Satellite and Numerical Model Investigation of Two Heavy Rain Events over the Central Mediterranean

SANTE LAVIOLA
ISAC-CNR, Bologna, Italy

AGATA MOSCATELLO AND MARIO MARCELLO MIGLIETTA
ISAC-CNR, Lecce, Italy

ELSA CATTANI AND VINCENZO LEVIZZANI
ISAC-CNR, Bologna, Italy

(Manuscript received 18 December 2009, in final form 4 January 2011)

ABSTRACT

Two heavy rain events over the Central Mediterranean basin, which are markedly different by genesis, dimensions, duration, and intensity, are analyzed. Given the relative low frequency of this type of severe storms in the area, a synoptic analysis describing their development is included. A multispectral analysis based on geostationary multifrequency satellite images is applied to identify cloud type, hydrometeor phase, and cloud vertical extension. Precipitation intensity is retrieved from (i) surface rain gauges, (ii) satellite data, and (iii) numerical model simulations. The satellite precipitation retrieval algorithm 183-Water vapor Strong Lines (183-WSL) is used to retrieve rain rates and cloud hydrometeor type, classify stratiform and convective rainfall, and identify liquid water clouds and snow cover from the Advanced Microwave Sounding Unit-B (AMSU-B) sensor data. Rainfall intensity is also simulated with the Weather Research and Forecasting (WRF) numerical model over two nested domains with horizontal resolutions of 16 km (comparable to that of the satellite sensor AMSU-B) and 4 km. The statistical analysis of the comparison between satellite retrievals and model simulations demonstrates the skills of both methods for the identification of the main characteristics of the cloud systems with a suggested overall bias of the model toward very low rain intensities. WRF (in the version used for the experiment) seems to classify as low rain intensity regions those areas where the 183-WSL retrieves no precipitation while sensing a mixture of freshly nucleated cloud droplets and a large amount of water vapor; in these areas, especially adjacent to the rain clouds, large amounts of cloud liquid water are detected. The satellite method performs reasonably well in reproducing the wide range of gauge-detected precipitation intensities. A comparison of the 183-WSL retrievals with gauge measurements demonstrates the skills of the algorithm in discriminating between convective and stratiform precipitation using the scattering and absorption of radiation by the hydrometeors.

1. Introduction

Severe weather over the Mediterranean has only recently become the object of thorough analyses despite its prominent scientific interest and its strong effects on the heavily populated countries surrounding the basin. Preliminary studies have concentrated on the Western Mediterranean (e.g., Romero et al. 1999; Jansa et al. 2001) and the Eastern Mediterranean (e.g., Nicolaides et al. 2004; Ziv et al. 2009). A general classification of cloud systems associated with the large-scale circulation was published by Chaboureau and Claud (2006) based on satellite data. More recently, Levizzani et al. (2010) have carried out a 10-yr study on the span, duration, and phase speed of propagating cloud systems in the warm season over the Mediterranean using half-hourly Meteorological Satellite (Meteosat) infrared data.

a. Intense Mediterranean cyclones

Mediterranean storms are often characterized by heavy precipitation, intense wind shear, and deep atmospheric lows, and heavily affect coastal and continental regions.
The causes of such severe events are generally attributed to the geographic complexity of the Mediterranean basin especially at the local scale where the orography plays an important role in the destabilization of the westerly oceanic systems reaching the area. The mountain chains provide the necessary uplift to air parcels to reach the level of free convection, thus contributing to heavy rainfalls over the surrounding areas. The importance of orography in the development of Mediterranean severe storms is detailed by Miglietta and Regano (2008) who investigated a flash flood event via numerical simulations using the Weather Research and Forecasting Model (WRF; Michalakes et al. 2004) developed at the National Center for Atmospheric Research (NCAR). Observations reported in Moscatello et al. (2008b) where a more intense phenomenon was described, point to the orographic flow deflection as the baroclinic origin of cyclones in the Mediterranean basin. The Alps are responsible for such deflections for the Northern Atlantic systems and the Atlas Mountains for the southern ones. These systems transit over the warm Mediterranean and western Europe, and find favorable conditions for cyclogenesis over the Western Mediterranean (Buzzi and Tibaldi 1978). Also, Mediterranean disturbances frequently develop as a consequence of the interaction of an unusually deep upper-tropospheric trough and cold air with the relative warmth of the sea surface (Rasmussen et al. 1992; Emanuel 2005).

Two extreme Mediterranean storms are studied hereafter. The first is an intense mesoscale convective system (MCS), originally developing over West Africa, becoming reinforced while crossing the Mediterranean warm waters (for a complete analysis of the event see Mastrangelo et al. 2011). The MCS hits southern Italy and in particular the Apulia region (the heel of the Italian peninsula) on 12, 13, and 14 November 2004 with severe floods induced by heavy precipitation reaching as high as 200 mm in 24 h.

