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# Tropical cyclones in two atmospheric (re)analyses and their response in two oceanic reanalyses

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ABSTRACT

In this paper, we first evaluate the ability of the European Centre for Medium Range Forecast operational analysis and the ERA-Interim reanalysis to capture the surface wind signature of tropical cyclones (TCs). In those products, the error on the TC position is typically ~150 km, cyclones are too big (~250 km in ERA-Interim and > 100 km in the operational analysis against ~50 km in observations) and the maximum wind speed is on average underestimated by 15–27 $\mathrm{m \cdot s^{-1}}$ for strong TCs. These biases are generally reduced with the increase of horizontal resolution in the operational analysis, but remain significant at T1279 (~16 km).

We then assess the TCs oceanic temperature signature in two global eddy-permitting ocean reanalyses (GLORYS1 and GLORYS2) forced by the above atmospheric products. The resulting cold wake is on average underestimated by ~50% in the two oceanic reanalyses. This bias is largely linked to the underestimated TCs strength in the surface forcing, and the resulting underestimated vertical mixing. The overestimated TC radius also tends to overemphasize the Ekman pumping response to the cyclone. Underestimating vertical mixing without underestimating Ekman pumping results in the absence of the observed subsurface warming away from the TC tracks in the two reanalyses. Data assimilation only marginally contributes to reducing these errors, partly because cyclone signatures are not well resolved by the ocean observing system. Based on these results, we propose some assimilation and forcing strategies in order to improve the restitution of TC signatures in oceanic reanalyses.

## 1. Introduction

Tropical cyclones (TCs) induce a negative Sea Surface Temperature (SST) anomaly in their wake (hereafter, the "cold wake"). Many studies (Chang and Anthes, 1978; Schade and Emanuel, 1999; Schade, 2000; Bender and Ginis, 2000; Cione and Uhlhorn, 2003) have suggested that this cold wake results in a significant reduction of upward latent heat fluxes to the atmosphere, and hence provides a negative feedback affecting the TC development. This is hence a strong motivation to understand and model the oceanic response to tropical cyclones, and in particular the cold wake.

Early case studies have noted that the abrupt wind stress changes associated with TCs drive an intense inertial current response in the mixed layer, and strong vertical shear at the bottom of the mixed layer. This results in enhanced vertical mixing, which has usually been identified as the dominant driver of the cold wake for strong cyclones (Price, 1983; Greatbatch, 1984; D'Asaro, 1985; Shay et al., 1989). Vertical mixing transfers heat from the upper layers to below the mixed layer and acts to warm the upper thermocline (e.g., Price, 1981). Recent studies have shown that this description of the ocean response is actually found further than two radii of maximum wind speed (~100 km) away from the TC center (Jullien et al., 2012; Vincent et al., 2013). In contrast, right under the TC eye, the upwelling of deep cold water induced by Ekman pumping overwhelms the mixing-induced warming signal (Jullien et al., 2012; Vincent et al., 2013).

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While early studies emphasizing the role of vertical mixing have generally focused on case studies of strong cyclones, the modeling study of Vincent et al. (2012a) have examined the processes responsible for the cold wakes of more than 3000 TCs over the last 30 years. They have confirmed that vertical mixing accounts for more than 75% of the cold wake amplitude (over a 200 km-radius disk) for the 25% most powerful cyclones. On the other hand, when considering the 25% least powerful cyclones, vertical mixing accounts for less than 30% of the surface cooling, with air-sea heat fluxes explaining the remaining 70%.

The first factor that controls the amplitude of the mixing-induced cooling is the amount of kinetic energy that the cyclone deposits in the upper ocean, which is then available for enhancing vertical mixing. Vincent et al. (2012a,b) have recently demonstrated that this amount of energy can be easily evaluated from the power dissipation (PD) introduced by Emanuel (1999) (i.e., the power dissipated by the hurricane at the ocean surface, that can be estimated from the time and spatial integral of the cubed surface wind). Vincent et al. (2012b) have also shown that the cooling roughly grows as the cubic root of PD (a normalized quantity that they have named ″wind power index″ or WPi). A high WPi corresponds to a slow moving and/or intense TC, able to transfer a substantial amount of mechanical energy from the winds to the ocean, and thus able to induce a large cooling. A weak WPi corresponds to a fast and/or weak TC, that induces little mixing and thus little surface cooling.

The second factor that controls the surface cooling is the ocean vertical stratification: stronger temperature stratification makes cold water available closer to the surface and hence favors strong surface cooling through vertical mixing. This effect competes with the inhibition of vertical mixing by the strong temperature and salinity stratifications that act as a barrier for vertical mixing (Vincent et al., 2012b; Jourdain et al., 2013a; Neetu et al., 2012). Vincent et al. (2012b) for example, have demonstrated that, for a given WPi, the ocean cooling can be modulated by up to a factor of 10, depending on the underlying temperature stratification. Oceanic mesoscale eddies are for example, associated with upper ocean heat content anomalies that can influence TC intensifications (e.g., Shay et al., 2000; Hong et al., 2000). As a result, the ocean heat content above the 26 °C isotherm (OHC) has been used to account for ocean stratification in statistical operational TC intensity forecasts, with a resulting 5% improvement of errors in the 72–96 h forecasts (DeMaria et al., 2005; Mainelli et al., 2008). This illustrates the potential benefits of an accurate estimate of the ocean state for TC intensity forecasts.

