NASA Technical Memorandum 81332

Biological and Physical Oceanographic Observations Pertaining to the Trawl Fishery in a Region of Persistent Coastal Upwelling

John T. Howe, David B. Gibson, Travis O. Evans, Larry Breaker, Robert C. Wrigley and William W. Broenkow

(NASA-TM-81332) BIOLOGICAL AND PHYSICAL OCEANOGRAPHIC OBSERVATIONS PERTAINING TO THE TRAWL FISHERY IN A REGION OF PERSISTENT COASTAL UPWELLING (NASA) 19 p HC A02/MF A01 CSCL 08A

N82-13637

Unclas G3/48 08445

November 1981

National Aeronautics and Space Administration

NASA Technical Memoradum 81332

Biological and Physical Oceanographic Observations Pertaining to the Trawl Fishery in a Region of Persistent Coastal Upwelling

John T. Howe, Ames Research Center, Moffett Field, California
David B. Gibson, Seeadler Co., Morgan Hill, California
Travis O. Evans, Captain, Trawler Bountiful, Port of Avila, California
Larry Breaker, National Earth Satellite Service, Redwood City, California
Robert C. Wrigley, Ames Research Center, Moffett Field, California
William W. Broenkow, Moss Landing Marine Laboratories, Moss Landing, California

NASA
National Aeronautics and
Space Administration

Ames Research Center
Moffett Field, California 94035

BIOLOGICAL AND PHYSICAL OCEANOGRAPHIC OBSERVATIONS PERTAINING TO THE TRAWL FISHERY IN A REGION OF PERSISTENT COASTAL UPWELLING

John T. Howe, David B. Gibson,* Travis O. Evans,† Larry Breaker,‡ Robert C. Wrigley, and William W. Broenkow§

Ames Research Center

SUMMARY

An upwelling episode in the Point Sal region of the central California coast is examined by using data obtained in April 1981, by a data buoy operated by the National Oceanic and Atmospheric Administration (NOAA). The episode was interrupted by the abrupt abatement of the strong wind which promotes coastal upwelling. The mean hourly upwelling index from April 4 through April 13 was calculated to be higher than the 20 year mean monthly value. During 3 days of light wind on April 13, 14, and 15, commercial bottom trawl operations were possible. Shipboard estimates of chlorophyll content in surface waters during trawling, on April 14, showed the high concentrations that are indicative of a rich biomass of phytoplankton, probably a result of the upwelling episode. Satellite imagery showed the extent to the upwelled water to be of the order of 100 km offshore — the result of many upwelling episodes. Shipboard echo-sounder data showed the presence of various demersal species and of zooplankton; the latter presumably graze on the phytoplankton in the upper euphotic layers. The fish catch data are recorded according to species for 2 days of trawling, and the catch per trawl-hour is recorded.

INTRODUCTION

Although coastal upwelling has long been known to be of great importance to the fishing industry, it has been studied intensively for only the past two decades (refs. 1-4). The combined effect of Earth's rotation and an equatorially directed wind contributes to the movement of surface layers of water offshore along the California coast. These surface waters are replaced by cooler water drawn from greater depths — perhaps as deep as 100 m. These deeper waters, which bring nutrients to the surface, are then transported offshore in turn, gradually warming as they go. The nutrients nurture phytoplankton, which bloom and grow by photosynthesis in surface waters. Chlorophyll pigments in the phytoplankton absorb sunlight at discrete wavelengths that penetrate seawater to considerable depth. This is the primary source of energy that supports the food chain in the sea.

In a region of persistent upwelling, the process is sporadic — as variable as the wind itself. But for all of the variability, extensive upwelling structures are formed and maintained, such that the biological effects of coastal upwelling extend

*President, Seeadler, Co., 65 Acron Court, Morgan Hill, California 95037.
†Captain, the trawler Bountiful, Port of Avila, California.
‡Oceanographer, National Earth Satellite Service, Redwood City, California 94063.
§Professor, Moss Landing Marine Laboratories, Moss Landing, California 95039.

hundreds of kilometers into the ocean and bring life to what would otherwise be a wet desert (in the region south of Cape Blanco).

It is provident that the process is variable, for if the wind persisted and was continuously strong, the rich food of the sea would not be accessible. Men can only venture upon the sea when it allows, and fishing gear (particularly bottom trawl gear) can be deployed only when the wind and waves allow.

Modern technology has greatly facilitated the study of coastal upwelling. Permanent data buoys provide a wealth of detail on the course of local events, and satellite imagery shows the vast extent of upwelled water and the development of ocean fronts associated with upwelling (refs. 5, 6).

When the wind abates sufficiently, coastal trawl vessels venture forth. Such vessels provide an opportunity to make in situ biological and physical measurements in coastal waters that are of particular interest to commercial fisheries. And the benefit to the oceanographic community can scarcely be overstated in this time of severely diminished oceanographic research vessel support. But the commercial fisheries community is also experiencing economic hardship, and oceanographic research that enhances the understanding of phenomena related to fisheries should be useful. Indeed, this paper is addressed primarily to the fishing community, and it is hoped that it will merit their interest.

Thus, as a practical matter, we shall report on the content of the trawl, an interesting variety of bottom dwellers composed of marketable species (e.g., bocaccio, various kinds of sole, cod, octopus, and large prawns) and an equal mass of unmarketable trash fish (skates, small sharks, ratfish, and undersized specimens of otherwise marketable fish); the latter are usually wasted but are a potentially important resource.

Bottom trawling is terminated when wind and sea, broken gear, a market opportunity, or fatigue interrupt and the fishermen return to port. Quite likely, another episode of coastal upwelling begins, once more to contribute to the extensive surface biomass which is the basic nourishment of life in the sea.

We shall trace these events from measurements, estimates, and observations, and then relate them to predictions by others concerning ocean phenomena in this region, and to economic considerations of the coastal bottom trawl industry of central California.

