Impact of Scatterometer Surface Wind Data in the ECMWF Coupled Assimilation System

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ABSTRACT

The European Centre for Medium-Range Weather Forecasts (ECMWF) has developed a coupled assimilation system that ingests simultaneously ocean and atmospheric observations in a coupled ocean–atmosphere model. Employing the coupled model constraint in the analysis implies that assimilation of an ocean observation has immediate impact on the atmospheric state estimate, and, conversely, assimilation of an atmospheric observation affects the ocean state. In this context, observing system experiments have been carried out withholding scatterometer surface wind data over the period September–November 2013. Impacts in the coupled assimilation system have been compared to the uncoupled approach used in ECMWF operations where atmospheric and ocean analyses are computed sequentially. The assimilation of scatterometer data has reduced the background surface wind root-mean-square error in the coupled and uncoupled assimilation systems by 3.7% and 2.5%, respectively. It has been found that the ocean temperature in the mixed layer is improved in the coupled system, while the impact is neutral in the uncoupled system. Further investigations have been conducted over a case of a tropical cyclone when strong interactions between atmospheric wind and ocean temperature occur. Cyclone Phailin in the Bay of Bengal has been selected since the conventional observing system has measured surface wind speed and ocean temperature at a high frequency. In this case study, the coupled assimilation system outperforms the uncoupled approach, being able to better use the scatterometer measurements to estimate the cold wake after the cyclone.

1. Introduction

Coupled data assimilation methods are designed to assimilate ocean and atmospheric observations through the use of a coupled earth model. A number of numerical weather prediction (NWP) centers are investigating different coupled assimilation methods exhibiting varying levels of coupling between the ocean and atmosphere (Saha et al. 2010; Lea et al. 2015; Alves et al. 2014). To produce consistent ocean–atmosphere estimates, it is clear that the constraint applied by the coupled model across the component interfaces has to be enforced in the assimilation process. The European Centre for Medium-Range Weather Forecasts (ECMWF) has developed the Coupled ECMWF Re-Analysis (CERA) system following this approach. The ECMWF ocean–wave–atmosphere coupled model is used in an incremental variational method (Courtier et al. 1994) to assimilate simultaneously ocean and atmospheric observations from a common 24-h assimilation window (Laloyaux et al. 2016). The ocean and the atmospheric components use separate background error covariance models meaning that no explicit cross correlation are generated. However, the computation of several outer iterations in the incremental variational method generates implicit correlations between the ocean and atmosphere through the exchange of physical fields during the coupled model integrations. This allows the ocean observations to have immediate impact on the atmospheric state estimate, and, conversely, assimilation of atmospheric observations affects the ocean state. Some work is ongoing to study the quality of these implicit correlations between near-surface variables looking at their size, horizontal length scale, and vertical extent to ensure that they represent correctly physical processes. The quality of the coupled analysis produced by the CERA system has been assessed over short recent periods. This shows that using a coupled model in the incremental variational approach provides an

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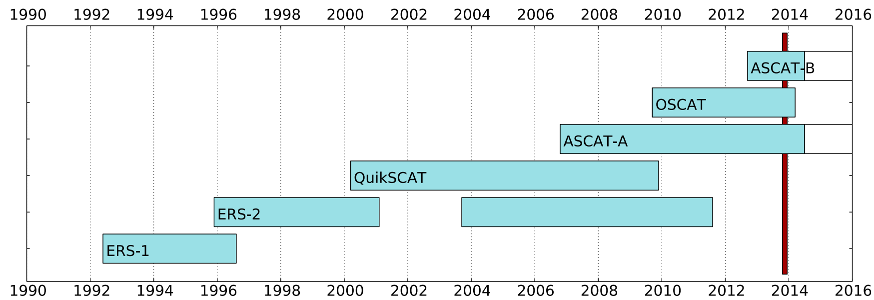

FIG. 1. Timeline of the measurement availability for the different scatterometer instruments used at ECMWF. Experiments have been carried out during the period September–November 2013 when ASCAT-A, ASCAT-B, and OSCAT data were available.

analysis that is consistent with the coupled model and improves the ocean–atmospheric temperature estimate (Laloyaux et al. 2016).

Coupled assimilation systems may make better use of near-surface measurements because any adjustment due to observations near the surface should impact both atmospheric and oceanic variables through the use of the coupled model in the assimilation process. The purpose of this paper is to evaluate the impact of scatterometer surface wind data in the CERA system compared to the uncoupled approach used in ECMWF operations where atmospheric and ocean analyses are computed sequentially. Using the same model resolutions and model versions in the coupled and uncoupled experiments provides a fair comparison that could demonstrate some potential benefits of the CERA methodology with respect to the current operational approach. Observing system experiments (OSEs) have been carried out with the two assimilation systems withholding scatterometer data from the Advanced Scatterometers A and B (ASCAT-A, ASCAT-B) and the OceanSat Scatterometer (OSCAT) instruments over the period September–November 2013. Emphasis has been put on the role of scatterometer measurements during Cyclone Phailin over the Bay of Bengal as tropical cyclones are coupled phenomena with strong interactions between atmospheric wind and ocean temperature (Ginis 2002).

The paper is organized as follows. Section 2 reviews the importance of scatterometer instruments to estimate atmospheric fluxes, focusing on the description of ASCAT-A, ASCAT-B, and OSCAT used operationally during the period when the experiments have been conducted. Section 3 describes the coupled assimilation system and its uncoupled counterpart. The configuration of these two systems and the observing system experiments are detailed in section 4. The impact of scatterometer data is first assessed in section 5 looking at the background and analysis root-mean-square errors in the tropics with respect to atmospheric and ocean conventional observations recorded in October–November 2013. A case study is then presented in section 6 illustrating the specific impact of scatterometer data during Cyclone Phailin. Finally, section 7 presents conclusions and perspectives for future work.

2. Scatterometer instruments

The reliable estimation of fluxes at the interface between atmospheric, wave, and ocean models is a key component to estimate accurately the ocean and atmospheric state. In NWP, conventional and satellite surface wind observations are assimilated over oceans to keep the air–sea interface as close as possible to the reality. Conventional ocean surface wind observations are obtained from anemometers located on ships and on buoys floating over the ocean. These observations are valuable but their benefit is limited due to the restricted coverage and the ships' tendency to avoid extreme weather. Since the ocean regions are so large, knowledge of the wind characteristics over this vast space is important to weather forecasting and climate study. In this context, satellite wind measurements are crucial and scatterometer instruments are used to measure indirectly ocean surface winds. Scatterometers are radars that transmit well-characterized pulses of microwave energy down to the earth's surface and then measure the power that is returned back to the instrument (Moore and Fung 1979; Stoffelen 1998). The measuring principle relies on the fact that winds over the sea cause small-scale disturbances of the sea surface, which modify its radar backscattering characteristics. These can be translated using a geophysical model function into a 10-m neutral wind that does not depend on the atmosphere stability and on the surface ocean current. This 10-m neutral wind is assimilated in the ECMWF four-dimensional variational data assimilation (4D-Var) system using an observation operator that constructs from the model variables an equivalent of 10-m neutral wind observation (Hersbach 2010a).

The timeline of the measurement availability for the different scatterometer instruments used at ECMWF is illustrated in Fig. 1. The European Remote Sensing

(ERS) satellites (*ERS-1* and *ERS-2*) were launched by the European Space Agency (ESA) and have provided observations in operational mode until the end of their mission in June 1996 and July 2011 (excluding a suspension of about 3 years from 2001 to 2004). The assimilation of their measurement in the ECMWF operational Integrated Forecast System (IFS) started on 30 January 1996 improving medium-range weather and wave forecasts (Isaksen and Janssen 2004). Data from the QuikSCAT satellite were assimilated operationally from January 2002 to November 2009 when the data dissemination was interrupted after a failure occurred to the satellites antennae.

