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# A global study of temporal and spatial variation of SWH and wind speed and their correlation

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**Abstract**

The climatology of significant wave height (SWH) and sea surface wind speed are matters of concern in the fields of both meteorology and oceanography because they are very important parameters for planning offshore structures and ship routings. The TOPEX/Poseidon altimeter, which collected data for about 13 years from September 1992 to October 2005, has measured SWHs and surface wind speeds over most of the world's oceans. In this paper, a study of the global spatiotemporal distributions and variations of SWH and sea surface wind speed was conducted using the TOPEX/Poseidon altimeter data set. The range and characteristics of the variations were analyzed quantitatively for the Pacific, Atlantic, and Indian oceans. Areas of rough waves and strong sea surface winds were localized precisely, and the correlation between SWH and sea surface wind speed analyzed.

**Key words:** TOPEX/Poseidon, SWH, wind speed, correlation

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## 1 Introduction

The climatology of significant wave height (SWH) and sea surface wind speed are important dynamic factors that have a fundamental influence on both coastal engineering and offshore projects. These data are of interest not only scientifically to oceanographers and to meteorologists, but also economically to marine technologists designing oil-drilling platforms, as well as to all involved in the planning of shipping routes. Wave heights that exceed a critical value might threaten oceanographic engineering construction and navigation, which could result in disaster. Additionally, sea surface wind speed is another essential parameter in the design of oceanographic engineering projects. Therefore, it is critically important for the design, construction, and management of engineering projects that fundamental data are available. Over a long period, many oceanographers and meteorologists have devoted themselves to the research of wave and wind speed climatology, but observations obtained via traditional methods (e.g., stations, buoys, and ships) are sparse relative to the scale of the oceans.

The development of space technology has made satellite-based remote sensing available since the 1970s. Satellite remote sensing technology makes it possible to collect high-resolution data on ocean elements over a wider range of time and space in real-time fashion. The overhead geodetic collection contributes considerably in terms of data collection, and it plays an important role in the research of ocean elements.

Launched on August 10, 1992, the TOPEX/Poseidon satellite altimeter was a joint project between the CNES (France) and NASA (United States) space agencies. At that time, this satellite was the only one using dual-band radar, and it has provided us with simultaneous survey information on global sea surface wind speed, as well as wave and sea surface topography of the longest duration and best quality. Measurements over more than ten years have been accumulated, and studies linked with 17 observation stations in the tropical Pacific have shown that the absolute error for wave height is within 4.7 cm (Tapley et al., 1994). Thus, these data represent one of the most important acquisitions of information regarding satellite remote sensing research. Sandwell and Agreen (1984), Lin and Chen (2002), Han, Zhao et al. (2003), Han, Zhu et al. (2003), Mognard et al. (1983), and Toumadre and Ezraty (1990) have analyzed the wave height distribution and change rules; and Wang et al. (2000), Yin et al. (2002), and Han, Wang et al. (2003) have continued work on extreme value forecasting. Furthermore, wave heights, sea surface roughness, tidal waves, and ocean circulation have also been subjects of research. Thus, it can be deduced from the range of the above studies that it is reasonable and significant to study the spatiotemporal characteristics of SWH and wind speed using the TOPEX/Poseidon altimeter data set.

One principle factor in forecasting both ocean waves and sea surface wind speed is the long-term statistical data regarding the degree of rough waves and gales. In this paper, a study of the global spatiotemporal distributions and variations of the SWH and sea surface wind speed is presented based on data from the TOPEX/Poseidon altimeter from September 1992 to October 2005. The range and characteristics of the variations were analyzed quantitatively for the Pacific, Atlantic, and Indian oceans. Areas of rough waves and strong sea surface winds were localized precisely, and the correlation between SWH and sea surface wind speed analyzed.

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## 2 Data set and methodology

Information regarding the SWH and wind speed at sub-satellite points can be derived by analyzing the intensity and wave shape of the radar pulse (Lin and Chen, 2002). In this thesis, 480 satellite orbit repetition intervals and a continuum of 158-month-long TOPEX/Poseidon altimeter data, obtained between September 1992 and October 2005, were analyzed to derive the SWH and sea surface wind speed. The data set of SWH and sea surface wind speed is state-of-the-art with long temporal coverage, fine resolution, and high density, which makes it suitably accurate and reliable for use in this thesis. However, the data were preprocessed and subject to quality control. According to the flag bits of the wave-counting parameter, tropospheric correction, satellite attitude ratio, and other flag bits (e.g., dry land and ice), the unqualified data were eliminated. Following the quality control, the individual SWH and sea surface wind speed measurements from 66°S–66°N were arranged in 1°×1° pixel bins using a distance-weighting interpolation method.

