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Key Points:

- The role of SST initial field in numerical simulations of flash floods in Liguria (Italy) is shown
- Quantitative precipitation forecast is strongly sensitive to small-scale SST inhomogeneities
- The operational use of fully atmosphere-ocean coupled modeling systems is strongly encouraged

Supporting Information:

- Supporting Information S1

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The role of the sea on the flash floods events over Liguria (northwestern Italy)

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Abstract The sensitivity to sea surface temperature (SST) of small-scale, flood-causing convective systems in Mediterranean coastal areas is analyzed by means of mesoscale numerical simulations. Two different SST initializations are considered: a coarse field provided by a global atmospheric model and a high-resolution multisatellite analysis. Quantitative precipitation forecasts are evaluated for a number of recent severe rainfall episodes in Liguria (northwestern Italy). In several cases, using a higher-resolution SST leads to more realistic precipitation estimates in the forecasting range 36–48 h. In the shorter range, the satellite SST has a limited, or even negative, impact, due to the relatively slow adjustment of initial atmospheric fields. In one case, the satellite SST is beneficial for the only run forced with accurate large-scale initial conditions. The results of this work suggest that a potentially significant improvement in severe precipitation forecasting in the Mediterranean could be achieved using realistic small-scale SST fields.

1. Introduction

Many studies in the last decades have highlighted the existing relationship between sea surface temperature (SST) and large-scale atmospheric phenomena. It is well known, for example, that intensity and track of tropical cyclones are strongly influenced by SST patterns [*Emanuel*, 1986; *Zhu and Zhang*, 2006]. Also widely studied is the impact on the global atmospheric circulation of large and persisting SST anomalies, such as those associated to the El Niño–Southern Oscillation [*Glantz*, 2001; *McPhaden et al.*, 2006].

Conversely, the effects that SST inhomogeneities can produce on mesoscale atmospheric systems in midlatitudes are currently not fully understood. This is mainly because small-scale SST patterns (of the order of 1–10 km) are typically not well represented in the initial conditions used to force meteorological models. Also, only recently, the time evolution of SST can be provided to atmospheric models as an updated boundary condition for real-time simulations, after the advent of coupled atmospheric-ocean models [*Brossier et al.*, 2009; *Warner et al.*, 2010; *Berthou et al.*, 2015; *Ricchi et al.*, 2016].

Unfortunately, mesoscale systems, often associated with intense convection, in some cases are able to produce huge amounts of precipitation in a very short time, causing severe damages and even casualties. In particular, Mediterranean coastal regions are regularly affected by localized heavy precipitation events, resulting in very dangerous flash floods, often of limited predictability [*Ricard et al.*, 2012]. The high social and economic impact in the Mediterranean has been the motivation for intensive research and cooperation efforts to investigate the mechanisms leading to extreme precipitation, such as the recent MEDiterranean EXperiment (MEDEX) and Hydrological cycle in the Mediterranean eXperiment projects [*Jansa et al.*, 2014; *Drobinski et al.*, 2014].

Due to its position, exposed to southerly moist flows from the Mediterranean Sea, and the steep orography near the coasts, one of the most affected areas is Liguria region in northwestern Italy [*Silvestro et al.*, 2012; *Rebora et al.*, 2013; *Buzzi et al.*, 2014; *Cassola et al.*, 2015]. Extreme precipitation is usually observed between late summer and midautumn, when heat and moisture fluxes from the Mediterranean Sea are the highest, thus suggesting a fundamental role of SST in the generation and evolution of convective systems. However, while the importance of air-sea interactions has been intensively assessed in tropical regions, also from a climate change point of view [*Trenberth*, 2005], in the case of Mediterranean storms this topic clearly emerged just in recent years [*Lebeaupin et al.*, 2006; *Meredith et al.*, 2015]. For instance, *Miglietta et al.* [2011] found that SST variations could weaken or intensify a Mediterranean "tropical-like" cyclone, while *Pastor et al.* [2015] investigated the sensitivity to artificial SST patterns for torrential rainfall events in the Valencia region (Spain).

