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Intense air-sea exchange and heavy rainfall: impact of the northern Adriatic SST

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Abstract. Over the northern Adriatic basin, intense air-sea interactions are often associated with heavy precipitation over the mountainous areas surrounding the basin. In this study, a high-resolution mesoscale model is employed to simulate three severe weather events and to evaluate the effect of the sea surface temperature on the intensity and location of heavy rainfall. The sensitivity tests show that the impact of SST varies among the events and it mainly involves the modification of the PBL characteristics and thus the flow dynamics and its interaction with the orography.

1 Introduction

Northeastern Italy (NEI) is often affected by heavy rainfall events. Sometimes they produce a daily accumulation that can reach values as high as 40 % of the mean annual amount, even in less than 12 h, thus leading to severe flash floods, damages and human casualties (Barbi et al., 2012). Heavy precipitation over the Alps is directly (e.g., by orographic uplift) or indirectly (e.g., by orographic cyclogenesis) related to the influence of mountain ranges on atmospheric motions. Heavy precipitations over NEI are often associated with Sirocco or Bora winds (Manzato, 2007; Davolio et al., 2015, 2016), thus involving intense air-sea interactions. In this situation, the Adriatic Sea acts as a source of moisture and heat for the atmosphere and contributes to destabilize the air mass in the boundary layer (PBL), which is then transported toward the mountains where convective instability is released. As pointed out by Dorman et al. (2007) and Pullen et al. (2007) turbulent surface heat fluxes and sea surface temperature (SST) variations are important parameters that characterize intense air-sea exchanges.

The relationship between SST and precipitation is well recognized in the tropics, where ocean conditions drive the atmosphere and higher SSTs are generally accompanied by increased convection and precipitation (Trenberth and Shea, 2005). Toy and Johnson (2014) highlighted that even mesoscale SST fronts influence the PBL stability, resulting in an enhancement of horizontal convergence and precipitation. At mid-latitudes, however, the impact of the SST on atmospheric phenomena is still debatable and different studies have addressed the possible role of the SST during severe weather events (Miglietta et al., 2011; Pastor et al., 2015).

In the last decade, the importance of Mediterranean SST representation in meteorological models has been investigated for heavy rainfall events. In particular, Lebeaupin et al. (2006) showed that an averaged variation of SST ($\pm 1.5\,^{\circ}$C) impacted the intensity and localization of rainfall, while high-resolution SST analyses did not produce relevant improvements in precipitation forecasts. Other studies (e.g. Berthou et al., 2014) based on coupled models simulations confirmed that intense rainfalls can be sensitive to the evolution of SST during the event.

Numerical weather prediction (NWP) models usually keep SST fixed at its initial value or allow just slow changes according to surface fluxes. This SST representation is generally unrealistic even for short-range forecasts, especially in small and shallow basins like the Adriatic Sea (Davolio et al., 2015; Ricchi et al., 2016). This framework motivated the present study aimed at investigating the impact of the northern Adriatic SST on the intensity and location of the rainfall, identifying the relevant physical mechanisms involved. We focused on representative severe events that occurred over NEI, in different months of late Sum-

