



Urban modifications of boundary layer heights along a ceilometer transect through Paris

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Abstract. Atmospheric boundary layer (ABL) processes over cities impact the distribution and advection of pollutants, moisture and heat. To investigate urban modification of BL dynamics we deploy seven automatic lidar-ceilometers along a 100 km transect upwind, across and downwind of Paris, for clear days with consistent synoptic flow conditions. The average growth rate (GR) varies between days, but on average consistently increases over the city (+ 21 %) and downwind (+ 23 %). The effect is most pronounced for the maximum GR. We observe an enhancement in the maximum mixed-layer height (MLH) over the city (+ 14 % and +28 %) and downwind (+ 15 % and +19 %) in summer and winter, respectively. Seasonal differences in the spatial extent of the downwind effect indicate they are greatest in summer (>60 km). The MLH at the start of the morning transition (MT) is deeper over the city (+ 12 %). However, the onset of the MT and the time of maximum GR show no clear link to their location on the transect. A key driver for the elevated MLH is found in the observed turbulent sensible heat fluxes, which are relatively stronger over the city, especially in winter and during nighttime.

1 Introduction

The atmospheric boundary layer (ABL) depth impacts air quality (Wang et al., 2021) and surface variables such as humidity and temperature (Stull, 1988), as it is indicative of the volume of air that pollutants, heat, moisture, momentum and scalars have for mixing (Seibert et al., 2000). Urban BL dynamics are very complex because of the large spatial heterogeneity in roughness, heat and moisture of an urban surface that alters the surface energy balance (SEB) and impacts flow characteristics (Halios and Barlow, 2018). The urban BL remains understudied (Muller et al., 2013; Barlow, 2014; Dupont et al., 2016; Barlow et al., 2017; Wang et al., 2024), as profile observations in cities are still relatively scarce. Forecasts of the BL height or, during daytime, mixed-layer height (MLH) are crucial for effective air quality predictions as the MLH development plays a key role in the distribution of near-surface pollutants (Dupont et al., 2016; Stirnberg et al., 2021). Given the same surface emissions and wind conditions a deep ML lowers pollutant concentrations, compared to a shallow ML (Yin et al., 2019). The morning transition period is important as high emissions occur during morning rush hours (Halios and Barlow, 2018).

MLH dynamics also interact with heatwaves in a city (Kong et al., 2021). During heat-wave conditions, the MLH is higher, as convection is intensified, but with additional warmer air entrained from above, the dilution effect is counteracted from the



deeper MLH (Miralles et al., 2014). The effect of urban BL modifications is not limited to within the city, but heat (Kittner et al., 2025) and pollutants (Stohl et al., 2003) can be advected downwind in an urban plume (Oke et al., 2017; Varentsov et al., 2018). Urban enhanced BL growth rates can trigger convection and increased convective precipitation over and downwind of cities (Liu and Niyogi, 2019), plus alter cloud cover (Theeuwes et al., 2019, 2022). Given these complex urban boundary layer modifications, comprehensive observational strategies are required to assess the magnitude of these effects under different situations and to test models. Reviews on research strategies for observing urban atmospheric processes (Barlow et al., 2017) and urban meteorological networks (Muller et al., 2013) highlight the need for multi-dimensional observations on different spatial and temporal scales.

Past field campaigns of urban boundary layer dynamics include short-term extensive studies, such as METROMEX in St. Louis (Auer, 1981) to year-long campaigns (e.g. BUBBLE (Rotach et al., 2005)). More recent studies in London include the ACTUAL (Barlow et al., 2015; Halios and Barlow, 2018), ClearfLo (Bohnenstengel et al., 2015; Kotthaus and Grimmond, 2018), and other projects Tsiringakis et al. (2022), Theeuwes et al. (2019) and Theeuwes et al. (2022). Other large city observational studies include those in Beijing (Wang et al., 2021; Huang et al., 2017; Hertwig et al., 2021), New York (Li et al., 2022; Rios and Ramamurthy, 2023), Delhi (Murthy et al., 2020) and Stuttgart (Zeeman et al., 2022).

Paris' urban climate studies have described effects on solar radiation, frost and fog days, as well as rainfall and wind (Escourrou, 1983, 1990). Investigations of the Paris UBL use a multi-year dataset observed at an urban fringe site (Pal and Haefelin, 2015; Cimini et al., 2020; Hertwig et al., 2021), plus a four-day campaign with four ALCs operating in urban, suburban and rural locations (Pal et al., 2012). Klein et al. (2019) used a lidar to study nocturnal ozone transport and vertical mixing during daytime development of the BL. More recently, nocturnal situations have a focus; the low-level jet (Céspedes et al., 2024) and thermal stratification's influence on park cooling and heat island intensity (Haefelin et al., 2024). Using modelling Forster et al. (2024) find an enhanced MLH, together with increased vertical velocities, affects cloud formation and leads to increased cloud cover over Paris. Additionally, this suggests that Paris can trigger deep convection and impact thunderstorm precipitation.

Whilst short-term observations may use numerous sensors, they can not capture seasonal variability. Conversely, long-term studies rarely collect multi-dimensional observations across scales. Within the *urbisphere* framework, the year-long *urbisphere*-Berlin campaign (Fenner et al., 2024) is an initial effort to address such limitations by bridging the gap of missing multi-scale, longer-term measurements. Building on this approach, and lessons learnt in Berlin, here we present results from the *urbisphere*-Paris campaign. Paris urban - suburban - rural MLH differences exist (Pal et al., 2012), it is evident that the heat (Kittner et al., 2025) and air pollution (Lian et al., 2023) urban influences extend beyond city boundaries, but may be city-specific and wind-speed dependent. Although chemical plumes downwind of cities are well-studied (Tulet et al., 1999; Dillon et al., 2002; Stohl et al., 2003), thermodynamic plumes and their implications are investigated less frequently.

Here we move beyond urban-rural differences to investigate urban-induced modifications to the ML along an ≈ 100 km long transect with seven instruments across the city plus up- and downwind rural surroundings. We investigate intra-urban differ-



ences by contrasting inner and outer city observations, as well as peri-urban (urban fringe) observations. Using a year-long dataset, upwind-city-downwind signatures are quantified along the transect, allowing seasonal variations of the ML modifications to be explored. We address the following questions:

(1) What are the differences in the average and maximum growth rate during the morning transition between city, upwind, and downwind locations?

(2) What are the differences in timing of the boundary layer evolution between city, upwind, and downwind locations?

(3) What are the differences in overall and maximum mixed-layer height between city, upwind, and downwind locations?

We address these questions, using 15-min observations from throughout the year. The transect is aligned with the dominant wind directions to run SW to NE. To capture surface-driven boundary-layer processes under (relatively) direct surface-atmosphere coupling with no cloud effects, we restrict the analysis presented here to daytime clear-sky conditions. We characterise the airflow using concurrently operating Doppler wind lidars (DWLs) also located along this transect (Morrison et al., 2025a). As BL processes are impacted by surface energy exchanges, we utilise data from five eddy-covariance towers operated over various urban and rural surfaces in the Paris region.

2 Methods

2.1 Study region and period

Across the Paris agglomeration (Île-de-France) there are 12 million people, of which over 2 million live within the city of Paris (Insee, 2025b). The population density, in 2022, was 3875 inhabitants per km² across the 2824 km² area (Insee, 2025a). With the closest coast to Paris about 150 km to the north, sea breeze circulations rarely impact the UBL.

The region has relatively flat topography, with the highest point 230 m above sea level (asl) (Fig. 1). While urban - topography induced effects have been neglected (Dupont, 1999), topography does influence vertical motions within the ABL (Troude et al., 2002) and may have implications for nocturnal low-level jet dynamics (Céspedes et al., 2024). Despite slight elevation changes, we expect urban effects from heat fluxes and roughness differences to dominate over the orographic effects, but do consider potential topographic influences in this analysis. Paris is surrounded by a homogenous mix of forest and agricultural areas (Fig. 1), with slightly more forest at the NE and more agriculture at the SW of the transect.

During the study period (March 2023 to February 2024), the prevailing wind direction was south-westerly (SW, 24 %), but with north-easterly winds occurring (NE, 14 %) (Eiffel tower wind rose, Fig. 1). Compared to the Climate Normal (CN, 1991-2020), the study year is wetter (820 mm cf. CN of 634.3 mm) (Météo France, n.d.a, n), on average warmer for both the minimum (10.6 °C cf. CN of 9.2 °C) and the maximum (18.1 °C cf. CN: 16.5 °C) and with more sunshine hours (1815 h cf. CN: 1717 h) (Météo France, n.d.a, n).

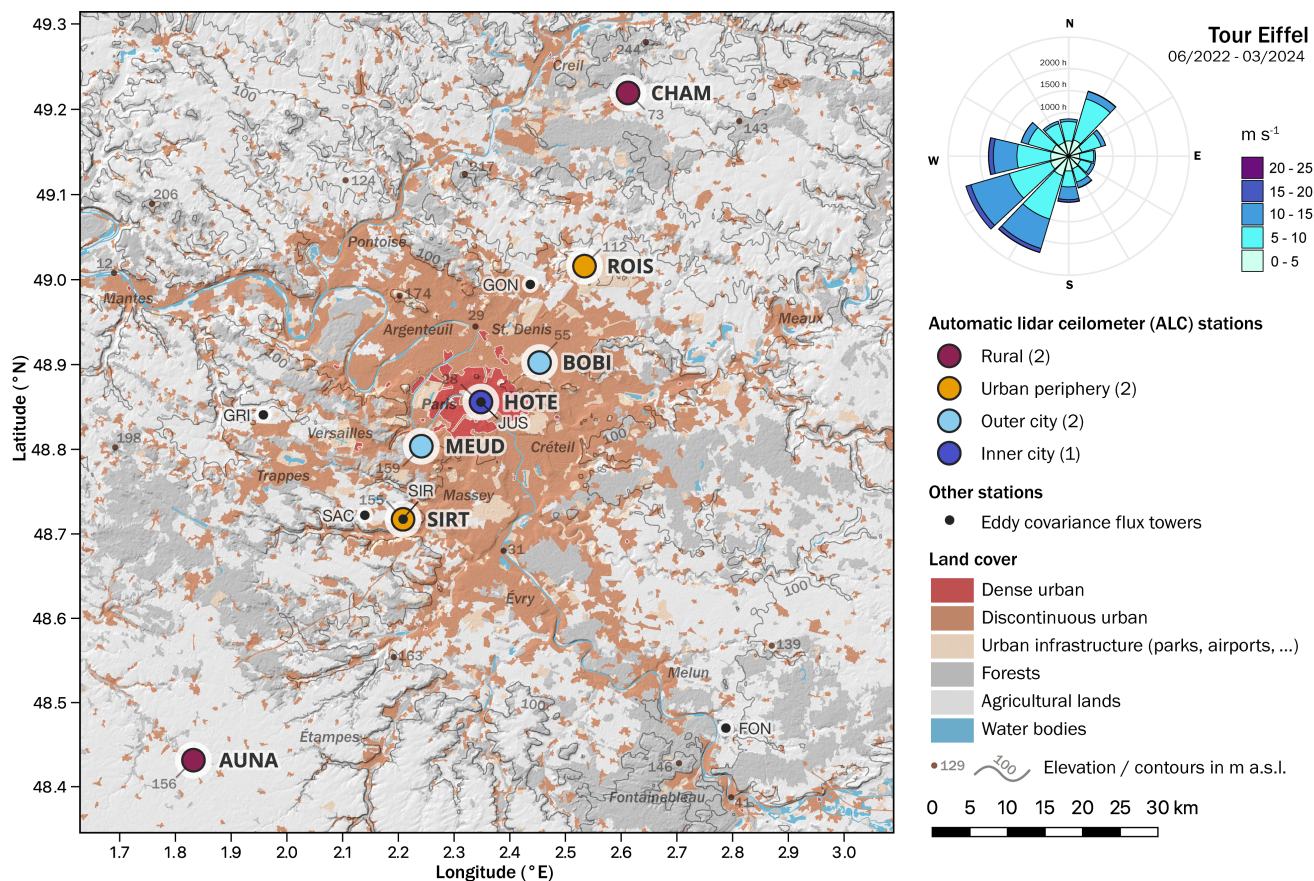


Figure 1. Transect of automatic lidar-ceilometer (ALC) sites (with colour indicating location type) across the Paris region aligned with the predominant wind (study period Eiffel Tower wind rose, Sect. 2.2.4) and other sensors (eddy covariance flux towers, Doppler wind lidar site (JUS)), plus land cover based on Corine (Copernicus Land Monitoring Service, 2019) and elevation. Section 2.2 provides more details about sensors and sites.

2.2 Observational layout and instrumentation

2.2.1 Transect of automatic low-power lidar-ceilometers (ALC)

The mixed-layer height (MLH) and growth characteristics of the morning transition (MT) are derived from seven Vaisala CL61 ALC installed along the SW to NE 105 km long transect (Fig. 1). The site characteristics (Table S1) vary between the rural and the densely built areas of central Paris. Oriented as a roughly linear transect SW-NE (214° to 34°, from N), it follows the predominant wind directions (Fig. 1), and is designed to allow detection of upwind-city-downwind changes. The ALC sites are classified dynamically by time step depending on wind direction into along- or across-transect cases. At the centre of the transect is the inner city site (HOTE). Two outer city sites, in the *banlieus* of Paris, to the SW (MEUD) and NE (BOBI) are



classified as upwind or downwind outer city, respectively as appropriate for NE or SW flows. Two up-/downwind urban fringe sites (SIRT, ROIS) are further out near the SW and NE ends of the contiguous built-up area. The rural sites transect endpoints are AUNA in the SW and CHAM in the NE (Fig. 1). For winds perpendicular to the transect ("across"), sites are classified as in or outside of the city, and either left or right of Paris city centre in the respective direction of the flow (Sect. 2.3).

