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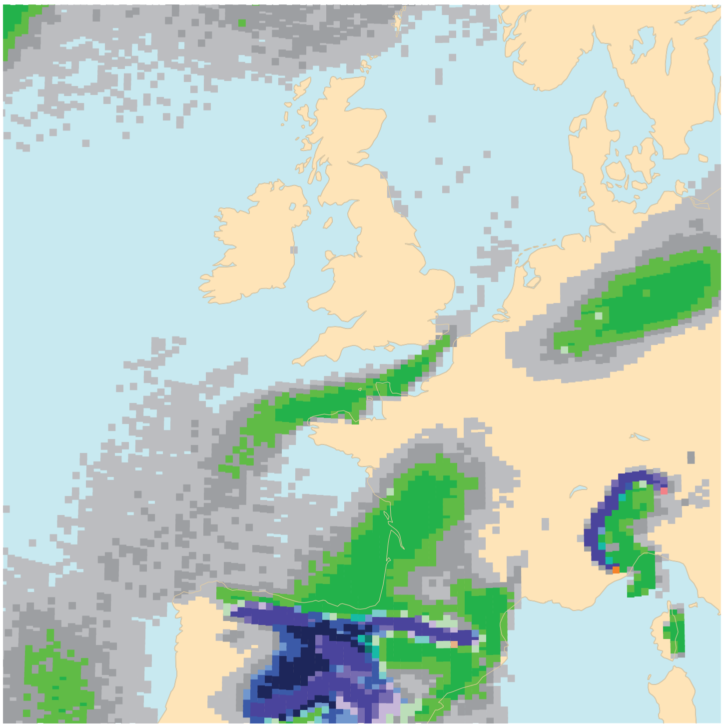

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Ocean coupling in tropical cyclone forecasts

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Tropical cyclones (TCs) are one of the deadliest weather phenomena. Typhoon Haiyan, for example, caused more than 6,000 fatalities when it struck the Philippines in November 2013. TCs give rise to a devastating combination of extreme winds, storm surges, high waves and heavy rainfall. Correctly forecasting intense TCs several days in advance makes it possible to evacuate coastal regions and prepare society for the event. This happened, for example, with Hurricane Irma in September 2017, when hundreds of thousands of people in Florida had to leave areas deemed to be at risk. To decide whether such action needs to be taken, local authorities need high-quality forecasts of the cyclone path and intensity. One of the avenues being pursued at ECMWF to improve TC forecasts is to better take into account interactions between the ocean and the atmosphere during the forecast period. Experiments have shown that taking into account such interactions by coupling the ocean and the atmosphere leads to better predictions of TC intensity. Coupling is already operational for ECMWF's ensemble forecasts (ENS) and is due to be extended to high-resolution forecasts (HRES) in the next upgrade of ECMWF's Integrated Forecasting System (IFS).

In this article we present key points from ongoing research at ECMWF on the influence of ocean–atmosphere coupling on tropical cyclone intensity. We have selected two very different TCs for a case study. For TC Neoguri (2014), the operational forecast made at the time overpredicted the intensity significantly, and tests with the current 9 km (TCo1279) horizontal resolution in HRES lead to even more pronounced overpredictions. However, the forecast improves considerably with ocean–atmosphere coupling. For TC Haiyan (2013), the operational forecast severely underpredicted the intensity, and even with the current operational resolution we are unable to simulate the intensity accurately regardless of whether we use a coupled or an uncoupled model.

Significance of coupling

In the past ECMWF forecasts have tended to underpredict the intensity of TCs. This continues to be the case in ENS forecasts, whose horizontal resolution is currently 18 km. However, as the horizontal resolution of atmospheric forecasts has increased to currently 9 km in the HRES, we have seen a growing number of overpredictions of TC intensity. A possible reason for this is the fact that the main energy source for TCs is heat transport from the ocean. By not coupling the atmosphere and the ocean, the heat exchange at the surface is misrepresented and the ocean acts as an undiminished source of energy for the atmosphere during the forecast period. This allows the TC intensity to increase unrealistically. Previously errors resulting from the lack of coupling were partly compensated for by opposite-sign errors in predicted core pressure resulting from the low atmospheric resolution.

