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The impact of global navigation satellite system (GNSS) zenith total delay data assimilation on the short-term precipitable water vapor and precipitation forecast over Italy using the Weather Research and Forecasting (WRF) model

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S1 Precipitation characteristics for October 2019

S1.1 Rainfall examples and classification used in the paper

The month of October is usually characterized by several precipitation events over Italy, and the synoptic scale forcing, the orography of Italy and the presence of a warm sea can result in severe and convective events that can lead to casualties and damage of properties. Specifically, all days of October 2019 were characterized by some rainfall over Italy.

In the paper, we introduced the widespread, localized and weak rainfall classes. Here, we show two examples of localized and widespread rainfall observed in October 2019 to define the two classes of events. The classification of localized, widespread or weak precipitation was based on subjective analysis of the daily precipitation maps and on an objective criterion: to have a widespread event, more than 30 raingauges must report more than 20 mm/day and these raingauges must spread at least over three Italian Regions (Italy is divided in 20 Regions). The days not classified as widespread precipitation are classified as localized precipitation days or weak rainfall days. The latter occur when a widespread or localized weak rainfall (< 10 mm/day) is observed over Italy with few exceptions (less than 10 rain gauges recorded more than 10 mm/day).

A representative example of localized rainfall occurred on 8 October 2019. In this case, rainfall larger than 30 mm/day was reported in few stations in southeastern Sicily, with a maximum between 70 and 80 mm/day. Precipitations occurred also in other parts of Italy, but their intensities were lower than 10 mm/day except for one station over the Alps.

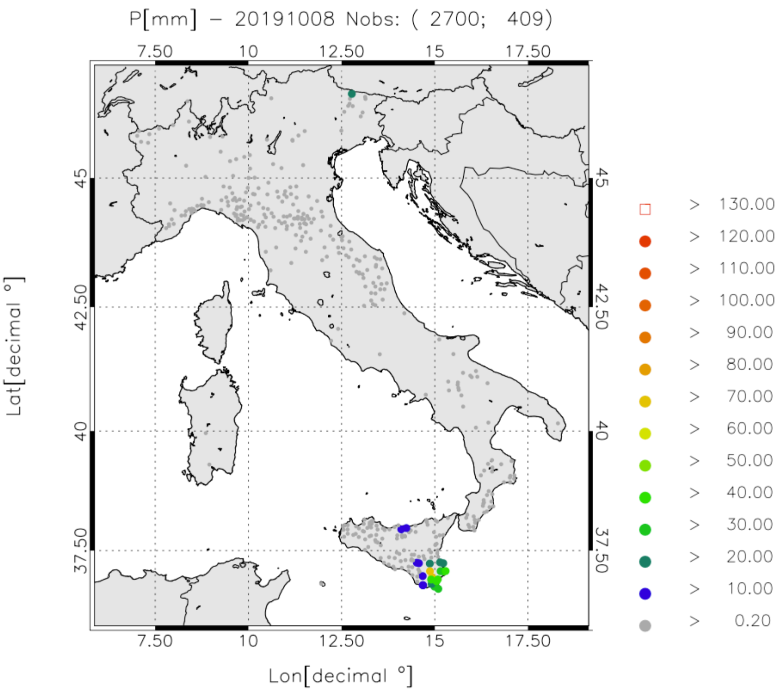


Figure S1: Example of localized precipitation: 8 October 2019. The figure shows the precipitation accumulated for the whole day. The first number inside the parentheses in the title is the number of stations with valid data on that day, while the second number into the parentheses is the number of rain gauges with rainfall larger than 0.2 mm.

A good example of widespread precipitation was the day before that shown in Figure S1, i.e. is the 7 October 2019, for which the recorded rainfall is shown in Figure S2.

