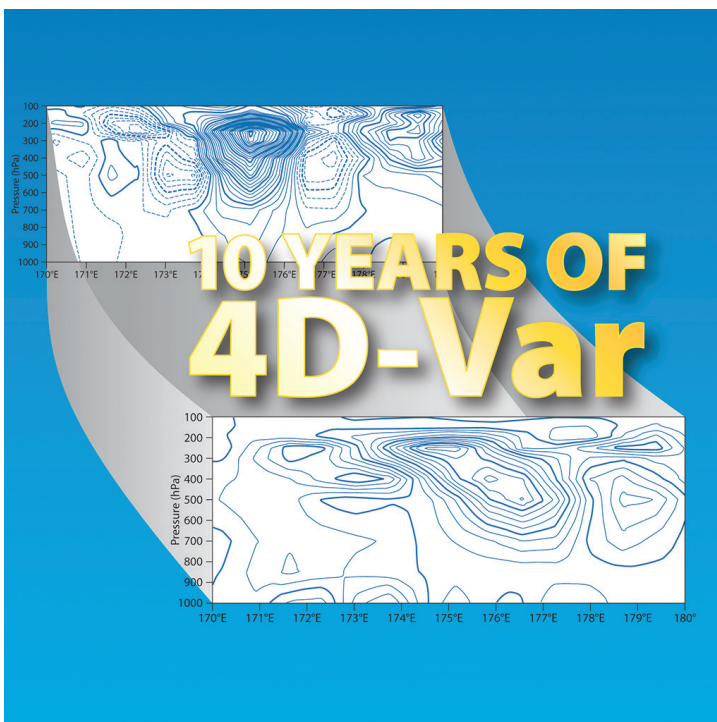


METEOROLOGY

Coupled ocean-atmosphere
medium-range forecasts:
the MERSEA experience



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Coupled ocean-atmosphere medium-range forecasts: the MERSEA experience

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It is common practice at ECMWF, and other weather forecasting centres, to use atmospheric models with fixed boundary conditions over the ocean to produce medium-range weather forecasts. Yet there is evidence that the atmosphere can, on occasion, substantially affect the sea surface temperature (SST), and that SST changes could possibly influence the atmosphere. Here we investigate the impact of allowing the SST to evolve throughout the forecast, rather than using fixed SST, by using an ocean model coupled to the atmospheric model. In order to allow maximum interaction between the two media, we will use an ocean model at a resolution comparable to or better than that of the atmospheric model.

Particular attention is given to assessing the impact of using a coupled atmosphere-ocean model on forecasts of tropical cyclones as these are likely to be influenced by an evolving SST. Integrations at such high resolutions are computationally extremely demanding and so only a limited number of cases has been considered.

Although the work was primarily a proof of concept, we obtained some interesting results. The influence of the two selected tropical cyclones on the ocean is well reproduced, with a realistic evolution of the cool trail of SST in the wake of the cyclones. There is certainly scope for improving the interaction between the atmospheric model and its lower boundary, and a few pointers for further investigation have been suggested. Overall, we show how the coupling of a high-resolution ocean model to a weather-forecasting atmospheric model can be beneficial to features such as SST evolution and possibly cyclone tracks even at relatively short timescales.

It is worth noting that coupling the operational atmospheric model used for the medium-range forecasts to an ocean model from day zero is an objective of the ECMWF 10-year strategy (2006–2015). The present study offers a contribution towards this goal.

This work was carried out under the EU project MERSEA (www.mersea.eu.org), the main objective of which is to provide an integrated service of global and regional ocean monitoring and forecasting to intermediate users and policy makers. Such services would support safe and efficient offshore activities, environmental management, security, and sustainable use of marine resources.

Description of the medium-range coupled forecast system

The coupled model used for the medium-range forecast experiments consists of two main configurations, which differ from each other in the resolution of the atmospheric model. Both use the atmospheric model of the ECMWF Integrated Forecast System (IFS) at Cy31r1. The resolutions are:

- T399 (~50 km horizontal resolution), 62 vertical levels, for the Ensemble Prediction System (EPS) integrations.
- T799 (~25 km horizontal resolution), 91 vertical levels, for the deterministic integrations.

These resolutions match those of the operational EPS and deterministic systems.

The ocean general circulation model is OPA/NEMO version 9.0, ORCA025 grid ($\frac{1}{4}^\circ$ horizontal resolution), with 50 vertical levels. Coupling between the ocean and the atmosphere is via the OASIS coupler (version 3) and carried out every hour: the atmosphere is driven by SST and sea-ice, with the ocean being driven by heat, momentum and moisture fluxes. Solar radiation, needed to calculate the effect of penetrative radiation within the upper layers of the ocean, is passed separately from the other heat fluxes.

