AVANCES
EN CIENCIAS E INGENIERÍAS
ARTÍCULO/ARTICLE
SECCIÓN/SECTION C

Observations of directional wave spectra in the Colombian Pacific

Jesús Portilla-Yandún[1]*, Ana Caicedo-Laurido[2] y Roberto Padilla-Hernández[3]

[1]*Universidad San Francisco de Quito (USFQ)*
Av. Diego de Robles y Vía Interoceánica, Quito - Ecuador.

[2]*Dirección General Marítima de Colombia*
Centro de Investigaciones Oceanográficas e Hidrográficas del Pacífico (DIMAR-CCCP).
Vía El Morro, Capitanía de Puerto San Andrés de Tumaco, Nariño, Colombia.

[3]*National Oceanic and Atmospheric Administration*
Environmental Modeling Center (NOAA-EMC-MMAB-IMSG)
NOAA Center for Weather and Climate Prediction 5380 University Research Court,
College Park MD 20740, Maryland, USA.

Autor principal/Corresponding author, e-mail: jportilla@usfq.edu.ec
Editado por/Edited by:
Recibido/Received: 20/09/2013. Aceptado/Accepted: 14/11/2013.
Publicado en línea/Published on Web: 09/12/2013. Impreso/Printed: 09/12/2013.

Abstract

Directional wave spectra in the Colombian Pacific have been observed systematically since 2009 by a network of four buoys owned by the *Dirección General Marítima de Colombia*. The data consist of estimates of the full 2D spectrum in frequency and direction obtained from the network of Triaxys wave sensors. This network is arranged along the Colombian Pacific coast at Tumaco, Gorgona, Buenaventura, and Solano locations. The buoys have been moored near the edge of the continental shelf, corresponding to water depths of about 130m. Complementary, wind data from nearby meteorological stations, and from the ECMWF model are available. In this study, the analysis emphasizes on parameters of the wave spectrum and on the different wave systems composing the local wave climate. From the analyzed data, four wave systems are clearly observed, two of them with Southwesterly origin and two with Northwesterly origin. The pairs of wave systems with similar directions are distinct because of their different typical peak frequencies, two around 0.07Hz and the other two around 0.16Hz. A fifth wave system is apparent from the data at very low frequencies and Southwesterly directions. However, its typical frequencies are near the lower cut-off limit of the instrument so the error associated to this system is difficult to assess. From the overall statistics we can say that typical wind and wave conditions in the region are found to range from low to moderate, with wave heights on the order of 1m, and wind speeds on the order of 3m/s. Specific meteorological and wave events however, may be of considerable magnitude, with wind speeds above the 10m/s, and wave heights above 2m and mean wave periods above the 15s.

Keywords. Colombian Pacific Ocean, Tryaxis buoy, wave spectrum, wave climate.

Resumen

En este estudio se presenta el análisis de datos de oleaje recopilados, en el Pacífico Colombiano, por la Dirección General Marítima de Colombia desde el año 2009 hasta el presente. Estos datos constan de espectros bidimensionales (dirección y frecuencia) del oleaje, registrados por boyas del tipo Triaxys. La red de observación está constituida por cuatro boyas dispuestas a lo largo de la costa Pacífica Colombiana, en las localidades de Tumaco, Gorgona, Buenaventura, y Solano. Las boyas se encuentran ancladas cerca del borde de la plataforma continental, donde la profundidad es de alrededor de 130m. Para el análisis se cuenta además con datos de viento de estaciones meteorológicas cercanas a las boyas, y también datos de viento del modelo del Centro Europeo para el Pronóstico del Tiempo a Corto Plazo (ECMWF, por sus siglas en Inglés). El análisis de los datos de olas se aborda con énfasis en los parámetros del espectro y los diferentes sistemas de oleaje que conforman el clima local del oleaje. Los resultados permiten apreciar claramente cuatro sistemas de oleaje, dos de ellos con procedencias del Sur-occidente y los otros dos procedentes del Nor-occidente. Los pares con direcciones similares se diferencian entre si por sus frecuencias pico, dos de ellos alrededor de 0.07Hz y los otros dos alrededor de 0.16Hz. Se detecta además la presencia de un quinto sistema procedente del Sur-occidente con muy bajas frecuencias. Sin embargo su rango de frecuencia es muy cercano al del límite inferior de registro del instrumento, por esta razón su error asociado podría ser alto. De las estadísticas generales se puede inferir que las condiciones de viento y de oleaje en la zona varían entre bajas y moderadas, con alturas significativas de ola del orden de 1m, y vientos del orden de 3m/s. Sin embargo, algunos eventos específicos pueden superar velocidades del viento de 10m/s, y alturas de ola de más de 2m con periodos promedio sobre los 15s.

Palabras Clave. Océano Pacífico Colombiano, boya Tryaxis, espectro de oleaje, clima de oleaje.

ISSN 1390-5384

Introduction

With the purpose of giving support to several coastal and marine activities in Colombia, the *Dirección General Marítima Nacional* (DIMAR) has implemented a program to monitor atmospheric and oceanic variables. This program, called "*Sistema de Medición de Parámetros Oceanográficos y de Meteorología Marina*" (SMPOMM, [1, 2]), includes both the Pacific Ocean and the Caribbean Sea. The present study however, focuses specifically on wave data collected in the Pacific, namely at the locations Tumaco, Gorgona, Buenaventura, and Solano (see Figure 1, and Table 1). The SMPOMM program is particularly relevant because it constitutes the first systematic wave data collection network in the region. In SMPOMM, waves are observed by means of Triaxys buoys, which are heave-pitch-and-roll type of devices [3, 4], and provide estimates of the distribution of wave energy over the whole frequency-direction spectrum. The network includes a transmission system for the data and foresees near real time services and applications. In the future, the coverage of the measuring network is to be extended to incorporate other Triaxys buoys in the Pacific, and also directional pressure sensors of the type MIDAS DWR for the monitoring of the shallow zone. In addition to the observing system, DIMAR is implementing a wave forecast system [5], which is operated by the *Centro de Investigaciones Oceanográficas e Hidrográficas del Pacífico* (DIMAR-CCCP). The forecast system is based on computations of the state-of-the-art numerical wave model WaveWatchIII [6].

Notwithstanding the detailed information provided by the Triaxys buoys, it should be noted that the analysis and presentation of spectral wave data is relatively complex, in the sense that the variable measured consists of the full wave spectrum. This wave spectrum includes several discrete bins of frequency and direction, namely 129x120 spectral bins, and a wave burst is done every hour. This wealth amount of data, that on the one hand provides us with a thorough description of the wave energy distribution, may become on the other hand overwhelming and difficult to interpret. Those data have to be therefore summarized into fewer parameters that allow the characterization of the wave climate.

To that end, a number of statistical indicators have been used in this study. Particularly, the directional occurrence probability computed for wave height and peak period (H_{m0}, T_p) of spectral partitions, has shown a good ability to depict relevant features. This function is computed as the bivariate probability density function in the domain of the direction and the magnitude of the variable itself (e.g., H_{m0}). This function can be expressed as (Eq. 1):

$$\Pr\left(\theta_1 \leq \Theta \leq \theta_2 | x_1 \leq X \leq x_2\right) = \int_{\theta_1}^{\theta_2} \int_{x_1}^{x_2} f\left(\theta, x\right) d\theta dx \tag{1}$$

where θ represents the direction, *x* the analyzed variable, and $f\left(\theta, x\right)$ is a non-negative distribution function that satisfies the condition:

$$\int_0^{2\pi} \int_{-\infty}^{\infty} f\left(\theta, x\right) d\theta dx = 1 \tag{2}$$

In addition, the mean 1D spectrum evaluated on monthly basis is able to show the seasonal variation of the different wave systems. Furthermore, statistics of typical integral parameters like significant wave height and mean wave period ($H_{m0}, T_{m-1,0}$) provide an overview of the general wave conditions. For the sake of completeness, the definitions of significant wave height, and mean wave period are given in equations 3, 4, and 5. The peak period is defined here in a straightforward manner as the inverse of the frequency at which the maximum energy of the spectrum occurs.

$$E_m = \int_0^{\infty} \int_0^{2\pi} S\left(f, \theta\right) df d\theta \tag{3}$$

$$H_{m0} = 4\sqrt{E_m} \tag{4}$$

$$\left(T_{m-1,0}\right)^{-1} = \frac{E_m}{\int_0^{\infty} S\left(f\right) f^{-1} df} \tag{5}$$

In these equations, $S(f, \theta)$ represents the directional spectrum, $S(f)$ is the frequency (1D) spectrum, and E_m is the total wave variance.

From previous studies in the region, based on data from the ECMWF model [7], four wave systems were expected to show up in the data set analyzed in this study. These four wave systems, sorted according to their relative magnitude, are: a Southwesterly, a Northwesterly, a relative high frequency Southerly, and a Northerly system. However, these wave systems have not been identified from the buoy data. In turn, four wave systems with slightly different characteristics, than those derived from the ECMWF model, were detected. These wave systems, identified from the buoy data, are: two Northwesterly systems with frequencies of 0.07Hz, and 0.16 Hz, and other two Southwesterly systems with the same characteristic frequencies as the Northwesterly systems. There are plausible reasons for this discrepancy. One reason may be the fact that typically the 2D modeled spectra have low variability. Other reason may be the difference in water depth conditions between model and observations. The ECMWF model data correspond to deep water conditions because the model is implemented on a global grid, with relatively low resolution (0.5 geographical degrees), and therefore not intended to resolve shallow water processes [8]. In contrast the buoys are located close to the coast. Although, at 130m depth, the measurements do not actually correspond to shallow water conditions, the longer waves might be affected by the contact with the bottom, and phenomena like shoaling, refraction and bottom friction could be playing a role. The influence of the interaction with the bottom cannot be directly quantified from the available data, but it can be assessed for instance using measurements in deeper and shallower conditions, and also from numerical model results with the proper resolution. Yet another reason for the differences between ECMWF data and the buoy observations may be the low variability of modeled wind fields, due to the low resolution in time and space of the meteorological model.

The outline of this document is as follows: the description of the data (waves and wind), the measuring devices, the wave parameters to be discussed, and the quality control algorithm are briefly summarized in the section *Data description*. Wave data analysis is described in the section *Wave data analysis*. And in the last section we summarize the main findings and conclusions.

Data description

The TRIAXYS wave sensor

The Triaxys wave sensor is a spherical buoy of 1.10m of diameter [3, 4] consisting of three accelerometers disposed orthogonally (in the *x*, *y*, and *z* axes), three rate gyros, and a reference compass. These sensors provide information about the heave, pitch, and roll motions by means of standard Fourier analysis techniques [9, 10]. Since this conventional measuring technique provides restricted information about the directional wave spectrum (i.e., only four Fourier coefficients), the full directional spectrum is estimated using further assumptions. In the case of the Triaxys data, the Maximum Entropy Method, MEM, is used [11]. The buoy stores data in binary format and wave parameters are decoded in post-processing mode using the manufacturer's software in a PC.

