Investigation of the capabilities and benefits of Doppler lidars in an operational European observation network: the TOPROF European Action

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Abstract: The new generation of high-resolution (~1 km) weather forecast models now operational over Europe promises to revolutionise predictions of severe weather and poor air quality. To realise this promise, a dense observing network is required, focusing especially on the lowest few km of the atmosphere, so that forecast models have the most realistic state of the atmosphere for initialisation, continuous assimilation and verification. To do so, a European Concerted Research Action designated as COST Action ES1303: Towards operational ground based profiling with ceilometers, Doppler lidars and microwave radiometers for improving weather forecasts (TOPROF) was launched in 2013 This Action focuses on developing three types of instruments available throughout Europe: i) Several hundreds of ceilometers, ii) 20+ Doppler lidars, and iii) 30+ microwave profilers. These instruments are robust, relatively inexpensive and have proven suitable for unmanned network operations. Here, we describe the efforts of the working group dedicated to Doppler lidars. This type of sensor is based on a new technology, providing vertical and horizontal winds, turbulent quantities, attenuated backscatter and cloud/aerosol layers in the lower atmosphere with a resolution of at least 30 m every 5 minutes. The working group is coordinating multiple studies in order to characterise the performances of Doppler lidars systems. Understanding the system performance and uncertainties in the basic measurements of radial Doppler velocity and signal-to-noise ratio is vital for providing reliable products. The uncertainties in the radial measurements can then be propagated through to the higher-level products that are created, such as wind speed and direction, and turbulent properties. The measurement setup, scan selection and processing chain was evaluated with the objective of providing harmonized retrievals so that any suitable Doppler lidar system can fit within an emerging European Doppler lidar network capable of providing reliable wind products and turbulent parameters in the boundary-layer.

Keywords: Coherent Doppler lidar, observing network, weather forecasts, standardization, data assimilation, data quality

1. Introduction

In spite of the constant effort to improve weather forecasts, weather forecasts extending beyond a few days still remain relatively inaccurate at a local scale. Today, there is a growing interest to focus on local and regional scales. Indeed, in case of severe weather, weather forecasts are crucial to drastically reduce the impact on human lives and economical activities where weather risk exposure is the highest (urban, business, industrial area). The goal is to be able to quantify weather risk and thus support local authorities and decision makers. To reach this objective, numerical weather prediction (NWP) models must be improved by increasing their spatial resolution. There has been rapid increase in horizontal resolution during the last decades with horizontal grid sizes decreasing from 50 km to 1-5 km, with even higher resolution in testing. With increased resolution the need for local observations to provide the necessary initial conditions increases. But, existing weather observation networks were designed for national weather monitoring, not for providing a densely populated set of observations to high resolution NWP models. New sensors are thus required that can provide more local, dense, accurate observations with high spatial resolution, in particular inside the planetary boundary layer and close to the ground. Development of a new generation of wind lidar technologies began in the 1990s and expanded rapidly in the 2000s with the introduction of commercial off-the-shelf fiber-optic components developed for the telecommunication industry. This lidar technology permitted cost effective sensors thanks to industrial manufacturing. Today, coherent pulsed Doppler lidars are being evaluated worldwide in various projects to determine their potential benefits for weather observing networks [1][2]. In this paper, their capabilities in terms of wind and aerosol/cloud measurements are described, and potential benefits for future observing networks are demonstrated with two examples related to severe weather monitoring and weather forecast improvements. The main constraints in building future weather observing networks composed of coherent Doppler lidars are detailed.

2. State of the art and capabilities of coherent Doppler lidars

Roughly one thousand Coherent Doppler lidars (CDL) are used worldwide for different applications with the majority used for wind energy applications. Wind lidar profilers allow measurements of wind speed and direction from a few tens of meters above the ground up to the top of the planetary boundary layer (PBL, 1-2 km) for long range lidars. The typical accumulation time for providing individual measurements is 1s but usually raw wind data are averaged over 10 minutes. Scanning Doppler lidars are based on the same technology but can provide full hemispheric scanning up to about 10 km in range. There are several standard scanning scenarios that can be employed, such as Plan Position Indicator (PPI) or Velocity Azimuth Display (VAD), Range Height Indicator (RHI), Line of Sight (LOS) and Doppler Beam Swinging (DBS). Both types CDL provide winds at high spatial and temporal resolution, typically 20 to 200 m and 1 s to 1 min. The demonstrated wind accuracy compared to reference met masts is usually better than 0.3 m s^{-1} [3][4]. Figure 1 shows a typical example of the time-height structure of the horizontal wind speed and the cloud and aerosol layers that these instruments can provide.