The second event is a relatively rare tropical stormlike system characterized by two twin cyclones over the Tyrhenian and Ionian Seas. These tropical stormlike cyclones, named “medicanes” by Emanuel (2003), normally develop in September, October, and November, when the Mediterranean sea surface temperature is high, and can induce extreme weather and hazards on islands and coastlines. A couple of such hurricane-like cyclones in the Mediterranean were described by Rasmussen and Turner (2003), who compared them with polar lows. The intense, persistent, and localized precipitation associated with such phenomena is often followed by floods. Medicanes show a structure similar to that of tropical depressions with a clearly defined eye and spirally organized cloud bands. Note that they develop and evolve under very different environmental conditions with respect to classical tropical cyclones; above all, the environmental wind shear, the tropical sea surface temperature, and humidity level are markedly different from the conditions observed in the Mediterranean basin in fall. However, the dynamics and physics of the medicanes are not yet accurately described owing to data sparsity, but have been simulated by several authors (e.g., Lagouvardos et al. 1999; Pyhartaous et al. 2000; Reale and Atlas 2001). Homar et al. (2002) have numerically investigated the role of the precursor upper-level cold disturbances and air–sea interaction processes in inducing conditions favorable to the development of medicanes. Finally, it must be noted that not all systems classified as medicanes show hurricane-like structures, so the matter needs to be settled via systematic studies.

The two extreme events will be first simulated using WRF version 2.2 implemented with the microphysical configuration scheme proposed by Thompson et al. (2004) and the Kain (2004) cumulus parameterization.

b. Rainfall retrievals

The WRF modeling results, which effectively simulate the storm dynamics, are compared with satellite-derived rainfall products. Several studies (e.g., Staelin 1976; Staelin and Chen 2000; Kongoli et al. 2007) have demonstrated the sensitivity of high-frequency passive microwaves (PMWs) in the water vapor band at 183.31 GHz for the retrieval of rainfall rates. More recent studies (Ferraro et al. 2000, 2005; Noh et al. 2006) went further by applying these frequencies to the detection of snowflakes in frozen clouds, and Shige et al. (2009) have used them in a global estimation algorithm showing good skills at high latitudes where normally other algorithms based on lower frequencies fail. The reader is referred to Levizzani et al. (2007) for a review of the basic principles of satellite precipitation estimation methods.

The Advanced Microwave Sounding Unit-B (AMSU-B) on board the National Oceanic and Atmospheric Administration polar-orbiting satellites is a PMW sensor based on the high frequency and high spatial resolution module of the AMSU instrument. It is a cross-track scanning instrument covering the sounding range angles ±48.5° with a nominal field of view of 1.1° (~15 km at nadir) (Saunders et al. 1995). It has five spectral channels: 89, 150, 183.31 ± 1, 183.31 ± 3, and 183.31 ± 7 GHz. The first two channels are centered within two atmospheric windows, particularly suited for surface emissivity studies and cloud ice particle detection. As documented by several authors (e.g., recently by Bennartz and Bauer 2003), the radiation at 89 GHz is strongly absorbed by cloud liquid water whereas the signal at 150 GHz is markedly affected by the presence of ice particles. Since the brightness temperature (\(T_B\)) depression at 150 GHz is mainly due to the amount of growing ice particles within convective clouds, scattering index approaches are adopted to estimate
the probability associated to the surface rain intensities (Bennartz et al. 2002; Laviola 2006). Scattering index methods at higher frequencies dwell on the value of the $T_B$ difference between 89 and 150 GHz ($\Delta \text{win} = T_{B89} - T_{B150}$) to define precipitation intensity classes and classify surface rain into a number of categories. The other three AMSU-B channels are selected within the water vapor absorption band at 183.31 GHz and are dedicated to the profiling of the atmospheric water vapor. From the physical point of view, algorithms based on the absorption–emission processes of radiation at 183.31 GHz can be devised. Rainfall estimation through emission is in this case based on Kirchhoff’s law. However, note that when large ice particles coexist with liquid drops in cold clouds the scattering processes become dominant especially around 190 GHz, where also surface effects (i.e., snow cover over the mountains, surface roughness, etc.) can play an important role. In such situations, the retrieval quality may be similar to that of the scattering index algorithms, which generally sense only more intense precipitation associated with frozen hydrometeors.

The present work concentrates on a first assessment of the capabilities of the two selected approaches in the description of the two case studies. Sensitivities to the different precipitation types and amounts will be explored via a statistical analysis based on various rain intensity categories. Finally, the WRF-simulated and the satellite-retrieved rain products will be compared to surface observations when precipitation measurements over land are available. Section 2 describes the analysis methods while section 3 is dedicated to the analysis of the two case studies. A discussion is presented in section 4.

