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A fully-coupled atmosphere-ocean-wave model of the Caspian Sea

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ABSTRACT

Located in the mid-latitudes, the Caspian Sea is the largest enclosed basin in the world. A fully-coupled atmosphere-ocean-wave model of the Caspian Sea at high resolution (8 km) for a period of three years is presented. After validating each component of the modelling platform, the wave state of the Caspian Sea is studied. Results show very different wave regimes between the three different basins, a strong seasonality and an almost swell-free state. It is shown here that waves modify the horizontal eddy viscosity and vertical heat diffusion. However, due to a reasonably weak annual wave state, these effects are restricted to the upper-ocean layer (< 30 m) except during the most severe events (100 m).

Three main experiments are conducted: 1) the ROMS ocean model forced by atmospheric reanalysis (CFSR), 2) ROMS coupled with the atmospheric model WRF and 3) the impact of wave-induced processes. The seasonality of the Caspian Sea is accurately captured in each experiment which highlights a rapid warming of the sea surface temperature (SST) in spring while the mixed layer depths (MLD) become very rapidly shallow (shifting from over 100 m to 15 m in two months). Contrarily, a gentle cooling of the SST accompanied with a deepening of the MLD is modelled during autumn and winter. The results also show a significant improvement of the model skill in the representation of the dynamics when ROMS is coupled to WRF.

Finally, as ocean surface waves imply feedback at the interface atmosphere-ocean through the transfer of momentum, mass and heat, we investigate their potential effects on the Caspian Sea dynamics. Results are mixed and show a reasonably weak impact of wave-induced processes. While waves have a negligible effect during the winter as wave-induced mixing is confined to the MLD, the summer global SST are less accurately modelled due to the enhancement of mixing in shallow MLDs. However the SST bias, temperature at a subsurface location are improved.

1. Introduction

The Caspian Sea is located in mid-latitudes (from 37°N to 47°N) between Russia, Azerbaijan, Kazakhstan, Iran and Turkmenistan, and is the largest enclosed body of water in the world extending to around 1000 km (North-South) by 600 km at its largest (West-East). While the bathymetry in the Northern basin (*NCS*) is extremely shallow (depth < 25 m), the central (*CCS*) and the Southern basins (*SCS*) exhibit deep regions where depths reach approximately 800 and 1000 m, respectively (Gunduz and Őzsoy, 2014). Three main sources of inflows are present: river runoff (79% with 80% of it coming from the Volga river), rainfall (20%) and groundwater inflow (1%) (Klige and Myagkov, 1992) while outflow is exclusively a result of evaporation. The salinity of the Caspian Sea is around a third of that of the oceans.

From satellite-derived products, Gunduz (2014) provided a description of geostrophic currents and highlighted the strong inter-annual variability of the Caspian Sea circulation. The *CCS* is dominated by a cyclonic gyre in the winter which briefly switches to an anti-cyclonic circulation during summer while the *SCS* exhibits a dipole pattern (anticyclonic in the north and cyclonic further south). Inertial currents (most energetic form of internal waves) in the Caspian Sea have been investigated by Nicholls et al. (2012) and shown to be maximum in summer, around twice as great as during the winter. As pointed out by Gunduz and Őzsoy (2014), the different basins exhibit contrasting behaviours in term of dynamics (gyres, temperature, mixed layer depth and a strong inter-annual variability) and it is challenging to model the complex Caspian Sea dynamics strongly driven by atmospheric conditions and river runoff. Nicholls and Toumi (2014) showed the impact of the Caspian Sea on atmosphere dynamics (surface air pressure, wind speed and precipitation), particularly the over-lake precipitation is attributable to the lake effect and they highlighted the significance of the Caspian Sea for local and regional climates. During the winter (from mid-November to mid-March), sea ice cover

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develops and extends in the *NCS* with some strong spatial variability from one year to another (Kouraev et al., 2004). Linking ice conditions to air temperatures in the *NCS*, Tamura-Wicks et al. (2015) showed critical temperatures required for ice formation and suggested that the *NCS* could be ice-free by 2100. We investigate in the present work the impact of high resolution atmospheric forcing on the dynamic of the Caspian Sea.

Few studies have looked at the wave properties in the Caspian Sea using artificial neural network methods, statistical analysis and chaos theory for a set of wave gauges (Zamani et al., 2009; Zamani and Badri, 2015; Zounemat-Kermani and Kisi, 2015). Golshani et al. (2007) produced a wave climate atlas and an extreme value analysis for the Caspian Sea with a main focus on the *SCS* based on eleven years of wave simulation; as highlighted in Figure 11 of Zounemat-Kermani and Kisi (2015), severe wave events can occur.

Ocean waves influence a wide range of processes (such as the alteration of surface roughness, generation of turbulence, modification of heat fluxes, amongst others) occurring at the ocean-atmosphere interface and they modify the boundary layer of each fluid (Babanin et al., 2012; Cavaleri et al., 2012; Jenkins et al., 2012). They play therefore a key role in the global climate system. Previous studies have pointed out the importance of gravity waves in upper-ocean mixing and the need for global climate models to represent these processes (Belcher et al., 2012; Shuckburgh, 2012; D'Asaro, 2012; Wu et al., 2015). While ocean waves have been widely studied (see Babanin et al., 2012 for an extensive review), their integration in climate models is still limited and the impact of waves remains poorly understood.

