Impact of Forcing/Coupling on Atmospheric and Oceanic Forecasts

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1 Abstract

The south-eastern France is prone to heavy rain events during the fall season. For these extreme precipitating events, the Mediterranean Sea fuels the atmospheric boundary layer in heat and moisture and contributes sometimes to accentuate flooding. This study aims at examining on what extent the SST, the surface heat fluxes and the coupling of an oceanic mixed-layer to an atmospheric model affect severe Mediterranean mesoscale convective systems. The feedbacks on the ocean mixed-layer are also presented. This study could help us at defining the best coupling strategy for mesoscale atmospheric forecasting.

2 Introduction

It is well known that the spatial distribution of **S**ea **S**urface **T**emperature (SST) and associated surface heat / momentum fluxes induces strong modifications of the flow in the Marine Atmospheric Boundary Layer (MABL) over a large range of spatial scales, specially at mesoscale. For example, intense thermal gradients frequently form within the MABL in presence of major oceanic currents, such as the Gulf Stream, Kuroshio and Azores currents, in response to the large differential surface energy fluxes. The MABL takes therefore a baroclinic structure which induces ageostrophic circulations dynamically similar to a sea breeze (Khalsa and Greenhut, 1989). Such SST-induced MABL baroclinicity can trigger explosive cyclogeneses at middle latitudes (Giordani and Caniaux, 2001) or secondary circulations in the MABL as strong as the synoptic flow either in equatorial/tropical regions (Zhang and Busalacchi, 2008) or at middle latitudes (Giordani and Planton, 1998). Intense surface fluxes associated with high SST can also destabilize the MABL, increase the convection activity and the cyclogenesis intensity during its initial stage (Homar et al., 2003).

However, it has also been shown that not only the SST has to be considered when analysing the influence of the ocean on meteorological phenomena, but also the upper ocean thermal structure. As instance, it has been found that the Atlantic hurricanes intensify when passing over deep warm ocean cores (Goni and Triganes, 2003). Some studies have also shown that tropical cyclone are more sensitive to the mixed-layer heat content than to the SST (Wada et al., 2007). As consequence, coupled **O**cean-**A**tmosphere (OA) models are more suited to simulate such events with more realism because the oceanic heat content evolution is taken into account. Few studies have examined the interaction between the Mediterranean sea and the mesoscale atmospheric events using a kilometric-scale OA coupled system. They have mainly focused on the study of Bora events over the Adriatic sea. Coupled high-resolution simulations performed on these situations have shown that the full interactive coupling provided more accurate SST than the forced ocean simulations (Loglisci et al., 2004; Pullen et al., 2006).

Heavy precipitating events frequently occurred over the Western Mediterranean basin during the fall season, often leading to floods and damages. Heavy rainfall events are characterized by **M**esoscale **C**onvective **S**ystems (MCS) generating large precipitation totals that could persist during several days. The synoptic patterns leading to these events are generally well known, but the intensity and the stationarity of these systems are mainly controlled by various mesoscale factors (Mediterranean Sea surrounding mountains, cooling beneath the convection due to precipitation evaporation, low-level wind convergence and moisture transport; Ducrocq *et al.*, 2002, 2003; Nuissier *et al.*, 2008) including the Mediterranean sea. Indeed the Mediterranean Sea contributes to fuel these heavy precipitating systems in heat and moisture (Millan *et al.*, 1995; Romero *et al.*, 1997; Pastor *et al.*, 2001; Homar *et al.* 2003; Lebeaupin *et al.*, 2006) and could also play a part in amplifying floods when the swell and waves perturb the river runoff.

This paper presents a sensitivity study of three Mediterranean MCSs during the fall season to the **i)** SST **ii)** the surface fluxes parameterization and **iii)** the coupling of an ocean mixed-layer model to an atmospheric model. The mixed-layer sensitivity to the surface fluxes is also presented. Both oceanic and atmospheric responses are investigated in order to identify the key oceanic parameters for MCS forecasting.