Some remarks need to be made regarding the post-processing tasks. a) The first is the removal of very low frequency components. In practice, during data processing, the user has the ability to remove those wave components (*Running Motion* option in the processing software). However, that option is not advised unless one is certain that such low frequency components are not part of the waves that need to be measured. In some cases, indeed, wave observations might be affected by low frequency components that do not actually correspond to wind waves. In other cases however, swells with very low frequencies might occur. In our study area, we do not exclude the existence of low frequency swells because the Colombian Pacific coast is exposed to the vast extensions of the Pacific Ocean. b) The second is related to the current protocol of output files produced by the post-processing software. Apart from the formatted files containing the parameters of interest, a second level of raw data is created. Re-processing that second level of raw data produces wave spectra with different resolution than those spectra produced using the original binary files (typically with half the original resolution in frequency). Re-processing these second level binary files is discouraged to guarantee data homogeneity.

Spectral wave data and wind data

Different spectral data are produced by post-processing: heave motions, horizontal *x*, and *y* motions, four Fourier coefficients, directional spectral data like mean wave directions and directional spreading, the frequency (1D) spectrum, and the frequency-direction (2D) spectrum. The present analysis is focused on these last three sets of data. Specifically, the frequency-direction spectrum is the most relevant source of information for the present analysis. The variable corresponds to the variance density, which is a measure of the wave energy. Integral parameters (e.g., significant wave height and mean wave period) can be obtained from the wave spectrum. The measured spectrum has 129 frequencies, from 0 to 0.64 Hz at regular intervals of 0.005 Hz, and 120 directions, from 0° to 360° also at regular intervals of 3°. The nautical convention is used in this study because this is the most used convention for wave data. This means, 0° corresponds to the geographical North, the angle is measured in the clockwise direction, and the specific directions are flow directions, this is, waves going to the indicated direction. The time span of the measurements goes from 2009 to 2013 (see Table 8). Complementary, wind data is available from nearby meteorological stations. This data consists of wind speed and direction measured at different reference heights.

Quality control

Understanding that errors are ubiquitous in observations, in the present data set, systematic data errors were found to be related mainly to erroneous spectra with typically low values of variance density. These errors can be detected looking at the high frequency spectral bins. Other erroneous records have been detected that behave as outliers. And additionally, although far less frequent, specific spectral bins are seen to have too large values of variance density. So far, the quality control procedure designed to tackle these three aspects has shown good skills to detect most systematic errors. These erroneous spectra have been excluded from the analysis.

The buoy data quality control algorithm is thus designed to detect the following issues:

- Erroneous spectra with too low values of variance density are detected at the high frequency tail of the spectrum. The reference high frequency ranges from 0.4 Hz to 0.64 Hz. Spectra are quality flagged if any spectral bin in that range contains values lower than an empirical threshold value (e.g., 1E-4).
- Outliers are quality flagged if the corresponding wave height exceeds 5m, or if it is lower than 0.1m.
- Finally, if any spectral bin exceeds a threshold value (e.g., 10 m^2/Hz.deg) the spectrum is quality flagged.

Station	Longitude	Latitude	Mooring water depth
Solano Bay	77° 30’ 39.6” W	6° 15’ 28.6” N	130
Buenaventura	77° 43’ 47.71” W	3° 32’ 0.87” N	150
Gorgona island	78° 15’ 57.24” W	2° 58’ 3.41” N	135
Tumaco	78° 52’ 55.11” W	1° 54’ 14.19” N	146
Malpelo island*	81° 34’ 48” W	3° 58’ 30” N	-

* Meteorological station only

Table 1: Monitoring buoy locations

	Start date	End date	N	Mean	Median	Max
Buenaventura	Mar 2009	Mar 2013	179624	2.6	2.0	14.1
Tumaco	Feb 2009	Apr 2013	207815	2.6	2.6	10.8
Malpelo	Jan 2010	Dec 2012	135825	3.5	3.2	19.1

Table 2: Observed Wind statistics, N is the number of data and the values are in m/s.

	Start date	End date	N	Mean	Median	Max
Buenaventura	Jan 1979	Dec 2011	48212	3.48	3.19	15.05
Tumaco	Jan 1979	Dec 2011	48212	3.44	3.36	10.79
Malpelo	Jan 1979	Dec 2011	48212	4.43	4.47	12.14

Table 3: ECMWF model Wind statistics, N is the number of data and the values are in m/s.

Monitoring buoy locations and local bathymetry

The study area, which corresponds to the Colombian Pacific zone, is shown in Figure 1. The mooring locations: Tumaco, Buenaventura, Gorgona, and Solano are indicated with green dots. The mooring coordinates and depth are specified in Table 1. The bathymetry of the area is also given for reference. The bathymetric data corresponds to the Smith and Sandwell database [12].

It is worth to notice the configuration of the oceanic basin, which is characterized by a very narrow continental shelf, whose dimensions are in the order of few tens of kilometers. Beyond this margin, also a narrow slope zone is observed, and directly further, deep ocean conditions are found. The continental border is remarkably narrow in the zone of Solano bay.

Having in mind the bathymetric and geographic conditions, long waves at the measuring locations are expected to represent the transition from deep to intermediate water conditions. It should be noted also that the buoys at Tumaco, Gorgona, and Buenaventura are, to a considerable extent, sheltered from Southwesterly waves due to both the configuration of the continental shelf and the presence of a series of peninsulas in the Southern part of the measuring site. These three sites are therefore expected to be more exposed to Northerly and Northwesterly waves. The opposite case is expected at Solano. The bay is mainly exposed to Southwesterly waves and sheltered from Northwesterly waves. These expectations are also consistent with previous analysis of the data [2].

Wind data analysis

Wind speed and direction have been observed at the locations of Tumaco, Buenaventura, and Malpelo, and could be used complementary for the analysis of the wave conditions, especially in regard to the main wave systems and particularly to the wind sea component. Observed wind data is measured at the heights of 15m in Tumaco, and 10m in Buenaventura, these two meteorological stations are located near the shoreline. In Malpelo, the meteorological station is located inland at a total height of 360m Above Mean Sea Level. The analysis of observed wind data has been complemented with model data from the *European Centre for Medium-Range Weather Forecast* (ECMWF), which has a geographical resolution of 0.75 degrees, and is given at the height of 10 m. In Tables 2 and 3, statistical parameters from these two data sources are shown. In addition, Figures 2, 3, and 4 show other statistical parameters such as the directional occurrence probability, and the non-directional probability for wind speed. It is worth noticing that contrarily to the convention of wave data, the directional convention of the wind data is meteorological, this means that 0° corresponds to the geographical North, directions are measured clockwise, and they indicate winds “coming from” the indicated direction.

From Tables 2, and 3, and Figures 2, 3, and 4, it can be said that wind conditions in the area vary from low to moderate, with a reference wind speed of about 3m/s for the area. The anemometer in Malpelo Island is placed at a higher elevation (360m) than those at the coast, therefore it measures larger magnitudes of wind speed. There is a significant difference between the observed values and those from the ECMWF (about 1m/s higher for the ECMWF), and this is also true for the maximum values, except at Malpelo station, but that could be due to the sensitivity associated to the maximum value as parameter.

From the observed occurrence probability at Tumaco (Figure 2), it is possible to see that the site is affected by three wind regimes. Northwesterly ($\sim$ 3 m/s, 310°),

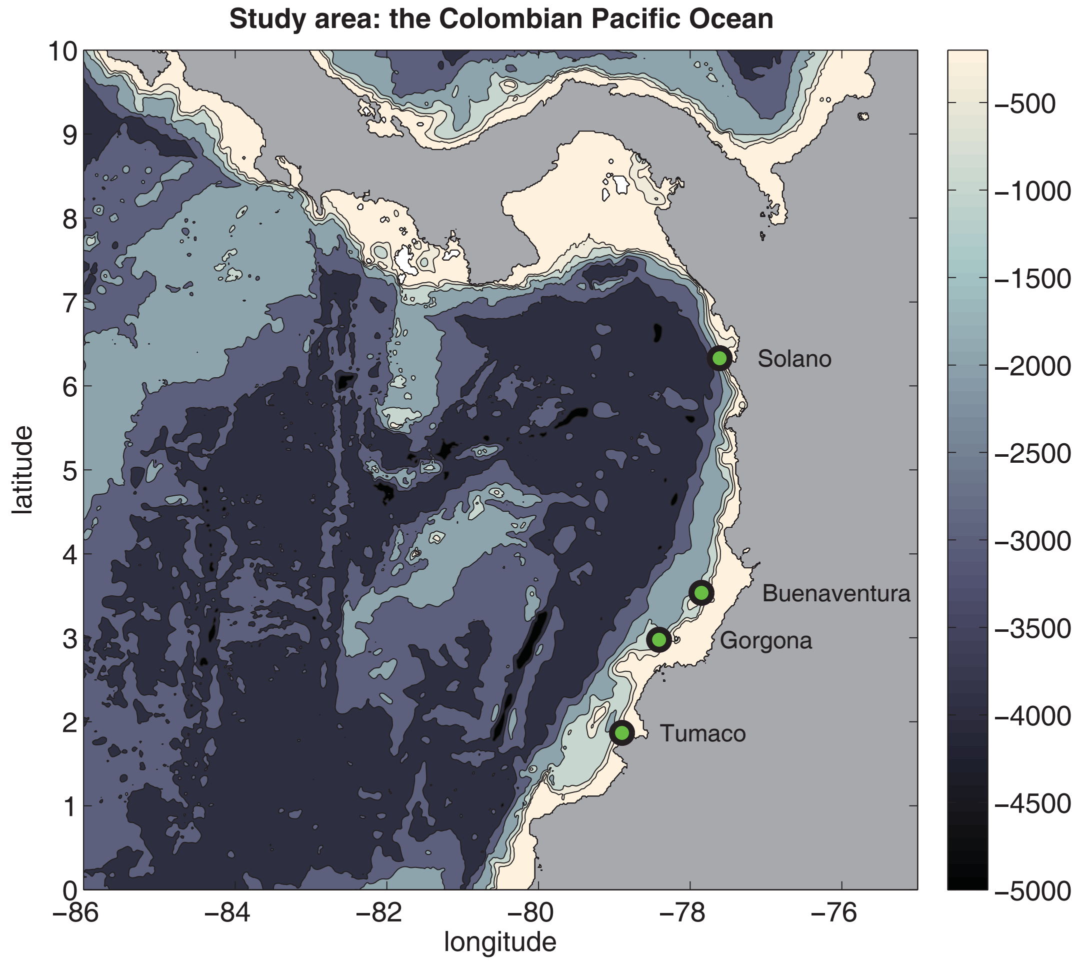

Figure 1: Study area: the Colombian Pacific, and buoy locations. Bathymetric data correspond to Smith and Sandwell (the color scale is given in meters).

Westerly (∼ 2 m/s, 260°), and Southwesterly (∼ 2 m/s, 210°). The ECMWF model data is not consistent with the observations, these data show the dominance of a Southwesterly regime (∼ 4 m/s, 200°) with secondary Westerly and Northwesterly regimes, and the lower occurrence of a Northeasterly regime. The large differences between observed and modeled data at this location deserve specific attention, particularly in regard to the quality of observations.