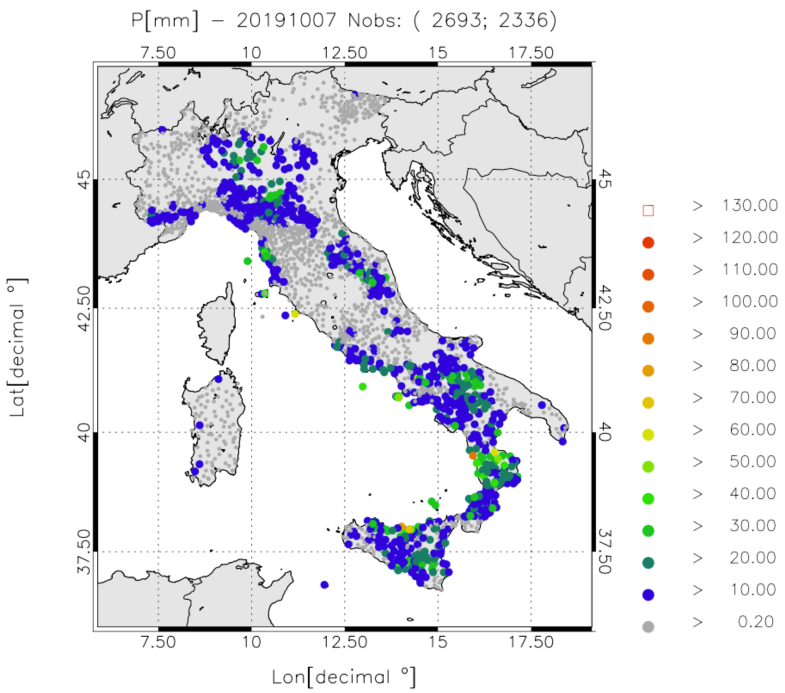
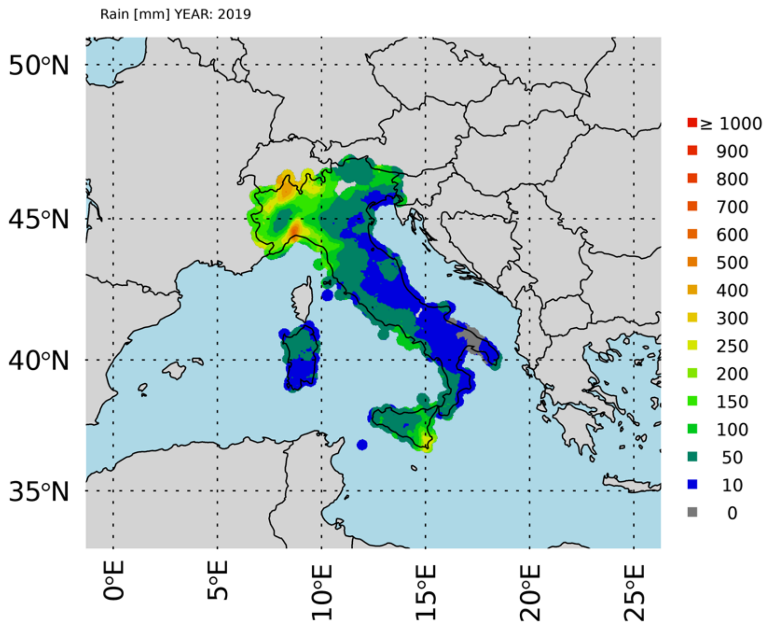


Figure S2: Example of widespread precipitation: 7 October 2019. The map shows the precipitation for the whole day. The first number inside the parentheses in the title is the number of stations reporting data on that day, while the second number into the parentheses is the number of raingauges with rainfall larger than 0.2 mm.