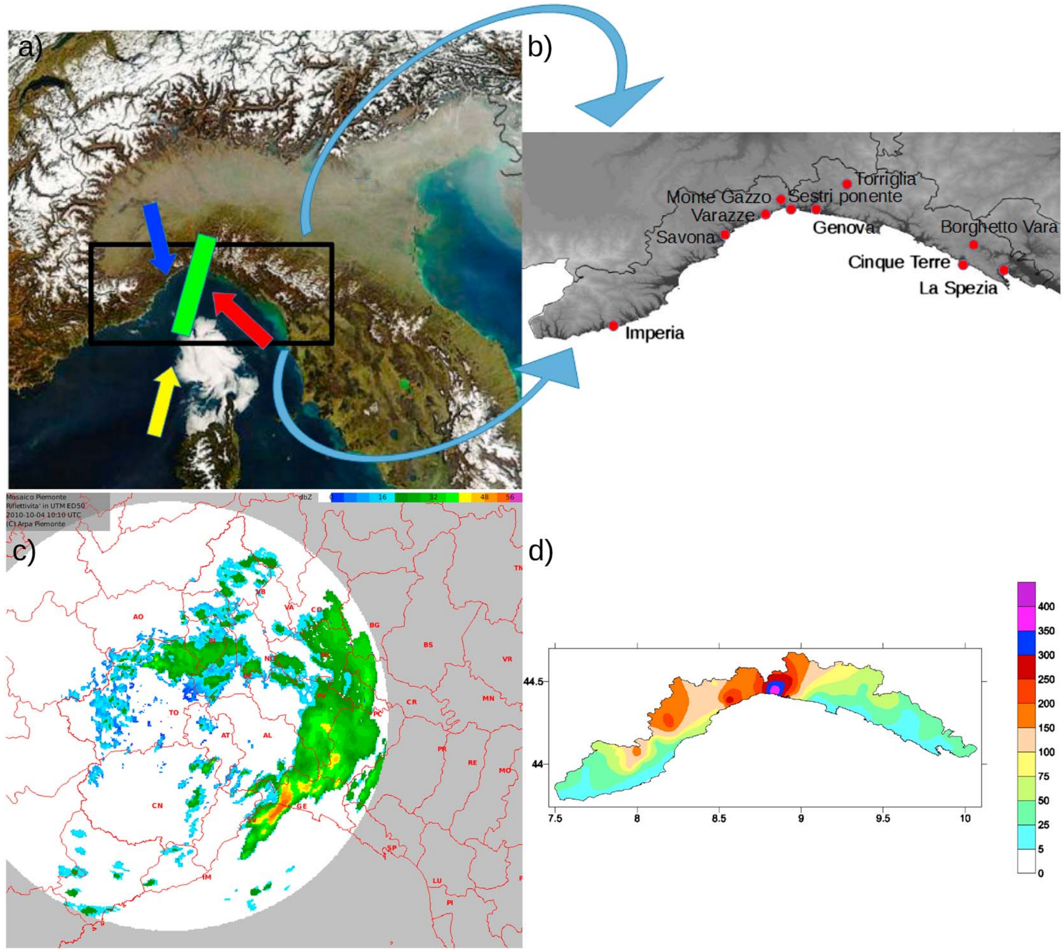

Figure 1. (a) Schematic representation of a convergence line (green) over Liguria between the southeasterly low-level jet (red arrow) and the northerly cold flow from the Po Valley (blue arrow). A southwesterly upper level flow (yellow arrow) contributes to advecting towards the coast the convective cells originated offshore. (b) Map of Liguria region showing the main urban centers and locations cited in the paper. (c) Radar reflectivity (dbZ) at 10:10 UTC of 4 October 2010. (d) A 24 h accumulated precipitation (mm) recorded by the regional observing network in the period ending at 00 UTC, 5 October 2010. Adapted from *Cassola et al.* [2015].

Also, *Davolio et al.* [2015] found that an accurate SST initialization is crucial for a correct description of an exceptional Bora wind storm in the Adriatic Sea. However, no study has addressed so far the role of SST in driving catastrophic rainfall episodes in the Ligurian Sea.

The main aim of this work is to analyze through numerical simulations how the mesoscale convective systems, responsible for some major flood events recently occurred in Liguria, respond to small SST variations (less than 1°C), obtained by replacing a coarse large-scale field with a multisatellite high-resolution analysis.

2. The Analyzed Case Studies

Extreme, flood-causing precipitation in Liguria region as well as in other coastal Mediterranean areas is typically generated by small-sized, quasi-stationary V-shaped [*McCann*, 1983] mesoscale convective systems. These systems are triggered and maintained by complex low-level temperature distributions (e.g., cold pools) and/or convergence patterns, due, for example, to sea-land inhomogeneities [*Davolio et al.*, 2009] or deflections due to the orography [*Buzzi et al.*, 2014; *Fiori et al.*, 2014]. Specifically, the onset of convective systems leading to severe rainfall events over the region is favored by the convergence between two different flows: a warm, moist southeasterly low-level jet on the eastern side, channeled between Corsica and Central Italy and impinging over the Ligurian Appennines, and a northerly shallow cold flow, moving from the Po Valley through the lowest orographic gaps and affecting the western part of Liguria (Figure 1a).

