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A line in the sea

Induction of Kaposi's sarcoma in AIDS

Blocking emotional memories

Is Tibet buckling?

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A line in the sea

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THE ocean has considerable spatial and temporal heterogeneity in biomass and productivity owing in part to the effects of ocean circulation and mixing[1,2]. Water mass boundaries (fronts) in coastal waters are well-known sites of enhanced biological activity[3,4]. Comparatively little is known of open-ocean fronts, and one of the few biological studies of an oceanic front showed phytoplankton biomass at only slightly higher densities than in surrounding waters[5]. Here we present photographs and measurements from satellites, aircraft, ships and the Space Shuttle Atlantis which show

dramatic biological responses to circulation and mixing processes associated with an open-ocean front. Breaking waves (whitecaps) caused by water turbulence and mixing, and very dark green water caused by extremely high concentrations (>20 mg of chlorophyll *a* per m^3) of buoyant diatoms (*Rhizosolenia* sp.) made a distinct line in the sea visible for hundreds of kilometres. The line traced the northern edge of a westward-progagating (50 km per day) tropical instability wave (1,000-km wavelength) delineating the boundary between cold, upwelled waters and warmer waters to the north. High phytoplankton biomass and primary production associated with the extensive diatom patches may explain anecdotal observations of high animal abundance along this frontal boundary.

During the Joint Global Ocean Flux Study (JGOFS) research program in the equatorial Pacific in 1992 (refs 6, 7) a series of sea surface temperature (SST) images were obtained by the advanced very high-resolution radiometer, AVHRR, on the NOAA-11 weather satellite. These images (Fig. 1) showed westward movement (55 km d^{-1}) of a tropical instability wave[8–10] near 140° W longitude—the site of JGOFS ship and aircraft measurements during late August and early September 1992. As illustrated in Fig. 1, tropical instability waves propagate along the density (thermal) front delineating the boundary between cold, upwelled waters of the south equatorial current (SEC) and the warmer waters of the north equatorial countercurrent (NECC)[8–10]. Although the thermal front between the NEC and SECC is present year-round in the equatorial Pacific, tropical instability waves are observed in SST imagery only during the summer and autumn when the westward-flowing SEC is strongest[8–10]. Waves are normally observed between about 90° W to at least as far west as 160° W longitude[11].

Figure 2 shows laser-induced chlorophyll fluorescence (LICF) and SST measurements acquired from a NASA P-3 research aircraft flying at 150 m altitude along 140° W on 21 August 1992, and LICF measurements in the same area on 25 August. LICF was obtained from the airborne oceanographic lidar (AOL) which employs a blue-green laser to excite chlorophyll *a* fluorescence at 683 nm (refs 12, 13). LICF and other radiance signals from the upper 1 m of the ocean were focused by telescope onto a photomultiplier array and after digital processing of the spectra, the strength of the LICF signal was determined at 100-m spatial resolution along the flight path of the plane. This signal is an approximate measure of chlorophyll *a* concentration and thus of phytoplankton biomass[12,13]. Results from 21 August show a narrow (<20 km wide) spike in LICF centred near 1.8° N latitude coincident with an SST front separating the warm waters of the NECC from the colder, upwelled waters of the SEC (Fig. 2). Four days later on 25 August, the spike was observed near 2.4° N latitude, and peak LICF was now as much as 10 to 50 times higher than nearby waters (Fig. 2).

Acoustic Doppler current profiler (ADCP) measurements from the RV *Thompson* on 24–26 August showed the east–west current component on both sides of the front was to the west at 80–90 cm s^{-1}; the north–south component was strongly convergent at up to 40 cm s^{-1} in the upper 100 m of the water