The SWH in a given area can be defined as follows:

$$\overline{H}_{1/3}(i,j,t)=\frac{1}{M_k}\sum_{k=1}^{M_k}H_{1/3}(i,j,t,k)\ ,$$

where $k$ is the serial number of the altimeter data set, and $M_k$ is the total number of SWHs in the considered area ($i$, $j$) and considered time domain ($t$).

The sea surface wind speed statistics were determined using the same technique.

## 3 Results and discussion

### 3.1 *Spatial variation of the multi-year-averaged SWH and wind speed data*

The spatial distribution characteristics of the SWH and sea surface wind speed can be appraised based on the statistical results of multi-year averages of the data set. The TOPEX/Poseidon altimeter data of SWH and sea surface wind speed, from September 1992 to October 2005, were averaged in 1°×1° pixel bins from which the contour maps shown in Fig. 1 were produced. The common characteristics of the distribution of the SWH and the sea surface wind speed in the Pacific, Atlantic, and Indian oceans are the latitudinal belt shapes and meridional vibrations; these characteristics can be seen more obviously in Fig. 2. The lowest-averaged sea surface wind speed (<3 m/s) and SWH (<0.5 m) appear near Indonesia at approximately 100°–120°E. The primary cause for this might be that this area is under the influence of the doldrums, and it is sheltered by the land. Open to the broad stormy westerlies, the Indian Ocean is seen as the roughest region with large areas at about 50°S covered by the maximum multi-year-averaged wind speed of >12 m/s and maximum SWH of >4.5 m.

Figures 1b and 2b show that sea surface wind speed is lowest near the equator, ranging from 4.6 m/s (Indian Ocean) to 5.4 m/s (Atlantic Ocean). Except for the Indian Ocean, the Northern and Southern Hemisphere sea surface wind speeds present an obvious split-blip characteristic to the distribution, taking the equator as the axis. Under the control of the Intertropical Convergence Zone (ITCZ), the sea surface wind speed is only