OBSERVATIONS

Weather and Sea Conditions

On April 14, 1981, measurements related to oceanographic conditions and to commercial trawl fishing were made during trawl operations off the Point Sal area near Point Conception, California, in the region shown by the solid circles in figure 1 (ref. 7). During the day, light fog prevailed, with visibility of 0.5-2 miles, and the wind was negligible. Figure 1 is a chart from the National Oceanic and Atmospheric Administration (NOAA) of sea surface temperature and thermal fronts as of April 9, 1981; the data were obtained from satellite and shipboard observations. Intense upwelling along the central coast is noted. A chart for April 16 of the same region is similar (approximately lat. 34°50'N and long. 120°50'W), except that intense

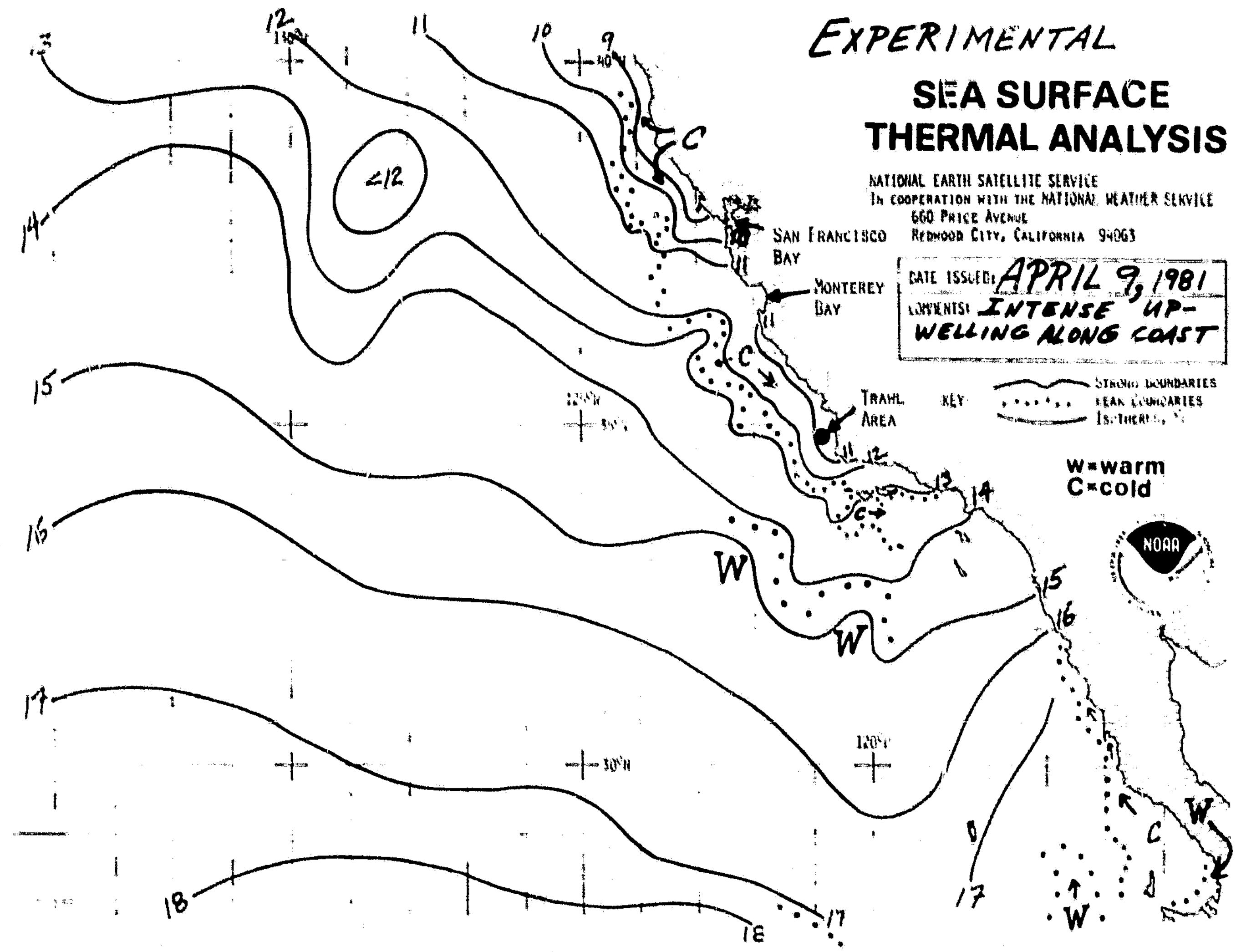

Figure 1.- NOAA sea surface chart showing trawling area.

upwelling along the coast was not noted. We note that the winds favorable to upwelling vanished on April 13. We may consider figure 1 to be generally representative of the sea surface temperature on April 14, the day when shipboard observations were made, as well as through April 16. We also note that sea surface temperature was about 11°C (52°F) in the trawl area.

Figure 1 also shows weak temperature boundaries offshore of the trawling location. These boundaries are as far as 200 km offshore, and may represent the seaward extent of water that was upwelled near the coast. The boundaries may be divergent, and thus represent a region of mixing with oceanic water rather than a convergent front that downwells offshore.

The environmental events that occurred before April 14 are informative because they contribute to the upwelling. Figure 2 shows wind speed data from April 4 through April 15, 1981. These data were obtained from the recently deployed NOAA Environmental Data Buoy, that records information hourly, at 34.9 N, 120.9 W (ref. 8). During the 9 day period from April 4 through April 12, the wind speed was fairly high — up to 13 m/sec (24 knots) on April 6, 8, and 9. Bottom trawl operations are feasible when the wind does not exceed about 10 m/sec (19 knots) (depending on wave and current