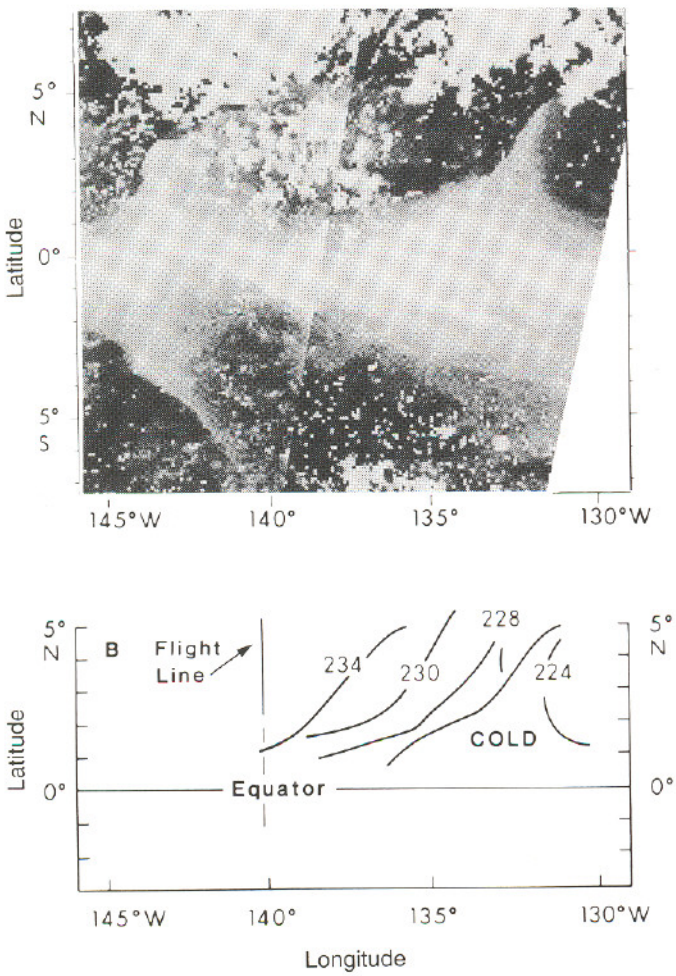


FIG. 1 Top, AVHRR-SST composite image from 11 August 1992 (day 224 of the year), showing surface temperature in the equatorial Pacific. Lightest shades of grey are cold (~24 °C) upwelled waters (centred around the Equator) of the south equatorial current (SEC), whereas darkest shades are warmer waters (~28 °C) of the north equatorial countercurrent (NECC). Clouds are white. Note the tropical instability wave (upper right) along the boundary between the SEC and the NECC. Bottom, Drawing based on a 10-d time series (224–234) of AVHRR-SST images showing the westward progression of the wave. The flight line of the NASA P-3 aircraft on 21 August 1992 (234) is also shown.

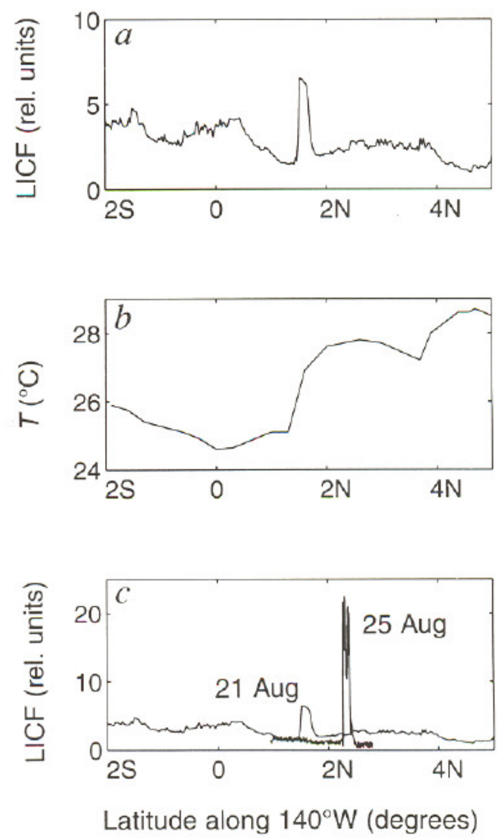


FIG. 2 *a*, Laser-induced chlorophyll fluorescence (LICF), and *b*, surface temperature (*T*) along 140° W on 21 August 1992. *c*, LICF on 21 and 25 August 1992.

