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Impact of Sea Surface Temperature on COSMO Forecasts of a Medicane over the Western Mediterranean Sea

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Abstract: The paper describes and analyzes the sensitivity of an operational atmospheric model to different SST (sea surface temperature) estimates. The model's sensitivity has been analyzed in a Medicane (Mediterranean hurricane) test case. Numerical simulations have been performed using the COSMO (consortium for small-scale modeling) atmospheric model, in the COSMO-ME configuration. The model results show that the model is capable of capturing the position, timing and intensity of the cyclone. Sensitivity experiments have been carried out using different SSTs surface boundary conditions for the COSMO forecasts. Four different experiments have been carried out: the first two using SST fields obtained from the OSTIA (operational sea surface temperature and sea ice analysis) system, while the other two using the SST analyses and forecasts from MFS (Mediterranean Forecasting System, Tonani et al., 2015; Pinardi and Coppini, 2010). The different boundary conditions determine differences in the trajectory, pressure minimum and wind intensity of the simulated Medicane. The sensitivity experiments showed that a colder than real SST field determines a weakening of the minimum pressure at the vortex center. MFS SST analyses and forecasts allow the COSMO model to simulate more realistic minimum pressure values, trajectories and wind speeds. It was found that MFS SST forecast, as surface boundary conditions for COSMO-ME runs, determines a significant improvement, compared to ASCAT observations, in terms of wind intensity forecast as well as cyclone dimension and location.

Key words: Mediterranean Sea, Medicane, atmospheric model, oceanic model.

1. Introduction

In recent years, the scientific community has started to detect and analyze tropical-like cyclones in the Mediterranean Sea [1]. The Mediterranean is a large and sometimes warm body of water, thus it can be an area of cyclogenesis influenced by convective instability and air-sea interaction, producing cyclones with some of the characteristics of hurricanes [2, 3]. The western Mediterranean Sea is an important cyclogenetic area [4]. These cyclones are characterized by strong winds and a pressure minimum in the middle (calm eye). Such systems are referred in the literature as Medicanes (Mediterranean Hurricanes) and are rare phenomena (only one or two per year) [1, 5].

Since the early 1980s, satellite images have enabled identification and structure analysis of cyclones. The horizontal scale of cyclones ranges from some tens to a few hundreds of kilometers, with typical lifetime of about one to three days.

We analyzed the results of numerical simulations of a Medicane, occurring over the western Mediterranean Sea from 7 to 9 November 2011. The aim was to understand the impact of air-sea interactions in the maintenance/formation and the characteristics of the cyclone. In recent hurricane-like cyclones in the Mediterranean, convective instability has been shown to play an important role [6]. The means by which convective instability is produced has been the subject

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of many numerical studies examining the role of heat and moisture fluxes rising from the Mediterranean Sea. Some numerical experiments [7] illustrate that both the surface heat and moisture fluxes are fundamental for this type of hurricane-like cyclogenesis and they play also an important role in the subsequent development of the cyclone. Sensitivity simulations [8] have highlighted the sea-air fluxes role in the formation of the storm as well as the strong influence of the latent heat release associated with convective motions during its mature stage. It has been hypothesized [9] that a hurricane-like cyclone can intensify in a similar way to tropical cyclones.

2. The Meteorological Events

On 3 November 2011, a wide trough between the British Isles and the Strait of Gibraltar produced a pressure minimum near Ireland (Fig. 1a). The following day, the trough moved eastward, approaching the southern Mediterranean Sea and its axis tended to rotate counter-clockwise, resulting in a split of the jet bordering the trough. On November 5, the low pressure of the trough almost split into an isolated minimum, slowing down its eastward motion (Fig. 1c), while an ascending branch of the polar jet, associated with a negative anomaly in the high tropopause, was further displaced toward the central Mediterranean (not shown). This baroclinic structure caused a marked area of instability in the central Mediterranean. On November 6, the cyclonic depression disengaged completely from the main mid-latitude westerly jet producing a low cut-off between the Balearic Islands and Sardinia (Fig. 1d). On November 7, the minimum pressure tends widened horizontally and took on an increasing barotropic structure, with the cloud cover having the typical characteristics of tropical-like cyclones. Fig. 2 shows the cloud cover evolution captured by the Meteosat 9 satellite images in the IR channel (10.8 micrometers).

These satellite images show the persistence of the vortex throughout the first 12 hours of November 9, when the Medicane progressively loses its intensity and expires in the Gulf of Lyon.

The NOAA SSD (Satellite Service Division) categorized this system as a 01M tropical storm (http://www.ssd.noaa.gov/PS/TROP/DATA/2011/tdata/med/01M.html) to indicate that the cyclone is "almost perfectly barotropic" and that the Mediterranean Sea basin is capable of developing this type of cyclone.

3. COSMO and MFS

The meteorological event described was simulated using the COSMO (consortium for small-scale modeling) atmospheric model which is a limited-area, non-hydrostatic forecasting model (http://www.cosmo-model.org/). It was designed both for operational numerical weather prediction and various scientific applications at meso-β (20-200 km) and meso-γ scales (2-20 km). The basic version of the COSMO model was designed at the German weather service (DWD) and developments are carried out within the consortium formed by the national meteorological services of seven European countries:

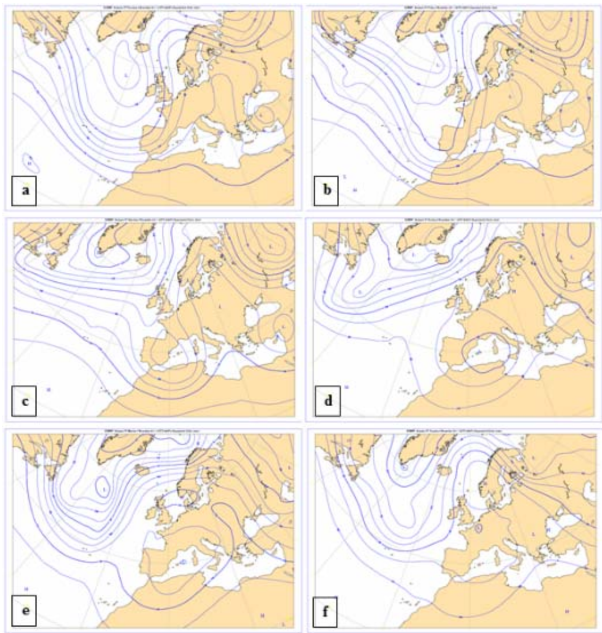

Fig. 1 Geopotential height (500 hPa) from 3 to 8 November 2011 by ECMWF analyses at 12:00 (corresponding to a), …, f) panels).

