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INSTRUMENTAL CONFIRMATION OF THE ARRIVAL OF NORTH ATLANTIC SWELL TO THE CEARA COAST

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ABSTRACT

Measured wave data at Ponta de Mucuripe, Ceará was used to confirm the arrival of north Atlantic swell to the Ceará coast. By analyzing Spectra evolution in time using the Ridge Line Method we were able to identify and locate atmospheric conditions that seemed favorable for swell generation in seven swell events that displayed dispersive arrival characteristics.

1. INTRODUCTION

Ocean waves are known to be the main source of energy for coastal processes and are also of paramount importance for the design of practically all coastal works. Therefore, a sound knowledge of the wave climate of any given region is a matter of major importance for coastal and ocean engineering practice. This work presents new results about an important aspect of the wave climate of the Ceará coast (northern Brazil): the arrival of North Atlantic Swell.

2. CLIMATIC CHARACTERISTICS OF THE CEARÁ COAST

Due to its orientation (approximately NW-SE) and geographical situation (just south of the equator, at about 4° S), the Ceará coast possesses some quite interesting characteristics (Melo, 1993). For example, the wind at Ceará is incredibly persistent, blowing practically all year round from the E quadrant (Trade Winds). Curiously, as opposed to other regions at similar latitudes (in the Indian Ocean, for ex.), monsoon-like reversals of the prevailing wind direction during part of the year do not occur at Ceará. Furthermore, the remarkable absence of hurricanes and tropical storms (typhoons) in the equatorial South Atlantic (due, it is believed, to its relatively cool waters) sets the

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area free from this type of natural disaster. As a result, the wave climate at Ceará and along all the northern Brazilian coast is dominated by short period locally generated sea waves from the E quadrant.

Because of the action of such steady winds and waves from the E, the coast at Ceará undergoes an intense westward sand transport. In fact, there have been several reports of coastal villages that have been slowly invaded by westward migrating sand dunes. In addition, coastal works in the area have to deal with a heavy westward littoral drift of sediments (Bandeira, Araújo & Valle, 1990).

3. EVIDENCE OF NORTH ATLANTIC SWELL

Nevertheless, observations performed in the area indicate an interesting phenomenon taking place at Ceará from December to March. During this time of the year, long period (up to 20 sec.), swell-type waves coming from a more northerly direction are frequently observed. Melo (1993) pointed out that these waves might have as source distant, extra-tropical storms in the North Atlantic.

In a later work, Melo & Alves (1993) presented evidences in support of this hypothesis by analyzing a couple of major swell events that occurred in Ceará during the month of January of 1992. Based on *visual* observations taken by a member of the "Sea Sentinels Project" - a wave watch group organized by the senior author (Melo, 1993) - Melo & Alves (1993) found that these swells had been generated by a couple of major storms near the Azores Islands (40°N), over 4000 km away from the Ceará coast.

As it was later discovered, these same (visually) observed swell events were also measured by Instituto de Pesquisas Hidroviárias - INPH which kindly made the records available to us. Therefore, the present paper complements the previous works by presenting results based on *instrumental* wave measurements that confirm the arrival to the Ceará coast of Northern Hemisphere swell.

4. DISPERSIVE ARRIVAL

The mathematical solution for the problem of small amplitude surface gravity waves is well known (see, for ex., Dean & Dalrymple, 1984). One of the main results of this theory is the establishment of the so called *dispersion relation* which relates the period (T) to the length (L) of a given (periodic) wave train. For waves propagating in deep water (the case of interest for us) the dispersion relation reads:

$$\sigma^2 = g \cdot k \qquad (1)$$

where $\sigma = 2\pi/T$ and $k = 2\pi/L$ are the wave radian frequency and wave number, respectively.

Eqn. (1) allows the evaluation of the velocities of crest propagation (C = phase velocity) and of energy propagation (Cg = group velocity) which are:

$$C = \frac{\sigma}{k} = [\frac{g}{k}]^{1/2} \qquad (2)$$

and

$$C_g = \frac{\partial \sigma}{\partial k} = \frac{1}{2} C \qquad (3)$$

An important consequence of eqns. (2) and (3) is that surface waves in deep water are *dispersive*, that is, waves of different periods will travel at different velocities with the longer period waves propagating faster than the shorter period ones. Wave dispersion gives rise to a remarkable phenomenon when waves have to propagate over long distances in the deep ocean. In these cases, longer period waves may precede slower, shorter period waves by many hours or even days. This property of surface gravity waves, known as *dispersive arrival*, may be used to locate the source of long traveled swells if detailed measurements are available.

