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Swell waves at Saint Helena related to distant storms

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SUMMARY

This paper discusses the relationship between a frequency–time plot of energy density of swell, from records taken at St Helena in December 1970 and January 1971, and meteorological records of distant storms. A similar exercise in 1969 had suggested that some of the swells originated from the southern hemisphere, even possibly from the Pacific Ocean, but wave amplitudes were all very low. Higher waves were recorded in the present exercise, but all the major events in the energy spectra were attributable to northern hemisphere storms, a few minor events only to the southern hemisphere, and none to the Pacific Ocean. It is concluded that large northwesterly storms in the area southeast of Newfoundland are probably responsible for the spectacular 'rollers' which are frequently reported from St Helena.

1. INTRODUCTION

In the 18th and 19th centuries, when the island of St Helena was frequently visited by sailing ships on the Cape route, many lurid accounts were given of the 'rollers' which were liable to invade the landing place at Jamestown, principally between December and March. The Dutch Captain F. Fokkens gives the following (translated) eye-witness account in *The Nautical Magazine* for 1852 (p. 21): 'The atmosphere is bright and clear, the barometer remains as ordinarily and the sea smooth in the distance. . . . In an instant, all is confusion around, from a sudden, upheaving wave rolling onwards and breaking in the outer shallows with tremendous force. Instantly the surf follows, one wave succeeded by another with redoubled force towards the shore breaking upon the rocks. . . . The rollers or extraordinarily high swells, first appear in the form of a high, steep, long mountainous ridge and gather fresh strength as they approach, astonishing the beholder; water mountains seem to follow each other with redoubled violence until they reach the receding waters from the shore, meeting them as walls, and with irresistible fury dash over the beach. The shore is a mass of foam, while the houses in the town are shaken almost to their foundations. Such was the case in February 1838 while I was on board the *Elizabeth*. . . . In February 1846, there was a similar visitation attended with much damage, when many of the condemned slave vessels were stranded and lost.'

Although the cause of such phenomena was hardly understood and certainly not proven in those days, the description tallies with what is now understood about ocean swells generated by distant storms. The waterfront at Jamestown faces northwest, and the bottom there descends abruptly from 50 m at about 1 km from the shore to 4000 m at about 25 km from shore. A long swell of typical amplitude 0·5 m and wavelength 350 m in the deep water, where it would be barely perceptible, would rapidly increase in amplitude and shorten in wavelength with little dissipation until breaking-point is reached near the shore (Fig. 1). The suddenness of onset of rollers is accounted for by the first arrival of the 'front' of narrow-band spectral energy, radiating from some distant storm centre at a group velocity of order $12\,\mathrm{m\,s^{-1}}$.

During the second half of the 19th century, extensive records were kept of observations of roller activity at St Helena and also at Ascension Island, some 500 miles to the northwest. Most of the original records are now lost, although once held by the Meteorological Office in London. An unpublished paper entitled *The Rollers* by Mr J. C. Mellis, Colonial Engineer,

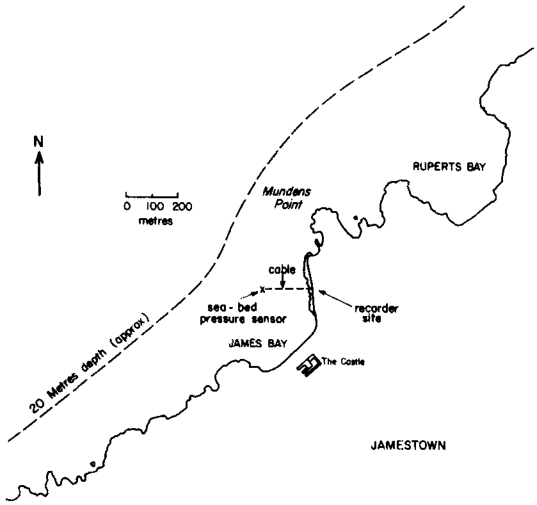


Figure 1. Map indicating position of pressure sensor and recording site off the jetty at Jamestown, St Helena (15°55′S 5°43′W).

accompanying a year of simultaneous observations of roller activity at the two islands in 1867–1868 attracted the attention of Sir George Stokes. Stokes's letter* about Mellis's paper, to Sir Edward Sabine, dated 22 September 1870 (Stokes 1907), showed a clear appreciation of the probable origin of the rollers. His suggestion that distances of the generating storms could be determined from measured changes in wave period is historically important as the real origin of the now standard method. Stokes then had full instructions issued officially (Anonymous 1876, pp. 564–568) for observers at such island stations to record the mean period of swell for the purposes of scientific analysis. A set of such records sent by Captain J. W. East, R.N., Governor of Ascension, covering March 1876 to January 1877, is still held in the Meteorological Office archives and has been seen by the authors. It appears that the observing technique was too rough for any reliable scientific deductions. Indeed, Stokes's suggested approach was not fully realized until Barber and Ursell (1948) introduced spectral analysis to ocean wave studies.

The one set of 19th century observations of rollers to have found a place in current oceanographic literature is the monthly statistics from 20 years' records at St Helena, 1856–1875, communicated to the Meteorological Office by the island governor H. R. Janisch. The records were collated by the marine superintendent, Captain H. Toynbee, and first published by him in 'Anonymous' (1856, p. 497). Toynbee's figures were later reproduced in a sequence of books on oceanography by German authors, of which the most recent is Defant (1961, p. 101). In brief, Toynbee showed that monthly frequencies of occurrence of rollers correlated roughly with monthly frequencies of northwesterly storms in the North Atlantic. However, the correlation is not too convincing; Defant showed that it was improved if one used statistics of all North Atlantic storms regardless of wind direction. The implication, that storms can generate large amounts of energy in directions very different from the dominant wind direction, does not accord well with modern theory and observations (for example, Snodgrass *et al.* 1966).

A final point in Toynbee's summary of Janisch's report is worth mentioning. Occasionally, high rollers were reported in the northern summer, notably in May 1821. Since the Jamestown shoreline faces northwest, swell from the South Atlantic is unlikely to have such a remarkable effect, and Toynbee suggested that the waves may have been induced

* In this and his following letter, Stokes erroneously refers to Mellis as 'Mr Melsens', probably owing to a slip of memory.

by a sub-marine earthquake somewhere to the north. Large seismically induced sea waves, or 'tsunamis', are rare in the Atlantic, and would have wave periods greatly in excess of the 12–20 seconds usually recorded. However, the possibility should not be entirely ruled out when the reports originate from unscientific observers.

In November–December 1969, two of the authors (D.E.C. and J.S.D.) made the first instrumental recordings of waves off Jamestown. The results of the exercise, which was also concerned with tides and medium-frequency waves, are described in Cartwright (1971). No rollers occurred during either month, and the highest amplitude recorded close to shore was about 0·5 m, but plots of spectral energy of the continual low swell motion showed a number of interesting features. Following the method first devised by Barber and Ursell (1948), later improved by Munk *et al.* (1963), ridges were identified on the contoured plot of energy density with respect to frequency and time, each corresponding to the time and distance of the generating storm. Only two of these ridges clearly corresponded to storms in the North Atlantic. The rest, including the highest swell waves recorded, came from the southern hemisphere. The highest swell was in fact observed, from a high part of the island, to approach from the southwest. Two ridges of low energy appeared to point to events more than 120° distant, which was possible only from the South Pacific Ocean via Drake Passage. However, no corresponding storms were indicated in the available weather maps for the South Pacific.

The general picture which then emerged from the 1969 recordings was that the background swell in November–December could come at least equally from the southern as from the northern hemisphere, but in no case observed could the swell be identified with, or even remotely suggest, the phenomena described in our first paragraph.

Ironically, the first heavy swell which arrived after the recording party had left St Helena destroyed the connecting line between the sea-bed pressure sensor and the recording unit. From the date of that event, 3 January 1970, the swell probably originated in a northwesterly storm off Newfoundland, about eight days previously.

A further period of wave recording, preferably in the early months of the year, was clearly desirable, and this was backed by a request from the island government for wave statistics for a possible harbour construction project. To achieve this, one of us (J.S.D.) made a second journey to St Helena in late November 1970 and installed a new wave recorder, designed to withstand heavier conditions than the first and to be operable by island government staff for some months. As on the first occasion, we were greatly helped by the Hydrographic Dept, Ministry of Defence, who transported personnel and equipment to the island and helped with the initial stages of installation. The rest of this paper describes and discusses the results from the second installation.

2. Instrumental details

(*a*) *Sensor and recording equipment*

An absolute pressure gauge of the variable capacitor type, developed and manufactured by IOS, was used to sense pressure fluctuations from both swell waves and tides. (The tidal records were not used for the present study, but formed an integral part of the recording exercise.) The information was transmitted to the recording equipment in the form of frequency modulation on a nominal 100 kHz carrier. Demodulation, filtering and amplification took place before applying the wave and tide signals to separate chart recorders. The wave filter had a low frequency cut-off at 1/60 Hz (a time-constant of 60 s) whilst the high-frequency attenuation became significant at frequencies higher than 0·5 Hz. The tide filter time-constant was arranged to coincide with that of the wave filter at 60 s; thus its pass-band extended from 1/60 Hz to 0. A sensitivity of +2·5 m full-scale deflection was chosen for the wave chart recorder with a chart speed of 120 mm/min and 2·5 ± 1·25 m full-scale deflection for the tide recorder with a chart speed of 1 mm/min. A sampling clock was fitted which switched on both chart recorders for $1\frac{1}{4}$ hours at nominal times of 1000 and 2000 GMT each day. Additionally a self-contained quartz crystal-controlled clock was fitted to provide a facility for precise time checks when marking up records.

(*b*) *Calibration arrangements*

Although the equipment had been calibrated before leaving the UK it was considered necessary to carry out careful checks after deployment. A portable stilling well was used as a means of establishing water level to an accuracy of ± 1 cm. The device consisted of a long rigid polypropylene tube of 80 mm internal diameter, closed at the bottom but for a 4 mm hole, and held vertical by a light rigid framework at the top which could be rested securely on one of the wharf steps. The time-constant of the well was about a minute and readings were taken at hourly intervals for spells of up to eight hours during several consecutive days. Thus the pressure transducer and electronics for the tide recorder could be calibrated and an estimate of sensor drift made. Because the wave recorder circuit contained a high pass filter, calibration involved applying a frequency-modulated input signal of known deviation which could itself be directly related to transducer sensitivity by means of the stilling well checks. Land datums had been established by naval staff from HMS Vidal in 1969 and it was possible to relate the level of the wharf steps to these.

(*c*) *Installation*

Jamestown harbour was chosen, as in the 1969/70 expedition, to be the site for the wave and tide recording instrument. Apart from the requirement to gather wave statistics in James Bay, no other location on the island offered the same combination of availability of mains power supplies, protection for the recording equipment, and accessibility for day-to-day servicing. The pressure transducer was installed on a 1·5 m high tripod in 12·2 m of water approximately 180 m from the wharf. Fig. 1 shows the position of the transducer and recording electronics. A double armoured cable of 1·6 cm diameter was used to transmit the pressure signal from the sea to the recorder and this was secured as it came ashore over rocks by sacks of concrete wedged around the cable and between the rocks. A quick-setting compound was used to assist in this operation. Unfortunately, before the work could be completed the incidence of swell (from Bermuda - see section 4) started to damage and remove some of the sacks. Four days elapsed before the sea was calm enough to resume work on placing concrete sack protection around the cable, but suitable conditions (coincidental very low tide and calm sea) to enable such protection to be applied to our complete satisfaction were not forthcoming during the remainder of Mr Driver's stay on the island.