3 Experimental Design

3.1 Heavy Precipitation events

The three selected heavy precipitation events are the same than in Lebeaupin et al. (2006). The events, named from the French department[1] that received the most important precipitation amount, occurred on:

- 12-13 November 1999 (hereafter *Aude* case),
- 8-9 September 2002 (hereafter *Gard* case),
- 3 December 2003 (hereafter *Hérault* case).

These three cases are major torrential rain events that occurred over South-eastern France; huge precipitation totals (more than 500 mm in less than 24 hours), mainly induced by quasi-stationary mesoscale convective systems, have been recorded. These events resulted in major flash floods with more than 30 and 20 fatalities, respectively. A comprehensive description of these cases can be found in (4), (5) and (3), only a brief overview is given here.

The Aude case was characterized by an upper-level low-pressure area centred over Spain on 12 November 1999 at 1200 UT that induced a vast southerly flow from North Africa to southern France. Within the warm air mass transported by the southerly flow, surface lows formed and accelerated the low-level easterly to south-easterly jet over the Mediterranean Sea with winds of more than 25 m s^{-1}. The convergence is also enhanced by the deflection of the low-level flow by the Southern Alps. The surface rainfall totals reached the maximum value of 624 mm in less than 48 hours in Lézignan-Corbières (Aude department).

The Gard case was characterized by an upper-level cold pressure low centred over Ireland and extending to the Iberian Peninsula during the morning of 8 September 2002, resulting in a southwesterly diffluent flow over South-eastern France. Associated with the upper-level low-pressure area, a surface cold front undulated over western France. An intense southerly low-level flow, conditionally unstable, established over the French South-eastern coast. Convection organized in a MCS and became quasi-stationary and affected mainly the Gard region. The precipitating system has stayed over the region for almost 24 hours. During this period, surface rainfall totals reached until 691 mm in 24 hours recorded near the Alès town (Gard Department).

The Hérault case was characterized by an upper-level low-pressure area centred over Spain that established a southerly flow over southern France, and, a slow moving surface frontal system with embedded convection. The cold surface front stationned over the Gulf of Lions area and South-eastern France from 1 to 4 December 2003. The 3 December 2003, which was the most convective day, daily rainfall totals reached about 150 mm. Low-level winds also intensified during this day: easterly wind gusts up to 25-40 m s^{-1} over the Gulf of Lions

[1] A department is a subdivision of France administered by a prefect.

were observed and a strong swell, with associated beachcombers waves reaching 9 meters, disturbed the river water run-off to the sea. The flooding resulted in a major flood of the Rhône river.

4 The Numerical Tools

4.1 The MESO-NH Atmospheric Model

Atmospheric simulations were performed with the non-hydrostatic mesoscale MESO-NH model (13). The same model configuration as in Lebeaupin et al. (2006) is used with two interactive nested grids running at horizontal resolution of 9.5 km and 2.4 km respectively (Figure 1), centered over the mesoscale system with location and size depending on the studied case. The sub-grid scale convection is parameterized following (2) at 9.5 km resolution whereas no convective scheme is used at 2.4 km. We focus in the following on the 2.4km-domain that covers approximately a 600km x 600km area around the Gulf of Lions. The atmospheric initial states are provided by the ARPEGE analyses.

4.2 The 1D Ocean Model

The one-dimensional kinetic energy model described by Gaspar et al. (1990) has been used for simulations of the oceanic vertical mixing. By analogy with the atmospheric turbulence, this model includes a prognostic equation for the turbulent kinetic energy with a 1.5 closure. The prognostic variables are the temperature, the salinity and the current defined on 40 vertical levels, spaced by 5 m near the air-sea surface up to 1000 m for the deeper ocean. The ocean temperature and salinity are initialized by a MERCATOR analysis (1). The current are initially supposed to be null.