In fact, this was done by Barber & Ursell (1948) who detected the arrival at Cornwall, England, of waves generated off Cape Horn at a distance of over 11000 km (100° = 6000 nautical miles). Subsequent work for the Pacific Ocean (Munk, Miller, Snodgrass & Barber, 1963; Snodgrass, Groves, Hasselmann, Miller, Munk & Powers, 1966) confirmed the arrival at the coast of California of swells generated at distances as far as 20000 km (180° i.e. the antipodal point).

In the next section we apply to the Ceará coast data a method based on the dispersive property of surface waves - the Ridge Line Method (see Munk et al., 1963) - in order to locate the source of some swell events that displayed dispersive arrival characteristics.

5. THE RIDGE LINE METHOD

5.1 Theory

Since the wave energy travels at the group velocity, the time of arrival of surface gravity waves at a distance X from a storm occurring at a time t_o is given by,

$$C_g(f) = \frac{X}{t - t_0} \qquad (4)$$

In view of eqn. (1), we may arrange (4) as,

$$\frac{df}{dt} = \frac{g}{4\pi X} \qquad (5)$$

which shows that the frequency (f) of waves coming from the same source and reaching a distant point is a *linear* function of time of arrival.

Therefore, if one is able of measuring the time evolution of the Spectrum of sea waves at a given location it may be possible to infer both the time of generation and the distance of the source of a given event of distant swell arrival. We recall that the source in these calculations is assumed to be a point in space-time. This implies that the dimensions and duration of the generating storm should be small compared to travel distances and travel time.

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Now, the best procedure to apply this theory in practice (Munk et al., 1963) is: (i) plot a contour map of the energy density as a function of frequency and time ($E(f,t)$), (ii) trace lines through each one of the ridges in this map and (iii) look for ridges that slant towards the lower left-hand side corner along an approximately *straight* line. According to the above theory, each of these ridge lines can be associated with a swell source.

The time of generation is obtained directly from the plot by just prolonging the ridge line down to the time axis: the point of interception is t_o. This is so because $f = 0$ occurs at $t = t_o$ in eqn .(4).

The distance can be calculated from eqn (5) which may be rewritten as

$$X = \frac{g\,\Delta t}{4\pi\Delta f} \qquad (6)$$

where $\Delta f / \Delta t$ is the slope of the ridge line with respect to the time axis.

5.2 Application to the Ceará coast data

Wave measurements were made by INPH off Ponta de Mucuripe, Fortaleza, Ceará with a non-directional accelerometer buoy ("Wave Rider") installed at a depth of about 16 m, which collected 20 min. records every 3 hours from Jan/05 to Jan/30 of 1992. The instrument produced a paper record that had to be digitized for spectra computations on a micro computer. The procedure used for spectral analysis of the records is described in detail on Appendix.

Fig. 1 is the $E(f,t)$ contour map compiled from the computed spectra for the month of January of 1992. We used a cut-off frequency of 0.1 Hz and plotted the energy density on a *relative* scale using the energy content of each given spectrum as reference (i. e., we plotted . $E(f,t) / E_{total}$, for each spectrum). As a complement we show in Fig. 2 the time evolution of the significant wave height in the "swell" frequency band.

As Snodgrass et al. (1966) pointed out, the exact location of the ridge lines may be somewhat arbitrary because it depends on how one defines them. We use the same definition as those authors and consider as a ridge line the set of points underneath the spectral peaks (where $dE/df=0$). As an aid for the tracing of the lines (and striving to be as faithful as possible to the data), we also indicated in Fig. 1 the location of each spectral peak. With that, we were able to sort out a number of slanted ridges in the $E(f,t)$ contour map which should represent dispersive arrivals episodes. In the next section we attempt to associate these ridge lines to atmospheric events in the North Atlantic.

6. ANALYSIS OF RESULTS

We used the Royal Meteorological Society's *Weather Log* to obtain the necessary information. Our Fig. 3 is a sequence of daily weather maps for January of 92 reproduced directly from the above reference.

