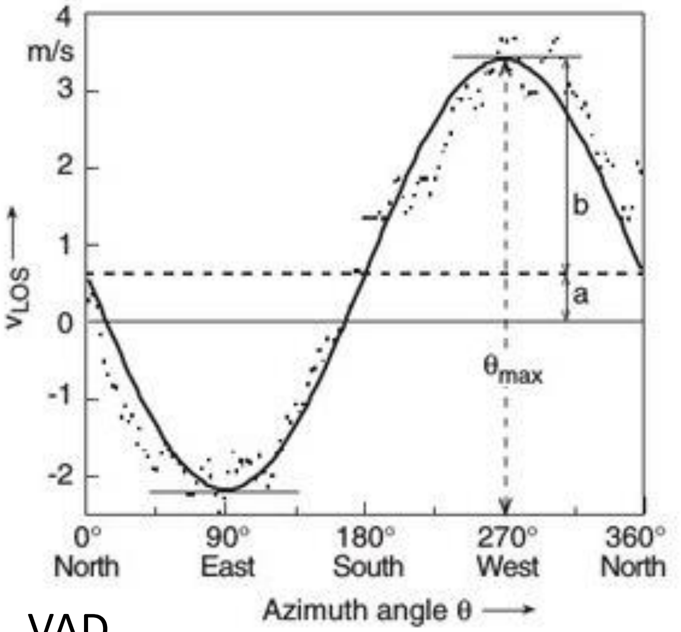
	Sodar	Radar wind profiler	Doppler wind lidar
Signal	Sound	for ABL usually UHF ~1GHz/L-Band	Light (~1550 nm, ~2000 nm)
Response	Atmospheric turbulence	Clean air	Aerosols
Observed quantity	Refractive index structure parameter Cn2	Radial velocity (Doppler shift)	Radial velocity (Doppler shift)
Capabilities	Very good in near-range = advantage for shallow layers	Observations inside clouds/fog, precipitation	Compact sensors, many advanced products, scanning DWL can alternate complex scan patterns
Limitations	Limited vertical range (sensitive to background noise), no measurements during precipitation, sound signal inconvenience	Birds affect signal, few sensors	Full attenuation by thick clouds/fog, uncertainty during precipitation or pristine conditions

Doppler wind lidar (DWL)

- DWL usually set to measure radial velocity at a set number of beam directions (“line-of-site” - LOS)
- Vertical profile of horizontal (vertical) wind reconstructed from a combination of beams using Doppler beam swinging (DBS), velocity azimuth display (VAD) or plan position indicator (PPI)
- At nadir, radial velocity = vertical velocity; variance can be derived if sampling at high-frequency



PPI



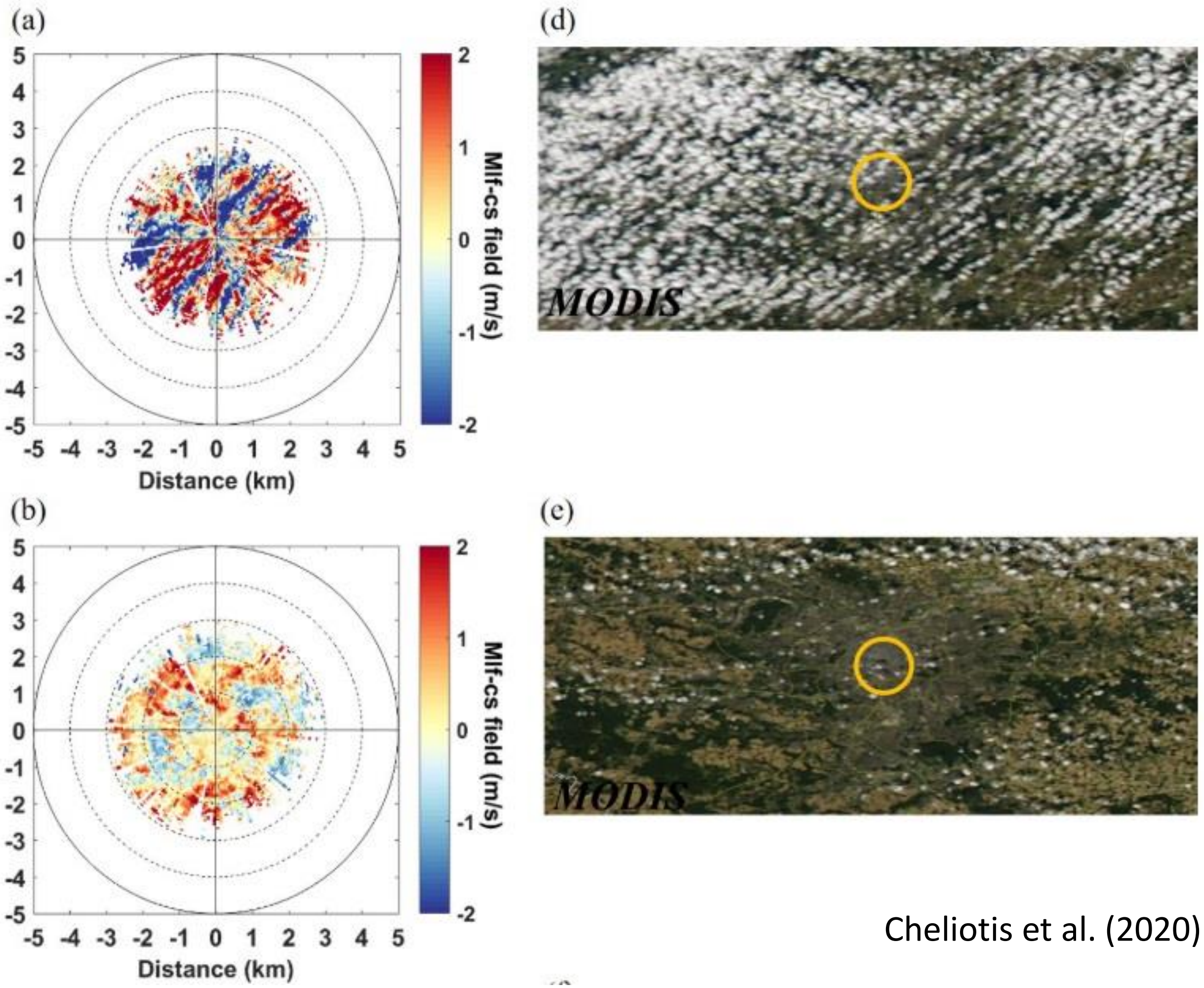
VAD

DBS

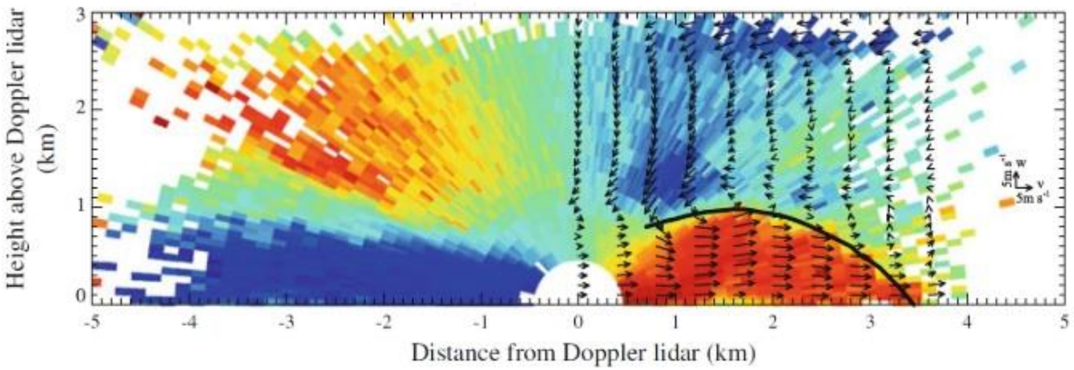
Doppler wind lidar (DWL)

- Scanning DWL can also sample 3D wind field variations
- Recent systems allow for complex combination of scan patterns
- Sampling at low elevation angles helps to reduce blind zone and capture horizontal velocity variance

Horizontal slice:
Turbulent structures from plan position indicator (PPI)



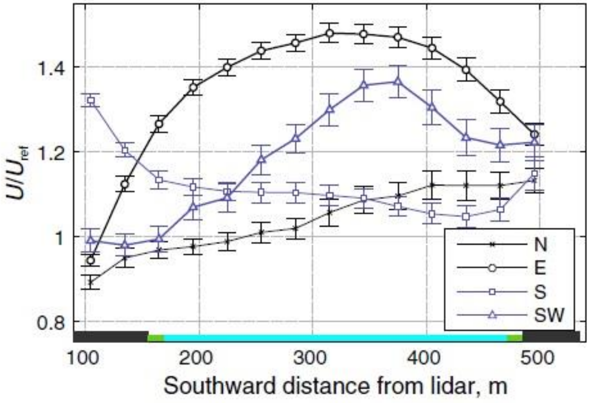
Vertical slice:
Radial velocity from range height indicator (RHI)



Cheliotis et al. (2020)

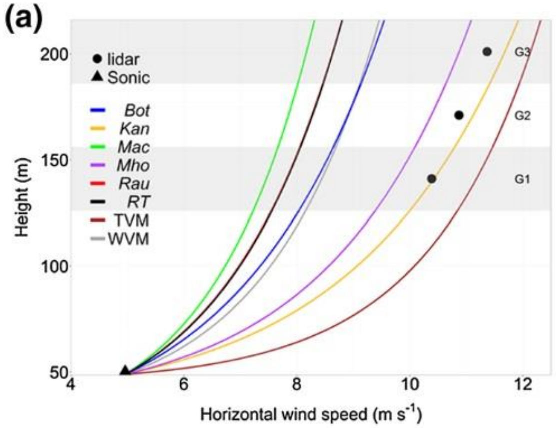
Influence of urban morphology on wind field