2. Methods of analysis

The 183-WSL algorithm is a satellite-based rainfall retrieval technique. The rainfall intensity (in mm h$^{-1}$) is deduced from the signal perturbation toward the satellite and is thus an indirect appraisal of the physical quantity. However, the rain fields are accurately delineated through delimiting precipitating clouds and discriminating high and low intensity areas. The WRF parameterization and simulations are also evaluated and the model results are used to explore the extreme events in “controlled” conditions.

a. The 183-WSL retrieval algorithm

The 183-WSL algorithm (Laviola and Levizzani 2008, 2009, 2011) is a PMW fast rainfall retrieval method, which infers rain rates on the basis of a linear combination of the AMSU-B $T_B$ values of the opaque channels at 183.31 GHz. A multiple regression analysis between the $T_B$ values in the three 183.31-GHz bands of the AMSU-B and radar-derived rainfall rates convolved at the same satellite spatial resolution were employed to calculate the retrieval equations. On the basis of the signal perturbation in the resonant water vapor absorption band at 183.31 GHz measured by the AMSU-B sensor, the 183-WSL algorithm package retrieves a wide range of cloud parameters, such as cloud liquid water and cloud droplet amounts, classifies
rain type, and estimates rain rates. Additionally, the delineation of the snow-covered areas is being implemented by means of a built-in snow cover mask. The 183-WSL method evaluates rainfall rates by classifying precipitation as convective and stratiform.

The 183-WSL algorithm is divided in four main steps: 1) data ingestion and preprocessing, 2) land/sea and water vapor/snow cover filters, 3) convective/stratiform rain discrimination, and 4) final rain intensity retrieval. The reader is referred to Laviola and Levizzani (2011) for details on the algorithm working principles.

The discrimination between rain and no-rain regions is fully entrusted to the threshold $\Delta_{\text{win}}$, which acts as a filter for nonprecipitating droplets on the basis of their attitude to extinguish radiation at 89 and 150 GHz. This threshold exploits the absorption-and-scattering effects due to the presence of large rain drops and growing ice crystals in the observed region. As demonstrated by Laviola (2006), large amounts of liquid water in the observed nonprecipitating clouds could drastically affect the signal at 89 GHz over the open sea surface and consequently the $\Delta_{\text{win}}$ could be contaminated. To mitigate this effect, two different threshold values are computed. Over land it is found that, when $\Delta_{\text{win}} < 3$ K, the observed pixels belong to no-rain areas and are therefore removed from the computation. Over open water, where the impact of atmospheric parameters is greater than over land, the previous threshold is reduced to 0 K.

The $\Delta_{\text{win}}$ is also applied to differentiate stratiform and convective rain. The strong scattering by growing ice hydrometeors, which typically characterize convective cell formations, induces a clear signature at 150 GHz by depressing the $T_B$ values by several tens of kelvin with respect to what happens at 89 GHz; these different sensitivities to the presence of ice are thus exploited to calculate a threshold value. Generally, pixels with $\Delta_{\text{win}} < 10$ K are associated with stratiform precipitation whereas higher values are correlated to the more scattering convective cells. Due to the presence of ice mostly concentrated into the cloud cores, the borders of precipitating clouds appear somewhat “warmer” and are thus recognized as stratiform rain. Nevertheless, the signal coming from such regions, especially when located within the first atmospheric cold layers, could be equally due to the formation and accretion of snowflakes. Studies are being conducted, and a snowfall detection module is currently being designed.

b. The numerical model WRF

The numerical system used for this study is the Advanced Research WRF (ARW-WRF), version 2.2 (Skamarock et al. 2005; Michalakes et al. 2004; more information is available online at http://www.wrf-model.org), which is a mesoscale numerical weather prediction (NWP) model for operational forecasting and atmospheric research needs.

The simulations are carried out using a two-way nesting technique; two grid domains, the outer with a horizontal resolution of 16 km and the inner of 4 km, are nested to adequately describe the targeted phenomena. In both cases, that mostly generated and developed in the Central and Western Mediterranean basins, a larger external domain (G1a in Fig. 1) including the Atlantic area is applied to better describe the genesis and the development of the pressure minimum responsible for the heavy rain episodes in southern Italy. The inner grid covers southern Italy and the immediate surrounding areas where the precipitating systems were more vigorous (see G2a box in Fig. 1). The other two boxes, G1b and G2b in Fig. 1, are used to study local convection cases (not discussed in the present paper), mainly influenced by the orography, which require a finer grid mesh. In the present study, only the outer grid output fields will be considered, in order to compare model and satellite products having similar resolution.

Since the model is developed having research and experimentation in mind, different parameterization schemes are available for microphysics, convection, turbulence, soil
processes, boundary layer, and radiation. In the model configurations used here the following parameterizations were selected: 1) the Thompson et al. (2004) microphysics module, which includes six classes of moisture species plus ice-phase and mixed-phase processes resulting from the interaction of ice (graupel or hail) and water particles; 2) the Kain–Fritsch cumulus parameterization (Kain 2004, on the coarser grid; no parameterization is used on the inner finer grids); 3) the Rapid Radiative Transfer Model (RRTM) for longwave radiation (Mlawer et al. 1997); 4) the Dudhia (1989) scheme for the shortwave radiation; 5) the Yonsei University (YSU) scheme for the boundary layer (Hong and Pan 1996); 6) the surface layer parameterization based on the stability functions of Paulson (1970), Dyer and Hicks (1970), and Webb (1970); and 7) a five-layer thermal diffusion soil scheme (Skamarock et al. 2005).