The occurrence probability at Buenaventura (see Figure 3) shows the existence of three wind regimes, which are considerably different from those at Tumaco. The most significant regime, in terms of magnitude and recurrence, is the Southwesterly, with velocities around 6 m/s and along shore direction (∼220°). This regime is observable in the non-directional probability graph as a hump at the tail of the distribution. The other two wind regimes are of lower magnitude (∼2m/s), the more relevant coming from South and the other from Northeast (along shore). From the ECMWF data, the dominance of the Southwesterly regime is confirmed but with lower magnitudes (about 4 m/s). A possible reason for this large difference in magnitude is the low model resolution. The Northeasterly regime is also noticeable but the Southerly regime is not. In turn, from the ECMWF data it seems that Westerly and Northwesterly winds are also recurrent.

At the station Malpelo (Figure 4), two wind regimes are depicted from the observed data. The most recurrent is a Southwesterly (∼ 4 m/s, 200°). In addition, a Northeasterly regime with large wind magnitudes is detected. Looking at the plot of the actual data points it can be seen that they are regularly aligned over the 30°. It is worth noting that such an alignment is suspicious for observed data. One could be tempted to think that this feature corresponds to a gust system from the Panama isthmus, corresponding to the Central America wind systems like those from Tehuantepec, Papagayo, or Panama [13]. However, Malpelo station is sufficiently offshore for the wind to be that channeled. Therefore, this aspect needs to be regarded more in detail. In the ECMWF data set, such a system is not present. In turn, the pattern is similar to that from the other two stations, with the Southerly as principal system (∼ 6.5

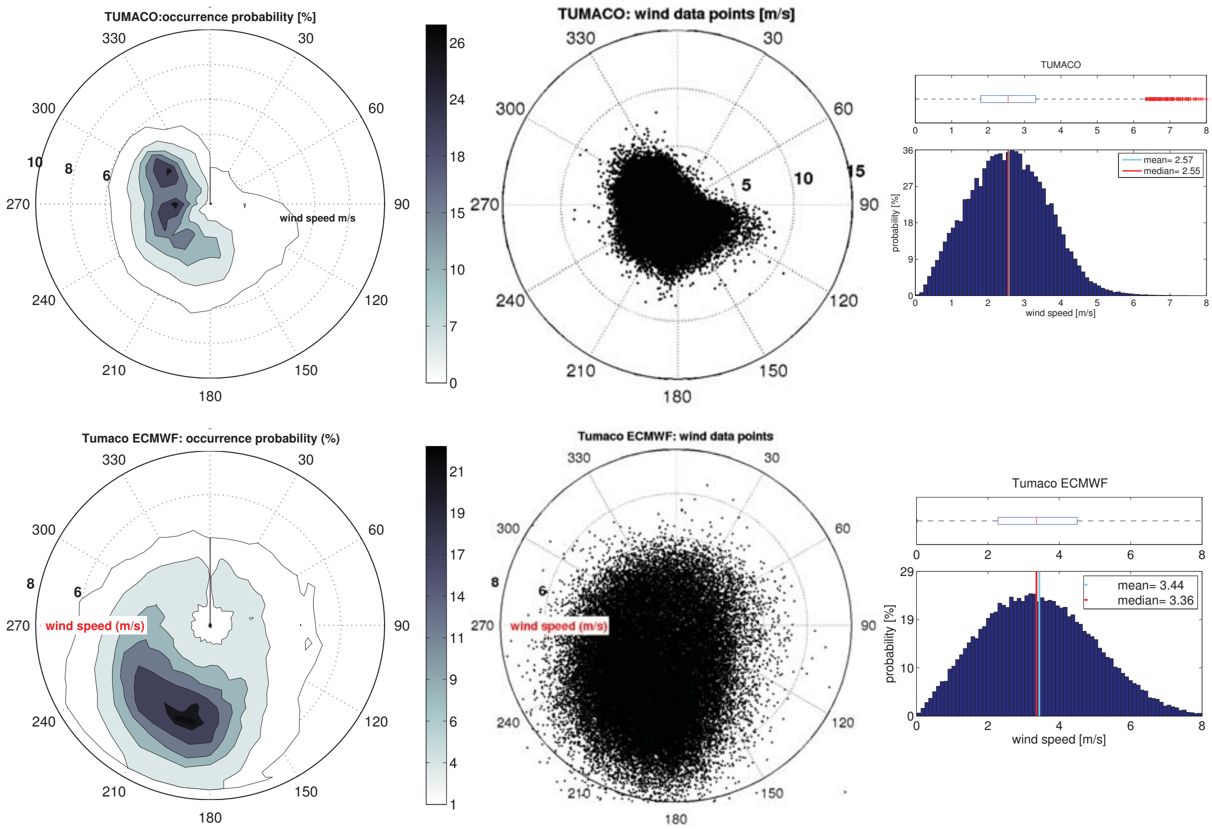

Figure 2: Wind statistics from observed records (upper panels), and from the ECMWF model (lower panels) at Tumaco.

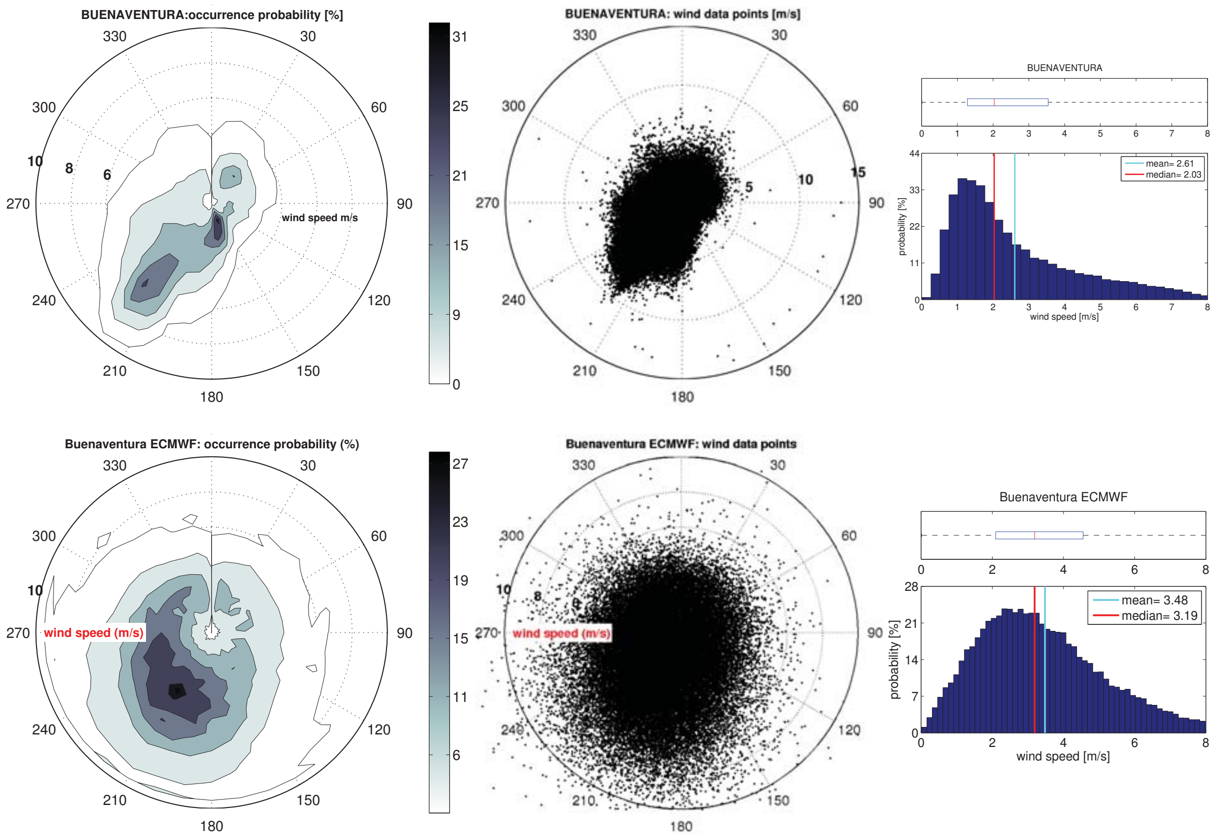

Figure 3: Wind statistics from observed records (upper panels), and from the ECMWF model (lower panels) at Buenaventura.

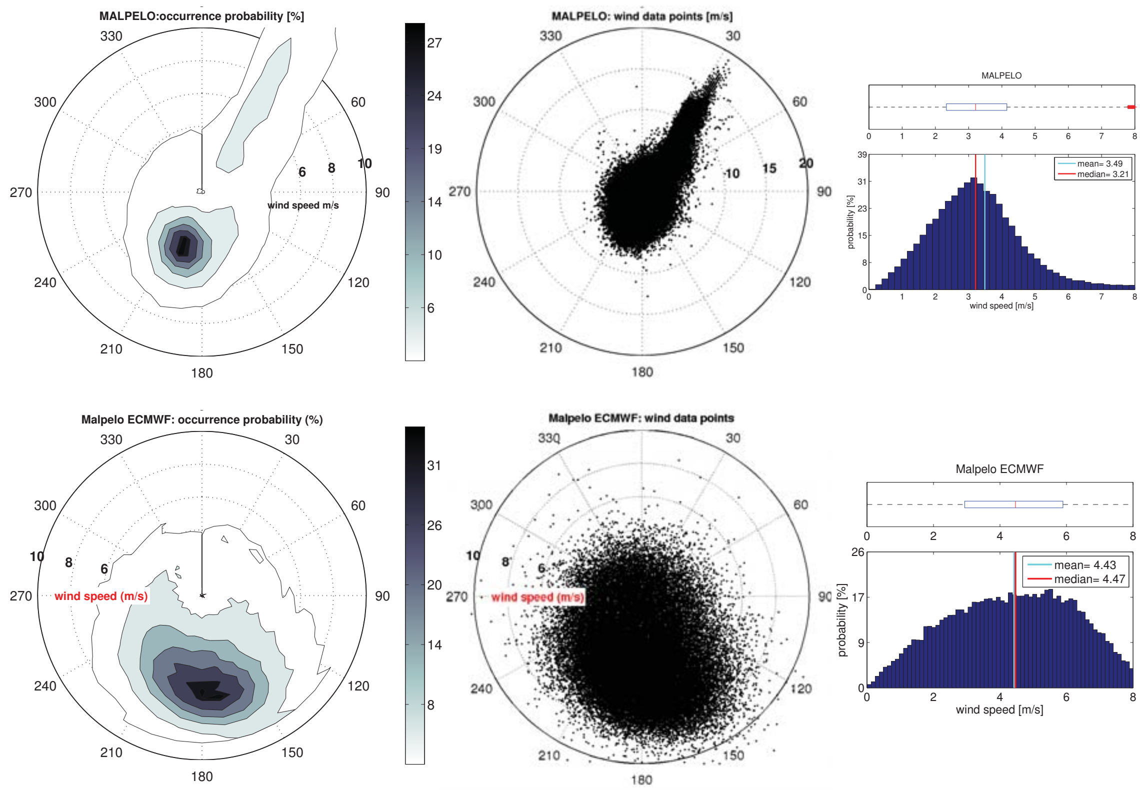

Figure 4: Wind statistics from observed records (upper panels), and from the ECMWF model (lower panels) at Malpelo.

m/s) and minor Westerly regimes.