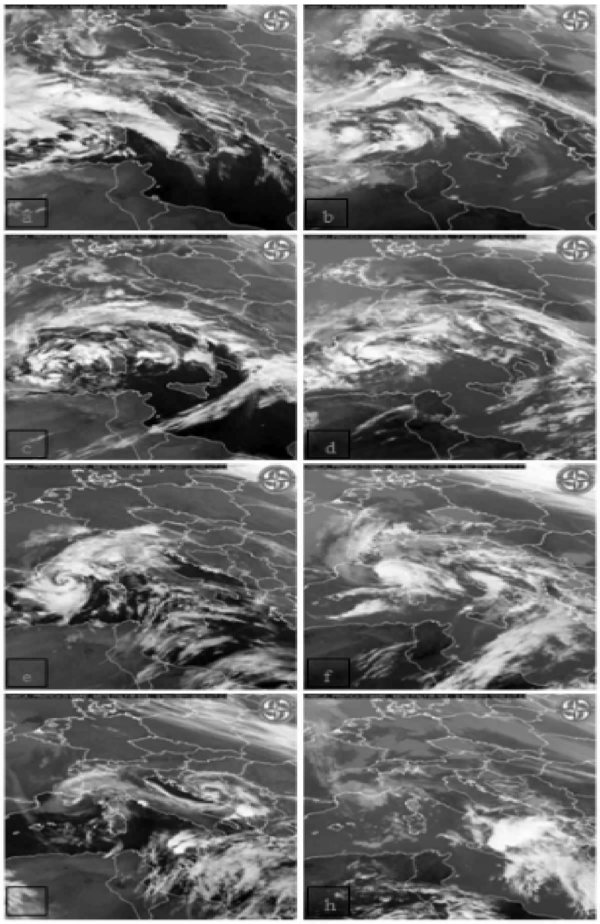

Fig. 2 Meteosat 9 satellite observations in the infrared channel (10.8 micrometers) from 00:00 UTC on 6 November to 12:00 UTC on 9 November every 12 hours (corresponding to a), …, h) panels).

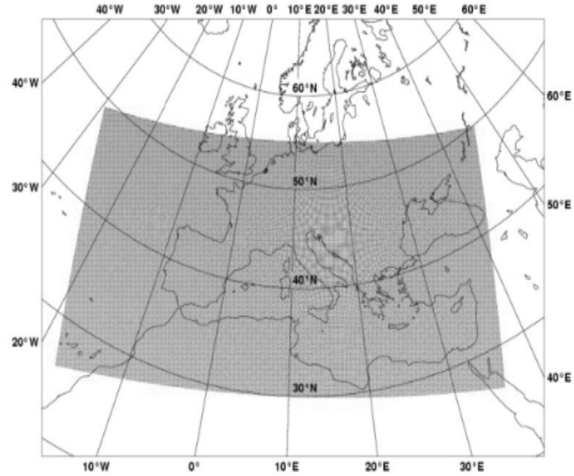

Fig. 3 Domain of the COSMO model in the COSMO-ME configuration.

Germany, Greece, Italy, Poland, Romania, Russia and Switzerland. Operational applications of the model within COSMO mainly have a grid spacing of 1/16° (about 7 km).

The Italian Meteorological Centre (CNMCA) uses the configuration COSMO-ME which covers most of Europe (Fig. 3) with a horizontal grid of 7 km and 40 vertical levels with a top at about 22 km. The model's time integration step is 60 seconds. The operational integration of COSMO-ME is driven by the boundary conditions provided by the IFS (integrated forecast system) global model of ECMWF and is initialized with atmospheric analysis fields produced by the LETKF ensemble data assimilation system implemented at CNMCA [10, 11]. Both IFS and COSMO-ME use optimally interpolated SSTs (sea surface temperatures) from the OSTIA system (Operational Sea surface Temperature and sea Ice Analysis [12]), which includes satellites and in situ data. The initial SST fields are kept constant as boundary conditions during the COSMO-ME forecast time.

In this paper, SST forecast fields produced by the MFS (Mediterranean forecasting system) will be also used as initial and boundary conditions. MFS (http://medforecast.bo.ingv.it/) is an operational forecasting system [13-15] consisting of a near real-time observation system with satellite and in situ elements, a numerical ocean forecasting model at a basin scale, based on a primitive equation model [16, 17], and a data assimilation scheme [18]. The MFS spatial domain is shown in Fig. 4. The numerical ocean model has a resolution of 1/16° × 1/16° on the horizontal and 72 unevenly spaced vertical levels [16]. The system produces daily ten-day ocean forecasts and ocean analyses using a daily assimilation cycle [19, 20] where a different optimally interpolated SST from satellites [21] is used to constrain the model surface temperature.

4. Event Description Using COSMO-ME Forecasts: Dynamics, Heat Fluxes and Thermal Structure

COSMO-ME forecasts were used to detect the main features of the vortex and its intensity from initial stages. To classify the type of cyclone, the expected wind speed at 10 meters and in particular the maximum speed value in the area was considered. We refer to the modified Saffir-Simpson hurricane wind-scale (http://www.nws.noaa.gov/directives/sym/pd01006004curr.pdf) to classify the cyclone.

The best estimate of maximum forecast wind was obtained from three different 00 UTC operational runs of the model for 6, 7 and 8 November (Fig. 5).