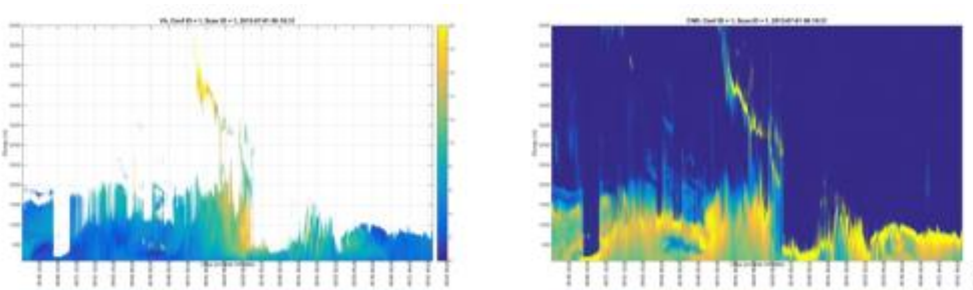

Figure 1. Time-height plot of the evolution of the wind speed (left) and lidar signal (right) from 1st to 2nd of July 2013 in Orsay, France

The vertical measurement range is limited by the necessary presence of enough aerosol to provide a signal, and is typically the height of the planetary boundary layer. When pointing horizontally, the range is limited by both the necessary presence of enough aerosol to provide sufficient signal, and how much attenuation the lidar beam experiences due to atmospheric extinction by the same aerosol. In both cases, the presence of hydrometeors (clouds or precipitation) entails rapid attenuation of the lidar beam. Nominal range performance can be obtained under clear air conditions (aerosol is present but visibility is above 10 km). Due to these limitations, an all-weather system should therefore utilize both lidar and radar methodologies. In addition to measuring wind, a profile of attenuated backscatter coefficient is derived from the signal strength. This permits the development of algorithms to detect atmospheric structures such as cloud, aerosol layers, PBL height [5][6] similar to those designed for ceilometers and aerosol lidars. Some examples of the combined use of wind and aerosol products are described in section 4 to demonstrate the potential benefits of CDL for building future weather observing networks.

3. TOPROF activities

a) Description

In 2013, the European framework for Cooperation in Science and Technology, COST (http://www.cost.eu/), launched the four-year Action ES1303: Towards operational ground based profiling with ceilometers, Doppler lidars and microwave radiometers for improving weather forecasts (TOPROF, http://www.toprof.imaa.cnr.it/). The role of the Doppler lidar working group in TOPROF is to ensure that a coherent set of Standard Operating Procedures and a data processing framework is available for operators of all viable Doppler lidar systems that might be utilized within an emerging European meteorological Doppler lidar network with the goal of providing harmonized retrievals. This requires a thorough evaluation of the measurement setup, scan selection and processing chain of each system to enable them to become members of a network capable of providing reliable winds and turbulent parameters in the boundary-layer.

Activities have concentrated on:

- rigorous measurement uncertainty analysis [5][8], since full error characteristics are a requirement for providing data for assimilation into high-resolution NWP models,
- defining operational procedures for retrieving profiles of horizontal wind from different instruments, and instrument configurations [4],
- methods for retrieving turbulent properties from different instruments and instrument configurations [5][9],
- harmonisation of the processing chain for integrating observations from different instruments with different scan strategies from different locations.

The working group in TOPROF has assessed instrument performance, assisted through continual dialogue with manufacturers and intercomparison campaigns [4], and has defined suitable scan strategies that combine zenith viewing operation to sense vertical wind structure and turbulence with azimuth scanning operation to provide accurate and representative high resolution profiles of horizontal winds. This has enabled operational procedures to be established for generating quality-controlled wind and turbulence profiles at high spatial and temporal resolution from Doppler lidar across Europe.