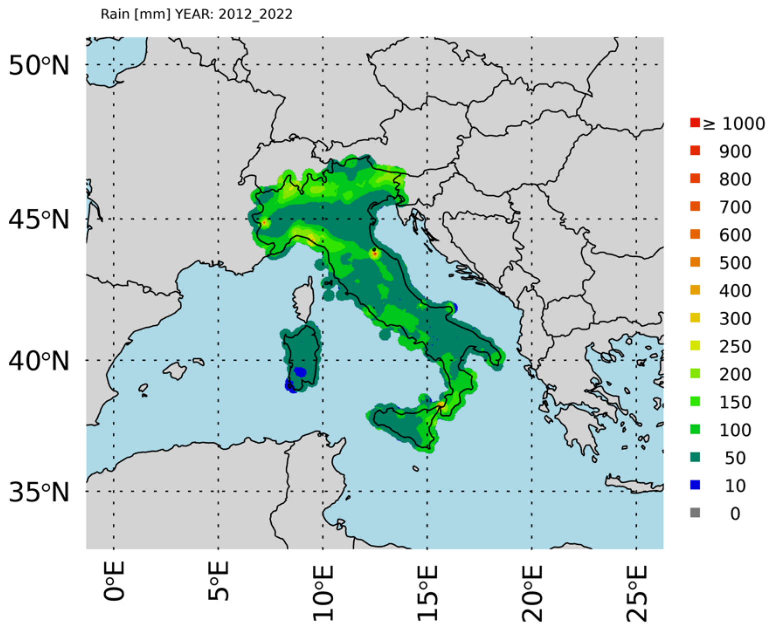
From Figure S2 it is apparent that several rain gauges recorded rainfall larger than 20 mm/day and these rain gauges are widespread over the Italian peninsula and Sicily.
Considering the period from 2 October to 31 October 2019 the days classified as local are: 4,5,6,8,10,14,17,18,26,27,29,30; the days classified as widespread are: 2,3,7,9,15,16,19,20,21,22,23,24,25,31; and, the days characterized by weak rainfall are 11,12,13 and 28 October. The days between 5 and 10 October and those between 13 and 23 October were characterized by local or widespread rainfall. Among these days there were several occasions of heavy rain (see Section S2 for a description of the synoptic scale conditions during the periods) and for this reason they were selected for sensitivity experiments.

S1.2 Total precipitation and comparison with the last 11 years
In this section we analyze the total precipitation recorded in October 2019 over Italy and we compare this distribution with the same analysis for the period 2012-2022. The period 2012-2022 was selected as reference to have a rough estimate of the rainfall climatology. A longer period could not be selected because the years before 2012 had a considerable lower amount of rain gauges data. To represent the precipitation distribution over the map (Figure S3) an interpolation on a 5 km horizontal grid was used. The interpolation is done by the inverse distance method and, for each grid point, a weighted average of all stations distant less than 25 km from the grid point is considered in the weighted average.

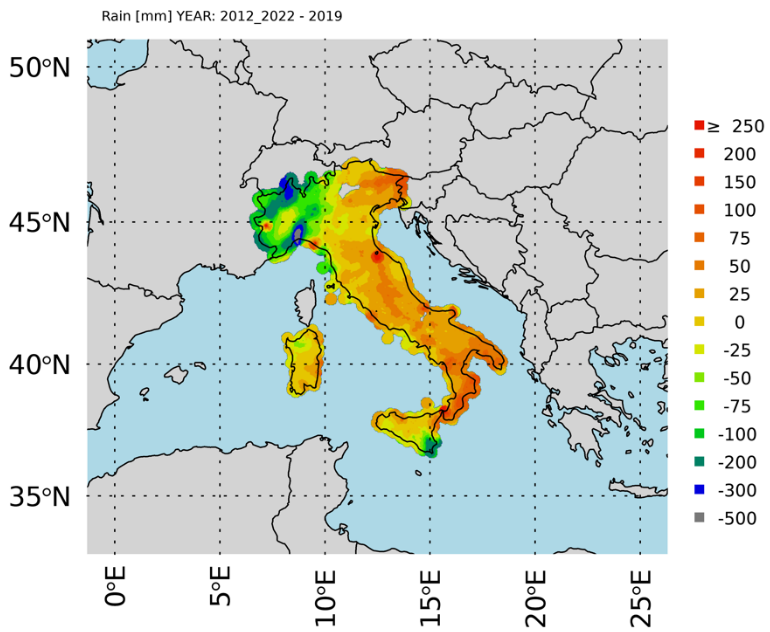
a)


Rain [mm] YEAR: 2019
50°N
45°N
40°N
35°N
0°E
5°E
10°E
15°E
20°E
25°E
≥ 1000
900
800
700
600
500
400
300
250
200
150
100
50
10
0

b)


Rain [mm] YEAR: 2012_2022
50°N
45°N
40°N
35°N
0°E
5°E
10°E
15°E
20°E
25°E
≥ 1000
900
800
700
600
500
400
300
250
200
150
100
50
10
0

c)



d)