The Medicane can be classified as a tropical storm, with maximum winds between 18 and 32 m/s in its mature phase. The most intense phase of the vortex lasted for about two and a half days from 00:00 UTC on November 7 to 12:00 on November 9. The evolution of the Medicane was characterized by a growth phase of about 40-44 h, during which the maximum intensity of the wind increased from 18 to 28 m/s, and by a more rapid decrease of approximately

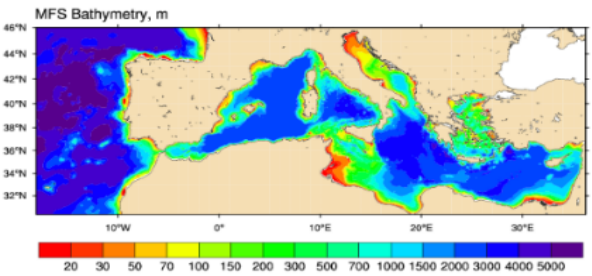

Fig. 4 Domain and bathymetry (m) of the MFS model configuration.

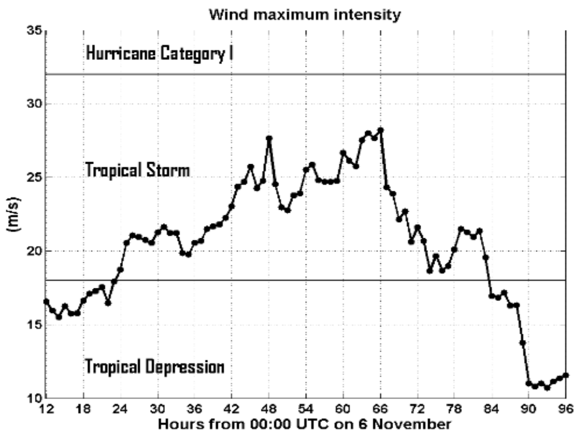

Fig. 5 Wind maximum intensity (m/s) from 12:00 UTC on 6 November to 00:00 UTC on 10 November. Black horizontal lines mark the separation between different categories: tropical depression, tropical storm and hurricane category I.

16-20 hours with a maximum intensity that returned below the threshold of 18 m/s.

The vortex trajectory was also calculated considering the minimum pressure for the same period. The cyclone became a tropical storm from the first hours of the day on November 7, in the area south of the Balearic Islands. Initially, the vortex moved from the Balearic Islands to the north-east; thus it moved in an irregular manner between parallels 41°-42° for several hours.

The minimum pressure was about 994 hPa at 15:00 UTC on 8 November. Finally, it moved a north-west towards the Gulf of Lyon where, approaching the coast, it gradually lost its intensity and died out. The intensity of air-sea latent and sensible heat fluxes was linked to differences between the SST and the low level atmospheric air temperature.

In the vortex growth phase, the sea surface was quite warm, up to 21-22 °C in the area south of the Balearic Islands (Fig. 6, medium and bottom panel). For the same period, the 10-meters air temperature, as obtained by LETKF data assimilation system, was between 17 °C and 20 °C (Fig. 6, top panel), creating an air-sea temperature difference of 1-5 °C.

The temporal variability of the air-sea temperature differences was monitored from data collected by the Dragonera buoy (Lat. = 39.56 °C; Lon. = 2.11 °C) from Puertos del Estado (Spain) [22]. The SST values measured from buoy are consistent with the SST forecast values produced by MFS (Fig. 7).

This notable air-sea temperature difference created large heat fluxes from the sea surface, which thereby maintained the vortex. The vertical thermal structure of the cyclone was characterized by a surface warm core, which is a characteristic structure of tropical-like cyclones (Fig. 8).

5. SST Sensitivity Studies: Trajectory and Heat Fluxes

In order to assess the impact of different SST estimates on the formation and maintenance of the vortex itself, four different simulations were performed using COSMO-ME (Table 1).

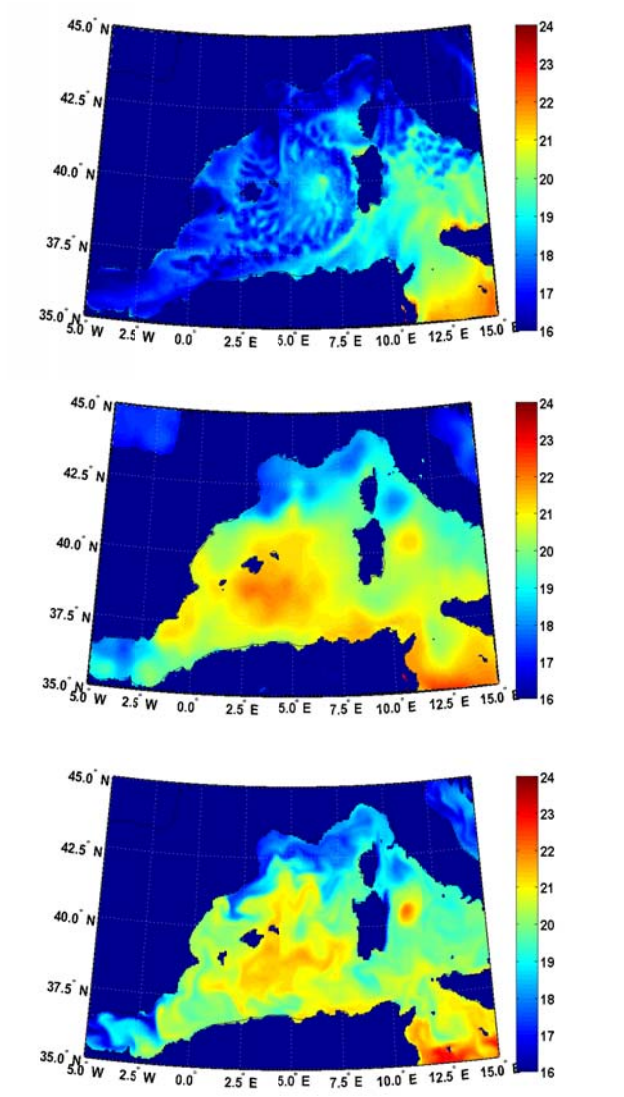

Fig. 6 Air temperature at 10 meters obtained by LETKF data assimilation system (top panel), SST field by OSTIA system (medium panel) and by MFS system (bottom panel) at 12:00 UTC on 7 November.