(*d*) *Operational details*

Deployment of the equipment, with the exception of concreting work on the armoured cable, was completed three days after arrival, enabling calibration and checking to take place. The first usable records were taken on 1 December and recording continued until 2 February 1971 when the drive gears on the wave chart recorder sheared. Tide records continued to be made until the cable severed on 27 February during a period of high swell activity. Over the period 1 December to 2 February rather less than 5% of the data were lost, ink blockage problems and chart drive inconsistencies being the main causes of faulty records. Checks on transducer drift over a 15-day period indicated an apparent increase in pressure equivalent to only 2 cm of water.

3. Digital analysis and statistics of wave height

(*a*) *Spectral analysis*

All wave records were digitized 'by eye' at 2·5 s intervals and punched on to cards. Each digital series of approximately 1 800 numbers was then checked for smoothness by computer, and dubious values checked for possible reading or translation errors. The corrected series, z_r, were then divided into consecutive blocks of 128, each of 320 s duration, and each block processed by the standard fast Fourier transform routine to produce spectral ordinates

$$H_n = (1/64)\sum_{r=1}^{128} z_r \exp(2\pi i r n/128), \quad n = 1(1)63, \qquad (1)$$

corresponding to frequencies $(3{\cdot}125n)$mHz. The 13 or so sets of energy density from each wave record,

$$E_n = 0{\cdot}16\beta_n^2|H_n|^2 \quad (\mathrm{cm}^2(\mathrm{mHz})^{-1}), \qquad (2)$$

were ensemble-averaged to produce the mean spectrum, $\bar{E}_n$. (β_n is a set of computed correction factors from bottom pressure to deep-water surface elevation, as discussed in (*b*) below.) The values of $10\log\bar{E}_n$ were then plotted as mean log spectral density in decibels on a grid with date as abscissa and n as ordinate. Finally, contours of equal decibel level were drawn through the full array of numbers, to produce the time-spectral plots in Figs. 3(a) and (b). These are similar in form and scale to those first published by Munk *et al.* (1963), and also to Fig. 10 of Cartwright (1971).

The relative standard sampling error of each $\bar{E}_n$ is $13^{-\frac{1}{2}}$, so the standard error of all plotted decibel levels is approximately $13^{-\frac{1}{2}} \times 10\log e = 1{\cdot}2$. Most of the spectral structure on which we have based our interpretation of Figs. 3(a) and (b) involves decibel variations considerably greater than this, so the variability is acceptable for our purpose.

(*b*) *Hydrodynamic corrections*

In interpreting the spectrum of the recorded signal, as in (*a*) above, in terms of the spectrum of the surface elevation, we have first to allow for the relation between the amplitude of bottom pressure, a_h (in units of static head of sea water), and the local wave elevation, a_0:

$$a_0/a_h = \cosh kh \qquad (3)$$

Here h, = 12 m, is the total depth of water, the sensor itself being effectively on the bottom, and k is the local wavenumber, determined from the spectral frequency fmHz by the dispersion relation

$$kh\tanh kh = (2\pi f)^2 h/g, \qquad (4)$$

where g is the acceleration due to gravity.

Second, since we shall be considering the wave spectrum as if in deep water, we have to allow for the amplification of the wave on entering the island's shelf. By the linear theory of refraction for a wave approaching normally to a gently shelving coast (Longuet-Higgins 1956), the amplitude of the wave in deep water, a_0', is given by

$$\alpha(f) = a_0'/a_0 = \{(\partial/\partial k)(k\tanh kh)\}^{\frac{1}{2}} \qquad (5)$$

For an oblique approach, the correction factor is slightly greater than this, according to the

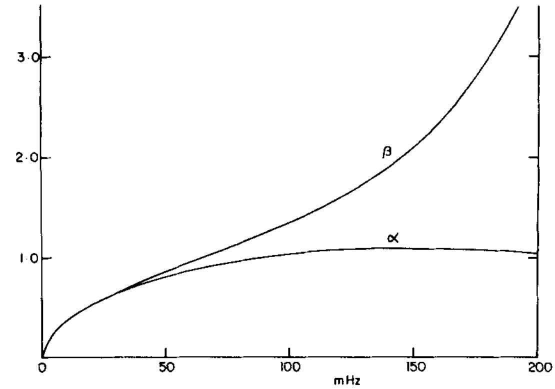


Figure 2. Correction factors applied to spectra of bottom pressure in 12 m depth, as function of frequency. α: the ratio of wave amplitudes in deep and shallow water, having a maximum of 1·095 at 145 mHz. β: the total correction, involving also the ratio of surface wave amplitude to bottom pressure.

theory of Longuet-Higgins. Since we have no direct means of assessing wave direction here, the effect of obliquity has been ignored, but the error is likely to be very small. Thus, from Eqs. (3) and (5) the total correction applied to the spectral wave amplitudes was

$$\beta(f) = a_0'/a_h = (\sinh kh \cosh kh + kh)^{\frac{1}{2}} \qquad . \qquad . \qquad (6)$$

The factor β_n appearing in formula (2) for the spectral energies $\bar{E}_n$ is simply

$$\beta_n = \beta(3{\cdot}125n). \quad . \quad . \quad . \quad . \quad . \qquad (7)$$

The functions $\alpha(f)$ and $\beta(f)$ are plotted in Fig. 2. Most of the spectral energy falls in the range 60–75 mHz, for which the total correction factor β varies between 0·96 and 1·10, that is, near unity. The shallow–to–deep factor α is more typically 0·93 in this range.

(*c*) r.m.s. *wave elevation*

For a simple statistic of the general amplitude of the waves in each record, we computed the variance of surface elevation m_0 from the integral of each corrected mean spectrum:

$$m_0 = \sum_{n=1}^{50} (0{\cdot}32)^{-1} \bar{E}_n \quad (\mathrm{cm}^2) \quad . \quad . \quad . \qquad (8)$$

Here the summation was terminated arbitrarily at $n = 50$ (156 mHz) because there were signs that $\bar{E}_n$ values for $50 < n < 64$ were affected by the background spectrum of noise, artificially inflated by the rising factors β_n. The range 1–50 covers the spectral plots of Figs. 3(a) and (b), which appear to be adequate.

The r.m.s. wave elevations or surface displacements, $m_0^{\frac{1}{2}}$, are plotted in Fig. 6. They are generally in the range 10–20 cm, but exceeded 30 cm on two occasions in February 1971. From the statistical theory of sea waves and similar Gaussian variables (Cartwright and Longuet-Higgins 1956) it is well-known that the 'significant wave height', H_s, defined as the mean of the one-third highest peak-to-trough wave heights, is given very closely by

$$H_s = 4{\cdot}0 m_0^{\frac{1}{2}}. \quad . \quad . \quad . \quad . \quad . \qquad (9)$$

So our largest values of H_s were about 1·2 m, calculated as in deep water. Near the shore line, using Eqs. (4) and (5) for a depth of, say, $h = 5$ m, and a representative frequency $f = 65$ mHz, this is equivalent to a 'significant height' of 1·6 m. This is about three times the largest swell waves recorded in November 1969, but must be considered to fall considerably short of what would be termed 'severe rollers'.

4. IDENTIFICATION OF STORMS WITH RIDGE LINES

(a) *Interpretation of swell spectral energy diagram*

The wave energy at frequency f is propagated over deep water at the speed of the group velocity $c_g = g/4\pi f$. Therefore, of the mixture of waves generated by a storm in mid ocean, those of the lowest frequency travel fastest and arrive at the distant shore first, $f = 0$ corresponding to t_0, the time origin of the source. A station at distance Δ from the storm receives wave energy at time $t = t_0 + 4\pi f\Delta/g$. Hence relating t to f shows that the frequency of the leading edge of the spectrum increases linearly with time at a rate proportional to Δ. In Fig. 3 the individual storm events are designated by the ridge lines marking the arrival of maximum energy for each frequency. The intersects of the ridge lines at $f = 0$ give the time origins t_0, whilst the gradients $\partial f/\partial t$ are inversely proportional to the distance of travel, Δ.

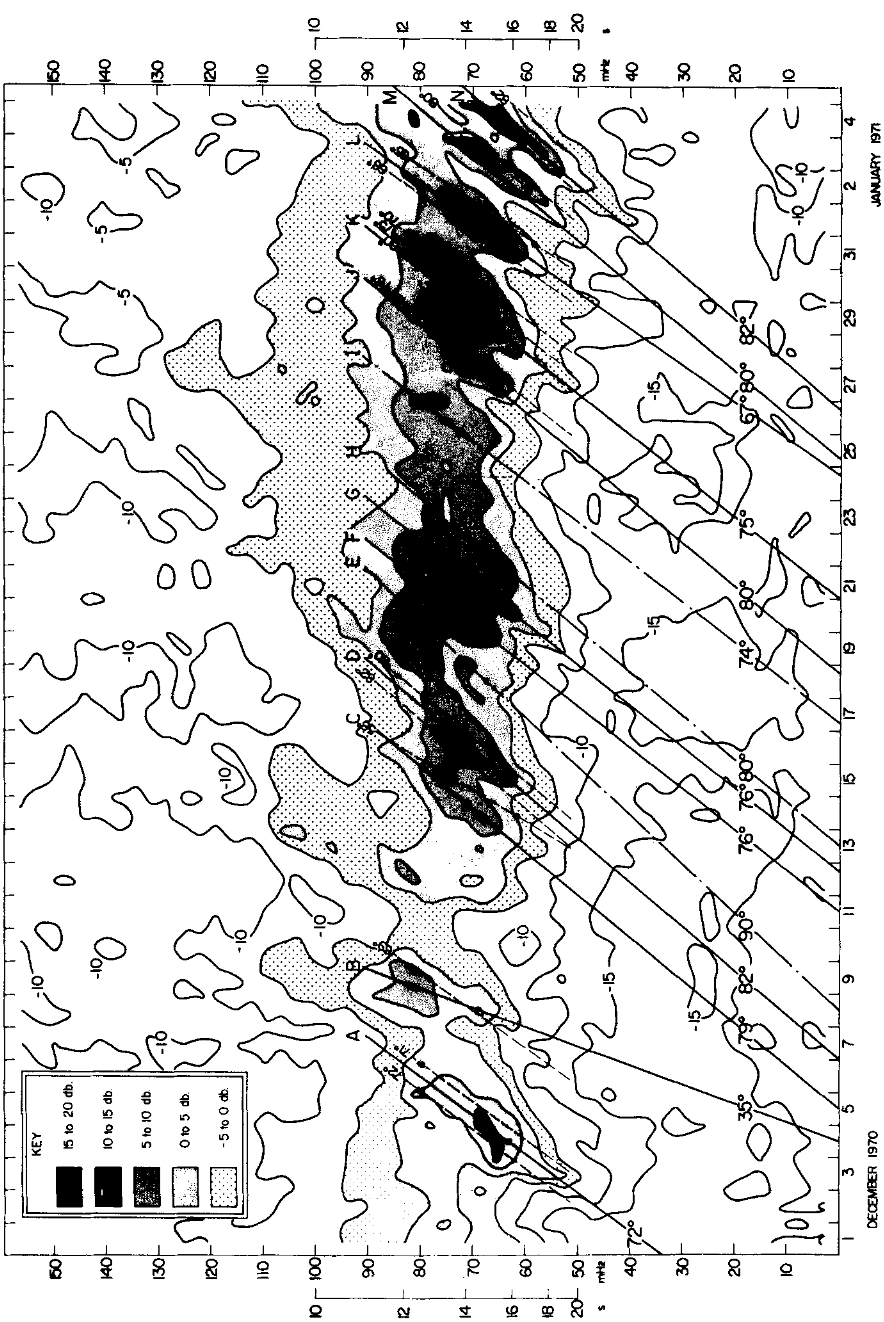
(b) *Route travelled by swell*

Swell reaches St Helena by travelling along the shortest path, that of an unobstructed great circle. Hence origins remote from St Helena – in the other hemisphere or in oceans other than the Atlantic – must be contained within the viewing angle defined by the continents. Fig. 4 shows great-circle paths through the island, tangential to the land masses, and marks along them the distance from St Helena in terrestrial degrees. For any particular date and displacement of swell origin specified by the ridge lines, meteorological conditions suitable for generating swell can be sought at the appropriate distance within the segments of the ocean shown. It is worth noting that, for the Atlantic Ocean, only storms over the northeast are in a shadow region from which swell cannot be propagated directly towards St Helena. However, most of any wave energy from the southeast sector through into the southern Indian Ocean will be reflected and refracted by the island before reaching the recorder sited on the northeast side. It is therefore unlikely that the swell records will contain any appreciable contribution from this sector, and the search for storm origins can be concentrated in the North Atlantic, the western part of the South Atlantic, and the sector through the Drake Passage.