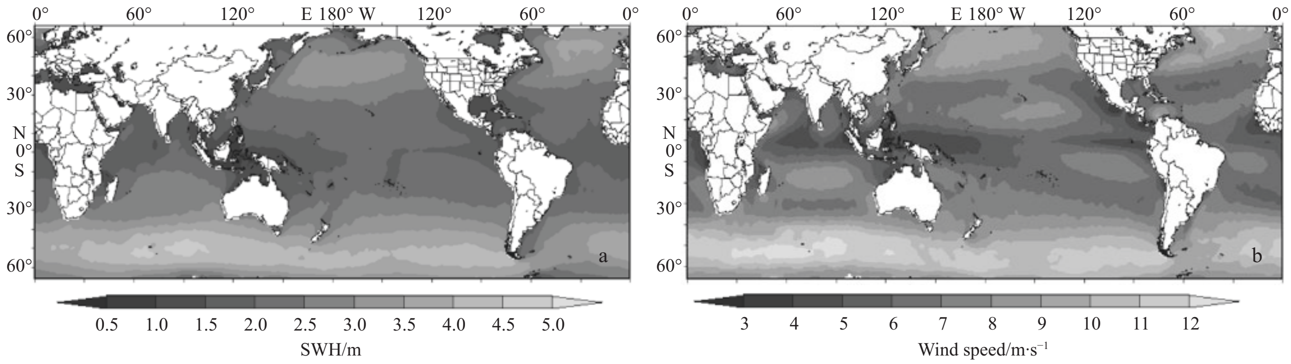


**Fig.1.** Multi-year-averaged SWH (a) and sea surface wind speed (b).

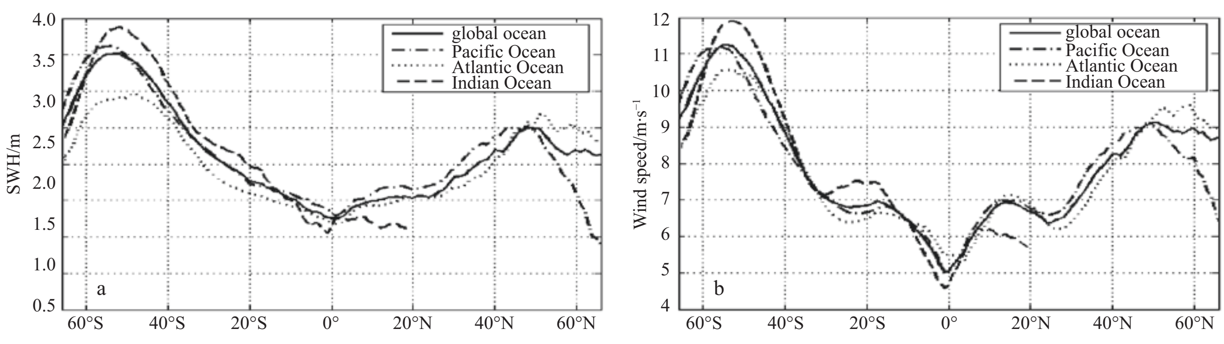


**Fig.2.** Variation of multi-year-averaged SWH (a) and sea surface wind speed (b) with latitude.

about 5 m/s near the equator. As latitude increases, the sea surface wind speed increases gradually, becoming the southeast and northeast trade wind zones located on the southern and northern sides of the ITCZ, respectively. The global sea surface wind speed achieves an extreme value of about 6.6–6.8 m/s in the areas about 15°–20°S and 15°–20°N. At around the same latitudes, the sea surface wind speed in the Indian Ocean is about 7.5 m/s, which is a little larger than in the Pacific and Atlantic oceans. The sea surface wind speed then decreases slowly with further increase in latitude, reaching a narrow zone of low winds named the Horse Latitudes. Here, the sea surface wind speed has a value of about 6.4–6.6 m/s near 25°S and 25°N in the Pacific and Atlantic oceans, whereas the value is about 7.2 m/s at about 30°S in the Indian Ocean. Extending toward the poles, the sea surface wind speed increases rapidly in the Pacific, Atlantic, and Indian oceans. There is the region of the so-called 'stormy westerlies', where sea surface wind speed reaches maximum values at 50°–55°S and 50°–55°N. Thereafter, the sea surface wind speed decreases gradually; dropping much more quickly in the Pacific Ocean from 9.1 to 6.4 m/s. Note that this region presents different characteristics in the Northern and Southern hemispheres: narrow in span but strong in intensity in the Southern Hemisphere, and the opposite in the Northern Hemisphere. The maximum value of the sea surface wind speed in the South Pacific is 2 m/s greater than in the North Pacific; the difference is smaller between the North and South Atlantic (0.8 m/s). The maximum sea surface wind speed in the Indian Ocean is the highest with a value of 11.9 m/s.

Regarding the SWH (Figs 1a and 2a), there is also an area corresponding to the ITCZ where the SWH is below 2 m, and the lowest SWH is <1.8 m. However, the characteristic is not as obvious as that for the sea surface wind speed, mainly because of the propagation of rough waves induced by gales in high latitudes. Different from the latitudinal characteristics of sea surface wind speed, there is no symmetrical distribution in the two hemispheres. The SWH presents an obvious unimodal distribution in the Southern Hemisphere. The SWH increases with latitude and reaches a maximum around 50°–55°S with a value >4.1 m in both the Pacific and Indian oceans; the roughest SWH in the Indian Ocean is 4.4 m, whereas it is 3.5 m in the Atlantic. With further increases in latitude, the SWH decreases rapidly in the Pacific, Indian, and Atlantic oceans toward Antarctica with values of 3.2, 2.7, and 2.5 m, respectively; whereas in the Northern Hemisphere, the SWH is less than 1.8 m in the Indian Ocean. Similar to the sea surface wind speed, the SWH also presents a split-blip distribution with increasing latitude, reaching an extreme value of 2.2 m at about 15°N. After a slight decrease, the SWH increases gradually to reach a maximum of 3.0 m at 45°N, following which it reduces rapidly to less than 1.5 m near the land. The SWH appears to be a weak multi-peak distribution in the Atlantic, but only the peak centered at approximately 52°N is obvious.