The observing system experiments carried out in this paper have been run over the period September–November 2013 when ASCAT-A, ASCAT-B, and OSCAT instruments have provided measurements. The Advanced Scatterometer (ASCAT) is one of the new-generation European instruments carried on Meteorological Operational (MetOp) suite of satellite (Figa-Saldana et al. 2002). Like its predecessors on *ERS-1* and *ERS-2*, ASCAT operates at a frequency in C band (5-GHz frequency) and provides a continuous measurement capability over the sea that is unaffected by cloud cover or rain. ASCAT measures sea surface backscatter in two 500-km-wide swaths and an observation thinning is applied in the assimilation process to keep one measurement every 100 km. The first ASCAT scatterometer (ASCAT-A) was launched on the EUMETSAT *MetOp-A* satellite in October 2006 and a second identical ASCAT instrument (ASCAT-B) was launched on *MetOp-B* in September 2012. Sea surface neutral winds are obtained by applying a wind inversion by means of a geophysical model function (GMF) that describes the relation between the backscatter measurements and the zonal and meridional components of the wind (Hersbach 2010b). From this inversion, two wind solutions are retrieved and the most appropriate is dynamically determined by comparison with the background wind estimate. ASCAT-A and ASCAT-B data were assimilated operationally in the IFS system between February 2007 and July 2013, respectively (Hersbach and Janssen 2007; De Chiara 2013).

The OSCAT is a Ku-band (14-GHz frequency) scatterometer system designed and built by the Indian Space Research Organization (ISRO). OSCAT was launched aboard the *Oceansat-2* satellite in September 2009. This instrument provides backscatter measurements with a 1400-km-wide swath and a 50-km resolution. Since OSCAT measurements are sensitive to rainfall, any rainfall affected data are removed in the quality control step. OSCAT data have been assimilated in the IFS system from December 2011 until an irrecoverable instrument failure on 20 February 2014, shortly before the completion of the intended 5-yr instrument life span (De Chiara 2012).

3. Assimilation systems

The assessment of scatterometer data is evaluated in the coupled assimilation system (CERA) and in an uncoupled assimilation system (UNCPL) follows the existing approach used in ECMWF operations. In the CERA system, coupled ocean–atmosphere analyses are computed with an incremental variational approach that uses the ECMWF coupled model to assimilate simultaneously ocean and atmospheric observations from a common 24-h assimilation window (Fig. 2). The ECMWF coupled model includes the IFS atmospheric model (ECMWF 2013), the wave model (WAM; Komen et al. 1996), and the Nucleus for European Modeling of the Ocean (NEMO) ocean model (Madec 2008). In the newly developed coupled ocean–wave–atmosphere system all components are integrated into the same executable with a sequential calling of each component (Mogensen et al. 2012). In the outer loop of the incremental variational approach, the coupled model is integrated over the assimilation window, producing a four-dimensional state estimate and observation misfits. During this coupled integration, fluxes are exchanged between the different components each hour. The inner loop then solves in parallel a linearized version of the variational formulation using a 3DFGAT method (Massart et al. 2010) for the ocean and a 4D-Var method for the atmosphere. In the current implementation, the CERA system computes two outer iterations to produce the ocean and atmospheric analysis. In the context of coupled assimilation, performing several outer iterations provides an extra advantage as it allows the observations from one component to affect the other component through the exchange of physical fields during the coupled model integration used to compute the observation misfits. Because observations in one component affect both components this should result in a better balanced coupled state. The sea surface temperature (SST) has to be constrained to avoid the rapidly growing bias of the coupled model while allowing the simulation of relevant coupled interactions. Rather than assimilating SST observational data, a gridded SST analysis product is used to constrain the upper-level ocean temperature via a Newtonian relaxation scheme. A weighted relaxation term is added on the right-hand side of the SST prognostic equation that forces the integration toward the analysis product. The relaxation coefficient is set to $-200\,\mathrm{W\,m^{-2}\,°C}$, equivalent to about a 2–3-day time scale over a depth of

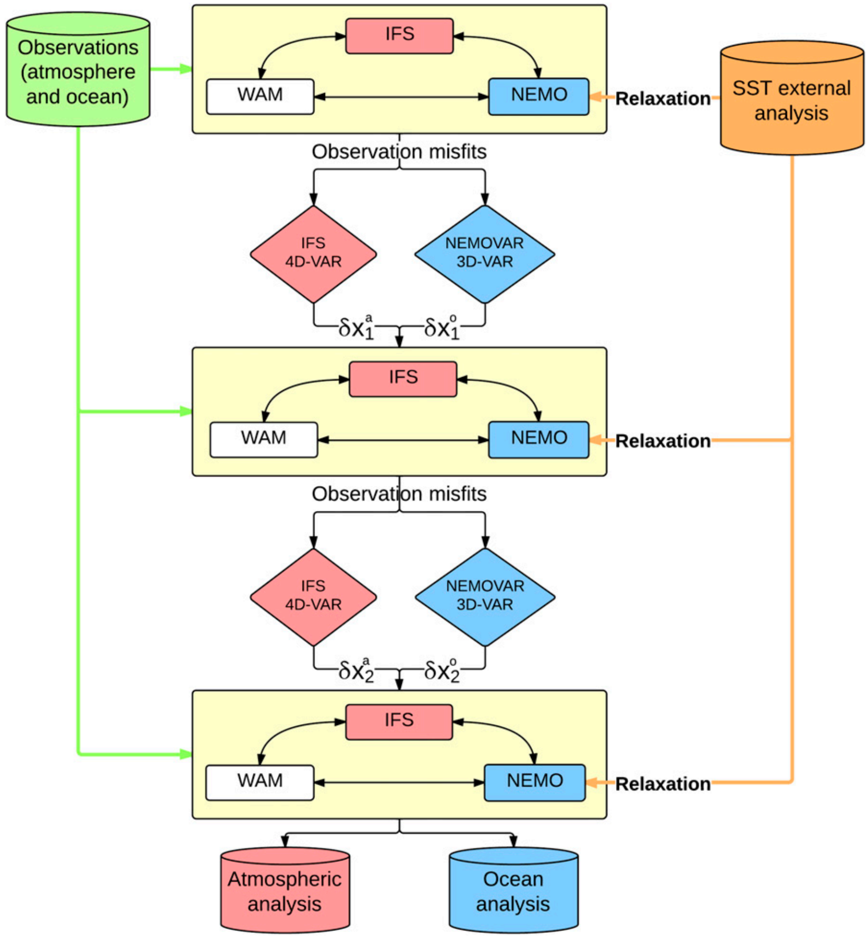

FIG. 2. Schematic diagram of the CERA coupled assimilation system. Yellow boxes represent model integrations, while diamonds represent increment computations. This diagram illustrates the computation of two outer iterations of the incremental variational method.

10 m (Balmaseda et al. 2013). This relaxation scheme computes a SST analysis in the ocean component of the CERA system that is transferred to the atmospheric component every hour. Finally, the coupled ocean–atmosphere analysis is carried forward in time by the coupled model to the next assimilation window.

