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Time variations in the spatial scales and intensities of ocean circulation in the vicinity of the Cape of Good Hope

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ABSTRACT

A spatial structure function analysis has been carried out on the physical oceanologic data collected during a series of regular monthly cruises from 1962 to 1967 in the vicinity of the Cape of Good Hope. The distribution of energy on the spatial spectrum shows that during most months there is a predilection for all disturbances to be smaller than 150 km. The area is subject to large variations in energy, but these variations involve the whole measured spectrum showing no preference for any specific spatial scales. No significant periodicity in the monthly energy variations is found.

1. Introduction

The parameters defining the dynamic physical structure of the ocean areas off the South African coast are subject to variations of a seasonal and non-seasonal nature with a magnitude and complexity that is experienced in few other ocean areas of this size. On the east coast the Agulhas Current shows twice yearly cycles in strength (Tripp, 1967; Barlow, 1935) and shorter term variations with cycles of less than a month (Anderson, 1967). On the west coast the upwelling shows yearly cycles (Duncan, 1964; du Plessis, 1967; Schell, 1968) but is readily influenced by non-cyclic changes in the local meteorology (Andrews & Cram, 1969; Bang, 1970). In the geographic area between these two systems (Fig. 1B) the time variability of the ocean may be inherently more complicated since it is influenced by both systems (Dietrich, 1935a, 1935b; Shannon, 1966; Bang, 1970).

To investigate this variability in the vicinity of the Cape of Good Hope, the estimated spatial structure function is used to give a quantitative description of the spatial scales and intensities of circulation in this ocean area for each month of a 6-year period. The conjecture that certain parts of the spatial energy spectrum may be comparatively enhanced during certain seasons is not supported; instead, it is shown that the system undergoes great energy changes as a whole, changes which do not seem to show any regular periodicity. A length scale of 150 km is prevalent at almost all times. This has not been noted before.

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2. Data and methods

The only extensive, fixed network of relatively closely-spaced stations in South African waters that has been covered regularly for a long period was employed by the South African Division of Sea Fisheries in the vicinity of the Cape of Good Hope (Fig. 1). This oceanic area has been investigated on a regular basis since 1959. Data selected for the present study were from the period of April 1962 to June 1967. Two slightly dissimilar networks of stations were used during this time; the latter, in use since July of 1963, is depicted in Fig. 1A.

Since it has been demonstrated (Lutjeharms,

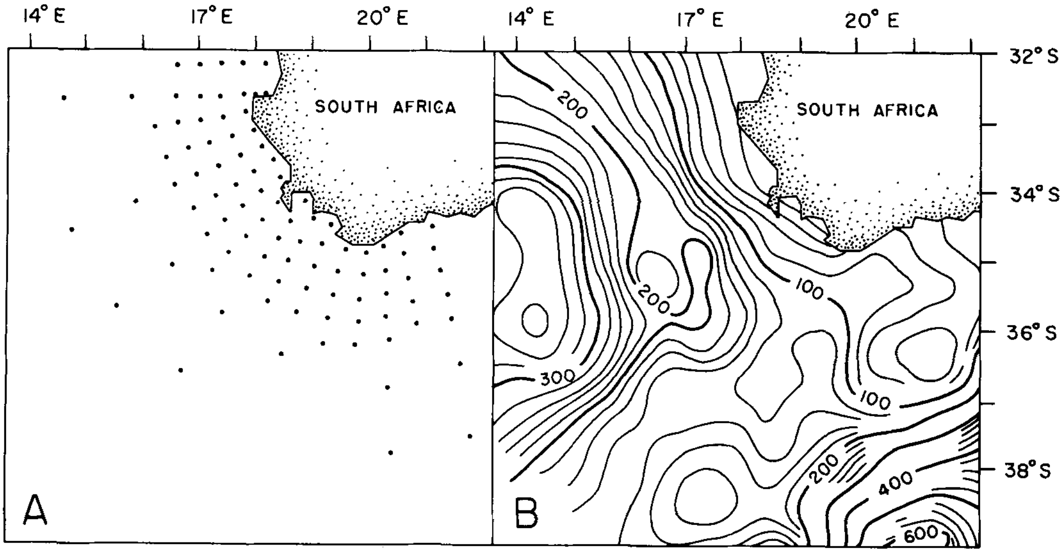

Fig. 1. (A) The oceanologic station network used by the South African Division of Sea Fisheries for their routine investigations into the hydrology of the ocean area surrounding the Cape of Good Hope. Stations were occupied by the R/S *Sardinops* from July 1963 to June 1967 and by the R/S *Africana II* from July 1963 to April 1967. (B) Depth of the 26.40 sigma-t surface in the vicinity of the Cape of Good Hope during March of 1969. Heavy contours are at intervals of a hundred meters; lighter lines at intervals of twenty meters. In areas of excessive crowding intermediate isobaths have been omitted.

