Preliminary activities for the establishment of CyMETEO strategic meteorological infrastructure in collaboration with the Department of Meteorology

Christina Oikonomou *[a,c], Haris Haralambous[a,b], Filippos Tymvios[d], Demetris Charalambous[d], Margarita Satraki[d], Vassiliki Kotroni[e], Konstantinos Lagouvardos[e] and Eleftherios Loizou[f]

[a]Frederick Research Center, Nicosia 1036, Cyprus; [b]Frederick University, Nicosia, 1036, Cyprus; [c]Cloudwater Ltd, Nicosia, 1026, Cyprus; [d]Cyprus Department of Meteorology, 1086, Nicosia, Cyprus; [e]National Observatory of Athens, 11810, Athens, Greece; [f]Nicosia Development Agency, 2253, Nicosia, Cyprus;

Abstract

The present work aims to describe the main objectives and activities of the research project "Cyprus GNSS (Global Navigation Satellite System) Meteorology Enhancement" (CYGMEN) funded (€1.500.000) by the Cyprus Research Innovation Foundation (RIF) in the frames of "Strategic Research Infrastructures" Call for Proposals. CYGMEN was initiated at December 2023 with the aim to establish a Meteorological cluster (CyMETEO) in Cyprus that will strategically augment existing Frederick Research Center and Department of Meteorology infrastructure, through the introduction of: a Lighting detection network, b) a dense GNSS network for atmospheric water vapor estimation (supported by Cloudwater Ltd and Nicosia Development Agency, c) a Radar Wind Profiler (RWP) and d) a Microwave Radiometer (MWR). Within this framework, preliminary activities for the establishment of CyMETEO infrastructure will be presented here. The CyMETEO infrastructure will be also accompanied by an advanced CyMETEO service that will be developed in order to: a) process and provide in near real-time all different types of data generated by CyMETEO infrastructure (CyMETEO Observational Analysis Component) and b) provide advanced short-term weather forecasting through the assimilation of CyMETEO data into the state-of-the-art Weather Research and Forecasting (WRF) model currently employed operationally by the Cyprus DoM without, however, performing any Data Assimilation (CyMETEO Simulation Analysis Component). Thus, preliminary results from the CyMETEO service design and development will be also shown.

Keywords: GNSS, water vapor, Radar Wind Profiler RWP, Microwave Radiometer MWR, Lightning Detection Network, severe weather service, meteorology

1. INTRODUCTION

Coastal areas around the eastern Mediterranean (EM) Sea have been very frequently subjected to severe convective storms during the last 10 years [1]. "Medicanes", hurricane-like cyclonic systems in the Mediterranean Sea, are becoming an increasingly severe problem for many countries, causing loss of lives and extensive damage [2]. There is a clear demand to combine meteorological data from different sources, such as satellites, weather radar, wind profilers, radiometers into weather prediction models in order to synthesize a more comprehensive picture of these fast-developing intense storms over the EM region. The assimilation of space and ground-based data into weather prediction models/services comprises a significant step forward to improve short-term forecasting of rapid convective storms and heavy precipitation events.

Water Vapour (WV) is the most significant greenhouse gas (accounting for ~70% of global warming) and forms an important link between the land and the ocean, as it constitutes a major driver of weather patterns and severe weather events. Based on the signal propagation delay in the troposphere, a GNSS station can provide estimates of the total WV content (Integrated Water Vapour, IWV), which can be assimilated in high resolution limited area NWP models. On the other hand, ground-based weather radars detect convective systems with a very high spatial and temporal resolution radar reflectivity data that can also be exploited for convective-scale data assimilation into NWP models. Geostationary-satellite and ground-based Lightning data, at a high spatial and temporal resolution, can also be ingested into NWP models to simulate convective cores of mesoscale convective systems (MCSs) [3], whereas simulations of the location and intensity of MCSs are improved from high-spatial and near vertical satellite-based wind profiles (such as those delivered by Aeolus ESA satellite mission) [4]. These heterogeneous data reflect different information on convective systems and thus, the integration of such augmented information into NWP models in order to provide more accurate short-term forecasts of severe convective events remains a challenging task. In this regard, the scientific and technological objective of CYGMEN