4.3 The Ocean-Atmosphere Coupled System

MESO-NH can be coupled to the ocean mixed-layer model at each grid point of the atmospheric sea domain through the surface module SURFEX. Given that the ocean model is attached to the atmospheric horizontal grid, no coupler is required. When the coupling is activated, the atmospheric model supplies the ocean model with forecasts of radiation, turbulent heat and momentum fluxes and precipitation rates. The ocean model upadates the SST that is used as the bottom boundary conditions of the atmospheric model at the coupling frequency.

Forced and coupled simulations of the Aude, Gard and Hérault cases were carried out with this system over the domain shown Figure 1.

5 Forced Simulations

5.1 MCS Sensitivity to Sea Surface Turbulent Fluxes

Figure 2 displays the sensible (H) and latent (LE) heat fluxes for ORI, ECUME and COARE experiments during the Aude case. ORI (Louis, 1979), ECUME (Weill et al., 2003) and COARE (Fairall et al., 2003) are three surface fluxes parameterizations used in the atmospheric simulations. The differences are especially large under the low-level jet. Indeed, the Aude case is characterized by strong southeasterly/easterly low-level jets ($\geq$25 m s^{-1}) converging over the Gulf of Lions. Associated with the strong convergent winds, large latent heat fluxes over the sea are therefore simulated, until more than 500 W m^{-2} near the French coasts at 0600 UT, 13 November 1999 in ORI experiment. The COARE and ECUME experiment simulates latent heat fluxes in that

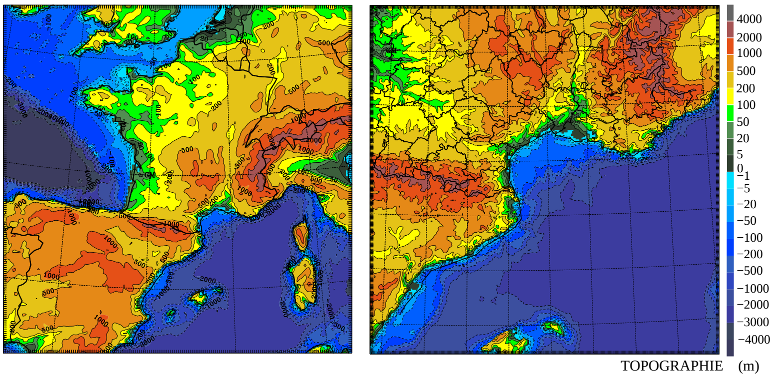

Figure 1: Simulation domains. Large domain at the resolution 9.5 km (left). Small domain in the Western Mediterranean basin at the resolution 2.4 km (right).

area that can be 200 W m^{-2} weaker than the ORI ones. In average over the sea domain the difference reaches $60W/m^2$. The sensible heat fluxes are not significantly different between the two parameterizations.

For the three cases, the COARE3.0 and ECUME parameterizations result in a reduction of the maximum of precipitation by 5 to 10 %. Weaker latent heat fluxes and less unstable low-levels result in a decrease by about 10% of the precipitation amounts and of its maximum without having a significant impact on the location of the convective system in the Aude case (Fig. 3). Although the mean precipitation surface totals on the domain are very close between the two experiments, the local maximum value of 24h-precipitation totals is lower by 30 mm in COARE and ECUME compared to ORI (Fig. 3). Scores against the observations show that for that case the 24h-precipitation totals simulated by COARE are slightly improved, with reduced bias and root mean square and higher correlation (not shown).

5.2 Oceanic Mixed-Layer response to MCS forcing

The strong heat and momentum surface fluxes associated with MCSs result in strong cooling and deepening of the mixed-layer typically of $0.5^oC/day$ and $30m/day$, respectively (Lebeaupin et al., 2006). In order order to analyze the precipitation effect on the mixed-layer, two simulations were performed by desactivating and activating the precipitation on the Hérault case (Fig. 5). Without precipitation (Figure 4), the mixed-layer strongly deepens up to $200m$ in accordance with the strong surface heat loss and surface wind-stress. When activating the precipitation, the rain band at sea rapidly decreased the mixed-layer depth by decreasing the salinity in the oceanic upper layers. A marked internal and stably boundary layer developed as shown on the Figure 6. The underlying question is what impacts could have such oceanic structures on surface fluxes and finally on MCSs ?