From the previous analysis it is apparent that seasonal variations might be important in the wind conditions and therefore also for the wave conditions because trade winds in the area switch between Southwesterly and Northeasterly depending on the season [14]. We emphasize that the characterization of the meteorological conditions deserves further analysis. Another aspect that needs attention is the quality control of the wind data because the comparison of wind data among the different stations and also in reference to the ECMWF data shows inconsistent statistical footprints.

Wave data analysis

Spectral statistics of wave partitions

One of the most important aspects of the directional analysis is the possibility to identify wave climate patterns. This can be done for instance evaluating statistics over the whole wave spectrum. In order to do that, overall directional statistics have been obtained on the bases of wave partitions [15]. The procedure in this case is as follows: a) to identify all partitions in the spectrum, b) compute their integral parameters like significant wave height (H_{m0}), and peak period (T_p) and c) compute the statistics of these integral parameters. The indicator that shows a higher ability to depict wave systems is in this case the occurrence probability. In Figures 5, 6, 7, and 8, the results of this analysis are presented for the locations of Tumaco, Gorgona, Buenaventura, and Solano respectively. A remark needs to be made regarding the magnitude of significant wave height (H_{m0}) on those plots. Actually, the magnitude shown in the plots has little physical meaning because they correspond to H_{m0} from individual partitions that have been separated from the spectrum as a whole. In fact, several partitions can, and do occur simultaneously in a single spectrum, so the magnitude of the total wave height can not be assessed from these plots. The valuable information given by those figures is the frequency-directional positions of the wave systems, which allow identifying wave systems in a more precise manner than if we had considered the whole spectrum. This remark does not apply to the peak period. For this variable, the value of the partition is related to the physical value of the wave systems because the peak period is associated to frequency and does not depend on the integration of the spectrum.

Looking at Figure 5, all panels, at the location of Tumaco, two principal wave systems can be clearly identified. The first is a Southwesterly-Westerly system found between 60° and 90°. This is the dominant wave system. The peak period ranges from 3 to 6 seconds, so we can say a-priori that it has wind-sea like characteristics. The second wave system is a Northwesterly-Northerly system, found between 150° and 180° with a peak period range between the 5 and 8s. This wave system is less recurrent than the previous one. Besides these principal systems, other less marked features are observed. In the occurrence probability plot of peak period, Westerly wave systems are observed with large peak periods,

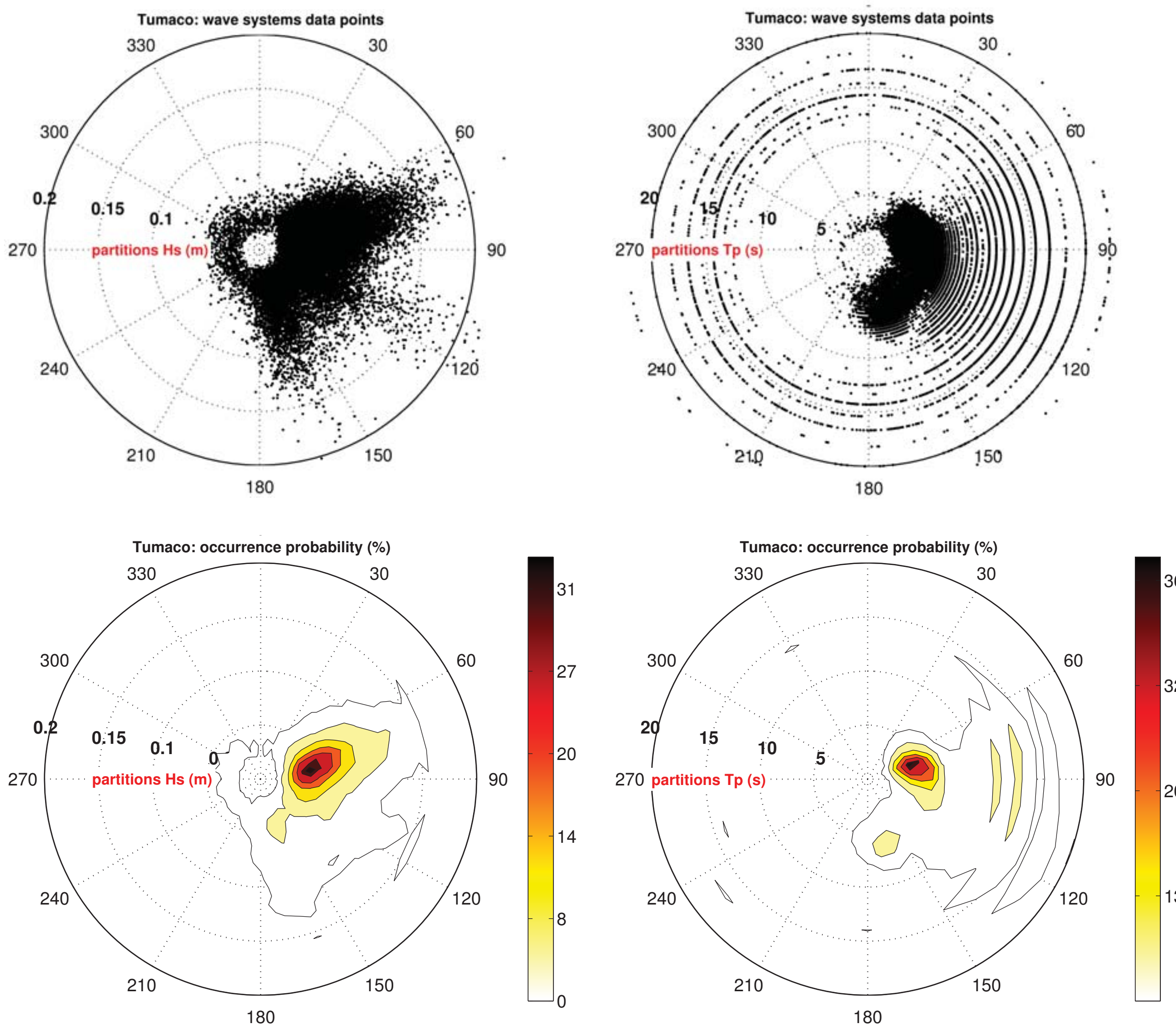

Figure 5: Statistics of H_{m0} (left) and $T_{m-1,0}$ (right) for wave spectral partitions at Tumaco.

ranging from 10 to 17 s. However, these wave systems do not have a corresponding footprint in the wave height plots. It is possible that they have too low energy or they make part of the dispersion seen from the primary wave system. This second hypothesis is supported by the fact that the primary wave system is located closer to the 90° in the H_{m0} plot than in the T_p plot. Other feature corresponds to a Northwesterly system depicted in the H_{m0} plots, especially in the actual data points (left upper panel). It is not clearly shown in the T_p plots but it is apparent around the 5s and 120°. This system seems to be blurred in the occurrence probability plots. Yet another feature is visible, this time probably more related to spurious observations. In the easterly directions from 210° and 360°, and also from 0° to 30°, several data points are found. The direction of the first set of points is offshore, and the peak periods are larger than 10s. Because of these characteristics, they are not physically realistic because these characteristics imply that they have been generated inside the continent, so they may correspond to observation errors. A remark is stated here in the sense that an extra criterion for quality control has to be added to remove these partitions.

At Gorgona station (Figure 6), one primary wave system is found with direction Southwesterly-westerly between 60° and 90° and peak periods between 3 and 7s. A secondary wave system is found in the same range of directions but with larger periods from 10 to 15s. The presence of a third North-westerly wave system is only apparent between 150° and 180° and periods of around the 5s. Similarly to the data at Tumaco, data points in the offshore directions are also found, but they are considered spurious because of the reasons stated previously.

The wave patterns at Buenaventura (Figure 7), correspond well with those from Tumaco. A primary Southwesterly-westerly wave system is depicted in the range of directions from 60° to 90° and wave periods from 3 to 8s. The Northwesterly wave system in the direction 150° and peak periods of about 5s is also clearly visible. In addition, the secondary Southwesterly-westerly wave system with larger periods (from 10 to 17s) is also present. A cloud of points around the 120° is also appar-

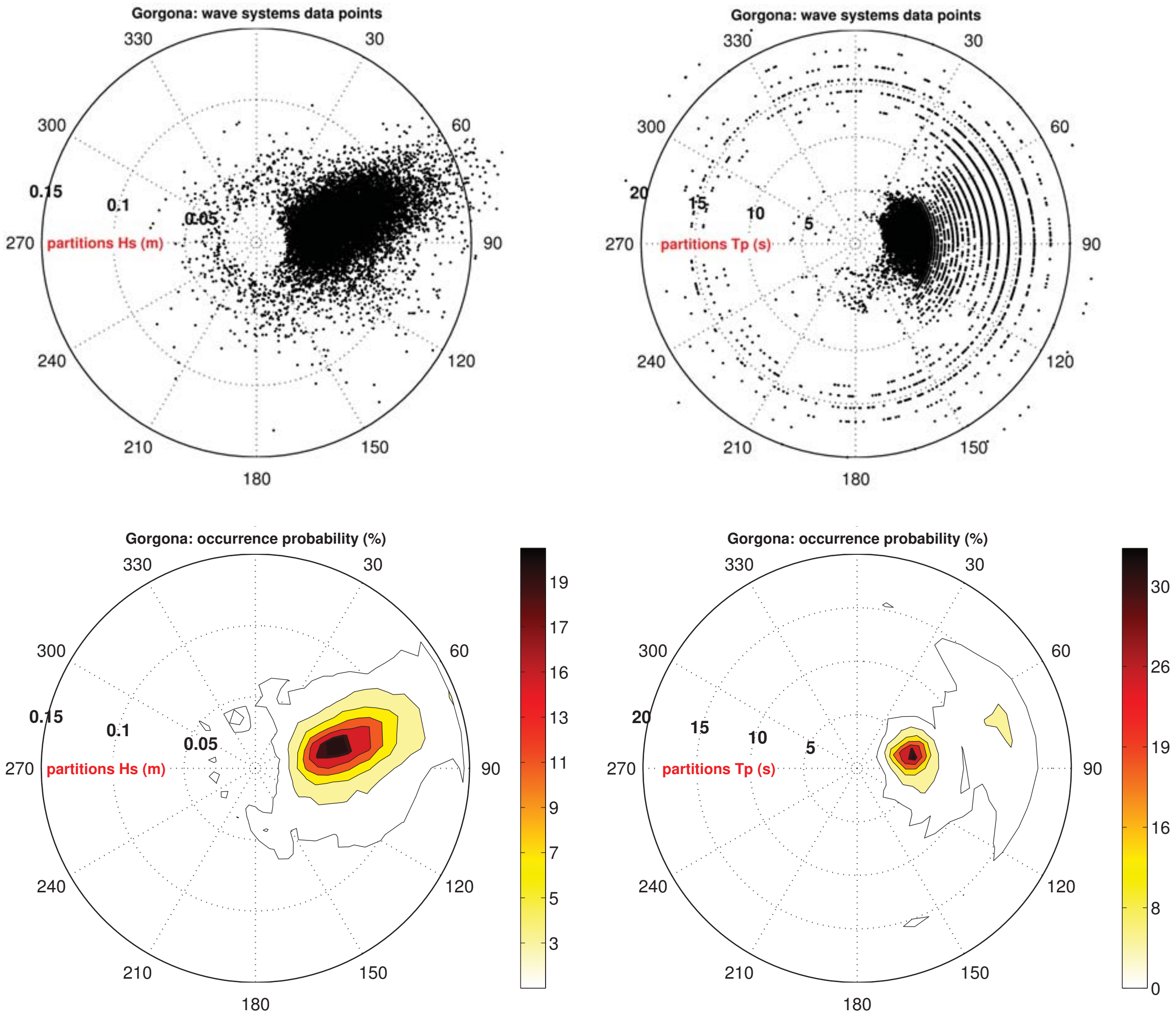

Figure 6: Statistics of H_{m0} (left) and $T_{m-1,0}$ (right) for wave spectral partitions at Gorgona.

ent but not clearly defined. The detection of this wave system requires a more detailed analysis. Spurious partitions in the offshore direction are also present in these measurements.

