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Propagation characteristic and intraseasonal oscillation of the swell energy of the Indian Ocean

C.W. Zheng [a,b,c,*], C.Y. Li [a]

[a] College of Meteorology and Oceanography, People's Liberation Army University of Science and Technology, Nanjing 211101, China
[b] Key Laboratory of Renewable Energy, Chinese Academy of Sciences, Guangzhou 510640, China
[c] Dalian Naval Academy, Dalian 116018, China

HIGHLIGHTS

- Propagation characteristic of swell energy is explored.
- Propagation route of swell energy is exactly depicted.
- Propagation speed of swell energy is quantitatively calculated.
- A new method is designed to reveal the propagation destination of swell energy.
- Intraseasonal oscillation of swell energy is revealed.

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ABSTRACT

The propagation characteristics of swell energy are important for applications such as swell wave power generation, ocean wave forecasting, disaster prevention and reduction, etc. However, the study on the propagation of swell energy is still relatively rare. This study proposed a new method to exhibit the exact propagation route and speed and intraseasonal oscillation of swell energy. The Indian Ocean is selected as a case study, using the 45-year (1957.09–2002.08) European Centre for Medium-Range Weather Forecasts (ECMWF) Reanalysis (ERA-40) wave reanalysis dataset. The main results are as follows. (1) empirical orthogonal function (EOF) analysis and 6-hourly zonal averages of swell wave power density (WPD) show that the Indian Ocean swell energy has an obvious but fluctuating northeastward propagation. (2) The swell energy of the southwest Indian Ocean generally spreads to two regions: the main body propagates in a NE–NNE direction to Sri Lankan waters, while a small branch propagates to Christmas Island waters. (3) Swell energy in the west of the southern Indian Ocean westerly (SIOW), in Sri Lankan waters, and in Christmas Island waters share a common period of quasi-weekly oscillation. Swell energy takes ~6 days to propagate from the west of the SIOW to Sri Lankan and Christmas Island waters. Swell energy propagates faster during June–September than in other months.

1. Introduction

Swell can be surprisingly destructive in the actual ocean; it can lead to phenomena such as hogging and sagging that can cause serious damage to ships [1,2]. As a vast and reliable source of energy, swell has also been the focus of increasing attention for power generation because of its potential contribution to alleviating energy and environmental problems. Swell waves are persistent: they can propagate thousands of kilometers along great circle paths with little attenuation [3–7]. Chen et al. [8] and Zheng et al. [9] pointed out that swell dominates the mixed wave field in most of the global oceans. The above characteristics determined that it is possible to improve the forecasting ability of ocean wave and wave energy to service for the wave energy devices, by monitoring the propagation path and speed of swell energy, combined with the swell index (proportion of swell in the mixed wave). In addition, mastering the propagation path and direction of swell energy is conducive for equipment to adjust the attitude, thus to improve the efficiency of wave energy equipment. Therefore, a thorough analysis of the characteristics of swell energy has a practical value, both for wave power generation [10–12,2,13] and in other areas such as ocean wave forecasting [14–17], disaster pre-

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* Corresponding author at: College of Meteorology and Oceanography, People's Liberation Army University of Science and Technology, Nanjing 211101, China.
E-mail address: chinaoceanzcw@sina.cn (C.W. Zheng).

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vention and mitigation, marine construction, global climate change, etc.

Previous researches have made great contribution to the wave energy characteristic analysis, which mainly focused on the mixed wave energy. However, the research on the swell energy is still rare. Arinaga and Cheung [18] presented an atlas of global wave energy from 10 years of reanalysis and hindcast data. Their Fig. 5 exhibits that the contour of significant wave height (SWH) has a pronounced northward feature in the Indian Ocean, even northward stretch to the Bay of Bengal waters from June to September. Zheng et al. [19] analyzed the seasonal characteristics of wave power densities of wind-sea, swell, and mixed wave, showing that the WPD of Indian Ocean swell is enhanced from west to east, piling up on the west coast of Australia and then spreading to the north. Alves [5] divided the global ocean into 13 regions to analyze the propagation characteristics of swell, reporting that a large proportion of SIOW swell propagates freely eastward into the tropical and subtropical latitudes of the Indian and Pacific oceans. Pérez et al. [20] presented a new methodology referred to as a method for Evaluating the Source and Travel-time of the wave Energy reaching a Local Area (ESTELA) for understanding regions of wave generation and the extent of swell propagation over the global ocean. Then four target points are selected to show the suitability of the ESTELA method. Semedo [21] found that the global ocean mixed wave field is dominated by swell and that the winter swell in the North Atlantic Ocean has a north–south propagation pattern. Ardhuin et al. [6] found that swell waves are in fact very persistent, with energy *e*-folding scales in excess of 20,000 km, half of the Earth's perimeter. Zheng and Li [22] contoured the wave direction and wave height of Indian Ocean swell based on the ERA-40 wave reanalysis from the ECMWF, showing that the swell wave height (H^s) contour has a pronounced northward feature and the dominant swell direction from the south all year round. They also found that the strength of the SIOW is closely related to the northward diffusion acreage of swell.

