6.2 ROLE OF THE SEA STATE ON THE AIR-SEA EXCHANGES DURING A MEDITERRANEAN HEAVY PRECIPITATION EVENT IN A KILOMETER-SCALE FORECAST SYSTEM

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1. INTRODUCTION

During late summer and fall, the Mediterranean region is prone to heavy precipitation events (HPEs) characterized by large rainfall amounts in a short period (typically more than 100 mm in less than 24 hours) which often lead to devastating flash-floods (Ducrocq et al. 2016). For these events, the Mediterranean Sea is a source of heat and moisture that feed the mesoscale convective systems (Duffourg and Ducrocq, 2011). The air-sea exchanges are favored by a strong marine low-level jet (>20 m/s) blowing over a warm and thin ocean mixed layer. Frequently, such events are also associated with a sea surface elevation, submersion, which increase the coastal flooding risk, and rough sea that moderates the exchanges of heat, water and momentum at the air-sea interface.

The international HyMeX program (*Hydrological cycle in Mediterranean Experiment*, www.hymex.org) investigates the Mediterranean Sea hydrological cycle with an emphasis on the severe events that largely contribute to it (Drobinski et al. 2014; Ducrocq et al. 2014). A large part of HyMeX is devoted to the improvement of the prediction skill of high-impact hydro-meteorological events in the area, with notably the development of integrated (multi-components) forecast systems. Within this framework, the coupling between the Météo-France kilometer-scale AROME Numerical Weather Prediction (NWP) model (Seity et al. 2011), the NEMO ocean model (Madec et al. 2016) and the WaveWatchIII (WW3) model (Tolman 2002; 2009) is currently developed.

As preliminary work for coupling, this study aims to investigate the representation of air-sea exchanges that occur during such events, with a focus on the role of the sea state. Several sensitivity tests to sea surface temperature (SST) and turbulent flux parametrization were run with AROME for a HPE occurring between 12 and 14 October 2016 in South-Eastern France.

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2. SENSITIVITY EXPERIMENTS

Numerical sensitivity experiments were run with the high-resolution (1.3 km) non-hydrostatic AROME-France NWP model. The vertical grid has 90 η-levels with a first level thickness of ~5 m.

Operationally, AROME-France uses for the sea surface its own SST analysis (Taillefer, 2002) that is kept constant during the forecast and the bulk iterative ECUME sea surface turbulent fluxes parametrization (Belamari, 2005; Belamari and Pirani, 2007).

First, the sensitivity to the initial SST is investigated. For that, the SST analysis coming from the global operational analysis of Mercator-Océan (1/12°-resolution PSY4 system, Lellouche et al. 2013) is used instead of the AROME analysis. The sensitivity of HPE to SST in high-resolution simulations is already well documented in the literature (e.g. Rainaud et al. 2017 for AROME). So, this test serves here more as a ‘gauge’ for the following sensitivity tests (to the turbulent fluxes parametrization in this study, or, to interactive coupling, for example).

The second set of sensitivity experiments concerns the sea surface turbulent fluxes parametrization. First, the new version of ECUME, hereafter ECUME6 (Le Moigne 2018), is tested. The main difference is that ECUME6 uses for convergence, the three derived parameters P_{u10n}, $P_{\theta 10n}$, P_{q10n} defined as:

$$P_{u10n}=\frac{C_{D10n}}{\sqrt{C_{D10n}}}\Delta u_{10n} \qquad (1a)$$

$$P_{\theta 10n}=\frac{C_{H10n}}{\sqrt{C_{D10n}}}\Delta u_{10n} \qquad (1b)$$

$$P_{q10n}=\frac{C_{E10n}}{\sqrt{C_{D10n}}}\Delta u_{10n} \qquad (1c)$$

and as polynomial functions of the neutral vertical wind gradient between the surface and 10 m Δu_{10n} , that are fitted with data collected during several campaigns (while ECUME uses a multi-campaign calibration of the neutral exchange coefficients at 10 m, *i.e.* polynomial functions of C_{D10n}, C_{H10n}, C_{E10n}). Then, the COARE 3.0 (Fairall et al. 2003), available in the surface scheme (SURFEX, Masson et al. 2012) of AROME, is used. And, finally, the innovative turbulent flux parametrization, named WASP *(Wave-Age dependent Stress Parametrization)*, which takes into account directly the impact of the sea state, has been developed and introduced in SURFEX/AROME.