Recalling that swells travel on the earth's surface along great circles routes, we plotted in Fig. 4 the great circle window which indicates the regions of the North Atlantic Ocean where possible swell sources for Ponta de Mucuripe may lie.

Fig. 1 shows a set of *seven* ridge lines (numbered accordingly in the figure) that we proceed to discuss now.

Starting with the first event, the interception of ridge line #1 with the time axis indicates a generating time between days 03 and 04. Looking at the weather maps for early January we see a cyclone centered at about 37°N, 35°W (well within the Ceará window, Fig. 4), starting to develop on Jan/03 and continuing until Jan/06. It produced northerly winds over a considerable fetch on its western side during the period giving rise to a favorable situation for swell generation. The estimated distance, calculated from the slope of the line (eqn. 6), is 4200 km which gives (assuming that the swell comes from N) a latitude of about 35°N. We see that the inferred swell source for this case agrees quite well with the meteorological data

Events number 2, 3 and 4 had ridge lines of roughly the same slope which place the sources at latitudes near 60°N on days 02, 04 and 07, respectively (Fig. 1). Inspection of the weather maps show oceanic regions between Canada and Greenland (lat. 50°N to 60°N) subjected to N to NW winds on the right dates.

The fifth and sixth events are somewhat similar. Both can be traced back to low pressure systems that passed through latitudes 50°N to 60°N on days 13 and 17 as predicted by the ridge line method

The last events (#7 in Fig. 1) was the most impressive of all. significant wave heights measured at Ponta de Mucuripe reached 2 meters with peak periods up to 20 seconds. The spectral peak evolved in time (Fig. 5) in an amazingly linear fashion as predicted by theory (Fig. 1). The corresponding ridge line indicates Jan/21 as the generating time for this event with an estimated distance of 7500 km which places the source in latitude 64°N approximately.

Now, weather maps show a low pressure system near Greenland (way up north but still within the window) on Jan/19 Winds were rather intense but did not seem to have yet the right direction to send swells towards Ceará. However, on Jan/21, another low pressure system enters the map from the W (at about 50°N) and develops into a severe storm with very low pressures (968 mb) which lasted for the next 4 days. There is no question that this event must have generated rough seas in the whole North Atlantic with swells being probably sent towards Europe , North America and Ceará.

Assuming that the only swell source was the storm at 50°N on Jan/21, our calculations would show a tendency towards over predicting the source distance. We think this might have to do with the possibility that swell generation actually started within the first low near Greenland being further increased by the second storm. Thus, event #7 may not be a simple single "point" source case as assumed by theory. Although requiring some more investigation, we believe that the overall predictions of the ridge line method for this last event are not inconsistent with the weather scenario over the North Atlantic Ocean during the period.

7. CONCLUSION AND OUTLOOK FOR FUTURE WORK

Analysis of wave spectra based on the ridge line method confirmed the arrival of northern hemisphere swell to the Ceará coast. We were able to identify atmospheric conditions that seemed favorable for swell generation for seven detected swell events at Ponta de Mucuripe. According to the present results, possible generating zones extend to latitudes as far as 60°N. The two most energetic events were satisfactorily associated with storms near the Azores Islands as first indicated by Melo & Alves (1993).

We feel that a continuation of the present work would contribute to a better understanding of the wave climate in the northern Brazilian coast. For example, a similar analysis carried out for a longer period of time would certainly clarify the importance of long traveled swell on the overall dynamics of the coast of Ceará which is presently undergoing a severe erosion process.

Finally, it would also be of interest to investigate the atmospheric situations that lead to locally generated high seas. The coast of Ceará is particularly well positioned for this type of study because of its location nearly parallel to the equator; We believe that a lot can still be learned from the wave data that is being currently collected at Ponta de Mucuripe.

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9. APPENDIX: Digital Data Analysis

The set of wave measurements used in the present study consisted of analog records collected daily at 3 hour intervals (2h, 5h, 8h, 11h, 14h, 17h, 20h and 23h) and printed on papers rolls. After conversion to magnetic media (performed through exhaustive work with a digitizing tablet) with a sampling rate of 0.5 seconds, we produced sets of 2048 data points that covered 17.67 minutes of the 20 minute original records.