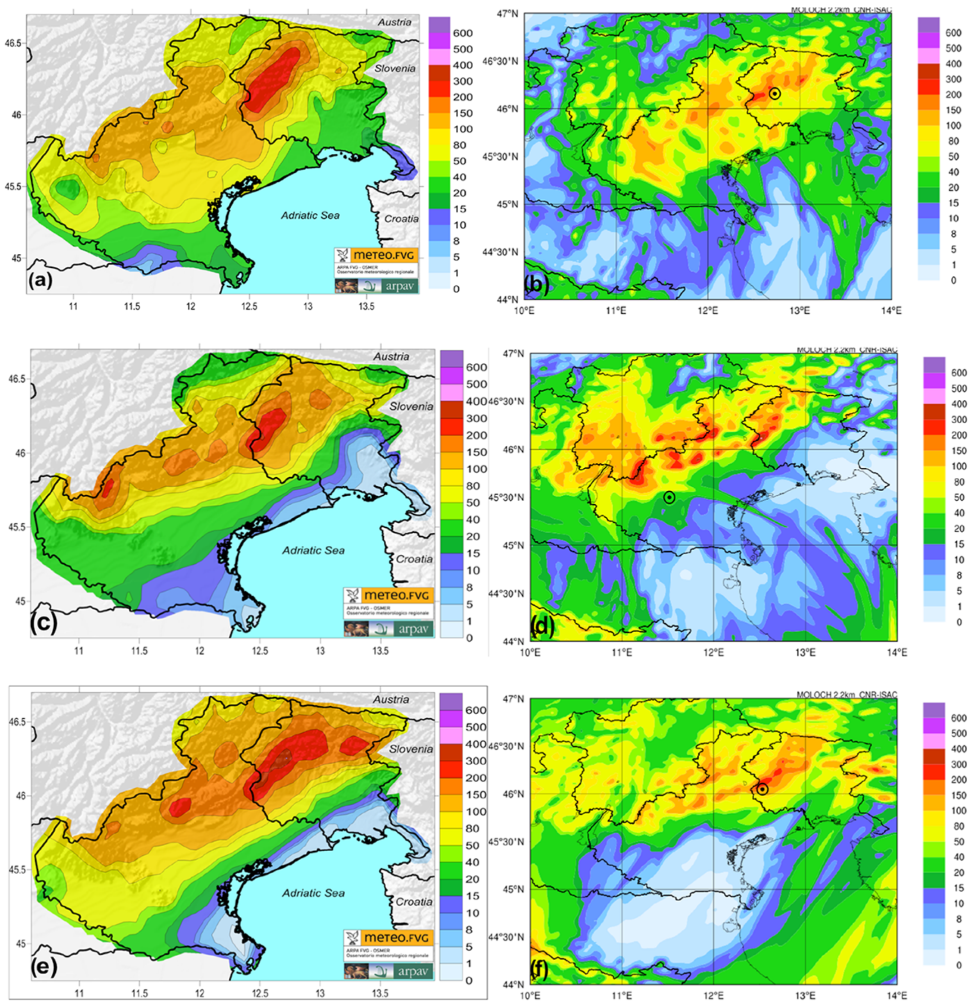

Figure 1. 24 h accumulated precipitation (mm). Observations **(a, c, e)** and MOLOCH control simulations **(b, d, f)** at: 00:00 UTC, 16 September 2006 (Chievolis case – **a**, **b**); 00:00 UTC, 2 November 2010 (Vicenza case – **c**, **d**); 00:00 UTC, 12 November 2012 (Piancavallo case – **e**, **f**). Only a portion of the MOLOCH integration domain is shown. Borders of Veneto region (west) and FVG region (east) are shown. Observed precipitation is obtained by interpolation of data provided by the dense network (about 260 rain-gauges) managed by the FVG regional meteorological agency (OSMER – ARPA FVG). Black circles in **(b)**, **(d)** and **(f)** indicate the location of Chievolis, Vicenza and Piancavallo, respectively.

mer/Autumn, which present different rainfall characteristics (orographic, stratiform and convective) and intense Sirocco wind. A high-resolution NWP system was used to simulate the heavy precipitation events and to perform sensitivity experiments. This study represents a first modelling analysis of the SST effect in this area, and a preliminary step toward a full coupling between atmospheric and ocean models foreseen in the framework of the Italian flagship project RITMARE (http://www.ritmare.it).

