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THE SOMALI CURRENT AND THE SOUTHWEST MONSOON:  
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## THE SOMALI CURRENT AND THE SOUTHWEST MONSOON: AN OCEAN ATMOSPHERE INSTABILITY

During the months May through August the Somali current accelerates from rest to become one of the world's major boundary currents, with a flow comparable to that of the Gulf Stream (1). Within this time period a strong low level air flow is established which crosses the equator in the western Indian Ocean and sweeps toward India as the southwest monsoon. The circular course of the Somali current, and the line of strongest monsoon flow, which were charted over 100 years ago (2, 3), can now be identified as arising from an ocean atmosphere instability. This instability is associated with the low latitude variation of the Coriolis force.

The spring and summer temperature contrast between land and ocean causes a sea breeze perpendicular to the coast at the equator, and a vigorous thermal wind parallel to the Somali coast to the north of the equator (see Figure 1). The strengthening atmospheric flow parallel to the coast causes the acceleration of the Somali current between the equator and 10° north. Surface divergence of the Somali current due to acceleration induces upwelling of colder underlying water, which enhances the ocean atmosphere temperature contrast and intensifies both air and ocean currents.

The absence of synoptic observations precludes an accurate description of the oceanographic and meteorological conditions in any single year. However, despite the variability from year to year a rather complete picture may be pieced together.

The southwest monsoon is a moist low level air flow toward India which crosses the equator in the western Indian ocean. When the monsoon is established this flow contains an intense jet which may carry almost half (4) of the total inter-hemispheric flow of the monsoon. In the vicinity of the equator this jet is typically several hundred kilometers wide, with a depth of 2-3 kilometers. Flow speeds in the jet average 15 m/sec, with frequent observations of 25 m/sec and above (5). This flow is in accord with observations by Bunker (6) of strong winds near the Somali coast and a pronounced thermal contrast between land and ocean. There exist few records of wind off the Somali coast, but during the month of June climatology shows strong and persistent surface winds (Beaufort 7, 14 m/sec or greater) (7) prevail more than 50% of the time. The air, cooled and dried from passing over the Somali current, regains heat and moisture as it flows toward India.

During this time period the Somali current flows northeastward parallel to the coast for 500-1000 kilometers at a speed up to 3.5 m/sec. (8). Once established

the total oceanic flow is an anticyclonic vortex, with a nearly equal return flow some 300-400 kilometers to the east. Results of the 1963 Indian Oceanographic Expedition (9) show a series of five such vortices alternating clockwise and counterclockwise toward the east and successively decreasing in strength. Although the interpretation of oceanographic measurements of an accelerated flow is difficult, we find verifying evidence in the measured periodicity of chlorophyll amounts in the region during the same time period (10).

I initiate a quantitative description of the instability by describing the effect of the coriolis force on the diurnal sea breeze flow (11). At the equator, in the absence of the coriolis force, the sea breeze is a shallow 1-2 kilometer deep flow of cool air inland at right angles to the coast line. The advection of cool air over the heated land decreases the temperature contrast between land and ocean to a considerable distance inland. In contrast, to the north of the equator, the coriolis force causes a gradual (in time) deflection of the sea breeze parallel to the coast, so that after  $1/4$  to  $1/2$  of an inertial period (12) no further cooling occurs due to advection inland of oceanic air. Thus the wind component parallel to the coast increases toward the northeast. It is this increase in wind strength which drives the instability. At  $10^\circ$  north  $1/4$  of an inertial period is about 18 hours, so that a sustained temperature difference between land and ocean is required to produce a strong flow parallel to the coast. This initial temperature difference occurs with the northward march of the sun in late spring. The diurnal variation of wind velocity superimposed on the averaged "sea breeze" has been observed in the western Indian Ocean (13).

Bunker's data show the sharp fall of isotherms near the Somali coast as air is chilled by contact with the cold water. The resultant thermal wind values ( $\Delta v \sim 90$  m/sec between  $1/2$  and 3 kilometers) indicates that horizontal and vertical transport effects must be included for reasonable quantitative estimates. The observed wind maximum of 24 m/sec between 1 and  $1-1/2$  kilometers agrees satisfactorily with the equatorial jet reported by Findlater.

