Latent Heat Flux and TKE measurements from the combined use of Water Vapour Raman and Wind Doppler Lidars during WaLiNeas Campaign.

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Abstract: Measurements of latent heat flux profiles in the daytime convective boundary layer were carried out in the frame of the WaLiNeAs field campaign, taking advantage of the combined use of two ground-based lidars: a water vapour Raman lidar and a wind Doppler lidar. Water vapour mixing ratio profile measurements were carried out based on the exploitation of the roto-vibrational Raman lidar technique in the UV, while vertical wind profile measurements were carried out with a Doppler wind lidar. Cloud-free 60-minute analysis periods from the WaLiNeAs campaign are considered as case studies, with a 10-second temporal resolution for several selected cases. The vertical turbulent flow is calculated as the covariance between the time series of the vertical velocity (*w*) and the water vapor mixing ratio fluctuations (*q*). The TKE (Turbulent Kinetic Energy) is also computed as a further parameter by the wind lidar for the same selected cases, revealing good agreement with the flow measurements.

1. Introduction

In the present work, the latent heat flux *Q(z)* is obtained based on the combined use of two instruments, i.e. a wind lidar and a water vapour Raman lidar. Two such systems where co-located in an observational site in Southern France at the University of Toulon, La Garde (Lat.: 43.136040 N, Lon.: 6.011650 E, Elev.: 65 m) in the frame of the international field campaign WaLiNeAs (Water Vapor Lidar Network Assimilation). The Raman lidar is a research instrument developed by the University of Basilicata, known with the name of CONCERNING (Compact RamaN lidar for Atmospheric CO_2 and ThERmodyNamic ProfilING), while the wind lidar is a commercial instrument developed by Halo Photonics (model Stream Line XR, more detail below). Both lidars continuously operated during the period September 2022-January 2023. In the frame of WaLiNeAs a network of water vapour (WV) Raman lidars was created, with instruments deployed along the coast in Southern France and Eastern Spain, with the ultimate goal to improve heavy precipitation forecasting in the Mediterranean area through WV profile data assimilation. Eight Raman lidars were operated, which provided water vapor measurements with high spatial-temporal resolution and accuracy. (Figure 1).

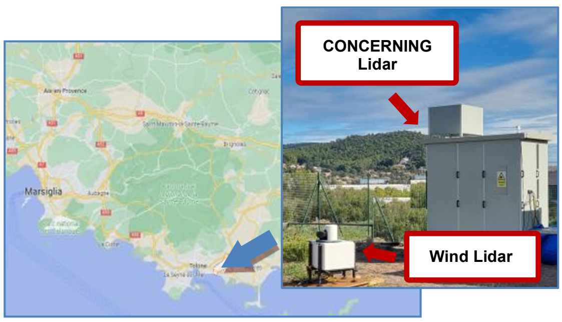


Figure 1. CONCERNING system during the WaLiNeAs campaign

The proposed water vapour lidar network has been conceived with the aim of monitoring all relevant WV sources and transport patterns known to contribute to the generation of heavy precipitation events (HPEs) in southern France. This network aims at demonstrating the benefit of the assimilation of vertically resolved WV data in the operational 1.3-km grid size

AROME-France NWP system, which enables ensemble-variational data assimilation for kilometer-scale prediction of heavy precipitation over southeastern France [1]. As part of the WaLiNeAs initiative, the WV Raman lidar CONCERNING operated continuously over more than three months. A wind lidar capable to perform profile measurements of the horizontal and vertical components of the wind speed was placed nearby. Overall, the combination of WV lidar and Doppler lidar provides a powerful tool for studying the Earth's atmosphere and advancing our understanding of complex physical processes such as the transfer of energy and moisture between the land surface and the atmosphere. Sensible and latent heat flux profile measurements, *H(z)* and *Q(z)* are of paramount importance to study the exchange of heat and moisture between the Earth's surface and the atmosphere [2]. Latent heat flux, on the other hand, is the transfer of heat from the Earth's surface to the atmosphere due to the evaporation of water. In general, the computation of fluxes using the eddy covariance method entails the collection of high-frequency measurements, data processing, (30m, and 10sec, as spatial and temporal resolution in our cases) and the application of suitable calculations to derive the turbulent fluxes of interest. Turbulence induced by buoyant eddies within the Convective Boundary Layer (CBL) results in an efficient vertical transport of humidity, either upwards or downwards, contingent upon the location of water vapor sources and sinks. In our specific case, the humidity transport within the CBL is oriented upwards, originating from surface evaporation, moving towards cloud condensation, and entrainment into the drier free troposphere as sinks, as will be demonstrated by the flux profiles in the subsequent section. A representative net flux is determined by examining the covariance of vertical velocity and specific humidity fluctuations, denoted as <w'·q'>, within a designated time or spatial domain, provided that the turbulence remains quasi-stationary over time and spatially uniform [3].

