Reply to the Anonymous Referee #2

A review of Earth System Dynamics. MS title:
"Water vapour fluxes at a Mediterranean coastal site during the summer of 2021: observations, comparison with atmospheric reanalysis, and implications for extreme events"
Madonna et al, 2024 an observational-core study that explores the use of high-quality observations and measurements of hydrological atmospheric features in a specific location where such measurements are deemed crucial for weather and climate predictability. They compare the results with global ECMWF ERA- 5 reanalysis in the roughly corresponding grid points, to highlight the large deviations between one of the most highly used meteorological tools and observations. An emphasis is given to the role of integrated water vapour transport in generating extreme weather events, and the importance of correctly evaluating these measurements in reanalysis.
The objective of improving the performance of reanalysis data using observations is important, especially in coastal areas that are affected by sub-grid processes, and the results presented in this MS are undoubtedly of interest to the scientific community. Indeed, it is evident that major efforts were invested in this campaign, and for good reasons.
However, I suggest a major revision of the MS, especially concerning the present structure, but also possibly the choices made by the authors:

Thank you for your detailed review and valuable feedback on our manuscript. We are glad to see that you recognize the importance of the study's objectives. We also appreciate your acknowledgment of the effort invested in the observational campaign and the relevance of the results to the scientific community. Below, we provide our responses (in bold) to each of the reviewer's comments.

Major comments:
1) The choice of comparing observations to a relatively coarse reanalysis is unclear. Would it not be more beneficial to compare against a higher-resolution alternative?
Theoretically, we agree with the reviewer. We also considered the idea of comparing with CERRA, the ECMWF regional reanalysis, but currently, data in the CDS are available only until June 2021. During the last C3S GA, we interacted with the ECMWF team producing CERRA, who offered updated datasets until 2024. However, they clarified that for RH, the advantage of using CERRA compared to ERA5 is quite limited. The recent paper by Ridal et al. (2024, QJRMS) confirms this outcome. Nevertheless, the manuscript text at lines 415-418, as suggested by anonymous reviewer #1, will be amended to properly discuss the limitations of a higher-resolution reanalysis in capturing orographic effects. In follow-up activities, the authors also plan to compare the data from the campaign with a downscaled ERA5 version using explicit convection parameterization or to carry out a comparison with the WRF model

2) In the introduction, the authors elaborate on the methods used at a highly technical level, while not emphasizing enough the motivation and knowledge gaps addressed by the study, and how the observations serve those objectives. I suggest moving the technical details to an appendix and expanding the introduction on the role of moisture fluxes in the atmosphere, why they are misrepresented especially in coastal areas in the Mediterranean, the implications, and the importance of the detailed observations you present for their better prediction.

In the introduction, the most technical paragraph is located between lines 61-68. This paragraph has been revised, and the introduction has been amended in accordance with the reviewer's suggestions as follows:

"The Mediterranean summer is often characterized by intense water vapour fluxes driven by significant evaporation. These fluxes feed zonal and meridional air mass transport, serving as a critical source for extreme precipitation events (Ciric et al., 2018). Severe precipitation in the Mediterranean Basin relies on both remote and local sources of anomalously high surface evaporation (Winschall et al., 2014). Water vapour fluxes primarily originate from the Atlantic, North Africa, and regional seas, contributing to the elevated relative humidity observed in the troposphere, particularly during the summer months. These fluxes play a vital role in the Mediterranean's atmospheric and hydrological systems, shaping precipitation patterns, extreme weather events, and overall climate dynamics (Drumond et al., 2018). Such fluxes have profound effects on the regional climate, intensifying rainfall in some areas while prolonging droughts in others. Persistent water vapour fluxes also influence the region's radiative balance, exacerbating surface radiation trapping and amplifying the effects of heatwaves. Consequently, understanding the role of water vapour fluxes in the Mediterranean is essential for predicting extreme weather events, such as the severe floods and heatwaves that frequently impact the region (Russo et al., 2017).

As a recognized climate change hotspot, the Mediterranean is particularly sensitive to changes in atmospheric moisture, which significantly impact weather systems, including the intensification of extratropical cyclones. However, water vapor fluxes are often poorly represented in weather and climate models, especially near coastal regions, due to the complexities involved in resolving mesoscale processes, convection and boundary layer dynamics, land-sea transitions, and aerosol interactions with moisture transport (Voulgarakis et al., 2018). These modeling challenges introduce biases in predicting extreme weather events.