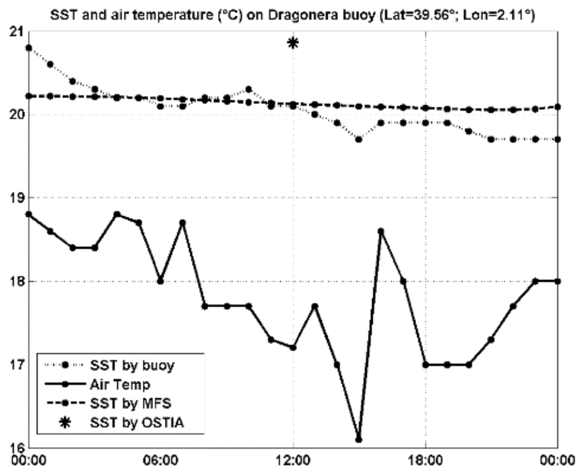

Fig. 7 Air temperature at 2 meters (°C) and SST (°C) observed by the Dragonera buoy (continuous and dot lines) for 7 November 2011. SST means on the box (0.25 × 0.25 deg) centered at Dragonera buoy position, by MFS (dash line) and OSTIA systems (star).

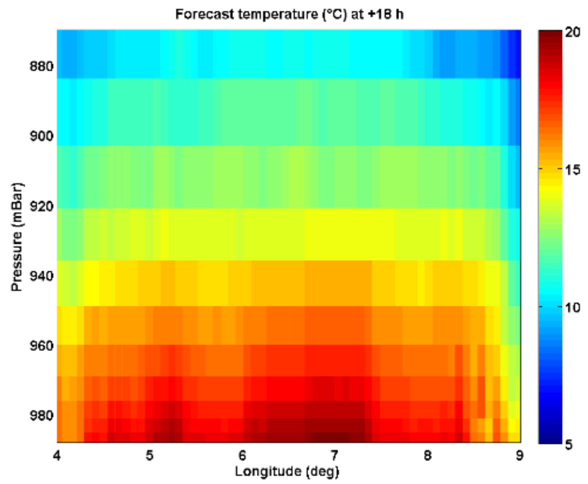

Fig. 8 Temperature (°C) vertical section along parallel 40.0 °C at hour 18:00 UTC on 7 November by COSMO-ME run at 00:00 UTC on 7 November.

Table 1 Configurations of the four different numerical experiments. Simulations started at 00:00 UTC on 7 November 2011 and lasted for 72 h.

Experiments	SST boundary conditions
EXP1	SST from Ostia (default configuration)
EXP2	SST fields by Ostia lowered by 2 °C
EXP3	SST fields from MFS (fixed to initial values)
EXP4	SST fields from MFS (variable)

An initial simulation was carried out with the COSMO-ME operational settings (EXP1) where the OSTIA initial condition SST are persisted as boundary conditions throughout the forecast time. In the second experiment (EXP2), the OSTIA SST field was uniformly lowered by two degrees Celsius over the domain and the same settings of EXP1 were used. In EXP3, the MFS initial analysis SST field was used and kept fixed as surface boundary conditions throughout the forecast time. In the last experiment (EXP4), the MFS forecast SST fields were imposed every three hours and linearly interpolated for each model time step during the COSMO-ME forecast time.

The Medicane trajectory, defined as the position of the pressure minimum, was monitored for 48 hours starting from 12:00 UTC on November 7, at six hours intervals, until 12:00 UTC on November 9. Trajectories resulting by EXP1, EXP2, EXP3 and EXP4 experiments are shown in Fig. 9 with respect to the NOAA trajectory analysis (http://www.ssd.noaa.gov/PS/TROP/DATA/2011/tdata/med/01M.html).

The forecast trajectory for the first 24 hours is quite similar for all four experiments (Fig. 9) and the difference respect to NOAA analysis is contained in 30-40 km (Fig. 10).

The trajectories for experiments EXP3 and EXP4 deviate significantly from the EXP1 trajectory for the next 24 hours, better reproducing the NOAA analysis, with a maximum difference of about 100 km. Thus, EXP3 and EXP4 trajectories are significantly different, compared to EXP1, in the Gulf of Lyon area. Such differences are attributable to the different SST fields used as boundary conditions for the COSMO-ME model (see also Fig. 6). The average SST in the Gulf of Lyon is 16.7 °C and 18.8 °C for experiments EXP1 and EXP3, respectively (domain of average: 41° < Lat. < 44°, 3.0° < Lon. < 7.0°). This temperature difference of about 2 °C determines notable differences in surface heat fluxes.

COSMO-ME latent and sensible heat fluxes are displayed for the four different experiments on the previous spatial area in Fig. 11, where the negative values indicate heat flux from the sea to the air. Heat fluxes for EXP2 are much smaller than in the reference EXP1 due to the smaller absolute value of SST imposed. There is a difference up to 100 W/m^2 and 35 W/m^2 for latent and sensible heat fluxes,

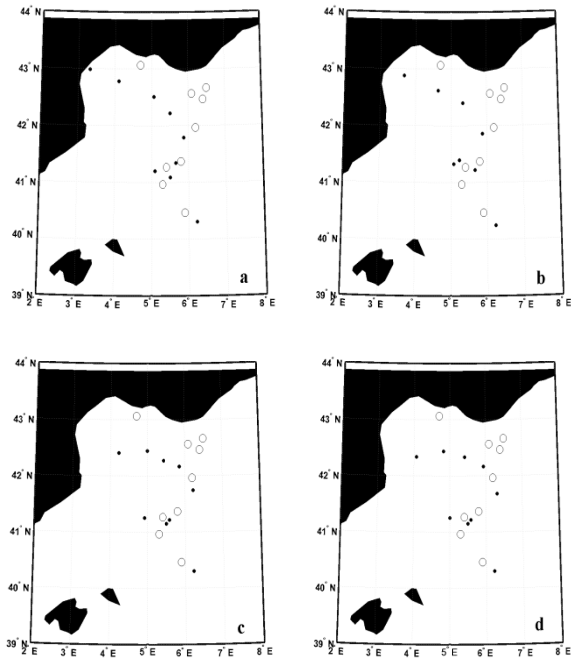

Fig. 9 Trajectories from 12:00 UTC on 7 November every 6 h until 12:00 UTC on 9 November, for the four different COSMO experiments with respect to the NOAA analysis: EXP1 (a), EXP2 (b), EXP3 (c) and EXP4 (d).

