An exceptionally intense hailstorm over the Mediterranean area: Observational analysis and role of the GPM Core Observatory

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Overview

The Mediterranean is a unique meteorological environment and a weather forecasting challenge, and is recognized as one of the major climate hot-spots in the world. Because of the complex orography of the Mediterranean coastal regions and of the need to improve the monitoring and forecasting of severe weather in terms of time, location, and strength (Panegrossi et al. 2016), conventional ground-based instruments (e.g., raingauges and weather radar networks) are often inadequate to provide observational details of severe weather on the whole region. For these reasons, the use of satellite measurements is a unique opportunity to study severe events over the sea and large part of the coastal regions.

In this study the GPM-CO observations of a violent hailstorm, that developed over the Tyrrhenian Sea and hit the Gulf and the city of Naples in Italy on 5 September 2015 (hereinafter referred to as the Naples hailstorm) are thoroughly analysed and discussed, in conjunction with other satellite and ground-based measurements. We illustrate the unprecedented capabilities of the GPM-CO satellite for characterizing the structure of this exceptionally severe storm. We show that the combined use of measurements from GMI and DPR with those available from other sensors provides observational evidence of extremely rare features of the Naples hailstorm, while demonstrating the potential of GPM-CO to enhance the understanding of these severe convective systems by providing unique spaceborne measurements of the 3-D structure of precipitation.

Figure 1: Hailstone bombing observed by a boat 2 km off the coast, north of Procida Island (40.78°N, 14.02°E) around 09:00 UTC (left panel). Baseball-size hailstones (right panel). Photographs extracted from the videos available at http://www.youreporter.it/video_Eccezionale_tempesta_di_grandine_nel_golfo_di_Napoli (courtesy of Rosario Chiocca) and at https://www.youtube.com/watch?v=yarARzbkjI4.

Goal

The purpose of this work is to show that the use of advanced cross cutting observational tools, combining data from different platforms, is essential for the characterization of such severe and rapidly evolving convective systems, which periodically devastate the Mediterranean coastal regions, and to document how the GPM integrates the established observational ground-based and satellite-borne tools in monitoring, understanding, and characterizing severe weather.

Observational dataset

MSG, lightning, and ground-radar

MSG SEVIRI IR and VIS images;
LINET lightning ground-based network data;
Ground-based C-band polarimetric radar at Monte il Monte (41.94°N, 14.62°E, 710m ASL), 130 km away from the storm.

GPM constellation: GPM-CO and MHS

GPM-CO (GMI and DPR) overpass at 8:47 UTC;
MetOp-A and MetOp-B (AMSU/MHS) overpasses (8:34 UTC and 9:28 UTC respectively);

Analysis and Discussion

Temporal evolution of the storm as inferred by MSG IR, lightning and ground radar observations

The mesoscale storm under study developed off shore and moved inland in its mature phase dropping 7-10 cm sized hailstones along its path over the sea and over land. It consisted of a supercell followed by secondary cells. The supercell structure is clearly revealed by the presence of cloud top plumes observed by MSG SEVIRI (Fig. 2) and of a strong hook-echo in the C-band polarimetric ground radar (GR) measurements (Fig. 5). MSG SEVIRI analysis shows cooling rate of the updraft top around 1 K min^{-1} at the beginning, reaching its maximum of 4.5 K min^{-1} around 06:07 UTC. The peak updraft speed is estimated compatible with 8-10 cm sized hailstones at the ground. The coldest cloud-top IR brightness temperature was 197.9 K at 07:22 UTC.