At Solano station, Figure 8, the amount of measured data points is clearly meager (see Tables 7, and 8). At this station, two main Southwesterly wave systems are visible. The first with peak period around the 5s and direction 60°, and the second with periods ranging from 10 to 17s in the 50° direction. Some few points occur in the Northerly direction (180°), but there is not sufficient data to confirm the presence of a wave system from that direction. In agreement with the geographical information, the Westerly and Northwesterly wave systems seem not to be relevant at this location.

Monthly statistics of the frequency spectrum (1D)

In order to provide an insight of the seasonal variability of the different wave systems monthly statistics of the frequency (1D) spectrum have been evaluated. These are given for both variance density and mean direction in Figures 9, 10, and 11, and 12, for the locations of Tumaco, Gorgona, Buenaventura, and Solano respectively.

Detailed information can be derived from these plots and tables concerning the evolution of the wave systems along the year. In the following, we summarize this information, mainly in association with the information obtained from the directional analysis. In order to synthesize information, we refer to the three main peaks observable in the 1D spectrum, although in specific cases, and also because of the seasonality, a single peak in the 1D spectrum may correspond to different wave systems of the directional spectrum (e.g. Northwesterly and Southwesterly). The range values given below (and in Tables 4, 5, 6, and 7) are mainly referential, because in the different months, each system presents some variability.

The three spectral peaks considered for the monthly analysis refer to all four locations and can be described as follows:

1.- The first spectral peak can be found in the frequency range from 0.06Hz and 0.08Hz, and has typical direc-

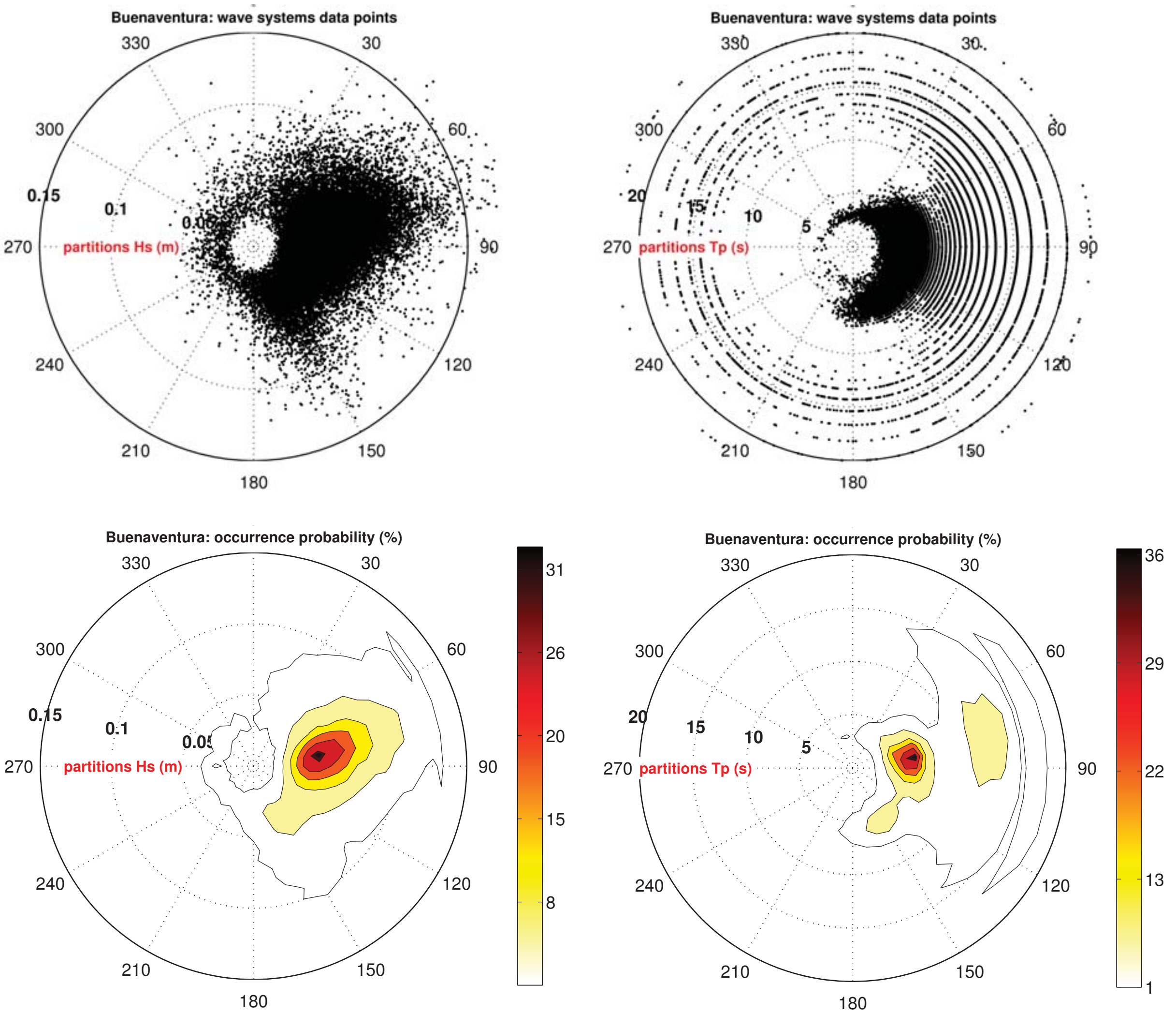

Figure 7: Statistics of H_{m0} (left) and $T_{m-1,0}$ (right) for wave spectral partitions at Buenaventura.

tions from 60° to 110°, thus a sort of Westerly system.

This system has swell characteristics, and has already been depicted in the 2D statistical plots at higher wave periods. In that case with occurrence probability of around 15% (Figures 5, 6, 7, and 8), thus it is not the most recurrent system. Nevertheless, this system can be quite energetic, especially in the months of the Boreal winter. Its directionality switches from Northwesterly in the Boreal winter to Southwesterly in the Austral winter. However, during the Austral winter its magnitudes are significantly lower. This means that Northwesterly and Southwesterly wave components are seen in the 1D spectrum as a single wave system. In addition, due to bathymetric effects, both Northwesterly and Southwesterly might be subject to refraction, with waves turning towards more Westerly directions. This effect makes them less distinct from each other at the observing location. At Solano station, there is data only from the months of June and July, and therefore only Southwesterly components are seen.

2.- The second spectral peak is found in the frequency range from 0.135Hz and 0.185Hz, with directions between 60° and 183°. That is also Westerly direction.

This is one of the dominant wave systems in the area, showing Southwesterly-westerly directions, with also Northwesterly components in the months of the Boreal winters. From the data available, this system is more energetic from May to September with Southwesterly waves. This is the case especially at Gorgona, however, one should bear in mind that the amount of data at that location in those months is limited.

3.- The third spectral peak is placed towards the very low frequencies, around the 0.035Hz, and directions from 35° to 90°, thus a Southwesterly system.

This other feature of the frequency spectrum is challenging to judge, since in some cases it is in the limit of the lower frequency range of the measurements. In the data from Tumaco this feature does not appear, the reason may be that at this station only reprocessed binary (second level) data is available, and this data suggests that the low frequency bins haven removed in the processing of the original binary data. Nevertheless, one is tempted to think that this is a real Southwesterly wave

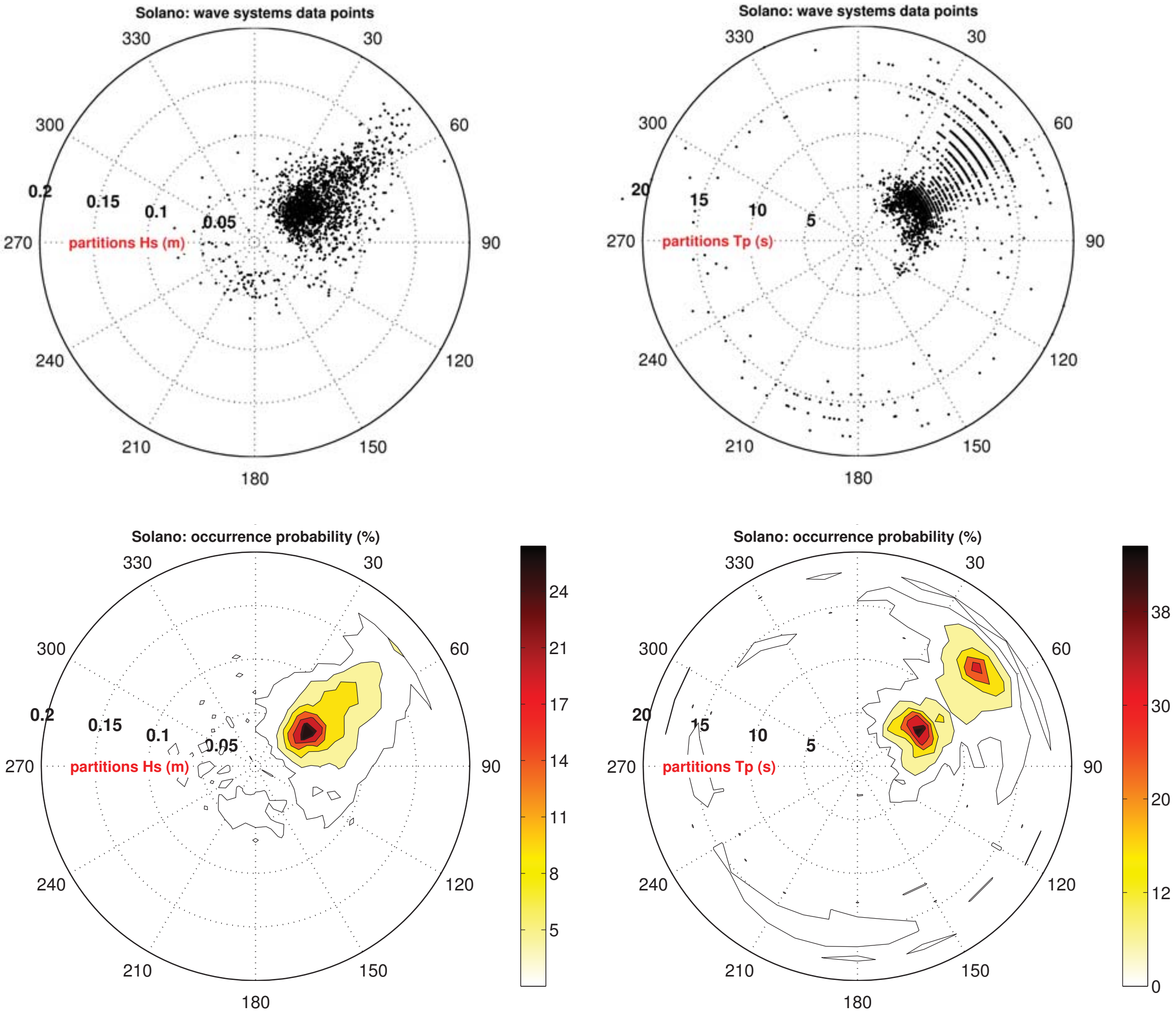

Figure 8: Statistics of H_{m0} (left) and $T_{m-1,0}$ (right) for wave spectral partitions at Solano.

system and if that is the case, this is very relevant for practical applications like navigation, coastal engineering, beach erosion processes, etc. It is recommended therefore to keep that system in the data for further analysis that confirm or rejects its physical existence. On the other hand, as it has been mentioned before, part of the low frequency data might be associated to observation errors and this can be detected with support of the directional information (e.g., offshore waves).