1977) that the spatial structure function is a valuable quantitative tool for describing the diverse physical structure of the ocean areas off the South African coast, it was used in this investigation for that purpose.

The spatial structure function B_f of a field f, where $f = f(\mathbf{r})$ and $\mathbf{r}_i$ are position vectors, is defined as the mean-square difference between the values of f for different $\mathbf{r}$ so that

$$B_f(\mathbf{r}_1, \mathbf{r}_2) = \overline{[f(\mathbf{r}_1) - f(\mathbf{r}_2)]^2}$$

where the overbar denotes averaging (Gandin, 1963). In this investigation the dynamical parameter-field under consideration was the depth of an isopycnal surface. Station pairs were grouped together according to their separation into 30 km intervals. The sum of the squared differences of the depths was then divided by the number of station pairs to average over that interval so that the estimated spatial structure function

$$E[B_f(r)] = \frac{1}{n} \sum^{n} [f(1) - f(1 + r)]^2$$

where n is the number of station pairs in that chosen interval and r the distance apart of the two stations in question. No theory concerning the assignment of confidence limits to structure functions seems to exist, so that the choice of a statistically sufficient set of station pairs in each interval is a subjective one.

If the spatial structure function of the depth of an isothermal surface is multiplied by the acceleration of gravity and by the density difference between water above and below the surface being considered, the product will represent the energy of the fluctuations as a function of separation (Wyrtki, 1967). Since we deal here with an isopycnal surface and since we may consider the variation of the acceleration of gravity to be negligible over such a small geographic area, structure functions calculated for the isopycnal surface represent the spatial energy spectrum.

Wyrtki (1967) has used this method to investigate the eddies of 200km radius superimposed on the general flow of the North Equatorial Current in the North Pacific Ocean. He states that they made their presence felt as distinct peaks at 200 km on the monotonically increasing function depicting the geographically extensive flow of the North Equatorial Current. The method has also recently been gainfully employed by Dantzler (1974), Düing (1972) and Hamon & Cresswell (1972) on similar problems.

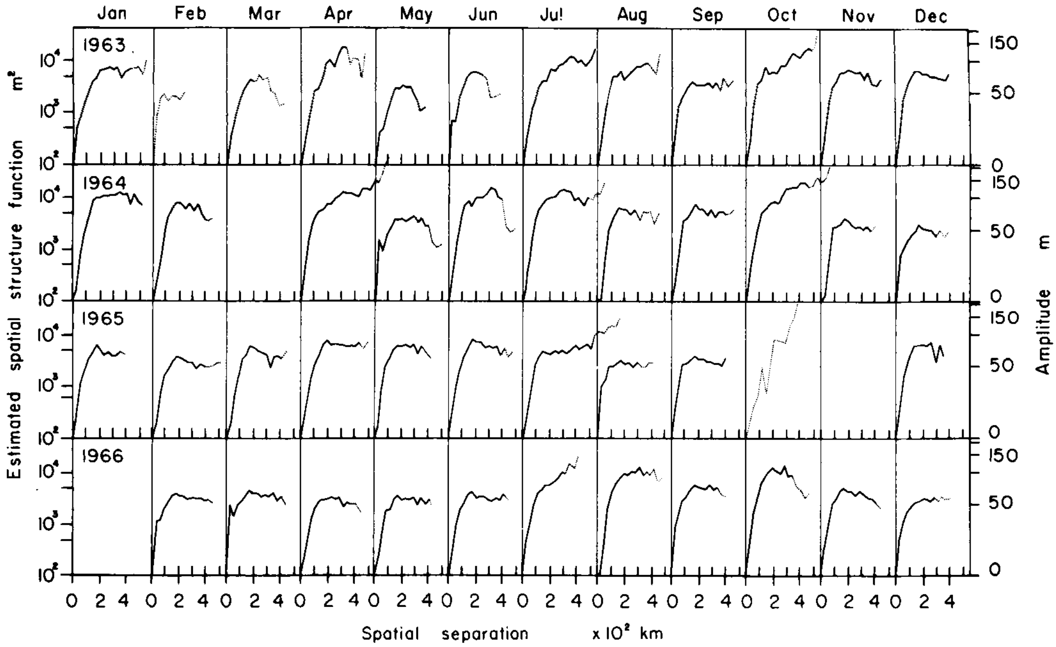

Fig. 2. Monthly estimated spatial structure functions for the depth of the 26.40 sigma-t surface in the ocean area surrounding the Cape of Good Hope from 1963 to 1966. Resolution is for 30 km intervals. Broken lines indicate areas of doubtful statistical significance.

