Synergy of ground-based weather radar and geostationary satellite observations for extending rain rate estimation beyond radar coverage

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1 Introduction

Microwave weather radars are considered a fairly established technique for retrieving rain rate fields over large areas. However, the spatial coverage of these instruments is usually limited to land and coastal regions. Here, a method to extend the rain rate estimate beyond the spatial coverage of a weather radar system is proposed, using the synergy with satellite geostationary infrared (GEO-IR) observations. This method builds on the heritage of other methods developed in the last decade to couple GEO-IR with low-resolution and low-repetition rain rate estimates from low-earth-orbit passive microwave (LEO-MW).

Indeed, the accurate retrieval of surface rain intensity (SRI) from spaceborne remote sensing systems on a global scale with high temporal and spatial resolutions is one of the major goals of current scientific research (Kucera, et al., 2013). Satellite-based methodologies offer several advantages with respect to ground-based techniques. The latter, such as rain gauges and radars, generally provide incomplete coverage on a global scale, particularly over the oceans where such instruments are sparse or not existing. On the other hand, presently there is not a single spaceborne platform which carry all the suitable instruments to ensure accurate and high spatial-temporal resolution to the rainfall product. In fact, satellite-based weather radars provide limited spatial and temporal resolution (only two of such a system are currently operational). Conversely, visible (VIS) and infrared (IR) radiometers, which are available on many satellite platforms, do provide high spatial-temporal resolution, but are most sensitive to cloud top layers and not to the rainfall below. On the other hand, microwave (MW) radiometers are sensitive to rain rate, but offer moderate spatial and temporal resolution. Regarding platforms, Geosynchronous Earth Orbit (GEO) satellites ensure a Earth's disk coverage with a high temporal sampling (~5-15 min), while Low Earth Orbit (LEO) satellites provide global coverage but with low temporal sampling (only twice a day in a given place at mid latitude).

Thus, LEO-MW and GEO-IR radiometry are clearly complementary for monitoring a highly variable phenomenon such as precipitation, and indeed this synergy has been largely exploited (Turk et al., 1999; Marzano et al., 2002; Marzano et al., 2004; Mugnai et al., 2013). In particular, the Microwave-Infrared Combined Rainfall Algorithm (MICRA) (Marzano et al., 2004) was developed for combining rain rate estimates based on LEO-MW observations to calibrate GEO-IR measurements. In this paper we build on the MICRA approach to develop a technique that deploys a weather radar network to provide the source of rain rate estimates to calibrate the GEO-IR measurements. The instruments and methods used here are summarized in the following sections.

2 Instruments and Methods

The method proposed here, called MICRAdria, deploys weather radar measurements to provide the source of rain rate estimates to calibrate the GEO-IR measurements. With respect to MICRA, the proposed approach offers few advantages. In fact, ground-based weather radars deliver rain rates more frequently (every few minutes) and with higher resolution (order of hundreds of meters) with respect to LEO-MW. In addition, weather radars offer a more direct measurement of the rain rate, thus resulting in a better source of calibration for GEO-IR. On the other hand, the drawback with respect to MICRA is that the method cannot be applied globally, because the SRI product from a single weather radar is limited to its areal coverage. To partially overcome this limitation, SRI derived from a radar network could be used, as shown later in this paper.

2.1 Ground-based Radar Network

The ground-based weather radars considered here are single- and dual-polarization systems belonging to the network coordinated by the Italian Civil Protection Department (DPC) (Vulpiani et al., 2008). Currently, the radar network is composed by twenty weather radars: ten C-band radars belonging to regional authorities (five of which are polarimetric), two C-band radars owned by Air Traffic Control service (ENAV), and six C-band radars (two of which are polarimetric) plus two X-band polarimetric radars owned directly by the DPC. The DPC collects radar data in near real-time, and processes the radar volumes to produce the so-called radar network composite (RNC) of products, such as surface rain intensity (SRI, mm/h). The SRI product is computed applying the Marshall and Palmer reflectivity-rainfall (Z-R) relationship to the Lowest Beam Map (LBM) product. The latter is the near-ground reflectivity map obtained from the corrected radars volume data using the lowest height reflectivity value in each vertical column. All products are obtained over a grid of 1400 by 1200 km^2 with spatial resolution of ~1 km and temporal resolution of 15 minutes. In this paper we make use of the SRI product, which covers nearly entirely the Italian territory and part of the surrounding seas. An example of the RNC SRI product is shown in Figure 1 for 16:00 UTC of 26 June 2014.

