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CIRCULATION IN THE NORTHERN GULF OF CALIFORNIA FROM ORBITAL PHOTOGRAPHS AND SHIP INVESTIGATIONS

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ABSTRACT

Biannually reversing cells driven by heating and cooling of the saline Colorado tidal estuary are curved by the Coriolis effect in the Northern Gulf of California. Oceanographic features observed on multiseason ERTS, SKYLAB, APOLLO and GEMINI photograps and during cruises taht led to this circulation model include: surficial turbydity gyres, cross-flowing undercurrents, internal waves, upwelling plumes, tidal phase velocities and wind driven surface layers. Biological implications of the proferred model are outlined.

RESUMEN

La circulación celular en la parte norte del Golfo de California, que se invierte dos veces al año, es producida por el calentamiento y enfriamiento del estuario salino del Río Colorado y desviada por la fuerza de Coriolis. Las características oceanográficas que sugieren este modelo de circulación, observadas en fotografías estacionales del ERTS, SKYLAB, APOLLO y GEMINI y en cruceros oceanográficos, incluyen: giros superficiales de turbidez, corrientes subsuperficiales, ondas internas, zonas de surgencia, velocidades con fase de mareas y capas superficiales movidas por el viento. Se mencionan las implicaciones biológicas del modelo citado.

From the onset of modern oceanography, knowledge of circulation in the Gulf of California north of the midriff islands (Fig. 1-A) has been hampered by lack of data (1). Shallow water, shoals, unpredictable storms and extreme tidal fluctuations contributed to the difficulties of shipboard investigations. The pressing need of Mexican scientists studying Gulf fisheries and pollutant contamination from the Colorado River (2) gave impetus to this synthesis of orbital photographs with data from new and previous oceanographic cruises.

Well known aspects of the northern Gulf of California (3) fundamental to this report are: a) The area is generally shallow with little relief and depth of less than 200 m. It forms the extreme end of a relatively small arm of the ocean in a structural trough over 1100 km long and typically less than 150 km wide it its northern portion, and is intruded into the climatically severe Sonoran Desert with its high aridity and an extreme temperature regime. b) The region is one of strong tidal mixing caused by semi-diurnal tides with amplitudes up to 10 m. This poduces maximal exposure of the sea water to the terrestrial climate as the tidal water is rhythmically spread over the tidal flats. c) Fine sediments of the Colorado River deposits at the head of the Gulf, under the mixing conditions prevailing, produce variably high turbidities in the sea water; these act as natural tracers, enabling unusually good perception of water movement patterns by synoptic space imagery.

Satellite data was well suited for documenting this area in that only a small proportion of the imagery suffered loss of detail from cloud cover, water masses were usually separable by their distinctly different turbidities (4), and the Gulf waters are very dynamic, showing high rates of tidal and net flow. Ninety-one color, color infrared, and multispectral film transparenices from the GEMINI, APOLO and SKYLAB missions and 588 multispectral (MSS) photographs from ERTS were analyzed. Due to the wide variance in water clarity in the northern Gulf, imagery in all four MSS bands was useful, especially in negative format wherein the gray levels of the images were more suitable than in the positives. Oceanographic and meteorologic data were collected in and around the Gulf above 31° N latitude. A grid of 47 oceanographic stations at 18 km spacing was occupied in a series of cruises between August 1972 and June 1973. Station routine included salinity, turbidity, meterological and sea state observations, and 10 m vertical plankton hauls. ERTS-matched reflectance spectra over the water surface was measured by four-channel radiometer.

The usual relationship in wich nearshore terrestrial environments are dominated by the adjacent marine climate is reversed in the northern Gulf. Temperatures of the surface waters in the Colorado Delta region are closer to those of the coastal desert than are temperatures farther out in the Gulf (5).

The Delta water--desert air couplet exhibits an annual variation of over 17°C as compared with under 11°C variation in the open water. Delta water and desert air are also 14% warmer in summer and colder in winter than is the general Gulf water. Evaporation in the upper Gulf exceeds precipitation by 250 cm per year (6) and there is a slight incrase in salinity with progression northward toward the Delta and toward the landward edges of major bays and stauaries (2, 7). This would ordinarily produce a haline-dominated situation where the dense, saltier water at the head of the Gulf would sink and flow southward on the bottom, being replaced by a south - to - north surface flow (8). Satellite imagery, however, confirms the suggestion (9) that the marked summer input of heat energy overrides the haline conditions and produced a thermally dominated (at the surface) flow from north - to - south during the warm portions of the year.