Statistics of overall integral parameters, H_{m0}, and $T_{m-1,0}$

Typically, wave data is provided to users in the form of integral parameters rather than parameters of the frequency-direction spectrum. For this reason in the present study, we provide also statistics of integral parameters. The remark is made however, that integral parameters might represent a whole range of situations from the different wave regimes, as it has been seen in the previous sections. Therefore, they do not allow pointing out details of the wave climate as such. Figures 13, 14, 15, and 16 show the occurrence probability of H_{m0}, and $T_{m-1,0}$. These parameters are summarized in Table 8. From these figures and table, we can say that wave conditions at the study area range from moderate to low, with expected values of wave heights in all locations of around 1m, and maximum values of 2m. The wave height distributions are skewed towards the higher values, indicating the eventual occurrence of extremes. Typical wave periods range from 6 to 10s, with maximum values around 20s, showing also a skewed distribution towards higher values. This is especially the case at Tumaco and Buenaventura, in which the presence of a second population is apparent. From our background knowledge of the wave climate, we know that such second population exists and correspond to the first swell system analyzed in the previous section.

The distribution of wave height data at Tumaco (Figure 13, left panel) resembles very much a normal distribution, slightly skewed at the higher values, so the presence of the four swell systems plus the variable wind sea system is not noticeable. Nevertheless, in spite of not being able to depict the details of the wave climate, a general idea about the overall wave conditions is given

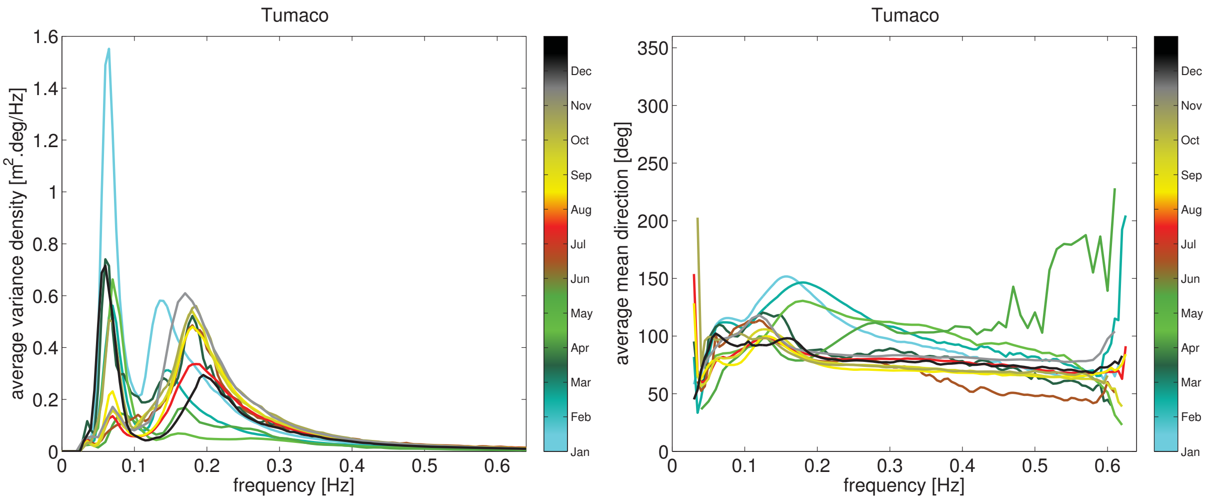

Figure 9: Monthly statistics of the frequency spectrum: variance density (left), and mean direction (right) at Tumaco.

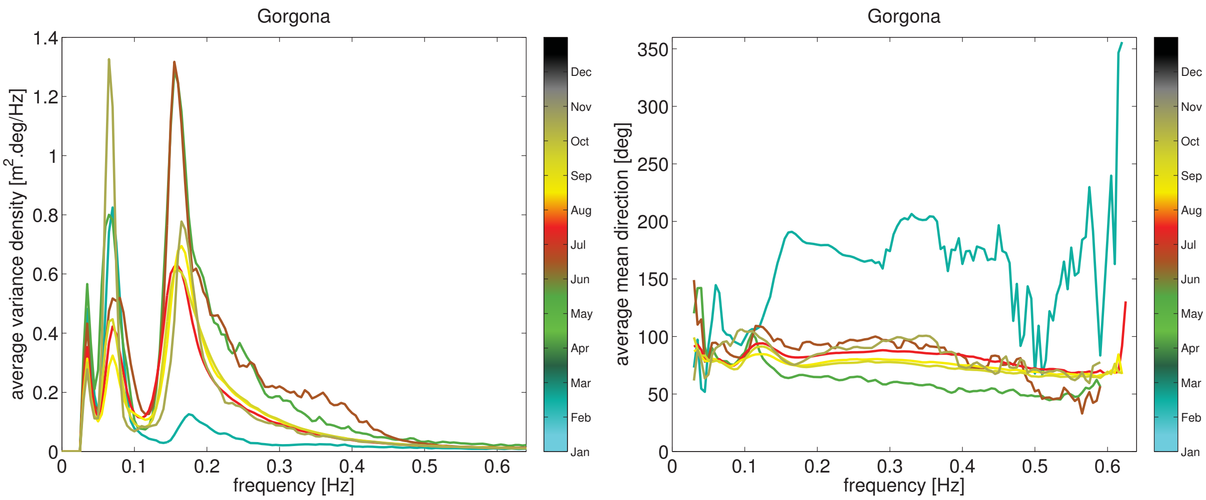

Figure 10: Monthly statistics of the frequency spectrum: variance density (left), and mean direction (right) at Gorgona.

	N	Vadens	Mdir	Fpeak	Vadens	Mdir	Fpeak	Vadens	Mdir	Fpeak
Jan	743	1.55	110	0.065	0.58	142	0.135	0.05	70	0.035
Feb	863	0.56	110	0.07	0.31	134	0.145	0.03	35	0.035
Mar	350	0.74	108	0.06	0.28	117	0.140	0.11	65	0.035
					0.52	88	0.180			
Apr	351	0.66	85	0.07	0.07	125	0.160	-	-	-
May	28	0.15	77	0.08	0.17	79	0.170	0.02	36	0.04
Jun	33	0.10	101	0.08	0.49	84	0.180	0.05	61	0.035
Jul	1169	0.14	82	0.07	0.34	84	0.185	0.04	67	0.035
Aug	1487	0.23	76	0.07	0.48	82	0.180	0.04	65	0.035
Sep	1483	0.15	81	0.07	0.54	84	0.180	0.03	66	0.035
Oct	451	0.51	97	0.065	0.56	79	0.185	0.03	202	0.035
Nov	199	0.17	98	0.07	0.61	90	0.170	0.06	69	0.040
Dec	1342	0.72	102	0.06	0.29	84	0.195	-	-	-

Table 4: Statistical parameters of the different wave components observed in the frequency 1D spectrum at Tumaco. N is the number of spectra, Vadens is the variance density (in m^2/deg/Hz), Mdir is the mean direction (in degrees), Fpeak is the peak wave frequency (in Hz).

by this graph. Typical waves at this station are on the order of 1 m. For mean wave period (Figure 13, right panel), the distribution is heavily skewed to the high values and the presence of high period systems (low frequency) is evident. Typical waves are on the order of 5s, but other systems are present with typical values of around 10s.

At Gorgona (Figure 14) two families of points are apparent both in wave height and wave period. In wave height there is a lower peak around 1m, and the overall

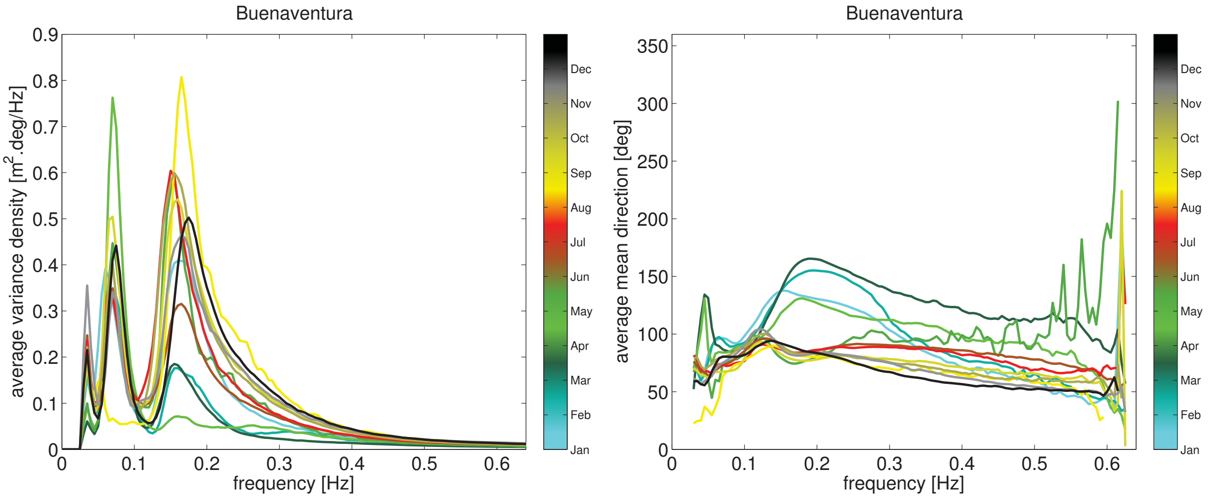

Figure 11: Monthly statistics of the frequency spectrum: variance density (left), and mean direction (right) at Buenaventura.