The Vaisala CL61 ALC operate with a pulsed laser diode (910.55 nm). They provide vertical profiles of attenuated backscatter over a range of up to 15.4 km above the sensor with a vertical resolution of 4.8 m and a temporal resolution of 15 s (Vaisala Oyj, 2022). From the attenuated backscatter, the instrument derives multiple cloud variables for up to five cloud layers. Range- and overlap corrections are applied internally to the attenuated backscatter (Vaisala Oyj, 2022). Distance measurements are calibrated by the manufacturer (Vaisala Oyj, 2021). Looschelders et al. (2025) provide additional information on the characteristics and operating principle of the CL61. Post-field deployment intercomparison of the instruments (Looschelders et al., 2025) found good agreement, with their precision allowing spatial differences in attenuated backscatter, cloud variables and MLH to be resolvable. The 15-min median absolute difference of MLH between sensors is 0 m (Looschelders et al., 2025).

2.2.2 Detection of mixed-layer heights (MLH)

The MLH is derived using the STRATfinder algorithm to obtain 15 min values (Sect. SM S1.1), and used to determine the following 6 metrics (Fig. 2). The growth rate (GR) of the MT was quantified as both the overall GR (GR_{avg}) and the maximum GR (GR_{max}). The MT timing is derived using a non-linear least-squares regression model with a generalised logistic function and from this empirical thresholds (Sect. SM S1.1). The MT mean growth rate (GR)(GR_{avg}) is the average of the non-normalised derivative between MT_{start} and MT_{end} (Fig. 2). The maximum GR (GR_{max}) at time MT_{max} is the maximum derivative within the same interval (Fig. 2). The initial MLH (MLH_{start} , m) is the MLH at the start of the MT (Fig. 2). To ensure a representative value for inter-site comparisons, the maximum mixed-layer height (MLH_{max} , m) uses the median in the 14:00 - 16:00 period, to remove individual short-term peaks caused by turbulent fluctuations (Fig. 2).

Comparisons between sites use two approaches: a) *Count-based*: percentage of timesteps when MLH at Site A > Site B, undertaken for all station pairs. b) *Linear mixed-effects model*: As sample sizes can vary between sites due to administrative delays in deployment (Table S1) and temporary malfunctioning of sensors, a linear mixed-effects model (Bates et al., 2015) is used. This treats the date D as a random effect to allow day-to-day variability and location L as a fixed effect. For each variable, V, i.e. daily site mean MLH_{start} , MLH_{max} , GR_{avg} , GR_{max} , as well as the time of MLH_{start} and GR_{max} ; a model of the form $V \sim L + (1|D)$ is fitted. From the resulting model, marginal means ($\bar{m}$) are estimated (Lenth and Piakowski, 2026), allowing comparison between sites, while accounting for day-to-day variability (e.g. synoptic or seasonal influences). The differences in modelled means for variable V are reported as both an absolute and relative (percent) $V_x - V_y / V_y$ value.

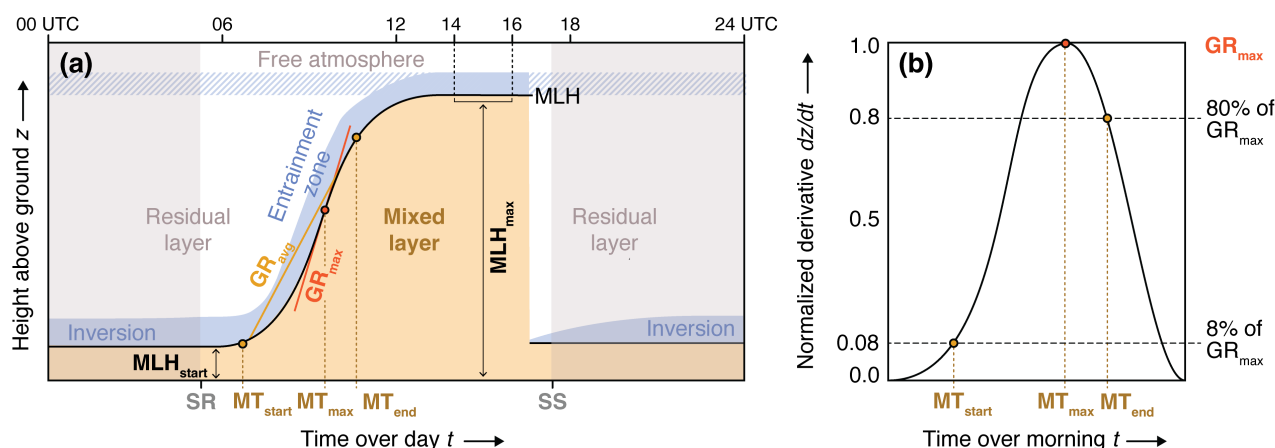


Figure 2. Idealised (a) mixed-layer height (MLH) evolution with solar times (SR: sunrise and SS: sunset), key timings including the start (MT_{start}) and end (MT_{end}) of the morning transition (MT), time of maximum growth (MT_{max}) and metrics including MLH at MT_{start} (MLH_{start}), average (GR_{avg}) and maximum (GR_{max}) growth rate (GR) during the MT, and maximum MLH (MLH_{max}) (Sect. 2.2.1) and (b) MT including empirical thresholds to determine MT_{start} and MT_{end} (Sect. SM S1.1).

2.2.3 Surface energy balance (SEB) fluxes

As SEB captures the energy exchanges between the surface and the atmosphere, they are indicative of the important dynamics driving the overlying mixed-layer (Stull, 1988). SEB observations undertaken at six eddy covariance (EC) sites in the Paris region (Fig. 1), provide turbulent latent (LE) and sensible heat (H) fluxes for representative land covers (Table S3) including dominant agricultural (GRI), grassland (SIR), forest (FON), suburban (GON) and dense urban (JUS) land cover in their footprint (Table S5). The city centre site FR-JUS is operated by ICOS cities (ICOS Ecosystem Thematic Centre, Bignotti, L., Loubet, B., Depuydt, J., Fortineau, A., Buysse, P., Coimbra, P., Viatte, C., Cailteau-Fischbach, C., Stagakis, S., Christen, A., Hilland, R., Nicolini, G., 2025), whilst the Met Office operated the Gonesse (GON) site NE of Paris. The SIRTa Observatory (Haeffelin et al., 2005) (SIR) long-term flux measurements and the Saclay plateau (Herig Coimbra et al., 2024) (SAC) tall tower sites are peri-urban sites in the SW. Rural sites include one in the Fontainebleau forest (FR-FON) (Delpierre et al., 2016) and another in Grignon (FR-GRI) over agriculture (Loubet et al., 2011). The operational data processing is described for each site in their respective references. Additional, analysis undertaken includes: exclusion of wind directions affected by flow distortions at the FON site, conversion to UTC (Tab S3); a common sign convention (positive (negative)- away (towards) the surface); and turbulent fluxes source areas are estimated (Sect. 2.3) following Kljun et al. (2015) (e.g. Fig. S2 - S7).



2.2.4 Doppler wind lidar (DWL) and other meteorological data

Boundary layer wind profiles are available from a DWL located in the centre of Paris (JUS, Fig. 1). Details of the sensor, site characteristics, and harmonisation of the data are described in (Morrison et al., 2025a). Météo-France's 2D ultrasonique Thies anemometer located 321.5 m above ground level on the Eiffel Tower is used to identify wind sectors. We use DWD's Hess and
150 Brezowsky (1969) synoptic classification (James, 2007).

To assess soil moisture state as a proxy for water availability, the SIRTA Observatory Delta-T ThetaProble ML2X sensor in 10 cm depth (Haeffelin et al., 2005) and Météo-France Park Montsouris precipitation data are used. Urban heat island (UHI) magnitude is determined using air temperature measurements at Nangis (rural) and Rue Royal (urban) (Météo France,
155 2024, 2025).

To determine the extent and direction of the chemical NO₂ plume from Paris, Copernicus Sentinel-5P satellite sensor TROPOMI (Tropospheric Monitoring Instrument) is used to analyse the tropospheric column densities (Veefkind et al., 2012). The daily 5.5 km x 3.5 km spatial resolution NO₂ product (processor version 2.5.0) is available at around noon. We apply the QA recommended filter of > 0.75 (Eskes et al.). To characterise typical urban surface-level NO₂ and PM₁₀ concentrations we
160 use the Airparif urban station PA15L (Paris stade Lenglen) (Airparif, 2025).

2.3 Case study and ensemble average characterisation

Given our focus on surface-driven urban modifications of the MLH, without cloud-surface feedbacks, we analyse clear-sky days when relatively direct surface-atmosphere coupling is expected. Following Morrison et al. (2025b), incoming shortwave
165 radiation is manually inspected to identify days with no or very few clouds. To detect along or across transect differences wind direction sectors (Table 1) with the city centre DWL (JUS) data analysed from 1 h after sunrise to 0.5 h before sunset, for gates between 300 m above ground level (agl) and the $\approx$ top ALC MLH (of sites used). Consistent flow criteria is met when >50 % of this part of the vertical profile wind data originate from one wind sector (Table 1). During the year-long study period, 25 clear-sky days had consistent along-transect winds (SW or NE) for analysis of the ensemble average. For both summer (S)
170 and winter (W), we select two along- and one across-wind days to analyse seasonal differences. Note the **W1** day, a SW winds case, but for slightly <50 % of the time. For the across-transect day **S3**, the flow is more easterly (83 °) than south-easterly. We astronomically split the year using the equinoxes (March 20, September 23) into summer and winter. In this analysis, all times given are Coordinated Universal Time (UTC).



Table 1. Station codes for different flow regimes. Weather conditions during the campaign. Wind direction at 300 m agl from Eiffel tower measurements (Sect. 2.2.4). Number of days when > 50 % wind observations from each sector (all: Eiffel tower data; clear: DWL data). Definitions (e.g. clear sky) see Sect. 2.3. Not considered were 204 (40 clear) days with a mixed flow regime.

Along-wind cases			Across-wind cases		
Wind direction	NE	SW		NW	SE
	11.5°–56.6°	191.5°–236.5°		229.5°–337.5°	112.5°–157.5°
upwind rural	CHAM	AUNA	left rural	CHAM	AUNA
upwind urban fringe	ROIS	SIRT	left urban fringe	ROIS	SIRT
upwind outer city	BOBI	MEUD	left outer city	BOBI	MEUD
inner city	HOTE	HOTE	inner city	HOTE	HOTE
downwind outer city	MEUD	BOBI	right outer city	MEUD	BOBI
downwind urban fringe	SIRT	ROIS	right urban fringe	SIRT	ROIS
downwind rural	AUNA	CHAM	right rural	AUNA	CHAM
No. of days (all)	30 (10%)	81 (22%)		25 (7%)	16 (5%)
No. of days (clear sky)	19	6		1	6

175 3 Results

We explore urban effects separately for wind along and across the transect (Sect. 2.2.1) on the mixed later height (MLH), and surface heat fluxes characteristics both for individual days, and across the six case study days (Sect. 3.1), before looking at an ensemble average of all clear sky days with along transect wind for the MT (Sect. 3.2.1), and MLH throughout the daytime (Sect. 3.2.2) and by season (Sect. 3.2.3).

180 3.1 Six typical days

Six days are chosen for their season (winter or summer) and for three wind directions relative to the transect (Table 2). Although associated with different synoptic conditions (supplementary material (SM) Sect. S1.2), five out of the six days occurred during anticyclonic conditions, giving clear skies.

The three summer days (**S1-S3**) have:

185 (a) *Northeasterly (NE) winds along transect on 5 June 2023 (S1)*: On a mostly clear-sky day with consistent NE wind, after more than 20 days without rain, the soils are relatively dry (Table 2, Fig. S9). A narrow tropospheric NO₂ plume aligned perfectly with the ALC transect (Fig. 3), extending southwest for ≈100 km from the city centre.

(b) *Southwesterly (SW) winds along transect on 10 July 2023 (S2)*: With the wind from the SW the up-/down-wind sites are reversed cf. **S1** (Table 1). Although **S2** winds are weaker (2.6 cf. 7.2 m s⁻¹), a downwind NO₂ plume is evident (Fig. 3) also
190 extending for ≈100 km but to the E/NE of Paris with more lateral spread.

(c) *Easterly (E) winds across transect on 3 May 2023 (S3)*: The consistent easterly winds, perpendicular to the transect, had



speeds similar to **S1** (Table 2). A NO₂ plume extends 120 km downwind to the W of Paris (Fig. 3).

The three snow-free winter days (**W1-W3**), with clear skies.

- 195 (a) *NE winds along transect on 11 January 2024 (W1)*: The coldest day had widespread air pollution, superimposed on the urban NO₂ plume (Fig. 3).
- (b) *SW along transect 16 January 2024 (W2)*: This day had a few high-level clouds in the morning and evening, and more variability in wind direction (both in time and with height) compared to the other case-study days. With low wind speeds, the NO₂ concentrations are high ($> 80 \mu\text{mol m}^{-2}$) but the plume only extends ≈ 50 km downwind of Paris (Fig. 3).
- 200 (c) *SE across 27 January 2024 (W3)*: This day had consistent SE flow perpendicular to the transect.

Table 2. Characteristics of the six days (values for 24 h) explored in more detail, including their wind direction (DWL at JUS) and speed (DWL, Eiffeltower) at 300 m agl; synoptic Hess and Brezowsky (1969) class: anticyclonic conditions as indicated by Y(es) and M(ixed); synoptic flow being M(eridonal), Z(onal) or Mixed; gravimetric soil moisture at 0.10 m - SIRTa; and PM₁₀ and NO₂ at the Airparif Paris stade Lenglen (PA15L, urban) site; and precipitation measured in Montsouris Park for the 7 prior days. All data sources and processing details are given in Sect. SM 2.2.4.