### 3.2 *Temporal variations of averaged SWH and wind speed*

The spatial distribution characteristics of SWH and sea surface wind speed can be displayed effectively using statistical results of the seasonally and monthly averaged data set of the given years. Using the TOPEX/Poseidon altimeter data in 1°×1° pixel bins, we analyzed the monthly and seasonal (winter: Dec.–Feb.; spring: Mar.–May; summer: Jun.–Aug.; autumn: Sep.–Nov.) variation of sea surface wind speed and SWH. The monthly and seasonal sea surface wind speed and SWH data are contoured in Figs 3 and 4, and in Figs 5 and 6, respectively. Both the SWH

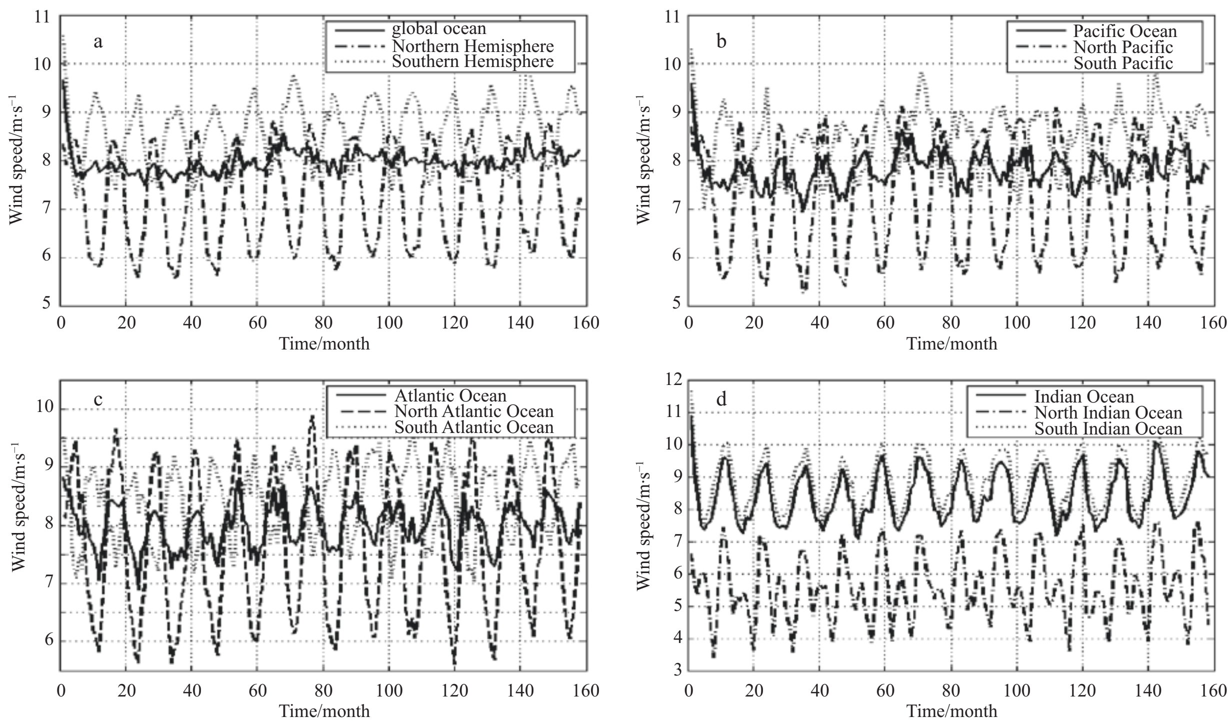


**Fig.3.** Variation of sea surface wind speed by month: global (a), Pacific (b), Atlantic (c), and Indian oceans (d).

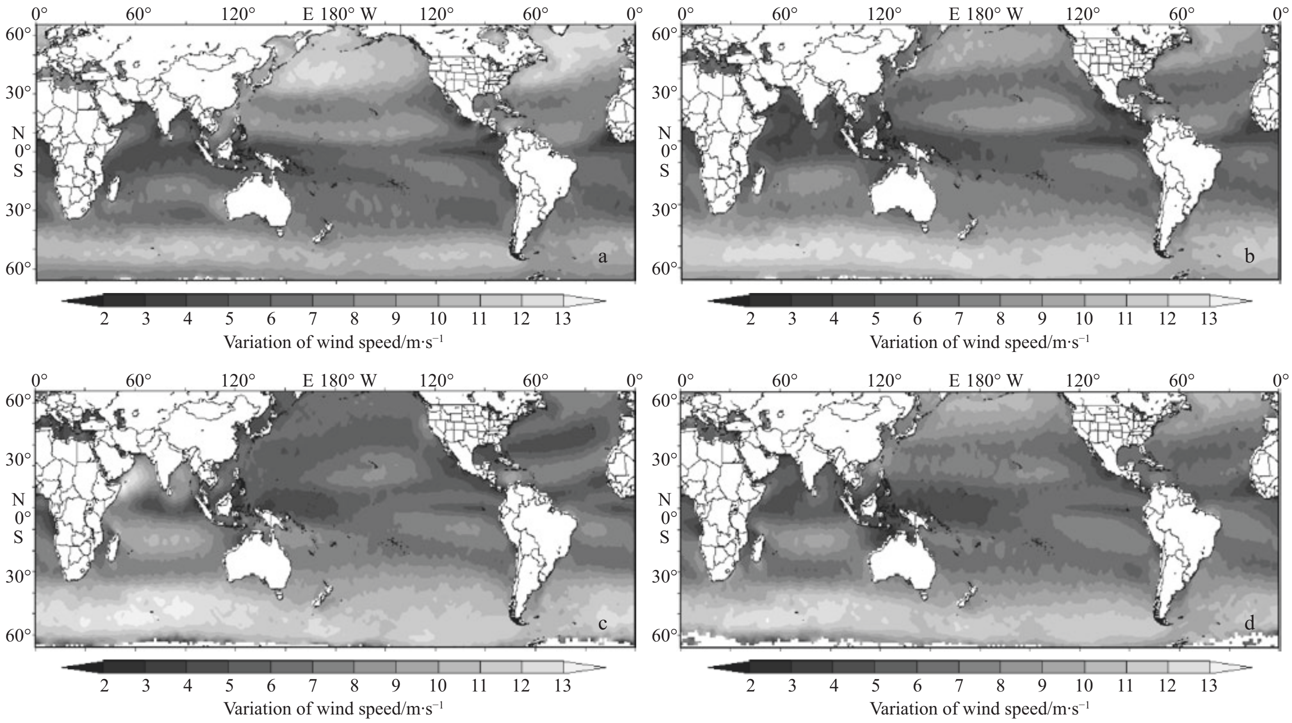