While tidal currents are the major factor controlling movement of water in the northern Gulf (6), previous knowledge of general circulation patterns in terms of net movements of the oscillating tidal masses was very limited (3,10). We propose the following model: Consider the waters of the Gulf of California north of the major midriff islands to be a semi-isolated cell of marine water operating as a seasonally-reversing heat engine. In this liquid engine, the lines of movement within it are curled by the Coriolis effect. Figure 1 shows schematically the thermally-driven convection system wich is suggested. During the warm part of the year from about April to about October, the principal heat source for the engine is the Colorado Delta region, with auxiliary heating along the Sonoran and Baja Californian shores (especially the major intertidal flats on these shores). The heat sink is in the center of the unit cell wich is the entire northern Gulf. Turbid, solar-heated water moves outward from the heat sources, losing bouyancy as its temperature diminishes,and eventually wells downward at the cell's center. The coriolis force tends to deflect the moving streams to the right. The main thrust of southeastward-flowing surface water from the delta region holds to its righthand (western) boundary on the Baja California shore. At the same time, the auxiliary currents off the Baja California and Sonoran shores are deflecting to the right as they move away from shore, contributing a spin effect which results in major counter-clockwise-moving gyre at the approximate center of the cell where downwelling occurs. Compensatory subsurface movements in accord with Coriolis effect and physical oceanographic theory are shown in Figure 1-C.

This model would produce upwelling near the coast (Fig. 1-D, E) to complete the cell. Plumes of clear water in generally turbid areas near the Sonoran and Baja Californian coasts are presumed to be such upwelling.

During the colder months of December, January and February, the heat engine is reversed. The heat sink is in the Delta and shallow shore areas and the "source" is in the center of the cell. Marked chilling effects of the desert climate augment the density increase produced by the next excess evaporation and cause the water to flow southward along the bottom, dropping its sediment and becoming warm and diffused.

Eventually, the water is displaced upward and expands outward again at the surface in a clockwise gyre of clear water, dpwn-welling when its is chilled in the shallow coastal regions. Shuch a south-to-north surface flow lends itself to a clockwise rotary movement in response to the Coriolis effect, and it explains the lack of gyres on space photographs because the relatively clear surface waters coming from the south in winter would not have the requisite turbidity to provide detectable traces. Reversal of all arrows in the summer model (Fig. 1-B to D) would represent the postulated winter model, which is apparently less strongly energized and shows less integrity than its summer counterpart.

The surface position of the gyre center migrates over a 40 km radius from the general center of the northern Gulf in response to surface winds and, possibly, changing pulse strenght between spring and neap tides. Satellite imagery in the near infrared wavelengths that sense only the superficial water show these wanderings and also fluctuations in the "tightness" of the gyre. Arcute, banded patterns with wavelengths of from 1 to 4.5 km are seen in images in all four spectral channels and in the SKYLAB photographs (Fig. 2). These bands are interpreted as slicks generated by divergent zones above the crests of internal waves, and have been noted repeatedly in the Gulf and other ocean regions by astronauts while in space (11) and from ERTS imagery off Long Island and Cape Town (12). We believe that the internal waves in the Gulf are formed on the interface under the thin, buoyant, estuarine layers of warmer water described in the summer circulation model. In the middle of the northern Gulf these overlapping arcuate sets are concave to the west and may be remnants of older estuarine gyres of previous tidal pulses that have drifted eastward. Further photographic interpretation (13) documents the influence of wind on surface water lenses, tidal phase velocities and other features.