	S1	S2	S3	W1	W2	W3
Date	2023-06-05	2023-07-10	2023-05-03	2024-01-11	2024-01-16	2023-01-27
Day of week	Mon	Mon	Wed	Thu	Tue	Sat
Day length (h:m)	15:59	15:55	14:41	08:34	08:44	09:11
Wind class	along	along	across	along	along	across
Wind dir. class	NE	SW	E	NE	SW	SE
Wind dir. (°)	27	240	83	33	142	126
Wind speed (m s⁻¹)						
DWL mean	7.0	3.9	8.3	8.2	3.5	5.8
Eiffel mean	7.2	2.6	8.5	7.9	3.6	5.8
Eiffel max	10.7	5.0	16.0	12.8	9.9	13.3
Synoptic class	HNa	Sa	HNa	HB	WS	NWa
Synoptic flow	M	M	M	M	Z	Mixed
Anticyclonic	Y	Y	Y	Y	M	Y
UHI (°C, max)	5.1	7.3	5.9	3.8	7.2	7.8
T_{air} (°C, min-max)	15 - 27	20 - 30	9 - 22	-1 - 3	0 - 5	4 - 9
Precipitation (mm week⁻¹)	0	16.7	12	1.2	0	5
Days since last precipitation	20	0	0	2	7	0
Soil moisture (kg m⁻³)	200	180	350	350	340	360
PM₁₀ (μg m⁻³)	24.8	16.4	18.9	41.5	26.1	21.5
NO₂ (μg m⁻³)	13.6	6.1	15.0	39.2	54.0	42.8

S1 - NE wind along transect

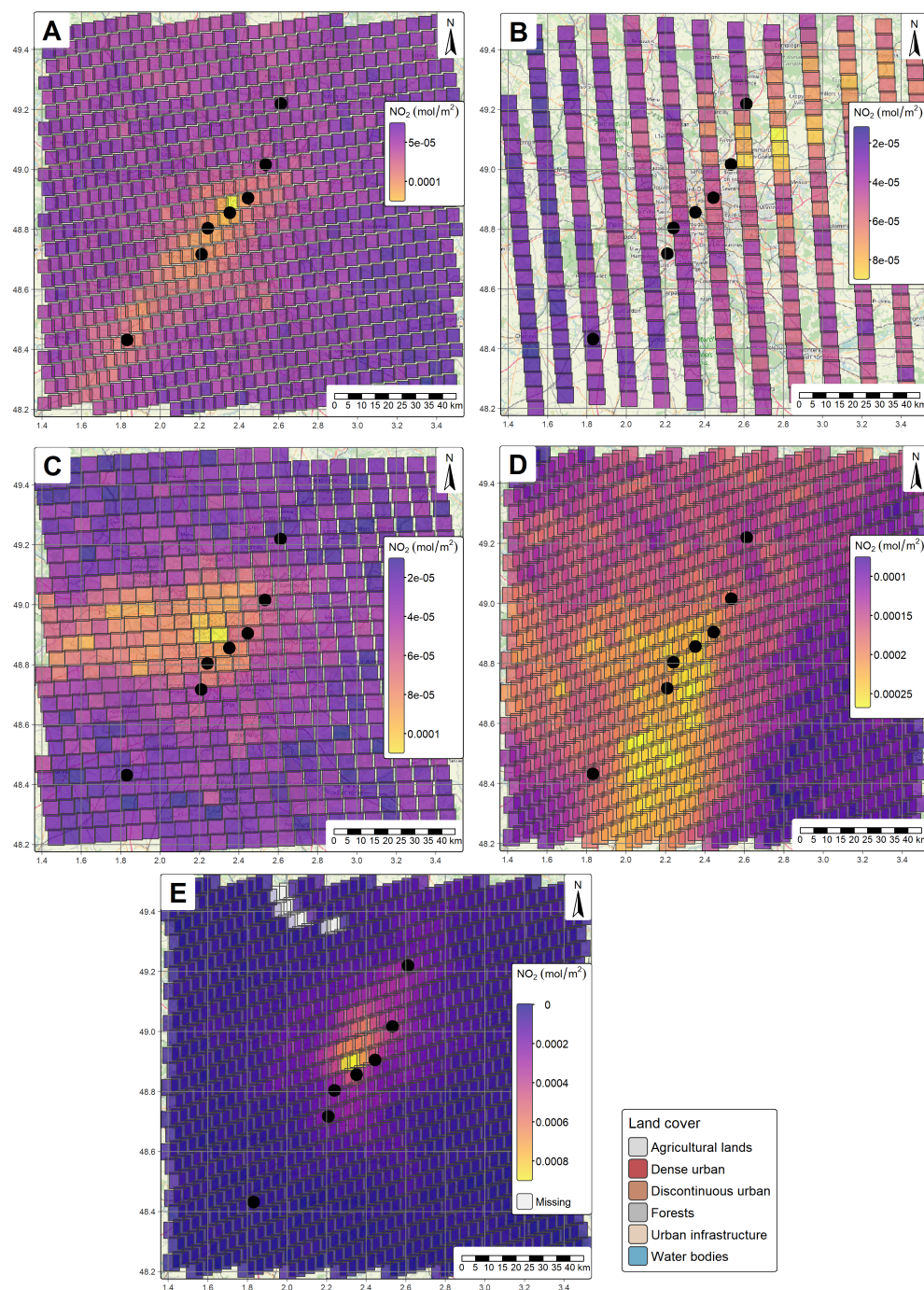


Figure 3. Copernicus SENTINEL-5P TROPOMI nitrogen dioxide (NO_2) tropospheric column data for (a) **S1** retrieval at 2023-06-05 12:02:18 UTC, (b) **S2** at 2023-07-10 12:45:51 UTC (Copernicus, 2023) with CORINE land cover (European Environment Agency, 2019) (background), (c) **S3** at 2023-05-03 12:19:41 UTC, (d) **W1** at 2024-01-11 11:21:03 UTC, (e) **W2** at 2024-01-16 11:27:39 UTC (Copernicus, 2024). ALC locations on transect (black dots) and JUSS Doppler wind lidar wind rose for 08:00 - 12:00 UTC from 300 m AGL to boundary layer height on each day. Note, subplot NO_2 scales differ and data unavailable on **W3** 2024-01-27.



The clear diurnal cycle in the MLH has distinct variations along the transect (Fig. 4). The MT growth rates are slower upwind of the city, faster in the city, but fastest downwind of the city (Table S6). The GR_{max} is also greater at both downwind locations with the highest values 20 km downwind of the city (SIRT, Table S6). The peak MLH is > 2 km at all but the upwind rural site. Compared to the latter, the MLH_{max} is 359 m (18%) higher over the inner city and 304 m (15.5 %) more than downwind rural (Fig. 6, Table S6).

The nocturnal boundary layer (NBL) starts to form before sunset (SS) at the upwind rural site (Fig. 5; at 19:00), but after SS within the city. The downwind (≈ 60 km from city centre) the rural NBL formation is further delayed by ≈ 1 h (21:15, Fig. 5). Hence, NBL formation is consistent along the transect (upwind, earliest to downwind, latest).

Inner city (HOTE) - upwind rural (CHAM) differences in attenuated backscatter (by height and time step) indicate greater backscatter at HOTE at the top of the nocturnal residual layer and within the NBL (Fig. 4). Daytime within ML differences are generally small, but near the top a region of higher attenuated backscatter occurs above HOTE (Fig. 4). Differences in NBL formation timing between the two sites are also visible as increased backscatter at the urban site (Fig. 4).

The rural turbulent (H) flux observations at the rural sites (Sect. 2.2.3, Fig. 1)) (Fig. 7, S2) maxima are up to 300 W m^{-2} at midday and slightly negative fluxes at night. In the inner-city (JUSS, Fig. 1) the H remains positive at night (Fig. 7). The cumulative H city centre over 24 h is greater than all other sites (Fig. 11). LE flux is near zero at the urban site, but peaks above 300 W m^{-2} at the rural and downwind urban fringe site (Fig. 7).

S2 - SW wind along transect: The city centre has the highest GR and GR_{max} , with both up- and downwind rural sites lower (Table S6, Fig. 6). The MLH is shallower than **S1** (< 1.8 km). Compared to upwind rural, the MLH_{max} is deeper both above the inner city (14.5 %; 214 m) and downwind rural (18.3 %, Table S6, Fig. 6). Similar to **S1**, the nocturnal H is near zero (Fig. 7), and the inner city has the largest cumulative H (Fig. 11).

S3 - E wind across transect: Smaller (cf. **S1**, **S2**) but similar GR_{avg} and GR_{max} rates (Table S6) occur, and a shallower ML (< 1.5 km). The inner and outer city MLH_{max} are 13 % greater than the urban fringe and rural values. The city daytime H are of similar magnitude to the outer city locations, reaching a peak $> 250 \text{ W m}^{-2}$ (Fig. 7). The rural locations diverge substantially, with maxima of $> 400 \text{ W m}^{-2}$ and 100 W m^{-2} . The city LE fluxes are close to zero (Fig. 7E).

W1 - NE wind along transect: For the GR, there were large contrasts between the sites, with the GR_{avg} being three times faster in the inner city than at the upwind rural location (Table S6). The inner city exhibited the fastest GR, but also both downwind locations were nearly twice as fast as upwind rural (Table S6). The MLH_{max} was < 700 m agl for all sites (Fig. 9). The MLH is elevated over the urban area and downwind of Paris, with differences being most pronounced in the late afternoon (Fig. 9). The difference in attenuated backscatter showcases the deeper urban ML both during day and night (Fig. 8). The city centre H flux is also higher at night and day, with peak values of 150 W m^{-2} at midday and continuous values of $> 50 \text{ W m}^{-2}$ at night (Fig. 10 and 11). During daytime, the mean difference between the city centre (JUS) and all other sites was $\approx 75 - 100 \text{ W m}^{-2}$ (Fig. 10). The LE flux is overall weak with values $< 40 \text{ W m}^{-2}$ and hardly any spatial variations (Fig. 10).

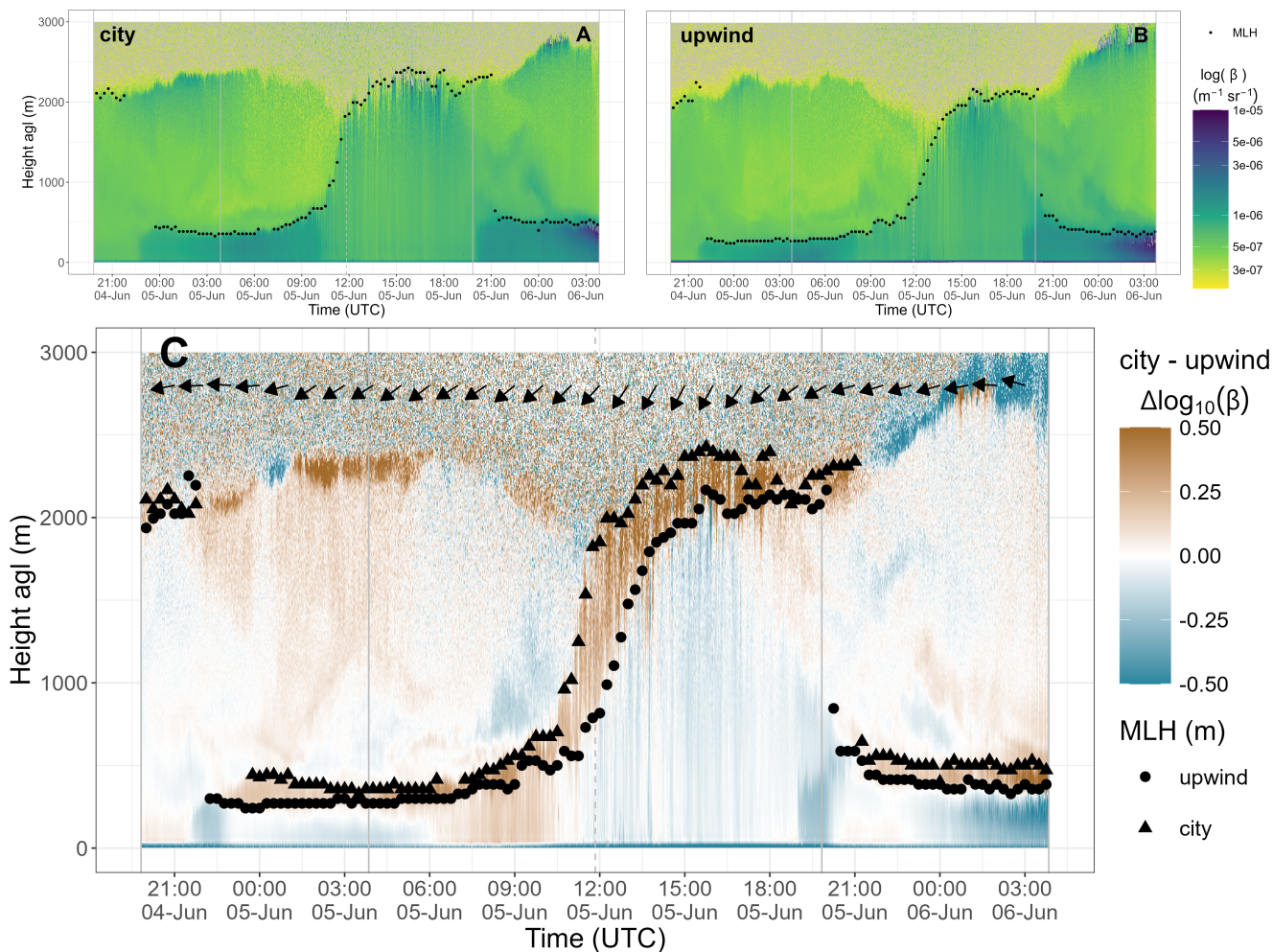


Figure 4. Attenuated backscatter (β , $m^{-1} sr^{-1}$) on S1 2023-06-05 at the (a) inner city (HOTE) and (b) upwind rural (CHAM) sites, and (c) their difference ($\Delta \log_{10}(\beta)$; %) with solar times (sunrise, solar noon, sunset) at HOTE (vertical lines, in UTC) indicated. The mixed-layer height (m, points) derived using STRATfinder (Kotthaus et al. (2020a), Sect. 2.2.1). $\beta > \pm 0.5 \Delta \log_{10}(\beta)$ are at colour-bar saturation. Hourly wind direction at JUSS (300 m agl - top of BL, arrows). $\beta < \pm 3.5 \cdot 10^{-8}$ (white) are within the inter-instrument variability (Looschelders et al., 2025).