3. Synoptic analysis and rainfall retrieval

The two case studies need to be analyzed in some detail, being radically different as to precipitation genesis and rain type. The first case is a seasonal MCS, which usually develops from a local instability over Africa and propagates toward Europe, becoming progressively more vigorous over the Mediterranean Sea where the warm sea surface enhances the evaporation rate. The event is particularly interesting as a sensitivity test bed both for the

---

1 As the absence of the Kain–Fritsch scheme in the inner grid (at 4-km resolution) might affect the possibility to adequately resolve deep convection, additional experiments with the convective parameterization scheme active on both grids were performed. Model results were found worse than (first case study, 2004) or comparable to (second case study, 2006) those obtained with explicit convection on the inner grid in terms of the mean sea level pressure minimum and the precipitation fields.
FIG. 4. (a) MSG-RGB cloud characterization method, (b) AMSU-B $T_{B150}$ (K), and (c) $T_{B184}$ (K) for 13–14 Nov 2004. (d),(g),(j) The 183-WSL pixel-type product for convective (red) and stratiform (yellow) precipitation, cloud droplets (cyan) and liquid water (blue) clouds, snow cover (light green), and snowfall (dark green); (e),(h),(k) the 183-WSL rainfall retrieval (mm h$^{-1}$); and (f),(i),(l) the WRF (external grid) rainfall simulation (mm h$^{-1}$). (m)–(o) The WRF simulation products (mm h$^{-1}$) filtered above a 1 mm h$^{-1}$ threshold.
183-WSL algorithm and for the WRF to describe an intense phenomenon and possibly recognize its inherent multicell structure.

The second case study is a comparatively rare event in the Mediterranean area during which a synoptic-scale cyclone formed over the Tyrrhenian and a mesocyclone acquired tropical-like features over the Adriatic Sea, and “symbiotically” rotated. The smaller of the two (the one over the Adriatic), though the more disastrous, revolved anticlockwise around the borders of the larger synoptic cyclone.

**a. 12–14 November 2004: Mesoscale convective system over southern Italy**

The MCSs are commonly classified as deep and localized thunderstorms with massive convective cloud decks and strong winds developing over a very short time scale (Zipser 1982) and being maintained for a long time (e.g., Maddox 1983; Laing and Fritsch 2000). The precipitation areas last several hours and consist of a series of convective showers mixed with and surrounded by large stratiform systems. The phenomenon discussed in this case study developed from a wide cyclogenesis originated in the lee of the Atlas Mountains where a shallow low-level vortex built up (Horvath et al. 2006) and started moving toward the Central Mediterranean basin, as can be observed in the surface and upper-level analyses of the European Centre for Medium-Range Weather Forecasts (ECMWF) in Fig. 2. On 12 and 13 November the cyclone moved northeastward while deepening. The ECMWF analysis shows an upper-level trough over northern Africa, originated 12 h before. The position and persistence of the low pressure system gave origin to intense south-easterly flows advecting warm and moist air over the Ionian Sea basin and southern Italy. The low-level advection of humidity supported an intense convective activity, which was responsible for the heavy rains over the area. The synoptic analysis as shown in Figs. 2a,b shows the progression of the deep depression initially located over the Western Mediterranean and successively “slipped” over the Central Mediterranean where the cyclone achieved a pressure value at the center of ~998 hPa. Conversely, a deep trough extended at upper levels over the Mediterranean and the western European sector. The persistence of the cyclonic circulation over the Mediterranean dragged warm and humid air over southern Italy, contributing to generate conditional instability over the Ionian Sea. Consequently, intense convection developed producing local intense rainfall. Then the pressure minimum moved toward southern Italy with values around 992 hPa at 1200 UTC 14 November (Fig. 2c).

Satellite retrievals and model simulations are discussed only for the days characterized by more intense precipitation on the basis of the surface rainfall measurements on 12, 13, and 14 November (Fig. 3). The 24-h accumulated rainfall value in the center of the Salento Peninsula is around 200 mm during the central day of the event, eventually decreasing to a minimum of 42 mm at the end of the last day. This trend agrees with the ECMWF pressure analysis of the cyclonic circulation on 12 and 13 November, which advects warm and moist air over southern Apulia, thus supporting the development of deep convection and the consequent production of heavy precipitation.