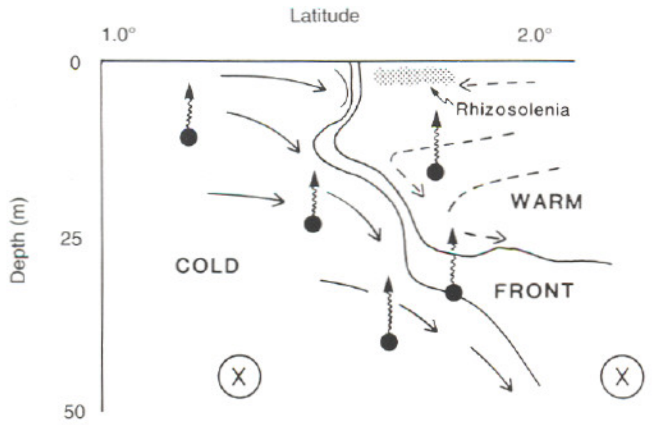


FIG. 3 Schematic drawing illustrating a possible mechanism for concentrating buoyant *Rhizosolenia* (filled circles) near the convergence. Solid and dashed arrows, northward and southward current components, respectively; solid lines, frontal boundary separating warm and cold waters; 'X' a westward component to surface flow. In this model, buoyant cells could grow on either side of the convergent front. However, cells rise to the surface and accumulate on the warm side of the front, where calculations based on ADCP measurements showed that downwelling velocities are weak compared to the strong downwelling (1 cm s^{-1}) on the cold side.

column at the frontal boundary[14]. Within the 2-km-wide frontal zone, calculations based on ADCP and hydrographic measurements indicate that a 70-m-deep slab of cold (24–25 °C) water was subducting (at downwelling velocities of up to 1 cm s^{-1}) and moving to the north beneath a 40 m-thick slab of warmer water[14].

Measurements on water samples collected within the frontal region on 25 August by the RV *Thompson* showed that dense aggregations (patches) of the buoyant diatom, *Rhizosolenia* sp. (tentatively identified as *R. castracanei*, Fig. 4*e*) caused the high LICF. The patches were 1–2 m deep and located within the relatively warm waters in the frontal zone. Chlorophyll *a* concentrations of the patches ranged from 5 to 29 mg m^{-3}, compared to typical concentrations in nearby waters of only 0.3 mg m^{-3}. Photosynthetic index from water samples collected from the patches averaged 68 mg C per mg chlorophyll *a* per day, indicating that the diatom cells were physiologically active and growing relatively fast (~ one cell division per day, assuming a diatom C:Chl *a* ratio of 60:1).

Figure 3 illustrates a possible mechanism for concentrating buoyant organisms at the convergence to form the observed *Rhizosolenia* sp. patches. This model is consistent with the ADCP results in that buoyant *Rhizosolenia* accumulated in the relatively warm water, where downwelling velocities were low compared to the colder water on the other side of the frontal boundary. An implication of this simple model is that *Rhizosolenia* may be taking up nutrients and growing most rapidly in the colder, upwelled waters, although it occurs at highest abundance in the warmer waters on the other side of the convergence. Previous studies show that some species of *Rhizosolenia* adjust their buoyancy and migrate vertically between surface waters and nutrient-rich waters deeper in the water column: Villareal *et al.*[15] report ascent rates for *Rhizosolenia* spp. as high as 6.4 m h^{-1}.