In the uncoupled assimilation system (UNCPL), ocean and atmospheric analyses are produced separately by two uncoupled assimilation systems based on the same 24-h assimilation window as the CERA system. The atmospheric analysis is produced by an incremental 4D variational approach (left panel of Fig. 3). The outer loop integrates the IFS atmospheric model and the WAM wave model, producing a four-dimensional state estimate and observation misfits. The inner loop then solves a linearized version of the variational formulation for the control atmospheric variables. The computation of several outer iterations is required to deal with the model nonlinearities and allow the convergence. During the assimilation process, the surface boundary condition of the atmospheric model is prescribed using a gridded SST analysis product. Once the atmospheric analysis has been computed, the ocean assimilation is performed with an incremental 3DFGAT variational approach where the observation misfits are computed by the uncoupled NEMO ocean model (right panel of Fig. 3). This ocean model is constrained by the instantaneous 10-m wind, temperature, and humidity analyses retrieved every 6 h and by the accumulated daily fields for precipitation, evaporation, and surface solar and surface thermal radiations. SST is treated with the same relaxation method as in the CERA system using the same gridded OSTIA SST product, but the SST analysis computed in the ocean component is not transferred to the atmosphere. To carry forward in time the atmospheric and ocean analyses to the next assimilation cycle, the uncoupled version of IFS and NEMO models are used, respectively. This uncoupled assimilation system

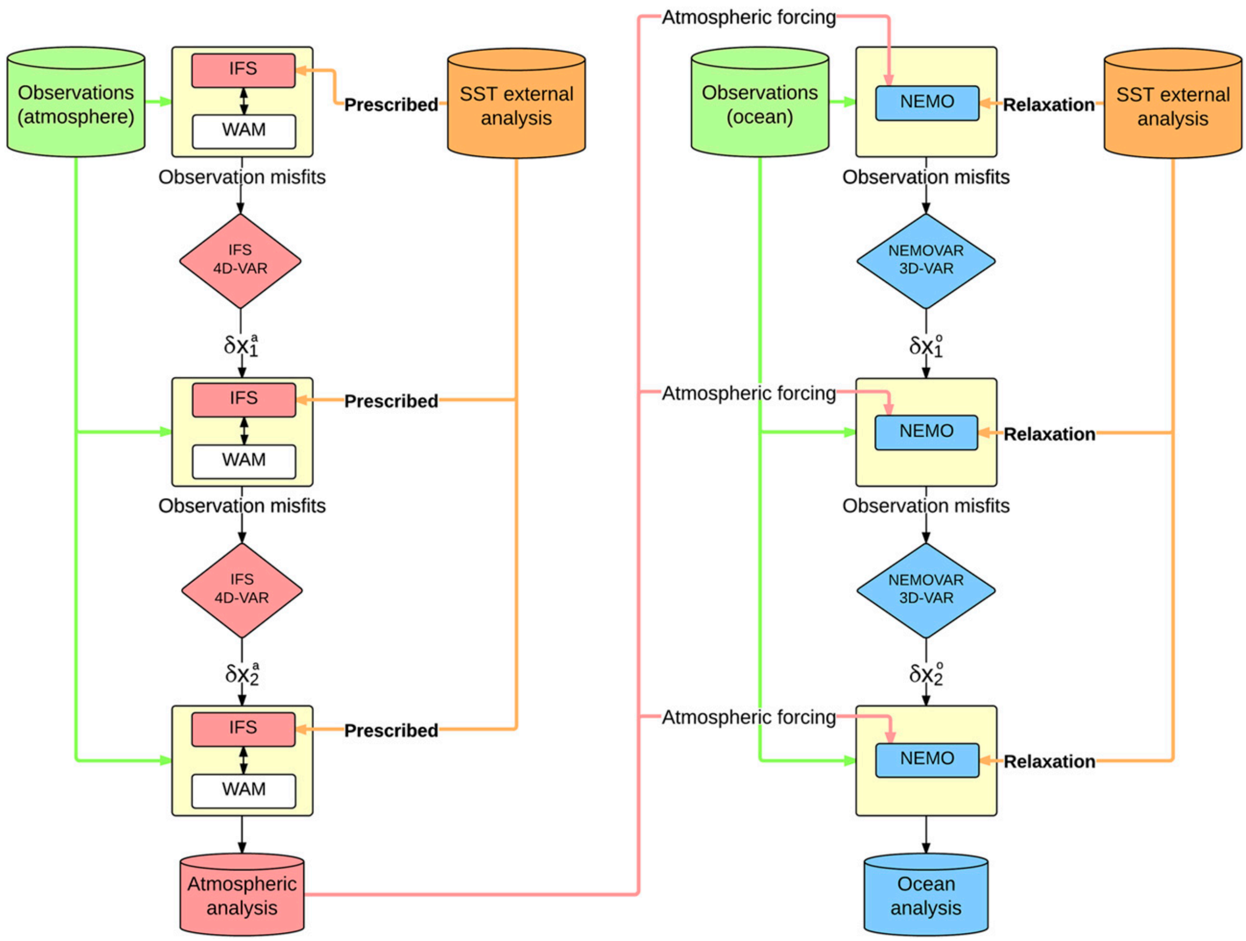

FIG. 3. Schematic diagram of the uncoupled assimilation system. Yellow boxes represent model integrations, while diamonds represent increment computations. This diagram illustrates the computation of two outer iterations of the incremental variational method.

shows, in fact, a one-directional coupling through the use of the completed atmospheric analysis during the ocean analysis. However, the CERA system with its two-way coupling should produce stronger dynamical ocean and atmospheric feedbacks during the assimilation process.

The background-error covariance models are key elements during the assimilation. They determine how the analysis spreads locally observed information in its vicinity and how it uses this information to adjust estimates of unobserved variables. The CERA and UNCPL systems use identical ocean and atmospheric background error covariance models that are constant in time without any explicit representation of correlations between the components. In the NEMO component, the background error covariance model includes several operators that estimate error correlations. The multivariate correlations present between different physical fields are modeled using balance operators (Weaver et al. 2005). The spatial univariate correlations between values of the same physical field at different grid points are computed by integrating diffusion equations that give the smoothing effect of the background error covariance matrix, as well as the length scales for the univariate correlation operators (Weaver and Courtier 2001). In the IFS component, the background error covariance model is based on a wavelet formulation that allows both spatial and spectral variation of the horizontal and vertical covariances of background error (Fisher 2004). More information about the coupled model and about technical details on the implementation of the CERA system can be found in Laloyaux et al. (2016).

4. Experiment setup

The CERA system has not been directly compared to the uncoupled assimilation system used in ECMWF operations because they are based on different model

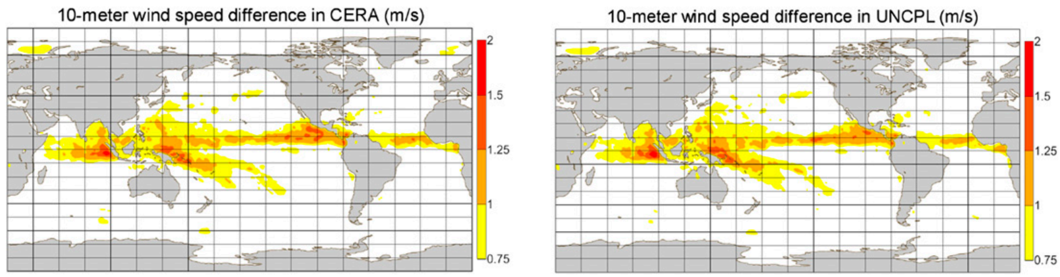

FIG. 4. RMS difference in the 10-m wind speed analysis between the FULL and NOSCATT experiments for the (left) CERA system and (right) the UNCPL system. No land–sea mask has been applied and RMS difference has been computed for October–November 2013.

versions and resolutions. To get a fairer comparison, an uncoupled assimilation system based on the operational approach has been developed with the same model version and resolution as the CERA system. The resolution of the atmospheric model is set to T159L137 (IFS version 40R1), which corresponds to a 1.125° horizontal grid (128-km grid) with 137 vertical levels going up to 0.1 hPa. The horizontal resolution of the wave model is 1.5° with a wave spectra discretized using 12 directions and 25 frequencies. The ocean model (NEMO version 3.4) uses the ORCA1 grid, which has roughly a 1° horizontal resolution. The ocean has 42 vertical levels going down to 5350 m with a layer thickness of 10 m in the first 100 m. In the uncoupled assimilation system, the SST is prescribed in the atmospheric component using the Operational Sea Surface Temperature and Sea Ice Analysis (OSTIA) analysis (Donlon et al. 2012). This OSTIA product is also used in the relaxation scheme implemented in the ocean component of the two systems. The atmospheric reanalysis ERA-Interim (Dee et al. 2011) and the Ocean Reanalysis System 4 (ORA-S4; Balmaseda et al. 2013) are used to initialized all the CERA and UNCPL experiments. Finally, the same computational effort is used in the two assimilation systems, computing two outer iterations of the incremental variational approach with the same number of inner iterations.