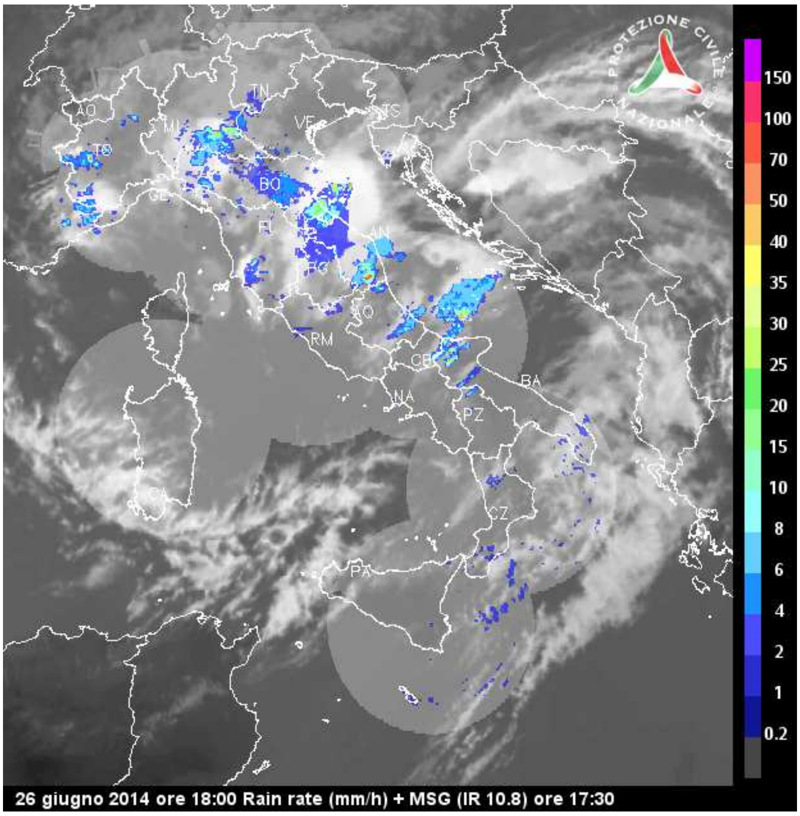

Figure 1: A graphical output of RNC (data courtesy of DPC). The surface rain intensity (SRI) product is color-coded according to the vertical bar (in mm/h) and layered over the Meteosat Second Generation (MSG) 10.8 μm image (in normalized inverted grey scale). Data obtained from RNC at 16:00 UTC and MSG observations at 15:30 UTC on 26 June 2014. Note that the time displayed at the bottom is in CEST (Central Europe Summer Time).

2.2 Satellite Radiometric System

The GEO-IR satellite observations considered here are provided by the Spinning-Enhanced Visible Infrared Imager (SEVIRI) onboard of the Meteosat Second Generation (MSG) geostationary satellite (Schmetz et al., 2002). SEVIRI is the main payload on board the MSG series. SEVIRI is a 50-cm-diameter aperture line-by-line scanning radiometer. It observes the Earth-atmosphere system in 11 channels at full-disk with a spatial sampling of 3 km at the sub-satellite point. In addition, the High Resolution Visible (HRV) channel covers half of the full disk with a 1-km spatial sampling at nadir. SEVIRI delivers images in near-real time at full-disk coverage every 15 minutes. Brightness temperatures (BT) measured by the SEVIRI channels number 7 (wavelength=8.7 μm), 9 (10.8 μm), 10 (12.0 μm), and 11 (13.4 μm) covering the central Mediterranean area are used in the approach proposed here. Figure 2 shows a false-color representation of BT measured by SEVIRI on 26 June 2014 at 16:00 UTC.