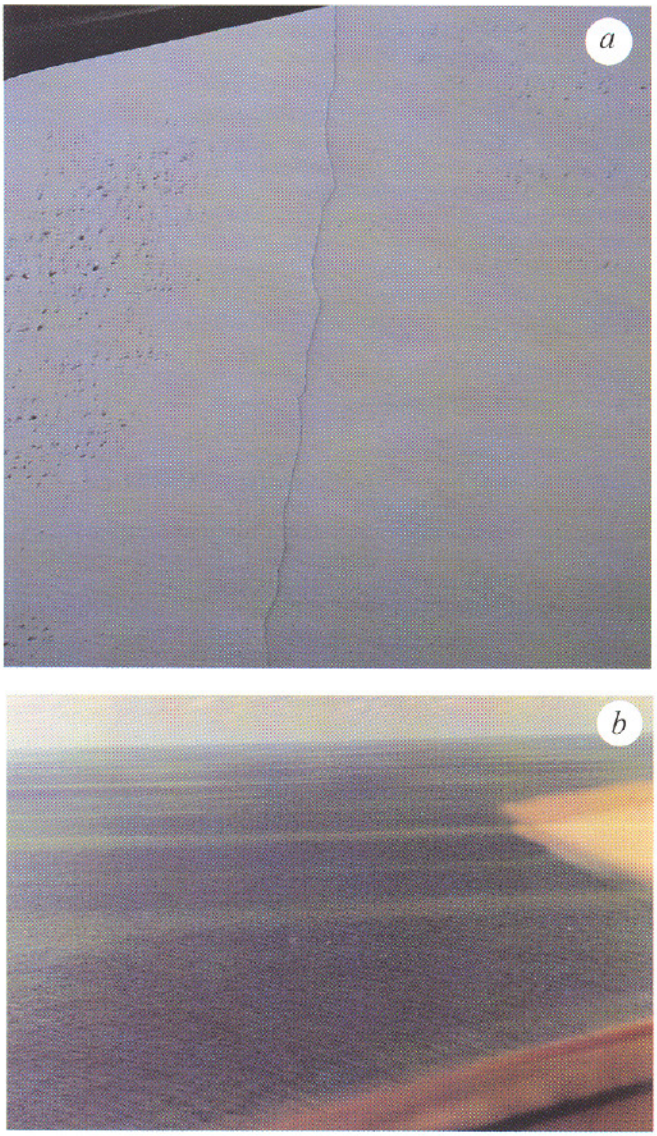
Photographs taken from viewing perspectives covering an $\sim 10^9$ range in scale illustrate the spectacular effects of this feature. The photograph on the cover shows a line tracing the edge of a tropical instability wave which, given its location, size and shape, is probably the same wave observed 4 days later in SST (Fig. 1). A higher-resolution photograph (Fig. 4*a*) from the Space Shuttle Atlantis shows the apparent vertical relief of the feature. Photographs from the aircraft and ship (Fig. 4*b–d*) show lines (patches) of dark-green water adjacent to the convergence, as well as breaking waves (whitecaps) localized in a narrow zone at the convergence. Based on close examination of a video taken from the cockpit of the P-3 as it flew over the convergence and associated *Rhizosolenia* sp. patches on 25 August, the apparent vertical relief of the line is caused by the apparent increase in sea level owing to the steep, breaking waves (whitecaps) localized within a narrow zone at the convergence. Backshading provided by the heavily pigmented diatom patches accentuates the whitecaps and contributes to the illusion of a rapid change in mean sea level.

NASA astronauts also photographed similar features in the tropical Pacific, between 2° and 7° N latitude and 105° to 170° W longitude, on six other occasions since 1984. All of these observations were made during the late boreal summer, autumn, or early winter (August to the following January). The association between instability waves and lines in the sea may be more than coincidental. Strong horizontal and vertical current shear and strong convergence of surface currents are associated with instability waves (refs 6, 7, 11 and P.F., R. Knox and P. Niiler, unpublished data). As illustrated in Fig. 3, strong convergence at the NECC and SEC boundary is a necessary condition for forming surface patches of the buoyant *Rhizosolenia* sp. The requirement for strong convergence may explain why visible fronts (caused by breaking waves and *Rhizosolenia* sp. patches) are observed in Space Shuttle pictures only during the instability wave season and within the latitude and longitude boundaries where the waves are common.

Extremely high concentrations and high primary productivity of *Rhizosolenia* at the NEC and SECC convergence may be an important element of a localized and productive food web, which may partially explain anecdotal observations of very high animal abundance there. Reporting from 2.5° N, 85° W (which is east of where tropical instability waves are commonly observed, but where the NEC/SECC front is still well-developed[8–10]), while drifting along a "distinct line" of whitecaps and flotsam delineating "the meeting place of the great ocean currents", Beebe observed:

". . . here was a concentration of organisms greater than I have ever seen—the larger dotting the water and making visible its depths, the minute so abundant that in places they were of the consistency of soup."[16] Another study[17] of a strong convergence near 2.75° N, 121° W, and having similar hydrographic characteristics to the one we observed, reports "High biological activity was associated with the front; . . . . most of the life appeared to be concentrated in the relatively narrow frontal zone."