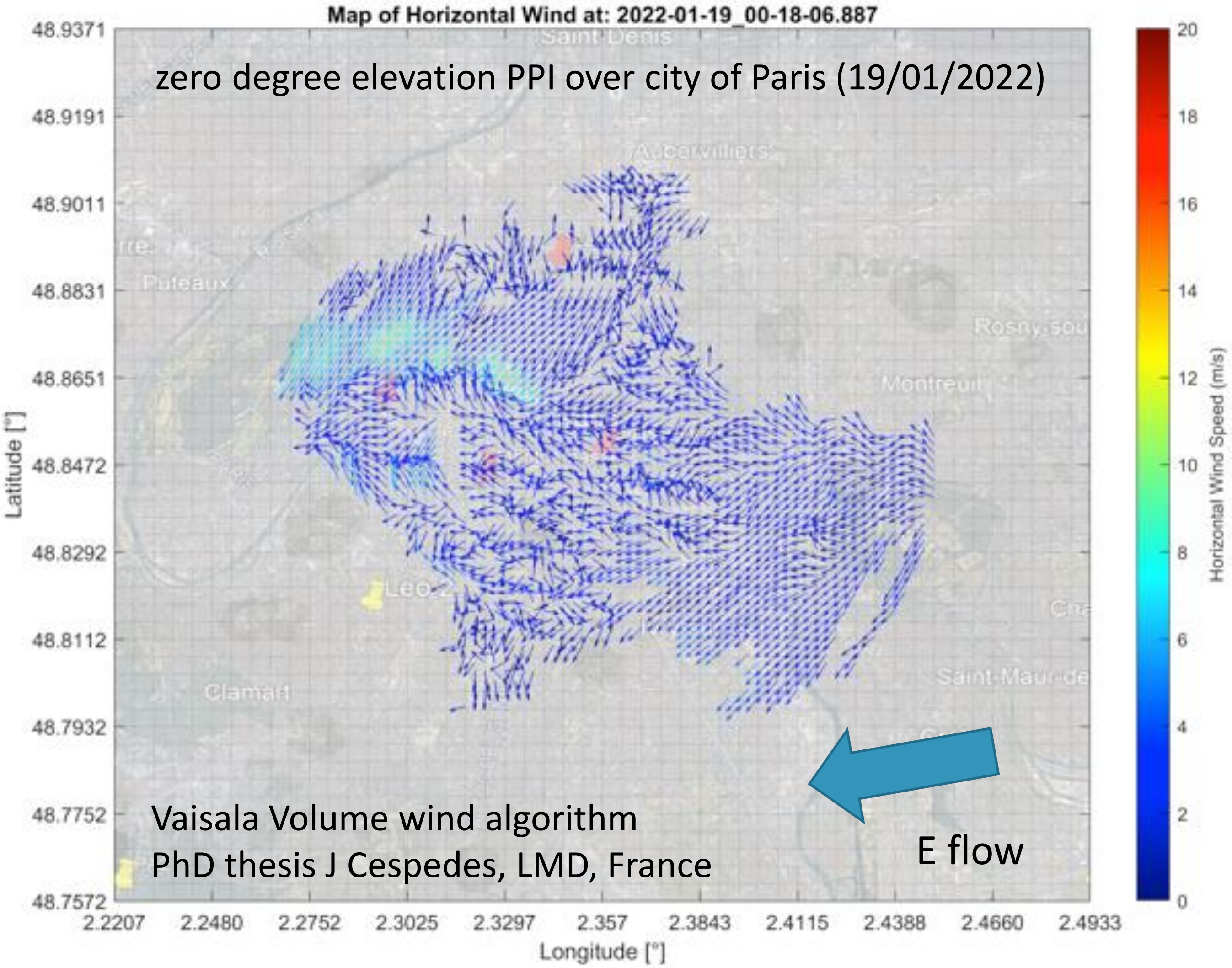
3D wind helpful to characterise
- ventilation pathways (e.g. along river)
- drainage flow
- UHI circulation



Scanning across river Thames, London: clear acceleration
(Wood et al. 2013)

Wind profile for evaluation of surface morphology parameterisations
(Kent et al. 2017)





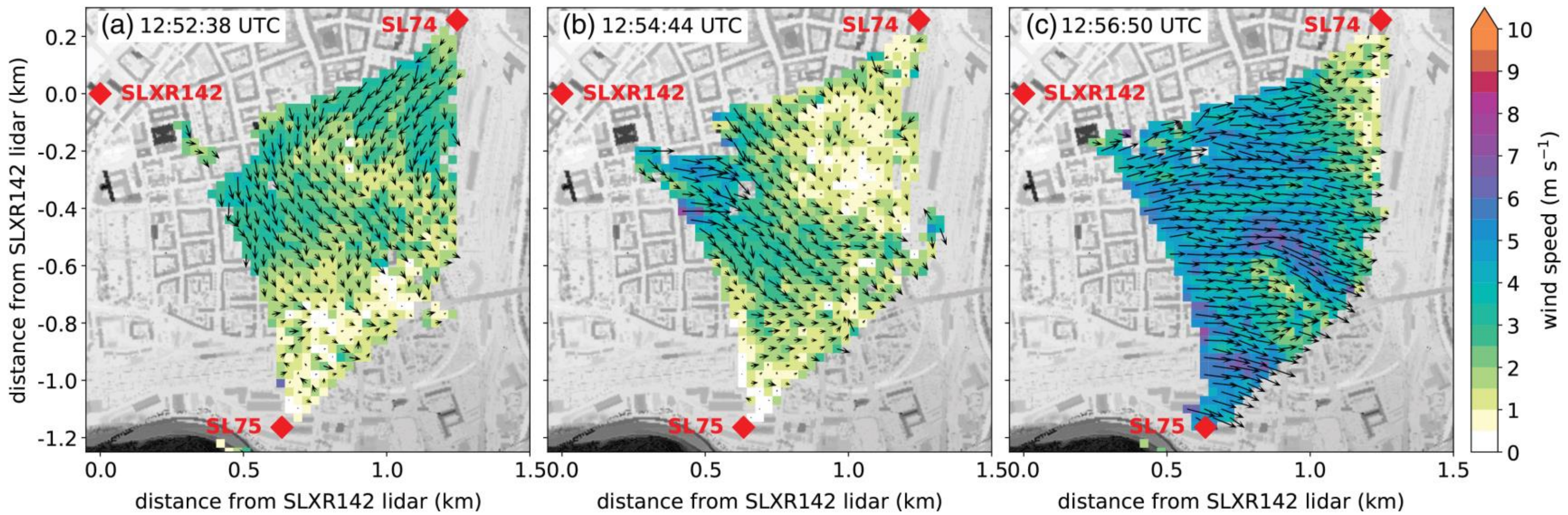
zero degree elevation PPI over city of Paris (19/01/2022)

Vaisala Volume wind algorithm
PhD thesis J Cespedes, LMD, France

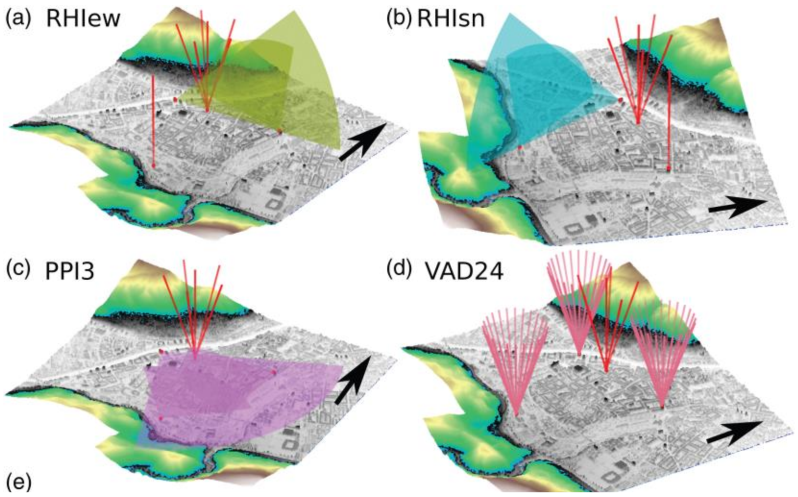
E flow

Wind field in the UBL

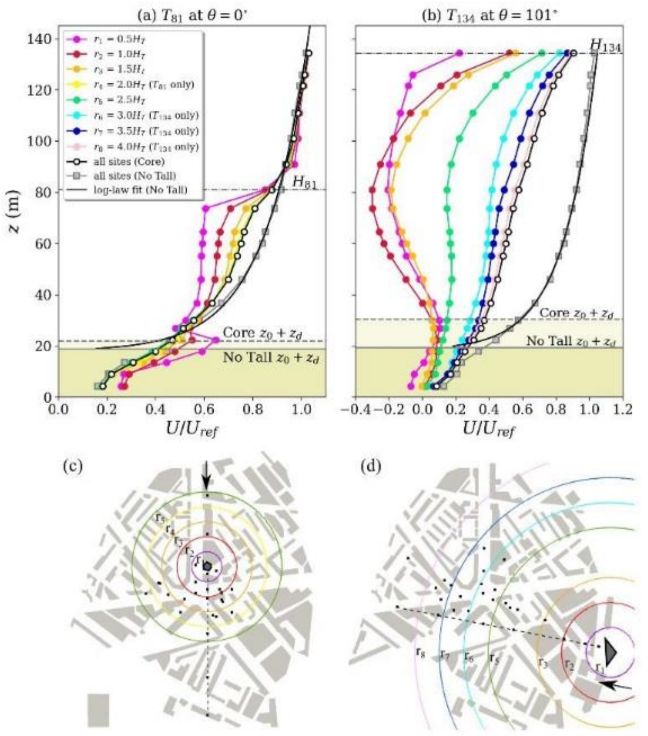
Foehn – cold pool interactions over Innsbruck (Haid et al. 2019)



