OCEANOGRAPHIC CONDITIONS IN THE NORTHEAST PACIFIC OCEAN AND THEIR RELATION TO THE ALBACORE FISHERY

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ABSTRACT

This paper describes initial environmental conditions encountered by albacore, *Thunnus alalunga* (Bonnaterre), in their annual entry to the region off the northwest coast of the United States, describes the physical mechanisms that produce these conditions, and indicates their influence on the highly variable number of albacore available to the fishery. The region studied extends from the coast of Oregon and Washington to long. 132° W. between lats. 41° N. and 48° N., within which the northernmost part of the American coastal fishery for albacore usually has been confined.

Upwelling, effects of runoff from land, and the excess of precipitation over evaporation produce annually recurrent patterns of distribution of variables. This recurrent aspect is used to distinguish three spatial provinces above and two provinces below the main halocline, each of which reflects the balance of processes affecting it. Variations in the distributions of variables from year to year are shown to be attributable to changes in wind field, in fresh-water discharge from land, and in advection. These variations do not, however, obscure the basic patterns generated by dominant processes.

The distribution of available albacore over the study area is inferred to be sensitive to spatial and year-to-year differences in temperature and in salinity. Higher temperatures, produced by greater retention of heat in the surface layer of the province dominated by effects of land runoff, may give rise to greater concentrations of albacore in this province. Salinity, to which temperature is inversely related, may control the degree to which spatial temperature differences can be effective, possibly by its influence on osmotic pressure. If future investigation confirms this hypothesis, success of the fishery will be predictable from preseason information on wind field, geostrophic flow, and Columbia River discharge.

The yield of the seasonal fishery for albacore (*Thunnus alalunga*) off Oregon and Washington is characteristically variable. Within the period 1951–64, annual landings in these States ranged from 0.6 to 13.5 million pounds. Nearly all albacore landed in Oregon and Washington in 1954 and 1955 were caught south of lat. 40° N.; consequently, the northern fishery was considered to have failed completely in these years.

The region off the Oregon-Washington coast usually represents the northernmost end of the range within which commercially harvestable concentrations of albacore have been found along the North American coast. The fishery spans a shorter time interval than that to the south, perhaps because environmental conditions are tolerable to albacore for a shorter time. Fishing usually begins there in mid-July, attains a maximum effort and catch in late August and September, and largely ends by the end of October. The California fishery, by contrast, often starts a month earlier and ends a month later. Moreover, fishing intensity off Oregon and Washington is more sensitive to weather, to the price of albacore, and to diversion from tuna trolling to salmon fishing and bottom fishing than off California. Variation in the yield of albacore from the Oregon-Washington fishery cannot be assigned solely, however, to variation in fishing intensity, because the yield also depends on the fluctuations in availability of albacore in the region.

The number of fish available to a fishery at a particular time is often a complex function of abundance and behavior, both of which may be markedly affected by the environment. Influence of the environment upon albacore off Oregon and Washington has been detectable only through relations of sea temperatures to landings of the commercial fishery (Johnson, 1962) and to catches by Bureau vessels (Alverson, 1961). Water clarity, which varies largely with the concentration of particulate matter, also has been thought to affect albacore availability (Murphy, 1959); to date, however, this hypothesis has not been tested off the Oregon-Washington coast. Powell and Hildebrand (1950) noted a relationship of tuna catches with observed ocean conditions; albacore were

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caught in blue, warm water but not in green, cold coastal water. As they noted, however, this effect probably is attributable to temperature rather than to water color. Other environmental variables that have received attention as possible determinants of albacore availability and abundance (or density) include salinity and concentration of forage. No examples of observed relations of these factors to numbers of accessible albacore are available, however, and the relation of temperature to albacore was only grossly defined in previous studies.

The purposes of this paper are to describe the environment that albacore encounter when they first enter the region off the coast of Oregon-Washington, to suggest the physical mechanisms that produce these conditions, and to indicate which of these conditions appear to influence the number of albacore available to the fishery.

DATA SOURCES

Data from which distributions of variables were derived were collected in July 1961–64 on Cruises 51, 55, 60, and 66 of M/V *John N. Cobb*, a cooperative program with the Bureau of Commercial Fisheries Exploratory Fishing and Gear Research Base, Seattle, Wash. (Owen, 1963, 1967a); in July 1961–62 on Cruises BB–290 and BB–310 of R/V *Brown Bear*, Department of Oceanography, University of Washington, Seattle; and in July 1963–64 on Cruises 6307 and 6407 of R/V *Acona*, Department of Oceanography, Oregon State University, Corvallis, Oreg. Data from which averages of catch per unit of effort for the commercial fishery were computed are from Ayers and Meehan (1963) and from James M. Meehan of the Fish Commission of Oregon (personal communication).