For a typical surface wind speed  $u = 15$  m/sec the frictional retardation (14) from the ocean is  $F = C \rho_{\text{air}} u^2 = 2.6 \times 10^{-3} \times 1.3 \times 15^2 = .76$  newtons/m<sup>2</sup>. This force may be balanced by a gravitational descent of 30 meters during a passage of 500 km over the cold surface of the Somali current. Such a drop is consistent with an average temperature drop of  $\delta T = 2T \delta h/h \sim 15^\circ$  in a 1 km column of air, which is higher than observed. However flow across the surface pressure gradient along the Somali coast yields an additional force tending to accelerate the wind toward the surface low pressure over the Indian sub continent.

I estimate the average atmospheric ocean temperature difference  $T_A - T_O$  as  $5^\circ$  (15) which produces a flux of sensible heat  $Q = C \rho_{\text{air}} (T_A - T_O) u$  of 55 cal/m<sup>2</sup>/sec and a heat loss of  $Qu/L$  of  $1.9 \times 10^6$  cal/m<sup>2</sup> as the air flows 500 km

over cold water. This heat flow corresponds to a temperature drop of  $6^\circ$  in a 1 kilometer air column. Although Bunker's data yield a Richardson number of order 1, the depth of observed atmospheric flow indicates fully developed turbulence, and the ocean-atmosphere fluxes are probably larger than estimated here. It is known that the total heat flux (latent and sensible) is downward from the atmosphere (16, 17) indicating that cooling of the air is produced solely by contact with the water of the Somali current.

The response of the ocean to frictional forcing is an accelerating current along the Somali coast, which is deflected toward the east and south near latitude  $10^\circ$  in response to the increasing coriolis force. The flow returns south until it nears the equator, where the equatorial sea breeze produces a deflection toward shore. This flow pattern, sometimes circular, sometimes elliptical, with southerly flow 300-500 km east of the Somali coast, duplicates in the horizontal plane the usual sea breeze flow in the vertical plane. Satellite infra-red imagery (Figure 2) provides the only synoptic verification of this flow pattern previously established by oceanographic data. Images of this nature give evidence for strong atmospheric forcing along the coast of Somali. It appears that a substantial part of the momentum flux from atmosphere to ocean goes into the spinup of this giant ocean eddy. I believe that the Somali current should not be considered a typical western boundary current, as oceanographic sections show little or no net northward flow (18, 19), when extended well off the Somali coast.

By assuming that the velocity of the Somali current decreases linearly to 0 at a depth of 200 meters (20) I find that the atmospheric drag acting on one third of the circular flow can accelerate the ocean current at the rate of .1 m/sec/day. Thus the minimum time for the instability to reach full strength (surface speed of 3 m/sec) is 15 days. Apparently geostrophic adjustment (21) takes place sufficiently rapidly so that the gradient current is a reasonable approximation. Using Bruce's values late in the monsoon season ( $v = 1.3$  m/sec,  $r = 200$  km) I compute a balance using a coriolis acceleration  $fv$  of .33 dynamic meters/100 km at  $10^\circ$  north, an observed potential gradient of .25 dynamic meters/100 km, and a centrifugal acceleration  $v^2/r$  of .08 dynamic meters/100 km.

Upwelling of cold water is produced by horizontal divergence as the Somali current accelerates parallel to the coast. The maximum velocity change between  $5^\circ$  and  $10^\circ$  north may be estimated by  $\Delta v \sim \int F/m dt \sim \int F/(m\bar{v}) dx = .76 \times 500 \times 10^3 / (200 \times 10^2 \times 2) \sim 1$  m/sec which is of the order of magnitude of observed values (22). This plus incompressibility yield a vertical velocity estimate  $v_z = \Delta z \partial u / \partial s = 3 \times 10^{-4}$  m/sec, which could raise water from 200 meters in only 7 days. Both estimates disregard the need to produce the observed circular flow pattern, and thus are overestimates.

Wyrski (22) has pointed out that the removal of warmer surface water during the upwelling of the Somali current may be identified with an eastward equatorial flow across the Indian Ocean, with a corresponding deepening of the warm surface layer off the coast of Sumatra. This accounts for the warm water displaced by the cold deep water off the Somali coast.

## CONCLUSION

I have shown that there is substantial evidence that an ocean atmosphere instability can explain the rapid acceleration of both the Somali current and the southwest monsoon. The sudden "burst" of the monsoon, and the difficulty in predicting its onset are both characteristics of an instability.