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project is to establish a unique comprehensive meteorological infrastructure (CyMETEO infrastructure) in Cyprus that will produce heterogeneous weather observations for the purpose of: a) enhanced operational weather forecasting (with a focus on precipitation and convection) by the Cyprus DoM, b) more effective risk management of weather-related hazards by local stakeholders and c) enhanced research activities in the field of Meteorology, weather prediction and atmospheric physics. CyMETEO infrastructure will be accompanied by an advanced CyMETEO service that will be developed in order to: a) process and provide in near real-time all different types of data generated by CyMETEO (CyMETEO Observational Analysis Component) and b) provide advance short-term weather forecasting through the assimilation of CyMETEO data into WRF model currently employed operationally by the DoM without, however, performing any Data Assimilation (DA) (CyMETEO Simulation Analysis Component). In this context, the aim of the present study is to present initial preliminary results from the CyMETEO service design and development.

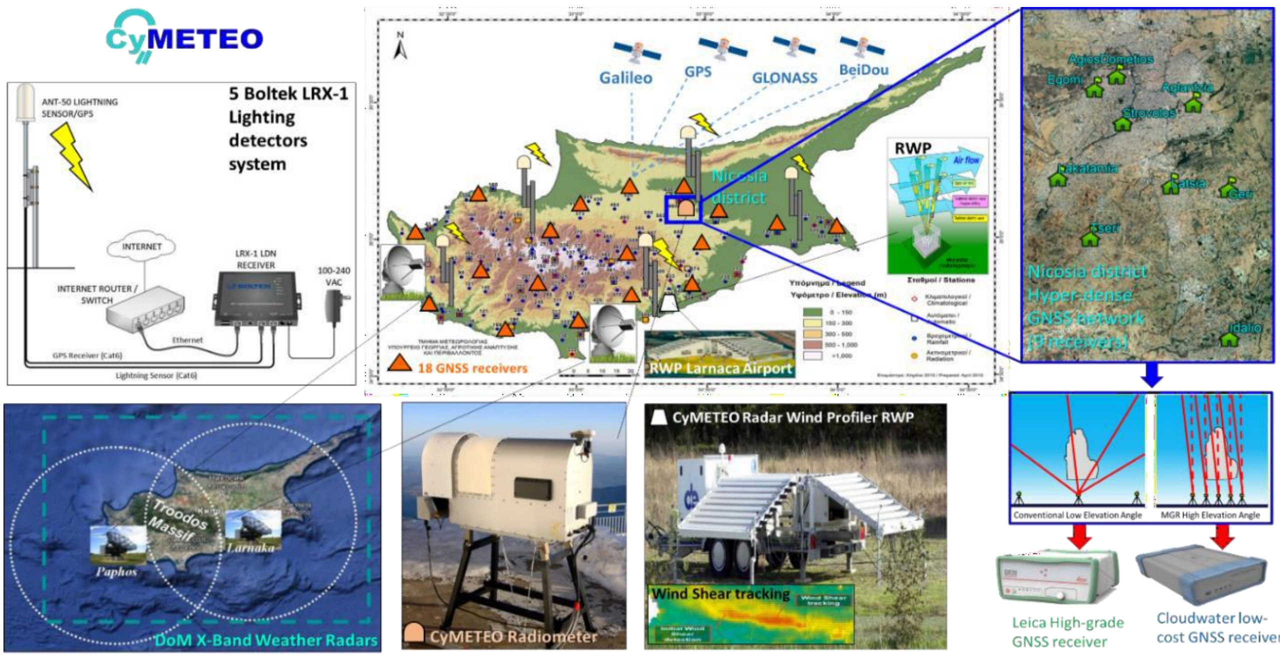

Figure 1. CyMETEO system and infrastructure to be built in the frames of CYGMEN project.