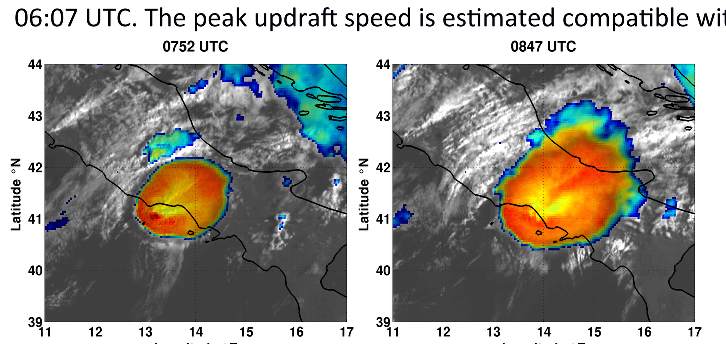


Fig. 2: Two snapshots of the storm at 07:52 UTC (left panel) and 08:47 UTC (right panel) reported by using the "sandwich" visualization technique to enhance the cloud top topography and thermal structure, by merging the HRV and IR information. The last one is the time of the GPM-CO overpass.

A total of 20846 LINET strokes were registered in two hours (07:00-09:00 UTC) during the most intense phase of the storm, with a maximum stroke rate around 300 min^{-1} (Fig. 3). The time series of positive and negative IC and CG strokes provides an indication of the variable electrical structure of the storm, characterized by an increased IC+ fraction and emission height during its most intense phases and by the highest IC+ stroke rates when very large hailstones were reported at the surface (Fig.4).

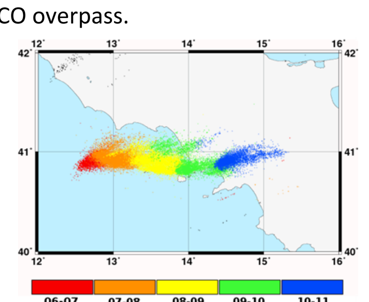


Fig. 3: Strokes registered by LINET between 06:12 UTC and 11:00 UTC over the area swept by the hailstorm (lat.: 40.5°N÷41.5°N; lon.: 12.5°E÷15.5°E), with colours from red to blue representing the strokes registered within each hour. The black crosses represent strokes registered at the same time outside the area of interest.

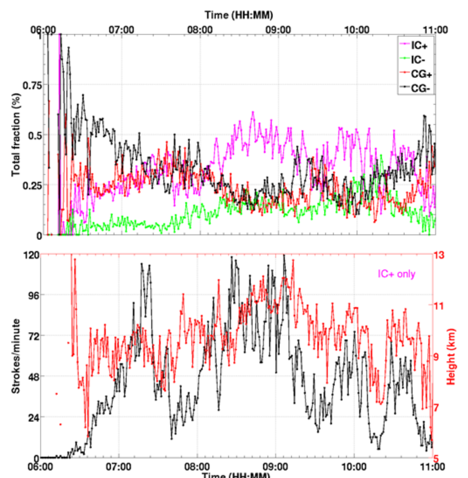


Fig. 4: Temporal evolution of LINET strokes.

Top panel: Fraction of each type of strokes registered every minute between 06:00 UTC and 11:00 UTC over the area swept by the hailstorm.

Bottom panel: rate and mean height per minute of IC+ strokes only.

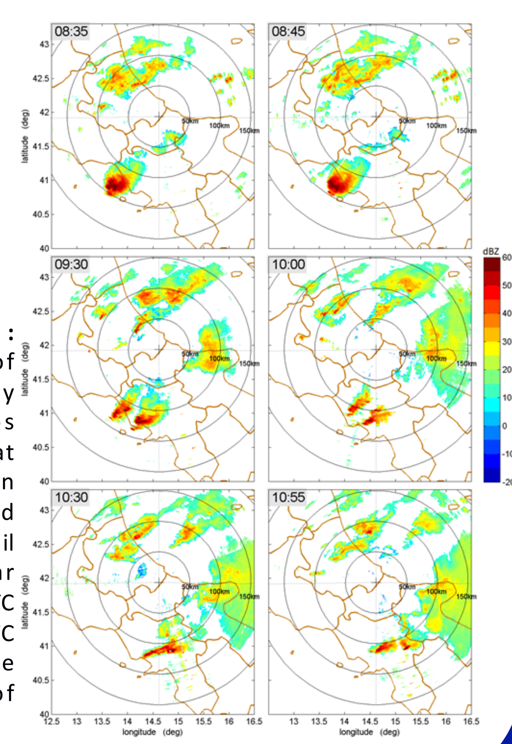


Fig. 5: Sequence of reflectivity factor maps (measured at 1.5°elevation angle) collected by the Monte il Monte radar from 08:30 UTC to 10:55 UTC highlighting the evolution of the hailstorm.