5.3 Effect of Time Frequency on the Oceanic Mixed-Layer

From the atmospheric simulation, three sets of atmospheric forcing for the ocean model were defined. The first one has a time resolution equal to the time step of the ocean model. The instantaneous fields of the atmospheric simulation are thus provided to the ocean model every 5 minutes (OWO_05m) then, we averaged the atmospheric fields over 1 hour (OWO_01h) and 6 hours (OWO_06h). The averaged values are used to drive the ocean model during each 1 hour and 6 hours period, respectively. Thus, the energy amount exchanged between the ocean and the atmosphere is the same at the end of the simulation for the three sets. Large differences in surface density between the experiments OWO_06h and OWO_05m are found beneath the heaviest rainfall and under the low-level jet (Fig. 7). In OWO_06h experiment, the low-level jet intensification after 14 UT (until locally 30 m s^{-1}) is not really captured in the 6-hour averaged wind stress. The currents simulated by

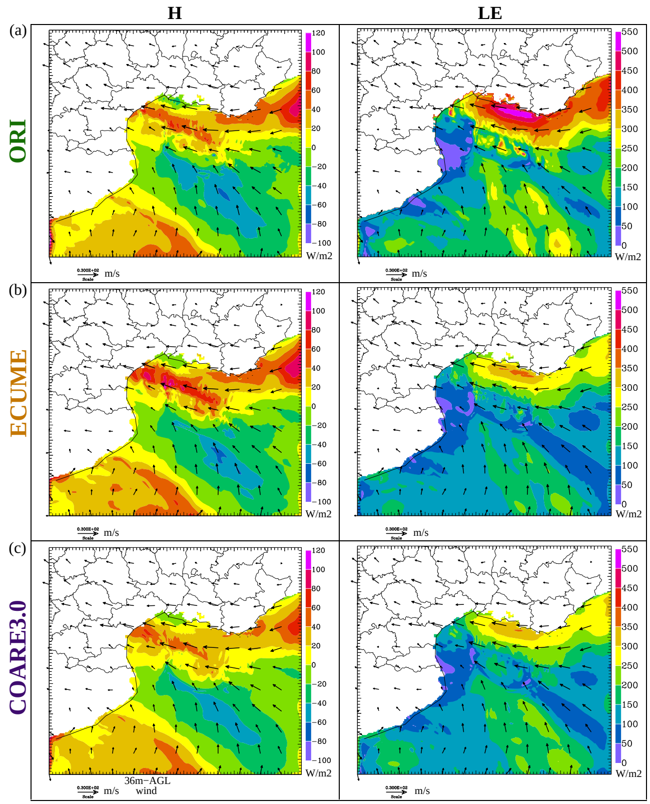

Figure 2: Aude case: Simulated surface wind superimposed to the sensible heat flux (left) and to the latent heat flux (right). Surface fluxes simulated by ORI (a); ECUME (b) and COARE (c).

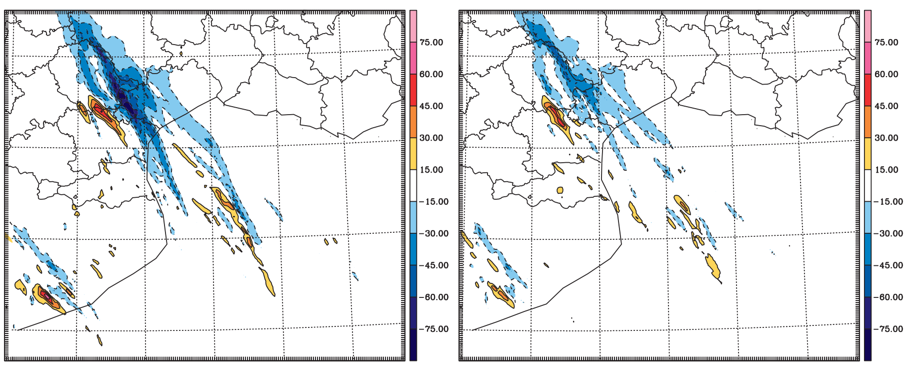

Figure 3: Aude case : 24h-accumulated precipitation differences between the simulations using the surface parameterizations ECUME and ORI (ECUME-ORI, left) and COARE and ORI (COARE-ORI, right).

