# Analysis of surface wave climate in the North Atlantic by satellite altimeter and scatterometer

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**Abstract.** Numerous activities require predictions of global ocean wave conditions. It is of growing concern by government officials for decision-making regarding the prediction and mitigation of ocean disasters, as well as sea-going rescue activities. The coastal and marine industry is another community to which wind and wave information is extremely important. This work describes how the wind sea and swell index can be used to analyze the sea surface wave fields. The methodology is to enable the use of collocated wind speed and significant wave height simultaneous satellite scatterometer measurements and sources altimeter to observe the spatial and temporal dominant pattern of swell and wind wave zones in the North Atlantic. The results shows strong distribution of swell fields for the entire study region, with "swell pools" located in areas near the east coast of Africa. In these major swell zones, with swell index of more than 97%. The seasonal maps of the wind sea index shows that wave growth is generally weak in major swell pools. However, the opposite statement is not always true, that is, there is not necessarily strong wave generation in weak swell zones. Given the reasonable results obtained and their general consistency with field observations and model predictions, the proposed scheme appears to be efficient in characterizing the swell and wind sea climate.

**Keywords:** Wind waves, North Atlantic, probability index, ondas gravitacionais, Atlântico Norte e índice de probabilidade.

## 1. Introduction

Numerous activities require accurate predictions of global ocean wave conditions (Young, 1999). It is of growing concern by government officials for decision-making regarding the prediction and mitigation of ocean disasters, as well as sea-going rescue activities. The coastal and marine industry is another community to which wind and wave information is extremely important. Historical wind and wave conditions at any specific location are crucial to the design of drilling platforms and seabed mining facilities (Chen et al. 2004).

Since many of these sites are now located in remote and hostile areas lacking in situ records, satellite observations are of particular significance to such environments. The earliest use of oceanic wave data is perhaps in shipping and fishing, which nowadays become highly systematic worldwide (Chen et al. 2004).

The dominant portion of the wave spectrum in terms of energy is known to be associated with gravity waves whose period ranges from 1 to 30 s (Kinsman, 1965). Therefore it comes as no surprise that a majority of ocean wave studies are devoted to gravity waves.

Two main classes of gravity waves exist in the ocean, namely, the so-called wind wave (or wind sea when emphasizing its state) and swell (Holthuijsen, 2007). The former refers to young waves under growth or in equilibrium with local wind, while the latter is defined as waves generated elsewhere and propagating over large distances. As a rule of thumb, a period of 10 s may be taken as separating swell from wind wave (Kinsman, 1965). Because of the different dynamics involved, studies on swell and wind wave usually have different motivations and concerns. Swell is of increasing concern because of its potentially destructive consequences on coastal structures and sea-going activities (Mettlach et al. 1994).

In view of the different natures and impacts of swell and wind sea of each individual process in terms of its frequency of occurrence and associated energy is highly desirable.

Analysis of wind-wave-related always seeks an ideal sea state with no swell presence, especially when time and site have to be determined or selected for a field experiment. Despite their different dynamics, swell and wind sea often overlap in wave characteristics. Moreover, they are usually a complex mixture at a given location. This sometimes makes it difficult to separate the two phenomena in real observations (Chen et al. 2002).

In this study we used simultaneous altimeter and scatterometer measurements for the analysis of wind wave fields in North Atlantic using the methodology described by Chen et al (2002). The advantage for this technique is to estimate the respective degree of swell and wind wave for each collocation site, on the basis of maps of swell and wind sea climate. Finally, major swell and wind wave zones in the North Atlantic Ocean are discussed and summarized in the years 2002 until 2008.

## 2. Methods

The most essential component of this study is a fusion of collocated scatterometer and altimeter data for the years 2002 until 2008. For the processing we used altimeter data products available in the AVISO website (http://www.aviso.oceanobs.com/) and Quickscat data available in Remote Sensing Systems website (http://www.ssmi.com/).

A further processing involved interpolating scatterometer and altimeter products to a common 2º x 2º lat/long grid to obtain a quarterly average field for each variable (wind and waves).

### 2.1. Wind-wave relation

According to Komen et al. (1994), the sea surface wind speed and significant wave height follow a monotonically relationship under a growing sea up to the fully developed stage. Normally, this final stage is usually reached when the phase velocity corresponding to the dominant peak wave slightly exceeds the wind speed (Sverdrup and Munk 1947).