AFFILIATIONS

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The ECMWF global wave model (WAM cycle 4) on a 0.5° regular grid with wave spectral resolution of 30 frequencies and 24 directions is also coupled to the atmospheric component. Although it does not interact directly with the ocean model, it influences the stress used to drive the ocean model through the Charnock parameter. It is worth noting that the use of such a high-resolution coupled model with comparable resolution in the atmosphere and ocean required extensive technical work. The ocean analyses are provided by Mercator Océan (*Drevillon et al., 2007*).

Because the atmospheric model cycle used in these experiments is slightly different to the one used operationally in February 2007, additional uncoupled experiments using the same atmospheric configuration as in the coupled model have also been run. This allowed a clean comparison of forecasts made using coupled versus uncoupled models. The current operational EPS consists of 51 ensemble members. For computational reasons, the ensemble size in the EPS experiments described here is restricted to 15. The ensemble members of the EPS differ from each other in their atmospheric initial conditions (by employing singular vectors) and the use of stochastic physics during the integrations. Unlike monthly and seasonal forecasts made with a coupled model, this investigation only needs a limited analysis period; a full reanalysis to calibrate the forecast results is not needed as the model drift should be small.

Case studies

The ocean analyses at a quarter degree resolution come from the MERSEA-1/4°v2 system. We have chosen case studies for two tropical cyclones in the Indian Ocean, FAVIO and GAMEDE. These are two of the strongest tropical storms in the Indian Ocean in 2007. Both occurred in the vicinity of La Réunion/Madagascar with FAVIO subsequently making a landfall in Mozambique.

- The first signs of what would become FAVIO were noticeable at around 12 February 2007, but the deepest low pressure was not attained until 21 February when it reached 930 hPa.
- GAMEDE developed around 20 February 2007, when FAVIO was still active, albeit about two thousand kilometres to the east. It peaked on 26 February with a core pressure of about 935 hPa.

Coupled forecasts starting from 14 February 2007 and 21 February 2007 have been performed.

It would have been interesting to consider the effect of ocean-atmosphere coupling on Atlantic hurricanes or Pacific typhoons and tropical cyclones, but this was not possible as the Mercator operational ocean analyses are only available for dates after 3 January 2007. Our work for the MERSEA project had to be completed before the summer of 2007, thus excluding the 2007 tropical cyclone season in the northern hemisphere.

Global sea surface temperature evolution

We first assess the evolution of the global SST in the deterministic case (T799/ORCA025) to evaluate the ability of the coupled model to reproduce the main features of the observed SST. Figure 1(a) shows the difference between the SST reproduced by the coupled model at day 5 and its initial condition (i.e. the SST at day 0) for 14 February 2007. When compared with the equivalent observed difference (Figure 1(b)), one can see that the main features are represented fairly well by the model. For example, the large-scale differences in the subtropics/mid-latitudes of the southern hemisphere in all three oceans and, more specifically, the large-scale positive difference between about 20°S and 60°S in the Pacific Ocean. The negative difference in the North Atlantic, east of Spain/North Africa, is also reproduced well, though the amplitude is not as large as that observed. Clearly not all the simulated features are satisfactorily reproduced but the results look promising when compared to the current approach of keeping the SST fixed throughout the forecast.

The SST analyses are themselves not without error. Comparison is later made with the OSTIA (Operational Sea Surface Temperature and Sea Ice Analysis) product which shows substantial differences from the Real Time Global (RTG) SST product used operationally at ECMWF (*Gemmill et al., 2007*) as in Figure 1(b).