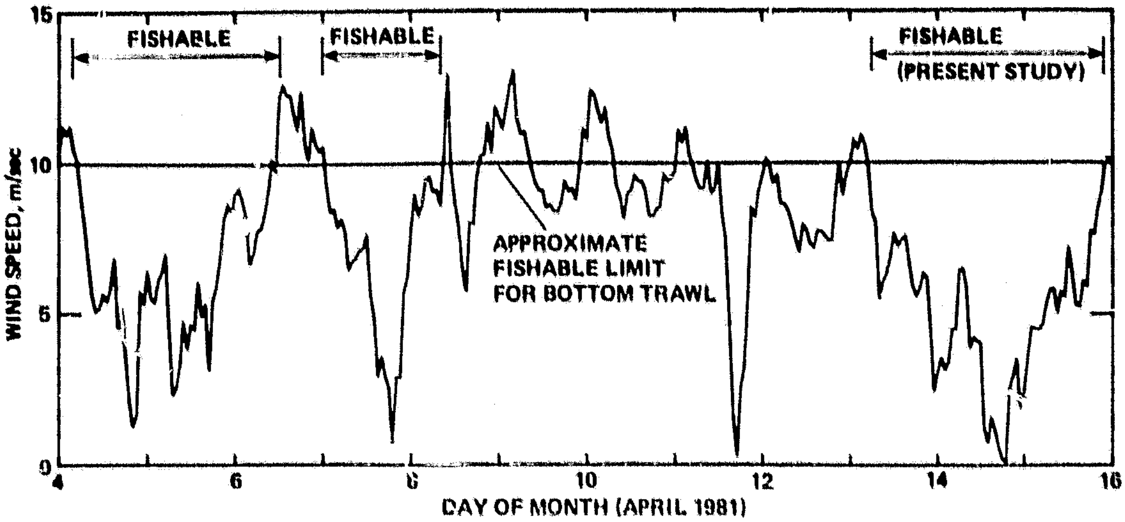

Figure 2.- Wind speed record showing bottom trawl fishing opportunities from NOAA Point Sal Data Buoy.

conditions). Thus, three fishing opportunities of varying duration occurred, as shown. We shall be concerned with the third fishing "window," from April 13 through April 15, 1981.

Figure 3 shows the component of wind parallel to the coastline and conducive to upwelling, during the 12-day period of interest. The coastline is taken to be 140° in direction (by interpolation from ref. 9), so that the corresponding wind component is from 320°. Comparison with figure 2 indicates that the wind was predominantly aligned with the coastline throughout the entire period. Figure 3 also shows the hourly surface water temperature record for the period. The temperature rose and fell, partly in response to the wind, tending lower to a minimum of 10°C (50°F) on

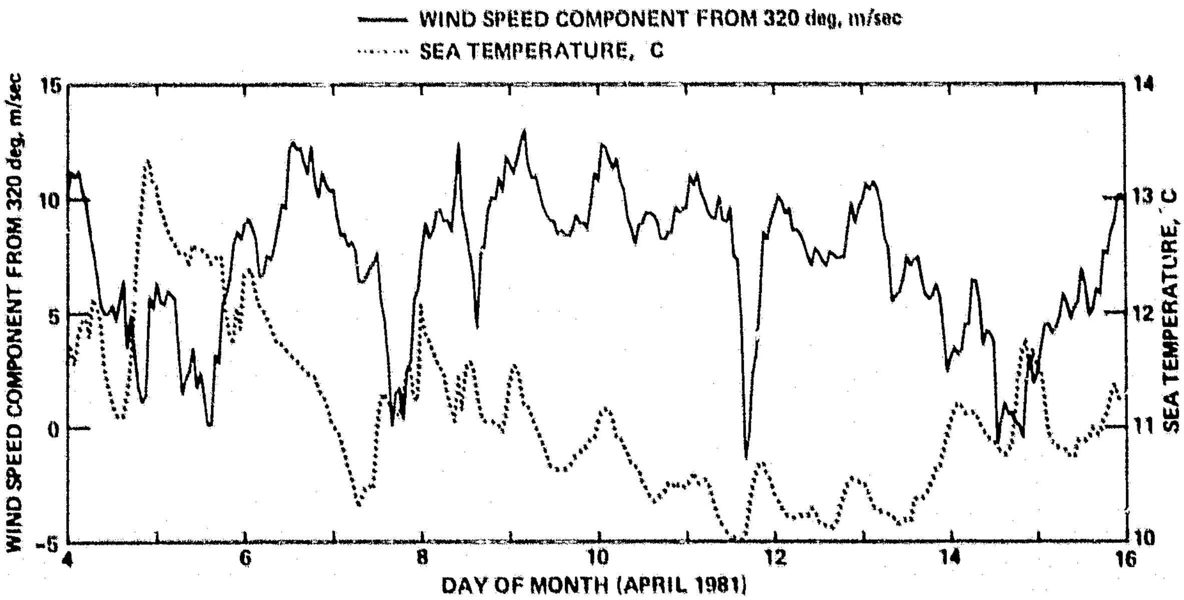

Figure 3.- Upwelling wind component and sea surface temperature record from NOAA Point Sal Data Buoy.

April 11 — following 4 days of fairly consistent strong winds.[1] This suggests increased upwelling near the coast, where surface waters have been replaced by cool deeper waters. Thus, nutrient-rich waters moved to the surface, where a phytoplankton bloom developed.

Early on April 13, the wind fell abruptly and remained light until early on April 16. During that time, bottom trawl operations were feasible because of light winds and seas that declined steadily from a wave-height peak of 2.4 m on April 13 to 1.4 m on April 15. (Peak wave height had been 3.3 m on April 10). It may also be noted in figure 3 that the sea surface temperature tended upward during the period of light winds, indicating diminished upwelling activity. April 14 and 15 show an interesting diurnal temperature change of less than 1°C in the absence of significant wind. Trawl operations took place on those 2 days and will be described subsequently.

It may be asked, incidentally, how rapidly the phytoplankton respond when the wind subsides. And is there an effect on fishing? Phytoplankton abundance can be affected in many ways — for example, by predation, by a diminished supply of upwelled nutrients (ref. 10), or by the phytoplankton sinking to a depth where solar radiation is significantly diminished. We shall see that the phytoplankton suffered no apparent trauma during the 2 days of trawling. Moreover, for present purposes, we can infer, from simple dynamic estimates where particle motion is influenced by bouyancy and by drag described by Stokes law (ref. 11), that sinking is not a significant effect. (A detailed description of plankton dynamics, beyond the scope of the present paper, is presented in ref. 12). In our consideration, we seek the time required for a particle to sink to a depth where sunlight of wavelength λ has been attenuated by a factor $1/e$. This simple approach yields a light-limited "half-life" of

$$t = \frac{18\mu}{K_\lambda d^2 \rho (\rho_p/\rho - 1) g} \tag{1}$$

where μ is the viscosity of sea water (13 g/cm·sec; ref. 13, p. 69); K_λ is the diffuse attenuation coefficient of light at a wavelength of 450 nm, which is absorbed by chlorophyll pigments; d is particle size; ρ is seawater density; ρ_p/ρ is the specific gravity of the particle (say, 1.04; ref. 13, p. 764); and g is the gravitational constant. Thus

$$t = \frac{6}{d^2 K_\lambda} \text{ sec} \tag{2}$$

where d is in cm, and K_λ is 1/cm.