For the purpose of this investigation the depth of the 26.40 sigma-t surface was selected as being most suitable and dynamically definitive. The depth in metres of this surface during March 1969, as observed by a multi-ship cruise in this, and surrounding areas (Bang & Pearse, 1970), is depicted in Fig. 1B. On the west coast, in an upwelling regime, it fell from about 3 m at the coast to 330 m at a distance of 470 km offshore. In the southeastern corner of the diagram the steep slope representing the retroflexion point of the Agulhas Current may be seen. Various eddy-like structures are visible.

The estimated spatial structure function of the depth of the 26.40 sigma-t surface was calculated for each individual monthly cruise from April 1962 to June 1967. Some of the results are depicted in Fig. 2. At the further ends of the structure functions the number of station pairs becomes too small to allow significant results but, the general trends nevertheless seeming of interest, these are depicted by broken lines.

If a dominant length scale is prevalent in the oceanic field, such as for example a field of eddies all with a certain diameter, then this will cause the spatial structure function to exhibit peaks at odd multiples of half that diameter. If more than one length scale is evident, the structure function at greater separations will become quite complicated. Individual features on the spatial struction are thus intelligible at shorter distances only.

3. Results

The estimated spatial structure functions calculated show a remarkable degree of similarity (Fig. 2). All rise strongly in the first 150 km and in the majority of cases exhibit some sort of peak in the vicinity of 200 km. Bearing in mind the difficulties inherent in distinguishing peaks at greater distances, this initial peak was considered the main one. In most cases the structure functions rise very little beyond this and soon start wavering due to poor statistics. In some cases (October 1963; April and October, 1964) the functions continue to rise strongly without the abrupt change in slope exhibited for other months. Large fluctuations in the value of the structure function and therefore in the amplitude of disturbances on the sigma-t surface occur from month to month. For the years depic-

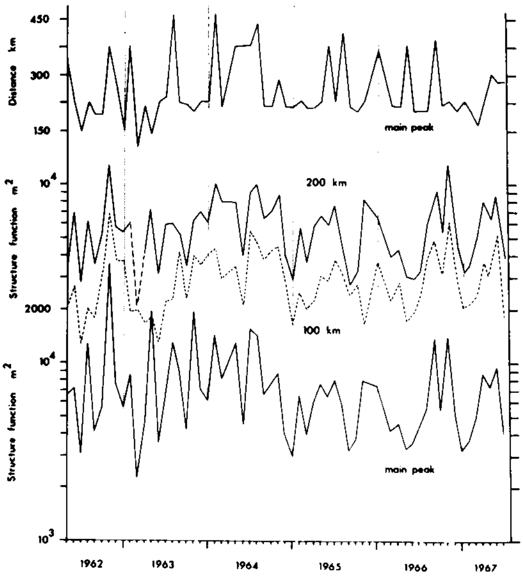

Fig. 3. Curves depicting the time variation of the estimated spatial structure function as calculated for the depth of the 26.40 sigma-t surface in the vicinity of the Cape of Good Hope. Time variation for the 100 km and 200 km distance is shown, as well as for the main peak of each individual monthly spatial structure function. The time variation of the distance of this main peak is shown in the topmost curve.

ted, the smallest disturbance occurred in December of 1964, not rising above 60 m; the largest occurring in October of the same year with definite disturbances of close on 150 m.

The value of the structure function for 50, 100, 200 and 300 km for each month was plotted against time (Fig. 3). This was also done for what was considered the main peak in each individual structure function. The distance at which these main peaks occurred was also plotted against time and forms the top curve for Fig. 3. In this figure the close similarity of the curves for the structure function for 100 and 200 km is noticeable. Since the other distances also exhibited this similarity they were not reproduced. The curve for the main peak is an exaggerated version of the former two.