In the present paper, four severe precipitation events affecting Liguria between October 2010 and October 2014 have been considered. In all cases, rainfall amounts of about 400 mm in 12 h were recorded, causing extensive damage and casualties. Three out of these four case studies (namely, 4 October 2010, 25 October 2011, and 4 November 2011) were already described and simulated by *Cassola et al.* [2015], while the most recent event, responsible for a devastating flash flood in the city of Genoa on 9 October 2014, is described in *Faccini et al.* [2015] and *Silvestro et al.* [2015]. More details about the synoptic framework and the observed precipitation for each event are reported in the supporting information (hereinafter SI).

3. Model Setting and Simulations

The Advanced Research Workshop core of the Weather Research and Forecasting (WRF) model, version 3.4, was used to simulate these events. The WRF model is a fully compressible nonhydrostatic, primitive-equation model with multiple nesting capabilities. A comprehensive description of the model formulation is given in *Skamarock et al.* [2008].

For this study, a configuration similar to those described in *Bove et al.* [2014] and *Cassola et al.* [2015] was used. Specifically, three two-way nested grids in a Lambert Conic Conformal projection were used, covering respectively western and central Europe with 10 km, northern Italy with 3.3 km, and the Liguria region with 1.1 km grid spacing (Figure S6). Further details about the model configuration are given in the SI.

Initial and boundary conditions were taken from the operational GFS (Global Forecast System) analysis and 3 h forecast fields, respectively ($0.5 \times 0.5°$ resolution). Three 48-h long WRF runs, with outputs saved every hour, were performed for each case study, starting respectively at 00 UTC of the same day of each event and at 00 and 12 UTC of the preceding day.

To quantify the sensitivity of simulated precipitation patterns to variations in the SST field, we performed two sets of simulations: one using the low-resolution SST field from the GFS analysis and one ingesting high-resolution satellite-retrieved SST data. Global models typically filter out fine-scale variations in SST due to their low horizontal resolution. In particular, the GFS model provides a coarse SST field, obtained through a daily Optimal Interpolation analysis that assimilates observations from the previous seven days [*Environmental Modeling Center*, 2003].

Two different satellite SST data sets were used in this study, developed by the Istituto di Scienze dell'Atmosfera e del Clima-Global Ocean Satellite group of the Italian National Research Council (CNR). For the three events occurred in 2010 and 2011, the reprocessed (REP) daily gap-free (L4) data at a resolution of $0.0417 \times 0.0417°$ were used, while for the October 2014 event, the CNR Mediterranean Sea High Resolution and Ultra High Resolution Sea Surface Temperature Analysis (MED HR-UHR SST) ultrahigh-resolution (corresponding to 0.01°) L4 SST data were adopted [*Buongiorno Nardelli et al.*, 2013]. Both data sets provide daily 00 UTC analyses (more details are given in the SI). To initialize simulations at 12 UTC, SST fields corresponding to 00 UTC of adjacent days have been interpolated. The error introduced with this approach is reasonably small since the intradaily SST variation should be quite negligible.

A posteriori, we found that for the October 2014 case the GFS-forced runs were not able to satisfactorily represent the development of convection. Thus, this event was also simulated using as atmospheric initial and boundary conditions the ECMWF (European Centre for Medium-Range Weather Forecasts) analyses ($0.125 \times 0.125°$ resolution), to investigate the impact of changes in large-scale forcing in comparison with that due to SST variations.

Model sensitivity was evaluated against rain gauge data provided by the observing network managed by the Ligurian Regional Environmental Protection Agency (ARPAL). Radar reflectivity images, made available by ARPAL every 10 min, have also been considered for the October 2010 event, on which most of the following analysis will be focused. Unfortunately, the radar sited on Monte Settepani in the Ligurian Apennines, just a few tens of kilometers from the area of interest, was out of order in that period and only data from a farther radar located close to Turin were available. Therefore, radar images were used just for a qualitative comparison with the simulated precipitation fields.