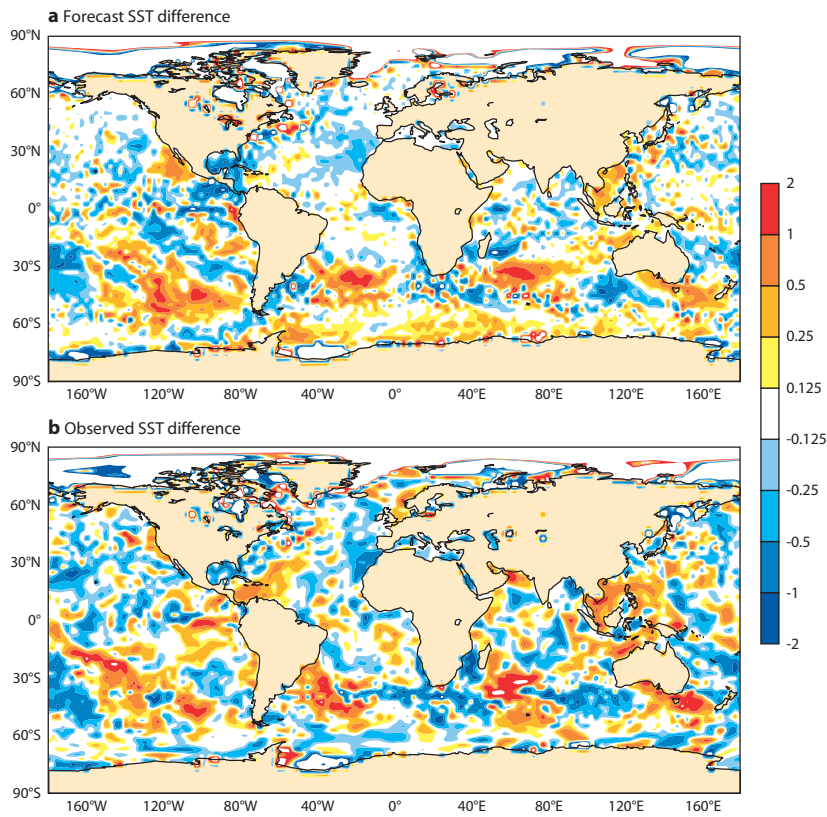


Figure 1 Sea surface temperature difference between day 5 and day 0 for (a) the coupled integration (ORCA025/T799) started on 14 February 2007 and (b) the Real Time Global (RTG) observations. SST differences range from -2°C to 2°C .

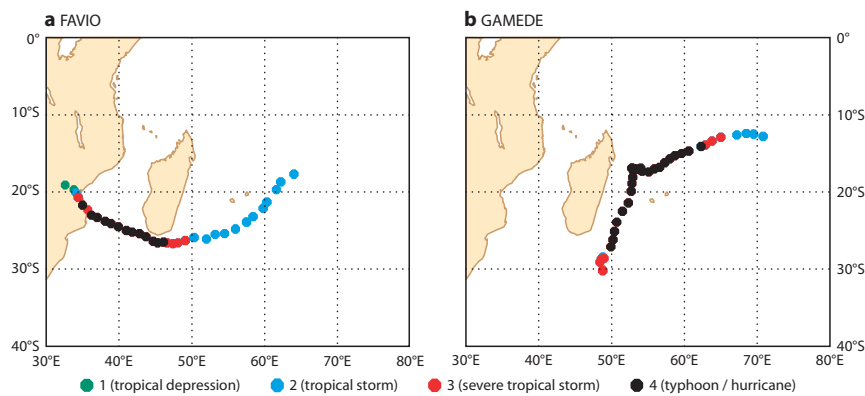


Figure 2 Observed track of tropical cyclones (a) FAVIO (15 to 23 February 2007) and (b) GAMEDE (21 February to 4 March 2007). The colour of the dots indicates the intensity of the cyclones based on 6-hourly observations: green = tropical depression, blue = tropical storm, red = severe tropical storm, black = typhoon/hurricane.

Tropical cyclones simulation using the deterministic model

The tracks of the two tropical cyclones we have chosen to study are shown in Figure 2 for FAVIO and GAMEDE. The colour of the dots represents the type of synoptic feature according to the World Meteorological Organization (WMO) convention (see the caption; note that this scale is different from the 5-grade Saffir Simpson scale). As can be seen from the plots, both FAVIO and GAMEDE reached hurricane strength. As remarked earlier, FAVIO just crossed the southern tip of Madagascar before making landfall over Mozambique.

The observed pressure values at the core of FAVIO and GAMEDE as a function of time are shown in Figure 3. The deepest pressure has been highlighted in black, whereas the day 5 considered in this article is shown in red (for GAMEDE day 5 coincides with the day of the deepest core pressure).

Figure 4(a) shows the SST difference between day 5 and day 0 for the coupled simulation. The mean sea level pressure at day 5 is superimposed. Not only does the coupled model reproduce well tropical cyclone FAVIO with a 5-day lead time (see the low pressure off the coast of Madagascar), it also simulates the cool trail of the cyclone in what looks like a realistic way (i.e. the negative SST differences east of the cyclone core). Of particular interest is the cold wake to the east of FAVIO seen in Figure 4(a). This is not seen in the RTG SST analysis used operationally at ECMWF (Figure 4(d)), where the SSTs at day 5 are warmer than at day 0. However, in the delayed mode OSTIA high-resolution SST product (*Stark et al., 2007*), a cold wake is clearly visible (Figure 5). The differences are smaller in the case of GAMEDE but it too shows a cold wake, well predicted by the coupled model (not shown).

The cold wake is not quite in the same position as in the model simulation because the tropical cyclone track is displaced slightly to the north. This is true of all forecasts shown in Figure 4: coupling has not had a significant impact on the cyclone track. The uncoupled (i.e. atmospheric-only) simulation is also able to reproduce the deep low pressure of FAVIO even if the SST remains unchanged throughout the integration. Similarly, the operational model captures well the low pressure (Figure 4(c)).

The analysis for 19 February in Figure 4(d), however, shows very little sign of the cyclone. This behaviour appears counter-intuitive as one would expect the analysis to be the closest to reality. The reason for the poor representation of the cyclone in the analysis is the broad structure functions used to produce the analysis. Other factors such as the wrong position of the cyclone in the first guess, due to shortage of data, and the low resolution used in the inner loops of the analysis may also contribute (*Isaksen & Janssen, 2004*). Nonetheless, the information of the presence of the cyclone in the circulation of the atmosphere is normally present in the three-dimensional analysis to some extent, which is why the forecasts are able to produce realistic cyclones.