Substantial changes in the plankton fauna may be expected to occur in relation to differences in turbidity, especially as these correlate with differences in nutrient levels. We should ask whether schools of anchovies and other plankton-feeding fish, as well as predators such as tunas, concentrate significantly in clear "windows" (seen on the orbital photographs) wich drift about the central and western portions of the northern Gulf. If such concentrations form at interfaces between turbid an non-turbid water, the use of satellite imagery would improve management of catch levels, fishing seasons, and spawning preserves for commercial fishes. The circulation patterns of the model suggest that organisms with larvae wich spend relatively long periods as plankton may have repopulation

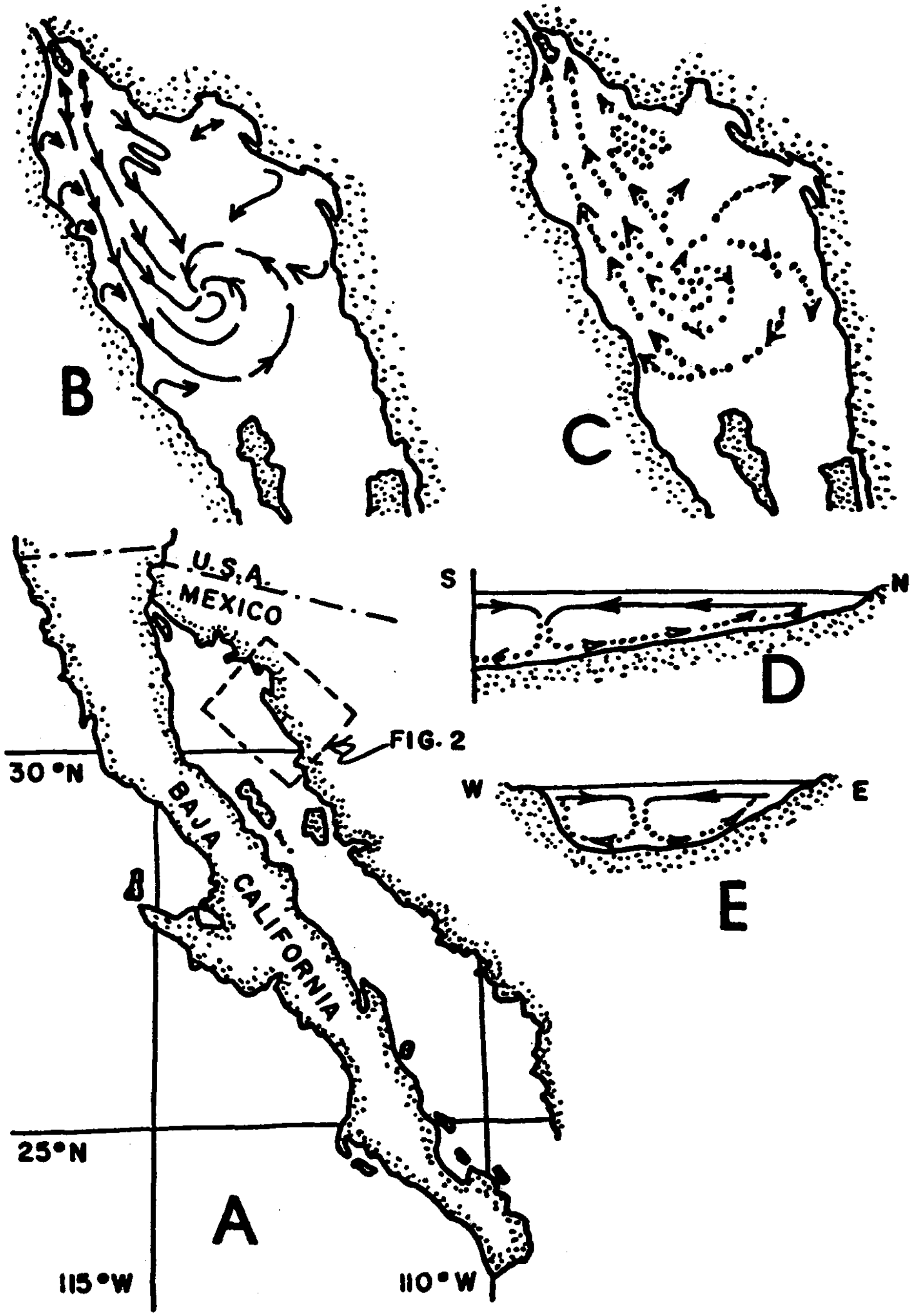

Figure 1- A. Location of the northern Gulf of California above the midriff islands and the area encompassed in Fig. 2.
B. Surface circulation--summer model proposed showing central gyre and directions of flow (arrows).
C. Bottom circulation--summer.
D. Summer; schematic north to south crossection.
E. Summer; east to west crossection; note upwelling along the coasts.