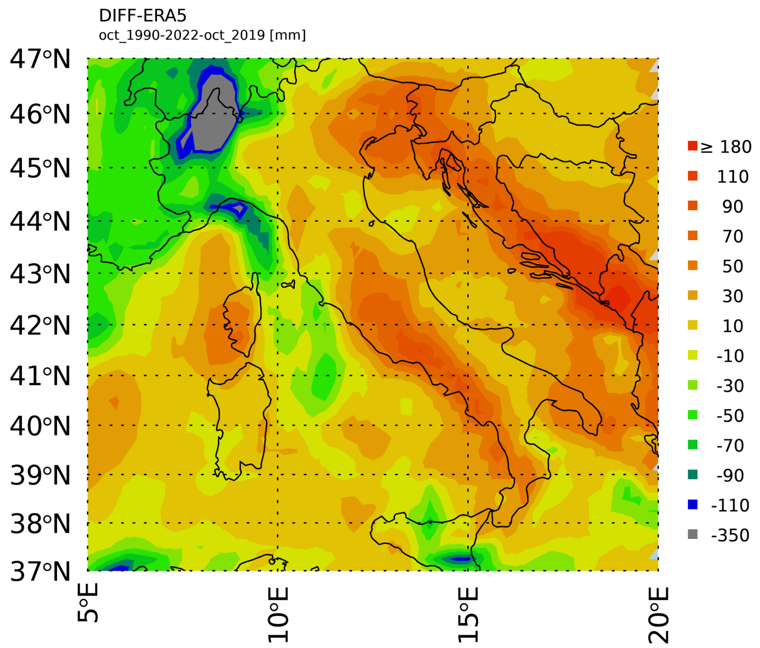


Figure S3: (a) Total precipitation for October 2019; (b) average total precipitation for the month of October for the years from 2012 to 2022; (c) difference between (b) and (a); (d) difference between the ERA5 precipitation climatology of October (years 1990-2020) and the precipitation of October 2019.

As shown by Figure S3a, the total precipitation had a notable west-east gradient with larger values on western Italy. Rainfall had a maximum in northwestern Italy with values reaching more than

500 mm (specifically over Genova) for October 2019. Damages to infrastructures were reported in several places, especially in the Liguria region. Another area interested by heavy precipitation was southeast Sicily.
The precipitation over Italy for the period 2012-2022, Figure S3b, is more uniform compared to 2019. Rainfall is larger on the western side of the peninsula compared to 2019 with the exception of Calabria peninsula (the southernmost tip of the Italian peninsula) and Sicily. Precipitation is larger than 200 mm over Liguria and northern Italy, in a belt at the piedmont of the Alps. Despite the average in time and space, there are few high-precipitating spots on the map caused by intense and localized events over these areas. The local maxima around Genova, for example, is partially caused by the maximum in 2019 (Figure S3a). The difference between Figure S3b and S3a is shown in Figure S3c. It is apparent that, compared to the years 2012-2022, the year 2019 had larger rain in the NW of Italy and lower rain in the eastern and southern part of Italy, with the exception of Sicily were larger precipitation were recorded in the southern and eastern part of the island in 2019 compared to years 2012-2022. Interestingly, the gross behavior of Figure S3 is confirmed by the analysis of the ECMWF-ERA5 reanalysis dataset (Hershback et al., 2018). We compared the October precipitation for 2019 and the same precipitation averaged for the period 1990-2020 and we found that 2019 was characterized by larger precipitation in northwestern Italy and lower precipitation in other parts of the country, with the exception of southeastern Sicily, as shown in Figure S3d.

S1.3 Distributions of the precipitation

It is interesting to analyze the distribution of the three-hourly rainfall events for the year 2019 and compare this distribution with the same distribution for the years 2012-2022. This analysis is based on raingauges data.

Rainfall Threshold (mm/3h)	Number of events - 2019	Fraction - 2019	Fraction – 11 years
D0-1	620521	93.63	92.04
1-5	25659	3.87	4.92
5-10	8520	1.29	1.66
10-20	5559	0.84	0.98
20-30	1489	0.22	0.24
30-50	749	0.11	0.12
50-70	153	0.02	0.02
> 70	110	0.02	0.02

Table S1: Distribution of the three-hourly precipitation for different rainfall classes for the year 2019 and for the period 2012-2022.