The core pressure of FAVIO for 19 February 2007 for the four cases presented in Figure 4, as well as for the directly observed value, are shown in Table 1. As can be seen, all three forecasts are close to the observed value.

In the case of tropical cyclone GAMEDE the coupled simulation is also quite successful. In fact, the negative SST anomalies, resulting from the interaction between the cyclone and the ocean, are well reproduced (compare Figures 6(a) and 6(d)). The intensity of the cyclone is also reasonably well represented but, even if visually very intense, the core pressure does not reach the very low value observed of 935 hPa (see Table 1). However, given errors in the positioning and strength of the cyclone in the initial conditions, model imperfections and the limited (even if very high) resolution for cyclone simulations, the value of 966 hPa in the coupled integration is encouraging.

Both the uncoupled integrations reproduce well the low pressure of GAMEDE, with the uncoupled run shown in Figure 6(b) reaching a lower core pressure (961 hPa) than the (uncoupled) operational forecast in Figure 6(c) (967 hPa). The uncoupled (non-operational) run simulates in both cases a lower core pressure than the coupled case as will be confirmed with the EPS experiments later. The reason seems to be related to the lower SST in the coupled case. Thus, even if this is closer to the observed SST than in the uncoupled case, there seems to be some deficiency in the interaction between the atmosphere and the ocean, with the lower SST inhibiting growth in the model cyclone. The lower SST in the coupled case may well be the correct response; it is just that the cyclone is too weak in the uncoupled case and the coupling makes it weaker, as it should.

Experiment	Core pressure (hPa)	
	FAVIO	GAMEDE
Coupled (ORCA025/T799)	970	966
Uncoupled (T799)	968	961
Operational (T799)	972	967
Analysis	1004	963
Observed	970	935

Table 1 Core pressure of FAVIO at 00:00 UTC on 19 February 2007 and GAMEDE at 00:00 UTC on 26 February 2007 for three integrations, plus analysed and observed values.

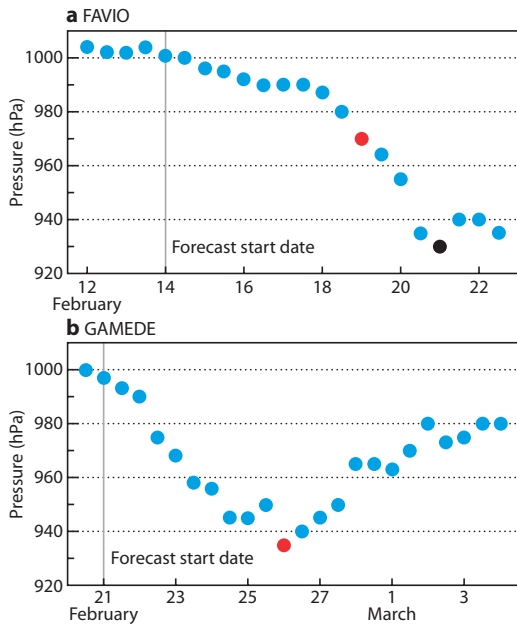


Figure 3 Time evolution of the observed core pressure for tropical cyclones (a) FAVIO and (b) GAMEDE. The red circle indicates the day 5 forecast lead-time whereas the black circle is the lowest recorded pressure (for GAMEDE red and black are superimposed).