Lightning activity and GMI/DPR observations

Most of the LINET strokes registered around the time of the GPM-CO overpass are concentrated within the main cell. The area of minimum TB at 19 GHz (V-polarization), identifying the presence of large hailstones or graupel, is in proximity of the region of lightning activity. This happens also when we look at the Ku-band radar reflectivity and ground radar reflectivity, where lightning activity is mostly located over the area of maximum radar reflectivity (Fig. 11).

The vertical distribution of IC lightning according to vertical DPR reflectivity Z_m and ground-radar reflectivity Z_h and differential reflectivity Z_{dr} (Fig. 12) reveals that the complex multi-polar electrical structure of the storm was connected to the presence of a very strong updraft (with more IC+ at higher levels than IC-, while in other regions of the storm the IC polarity distribution changes). The vertical cross-sections of the ground radar Z_h, with values around 60 dBZ up to 12-14 km, along the same directions of DPR show a really good agreement with Z_m, apart from the underestimation of the storm height and extension along the range direction in the ground radar observations. The analysis of Z_{dr} vertical cross-sections indicate that the IC+ are mostly located over regions of increased Z_{dr} aloft, associated to the updraft, while IC- are mostly located in regions of high Z_h found at the lower levels, and associated to precipitation.

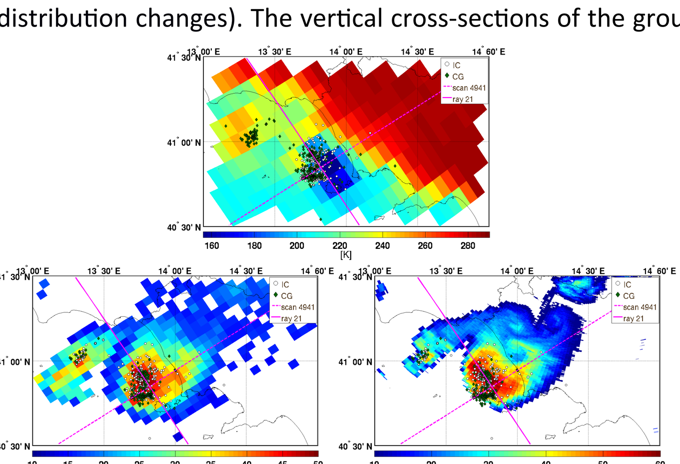


Figure 11: Map of LINET strokes (IC and CG) during a 4 min time interval around 08:47 UTC superimposed over GMI TB at 19 GHz V-Pol (top panel), over DPR Ku-band median Z_m (bottom left panel) and over GR reflectivity at 2.5° elevation at nominal 08:45 UTC (bottom right panel). The DPR-Ku ray 21 (cross-section A) and scan 4941 (cross-section C) are shown in pink.