The fraction of events in different precipitation classes were computed relative to the total number of events for 2019 (662760) and for the period 2012-2019 (5776646). Compared to the last 11 years the rainfall distribution for 2019 shows a larger fraction of events for very small or no rainfall (0-1 mm/3h) class, while it has lower fraction of events from 1-5 mm/3h up to 10-20 mm/3h. For larger thresholds the fraction of events occurred in 2019 is similar to the last 11 years. In any case the number of events considered in this work is high. For example, the events with rainfall larger than 30 mm/3h, i.e. the most intense threshold showing a significant difference between the control and the forecast using GNSS-ZTD data assimilation, are 1012.

S2 Synoptic conditions for October

In this section we shortly describe the synoptic conditions for the period, derived from the ECMWF operational analysis issued at 00, 06, 12 UTC and 18 UTC of each day of the period. The geographical references are set referring to the Figure 1 of the paper.

Days 2-4: A wave trough from NW Europe extends towards the Mediterranean. A cyclone is generated downwind of the western Alps and moves from NW to SE. During the day 4 the cyclone interested the southern and eastern part of Italy with low (< 10 mm/day) rainfall over Sicily, Apulia and Calabria.

Days 5-6: The cyclone of the days 2-4 moved towards Balkans and winds over Italy are from NW to SE at mid- and low-tropospheric levels. Winds are sustained and the interaction between the winds and Italian orography causes weak precipitation over Italy, especially along the Tyrrhenian coast.

Days 7-8: A new cyclone transits over Italy from NW to SE. The cyclone moves quickly and shows a cut-off at 500 hPa at 18 UTC on 7 October over western Sicily. During its movement it causes widespread convection along Italy, especially southern Italy (Figure S2). During the day 8 the cyclone moves towards South causing localized rainfall over southeastern Sicily (Figure S1).

Days 9-10: Two cyclones transit over the domain. The first moves over central Europe from NW towards NE. This cyclone generates a small cyclone on the lee of the Alps causing rainfall over northern Italy. The second cyclone is generated on the lee of the Atlas Mountains in the first hours of 9 October and moves from SW to SE. During its movement, precipitations are reported over southern Italy, especially Calabria and Sicily. The precipitation are higher for 9 October (maximum of 90 mm/day) compared to 10 October (maximum of 40 mm/day).

Days 11-13: As the two cyclones of 9-10 October slowly moved towards East, a high pressure pattern expanded from Africa towards Italy and Western Europe. The surface pressure is leveled over Italy and small precipitations are reported over the country. On 12 October, a local thunderstorm, likely thermally forced in the afternoon, caused heavy rain in two raingauges in Apulia (60 and 100 mm for the day, respectively).

Day 14: An Atlantic cyclone enter the Mediterranean and slowly propagates eastward. At 12 UTC on 14 October, the surface pressure minimum is over the Balearic Islands. Humid and unstable marine air is advected towards Liguria causing heavy rainfall over Genova and surroundings (more than 150 mm/day).

Days 15-16: the cyclone of day 14 propagates eastward and impacted the whole Italy. On day 15 heavy rainfall occurred over northern and central Italy with many raingauges (> 100) recording more than 150 mm. The rainfall occurred mainly over NE Italy on 16 October, caused by a smaller cyclone developed on the lee of the Alps. However, precipitation occurred also in southern Italy with moderate rainfall (10 stations recorded more than 20 mm/day).

Day 17: no specific weather systems where acting over Italy and surface pressure was leveled. The air masses impinged the Genova Gulf from the south causing some rain over Liguria and along the Tyrrhenian coast of the peninsula. Precipitation was small (< 10 mm/day with few exceptions).

Days 18-21: on 18 October a cyclone is acting over Western Europe with a cut off at 500 hPa over England. The cyclone is far from Italy, nevertheless the winds impinge the Liguria region from S-SW. The peaked orography of the region forces air masses to lift causing localized and heavy rainfall over Liguria with few raingauges reporting more than 150 mm on 18 October. During the 19 October, the cyclone starts to deepen at the surface, while at 500 hPa a wave trough elongates towards France and Spain. The cyclone center, i.e. the surface pressure minimum, is closer to Italy compared to 18 October, yet far from the country, and heavy rain occurs over NW of Italy, especially over Liguria and western and central Alps. Many raingauges recorded more than 100 mm/day in Liguria and over the Alps. The synoptic situation remained almost stationary on 20 and 21 October with the cyclone center over the western Mediterranean. Heavy precipitation occurred on both days, especially on 21. All in all, the period 18-21 was a heavy rain event for NW Italy, and several raingauges reported more than 300 mm over Liguria and western Alps for the period. Because of this huge event, the total precipitation map for the month of October 2019, Figure S3a, shows the largest precipitation amounts in the NW of Italy.