The main principle of WASP is the following. The peak period T_p is used to compute the Charnock's coefficient α_{ch} :

$$c_p = \frac{g\,T_p}{2\,\pi} \qquad (2)$$

where g is the gravity and c_p the phase speed;

$$\alpha_{ch} = A\,\frac{c_p}{u_*^{-B}} \qquad (3)$$

with u_* the friction velocity, A and B coefficients depending on the first atmospheric level wind speed U_a .

In the following, the peak period period T_p is provided by wave model analyses or forecasts (called 'real waves' hereafter) or derived from U_a (called 'ideal waves'), knowing that WASP is originally designed to be applied with a 'real waves' forcing or coupling.

In our experiments, AROME starts every day (12, 13 and 14 october 2016) at 00UTC, from ARPEGE (Courtier et al. 1991) analyses and boundary conditions come every hour from the ARPEGE forecasts. Each AROME forecast duration is 42 hours.

In the latter sensitivity test, *i.e.* using WASP and a 'real wave' forcing, the period peak comes from WW3 simulations done in the frame of the french MARC (*Modélisation et Analyses pour la Recherche Côtière*) initiative at LOPS. This product has a 1/10°-resolution and is available with a three-hourly frequency.

3. RESULTS

In this part, all the results shown and discussed are from the forecasts starting on 13 October 2016, 00UTC.

3.1 *Sensitivity to the SST*

Figure 1a presents the differences between the PSY4 and the AROME SST analyses for 13 October 2016 at 00UTC. Large differences appear locally, in particular over the North-Western Mediterranean area. The PSY4 SST is higher by ~+0.5°C between the Balearic Islands and Sardinia and lower (~-1°C) in the Ligurian Sea and around Corsica. The largest differences (up to ±2°C) are associated with meanders of the North Balearic Front (NBF), which is not well represented in the AROME SST analysis.

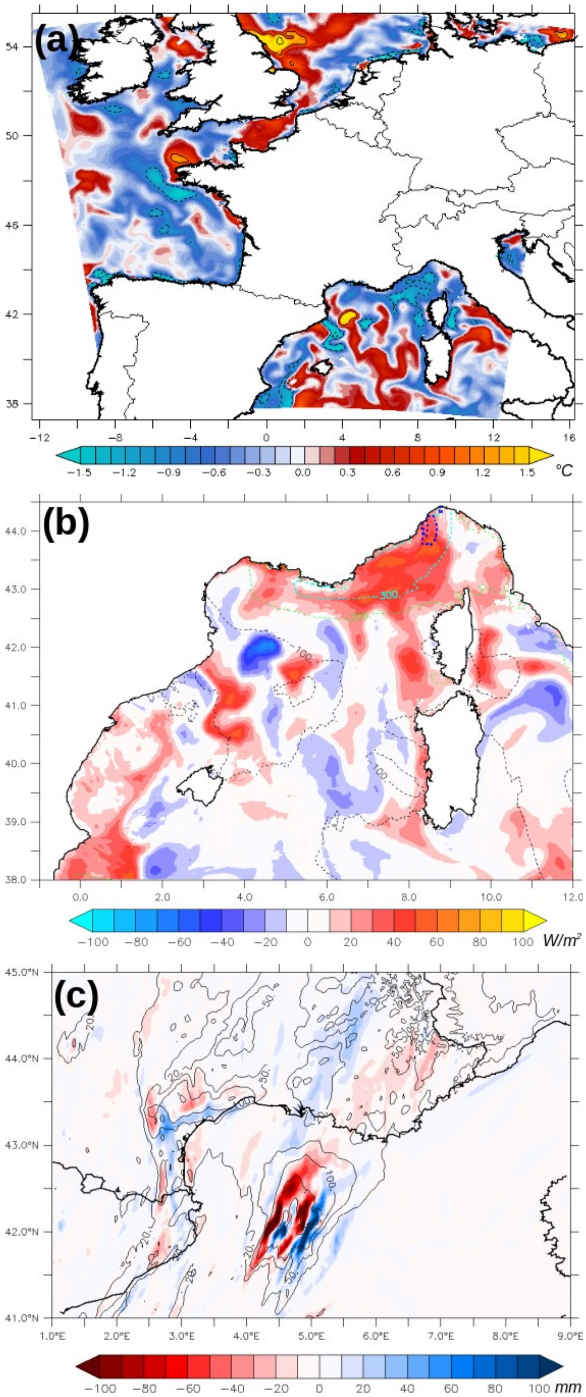

FIG 1. (a) Differences between the PSY4 and the AROME SST (°C) analyses. Differences between the forecasts using the PSY4 SST vs. the AROME SST (b) in the 24h-averaged latent heat flux (colors, W/m²) (the 24h-averaged latent heat flux in the reference forecast (using AROME SST) is indicated with contours, negative for ocean heat loss) and (c) in the 24h-cumulated rainfall amounts (mm) (the black contours indicate the 24h-cumulated rainfall amounts in the reference).

