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Madden Julian Oscillation impacts on global ocean surface waves

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ABSTRACT

We assess the impact of the tropical Madden Julian Oscillation (MJO) on global ocean wind waves using 30 years of wave data from a wave model hindcast that is forced with high resolution surface winds from the NCEP–CFSR reanalysis. We concentrate on the boreal winter season when the MJO has its greatest amplitude and is potentially a source of predictable wave impacts at intra-seasonal lead times. Statistically significant anomalies in significant wave height (H_s), peak wave period (T_p) and zonal wave energy flux (C_gE) are found to covary with the intra-seasonal variation of surface zonal wind induced by the MJO as it traverses eastward from the western tropical Indian Ocean to the eastern tropical Pacific. T_p varies generally out of phase with H_s over the life cycle of the MJO, indicating that these MJO-wave anomalies are locally wind-generated rather than remotely generated by ocean swell.

Pronounced H_s anomalies develop on the northwest shelf of Australia, where the MJO is known to influence sea level and surface temperatures, and in the western Caribbean Sea and Guatemalan–Panama Seas with enhanced wave anomalies apparent in the vicinity of the Tehuantepec and Papagayo gaps. Significant wave anomalies are also detected in the North Pacific and North Atlantic oceans in connection with the MJO teleconnection to the extratropics via atmospheric wave propagation. The impact in the north Atlantic stems from induction of the high phase of the North Atlantic Oscillation (NAO) about 1 week after MJO convection traverses the Indian Ocean, and the low phase of the NAO about one week after suppressed convection traverses the Indian Ocean. Strong positive H_s anomalies maximize on the Northern European coast in the positive NAO phase and vice versa for the negative NAO phase. The MJO also influences the occurrence of daily low (below the 5th percentile) and high (above the 95th percentile) wave conditions across the tropics and in the North Pacific and North Atlantic, emphasizing that the MJO may be a valuable source of intra-seasonal predictability of surface wave variability.

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1. Introduction

The tropical Madden–Julian Oscillation (MJO; Madden and Julian 1971; 1972; 1994) is a planetary-scale modulation of atmospheric convection and circulation (primarily zonal winds) that propagates eastward along the equator from the western Indian Ocean to the eastern Pacific with an average speed of ~5 m/s and a local period of ~40–50 days. The MJO exerts influences on global weather and climate with numerous and varied impacts, as summarized by Zhang (2013). These include intra-seasonal modulation of active and break cycles of the Asian and Australian summer monsoons, tropical cyclone activity in all major ocean basins, fire activity in the Indonesian archipelago, and onset and demise of El Nino and the Indian Ocean dipole. The MJO also excites teleconnections to the extratropics via dispersion of atmospheric Rossby waves, thereby influencing intra-seasonal variations of storminess, rainfall and temperatures and their extremes in North America (e.g., Bond and Vecchi 2003; Lin and Brunet 2009) and Europe (e.g., Cassou 2008; Lin et al. 2009). The long time scale of the MJO makes it a potential source of predictability of these societally relevant, intra-seasonally varying impacts.

Importantly, the MJO exerts a strong influence on surface heat and momentum fluxes and so interacts strongly with the upper ocean. For instance, the surface zonal wind anomalies of the MJO generate equatorially trapped Kelvin and Rossby waves that propagate along the equator in the Pacific Ocean (Hendon et al. 1998; Zhang 2001) and in the Indian Ocean (Fu 2007; Han et al. 2001), and subsequently along coastlines as trapped Kelvin waves (e.g. Marshall and Hendon 2014; Webber et al. 2012; Zhou and Murtugudde 2010), thereby

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influencing local surface temperatures and rainfall as well as upper ocean bio-geochemistry (e.g. Tian and Waliser 2011).

The purpose of this paper is to extend the study of the impact of the MJO on the global oceans and explore its impact on ocean wind waves, both locally in the tropics and remotely in the North Pacific and North Atlantic where the MJO is known to drive significant teleconnections. Although there is a wide body of work that addresses relationships between global ocean surface waves and large-scale atmospheric climate variability (e.g. Bosserelle et al. 2011; Dodet et al. 2010; Fan et al. 2012; Hemer et al. 2010; Kushnir et al. 1997; Semedo et al. 2011; Stopa et al. 2013; Wang and Swail 2001), little focus has been given to the MJO (e.g. Stopa et al. 2013; D. Waliser, personal communication 2014[1]). The MJO is a probable candidate for driving significant surface wave variations because although the amplitude of surface wind anomalies is relatively small (<5 m/s), the effective fetch of the surface forcing by the MJO is large (up to 10,000 km) and the time scale is long (up to weeks). Furthermore, the MJO significantly impacts tropical cyclones, which are a key source of extreme wave occurrences (e.g. Bowyer and MacAfee 2010; Cline 1920; Stephens and Ramsay 2014). Documenting and understanding the intra-seasonal modulation of global ocean surface waves by the MJO can help underpin development of intra-seasonal predictive capability, which could have practical benefits for anticipating wave-induced inundation, for instance, and for managing global shipping and off-shore mining.

Our approach to assessing the impact of the MJO on surface waves is to use the global output from a high resolution hindcast of a surface wave model forced by surface winds from a 30-year reanalysis. We focus on the extended boreal winter season, November to April when the MJO has its largest amplitude. A description of the global ocean wave hindcast and its suitability for our study, along with the compositing approach to extract the MJO signals, are provided in Section 2. The impacts of the MJO on tropical and extratropical waves are presented in Section 3, and a summary and conclusions are provided in Section 4 including implications for intra-seasonal prediction of global surface wave variations.