4. Discussion of results

The most conspicuous feature of the calculated spatial structure functions (Fig. 2) no doubt is the striking similarity in their general shapes and the strong coherence from month to month in the point at which an abrupt change in their slope occurs. The average spatial separation for this break is 148 km with a standard deviation of only 28 km, therefore well within the resolution of the 30-km interval chosen. Out of the 43 months displayed in Fig. 2 and for which data is statistically significant only 5 months may be considered as not exhibiting this break in slope. Of these, two are in October (1963, 1964), two in July (1963, 1966) and one occurs in April (1964).

A spatial structure function that rises rapidly to a certain value and stays approximately level beyond that point would indicate that most of the energy of that field is contained in spatial scales smaller than that value. This would be the case in a field of eddies with no geographically extensive trend. A field which consists of a trend with superimposed disturbances such as in the case of the North Equatorial Current (Wyrtki, 1967) or an upwelling regime (Lutjeharms, 1977) would be portrayed by a monotonically increasing spatial structure function with individual peaks. It would thus seem that the meso-scale field around the Cape of Good Hope consists of turbulence with a general upper limit of about 150 km during most months. The depth of the sigma-t 26.40 surface for March 1969, as depicted in Fig. 1, would seem to indicate that the eddies on the Agulhas Bank, southwest of Cape Agulhas and southwest of the Cape of Good Hope all exhibit about this size at this time. This is also shown in some Shannon's (1966) results for this area. The extensive trends indicated for the other months could be due to large scale upwelling of a transitory nature. It may be noted that the 150-km scale exhibited in this area is very similar to the one of about 200 km found for the ocean area east of here (Lutjeharms, 1977) which might be acting as an eddy-generating area (Bang, 1970).

The curves depicting the value of the structure function for 100 km and 200 km for each month (Fig. 3) demonstrate clearly that the energy for any one distance has no regular period over the years. From the close correspondence between the curves for these, and other, distances it becomes clear that the energy or intensity of circulation of the area or system investigated increases and decreases as a whole with no strong predilection for a feature of any particular size. This is also borne out by the values for what was considered to be the main peak of each month's structure function. This curve in

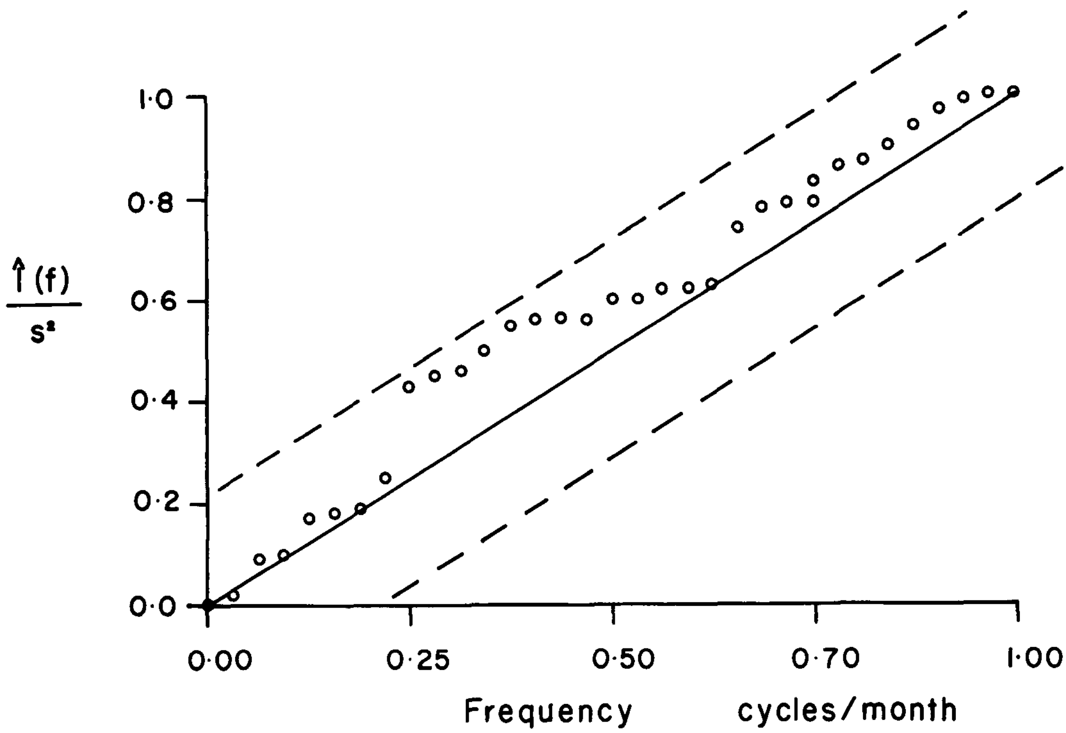

Fig. 4. The normalized sample integrated periodogram of the estimated spatial structure function's value at 200 km for the depth of the 25.40 sigma-t surface. The solid line through the origin depicts the theoretical line for white noise while the broken lines flanking it show the 75% confidence limits.