Figure 4 shows the satellite retrievals and the WRF model simulations. From the satellite point of view, the cyclonic vortex at 0950 UTC 13 November appears well structured and is rotating around the pressure minimum located over the African coastline. The observational analysis from the Meteosat Second Generation (MSG) red-green-blue (RGB) method (Zwatz-Meise and Kerkmann 2006) based on the Spinning Enhanced Visible and Infrared Imager (SEVIRI) imagery (Fig. 4a) and from AMSU-B $T_{B_{150}}$ (Fig. 4b) and $T_{B_{184}}$ (Fig. 4c) reveals the presence of two simultaneous factors that contribute to strengthening the system. The interaction of the cold air from the Balkans with the warm and moist current from Africa drastically amplified the exchange of condensation latent heat, remarkably increasing the vigor of the convection. In such conditions of pronounced instability the local orography, although not too steep, reinforced the air lifting. The PMW soundings show a cold front from the north, presumably located in the first kilometers of the atmosphere, where low intensity scattering from frozen hydrometeors aloft depressed $T_B$ values by ~40 K. At the same time, over the Mediterranean the convective towers considerably deepened within the cyclogenesis. Although the optical analysis qualitatively classifies this region as cold clouds, the PMW observations highlight the inner structure of the system showing only precipitating cores clustered into more scattering clouds. Noteworthy, the 184-GHz frequency, which generally senses water vapor at high levels, shows only the presence of the isolated system over the Apulia region that developed up to the tropopause and was responsible of the intense precipitation measured by the gauges.

A PMW-derived cloud scene classification and the precipitation fields are then retrieved from the 183-WSL algorithm and simulated by the WRF (Figs. 4d–f) for the same AMSU-B overpass at 0950 UTC 13 November. A first comparison shows good agreement of the two results, especially for the southern system where both shape and location of the system are reasonably well detected. On the contrary, the cold front from the north is not well reproduced by the model; cold clouds appear shifted southward with respect to the satellite imagery and the simulated rainfall intensities are lower than the corresponding satellite retrievals. In agreement with the
synoptic and local analysis both the 183-WSL and WRF identify more intense rains close to the Apulia region where the 24-h maximum rainfall value and the minimum pressure level were measured. Nevertheless, although both methods identify rainfall from developed convection (over Sicily or in correspondence of the convective cluster over the African coast), which typically brings heavy precipitation, WRF seems to underestimate rain intensity values in the cases of moderate rainfall. However, a rigorous assessment of these conclusions would require an extensive radar or rain gauge validating dataset. Hereafter only an attempt is made to verify the results using the satellite and the model results on one side and then comparing them with the available gauge data.

The relative frequency analysis distributions of the retrieved/forecasted rainfall values over the two days is shown in Fig. 5 adopting five intensity classes: 1) 0.1–1, 2) 1–3, 3) 3–5, 4) 5–10, and 5) 10–20 mm h\(^{-1}\). The analysis indicates that almost 80% of the computed rainfall from the model falls into the first two classes. This fact induces a marked bias on the modeled precipitation and is probably directly responsible for the general underestimation registered in both case studies. The underestimation of strong precipitation intensity and the tendency to diffuse the precipitation patterns spatially is a known problem of the meteorological models (Vasić et al. 2007), which can be considered mainly a consequence of the numerical diffusion (Tartaglione et al. 2002). The same analysis for the 183-WSL algorithm results shows that the low-intensity class 1 is less populated while the result for class 2 is well in agreement with the WRF value. As to the other three intensity classes (rain rates >3 mm h\(^{-1}\)), modeled rain distributions are significantly constrained under the 10% threshold whereas the 183-WSL continues to show a high sensitivity to different precipitation intensities up to the top of the scale (20 mm h\(^{-1}\)) where the percentages naturally decrease.

These considerations seem to be further supported by Fig. 6a in which the histogram distributions per each class relative to 0950 UTC 13 November 2004 are reported. The values confirm the substantial disagreement between satellite and model. This latter once more appears to aggregate the simulated rain rates mostly into the first two intensity classes. Additionally, the modeled rainfall follows a rapid percentage decrease from lower to higher rain values reflecting a progressively lower sensitivity to capturing moderate rainfall >10 mm h\(^{-1}\). On the other hand, the satellite retrieval is approximated by a normal distribution function with modal value between classes 2 and 3, and its capability to detect different precipitation classes is maintained up to the maximum value of 20 mm h\(^{-1}\).

All of the above considerations can be repeated to discuss the last part of the cyclone life cycle on 14 November when the system started losing energy and eventually reached the final stage of dissipation. By comparing retrievals and model forecasts in Figs. 4g–i (0145 UTC 14 November) and Figs. 4j–l (0535 UTC 14 November) a noticeable difference between satellite and model rain intensities is detected. While the satellite products adapt to rapid precipitation changes, the model keeps almost unaltered the main structure of the systems, which seemingly do not adapt to the quick evolution of new convective cells and, at the same time, the dissipation of the old ones. An example stems from the 183-WSL images where the cloud system A1 is missing altogether in the WRF simulations (Figs. 4i,l). This inability can be partially attributed to the fact that the system is not completely within the model domain, as it moves near the northwestern border of the external grid.
In this position (see the area flagged with P1 in Fig. 4g) the 183-WSL computational scheme discriminates between convective and stratiform rain, snowfall, and cloud droplets. On the contrary, close to the Alps the model simulates an elongated rain system (W1) with precipitation intensities less than 1 mm h\(^{-1}\) while the 183-WSL retrieves a cloudy but nonrainy area (cf. images in Figs. 4g,j). In the same position, snow cover pixels are also retrieved by the 183-WSL. In Figs. 4h and 5k the black arrows point to the asymmetric organization of the convective line, which generally appears during the mature stage of a midlatitude MCS (Houze 1993). The mature stage of mesoscale precipitation is structured in a quasi-symmetric-aligned group of convective cells where each core, more easily identified during the previous intensifying stage, dissolves and forms a large stratiform region with lower rain intensities. The analysis of the images in Fig. 4 contributes to clarify this concept. Convective cores in which precipitation intensities attain almost 20 mm h\(^{-1}\) are surrounded by a smoothed rainy area classified as stratiform (intensities less than 5 mm h\(^{-1}\)) and by a large region of cloud droplets probably generated from the convective cloud dissipation (see Figs. 4g,j).

