NOTES

THE MEAN ANNUAL CYCLE OF COASTAL UPWELLING OFF WESTERN NORTH AMERICA AS OBSERVED FROM SURFACE MEASUREMENTS

One of the world's major upwelling regions lies off the west coast of the United States and northern Mexico. This paper summarizes marine surface observations to describe the normal yearly cycle of intensity of upwelling for the major portion of the northeastern Pacific coastal upwelling region.

Sverdrup (1938) applied Ekman's (1905) theory to account for a coastal upwelling situation observed off southern California. He proposed a mechanism by which water is transported offshore in the surface Ekman layer due to the stress of the wind on the sea surface and is replaced by water upwelled from depth. Wooster and Reid (1963) presented evidence that this is, indeed, the dominant mechanism acting in regions of slow, diffuse eastern boundary currents wherein lie the major coastal upwelling areas of the world, including that of the northeastern Pacific.

Our approach is to define the mean annual cycle of offshore Ekman transport along the west coast of the United States and the immediately adjacent regions of Canada and Mexico and to correlate this with features indicative of upwelling which appear in the long-term mean monthly distributions of sea surface temperature.

Marine surface weather observations for this study were obtained from a version of the National Climatic Center's tape deck of marine surface observations (Tape Data Family-11) in use at the U.S. Navy Fleet Numerical Weather Central. The observations in this file come primarily from merchant and naval ships and sometimes contain various errors in position, measurement, or processing. Consequently, the sea surface temperature data were subjected to an editing process which consisted of two filters. First, a gross error check was performed to eliminate nontemperatures. Second, the data were checked by comparison with a running mean of 10 reports. When a report of sea surface temperature differed from the running mean by greater than 9°C, the report was rejected. Wind speeds of greater than 100 m/s were rejected. "Variable" winds (no direction reported, low reported speed) were treated as calms.

The Ekman transport was calculated by the following procedure. The stress vector was computed from each wind observation according to the classical square law:

$$\vec{\tau} = \rho_a C_D |\vec{\nu}|\vec{\nu},$$

where $\vec{\tau}$ is the stress of the wind on the sea surface, ρ_a is the density of air (0.00122 g/cm^3), C_D is an empirical drag coefficient (0.0013), $\vec{\nu}$ is the observed wind velocity vector, and $|\vec{\nu}|$ is the observed wind speed The resultant Ekman wind stress transport, $\vec{M}$, was computed according to,

$$\vec{M} = \frac{1}{f}\vec{\tau} \times \vec{k}$$

where $\vec{\tau}$ is the wind stress vector, f is the Coriolis parameter, and $\vec{k}$ is a unit vector directed vertically upward.

Figure 1 displays composite monthly values of these data for the 20-yr period, 1948-67. The plot on the left displays time series isograms of offshore component of Ekman transport while the central plot shows similar isograms of sea surface temperature. The coordinates are north-south distance on the ordinate and time by month on the abscissa. Each plot represents about 75,000 individual observations made within the 1° squares shown in the coastline plot to the right. The number of reports per 1° square per month was in the range 22 (in January off Vancouver Island) to 1,884 (in October off Los Angeles).

The sea surface temperature plot reveals a normal north-south gradation of temperature and a seasonal warming-cooling cycle with minima from February to April and maxima in August and September. The effects of upwelling are seen as distortions of this general pattern.[1]

In the northern portion, Cape Blanco to Vancouver Island, offshore Ekman transport is weak and occurs from about May through

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[1] The fine scale details of the temperature distribution are masked by the 1° square spatial averages. For a detailed treatment of the mean temperature cycle in the southern portion of the region the reader is referred to Lynn (1967).

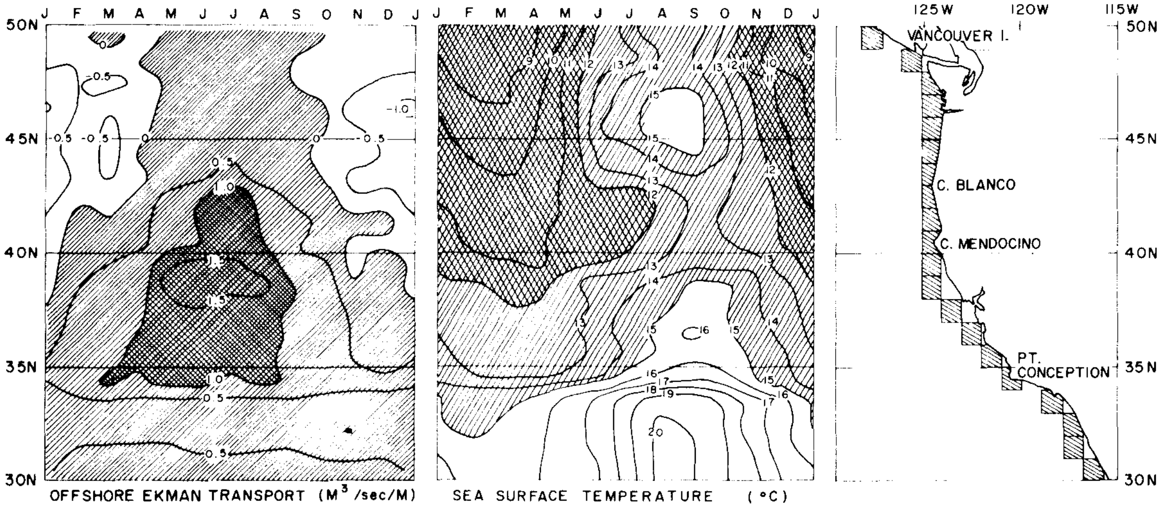

FIGURE 1.—Time series isograms of long-term composite monthly offshore Ekman transports (m^3/s per meter of coastline) and sea surface temperature (degrees Celsius) for the 20-yr (1948-67) period within the indicated 1° coastal squares.

September. The weakness of the transport is reflected by the presence of substantial seasonal warming. The region defined by temperatures greater than 15°C, located off Washington-Oregon during late summer, probably reflects the warming of the low-salinity Columbia River plume water which spreads over a large area of ocean surface. Some of the apparent warming may be due also to the concavity of the coastline in this area which could cause a greater proportion of the observations to be taken farther offshore, both because the 1° squares extend farther off the coast and because the coastwide shipping tracks may be displaced offshore.

South of Cape Blanco an abrupt increase of summer offshore Ekman transport is indicated, particularly during June and July. This is associated with a suppression of seasonal warming during early summer. Consequently, the period of maximum sea surface temperature is delayed until September when offshore transport has relaxed considerably.

South of Cape Mendocino Ekman transport is directed offshore for virtually the entire year and reaches its greatest value for the whole coast at about lat. 39°N during May through August. This maximum corresponds to an extreme suppression of seasonal warming indicated by nearly horizontal isotherms in the figure.

South of Point Conception, the offshore Ekman transport, although remaining generally positive throughout the year, is small and an abrupt southward increase in temperature, particularly during the summer, is apparent. Due to the tendency for a cyclonic eddy to form in the Southern California Bight (Reid, Roden, and Wyllie, 1958), warm advection not directly related to upwelling may be an important factor in this increase.

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