Let $K_\lambda = 6/D$ (W. W. Broenkow, private communication, 1981) where D is the Secchi depth in meters, about 4 m in the trawl area, as we shall see. For small particles, say $d = 2\times10^{-3}$ cm (ref. 13, p. 301), the half-life exceeds 2 years. Such small particles never sink out of the euphotic zone. For exceptionally large particles, say a millimeter in diameter, the half-life is about half a day. In the next section, we shall see that the phytoplankton abundance was high 36 hr after the wind ceased, and based on the fish catch shown subsequently, it is likely that the concentration was high after 2-1/2 days of no wind.

---

[1]A cross spectrum between temperature and wind from 320° suggests that about a day after the wind increases, the sea surface temperature falls.

Estimates of Chlorophyll Concentration

The Secchi disk is one of the oldest oceanographic tools and one of the most simple to use for making in situ estimates. Thus, shipboard estimates of chlorophyll concentration were made during trawl operations by using the Secchi disk. Water depths ranged from 150 to 200 m, and there was neither evidence of nor reason to expect ocean contamination from surface runoff. The measurements were made at convenient times during the day when the trawl was being brought aboard and the vessel was not under way. The technique was simply to lower the Secchi disk into the ocean on a measured line until it could no longer be seen. Then the disk was raised until it was just visible and the Secchi depth (in meters) D was noted. The measurements, performed as shown in figure 4, were repeated by a second observer. Atmospheric

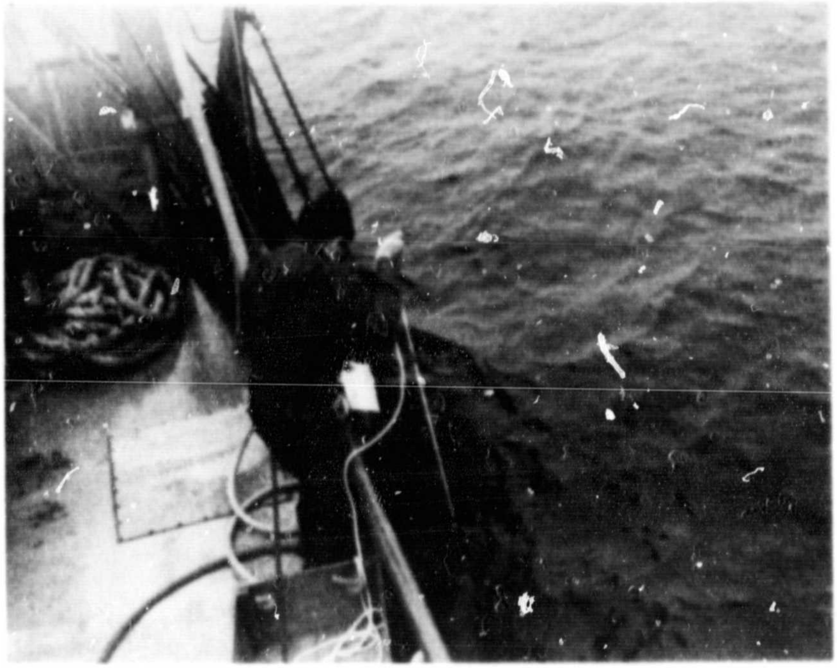

Figure 4.- Secchi disk and Munsell color measurement procedure.

illumination was generally diffuse because of the light overcast, and sun-glint was not apparent at any time.

A relationship between Secchi depth and chlorophyll content has been recognized for a long time (refs. 14, 15). A correlation of chlorophyll concentration with Secchi depth was obtained by comparing flow-through fluorometer measurements with Secchi measurements. Data were obtained off central and southern California, Baja California, the Gulf of California, the Gulf of Mexico, and the Atlantic coast from north of Cape Cod to southern Florida, including both the Gulf Stream and the Sargasso Sea. These measurements were described in reference 16. A plot of that data base, presented in reference 16, has been modified here to exclude samples that were influenced by terrestrial sediments in figure 5. A correlation of that data base is shown by the line that is represented by the expression

$$c_i = \left(\frac{15}{D}\right)^2 \tag{3}$$

where c_i is the chlorophyll-a concentration in milligrams per cubic meter, and D is the Secchi depth in meters.

The present Secchi depth data are shown on the correlation by the three solid square symbols (fig. 5). Although five measurements were made, two sets were identical (table 1) and only three symbols appear in figure 5. Thus, the top two symbols represent four measurements. It is noteworthy that the present observations are at the high end of the chlorophyll concentration scale; this finding will be discussed subsequently.

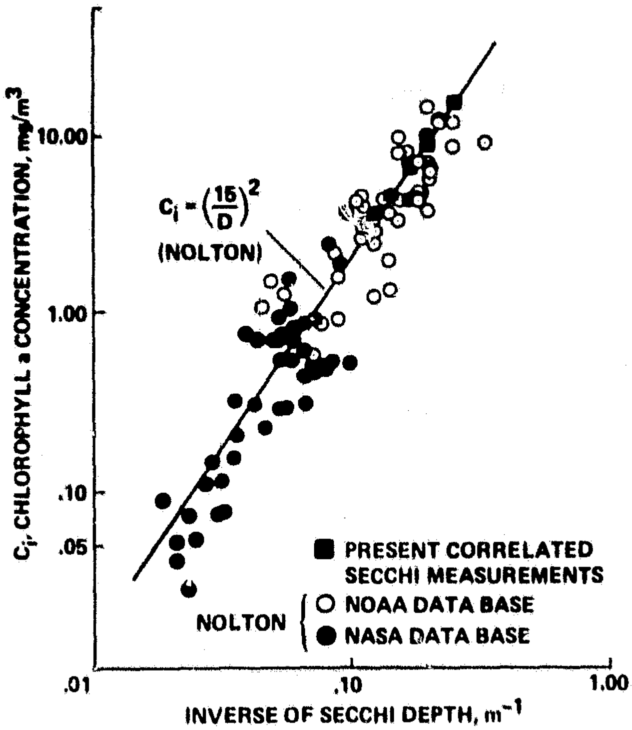

Figure 5.- Chlorophyll-Secchi data and correlation, present Secchi measurements.