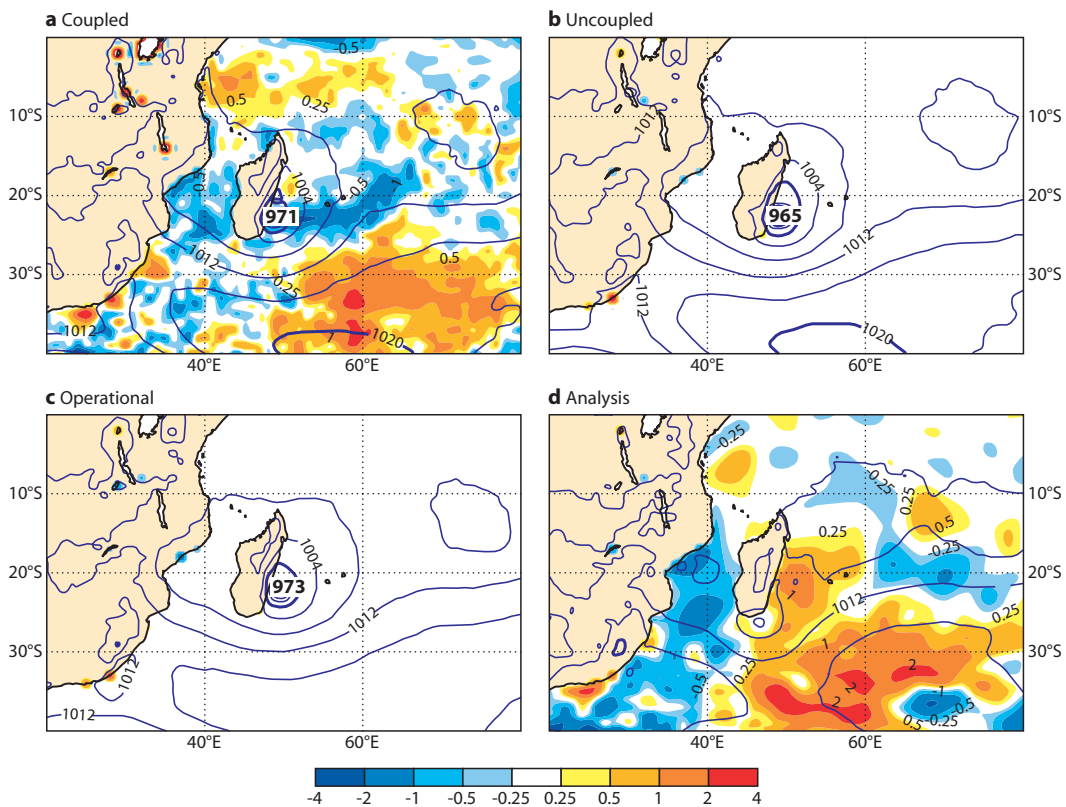


Figure 4 Sea surface temperature difference between day 5 and day 0 for (a) coupled integration (ORCA025/T799) starting on 14 February 2007 – the FAVIO case, (b) uncoupled integration, (c) operational ECMWF forecast (similar to the uncoupled but with a model version slightly different, and (d) ECMWF analysis at 00 UTC on 19 February 2007. SST differences range from -4°C to 4°C . The isobars of mean sea level pressure (MSLP) at day 5 are superimposed with a 4 hPa spacing. There is little evidence of the tropical cyclone in this analysis, probably as a result of the broad structure functions used in the analysis but also because the first guess cyclone may be in slightly wrong position due to shortage of data and because of the lower resolution (T255) of part of the analysis system (the inner loop).

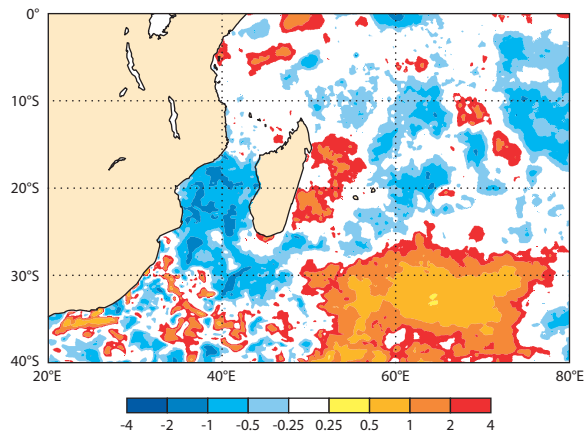


Figure 5 OSTIA high-resolution SST product for the difference between 19 February 2007 and 14 February 2007 (as in Figure 4(d)). Note the cooling along the cyclone track (c.f. Figure 2(a)).