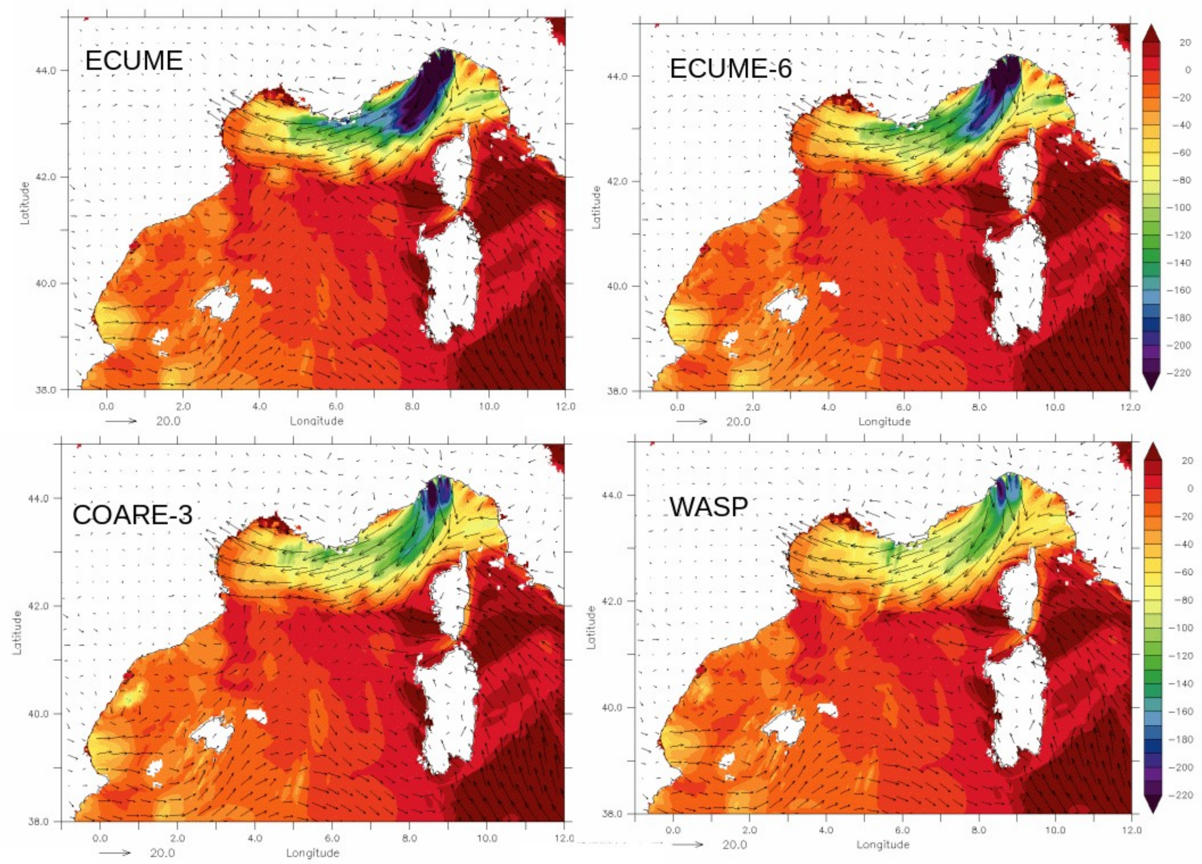

FIG 2. 14 October 2016 00UTC: Sensible heat flux (H, in W/m²) in the AROME forecasts using the ECUME, ECUME6, COARE3.0 and WASP sea surface turbulent flux parametrizations. Arrows are the wind speed (m/s) at 5m above ground level.

The SST differences directly impact the sensible heat flux and the latent heat flux (and evaporation), with an increase [decrease] in absolute value (up to 80W/m^2) over warmer [colder] sea surface (Fig. 1b). This result is robust whatever the sea surface turbulent flux parametrization used.