We note in passing that an attempt was made to estimate chlorophyll concentration by in situ color observations in accordance with procedures described in reference 16 and in an unpublished report by Austin et al., 1977. Color estimates of chlorophyll have been made by remote sensing radiometers aboard survey aircraft and satellites (refs. 17-19), as well as by the coastal zone color scanner aboard Nimbus 7 (ref. 20). For present purposes, carefully selected Munsell color chips (ref. 21) were compared with the color of the Secchi disk image color at half the Secchi depth, as described in reference 16. Although the color comparisons were reproducible, agreed with the family of colors selected in reference 16, and indicated generally high chlorophyll concentrations, the quantitative interpretation of concentrations were ambiguous. Thus, the Secchi disk alone is sufficient to estimate chlorophyll concentrations, which we believe was the inference of reference 16.

TABLE 1.- MEASURED SECCHI DEPTHS AND CORRELATED CHLOROPHYLL-a CONCENTRATIONS

Observed Secchi depth, m	Chlorophyll-a concentration = $(15/D)^2$, mg/m^3
4	14
4	14
5	9
5	9
6	6.25

Chlorophyll and Coastal Upwelling

Chlorophyll pigments are the primary absorbers of the solar radiation that sustains the photosynthetic production of organic material that is the basis of the food chain. The Secchi disk measurements reported here (fig. 5) indicate a high concentration of chlorophyll — of the order of 10 mg/m^3 (table 1 and fig. 5). At once a question arises concerning the reason for the richness of the biomass of phytoplankton inferred by these measurements.

The answer, quite likely, is that this is a region of persistent upwelling. In the central California coastal region, upwelling may occur at any time of the year, as indicated by the solid line in figure 6. That line, corresponding to the Point Sal region at lat. 35°N, long. 121°W, was obtained by interpolating between upwelling indices at lat. 36°N, long. 122°W and lat. 33°N, long. 119°W of mean monthly values over the 20 years from 1948 to 1967 (ref. 9). Those indices were computed from geostrophic wind and include surface friction and a constant drag coefficient. The line shows that the upwelling index varies seasonally, it reaches a maximum, and then relaxes, with a peak in June and a minimum in December. It is significant that upwelling may occur throughout the year in the Point Sal region. Thus, upwelling conditions conducive to the production of a phytoplankton bloom are often present.[2]

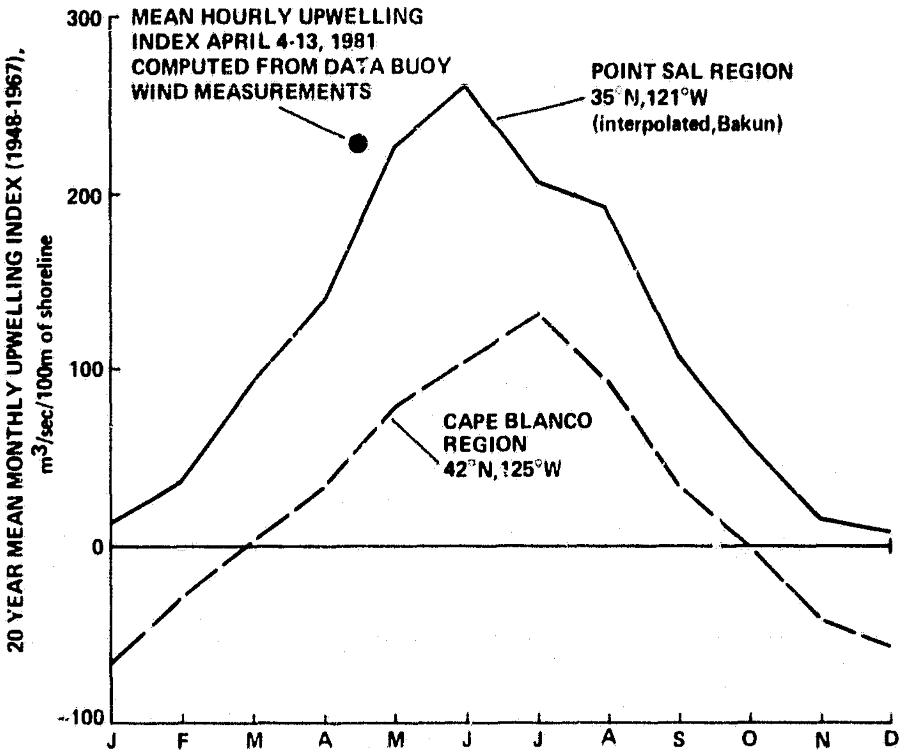

Figure 6.- Upwelling index comparison.

[2]We note that the relationship between upwelling persistence and upwelling intensity is subtle. Off Peru, for example, upwelling is persistent but generally not intense. However, on a yearly basis, productivity off Peru is the highest on Earth (ref. 22).