Using a coupled model introduces negative feedback between the TC and the sea-surface temperature (SST). As strong winds from the cyclone enhance the heat uptake from the ocean, the SST may decrease, which in turn reduces the energy available to the cyclone. Tropical cyclones interact with the SST in three ways: heat transport to the atmosphere, vertical mixing in the ocean, and upwelling by Ekman pumping. While the first process could be simulated by a slab ocean model, the second requires a model of the well-mixed layer at the top of the ocean, and to simulate all three processes a full three-dimensional model is required. This is especially important for slow-moving cyclones.

At ECMWF a coupled atmosphere–ocean model is currently used operationally for ENS, including the monthly extension, and seasonal forecasts (SEAS). It is due to be implemented for HRES in the next IFS upgrade, Cycle 45r1.

Coupled atmosphere–waves–ocean model

In the IFS, both the wave model (WAM) and the ocean and sea-ice model (NEMO with LIM2) are integrated into the time stepping in such a way that they can be called at every nth atmospheric time step to get updated ocean fields (surface roughness from WAM, SST, sea-ice concentration and surface currents from NEMO) based on updated atmospheric forcing inputs (such as winds for WAM and surface stress, heat and water fluxes for NEMO). On top of the two-way interaction between NEMO/WAM and the atmosphere, NEMO and WAM also exchange data: NEMO receives wave information to account for wave-induced mixing, Stokes-Coriolis drift and sea-state modified stress, and it passes back sea-ice concentration to WAM. The frequency of atmospheric time steps between WAM/NEMO calls determines the coupling frequency and is

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typically one time step (or 12 minutes) for WAM and 5 time steps (or one hour) for NEMO. While the LIM2 sea-ice model is active in all coupled integrations, it is not relevant to the issues discussed here.

In this article we will present results from simulations using the current operational HRES atmospheric resolution (9 km) and the oceanographic configuration used in NEMO (about 25 km horizontal resolution with a 1 m top layer) as implemented in IFS Cycle 43r1. For atmospheric initial conditions, operational analyses were used. For ocean initial conditions, we used the ocean reanalysis system 5 (ORAS5) for coupled integrations. The uncoupled simulations were carried out with persisted anomalies, with initial SST from the OSTIA product, as is currently done in operations for HRES.

The current ENS uses a partial coupling setup, which couples the SST tendencies rather than the actual SST field from the ocean model during the first four days of the model integration, with a gradual transition to full SST coupling over the next four days. The partial coupling is intended to maintain the high spatial variability in the analysed SST used by the atmosphere in the early part of the forecast, and to ensure that errors in the position of boundary currents in the ocean analyses do not degrade the atmospheric forecast. Tests have shown that this scheme produces better results than full coupling of the SST predicted by the ocean model across the globe. However, it is planned to introduce full coupling from day 0 in IFS Cycle 45r1 in the tropics, since here full coupling has been found to be beneficial.

Simulating TC Haiyan and TC Neoguri

We have selected two extreme cases in terms of the impact of ocean coupling: Haiyan, for which coupling has only a small impact, and Neoguri, for which coupling has a very large impact.

Central pressure and heat fluxes

Figure 1 shows the position and central pressure for five-day HRES (squares) and ‘best track’ data (triangles) for each case. For both TCs, the predicted tracks agree well with the observed ones for the coupled and uncoupled setups. Regarding the intensity, the uncoupled and coupled forecasts for Haiyan