Comparing the Quantitative Precipitation Forecasts (QPF, Fig. 1c), large differences are found over sea related to a eastwards displacement of a first Mesoscale Convective System (MCS) occurring in the Gulf of Lion [5°E; 42°N]. Significant differences are also found over the Hérault region [2.5-3.5°E; 43-44°N] with an increase in QPF along the coast when the PSY4 analysis is used. Here, only one sea surface flux parametrization is considered (WASP with 'ideal waves'). But, the values of the differences and the way the precipitating systems are moved are not similar when considering other pairs of SST sensitivity tests with the other sea surface flux parametrizations. This means that the SST has an indirect impact on precipitation through surface fluxes and several mechanisms acting notably on convection. Future work will investigate the possible involved mechanisms as the convergence, the stability and momentum mixing in the atmospheric boundary layer (ABL) and the pressure adjustment to SST anomalies.

3.2 *Sensitivity to the sea surface turbulent fluxes parametrization*

Figure 2 illustrates the sensible heat fluxes obtained when using the four different parametrizations described in section 2, *i.e.* ECUME, ECUME6, COARE 3.0 and WASP (with 'ideal waves').

Low to moderate changes are found between Sardinia and the Spanish coasts. Large modifications are obtained in the north-easterly to easterly flow over the Ligurian Sea (strong wind regime with cold and dry air at low-level). In particular, the three parametrizations ECUME6, COARE 3.0 and WASP, show a large decrease in absolute value (by 40, 80 and 100W/m², respectively) compared to ECUME, which is known to overestimate the sensible heat flux in such regime (Rainaud et al. 2016). The same conclusions stand for the latent heat flux, *i.e.* generally small differences except in the strong, cold and dry 'Ligurian' easterly flow (not shown).

Figure 3 shows the differences in wind stress and wind speed between simulations using ECUME and WASP parametrization. As for the heat fluxes, no significant wind stress differences are observed in the south-easterly flow. Large differences are found under the MCS [around 5.5°E-42.5°N] and the easterly flow, by more than ±0.3 N/m² for the wind stress and by more than ±3 m/s for the wind speed.

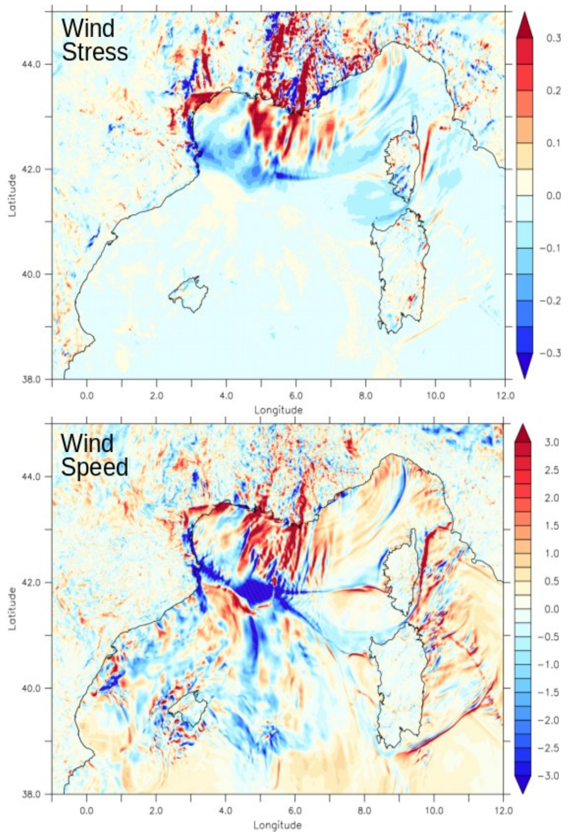

FIG 3. 14 October 2016 00UTC: Differences of wind stress (N/m²) and wind speed (m/s) between runs using ECUME and WASP parametrization.

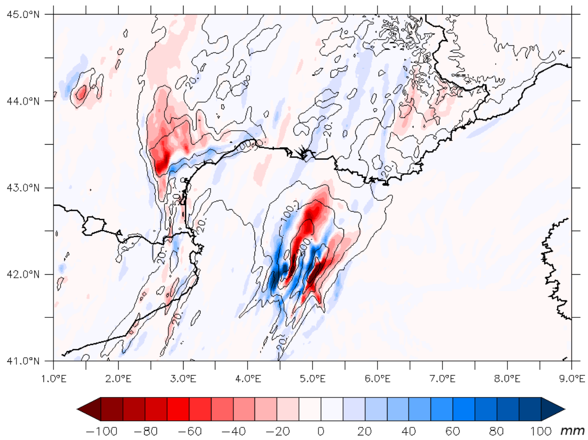

FIG 4. Differences in the 24h-QPF (mm) between runs using WASP and the ECUME parametrization – the black contours indicate the 24h-QPF in the reference (*i.e.* with ECUME).