As the analysis involved more than 10^5 points, slightly more than one percent among these (~10^3 points) presented errors typical of digitizing and data processing through digital media. These errors were detected and corrected numerically and replaced by interpolated values, as suggested in Munk et. al. (1963) and Snodgrass et. al. (1966).

Power spectrum of each record was obtained through the direct Fourier method by means of eqn. (A1).

$$\hat{P}_{xx}(f) = \frac{T}{N}\left|\sum_{n=0}^{N-1} x[n]\exp\{-j\,2\pi f\,n\,T\}\right|^2 \qquad \text{(A1)}$$

Where $P_{xx}(f)$ is the estimated spectrum and the right side is the discrete Fourier transform of the time series, with N = number of points in the series, f = frequency and T = lenght of each record (Marple, 1987).

Smoothing of the spectrum was performed as suggested in Melo (1982) using a moving average procedure known as Daniell technique or "Daniell periodogram" shown in eqn. (A2).

$$\hat{P}_D[f_i] = \frac{1}{2P+1}\sum_{n=i-P}^{i+P}\hat{P}_{xx}[f_n] \qquad \text{(A2)}$$

Where $\hat{P}_D[f_i]$ is the smoothed spectrum and i is the number of adjacent frequencies used to produce the averaged frequency f_n (Marple, 1987). The number of degrees of freedom chosen for the smoothed spectrum (given by $2i$) was 64, which means that 32 adjacent frequencies were used to calculate the average energy density of a given frequency.

The 12 hourly spaced grid showed in Fig. 1 was constructed with two representative spectra for each day. The morning spectrum was calculated as the average of the first four daily spectra (2h, 5h, 8h and 11h). The afternoon/night spectrum was calculated likewise with the remainder (14h, 17h, 20h and 23h).

