The Impact of Aeolus Wind Profile Measurements on Severe Weather Events: A COSMO NWP Case Study over Thessaly

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Abstract: The limited availability of wind profile measurements has hindered atmospheric models and climate systems’ understanding. The European Space Agency’s Aeolus mission’s space-based Doppler wind lidar technology could solve this issue by measuring wind profiles in Near-Real-Time, providing valuable data for Numerical Weather Prediction (NWP) models. A case study using the COSMO NWP model demonstrates the potential of Aeolus data in improving NWP models by examining the impact of Medicane IANOS in September 2020 over the Thessaly plain. The study aims to improve our ability to predict severe weather events and advance our understanding of Earth’s atmosphere.

Keywords: remote sensing; Aeolus; satellite; NWP; medicane; severe weather; precipitation; lidar; winds; COSMO

1. Introduction

The accuracy of Numerical Weather Prediction (NWP) forecasts depends on the accuracy of the initial state [1], which is produced through data assimilation—the combination of model information with various types of observations. Accurate observations of wind are crucial for the accuracy of NWP models, as they provide essential information for predicting weather patterns and patterns of atmospheric circulation. The importance of satellite radiances for NWP quality has been well established [2]. However, NWP models also rely on simulations of atmospheric winds. These winds are inherently uncertain due to several factors, including the spatial and temporal resolution of the model, approximations in the physical parameterization schemes, and uncertainties in the boundary conditions.

The World Meteorological Organization Rolling Review of Requirements has identified that wind profiles are the most important critical atmospheric variables that are not adequately measured by current or planned observing systems. Numerous studies [3–6] suggested the potential benefits of increasing wind profile observations for NWP.

The successful deployment of the Aeolus satellite by the European Space Agency (ESA) on 22 August 2018 marked a momentous achievement. This pioneering satellite carries an extraordinary payload, the first ever Doppler Wind Lidar (DWL) in space, signifying Europe’s debut in spaceborne lidar technology. Aeolus serves a crucial purpose in addressing the current deficiency of wind data within the global observing system. As a result, it holds immense scientific importance by presenting an exceptional opportunity...
to highlight the value of satellite-derived wind profiles in enhancing Numerical Weather Prediction (NWP) models.

Aeolus’s groundbreaking payload, the DWL, enables satellite to acquire precise wind profile measurements from space. By obtaining comprehensive and accurate data on atmospheric winds, Aeolus plays a vital role in filling the existing gap in global wind observations. This capability provides valuable insights into atmospheric dynamics, contributing to the improvement in NWP models. The scientific community eagerly anticipates the potential impact of Aeolus in demonstrating the utility and effectiveness of satellite-derived wind profiles, thereby enhancing our ability to forecast weather conditions with greater accuracy and reliability on a global scale.

The impact of Aeolus on short-range forecasts was discovered to be comparable to certain other significant satellite observing systems employed at the European Centre for Medium-Range Weather Forecasts (ECMWF) in recent times. This finding is particularly encouraging since Aeolus, as a single instrument on a satellite, represents less than 1% of the assimilated observations. With the confirmation that Aeolus was making a valuable contribution to the global observing system [7–10], it was determined at ECMWF on 9 January 2020 to activate Aeolus for operational data assimilation. In addition to the ECMWF studies, multiple other scientific investigations have corroborated the beneficial effects resulting from the assimilation of Aeolus wind data in global and limited area NWP models [7–11].

The objective of this study is to investigate the potential qualitative transfer of these improvements of assimilated data on global NWP to the performance of the Consortium for Small-scale Modeling (COSMO) NWP model. A numerical experiment was conducted using the COSMO model to simulate a severe weather event, specifically the Medicane IANOS, with the aim of evaluating the model’s ability to realistically represent precipitation variables from 24 h to 48 h forecast time over Thessaly.

Section 2 of this study encompasses the data sources and methodology employed. In this section, we provide an overview of the data sources used, including a detailed description of the Aeolus satellite, the Consortium for Small-scale Modeling (COSMO) NWP model, and Medicane IANOS. Section 3 presents the results obtained from our numerical experiment during the search along with the corresponding analysis. Finally, in Section 4, a summary and conclusion of the study are provided.