Days 22-26: the cyclone with impacts over NW Italy on 18-21 October, moved southwards and was reinforced by the interaction with the Atlas Mountains. Because of this interaction, a low pressure developed on the lee of the Atlas and propagated eastward. At 500 hPa a new cut-off originated and detached from the wave through. The whole system propagated from SW towards SE and impacted Italy during the period. The rainfall occurred over northwestern Italy on 22 and 23 October 2019 and was intense with maxima above 100 mm/day. Intense and widespread precipitation occurred on 24 October over Italy (all the country was interested by this event, as the cyclone moved from west to east). On 25 and 26 October, the rainfall occurred mainly over Sicily with maximum around 150 mm/day for both days.

Day 27: Remnants of the system that crossed Italy during the period 22-26 October were acting over Sicily. Moderate to intense rainfall were reported over the Island (maximum 65 mm/day in one rain gauge).

Day 28: The surface pressure and 500 hPa geopotential height didn't shown specific features. Winds were low and light precipitation was observed over northern and central Italy.

Day 29-31: Italy was under the action of a cyclone centered over NE Europe (between Poland and Ukraine). The interaction between the cyclone and Alps generated a low over northeastern Italy. The cyclonic circulation around the surface pressure caused widespread rainfall over the country, especially northern and central Italy, on 30 and 31 October, while precipitation was recorded in Tuscany and Liguria on 29 October. Rainfall was moderate to intense (50-150 mm/day).

S3 Scores for the phase 18-21 UTC on 15 October 2019

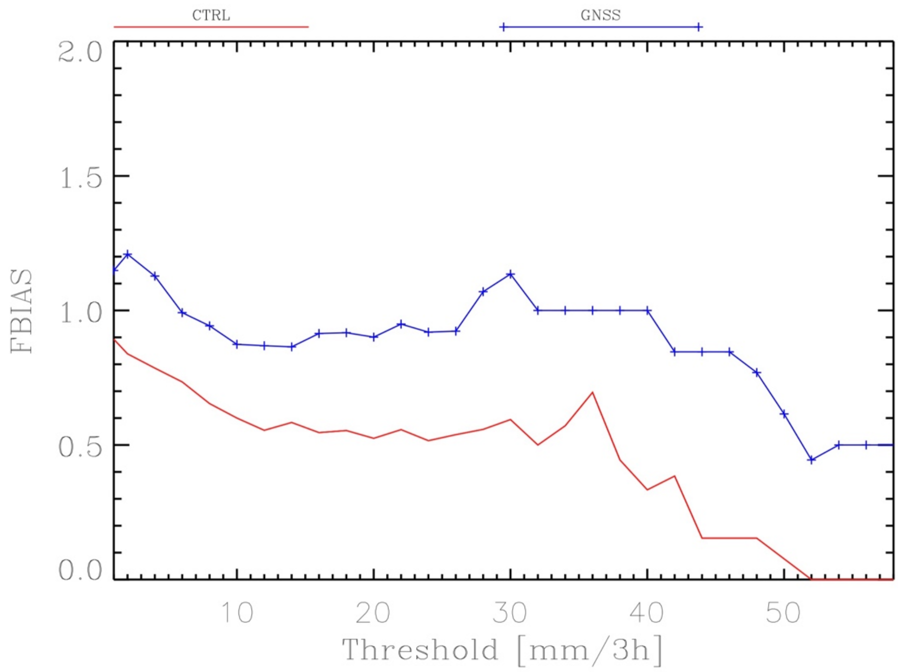
In this section we show the Frequency Bias (FBIAS), Equitable Threat Score (ETS) Probability of Detection (POD), False Alarm Rate (FAR) for the case study presented in the Section 3.2 of the paper. The case study refers to the phase 18-21 UTC on 15 October 2019, when three major thunderstorms occurred over Italy. As shown in the paper, the GPS-ZTD data assimilation improves the precipitation forecast by focusing the precipitation in the observed places, by increasing the precipitation amount in the NE of Italy and by predicting rainfall in places not predicted by the background, the main drawback being the increase of false alarms.