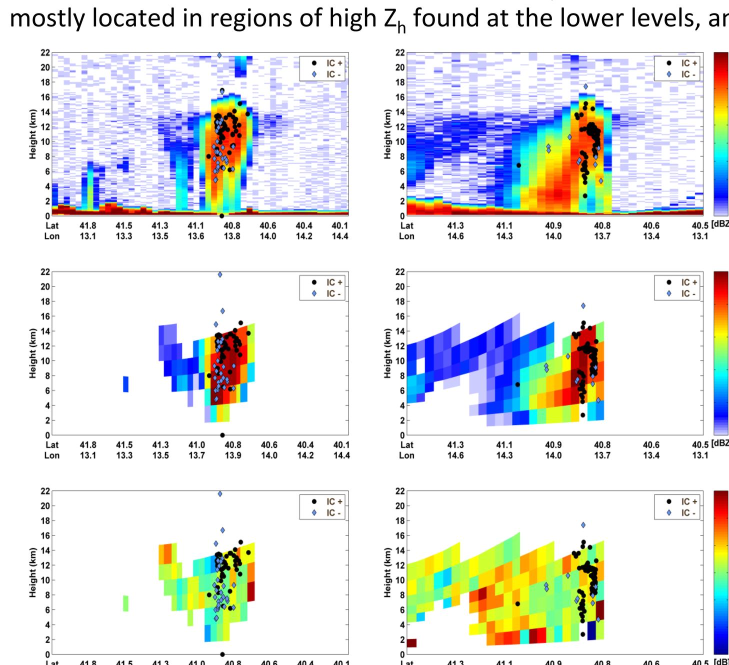


Figure 12: DPR and GR cross-section A (left panels) and C (right panels) with LINET strokes (IC+ and IC-) registered in 4 min around 08:47 UTC within a circular area of 2.5 km radius around each radar pixel.

Top panels: Ku measured reflectivity Z_m (dBZ).

Middle panels: GR C-band reflectivity Z_h (dBZ).

Bottom Panels: GR measured C-band differential reflectivity Z_{dr} (dB).

Event characterization at global scale

GPM measurements are useful to classify the severity of the Naples storm at global scale. The storm was exceptionally intense since it was characterized by the deepest 19V GHz TB depression (158 K) over a 26-months period of GMI global observation, and since it shared extremely low TBs (and PCTs) records at 23 and 37 GHz with only two storms in the CONUS, and also with tropical storms at higher frequencies. MetOp-A and MetOp-B MHS measurements confirm these findings because of the extremely low TBs (Table 2) as compared to a 12-year MHS hailstorm climatology over the U.S. (Ferraro et al., 2015), which are compatible with hailstone size larger than 7.5 cm.

GMI TB or PCT	Ranking	TRMM Area (no CONUS)	Mediterranean Area	CONUS	Other regions
19 GHz V	1	-	1 (100%)	-	-
23 GHz	2	-	1 (50%)	1 (50%)	-
37 GHz PCT	4	-	1 (25%)	2 (50%)	1 (25%)
89 GHz PCT	98	80 (81.63%)	3 (3.06%)	12 (12.24%)	3 (3.06%)
166 GHz V	1798	1740 (96.77%)	6 (0.33%)	33 (1.83%)	19 (1.06%)
183±3 GHz	1745	1704 (97.65%)	4 (0.23%)	23 (1.32%)	14 (0.80%)
183±7 GHz	2219	2161 (97.39%)	6 (0.27%)	32 (1.44%)	20 (0.90%)

Table 3: Analysis of Precipitation Features (PFs) found in 26 months of global observations (03/2014-04/2016, http://atmos.tamucc.edu/trmm/data/gpm) based on minimum TB and PCT values. Second column shows the ranking of Naples hailstorm (for each TB or PCT) with respect to over 15 millions (15,274,291) global PFs. Third to sixth column show the geographical distribution (in terms of number and %) of the PFs with TB and PCT minimum values equal to or lower than those found for the Naples hailstorm.

GPM observations of the hailstorm mature stage

The available measurements from the GPM constellation of radiometers (especially GMI and DPR onboard GPM-CO (Fig. 6), but also by the MHS onboard MetOp-A and MetOp-B (Fig. 9)) integrate the other observations available, and help overcoming many of the limitations suffered by ground based instruments and VIS-IR sensors on geosynchronous satellites.

Specifically, GMI measurements (Fig. 7) provide useful information on the different nature of the ice hydrometeors in the outflow region (low-density ice hydrometeors such as snowflakes and aggregates) and in the convective core (graupel or hail), while delineating well the structure of the storm because of their higher spatial resolution with respect to the other PMW radiometers of the GPM constellation (Fig. 9) .