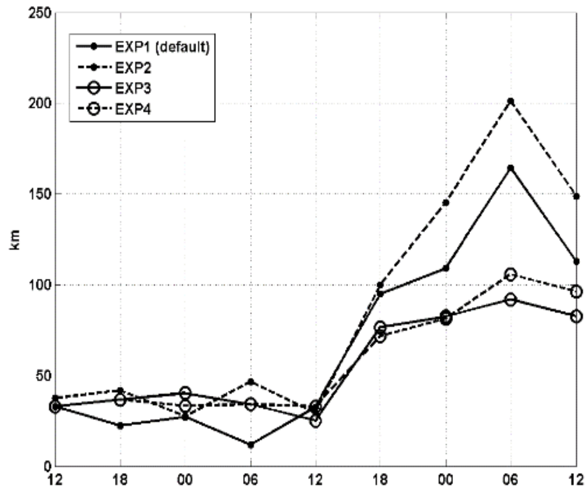

Fig. 10 Distances (km) of the pressure minimum positions respect to NOOA analysis, every 6 h from 00:00 UTC on 7 November.

respectively. Heat fluxes of EXP3 and EXP4 were substantially more intense than in EXP1 for the last part of the meteorological event. There is a difference up to 50 W/m^2 and 8-10 W/m^2 for latent and sensitive heat fluxes, respectively.

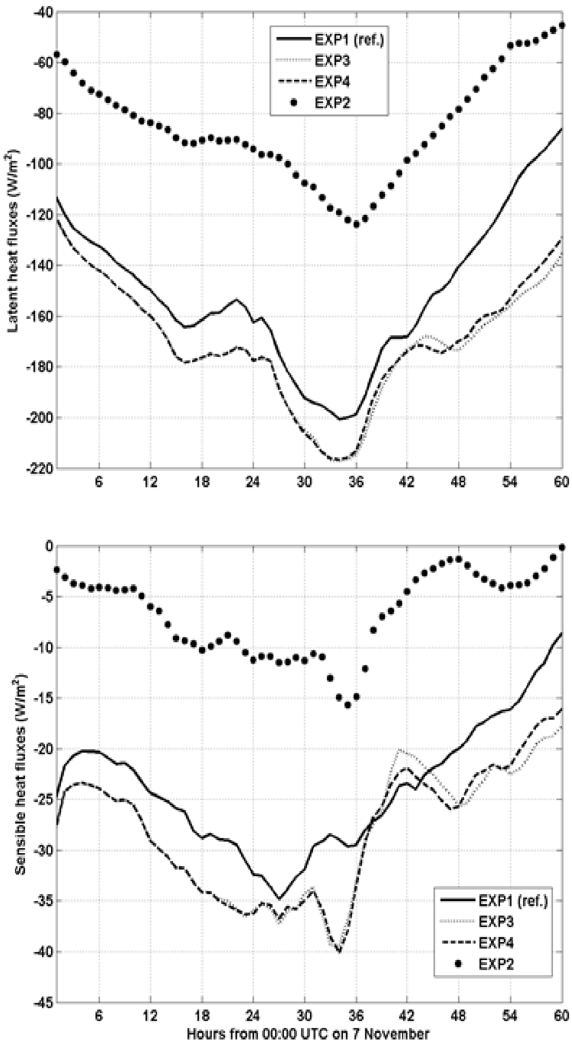

Fig. 11 Latent (top) and sensible (bottom) heat fluxes for the four experiments, averaged on domain 41° < Lat. < 44°, 3.0° < Lon. < 7.0°, every 1 h from 00:00 UTC on 7 November.

The larger energy released from the sea surface, and probably the different SST field structure in the Gulf of Lyon for experiments EXP3 and EXP4 led to a strengthening of the vortex itself and a different trajectory for the last hours of the meteorological event.

The pressure minimum was also monitored for 48 hours (Table 2). The experiments EXP3 and EXP4 reproduce pressure values closer to those obtained from NOAA analysis throughout the all considered period. Also, they are always minor compared to EXP1, indicating that in fact the vortex has a higher power respect to the control experiment, especially in the final phase of the weather event.

6. SST Sensitivity Studies: Pressure and Wind Intensity

In this section we analyze the forecast pressure and wind fields for the four different experiments. The forecast step +45 h, valid at 21:00 UTC on November 8 was considered to coincide with the cyclone maximum strength and intensity. The results are reported in Figs. 12 and 13 for pressure and wind, respectively.

A colder SST in EXP2 determined a lower minimum pressure (compare 12b with 12a), as expected. In EXP3 and EXP4, the minimum pressure was lower (about 996 hPa for both) than in EXP1 due to the different but warmer MFS forecast SST in the area around the Gulf of Lyon. Smaller pressure differences were found between EXP3 and EXP4 experiments.

Wind speed fields were clearly linked to the pressure fields and followed their structures and evolution (see Fig. 13). The wind field was much less intense in EXP2, compared with the control experiment. In EXP3 and EXP4 the vortex appeared more intense, with a smaller calm eye and asymmetric wind intensity around it.

The forecast wind speed can be compared with satellite wind estimates by ASCAT (Advanced SCATterometer) sensors on board the MetOp-A satellite (http://www.esa.int/Our_Activities/Observing_the_Earth/The_Living_Planet_Programme/Meteorological_missions/MetOp).

The wind forecast was valid at hour 21:00 UTC on 8 November (Fig. 13), while the satellite crossing (Fig. 14) was about 20 minutes before (exactly at 20:39 UTC). ASCAT wind intensity estimates indicated a velocity up to 21-23 m/s. The spatial resolution of satellite measurements was 12.5×12.5 km^2.