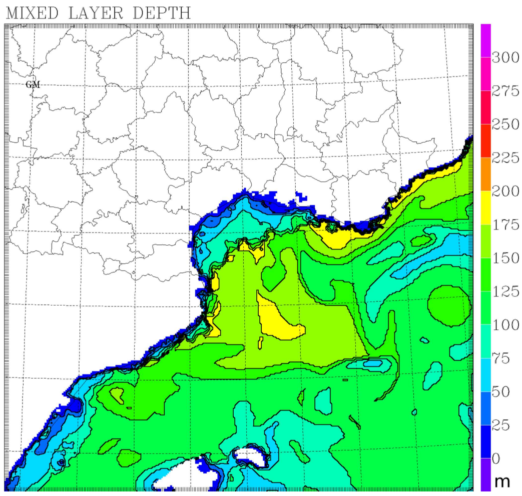

Figure 4: Hérault case : Simulated oceanic mixed-layer depth without precipitation.

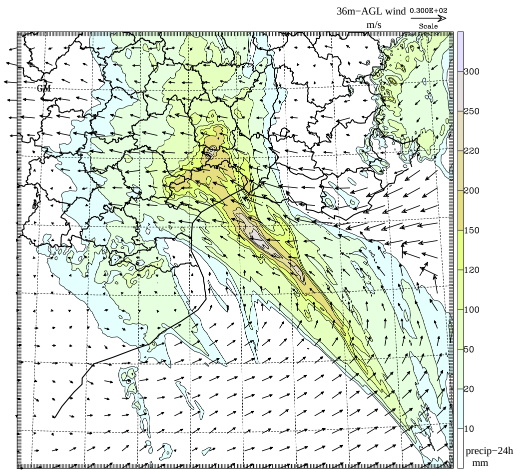

Figure 5: Hérault case : 24h-accumulated precipitation field.

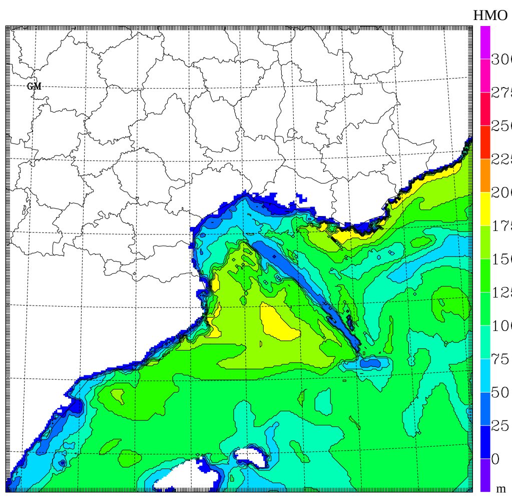

Figure 6: Hérault case : Simulated oceanic mixed-layer depth with precipitation. The shallow mixed-layer and the rain band at sea in the Gulf of Lions shown in Figure 5 are at the same location.

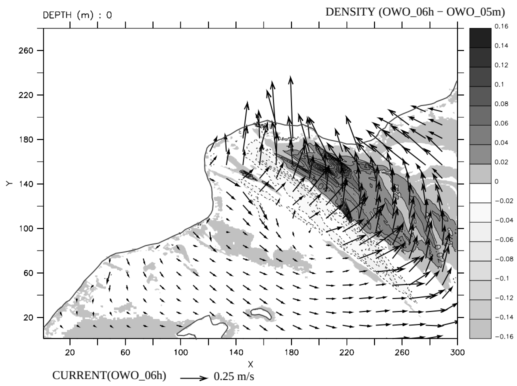

Figure 7: Hérault case : Surface water density difference between the simulations using the surface forcing frequency 6h and 5 min. The surface wind-induced current is superimposed to the difference density field.