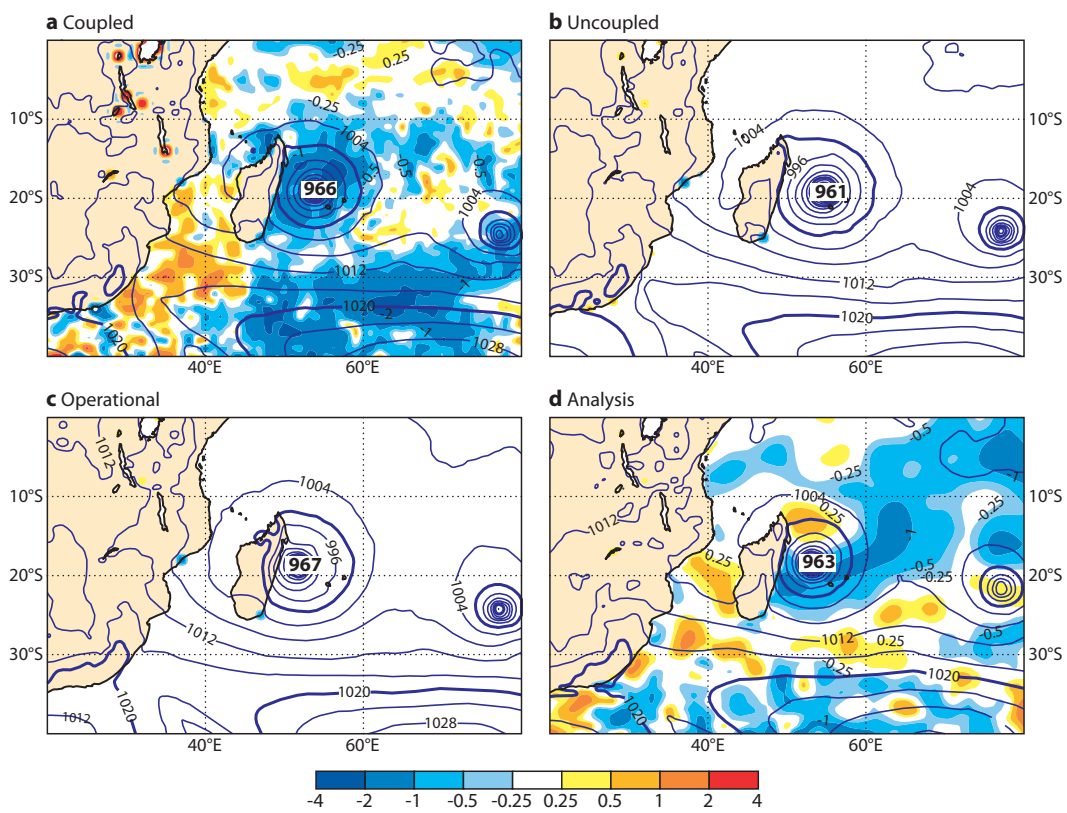


Figure 6 As in Figure 4 but for forecasts starting on 21 February 2007 – the GAMEDE case. In this case the MSLP analysis better captures the tropical cyclone, possibly due to its larger spatial scale than in the case of tropical cyclone FAVIO.

Sea surface temperature versus 2-metre temperature

In order to understand better the link between the surface and the upper atmosphere we now look at the temperature on a level just above the surface, i.e. the 2-metre temperature. Given the large differences in SST which develop during the first five days of integration (up to 4°C either way), one might expect similar differences in the 2-metre temperature field. This is not so clear, however, as can be seen from Figure 7. Despite the SST being fixed in the two uncoupled runs (Figures 7(b) and 7(c)) large differences develop in the 2-metre temperature field nevertheless. However, these differences are very similar to those in the coupled integration (Figure 7(a)). One exception is the cyclone track wake where the coupled model is able to produce the observed cool temperatures (Figure 7(d)).

A plausible explanation for the fact that the 2-metre temperature field does not seem to be influenced much by the SST is that the heat budget, which ultimately needs to be balanced, is little affected by the sensible heat (determined by the difference in temperature between the surface and that at a higher level, as well as by the wind speed) and is instead controlled more by the latent heat. Another explanation might be that the atmospheric model has been tuned to function with fixed SST and therefore the coupling with varying SST may not be as strong as it ought to be.

