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Assimilation of ocean wave spectra and atmospheric circulation patterns to improve wave modelling

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ABSTRACT

The modelling of waves associated with extreme events is fundamental to coastal engineering design and coastal vulnerability assessments. The storm systems that drive extreme wave events are associated with specific atmospheric circulation patterns (CPs). In this paper the link between these circulation patterns and wave spectra is explored as a means to improve wave modelling in engineering applications. The methodology involves partitioning wave spectra into low frequency swell and locally generated wind waves. The origin(s) of the swell waves can then be estimated in order to link them to the atmospheric circulation pattern(s) that generated them. A method based on fuzzy logic and fuzzy sets is used to identify and classify the atmospheric circulation patterns. Finally the spectral characteristics associated with specific circulation patterns can be obtained. The methodology is tested using a case study on the east coast of South Africa. The atmospheric circulation patterns driving low frequency swell events resemble those previously identified as the dominant drivers of significant wave events in the region. The link between wave spectra and CPs can be used to study the impacts of specific CPs on the coastline. For example the spectra associated with swell produced by tropical cyclones can be used to model their potential impacts. This new methodology may improve the inputs to spectral wave models and aid studies of climate change impacts. It may also help in identifying statistically independent storm events and improve multivariate statistical models of such events.

1. Introduction

The relationship between atmospheric features and ocean wave energy spectra is complex. However, understanding this relationship may improve the application of spectral wave models in coastal vulnerability assessments and in the analysis and design of coastal infrastructure.

Atmospheric states can be classified into distinct circulation patterns (CPs) that provide insights into regional wave climates (Pringle et al., 2014; Camus et al., 2014). The insights can be used to improve statistical models of extreme ocean waves and even to develop a means to simulate long term wave records (Espejo et al., 2014). Direct measurements of waves are often constrained by budgets that allow only short or intermittent data sets. In contrast atmospheric pressure data is globally available over the past century. This paper focuses on a new method of developing links that can help to improve the inputs required for spectral wave models such as SWAN (Booij et al., 1999). Spectral wave models use the wave action balance to perform wave transformations. This process requires the specification of the wave spectrum as a boundary condition. The spectral shapes defined by the default parameter values in spectral wave models may be inappropriate for waves driven by a particular forcing. The aim of this paper is to provide a method of estimating typical spectral characteristics that are applicable to specific forcing mechanisms. For example if the effects of a cyclone are to be modelled the proposed method can identify which spectral characteristics are appropriate for waves produced by that forcing mechanism.

In addition the method provides a means of identifying statistically independent events associated with synoptic scale features. For statistical analyses of extrema a set of independent events generally needs to be identified. Traditionally, independent storm events are defined from significant wave height data using a wave height threshold (e.g. Mendez et al., 2008; Callaghan et al., 2008; Corbella and Stretch, 2013). Storm events are assumed to begin when the wave height threshold is exceeded and to end when the wave height falls below and remains below the threshold for a specified time period. The minimum inter-event time period is a subjective choice but may be estimated using autocorrelation (e.g. Corbella and Stretch, 2013). This classical method has numerous flaws, the most significant of which is that it does not distinguish between wave events driven by different meteorological systems, each of which contains its own set of statistics. For example if a tropical cyclone occurs within the user defined inter-event time after a cut-off low both independent events will be recorded as a single event. The classical method would therefore produce an incorrect statistical distribution by containing two independent events

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within one. By partitioning the wave spectra and cross assigning the wave partitions we can define actual independent events without requiring a subjective inter-event time period.

In this paper we discuss a method of estimating the spectral characteristics of waves caused by various forcing mechanisms using a partitioning and swell tracking algorithm and then linking them to atmospheric CPs. We initially describe the proposed methods of linking wave spectrum characteristics to the CPs (Section 2). Results from our case study site at Durban, South Africa are then presented (Section 3). Finally we discuss the results and the limitations of our approach (Section 4).

2. Methods

In order to link wave spectral characteristics to CPs we need to estimate the origin(s) of the waves. The waves produced near the coast are typically forced by local winds that do not have a long enough fetch to develop a significant amount of wave energy. For this reason we are interested in swell waves that develop far offshore and are driven by large scale circulation patterns. These swell waves generally have higher energies and are of particular interest for coastal engineering applications.

To estimate the origin of swell waves we first have to ensure that we are only considering the swell component of the total wave energy. The energy spectra are therefore partitioned into unique swell and wind waves by means of a partitioning algorithm (Section 2.2). The spectral partitions are then cross assigned into a collection of independent swell events (Section 2.3). Using the linear wave theory deep water wave dispersion relationship and spherical geometry the swell origins can be estimated (Section 2.3.2). The origins of the events are then grouped by location or spectral characteristics (Section 2.3.3). The grouped origins are then used to search the global geo-potential height data during the times when the swell is estimated to have been produced (Section 2.5). The circulation patterns within the origin groups are then averaged into a characteristic circulation pattern for those swell events.