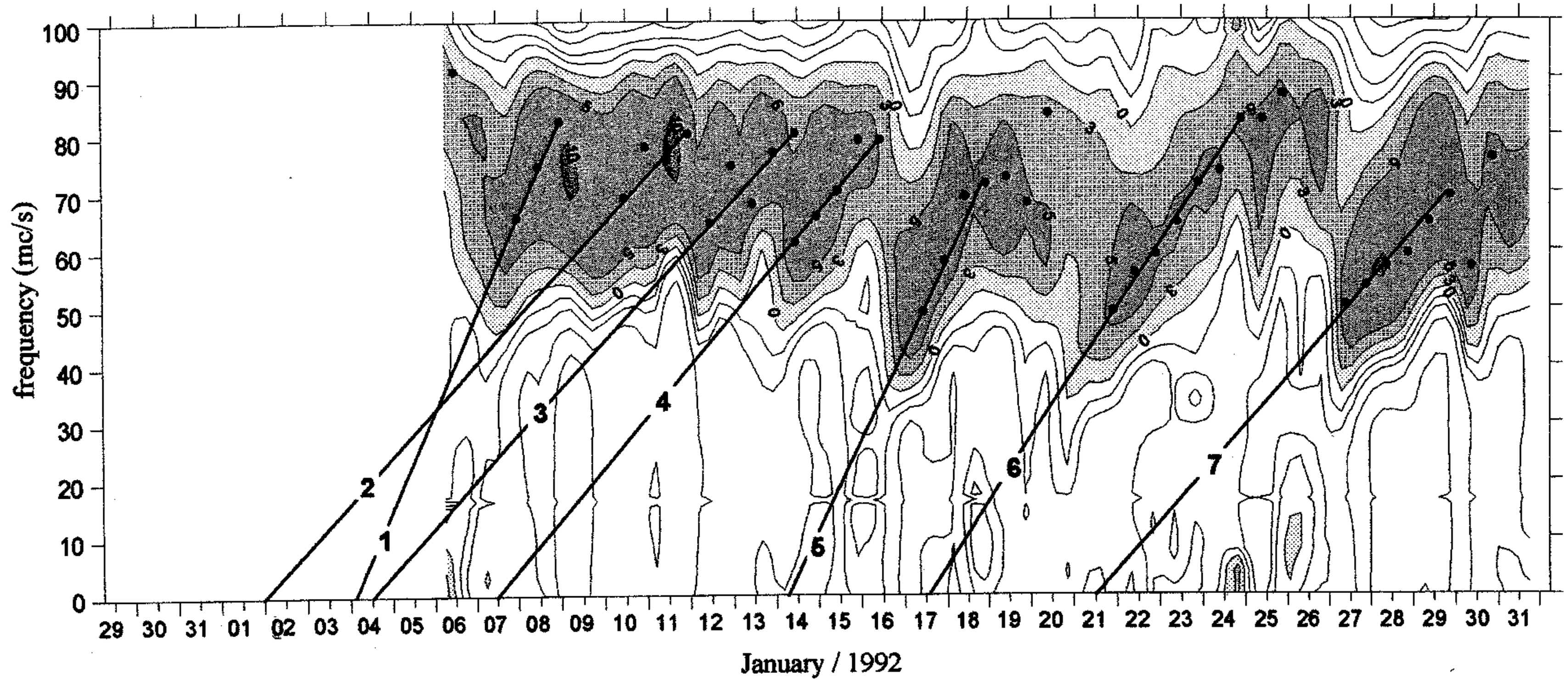


Fig. 1 - Energy density contour as a function of frequency and time.
Values of energy were normalized by the total energy of each given spectrum. Contours are drawn for -20, -10, ..., 10, 20 dB relative to adimensional energy value of 0.01 m2/Hz/m2. Dots represent spectral peaks.
Ridge lines are shown and numbered. Calculated distances/locations of sources are as follows: (#1) 4200 km / 35° N; (#2) 7000 km / 60° N; (#3) 7500 km / 64° N; (#4) 7500 km / 64° N; (#5) 5000 km / 42° N; (#6) 6000 km / 50° N; (#7) 7500 km / 64° N.

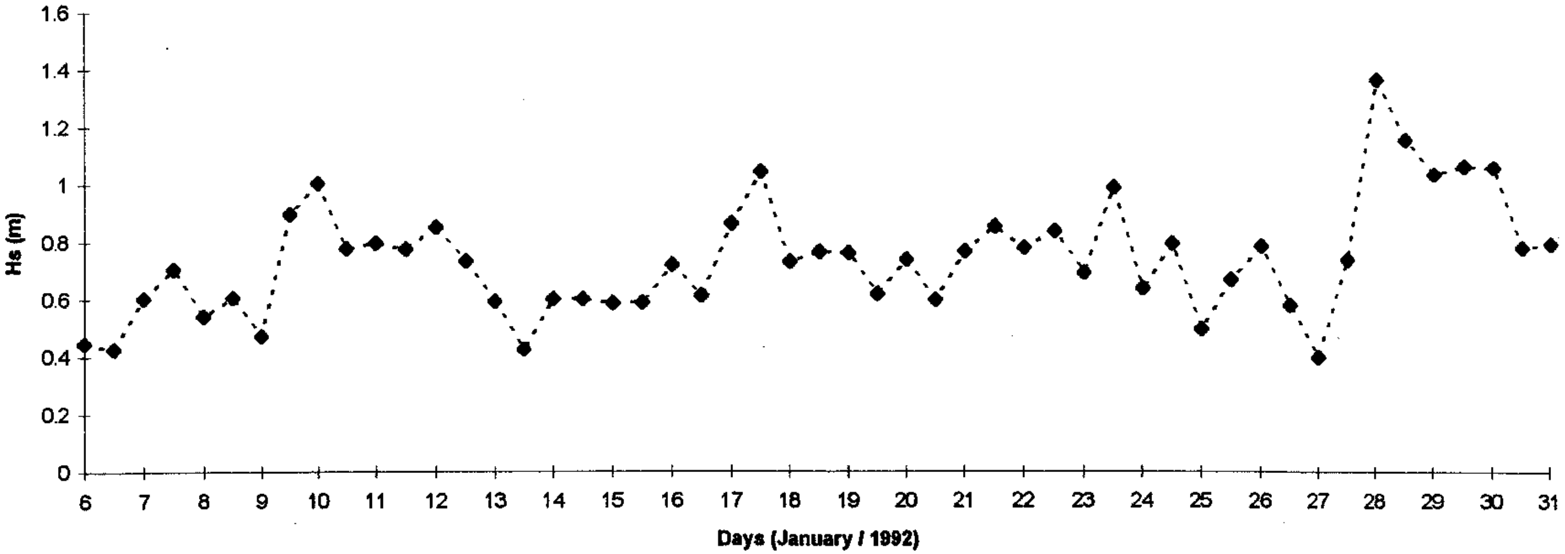


Fig. 2 - Time series of measured significant wave height (Hs) in the swell frequency band (up to 0.1 Hz) at Ponta de Mucuripe, Ceará, for January 1992.