(c) *Meteorological conditions to produce swell*

Following previous work by Cartwright (1971), the meteorological conditions for identifying swell with storm were that: (i) the wind strength should be in excess of 40 kt in order to generate swell with maximum energy occurring at the observed frequencies of 60 to 80 mHz; (ii) the wind field should either be directed towards St Helena or have components of suitable magnitude in that direction, that is, tangential to the great circle path to the island. In seeking these conditions on meteorological charts, whenever observed wind data were sparse, wind strengths were calculated only if the alignment and spacing of the isobars suggested that the winds would be suitably directed and strong. Gradient winds were calculated by standard formulae from pressure gradients, with a correction for curvature of isobars where necessary. Surface winds were then calculated from gradient winds using the (approximate) rule that wind over the sea is backed by about 15° from the isobars and is about two-thirds the gradient speed (Meteorological Office 1960, 1970; Findlater *et al.* 1966).

In seeking storm origins for the swell, reference was made to 12-hourly surface weather analyses for the southern hemisphere and tropics published by the US (NOAA) and to


KEY
15 to 20 db.
10 to 15 db.
5 to 10 db.
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DECEMBER 1970
JANUARY 1971
mHz
s

(a)

(b)

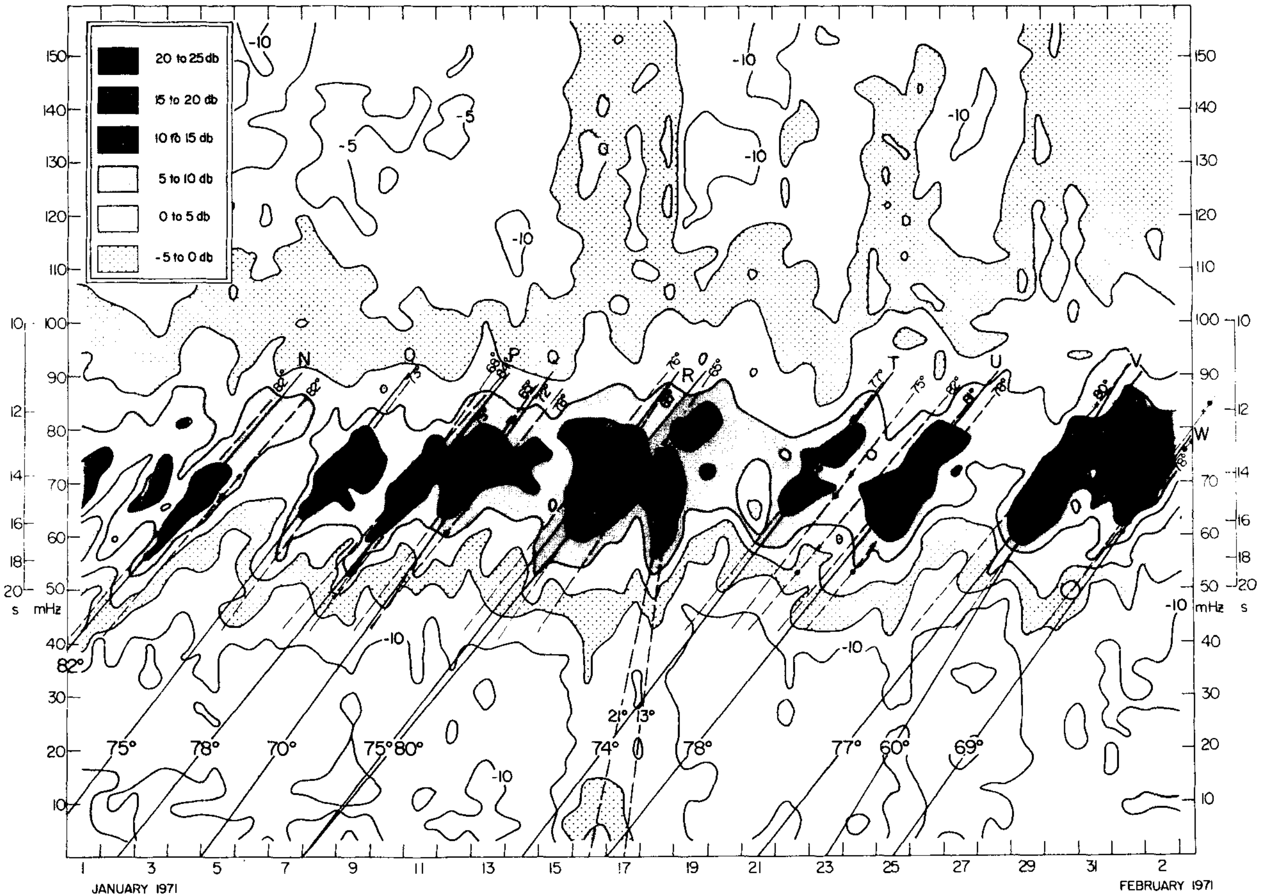
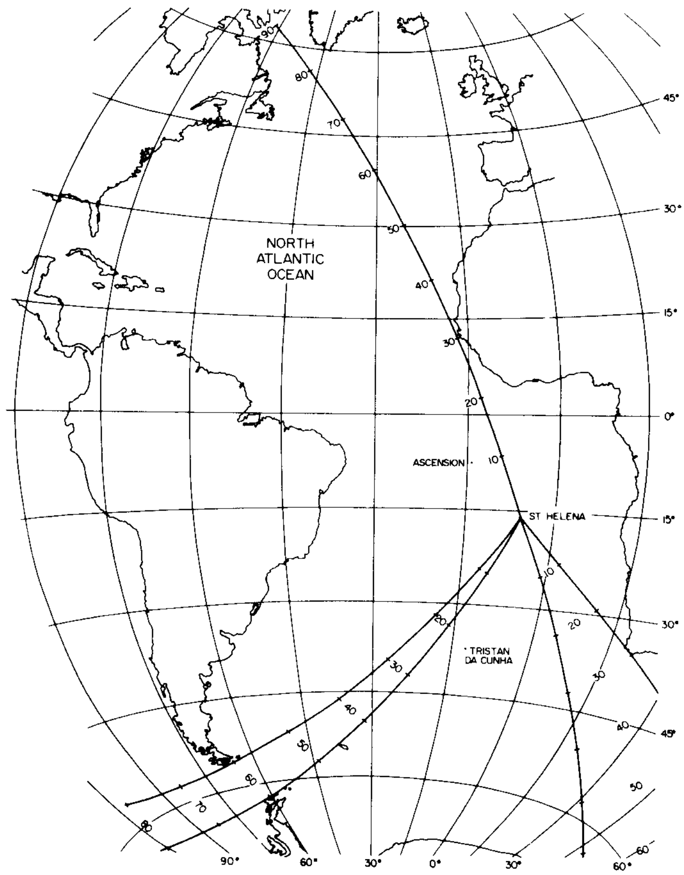


Figure 3(a) and (b). Contours of spectral energy density in decibels relative to $1\,cm^2(mHz)^{-1}$ plotted for 12 h 80 m wave records. Numbers along ridge lines are calculated distances of storm events in terrestrial degrees. Letters A · · · W reference the sets of ridge lines and the peaks.

Ridge lines: ——— defines main meteorological source of swell; – – – stems from associated meteorological conditions; —— – —— peak with little ridge structure; —— —— —— meteorological source not found.

(a)



(b)

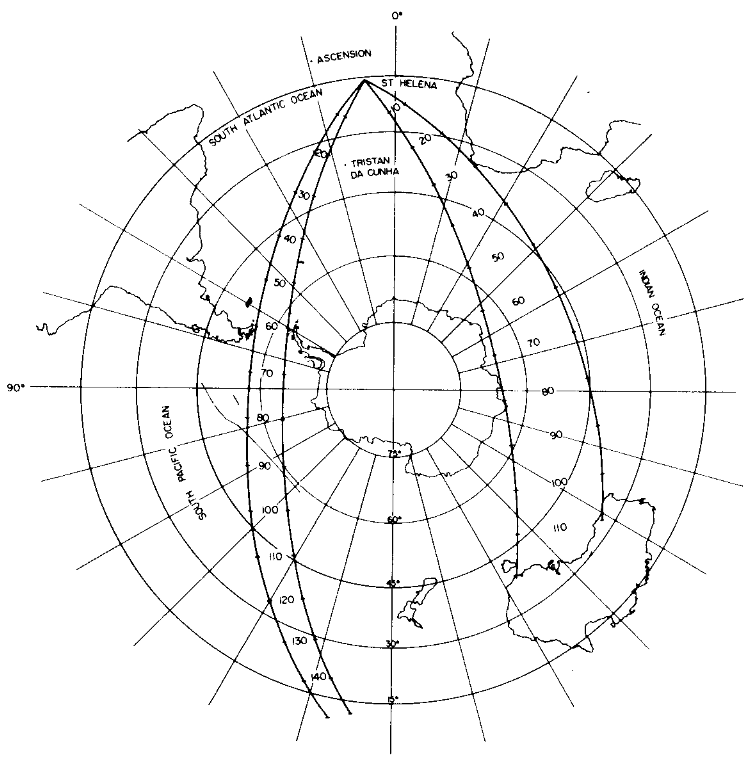


Figure 4(a) and (b). Great circles through St Helena tangential to the continental land masses with distances in terrestrial degrees.

daily weather reports for the northwest Atlantic published by the British and Venezuelan Meteorological authorities. Chart overlays showing great circle distances and routes to St Helena aided the search for location and for appropriately directed winds or isobars. It is worth noting that the determination of geostrophic wind from analysed synoptic weather charts can be biased, particularly at sea. There, lack of pressure observations has usually resulted in the drawing of isobars being influenced by the surface wind speed and direction. The derivation of wind speeds from drawn isobars is therefore not completely satisfactory and a note will be made of the origin of quoted wind speeds.

(*d*) *Storms identified through ridge lines*

Displacements and dates of storm origins indicated by the slopes and intercepts of ridge lines which had been subjectively drawn through the swell spectral energy contours are given in Table 1 columns 3 and 4. Although these ridge lines have been lettered (column 1) so that the energy peaks can be found on the energy diagram, ridges under discussion here, and listed in columns 3 and 4, were subjectively drawn and do not necessarily coincide with those in Fig. 3. These latter, some of which are listed in columns 6 and 7, will be discussed in subsection (*g*) below – they are more numerous and in many cases their slopes and intercepts differ from those of columns 3 and 4. However, referring to the energy diagram, it should be possible to picture the tabulated set relative to those drawn.