**Fig.4.** Variation of sea surface wind speed with season: winter (a), spring (b), summer (c), and autumn (d).

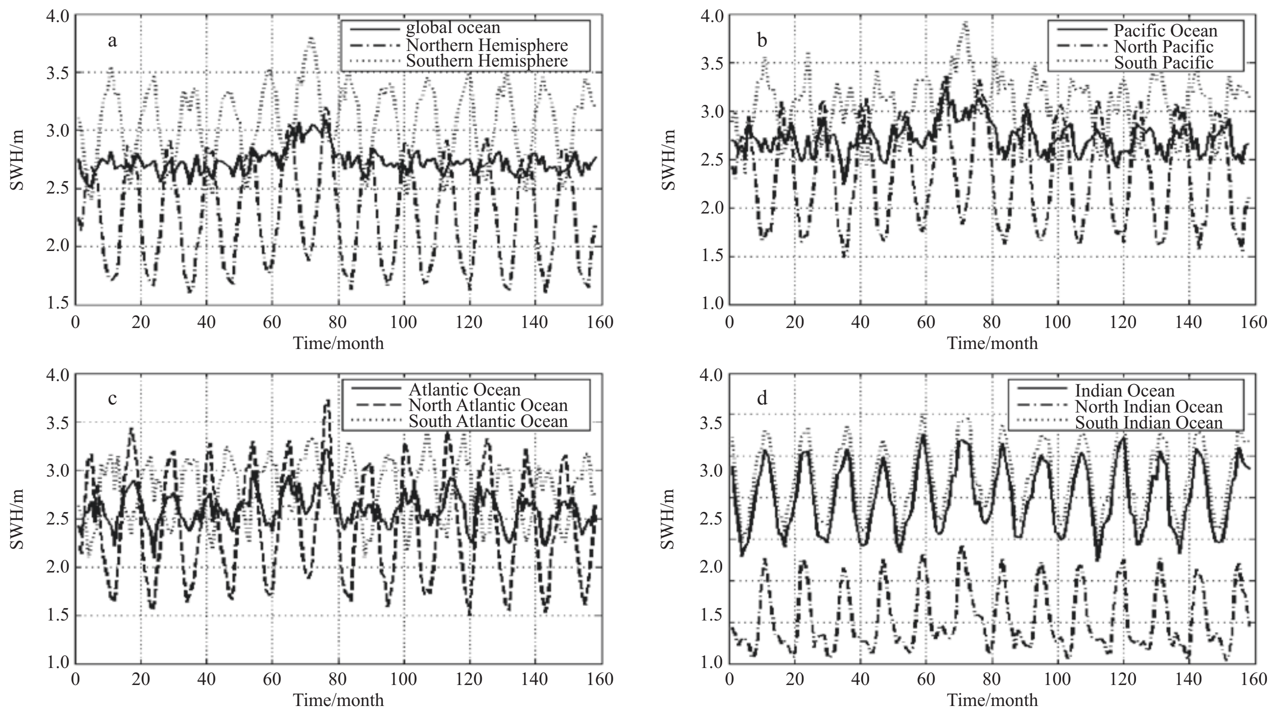


**Fig.5.** Variation of SWH by month: global (a), Pacific (b), Atlantic (c), and Indian oceans (d).

and the sea surface wind speed in the Southern and Northern hemispheres follow an annual variation as their main variation period, but both present almost symmetrical anti-phase distributions in the two hemispheres. Except in the northern Indian Ocean, where they reach a maximum in summer because of the monsoon, the sea surface wind speed and SWH of the entire

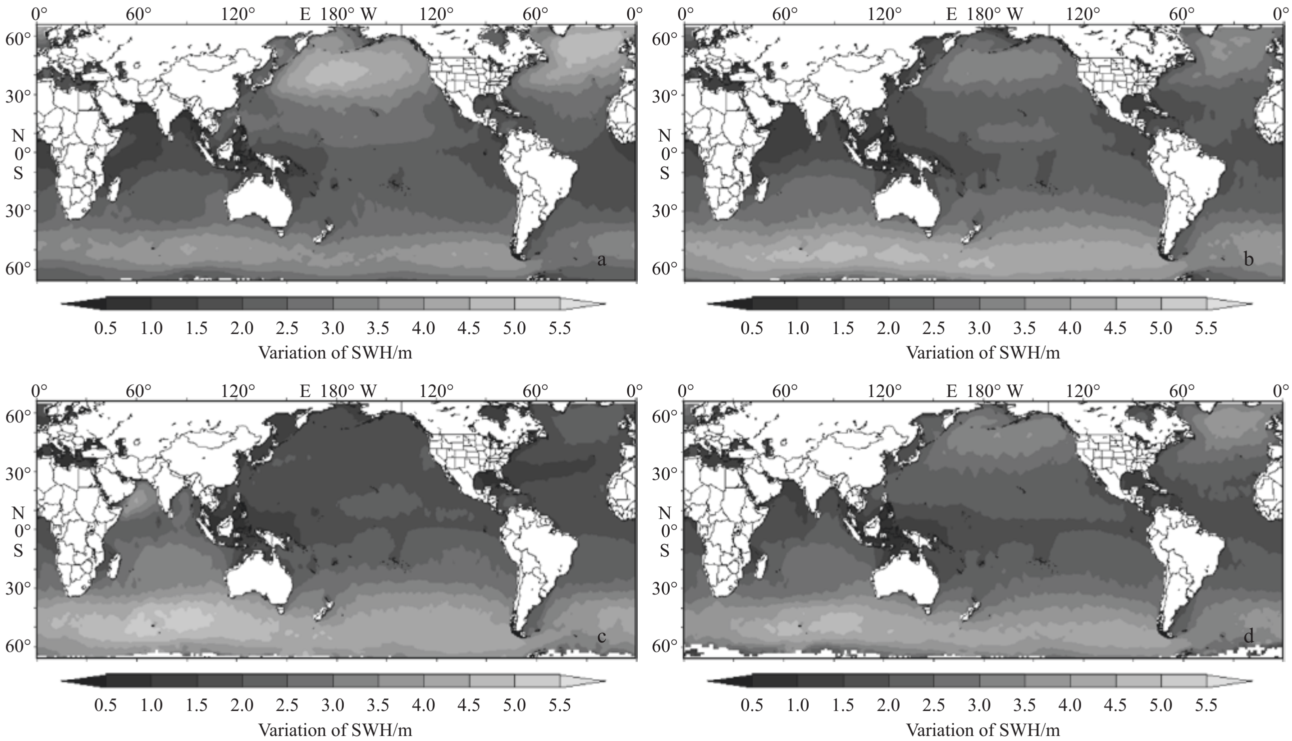


**Fig.6.** Variation of SWH with season: winter (a), spring (b), summer (c), and autumn (d).

Northern Hemisphere reach their maximum values in winter and their minimums in summer. The characteristics shown in the Southern Hemisphere are the reverse. With regard to the entire ocean, a half-year cycle is also noticeable. Maps of seasonal SWH show that in all the oceans, there are steady increases in SWH toward the south, ranging from about 2.5 m in the trade-wind belt to a maximum of 4.5–6.0 m in the region of the stormy westerlies. Unlike the sea surface wind speed, there is no SWH minimum corresponding to the Horse Latitudes. This is as expected, because the SWH measurement includes not only locally generated wind waves, but also the swell that propagates long distances and has the effect of smoothing the SWH field. However, we do see a band of rough waves corresponding to the maximum wind speeds of the westerlies, as shown in the contour maps of SWH.