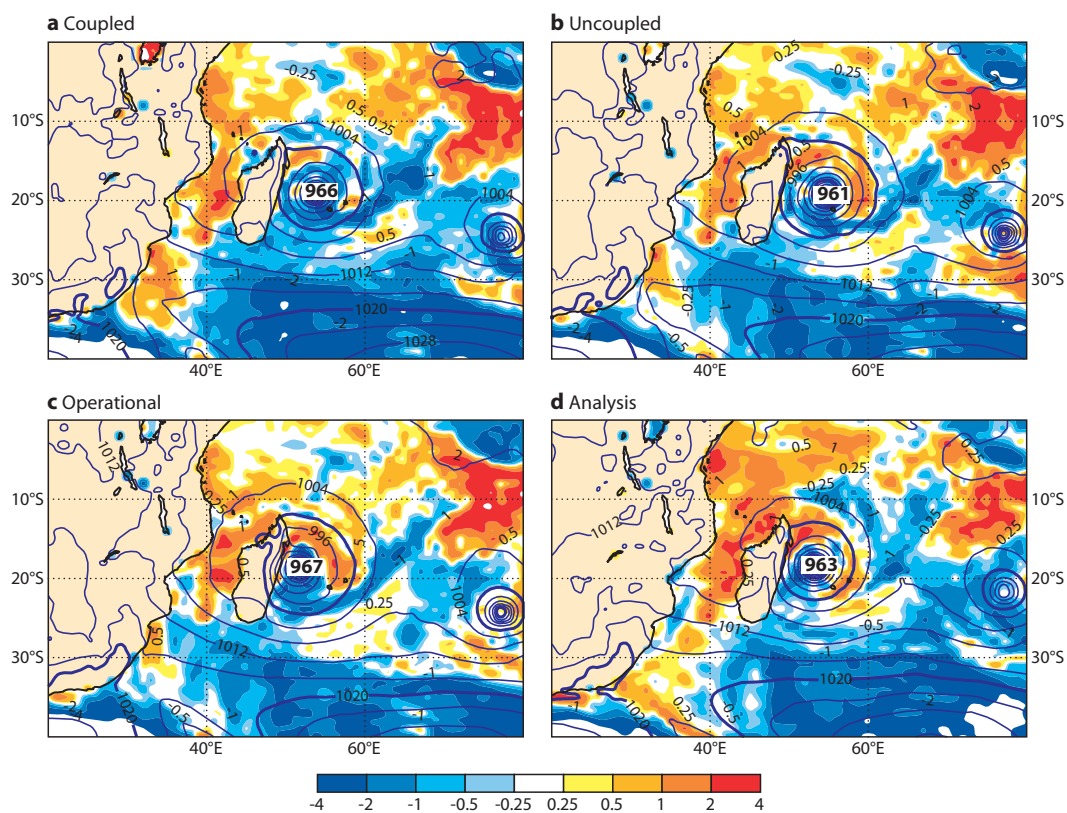


Figure 7 As Figure 6 but for 2-metre temperature instead of SST.

Tropical cyclones simulation in the coupled EPS

The same two cases of tropical cyclones have been run with a lower-resolution coupled model (T399 instead of T799) but for an ensemble of size of 15. Different diagnostics to those shown thus far are applied for this probabilistic approach.

Figure 8 shows the EPS Lagrangian meteogram for FAVIO. The meteogram is a diagnostic tool developed as part of the ECMWF operational tropical cyclone tracking software. This diagnostic highlights the EPS distributions of tropical cyclone core pressure and 10-metre wind speed as a function of time, along with the number of EPS members predicting the event.

Two main features can be noted from Figure 8. The first is that there is a difference in spread (the bars) in the coupled (left) and uncoupled (right) cases, with the latter having a larger spread than the former, especially in the cyclone core pressure (bottom panels). The same is true for GAMEDE (not shown). A larger number of cases would be needed to test its significance. If it was significant, the reason for this difference would

require further investigation but two initial hypothesis would be: (a) the presence of negative feedbacks in the radiation/cloud balances which would be more pronounced in the coupled case because of the lower SSTs and (b) the way in which the initial perturbations (via singular vectors) are calculated as they are currently tuned with a system which keeps SSTs fixed.

The second feature is that beyond day 5 neither coupled nor uncoupled forecasts are able to reproduce the very low observed core pressures for FAVIO (see the black dots in bottom panels of Figure 8), even if the uncoupled integrations reach slightly lower values than the coupled forecasts because of the lower SSTs in the latter integrations (it is a general feature of the EPS that the core pressure of tropical cyclones is systematically not low enough: according to Martin Leutbecher (ECMWF) this is a resolution-related issue). The same deficiency in the core pressure, even if to a lesser extent, is found for the GAMEDE case (not shown). However, up to day 5 both integrations simulate the observed core pressure well: the observations are within the spread and the spread is not very large. Note also that the deterministic integration (T799) reproduces the core pressure at day 5 much better than the corresponding T399 control run (compare Table 1 with the line in the bottom panels of Figure 8 on 19 February at 00 UTC). For instance, in the coupled case the core pressure in the T399 control is above 990 hPa whereas in the T799 it is 970 hPa (the same as observed!).

Lastly, we consider the strike probability maps based on the first 10 days of the integrations. The strike probability is based on the number of EPS members that predict the tropical cyclone. Figure 9 shows such a map for the FAVIO tropical cyclone in the coupled and uncoupled integrations. Both show that, albeit small, there is some probability that FAVIO makes a landfall over Mozambique with a lead-time of 10 days: a remarkable result. A sample of 15 members is not very large but the strike probability maps indicate that the coupled integration has a slightly higher probability that FAVIO makes a landfall (the purple over Mozambique). Interestingly, only one member, compared to two in the uncoupled integration, veers south of Madagascar.