Recent advances in observational programs have underscored the importance of accurately representing water vapor fluxes in forecasting severe weather. For example, marine flow-driven water vapor transport has been identified as a key factor in Mediterranean high precipitation events (HPEs), highlighting the need for realistic spatiotemporal variability of these fluxes in numerical weather prediction models (Lee et al., 2018). Furthermore, studies have shown that convection initiation in cloud-resolving models can be accurately predicted when water vapor estimates within and above the boundary layer are sufficiently detailed (e.g., Ducrocq et al., 2002; Bielli et al., 2012).

During the summer of 2021, one of the warmest on record for Europe in recent decades (Lhotka and Kyselý, 2022), several Mediterranean regions experienced severe soil moisture deficits. Southwestern Europe faced heatwaves in June, July–August, and September, with monthly average temperatures slightly below those of the warmest summer in Europe in 2022, as reported in the European State of the Climate (ESOTC) and recent studies. However, the warmest temperatures on record were observed in South Italy (ESOTC, 2023; Gandolfi et al., 2024; Merlone et al., 2024). Dry conditions in the northern Mediterranean basin extended into northern Tunisia, while soil moisture levels in other parts of northern Africa along the coastline were average to above average compared to climatological values (ESOTC, 2021).

This study investigates the effects of enhanced water vapor fluxes driven by intense Mediterranean Sea evaporation at a coastal site during the summer of 2021, using a combination of ground-based measurements from the mobile facility of the Atmospheric Observatory of the Institute of Methodologies for Environmental Analysis of the Italian National Research Council (CNR-IMAA), CIAO (Madonna et al., 2010), and the fifth-generation reanalysis data, ERA5 (Hersbach et al., 2020; Essa et al., 2022). The measurements were collected as part of the Mediterranean Experiment for Sea Salt and Dust Ice Nuclei (MESSA-DIN) in Soverato, South Italy (Latitude: 38.6894°N, Longitude: 16.545278°E, 30 m a.s.l.).

One of the primary objectives of the campaign was to study aerosol-water vapor-cloud interactions, with particular emphasis on sea salt and dust. A ground-based remote sensing facility operated at the coastal site from June 24 to November 8, 2021. This paper focuses on water vapor measurements collected until September 30, using a microwave radiometer and an infrared thermometer, which frequently recorded high relative humidity values in the mid-troposphere. Through a synergistic data analysis that incorporated the radiometer, sun photometer, aerosol lidars, and cloud radar, this study examined water vapor transport in the troposphere and compared the observations with ERA5 reanalysis data. The analysis also explored the role of aerosols in the scarcity of warm and cold cloud layers observed during the campaign. Finally, this paper highlights the potential correlation between enhanced tropospheric water vapor content from anomalous fluxes in the Mediterranean basin and severe weather events, such as the flooding that occurred in Central and Eastern Europe in July 2021. These findings emphasize the critical importance of increasing ground-based water vapor measurements across the Mediterranean region to support accurate flux predictions and improve the forecasting of extreme rainfall and flooding events.

Section 2 of the paper provides an overview of the instruments and datasets employed during MESSA-DIN. Section 3 presents the analysis of the ground-based measurements and related results, including comparisons with reanalysis data, a synoptic study of water vapour transport using ERA5, and an investigation of the role of aerosols in local cloud formation. The final section discusses the results and presents the conclusions of the study."

Added references:

- **Bielli, S., Grzeschik, M., Richard, E., Flamant, C., Champollion, C., Kiemle, C., Dorninger, M., and Brousseau, P.: Assimilation of water-vapour airborne lidar observations: impact study on the COPS precipitation forecasts, Q. J. Roy. Meteor. Soc., 138, 1652–1667, 2012.**
- **Ducrocq, V., Ricard, D., Lafore, J. P., and Orain, F.: Storm-scale numerical rainfall prediction for five precipitating events over France: On the importance of the initial humidity field, Weather and Forecast., 17, 1236–1256, 2002.**
- **Lee, K.-O., Flamant, C., Duffourg, F., Ducrocq, V., and Chaboureau, J.-P.: Impact of upstream moisture structure on a back-building convective precipitation system in south-eastern France during HyMeX IOP13, Atmos. Chem. Phys., 18, 16845–16862, https://doi.org/10.5194/acp-18-16845-2018, 2018.**
- **Voulgarakis, A. et al., Atmospheric Chemistry and Physics, 2018. On aerosol and greenhouse gas forcing impacts on Mediterranean precipitation dynamics.**
- **Drumond, A. et al., Water, 2018. Contributions of the Mediterranean to continental precipitation during extreme events.**