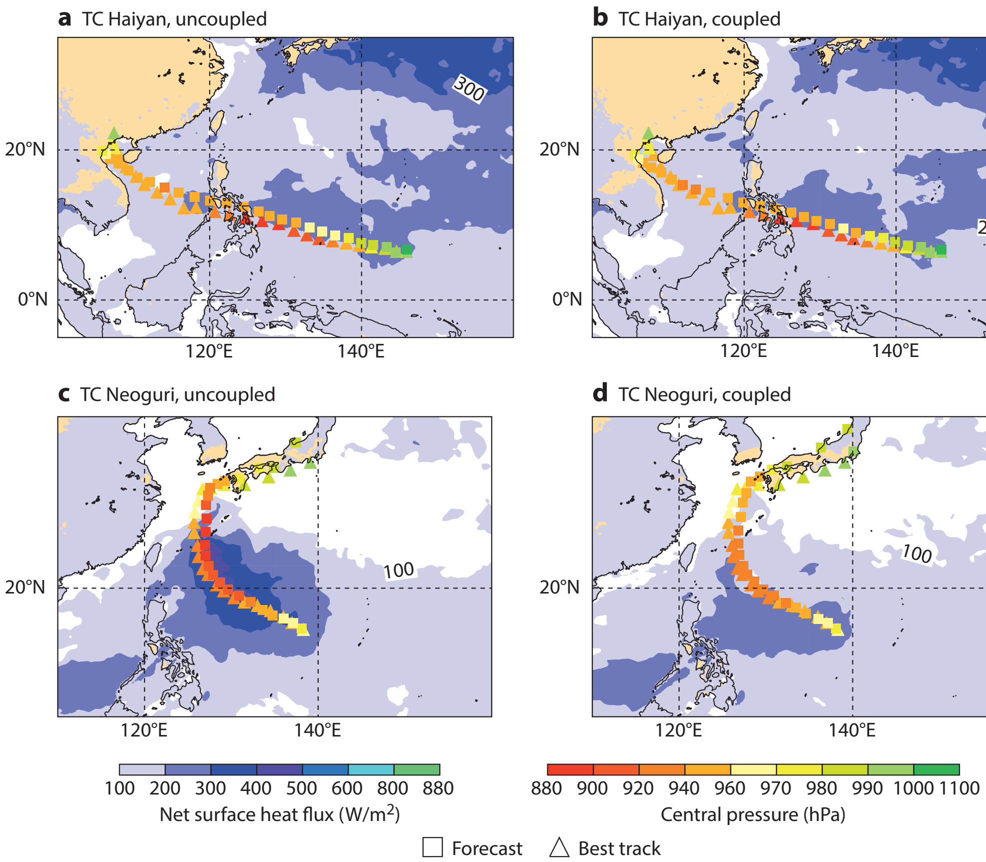

Figure 1 The plots show five-day HRES track and intensity forecasts (squares) together with ‘best track’ estimates (triangles) and the predicted net surface heat flux (shading) for (a) TC Haiyan (starting date 5 November 2013) using the uncoupled model, (b) TC Haiyan using the coupled model, (c) TC Neoguri (starting date 5 July 2014) using the uncoupled model, and (d) TC Neoguri using the coupled model.

both predict a cyclone which is too weak, with only minor differences between the two. For Neoguri, the uncoupled forecast overpredicts the cyclone intensity for forecast days 3–5, while the coupled forecast is better at this range. The plots also show the net surface heat flux (sensible + latent) to the atmosphere averaged over five days. For Haiyan there is little trace in the heat flux in the wake of the cyclone, while for Neoguri we find an increased heat flux from the ocean in the uncoupled forecast.

Figure 2 shows a comparison between uncoupled and coupled forecasts of the evolution of the net (sensible + latent) surface heat flux averaged over 6 hours in a radius of 150 km around the centre of the cyclone, and of the evolution of central pressure, for Haiyan and Neoguri. The plots show three forecasts with different starting dates for the two TCs. Coupled and uncoupled forecasts produce similar heat fluxes for Haiyan, while for Neoguri the heat flux for the uncoupled forecast is almost twice as large as for the coupled forecast during the most intense stage of the cyclone. For Haiyan, there is little difference between coupled and uncoupled simulations for central pressure, which is too weak in either case. For Neoguri, there are large differences in central pressure: the uncoupled simulations are too intense and the coupled simulations are more realistic compared to the ‘best track’ estimates.