Observing system experiments were performed to measure the impact of scatterometer data. On the one hand, the two assimilation systems have been run between September 2013 and November 2013 assimilating the full earth observational system with the conventional and satellite observations for ocean, wave, and atmosphere. The coupled experiment is called CERA/FULL and the uncoupled one is called UNCPL/FULL. On the other hand, two denial experiments have been run withholding scatterometer data from ASCAT-A, ASCAT-B, and OSCAT instruments. These experiments are called CERA/NOSCATT and UNCPL/NOSCATT, respectively. Differences in the analyses produced by the FULL and NOSCATT experiments will highlight the impact of scatterometer measurement in each assimilation system. Comparing these impacts could demonstrate some potential benefits of the CERA methodology with respect to the current operational approach. The comparison has been done for October–November 2013, considering the first month as the spinup of the assimilation process.

5. Global impact

ASCAT and OSCAT instruments provide global coverage measurements of surface wind over oceans. Figure 4 illustrates the impact of scatterometer data on the surface wind estimate for the CERA system (left panel) and the UNCPL system (right panel), plotting the root-mean-squared (RMS) difference in the 10-m wind speed analysis between the FULL and NOSCATT experiments for October–November 2013. The impact of scatterometer data is comparable in the two assimilation systems with similar patterns, mainly located over the tropical oceans. Conventional wind observations from buoys and radiosondes have been assimilated in the two systems and are used to assess the benefit achieved by the scatterometer assimilation. Buoys are moored in the ocean and provide surface wind observations several times a day while radiosondes are launched from land or ships and provide wind observation profiles through the atmosphere. Figure 5 represents in red the observations from buoys and in black the observations from radiosondes selected for the statistic computations. The impact of scatterometer data being located over oceans, a subset of radiosondes has been selected where less than 20% of the actual surface of the model grid box is land. This choice has been made in order to get a sufficient number of wind observations from radiosondes launched from small islands or near the coast. Figure 6 shows vertical profiles of the zonal wind background (dashed lines) and analysis (solid lines) RMS departures with respect to the selected buoys and radiosondes

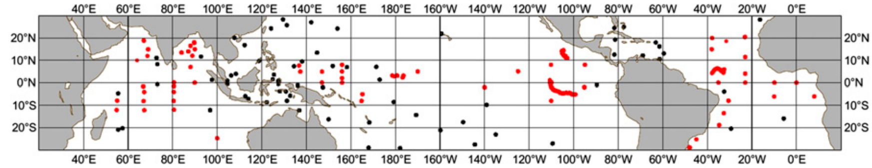

FIG. 5. Location of buoys (red) and radiosondes (black) used in the wind comparison for October–November 2013. Radiosondes have been selected where less than 20% of the actual surface of the model grid box is land.

observations in the tropical western Pacific, for the CERA experiments in the left panel and for the UNCPL experiments in the right panel. The comparison of the departures from the FULL and NOSCATT experiments of the CERA and UNCPL systems shows that the zonal wind background and analysis are closer to the observations when scatterometer data are assimilated in the two systems. Even though the impact is small, this means that both systems take advantage of the scatterometer instruments and are able to carry forward in time the benefits gained from the scatterometer assimilation. The impact of scatterometer data is slightly larger in the CERA system near the ocean surface in comparison with the UNCPL system. The RMS background and analysis departures at 1000 hPa have been reduced in the CERA system by 0.136 and 0.102 m s^{-1}, respectively, while they have been reduced by 0.058 and 0.057 m s^{-1}, respectively, in the UNCPL system. This might be explained by the larger variability of the coupled model where the SST is computed dynamically every hour by the ocean component. At ocean fronts and eddies, air–sea interaction exhibits positive correlation between SST and wind speed (Small et al. 2008). During the coupled model integrations performed in the CERA system, small modifications in SST can result in wind anomalies that feed back onto the ocean, possibly enhancing the air–sea interactions. In this context, the assimilation of extra near-surface observations has the possibility to further constrain the model, producing larger analysis and background RMS reduction. Note that similar conclusions can be drawn looking at other tropical oceans or studying the meridional wind speed departure statistics. The impact of scatterometer data on the ocean state has been studied focusing on differences in the ocean temperature estimation. The top panel of Fig. 7 shows the zonal cross section at 5°N of the mean ocean temperature analysis in October–November 2013 for CERA/NOSCATT on the left and UNCPL/NOSCATT on the right. The two experiments show similar temperature analysis with similar mixed layer and thermocline depth. The impact of scatterometer data on the ocean temperature analysis has been represented for the CERA and UNCPL systems in the bottom panel of Fig. 7 computing the difference between the FULL and NOSCATT experiments. A positive value means that the temperature analysis increases when the scatterometer data are assimilated. In the two systems, differences due to the assimilation of scatterometer data are located in the mixed layer and in the thermocline. These differences are globally similar in the two systems with a typical value around 0.3°C, except in the tropical eastern Pacific where the CERA system shows a difference

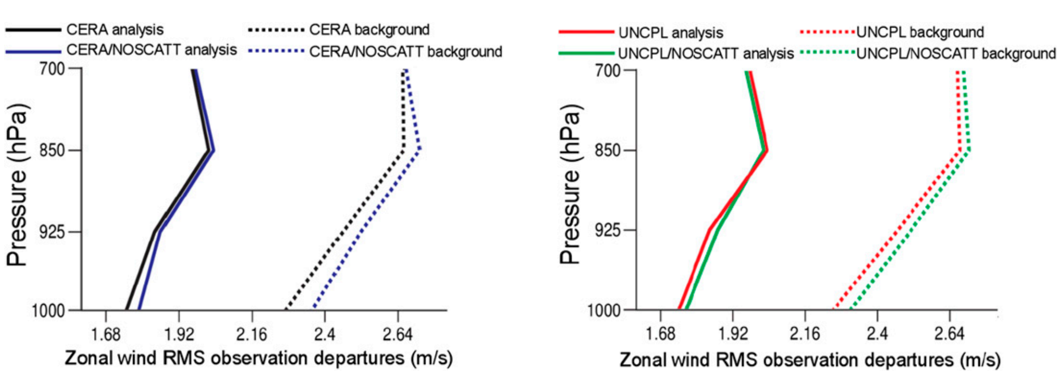

FIG. 6. Vertical profiles of the zonal wind background (dashed lines) and analysis (solid lines) RMS departures over the tropical western Pacific (30°S–30°N, 110°E–180°) with respect to buoys and radiosondes observations selected for October–November 2013. (left) CERA FULL and NOSCATT experiments and (right) UNCPL FULL and NOSCATT experiments.