Fig. 3 shows a clear correlation with the curves for the 200 km and 100 km distances. This is particularly so for the correlation with the 200 km curve from 1965 onwards. The size of the main peak (the top curve in Fig. 3) shows why this is so. During this period the main peak only occasionally is not of 200 km size.

A possible explanation for the rise and fall in the amplitudes of the structure functions (Fig. 2) may be that the retroflexion point of the Agulhas Current (see Fig. 1B) is not stationary, and hence, the energy of the whole system around the Cape of Good Hope will rise and fall in response to a greater or smaller extent of the Agulhas Current intruding into the area. The periodicity of these energy changes is of some interest. A visual inspection of the spatial structure functions in Fig. 2 seems to indicate some regularity in the amplitude changes. Low values in December and February of all years and high values in October and July are discernible. When the power spectral density function of the structure function value at 200 km was calculated for each month from 1962 to 1967, small peaks at periods of 3 and 8 months were found. To test the significance of the peaks a white noise test devised by Jenkins & Watts (1968) was employed (Fig. 4). If the sample spectrum estimate $Czz(f)$ has been computed at the harmonic frequencies $f_k = k/N\Delta$, $k = 0, 1, \ldots, N/2$, then the integrated spectrum $Izz(f)$ may be estimated from the sample integrated spectrum

$$I(f_k) = \frac{1}{N\Delta} \sum_{l=1}^{k} Czz(f_l).$$

If $I(f_k)$ is normalized by dividing by the sample variance S_z^2 and is plotted against $2\Delta f_k$ the points for a white noise process should lie along the line connecting the points (0, 0) and (1, 1) depicted by the unbroken line through the origin in Fig. 4. To judge more precisely the deviations from this line by the points representing a process, the

Kolmogaroff–Smirnov test of significance has been used. The 75% confidence limits according to this test are depicted in Fig. 4 by broken lines. The interpretation of these limits is that in one out of four plots, on the average, the maximum deviation from the theoretical white noise line will lie outside the limits if the process is in fact white noise. Since all the points for our analysis lie well within these bounds it is clear that there is no evidence that our sample does not come from a white noise source and any seemingly regular aspects in the values of the spatial structure functions have no statistical significance.

5. Conclusions

It may be concluded that the area is one of large variability. Whereas Wyrtki (1967), working in the North Pacific Ocean, showed amplitude changes in the depth of the 20 °C isotherm over distances of 260 km that did not exceed 15 m, the amplitude for the comparable 26.40 sigma-t surface over distances of 200 km in the area of the Cape of Good Hope during the years discussed varied by as much as 50 m. Not only are the energies in this ocean area much higher than those shown by Wyrtki (1967), but the changes are also greater and perhaps more sudden.

The energy or intensity of circulation of the ocean in this area changes as a whole with little preferential increase in the energies of any particular spatial scale. Energy distribution over the spatial spectrum shows two definite configurations; the most prevalent one having an abrupt slope change at 150 km, the other showing a monotonic increase for all distances measured. It is conjectured that the latter is due to sporadic extensive upwelling. The former indicates a predilection for disturbances in the field with dimensions of less than 150 km.

Changes in the intensity of circulation in this ocean area show no significant regularity for this 6-year period.

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ВРЕМЕННЫЕ ВАРИАЦИИ В ПРОСТРАНСТВЕННЫХ МАСШТАБАХ И ИНТЕНСИВНОСТЯХ ОКЕАНИЧЕСКОЙ ЦИРКУЛЯЦИИ ВБЛИЗИ МЫСА ДОБРОЙ НАДЕЖДЫ

Путем построения пространственных структурных функций анализировались физические океанологические данные, собранные в серии регулярных ежемесячных круизов вблизи мыса Доброй Надежды в период с 1962 по 1967 годы. Распределение энергии в пространственном спектре показывает, что в течение большинства месяцев есть тенденция для всех возмущений иметь масштаб меньше 150 км. Исследуемая площадь подвергается большим вариациям по энергии, но эти вариации касаются всего измеряемого спектра, не проявляя предпочтительности в каких-либо пространственных масштабах. Не найдено также существенной периодичности в месячных вариациях энергии.