The new turbulent retrievals allow the diagnosis of various aspects of the dynamical boundary layer, including type and height [10][11], and identifying the presence and source of mixing. TOPROF will also investigate the ability of the Doppler lidars to identify the various boundary layer states, such as, stable, unstable, coupled and decoupled, so that boundary layer classification and parameterization schemes implicit in NWP models can be evaluated [12].

b) Chosen configuration

For all lidars deployed in the TOPROF Europe emerging network, specific configuration and sequence of scanning scenarios have been chosen. The typical chosen spatial resolutions are between 30 and 50m and the range of measurements are from 100m up to 10km. The sequence of scanning scenarios consists in

- Two VAD scans at 15° and 75° elevation whose data are combined to provide one vertical wind profile with a better vertical resolution in the lowest part of the wind profile and get the first point of measurements at 39m instead of 145m. These VAD scans are repeated every 15minutes for providing 10 minutes averaged wind data. The VAD consists in 12 line-of-sight measurements obtained with 2 or 5 seconds of accumulation time.

- Continuous vertical line-of-sight measurements repeated during 5minutes to measure cloud and aerosol layers as well as boundary layers and turbulence quantities.

c) Standardized data workflow process

For ensuring the same data format between all lidar systems, a data workflow process has been developed. The input data are CSV files containing radial wind data and the output data consist in Netcdf files as standardized by several European projects. This data workflow process allows also to calculate horizontal wind components, wind directions and vertical winds through a VAD algorithm.