3) The title of the MS could be more specific, possibly naming the location or the campaign itself. Even the scope of the results discussed throughout is larger than suggested by the title. Furthermore, discussion of the water-vapor fluxes is brief and does not provide new insights as for the well- known importance of these fluxes for extreme weather events. The title suggests that the water vapor fluxes were derived from observation, but that's not the case. Therefore, I suggest rephrasing the title to describe the MS more accurately.

To better align the title with the content of the manuscript, the new title will be: 'Tropospheric water vapour enhancement from Mediterranean sea fluxes during summer 2021 in Soverato (Italy): observations, comparison with ERA5, and implications for extreme events.' Additionally, the discussion of water vapour fluxes in the revised manuscript will be expanded to emphasize their importance in the context of extreme weather events.

4) Some of the figures (4, 6, and 14) show raw data, with highly technical captions that are not intuitive for non-expert readers. Seeing that the focus of ESD is usually not set to such levels of technicality, I recommend adding a line to the captions that recalls the physical meaning of the observed quantity.

We will add an explanatory line to the captions of Figures 4, 6, and 14 to highlight the physical meaning of the quantities represented. Additionally, we will reduce the technical level of the text, simplifying the description of the results where possible, without compromising scientific rigor.

5) The summary should highlight the importance of the field campaign: what new information was gained and how can it be harnessed to improve our understanding or the model performance? Simply pointing out the biases seems like an underreaching conclusion, especially when comparing measurements to global reanalysis data that does not even have a corresponding grid point in the location of interest.

At lines 423-433, we already stressed the importance of profiling measurements for validating and improving forecasts and modelling activities, putting emphasis also on the most extreme events. However, these lines, and the following, have been amended according to the reviewer's recommendations as follows:"Despite the coarse resolution of MWPs in the free troposphere, the analysis presented confirms how atmospheric profilers can be extremely valuable for validating and improving forecasting and modeling activities, especially under extreme or anomalous meteorological conditions. MWPs, for example, provide continuous measurements of temperature and water vapor in the atmosphere. In conjunction with upper-air soundings and Raman lidars, which offer higher vertical resolution, they can significantly enhance our understanding of water vapor fluxes, particularly in regions like the Mediterranean Basin.

Given the high spatial variability of water vapor, it is essential to conduct measurement campaigns with multiple ground-based stations to improve model validation and effectively address this variability. Despite the computational challenges, high-resolution forecasts at the kilometer scale, which can better capture mesoscale phenomena and resolve key processes like convection (rather than parameterizing them), should be beneficial for predicting extreme events. This has been demonstrated in recent studies (Caldas-Alvarez et al., 2022; Fosser et al., 2024; Chang et al., 2024) and is already being operationalized in early warning systems and meteorological services, such as the Limited Area Ensemble Prediction System (COSMO-LEPS) developed by the COSMO consortium and the German National Meteorological Service (DWD).

The results of the measurement campaign further highlighted the need for accurate water vapor measurements from sufficiently dense networks, particularly in regions like the Mediterranean, where the complexity of water vapor fluxes arises from the merging of remote and local sources. Current atmospheric models still struggle to reproduce the variability of water vapor due to the complexity of the underlying processes. However, these models could significantly benefit from the assimilation of high-quality measurements, which would reduce biases relative to observations and enhance their ability to predict the intensity of extreme events.

While reanalysis successfully replicated observations of water vapor layering and temporal evolution in the troposphere during the MESSA-DIN campaign, they still face challenges in estimating the presence of both warm and cold clouds. Aerosols played a crucial role in this context, particularly the coarse aerosol fraction associated with the transport of marine aerosols and, to a lesser extent, Saharan aerosols. These aerosols may have inhibited cloud formation, particularly in conjunction with the stable atmospheric conditions that dominated the campaign period. This further underscores the importance of improving model and reanalyses, particularly in terms of cloud formation parameterization and the representation of aerosols, especially for their type and size distribution. This study also underscores the need to improve model parameterization of the complex atmospheric processes characterizing coastal regions.