Several authors (Sverdrup and Munk, 1947; Pierson and Moskowitz, 1964; Ewing and Laing, 1987), suggested different relationships for the calculation of the significant wave height (H) for fully developed seas. For this study, we adopted the wind-wave relation for fully developed seas described by Hasselmann et al. (1988) than can be expressed by the equations 1 and 2:

$$H = 1.614\text{x}10^{-2} U^2 \left(0 \leq U \leq 7.5\text{ms}^{-1}\right) \quad (1)$$

$$H = 10^{-2} U^2 + 8.134\text{x}10^{-4} U^3 \left(7.5\text{ms}^{-1} < U \leq 50\text{ms}^{-1}\right) \quad (2)$$

Where U ($ms^{-1}$) is the wind speed at 10-m height and H (m) is the significant wave height.

### 2.2. Collocation dataset

If measurements of U and H are available with reasonable accuracy for some location and a given time, an estimate of the swell or wind sea components could be possible. A potential source of data for such estimation is from satellite altimeters, which provide coincident measurements of U and H at nadir. However, studies suggest that altimeter wind speed measurements can be affected by long waves or swells, not directly coupled with the local wind field (Glazman and Pilorz 1990; Lefevre et al. 1994; Hwang et al. 1998; Gourrion et al. 2000). In this case is not totally correct the assumption that the radar cross section ($\sigma^0$) measured by an altimeter is purely a reflection of the short wave roughness due to local wind action.

As put by Chen et al. (2002), the use of coincident U and H measurements from independent scatterometer and altimeter, respectively, would be preferred. Scatterometer wind speed measurements should be, in principle, less affected by sea state because of its dominant Bragg resonant scattering mechanism (Quilfen et al. 1999).

### 2.3. Swell and wind sea indices

The first studies aiming to derive algorithms to estimate the statistical indices of wind sea and swell obtained remotely are attributed to Chen et al. (2002). According to the authors, a relationship that describes the degree of swell dominance, using altimetry and scatterometer is given as the fraction of the swell energy ($E_s$), derived from equations 1 and 2 using scatterometer winds, to total wave energy ($E_o$), as given by the altimeter, and using the relation $H_s = 4E^{1/2}$ (equation 3):

$$S = \frac{E_s}{E_0} = 1.0 - \left[ H_p \left( U_{scat} \right) / H_{alt} \right]^2 P_w \quad (3)$$

Where $H_{alt}$ is the altimeter measured significant wave height, and $H_p$ is the fully developed wave height, which can be determined through the equations 1 and 2, by using scatterometer wind speed, $U_{scat}$. The parameter $P_w$ is given by equation 4:

$$P_w = N_w / N \quad (4)$$

Where $N_w$ is the number of wind sea events, and $N=N_w+N_s$ with $N_s$ is the number of swell events. The parameters $P_w$ is an index giving the frequency of wind sea occurrences, and can be associated to the probability of wind sea. Similarly, it is possible to define the index $P_s$, the frequency of occurrence of swell, associated to the probability of swell (equation 5):

$$P_s = N_s / N \quad (5)$$

The $N_s$ and $N_w$ are calculated at a given crossover point. Since $N= N_s + N_w$, $P_s + P_w= 1$. In this study, we considered the $P_s$ and $P_w$ calculated by Chen et al. (2002) for the North Atlantic. Following similar procedures for the swell index, is possible to define a the wind sea index W, which is interpreted as a “growing potential” for wind waves, given by equation 6:

$$W = \frac{E_p - E_w}{E_p} = 1.0 - \left[ H_{alt} / H_p \left( U_{scat} \right) \right]^2 P_w \quad (6)$$

$E_w$ is the wave energy of the wind sea component which can be estimated as $E_o x P_w$.

It is important to note that, for a purely swell regime, $U_{scat}=0$ and $H_{alt}>0$, making S=1. For a purely wind sea in its beginnings, $U_{scat}>0$ and $H_{alt}=0$ and W=1. For a fully developed wind sea, $U_{scat}$ and $H_{alt}$ follow the equations 1 and 2 and S=W=0.