A seasonal variation of sea surface wind speed can be clearly seen in Fig. 3. In winter, the sea surface wind speed of the Northern Hemisphere is much greater than in the Southern Hemisphere in the Pacific and Atlantic oceans. The characteristics of the SWH in the Indian Ocean and in the other three seasons (spring, summer, and autumn) in the Pacific and Atlantic are the reverse, with the SWH in the Northern Hemisphere less than in the Southern Hemisphere. The range of seasonal variation of SWH in the Northern Hemisphere is greater than in the Southern Hemisphere, which can be seen in Fig. 4. The monthly averaged sea surface wind speed in the North Pacific is between 5.23 and 9.11 m/s, whereas it is between 7.00 and 10.29 m/s in the South Pacific. The ranges of variation of sea surface wind speed in the North and South Atlantic oceans are 5.60–9.88 m/s and 7.03–9.83 m/s, respectively. The difference in sea surface wind speed in the Indian Ocean is more obvious with a range of 3.41–7.63 m/s in the northern Indian Ocean and 7.36–11.64 m/s in the southern Indian Ocean. The monthly and seasonally averaged SWH (Figs 5 and 6) show similar features to the sea surface wind speed: in winter, they are rougher in the southern Pacific and Atlantic oceans, but this trend is reversed in the other three seasons. The SWH in the southern Indian Ocean is greater than in the north, but the range of seasonal variation of SWH in the northern Indian Ocean is greater. The remarkable difference between the Southern and Northern hemispheres appears primarily because of the dissimilarity of the land–sea distribution between the two hemispheres.

### 3.3 *Correlation between SWH and sea surface wind speed*

As stated above, it can be seen that the SWH and the sea surface wind speed vary synchronously and have almost uniform spatial characteristics in most regions. To establish the correlation using the monthly averaged sea surface wind speed and SWH data, a one-step fitting was performed for both the Southern and Northern hemispheres (Figs 7a and b, respectively), and the correlation coefficient $R$ calculated ($R$=0.91 in the Southern Hemisphere and $R$=0.97 in the Northern Hemisphere), which demonstrates the close correlation between the sea surface wind speed and SWH. The global correlation coefficient is shown in Fig. 7c, based on the annually averaged data of the sea surface wind speed and SWH from 1°×1° pixel bins. It can be seen that the correlation between the sea surface wind speed and SWH is high; the value of $R$ is >0.95 for 30°–50°S and 30°–50°N, and therefore, the sea surface wind speed can be considered an important factor affecting the SWH in these regions. However, the correlation is not as strong ($R$ < 0.5) in certain areas, e.g., the southern equatorial Pacific, regions near 20°S and