3D wind field can also be obtained by combining multiple DWL



Wind tunnel modelling London (Hertwig et al. 2021)



To evaluate urban LES or wind tunnel modelling, DWL with high range resolution but limited extent are required

→ Observations start to become available

Profiling the ABL

Aerosol

Aerosol lidar
- High-power lidar
  - Elastic backscatter lidar
  - Raman lidar
- **Automatic lidars and ceilometers (ALC)**

Doppler lidar (after focal correction)

Monitoring aerosols

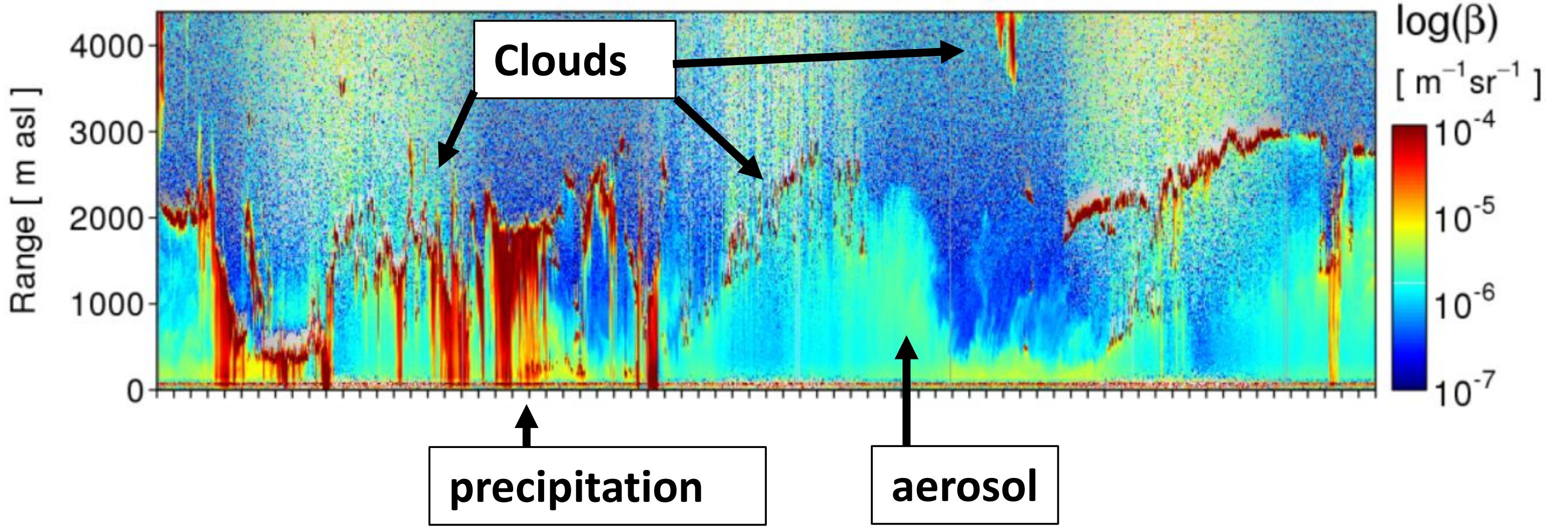
Backscatter coefficient β   Extinction coefficient α

Recorded signal *P*

$$P(z) = C_L \frac{\beta(z)}{z^2} \exp\left\{-2\int_0^z \alpha(z')\mathrm{d}z'\right\}$$

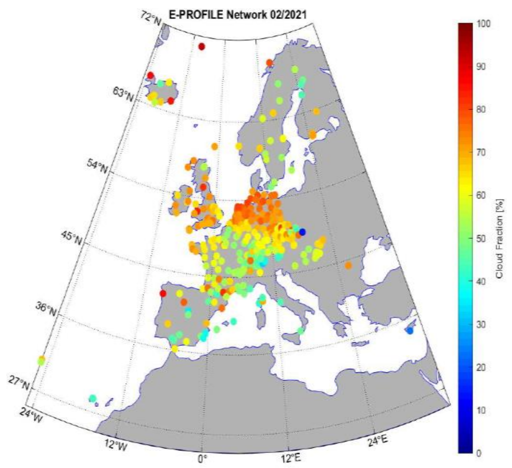
"lidar equation"

Distance from sensor z   Lidar constant C_L



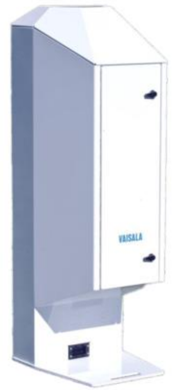
Automatic lidars and ceilometers (ALC)

- ALC: automatic lidars (aerosol profiling) + ceilometers (CBH recorders)
- *Simple* aerosol backscatter lidar with low maintenance
- Common ALC wavelengths: 532 nm, 910 nm, 1064 nm
- Some with depolarisation channel (distinguish liquid/solid, dust/smoke/ash/pollen)
- Capabilities, data quality, advanced products differ between models
- Limitation: Lower SNR compared to research lidars



EUMETNET E-PROFILE

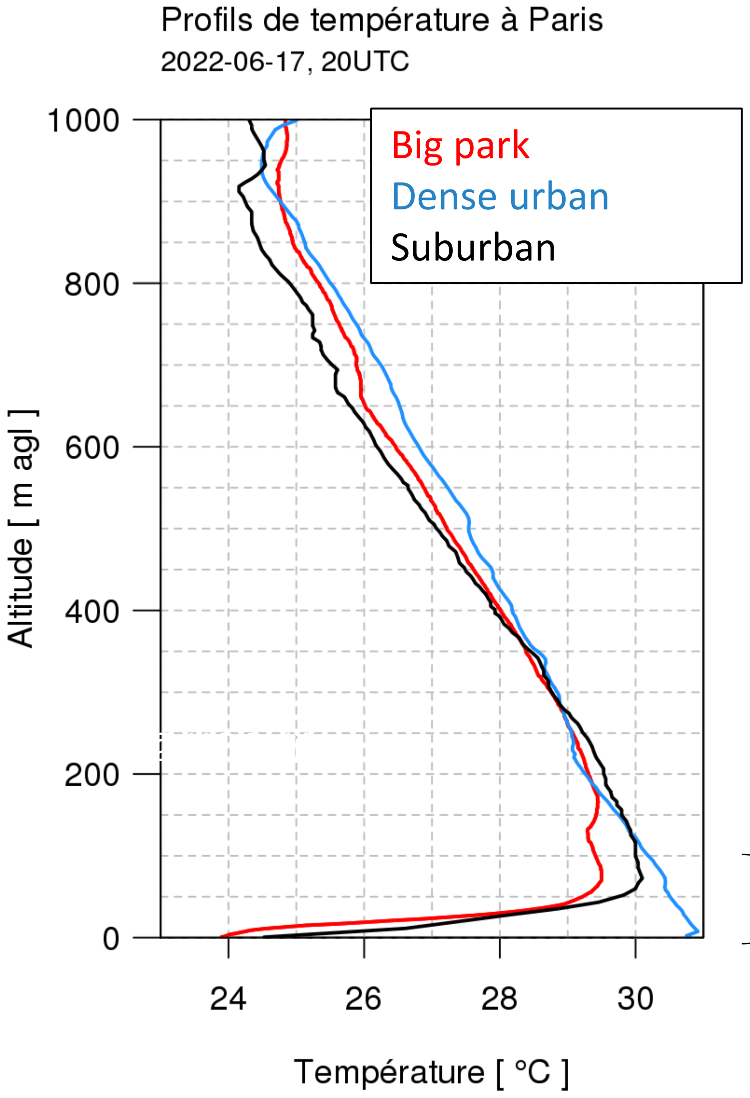
- Capabilities:
  - Continuous, automatic data acquisition
  - Most-widely deployed ABL profiler (> 400 organised in EUMETENET E-PROFILE network)
  - Complete optical overlap at few tens/few hundreds of meters