In particular, the fact that the convective core of the storm shows a deep GMI TB depression at 19 GHz and that the minimum TBs at 166 GHz are 20 K higher than at 89 GHz is an indication of the presence of large, high-density ice particles at different levels of the updraft region.

Finally, the newly available 166 GHz polarization differences (Fig. 8) show patterns indicating a complex physical structure and different hydrometeor characteristics in the upper cloud layers: randomly oriented/tumbling ice particles brought to the upper levels by the strong updraft in the convective core, and non-spherical ice crystals with preferential orientation in the convective outflow region (likely horizontally oriented oblate ice particles).

DPR measurements (Fig. 10) provide further support to the GMI analyses and findings, while highlighting the slanted structure of the main updraft and its vertical structure, and measuring the overshooting top height at 16.25 km a.s.l., with the presence of large ice particles in highest cloud layers (i.e. Z ≥ 45 dBZ at 14 km a.s.l.).

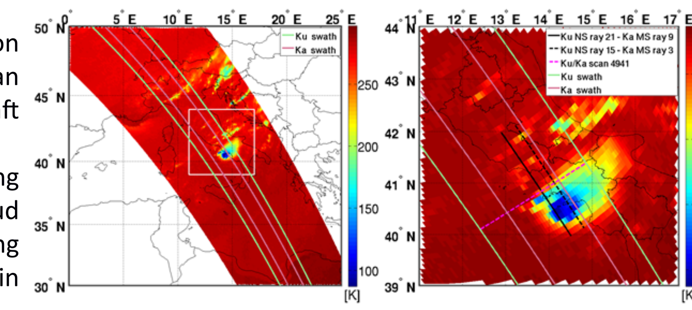


Fig. 6: GMI orbit 8630 on 5 September 2015.

Left panel: TB in the 166 GHz H-polarization channel, with the width of Ku and Ka swaths superimposed (green and magenta lines respectively).

Right panel: as in left panel, with a zoom over the area of interest. The direction of storm cross-section "A" (for Ku ray 21 – Ka ray 9) and "B" (for Ku ray 15 – Ka ray 3) are also shown (black solid and dashed lines respectively).