2. CYMETEO SYSTEM METHODOLOGY

2.1. CyMETEO system methodology

The development of CyMETEO system is based on the following technical steps:

a) Deployment of: a) a dense GNSS network over Cyprus, b) a Lighting detection network (five lighting detectors), c) a High-tech Radar Wind Profiler (RWP) and d) a Microwave Radiometer (MWR)
b) Exploitation of the existing GNSS station network in Cyprus jointly with the data products of the new CyMETEO infrastructure for the purpose of assimilation experiments with WRF-GSI model [5]
c) We are now in the process of installing a hyper-dense network of 9 GNSS stations in the Nicosia district (area of ~25 km^2), 3 new Leica high-grade GNSS stations, to enrich the existing CYPOS system of the Dep. of Lands and Surveys (DLS) (Figure 1), and we are also exploiting all available 7 CYPOS GNSS stations, as well as 4 high- grade FRC [6] and 4 low-cost Cloudwater receivers [7] already in place. The proposed network density as it appears on Figure 1 ensures an average separation between stations of <25 km (<10 km within Nicosia district at a high elevation GNSS satellite cut-off angle). This corresponds to almost a full coverage of the island and can be exploited for monitoring the ionosphere (Total Electron Content, TEC) as well [8]
d) Exploitation of the DoM weather radar network that consists of two X-Band, dual-polarization Doppler radars to ensure the real time (10 min) provision of radar reflectivity (converted to humidity) over the Cyprus region
e) Retrieve and pre-processing (includes quality control, QC) of raw wind profiles from the Radar Wind Profiler (Figure 1) and of lighting observations deriving from the new CyMETEO lighting detection network in order to provide time, latitude, longitude and intensity of the occurrence of cloud-to-ground lightning

f) Processing and provision in near real-time of temperature and humidity profiles from the customized software of the CyMETEO Microwave Radiometer that is planned to be installed at the Athalassa (in Nicosia) DoM meteorological station within the next two months (Figure 1)

g) Conduct Data Assimilation (DA) experiments to WRF-GSI model by ingesting GNSS WV, radar reflectivity, lighting and conventional surface weather observations. To secure the effectiveness of DA, we will compute the WRF model background errors (BEs) on a monthly basis [9]

h) All CyMETEO products will be freely available in near-real time to end-users for immediate exploitation in the context of short-term forecasting, warnings, operational NWP data assimilation, risk management and for long- term climatology research

i) Perform independent verification of CyMETEO through both space and ground observational data. For this, we will utilize integrated multi-satellite retrievals from global precipitation measurement (e.g. GPM-IMERG) mission, as well as in-situ precipitation measurements from the DoM [10] (Figure 2).