In seeking storm origins, a small error margin was allowed for distance ($\pm 5^{\circ}$) and time origin (two mid-day weather charts closest to the time sought). Despite this, only four or five of the ridge lines pointed to locations which had indubitably experienced wind fields of the strength required, i.e. over 40 kt. Three of these identified major storms with the swell. They were ridges G, N and O, and all occurred in the North Atlantic in December 1970: on the 12th at 75° from St Helena, on the 26th at 82° and on the 31st at 75° respectively. These three ridge lines actually appear in the contour diagram, Fig. 3. Ridges U and V recording swell in January 1971 gave a promising correspondence with North Atlantic storms at 82° on the 17th and 73° on the 22nd. For these two events it was later noticed that slight alterations of distance of up to 4° (see Fig. 3) or of time origin up to 16 hours, would give a better fit to the energy ridges.

Detailed analyses of all five storm events are given in Table 2 and will be discussed in section (*g*). The main considerations will be: (i) to relate the frequency of the maximum energy in the observed swell to the wind speed required to generate it, noting its occurrence; (ii) to compare the actual recorded time of peak swell with the arrival time expected from the displacement of the source from St Helena and the speed of the swell produced by the observed wind.

Besides these five ridge lines which were clearly associated with major storms, there were others with dubious identification with storms in either or both hemispheres, and still others for which no suitable conditions could be found. Although alternative fits to some of the contours were attempted, satisfactory storm origins for nine of the ridges could not be located. Clearly the subjective marking of these ridge lines could be giving a poor indication of the storm origin and so the following alternative approach was attempted.

(*e*) *Inspection of all available meteorological data for the period*

Instead of utilizing ridge line information from the swell energy diagram to locate the source of the swell, the reverse approach was tried. For the period under consideration all available meteorological data were inspected for major storms with strong wind fields, or strong components directed towards St Helena and therefore capable of propagating swell towards the island. After drawing a line on the energy diagram, Fig. 3, to meet the specifications of storm date and displacement, evidence of the arrival of swell would be given if the line defined a ridge and passed through a peak in the energy contours.

(*f*) *Properties of the meteorological data related to properties of the swell*

As before, wind speeds in excess of 40 kt were still sought as a guide to potential interest in any storm. Wherever a suitable wind field existed the wind strength W was used to estimate the frequency f_p, known as the saturation frequency, at which the maximum energy of the swell should occur. A comparison of this frequency with that which actually occurred gave an indication of the association of the wind source to the swell.

An approximate but simple rule for the relation between f_p and W is

$$f_p = g/2\pi W, \qquad (10)$$

obtained by equating the phase speed of the dominant waves to the wind speed. Such an equation is suggested by Phillips's (1966) resonance theory of generation (see also Kinsman 1965), although this is now known to apply only to the initial stages of generation. Nevertheless, recent work on generation of waves by turbulent instability (e.g. Gent and Taylor 1976) also confirms a low-frequency cut-off of energy input to waves near the frequency given by Eq. (10).

Alternatively, we also tried using an empirical formula obtained by Darbyshire (1959) for waves produced by winds over a fairly large fetch, relating the saturation period T_p to the surface wind speed in knots by

$$T_p = 1{\cdot}94W^{\frac{1}{2}} + 2{\cdot}5 \times 10^{-7} W^4 \quad \text{(s)} \qquad (11)$$

where T_p is the period for which the spectral density with respect to period is maximum. For the present purpose we may equate f_p with $1/T_p$ without serious error.

The energy contours in Fig. 3 show that peaks were usually associated with spectral periods of between 12·3 and 15·2 s. These correspond to wind speeds of 37 to 50 kt using Darbyshire's formula, or 37 to 46 kt using the wind–wave resonance condition. Hence when scanning the weather charts, calculated or observed winds suitably directed with speeds in excess of 37 kt were considered significant. By equating c_g with $gT_p/4\pi$ attempts were made to identify the corresponding swell energy on arrival at St Helena.

(*g*) *Discussion of results*

This search for strong wind fields over every segment of ocean connected to St Helena led to plausible identification of all except one of the ridges in the spectral diagram. Fig. 3 shows these ridges; all lines through the ridges were drawn so that their intercepts on the time axis corresponded to the dates of the wind fields and the gradients corresponded to the distance of the field from St Helena. Full lines denote wind fields which best correspond with the energy dispersion in the swell; dashed lines are wind fields which, while not the major cause of the swell, are felt to be contributing to the energy build-up.

The period December to January is summer in the southern hemisphere and only occasionally are there strong winds capable of generating low-frequency swell. Not surprisingly, only a few southern sources were located. Most sources were found in the North Atlantic where winter meant the frequent occurrence of storms. This can be seen from Fig. 5 which, on a single sheet, displays a month of mid-day weather maps in miniature and so gives a useful view of the movement and relative intensity of depressions. These charts, taken from weather logs published by the Royal Meteorological Society, were first used as a

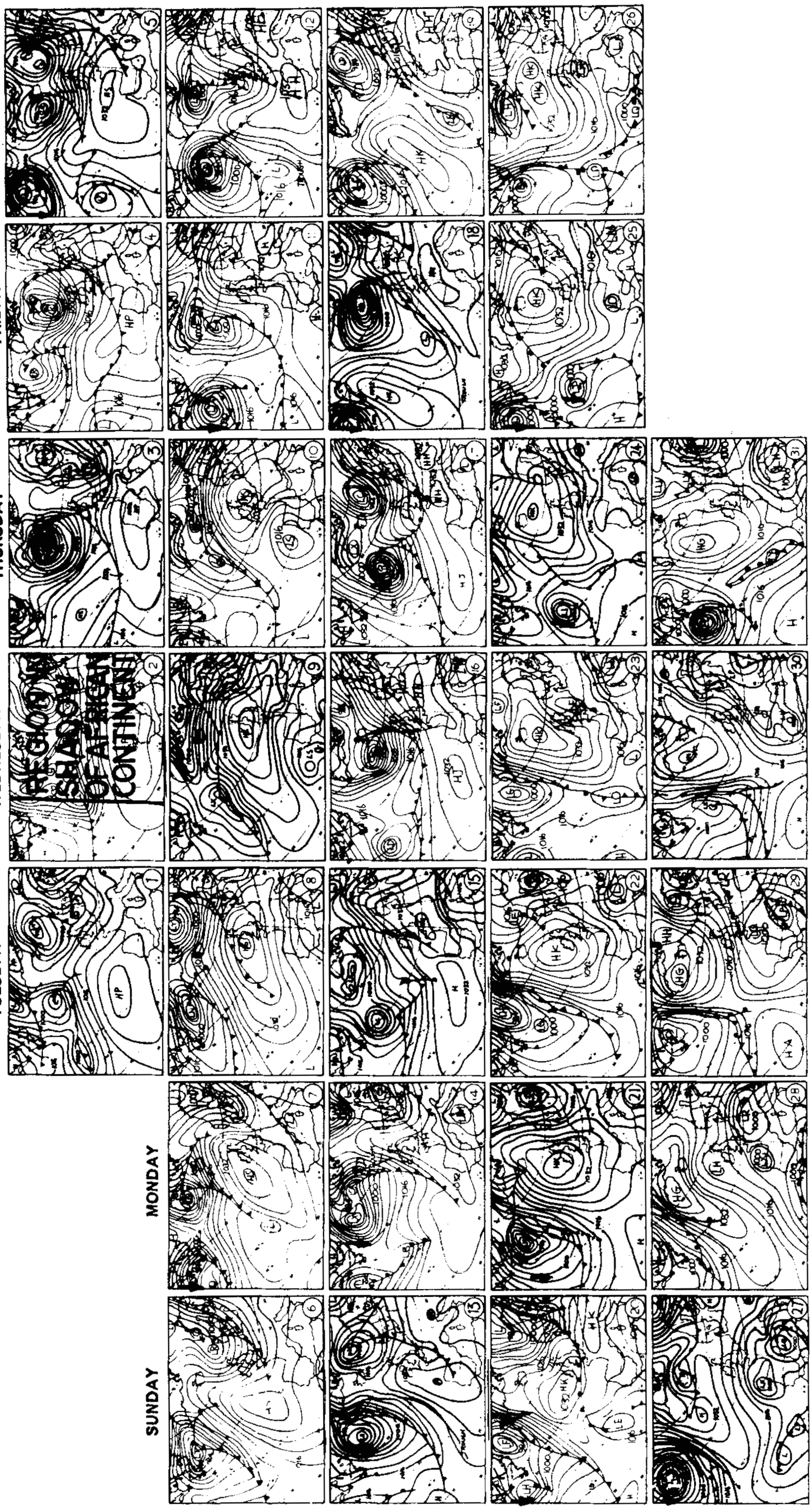


Figure 5(a). Daily weather maps for 1–31 December 1970, at 12 h GMT from R. Met. Soc. (1971). Dates are ringed at lower right-hand corner of each map. Isobars are at 4-millibar intervals. Arrows indicate direction and location of wind fields of interest.

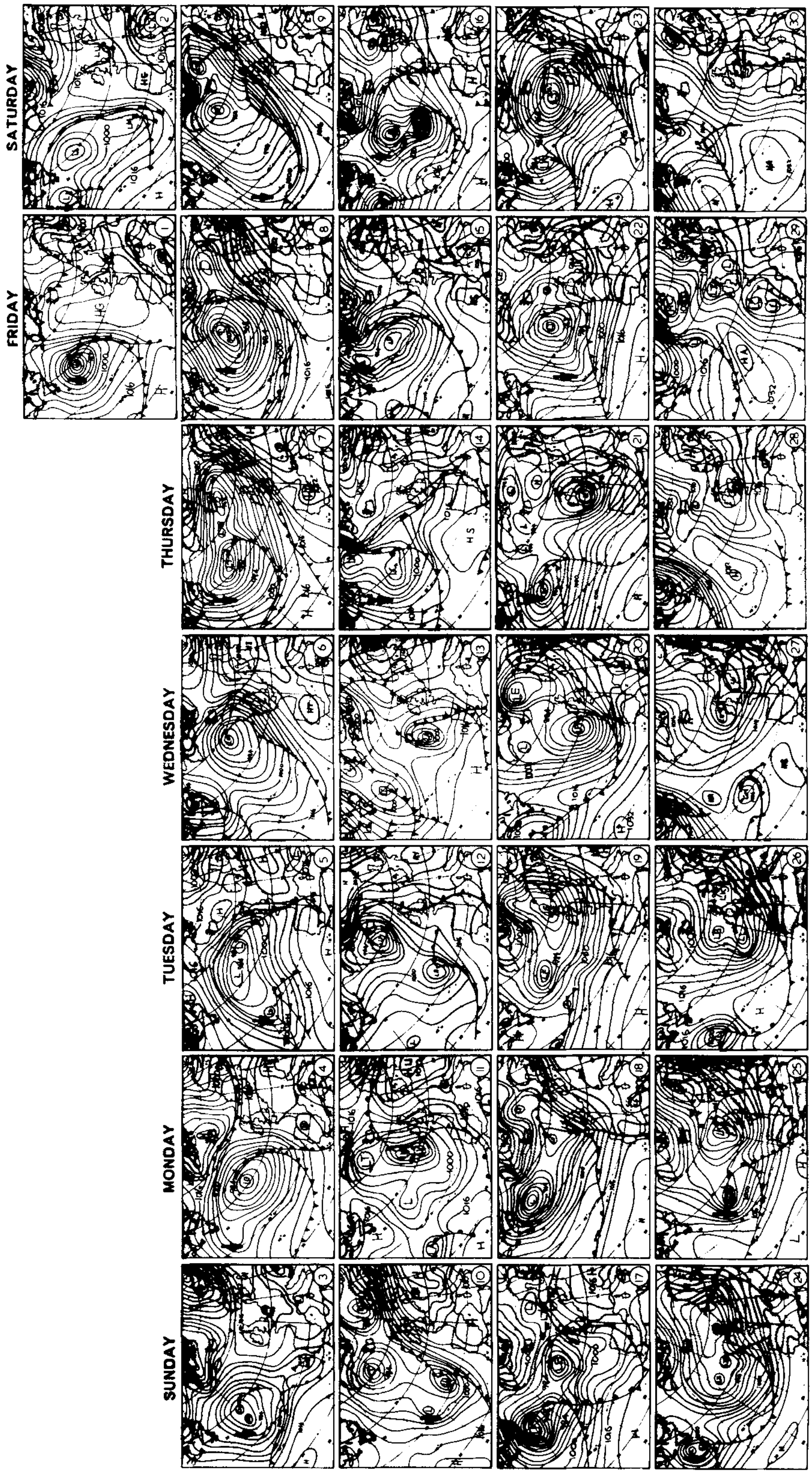


Figure 5(b). Daily weather maps for 1–31 January 1971, at 12 Z.

guide to possible dates and displacements of potential wind fields before a day by day examination of daily weather reports was finally embarked upon. It was interesting to discover that the detailed examination of daily charts did not unearth any sources overlooked when inspecting the monthly miniatures. Of course, examination of the larger charts was essential for discerning the exact dates and locations of the storms and determining the strength and direction of the most suitable wind fields.