Finally, the spatial extent of the WRF-simulated rainfall areas is larger than that of the satellite-retrieved ones. For example, considering the cloud system approaching southwestern Sicily (Figs. 4h,k) one can observe how the model output amplifies the rain area by locating a very low rain intensity region on the border of the cloud system. Analogous considerations can be extended to all other precipitating situations. To possibly mitigate the observed enhancement effect of low-rain-rate spatial extent, which is crucial both for satellite and for numerical approaches, it is important to quantify the displacement between the WRF rainy regions and those classified by the 183-WSL as no rain. The outcome of such an investigation quantifies the disparity at ~1 mm h\(^{-1}\). After the application of a 1 mm h\(^{-1}\) threshold the comparison of the filtered numerical simulation in Figs. 4m–o with the corresponding satellite products in Figs. 4e,h,k shows an improved overlapping in these areas while the other rain areas simultaneously seen by the satellite and the model are more or less unchanged.

Up to this point only a comparison between the rainfall rates retrieved by the 183-WSL satellite method and the WRF simulations was presented. The different performances of the two retrievals does not necessarily suggest that one outperforms the other, although a general skill of the satellite method in delineating rain areas is to be noted. Figure 7 shows a comparison between the satellite retrieval, the WRF simulation, and the rain rates measured by the Apulia region gauge network (33 stations) at five different times corresponding to AMSU-B overpasses in the area. The values refer to averages over the entire area covered by the gauge network, that is, more or less the entire Apulia region; see also Fig. 3. The first feature to be noted is the large difference between the 183-WSL retrievals in the stratiform and the convective case. Moreover, the convective rainfall intensities are 2–3 times higher than the corresponding values measured by the pluviometers at the 15–30-min accumulation
interval, while the stratiform values are very close to those of the pluviometers. This fact is mostly due to the different radiative response of the two cloud types, stratiform and convective. In the convective case the ice at cloud top scatters radiation much more than in the stratiform case where the ice quantity is considerably lower. Thus, in the convective areas a $TB_{150}$ depression is registered, which induces an increase of the $D_{\text{win}}$ parameter. The algorithm in this case works more like a scattering-based algorithm and the rainfall estimate is more indirect because it is based on the assumption of melting of cloud ice into rain drops. Conversely, in the stratiform portion of the clouds, where the absorption processes play a larger role in the extinction of radiation, the $D_{\text{win}}$ balance is normally confined within $\sim 10$ K and the algorithm estimates rainfall in a more direct way, being sensitive to the emission of radiation from liquid hydrometeors. Note that, however, this comparison with the Apulian pluviometers does not represent a validation of the method, which is now under way using the Nimrod radar data network over northwestern Europe.

b. 26 September 2006: Medicane over southeastern Italy

A subsynoptic-scale vortex originated after orographic cyclogenesis in the lee of the Atlas Mountains and approached the Mediterranean central basin on 26 September 2006, meanwhile generating a complex twin structure located between the Adriatic and Tyrrenhian Seas, the first one with structure and mesoscale features typical of tropical cyclones. In correspondence with the maximum intensity of the cyclogenesis, polar-low-like pressures were measured over southeastern Italy. The system can be classified as hurricane-like and is named medicane. In Fig. 8 the position of the 500-hPa geopotential and pressure values at sea level can be spotted. At 0000 UTC (left panel) the synoptic analysis reveals the presence of a cyclonic circulation over the Tyrrenhian Sea with a minimum pressure of 1004 hPa close to the central Italy coastlines (C1 hereafter). At the same time, a small-scale depression of $\sim 1006$ hPa over the Ionian Sea (C2 hereafter) is registered. These synoptic conditions are already a prelude to the situation described in the second map in Fig. 8 where the surface pressure analysis at 1200 UTC discloses the presence of two marked depressions. A sudden deepening of the C2 minimum evolves into a wide rotating structure with the eye centered over the southern Adriatic Sea and in turn revolving anticlockwise around the larger-scale cyclone C1. The cumulated 1-h rain gauge measurements at two different times of the event are presented in Fig. 9.