Examples of UBL profiling applications

1. ABL heights and characterisation
2. Low-level jet
3. UBL dynamics during summer heat event

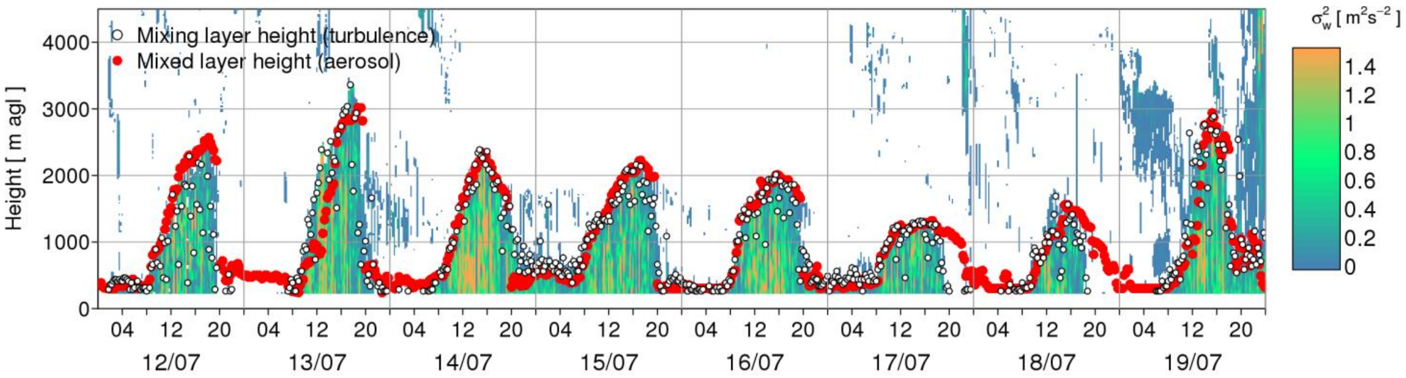
In-situ profiling

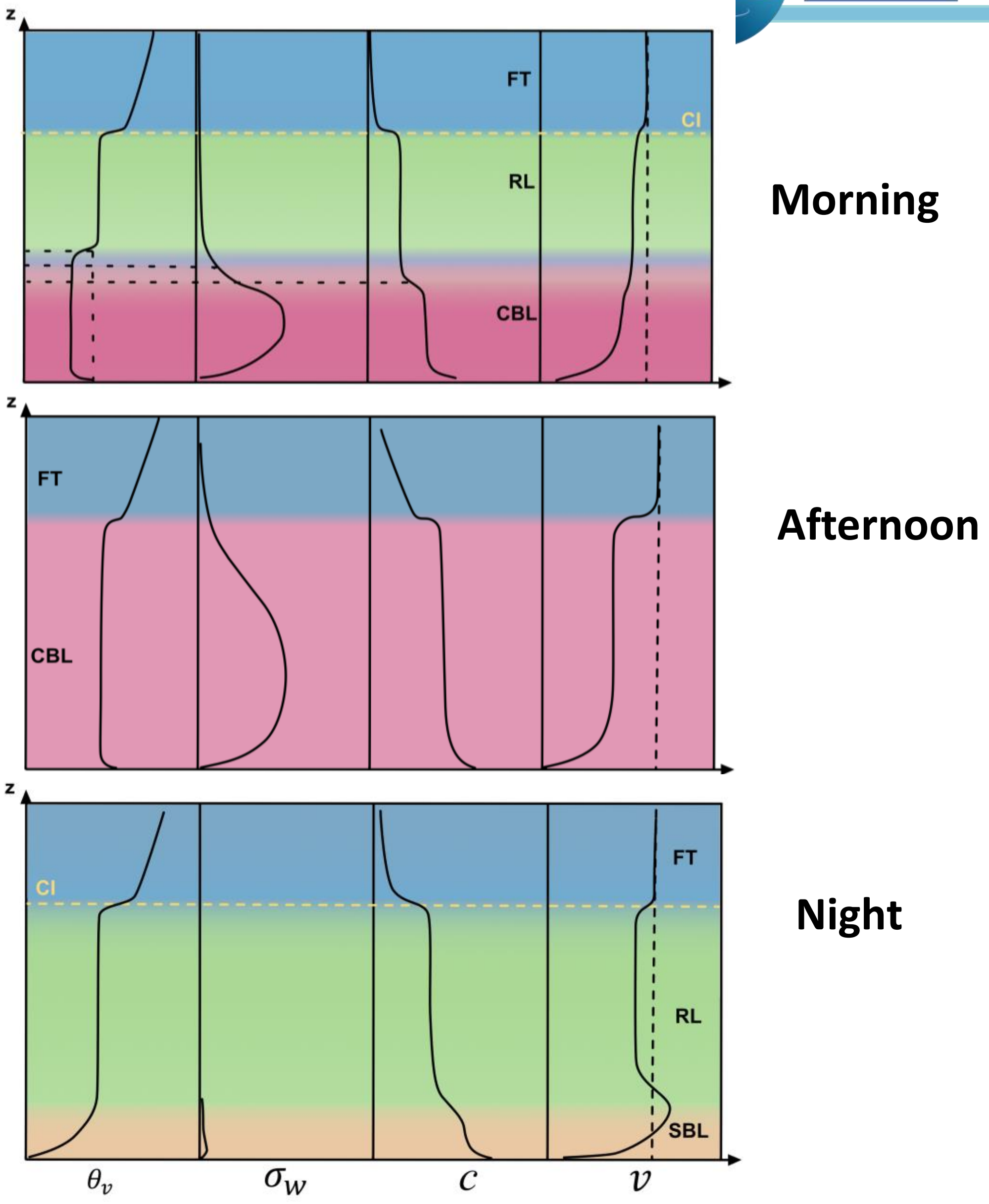


How strong/deep is the cooling effect of large green spaces?

Characterising the ABL

- Heights of the ABL sublayers can be inferred from atmospheric profile observations
- Ground-based remote sensing data particularly useful due to continuous observations
- See review on ABL height detection from ground-based profile data: Kotthaus et al. (2022)

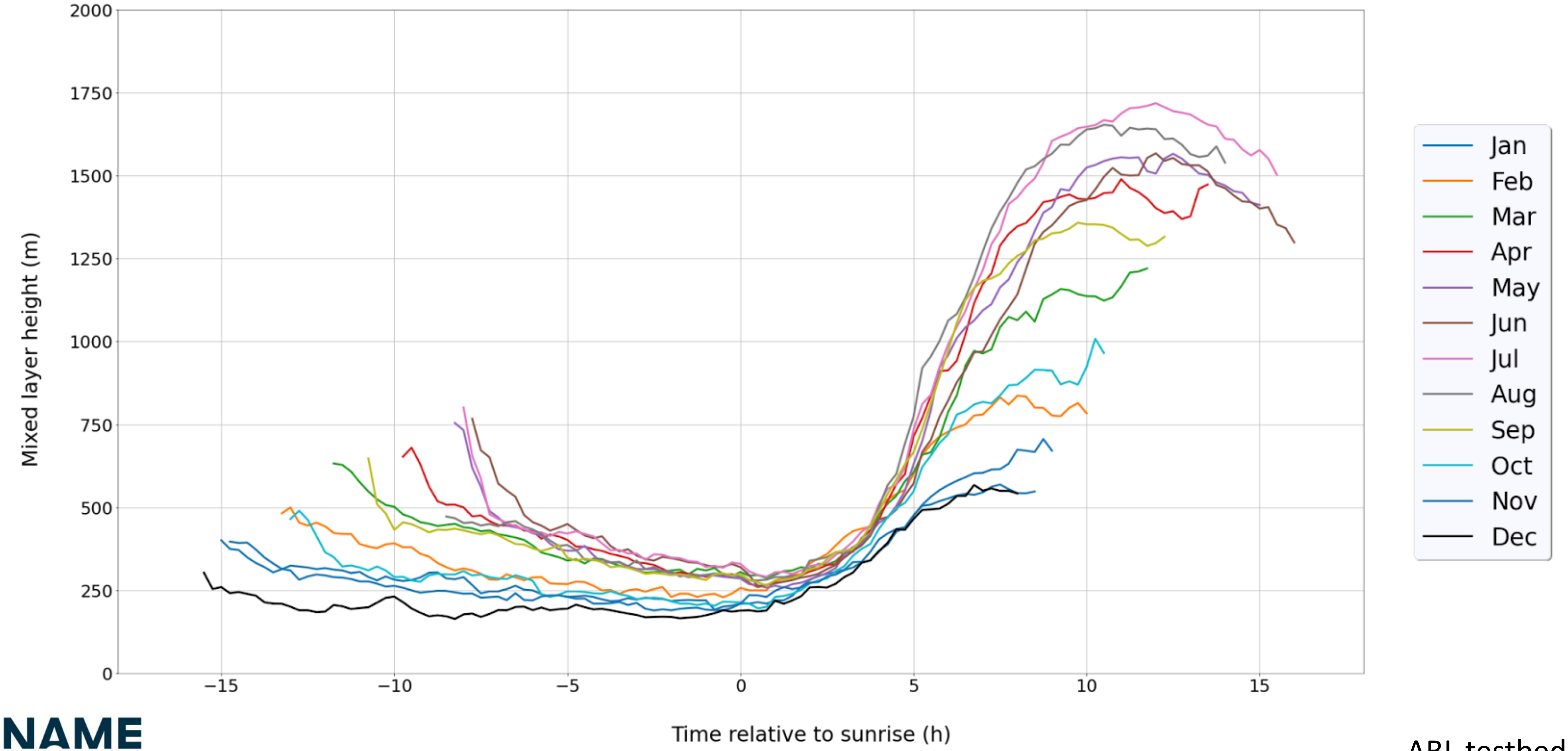




- Layer heights depend on atmospheric quantity analysed
- Sensor sensitivity and vertical resolution in respective range is key
- Synergy studies and applications that combine multiple profiles are especially valuable

Boundary layer height detection

Monthly median diurnal cycle of mixed layer height (MLH) over suburban Paris (2010-2021)