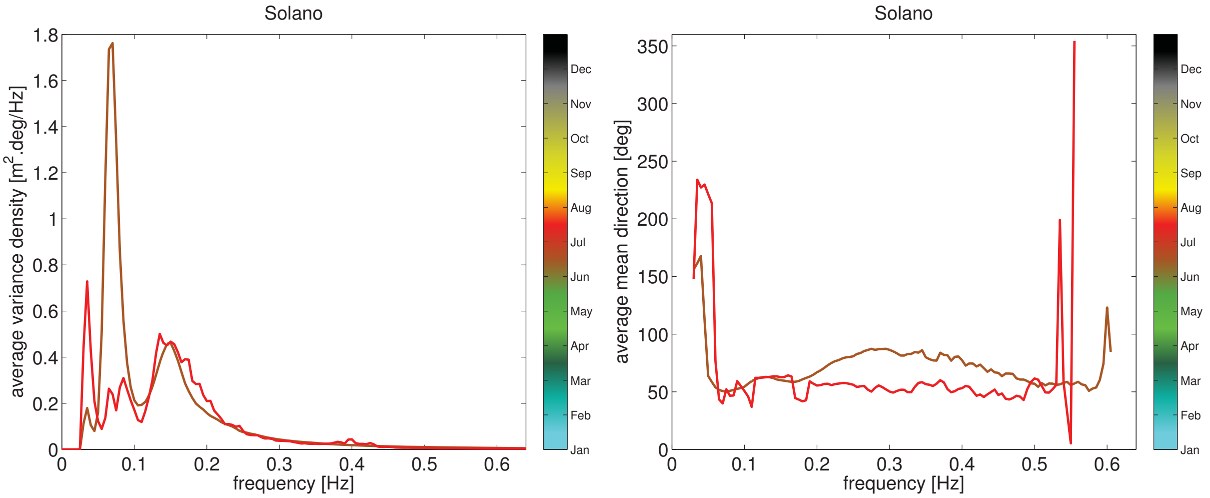

Figure 12: Monthly statistics of the frequency spectrum: variance density (left), and mean direction (right) at Solano.

	N	Vadens	Mdir	Fpeak	Vadens	Mdir	Fpeak	Vadens	Mdir	Fpeak
Jan	-	-	-	-	-	-	-	-	-	-
Feb	37	0.83	105	0.07	0.13	183	0.18	0.48	96	0.035
Mar	-	-	-	-	-	-	-	-	-	-
Apr	-	-	-	-	-	-	-	-	-	-
May	19	0.80	79	0.07	1.30	64	0.16	0.57	142	0.035
Jun	58	0.51	87	0.075	1.35	91	0.16	0.43	111	0.035
Jul	923	0.42	79	0.07	0.62	83	0.16	0.35	93	0.035
Aug	1390	0.32	77	0.07	0.69	76	0.16	0.31	88	0.035
Sep	719	0.45	77	0.07	0.61	78	0.16	0.30	89	0.035
Oct	40	1.32	92	0.065	0.77	77	0.16	0.28	87	0.035
Nov	-	-	-	-	-	-	-	-	-	-
Dec	-	-	-	-	-	-	-	-	-	-

Table 5: Statistical parameters of the different wave components observed in the frequency 1D spectrum at Gorgona. N is the number of spectra, Vadens is the variance density (in m^2/deg/Hz), Mdir is the mean direction (in degrees), Fpeak is the peak wave frequency (in Hz).

peak at around 1.13m. In wave period (Figure 14, right panel), the overall peak is around 7s, and a secondary peak is found at around 8s.

Wave heights at Buenaventura (Figure 15, left panel) show a more marked skewed distribution towards the high values than at Tumaco, for this reason the mean and median values do not match with the peak of the distribution. The typical values are around 0.8m to 0.9m. The mean period distribution (Figure 15, right panel) shows a similar shape than that of H_{m0}, skewed to the higher values. Differently than the distribution at Tumaco, the presence of high period waves is not depicted in these

	N	Vadens	Mdir	Fpeak	Vadens	Mdir	Fpeak	Vadens	Mdir	Fpeak
Jan	744	0.39	94	0.06	0.41	137	0.16	0.15	60	0.035
Feb	245	0.33	95	0.07	0.17	145	0.16	0.17	67	0.035
Mar	734	0.43	86	0.07	0.19	151	0.16	0.06	87	0.035
Apr	350	0.76	84	0.07	0.07	124	0.16	0.09	85	0.035
May	39	0.45	73	0.07	0.59	76	0.16	0.10	75	0.035
Jun	1440	0.35	73	0.07	0.31	85	0.165	0.24	72	0.035
Jul	1196	0.36	74	0.065	0.60	87	0.15	0.23	77	0.035
Aug	79	0.15	34	0.05	0.80	83	0.165	0.21	25	0.035
Sep	718	0.50	67	0.07	0.54	79	0.16	0.18	67	0.035
Oct	743	0.40	80	0.07	0.60	88	0.155	0.22	79	0.035
Nov	720	0.34	75	0.07	0.46	82	0.165	0.35	60	0.035
Dec	744	0.44	80	0.075	0.50	87	0.175	0.21	60	0.035

Table 6: Statistical parameters of the different wave components observed in the frequency 1D spectrum at Buenaventura. N is the number of spectra, Vadens is the variance density (in m^2/deg/Hz), Mdir is the mean direction (in degrees), Fpeak is the peak wave frequency (in Hz).

	N	Vadens	Mdir	Fpeak	Vadens	Mdir	Fpeak	Vadens	Mdir	Fpeak
Jan	-	-	-	-	-	-	-	-	-	-
Feb	-	-	-	-	-	-	-	-	-	-
Mar	-	-	-	-	-	-	-	-	-	-
Apr	-	-	-	-	-	-	-	-	-	-
May	-	-	-	-	-	-	-	-	-	-
Jun	449	1.75	50	0.07	0.46	60	0.15	0.18	160	0.035
Jul	22	0.31	47	0.085	0.5	63	0.135	0.73	234	0.035
Aug	-	-	-	-	-	-	-	-	-	-
Sep	-	-	-	-	-	-	-	-	-	-
Oct	-	-	-	-	-	-	-	-	-	-
Nov	-	-	-	-	-	-	-	-	-	-
Dec	-	-	-	-	-	-	-	-	-	-

Table 7: Statistical parameters for the different wave components observed in the frequency 1D spectrum at the location Solano. N is the number of spectra, Vadens is the variance density (in m^2/deg/Hz), Mdir is the mean direction (in degrees), Fpeak is the peak wave frequency (in Hz).

	Start date	End date	N	Mean $\mathbf{H_{m0}}$	Median $\mathbf{H_{m0}}$	Max $\mathbf{H_{m0}}$	Mean $\mathbf{T_{m-1,0}}$	Median $\mathbf{T_{m-1,0}}$	Max $\mathbf{T_{m-1,0}}$
Tumaco	Dec 2009	Dec 2012	8453	1.01	1.00	2.19	6.86	6.14	17.79
Gorgona	May 2011	Oct 2012	3186	1.13	1.12	2.27	7.76	7.53	21.46
Buenaventura	May 2011	Feb 2013	7753	0.96	0.92	2.18	8.21	7.83	17.23
Solano	Jun 2011	Jul 2011	471	1.17	1.15	1.91	10.61	10.77	24.45

Table 8: Observed Wave Integral Parameters statistics, N is the number of records, H_{m0} is the significant wave height (in meters), $T_{m-1,0}$ is the mean wave period (in seconds).

plots.
At Solano station (Figure 16) the amount of information available is lower and also corresponding only to a couple of months of the year (June and July). From those data, it is seen that typical wave height are on the order of 1.16m. The man period is around 10.7s, but the distribution of the data is relatively irregular to assess this value precisely. In any case, a general idea of the wave conditions is depicted, but we should bear in mind that the conditions represent only those specific months for which data is available.

Summary and conclusions

In the present study, directional wave spectra collected over the past four years by the *Dirección General Marítima de Colombia* are analyzed. The purpose is to obtain a quantitative picture of the wave climate in the study area: the Colombian Pacific. The data consists of spectral wave data measured with Triaxys buoys at four locations along the Colombian coast, Tumaco, Gorgona, Buenaventura, and Solano. The buoys have been moored at water depths of about 130m, corresponding to about 7 to 40km offshore. The mooring positions are on the limits of the continental shelf, which is remarkably narrow in the region. Therefore, measured wave conditions correspond to the transition between deep to shallow waters, and the effects of the interaction with the bottom, like refraction and shoaling, are apparent from the data.

The methodology for wave data analysis has been designed in such a way as to extract the most possible information from the spectral observations. It is important to note that the choice of the statistical parameters to describe the spectra, and also the analysis method

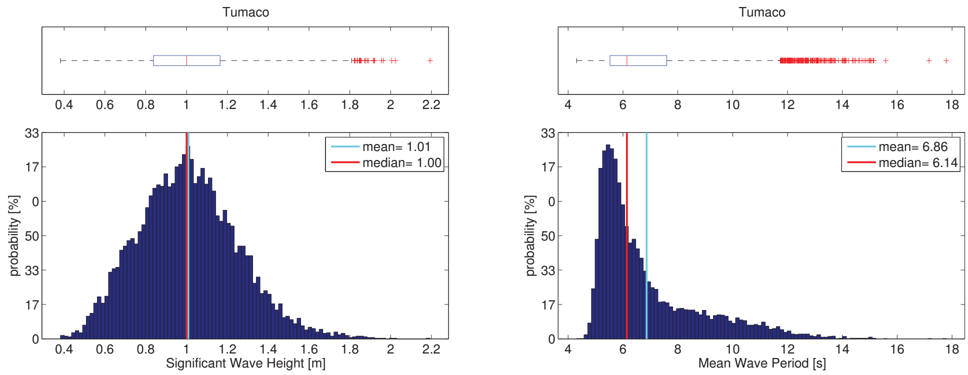

Figure 13: Statistics of integral parameters over the whole spectrum, H_{m0} (left) and $T_{m-1,0}$ (right) at Tumaco.

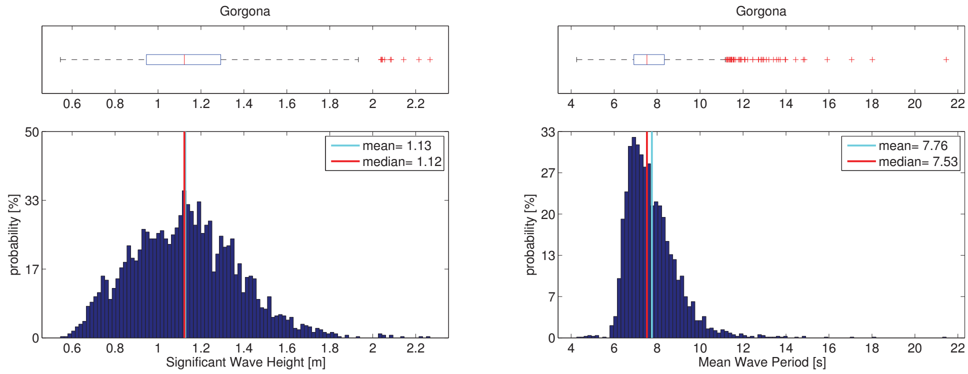

Figure 14: Statistics of integral parameters over the whole spectrum, H_{m0} (left) and $T_{m-1,0}$ (right) at Gorgona.