PMW observations: GMI and MHS

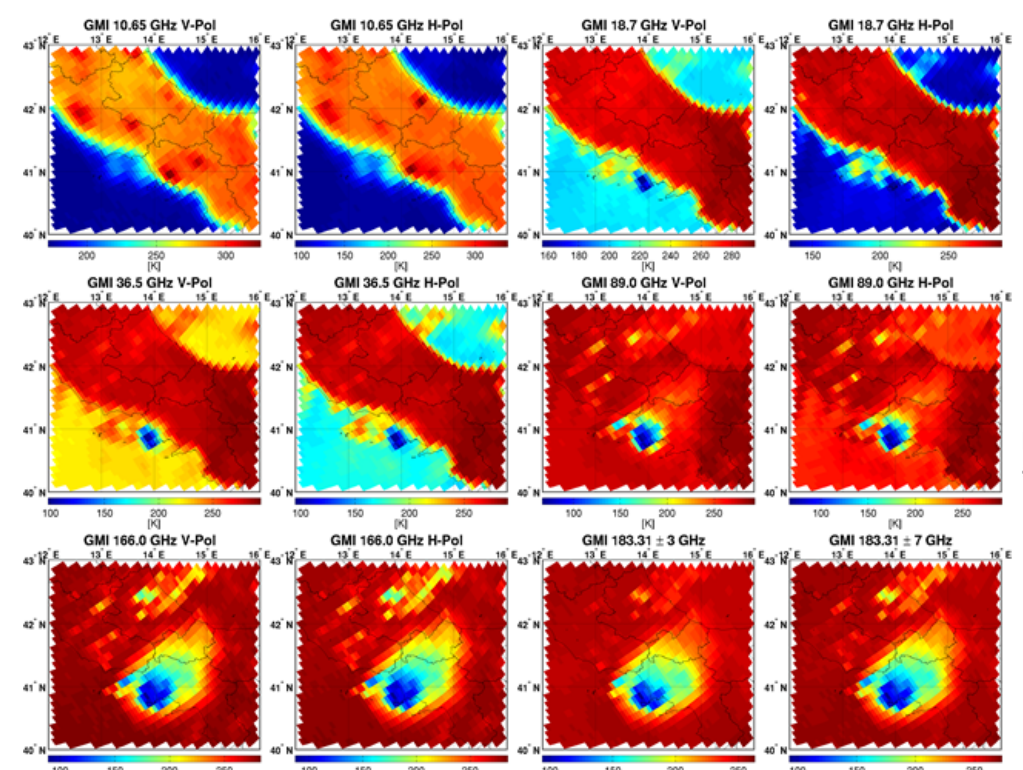


Figure 7: TBs from GMI overpass at 08:47 UTC. From left to right, first row 10.65 GHz V/H, 18.7 GHz V/H, second row 36.5 GHz V/H, 89.0 GHz V/H, third row 166 GHz V/H, 183.31±3 GHz, 183.31±7 GHz.

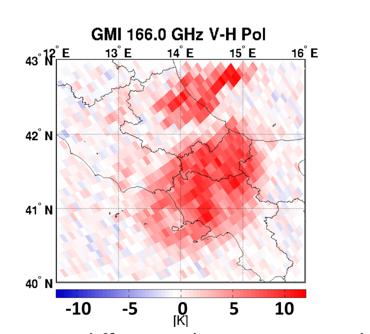


Figure 8: TB difference between vertical and horizontal polarization channels (V-H) at 166 GHz from GMI overpass at 08:47 UTC.

GMI channels	min TB value (K)	IFOV (km^2)
19 GHz V	158	11x18
23 GHz	138	9.2x15
37 GHz PCT	100	8.6x14
89 GHz PCT	68	4.4x7.2
166 GHz H	86	4.4x7.2
166 GHz V	87	4.4x7.2
183±3 GHz	94	4.4x7.2
183±7 GHz	92	4.4x7.2

Table 1: Minimum values of TBs and Polarization Corrected Temperature (PCTs) for the GMI overpass of Naples hailstorm at 08:47 UTC. The corresponding instantaneous field of view (IFOV) size is also indicated. TB thresholds for hail detection based on TMI climatology are **70 K at 85 GHz, 180 K at 37 GHz, or 230 K at 19 GHz (PCTs)** (Cecil, 2009).

Satellite	Min 89 GHz	Min 157 GHz	Min 183±1 GHz	Min 183±3 GHz	Min 183±7 GHz	IFOV (km^2)
MetOp-A	121 K	111 K	146 K	123 K	118 K	34.4x21.4
MetOp-B	151 K	129 K	156 K	137 K	134 K	28.9x19.7

Table 2: Minimum values of TBs for the MHS overpasses of Naples hailstorm at 08:34 UTC and 09:28 UTC. The corresponding IFOV size is also indicated. TB values are well below the mean TB thresholds for large hail (7.5 cm) occurrence found for 2000-2011 AMSU/MHS U.S. climatology (Ferraro et al. 2015).