Spectral wind-wave models have been in use for decades. In these models, the sea state is spectrally decomposed (directions and frequencies) and the wave action balance equation is solved, modelling the wind-growth, the non-linear transfer of energy and the dissipation of energy by breaking, shallow water effects and bottom friction. The first attempts to model wave-induced processes in global climate models have shown reduction in some biases. However, taking into account wave-induced dynamics is extremely challenging and the number of studies modelling the ocean - atmosphere responses of waves is still limited (Rutgersson et al., 2010; Jenkins et al., 2012; Olabarrieta et al., 2012; Renault et al., 2016; Fan and Griffies, 2014; Breivik et al., 2015; Li et al., 2015; Wu et al., 2015; Alari et al., 2016; Carniel et al., 2016; Ricchi et al., 2016). Fan and Griffies (2014) have investigated the impacts of parametrised upper-ocean wave mixing in a coupled atmosphere-ocean-wave global climate model and have demonstrated the sensitivity of mixing resulting from the parametrisation; they highlight the need for properly capturing the vertical mixing and lateral transport to accurately capture the upper-ocean dynamic. In a recent study, Breivik et al. (2015) analysed the effects of three wave-induced processes (roughness, mixing and Stokes drift-Coriolis) on sea surface temperature (SST) climatology and highlighted the importance of mixing as the strongest effect. In a semi-enclosed basin, Benetazzo et al. (2014) and Carniel et al. (2016) showed the significance of waves for thermohaline properties and energy content as they play a key role for dense water production and spreading.

Longuet-Higgins and Stewart (1964), Phillips (1977) and Smith (2006), amongst others, have studied wave-current interactions through the depth-integrated approach. Recently, different theories on three-dimensional wave-current interactions have emerged (Mellor, 2008; Ardhuin et al., 2008b; Bennis et al., 2011; Mellor, 2011b; 2015) and, led to debates on the consistency of these equations (Ardhuin et al., 2008a; Bennis and Ardhuin, 2011; Mellor, 2011a). Recent work has integrated these developments within circulation models (Warner et al., 2008; Uchiyama et al., 2010; Bennis et al., 2011; Kumar et al., 2012) and mostly applied them to idealized cases or nearshore regions (Warner et al., 2010; Sheng and Liu, 2011; Kumar et al., 2012; Michaud et al., 2012; Mellor, 2013; Bennis et al., 2014). As around half (2/3) of the Caspian Sea exhibits bathymetry level shallower than 50 m (100 m), potential wave-current interactions might affect the dynamics during severe wave events.

In the present study, for the first time, we present the wave state for the whole Caspian Sea as well as a fully-coupled atmosphere-ocean-wave system for the Caspian Sea and we investigate wave-induced processes at high-resolution in a real ocean scale setting. Section 2 describes the data available and method used to process them. In Section 3, the modelling strategy is presented, including each component of the Coupled-Ocean-Atmosphere-Wave-Sediment Transport Modelling System (COAWST - Warner et al., 2008) as well as the wave-induced processes. A validation of the atmospheric predictions is given in Section 4.1 while Section 4.2 presents a validation of the wave model and describes the wave state of the Caspian Sea. The ocean dynamics of the Caspian Sea is presented in Section 4.3 through three experiments at both long-term (seasonal) and short-term (daily/weekly) scales. Finally, the results are discussed in Section 5.

2. Data and methods

The present paper aims to investigate the impact of waves on the dynamic of the Caspian Sea based on a fully-coupled atmosphere-wave-ocean model. To validate the model, a wide range of data have been used:

- three PACE automatic weather stations manufactured by Muir Matheson ($G_1 - G_3$ in Fig. 1) provide high temporal resolution (5 min) time series of wind speed, 2 m air temperature and mean sea level pressure as well as significant wave heights and zero-crossing wave periods (available almost continuously from 2006 to 2010),
- a RDI WorkHorse Sentinel Acoustic Doppler Current Profiler (ADCP) deployed in G_1 provide a complete vertical profile of currents at high temporal and spatial resolution (5 min, 2 m bins) as well as sea temperature at 46 m water depth (Dec. 2007–Sep. 2008),
- along-track delayed-time wave heights from AVISO Corrected Sea Surface Heights (AVISO-CorSSH) product (Fig. 1 displays the tracks),
- 6 h Blended Sea Winds (0.25° grid) BSW dataset (Zhang et al., 2006a,b; Peng et al., 2013),
- Daily 9km gridded GHRSST Level 4 MicroWave (MW) infrared (IR) optimally-interpolated (OI) Sea Surface Temperature (SST) Analysis product produced by Remote Sensing Systems,
- Daily Global Sea Ice Concentration reprocessing dataset (OSI-409-a; EUMETSAT, 2015).

Wind speed data over sea ice may lead to large inconsistancies and has been removed in the present study when EUMETSAT sea ice concentration was exceeding 15%. The presence of sea ice near the coasts as well as in the Southern part of the Caspian Sea has also been removed from the analysis as they are not realistic.

To characterise the influence of waves on the Caspian Sea, the study mainly focuses on thermal properties such as Sea Surface Temperature (SST) but also on the Mixed Layer Depth (MLD). The MLD was calculated as the depth where the potential density (referenced to the surface) changes by 0.125 kg.m^{-3} in agreement with Fan and Griffies (2014) and using the Gibbs SeaWater Oceanographic Package of Thermodynamic Equation Of Seawater, 2010.

3. Modelling strategy

The Caspian Sea dynamics and the interactions between waves, ocean and atmosphere are modelled with the Coupled-