2. Data and Methodology

2.1. Aeolus Satellite

The successful deployment of the Aeolus satellite by the ESA on 22 August 2018 brought a remarkable advancement in the field of Earth observation. Aeolus has a primary objective of providing highly accurate and detailed wind component profiles spanning from the Earth’s surface to the lower stratosphere. This mission is made possible through the utilization of the groundbreaking DWL instrument known as the Atmospheric Laser Doppler Instrument (ALADIN).

ALADIN operates in the ultraviolet range of the electromagnetic spectrum, emitting pulses of laser light at a stable frequency of 50.5 Hz and a wavelength of 354.8 nm. The emitted light interacts with the Earth’s atmosphere, encountering various scattering phenomena. Rayleigh scattering, caused by interactions with air molecules, and Mie scattering, resulting from interactions with particulates such as aerosols, cloud droplets, and ice crystals, play a pivotal role in capturing the backscattered light [12,13].

Within the ALADIN instrument, the backscattered signals undergo further analysis. The Rayleigh Channel, employing a Double Fabry-Perot spectrometer, focuses on capturing the backscatter from clear air molecules. On the other hand, the Mie Channel utilizes a Fizeau spectrometer to capture backscatter specifically from particulate matter. The returned signals exhibit a Doppler shift, which arises from the movement of atmospheric scatterers relative to the instrument’s field of view [12,13]. This Doppler shift is
carefully measured by comparing the backscatter frequency to the emitted frequency of the instrument.

To generate comprehensive wind component profiles, ALADIN separates the signals into height bins using sophisticated on-board hardware. Aeolus is equipped with 24 vertical bins, each tailored to a specific altitude range. The size of these bins gradually increases with altitude, conforming to integer multiples of 250 m. The flexibility of Aeolus’s vertical sampling allows for adjustments in the range bin settings, optimizing the sampling strategy based on the specific climate zone encountered during the mission. A comprehensive analysis of ALADIN’s design, performance, and accomplishments, including the laser transmitter, receiver optics, and initial mission results, can be found in previous studies [12,13].

2.2. Medicane IANOS

Medicanes may cause a significant impact over the Mediterranean area [14]. During the period of 15–21 September 2020, Medicane IANOS, an intense Mediterranean cyclone, was formed over the warm waters of the Mediterranean Sea. It had a path spanning approximately 1900 km and primarily impacted Greece, resulting in significant consequences in the western and central parts of Greece.

Notably, the region experienced persistent gale force winds reaching up to 44 m/s, with gusts recorded as high as 54 m/s on Cephalonia Island in the Ionian Sea. Additionally, the storm brought record-breaking amounts of rainfall to several Ionian islands and parts of central Greece. This excessive precipitation led to flash floods and river flooding in various areas, particularly impacting the islands of Kefalonia and Zakynthos, as well as central Greece.

The strong winds accompanying Medicane IANOS caused significant damage to infrastructure, resulting in power outages and uprooted trees. Coastal areas also faced the impact of heavy seas, leading to coastal erosion and storm surge along the affected coastlines. Several scientific studies have documented the significant impact of IANOS [15–19].

2.3. COSMO Model Investigation

To investigate the potential qualitative transfer of these improvements to local NWP, the latest version of the COSMO.v6 (formerly LM) NWP model was employed [20,21]. The COSMO model, which has been extensively used by the COSMO consortium (www.cosmo-model.org) for operational purposes, research, and development, has served as a reliable resource until 2022, when it began to be gradually replaced by the ICON model [22]. However, the COSMO model still stands as a state-of-the-art tool due to its continuous development and adherence to the highest standards over the course of nearly 25 years [20,23,24]. Over time, significant progress has been made in terms of refining its physical parameterizations, enhancing the understanding of model sensitivity, and optimizing its overall performance [25,26].

The model was executed on a horizontal grid with a resolution of approximately 0.030° (~3.5 km), encompassing a total of $1367 \times 834$ grid points and featuring 60 vertical levels. This fine-grained resolution allows for capturing local-scale weather phenomena and provides a comprehensive representation of atmospheric processes in the wider Mediterranean area, which is known for its complex and diverse meteorological conditions. The inclusion of high-resolution data from Aeolus offers a unique opportunity to study the impacts of this novel observational resource on improving regional weather predictions.