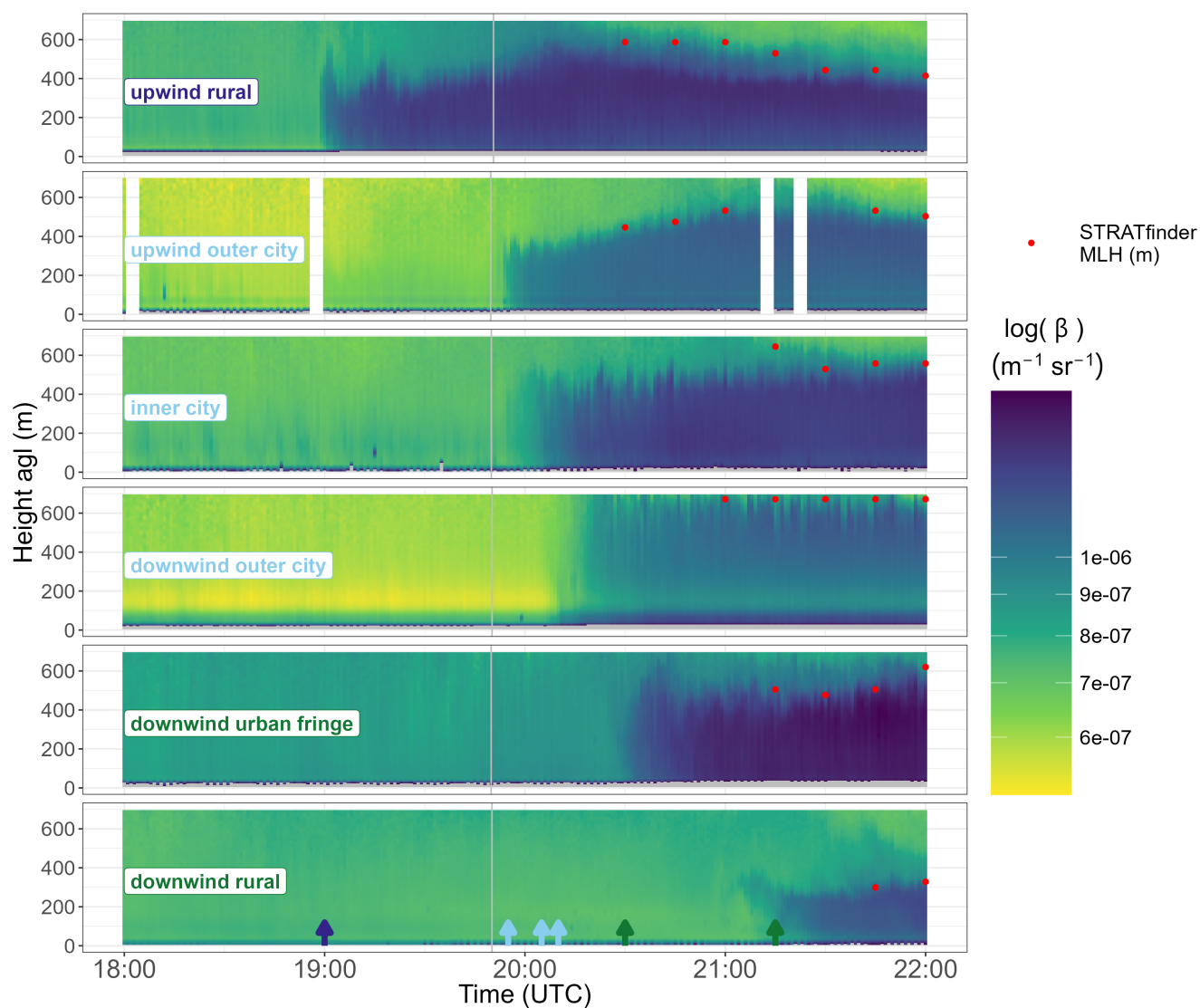


Figure 5. Total attenuated backscatter (β ; $\text{m}^{-1} \text{sr}^{-1}$) L0 data (colour-bar) below 700 m agl with STRATfinder (Kotthaus et al. (2020b), Sect. 2.2.1) derived mixed-layer height (MLH) for six locations along the transect. Timing of nocturnal boundary layer formation (arrows) based on gradient change (by eye).

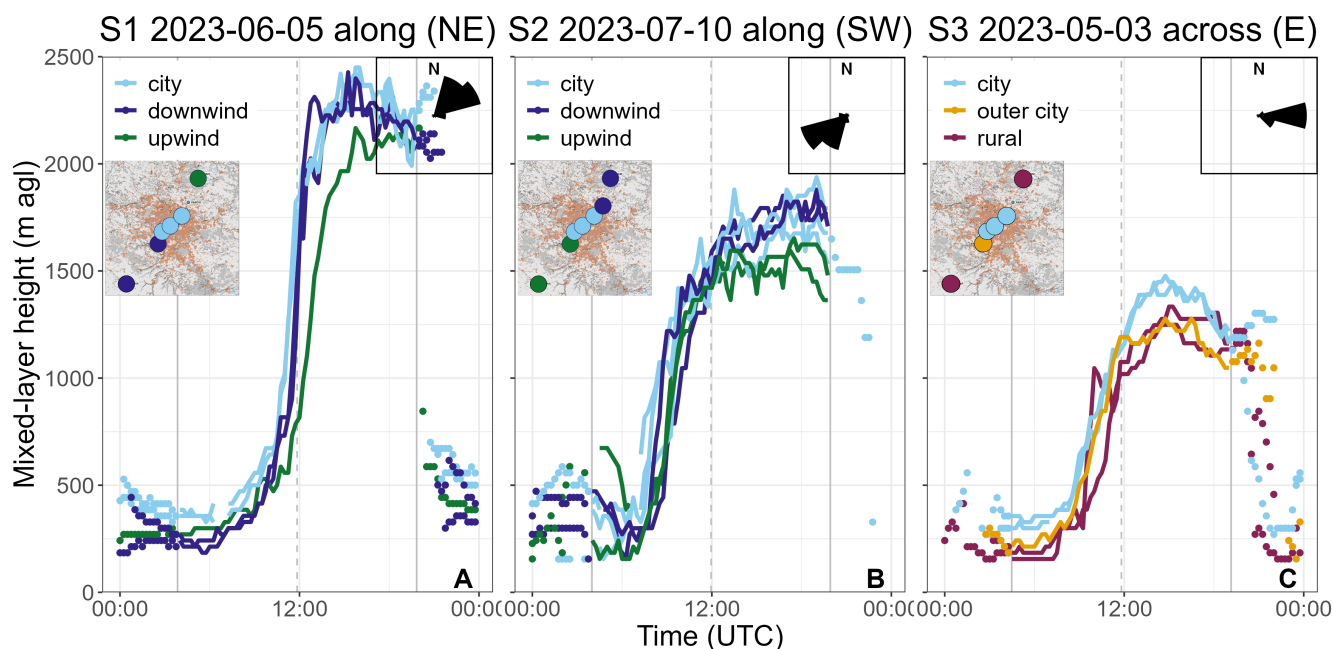


Figure 6. STRATfinder (Kotthaus et al. (2020a), Sect. 2.2.1) derived mixed-layer height (m, lines and points), with times of sunrise, solar noon (dashed), and sunset shown on three summer days (**S1-S3**). Doppler wind lidar windrose at JUSS from 300 m agl to mean MLH_{max} , (Fig. 1, Sect. 2.2.4) for sunrise plus 1 h to sunset minus 0.5 h. Inset maps indicate transect sites.

W2 - SW wind along transect: Except for the upwind rural site (126 m h^{-1}), the GR_{avg} is $> 300 \text{ m h}^{-1}$ (Table S6), with values faster in the city and even faster downwind. Unexpectedly, the upwind urban fringe site has the highest GR_{avg} and GR_{max} of all sites (Table S6). The maximum ML is deeper than **W1**, peaking at $>1 \text{ km agl}$ (Fig. 9) and MLH differences are more pronounced. Consistently, a deeper ML occurs over urban and downwind areas (Fig. 9, Table S6).

W3 - SE wind across transect: A late onset of the MT occurs, with some even after solar noon (Fig. 9). Similar to **S3**, there are no detectable differences in GR_{avg} and GR_{max} between city and rural sites, but much more inter-site variability (Table S6). The MLH is shallow (cf. **W1**) with a $MLH_{max} < 600 \text{ m}$ (Fig. 9). The MLH is only elevated above the inner city, while remaining comparatively low over outer city and rural sites (Fig. 9).

Generally for the six days, the MT GR_{avg} is lower upwind of the inner city, but with substantial intra-urban variability (Fig. 12). All four along-transect flow days have faster MLH growth downwind of the city cf. upwind rural (Fig. 12). Typically, GR_{avg} decreases along the urban gradient going downwind of the city centre from urban fringe to rural locations (Fig. 12). Across-transect flow days have small GR_{avg} differences between sites in summer (**S3**) but not in winter (**W3**; Fig. 12).

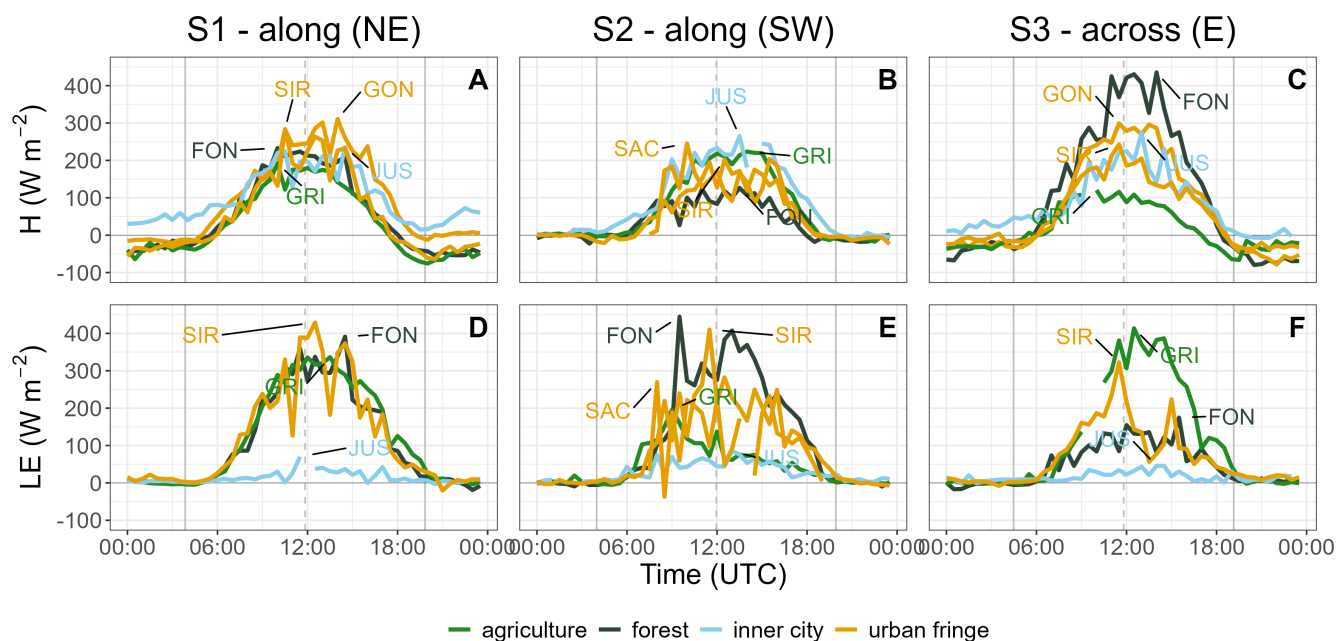


Figure 7. Sensible (H) and latent (LE) heat fluxes ($W m^{-2}$) derived eddy covariance observation at six sites (Sect. 2.2.3, Fig. 1) on three days (S1-S3), with sunrise, sunset (solid line) and solar noon (dashed) indicated. Source area shown in Fig. S2-S7.

All six days show an urban increment in MLH_{max} (Fig. 12) with along-transect flow days having elevated MLH_{max} at downwind locations (cf. upwind, Fig. 12). The most pronounced plume effect occurs on S2, with MLH_{max} greatest at the downwind rural site and higher at the downwind outer-city than at the inner-city site (Fig. 12). Across-transect flow days have elevated inner and outer city sites MLH , cf. urban fringe and rural sites (Fig. 12), with little (W3) to no (S3) differences detected between locations left or right of the city.

3.2 Ensemble average of along-transect days

To quantify along-transect flow effects (Sect. 3.1) 25 clear-sky days are analysed by time of day and season using both pairwise differences and linear mixed-effects modelling (Sect. 2.2.1).