Not every major wind field could be identified with a swell recording at St Helena; the few which could not be traced will be mentioned later (section (*i*)). Altogether, using this approach, a total of 22 energy peaks were related to their sources and so Table 2 was compiled to simplify the presentation of such a number of events. The table gives particulars of the swell (columns I to V) and particulars of the meteorological events at its source (column VI onwards).

Distances and dates in column V relate to meteorological events chosen as best identifying with the dispersive ridges in the swell energy diagram. The ridge lines so defined should be the best fit to the energy contours and their slopes and intercepts should be unique, whether ascertained from energy contours or meteorological data. Unfortunately this was not always the case; the contours of ridge B for example pointed to a source at 63° at 14 z on 30 November whereas the meteorological conditions suggested that the swell propagated from 69° at 12 z on the 30th. In this case, as generally whenever a better fitting ridge line could result from any slight displacement of the source, six-hourly meteorological charts have been inspected where available. There are some instances (see ridge V) of two meteorological events defining separate dispersive routes to a single energy peak, as when meteorological events in the two hemispheres generated swell waves which arrived at St Helena simultaneously. The alphabetic reference labels given to the ridge lines shown in the energy diagram can also be found in column I of the table.

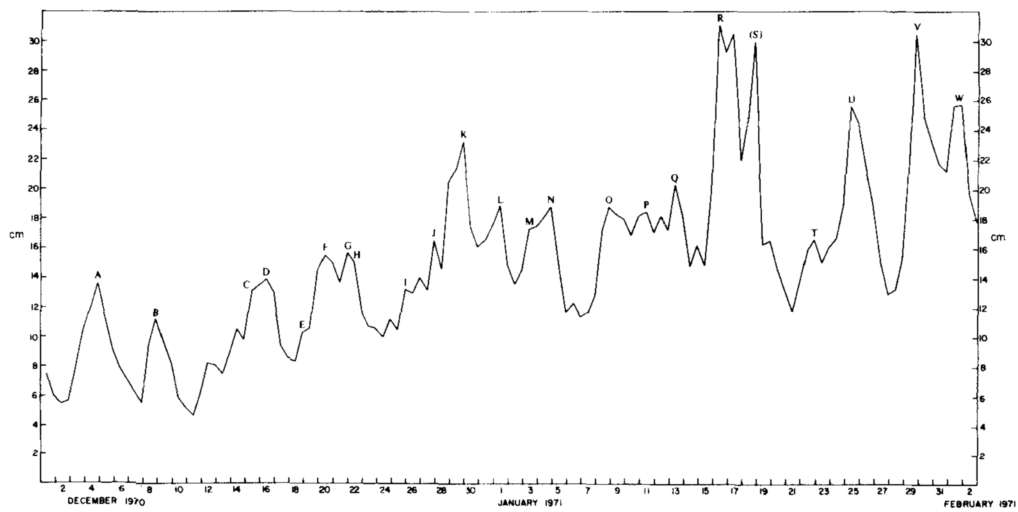


Figure 6. r.m.s. surface displacement of swell. Letters A · · · W refer to the energy peaks of Fig. 3.

The actual amplitude of the swell waves (given in Table 2 column II) can be seen from Fig. 6. This shows variations of the r.m.s. surface displacement with time, as discussed in section 3(*c*). Throughout the period of the records, the height of the swell gradually increases from the beginning of December to the end of January. The greatest peaks, over 25 cm, occur in the latter half of January. These peaks and the first two in December are distinct rises and falls in energy level, the others consist of multiple small peaks on a background of generally high wave activity. All lettered peaks except S have been related to meteorological sources in the table. Peak S on 19 January corresponds to a clearly defined ridge in Fig. 3 but we were unable to find a source at the suggested time and distance (see Table 2). Minor peaks in Fig. 6 which are unlabelled are apparently insignificant.

Daily comments on the sea state as visually observed throughout the period were noted in a log, firstly kept by one of the authors and later by the harbour master at James Bay. All notes of high swell were identified both with an energy peak and a source. Log entries made on the dates of peak swell are of interest and have been reproduced in the table. During his stay the author whenever possible noted the direction of the approaching swell; this was of particular interest in the case of ridges A and B where the source locations were found to agree with his comments.

Energy in the swell mostly lay within a band of 50 to 100 mHz, i.e. periods 20 to 10 s. Saturation periods varied from 12·3 to 15·2 s with each occurrence of swell; the peak energy levels ranged from 7·1 to 20·1 db (see Table 3). Energies of the order of 7 db only record the arrival of swell waves but 20 db peaks have been observed by Snodgrass *et al.* (1966) to correspond to periods of rollers. Between 16 January and 2 February five energy peaks were close to this value, being greater than 17·4 db (Table 2 column IV). Four of the five had saturation periods of 15·2 s, and the other 14·5 s, so that each demanded wind

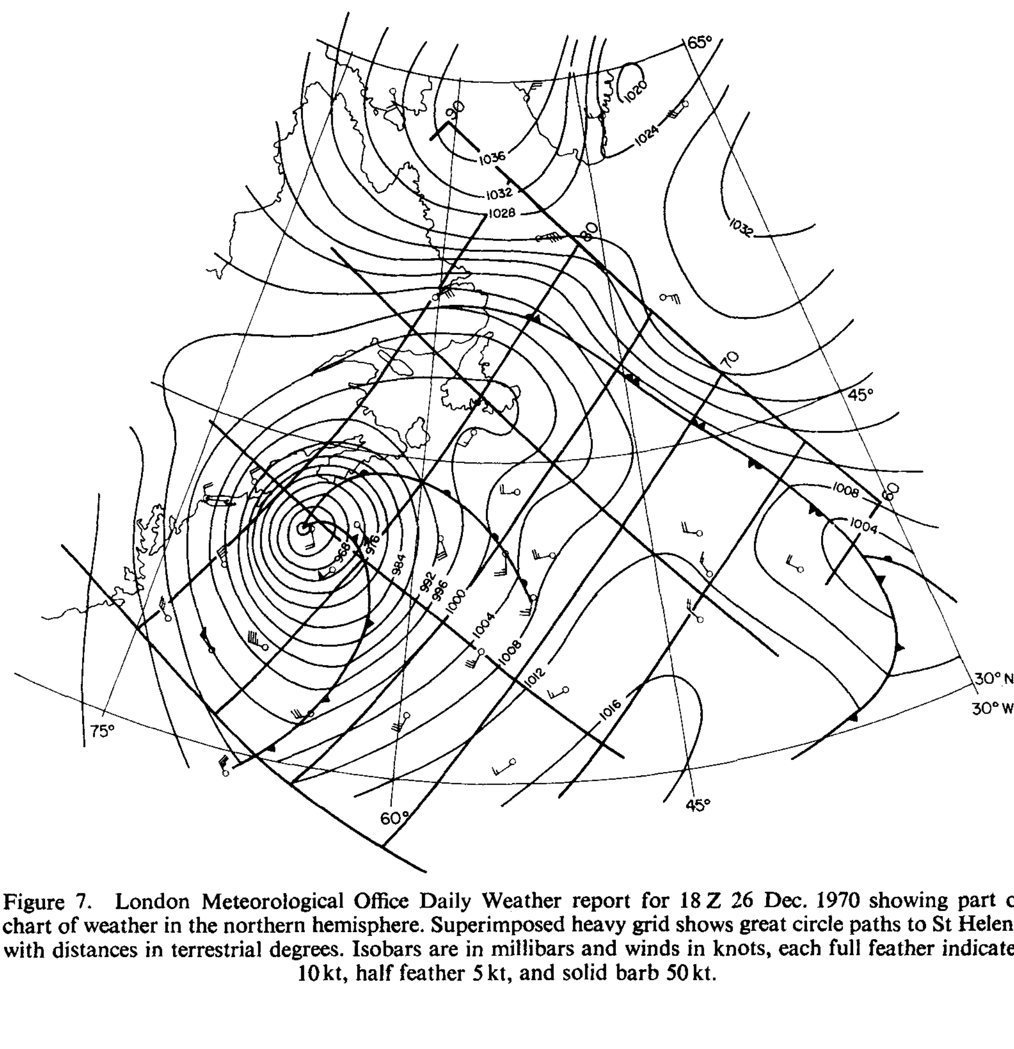


Figure 7. London Meteorological Office Daily Weather report for 18 Z 26 Dec. 1970 showing part of chart of weather in the northern hemisphere. Superimposed heavy grid shows great circle paths to St Helena with distances in terrestrial degrees. Isobars are in millibars and winds in knots, each full feather indicates 10 kt, half feather 5 kt, and solid barb 50 kt.

speeds at source in excess of 45 kt. To help confirm the identity of source fields with swell peaks, the magnitudes of the winds required to generate swell at the spectral period of the peaks are given in Tables 2 and 3. These wind speeds are marked D and R to denote calculations from Darbyshire's and the resonance equations, respectively.

(*h*) *General properties of storms generating swell at St Helena*

The meteorological events for which swell was recorded have been detailed in Table 2 so that their properties can be compared with those of the swell. A brief description of the meteorological picture, highlighting the geographical location of the storm, is given in column VI. Three of the major storms, corresponding to ridges N, P and V, can be seen in the weather charts of Figs. 7 to 9. Usually winds were directed towards St Helena over a period of hours and at distances varying by one or two degrees. Over this period wind speeds might increase to a maximum and then subside again. Hence there would be a small choice, dependent on location, date and strength, in determining the wind field which gave best fit to the swell energy contours. This field would be regarded as the main source and the remaining related wind fields would be described as associated meteorological data which contribute to the magnitude and duration of the swell.