2.3 Statistical Integration

MICRAdria consists in a background process and a foreground process. The block diagram of MICRAdria is schematically sketched in Figure 3. During the background process, the latest nearly-simultaneous SRI product from the weather radar network and GEO-IR observations from SEVIRI are spatially colocated. The set of SRI-BT matchups is then used to calibrate a SRI-BT relationship through a statistical integration technique. During the foreground process, the latest established relationship is applied to estimate rain rate from the GEO-IR observations over a larger domain, which goes beyond the actual radar network coverage. In the development phase, two statistical integration techniques have been tested to establish the SRI-BT relationship. The first technique relies on multivariate regression method while the other on multivariate probability matching formulations (Marzano et al., 2004).

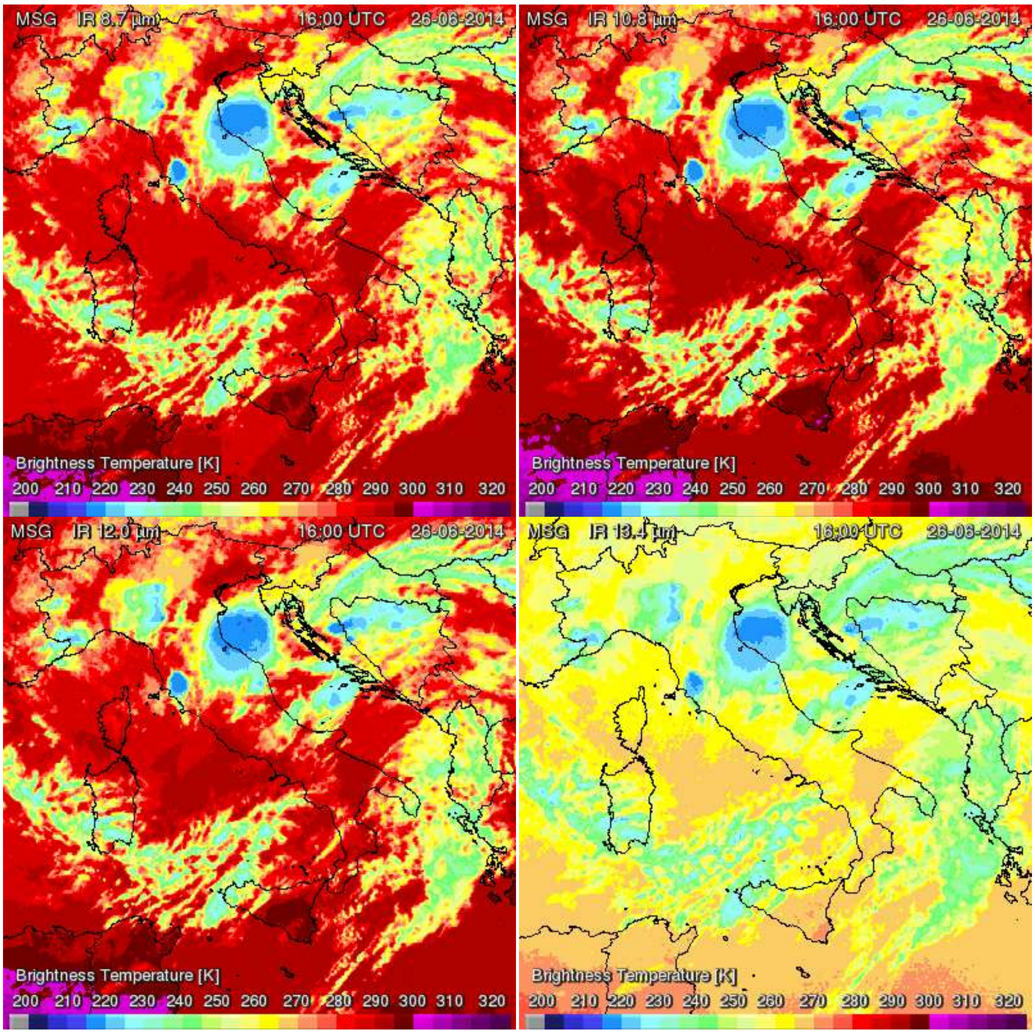

Figure 2: Example of Brightness Temperatures (BT) measured on 26 June 2014 @ 16:00 UTC by the four SEVIRI IR channels considered here. BT is color-coded according to the horizontal bar (in K).

While for multiple regression (MR) we refer to Marzano et al., (2004), for probability matching here we adopt a slightly different version. The basic idea behind this technique is to derive the inverse relationship between measured GEO-IR observations and SRI using the corresponding histograms of the occurrences. If p_{SRI} and p_{BT} are the probability density functions (PDF) of SRI and BT at wavelength λ, respectively, this concept is formalized by the following equality:

$$p_{RR}(SRI)dSRI = p_{BT}(BT_\lambda)dBT_\lambda \qquad (1)$$

where SRI and BT are positive defined. Note that the correlation between SRI and BT is negative. This indicates that higher rain rates are associated to lower IR brightness temperatures due to the increasing cloud opacity and top height. Thus, the Univariate Probability Matching (UPM) can be stated as:

$$\int_{SRI_0}^{SRI} p_{SRI}(SRI)dSRI = \int_{BT_\lambda}^{BT_{\lambda 0}} p_{BT_\lambda}(BT_\lambda)dBT_\lambda = \int_{0}^{BT_{\lambda 0}} p_{BT\lambda}(BT_\lambda)dBT_\lambda - \int_{0}^{BT_\lambda} p_{BT\lambda}(BT_\lambda)dBT_\lambda \qquad (2)$$

where $BT_{\lambda 0}$ is the threshold value corresponding to the minimum detectable SRI_0. The Multivariate Probability Matching (MPM) can be generalized from the UPM by considering multiple channels and the joint cumulative distribution function. However, the MPM inherently implies the ambiguity of the multidimensional integration, leading to the non-uniqueness of the SRI estimator. Therefore, in our implementation, we adopt a trade-off between UPM and MPM, that is a multiple UPM (MUPM). In the MUPM, multiple realizations of the SRI field are computed from the considered GEO-IR channels using an independent UPM for each channel. The resulting SRI field is taken as the average of the multiple SRI realizations. In addition, the standard deviation of the multiple SRI realizations is taken as a measure of SRI confidence: the larger is the number, the less confidence is associated to the resulting SRI field.