2.1. Case study site

The province of KwaZulu-Natal on the east coast of South Africa has two relatively long records of wave data measured at Durban and Richards Bay (Fig. 1). Descriptions of the wave characteristics for this region, including directional energy spectra, are given by Corbella and Stretch (2012b, 2014). The spectral wave data are derived from wave

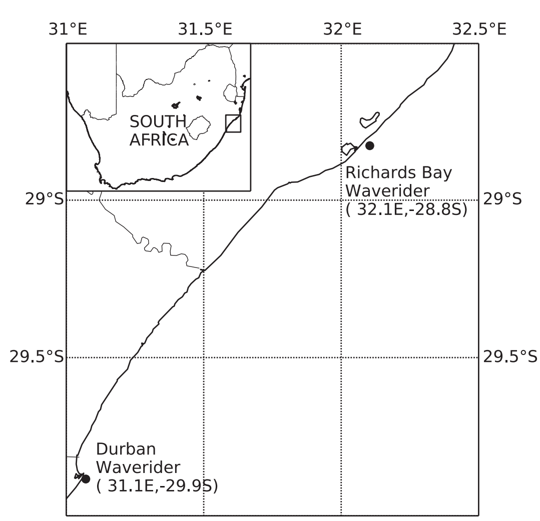

Fig. 1. Map of South Africa showing KwaZulu-Natal with locations of the wave recorders.

recording buoys that are listed in Table 1. The wave recording buoys sample at a rate of 1.28 Hz and the data sets have spectral data available at 3-hour, 1-hour and 0.5-hour intervals.

Data for geo-potential heights that are required to investigate atmospheric circulation patterns were obtained from the ERA-Interim data set (http://apps.ecmwf.int/datasets/) for the period 1979–2013 at 6 hourly intervals. Circulation patterns are defined in this study as normalized anomalies derived from the 700 hPa geopotential with a grid resolution of 2.5° (10°S 0°E-50°S 50°E). The 700 hPa geopotential anomalies indicate regions of relatively high and low pressures and can be used to infer wind fields without accounting for boundary layer effects (Bárdossy et al., in press). Furthermore they are less noisy than those based on surface pressures which facilitates the automated CP classification procedure.

Wind data is required to identify the locally generated wind wave components of the wave energy spectra. Durban and Richards Bay both have land based wind recording instruments for their port control. Durban and Richards Bay wind data was available from 31/05/2002 to 31/07/2013 and 19/08/1993 to 31/07/2013 respectively. It should be noted that coastal wind gradients may produce dramatically different wind velocities between offshore and onshore locations. In this case the buoys are within 2 km of the wind recording instruments and are a representative measurement. Since the data period is restricted by the availability of the wave data (Table 1) Durban was only analysed for approximately 6 years and Richards Bay was analysed for approximately 16 years.

Mid-latitude cyclones (with associated cold fronts), coastal lows, cut-off lows and tropical cyclones have been cited as the main swell producing mechanisms along the KwaZulu-Natal coast (Mather and Stretch, 2012; Corbella and Stretch, 2012a; Rossouw et al., 2011). The reader is referred to Hunter (1987), Preston-Whyte and Tyson (1993) and Taljaard (1995) for a detailed description of South African weather systems. Coastal lows form closer to the coast than cut-off lows, mid-latitude and tropical cyclones. Therefore they are typically associated with smaller wave heights and shorter periods. Mid-latitude cyclones that traverse west to east in the region south of the country, drive long period southwesterly–southeasterly swell waves and occur during the austral winter months. Cut-off lows are deep, low pressure systems that become cut-off from the west–east moving mid-latitude cyclones (Preston-Whyte and Tyson, 1993). Their persistence can produce large swell waves with long periods. Tropical cyclones produce long period waves typically from the northeast or east-northeast and occur during late austral summer/early autumn months. However Mather and Stretch (2012) argue that tropical cyclones that become stationary south of Madagascar can drive severe wave conditions resulting in extensive coastal erosion. Seasons are defined in Table 2.

The wave data from Durban and Richards Bay will be used to demonstrate a method of linking spectral wave data to the above-mentioned circulation patterns.

2.2. Partitioning of spectral wave energy

The partitioning of spectral wave data is the separation of spectral energy into swell energy and wind-wave or sea energy. The swell energy that is usually characterised by waves produced large distances

Table 1
Historical wave recording instruments at Durban and Richards Bay, their operating periods and water depth (from Corbella and Stretch, 2014).

Instrument	Date	Depth (m)
Durban Directional Waverider	23/08/2007–30/04/2013	30
Richards Bay 3D Directional Buoy	11/06/1997–14/10/2002	22
Richards Bay Directional Waverider	08/11/2002–30/04/2013	22