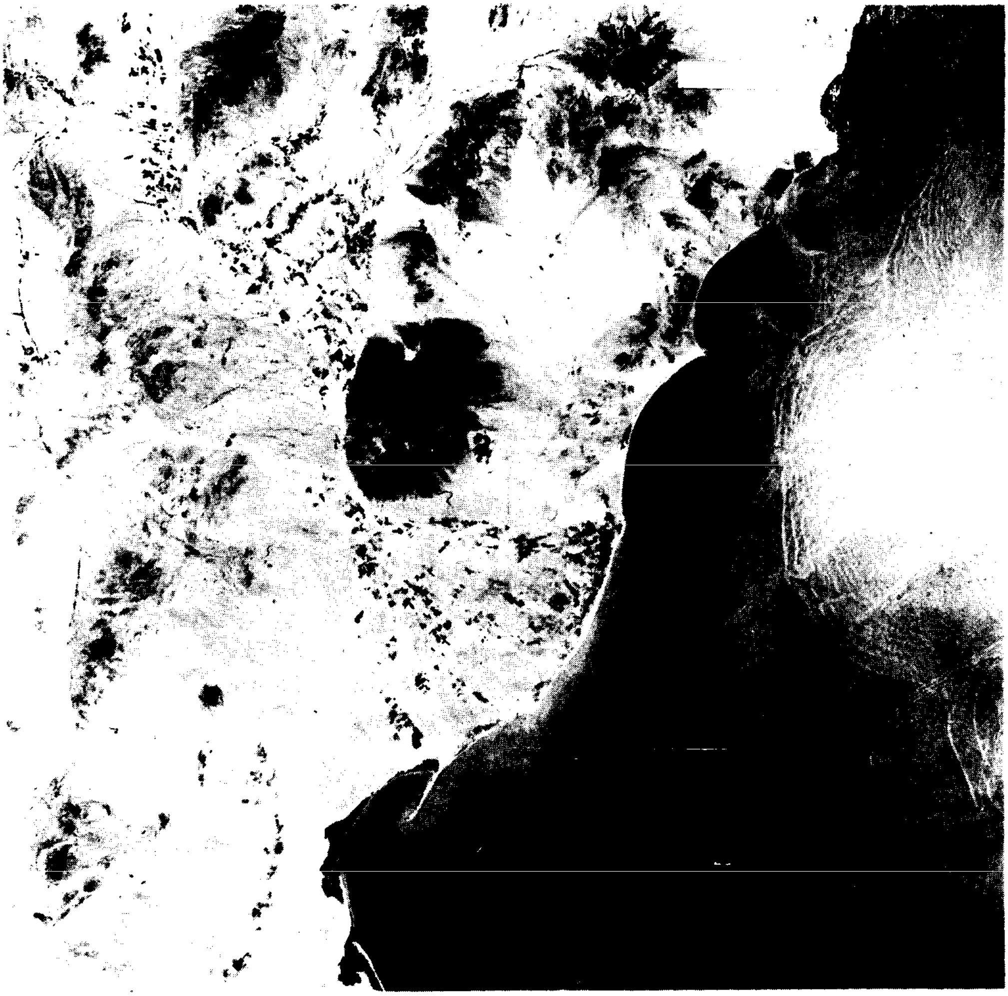

Figure 2- Skylab photograph taken Jan., 1974, showing packets of surface slicks generated by internal waves. Arcuate refraction likely caused by shoals, Scale = 20 km.

mechanics different from what otherwise might be assumed. Some Sonoran tidal flats might for instance, be vital sources of seed stock for Baja Californian clam beds. Current patterns suggested by the model also would provide better understanding of the life cycles of the commercial shrimp species of the northern Gulf. The indicated onshore flow of presumably enriched bottom waters in the summer is particular interesting in this regard. The circulation model has special applicability in planning monitoring sites for pesticides and heavy metal pollutants. For instance, a mass of heavily contaminated water moving into the Gulf from the Colorado River in mid-summer would show up strongly in samples taken a few kilometers off the Baja California coast but would be virtually undetectable near the Sonoran shore. The chances for long residence time in water near the Delta could be much greater in summer than in winter. Refinement of this model is need over the next few years to help in decision making for such matters as the sewage disposal problems of tourist beach developments, the impact of suggested nuclear power plants on fisheries, and the sitting of maricultural activities in the northern Gulf.

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