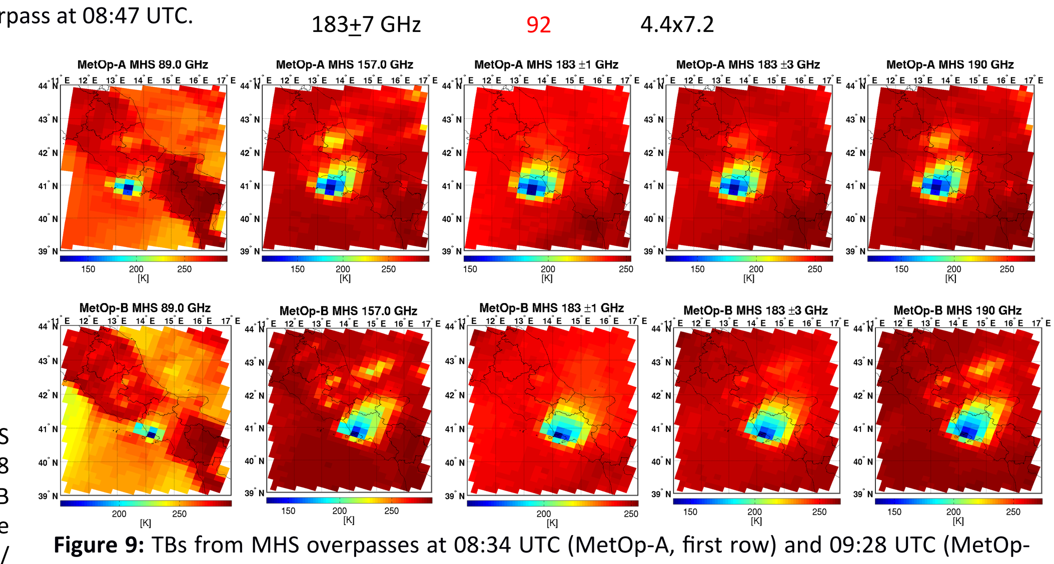


Figure 9: TBs from MHS overpasses at 08:34 UTC (MetOp-A, first row) and 09:28 UTC (MetOp-B, second row). From left to right, 89 GHz, 157 GHz, 183±1 GHz, 183±3 GHz, 183±7 GHz.

GMI and DPR

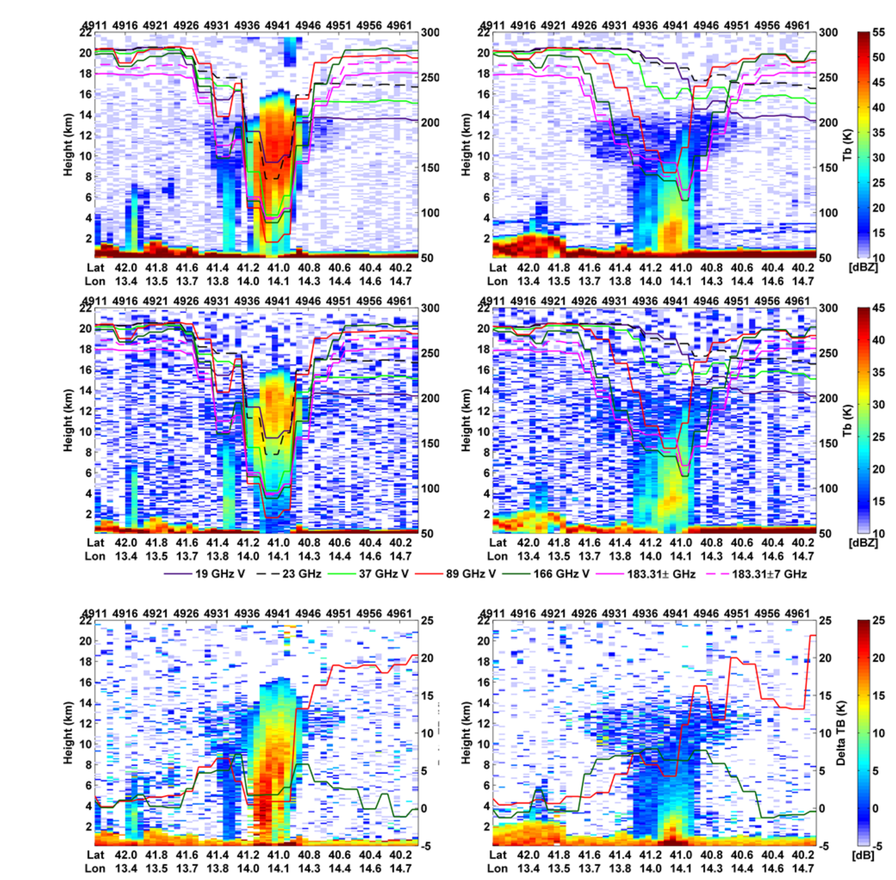
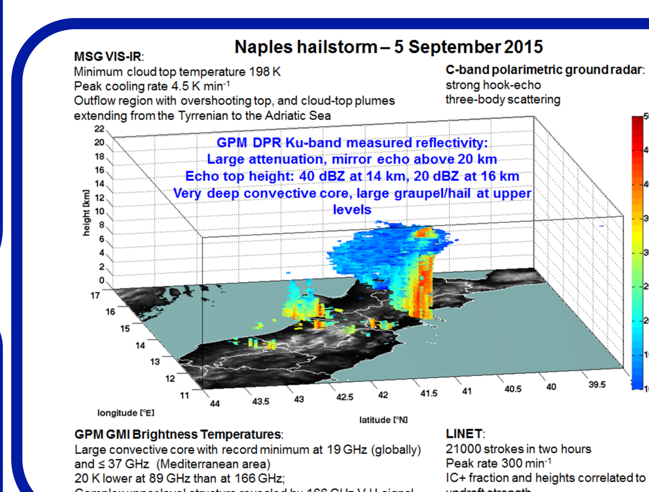