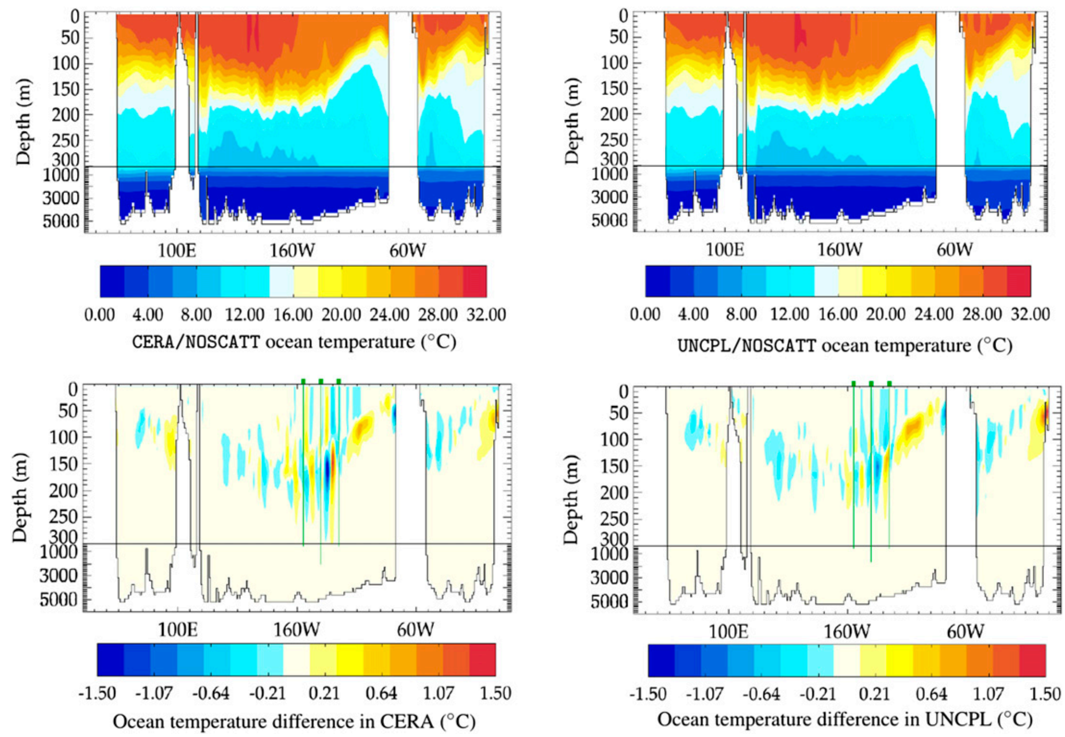

FIG. 7. (top) The zonal cross section of the mean ocean temperature analysis at 5°N in the (left) CERA/NOSCATT experiment and (right) UNCPL/NOSCATT experiment for October–November 2013. (bottom) The zonal cross section of the difference between the FULL and NOSCATT ocean temperature analyses at 5°N in the (left) CERA system and (right) UNCPL system. A positive value means that the temperature analysis increases when the scatterometer data are assimilated. The green dots represent the stations that measured temperature profiles in the tropical eastern Pacific Ocean for October–November 2013, while the green lines show the maximal measurement depths [(left) TAO mooring 51020, (middle) Argo float 5903873, and (right) TAO mooring 51015].

higher than 1°. For this reason, the tropical eastern Pacific Ocean between 4° and 6°N is investigated in more detail using the temperature observations from the EN3 conventional dataset (Ingleby and Huddleston 2007) that have been assimilated in the two systems. Three stations have measured temperature profiles in that region during the period October–November 2013. Two TAO moorings have recorded one temperature profile every day up to a depth of 500 m. They are located at 5°N, 154.9°W (WMO Identifier 51020) and at 5°N, 124.9°W (WMO Identifier 51015). These two positions are represented in the bottom panel of Fig. 7 by the left and right square dots and the depths of the observation profiles is represented by the thin green vertical lines. One Argo float was drifting near 5°N, 140°W during that period and has recorded one temperature profile up to 2000 m every 10 days (WMO Identifier 5903873). This float is represented by the middle green dot in the bottom panel of Fig. 7. No measurements have been made where the largest temperature differences were noticed, but an assessment of the scatterometer data on the ocean temperature estimate is possible at three other locations. The left column of Fig. 8 shows vertical profiles of ocean temperature observations and analyses (CERA system at the top and UNCPL system at bottom) for the Argo float 5903873 at 0914 UTC 15 October. In the CERA system, the assimilation of scatterometer data has improved the temperature estimate in the mixed layer and at the top of the thermocline (top-left zoomed-in plot in Fig. 8). Differences are also observed with the UNCPL system at the same depths (bottom-left zoomed-in plot in Fig. 8), but with a neutral impact. The right column of Fig. 8 shows the same diagnostics for the observations profile from the TAO mooring 51020 measured at 2100 UTC 21 October. Scatterometer data improves slightly the temperature estimate in the mixed layer of the CERA and UNCPL systems. Other profiles for different dates and for the three stations have been produced showing a positive impact of scatterometer data in the mixed layer and at the top of the thermocline with the CERA system, while there is a more neutral impact in the UNCPL analysis. This improvement in the CERA system might be explained by the coupled model used inside the

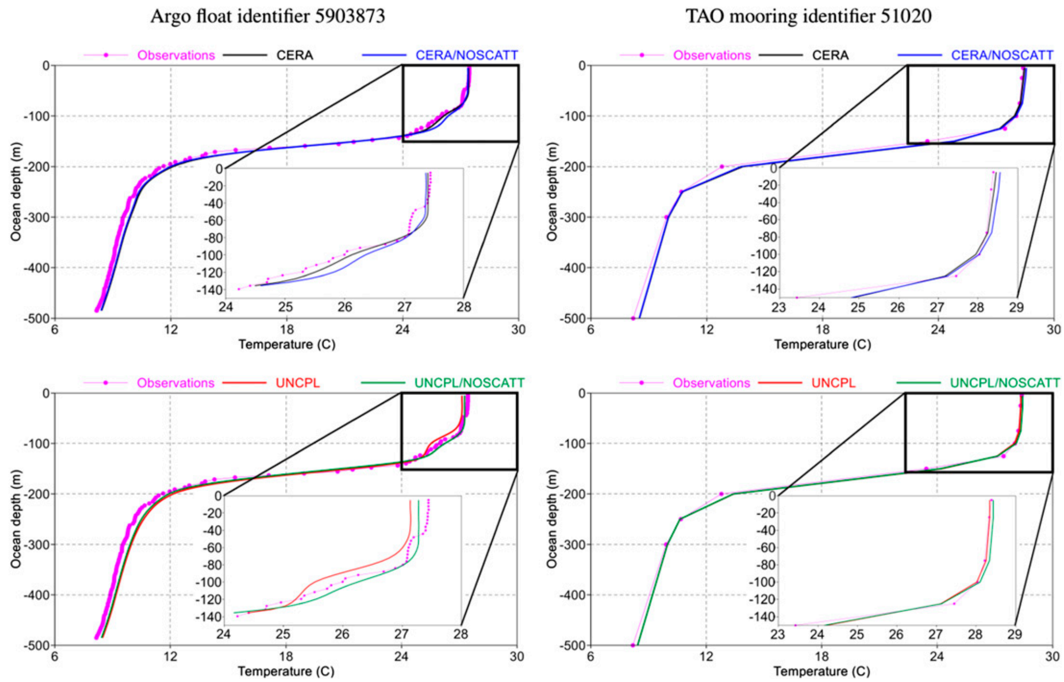

FIG. 8. Observation and analysis vertical profiles (left) for the Argo float 5903873 at 0914 UTC 15 Oct 2013 and (right) for the TAO mooring 51020 at 2100 UTC 21 Oct 2013 with (top) the CERA system and (bottom) the UNCPL system.

assimilation process which transfers fluxes between atmosphere and ocean every hour, compared to the one-way coupling used in the UNCPL system based on 6-h frequency retrievals of atmospheric fluxes.