PRECEDING PAGE BLANK NOT FILMED

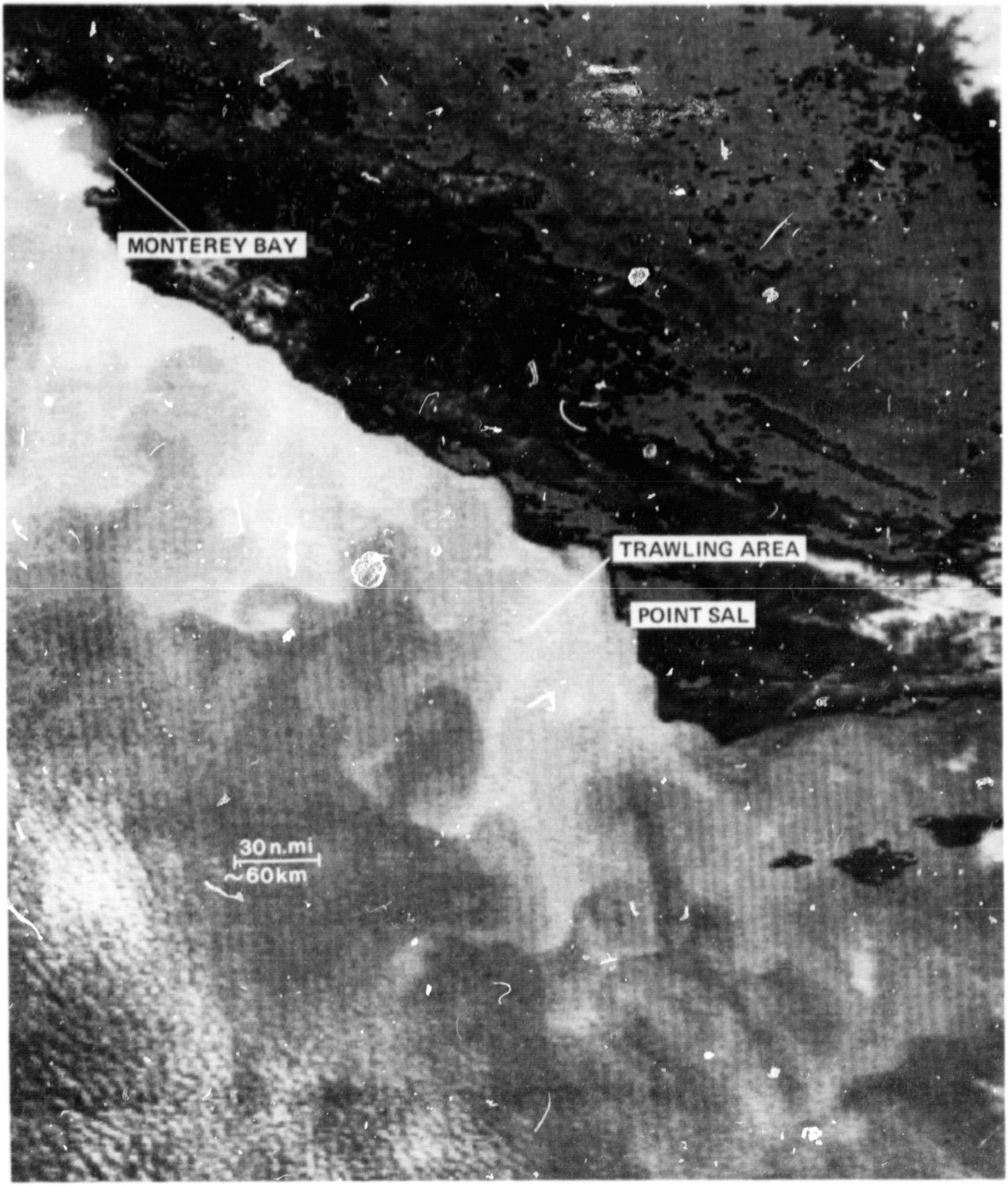

Figure 7.- Computer enhanced infrared satellite image (NOAA-6 satellite), April 13, 1981; light water tones along coast are cool upwelled water.

thermal analysis chart shows that this was the case 2 days after; figure 7 shows the same weak thermal boundaries the day before the measurements were made. Trawling operations were conducted inshore of these boundaries, and no distinct fronts were encountered.

Echo-Sounder Data

Next we consider subsurface acoustic sounding data in the water column beneath the vessel. Figure 8 shows a segment of the water column near the bottom, indicated

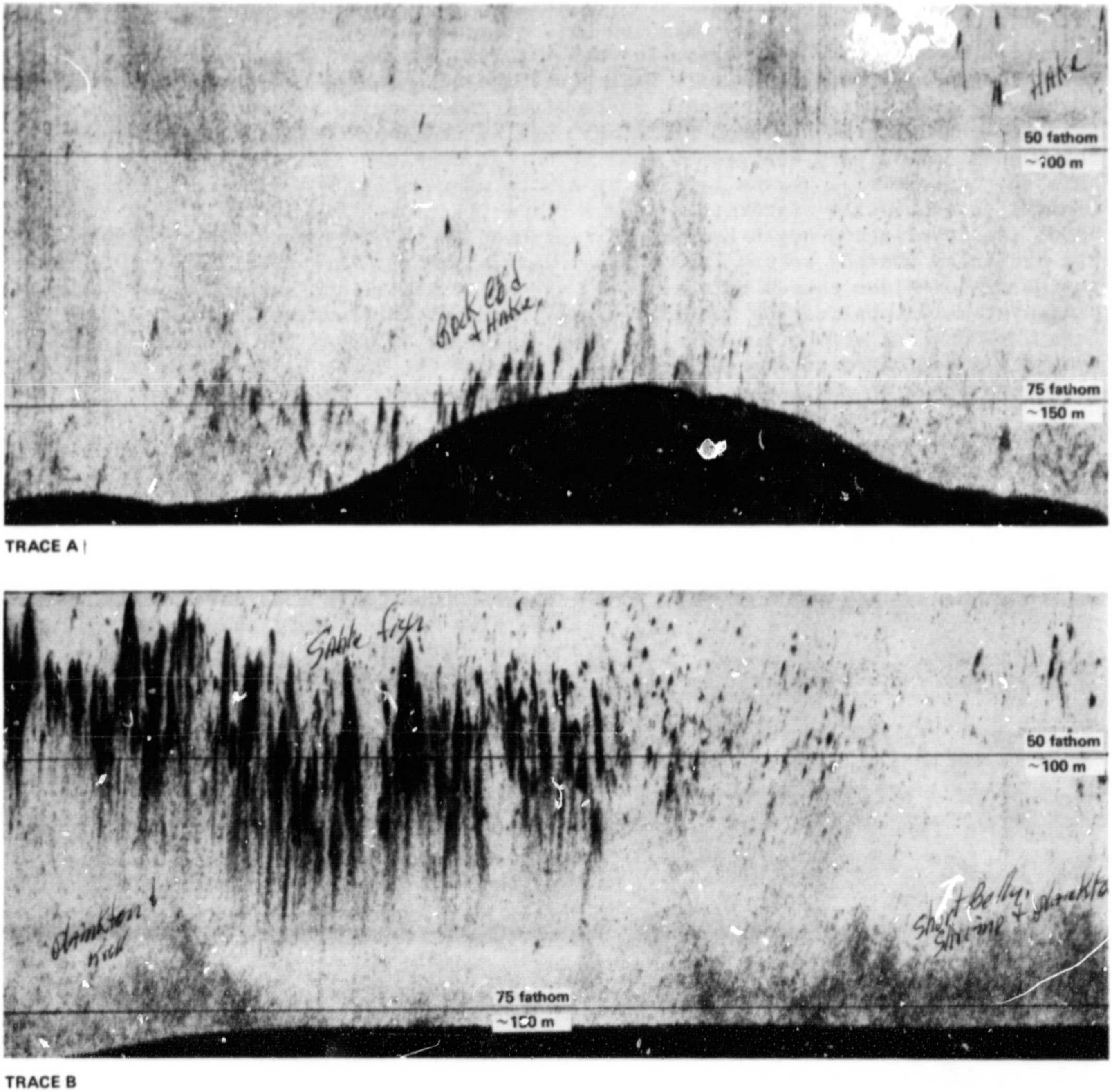

Figure 8.- Typical echo-sounder traces in lower part of water column with species noted.

by the dark outline in the lower part of the figure. In the figure, the water column shown is from about 80-160 m below the surface. Dark masses in the water column represent schools of fish that were individually identified on the echo sounder; the identification was based on experience. Near the bottom, rock cod and hake are indicated, and from about 100-150 m, hake and sablefish are shown. (Sablefish, or black cod, are often marketed for the "fish and chips" industry.) Near the bottom of the figure, gray areas are noted as short-belly, shrimp, plankton, and krill. In other portions of the record that are not shown, schools of young hake were found close to the bottom.