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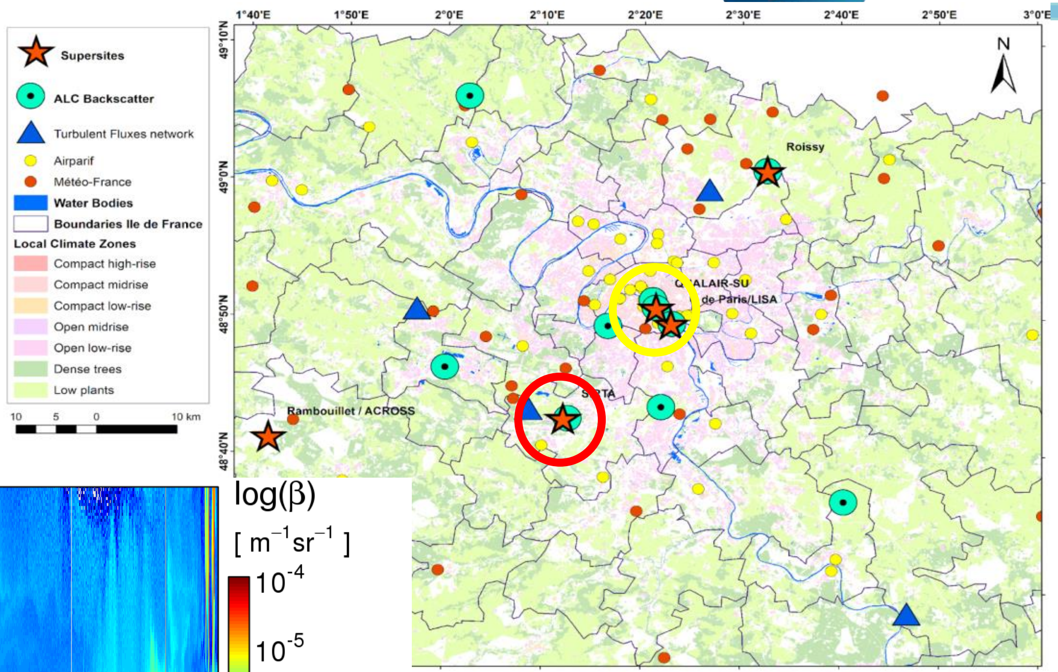
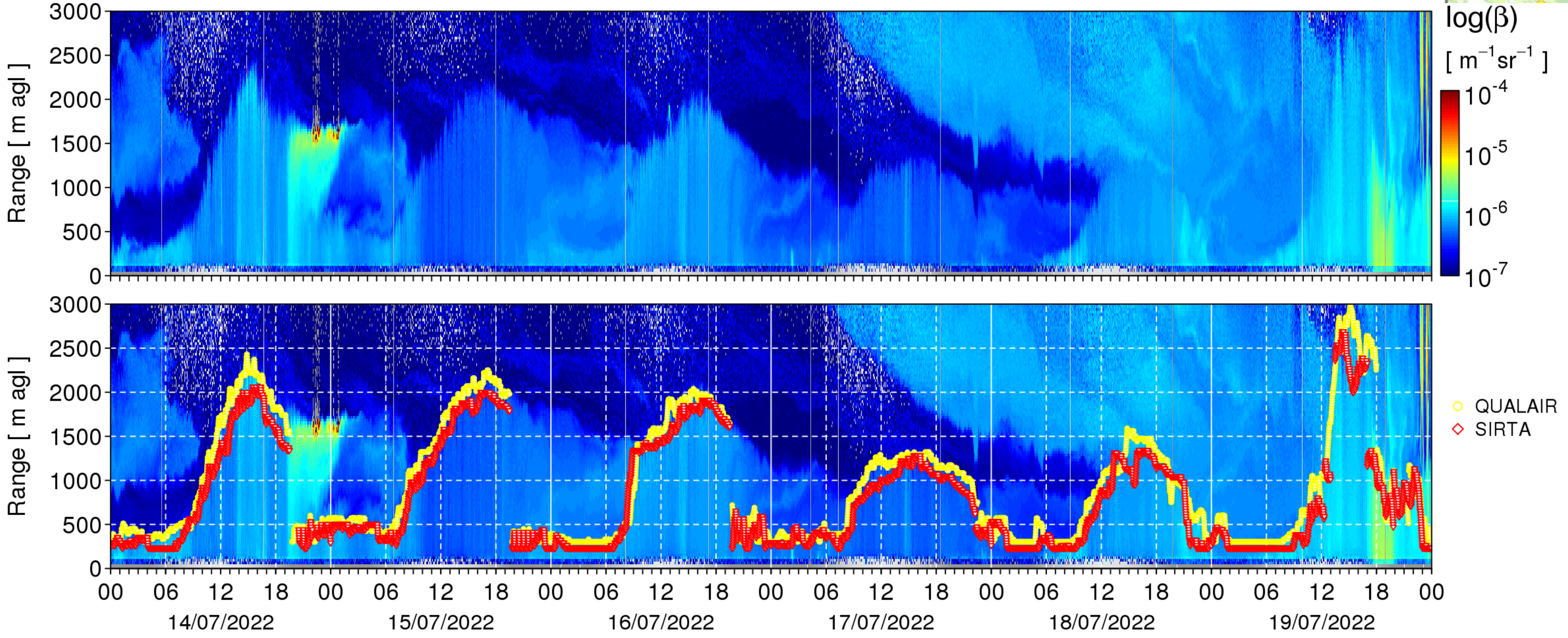
ABL testbed - Paris

Intra-urban variations in UBL dynamics

- Automatic retrieval of MLH from ALC backscatter profiles: *ABL testbed - Paris*
- Daytime MLH over city > suburban site (~ 30 km SW)
- Now studying role of topography, urban heat, surface roughness





Paris: high-density network of ABL profiling sensors (ALC, DWL,MWR, DCR, DIAL)

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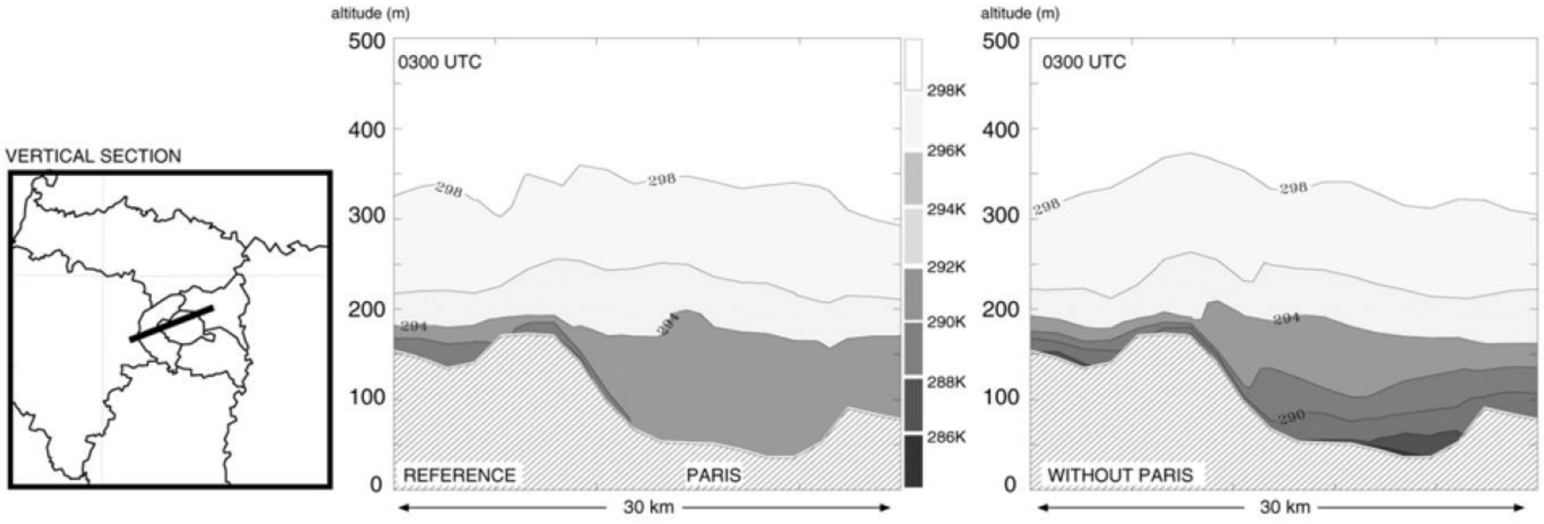
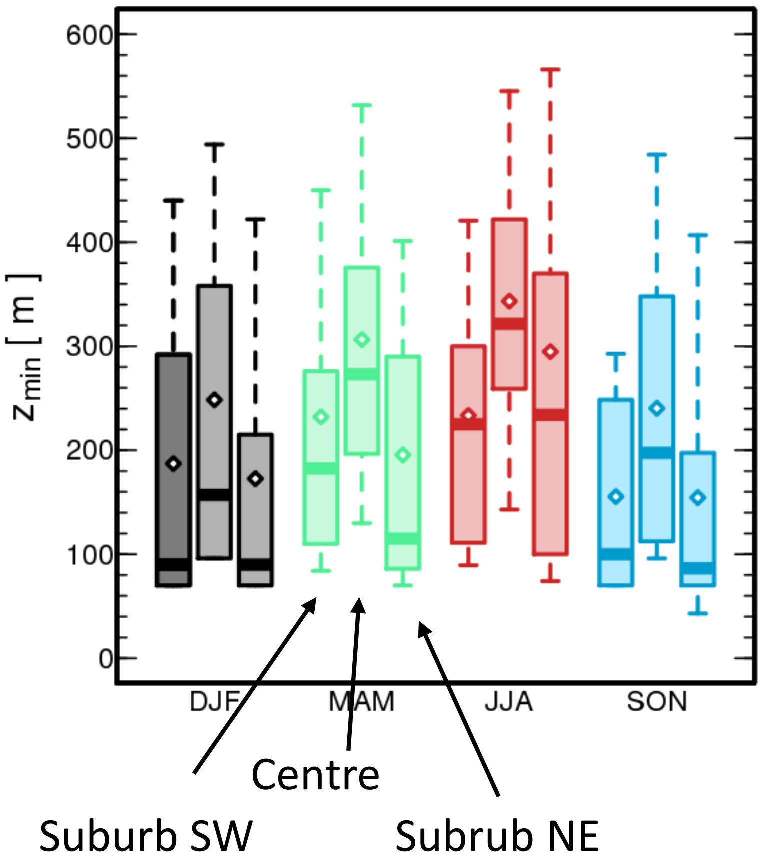
Intra-urban variations in UBL dynamics