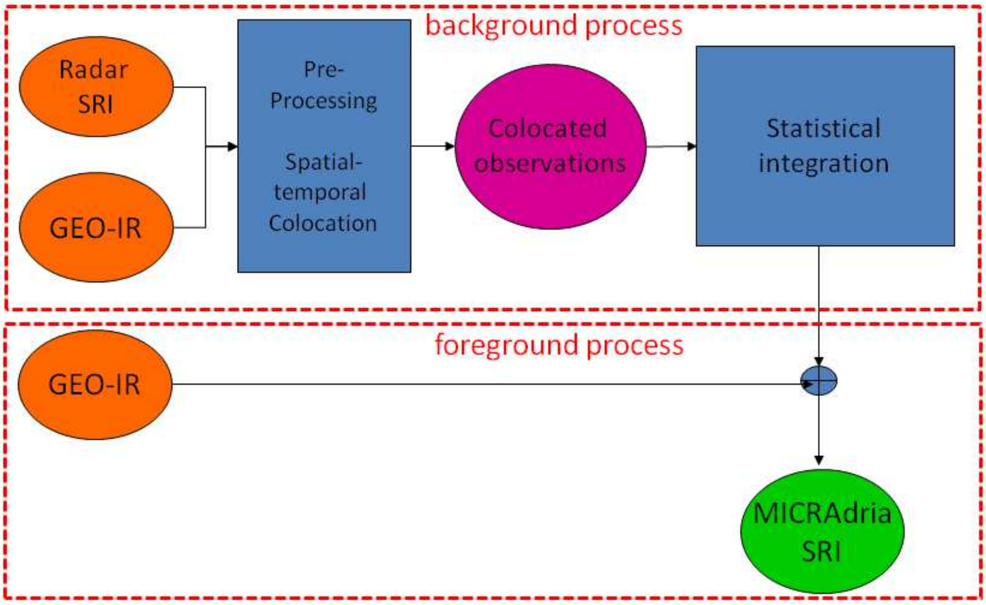

Figure 3: Schematic diagram of the MICRAdria flow-chart.