The plankton shown here are not the surface phytoplankton mentioned previously. Rather these are zooplankton, which consist of great numbers of small crustaceans, jellyfish, worms, mollusks, eggs, and other larval stages. These animals consist of both floaters and weak swimmers. This heterogeneous mass is characterized by diurnal vertical motion. At night, such a trace would show them to be near the surface, supposedly grazing on the phytoplankton. During the day, these small fish return to the bottom and in turn are grazed upon by bottom dwellers. As the sun begins to set, this zooplankton mass begins to rise at a rate approaching 7 m/min (ref. 27). Generally, the entire migration to the surface is complete by 10 to 11 p.m. Near dawn, the zooplankton begin the return migration to the bottom. This appears to be the mechanism whereby bottom fish that are not scavengers are nourished by a surface phytoplankton bloom caused by the upwelling of nutrients into surface layers where photosynthesis supplies the needed energy. Thus bottom (demersal) fisheries may be less dependent on offshore convergent downwelling fronts than the pelagic fisheries. However, a region of persistent upwelling, such as the Point Sal area, is well suited to bottom trawling and perhaps midwater trawling as well.

Fish Catch

Figure 9.- Trawl catch.

The fish catch from a typical net tow is shown in figure 9; it consists of many species. It is noteworthy that approximately half of the catch is considered waste. These trash fish include small sharks, skates, a considerable number of small ling cod and black cod and several other species. This is a wasted resource the potential utility of which should be re-examined[3] as a possible means of strengthening the economic condition of the trawl industry. The industry was developed on the basis of low-cost fuel ($0.13/gal vs the present $1.00/gal), low-cost labor, and relatively stable markets. That basis no longer exists, and the survivors in the trawl fishery find it difficult to continue.

The marketable fish catch for April 14 and 15, 1981, is shown in table 2, where the

---

[3]Such an evaluation was made by the Alpine Geophysical Association concerning fish protein concentrate in the early 1960's.

TABLE 2.- MARKETABLE FISH CATCH

Variety	Catch			
	April 14, 1981		April 15, 1981	
	lb	kg	lb	kg
Bocaccio	2900	1315	3400	1542
Petrale sole	475	215	400	181
English sole	275	125	225	102
Rex sole	125	57	25	11
Ling cod	85	39	95	43
Total	3860	1751	4145	1879
Prawns	10 gal (37.85 ℓ)		1 gal (3.79 ℓ)	
Tow time	9 hr		7.5 hr	
Production	432 lb/hr (195 kg/hr)		553 lb/hr (251 kg/hr)	

catch is listed according to species.[4] These catches resulted drom four tows on April 14, and three tows on April 15. The primary marketable fish on those days was the bocaccio (Sebastes paucispinis), some of which are evident in the space below the net in figure 9; some that have been sorted appear under the plywood at the bottom left of the photo. These are adult migratory fish that feed in the strong upwelling region but do not spawn there. Rather they are thought to spawn south of Point Conception in the southern California Gyre, where there is generally a local minimum of offshore transport of coastal waters (ref. 25) — a more hospitable environment for spawning. Adult hake (fig. 8) are believed to follow a similar pattern.

If the catch is sold for an average of $0.25 per pound, the return is $108/tow-hour on April 14 and $138/tow-hour on April 15. Roughly half of the return supports vessel expenses and the other half supports the captain and crew (there is very little return on investment). Trawling can only be done when the weather allows, and the balance of the time is occupied in vessel maintenance. Thus, the survivors in this economically marginal industry often barely break even.

The events following April 15 are of interest. During the last tow on the afternoon of April 15, the wind increased (figs. 2, 3), reaching a peak of 10 m/sec on April 16. Although the sea was marginally fishable on April 16, fishing operations were not conducted. The wind abated somewhat on April 17 and trawling was resumed. The catch was small and the trawl gear became fouled on the bottom. Trawling was also undertaken on April 20, 23, and 24. April 23 is noteworthy because of a large prawn catch.

[4]The catch by species, location, and month is presented in reference 28, for 1976. Similar reports are available for previous years. Reports after 1976 are in preparation.

CONCLUSIONS

Upwelling of coastal waters near Point Sal, California, was examined by use of wind, sea surface temperatures, and shipboard data, as well as surface estimates of chlorophyll concentrations. Strong equatorward winds produced an apparent upwelling episode lasting about 9 or 10 days. The mean hourly upwelling index for 10 days exceeded the 20 year monthly mean value. The nutrients that were recycled to surface waters during the episode together with photosynthesis produced a phytoplankton bloom. From April 13 through April 15, the wind and seas abated. Those 3 days offered a period during which commercial trawl operations were feasible. Estimates of chlorophyll concentrations were made on April 14 from the deck of a vessel during trawl operations. The estimates, made by Secchi disk observations, showed high chlorophyll concentrations — as high as 14 mg/m^3, according to correlations with fluorometric data. This indicates that the phytoplankton were abundant immediately following the 9 or 10-day wind episode. An infrared satellite image for April 13 indicated that upwelled waters extended offshore about 100 km, and that a weak thermal boundary marked the interface between upwelled and oceanic waters.

Climatological wind data indicate that the Point Sal region is characterized by persistent and sometimes strong coastal upwelling the year around. This is in contrast with coastal regions north of Cape Blanco, Oregon, where upwelling is more seasonal. The persistent Point Sal upwelling is probably the cause of the high chlorophyll concentration. The apparent offshore extent of upwelling near Point Sal suggests the possibility of an offshore fishery accessible by midwater trawling.

