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Correction

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In a previous paper [1], we traced the summer ocean swell in California to winter storms in the Southern Hemisphere. Storms were located from their arrival azimuth $\alpha(t)$ measured by an offshore directional array and the range $R = g/(4\pi\, \mathrm{d}f/\mathrm{d}t)$ computed from the measured frequency $f(t)$ (figure 1). Some events could be attributed to antipodal storms in the Indian Ocean with the resulting waves entering the Pacific Ocean through a narrow window between New Zealand and Antarctica. An awkward detail, however, located three out of 30 wave-inferred sources on the Antarctic continent. Gallet & Young [2] have now discovered that when allowance is made for the refraction of the waves by the vorticity associated with ocean currents, Antarctic sources can be relocated from Antarctica to the Pacific Ocean.

Gallet & Young [2] compute the vorticity field from global compilations of surface currents provided at 5-day intervals by the OSCAR program; high eddy vorticities are associated with the Antarctic and equatorial current systems. They find that a typical deviation from the great circle wave direction at San Clemente Island (site of the directional array) is r.m.s. $(\theta) = 10^\circ$. Waves of very low-frequency travel relatively fast and are less refracted by the vorticity field.

The storm of 4.5 September 1959 illustrates their findings. Figure 2 shows three ray paths from the Indian Ocean storm to the California wave recorder. Vortex refraction is very roughly modelled by a $\pm 10^\circ$ change in course at the equator (solid to dashed line). The great circle route (line B) is of such low frequency ($f = 0.03$ Hz) and corresponding high group speed ($v_g = 26\,\mathrm{m\,s^{-1}}$) that vorticity refraction can be neglected. In contrast, the higher frequency waves (lines A and C) are relatively slow ($v_g = 11\,\mathrm{m\,s^{-1}}$) and significantly scattered.

Representative numerical values are given in table 1. The great circle waves leave the storm in the direction $\theta = 107^\circ$ (0° is northward and 90° is eastward, etc.), cross the

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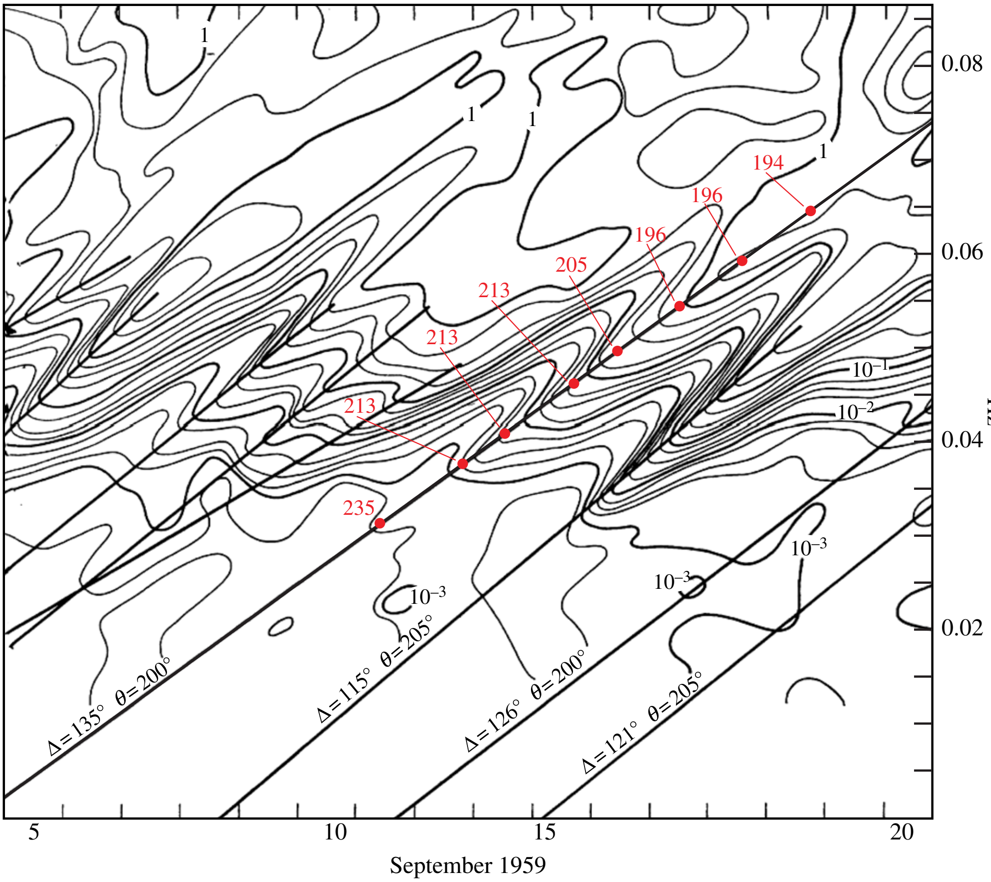