The persistent and large scale exchange of heat and momentum between ocean and atmosphere make the Somali coast region suitable for studies of turbulent processes and for computer modeling of the resulting flows.

In addition it is apparent that the interruption of the required atmospheric flow by synoptic disturbances during spring and early summer may permit solar heating of surface water of the Somali coast, with resultant failure of the monsoon flow to develop.

Conversely, we may consider varying the albedo of the Somali coast in order to influence the ocean atmospheric temperature contrast and control the onset of the southwest monsoon.

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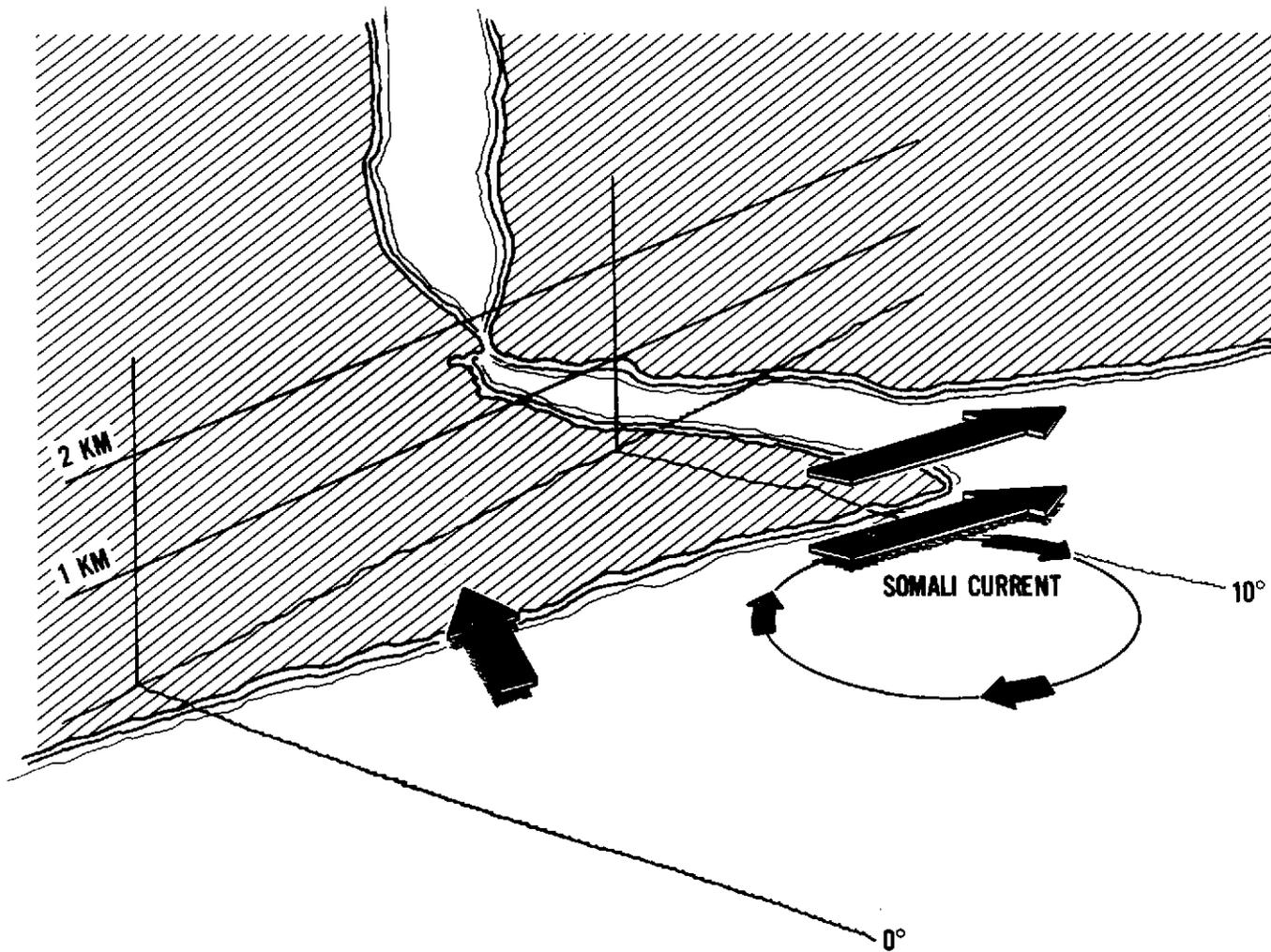


Figure 1. Air and ocean currents along the Somali coast.