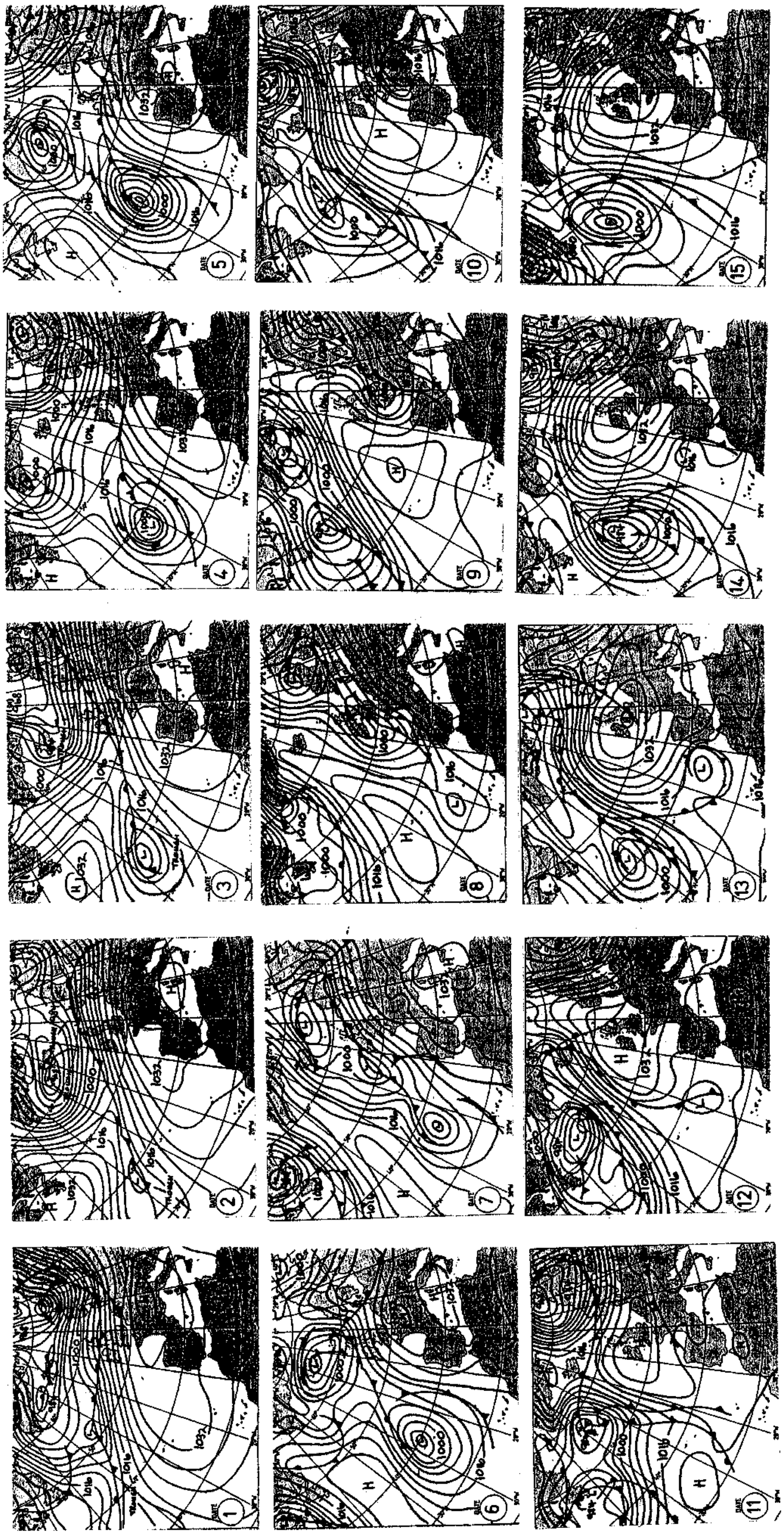
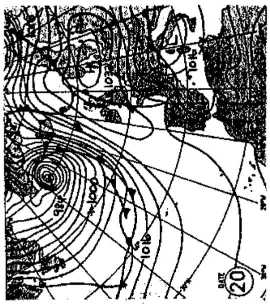