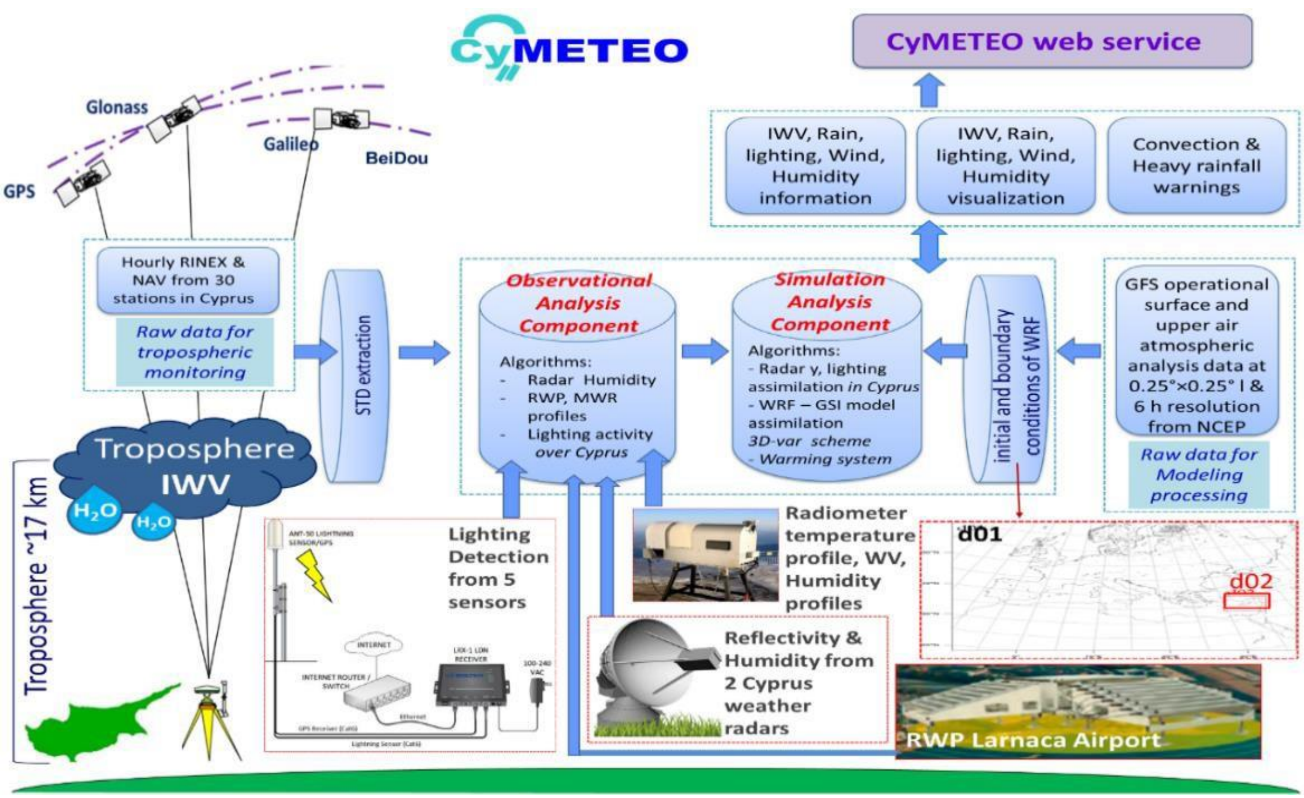

Figure 2. CyMETEO system architecture in the frames of CYGMEN project.

2.2. CyMETEO GNSS tropospheric analysis component development

At present, the deployment of GNSS network over Cyprus is being developed. Currently, 13 GNSS stations are fully operational and provide near-real time (every 15 min) raw tropospheric data (IWV, ZTD, Zenith Tropospheric Delay) that will comprise the Observational component of CyMETEO system. The retrieval of IWV from GNSS ground receiver is based on converting the estimated zenith wet delays (ZWD) onto Precipitable Water (PW). In particular, Radio signals transmitted on two L-band frequencies from GNSS satellites are delayed by the neutral part of atmosphere, before being received on earth surface by GNSS antennas. This ZTD consists of: 1) the hydrostatic (dry) (ZHD) component which depends on dry air gases in the atmosphere, accounts for the greatest part of delay and can be accurately estimated using surface atmospheric pressure at the GNSS receiver (P) following [11] and [12]:

$$\mathrm{ZHD}(P,\Phi,h)=\frac{0.0022768P}{1-0.00266\cos(2\Phi)-0.00028h} \quad (1)$$

with $f(\Phi, h) = 1 - 0.0026 \cos 2\Phi - 0.00028h$, where Φ is the latitude and h is the height (km) and 2) the wet component (ZWD) depends on water vapour of the atmosphere [13]:

$$\mathbf{ZWD=ZTD-ZHD} \quad (2)$$

Integrated Water Vapor (IWV) is derived from equations (3), (4) and (5) following [14]:

$$\Pi = 10^6 \left[\rho R_u \left(\frac{k_3}{T_m} + k_2' \right) \right]^{-1} \quad (3)$$

where k_3 = 3.776·105 K^2mbar^{-1} , k'_2 = 64.79 $mbar^{-1}$ and R_υ = specific gas constant for IWV and T_m is the weighted mean atmospheric temperature, given by [15] for mid-latitudes:

$$T_m = 50.4 + 0.789\ T_s \quad (4)$$

where, T_s is the surface temperature in Kelvin, and

$$\mathbf{IWV = \Pi\ ZWD} \ (5)$$

We calculated the ZHD using Saastamoinen model (equation 1), where the atmospheric pressure is retrieved from an improved version of the Hourly Global Pressure and Temperature 2 (HGPT2) model [16]. In the frames of CYGMEN project, we are using the multi-GNSS Precise Point Positioning (PPP) technique [17] in static mode. The open-source software RTKLib [18] is adopted in order to process the RINEX data, in near-real time with broadcast navigation orbits. In addition, the Iono-free model is used to correct ionospheric errors [19].

3. RESULTS OF FINAL CYGMEN TROPOSPHERIC PRODUCTS

The near-real time tropospheric estimations stored on CYGMEN Database (FTP) server, every 15 minutes, following the recommendations of the IGS/EPN analysis centers. Figures 3, 4 and 5 depict the main GNSS tropospheric products (IWV and ZTD and ZWD) offered within the CyMETEO Observational Analysis Component. They illustrate daily fluctuations estimated at 15-minute intervals at KLIR GNSS station, offering insights into the atmospheric moisture content in Klirou station.

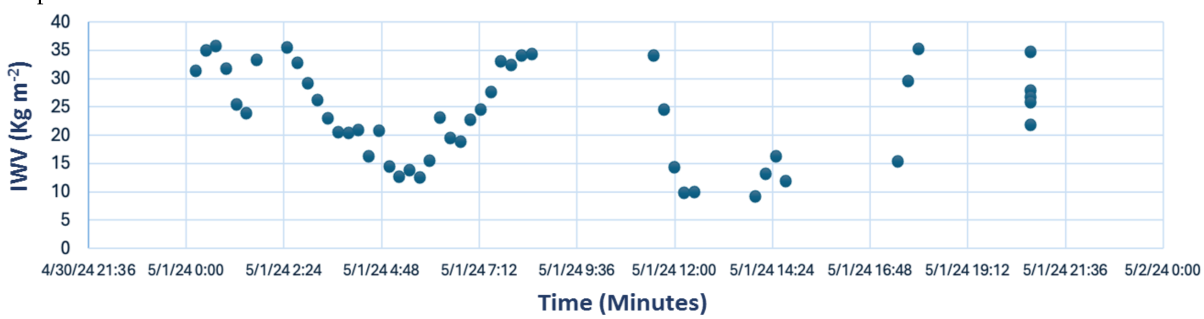

Figure 3. IWV daily time series for KLIR GNSS station in 15-min interval.

Figure 4 displays the ZTD daily time series for the KLIR GNSS station, also provided in 15-minute intervals. It highlights the changes in ZTD throughout the day, aiding in the understanding of atmospheric delay effects on GNSS signals.