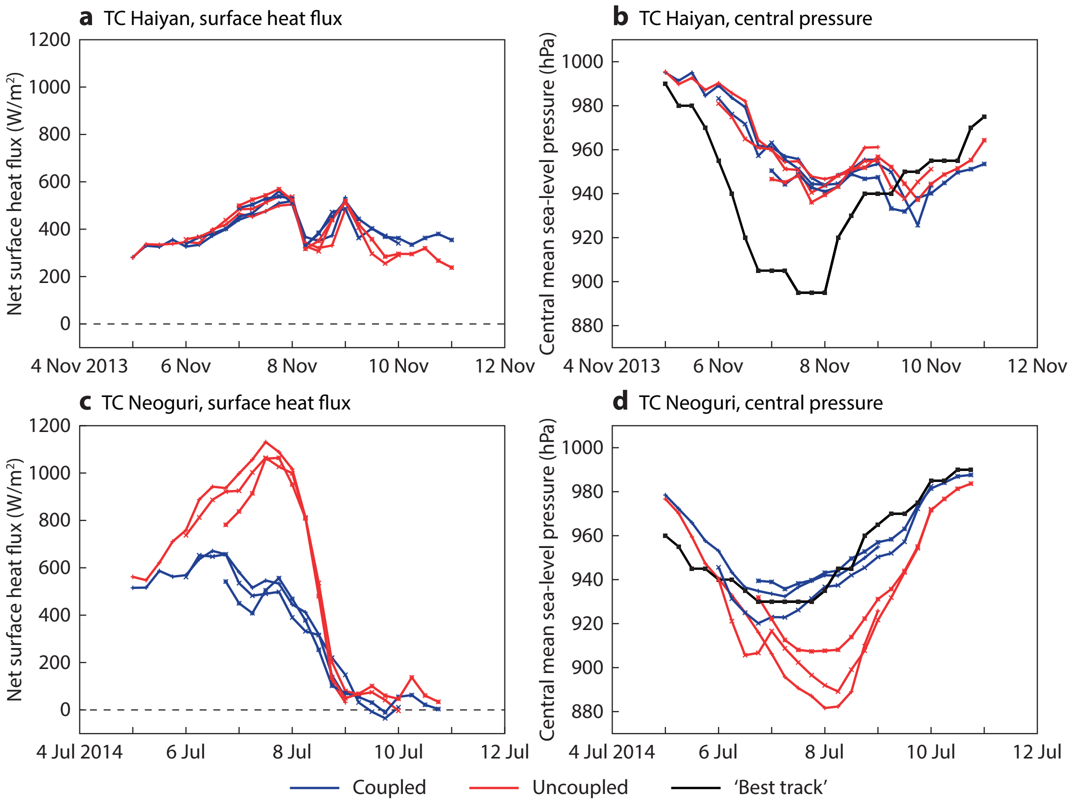

Figure 2 The plots show HRES forecasts of (a) net (sensible + latent) surface heat flux for TC Haiyan, (b) central pressure for TC Haiyan, (c) net surface heat flux for TC Neoguri, and (d) central pressure for TC Neoguri. ‘Best track’ estimates for central pressure are also shown.

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Sea-surface temperature

To verify whether the ocean response to the tropical cyclone forcing described above is realistic, we have compared the predicted SST to observations from drifting buoys and ships. Figure 3 shows the SST in 5-day coupled and uncoupled forecasts as well as observations of SST at the verification date. By construction, we do not find a cold wake in the uncoupled experiment as it uses SST from the analysis evolved daily with seasonal anomalies. There is no clear trace of a cold wake after Haiyan in the coupled forecast, either, nor is there such a trace in the small number of available observations. The opposite holds true for Neoguri, where we find a strong cold wake east of the track in the coupled forecast, where the cooling reaches 5°C. The SST in the coupled forecast is in good agreement with the two observations inside the cold wake of the cyclone. To further quantify this agreement, Figure 4 shows time series of four drifting buoys (DRIBU) near the path of Neoguri. Especially in Figure 4a, the evolution of the SST in the coupled forecast agrees well with the buoy observations, which show a cooling of 5°C over 24 hours. Overall the conclusion is that the cold wake predicted by the coupled IFS model is in reasonable agreement with observations for Neoguri, while for Haiyan the lack of a cold wake is also consistent between the model and observations.