2. Surface wave jindcast and MJO compositing

2.1. Surface wave hindcast

In lieu of continuous global records of ocean surface waves, historical output from surface wave model hindcasts forced by high quality surface winds, or reanalyzes which also include assimilated altimeter derived wave heights, have been successfully used in a wide range of studies of the global ocean surface wave mean climate and variability (e.g., Hemer et al. 2010; Rogers et al. 2005; Semedo et al. 2011; Stopa et al. 2013; Wang and Swail 2001). A key to the quality of such hindcast products is the quality of the prescribed surface winds (e.g. Durrant et al. 2014; Rogers et al. 2005), including sufficient horizontal and temporal resolution so as to adequately capture small scale-high amplitude wind variability that is critical to forcing of wave extrema (Hemer et al. 2011). However, Hemer et al (2011) examined existing wave hindcasts and reanalyzes in the Pacific region and found that the data available at that time was too coarse, both spatially and temporally, to adequately capture the complex wave environment. The recently completed cimate forecast system reanalysis (CFSR; Saha et al. 2010) provides hourly surface winds on a 0.3° by 0.3° latitude–longitude spatial grid, creating an opportunity to produce a significantly higher resolution wave hindcast than has previously been possible.

The CSFR reanalysis supersedes the widely used NCEP reanalyzes 1 (NNR1; Kalnay et al. 1996) and 2 (Kanamitsu et al. 2002). Improvements include significant upgrades in spatial and temporal resolution: horizontal resolution has increased from 2.5° to 0.3°, the number of vertical levels has increased from 28 to 64, and output frequency has increased from six-hourly to hourly. The CFSR also includes improvements to the atmospheric model so that diabatic circulations such as associated with the MJO are better depicted. The atmospheric model is also now coupled to an ocean circulation model and an interactive sea ice model so as to more consistently represent coupled atmospheric circulations. The data assimilation scheme has also been improved in terms of both the sophistication of the methods employed and the volume and quality of the observations ingested. The quality and temporal/spatial resolution of the CFSR provide for unprecedented depiction of global surface winds over an extended 31 year period that can be used to drive a global wind wave model.

The availability of the CFSR winds has spawned several parallel efforts to utilize these data in the production of wave hindcasts. Chawla et al. (2012) performed a 30 year hindcast on a 0.5° global grid, with a number of higher resolution nested grids around the U.S, European and Australian coasts, as well as the U.S. Territories in the Pacific. Similarly, Rascle and Ardhuin (2013) have produced a similar global hindcast at 0.5°, with nested grids concentrating on the European coast, as well as French territories in the Pacific covering the period 1994–2012. Here, we analyze the centre for Australian weather and climate research (CAWCR) wave hindcast described by Durrant et al. (2014). This hindcast uses the WAVEWATCH III™ model version 4.08 (Tolman 1991; Tolman 2014), employing the source term parameterizations of Ardhuin et al. (2010), appropriately configured for utilization with CFSR winds. The model was forced with the hourly 10 m winds and sea ice concentration from the CFSR reanalysis for the period 1979–2009. This hindcast provides wave data over the globe at a spatial resolution of 0.4° at an hourly temporal resolution. While all three hindcasts use WAVEWATCH III and CFSR forcing, Durrant et al. (2014) and Rascle and Ardhuin (2013) use Ardhuin et al. (2010) source terms, promising improved accuracy over the older Tolman and Chalikov (1996) terms used by Chawla et al. (2012). The CAWCR hindcast was chosen over the Rascle and Ardhuin (2013) hindcast for its longer available record. The CAWCR hindcast also has a slightly higher global resolution at 0.4°, compared with 0.5° for the other two hindcast products. Further, this hindcast has a specific focus in the central Pacific Ocean with a number of high resolution grids in this area. Although we use the global data in the present study, the accuracy in the Central Pacific benefits from these grids due to the two-way nesting used, following Tolman (2002).

A large number of gridded variables are available, and here we focus on significant wave height (H_s), peak period (T_p) and wave energy flux (C_gE). These variables are chosen as they represent the most commonly observed wave variable (H_s), the length of the waves and thus indication of the source of waves (T_p, where locally generated wind-sea will have short wave periods and distally generated swell will have longer wave periods), and the power of the waves (C_gE, providing an indication of the potential force of the waves on coastal or offshore infrastructure). We are interested in assessing impacts of the MJO on both the magnitude and direction of surface wave energy, so we express the C_gE scalar field as a vector quantity by using peak wave direction (D_p) for deriving zonal and meridional components of C_gE (where D_p is decomposed into vector components and the C_gE scalar quantity comprises the magnitude of the total vector). For all surface wave fields assessed in this study we calculate anomalies relative to the annual climatology to depict wave variations over the MJO lifecycle.

A detailed assessment of the quality of this wave hindcast is provided in Durrant et al. (2013). Good agreement is found globally in terms of bias and root mean square error relative to available satellite altimeter and buoy observations. The CAWCR hindcast accounts for temporally varying sea ice concentration using the approach outlined

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[1] https://ams.confex.com/ams/94Annual/webprogram/Paper233244.html

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