The position and the size of the Medicane were computed for the various COSMO experiments, at

Table 2 Pressure minimum by the four different numerical experiments and NOAA analysis.

	12	18	00	06	12	18	00	06	12
EXP1	1001	1001	999	999	1000	1001	1003	1006	1010
EXP2	1002	1003	1001	1002	1003	1006	1010	1013	1016
EXP3	1001	1001	998	997	996	995	996	999	1002
EXP4	1001	1001	998	997	996	995	997	1000	1003
ANALYSIS	-	997	991	991	991	991	991	1000	1006

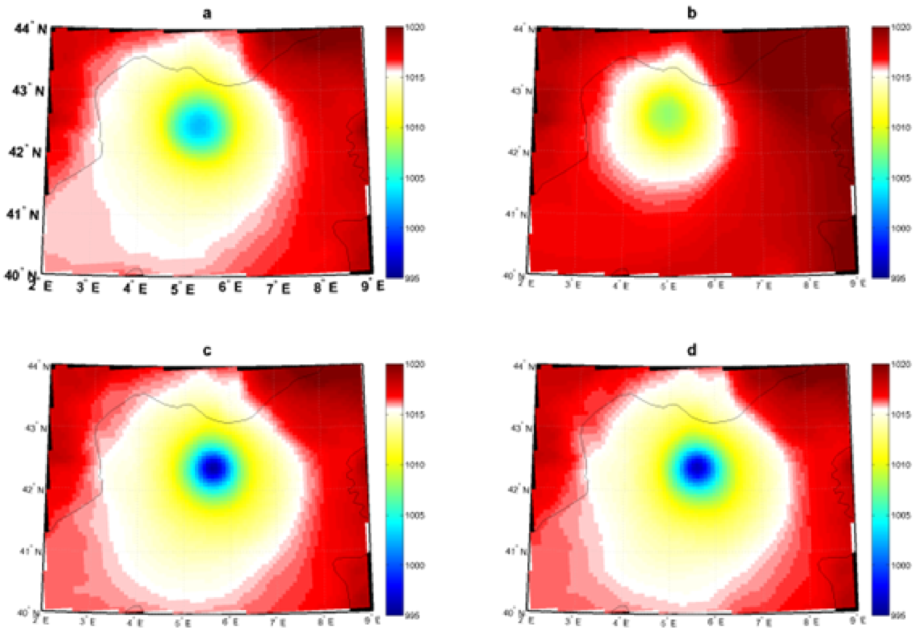

Fig. 12 Forecast mean sea level pressure (hPa) at 21:00 UTC on 8 November for EXP1 (a), EXP2 (b), EXP3 (c) and EXP4 (d) experiments.

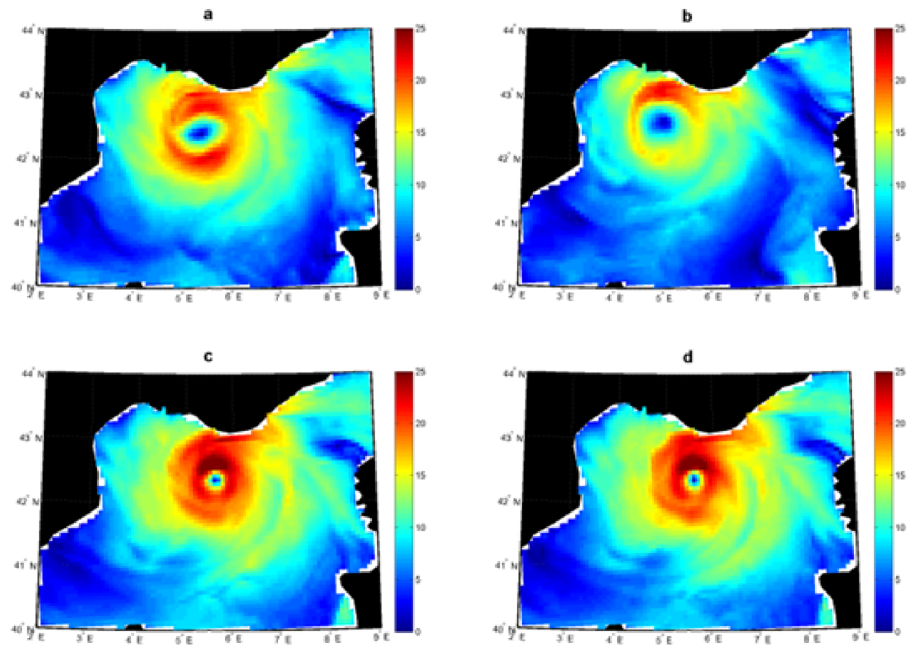

Fig. 13 Forecast wind intensity (m/s) at 21:00 UTC on 8 November for EXP1 (a), EXP2 (b), EXP3 (c) and EXP4 (d) experiments.

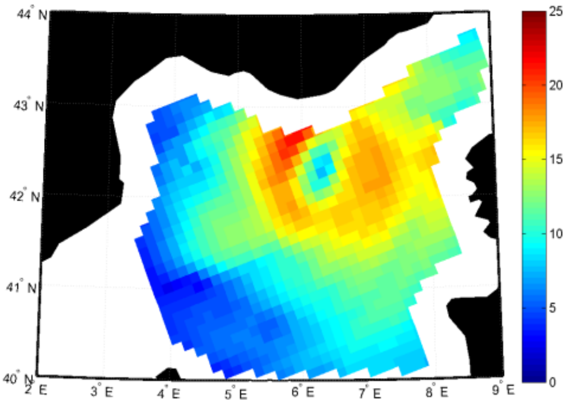

Fig. 14 Wind intensity estimate (m/s) from ASCAT sensors on board of MetOp-A satellite at 20:39 UTC on 8 November 2011.

21:00 UTC, and compared with the ASCAT measurements. The size of a tropical-like cyclone is difficult to define objectively; different definitions are currently used by researchers and operational weather forecasters [23]. In the following, the cyclone size was defined as the radius of the area with wind speeds larger than 15 m/s.