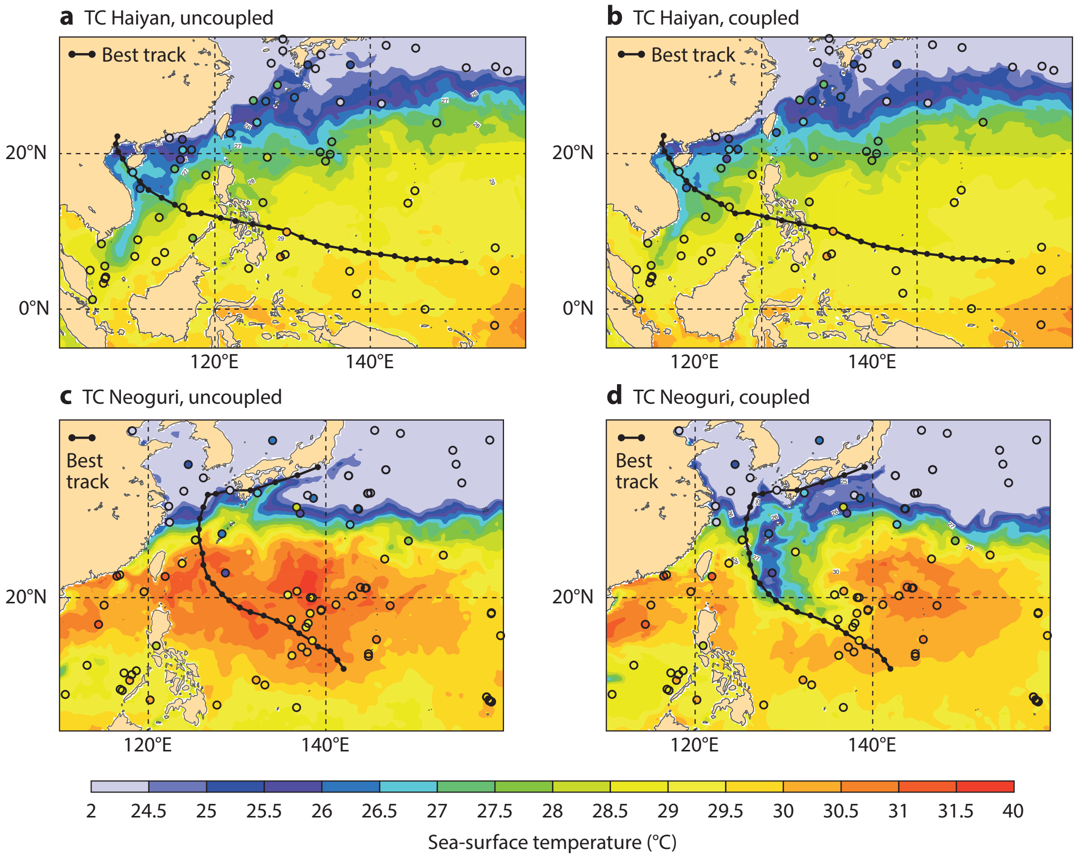

Figure 3 Five-day sea-surface temperature forecasts for (a) TC Haiyan (starting date 5 November 2013) using the uncoupled model, (b) TC Haiyan using the coupled model, (c) TC Neoguri (starting date 5 July 2014) using the uncoupled model, and (d) TC Neoguri using the coupled model, with SST observations (circles) valid at 00 UTC on 10 November 2013 and 00 UTC on 10 July 2014, respectively.