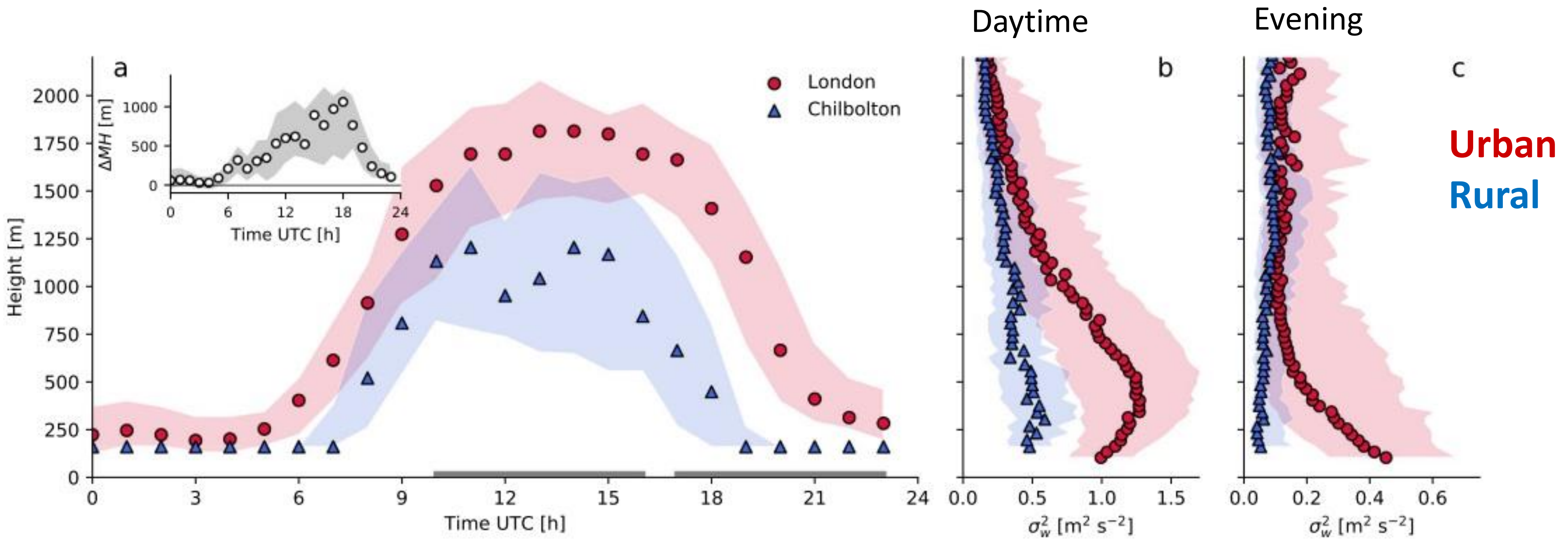
- Paris: urban increment in shallow layers heights ~depth of Seine river valley (120-150 m)
- Layers do not follow terrain
- In agreement with modelling studies (Lemonsu and Masson 2002): urban heat reduces nocturnal cooling





Characterising UBL buoyancy

- Vertical velocity variance (e.g. DWL): direct measure of turbulent exchange
- Enhanced buoyancy over large cities (London, Paris) leads to urban increment in mixing height
- Also cloud base height is higher over the city
- Vertical mixing maintains convective cloud activity over London and Paris in afternoon



(Theeuwes et al. 2019)

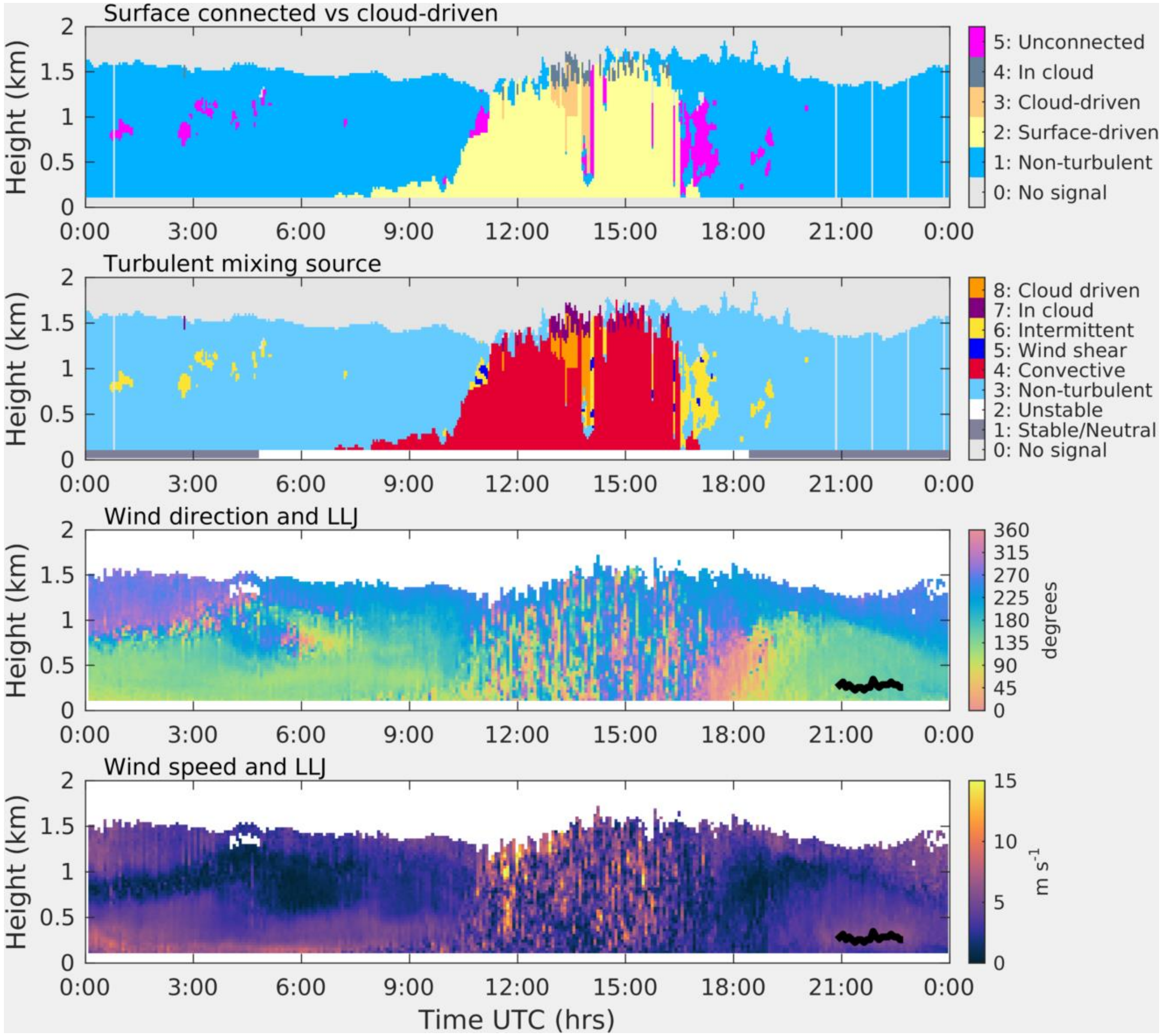
ABL characterisation

Automatic ABL classification from advanced DWL products

- Mixing region
- Connected to surface?
- Turbulent source
    - Surface-driven
    - Cloud-driven
    - Shear-driven

Products:

- Winds,
- wind shear,
- skewness,
- Eddy dissipation rate
- LLJ detection



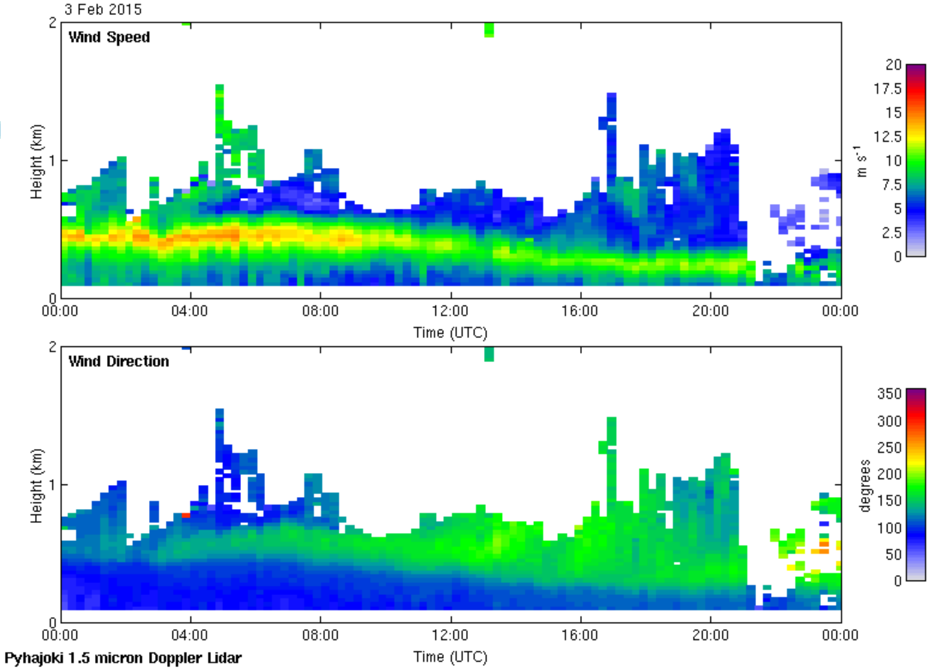
Manninen et al. (2018), Kotthaus et al (2022)

Examples of UBL profiling applications

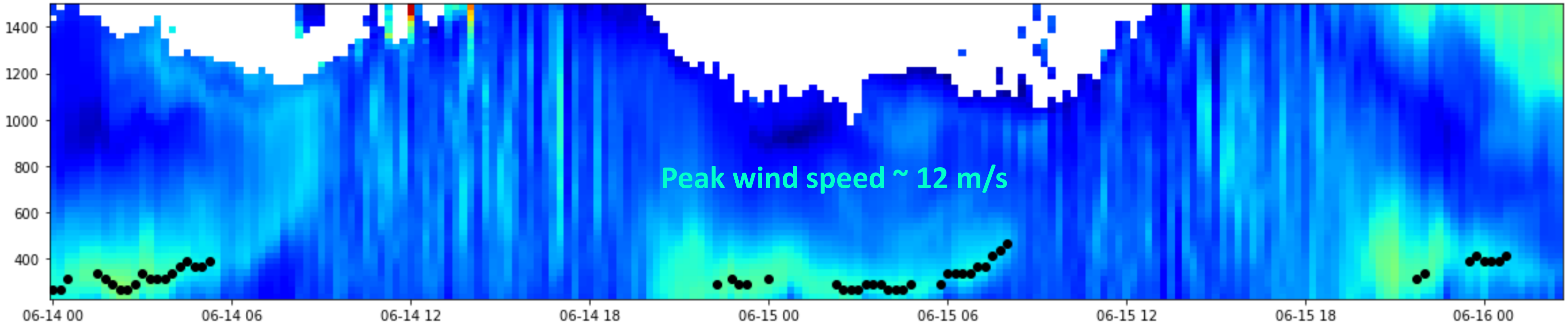
1. ABL heights and characterisation
2. **Low-level jet**
3. UBL dynamics during summer heat event

Low-level jet (LLJ)

- Regional scale phenomenon
- High wind speeds and wind shear in low layers when flow 'decouples' from surface roughness influence
- *Super-geosptrophic* wind speed possible
- LLJ receiving increasing attention with high resolution urban modelling (LES, NWP)
- Implications for UBL dynamics, transport of heat & pollutants

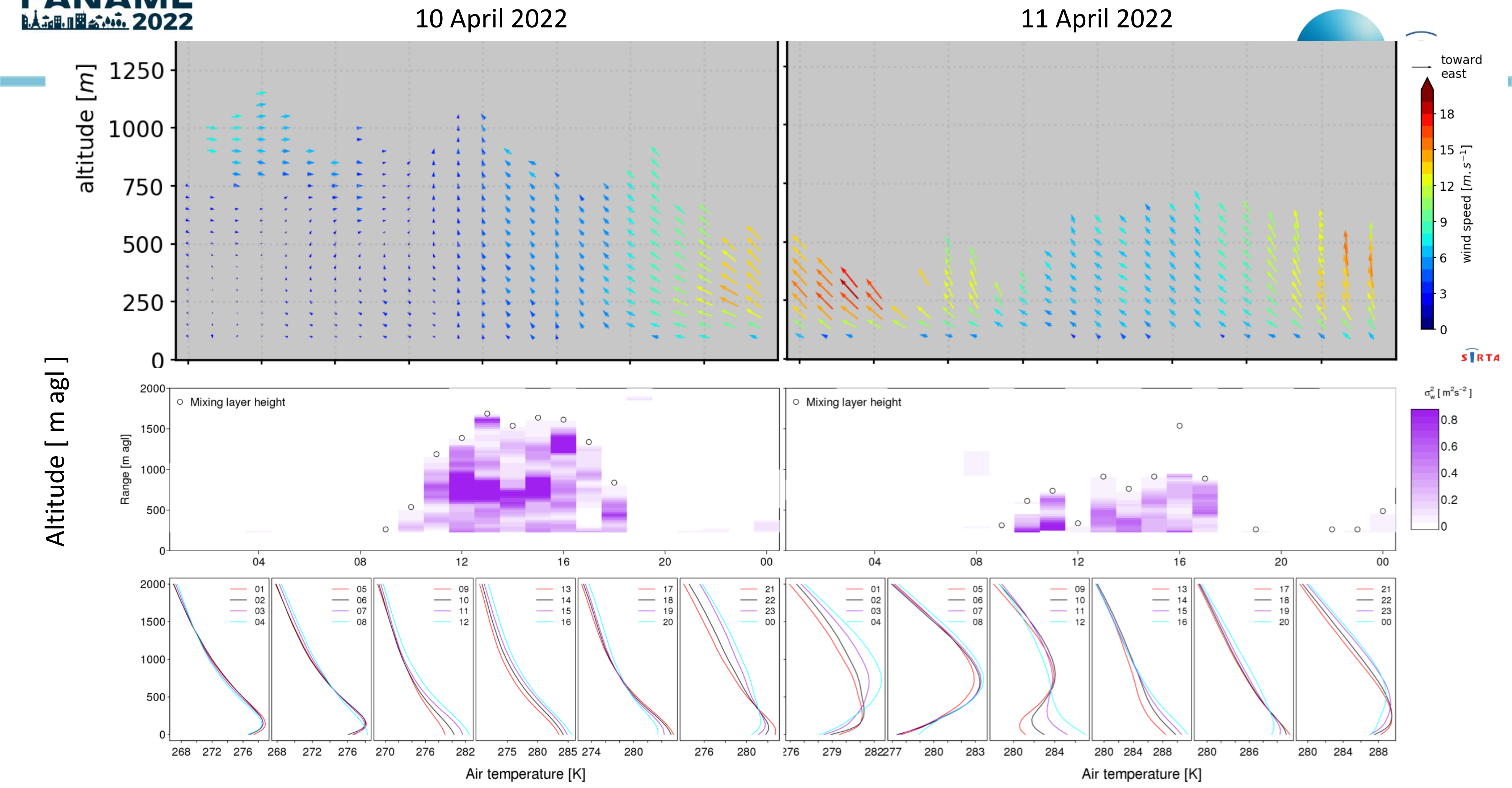


Automatic LLJ detection: Tuononen et al. (2017)



PhD thesis J Cespedes, LMD, France

PANAME 2022

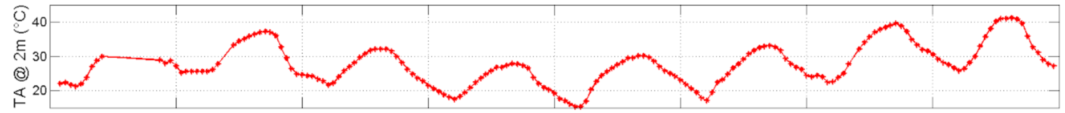


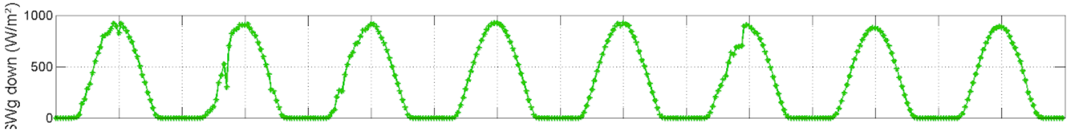
10 April 2022
11 April 2022
altitude [m]
toward east
wind speed [$m.s^{-1}$]
SIRTA
Altitude [m agl]
Range [m agl]
Mixing layer height
σ_w^2 [m^2s^{-2}]
Air temperature [K]

Examples of UBL profiling applications

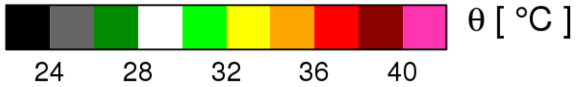
1. ABL heights and characterisation
2. Low-level jet
3. **UBL dynamics during summer heat event**