The scores are computed for the 1mm/3h precipitation threshold and for the thresholds from 2 to 60 mm/3h every 2 mm/3h and are shown in Figure S4.

Results for the FBIAS (Figure S4, panel a) show a substantial improvement for the forecast assimilating GNSS-ZTD. The score is larger than 0.8 up to 46 mm/3h for GNSS, while the correspondent value for CTRL is lower. Results for POD are similar: the score for the forecast

assimilating GNSS-ZTD is larger than 0.7 up to 48 mm/3h while the POD for CTRL is less than 0.2 for thresholds larger than 42 mm/3h. The results of FBIAS and POD show a poor performance of the CTRL forecast for thresholds larger than 40 mm/3h.
The main drawback of GNSS forecast compared to CTRL is the increase of false alarms, especially over Central Italy, as discussed in the paper. For the case study this is quantified in Figure S4, panel c, which shows larger FAR values for GNSS compared to CTRL.
Figure S4, panel d, shows the ETS for CTRL and GNSS forecasts for the case study. The improvement of ETS for GNSS simulation occurs at all thresholds and is larger for rainfall greater than 40 mm/3h. For thresholds larger than 50 mm/3h, the ETS of CTRL is close to 0 while it is greater than 0.4 for GNSS, showing the added value of GNSS forecast compared to a random forecast in which the occurrence/non occurrence of the precipitation is independent from the observation/non observation of the event.
All in all, the results of Figure S4 show a substantial improvement of the forecast assimilating GNSS-ZTD compared to the control forecast. Interestingly, this is confirmed by the analysis for the whole period with statistically significant improvement for low and moderate rainfall thresholds (up to 30 mm/3h).

a)



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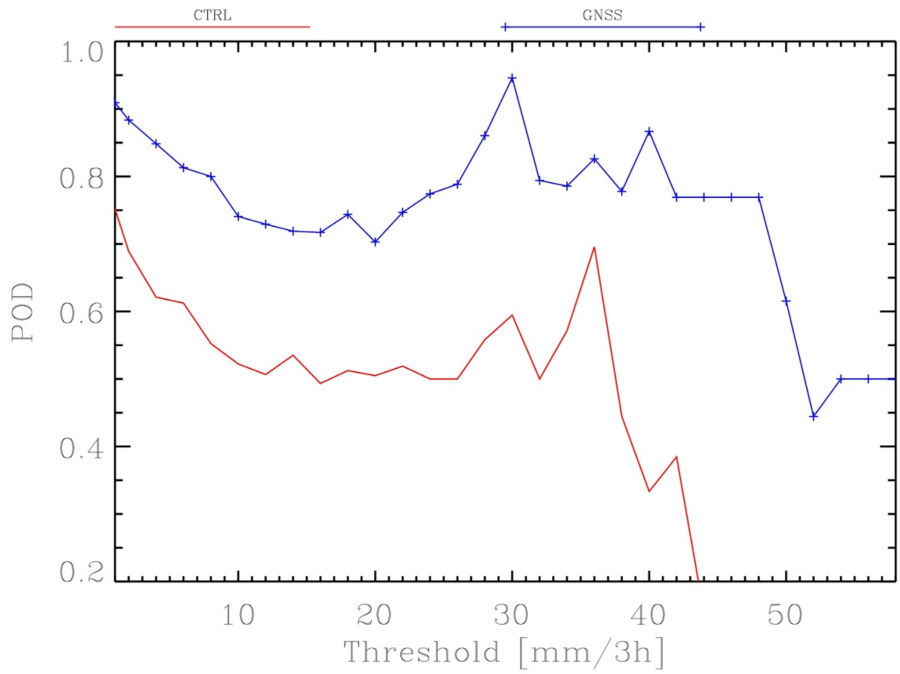