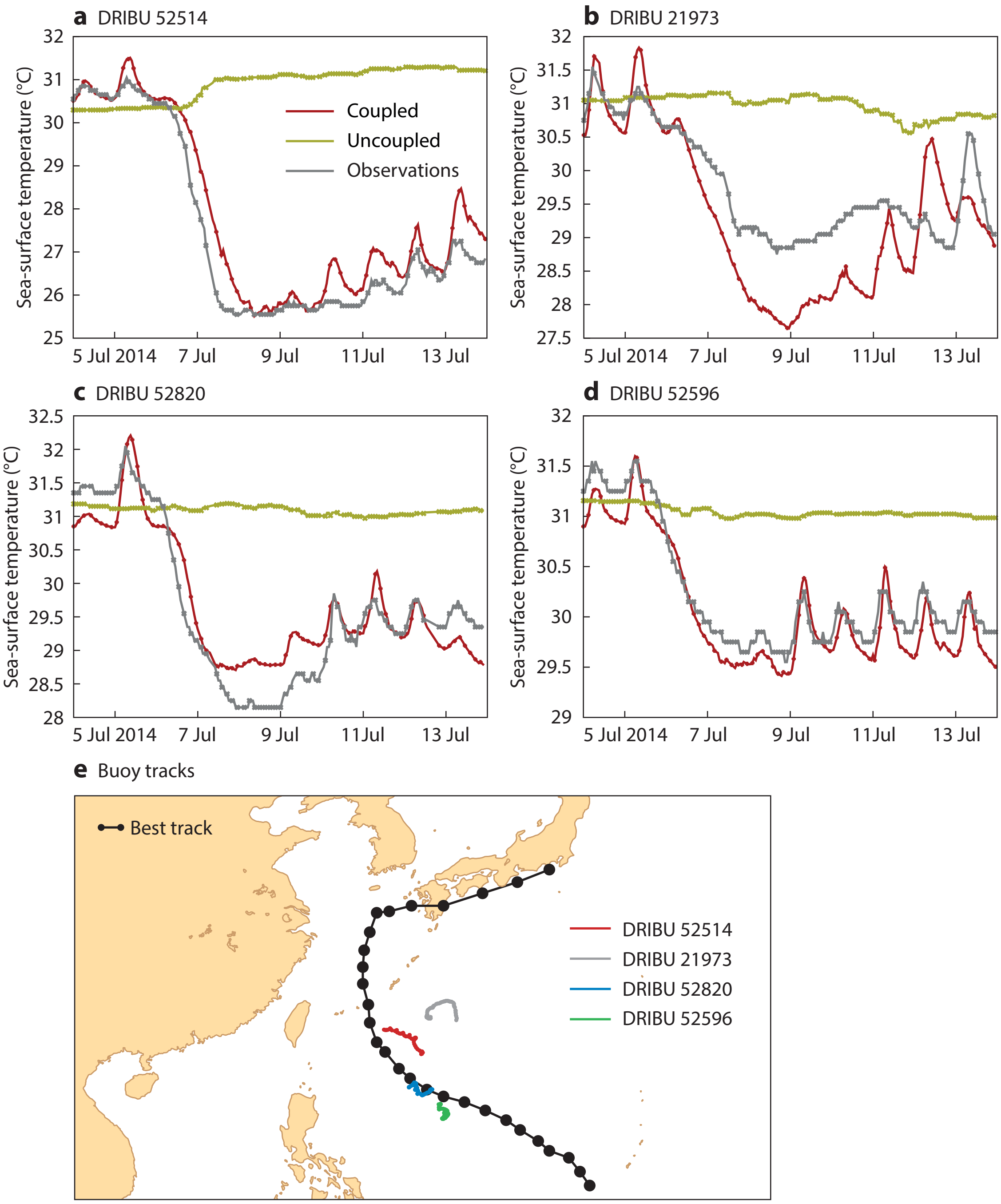

Figure 4 Observations from four DRIBU buoys and SST forecasts starting on 4 July for the same locations in the Neoguri case for (a) DRIBU 52514, (b) DRIBU 21973, (c) DRIBU 52820 and (d) DRIBU 52596, along the tracks shown in (e).

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Sub-surface oceanic response

The small effect of the coupling for Haiyan could be connected to the deep and well-developed ocean mixed layer present in this case, but it could also be due to the fact that the weak cyclone in the forecast is not able to increase the heat flux. In order to investigate this further, together with the strong effect of the coupling for Neoguri, we will now look at the sub-surface response in the ocean in the two cases. Figure 5 shows time series for predicted ocean fields of temperature and currents for the point on the model track closest to the Haiyan 'best track' position at 00 UTC on 7 November 2013, and for Neoguri for 18 UTC on 7 July 2014. The points were chosen to reflect the response in the open ocean. Other nearby points and different starting dates for the two cases show very similar behaviour.