Over the last decades, advances in ocean observing systems have enabled the production of increasingly accurate ocean analyses and reanalyses. While data assimilation of a few kinds of observations are sufficient to improve the large scale circulation in ocean (re)analyses, many different kinds are needed to improve the mesoscale circulation (Oke and Schiller, 2007). These authors have noted that assimilation of SST data improves the vertical stratification in the first 50 m in absence of ARGO (Array for Real-time Geostrophic Oceanography) observations, while assimilation of Sea Surface Height (SSH) improves the location of fronts and eddies. Assimilating these observations in an eddy-permitting ocean (re)analysis, should thus enable a reasonable estimate of the ocean state ahead of TCs to be obtained, a necessary condition for TC intensity forecast purposes. However, no study so far has investigated how oceanic reanalyses reproduce the ocean surface and subsurface response to tropical cyclones: this is the main question that we address in this paper. A real-time estimate of the surface cooling below the cyclone could indeed be used as a proxy of the negative feedback that the ocean exerts on the cyclone (not available even from microwave satellite instruments, because of the shading effect of rain during the TC passage). A real-time estimate of the subsurface response to a cyclone is also potentially beneficial for estimating the oceanic influence of ensuing cyclones over the same region.

Ocean (re)analyses are generally forced by atmospheric operational analyses or reanalyses. Bengtsson et al. (2007) and Schenkel and Hart (2012) have shown that TC intensities are substantially underestimated in several atmospheric re(analyses). They have also noted significant biases in TC positions and a delay in peak intensity. TCs also generally suffer from a too broad horizontal extent (Isaksen and Stoffelen, 2000), resulting from a combination of the coarse resolution of the assimilated scatterometer gridded data (Quilfen et al., 1998), the horizontal scales of background error covariances in the data assimilation system, and the resolution of the forecasting model (Isaksen and Stoffelen, 2000). The ocean response to TCs in an ocean reanalysis does however not only rely on atmospheric forcing, but also on the assimilated oceanic data. In this paper, we will explore whether ocean data assimilation is able to compensate for the poorly resolved TC surface forcing in atmospheric analyses.

Two eddy-permitting ocean reanalyses have recently been released in the framework of the French GLobal Ocean ReanalYses and Simulations (GLORYS) project (Ferry et al., 2010, 2012). The two ocean reanalyses, GLORYS1 and GLORYS2, are based on the operational ocean forecasting system that has been used by the French monitoring and forecasting group Mercator-Ocean since 2001 to produce ocean forecasts and analyses. GLORYS1 and GLORYS2 are designed to capture mesoscale features, as well as the variability of the oceanic large-scale circulation. As described in Section 2, GLORYS1 is forced by the European Centre for Medium-range Weather Forecasts (ECMWF) atmospheric operational analysis (hereafter ECMWF-OA), while GLORYS2 is forced by the ERA-interim atmospheric reanalysis. In Section 3, we examine characteristics of surface wind forcing associated with TCs in these two atmospheric products. In Section 4, we assess the ability of the two ocean reanalyses to capture the ocean response to TCs over the 2002–2008 period. We show in particular that the cold wake of tropical cyclones is underestimated in both ocean reanalyses, due to weaker than observed cyclonic winds in the surface forcing, and to the absence of correction by data assimilation. We summarize our results and discuss their implications in Section 5.

## 2. Datasets and methods

### 2.1. Atmospheric (re)analyses: ECMWF-OA and ERA-Interim

ECMWF has been providing a model-based atmospheric analysis (ECMWF-OA) since 1985, and on-going releases of the Integrated Forecast System (IFS) have been used to produce these analyses since 1994. The resolution of the spectral model has evolved gradually from T106 (~125 km on a reduced gaussian grid) in 1985, to T511 (~40 km) in November 2000, T799 (~25 km) in February 2006, and T1279 (~16 km) in January 2010. The 4D-Var data assimilation system is based on a 12-h window, and was implemented in November 1997 (Andersson and Thépaut, 2008). IFS has been 2-way coupled to a wave model since 1998: marine surface wind induces wave growth that in turn affects wind through a change of surface roughness (Janssen et al., 1997; Janssen, 2008). Surface wind measurements from ships, buoys and scatterometers are assimilated in ECMWF-OA, while ground stations measurements are not. More details on ECMWF-OA can be found on http://www.ecmwf.int/research/ifsdocs/.

ERA-Interim is the latest global atmospheric reanalysis produced by ECMWF (Dee et al., 2011). It covers the period from 1979 to present, and is available with a 3-h temporal resolution. The version of IFS that was operational in 2006–2007 was used