Paris summer '22 heat event

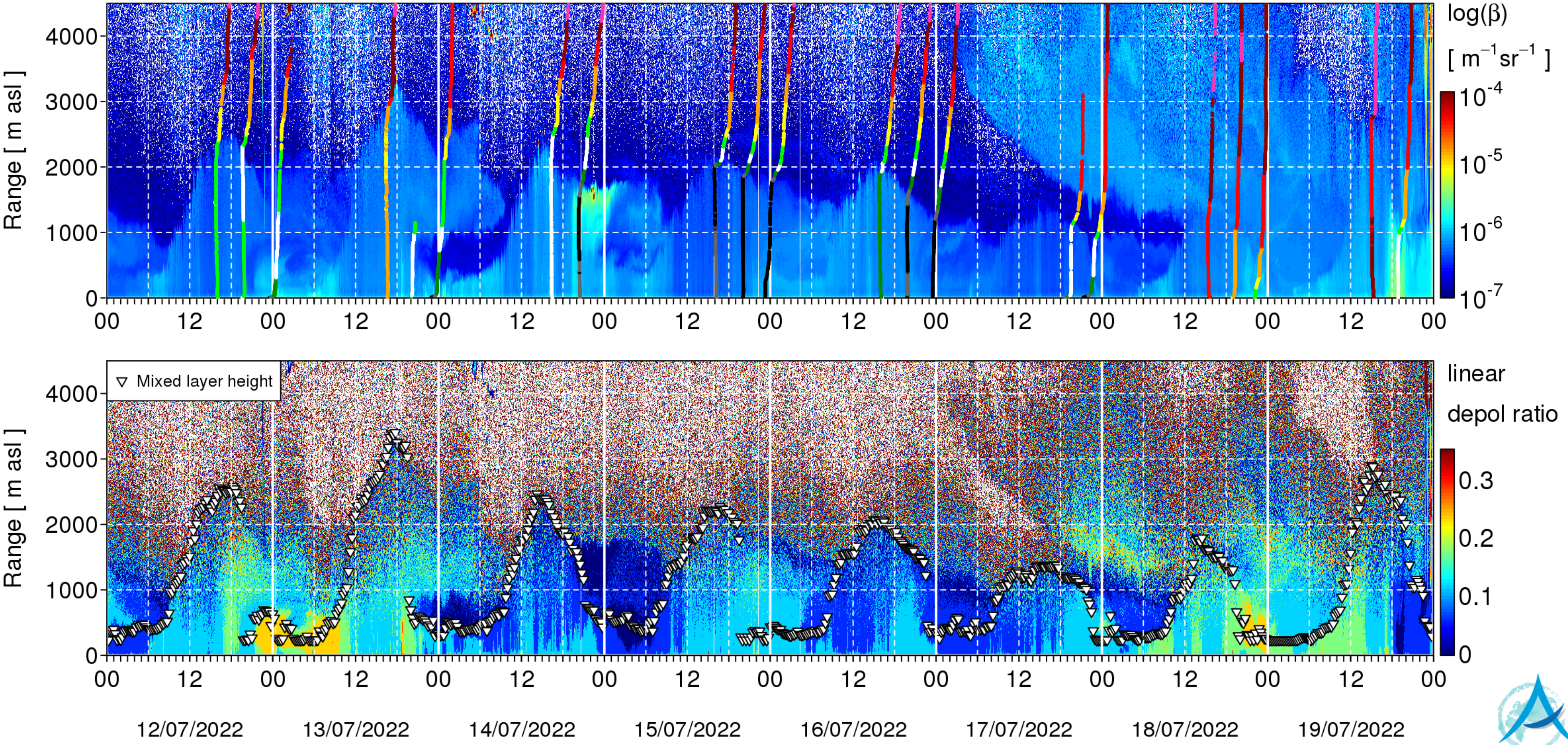




ALC central Paris
+ balloon ascents



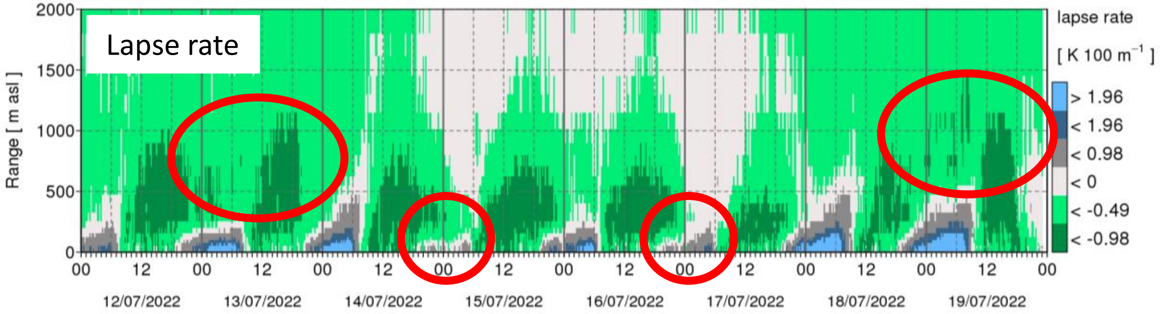
PANAME 2022



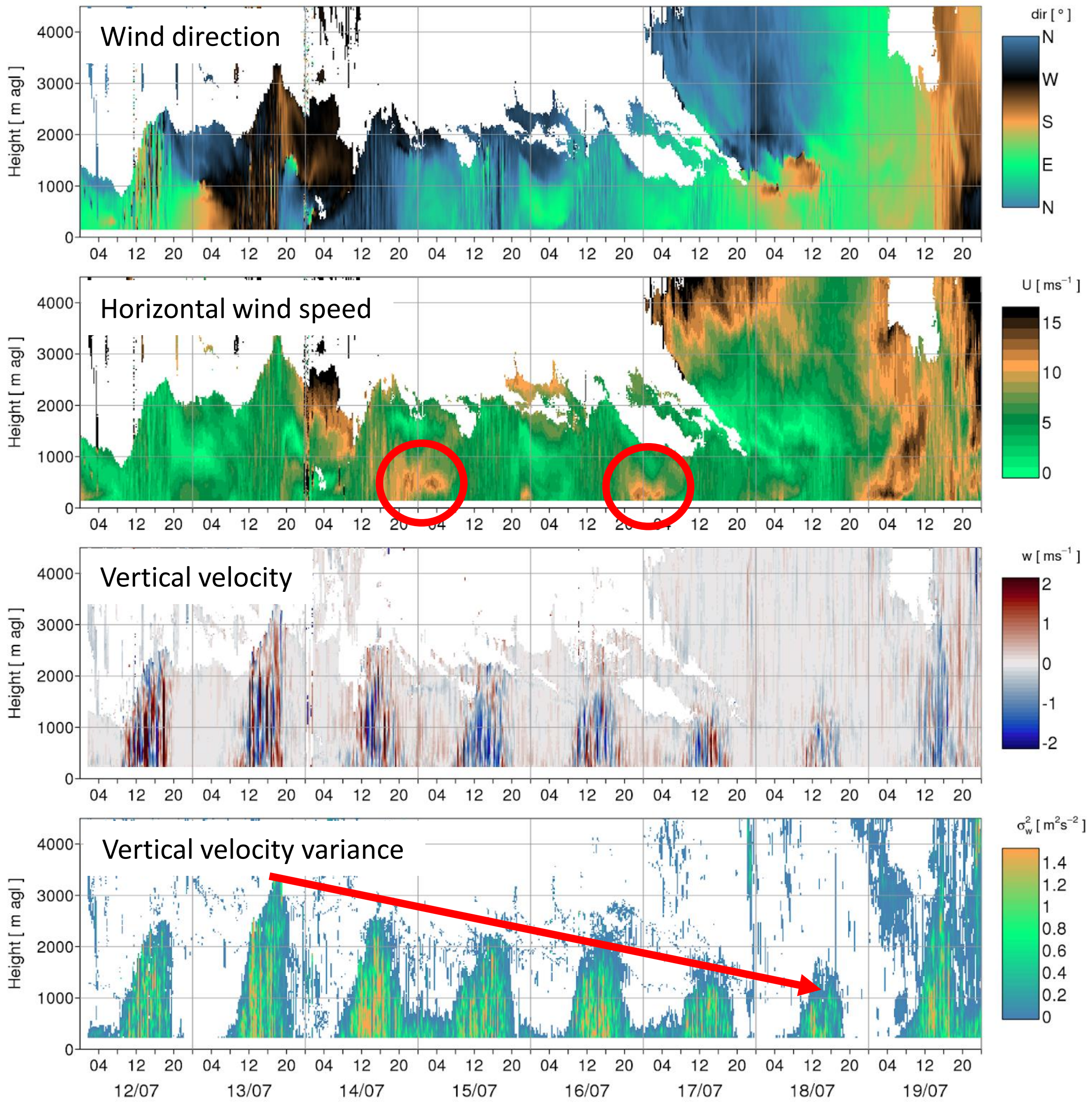
AERIS

Process studies: synergy application

MWR suburban



DWL urban



- Synergy of multiple measurements very useful for process understanding
- Nights with LLJ enhanced mixing, neutral thermal stratification
- MLH development according to turbulent activity driven by temperature lapse rates
- Advection of hot air above ABL supresses MLH development on 18th and favours explosive growth on 19th

Resources

Review article on ground based remote sensing instruments and boundary layer retrievals: Kotthaus et al.: *Atmospheric boundary layer height from ground-based remote sensing: a review of capabilities and limitations*, AMTD, https://doi.org/10.5194/amt-2022-14

PROBE COST Action on Profiling the atmospheric boundary layer at European scale

Subgroups on *Urban Environments* and *ABL characterisation*

https://www.probe-cost.eu/

ABL testbed (AERIS, IPSL, ICOS, ACTRIS, E-PROFILE)

https://ablh.aeris-data.fr

Automatic ABL height retrievals from diverse ground-based remote sensing networks

PANAME: initiative to promote collaborations & develop project synergies on Paris urban environment research