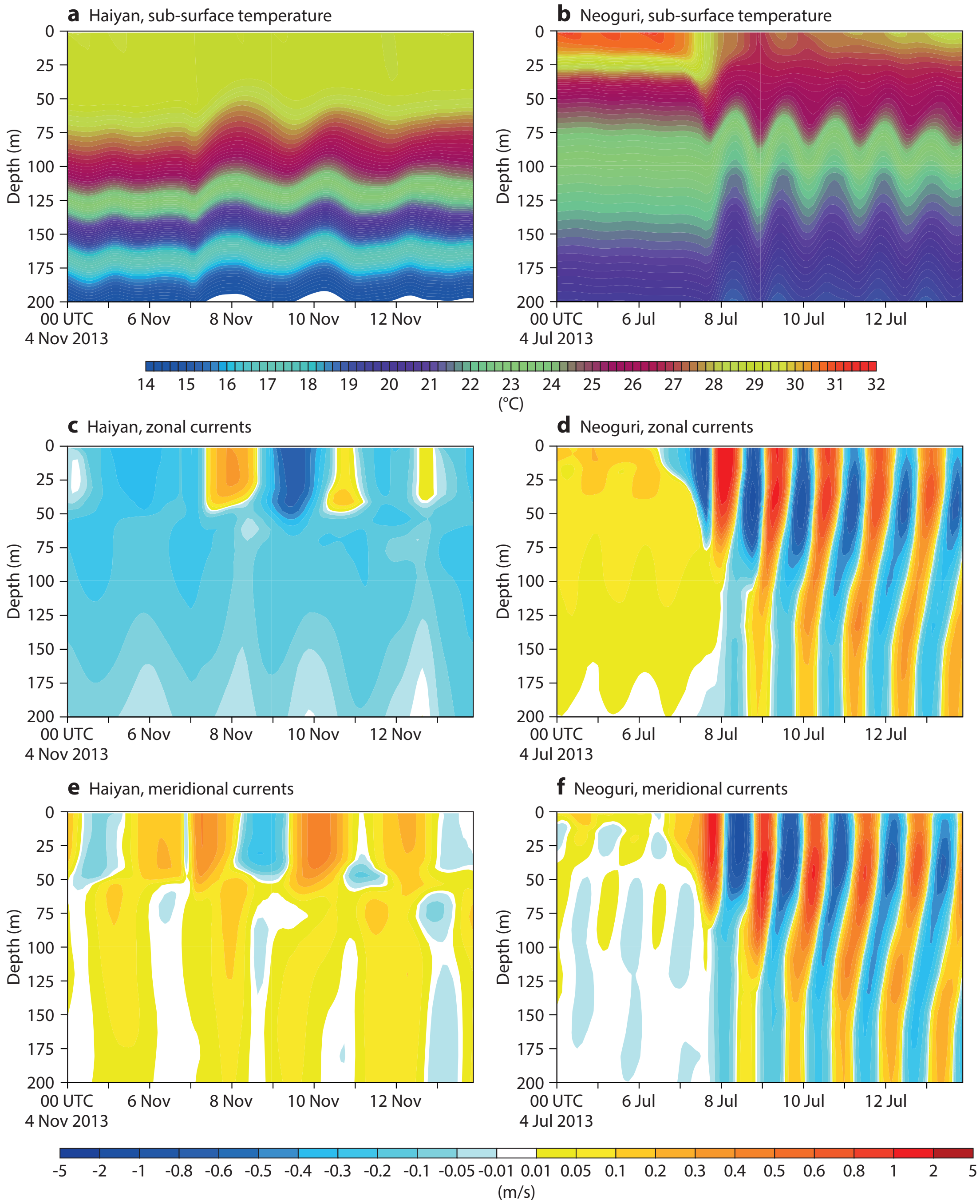

Figure 5 Plots of sub-surface temperature and currents for the two points on the model track closest to the estimated Haiyan 'best track' position at 00 UTC on 7 November 2013 and for Neoguri at 18 UTC on 7 July 2014, showing ocean forecasts of (a) sub-surface temperature for Haiyan, (b) sub-surface temperature for Neoguri, (c) zonal (east–west) currents for Haiyan, (d) zonal currents for Neoguri, (e) meridional (north–south) currents for Haiyan, and (f) meridional currents for Neoguri.

Looking at the temperature at initial time in the Haiyan case, it is clear that the ocean has a deep layer (about 80 metres) of warm water, whereas for Neoguri, the thermocline is steeper. This means that, even though the temperature at the surface is higher, for Neoguri the heat content in the surface region is lower. When the TCs reach the respective points (after 3 days for Haiyan and 3.75 days for Neoguri), the response is quite different. For Haiyan there is a small amount of cooling (not visible in the plot) of the whole of the thick warm layer, whereas for Neoguri the shallow warm layer is depleted of heat, causing a large amount of cooling in the upper ocean. It is worth noting that both TCs have a similar response in the currents, but of different magnitude, suggesting that the basic physics of the coupled response is the same even if the magnitude of the response is different.