3.2.1 Morning transition (MT) and growth rate

The inner city initial MLH (MLH_{start}) is deeper than all other locations, for > 68 - 96 % of the cases (Fig. 13). It is 51 m (17 %) deeper than the upwind rural locations (Fig. 13), which are lower than other locations (>67% of the cases). Similarly, downwind rural cases (> 78 %)(Fig. 13) are shallower than the upwind rural site (36 %, 80 m) (Fig. 13). MT onset timing

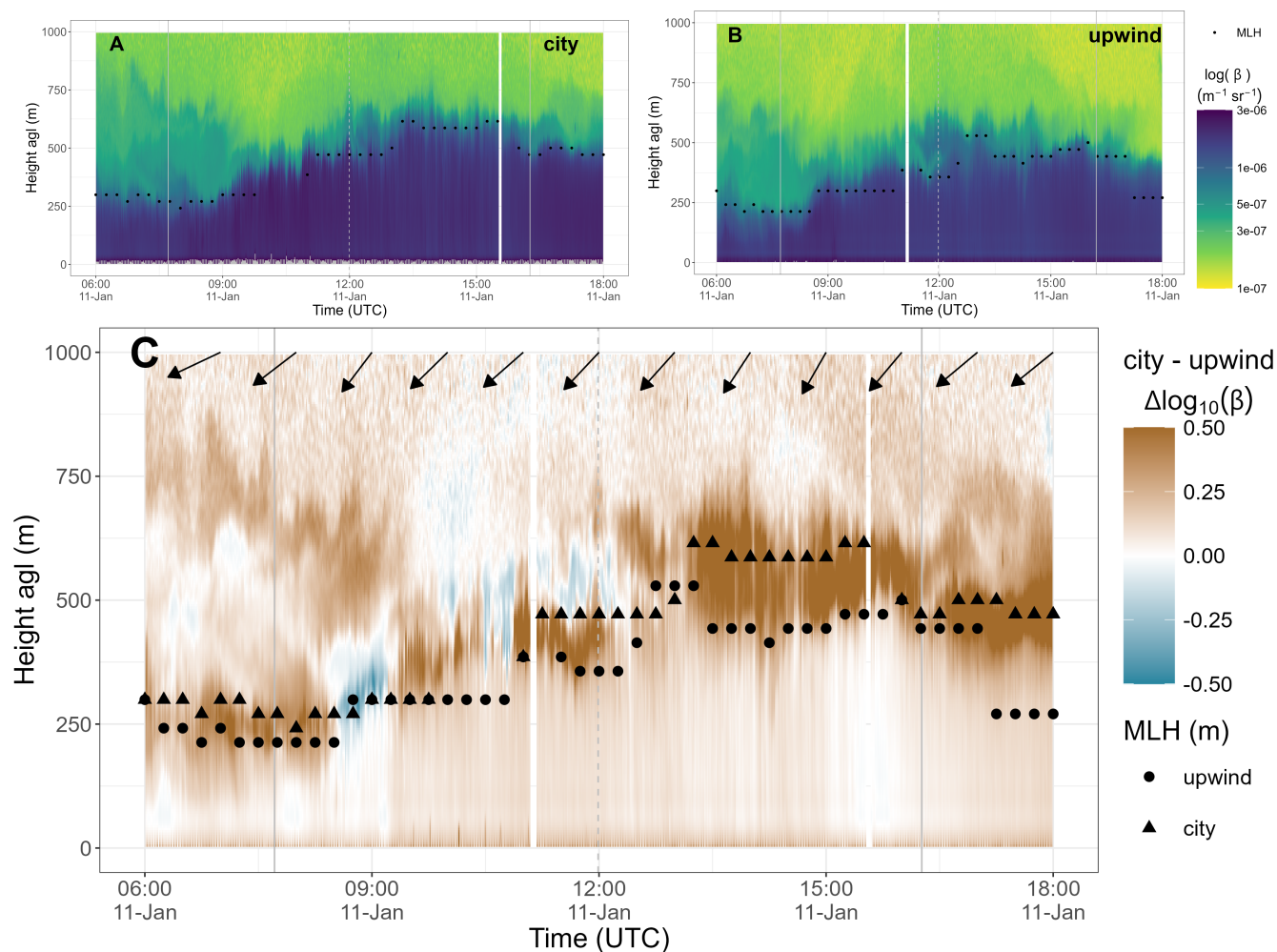


Figure 8. As Fig. 4, but for on **W1** 2024-01-11.

varies by <1 h between locations, with no clear spatial signature detected (Fig. S10).

Consistent with Sect. 3.1, GR_{avg} and GR_{max} increase along the transect from upwind to city and downwind locations (Fig. 13). Compared to upwind rural locations, MLH grows 31 m h^{-1} (21 %) faster at the three city sites and 35 m h^{-1} (23 %) faster than downwind rural locations (Fig. 13). The same pattern holds for GR_{max} . Although upwind urban fringe locations differ from this pattern, with high GR_{avg} and GR_{max} on most days (Fig. 13), there are very low sample sizes. GR_{avg} increases along the transect from upwind to downwind urban fringe, whereas GR_{max} continues to increase to the downwind rural locations. The downwind urban fringe has the fastest GR_{avg} on the majority of days (Fig. 13). Timing of GR_{max} shows no clear trend along

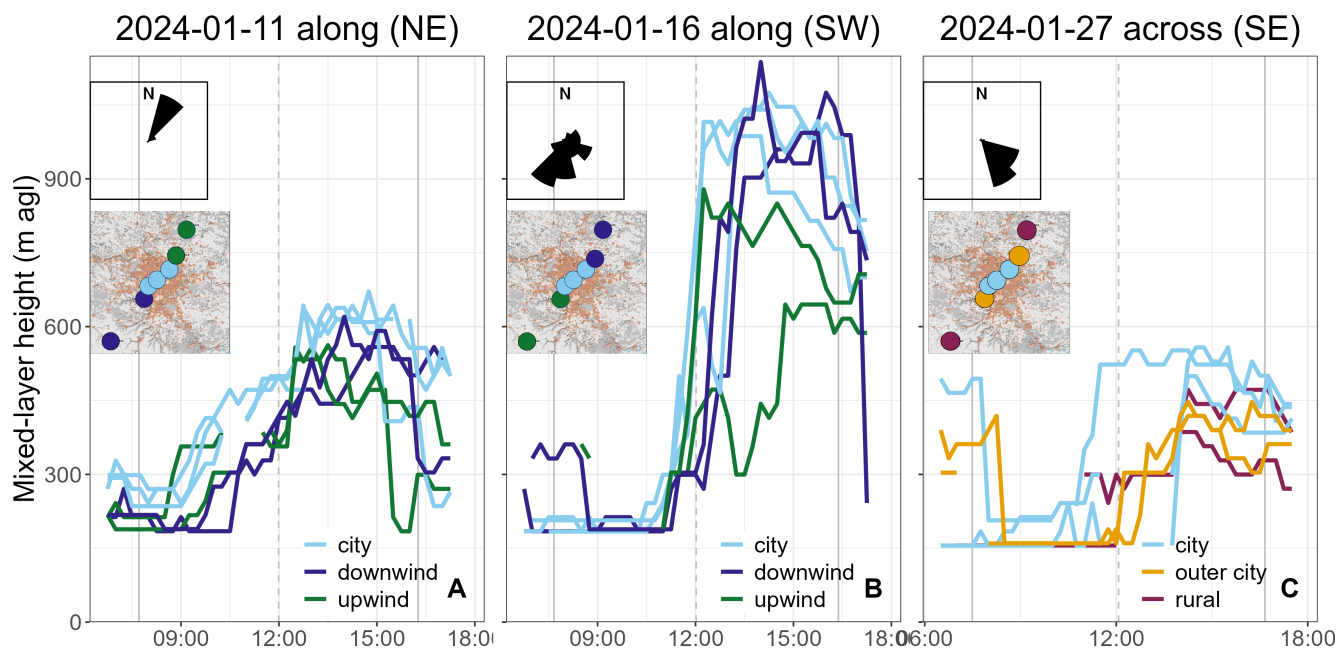


Figure 9. As Fig. 6, but for three winter days (W1-W3).

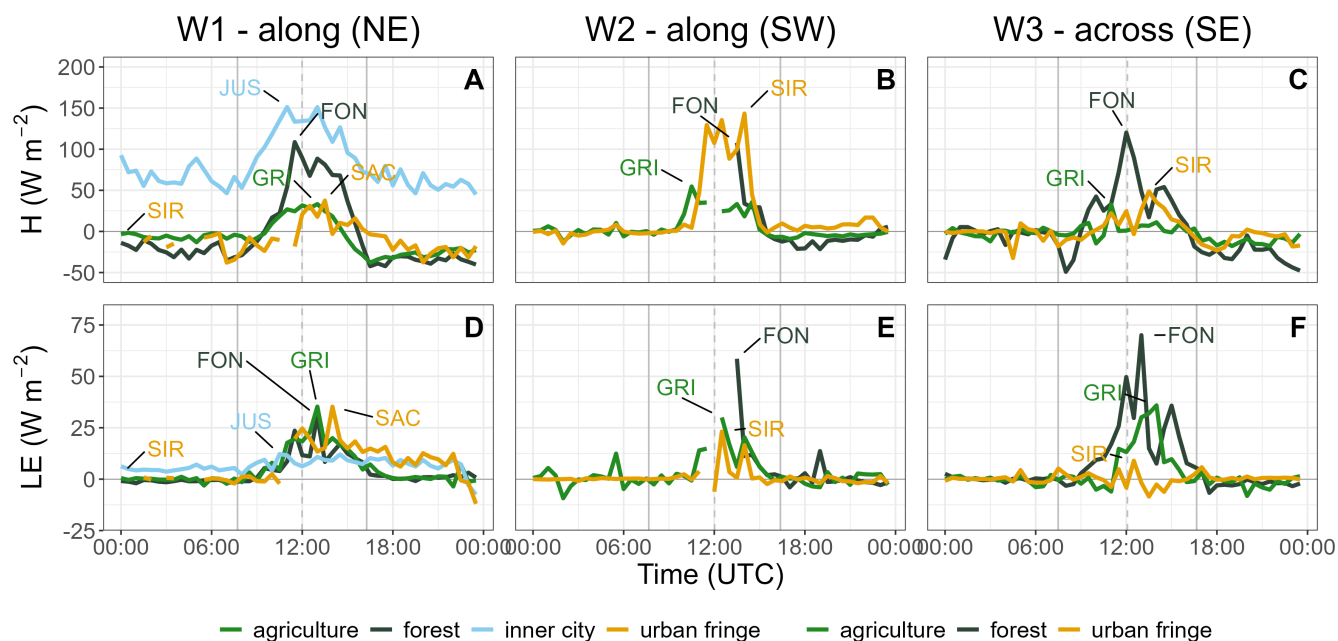


Figure 10. As Fig. 7, but for winter. Note sparse data availability on W2 and W3. For source areas see Fig. S2-S7.

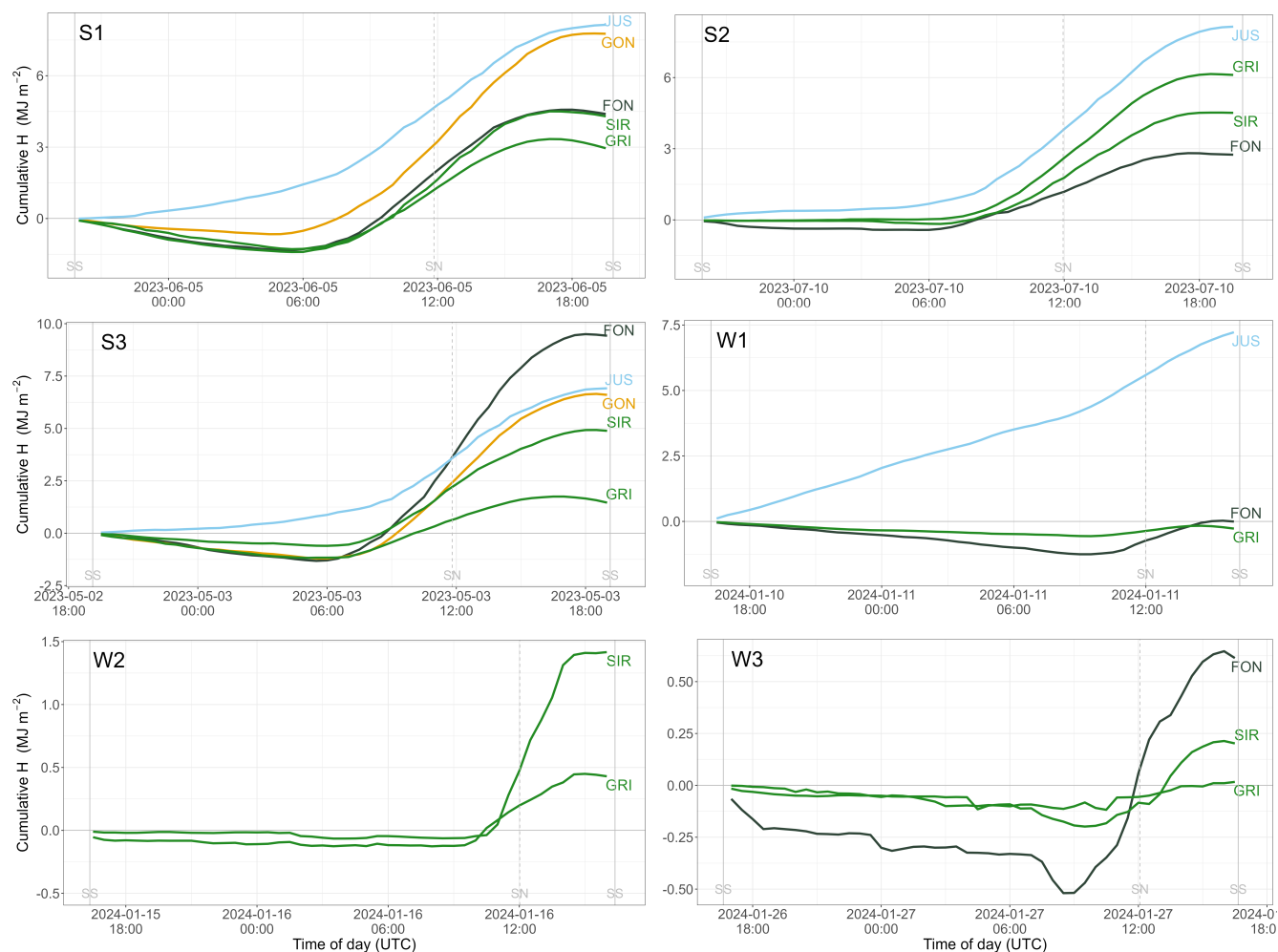


Figure 11. Cumulative sensible heat flux (MJ m^{-2}) from sunset (SS, line) of previous day to SS of case study day. Note y-axis differs between days.