Shipboard echo-sounder data showed the presence of groundfish, midwater species, and zooplankton that graze on the phytoplankton diurnally and in turn are grazed upon by the adult fish. The most prominent marketable species caught by the trawling was boccacio (Sebastes paucispinis), which are thought to spawn in the southern California Gyre, but which feed in the rich upwelled waters north of the Gyre. The fish catch by species, and trawl-tow times for April 14 and 15 have been tabulated for future reference. It was noted that presently unmarketable trash fish composed half the catch. Serious consideration should be given to developing ways to utilize this wasted resource and thus bolster an economically marginal trawl industry.

Finally, because of the great expense of obtaining oceanographic data, cooperation with the fishing industry is very advantageous, economically. Moreover, for studies that relate to commercial fisheries the advantage is greater — the fishing vessels strive to be where the fish are.

REFERENCES

1. Yoshida, K.: Coastal Upwelling Off the California Coast and Its Effect on Productivity of the Waters. Proc. UNESCO Symposium, Physical Oceanography, 1955, pp. 104-106.

2. Yoshida, K.: Coastal Upwelling Off the California Coast. Records of Oceanographic Works in Japan, vol. 2, no. 2, Oct. 1955.

3. Smith, R. L.: Upwelling. Oceanogr. Mar. Biol. Ann. Rev., vol. 6, H. Barnes, ed., George Allen and Unwin Ltd., London, 1968, pp. 11-46.

4. Boje, R.; and Tomczak, M., eds.: Upwelling Ecosystems. Springer-Verlag, 1978.

5. Mooers, C. N. K.; Collins, C. A.; and Smith, R. L.: The Dynamic Structure of the Frontal Zone in the Coastal Upwelling Off Oregon. Phys. Oceanogr., vol. 6, no. 1, 1976.

6. Bowman, M. J.; and Esaias, W. E., eds.: Oceanic Fronts in Coastal Processes. Springer-Verlag, 1978.

7. Sea Surface Thermal Analysis. National Earth Satellite Service, National Weather Service, 660 Price Avenue, Redwood City, Calif. 94063, Apr. 9, 1981.

8. Hamilton, G.: NOAA Data Buoy Office Programs. American Meteorological Society Bulletin, vol. 61, no. 9, Sept. 9, 1980.

9. Bakun, A.: Coastal Upwelling Indices, West Coast of Northern America, 1946-1971. U.S. Department of Commerce, NOAA Tech. Report NMFS SSRF 671, 1973.

10. O'Brien, J. J.; and Wroblewski, J. S.: Analysis of a Nutrient Limited Phytoplankton Model. Contribution 000 of the Geophysical Fluid Dynamics Institute of Florida State University, 1972.

11. Binder, R. C.: Fluid Mechanics. Second ed., Prentice Hall Inc., N.Y. 1949, p. 172.

12. Longhurst, A. R.: Vertical Migration. The Ecology of the Seas, D. H. Cushing and J. J. Walsh, eds., W. B. Saunders Co., Philadelphia, 1976, pp. 116-137.

13. Sverdrup, H. U.; Johnson, M. W.; and Fleming, R. H.: The Oceans. Prentice Hall Inc., 1942.

14. Carlson, R. E.: A Trophic State Index for Lakes. Limnology and Oceanography, vol. 22, 1977, pp. 361-369.

15. Saijo, Y.; and Ichimura, S.: Primary Production in the Northern Pacific Ocean. J. Oceanogr. Soc. Japan, vol. 16, 1960, pp. 139-145.

16. Nolton, J. W.: In Situ Optical Methods for Chlorophyll Estimation in the Sea. Thesis, Moss Landing Marine Laboratories and Department of Biology, San Jose State University, 1980.

17. Clarke, G. L.; Ewing, G. C.; and Lorenzen, C. J.: Spectra of Back-Scattered Light from the Sea Obtained from an Aircraft as a Measure of Chlorophyll Concentration. Science, vol. 167, 1970, pp. 1119-1121.

18. Arvesen, J. C.; Millard, J. P.; and Weaver, E. C.: Remote Sensing of Chlorophyll and Temperature in Marine and Fresh Waters. Astronautica Acta, vol. 18, 1973, pp. 229-239.

19. Mueller, J. L.: Ocean Color Spectra Measured Off the Oregon Coast: Characteristic Vectors. Appl. Opt., vol. 15, 1976, pp. 394-402.

20. Hovis, W. A.; Clark, D. K.; Anderson, F.; Austin, R. W.; Wilson, W. H.; Baker, E. T.; Ball, D.; Gordon, H. R.; Mueller, J. L.; El-Sayed, S. Z.; Sturm, B.; Wrigley, R. C.; Yentsch, C. S.: Nimbus 7 Coastal Zone Color Scanner: System Description and Initial Imagery. Science, vol. 210, Oct. 3, 1980, pp. 60-63.

21. Munsell Book of Colors. (ASTM) Munsell Color Co., 2441 North Calvert St., Baltimore, Md. 21218, 1968.

22. Dugdale, R. C.: Nutrient Cycles. The Ecology of the Sea, D. H. Cushing and J. J. Walsh, eds., W. B. Saunders Co., Philadelphia, 1976, pp. 141-172.

23. Bakun, A.: Daily and Weekly Upwelling Indices, West Coast of North America, 1967-73. U.S. Dept. Commerce, NOAA Tech. Report NMFS SSRF 693, 1975.

24. Howe, J. T.: Coastal Upwelling and the Production of a Biomass. NASA TM-78614, 1979.

25. Bakun, A.; Nelson, C. S.; and Parrish, R. H.: Determination of Surface Drift Patterns Affecting Fish Stocks in the California Current Upwelling Region. Paper presented at Workshop on Ocean Products and IGOSS Data Processing and Services Systems, Moscow, 1979.

26. Nelson, C. S.: Wind Stress and Wind Stress Curl Over the California Current, NOAA Tech. Report NMFS SSRF 714, Aug. 1977.

27. Starkey, R. J., Jr.: Antisubmarine Warfare Oceanography. Part II. Military Electronics/Countermeasures, June 1981, p. 65.

28. Oliphant, M. S.: California Marine Fish Landings for 1976. State of California Department of Fish and Game, Fish Bulletin 170, 1979.