Figure 1. Contours of power density $E(t,f)$ in units $m^2\ Hz^{-1}$ (ticks on the t-axis designate midnight Universal Time) recorded at San Clemente Island. Ridge lines $f = m(t - t_0)$ correspond to the dispersive arrivals from a single source at time t_0 and range $g/(4\pi\ m)$. For the 4.5 September 1959 event (centred midday 4 September), the range is 15 390 km; measured azimuths ($\alpha = 180°$ *from* south and 270° *from* west) at the points along the ridge line vary from $\alpha = 213°$ on 12 September ($f = 0.037$ Hz) to $\alpha = 196°$ on 17 September ($f = 0.06$ Hz). (Online version in colour.)

equator in direction 29°, and arrive at Cortez Bank in direction $\theta = 35°$. The scattered waves A and C arrive at Cortez in directions 50° and 20°, respectively. Cortez Bank blocks San Clemente Island for rays A and B; tracing C waves backwards across the equator (ignoring the equatorial scatter) intersects the Antarctic continent (blue dashed line). This is a plausible interpretation of the misplaced source locations described in our 1963 paper.

Bathymetric refraction was not properly considered in the 1963 paper. (We are indebted to William O'Reilly for the refracted rays in inset, figure 2). Waves are subject to bathymetric refraction in water of depth less than $\lambda/2\pi$ (λ is deep water wavelength; table 1). The San Clemente directional array was located at 100 m depth, causing the 0.03 Hz waves to suffer severe bathymetric refraction, whereas the 0.07 Hz waves are hardly affected. Accordingly, the slow high-frequency waves are most vulnerable to vortex refraction whereas the deep low-frequency waves are most vulnerable to bathymetry refraction.

Cortez and Tanner Banks provide partial obstruction to path A; high waves are known to break over the banks at low tide. On the other hand, the wave array was completely exposed to C waves from the south. We interpret the recorded counter-clockwise rotation with time and frequency (figure 1) to vortex refraction of C arrivals, somewhat reduced by bathymetry refraction.