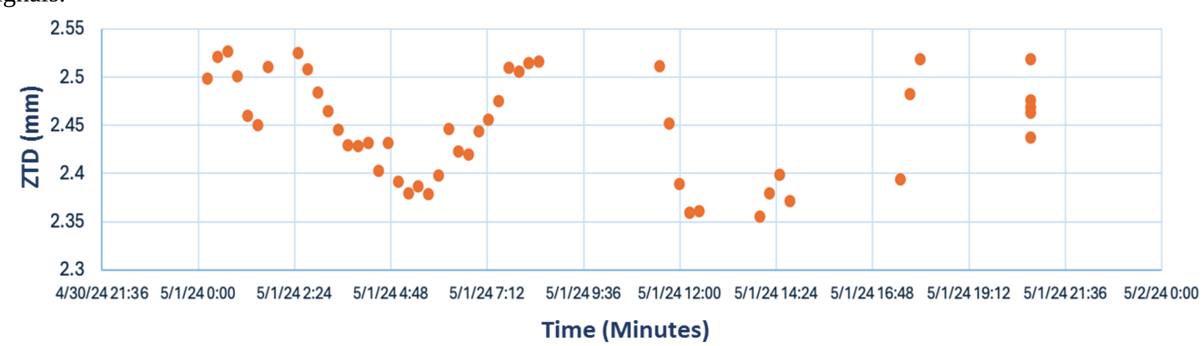

Figure 4. Zenith Total Tropospheric Delay (ZTD) daily time series for KLIR GNSS station in 15-min interval.

In Figure 5, daily time series of ZWD is displayed for the same station with 15-minute time resolution. It shows the variation of the wet component of tropospheric delay during a day, contributing to the characterization of atmospheric moisture effects on GNSS signals. ZWD is related both to the surface temperature and pressure as it can be understood from the above equations (1, 2 and 3). Temperature comprises the largest source of error in the determination of integrated water vapor from GNSS observations which is mainly induced by the coarse representation of the orography and terrain by the HGPT2w model [20].

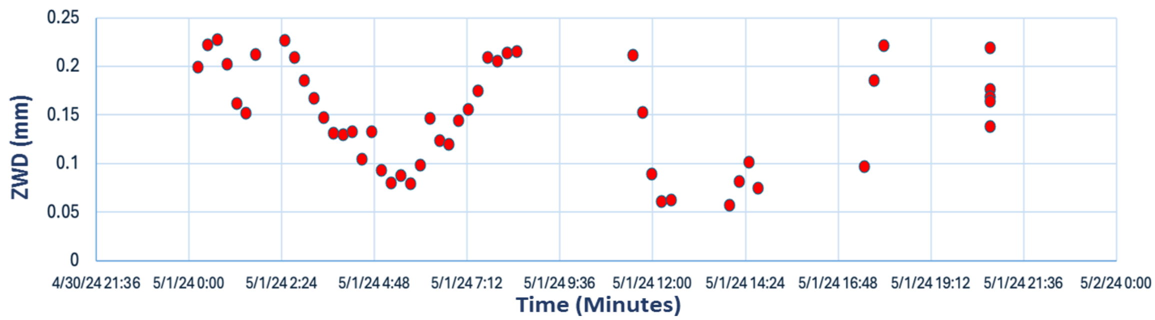

Figure 5. Zenith Wet Delay (ZWD) daily time series for KLIR GNSS station in 15-min interval.

4. CONCLUSIONS

CyMETEO is the first coordinated effort to provide improved short-term rainfall prediction related to severe rainfall events over Cyprus, by developing new sophisticated modelling techniques (heterogeneous DA into NWP model) supported by the exploitation of GNSS remote sensing techniques. The densification of GNSS network in Cyprus will facilitate the precise GNSS tropospheric monitoring. In figure 1 (light blue panel), we attempt to demonstrate the novelty of this concept more clearly. In particular, the conventional low-density GNSS network attempts to satisfy tropospheric monitoring at lower elevation values. In this way, the cloud that can also be moving fast during a storm cannot be spatially tracked adequately. In comparison, the right panel of the same figure demonstrates the benefit of a hyper-dense network (~5km spatial res.) higher elevation angle. This approach will enable a superior spatiotemporal resolution of the clouds and subsequently of their IWV content in the troposphere.

***res.ec@frederick.ac.cy; phone: 00357 96522955**

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