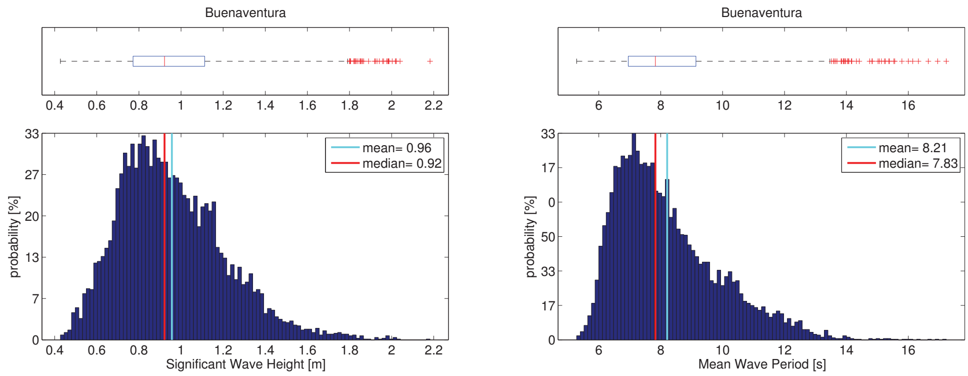

Figure 15: Statistics of integral parameters over the whole spectrum, H_{m0} (left) and $T_{m-1,0}$ (right) at Buenaventura.

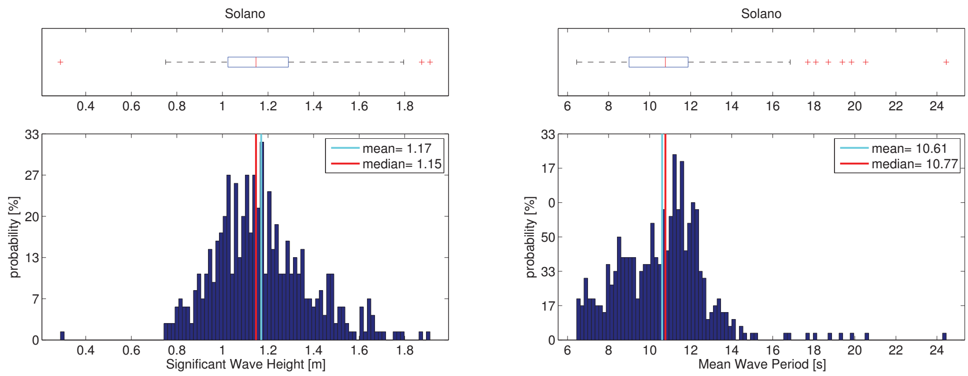

Figure 16: Statistics of integral parameters over the whole spectrum, H_{m0} (left) and $T_{m-1,0}$ (right) at Solano.

are important to depict the wave systems. Some parameters (e.g. the mean over the whole spectrum, not shown) tend to show all these wave systems as a single Westerly wave system, which is physically inconsistent with the meteorological conditions of the area [16]. For this reason, we analyze the spectral data from different points of view. That is, using directional statistics of wave partitions (section 3.1), looking at the seasonal trends of the frequency-direction spectrum (section 3.2), and also from statistics of the integral parameters (section 3.3). The use of spectral partitioning techniques has been useful to detect directional features of the wave climate. These have been verified by means of the seasonal analysis on the 1D spectral data. The integral parameters on the other hand provided an idea of the overall wave conditions in the region. A brief analysis of the available wind data, indicates that wind-sea systems are in general low and might only be important in eventual conditions.

From the available data, four wave regimes are clearly identified: two from Southwesterly origin and two from Northwesterly origin. The pairs of systems with similar directions differ in their characteristic wave periods. One is found at lower frequencies (around 0.07Hz) and the other at higher frequencies (around 0.16Hz). Their directions range over the first and four Cartesian quadrants. In addition, these four wave systems vary significantly in magnitude over the different seasons. The higher frequency systems might be influenced by wind, but it is also possible that those systems are generated rather remotely over a long fetch and are present in the area as mature wind-seas. The wind influence on those systems cannot be assessed precisely due to quality issues in the wind data.

Other marginal wave systems are also detectable. The most notable probably is a wave system found at very low frequencies, with mainly Southwesterly directions. However, it is difficult to say whether that system is real or spurious since it is close to the frequency limits of the instrument. That swell system might have important implications for practical applications because of its large wave periods. In this context, it is important to note that the processing software gives the option to remove low frequency components. The removal of those low frequency bins has to be avoided until a dedicated analysis is made to determine whether those features are real or spurious. Other wave systems with offshore directions and very low frequencies are considered spurious and should be removed from the series for further analysis.

Integral parameters show that the dominant wave conditions range from low to moderate, with typical wave heights and peak periods on the order of 1m and 8s, respectively. Wind conditions are in general low in the order of 3m/s, with specific events that can reach moderate values of up to 15m/s.

Acknowledgments

The data subject of the present study have been collected and delivered in the framework of the project *Sistema de Medición de Parámetros Oceanográficos y de Meteorología Marina* (SMPOMM). The modelled wind data have been kindly provided by the *European Centre for Medium-Range Weather Forecast* (ECMWF). We gratefully acknowledge the *Dirección General Marítima de Colombia*, and the *Centro de Investigaciones Oceanográficas e Hidrográficas del Pacífico* (DIMAR-CCCP), specially to its director, Captain José Manuel Plazas Moreno, for all the institutional, technical, and logistic support provided for the development of this study, which has been funded in the framework of the project *Implementación operacional del sistema de modelamiento hidrodinámico y de oleaje para la Cuenca Pacífica Colombiana*. We also express our gratitude to our colleagues from the operational oceanography department at DIMAR-CCCP, especially to Javier Enrique Gomez Torres, Jesús Peñaranda and Ricardo Romero for their help with data processing and analysis, and also to Sadid Latandret for his collaboration in related works. We specially acknowledge the support of *Universidad San Francisco de Quito* (USFQ), its *Chancellor Grants* initiative, and particularly the selfless support from César Zambrano. The contributions of Jeison Sosa in related works and also the editorial work of Javier Torres for the preparation of the manuscrip are highly appreciated. We are also much indebted to *Universidad Tecnológica de Bolívar* (Cartagena) for all the institutional and administrative support.

References

[1] Centro de Investigaciones Oceanográficas e Hidrográficas del Caribe. 2013. “Sistema de Medición de Parámetros Oceanográficos y de Meteorología Marina (SMPOM)”. *http://www.cioh.org.co/index.php/noticias-mainmenu2-677/18-oceanografoperacional/519-sistema-de-medicie-partros-oceanogrcos-y-de-meteorologmarina-smpom*.

[2] Gómez, J.; Guerrero, D.; Latandret, S.; Peñaranda, J.; Martínez, C.; Romero, R.; Guzmán, M. 2011. “Comportamiento del oleaje en la franja marítima Pacífico-colombiana (Tumaco, Isla Gorgona, Buenaventura y Bahía Solano) durante el período dic2011 - nov2012 a partir de datos de las boyas de oleaje direccional TRIAXYS”. *Centro de Investigaciones Oceanográficas e Hidrográficas del Pacífico*.

[3] Shih, H. 2003. “Triaxys Directional Wave Buoy for Nearshore Wave Measurements - Test and Evaluation Plan”. *NOAA Technical Report NOS CO-OPS 38 Silver Spring, Maryland. http://tidesandcurrents.noaa.gov/publications/techrpt38.pdf*.

[4] Skey, S.; Miles, M. 1999. “Advances in buoy technology for wind/wave data collection and analysis”. *OCEANS ’99 MTS/IEEE, Riding the Crest into the 21st Century. http://ieeexplore.ieee.org/xpl/freeabs_all.jsp?arnumber=*

799716&abstractAccess=no&userType=inst, 1:113 – 118.

[5] Caicedo-Laurido, A.; Portilla, J.; Latandret, S. 2013. "Predicción Operacional de Oleaje en el Pacífico Colombiano". *Boletín del Centro de Investigaciones Oceanográficas e Hidrográficas de la Dirección General Marítima (in press)*.

[6] Tolman, H. 2009. "User manual and system documentation of WAVEWATCH-III version 3.14. NOAA / NWS / NCEP / MMAB". *Technical Note 276. http://polart.ncep.noaa.gov/mmab/papers/tn276/MMAB _276.pdf*: 194.

[7] Portilla, J. 2012. "Storm-Source-Locating Algorithm Based on the Dispersive Nature of Ocean Swells". *Avances-USFQ. http://www.usfq.edu.ec/Publicaciones/Avances/C22-4-1-2012*, 4(1):C22 – C36.

[8] Simmons, A.; Uppala, S.; Dee, D.; Kobayashi, S. 2006. "ERA-Interim: new ECMWF reanalysis products from 1989 onwards". *ECMWF Newsletter. http://www.ecmwf.int/publications/newsletters/pdf/110 _rev.pdf*, (110).

[9] Kuik, A.; van Vledder, J.; Holthuijsen, L. 1988. "A method for the routine analysis of pitch-and-roll buoy wave data". *J. Phys. Oceanogr. http://journals.ametsoc.org/doi/pdf/10.1175/1520-0485%281988%29018%3C1020%3AAMFTRA%3E2.0.CO%3B2*, 18:1020 – 1034.

[10] Benoit, M.; Frigaard, P.; Schaffer, H. 1997. "Analysing multidirectional wave spectra: A tentative classification of available methods". *Proc. Int. Association of Hydraulic Engineering and Research: Multidirectional Waves and Their Interaction with Structures, San Francisco, CA, National Research Council of Canada*: 131 – 157.

[11] Nwogu, O. 1989. "Maximum entropy estimation of directional wave spectra from an array of wave probes". *Applied Ocean Research. http://axystechnologies.com/Portals/0/Services/Technical %20Papers/techp_nwogu.pdf*, 11:176 – 182.

[12] Smith, W.; Sandwell, D. 1997. "Global Seafloor Topography from Satellite Altimetry and Ship Depth Soundings". *Science. http://www.sciencemag.org/content/vol277/issue5334/*, 227:1956 – 1962.

[13] Schultz, D.; Bracken, E.; Bosart, L. 1998. "Planetary- and Synoptic-Scale Signatures Associated with Central American Cold". *Monthly Weather Review, American Meteorological Society. http://www.cimms.ou.edu/schultz/pubs/schultzetal98. PDF*, V126:5 – 27.

[14] Holton, J. 2004. "An Introduction to Dynamic Meteorology". *Fourth Edition, International Geophysics Series, ISSN 0074-6142, Academic Press*: 535.

[15] Portilla, J.; Ocampo-Torres, F.; Monbaliu, J. 2009. "Spectral partitioning and identification of wind-sea and swell". *J. Atmos. Oceanic Technol. http://journals.ametsoc.org/doi/abs/10.1175/ 2008JTECHO609.1*, 29:107 – 122.

[16] Alves, H. 2006. "Numerical modeling of ocean swell contributions to the global wind-wave climate". *Ocean Modelling*, 11:98 – 122.