Fig.3 - Daily weather maps for 12 GMT January 1992.
Pressure levels in milibars. Dates are ringed at lower left-hand corner of each map.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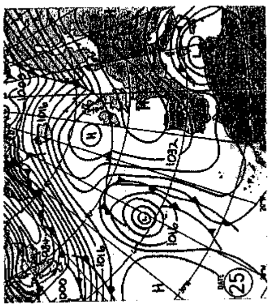
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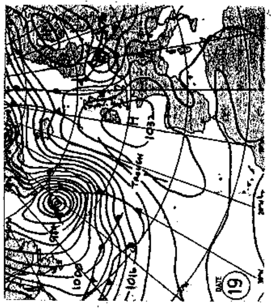
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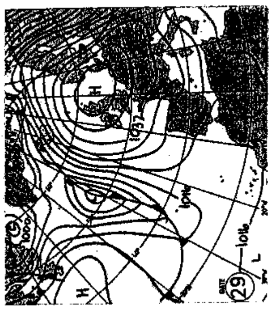
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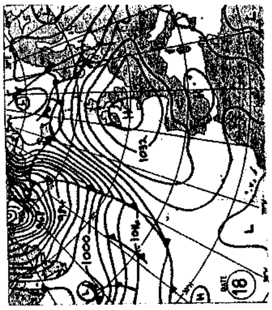
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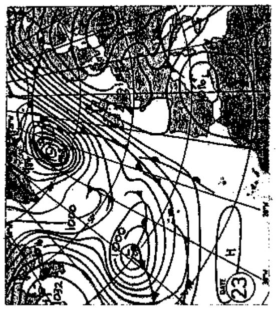
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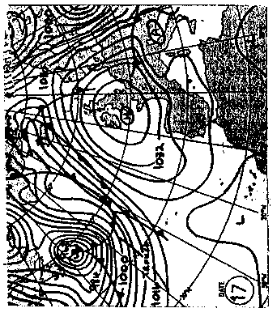
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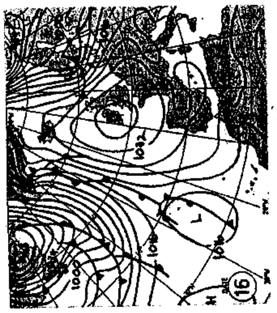
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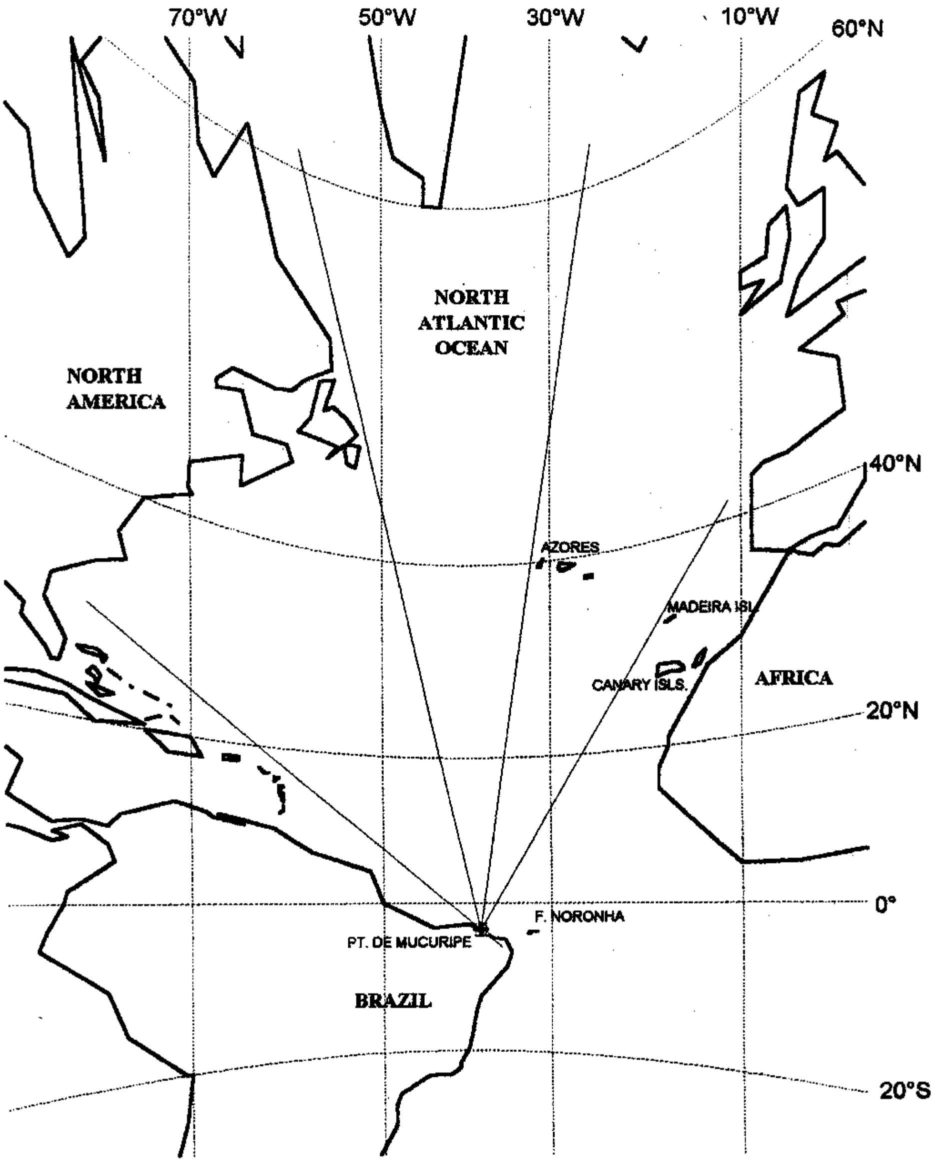