OWO_06h are consequently weaker than those simulated by OWO_01h and OWO_05m. The intense rainfall rates are also smoothed and replaced by moderate rainfall rates in OWO_06h, so the fresh-water input by the precipitation is more easily integrated to the ocean mixed layer by the turbulent vertical mixing in OWO_06h. On the opposite, in OWO_05m or OWO_01h, heavy precipitation that reach 60 mm/h locally, perturb or even stop during several hours the ocean vertical turbulent mixing, and forms relatively thin internal boundary layer near the interface with relative low-salty water.

6 Impact of Coupled Simulations to Heavy Rainfall Events

As shown by Lebeaupin *et al.* (2006), the intensity of the atmospheric deep convection and the precipitation totals are sensitive to the total energy available in the atmospheric low-layer over the sea. As SST decreases with time during the full interactive mode (CPLCO), it induces a steady decrease of the air-sea heat fluxes and therefore of the energy available from the Mediterranean Sea for the atmospheric deep convection. Consequently, the precipitation systems are slightly less intense and generate weaker surface rainfall totals. For example, for the Gard case (Fig. 6), the maximum 24-h precipitation amount in CPLCO is 24mm weaker than the one simulated by the forced mode CFCOA. The accumulated precipitation patterns are however very similar between the two experiments.

To sum-up, the comparison between the one-way forcing and the two-way coupling shows that the full two-way coupling tends to attenuate the two boundary layer responses. During the Mediterranean heavy precipitation events, large sea-air fluxes prevail and cools the ocean mixed layer which in turn tends to lower sea-air fluxes in the two-way coupling. For the short-range simulations performed here, the differences between the full two-way coupled and the one-way forced modes are however relatively small.

7 Conclusions

This study has shown a significant sensitivity of mesoscale convective system to the surface fluxes and to the SST because both these elements drive the atmospheric stability (CAPE) at least in the boundary layer. Using a higher-resolution SST field produces smaller-scale patterns in the surface heat fluxes fields, but has minor impacts on the convection and on low-level jets (not shown, see oral presentation or Lebeaupin et al., 2006). Also a modification in SST field can induce different atmospheric dynamical responses according to the meteorological case (not shown, see oral presentation or Lebeaupin et al., 2006).

The oceanic mixed-layer has also shown a great response to strong surface heat loss and surface wind stress as-

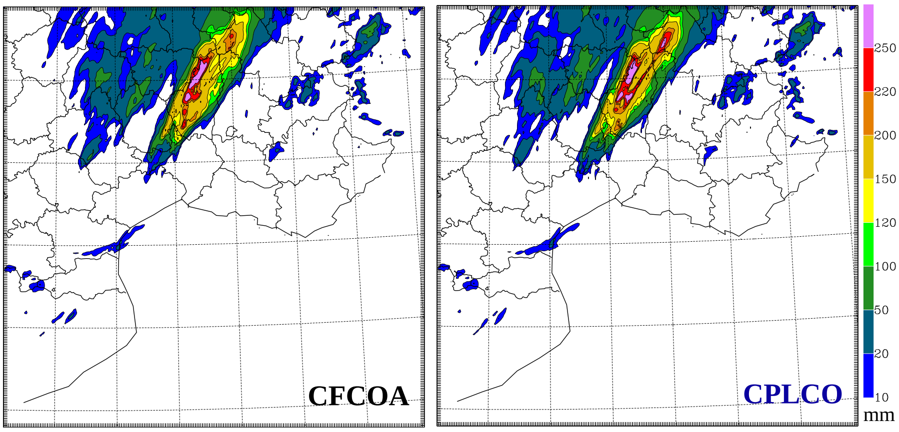

Figure 8: Gard case : Simulated 24h-accumulated precipitation field in the forced mode (left) and in the coupled mode (right).

sociated with mesoscale convective systems. Particularly, the development of fresh and stably internal boundary layers induced by intense precipitation rates is strongly affected by the surface forcing frequency.