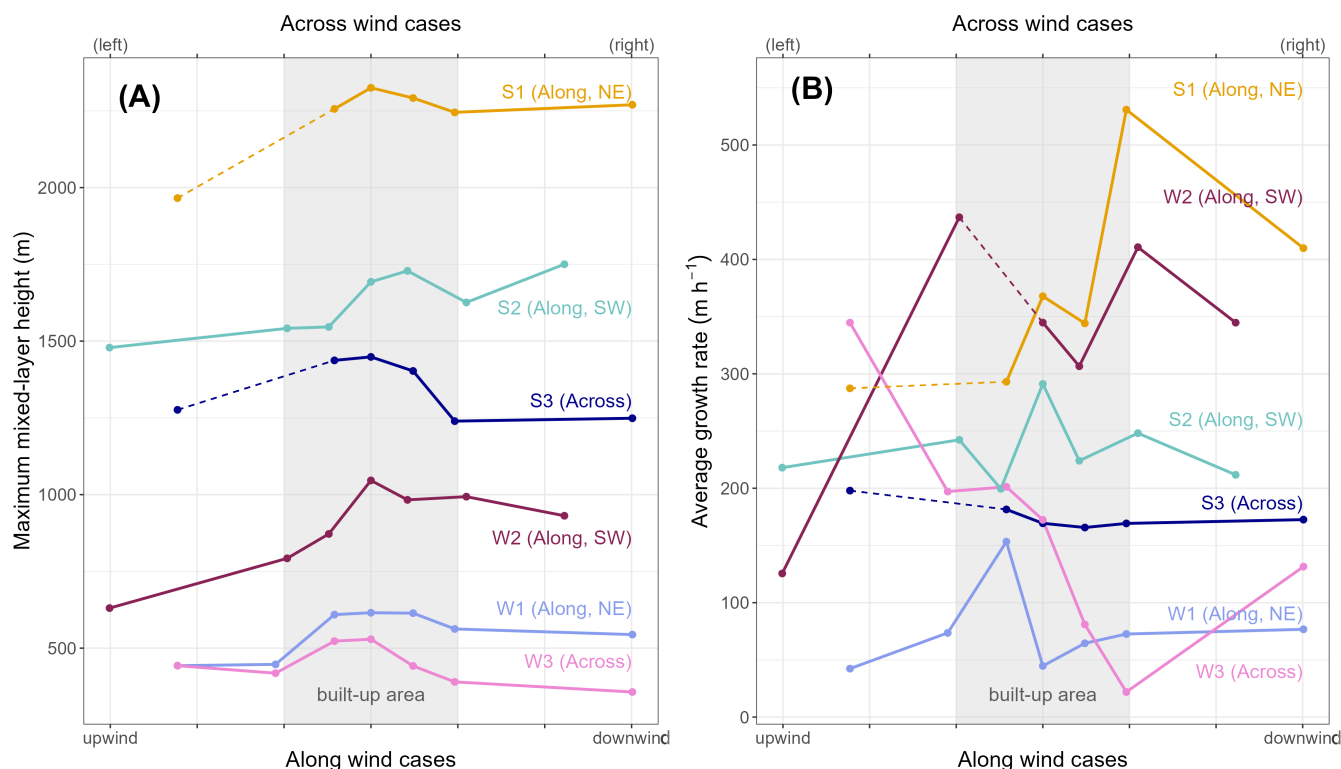


Figure 12. Six days (S1-S3, W1-W3) cross-section of STRATfinder-derived mixed-layer height (MLH) showing (a) maximum MLH (MLH_{max}) and (b) morning transition average growth rate ($GR_{avg}, m h^{-1}$) (Sect. 2.2.1). Dual x-axis indicates "Along" (lower) and "Across" (upper) wind cases, with densely built-up area shaded.

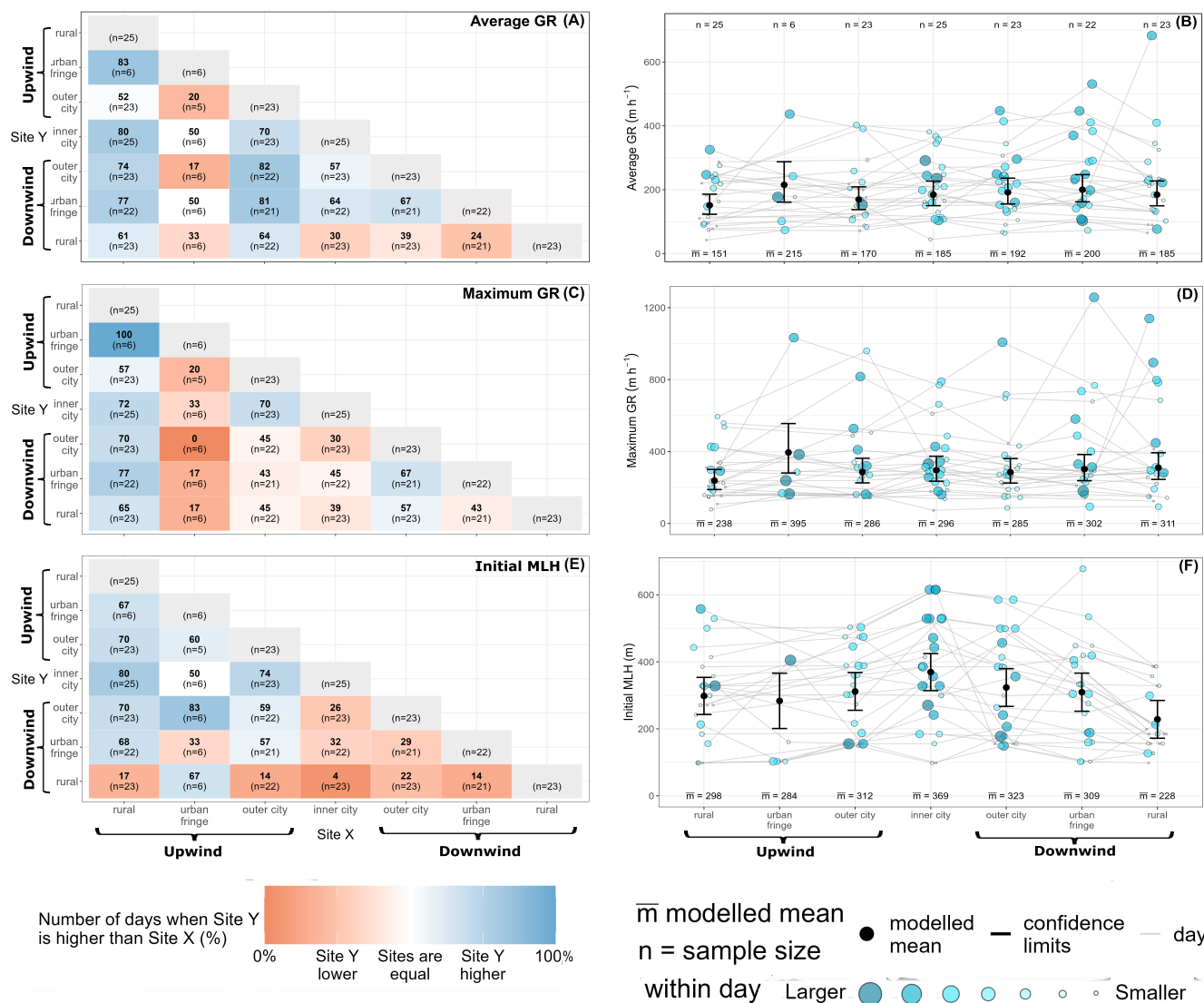
the transect, with temporal variation <1 h (Fig. S10). These MT and growth rates metrics are independent of along-transect flow being from NE or SW (not shown).

275 3.2.2 Mixed-layer height (MLH)

Overall, the diurnal MLH differences along the transect are similar to Sect. 3.1 cases, with the deepest MLH over the city and downwind, and shallower MLH at upwind rural location. Spatial variations are most pronounced in the late afternoon (Fig. 14).

280 Relative to the daytime upwind rural location, the median MLH at city sites are consistently elevated by 10 - 14 % in summer (daytime: 07:00 - 20:00) and by 21 to 24 % in winter (daytime: 09:00 - 17:00). The downwind urban fringe site is elevated by 8 % in summer but 25 % in winter, while the downwind rural site is elevated by 4 % in summer and 9 % in winter (Fig.14).

Pairwise comparison of 15-min MLH shows that any downwind or inner-city sites MLH are higher than any upwind site for >62 % of the time in summer and >56 % in winter (Fig. 15). This increases closer to the city centre, with differences largest





285 for inner city comparisons to the upwind rural site in summer (90 %) and to the downwind urban fringe site in winter (88 %)
(Fig. 15). This is consistent irrespective of flow direction along the transect (not shown).

The linear mixed-effects model mean MLH_{max} (cf. upwind rural site) is elevated over the inner city by 240 m (15 %) in
summer and 209 m (32 %) in winter (Fig. 15). Downwind sites have similar MLH_{max} as city sites. Summertime downwind
290 outer city locations have the deepest MLH, which is 278 m (17 %) greater than upwind rural locations (Fig. 15). The median
NBL is shallowest at downwind and upwind rural sites, whilst inner city and downwind outer city locations are the highest
(Fig. 13).

3.2.3 Seasonal differences

Along-transect urban-induced MLH variations are the same for the summer and winter ensembles, but the absolute differences
295 are slightly greater in summer (cf. Winter) (Fig. 14). Pairwise (Fig. 15) differences are larger, with the winter MLH_{max} upwind-
city relative difference twice as large as summer (Fig. 15).

In summer, there are larger intra-urban differences with downwind outer city MLH being slightly elevated (cf. inner city)
and upwind outer city being lowest most of the afternoon (Fig.14, 15). In winter, no consistent intra-urban differences in MLH
are found.

300

In summer, the two downwind locations are similar to city sites until the afternoon. The downwind rural MLH is shallower
than upwind rural until after midday (Fig. 14). In summer, the MLH and MLH_{max} peak downwind, increasing from the down-
wind urban fringe to the downwind rural location. Wintertime peak MLH occurs in the inner city, and decreases downwind
from the urban fringe to the rural location (Fig. 15, 14).

305

Summer GR tend to be higher, but some winter days have fast growth during the MT (e.g. **W2**, Fig. 12). The summer MT
onset occurs later relative to sunrise and is more variable (cf. winter; not shown). The MLH_{start} , GR_{avg} and GR_{max} have very
similar characteristics in summer and winter (not shown).

4 Discussion

310 Here we discuss the methodological benefits of the transect approach (Sect. 4.1), spatial differences in turbulent heat fluxes
(Sect. 4.2), temporal evolution of the boundary layer (Sect. 4.3), the underlying processes and potential drivers of the morning
transition (MT) growth rates (GR) (Sect. 4.4), mixed-layer height (MLH) (Sect. 4.5), seasonal differences (Sect. 4.6) and study
limitations (Sect. 4.7).

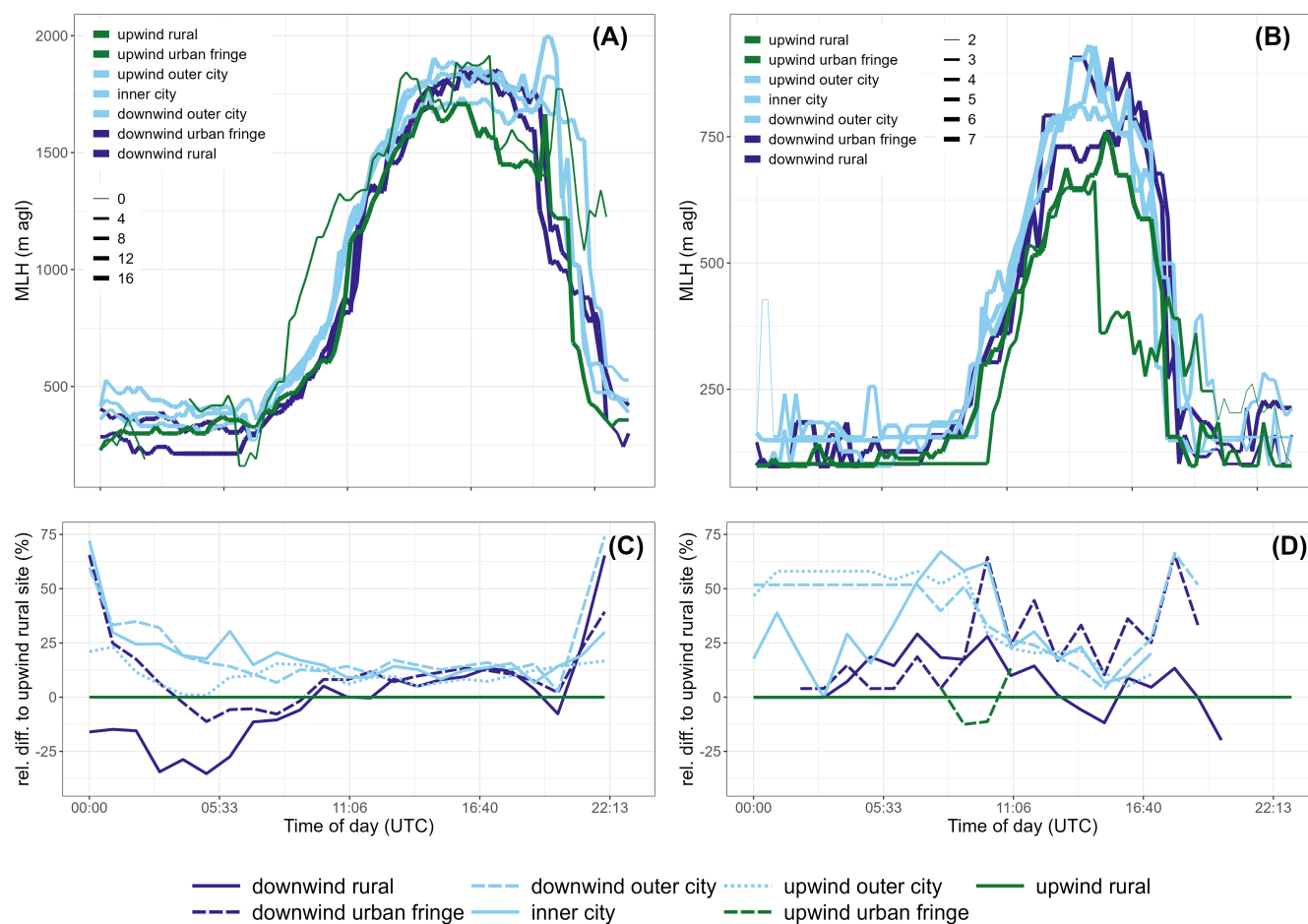


Figure 14. Clear-sky, along-transect wind conditions diurnal ensemble mean of the mixed-layer height (MLH) for astronomical: (a,c) summer (2023-03-22 to 2023-09-22)(SW: 2 days; NE: 14 days) and (b,d) winter (2023-09-22 to 2024-03-22) (SW: 4; NE: 3) (a,b) Note, y-axis scale differ, and number of days (N) indicated by line width.; and (c,d) relative differences to upwind rural site, when > 50 % data availability, shown as % of hourly mean.