Comparing the QPF using WASP or ECUME parametrizations (Fig. 4), a strong impact is found locally over sea, with a westwards displacement of the rain bands. A lower but significant impact is also found for the inland rainfall amounts over the Hérault region (up to -80 mm in the western part and +40 mm along the coasts).

3.3 ***Sensitivity to the sea state: impact of the peak period of waves***

In this part, we compare the two AROME forecasts both using WASP, but with a peak period as a function of the wind (hereafter 'ideal waves') or using the MARC WW3 three-hourly analyses (hereafter 'real waves'). Figure 5 illustrates the differences in the two T_p fields. In the case of 'ideal waves', large gradients and small scale patterns are obtained with the strongest T_p (>8 s) in the Ligurian Sea and the Gulf of Lion and very small T_p (<2 s) between Catalonia (Spanish coasts) and Sardinia (Fig. 5a). In the WW3 analysis, the gradients are smoother. The largest T_p are located in the north-western part and no T_p values go below 5 s (Fig. 5b).

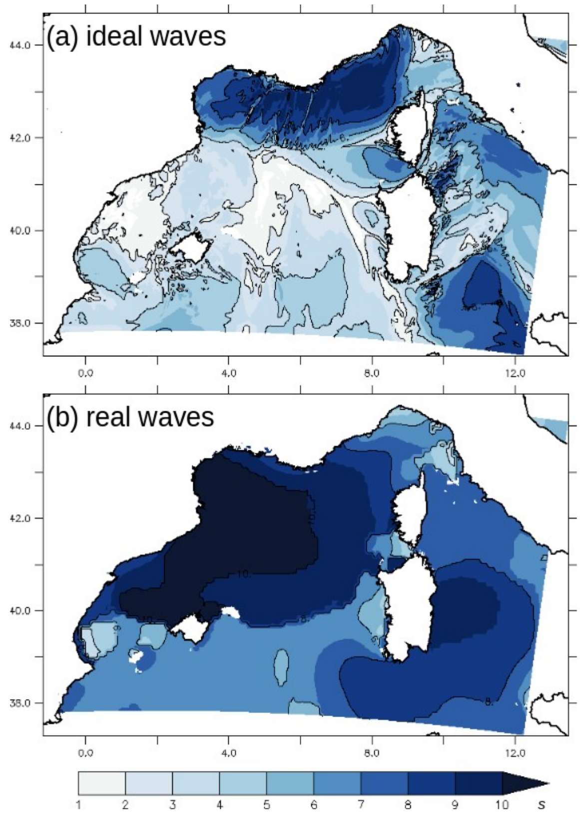

FIG 5. Peak period (T_p, in s) for 14 October 2016 00UTC: (a) for the 'ideal waves' case [T_p=f(U_a)] and (b) from the MARC WW3 product ('real waves' case).