6. Cyclone Phailin

The overall impact of scatterometer data in the tropics has been studied in section 5 looking at observation departure statistics. This approach has shown some limitations especially in the ocean part where the largest temperature differences cannot be assessed with such statistics due to a lack of observations. Tropical cyclones are coupled phenomena with strong interactions between the atmospheric winds and the ocean temperature and the impact of scatterometers is expected to be accentuated during such severe weather systems. During the period October–November 2013, the north Indian Ocean cyclone season and the Pacific typhoon season were active with several strong tropical cyclones. However, conventional observations measuring surface wind speed and ocean temperature at a high frequency (several times a day) have been only recorded for Cyclone Phailin. For this reason, Cyclone Phailin has been selected as the only case study to illustrate the impact of scatterometer data. Note that these conventional observations are assimilated in the CERA and UNCPL systems and are therefore not independent. Cyclone Phailin formed on 4 October 2013 over the Bay of Bengal and dissipated on 14 October 2013. It was the second-strongest tropical cyclone ever to make landfall in India causing 45 fatalities and $696 million (U.S. dollars) of damages.

The mean sea level pressure analysis computed by the CERA/FULL experiment has been plotted in black on the left panel of Fig. 9 for 11 October. Purple isobars represent the ECMWF operational mean sea level pressure analysis. This operational analysis is computed with an uncoupled assimilation system similar to the one described in section 3, but using a higher resolution in the atmospheric model (T1279L137, 16-km grid). The comparison shows that the location of the low pressure system in CERA is correct, looking at the 1005- and 1000-hPa isobars. However, the central pressure in the CERA system is 994 hPa, which is too high compared to the central value of 989 hPa in the operational analysis. This is expected as the resolution of the atmospheric component used in the CERA system is lower at T159L137 (128-km grid). The right panel of Fig. 9 compares 10-m wind analysis for the CERA and operational systems. Wind patterns are similar except near the center of the low system where the CERA winds are too low by a factor of 2.

During Cyclone Phailin, scatterometer data have been provided by ASCAT-A, ASCAT-B, and OSCAT instruments. Figure 10 represents the scatterometer

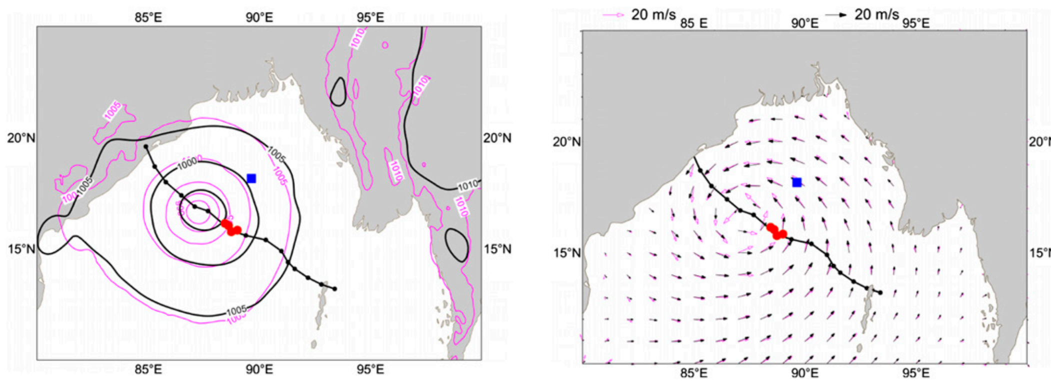

FIG. 9. Mean sea level pressure and winds analyses at 1200 UTC 11 Oct for the CERA system (black) and the operational ECMWF system (purple). The blue square represents the moored WMO-23091 buoy and the red dotted line represents the position of the Argo float 2901335. Black line shows the track of Phaillin derived from the ECMWF operational analysis, starting at 13.20°N, 93.4°E on 9 Oct and ending at landfall at 19.60°N, 84.90°E on 12 Oct.

measurements for the ascending pass on 11 October. Green dots represent the measurements that have been assimilated by the CERA system and red dots represent the measurements that have been rejected because the first-guess departure was too large. This situation occurs near the center of the low system where the CERA system cannot produce strong enough winds due to the coarse resolution of its atmospheric component. Figure 10 also illustrates the smaller swath of ASCAT compared to OSCAT. White areas in the OSCAT swath are due to rainfall, which corrupts the measurements within a wind vector cell.

The impact of scatterometer data on the surface wind analysis has been measured during the cyclone with respect to conventional observations. The National Institute of Ocean Technology (NIOT) is an autonomous society under the government of India, which operates several meteorological ocean buoys in the Bay of Bengal. These buoys are moored floating platforms that carry sensors to measure, among others, atmospheric pressure, air temperature, and wind. The WMO-23091 buoy located at 18.1°N, 89.6°E has been represented in Fig. 9 by the blue squared marker. This buoy was the nearest to the observed cyclone track that has provided wind observations during the cyclone. For this reason, its observations have been used to assess the impact of the scatterometer data on the surface wind analysis. Figure 11 represents the daily mean surface wind speed observations of the WMO-23091 buoy (black circles), as well as the time series of daily mean surface wind speed analyses at the same location. The CERA system is represented in the left panel and the UNCPL system is represented in the right panel. The peak in the wind speed observations is due to the passage of the cyclone with a maximal daily mean speed observation of $14\,\mathrm{m\,s^{-1}}$ on 11 October. The comparison between the NOSCATT and the FULL experiments in the CERA and UNCPL systems shows a similar benefit when scatterometer data are assimilated in the two systems.

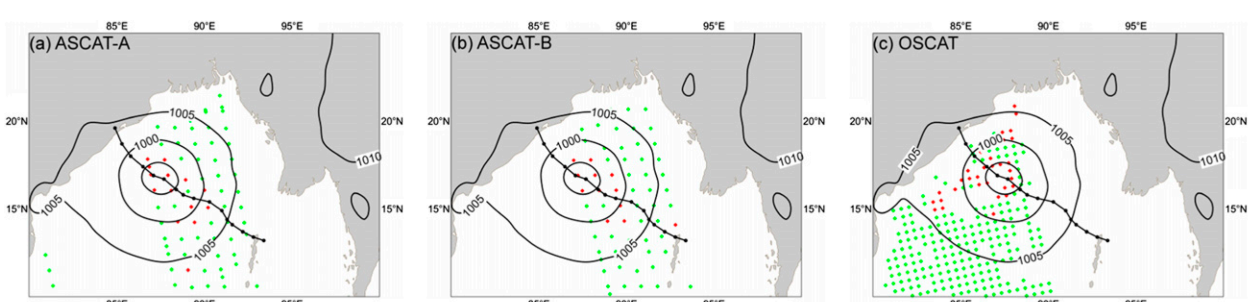

FIG. 10. Surface wind observations from the (a) ASCAT-A, (b) ASCAT-B, and (c) OSCAT ascending pass on 11 Oct 2013. Green dots represent the active observations and red dots represent the rejected observations. Black line shows the track of Phaillin derived from the ECMWF operational analysis and black contours represent the mean sea level pressure analysis computed by the CERA/FULL experiment at 1200 UTC 11 Oct 2013.