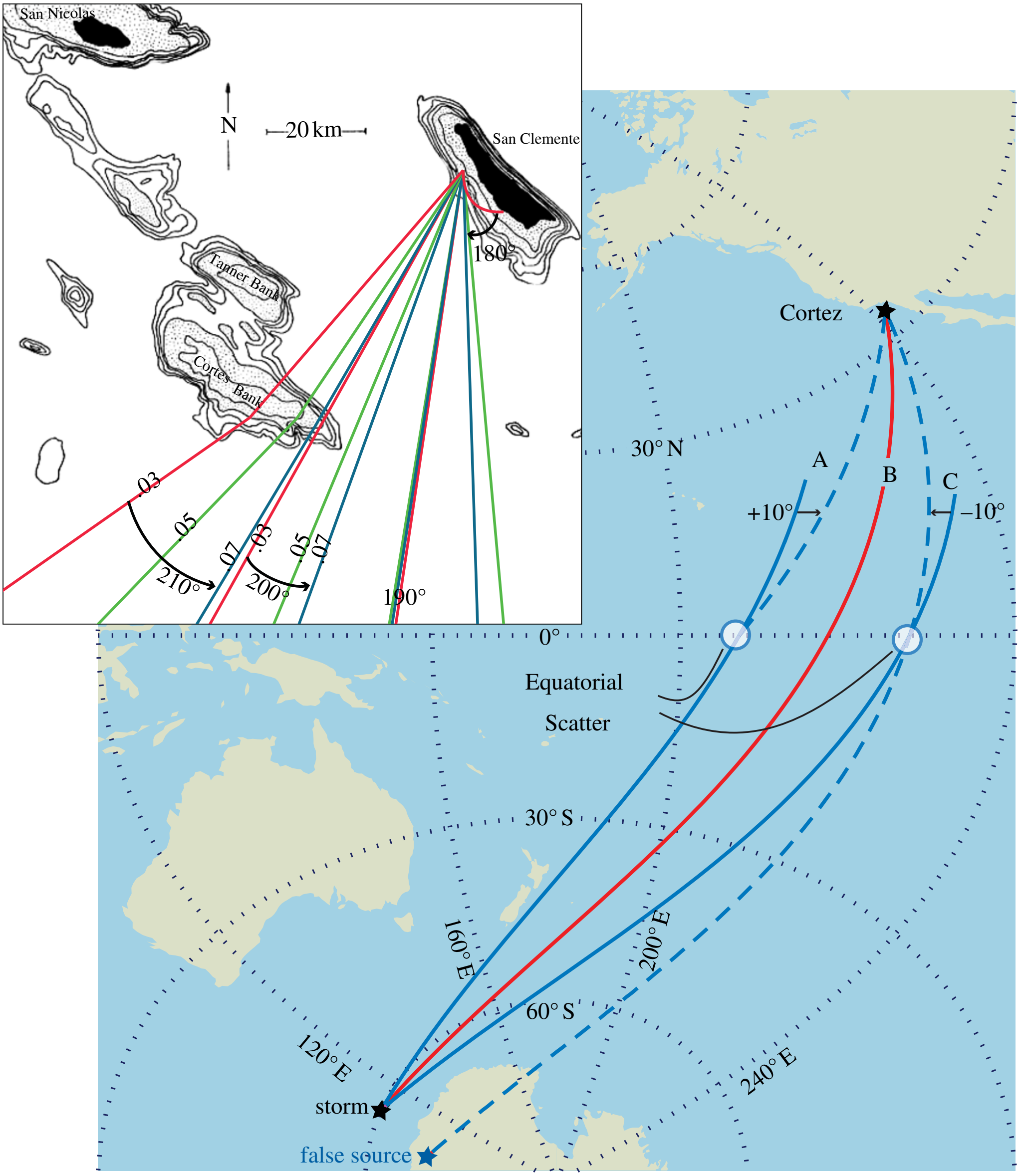

Figure 2. Wave trajectories from the Indian Ocean to California. Early low-frequency arrivals clearly follow a great circle trajectory (line B) leaving the storm in indirection $\theta = \alpha - 180^\circ = 107^\circ$ ($\theta = 0^\circ$ *towards* north and 90° *towards* east), crossing the equator at $\theta = 29^\circ$ and arriving at Cortex Bank at $\theta = 35^\circ$, $\alpha = 215^0$ (table 1); further progress is impeded (Inset by O'Reilly shows bathymetric refraction, depth contours 0, 50, 150, 200, 250 fm). Later high-frequency arrivals are scattered at the equator by $\pm 10^\circ$ (dashed line A, C). Rays A and B are partially blocked by Cortez Bank, C reaches the San Clemente wave array with $\theta = 19^\circ$, $\alpha = 199^\circ$. Neglect of equatorial scatter places the wave-inferred source on Antarctica (dashed). (Online version in colour.)

Vortex refraction provides a new chapter in the interaction of waves and currents; deep and unobstructed directional wave arrays are required. Bathymetric refraction and blockage introduced an undesirable complexity in our 1963 experiment. The assumption of a stationary point source (space and time) needs to be reexamined. Time for a new experiment!

Table 1. Parameters for transmission from Indian Ocean storm of 4.5 September 1959 at 111° E and 60° S.

		directions of wave propagation E of N				
		storm	equator	Cortex Bank San Clemente Island	range (km)	time (days)
A	$f = 0.07$ Hz $v_g = 11.4\ \mathrm{m\,s^{-1}}$ $\lambda/2\pi = 51$ m	96°	$30° + 10° = 40°$	$50° - 2° = 48°$ (from 228°)	15 310	15.5
B	$f = 0.03$ Hz $v_g = 26.5\ \mathrm{m\,s^{-1}}$ $\lambda/2\pi = 276$ m	107°	$29° + 0° = 29°$	$35° - 8° = 27°$ (from 207°)	15 390	6.7
C	$f = 0.07$ Hz $v_g = 11.4\ \mathrm{m\,s^{-1}}$ $\lambda/2\pi = 51$ m	115°	$27° - 10° = 17°$	$20° - 1° = 19°$ (from 199°)	15 411	15.6

Reference

1. Munk WH, Miller GR, Snodgrass FE, Barber NF. 1963 Directional recording of swell from distant storms. *Phil. Trans. R. Soc. A* **255**, 505–584. (doi:10.1098/rsta.1963.0011)
2. Gallet B, Young WR. 2012 Refraction of swell by surface currents. *Proc. Natl Acad. Sci. USA*.