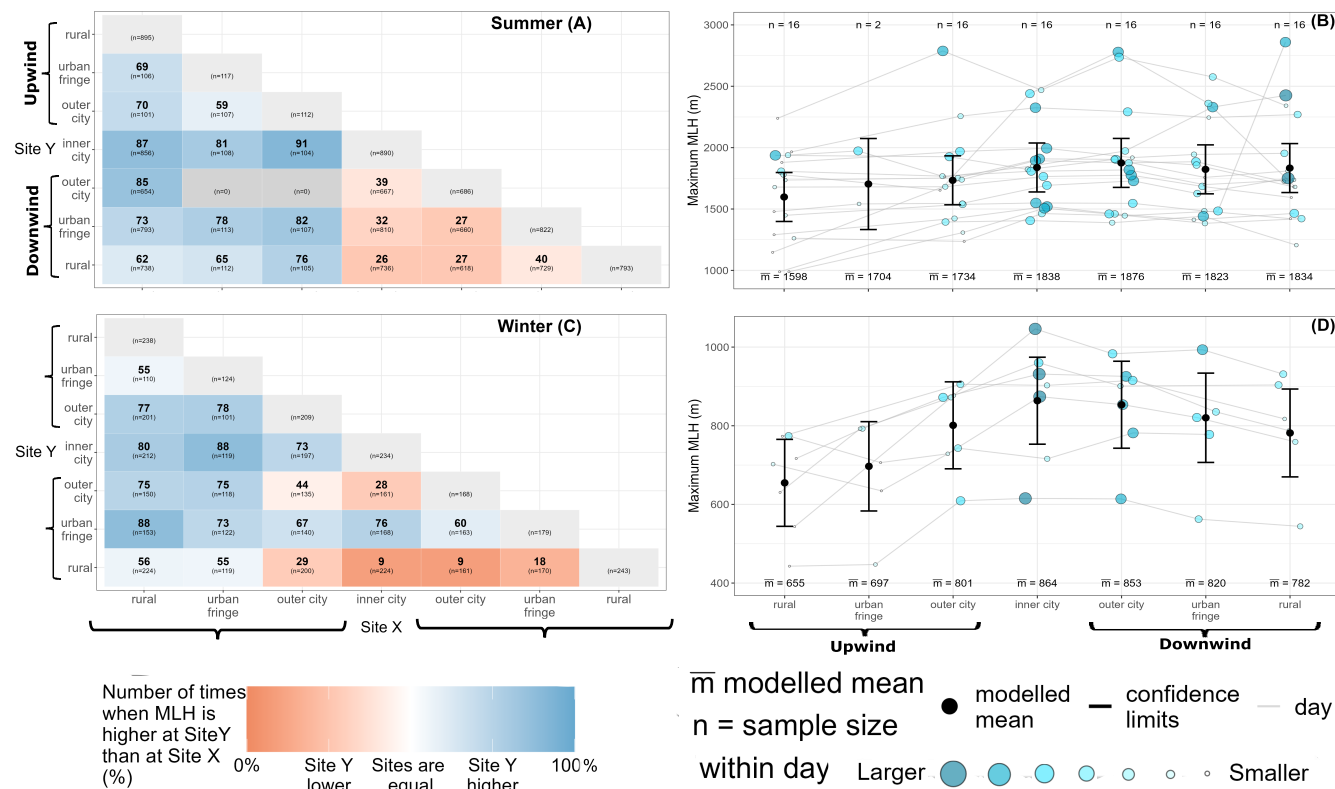


Figure 15. As Fig. 13, but for (a,c) MLH from $t1_{MT}$ to SS and (b,d) MLH_{max} in astronomical (a,b) summer (2023-03-21 to 2023-09-23) (SW: 2 days; NE: 14 days) and (c,d) winter (2023-09-24 to 2024-03-20) (SW: 4; NE: 3).

4.1 Transect design and methodological benefits

Urban ML effects are evident on days with along-transect flows in summer (**S1-S2**) and winter (**W1-W2**, Sect. 3.1), with ML modifications detectable downwind of Paris, which we attribute to urban plume advection effects. Deploying sensors along a transect allows isolation of urban effects (Fig. 1). With an urban plume observed symmetrically, i.e. for both NE and SW wind directions, we can clearly attribute the primary effects to the built-up area. Given Lowry's (1977; 1998) methodology for isolating urban effects, we eliminate land cover, orography and synoptic conditions differences. Further support arises from the concurrent formation of an urban NO_2 plume downwind of Paris on all case days (Fig. 3). Additionally, no distinct MLH variations or plume occur along the transect on across-transect flow days (**S3, W3**), with only urban-rural contrasts detected.

4.2 Cumulative heat fluxes as drivers

Differences in GR and MLH are driven by differences between urban and rural areas via: (1) land cover as the surface energy balance (SEB) modifies the partitioning of the fluxes (Loridan and Grimmond, 2012; Li et al., 2015), (2) atmospheric con-



stituents as pollutants and water vapour emissions modify radiation absorption and clouds (Fan et al., 2020), and (3) surface roughness (Barlow et al., 2015). Beyond surface drivers, synoptic conditions control the free atmosphere above (Stull, 1988) and residual layer properties (Blay-Carreras et al., 2014), so are important for GR. The GR is enhanced by entrainment, when more buoyant air is entrained into the mixed-layer by overshooting thermals (Conzemius and Fedorovich, 2006). We assume the synoptic-scale tropospheric lapse rate has no significant spatial differences over Paris, but will have day-to-day variability. Latitudinal along-transect radiative differences are assumed to be negligible, as sunrise differences between sites is only a few minutes.

Focusing on (1) the SEB, we observe differences in cumulative H flux magnitude (Sect. 4.2) that are approximately proportional to the relative differences in MLH (Sect. 4.5) between sites on the same day. The 24 h cumulative H flux over the city centre are larger than all other locations in almost all cases (Fig. 11). This is often driven by the enhanced urban nocturnal heat flux (Fig. 7, 11). These spatial signatures are consistent with the literature (e.g. synthesised by Oke et al. (2017)), with more energy stored in densely built areas during the day for nocturnal release. In central Paris (JUS), Dupont (1999) found H fluxes to be 20 - 60 % larger than in the outer city. Our summer daytime differences are 18 % (S3) to 65 % (S2) between outer (SIR) and inner city (JUS, Fig. 7). Daytime LE flux differences between the inner city (close to 0) and all other sites (100 to 300 W m⁻² are more pronounced (Fig. 7). Cities are known to partition less energy into LE, as impervious surfaces are designed to shed water (Oke et al., 2017). However, we do not see a spatial upwind-downwind signature in the fluxes, which suggests that advective processes must be important. Differences in (2) the atmospheric constituents are not analysed in this study. Differences in (3) surface roughness can lead to more turbulent kinetic energy (TKE) being generated by mechanical production of turbulence from the high roughness in the city (Barlow et al., 2015).

4.3 Temporal evolution of the boundary layer

Distinct spatial variations are not evident for the MT onset (Fig. S10) or maximum growth (Fig. S10), consistent with Barlow et al.'s (2015) and Fenner et al.'s (2024) findings between urban and rural locations in London and Berlin, respectively. Similarly, in Paris Pal et al. (2012) finds no clear spatial variations in the strongest growth rates timing.

STRATfinder's inability to accurately detect the nocturnal boundary layer (NBL), partly due to fine gradients making it difficult to systematically analyse ML decay - NBL onset timing. However, for S1 (Sect. 3.1, Fig. 5) differences in NBL onset occur from NE to SW along the transect, with greater delay in NBL formation along the upwind - city - downwind transect. Delayed decay has been observed before in central Paris (cf. outer city) (Pal et al., 2012), and in London during heat island conditions (Barlow et al., 2015). Further delay in NBL formation downwind is unexpected, as rural surfaces cool more quickly facilitating formation of a stable layer.

Several factors could explain this effect. (1) Turbulence being advected along the transect, impeding stable stratification by continued mixing. (2) Nocturnal low-level jet (LLJ) occur in Paris frequently (Céspedes et al., 2024), including on S1 (Fig. S8). As Céspedes et al. (2024) describe, mechanical turbulence is generated by the wind shear below the jet core, which may inhibit the formation of the stable layer. (3) Flow interactions with the topography, despite Paris region being relatively flat (Pal and Haeffelin, 2015; Dupont, 1999), but Céspedes et al. (2024) note its impact on the low-level jet in this region requires further



investigation. The Saclay plateau in the SW (Fig. 1), could perturb flow by introducing mechanically generated turbulence. (4)

360 Regional or synoptic conditions may delay NBL formation.

4.4 Morning transition (MT) and growth rate differences along-transect

The MT of the mixed-layer generally follows the expected evolution. In the early morning there is a slow increase, followed by a period of rapid growth until the ML reaches the top of the residual layer and growth decreases (Stull, 1988). As duration of the MT strongly influences GR_{avg} (Halios and Barlow, 2018), this leads to variability between days. As Kotthaus and Grimmond (2018) note, the definition of the start of the MT obviously affects statistics. Baars et al. (2008) identify that very short MT duration is often associated with extremely high growth rates.

365

4.4.1 Mixed-layer height at the start of the MT (MLH_{start})

The MLH varies between locations at the start of the MT, with MLH_{start} increasing from downwind rural to upwind rural to inner city (Fig. 13). The initial deeper inner city MLH_{start} is supported by nocturnal release of H fluxes (Grimmond and Oke, 1999a, 2002) at night. This is observed in Paris, and linked to urban heat island intensity (Pal et al., 2012), as expected (Oke, 1982). The greater mechanical turbulence from the larger surface roughness (Grimmond and Oke, 1999b) may contribute. The shallower downwind rural MLH_{start} than upwind rural, may be explained by horizontal heat advection. If near-surface advection occurs, as Kittner et al. (2025) describes in the Paris region, warmer urban air may replace cooler rural air, hindering the deepening of a stable layer. When warmer air is advected downwind aloft in an urban plume over a cooler rural surface, it would strengthen stable stratification of the rural NBL, restricting NBL growth.

375

4.4.2 Average (GR_{avg}) and maximum GR_{max} growth rates

Across the clear sky days analysed GR_{avg} is between 100 and 300 $m h^{-1}$, but individual 15-min GR can be > 300 or even > 400 $m h^{-1}$ (Fig. 13). This is consistent with previous Paris ABL studies. Analysis of 5-year ALC all weather conditions at an urban fringe site SW of Paris, finds growth rates of $149 \pm 119 m h^{-1}$ in winter (DJF) and $247 \pm 142 m h^{-1}$ in summer (JJA) (Pal and Haeffelin, 2015).

380

Along-transect flow on individual days (Fig. 12) tends to have larger GR_{avg} in the city and downwind. However, the variability between sites may be due to local forcing, such as site convective velocity scale and/or other turbulence effects. In London, Halios and Barlow (2018) observe a strong positive relation between mixing layer growth rate and convective velocity scale. In Paris, Pal et al. (2012) associate growth rates with near-surface lapse rate. These are both consistent with boundary layer models (e.g. Raupach (1991), Cleugh and Grimmond (2001)). From the original observations, short events are visible (Fig. 6) that will modify growth rates through the MT period, but these instantaneous spatial variations are unrelated to upwind-urban-downwind effects between sites on the transect (Fig. 12).

385

Despite large day-to-day variability, a systematic enhancement of GR_{avg} in the city (21 %) and downwind (23 %) occurs relative to upwind rural areas (Sect. 3.2.1). It is probable that sensitivity to local effects hypothesised to explain the variability



390 between sites on different days average out across the ensemble. *urbisphere*-Berlin observations (Fenner et al., 2024) found similar upwind-urban-downwind GR_{avg} as here (Fig. 13). For an April day, median growth rates increase from 248 m h^{-1} (upwind) to 304 m h^{-1} (city) to 329 m h^{-1} (downwind) (Fenner et al., 2024). Although these growth rates are for only one day, they are derived from > 25 sites (Fenner et al., 2024).

Enhanced MLH growth rates over cities, cf. upwind locations, are expected due to differences in the SEB and surface roughness (Sect. 4.2). However, GR_{max} can be decoupled from the surface heat flux, since high buoyant turbulence can occur even when average surface H flux is moderate (Saunders et al., 2024). As GR_{avg} depends on MT duration, we use GR_{max} to identify periods of strong turbulent mixing in the boundary layer during convective "bursts". The occurrence of such turbulence intermittency for both buoyancy and shear over urban areas is described by Gowardhan et al. (2021) and Wang et al. (2025). Since buoyant turbulence dominates over shear in urban boundary layers (Barlow et al., 2015), periods of strong buoyant mixing may correspond with the GR_{max} . Cotlier et al. (2025) and Saunders et al. (2024) demonstrate that thermal instabilities driven by uneven surface heating can produce intermittent convective turbulence in urban areas. As a result, GR_{max} highlights differences between sites more clearly than GR_{avg} (Fig. 13). The most notable difference is downwind of Paris as the largest GR_{avg} occurs at the urban fringe location (Fig. 13) but the highest GR_{max} is at the rural location (Fig. 13). Godowitch et al.'s (1987) helicopter-based observations found highest GR_{max} rate downwind of St Louis urban area, which they attributed to advection. In our observations, advection of urban H and TKE could contribute to enhanced vertical mixing, and thus increase GR_{max} downwind.