Recent studies of equatorial Pacific sediment cores reveal vast deposits of laminated diatom ooze formed during the Neogene by the rapid accumulation of the mat-forming diatom, *Thalassiothrix longissima*[18]. Most cores showing the major intervals of laminated diatom ooze were collected between 90° and 130° W longitude and between the Equator and 10° N latitude[18], that is, the region where tropical instability waves are most common in the modern equatorial Pacific Ocean. Making an analogy with the *Rhizosolenia* sp. patch observed during the 1992 JGOFS study, previous investigators proposed that the "massive flux of *T. longissima* mats may represent the fall out from major frontal systems"[19]. Based on our results, we speculate that tropical instability waves may also have been the mechanism for accumulating *Thalassiothrix* sp. mats at the Neogene equivalent of the



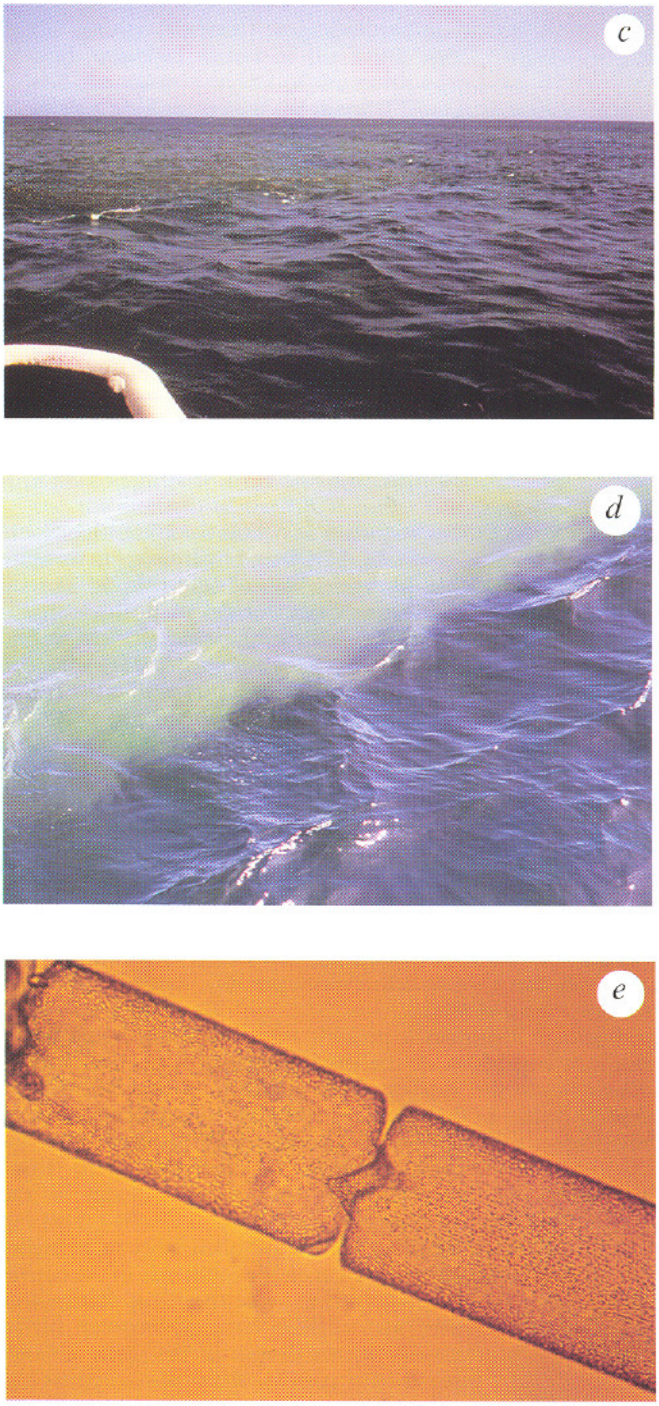


FIG. 4 Photographs of the line in the sea taken from viewing perspectives covering a range of $\sim10^9$ in scale. *a*, 57-km-long portion of the same instability wave shown on the cover photographed from the Space Shuttle Atlantis using a telephoto lens (NASA photograph S46–77–17). The centre of this photograph is the same as that of the cover photograph. The convergence front is displayed in much higher detail, giving the illusion of a rapid change in sea surface slope. *b*, *Rhizosolenia* patch(es) photographed from the cockpit of the P-3 flying at 150 m altitude on 25 August 1992, near 2° N, 140° W. *c* and *d*, *Rhizosolenia* patch photographed from the deck of the RV *Thompson* on 25 August 1992, near 2° N, 140° W. *e*, Photomicrograph of two *Rhizosolenia* cells collected from the patches illustrated above. The diameter of the cylindrically-shaped cells is $\sim200\times10^{-6}$ m.

NEC/SECC frontal boundary—a first and essential step in a sequence of physical and biological processes which eventually led to a rapid accumulation of diatom biomass in equatorial Pacific sediments[18]. □

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