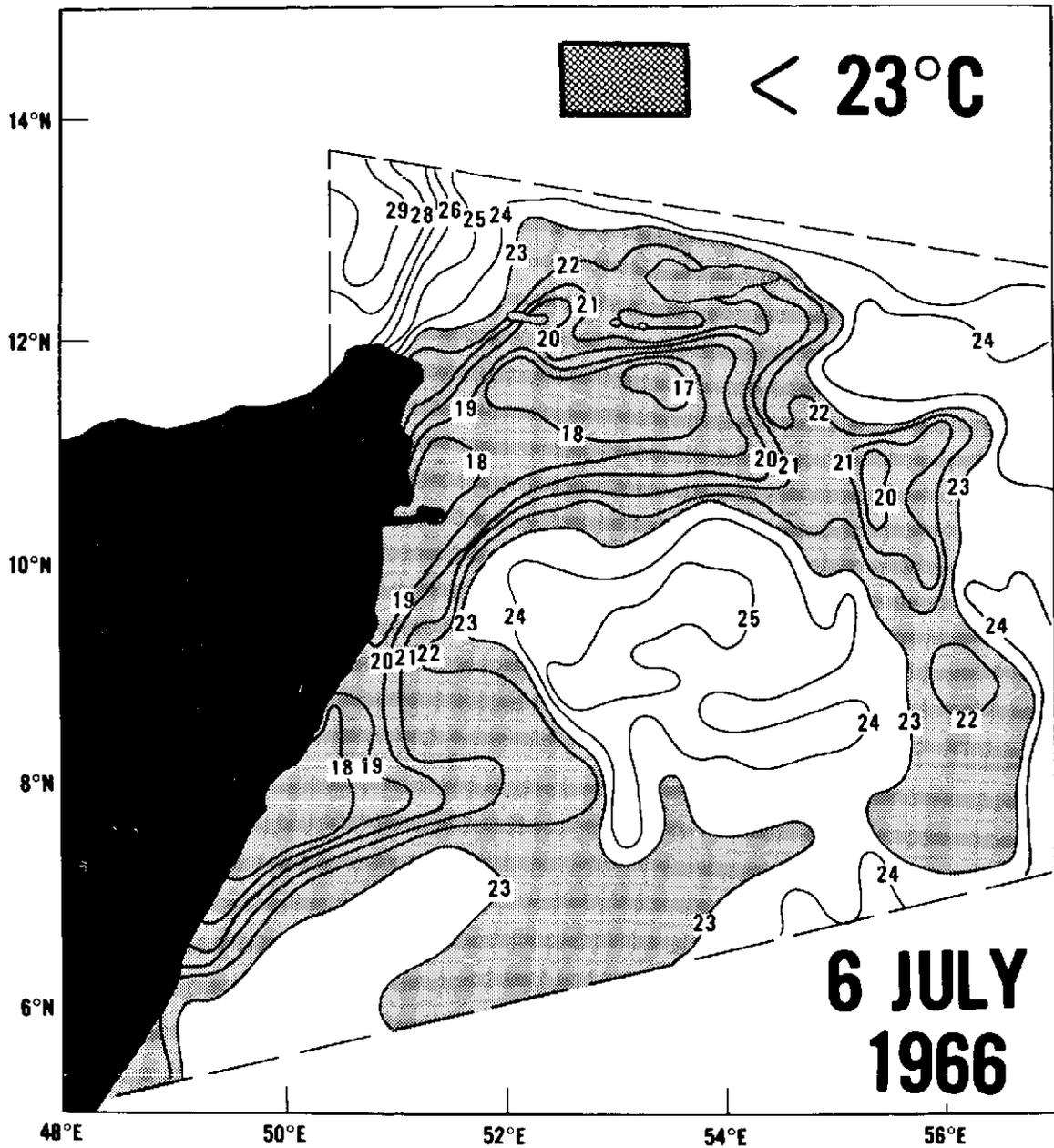


Figure 2. Nimbus satellite radiance temperatures illustrating upwelling along the Somali coast.