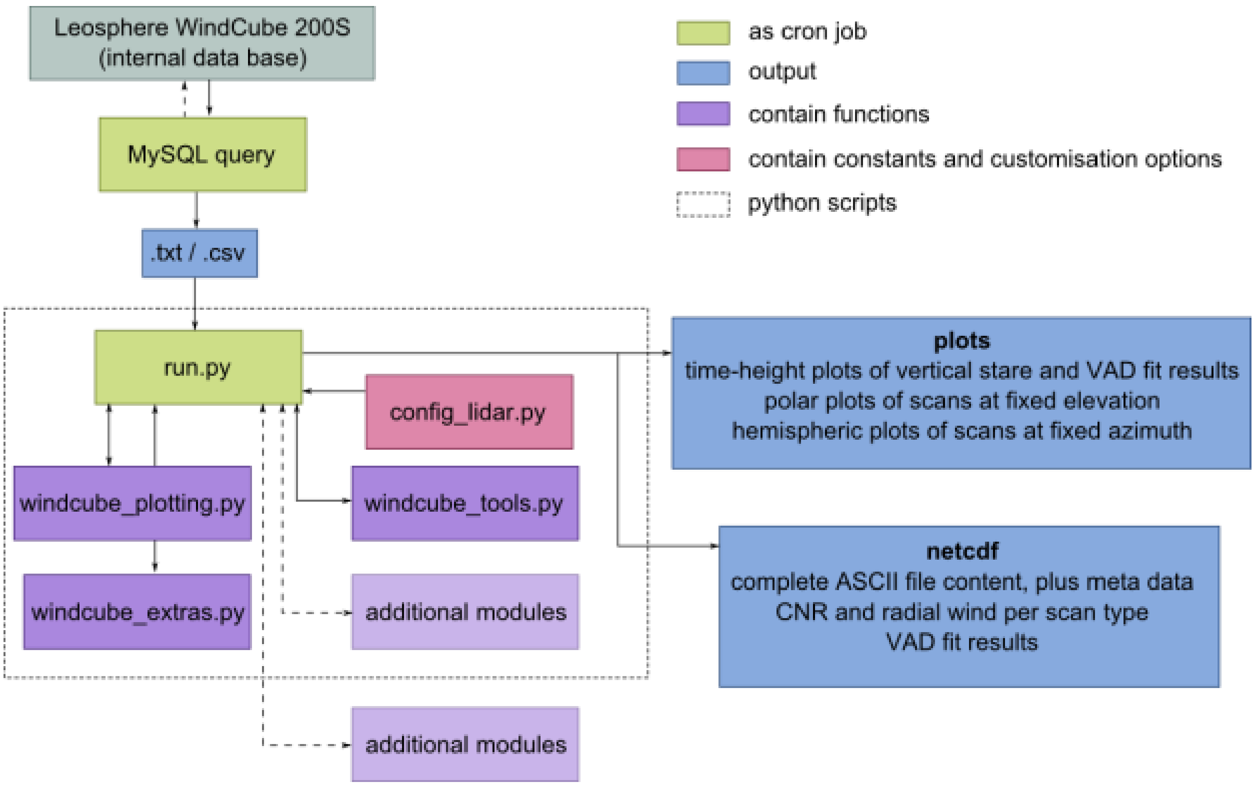

Figure 2. Data workflow process developed in TOPROF project

d) Example of data displayed by the TOPROF data workflow process

Finally, this tool allows displaying the temporal evolution over one day of the vertical wind speed, the horizontal wind speed and direction and the backscattered signal. The measurements performed by a Windcube200S installed at Mace Head in Ireland the 14th of July 2016 are shown on Figure 3.

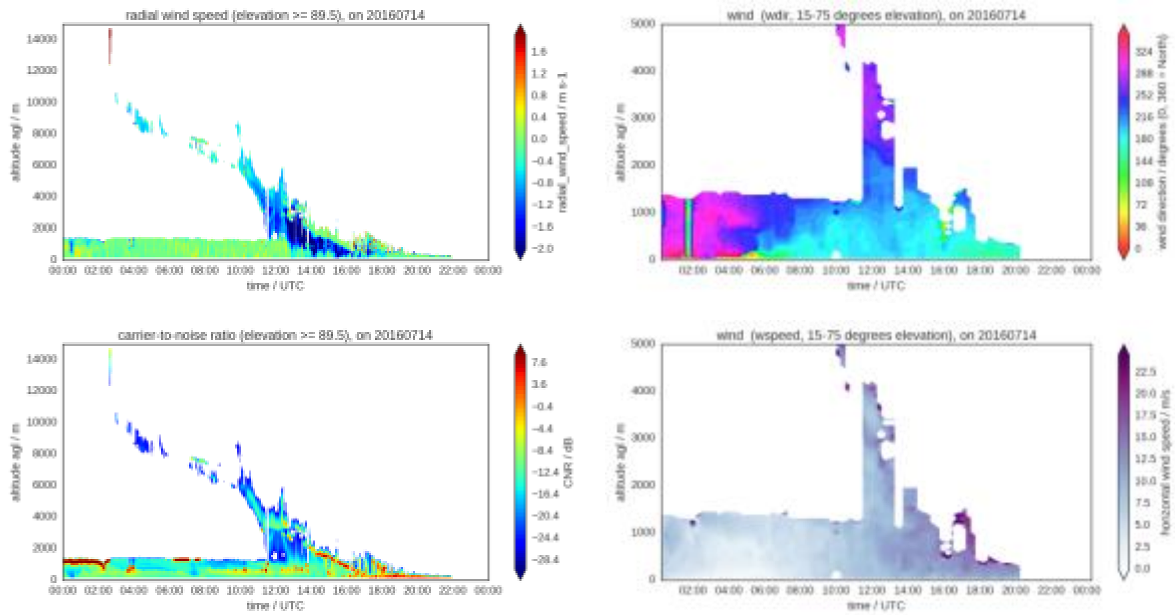

Figure 3. Vertical wind speed (top left), wind direction (top right), lidar signal (bottom left), horizontal wind speed (Bottom right). The maximum altitude (y-axes) is 15 km on the left and 5 km on the right.

4. Conclusions

The current capabilities of CDLs reveal their potential benefits for improving weather monitoring and forecasting. CDLs are under evaluation worldwide by expert groups such as TOPROF [http://www.toprof.imaa.cnr.it/] to determine how to integrate them into operational weather networks. Other CDL networks are also currently under construction including the NYC Mesonet in USA and the ARM program, showing the interest of using lidar to better anticipate severe weather.

5. References

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