2 Overview of the events

The three analysed cases represent typical rainfall events affecting eastern Alps. Only a short description is provided in the following. Associated with an approaching upper-level trough, deepening in the Mediterranean and slowly moving eastward, winds blew from southwest in the middle troposphere while close to the surface, over the Adriatic Sea, Sirocco wind from southeast impinged on the Alpine barrier. The advection of warm and moist air favoured intense orographic precipitation, with embedded convective activity, due to thermodynamic profiles becoming progressively more unstable in the course of the event. The three selected cases are: 14–16 September 2006 (Chievolis), 30 October–2 November 2010 (Vicenza) and 10–12 November 2012 (Piancavallo). For the last two cases, a more detailed description can be found in Davolio et al. (2016). Chievolis event occurred in the Friuli Venezia Giulia (FVG) region in late summer and was characterized by convective precipitation exceeding 300 mm in 24 h. The other two cases (Piancav-

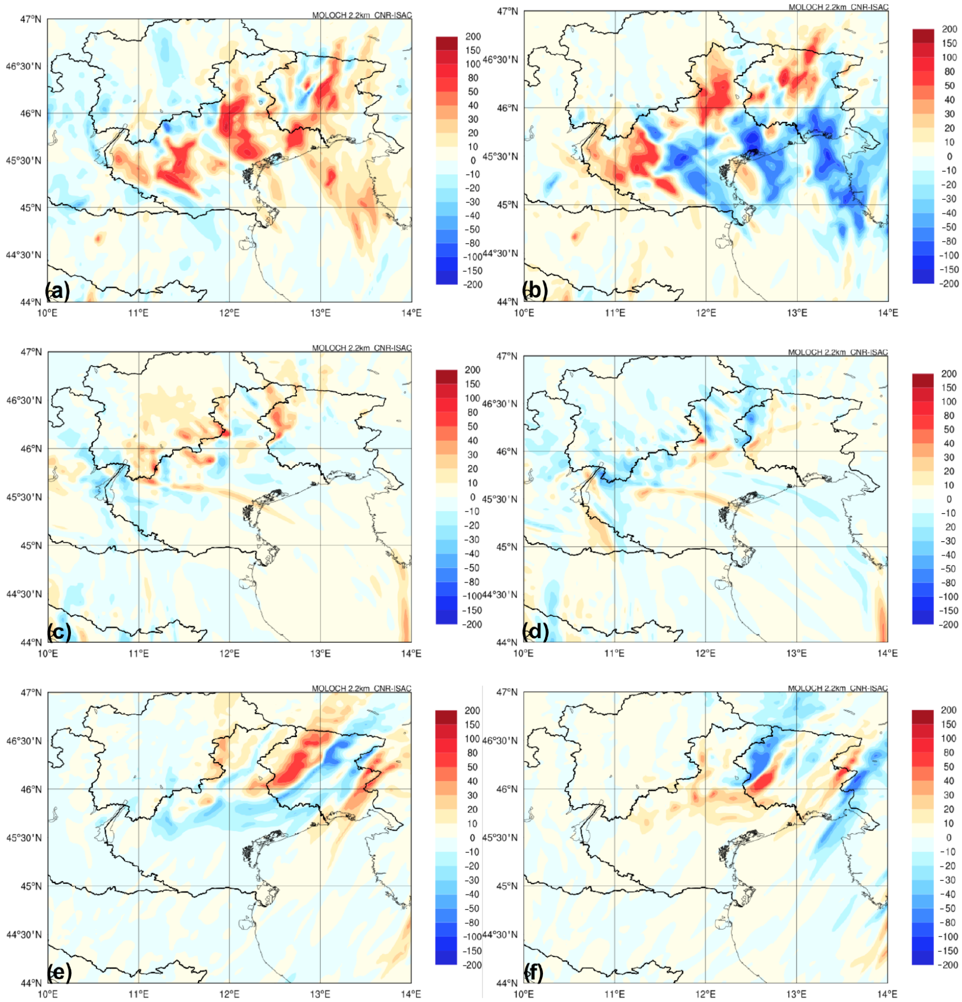

Figure 2. Difference of 24 h accumulated precipitation (mm) fields between CNTRL and SST2M **(a, c, e)** or SST2P **(b, d, f)** at: 00:00 UTC, 16 September 2006 (Chievolis case **a**, **b**); 00:00 UTC, 2 November 2010 (Vicenza case **c**, **d**); 00:00 UTC, 12 November 2012 (Piancavallo case **e**, **f**).

allo and Vicenza), occurred in autumn, were responsible for floods and affected both FVG and Veneto regions with orographic rainfall up to 250 and 300 mm in 24 h, respectively (Fig. 1).