4. The Role of the Sea Surface Temperature

The results of all the numerical experiments performed in this study are summarized in Table 1, where the 24 h accumulated precipitation simulated by WRF at 1.1 km resolution with different initialization setups is

Table 1. Maximum 24 h Accumulated Rainfall Simulated With WRF Model at 1.1 km Grid Spacing for Each Considered Event and for Different Forecasting Ranges[a]

Initial Conditions	Simulations	Maximum +24 h Forecast (mm)	Maximum +36 h Forecast (mm)	Maximum +48 h Forecast (mm)	Maximum Observation (mm)
4 October 2010					
GFS	GFS-CTL1	218.1	166.5	209.5	411.2
GFS + satellite SST	GFS-SAT1	237.1	172.3	276.1	·
25 October 2011					
GFS	GFS-CTL2	361.9	243.7	224.4	538.2
GFS + satellite SST	GFS-SAT2	273.6	275.9	254.2	·
4 November 2011					
GFS	GFS-CTL3	310.0	274.0	256.1	477.6
GFS + satellite SST	GFS-SAT3	284.3	306.3	281.9	·
9 October 2014					
GFS	GFS-CTL4	142.2	157.7	97.8	374.0
GFS + satellite SST	GFS-SAT4	135.0	112.6	94.7	·
ECMWF	ECM-CTL	205.2	125.3	118.2	·
ECMWF + satellite SST	ECM-SAT	250.2	103.5	100.0	·

[a]Initial conditions (global model with or without satellite-derived SST) and simulations acronyms (where CTL means "control", i.e. just global model data are used to drive WRF runs) are specified in the first and in the second column, respectively. Third, fourth and fifth columns refer to runs initialized at 00 UTC of the day when the event occurred (+24 h) and at 12 and 00 UTC of the previous day (+36 h and +48 h), respectively. The observed precipitation maximum is shown in the last column; ECMWF, European Centre for Medium-Range Weather Forecast.

compared with the corresponding observed values for each event. The impact on simulated precipitation of the satellite-derived SST appears to be significant in most cases. It is worth noting that the ingestion of a more detailed SST analysis in the model leads to more intense and, consequently, more realistic precipitation peaks especially for simulations initialized the day before the event (36 h and 48 h forecasts). The effect on shorter-term simulations is less evident and, at least in one case (October 2011), is significantly negative. The effect of SST on the precipitation peaks location is limited, due to the role of the orography in anchoring precipitation once the convective system is advected toward the coast and inland.

Further work is needed to disentangle the complex interactions between large-scale forcing and SST-induced phenomena leading to precipitation. The rainfall simulated in the short range (+24 h) run is closer to the observations, possibly due to a better description of the atmospheric conditions conducive to heavy rain by the most recent large-scale analysis driving the simulation. The reasons for the limited or sometimes negative impact of satellite SST in shorter range simulations might be due to a sort of "spin-up" problem; that is, the boundary layer requires some time to adjust to a satellite-retrieved SST (which is not consistent with the large-scale atmospheric forcing). For runs forced with large-scale SST analysis, both SST and atmospheric fields are defined by the same model and no spin-up occurs. On the contrary, for simulations initialized the day before, the marine boundary layer has enough time before the triggering of convection to adjust to the high-resolution SST fields and influence mesoscale dynamics and convective processes. This issue emerges more clearly for the 2010 and 2011 case studies, while different considerations are needed for the October 2014 event. In that case, the benefits of a detailed SST field are relevant just in the very short term and only using higher-resolution ECMWF initial and boundary conditions.

Indeed, the October 2014 event is somewhat different and more complex than the previous ones, being characterized by a weaker synoptic forcing (see the description given in the SI), and the accuracy of large-scale initial and boundary conditions appears as the main issue. In this case, the ECM-CTL run initialized at 00 UTC of 9 October 2014 provides significantly better results in terms of localization and timing of the convective cells and of quantitative precipitation forecast with respect both to the GFS-forced runs initialized on the same day and to runs forced with ECMWF and GFS analyses on the previous day (see Figures S7–S9). Interestingly, the SST effect is beneficial only for the ECMWF-driven simulation initialized on October 9. This may suggest that considering a detailed SST initial field can improve the prediction of severe rainfall episodes in the area, provided that the large-scale forcing is accurate enough to allow an adequate description of the