For EXP1, EXP3 and EXP4, the mean sizes were similar, in the range 125-130 km (see Table 3) consistent with the ASCAT data if an error corresponding to the 12.5 km bins is considered for ASCAT and the grid size of 7 km for the COSMO-ME data. The difference in longitude was about 1 deg for EXP1 but only 0.6 deg for EXP4 and the ASCAT estimate. Thus mean size and position of the cyclone are best depicted by EXP4.

To characterize the wind horizontal structure, Fig. 15 shows normalized histograms of wind intensity at 21:00 UTC on November 8 for the region of the Gulf of Lyon. The wind intensity is subdivided into classes of 1 m/s and the number of events is reported as a percentage with respect to the total number of events.

The modal values are 11, 13 and 16 m/s respectively for EXP1, EXP4 and ASCAT. The histogram for EXP1 is wider and more symmetric than EXP4 and ASCAT, with a modal value that occurs in about 10% of the cases (14% and 13% for the EXP4 and ASCAT, respectively). ASCAT data show a smaller tail for high values of wind speed. In general, the comparison shows that the velocity distribution in EXP4 is more similar to ASCAT.

7. Conclusions

A sensitivity study of an operational atmospheric forecast model, COSMO-ME, with different SST estimates and impositions was carried out. The sensitivity of the model was studied for a Medicane (Mediterranean Hurricane) test case, observed over the western Mediterranean Sea from November 7 to 9, 2011. ASCAT wind estimates by MetOp-A satellite indicated an intensity up to 21-23 m/s. Four different forecasts, using different SST fields, were carried out with the COSMO atmospheric model. The operational SST used as initial surface and boundary conditions from OSTIA optimally interpolated analyses (EXP1) was compared with SST from MFS analyses (EXP3) and forecasts (EXP4). The numerical simulations identified the most intense phase of the vortex from 00:00 UTC on November 7 to 12:00 on November 9, for about two and a half days. For this period, the Medicane can be classified as a tropical storm with maximum winds between about 20 and 30 m/s.

The different SSTs impacted the trajectory of the vortex, changing its direction especially in the last part

Table 3 Positions and sizes of the Medicane for the four COSMO-ME experiments (at 21:00 UTC) and for the ASCAT satellite measurements (at 20:39 UTC).

Experiments	Lat (deg)	Lon (deg)	Mean radius (km)
EXP1	42.405°	5.342°	126
EXP2	42.577°	4.989°	117
EXP3	42.352°	5.601°	128
EXP4	42.352°	5.601°	129
ASCAT	42.230°	6.285°	144

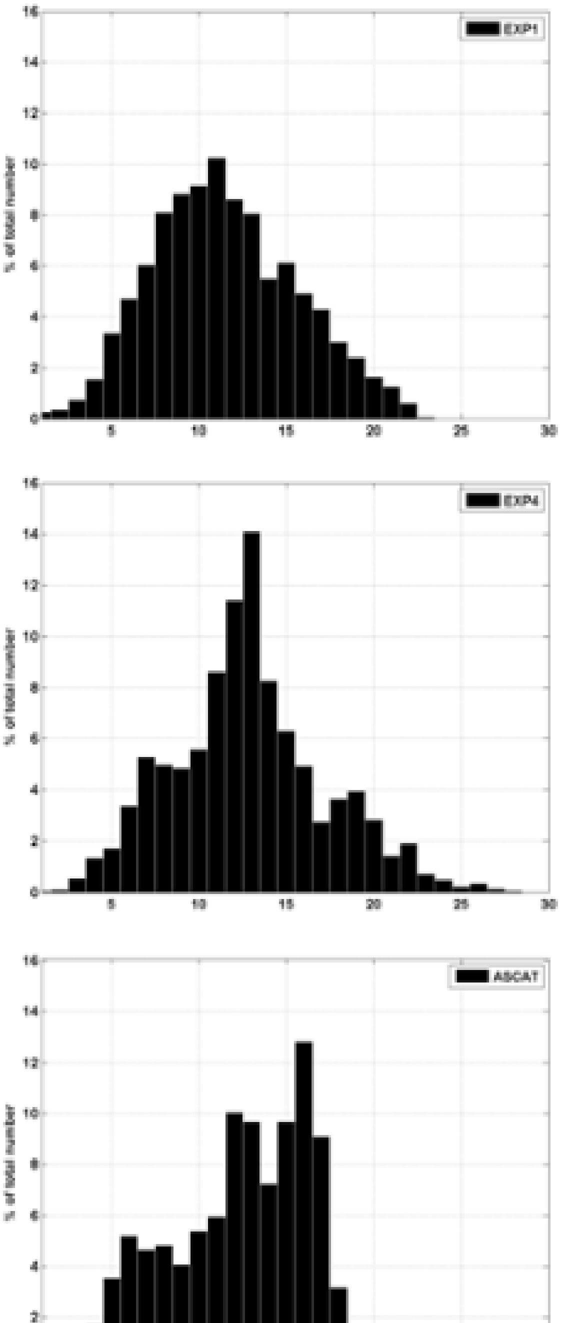

Fig. 15 Histograms (% of total number) of wind for EXP1 (top), EXP4 (middle) and ASCAT (bottom) at 21:00 UTC on 8 November for the model and 20:39 UTC for the ASCAT observations.

of the meteorological event, with EXP3 and EXP4 better reproducing the NOAA trajectory analysis.

Latent and sensible heat flux intensities varied up to 10 and 50 W/m^2 respectively, in the experiments EXP1, EXP3 and EXP4. The major heat fluxes in EXP3 and EXP4 determined a minimum pressure lower than in EXP1, according with NOAA analysis.

The wind intensity and its horizontal distribution is however the major difference between EXP1 and EXP4, with the latter better reproducing the ASCAT data. The mean size of the vortex, in the range of 125-130 km, was quite similar between the experiments EXP1, EXP3 and EXP4.

Our results highlight that the type and value of the SST boundary conditions play an important role in determining the distribution of forecast wind velocities, minimum pressure and location of the cyclone eye. A three-hour forecast SST from the operational MFS ocean forecasting model seems to increase the accuracy of Medicane forecasts with respect to all other measurements currently available.