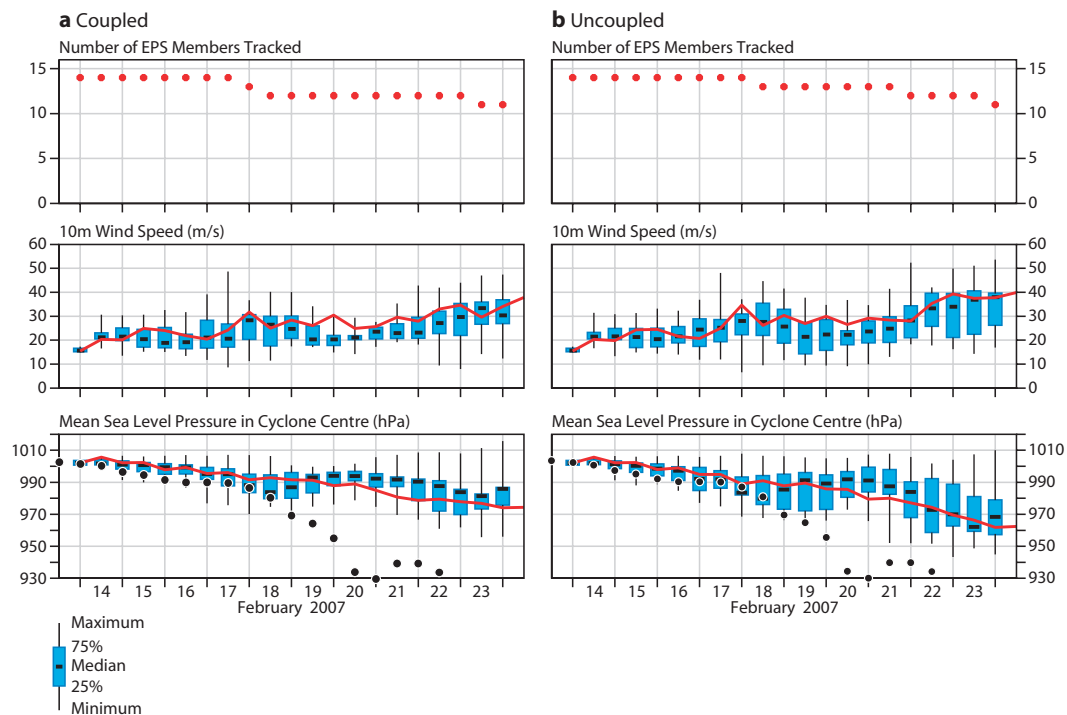


Figure 8 EPS Lagrangian meteograms for (a) the coupled ORCA025-T399 model and (b) the uncoupled T399 model for the FAVIO case starting at 00 UTC on 14 February 2007. Top panel: number of EPS members predicting the event. Middle panel: 10-metre wind speed. Bottom panel: mean sea level pressure in cyclone centre. The line represents the evolution of the member number 1 (control run) and the box-and-whiskers the spread of the remaining 14 members. The EPS distribution is determined in a 7×7 degree box centred on the tropical cyclone location. The black dots on the bottom panels are the observed values of the cyclone pressure.

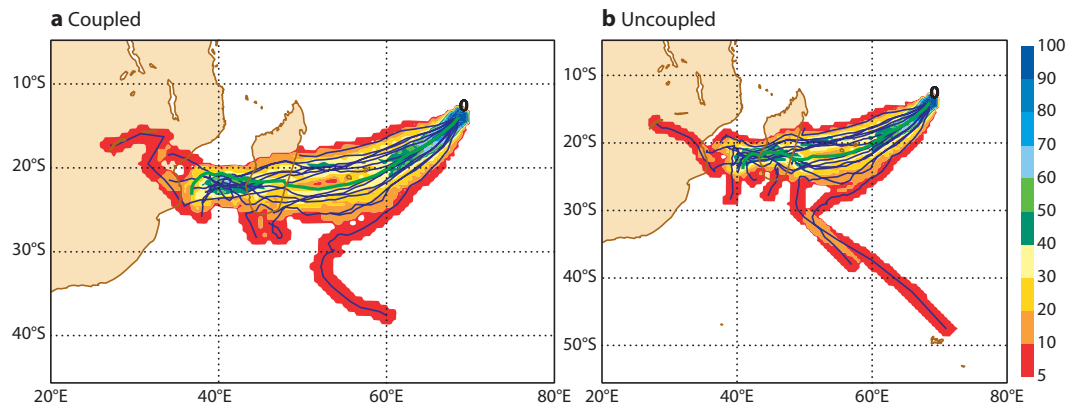


Figure 9 Strike probability maps for the FAVIO case in (a) coupled and (b) uncoupled integrations starting at 00 UTC on 14 February 2007. The strike probability is based on the number of EPS members that predict the tropical cyclone and is defined as the probability that a tropical cyclone will pass within a 120 km radius from a given location at anytime during the next 240 hours. The time dimension is thus eliminated, which allows for a quick assessment of high-risk areas regardless of the exact timing.

What next?

A high-resolution ocean model has been coupled to the atmospheric model used for medium-range weather forecasts at ECMWF. Such a coupled model has been tested on two tropical cyclone case studies.

Encouragingly, the coupled model shows a physically reasonable behaviour in the evolution of the global sea surface temperature (SST). The two tropical cyclones are nicely reproduced by the coupled model. However, despite the well simulated SSTs, differences with analogous uncoupled integrations for which SST is held fixed throughout the integrations are generally not striking, at least in terms of minimum pressure and winds. It has been argued that a possible explanation is that the IFS Cycle of the atmospheric model used in the study has been tuned to function with fixed SST and therefore the coupling with varying SST may not be as realistic as it ought to be. Indeed, no specific tuning of the coupling has been attempted. Other possible causes have been discussed as well.

Now that such a coupled model has been implemented it could be used for similar case studies, Atlantic hurricanes for example. Work is already under way to study the behaviour of this coupled model on the simulation of the intra-seasonal oscillation.

Further Reading

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