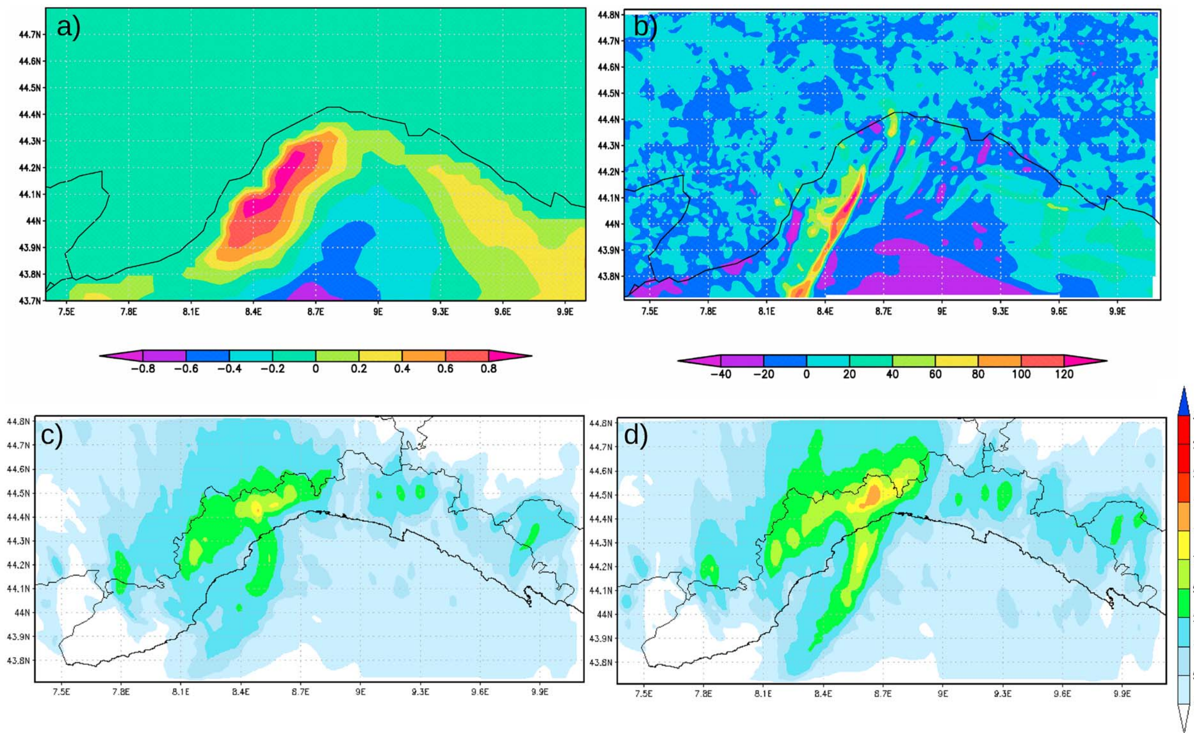

Figure 2. (a) SST difference (°C) between satellite-derived and GFS analyses at 00 UTC, 3 October 2010. (b) Surface latent heat flux difference (W m^{-2}) between GFS-CTL1 and GFS-SAT1 runs at 06 UTC, 4 October 2010. A 12 h accumulated precipitation (mm) predicted over Liguria at 12 UTC, 4 October 2010 by (c) GFS-CTL1 and (d) GFS-SAT1 simulations.

convective initiation by the mesoscale model. The aforementioned spin-up issue appears less important in this case, maybe also because a large part of the precipitation was observed in the evening (contrary to 2010 and 2011 events), which is at a longer distance from the analysis. Furthermore, ECMWF SST has a finer resolution than GFS, closer to that of satellite analysis; thus, the inconsistency between large-scale atmospheric fields and SST is limited compared to GFS-driven runs.

From Table 1, the simulation improvement associated to the use of a high-resolution SST is particularly significant for the October 2010 event (+48 h run). The synoptic and mesoscale configuration is described in *Cassola et al.* [2015] and in the SI. An intense low-level convergence between a warm, moist southeasterly flow from the Tyrrhenian Sea and cooler offshore winds very close to the coast, blowing from Savona to Genoa, triggered the development of several convective cells, moving eastward very slowly and persisting over the same area for about 6 h (Figure 1c). Torrential rainfall affected central Liguria, specifically the area surrounding the municipalities of Varazze and Arenzano and the western Genoa district of Sestri Ponente. Total precipitation reached 400 mm at Monte Gazzo (Figure 1d), with a maximum intensity of 140 mm/h [*Brandolini et al.*, 2012].