Impact for many cases

To quantify the effect of ocean coupling on predicted TC intensity in general, rather than just for a few special cases, we have looked at a large set of coupled versus uncoupled forecasts at the HRES operational resolution. Two one-year periods were selected to test various aspects of HRES coupling: from 1 March 2015 to 1 March 2016, and from 1 June 2016 to 1 June 2017. An example of a comparison of coupled versus uncoupled forecasts is given in Figure 6, which shows a histogram of forecast errors for all identified TCs in the two periods for a lead time of 168 hours. There are a large number of uncoupled forecasts which are too intense, with negative errors of more than 25 hPa. Such errors are virtually absent from the coupled forecasts. There is a slight increase in the number of underpredicted TC intensities with ocean coupling, but overall the distribution of errors looks much more reasonable with ocean coupling than without it. The issue that TC intensities are underpredicted in some cases cannot be addressed by coupling. Reducing such errors will require other improvements, such as higher resolution in the atmospheric model.

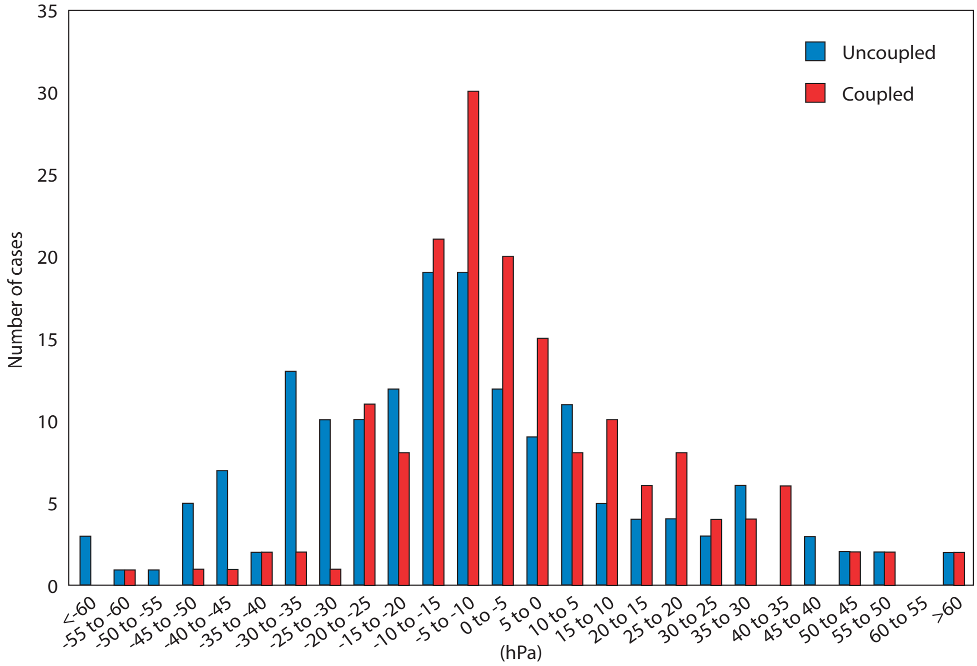

Figure 6 Distribution of 7-day TC intensity forecast errors for coupled and uncoupled high-resolution forecast experiments. The experiments cover the period of March 2015 to June 2017 and were carried out over all basins for a total of 163 TCs.

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Conclusion

From the comparison of the behaviour of the upper ocean in the cases of Haiyan and Neoguri, we conclude that knowledge of the vertical stratification of the ocean is crucial in order to be able to predict the ocean–atmosphere interactions and thereby to predict more accurately the evolution of TCs. For Neoguri, we have shown that a shallow warm layer is the key to a strong coupled SST response, whereas for Haiyan the thick warm layer leads to a weak coupled SST response. The sea-surface temperature was actually warmer for Neoguri than for Haiyan, but we have shown that the ocean stratification is the main determining factor for the magnitude of the coupled response. This also means that good ocean initial conditions are vital for high-quality TC forecasts, since errors in the initial stratification in the coupled model will result in errors in the ocean response.

Ocean coupling will be even more important in the future, at higher atmospheric resolutions. At such resolutions the ability to generate stronger winds means that using a coupled model will be essential for cases with moderate to low upper ocean heat content.

Further reading

Mogensen, **K.S.**, **L. Magnusson** & **J-R. Bidlot**, 2017: Tropical cyclone sensitivity to ocean coupling in the ECMWF coupled model. *J. Geophys. Res. Oceans*, **122**, 4392–4412.

Mogensen, **K.S.**, **L. Magnusson** & **J-R. Bidlot**, 2017: Tropical Cyclone Sensitivity to Ocean Coupling. *ECMWF Technical Memorandum*, **794**.

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