The complex situation is monitored from satellite as shown in Fig. 10. The MSG-RGB cloud characterization method identifies the eyes of the twin cyclones and the compact and cold structure spread over Apulia. From a combined analysis of the AMSU-B $TB_{150}$ (Fig. 10b) and $TB_{186}$ (Fig. 10c) two features emerge. First, the cold clouds retrieved by the MSG-RGB method are constrained to the first 6 km. This is confirmed by the 186-GHz image characterized by a weighting function peaking around that altitude. Moreover, the absorption features of the water vapor at the top of the system, which contribute to enhance the medicane motion, appear as a “cold” area ($TB < 240$ K) over a warmer background where $TB \approx 255$ K on the average. Additionally, scattering effects of the deeper cores approaching Apulia are detected. By the same token, at 184 GHz (not shown), where the weighting function usually extends higher up to 8 km, no trace of the latter is found. Second, more scattering clouds, responsible for the early morning heavy precipitation, persist over...
Apulia where rain intensity >30 mm is cumulated over 1 h (Fig. 9). Considering the signal attenuation of ~70 K at 150 GHz, and with the support of the observational study by Moscatello et al. (2008b), it is possible to conclude that in the cloud associated with the maximum rain intensity a large amount of frozen hydrometeors (millimeter-size ice crystals) were forming and accreting aloft within the precipitating cells. To corroborate such a finding and to quantify rainfall rates a simultaneous examination is deemed necessary of the cumulated 1-h rain gauge measurements in Fig. 9 and of the satellite-retrieved and WRF-simulated rainfall rates in Fig. 10. A clear similarity of satellite–model precipitation and surface rain distribution is evident, in particular for the location where the maximum intensities were measured. Isolines of maximum precipitation from the model (not shown) progress from north to south in agreement with the anticlockwise cyclonic circulation from northeast to north. Similarly, the satellite and model effectively collocate more intense precipitating areas, where rain rates around 20 mm h⁻¹ are retrieved, in correspondence with the measured high rainfall values. Some differences in the location of precipitation simulated by WRF can be partially ascribed to the fact that the model anticipates the evolution of the cyclone by a couple of hours (Moscatello et al. 2008a).

By comparing satellite and numerical model results and on the basis of the driving concepts applied to the analysis of the previous case study, the correspondence between the two methods is found by dividing rainfall intensity into classes and determining the relative frequencies per each class. Figure 11 describes a histogram distribution very similar to that discussed for the MCS case study; rain intensities from the numerical model are constrained to the first two classes with rainfall amounts <3 mm h⁻¹. On the contrary, higher intensity classes are less populated, as seen in Fig. 10f where the WRF model retrieves some “black spots” (in terms of the adopted lookup table) with a rain intensity value >20 mm h⁻¹. Except for class 2 (1–3 mm h⁻¹) relative to the satellite overpass at 0445 UTC when the algorithm and model
FIG. 10. Coupled depression (C1 and C2) over southern Italy on 26 Sep 2006: (a) MSG-RGB cloud characterization method, (b) AMSU-B $T_{B1850}$ (K), and (c) $T_{B186}$ (K). Two cyclone eyes are detected together with the revolving trajectory of C2 around the borders of C1. At the same time the PMW channels distinguish more scattering regions, typically associated with large ice crystals on top of clouds and heavy precipitation, from the more absorbing ones, which can be correlated to light rainfall or water vapor absorption. In particular, a strong scattering area over Apulia and absorption by the water vapor surrounding the cyclones are spotted. (d),(g) The 183-WSL pixel-type product (see color legend in Fig. 4); (e),(h) the 183-WSL rainfall retrieval (mm h$^{-1}$); and the (f),(i) WRF rainfall simulation (mm h$^{-1}$). The 183-WSL pixel characterization shows an isolated system rotating over southeastern Italy. An intrusion of cloud droplets and low-layer water vapor seems to reinforce the cyclone C2 from the southwest. The red dashed lines mark the satellite orbital path. Over the Apulia region, a few pixels are misclassified as snow cover (light green). (j),(k) The WRF simulation products (mm h$^{-1}$) filtered above a 1 mm h$^{-1}$ threshold.
converge around a 20% relative frequency, all other 183-WSL rain values are widely distributed among the various classes. This seems to suggest that the dynamic performances of the 183-WSL are higher than WRF’s and, consequently, the algorithm is efficient in categorizing the different rain types. Note, however, that in this case a similar behavior is found between the model and the satellite retrieval algorithm for class 2.