An extra indication of the relation of source to swell was obtained by comparing the expected time of arrival of energy from the source (column IX) with the time recorded at St Helena (column I). Knowing the source distance from the island and the speed of the

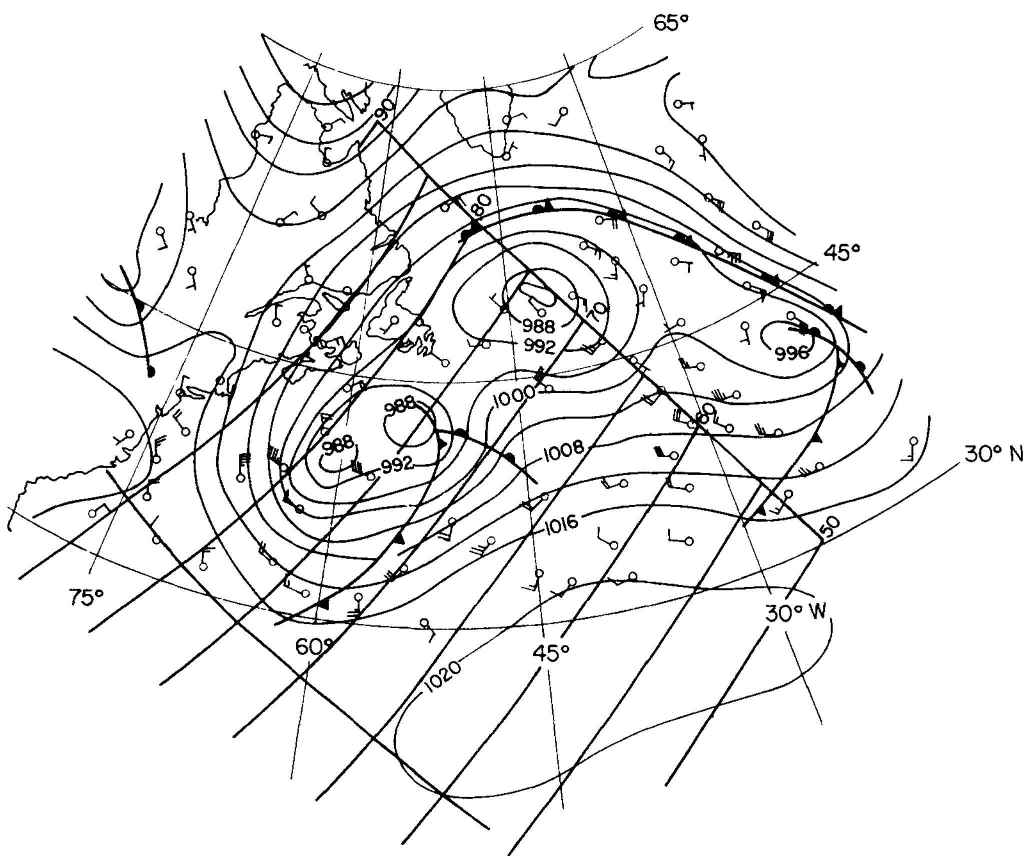


Figure 8. London Meteorological Office Daily Weather report for 12 Z 2 Jan. 1971.

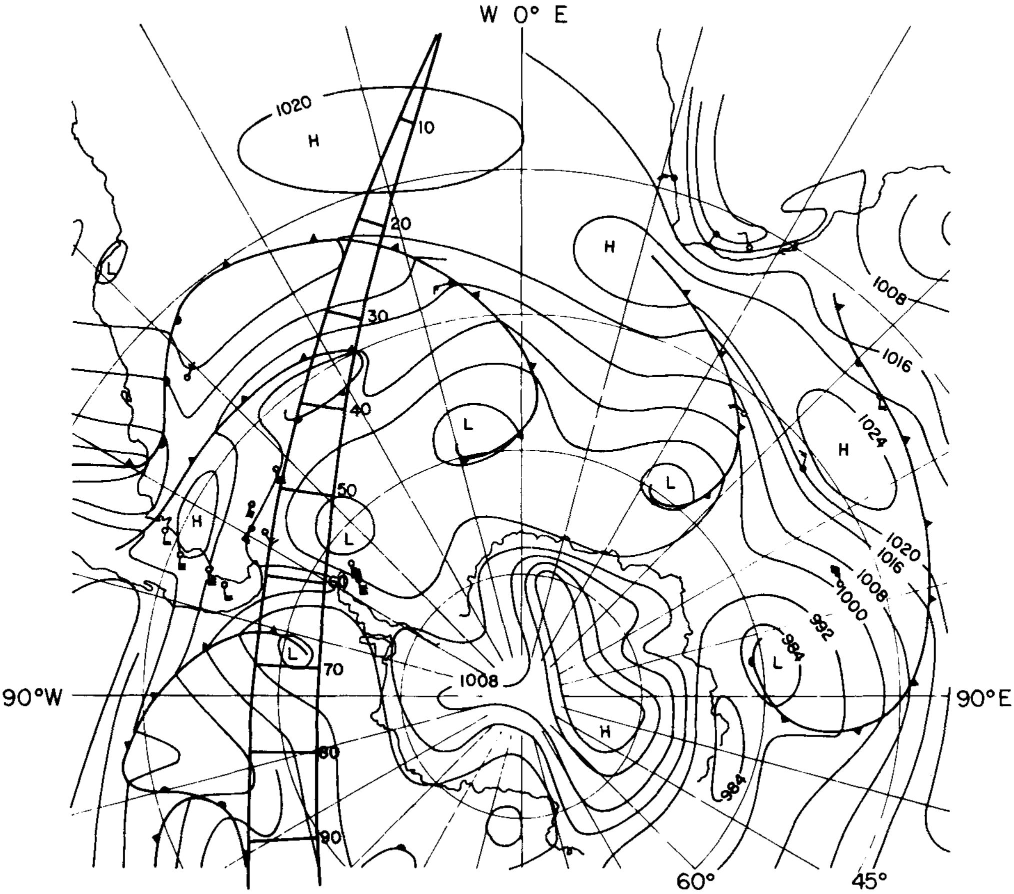


Figure 9. US Weather Bureau chart of weather in the southern hemisphere at 12 Z 23 Jan. 1971.

swell, the time of travel can be calculated from $t = \Delta/c_g$. Time of travel added to time at source gives the expected time of arrival. These times mostly differed from recorded arrivals of peak swell by less than 18 hours. Two-thirds differed by less than half a day. Only in four instances, ridges F, R, U and G, were the differences of the order of one day. The first three occurred when using the empirical equation to relate wind speed to saturation frequency and the last when using wind–wave resonance.

Agreement between source and swell is best seen from the energy diagram (Fig. 3). Each ridge line has a plus and a dot marked on it. These relate to the wind speed at source; the saturation period associated with it (Table 2 column VIII) can be read from the ordinate, and the expected arrival time, discussed above, can be read from the abscissa. Deviations from the periods and times of peak energy either reflect deficiencies in the wind field at source or in the equations relating wind speed to swell frequency. (Plusses correspond to the empirical and dots to the resonance equations.) Discrepancies in the time or location of a source are revealed by the fit of the ridge line to the contours. General comments on the appropriateness of the fit are given below each set of data.

(*i*) *Some failures*

All the storms discussed above were found to be associated with swell at St Helena. However, not all instances of suitably directed high winds discovered in the day by day inspection of meteorological charts were traced through to a swell recording at the island. On 6 December, a depression to the northwest of Bermuda (ridge D) was related to a recording of swell on the 16th. By midday on the 8th the depression had progressed further to the northwest and the isobar alignment at $\Delta = 80°$ indicated west-northwest winds towards St Helena. Observations in the vicinity suggested wind strengths of 40 to 50 kt. This gave the estimated arrival time for a swell recording as between 12 Z on 16th and 12 Z on 18th depending on the wind speed, but no ridge could be found to verify this. A calculation of wind strength from the pressure gradient gave only 30 kt winds, weak by comparison with surrounding observations and certainly not strong enough for swell. The most likely explanation of this missing ridge is that wind strengths were either much less than observations suggested, or were very short-lived.

Another occasion when suitably directed and very high winds could not be identified with a peak or ridge in the energy diagram is mentioned in the comments on the peak of 22 December in Table 2. On 14 December the depression associated with this peak was moving out of the area but there still existed 50 kt observed winds (55 kt calculated from the pressure gradient) suitably directed at 82° distance. This gives an estimated arrival time of 17 Z on the 22nd, 50 kt winds generating a swell which travels at 10°/day.

Sometimes, in the aftermath of a storm which had been identified with swell, there still remained high winds for which no swell was recorded. For example at 12 Z on 10 January a secondary low developed within a depression already associated with an energy ridge. Northwest of Corvo, 63° from St Helena, 50 kt winds were observed which could not be related to a swell peak. Other examples of this, among the cases listed in Table 4, could possibly relate to the retention of energy in the swell.

Three meteorological events which did not define a ridge but which were associated with peaks of swell energy should finally be mentioned. One occurred in the southern hemisphere on 8 December, the other two occurred in the northern hemisphere on 13 and 17 December. They are commented on in Table 2 entries E, H and I, respectively. Each peak was linked to winds at source of over 40 kt and close to that required to produce peak energy at the saturation period of the swell. Two of the peaks, H and I, were recorded in the log as heavy swell, the peak energy reaching 12·1 db; peak E, recorded as small, reached 7·1 db. All three peaks were of short duration as was the duration of the wind field observed at the source. This may account for the lack of ridge structure in the energy contours.

5. Conclusions

None of the swell systems encountered had the spectacular height dimensions to inspire the sort of description quoted in our first paragraph, so strictly we have again failed to record genuine 'rollers'. Still, many of the wave amplitudes were considerably greater than the largest recorded in our 1969 session, so it seems even more reasonable to suppose that 'rollers' are indeed of the same character as the swell considered here, but with further increased amplitude. In this connection it is relevant to note that many of the wave conditions observed at Ascension Island in 1876–77 by Captain East (see section 1), and described as 'heavy rollers', still had wave periods of order 16–18 seconds as in lesser swells there, and as in the present recordings. Admittedly, 15–16 s is more typical of the present recordings (Fig. 3), but it is well known that the higher wind speeds and greater fetch distances necessary to generate higher wave amplitudes also lower the dominant frequency of the energy spectrum.

The identification of most of our strong spectral ridge lines with North rather than South Atlantic wind systems shows that the northern area is more effective for generating the swell apparent at Jamestown, and probably for producing genuine rollers also. This is in keeping with the northwesterly aspect of the Jamestown waterfront, but contrasts with our findings in 1969, when the largest swells were actually observed to approach the island from the southwest. It is probable that gales from the southwestern Atlantic frequently provide low background swells at all times of the year, but these are masked by more energetic systems from the northwest as soon as the northern winter sets in. At all events, the commonest origin seems to be large deep depressions centred around 45°N 45°W, southeast of Newfoundland, and these appear most frequently in the earliest months of the year.

The suggestion made by Cartwright (1971), that occasional bursts of swell may correlate with tropical typhoons in the southwest Pacific, having travelled along the great circle route through Drake Passage, was not substantiated in the present series of recordings. Possibly our method of detection was too rough. Clearly, distinction between northern and southern swell directions would be greatly helped by using a pair of wave sensors (Munk *et al.* (1963) used a triad of sensors), by which wave direction can be objectively determined from phase differences. Alternatively, simultaneous swell recording at St Helena and Ascension would give useful information from the times of arrival of given spectral bands, as in the much more ambitious Pacific experiment of Snodgrass *et al.* (1966).

The detailed process of identifying (a) the precise orientation of the ridge lines on the spectral diagram, and (b) the presence of sufficiently strong winds over a reasonable area of ocean, proved more difficult, or subject to error, than we anticipated. Part of the difficulty may be attributed to the relative shortness of our wave records (1¼ hours compared with 3½ hours used by Munk *et al.* (1963)), which enhances the random variability of their energy spectra. Some sampling variability must also be present in the weather charts, and some degree of subjective interpretation is inevitable in drawing both sorts of diagram. The detail of the weather charts also depends on the density of reporting ships, which tend if possible to avoid areas of strong winds. Nevertheless, the few outstanding events such as the apparently well-defined spectral ridge on 18 January, for which no corresponding storm could be traced on any weather chart, suggest that some weather anomalies pass over the ocean without record.

Finally, we may be criticized for not having attempted any analysis of the relation between the amplitude of the observed swell and that of the much higher waves generated in the original storms, or of the considerable change in spectral shape from storm waves to swell. It would indeed have been nice to model the generation and propagation of the spectral energy from source to observing point, with due allowance for nonlinear scattering and for shadowing by the continental boundaries, and compare the results with Fig. 3. Our excuse is that the work involved would be an order of magnitude greater than we were prepared to devote to this experiment. Many of the relevant problems suggested by such a scheme were tackled and answered more conclusively in the much more elaborate experiment of Snodgrass *et al.* (1966), where the history of the propagation could be traced through a chain of recorders across the whole Pacific Ocean. Our one recorder at St Helena with its ambiguity of direction hardly justifies such an effort. Nevertheless, we feel that the present limited exercise gives useful results.