These relations assume that, any sea state is considered as either swell dominated or wind sea dominated. The values of $P_s$ and $P_w$ vary geographically and seasonally. In our study we analyze the seasonal variability of these parameters proposed by Chen et al. (2002).

## 3. Results and discussion

For this study, monthly average data were analyzed between the years 2002 to 2008, representing seven years of data, which are distributed by quarters as shown in figures 1 and 2. The color bar to the right of the figures shows the swell or wind sea statistical indices.

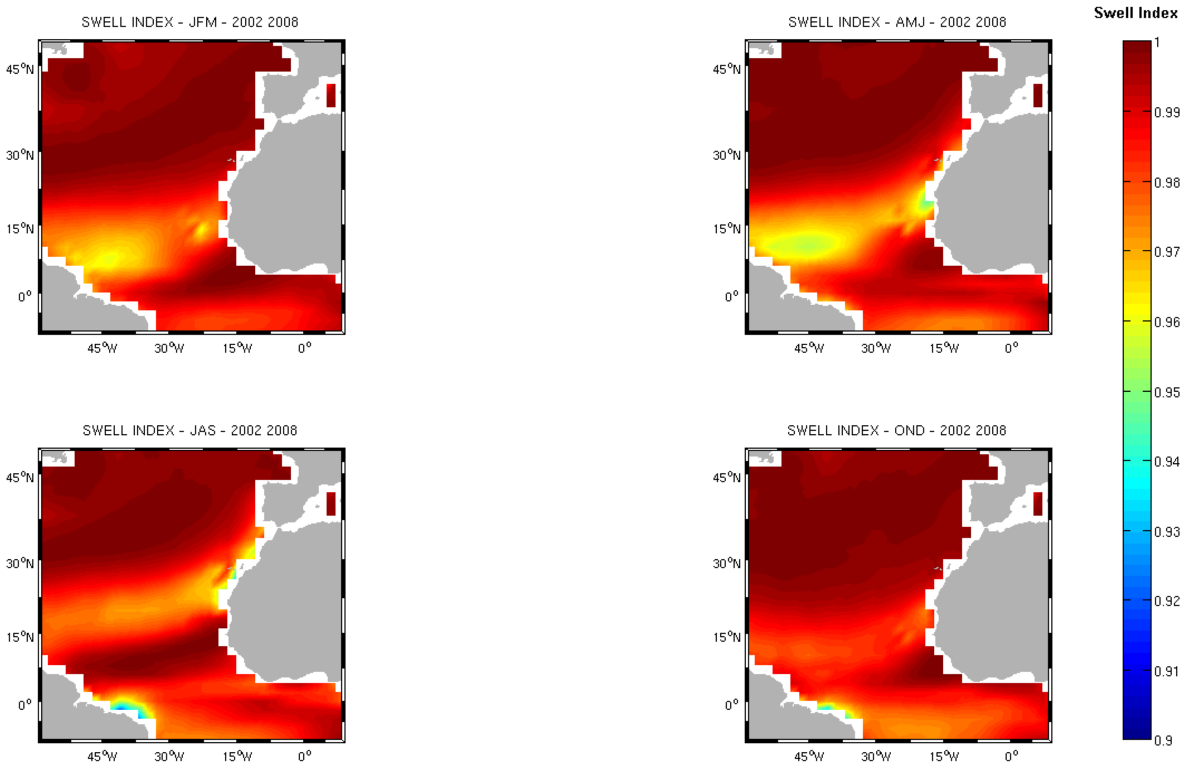


Figure 1. Distributions of swell index for January/ February/ March (JFM); April/ May/ June(AMJ); July/ August/ September (JAS) and October/ November/December (OND).

Figure 1 shows the spatial/seasonal patterns of swell probability as given by equation (3), while the figure 2, gives the patterns of wind sea fields for the North Atlantic. It can be seen that the seasonality of the averaged swell probability is insignificant due to the high levels found in all quarters.

The results are consistent with Chen et al. (2002) that show strong distribution of swell fields for all North Atlantic, with "swell pools" located in areas near the east coast of Africa. In these major swell zones, which we have a swell index with value of more than 97%. Although Chen et al. (2002) showed that in regions of the high winds as this region there is a growing tendency of finding underdeveloped seas for winds greater than 10 $ms^{-1}$ and that for winds greater than 20 $ms^{-1}$ wind waves were almost always not fully developed.