Fig. 4 - Great circle "window" indicating the regions of the North Atlantic Ocean where possible swell sources for Ponta de Mucuripe, Fortaleza, Ceará, may lie. Great circles are drawn as straight lines on this projection.

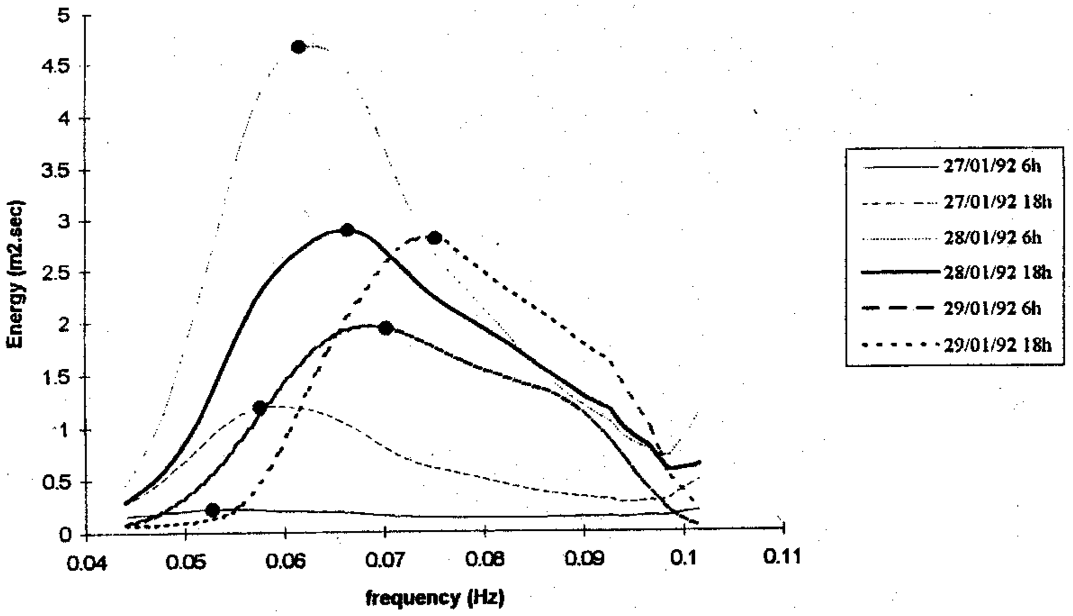

Fig. 5 - Time evolution of spectra for event #7.
Peak frequencies are enhanced by black dots.