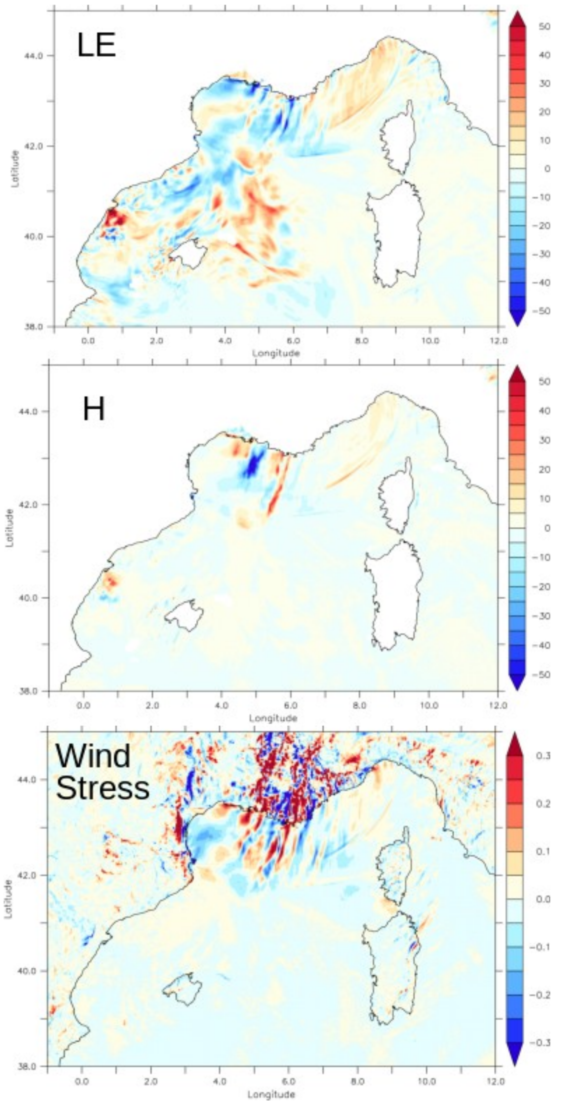

FIG 6. 14 October 2016 00UTC: Differences of latent (LE) and sensible (H) heat fluxes (W/m²) and wind stress (N/m²) between the ‘real waves’ and the ‘ideal waves’ forecasts.

Figure 6 shows the latent (LE) and sensible (H) heat fluxes and the wind stress differences between the two simulations. The main differences appear for three areas that can be distinguish due to different causes possibly involved. In the Ligurian Sea, below the easterly flow, a decrease in absolute value of the heat fluxes is found, associated with an increased wind stress and a decrease in wind speed (about 1.5 m/s, not shown) in this area. Large differences are found below the MCS [around 5.5°E-42.5°N], possibly due to differences in the convection dynamics and the related low-level winds. For LE and wind stress, significant differences are also found in the western part of the Gulf likely related to the differences in T_p. In the Balearic Sea, large modifications of LE are found, possibly related to the large differences in T_p in the moist southerly flow.

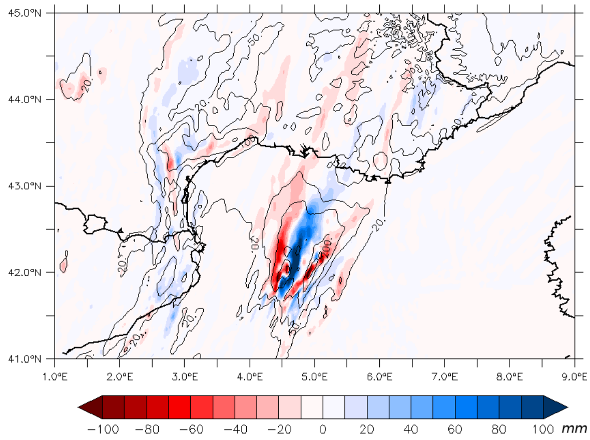

FIG 7. As Figure 3 but between forecasts using WASP with 'real waves' and 'ideal waves' - the black contours indicate the 24h-QPF in the simulation with 'ideal waves'.

Local changes on the QPF are seen (Fig. 7) mainly over sea. The precipitation inland seems not significantly affected by taking the sea state into account.

In fact, all the differences found between the ‘ideal waves’ and the ‘real waves’ forecasts are less important than when changing the SST or the parametrization of sea surface turbulent fluxes. Nevertheless, further investigation is needed to better attribute the processes leading to the heat fluxes and precipitation responses.

4. PRELIMINARY CONCLUSION AND FUTURE WORK

Several sensitivity tests were run in order to investigate the representation of the air-sea exchanges in the AROME model for the forecast of a Mediterranean HPE.

The sensitivity to the initial SST was re-assessed, in particular the direct impact on the heat fluxes related to SST anomalies. Further work is now needed to identify what are the main mechanisms involved in the indirect impact on convective systems and precipitation for that case.

The choice of turbulent flux parametrization appears of great importance as large differences are found in terms of fluxes, low-level conditions and QPF. This will be now further examined through ocean - atmosphere - waves coupled simulations which ensure more consistency at the air-sea interface for the fluxes computation.

The sea state impact was finally investigated with WASP. The comparison of forecast using two different waves forcing shows significant differences related directly to difference in T_p but also some indirect effects such as modification of the low-level wind related to surface roughness or of the MCS intensity/dynamics that must be studied in more details.