In the following, a deeper analysis of the October 2010 event is presented, to investigate the mechanisms underlying the simulation improvement induced by the use of a higher-resolution SST field. Indeed, this case study was quite poorly reproduced by GFS-driven runs, while the introduction of the satellite-derived SST allows for a better description of the convective system structure and, consequently, more realistic precipitation estimates. All figures hereinafter were obtained from WRF simulations at 1.1 km initialized at 00 UTC of 3 October 2010, if not otherwise specified.

In Figures 2c and 2d, 12 h accumulated precipitation at 12 UTC of 4 October 2010, obtained from GFS-CTL1 and GFS-SAT1 runs, is compared, while the difference in the SST initial field is shown in Figure 2a. Positive SST differences are found in a large portion of the Ligurian Sea, especially close to western coasts, where the satellite analysis is about 1°C warmer than GFS. Conversely, slightly cooler temperatures are found in the open sea. The different SST distribution is consistent with the surface latent heat flux discrepancies between the two simulations in the proximity of the convective initiation (06 UTC of 4 October 2010), depicted in Figure 2b: stronger fluxes are found in areas where satellite SST is warmer (up to 100 W m^{-2} off the western coast), which

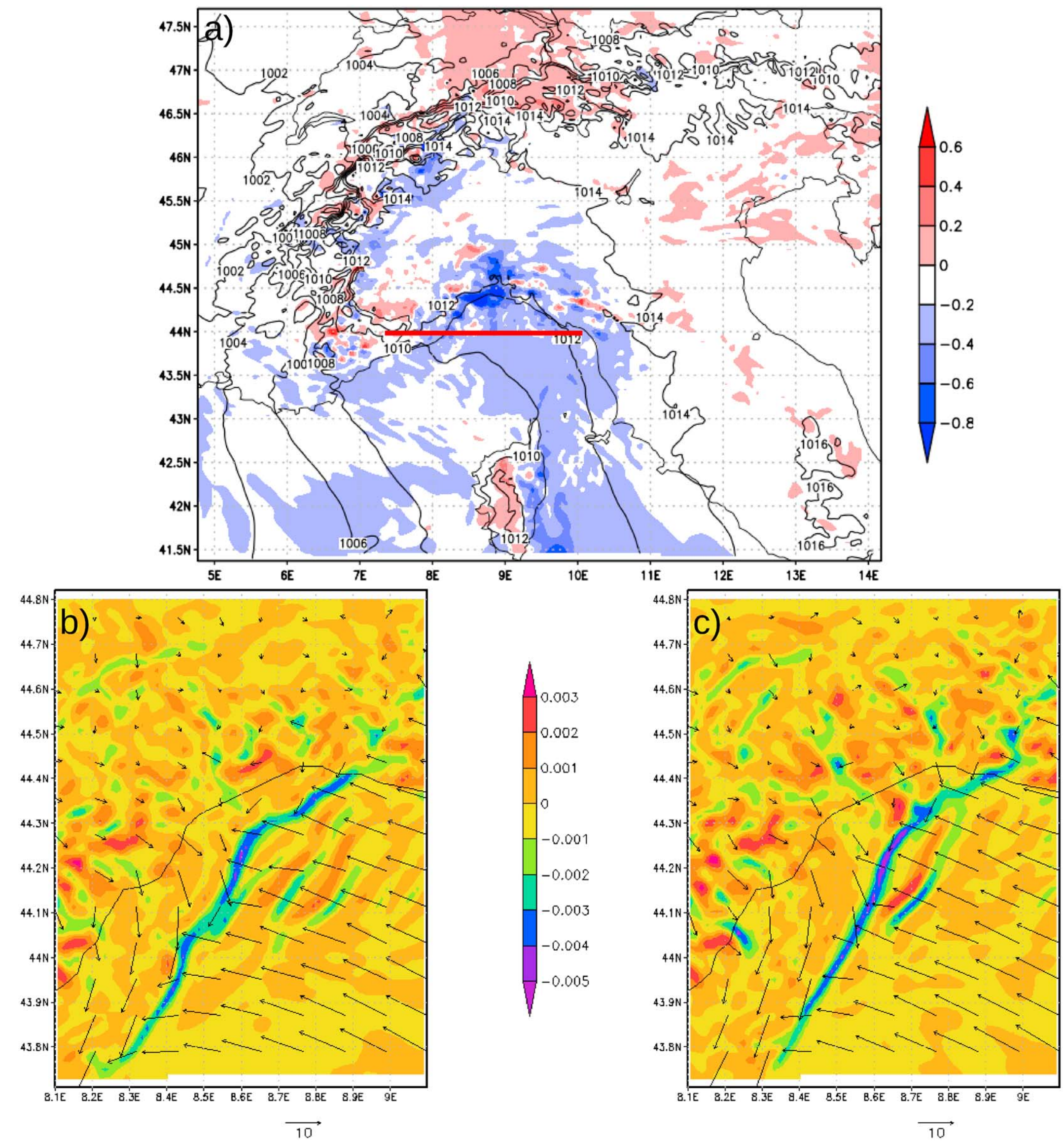