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TABLE 1. RIDGE LINES INDICATED BY (a) SWELL ENERGY CONTOURS AND (b) THE OCCURRENCE OF STORMS

(NA: North Atlantic; DP: Drake Passage; EA: Eastern Antarctic; StH: St Helena. Distances in terrestrial degrees.)

Reference letter	Time and date of swell energy peak (Z)	1970	Swell contours: Time and date of origin (Z)	1970	Swell contours: Distance (degrees)	Swell contours: Meteorological conditions	Storm: Time and date of origin (Z)	1970	Storm: Distance (degrees)	Storm: Meteorological conditions
A	18	4/12	09	29/11	47	Nothing suitable	00	27/11	72	NA depression 48 kt winds
D	12	16/12	14	8/12	66	NA, DP, nothing suitable, EA 40 kt	00	7/12	81	NA depression 45 kt winds
G	12	21/12	19	12/12	75	12z 12/12 depression NW of event in NA 40 kt winds, EA 40 kt	18	12/12	76	NA depression 48 kt winds
K	00	30/12	02	22/12	64	NA 35 kt winds	00	21/12	75	NA depression 42 kt winds
		1971								
L	12	1/1	10	25/12	60	DP 30 kt winds	18	24/12	67	Central NA depression 48 kt winds
M	12	3/1	18	25/12	77	Nothing of suitable magnitude. Although this line was a better fit to the contours than the accepted 80° identity	06	25/12	80	Depression off Nova Scotia, 44 kt winds
N	00 (from Fig. 3(a))	5/1	00	28/12	69	Nothing suitable	18	26/12	82	Intense depression in Philadelphia region, 50 kt winds
	above ridge from Fig. 3(b)		18	26/12	82	Intense depression 50 kt winds in NA				

O	00	9/1	06	31/12	75	NA deepening depression 40 to 50 kt winds	00	31/12	75	NA depression winds 40 kt intensifying to 50 kt
				1971				1971		
Q	12	13/1	22	3/1	62	Nothing suitable	00	5/1	70	Depression in mid NA, 40 kt winds
R	12	16/1	00	7/1	91	Nothing suitable	00	8/1	75 to 80	Depression in mid NA, 43 kt winds
S	00	19/1	12 to 12	16/1 17/1	20 to 12	Nothing suitable	Not shown in meteorological charts			
U	12	25/1	00	17/1	82	NA depression 40 to 50 kt winds not quite towards StH, better directed at 78°	00	17/1	78	Well-formed NA depression winds 42 kt
V	00	30/1	04	22/1	73	NA depression 35 kt winds. Winds further away and 18 h earlier are better suited	12	21/1	77	Depression off Newfoundland, winds 45 kt.
							12	23/1	60	Southern hemisphere off Graham Land, winds 45 kt
W	00	2/2	02	24/1	78	NA wind direction suitable but strength weak. Probably contributing but better later and nearer to StH	12	25/1	69	Central NA depression winds of order 50 kt. Suitably directed over previous 24 h starting at 30 kt

TABLE 2. BEST METEOROLOGICAL FIT TO PEAK SWELL

Column
I Date of energy peak (day and tenths/month).
II r.m.s. swell height (cm).
III Maximum energy density (db).
IV Period at which peak occurs (s).
Wind speed required for energy saturation at this period (kt).
R – derived from Eq. (10)
D – derived from Eq. (11)
ll and ul – lower and upper limits associated with quoted highest level energy contour of ridge
V Event distance (terrestrial degrees): time (Z) and date of origin.

Column
VI General meteorological position.
VII Wind speed (kt) and direction to St Helena.
obs – observed
cgs – calculated from geostrophic winds
cgr – calculated from gradient winds
VIII Period of energy saturation of swell associated with surface wind speed at origin (s).
R – derived from Eq. (10)
D – derived from Eq. (11)
IX Date of swell at St Helena based on distance and speed of travel.
R and D as above

Column
X Hemisphere; meteorological event distance (terrestrial degrees); time (z) and date.
XI Wind speed (kt) and direction.
obs – observed
cgs – calculated from geostrophic winds
cgr – calculated from gradient winds
XII Period of energy saturation associated with wind speed (s).
R – derived from Eq. (10)
D – derived from Eq. (11)

I	II	Particulars of swell III	IV			V			VI	Best meteorological fit to ridge VII	VIII		IX		Associated meteorological data X			XI	XII	
				R	D						R	D	R	D					R	D
date	(cm)	(db)	(s)	(kt	kt)	(°)	(Z)	date		(kt)	(s	s)	date	date	(°)	(Z)	date	(kt)	(s	s)
4·9/12	13·5	13·1	15·2 Over 10 db	46	50	72	00	27/11	Low 36N 60W at 00 27/11. Winds directed to StH at 72°. Wind compts at 77° also effective.	48 WNW cgs	15·8	14·8	4·5/12	5·0/12	N 72	12	26/11	38 WNW cgr	12·5	12·5
A			ll 12·1	37	37										N 77	00	27/11	49 compt of obs	16·2	15·0
			ul 16·1	50	54										N 71	12	27/11	38 WNW cgr	12·5	12·5
Comments:	72° event at 00 27/11 ties in with peak of ridge, thus acceptable as origin. Wind strengths sufficient for period of energy saturation. Extent of effective wind field ranges 72° to 77°, the latter defining a line through edge of ridge. Events at 72° 26/11, 71° 27/11 define width of ridge; contributions may be significant.																			
8·9/12	11·2	9·3	12·3 Over 5 db	37	37	63	14	30/11							N 69	12	30/11	37 WNW cgr	12·2	12·3
						35	12	4/12	Low 40S 35W.	37 WSW obs max	12·2	12·3	9·3/12	9·2/12						
B			ll 11·3	34	33															
			ul 13·1	40	41															
Comments:	At 69° winds of 37 kt are enough to generate swell of saturation period 12·3 s but displacement should be 63° hence poor fit. At 35° observed wind strength agrees with saturation period of energy peak and the 35° ridge line is good fit to contours of weak ridge. Also this agrees with observation that much swell activity came from south.																			
14·4/12	10·5	10·0	14·5 Small peak	44	47	79	12	5/12	Low 48N 60W. Suitable winds recorded at 35N 65W.	40–45 WNW–NW obs	14·8	14·0	14·3/12	14·8/12	S 58	12	8/12	41 WSW to	13·5	13·1
15·4/12	13·1	11·8	13·3 Over 5 db	40	42						13·2	12·9	15·4/12	15·6/12				49 WSW cgs	16·2	15·0
C			ll 12·9	39	40															
			ul 15·2	46	50															
Comments:	Swell spectrum has small peak on 14/12 and another on 15-16/12. Period at 14/12 tallies with 45 kt wind; period at 15/2 tallies with 40 kt. The 58° event may be associated with ridge, but not with contour *alignment; 41 kt winds match peak at 11·8 db. Heavy swell reported at St.H at 15·0/12.*																			
16·4/12	13·9	12·7	13·9 over 10 db	42	45	82	00	7/12	Low NW Bermuda. Suitable winds 82° from StH at 12 6/12, 40–45 kt.	42 WNW–NW obs	13·9	13·4	16·8/12	17·1/12	N 82	12	6/12	40 WNW obs	13·2	12·9
			ll 12·9	39	40										N 80	12	7/12	35 WNW obs	11·6	11·9
			ul 15·0	46	69										S 81	12	7/12	38 WNW to	12·5	12·5

D							Similar conditions until 12 7/12.										32 WNW cgs		

Comments: Period of peak energy corresponds to 42 kt winds from 82° event at 00 7/12. Conditions from 6/12 to 7/12 seem to define trailing edges of ridge, suggesting winds suitably directed for 24h. The southern event may be responsible for persistence of peak until end of 16/12. Heavy swell reported at StH.

18·9/12 E	10·3	7·1	13·9 42 45 over 5 db ll 11·9 36 35	90	12	8/12	Low 60S 120W.	37–45 WNW cgs	14·8 12·2	14·0 12·3	18·5/12 20·7/12	19·1/12 20·6/12

Comments: Significance of small peak without obvious ridge structure only suggested by weather event. Reports from StH were calm to small swell at 10 19/12.

19·9/12 F	15·5	12·7	14·5 44 47 over 10 db ll 12·9 39 40	76	12	11/12	Low 45N 52W. Winds about 40 kt towards StH, 75° distant.	42 WNW obs	13·9	13·4	20·6/12	20·9/12

Comments: 76° line follows contours through peak; 42 kt wind corresponds to observed period. Heavy swell reported at StH.

21·9/12 G	15·6	12·0	13·9 42 44 over 10 db ul 15·2 46 50	76	18	12/12	Low 50N 47W. Winds at 76° stay towards StH until 00 13/12	48 WNW cgr	15·8	14·8	20·7/12	12·2/12

Comments: Observed winds 35–65 kt at 76° distance, but not all in proper direction. Conditions at 18 12/12, 76° give excellent fit to contours, with correct saturation period for 48 kt wind. Heavy swell reported at StH.

22·4/12 H	15·0	12·1	14·5 44 47 over 5 db ll 12·9 39 40 ul 16·0 49 53	80 to 83	12	13/12	Low 56N 45W. Steep gradients in rear.	47 WNW cgs	15·5	14·5	22·0/12	22·6/12

Comments: Isobars correctly aligned from 00 13/12 to 06 14/12 at distance 83°, but no wind strengths recorded. No very clear spectral ridge, but small peak is in appropriate place. Heavy swell reported at StH.

No identifiable ridge in spectrum				82	12	14/12	Same low as for H, later date.	50 WNW obs 55 WNW cgs	16·5	15·3	22·7/12	23·4/12

26·9/12 I	14·0	12·1	12·8 39 40 over 10 db ll 12·3 37 37 ul 13·4 41 42	74	06	17/12	Low 51N 35W. 38–48 kt towards StH.	42 NW cgs	13·9	13·4	26·1/12	26·4/12

Comments: No clear ridge, but small peak identifies with line. Wind correct for saturation period. Heavy swell reported at StH.

27·9/12 J	16·5	14·8	14·5 44 47 over 10 db ll 13·4 41 42 ul 15·2 46 50	80	18	18/12	Belt of high winds around 40N 65W.	42 WNW obs	13·9	13·4	28·3/12	28·6/12	N 80 N 78	00 12	19/12 19/12	40 WNW 35 WNW obs	13·2 11·6	12·9 11·9

Comments: 42 kt winds account for peak with about the right saturation period, although 44 kt would have been more convincing. The associated events near 80° distance may account for persistence, but winds are rather too low for peak energy. Heavy swell reported at StH.