2. Instrumental setup

The system CONCERNING includes a powerful laser source, capable to generate single pulse energies at 355 nm of 100 mJ, which corresponds to an average power of 10 W at a pulse repetition frequency of 100 Hz. The receiver is developed around a Newtonian telescope, with a primary mirror diameter of 0.50 m. The key feature of CONCERNING is represented by its capability to perform day-time and night-time high-resolution and accurate measurements of atmospheric temperature and WV based on the application of the rotational and vibrational Raman lidar technique (i.e. 10 s and 3.5 m resolution). Raman lidar measurements of the water vapour mixing ratio profiles have been extensively reported in literature [4-6]. The approach relies on the use of the roto-vibrational Raman lidar signals from water vapour, $P_{H_2O}(z)$, and molecular nitrogen, $P_{N_2}(z)$, at the two Raman shifted wavelengths λ_{H2O} and λ_{N2}, respectively. The signal in terms of generic wavelength λ are expressed, as the number of detected photons from a given altitude (z) above the station level, by the following expression:

$$P_\lambda(z) = P_0\left(\frac{c\Delta t}{2}\right)\frac{A}{z^2}\,\xi_\lambda(z)\,\sigma_\lambda\,T_\lambda(z)\,T_{\lambda_0}(z) \quad (1)$$

where P_0 is the number of emitted photons for each laser pulse at wavelength λ_0, c is the speed of light, A is the telescope aperture area, $\xi(z)$ is the overall transmitter–receiver efficiency at wavelength λ, Δt is the laser pulse duration, and $T_\lambda(z)$ and $T_{\lambda_0}(z)$ are the atmospheric transmission profiles from station level up to the scattering volume altitude z at λ_0 and λ respectively. The vertical profile of the water vapour mixing ratio is obtained through the following equation [7,8]:

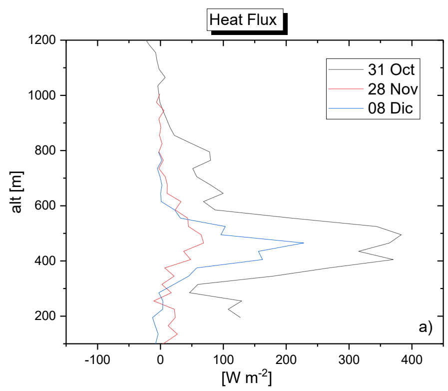
$$x_{H_2O}(z) = K\,\frac{P_{H_2O}(z)T_{N2}(z)}{P_{N2}(z)T_{H2O}(z)} \quad (2)$$

where K is a calibration constant and $T(z)$ is a transmission term, which accounts for the different atmospheric transmission by molecules and aerosols at λ_{H_2O} and λ_{N_2} through the altitude interval from the lidar station level to scattering volume z.

During the measurement campaign, a Doppler lidar moved from the CNR-IMAA (National Research Council of Italy - Institute of Methodologies for Environmental Analysis) Atmospheric Observatory (CIAO) was used. This is a Stream Line XR model manufactured by Halo Photonics, emitting near infrared (1.5 μm) laser pulses with 100 μJ energy per pulse, 0.2 µs duration, and 10 kHz repetition frequency. The lidar, capable of full upper hemisphere scanning, is equipped with a heterodyne detector, measuring range-resolved elastic backscattered radiation from atmospheric particles (aerosols, clouds, fog and precipitation) and particles' radial velocity (parallel to the laser beam), derived from the Doppler shift of the backscattered radiation. Doppler lidar measurements have raw range and temporal resolution of 30m and 1s, respectively. The system was continuously operated mainly in zenith pointing configuration, but also performed a velocity-azimuth display (VAD) scan every 2 minutes. This scan was characterized by 6 off-zenith beam pointing directions with a constant elevation angle ε = 75°, equally spaced (60°) azimuth angles starting from north, measurement temporal averaging for each direction of 3 s (30000 laser pulses), and full scan duration of about 30 s, considering the time for the scanner movement.

3. Results

In the present work measurements of latent heat flux profiles *Q(z)* and TKE in the diurnal convective boundary layer (CBL) have been carried out with remote sensing from the ground. Water vapour (*q*) was obtained from UV rotational Raman lidar measurements while vertical wind (*w*) measurements were made with the Doppler wind lidar. Cloud-free 60-minute analysis periods at full 10-second time resolution during the campaign were considered for selected case studies. Considered analysis periods are extracted for the days of October 31th, November 28th, and December 8th 2022 (see Figure 2a, 2b).



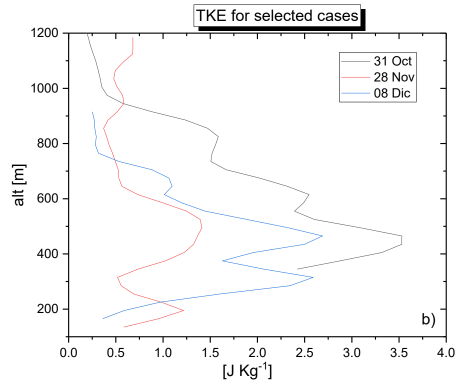


Figure 2. Profiles of latent heat flux (a) and TKE (b) for selected cases.

The results show a typical *Q(z)* profile with positive values in the lower and middle CBL (500-600 m), while values around zero of *Q(z)* are reported in the upper CBL

A strong positive flux divergence is apparent, it represents a significant upward humidity transport drying out the mid and lower CBL by entrainment of dry air from above. Turbulent Kinetic Energy (TKE) was also computed for the same selected cases. The results are in agreement with each other and are compatible with the precipitation events following the selected case studies.

4. Acknowledgments

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