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Implementation of a two-way coupled atmosphere-ocean wave modeling system for assessing air-sea interaction over the Mediterranean Sea

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ABSTRACT

It is generally accepted that the fluid layer surrounding Earth should be considered as a single system at short and longer spatiotemporal scales. The current knowledge on the complex mechanisms of atmosphere-ocean interactions is still insufficient. This translates to the simulation of atmosphere and ocean as a single fully coupled system constructing multi-scale, multi-model integrated modeling systems. In this study, a new two-way coupled atmosphere-ocean wave modeling system is introduced with overarching aim to thoroughly unveil the impact of waves on the sea surface roughness and the atmospheric properties. The newly developed system consists of the Weather Research Forecasting (WRF) model with Chemistry (WRF-Chem) and Hydrology (WRF-Hydro) as the atmospheric component and the Wave model (WAM) as the ocean wave component. WRF and WAM models are coupled using the OASIS Model Coupling Toolkit (OASIS3-MCT) that enables models to communicate and exchange the information required to refine their simulation results. CHAOS (Chemical Hydrological Atmospheric Ocean wave System) has been tested in a high-impact cyclonic system over the Mediterranean Sea employing one-way and two-way coupling simulations to assess the air-sea interactions, currently neglecting the chemical and hydrological capabilities. The encapsulation of the ocean waves in the atmospheric surface layer processes modifies the characteristics of atmospheric flow and determines the ocean wave generation. A remarkable finding is that the coupling of the two systems affects the air-sea momentum, enthalpy and moisture transfer determining the evolution of the cyclonic system. The interactions along the air-sea interface are also reflected in the vertical structure of troposphere and its properties. CHAOS in two-way coupling mode shows an overall improvement of the forecast skill up to 20% over the sea while positively affects the atmospheric predictability over the land.

1. Introduction

Due to the complexity of the atmosphere-ocean wave interactions, a major scientific issue is a more complete understanding of the impact of ocean waves on the sea surface roughness and, consequently, on the atmospheric properties through momentum, heat and moisture fluxes. Near surface winds and medium to high-frequency gravity waves determine the sea surface roughness which affects the air-sea momentum exchange (Janssen, 1991; Donelan et al., 1993). High frequency wind-generated waves increase the sea surface roughness and extract energy and momentum from the atmosphere. The momentum exchange is the focal point of a number of recent studies highlighting the impact of ocean waves on the dynamical processes across the air-sea interface (Jenkins et al., 2012; Rutgersson et al., 2012; Katsafados et al., 2016; Wahle et al., 2017). The sea surface roughness also modulates the enthalpy (latent and sensible heat) and the moisture transfer between the atmosphere and the ocean determining their properties (Fairall et al., 2003; Bruneau and Toumi, 2016; Ricchi et al., 2016, 2017). The modification of momentum, enthalpy and moisture exchanges by the sea surface roughness affects the marine atmospheric boundary layer (MABL) processes. Sullivan et al. (2008) showed that the waves support turbulence generation and change the mixing of MABL. Jenkins et al. (2012) observed that the waves act as roughness elements in MABL, affecting the turbulent flow and the vertical wind speed profile as well as inducing oscillatory motions in the atmospheric flow.

Nowadays, there are still open questions regarding the impact of the sea surface roughness on the momentum exchange as well as its effect on the dynamical and thermodynamic processes of the atmosphere. A

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number of limitations in the knowledge of how ocean waves affect the atmospheric properties is attributed to the representation of wind-induced wave breaking accompanied by sea spray production (Andreas and Decosmo, 2002; Bao et al., 2011; Wu et al., 2015). Moreover, a source of uncertainty is the description of the interactions between the waves and the ocean boundary layer (Chen et al., 2007; Breivik et al., 2015). Another issue is the lack of universality of the relations between atmospheric and ocean wave parameters mainly under extreme wind and sea state conditions (Donelan et al., 2004; Soloviev et al., 2014).

In this context, it is essential to develop appropriate multi-model, multi-scale advanced prediction systems that simulate the atmospheric, wave and oceanic processes in a cross-talking way. First, large-scale atmosphere-ocean coupled systems developed targeting to simulate the major climatic interactions (Battisti, 1988; Philander et al., 1992; Webster et al., 1999). A number of centers and institutes worldwide developed operational atmosphere-ocean coupled systems managing to resolve finer spatiotemporal scales. In the middle 1990s, the United States Naval Research Laboratory (NRL) developed the 3-dimensional Coupled Ocean/Atmosphere Mesoscale Prediction System (COAMPS) specialized in tropical cyclones (Hodur, 1997). In 1998, the European Centre for Medium-Range Weather Forecasts (ECMWF) was the pioneer in the implementation of an atmosphere-ocean wave coupled system. The coupled system consisted of the ocean wave model of ECMWF (ECMWF WAM or ECWAM) and the Integrated Forecasting System (IFS) which is the operational global atmospheric model of ECMWF (Janssen et al., 2002).