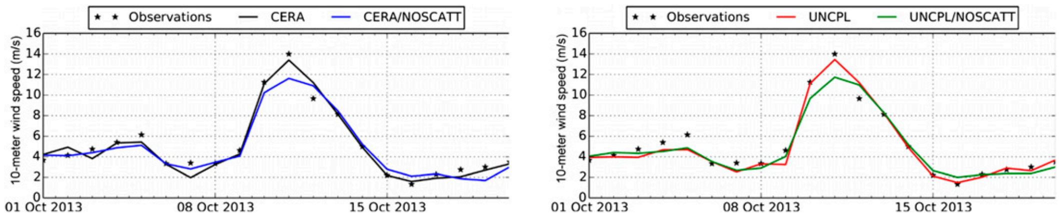

FIG. 11. Time series of daily mean surface wind speed observations from the WMO-23091 buoy (black circles). The daily mean surface wind speed analyses produced by the (left) CERA and (right) UNCPL systems are plotted for the full and denial observational configurations.

The OSTIA system is an optimal interpolation (OI)-type method that uses satellite data together with in situ observations to compute a daily mean SST analysis product (Donlon et al. 2012). The OSTIA SST analyses are plotted in the top panel of Fig. 12 before the cyclone on 9 October (left) and after the cyclone on 13 October (right), showing the cold wake generated by Cyclone Phailin. In the CERA system, the SST analysis is computed by a relaxation scheme that constrains the SST estimate toward the OSTIA product using a relaxation coefficient of $-200\,\mathrm{W\,m^{-2}\,°C}$, which is equivalent to about a 2–3-day time scale over a depth of 10 m. The CERA SST analysis is computed every hour and is plotted on the bottom panel of Fig. 12 at 1200 UTC 9 and 13 October. The CERA system is able to capture the cold wake generated by the cyclone, producing a similar pattern compared to the OSTIA product with a slightly colder spot on 13 October near the Argo float (27.8°C in CERA and 28.1°C in OSTIA). This might be explained by the strong winds produced over ocean that can induce the cold water from the deep ocean to rise to the surface, generating a larger SST anomaly in the tropical cyclone wake. The current choice for the relaxation coefficient is somewhat heuristic aiming to find a balance between allowing coupled phenomena and avoiding large SST biases. The use of relaxation techniques to constrain the atmosphere–ocean interface based on external SST products is far from optimal and needs further investigations. A two-time scale approach is currently assessed where the monthly mean of the model SST is also relaxed (Boisseson et al. 2015). Direct assimilation of SST observations in the coupled model could potentially improve the use of scatterometer data and other near-surface observations.

The impact of scatterometer data on the ocean temperature has been assessed with respect to observations measured by one Argo float. In most cases probes drift at a depth of 1000 m and, every 10 days, by changing their buoyancy, dive to a depth of 2000 m and then move to the sea surface, measuring salinity and temperature profiles. The Indian National Centre for Ocean Information Services (INCOIS) operates several Argo probes in the Bay of Bengal. They have initiated a project to monitor the upcoming disturbed weather conditions and to acquire higher temporal resolution of temperature and salinity profiles for the upper ocean. The dotted red lines in Fig. 9 shows the drift of the Argo float 2901335 operated by INCOIS during the cyclone passage. As this float was located on the cyclone forecasted track, the probe setup has been changed by a satellite transmission on 9 October to measure profiles approximately every 3 h between the surface and a 300-m depth. This configuration has been kept until 15 October. The Argo float is unfortunately not located close to the moored buoy that has measured wind observations. This observing configuration makes the assessment of scatterometer data more difficult as no observation profile of the whole ocean–atmosphere column at a single location is available. This means that it will not be possible to link directly ocean and atmospheric improvements as they are not measured at the same location. However, it is possible to assess separately the impact of scatterometer data in the atmosphere and in the ocean using the observations from the moored buoy and the Argo float.

The black dotted lines in Fig. 13 represent the observations at 40-m depth from the Argo float 2901335. The observed cold wake appears on 11 October with a 3° temperature drop. The temperature analyses produced by the CERA and UNCPL systems at 40-m depth have been plotted for the full and denial observational configurations. Focusing on the CERA system in the left panel, the assimilation of scatterometer data has improved the temperature estimate producing an analysis closer to observations. This demonstrates that the use of the coupled model in the assimilation process has produced dynamical ocean and atmospheric feedbacks during the assimilation process. Indeed, the left panel of Fig. 11 showed that the assimilation of scatterometer data has increased the CERA surface wind speed at the peak of the tropical cyclone. This study has not been performed above the Argo float, but a similar behavior would be expected at that location. These stronger winds affect the air–sea interactions through the wave

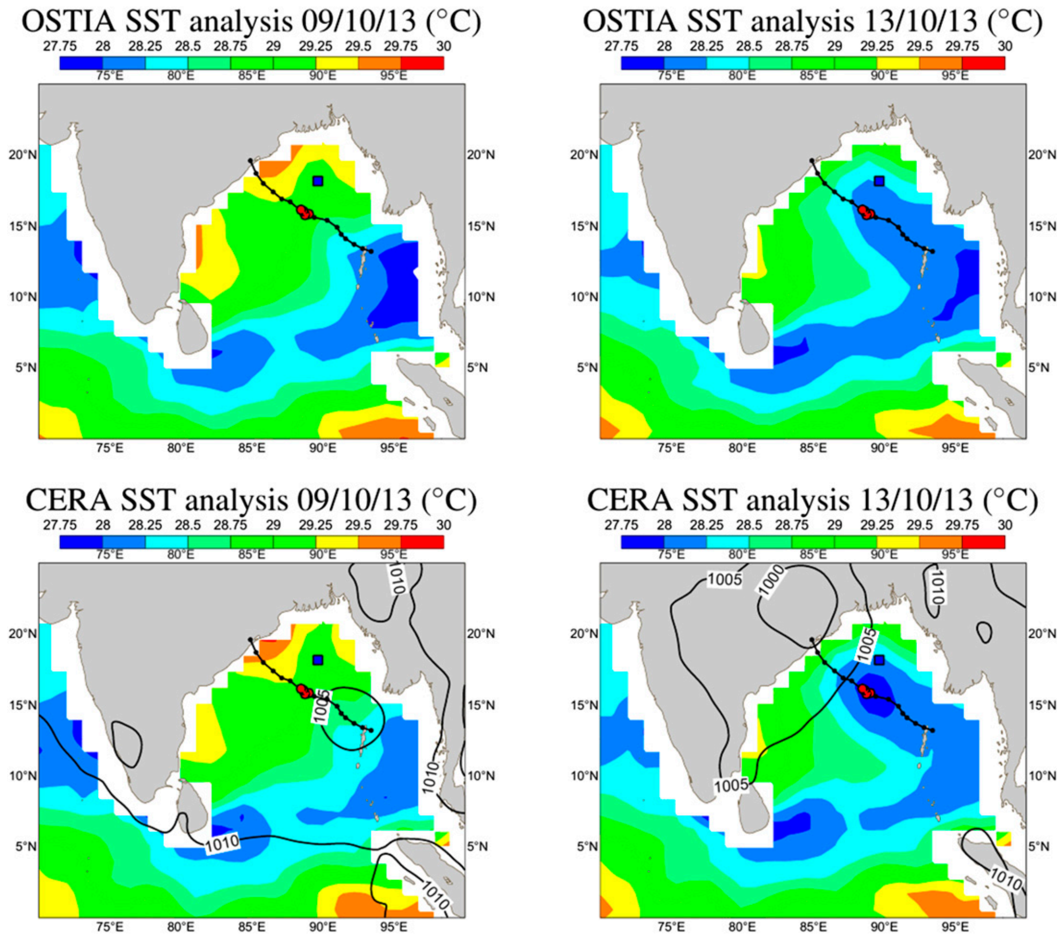

FIG. 12. SST analyses from the (top) OSTIA and (bottom) CERA systems on (left) 9 Oct 2013 and (right) 13 Oct 2013, illustrating the cold wake generated by Cyclone Phailin. The OSTIA analysis is a daily product, while the CERA analysis is produced every hour and has been plotted at 1200 UTC.