REFERENCES

Belamari, S., 2005: Report on uncertainty estimates of an optimal bulk formulation for turbulent fluxes. MERSEA Integrated Project, Tech. Rep., 29pp.

Belamari, S., and A. Pirani, 2007: Validation of the optimal heat and momentum fluxes using the ORCA2-LIM global ocean-ice model. MERSEA Integrated Project, Tech. Rep., 88pp.

Courtier, P., C. Freydier, J.-F. Geleyn, F. Rabier, and M. Rochas, 1991: The ARPEGE project at Météo-France. ECMWF workshop on numerical methods in atmospheric modeling, **2**, 193–231.

Drobinski, P., et al., 2014: HyMeX, a 10-year multidisciplinary program on the Mediterranean water cycle. *Bull. Amer. Meteorol. Soc.*, **95**, 1063-1082.

Ducrocq, V., et al., 2014: HYMEX-SOP1, the field campaign dedicated to heavy precipitation and flash flooding in the northwestern Mediterranean, *Bull. Amer. Meteorol. Soc.*, **95**, 1083–1100.

Ducrocq, V., S. Davolio, R. Ferretti, C. Flamant, V. Homar Santaner, N. Kalthoff, E. Richard, and H. Wernli, 2016: Advances in understanding and forecasting of heavy precipitation in Mediterranean through the HyMeX SOP1 field campaign. *Quart. J. Roy. Meteorol. Soc.*, **142**, 1-6.

Duffourg F, and V. Ducrocq, 2011: Origin of the moisture feeding the heavy precipitating systems over Southeastern France. *Nat. Hazards Earth Syst. Sci.,* **11**, 1163-1178.

Fairall, C., E. Bradley, J. Hare, A. Grachev, and J. Edson, 2003: Bulk parameterization of air-sea fluxes updates and verification for the COARE algorithm. *J. Clim.*, **16**, 571-591.

Lellouche, J.-M., O. Le Galloudec,M. Drévillon, C. Régnier, E. Greiner, G. Garric, N. Ferry, C. Desportes, C.-E. Testut, C. Bricaud, R. Bourdallé-Badie, B. Tranchant, M. Benkiran, Y. Drillet, A. Daudin, and C. De Nicola, 2013: Evaluation of global monitoring and forecasting systems at Mercator Océan. *Ocean Sci.*, **9**, 57–81.

Le Moigne, P., 2018: SURFEX v8.1 Scientifique Documentation. Tech. Rep. 304pp.

Madec, G., and the NEMO team, 2008: NEMO ocean engine, Note du Pole de modélisation, Institut Pierre-Simon Laplace (IPSL), France, **27**, 1288-1619.

Masson, V. et al., 2013: The SURFEX v7.2 land and ocean platform for coupled or offline simulation of earth surface variables and fluxes. *Geosci. Model Dev.,* **6**, 929-960.

Rainaud, R., C. Lebeaupin Brossier, V. Ducrocq, H. Giordani, M. Nuret, N. Fourrié, M.-N. Bouin, I. Taupier-Letage, and D. Legain 2016: Characterization of air-sea exchanges over the Western Mediterranean Sea during HyMeX SOP1 using the AROME-WMED model. *Quart. J. Roy. Meteorol. Soc.*, **142** (S1), 173-187.

Rainaud, R., C. Lebeaupin Brossier, V. Ducrocq, and H. Giordani, 2017: High-resolution air-sea coupling impact on two heavy precipitation events in the Western Mediterranean. *Quart. J. Roy. Meteorol. Soc.*, **143**, 2448-2462.

Seity, Y., P. Brousseau, S. Malardel, G. Hello, P. Bénard, F. Bouttier, C. Lac, and V. Masson, 2011: The AROME-France convective-scale operational model. *Mon. Wea. Rev.*, **139**, 976-991.

Taillefer, F., 2002: CANARI (Code for the analysis necessary for Arpege, for its rejects and its initialization): Technical documentation. Tech. Rep. Groupe de Modélisation pour l'Assimilation et la Prévision, Centre National de Recherches Météorologiques, Météo-France, Toulouse, France. www.umr-cnrm.fr/gmapdoc/spip.php?article3.

Tolman, H. L., 2002: Validation of WAVEWATCH-III version 1.15. Tech. Rep. no 213, 33 pp., NOAA/NWS/NCEP/MMAB.

Tolman, H. L., 2009: User Manual and System Documentation of WAVE-WATCH III TM Version 3.14. NCEP Tech. Note, 220 pp.