The rainfall retrieval results evidence a different behavior of the satellite and of the model in distributing rainfall intensity across the whole intensity range. Usually extreme phenomena such as those described in this work show a wide range of rainfall intensities typically distributed among coexisting stratiform and convective rain clusters. Therefore, precipitation intensities from a few to many tens of millimeters per hour are generally retrieved. On this ground, the relative frequency analysis based on five intensity rain classes reveals that precipitation rates as retrieved by the 183-WSL algorithm seem to better describe the rainfall distribution by spreading the precipitation amount over several intensity values. This reflects the

![Relative frequency histograms for the five rain intensity classes as in Fig. 6 at (top) 0445 UTC and (bottom) 0930 UTC 26 Sep 2006. The histograms describe a situation where the numerical model is drastically biased toward the first two classes as for the other case study (see Fig. 7). Correspondingly, the 183-WSL rain rates are well distributed reflecting a higher sensitivity to discern different rain types. Note, however, that in this case a similar behavior is found between the model and the satellite retrieval algorithm for class 2.](image)

**Fig. 11.** Relative frequency histograms for the five rain intensity classes as in Fig. 6 at (top) 0445 UTC and (bottom) 0930 UTC 26 Sep 2006. The histograms describe a situation where the numerical model is drastically biased toward the first two classes as for the other case study (see Fig. 7). Correspondingly, the 183-WSL rain rates are well distributed reflecting a higher sensitivity to discern different rain types. Note, however, that in this case a similar behavior is found between the model and the satellite retrieval algorithm for class 2.

4. Summary

The simulations of the WRF were compared with PMW satellite observations and precipitation retrievals using the 183-WSL algorithm. Two heavy rainfall events over the Central Mediterranean were selected, rather different as to genesis, evolution, and amount of rain over land. Surface rainfall measurements and satellite image interpretation further support the analysis.

The first result of the analysis consists in demonstrating the capabilities of the satellite sensing and the model in localizing the precipitating areas and possibly describe the precipitating system evolution. The analysis is also supported by the multifrequency MSG RGB investigations used to characterize the cloud types and discriminate the precipitating sectors. The two case studies were instrumental to better understand the initial instability conditions generating the extensive cloud systems over the area. PMW observations in the AMSU-B frequency range have surely helped the preliminary exploration based on Meteosat SEVIRI visible and infrared wavelengths by adding information about rain/no-rain clouds, rain top height, and phase of hydrometeors aloft.

The rainfall retrieval results evidence a different behavior of the satellite and of the model in distributing rainfall intensity across the whole intensity range. Usually extreme phenomena such as those described in this work show a wide range of rainfall intensities typically distributed among coexisting stratiform and convective rain clusters. Therefore, precipitation intensities from a few to many tens of millimeters per hour are generally retrieved. On this ground, the relative frequency analysis based on five intensity rain classes reveals that precipitation rates as retrieved by the 183-WSL algorithm seem to better describe the rainfall distribution by spreading the precipitation amount over several intensity values. This reflects the
sensitivity of the algorithm to a wide range of rainfall intensities. On the contrary, the frequency distribution of the WRF-simulated rainfall shows a large bias concentrated on very low rain rates (about 50%–60% of rainy pixels are placed below 1 mm h\(^{-1}\)) thus drastically under-populating moderate and high rain intensity classes, probably a consequence of the numerical diffusion present in the models. In these classes, which span from 3 to 10 mm h\(^{-1}\), the WRF simulations are not well represented except for values around 3 mm h\(^{-1}\), where an agreement with the satellite retrieval is found. Finally, for rain rates >10 mm h\(^{-1}\) (a scarcely populated class) both the 183-WSL and WRF produce similar precipitation amounts.

An average discrepancy value between the satellite retrievals and the WRF simulation is quantified in 1–2 mm h\(^{-1}\) by considering all precipitation classes. The rough implementation of a threshold of 1 mm h\(^{-1}\) in the WRF computational chain positively smoothes the low rain intensity peaks while preserving the general distribution of the simulated precipitation. These results coupled with considerations from the 183-WSL cloud type characterization indicate that the model scheme used in the analysis classifies as low-intensity rain rates the cloud regions surrounding the precipitating clouds that are generally classified as cloudy, but nonprecipitating by the 183-WSL.

Finally, an evaluation of the 183-WSL estimations by means of the rain gauges was conducted, revealing, as expected, large difference between the 183-WSL stratiform and convective retrievals. When the algorithm estimates convective precipitation, it works like a scattering-based algorithm, while in the stratiform portion of the clouds, it estimates rainfall in a much more direct way using the emission of radiation from liquid hydrometeors. However, the present comparison is by no means a validation of the method, which is now under way using the Nimrod radar data network over northwestern Europe.

**Acknowledgments.** Support is gratefully acknowledged by EUMETSAT’s Satellite Application Facility on Support to Operational Hydrology and Water Management, by the Progetto Strategico “Nowcasting avanzato con l’uso di tecnologie GRID e GIS” of Regione Puglia, and by the project “Prodotti di Osservazione Satellitare per Allerta Meteorologica” (PROSA) of the Agenzia Spaziale Italiana (ASI). AMSU-B data were made available by the NOAA Comprehensive Array-Data Stewardship System (CLASS; see online at http://www.class.ngdc.noaa.gov/saa/) and Meteosat imagery was provided and copyrighted by EUMETSAT. Surface and upper-air analyses were produced by ECMWF. NCAR is acknowledged for the ARW-WRF code and is sponsored by the National Science Foundation.

**REFERENCES**


Mediterranean Storms, Mallorca, Spain, Universitat de Illes Balears.