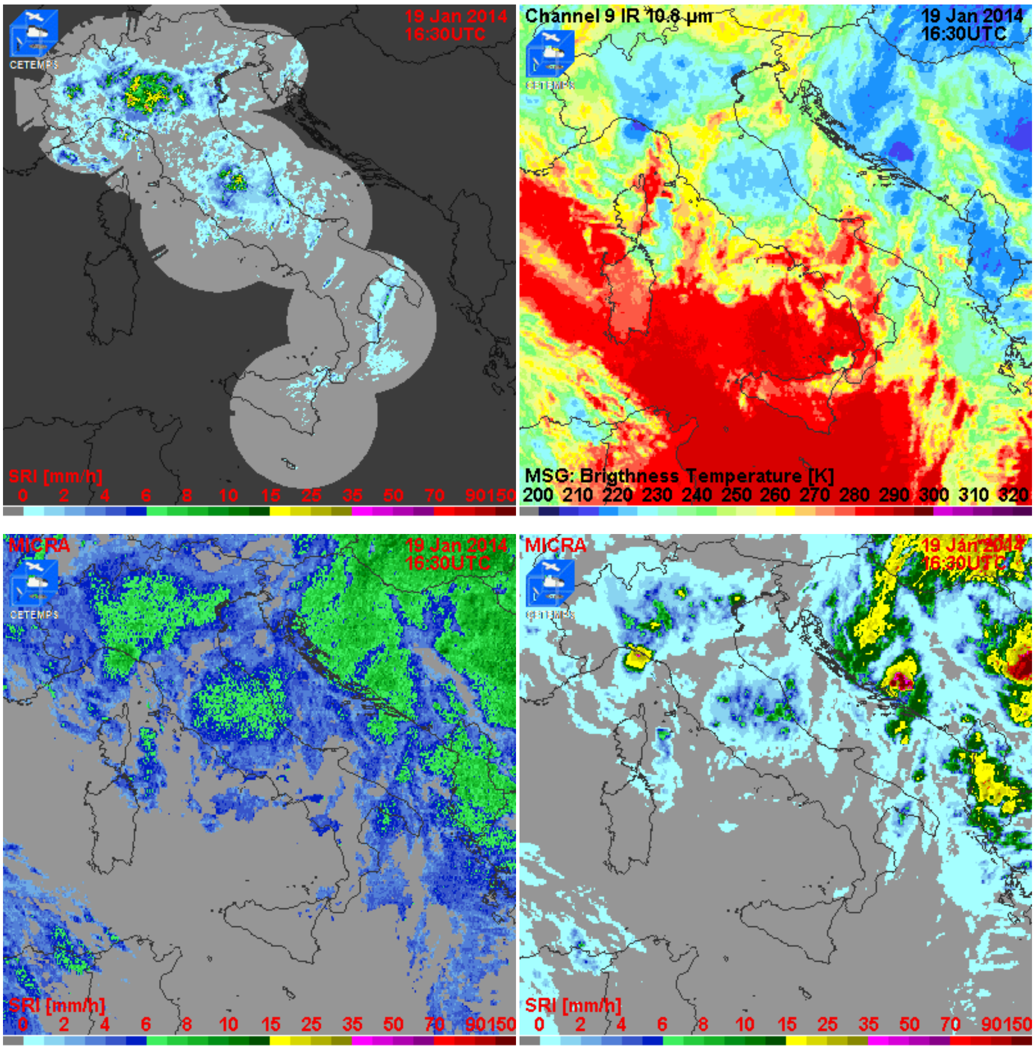

Figure 4: Case of 19 January 2014, 16:30 UTC. Top: SRI product from the RNC (left) and BT by MSG SEVIRI channel 9 (right). Bottom: Output of MICRAdria MR (left) and MUPM (right). The SRI product is color-coded according to the horizontal bar (in mm/h).