Melo et al. (1995) analyzed the temporal evolution of wave spectrum, identifying weather in the Northern Hemisphere (60 ° N) favor the generation of swell events dispersive arrivals in the Brazilian northeastern coast. In the data analyzed, the authors emphasize that the most energetic events were associated with storms in the vicinity of the Azores Islands. There is, however, a clear relevance to the global wind direction in mid latitude storms where the swell is generated, followed by the turning of swell to follow a Great Circle as it propagates.

Recently, Pianca et al. (2010) showed than the wave climate in the equatorial region of Brazil has its atmospheric system determined by the Intertropical Convergence Zone (ITCZ), giving rise to northeasterly and southeasterly trade winds which converge over this region. During the year, the ITCZ makes its southern migration towards the equator, exerting a significant control of the wind regimes, with its variation being attributed to the seasonal migration of the ITCZ.

The seasonal maps of the wind sea index are presented in Fig. 2. Comparison with Fig. 1 shows that wave growth is generally weak in major swell pools. However, the opposite statement is not always true, that is, there is not necessarily strong wave generation in weak swell zones.

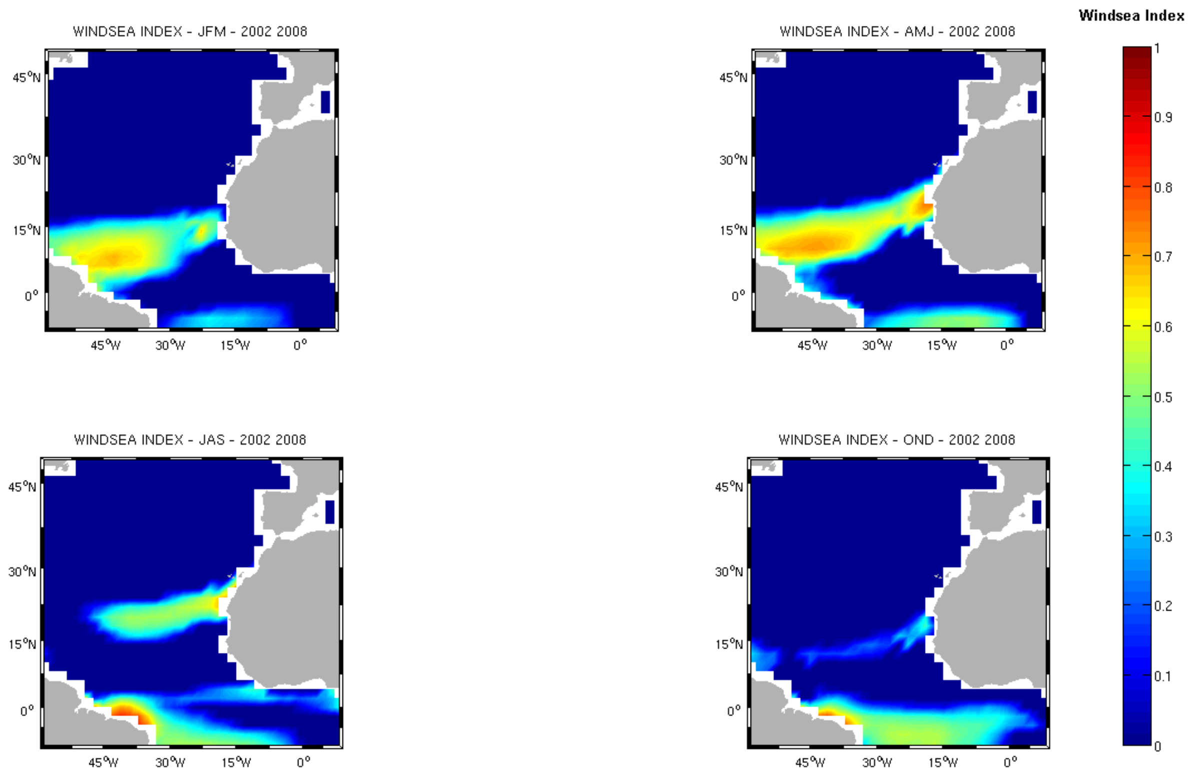


Figure 2. Distributions of windsea index for January/ February/ March (JFM); April/ May/ June(AMJ); July/ August/ September (JAS) and October/ November/December (OND).