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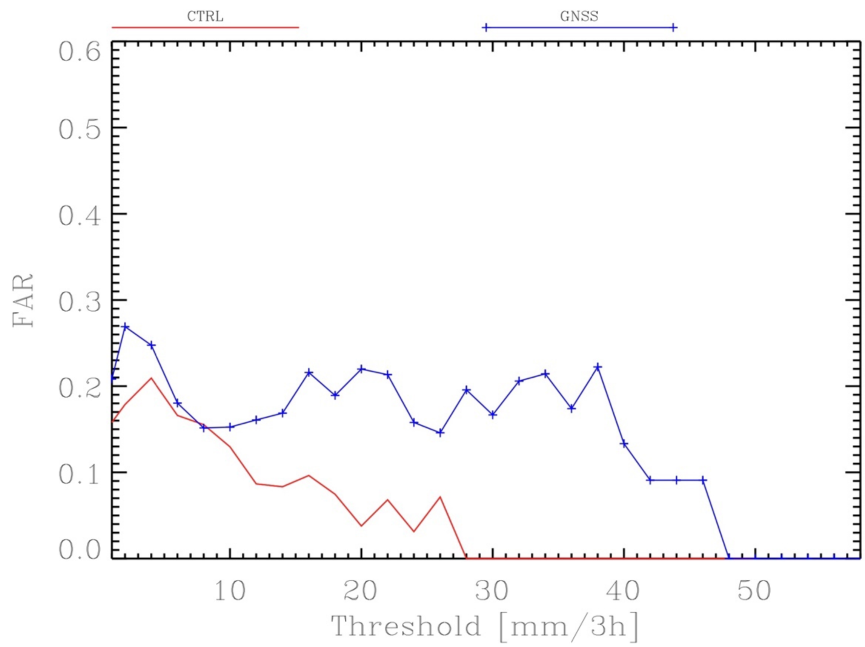

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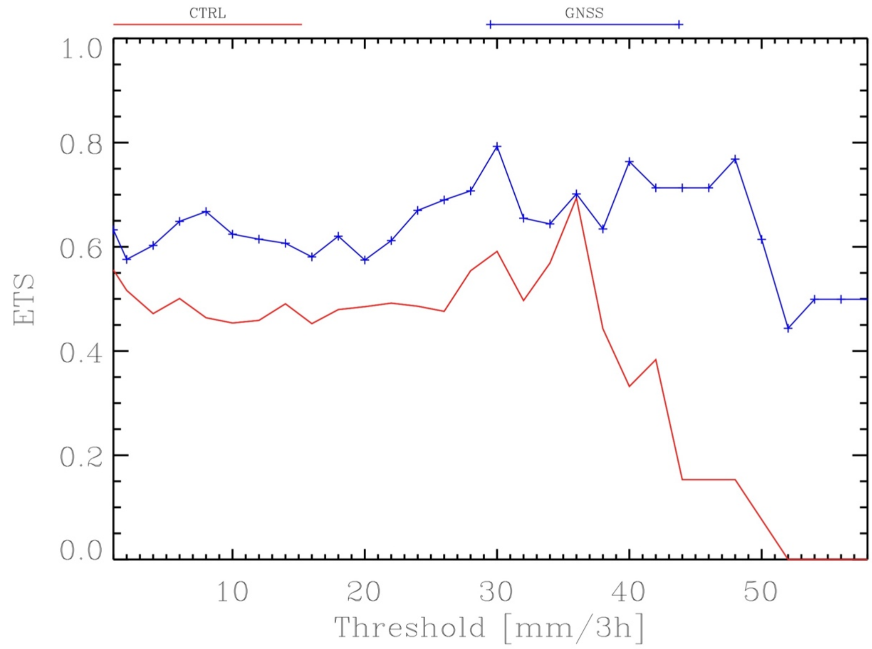

Figure S4: Scores for the precipitation forecast of the period 18-21 UTC on 15 October 2019. Scores are computed for 1mm/3h threshold and for all thresholds from 2 mm/3h to 60 mm/3h every 2mm/3h; a) Frequency Bias, b) Probability of Detection; c) False Alarm Rate; d) Equitable Threat Score.

References

Hersbach, H.; Bell, B.; Berrisford, P.; Biavati, G.; Horányi, A.; Muñoz Sabater, J.; Nicolas, J.; Peubey, C.; Radu, R.; Rozum, I.; et al. 418 ERA5 hourly data on single levels from 1979 to present. Copernicus climate change service (c3s) climate data store (cds) 2018, 10.