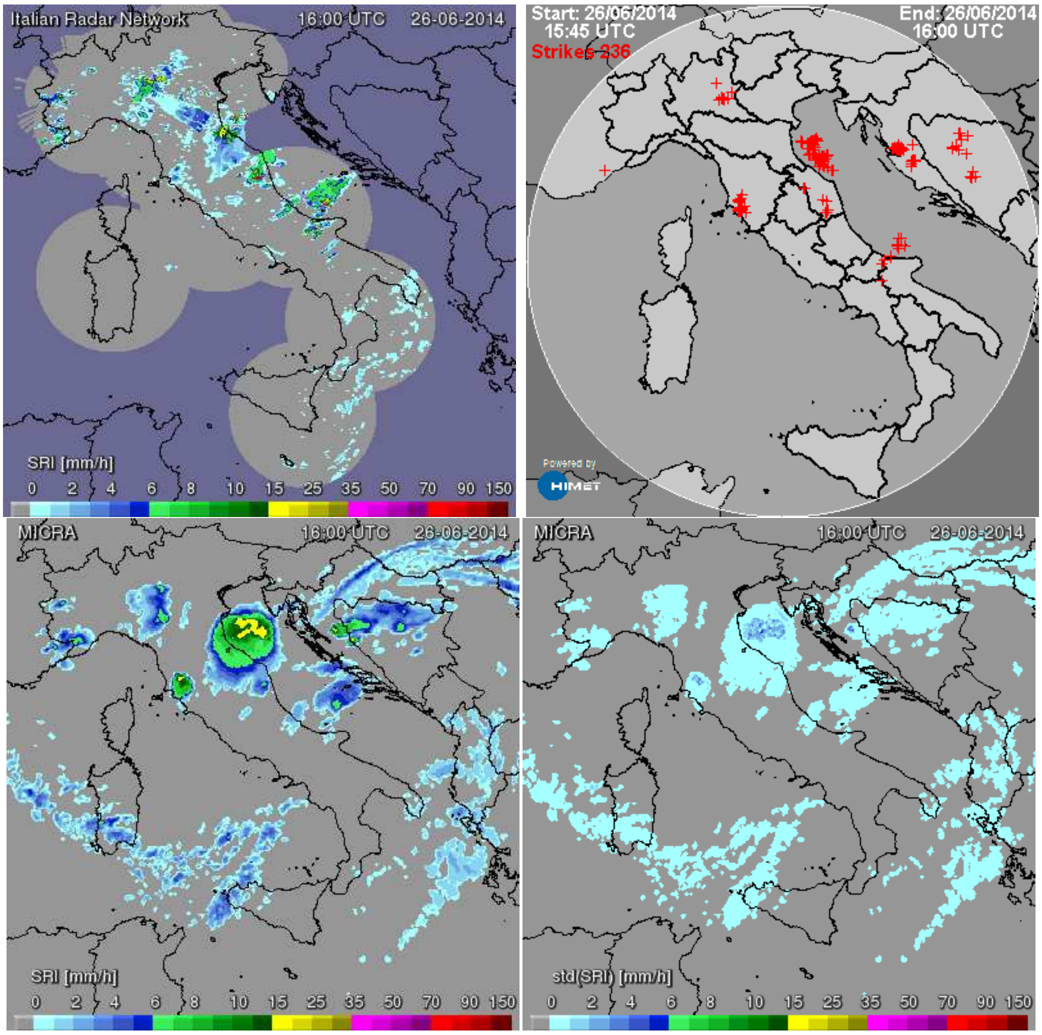

Figure 5: Case of 26 June 2014, 16:00 UTC. Top: SRI product from the RNC (left) and lightning strike activity over 15 minutes (right). Bottom: Output of MICRAdria SRI (right) and standard deviation of SRI (left).

3 Preliminary Results

The two techniques introduced above, namely MR and MUPM, provide SRI estimates at original MSG SEVIRI resolution (~4.4 km) with no spatial gaps over the full domain in Figure 1. Results were tested and compared against simultaneous radar data. Figure 4 shows for example the SRI fields estimated by the radar network and the satellite estimates (using both MR and MUPM) for the case of 19 January 2014 at 16:30 UTC. Large convective cells were developing in northern and central Italy and extended over the Ligurian and Adriatic seas, eventually reaching the coasts of Croatia. The rain patterns produced by MR and MUPM are similar, though two differences are evident; the MR shows (a) higher noise in the spatial distribution of SRI and (b) smaller dynamical range with respect to both weather radar and MUPM. Concerning the dynamical range, it appears that the MR tends to overestimate the raining areas and to underestimate the high SRI values. This feature is due to the large extent of the cloud top with respect to the relative small raining area. Based on these considerations, which apply to other case studies (not shown), the MUPM is chosen hereafter as the output of MICRAdria. Figure 5 shows an interesting case (26 June 2014 at 16:00 UTC) for which the RNC indicate thunderstorm activity near the western Adriatic coast. This region however is not well covered by RNC, with an unobserved gap of some 100 km of coastline extending up to the eastern coast of Croatia. At the same time, MICRAdria indicates intense rainfall covering most of the northern Adriatic, with relative small standard deviation (i.e. high confidence), associated with the large convective cell observed by MSG