Previous researchers have made great contributions to the analysis of swell propagation characteristics. However, the study on the propagation characteristic and intraseasonal oscillation of swell energy is relatively rare. Based on the 45-year ERA-40 wave reanalysis from ECMWF, we aim to propose a new method to exhibit the exact propagation route and speed and intraseasonal oscillation of swell energy, to provide a reference for swell power generation, ocean wave forecasting, and other areas of interest.

2. Data and methods

2.1. Data

The dataset used in this study is the ERA-40 wave reanalysis from the ECMWF [23], covering meteorological observations from September 1957 to August 2002. It can be downloaded from the website http://apps.ecmwf.int/datasets/data/era40-daily/levtype=sfc/. The ERA-40 has global coverage (90°S–90°N, 180°W–180°E), with a $1.5° \times 1.5°$ spatial resolution and 6-hourly temporal resolution. Besides atmospheric variables, it also includes wave parameters. It is the first global reanalysis product to couple the Wave Model (WAM) and an atmosphere circulation model. The ERA-40 wave reanalysis is not fully homogeneous over its length, due mainly to changes in the satellite products assimilated in the process. Low wave heights tend to be overestimated, and high wave heights tend to be underestimated [3,24]. This feature is a global characteristic of the ERA-40, and not a peculiarity of a particular location. These data are divided into four periods to accommodate the differences in data assimilation. The data derived between December 1991 and May 1993 has relatively large biases. Considering this, some researchers have used buoy data to amend the SWH, but little progress has been made in developing techniques for separation of the wind-sea and swell spectra. In general, the ERA-40 wave reanalysis is a good option for separating wind-sea and swell due to the high temporal and spatial resolution, and long time series, and it has been widely applied in studies of wind-sea and swell characteristics, especially in the North Atlantic, the North Pacific, and the Southern Ocean [3,25–27]. In this study, the precision of the ERA-40 wave reanalysis is verified against satellite altimeter measurements of SWH (Figures omitted). Clearly, the ERA-40 and observed SWH during JJA and DJF 2001 show a good consistency.

To quantitatively analyze the precision of ERA-40 SWH, the correlation coefficient (R), the mean error (bias), the root mean square error (RMSE), and the scatter index (SI) are calculated. In JJA, the R, Bias, RMSE, and SI are 0.86, 0.14 m, 0.61 m, and 20%, respectively. In DJF, the corresponding values are 0.89, 0.18 m, 0.65 m, and 16% respectively. From R, Bias, RMSE and SI, we find a close relationship between ERA-40 SWH and observed data. In comparisons with similar wave reanalysis products, the ERA-40 wave data proved to be of better quality [28]. In addition, the ERA-40 wave reanalysis is the product to couple the WAM and an atmosphere circulation model. Previous studies also show that the WAM wave model performs well for wave field simulation in the Indian Ocean [15,29,30]. Thus, the ERA-40 wave reanalysis is considered to be reliable in the Indian Ocean.

2.2. CC, EOF and wavelet analysis to exhibit the swell energy propagation

Combining the calculation method of WPD [31–34] and the 6-hourly ERA-40 wave reanalysis data, we obtained the 6-hourly swell WPD of the Indian Ocean for the period 1957.09–2002.08. Then the propagation characteristics of the Indian Ocean swell energy are analyzed using the 6-hourly swell WPD for the past 45 years (1957.09–2002.08). First, a strong swell field generated by the SIOW is selected to exhibit the spatial and temporal variations in swell WPD and swell wave direction. Combining the 6-hourly zonal average of swell WPD during this strong swell process reveals the northward propagation of swell energy. In addition, the EOF method [35] is used to depict the propagation pattern of Indian Ocean swell energy. Then the propagation route and propagation speed of swell energy are clearly presented, by calculating the simultaneous, lead, and lag correlation coefficients (CC) [36,37] between the source and destination of swell energy. Wavelet analysis and cross-wavelet analysis [38,39] are also used to reveal the intraseasonal oscillation of swell energy, including the periods of variability and the lead or lag correlation for a particular period range.

3. Results

3.1. Identifying the northward propagation phenomenon

A strong swell process (2002.08.10 00:00–2002.08.21 18:00) generated by the SIOW is selected to demonstrate the spatial and temporal variations of the swell WPD and swell wave direction (color[1] shading and arrows, respectively), as shown in Fig. 1.

The swell energy intensifies from August 10 to 14. On August 10, the swell energy in the SIOW is weak as a whole, while there is an area of relatively high energy in the waters around the Prince Edward Islands (in the west of the SIOW; 55°S, 40°E). In the follow-

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[1] For interpretation of color in Figs. 1, 3 and 7, the reader is referred to the web version of this article.