One unanticipated result is the relatively high GR_{avg} and GR_{max} at the upwind urban fringe site (Fig. 13, Sect. 3.2.1). That is disproportionately the SW urban fringe (SIRT) (Table S1, Sect. 4.7) located on a 10-km plateau about 160 m asl (Haeffelin et al., 2005). Pal et al. (2012) observe the highest GR at this location during NE to E wind conditions. The topographically exposed plateau may be more influenced by synoptically driven mechanical turbulence through shear. It is also conceivable the plateau's slight elevation impacts the NBL, interacting with the nocturnal LLJ as described by Céspedes (2024) although for a downwind situation. In that case, more downward-mixing turbulence could lead to faster NBL erosion and consequently an earlier MT_{start} . Due to the limited amount of data, it remains unclear whether enhanced growth rates are a systematic phenomenon at this location.

415 4.5 Mixed-layer height (MLH)

Within the ML, the difference in attenuated backscatter ($\Delta \beta$) between the inner city and the upwind rural site is surprisingly small in both summer and winter (Fig. 4, 8), and does not seem to reflect a strong signature of elevated aerosol emissions in the urban setting. Note our measured β does not directly translate to dry aerosol content (Warren et al., 2018). The measured signal is influenced by the respective wavelength and atmospheric composition, such as water vapour content (Wiegner et al., 2019; Hopkin et al., 2019), as hygroscopic growth of aerosols increases their size and optical properties (Warren et al., 2018). If the rural site is more moist, measured β may increase, although site-specific vertical gradients are used to determine MLH (Sect. 2.2.1). A counteracting influence arises from the increased MLH above urban sites (Fig. 4, 8) creating a larger mixing volume for aerosols. The strong positive $\Delta \beta$ at the top of the ML in both summer and winter (Fig. 4, 8) reflects the deeper ML



at the inner city site, as the free troposphere over the ML has much lower backscatter. The vertical extent of the positive $\Delta \beta$
425 corresponds to the difference in MLH between the sites (Fig. 4, 8).

4.5.1 Systematic differences along transect

Using ensemble averages (Sect. 3.2.2) we can further quantify systematic differences in MLH with along-transect flow (Table
1). An urban-induced increment is visible throughout the day, with more distinct signatures over the city than downwind (Fig.
14). Note, the morning and evening transition (discussed in Sect. 4.3) differences and temporal dynamics cannot be reliably
430 identified from Fig. 14.

As differences between locations are most obvious in the afternoon, when the ML is deepest (Fig. 14), this makes MLH_{max}
comparisons helpful (Fig. 12). As noted (Sect. 4.2), land-cover induced differences in H flux accumulate through the day (Fig.
11). Our results agree with earlier Paris studies. Daytime studies in March (08:00 to 16:00) observe central Paris MLH to be
27 % (70 m) greater than the SW urban fringe (Dupont, 1999) and urban 19 % (185 m) greater than rural (Pal et al., 2012). Our
435 winter (Sect. 2.3) daytime MLH_{max} differences are 24 % (167 m) larger for the inner city cf. upwind urban fringe (Fig. 14)
and our inner city cf. upwind rural are 21 to 25 % (Fig. 14). Both Dupont (1999) and Pal et al. (2012) also report high inter-site
difference variability between individual days, as we observe (Fig. 15).

While city - rural MLH differences are more common in the literature (e.g. Dupont, 1999; Barlow et al., 2015; Bohnenstengel
et al., 2015) than downwind effects. Although the urban plume was described decades ago by Clarke (1969), quantification of
440 downwind effects are needed. Our results show urban effects on the ML downwind of the city can be as pronounced as over the
urban area itself, especially for MLH_{max} (Fig. 15, Sect. 3.2.2). Our upwind-city-downwind differences corroborate the clear
spring day differences in Berlin of 24 % (370 m) for upwind cf. downwind median, and 11 % (174 m) for upwind cf. inner city
(Fenner et al., 2024). Our downwind-upwind (ensemble-mean) for summer days is slightly weaker (17 %, 178 m), while the
urban-upwind contrast is stronger (15 %, 240 m) (cf. to Berlin)(Fig. 15).

445 Given previous studies (Clarke, 1969; Fenner et al., 2024) and our observations, we hypothesise an urban plume is an uni-
versal urban modification downwind of large cities when the urban effects dominate over other geographical setting influences
(e.g., land/water, mountain/valley).

4.6 Seasonal differences

Generally, seasonal differences in ML evolution and height (Sect. 3.2.3) agree with continental boundary layers' expectations.
450 Long winter nights with strong radiative cooling often lead to deep and persistent stable nocturnal boundary layers over vege-
tated surfaces (Stull, 1988). Although this occurs over urban areas, it is less frequent (Varentsov et al., 2023). Thus, in winter
the ML may develop either very late in the day or not at all if unable to break through the previous day's residual layer.
Consistent with this, our observations have a MT delay in winter, sometimes even after solar noon (Fig. 9).

Consistent with (e.g. Pal and Haefelin, 2015; Baars et al., 2008), growth rates (GR) are generally higher in summer; asso-
455 ciated with larger H fluxes from greater solar irradiance and weaker nocturnal stratification (Batchvarova and Gryning, 1991;
Pal and Haefelin, 2015).



Overall, seasonal differences in GR are less distinct than MLH_{max} (Fig. 12), as winter days also have rapid growth (Fig. 12). This is in accordance with Kim's (2022) ERA5 reanalysis study in East Asia. Since GRs are modulated by the complex interactions with SEB partitioning and tropospheric stability (Sect. 4.2), they do not scale as simply with season as the MLH (Chu et al., 2025). Morning growth, detected using aerosol backscatter, also depends on the residual layer composition and its contrast to the nocturnal ML below.

We observe larger absolute MLH differences in summer, while relative differences are greater in winter (Fig. 14). In summer, warmer surface temperatures enhance H, thermal gradients and convective turbulence (e.g. Cotlier et al., 2025). The land cover and morphology differences modify thermal properties between local-scale areas, which can generate MLH variations. We expect that these will be stronger absolute contrasts in summer, as we only observe intra-urban differences in summer (Fig. 14).

Observations show seasonal differences in downwind ML in both MLH and NO_2 (Fig. 3). In winter the MLH is much lower at the downwind rural site than the downwind urban fringe site (Fig. 14; 15), but this is not seen in summer when the MLH maximum increases from the urban fringe to downwind rural sites (Fig. 15).

Thus, the spatial extent of the urban influence is larger in summer. The NO_2 plume also extends further downwind in summer than in winter (Fig. 3). Stronger summertime vertical mixing is transporting both aerosols and NO_2 within the boundary layer, and facilitating a greater horizontal spread (Kuhn et al., 2024). Similarly, in winter with weaker mixing the shallower boundary layer constrains the NO_2 nearer the surface (Kuhn et al., 2024) with higher local concentrations (Fig. 3).

4.7 Limitations

Our findings should be interpreted in light of some limitations, which aid identification of potential future research objectives.

- Our focus on daytime, clear-sky conditions with consistent wind reduces the 1-year dataset to 25 days, or fewer for some sites (e.g. NE urban fringe).
- Notably this focus excludes days with clouds, so we omit cloud thermodynamic feedbacks with the near-surface atmosphere (e.g. radiative exchanges or dynamic aerosol-cloud interactions).
- The algorithm to estimate morning transition (MT) growth rates (Sect. 2.2.1, SM S1.1) is reliable when continuous growth occurs, but has difficulties with substantial MLH decreases ($> 5\%$ of the maximum MLH between 15-min time-steps) that are greater than "expected" temporal variability during the growth period. This arises from STRATfinder having difficulties selecting the correct gradient when multiple narrow high concentration layers exist in the nocturnal BL (or the sensor not distinguishing small variations), resulting in the STRATfinder jumps or "flatlines". The algorithm appropriately excludes these periods from GR calculation as being erroneous, but we include after manual review of such conditions (i.e. GR detection failed).
- Eddy covariance observations (Sect. 2.2.3) over different land cover types require sensors to be mounted at different heights. If the areas are heterogeneous by wind direction the land cover composition affecting fluxes will vary (Table



S5), adding another source of uncertainty. Linking the flux data to MLH is not straightforward as there is currently no method to define the source area of a MLH derived from attenuated backscatter, as there is for radiosonde-based layer heights (Cleugh and Grimmond, 2001).

- Rural land-cover variations will impact spatial MLH variability through SEB modifications. This is not evaluated, but does differ between the transect ends (Table S2).
- Urban effects are still being detected at our most downwind sites (i.e. end of transect). Hence, the current transect length is insufficient to determine the spatial extent of urban effects. The question of how far urban effects extend into the surroundings is important and should be explored in future studies. Modelling of compounding cities also finds impacts more than 50 km downwind (Huang et al., 2019).

5 Conclusions

Using seven automatic lidar-ceilometers (ALC) along a 105 km transect in the Paris region, we investigate modifications of the mixed-layer height (MLH) dynamics. We observe changes in growth rate (GR), maximum height and timing, with sensors simultaneously observing upwind, urban and downwind locations. This study focuses on daytime and clear-sky conditions with consistent synoptic flow, excluding potential cloud-surface feedbacks.

We demonstrate that deploying sensors along a linear transect through an urban region, with an extent about twice the diameter of the built-up area (≈ 60 km), enables isolation of urban effects both above the city itself and downwind. We find comparable urban and downwind effects to both GR and MLH under different synoptic wind directions along and perpendicular to the transect. We conclude that in the Paris region, the urban effect on the mixed-layer dominates over orographic effects during the daytime. As urban effects are detected even at the end of the measurement transect (≈ 50 km from the city centre), future research should assess how far downwind urban influences on the boundary layer extend.

Analysis of the morning ML growth finds the average of three city sites (GR_{avg}) to be 31 m h^{-1} , which is 21 % faster than an upwind rural site, whereas the maximum (GR_{max}) is 51 m h^{-1} (21 %) faster. The rural downwind MLH GR_{avg} is 34 m h^{-1} (23 %) faster than the rural upwind, and the GR_{max} is 73 m h^{-1} (31 %) faster. The GR exhibits considerable variability between sites on individual days, which may possibly be explained by local surface forcing and random turbulence. However, once averaged, a clear pattern of increases in GR from upwind to downwind emerges. Seasonal differences in GR are less distinct than MLH. We observe winter cases with high growth rates. These may potentially be explained by residual layer properties and entrainment fluxes.

The overall MLH is enhanced in the inner city relative to upwind rural by 41 m (12 %) in summer (daytime 08:00 - 19:00) and by 58 m (41 %) in winter (daytime 10:00 - 17:00). Timestep pairwise comparison indicates that all downwind and inner city sites have a higher MLH than any upwind site for more than 62 % of the time. Differences are more distinct for MLH_{max} , as these differences accumulate through the day. In summer, the three city sites mean MLH_{max} is elevated by 218 m (14 %)



520 cf. the rural upwind site, while in winter this is 184 m (28 %). As MLH peaks are in the afternoon, rural downwind vs rural upwind site differences are evident in MLH_{max} both seasons (summer 236 m (15 %); winter 127 m (19 %)).

Larger absolute differences in MLH occur in summer, whereas the relative differences are greater in winter. Intra-urban differences in MLH are only observed in summer, with increasing MLH from upwind outer city to downwind outer city. There is evidence that the urban plume has larger spatial extent in summer, as MLH_{max} increases from the downwind urban fringe to downwind rural sites, but in winter it decreases. This is consistent with satellite-derived NO_2 observations (Fig. 3), which have larger downwind plumes in summer.

The observed differences in ML dynamics can be linked to urban modifications of the surface energy balance. We observe reduced LE fluxes and enhanced cumulative H fluxes at the urban sites. The H flux at the urban site remains positive throughout most nights. However, an upwind-downwind signature between these fluxes is not observed. This is partially related to the local-scale of the surface fluxes, relative to the integrative nature of the MLH observations. Hence, other processes, such as advection, entrainment, and momentum exchanges through the depth of the boundary layer are important.

Compared to upwind rural sites, a systematically enhanced MLH exists at the start of the morning transition (MLH_{start}) over the city (37 m, 12 %), whereas the opposite exists at downwind rural sites (-70 m, -30 %). The higher MLH_{start} over the city is attributed to the nocturnal urban heat island, i.e. sensible heat fluxes. Whilst the lower MLH_{start} downwind could potentially be caused by nocturnal heat advection from the city downwind over the already formed rural nocturnal boundary layer (NBL), hindering deepening of a stable layer.

Differences in morning transition onset timing and time of maximum growth do not show any conclusive link to transect location. On one day, we qualitatively observe a delay in NBL formation over the urban area and downwind.

The enhanced MLH can impact convective processes through stronger vertical exchange, such as cloud formation (Theeuwes et al., 2019) and precipitation (Forster et al., 2024), with growth rates controlling vertical transport of e.g. moisture or pollutants (Wang et al., 2019). Variations in turbulent surface heat fluxes also have implications for UHI intensity and therefore heat risks (Founda and Santamouris, 2017; Hou et al., 2022).

Future work will use these data to evaluate numerical weather prediction models (NWP) at hectometric scales (e.g. Glazer et al., 2025), and investigate the spatial and temporal variations, including spatial extent of the urban influence can be simulated; while exploring underlying processes. Combined, these can enable improved representation of urban effects in weather and climate models. Here we focus on daytime clear skies, but the role of cloud feedback mechanisms and NBL processes also should be addressed in future research.

Code and data availability. Eddy covariance observation data is publicly available for download from the ICOS data portals at <https://data.icos-cp.eu/portal/>, <https://citydata.icos-cp.eu/portal/> and the AERIS data centre catalogue at <https://paname.aeris-data.fr/data-catalogue-2/> (Price et al., 2025). Doppler wind lidar data are available at <https://doi.org/10.5281/zenodo.14761503> (Morrison et al., 2025b). The Mountsouris and Eiffel Tower observations are part of the harmonised ReOBS dataset (Chiriaco et al., 2018). The mixed-layer height data presented here



will be made available at <https://doi.org/10.5281/zenodo.19334310>. The analysis code is available at https://github.com/DanaLooschelders/urbisphere_Paris_ALC_MLH_GR.

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