SEVIRI (see Figure 2). This is confirmed by raingauge measurements in the coastal area, reporting up to 55 mm accumulated rain in 6 hours. The thunderstorm activity developing over the northern Adriatic is also confirmed by the large number of lightning strikes falling within 15 minutes (Figure 5).

4 Summary and Discussion

In this paper we present an approach to exploit the synergy of a weather radar system and satellite infrared observations to mitigate the limitations of each. The proposed approach, called MICRAdria, deploys surface rain intensity (SRI) measured by weather radars and Brightness Temperatures (BT) observed by the Meteosat Second Generation geostationary satellite. Radar and satellite observations are used routinely to establish and update a SRI-TB relationship used to extend the SRI estimates beyond the radar coverage. The implementation of MICRAdria is presented by using SRI data from the radar network coordinated by DPC. Preliminary results during high impact weather are discussed; these seem to demonstrate that MICRAdria provides a useful tool for operational meteorology and hydrology, which can be used to complement the information given by the weather radar network.

MICRAdria is currently operational at the Center of Excellence for the integration of remote sensing and modeling for the forecast of severe weather (CETEMPS), University of L'Aquila, Italy. The process is iterated every 30 minutes and it is continuously ongoing, as new RNC SRI and MSG SEVIRI BT data are continuously ingested. MICRAdria provides SRI estimates and confidence level at original MSG SEVIRI resolution (~4.4 km) over the whole domain in Figure 1, which effectively fills the gaps and extends beyond the coverage of the radar network. Future work include the validation of MICRAdria SRI estimates against reference data, as rain gauge and weather radar outside the Italian network.

Acknowledgements

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