TABLE 2. Best meteorological fit to peak swell (*continued*)

I	II	III	IV			V			VI	VII	VIII		IX		X			XI	XII	
		Particulars of swell							Best meteorological fit to ridge						Associated meteorological data					
				R	D						R	D	R	D					R	D
date	(cm)	(db)	(s)	(kt	kt)	(°)	(Z)	date		(kt)	(s	s)	date	date	(°)	(Z)	date	(kt)	(s	s)
29·9/12	23·2	16·6	13·9 over 15 db	42	45	75	00	21/12	Low 47N 50W. Winds towards StH at 75°.	42 WNW obs	13·9	13·4	29·9/12	30·3/12	N 80	12	20/12	42 WNW cgs	13·9	13·4
			ll 13·4	41	42										N 78	18	20/12	44 WNW	14·5	13·8
			ul 15·3	46	50										N 75	12	21/12	45 WNW obs	12·5	12·5
															S 77	12	21/12	38 WNW	12·5	12·5
K															to S 70	12	22/12	38 WNW cgs	12·2	12·3
Comments: 75° ridge line from 00 21/12 fits contours well with suitable winds for period. Winds at 80° and 75° identify with leading and trailing edges respectively. Southern events may contribute, but weakly. Heavy swell reported at StH.																				
1·4/1	18·9	16·6	14·5 over 10 db	44	47	67	18	24/12	Low 42N 40W.	48 NW cgs	15·8	14·8	31·7/12	1·2/1	N 68	06	24/12	43 WNW cgs	14·2	13·6
			ll 13·4	41	42										N 68	12	24/12	57 WNW cgs	18·8	17·3
			ul 16·0	49	53										N 65	00	25/12	44 WNW obs	14·5	13·8
L															N 65	12	25/12	52 WNW cgs	17·1	15·8
Comments: 67° ridge line fits contours well with suitable winds for period. Other events noted give less convincing fit but probably contribute to energy. Calm to heavy swell variably reported at StH.																				
3·4/1	17·3	14·5	14·5 Over 10 db	44	47	80	6	25/12	Low off Nova Scotia.	44 WNW cgs	14·5	13·8	3·4/1	3·8/1	N 84	18	24/12	39 WNW obs	12·9	12·7
			ll 13·4	41	42										N 82	12	25/12	36 WNW cgs	11·9	12·1
M			ul 15·2	46	50										N 80	18	25/12	48 WNW cgs	15·8	14·8
Comments: 80° ridge line fits fairly well with suitable winds for period. The earlier and later events noted give lines through peak but winds are rather too weak.																				
4·9/1	18·8	14·8	14·5 over 10 db	44	47	82	18	26/12	Low 40N 72W.	50 WNW obs	16·5	15·3	4·0/1	4·6/1	N 82	12	26/12	50 WNW obs	16·5	15·3
			ll 13·9	42	44					48 WNW cgs	15·8	14·8	4·3/1	4·9/1	N 82	12	27/12	45 WNW	14·8	14·0
N			ul 17·8	54	59															
Comments: The main weather event agrees well with energy ridge in all respects. The earlier and later events noted identify with the leading and trailing edges. Heavy to small swell reported at StH.																				
9·9/1	18·8	15·4	13·9 over 15 db	42	44	75	00	31/12	Low 38N 56W intensifying with increasing winds towards StH.	40 WNW cgs	13·2	12·9	9·4/1	9·6/1	N 73	12	31/12	44 WNW to	14·5	13·8
O			ul 14·5	44	47					possibly up to 50	16·5	15·3	7·5/1	8·1/1				67 WNW cgs	22·1	20·9
Comments: Main event at 75° gives suitable ridge line and wave period; associated event at 73° also gives suitable line, but wave periods corresponding to 67 kt winds are not evident in spectrum, probably due to inaccuracy of speed measurement or insufficient time for saturation. Heavy swell reported at StH.																				
11·4/1	18·5	15·6	14·5 over 15 db	44	47	78	12	2/1	Complex low spread about 40N 60W.	46 NNW obs	15·2	14·3	11·0/1	11·5/1	N 84	12	1/1	30 WNW cgs	9·9	10·8
			ul 15·2	46	50										N 75	00	3/1	39 NW obs	12·9	12·7
P															N 68	12	3/1	30 WNW cgs	9·9	10·8
Comments: The main event at 78° definitely defines ridge with suitable wave period. Associated events probably contribute weakly. Heavy swell reported at StH.																				

13·4/1	20·3	15·9	13·4 41 42 over 10 db ll 12·9 39 40 ul 15·3 46 50	70	00	5/1	Low 52N 30W with trough to SW producing 35–45 kt winds, 67–73° from StH.	40 NW obs	13·2	12·9	13·8/1	14·0/1	N 78	12	4/1	50 WNW obs	16·5	15·3
													N 72	12	4/1	37 WNW obs	12·2	12·3
Q													N 65	12	5/1	37 WNW obs	12·2	12·3

Comments: Retention of energy from previous peak. 70° ridge line represents winds from 67° to 73° distance. Coincidence of several roughly suitable events causes rather confused picture in spectrum. Only small swell reported at StH.

16·4/1	31·0	18·8	15·2 46 50 over 15 db ll 13·4 41 42 ul 16·0 49 53	75 to 80	00	8/1	Low 53N 38W moving through area with variably appropriate winds.	43 NW component towards StH of 50 W	14·2	13·6	17·3/1	17·7/1	N 76	12	7/1	44 WNW cgs	14·5	13·8
													N 78	12	8/1	42 WNW obs	13·9	13·4
													N 65	12	9/1	43 WNW obs	14·2	13·6
R													S65	12	10/1	40 WSW cgs	13·2	12·9

Comments: 80° line fits contours very well. Other associated events give lines through peak, but winds do not fit wave period convincingly. The 65° event from south may have prolonged peak. Heavy swell sometimes overtopping wharf at StH.

18·9/1	30·0	18·1	15·2 46 50 over 15 db ll 13·9 42 45 ul 16·0 49 53	21 to 13	12 12	16/1 17/1	No corresponding feature detectable in available weather charts.
S							

23·9/1	16·5	13·3	13·9 42 45 over 10 db ll 12·9 39 40 ul 15·3 46 50	74	12	14/1	Low 50N 40W. Winds towards StH at 74°.	42 WNW obs max	13·9	13·4	23·3/1	23·6/1	N 77	00	14/1	37 WNW obs	12·2	12·3
T													N 75	12	15/1	45 WNW obs	14·8	14·0

Comments: Main event at 74° fits contours with adequate wind strength for wave period. Associated events may contribute to leading and trailing edges of peak. Only small swell reported at StH.

25·4/1	25·5	17·9	15·2 46 50 over 15 db ll 13·4 41 42 ul 16·0 49 53	78	00	17/1	Complex low around 55N 50W. Another at 46N 52W, both with suitable winds.	42 WNW cgs	13·9	13·4	26·3/1	26·6/1	N 82	12	15/1	57 WNW cgs	18·8	17·3
													N 78	12	17/1	57 WNW cgs	18·8	17·3
U													N 63	00	18/1	40 WNW obs	13·2	12·9

Comments: Main event at 78° is fairly suitable. Observed 57 kt winds of first two associated events are too high for spectral period, so were probably of short duration or gusts. Report at StH was of small swell on 24/1 increasing to heavy swell breaking over wharf on 26/1.

29·9/1	30·3	20·1	15·2 46 50 over 15 db ll 12·9 39 40 ul 16·0 49 53	77	12	21/1	Low moving south at 45N 45W on 21/1 having suitable winds at 77°.	47 WNW obs max	15·5	14·5	29·7/1	30·3/1	N 80	12	20/1	45 WNW obs	14·8	14·0
													N 70	12	22/1	37 WNW	12·2	12·3
V							Another low at 60S 50W.	47 WSW obs max	15·5	14·5	29·9/1	30·3/1						

Comments: Both N and S events satisfy requirements and probably contribute equally to peak. Associated events may contribute weakly. Very heavy swell reported at StH.

1·9/2	25·7	17·4	14·5 44 47	69	12	25/1	Complex low around 46N 35W. Winds up to 52 kt at 69° towards StH.	50 NW cgs	16·5	15·3	1·4/2	2·0/2	N 78	12	24/1	40 WNW cgs	13·2	12·9
W													N 72	00	25/1	36 NW cgs	11·9	12·1

Comments: Both wind fields at 69° and 78° give ridge lines which roughly fit contours, but do not pass through peak energy. 72° ridge line passes through peak but winds weak. 69° winds are most appropriate to wave period. Heavy swell reported at StH.

TABLE 3. PROPERTIES OF RECORDED SWELL AND COMPARISON OF ANTICIPATED AND OBSERVED SOURCE WIND SPEEDS

Wind speed: R – from Eq. (10); D – from Eq. (11); c – calculated from pressure distribution; o – 'observed', from weather charts

Reference letter	Energy in swell (db)	Saturation period (seconds)	Wind speed (kt) R	Wind speed (kt) D	Wind speed (kt) Weather charts	Height of swell (cm)	Distance (degrees)	Elapsed time from observed source to recorded peak (days)
A	13·1	15·2	46	50	48c	13·5	72	7·4
B	9·3	12·3	37	37	(37c 37o)	11·2	69 35	8·4 4·4
C	10·0	14·5	44	47	45o	10·5	79	8·9
C	11·8	13·3	40	42	(40o 40 to 49c)	13·1	79 58	9·9 6·9
D	12·7	13·9	42	45	42o	13·9	82	9·9
E	7·1	13·9	42	45	37 to 45c	10·3	90	10·4
F	12·7	14·5	44	47	42o	15·5	76	8·4
G	12·0	13·9	42	44	48c	15·6	76	9·2
H	12·1	14·5	44	47	47c	15·0	83	8·9
I	12·1	12·8	39	40	42c	14·0	74	9·7
J	14·8	14·5	44	47	42o	16·5	80	9·2
K	16·6	13·9	42	45	42o	23·2	75	8·9
L	16·6	14·5	44	47	48c	18·9	67	7·7
M	14·5	14·5	44	47	44c	17·3	80	9·2
N	14·8	14·5	44	47	48c	18·8	82	9·2
O	15·4	13·9	42	44	40 to 50c	18·8	75	8·9
P	15·6	14·5	44	47	46c	18·5	78	8·9
Q	15·9	13·4	41	42	40o	20·3	70	8·4
R	18·8	15·2	46	50	43o	31·0	80	8·9
S	18·1	15·2	46	50	—	30·0	Nothing found	
T	13·3	13·9	42	45	42o	16·5	74	8·4
U	17·9	15·2	46	50	42c	25·5	78	8·4
V	20·1	15·2	46	50	(45 to 47o 45 to 47o)	30·3	70 60	8·4 6·4
W	17·4	14·5	44	47	50c	25·7	69	7·4

TABLE 4. SUITABLY DIRECTED AND STRONG WINDS WHICH DO NOT IDENTIFY WITH SWELL ENERGY

Time and date of occurrence	Meteorological picture	Hemisphere and distance from St Helena (degrees)	Wind speed (kt) and direction	Estimated time and date of swell arrival at St Helena (assuming wind–wave resonance)	Comments
(Z) 1970 12 8/12	Depression NW of Bermuda	N 80	40 (obs) to 50 (obs) WNW	(Z) 1970 12 18/12 12 16/12	No ridge. Calculated winds 31 kt weak by comparison with observations. See text
12 14/12	Depression south of Greenland	N 82	50 (obs) WNW	17 22/12	No ridge. See text. Possibility of deflection of swell
12 22/12	Depression north of Newfoundland	N 75	40 (obs) WNW	21 31/12	No ridge but may be associated with energy peak of 30/12 since at source winds of order 40 kt since 12 Z on 21/12
1971 12 10/1	Secondary low north of Corvo developing within depression previously associated with swell	N 63	50 (obs) but 30° deflection from St Helena	1971 19 16/1	No ridge. See text
12 18/1	Depression off Newfoundland	N 80	40 (obs)	01 28/1	May be associated with ridge peak of 25/1 but inclined to say these winds to not identify with swell
12 28/1	Depression over Newfoundland	N 81	50 (obs) W	15 5/2	No ridge but date of expected peak is beyond period of records so undetectable
1970 18 21/12	Depression off Newfoundland	N 80 N 75	59 (component of obs) to 45 (obs) WNW 40 (obs) WNW	1970 13 28/12 16 30/12 03 31/12	No ridge for the 80° event (the line falls between two major peaks). The 75° event may identify with the retention of energy in the peak of 30/12