The full two-way coupling tends to attenuate the oceanic and atmospheric boundary layer responses compared to the one-way mode. As a result, convective activity and rainfall intensity are weaker in the coupled simulations compared to the forced simulations. The limited feedbacks on the heavy precipitating systems must be tempered by the short duration of the simulations (24 h).

8 Major Issues for Coupled Mesoscale Models

Although this study has shown a limited impact of the ocean-atmosphere coupling on three mesoscale convective cases, this result cannot be considered as a general conclusion. A lot of other various atmospheric situations have to be studied to conclude on the relevance of the coupling at mesoscale. Nevertheless the results of this study help us to identify some key points of the coupling at mesoscale which are still open questions : what resolution for the SST fields ? what surface fluxes parameterization ? what coupling frequency ? what vertical mixing (diffusion/convection) in ocean models ? what would be the added value for operational atmospheric forecasting to couple an oceanic mixed-layer model ?

References

Bahurel, P., E. Dombrowsky, J.-M. Lellouche, and the Mercator project team, 2004: Mercator ocean monitoring and forecasting system, near-realtime assimilation of satellite and in-situ data in different operational ocean models. *Proc. 36th International Liège Colloquium on Ocean dynamics*, Liège.

Bechtold, P., E. Bazile, F. Guichard, P. Mascart, and E. Richard, 2001: A mass-flux convection scheme for regional and global models. *Quart. J. Roy. Meteo. Soc.*, **127 (573)**, 869–886.

Delrieu, G., V. Ducrocq, E. Gaume, J. Nicol, O. Payrastre, E. Yates, P.-E. Kirstetter, H. Andrieu, P.-A. Ayral, C. Bouvier, J.-D. Creutin, M. Livet, S. Anquetin, M. Lang, L. Neppel, C. Obled, J. Parent du Châtelet, G.-M. Saulnier, A. Walpersdorf, and W. Wobrock, 2005: The catastrophic flash-flood event of 8–9 September 2002 in the Gard region, France: A first case study for the Cévennes-Vivarais Mediterranean Hydrometeorological Observatory. *J. Hydrometeor.*, **6**, 34–52.

Ducrocq, V., D. Ricard, J.-P. Lafore, and F. Orain, 2002: Storm-scale numerical rainfall prediction for five precipitating events over France: On the importance of the initial humidity field. *Wea. Forecasting*, **17 (6)**, 1236–1256.

Ducrocq, V., K. Chancibault, F. Habets, and S. Anquetin, 2003: Meso-scale modelling of a flooding storm. Application to the extreme flood of Gard. *Proc. 5th Plinius Conf. on Mediterranean Storms*, Ajaccio, France, EGS, 43–52.

Fairall, C. W., E. F. Bradley, J. E. Hare, A. A. Grachev, and J. B. Edson, 2003: Bulk parameterization of air-sea fluxes : Updates and verification for the COARE algorithm. *J. Climate*, **16**, 571–591.

Gaspar, P., Y. Grgoris, and J.-M. Lefevre, 1990: A simple Eddy Kinetic Energy model for simulations of the oceanic vertical mixing: Tests at station Papa and Long-Term Upper Ocean Study site. *J. Geophys. Res.*, **95 (C9)**, 16 179–16 193.

Giordani, H., S. Planton, B. Bénech and B.H. Kwon, 1998: Atmospheric Boundary Layer Response to Sea Surface Temperature during the SEMAPHORE Experiment. *J. Geophys. Res.*, **103 (C11)**, 25 47-25 60.

Giordani, H. and G. Caniaux, 2001: Sensivity of cyclogenesis to sea surface temperature in the Northwestern Atlantic. *Mon. Wea. Rev.*, **129**, 1273–1295.

Goni, G. and J. Triganes, 2003: Ocean thermal structure monitoring could aid in the intensity forecast of tropical cyclones. *EOS, Tansactions, American Geophysical Union.*, **84**, 573–580.