To ensure reliable hindcast runs, the model was forced to use the available six-hourly IFS analysis data over a period of 48 h, starting from 17 September 2020, at 00 UTC. This extended time frame allows for capturing the evolution of weather patterns, including the development and progression of severe weather systems. The computations were performed utilizing the new supercomputing system at ECMWF [27], which is equipped with cutting-edge computational resources provided by the Hellenic National Meteorological Service (HNMS). The utilization of these advanced computing capabilities not only ensures
efficient model execution but also enables the exploration of a wide range of atmospheric processes and interactions.

3. Results and Discussion

In this section, we present the findings from an extensive numerical analysis of the Consortium for Small-scale Modeling (COSMO) model, specifically examining its performance in assimilating wind data from the Aeolus satellite during the investigation of the Medicane IANOS. The evaluation is focused on the model's ability to represent precipitation variables.

To evaluate the impact of assimilating Aeolus data, the specific case under consideration was run twice. The first run, denoted as hls0, incorporated the Aeolus assimilated data, while the second run, denoted as hlpv, excluded the assimilated data. Both sets of model output were stored at ECMWF for further analysis and comparison. By comparing the results from these two runs, we can quantify the influence of the Aeolus data assimilation on the accuracy and skill of the local NWP model, thus assessing the potential benefits of incorporating Aeolus observations into regional forecasting systems. The study aimed to comprehensively investigate the impact of assimilating Aeolus wind data on NWP, specifically focusing on the variable of precipitation.

During the occurrence of the Medicane IANOS in mainland Greece, the analysis revolved around examining the difference between assimilated and non-assimilated data (hls0-hlpv) to ascertain the extent of the positive or negative influence of Aeolus wind data on NWP. To provide visual representation, Figure 1 was employed, depicting the spatial distribution of impact in terms of precipitation, with red colors indicating a positive impact (resulting in increased precipitation) and blue colors indicating a negative impact (resulting in decreased precipitation), quantified in millimeters.

Delving deeper into the forecast period, noteworthy improvements were observed when assimilating Aeolus wind data. At the +24 h forecast time, the NWP model incorporating Aeolus assimilated data demonstrated enhanced precipitation forecasting accuracy over the western mainland of Greece, signaling a positive impact (Figure 1a). This positive signal persisted up to the +30 h forecast time, with its influence gradually extending to the southern regions of the mainland (although not explicitly shown).

As the forecast progressed to the +36 h time frame, the NWP model successfully captured the intensification of precipitation over the central parts of Greece. Subsequently, by the +42 h forecast, the area most significantly affected by increased precipitation shifted to Thessaly, where severe flooding occurred. Finally, by the +48 h forecast, the positive impact was prominently manifested, encompassing major portions of the mainland (Figure 1b).
4. Summary and Conclusions

The study highlights the importance of accurate wind observations for improving NWP models. The deployment of the Aeolus satellite, equipped with the first ever Doppler Wind Lidar (DWL) in space, addresses the deficiency of wind data in the global observing system. Aeolus provides precise wind profile measurements, contributing to the enhancement in NWP models and the accuracy of short-range forecasts. The study aims to investigate the transferability of these improvements to the COSMO NWP model by simulating a severe weather event, Medicane IANOS, and evaluating the model’s representation of precipitation variables.

By comparing two model runs—one with Aeolus assimilated data and one without—the study quantifies the influence of Aeolus data assimilation on precipitation forecasting accuracy. The results indicate that assimilating Aeolus wind data improves precipitation forecasting, with positive impacts observed over western mainland of Greece at the +24 h and +30 h forecast times and extending to other regions by the +36 h to +48 h forecast times, including areas affected by severe flooding.

The findings of this study highlight the valuable contribution of assimilating Aeolus wind data to the NWP model, ultimately leading to improved accuracy in predicting and capturing the spatial and temporal distribution of precipitation. This enhanced forecasting capability holds promise in terms of enhancing forecast reliability and potentially enabling early detection and monitoring of severe weather phenomena, such as the Medicane IANOS, thereby assisting in proactive disaster management and mitigation efforts.

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