Acknowledgments

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References

[1] Fita, J., Jansa, A., and Genoves, A. 2007. "Analysis of the Environments of Seven Mediterranean Tropical-Like Storms Using an Axisymmetric, Nonhydrostatic, Cloud Resolving Model." *Nat. Hazards Earth Syst. Sci.* 7: 41-56.

[2] Reale, O., and Atlas, R. 2001. "Tropical Cyclone-Like Vortices in the Extratropics: Observational Evidence and Synoptic Analysis and Effects." *Amer. Meteor. Soc*. 16: 7-34.

[3] Moscatello, A., Miglietta, M. M., and Rotunno, R. 2008. "Numerical Analysis of a Mediterranean 'Hurricane' over Southeastern Italy." *Amer. Meteor. Soc.* 136: 4373-97.

[4] Campins, J., Jansa, A., and Genoves, A. 2006. "Three-Dimensional Structure of Western Mediterranean Cyclones." *Int. J. Climatol.* 26: 323-43.

[5] Cavicchia, L., Von Storch, H., and Gualdi, S. 2013. "A Long-Term Climatology of Medicanes." *Clim. Dyn*. 43 (5-6): 1183-95.

[6] Homar, V., Romero, R., Stensrud, D., Ramis, C., and Alonso, S. 2003. "Numerical Diagnosis of a Small, Quasi-Tropical Cyclone over the Western Mediterranean: Dynamical vs. Boundary Factors." *Q. J. R. Meteorol. Soc.* 129: 1469-90.

[7] Pytharoulis, I., Craig, G. C., and Ballard, S. P. 2000. "The Hurricane-Like Mediterranean Cyclone of January 1995." *Meteor. Appl.* 7: 261-79.

[8] Miglietta, M. M., Moscatello, A., Conte, D., Mannarini, G., Lacorata, G., and Rotunno, R. 2011. "Numerical Analysis of a Mediterranean 'Hurricane' over South-Eastern Italy: Sensitivity Experiments to Sea Surface Temperature." *Atmos. Res.* 101: 412-26.

[9] Emanuel, K. 2005. "Genesis and Maintenance of Mediterranean Hurricanes." *Adv. Geosci* 2: 217-20.

[10] Bonavita, M., Torrisi, L., and Marcucci, F. 2008. "The Ensemble Kalman Filter in an Operational Regional NWP System: Preliminary Results with Real Observations." *Q. J. R. Meteorol. Soc.* 134: 1733-44.

[11] Bonavita, M., Torrisi, L., and Marcucci, F. 2010. "Ensemble Data Assimilation with the CNMCA Regional Forecasting System." *Q. J. R. Meteorol. Soc.* 136: 132-45.

[12] Donlon, C. J., Martin, M., Stark, J. D., Roberts, J. J., Fiedler, E., and Wimmer, W. 2011. "The Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA)." *Remote Sensing of the Environment* 116: 140-58.

[13] Tonani, M., Balmaseda, M., Bertino, L., Blockley, E., Brassington, G., Davidson, F., Drillet, Y., Hogan, P., Kuragano, T., Lee, T., Mehara, A., Paranathara, F., Tanajiura, C. A. S., and Wang, H. 2015. "Status and Future of Global and Regional Ocean Prediction Systems." *Journal of Operational Oceanography* 2 (2): 201-20.

[14] Pinardi, N., Allen, I., Demirov, E., De Mey, P., Korres, G., Lascaratos, A., Le Traon, P. Y., Maillard, C., Manzella, G., and Tziavos, C. 2003. "The Mediterranean Ocean Forecasting System: First Phase of Implementation (1998-2001)." *Annales Geophysicae* 21: 3-20.

[15] Pinardi, N., and Coppini, G. 2010. "Operational Oceanography in the Mediterranean Sea: The Second Stage of Development." *Ocean Sci.* 6: 263-7.

[16] Tonani, M., Pinardi, N., Dobricic, S., Pujol, I., and Fratianni, C. 2008. "A High-Resolution Free-Surface Model of the Mediterranean Sea." *Ocean Sci.* 4: 1-14.

[17] Oddo, P., Bonaduce, A., Pinardi, N., and Guarnieri, A. 2014. "Sensitivity of the Mediterranean Sea Level to Atmospheric Pressure and Free Surface Elevation Numerical Formulation in NEMO." *Geosci. Model Dev.* 7: 3001-15.

[18] Dobricic, S., and Pinardi, N. 2008. "An Oceanographic Three-Dimensional Variational Data Assimilation Scheme." *Ocean Modelling* 22: 89-105.

[19] Dobricic, S., Pinardi, N., Adani, M., Tonani, M., Fratianni, C., Bonazzi, A., and Fernandez, V. 2007. "Daily Oceanographic Analyses by the Mediterranean Basin Scale Assimilation System." *Ocean Sciences* 3: 149-57.

[20] Tonani, M., Pinardi, N., Fratianni, C., Pistoia, J., Dobricic, S., Pensieri, S., De Alfonso, M., and Nittis, K. 2009. "Mediterranean Forecasting System: Forecast and Analysis Assessment through Skill Scores." *Ocean Sci.* 5: 649-60.

[21] Buongiorno, N. B., Larnicol, G., D'Acunzo, E., Santoleri, R., Marullo, S., and Le Traon, P. Y. 2003. "Near Real Time SLA and SST Products During 2-years of MFS Pilot Project: Processing, Analysis of the Variability and of the Coupled Patterns." *Annales Geophysicae* 21: 103-21.

[22] Alvarez, F. E., Alfonso, M., Ruiz, M. I., Lopez, J. D., and Rodriguez, I. 2002. "Real Time Monitoring of Spanish Coastal Waters: The Deep Water Network." In: *Proceedings of the Third International Conference on EuroGOOS*, Athens, Greece.

[23] Liu, K. S., and Chan, J. C. L. 1999. "Size of Tropical Cyclones as Inferred from ERS-1 and ERS-2 Data." *Mon. Wea. Rev.* 127: 2992-3001.