3 NWP system setup

The NWP system is based on BOLAM hydrostatic and MOLOCH non-hydrostatic models, both developed at CNR-ISAC (Davolio et al., 2015). In the present study, BOLAM runs over an European domain, with horizontal resolution of about 11 km and 50 vertical levels. MOLOCH (its whole integration domain is shown in Fig. 4) is nested in BOLAM. Its integration, covering the Adriatic basin, is initialized with a 3 h BOLAM forecast in order to avoid a sudden change in the grid resolution from the global to the 2.2 km MOLOCH grid-spacing (50 vertical level), based on pure interpolation. The model chain is initialized at least 12 h before the onset of intense rainfall, in order to allow the PBL to adjust to the modified SST. Specifically, BOLAM is initialized at 12:00 UTC on 14 September 2006 (Cheivolis) and 10 October 2012 (Piancavallo), and at 18:00 UTC on 30 October 2010 (Vicenza). BOLAM-MOLOCH control simulation (CNTRL) is driven by IFS-ECMWF forecasts, thus the SST field is provided through the OSTIA analyses (Donlon et al., 2012). In order to analyse SST effects on forecast precipitation, for each event the analysed SST field is modified by increasing (SST2P) or decreasing (SST2M) its value over the Adriatic Sea by 2 °C. This value seems reasonable considering the uncertainties in different SST analyses (Lebeaupin et al., 2006; Davolio et al., 2015).

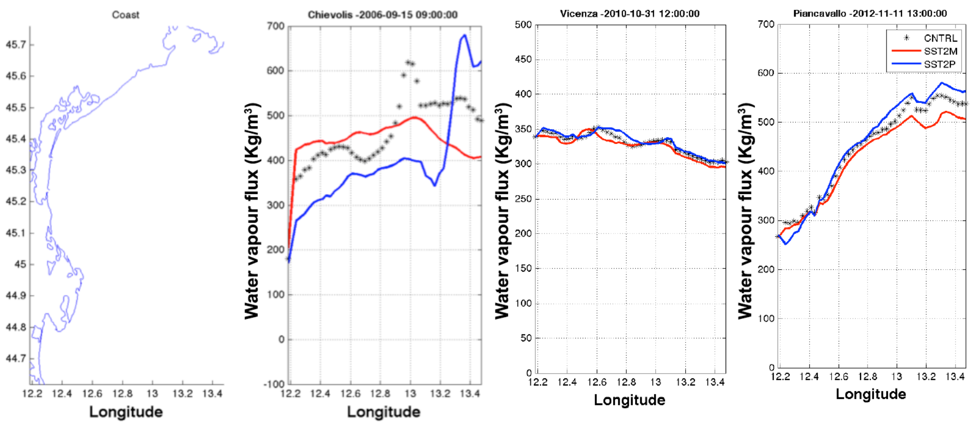

Figure 3. Vertically integrated water vapour fluxes across the Northern Adriatic coastline (shown in the left part of the panel) computed at: 09:00 UTC, 15 September 2006 (Chievolis); 12:00 UTC, 31 October 2010 (Vicenza); 13:00 UTC, 11 November 2012 (Piancavallo). Coloured lines indicate the results of MOLOCH experiments: CNTRL (black stars), SST2M (red) and SST2P (blue).

4 Results

4.1 Representation of the intense precipitation events

In all the analysed cases, the precipitation distribution is strongly correlated with the Alpine orography as shown by the observation (Fig. 1a, c, e). In particular for the Chievolis and Piancavallo events, high values of precipitation are recorded along the Pre-Alpine slopes in FVG region, with maxima exceeding 300 mm on the locations corresponding to Chievolis and Piancavallo. For the Vicenza case, precipitation maxima are distributed along the pre-Alps from Veneto to FVG, with two maxima exceeding 200 mm 24 h^{-1}.

The reference simulations (CNTRL) succeed in reproducing the precipitation fields in terms of intensity and distribution with only a slightly tendency to underestimate the maxima (Fig. 1b, d, f). Therefore, these simulations can be suitably used as a reference to perform sensitivity studies, aimed at understanding the role of SST during these events.