model where growing ocean waves play a role in the air–sea momentum and heat transfer, while breaking ocean waves affect the upper ocean mixing (Janssen et al. 2013). The match between the analysis produced by the CERA/FULL experiment and the Argo observations is not perfect. This can be explained by the coarse resolution of the ocean model with only 42 vertical levels with a layer thickness of 10 m in the first 100 m. The definition of the background and observation errors play also a role in the analysis fit as it determines the confidence given to the model and to the measurements in the 3D-Var method. Another reason is the SST relaxation scheme that may pull the model away from the in situ observations as the consistency between OSTIA analysis and in situ observations is not guaranteed. This OSTIA analysis is a daily mean product that causes the plateaus in the ocean analysis time series even at 40-m depth as no time interpolation of OSTIA is performed. In the UNCPL system (right panel in Fig. 13), the time series of the two analyses are similar showing that scatterometer assimilation has no impact on the ocean temperature during the cyclone. This might be explained by the weaker interaction between the atmosphere and ocean in the UNCPL system where fluxes come from instantaneous fields retrieved every 6 h and accumulated fields over 24 h, compared the 1-h coupling frequency in the coupled approach. The benefits of the CERA system with respect to the UNCPL system can be highlighted comparing the analyses produced with the full observing system (black and red solid lines in Fig. 13). Using a coupled model in the incremental variational approach with a 1-h coupling frequency produces an analysis closer to the observations.

To get more insight about the impact at other depths, vertical profiles of ocean temperature observations and the corresponding CERA analyses for the Argo float 2901335 at 1106 UTC 12 October are plotted in the left panel of Fig. 14. Assimilating scatterometer data

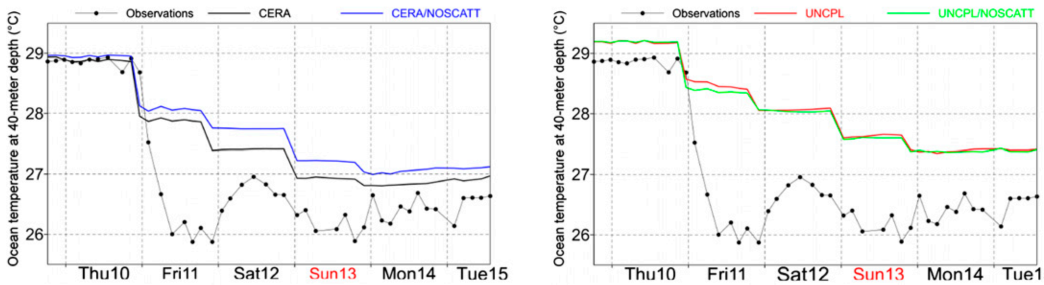

FIG. 13. Time series of ocean temperature observations at 40-m depth from the Argo float 2901335 (black stars). The temperature analyses produced by the (left) CERA and (right) UNCPL systems are plotted for the full and denial observational configurations.

improves the ocean estimate everywhere in the mixed layer depth. The results from the UNCPL system (right panel in Fig. 8) are neutral as scatterometer data improve or deteriorate slightly the temperature estimate depending on the depth.

7. Conclusions and perspectives

The ECMWF coupled assimilation system (CERA) has been designed to ingest simultaneously atmospheric and ocean observations in its coupled model. The use of the model constraint in the assimilation process allows the ocean observations to have immediate impact on the atmospheric state estimate, and, conversely, assimilation of atmospheric observations affect the ocean state. Observing system experiments have been conducted to illustrate the impact of scatterometer data in the CERA system for the period September–November 2013 with a comparison to the uncoupled (UNCPL) approach used in ECMWF operations. Focusing on the atmosphere, the benefit of scatterometer data is slightly larger near the ocean surface in the CERA system than in the UNCPL system. This might be explained by the larger variability in the coupled model that enhances air–sea interactions, compared to the atmospheric-only model that has a prescribed surface boundary condition. In the ocean component, the impact of scatterometer data on the temperature is localized in the mixed layer and in the thermocline for the two assimilation systems. Temperature observations from three stations located in the tropical eastern Pacific showed that scatterometer data improves the temperature estimate in the CERA system whereas the results are neutral in the UNCPL system. Cyclone Phailin has been studied as a case study since this weather system involves strong coupling between atmospheric winds and ocean temperature that has been observed at higher frequency. The assimilation of scatterometer data has improved the representation of the cold wake in the mixed layer of the CERA system while a neutral impact has been observed in the UNCPL system. This case study illustrates that the use of a coupled model in the incremental variational approach with a 1-h coupling frequency allows us to compute a coupled analysis where the ocean estimate takes advantage of the near-surface atmospheric observations.

The CERA system is a first prototype that has been developed to assess the benefits of a coupled data assimilation system for the ECMWF coupled model. The development of this system is still an ongoing work where several enhancements are possible. The current SST relaxation scheme toward a daily mean product has produced plateaus in the upper ocean temperature

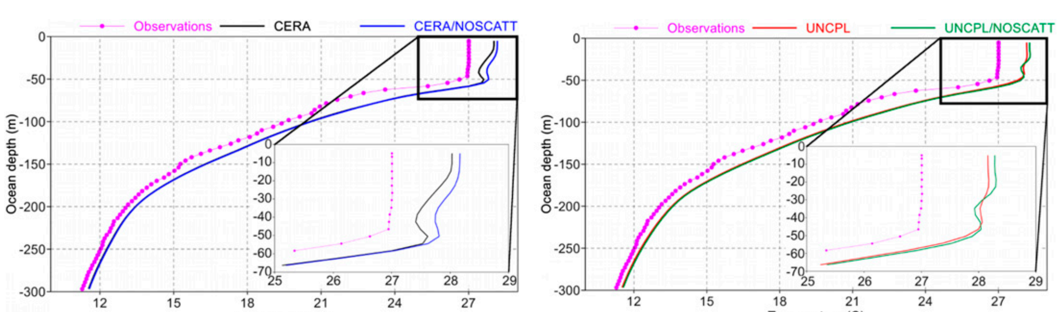

FIG. 14. Observation and analysis vertical profiles for the Argo float 2901335 at 1106 UTC 12 Oct 2013 with the (left) CERA system and (right) UNCPL system.

analysis during Cyclone Phailin. This might motivate the direct assimilation of SST observations that could improve the use of scatterometer data and other near-surface observations. In the current configuration, the ocean model has 42 vertical levels with a layer thickness of 10 m in the first 100 m. Increasing the vertical resolution should improve further the representation of the cold wake after a tropical cyclone. This should also introduce a SST diurnal cycle that will affect the atmospheric state through the use of the coupled model in the assimilation process.

This paper focused on the impact of scatterometer surface wind data with the study of Cyclone Phailin. To confirm our conclusions, it might be worth running the comparison over other periods studying other tropical cyclones where the atmospheric and ocean observing systems provide enough valuable measurements. A complementary future study would be to look at the impact of an ocean-observing system (e.g., Argo floats) on the lower atmosphere.

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