By improving the accuracy of water vapour flux predictions, we can better anticipate and mitigate the impacts of extreme weather events and climate variability in the Mediterranean. Persistent water vapour fluxes also impact the radiative balance, exacerbating the effect of surface radiation trapping, and potentially amplifying the effects of the heatwaves on human beings. Instead, large amounts of water vapour becoming available under these transport events can have profound impacts, particularly, affecting Central and Eastern Europe. An example is the meteorological situation in Europe from 12 to 15 July 2021, characterized by a cutoff low-pressure system over Central Europe, supplying warm and very humid air from the Mediterranean in its rotating movement. This low-pressure system led to heavy rainfall (more than 175 mm in 48 hours regionally), resulting in extensive flooding in Western Europe (Tradowsky et al., 2023). An incorrect prediction of moisture availability in the Mediterranean may become a critical factor in forecasting such extreme rain events."

Besides, in the comment regarding the mismatch between the reanalysis grid and the measurement station, it is important to note that this is related to the quantification of representativeness errors. This issue will be reported in the manuscript. However, as noted in our reply to reviewer #1, the nearest ERA5 grid point is located approximately 7.8 km from Soverato (38.6894°N, 16.5453°E), with the ERA5 point at (38.75°N, 16.5°E), both over land. This proximity should help minimize errors due to the spatial mismatch and, therefore, reduce the bias with respect to the true atmospheric conditions at Soverato during the 3-months study period.

Minor comments:
L65: "investigated to identify the contribution by the contribution of water vapour fluxes and convection" – unclear
Please see above the new version of the introduction
Fig.1: Consider adding a larger view pointing out the location of Soverato for geographical orientation.
Fig.1 has been replaced by the following:

Figure 1: left panel, the Landsat image of the Mediterranean Basin with the position of Sovertato site; right panel, an aerial photo of the measurement site in the town of Soverato where the MESSA-DIN campaign was carried out. Image obtained from Google Earth (version 7.3.3.7786), Accessed on December 14, 2024, Coordinates: 38.6894°N, 16.545278°E. © Google, images © 2024 Maxar Technologies.

L88: instruments
OK
L127: and smaller above.
OK
L148-149: this sentence seems interrupted
The sentence has be rephrased as follows: "Additionally, a sun photometer (SP) was used to estimate: column aerosol optical depth (AOD) at different wavelengths, column particle size distribution and precipitable water vapor through the data processing made by the AErosol RObotic NETwork program (AERONET).".
L173: ad→and
OK
L174: biased at
OK
L208: larger values
OK
L209: rephrase. The sentence is unclear.
OK
L219: highlighted that measurements
OK
L250-265: This fits better in the introduction

L304: noting→ to note
OK
L324: insisting→ persisting

OK
L325: of a heat wave
OK
L326: transporter→ transport?
OK
L334: contributing or that likely contribute.
OK
L343: representation of
OK
L376-380: long sentence, consider splitting.
The sentence has been rephrased as follows: “The dominance of the aerosol coarse fraction, along with evidence for the predominant contribution of marine aerosols and desert dust, suggests that the coarse particles observed during the summer of 2021 in Soverato played a key role. Under atmospheric conditions, typically dominated by persistent high pressures over South Italy, these particles contributed to a reduced likelihood of warm cloud formation at the measurement site.”.

L428-433: long sentence with several errors. Please rephrase.
The sentence has been rephrased as follows: "In light of the resolution and forecast models, having a km-scale forecast can significantly improve the ability to address mesoscale phenomena. Despite the computational challenges, this approach allows for the resolution of important processes such as convection, rather than relying on parameterization. Recent studies (Caldas-Alvarez et al., 2022; Fosser et al., 2024; Chang et al., 2024) have shown that this is beneficial for extreme events. Furthermore, such models have already been implemented in some early warning systems and meteorological services, including the Limited Area Ensemble Prediction System (COSMO-LEPS) developed by the COSMO consortium and the German National Meteorological Service (DWD)."