Figure 3. (a) Mean sea level pressure (MSLP) difference (hPa, shaded contours) between GFS-CTL1 and GFS-SAT1 simulations on the 3.3 km grid and MSLP (hPa, line contours) obtained from GFS-SAT1 at 06 UTC, 4 October 2010. The red line identifies the position of vertical cross sections shown in Figures 4a and 4b. A 10 m wind (vectors, m s^{-1}) and divergence (shaded contours, s^{-1}) fields on the 1.1 km grid at the same instant, from (b) GFS-CTL1 and (c) GFS-SAT1 runs.

implies a warming and moistening of the boundary layer favoring convective destabilization. As a result, a remarkable increase in precipitation intensity (up to 70 mm in 12 h), a more intense and better defined rainband, and a slight eastward shift of the precipitating system can be noticed in the GFS-SAT1 experiment. The latter simulates better the effective localization and intensity of the observed phenomena (cf. Figures 1c and 1d with Figure 2d).

A crucial role for the simulation improvement is also played by the low-level convergence observed over the sea. Figure 3a shows the mean sea level pressure (MSLP) difference between WRF simulations on the 3.3 km grid with and without satellite-derived SST, again at 06 UTC of 4 October 2010. A warmer (at least on average) SST corresponds to lower pressure values over the sea, so that the pressure gradient is higher. The modification of the pressure fields induces stronger winds, which are responsible for a line with stronger convergence and its slight eastward shift which, in turn, enhances convective development (Figures 3b and 3c). *Miglietta et al.* [2011] noted that a warmer SST produced faster cyclones, suggesting a stronger transfer of energy (and increased momentum) from the sea to the atmosphere. This picture is also consistent with the results by