Figure 10: DPR along-track section A (left column) and section B (right column) of measured reflectivity (Z_m) at Ku (first row), Ka (matched scan, MS) (second row) and of DWR (third row). GMI TBs for 5 window channels (V-Pol) and 183.31 GHz channels, corrected for parallax effects, are superimposed. V-H TB differences at 89 GHz and 166 GHz are shown over DWR. On top of each panel the GMI scan number along the cross-section is indicated. See Fig. 8 as reference for the position of section A and B.

Summary and Conclusions



In this study GMI and DPR measurements of an exceptionally severe hailstorm occurred in central Mediterranean on 5 September, 2015, taken when the main convective core was approaching the coast of Naples, are used in parallel with MSG SEVIRI IR observations, LINET strokes data, and ground-based C-band radar polarimetric measurements.

Unique spaceborne measurements available from GPM-CO provide observational evidence of extremely rare features of the Naples hailstorm, and, in combination with more established observational data, contribute towards our understanding of such severe and rapidly evolving convective systems.

In this regard, it is worth noting that operational and research Numerical Weather Prediction (NPW) models completely missed the forecast of this storm, thus fostering deeper research to increase knowledge of these events which often severely impact ground structures and human activities. The extremely rapid development over the sea (with no orographic forcing) of such localized and intense convective systems, together with the fact that often the local forcing is not represented in the data used as initial conditions in an operational setting, poses great challenges to a correct simulation of the dynamical and microphysical processes leading to their development. Nevertheless, we leave to future and dedicated studies the investigation of the mechanisms that have lead to the development and evolution of such exceptional hailstorm, as well as the quantitative retrieval of the storm microphysical structure using the GPM-CO GMI and DPR measurements (accounting for attenuation correction and multiple scattering). We anticipate that to this end, it will be necessary to combine cloud-resolving model and radiative transfer simulations with the observational dataset that has been analyzed in the present study.

Finally, this observational study indicates that the quantitative exploitation of the unprecedented tools available from GPM should be oriented not only to the retrieval of precipitation rates, but also to the retrieval of cloud structure and dynamics of extreme events which periodically devastate the Mediterranean coastal regions; moreover, the use of GPM data would help assessing climate change signatures in the Mediterranean area, where such severe events are becoming more and more frequent, while the available observation networks based only on raingauge and weather radar are unlikely to provide measurements with the needed space cover, detail and accuracy.

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