4.2 Impact of SST on precipitation

Figure 2 shows the difference of daily-accumulated precipitation between the CNTRL simulation and the simulations with modified SST (SST2P and SST2M) for each case study. Red colour indicates the areas where CNTRL run is more rainy. While for Vicenza event the precipitation differences due to SST changes can be explained in terms of rather small displacements of the rainfall location, for the Chievolis and Piancavallo events the impact of SST is larger. In this case, SST2M is generally drier than the CNTRL, while in SST2P rainfall is shifted closer to the coast and towards the eastern part of the domain. For Vicenza event the impact of SST is very limited. For Piancavallo event, a colder (warmer) SST is associated with upstream (downstream) displacement of the intense precipitation area with respect to the orography. Moreover, in SST2M intense rainfall is displaced over the plain and affects a large portion of the Po Valley. This behaviour can be explained in terms of interaction between the low-level southerly flow and the orography, as detailed in the following. However a more detailed analysis of the interaction between flow and orography in terms of the change of the Froude number with SST is ongoing.

4.3 Surface fluxes, water vapour and wind

In order to better understand which processes involved in an intense rain event are sensitive to the SST, heat and moisture surface fluxes as well as the low-level wind field and water vapour transport have been analysed.

The temporal evolution (not shown) of surface sensible and latent heat fluxes averaged over the northern Adriatic Sea for the three experiments shows a similar behaviour for the three events: an increase (decrease) of averaged fluxes in response to a warmer (colder) SST. Also the values of the fluxes are similar, ranging from about 200 W m^{-2} for SST2P to 50 W m^{-2} for SST2M, with CNTR in between. Maxima are associated with the most intense phase of Sirocco wind.

The evolution of vertically integrated water vapour fluxes across the northern Adriatic coastline has been also analysed in order to evaluate the amount of water vapour moving northward from the sea towards the Alps. It is worth noting that this does not provide information about the sources of moisture. For this purpose, the development of a diagnostic tool, aimed at providing water vapour budget in the atmosphere over the Adriatic Sea, is ongoing and it will be applied in a future work. Figure 3 provides an overall view of the spatial evolution of the moisture inflow associated with the southeasterly Sirocco wind, up to a prescribed altitude of 3000 m. The results refer to the time of strongest Sirocco and provide a comparison among the three experiments (CNTRL, SST2P and SST2M).