The zonal wind sea index is shown together with wind speed intensity in Hovmoller graphics present in Figure 3. These maps reveal important features about the seasonality in our study region. The most striking feature is the bending of the tongue-shaped observed in the wind sea index during NH summer season. This increase in indices for wind sea, is directly proportional to the wind intensity.

In fact, areas of intense wave growth are observed in the the northwest Atlantic during the interval January/February/March and October/November/December. However, it is possible to observe a wide range of growth between latitudes 10° until 20° north, for almost all quarters. Unlike swell, wind wave is directly related to local wind. The extensive northwest gales from the main continents at mid latitudes during the NH winter half of the year are the primary cause of the seasonal wind wave generation in the Northern Hemisphere (Young, 1999).

The seasonal variability of wind sea is found to be rather dramatic in the sense that a summer minimum of its overall intensity is followed immediately by an autumn maximum

(Fig. 3). Is important remember than during the NH winter, wind wave generation remains strong in the Northern Hemisphere.

The seasonal maps of the wind sea and swell index showed (Figures 1 and 2) are of more similarity in general pattern found by Chen et al (2002). Note that the two results are based on satellite data of different years (2002–2008 for ours and 1996–2001 for theirs), comparison of individual features show the great consistency between the results obtained from both studies.

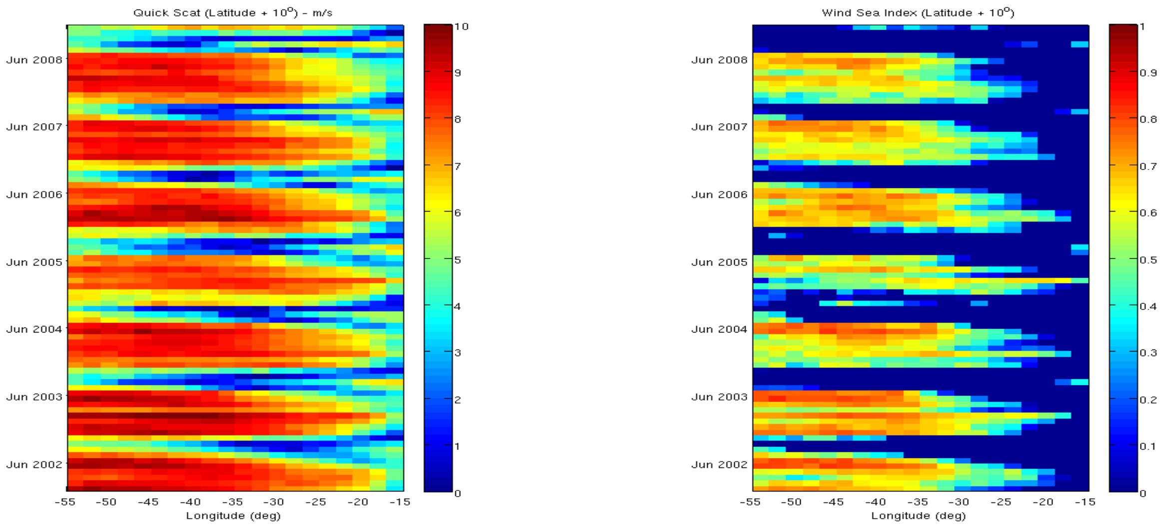


Figure 3. Distributions of wind intensity (QuickScat) and wind sea index for the latitude +10º between 2002 – 2008.

## 4. Conclusions

Knowledge on the structure of swell and wind sea probabilities is very important in a climatological analysis. In this context, our study showed than is possible benefited from the availability of simultaneous multisatellite missions, which provide independent measurements of wind speed and significant wave height with unprecedented accuracy.

Given the reasonable results obtained and their general consistency with field observations and model predictions, the proposed scheme appears to be efficient in characterizing the swell and wind sea climate. Further exploration based on this feasibility study with longer duration of remote sensing collocation dataset will undoubtedly lead to a more realistic and more complete description of the swell and wind sea conditions in the ocean, in particular, their interannual variability on a decadal timescale.

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