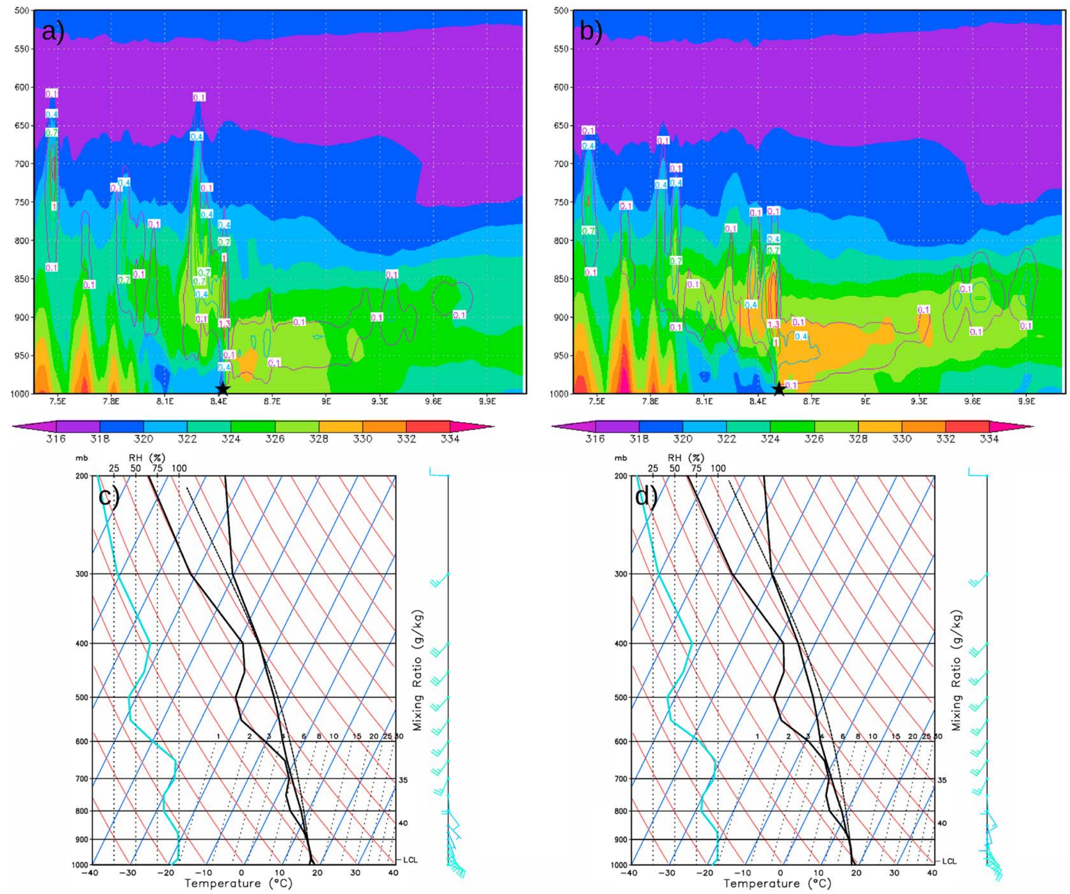

Figure 4. Equivalent potential temperature (K, shaded contours) and cloud water mixing ratio (g kg^{-1}, line contours) cross sections, taken at 44.0°N and at 06 UTC, 4 October 2010 from (a) GFS-CTL1 and (b) GFS-SAT1 simulations; black stars indicate the convergence zone between southeasterly and northerly flows. Simulated soundings extracted at 08 UTC, 4 October 2010 east of the convergence line (44.1°N, 8.6°E) from (c) GFS-CTL1 and (d) GFS-SAT1. Temperature and dew point profiles are plotted as thick, solid black lines, while pseudoadiabats are thin, dashed black lines.

Buzzi et al. [2014], who suggested that the magnitude of the low-level temperature gradient between the Po Valley and the Ligurian Sea can determine the extension and intensity of the cold northerly outflow and, as a consequence, the exact position of the convergence line.

West-east cross sections of equivalent potential temperature and cloud water mixing ratio, taken at 44.0°N and intersecting the convergence line, are shown in Figures 4a and 4b. The cold pool associated to the shallow northerly flow and the moist, warm southeasterly low-level jet can be easily recognized. Higher equivalent potential temperatures, indicating larger heat and moisture fluxes from the sea able to fuel deep convection, as well as a higher cloud water content, east of and aloft the convergence line, are found in the GFS-SAT1 simulation (Figure 4b).

Finally, Figures 4c and 4d show the simulated soundings extracted from the two runs 2 h later (08 UTC, when the convective system was reaching its maximum intensity) at (44.1°N, 8.6°E), just east of the convergence line at that time. Again, temperature and humidity profiles obtained from the GFS-SAT1 simulation appear more unstable.

In particular, surface temperature and dew point are about 0.5°C to 1.0°C warmer, and convective available potential energy values reach 562 J kg^{-1} with respect to 329 J kg^{-1} in the GFS-CTL1 run.

5. Conclusions and Perspectives

The present study investigated the sensitivity to the SST field ingested by a numerical weather prediction model in the development of severe flash flood events in Liguria (Italy), induced by quasi-stationary mesoscale convective systems. Most of the considered cases reveal significant sensitivity, with variations of less than 1°C in SST causing corresponding variations in the ground-accumulated precipitation field up to 50–70 mm in 12 h.

The response of heavy precipitation to SST is a complex one, which involves the modification of PBL and low-level flow characteristics and its interaction with topography. The impact of satellite-derived SST on total predicted precipitation appears beneficial especially for simulations initialized the day before the event, due to the relatively slow adjustment of atmospheric fields to the higher-resolution initial condition. Conversely, such an impact is generally neutral or even negative for 24 h forecasts.

The analysis of the most recent episode (October 2014) suggests that a satellite-retrieved SST initial field can improve the quantitative precipitation forecast only when the large-scale forcing is accurate enough. In fact, the assimilation of satellite SST appears beneficial for this event just in combination with the best available large-scale analysis (ECMWF at 00 UTC of 9 October), capable to reasonably describe the convective initiation and development.

The results presented in this paper encourage further research about the role of air-sea interaction in driving the formation and evolution of severe convective systems in Liguria and in other Mediterranean regions, possibly exploiting two-way atmosphere-ocean coupled modeling systems. The latter are capable to provide the atmospheric model with a high-resolution, continuously updated SST field, which represents the coastal SST much better than satellite analyses [*Ricchi et al.*, 2016] and is consistent with the atmospheric fields for the whole simulation.

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