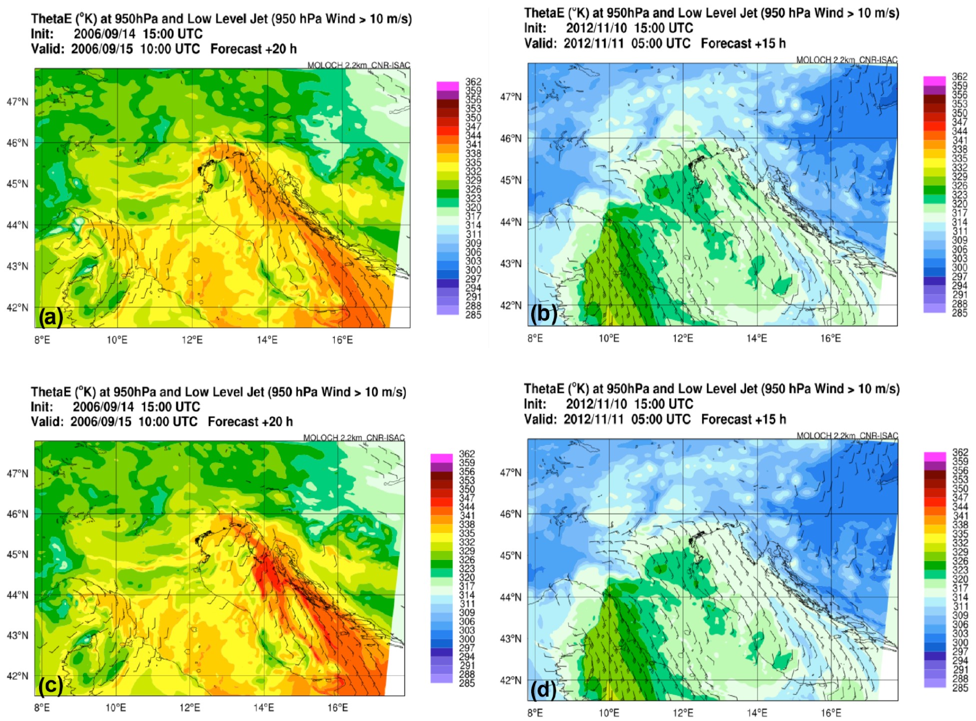

Figure 4. 950 hPa Equivalent potential temperature and wind barb (wind speed exceeding $10\,\mathrm{m\,s^{-1}}$) for Chievolis **(a, c)** and Piancavallo **(b, d)** events. CNTRL simulations **(a, b)** are compared with SST2P for Chievolis **(c)** and SST2M for Piancavallo **(d)**.

Contrary to the averaged surface fluxes, increasing SST does not lead systematically to an increase of inward water vapour transportation, along the northern Adriatic coast, which seems instead dependent on the single events. Vicenza case presents more constant water vapour fluxes during the event with values around $350\,\mathrm{kg\,m^{-3}}$ very weakly sensitive to the SST. For Chievolis event, a SST increase produces an evident shift from west to east of intense water vapour fluxes. For Piancavallo event, an increase of SST results in an increase of water vapour fluxes, although quite limited. These behaviours are consistent with the results obtained for the precipitation fields (Fig. 2) where the largest differences with respect to the CNTRL simulation are found for Chievolis and Piancavallo events.

The analysis of heat surface fluxes and water vapour fluxes across the coast suggests that changes in SST do not impact directly on the precipitation through a substantial modification of the amount of moisture impinging on the Alps and feeding the precipitation. Instead, SST seems to play an important but indirect role in determining the location of rainfall, influencing the PBL characteristics. In fact, the changes in moisture fluxes (Fig. 3), and consequently in precipitation (Fig. 2) can be ascribed to different low-level wind fields in the sensitivity experiments, as shown in Fig. 4.

In the Chievolis event, increasing SST (Fig. 4c) produces a weakening of the southeasterly Sirocco wind and more intense southwesterly winds descending from the Apennines and entering the northern Adriatic basin. Different characteristics of the PBL over the sea seem responsible for different superposition of these two flows, thus determining a southwestward shift of the moisture advection and of the precipitation (Fig. 2b). Also for the Piancavallo case (Fig. 4b, d), the SST variation impacts the PBL characteristics and thus changes the flow regime across the Alpine barrier. A colder SST (Fig. 4d) enhances the stability and thus the blocking of the low-level flow impinging on the orography. Therefore, flow-around is favoured (with respect to flow-over), producing an evident westward deflection of the wind and a shift of the precipitation upstream and over the Po Valley (Fig. 2e). For Vicenza events (not shown), no relevant differences appear.

5 Conclusions

Three intense rain events were simulated using a high-resolution model to evaluate the effect of the SST on heavy rainfall in the NEI Alps. Different SST fields have been imposed as low-level boundary conditions over the Adriatic Sea and these preliminary results show that the impact of SST on precipitation varies among different events.

A warmer SST increases the surface heat fluxes over the sea, but does not necessary affect the vertical integrated water vapour flux across the coast (i.e. water vapour available for the precipitations on the Alps), which is probably modulated mainly by large-scale/mesoscale circulation. The response of heavy precipitation to a SST change is complex: SST affects the PBL characteristics and thus the flow dynamics and its interaction with orography.

This study can be considered as a first step toward a more detailed investigation of the effect of the air-sea interaction in this area. In particular a more detailed evaluation of the water balance in the atmosphere is already ongoing together with further sensitivity simulations using high-resolution satellite SST analyses or SST field from an ocean model to evaluate the impact of small-scale SST features.

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