In the following years, atmosphere-ocean coupled systems were developed in order to model the air-sea interactions at even finer spatiotemporal scales. Powers and Stoelinga (2000) implemented a coupled air-sea numerical model and tested its performance during an event of frontal passage over a lake in North America. Bao et al. (2000) implemented an atmosphere-wave-ocean coupled system to better represent surface momentum and heat fluxes as well as the contribution of sea spray under hurricane-force winds. In 2001, the Geophysical Fluid Dynamics Laboratory (GFDL) of United States developed an operational atmosphere-ocean coupled system to support tropical cyclone predictions (Bender et al., 2007). Lionello et al. (2003) developed the Model of Interacting Atmosphere and Ocean (MIAO) to resolve the atmosphere-wave-ocean interaction processes over the Mediterranean Sea. Later, the Coupled Boundary Layer Air-Sea Transfer (CBLAST)-Hurricane program at United States aimed to analyze the internal mechanisms of tropical cyclones at 1 km spatial resolution by implementing an atmosphere-wave-ocean coupled system (Chen et al., 2007). In 2007, the National Center for Environmental Prediction (NCEP) of United States in collaboration with GFDL carried out the development of the Hurricane Weather Research Forecasting (HWRF) system in support of operational forecasting of tropical cyclones for all the tropical ocean basins (Gopalakrishnan et al., 2010). HWRF is an ongoing updated atmosphere-ocean modeling system involving new capabilities (Kim et al., 2014). In 2010, the United States Geological Survey (USGS) introduced the Coupled Ocean Atmosphere Wave Sediment Transport (COAWST) modeling system to better identify the dynamical processes affecting the coastlines (Warner et al., 2010). Later, Jenkins et al. (2012) implemented a modeling system involving the Weather Research Forecasting (WRF) model and the Wave model (WAM) coupled by MCEL coupler in order to study the impact of waves on the MABL over the North Sea and Norwegian Sea area. Chen et al. (2013) proposed a new directional wind-wave coupling method using the wave-stress vector calculated by two-dimensional wave spectra, which improves the simulation of the evolution and the structure of hurricanes.

Katsafados et al. (2016) presented a recently implemented two-way coupled atmosphere-ocean wave system (WEW), designed to reveal air-sea interaction research under extreme weather conditions. WEW consisted of the Workstation Eta as the atmospheric component and the WAM model as the ocean wave component. It was built in the MPMD environment where the atmospheric and the ocean-wave components are handled as parallel tasks on different processors. WEW was tested in a high-impact atmospheric and sea state case study of an explosive cyclogenesis in the Mediterranean Sea. Despite the increased underestimation, affecting both wind speed and significant wave height, WEW showed an overall improvement in their RMS error up to 11% compared against the offline coupled mode.

In this context, this paper describes the strategy and approach adopted to develop the next generation of WEW in order to improve the simulation of the air-sea interaction processes by state-of-art modeling components communicating in a more efficient way. The resulting system includes the WRF version 3.8 model as the atmospheric component and the WAM version 4.5.4 model as the ocean wave component. WRF and WAM models are coupled using the OASIS3-MCT_3.0 coupler (OASIS3-MCT hereafter) that enables the models to communicate and exchange the required information throughout the combined simulations. An additional issue that is emphasized here is the determination, parameterization and the sensitivity of air-sea momentum fluxes in a case study involving extremely high and time-varying winds.

2. Overview of the two-way coupled atmosphere-ocean wave modeling system

The two-way coupled atmosphere-ocean wave modeling system consists of the WRF model as the atmospheric component (Skamarock et al., 2008) and the WAM model as the ocean wave component (WAMDI group, 1988; Komen et al., 1994). The two models were selected due to their advanced capabilities to resolve atmospheric and ocean wave processes as well as to their forecast skill (e.g. Korres et al., 2011; Christakos et al., 2014, 2016).

WRF is a widely used next-generation mesoscale numerical weather prediction (NWP) model with high scalability (Michalakes et al., 2008). Its software architecture allows computational parallelism and system extensibility. More specifically, the atmospheric component is based on the version 3.8 of ARW (Advanced Weather Research) core of WRF. WRF-ARW uses the semi-staggered Arakawa C grid on which the wind grid points are not the same as the mass grid points (Skamarock et al., 2008).

The ocean wave component is based on the updated version 4.5.4 of the third-generation WAM Cycle-4 wave model (Komen et al., 1994). This version of WAM has parallel software architecture. Improvements in the short-fetch simulation of Hersbach and Janssen (1999) and the revised formulation of ocean wave dissipation of Bidlot et al. (2007) and Janssen (2008) are incorporated in this version. WAM runs for any given regional or global grid with a prescribed topographic dataset using latitudinal-longitudinal or Cartesian grid.

The coupling of WRF and WAM models is achieved using OASIS3-MCT (Ocean Atmosphere Sea Ice Soil - Model Coupling Toolkit) version 3.0 coupler (Valcke, 2013; Valcke et al., 2015) along with Message Passive Interface (MPI) routines. OASIS3-MCT is "the-state-of-the-art" of couplers with advanced capabilities in weather and climate modeling characterized by flexibility, portability and scalability. WRF and WAM models utilize different domain projection, integration time step, grid geometry and cell size. Therefore, in order to enable the two models to operate in two-way coupling mode, major effort has been undertaken in order to homogenize, synchronize and handle the data exchange between the atmospheric and the ocean wave components of the system through the coupler.

It is important to note that the latest version of the coupled system is appropriately implemented to exploit further capabilities of WRF model. WRF-Chem (Grell et al., 2005) version 3.8 and WRF-Hydro version 3.0 (Gochis et al., 2015) sub-components of WRF have been also integrated into the coupled system offering the feasibility to resolve chemical and hydrological processes (Fig. 1). Thus, the name of the system is Chemical Hydrological Atmospheric Ocean wave System (CHAOS).