Homar, V. and Romero, R. and Stensrud, D. J. and Ramis, C. and Alonso, S., 2003: Numerical diagnosis of a small, quasi-tropical cyclone over the western Mediterranean: Dynamical vs. boundary factors. *Quart. J. Roy. Meteor. Soc.*, **129**, 1469–1490.

Khalsa, S.J.S. and G.K. Greenhut, 1989: Atmospheric Turbulence Structure in the Vicinity of an Oceanic Front. *J. Geophys. Res.*, **94**, 4913–4922.

Lafore, J.-P., J. Stein, N. Asencio, P. Bougeault, V. Ducrocq, J. Duron, C. Fischer, P. Héreil, P. Mascart, V. Masson, J.-P. Pinty, J.-L. Redelsperger, E. Richard, and J. Vilà-Guerau de Arellano, 1998: The Meso-NH Atmospheric Simulation System. Part I: Adiabatic formulation and control simulations. Scientific objectives and experimental design. *Ann. Geophysic.*, **16 (1)**, 90–109.

Lebeaupin, C., V. Ducrocq, and H. Giordani, 2006: Sensitivity of mediterranean torrential rain events to the sea surface temperature based on high-resolution numerical forecasts. *J. Geophys. Res.*, **111**, D12 110, doi:10.1029/2005JD006541.

Loglisci, N. and Qian, M. W. and Rachev, N. and Cassardo, C. and Longhetto, A. and Purini, R. and Trivero, P. and Ferrarese, S. and Giraud, C., 2004: Development of an atmosphere-ocean coupled model and its application over the Adriatic Sea during a severe weather events of Bora wind. *J. Geophys. Res.*, **109**, doi:10.1029/2003JD003956.

Louis, J.-F., 1979: A parametric model of vertical eddy fluxes in the atmosphere. *Bound.-Lay. Meteorol.*, **17 (2)**, 187-202.

Millan, M. M. and Estrela, M. J. and Casseles, V., 1995: Torrential precipitations on the spanish east coast: The role of the mediterranean sea surface temperature. *Atmos. Res.*, **36**, 1-16.

Nuissier, O., V. Ducrocq, D. Ricard, C. Lebeaupin, and S. Anquetin, 2008: A numerical study of three catastrophic precipitating events over Western Mediterranean region (Southern France). part I: Numerical framework and synoptic ingredients. *Quart. J. Roy. Meteor. Soc.*, **134**, 111-130.

Pastor, F. and Estrela, M. J. and Penarrocha, P. and Millan, M. M., 2001: Torrential rains on the spanish Mediterranean coast: Modelling the effect of the sea surface temperature. *J. Appl. Meteor.*, **40**, 1180–1195.

Pullen, J. and Doyle, J. D. and Signell, R. P., 2006: Two-way air-sea coupling: A study of the Adriatic. *Mon. Wea. Rev.*, **135**, doi:10.1175/MWR3137.1.

Romero, R. and Ramis, C. and Alonso, S., 1997: Numerical simulation of an extreme rainfall event in Catalonia: Role of orography and evaporation from the sea. *Quart. J. Roy. Meteor. Soc.*, **123**, 537–559.

Wada, A. and N. Usui, 2007: Importance of tropical cyclone heat potential for tropical cyclone intensity and intensification in the Western North Pacific. *J. of Oceanogr.*, **63**, 427–447.

Weill, A. and Eymard, L. and Caniaux, G. and Hauser, D. and Planton, S. and Dupuis, H. and Brut, A. and Guerin, C. and Nacass, P. and Butet, A. and Cloch, S. and Pedreros, R. and Bourras, D. and Giordani, H. and Lachaud, G. and Bouhours, G., 2003: Toward better determination of turbulent air-sea fluxes from several experiments. *J. Climate*, **16 (4)**, 600–618.

Zhang, R.H. and Busalacchi, A., 2008: Rectified effects of tropical instability wave (TIW)-induced atmospheric wind feedback in the tropical Pacific. *Geophys. Lett.*, **35**, doi:10.1029/2007GL033028.