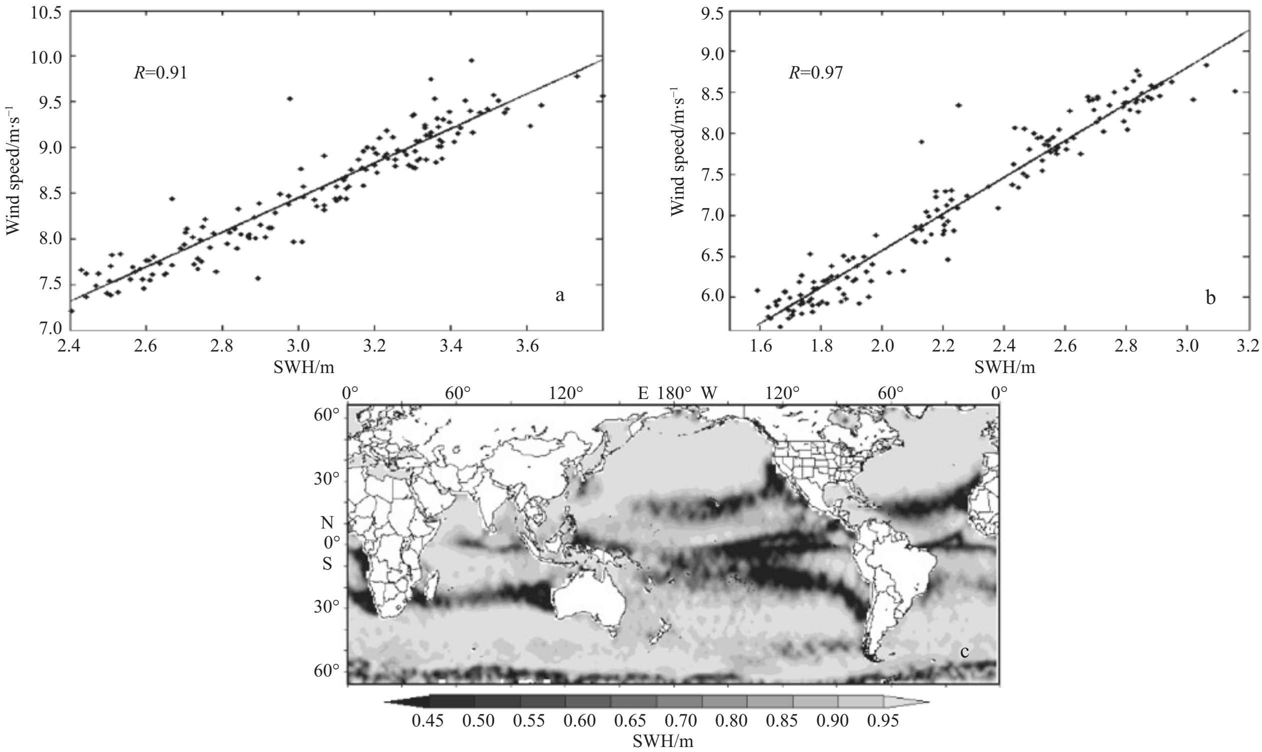


**Fig.7.** Correlation coefficient of sea surface wind speed and SWH: Southern Hemisphere (a), Northern Hemisphere (b), andglobal (c).

20°N, and near Antarctica, as well as near some surrounding islands. This is mainly due to the propagation of swell after gales, although topography is also an important factor for SWH, as is the proximity of islands and continents.

## 4 Conclusions

In summary, following the analysis of the TOPEX/Poseidon altimeter data set from September 1992 to October 2005, a more comprehensive description of the spatiotemporal variations of global sea surface wind speed and SWH has been advanced. The majority of the conclusions are consistent with those reached based on analyses of short-term data sets (Lin and Chen, 2002).

The following conclusions can be derived considering the spatial distributions. (1) The common characteristic between the SWH and sea surface wind speed distribution in the Pacific, Atlantic, and Indian oceans is the latitudinal belt-shaped pattern and meridional oscillation. (2) The SWH and sea surface wind speed in the Southern Hemisphere are greater than in the Northern Hemisphere. (3) The multi-year-averaged sea surface wind speed and SWH both appear to be smoother and weaker around 100°–120°E near Indonesia, whereas the southern Indian Ocean at about 50°S is the roughest area of the entire ocean. (4) The sea surface wind speed presents an obvious split-blip characteristic to the distribution in both the Southern and Northern hemispheres, taking the equator as the axis. The SWH presents an obvious unimodal distribution in the Southern Hemisphere, but it shows a weaker multi-peak distribution in the Northern Hemisphere with only the peak centered at approximately 52°N being obvious.

With regard to the temporal variations, a number of conclusions can be drawn. (1) The sea surface wind speed and SWH are both higher in the Northern Hemisphere than in the Southern Hemisphere in winter, but the opposite is true during the other three seasons. (2) Seasonal variations of both the SWH and sea surface wind speed are obvious, and the range of seasonal variations in SWH and sea surface wind speed in the Northern Hemisphere is greater than in the Southern Hemisphere. Both the SWH and sea surface wind speed reach maximum values in winter and minimum values in summer. The characteristics of the Southern Hemisphere are the reverse of the Northern Hemisphere. However, it can also be found that both the SWH and sea surface wind speed have a cycle period of half a year. (3) The range of seasonal variation in the Northern Hemisphere is much greater than in the Southern Hemisphere, except in the Indian Ocean.

The correlation between the SWH and sea surface wind speed was analyzed and the following conclusion obtained: there is a strong correlation between the SWH and sea surface wind speed, and it is confirmed that wind speed can be considered as an important factor that affects the SWH in most sea areas. However, the correlation is weaker in certain regions, which means that topography and the propagation of swell are also factors that influence the SWH.

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