OCEANOGRAPHIC PROCESSES AND DISTRIBUTIONS OF VARIABLES

The study area (fig. 1) is part of the subarctic Pacific Ocean and hence exhibits its principal characteristics: dilution of the surface layers by excess of precipitation over evaporation; and presence of a well-defined, permanent halocline in which year-round temperatures are nearly identical with winter temperatures of the surface layers (fig. 2). The oceanography of the subarctic Pacific was reviewed by Uda (1963), and by Dodimead, Favorite, and Hirano (1963).

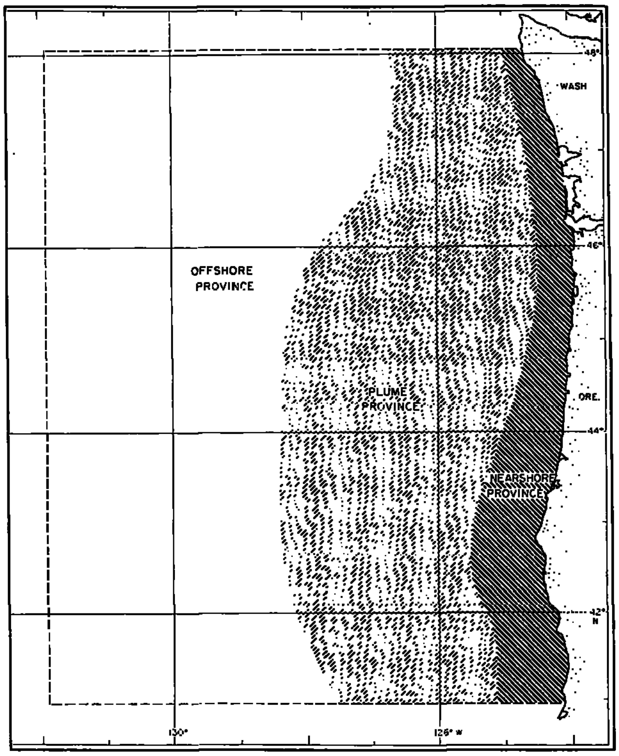

FIGURE 1.—Oceanographic provinces (schematic) off the Oregon-Washington coast in summer. Dashed line represents general limit of study area.

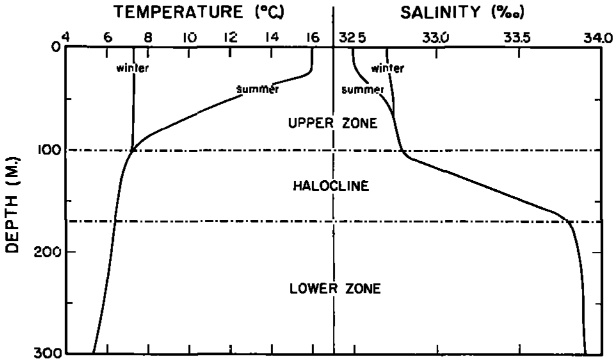

FIGURE 2.—Schematic diagram of vertical temperature and salinity structures in the eastern subarctic Pacific in summer and winter.

Processes that determine the distribution of salt and heat over the subarctic region combine in the study area with effects of nearshore upwelling, river discharge, and bottom topography to produce the distributions of variables reported here. Oceanography in part of the area was reviewed by Budinger, Coachman, and Barnes (1964), and an annotated bibliography on the area influenced by the Columbia River discharge was prepared by Anderson, Barnes, Budinger, Love, and McManus (1961). An atlas of July oceanographic conditions was prepared as a supplement to the present work by Owen (1967b).

RECURRENT FEATURES OF DISTRIBUTIONS OF VARIABLES

Both in the surface and deep layers, patterns of distribution of physical variables recur from summer to summer over the region off Oregon-Washington. This recurrent nature permits discussion of physical mechanisms that operate in the region.

Upper Zone

Above the main halocline (fig. 2) the area is divisible in summer into three meridionally bounded regions on the basis of physical processes believed to produce the distributions of variables characteristic of each. These regions may be termed nearshore province, plume province, and offshore province (fig. 1).

Nearshore Province.—The first subdivision, nearshore province, lies along the coast in summer as a band of cold, saline water about 50 nautical miles (90 km.) wide, interrupted only by fresher water from coastal sources. It is dominated by the effects of coastal upwelling. Intense horizontal gradients of temperature, salinity, density, and oxygen concentration are encountered from the sea surface to depths exceeding 250 m. (figs. 3, 4, 5, and 6). These gradients result from transformation of offshore vertical gradients, recognized there as the thermocline, halocline, pycnocline, and oxycline, into nearshore horizontal gradients by upwelling.

The offshore summer thermocline (fig. 7) does not coincide with the permanent halocline, but lies above it. Consequently, the corresponding horizontal temperature gradient of the nearshore regime lies farther from the coast than does the horizontal gradient associated with the permanent halocline (compare figs. 7 and 8). Once transported to the near-surface layer by upwelling, water of subsurface origin is warmed by local heat exchange across the sea surface. Because of this local heat gain neither temperature nor temperature gradient permits close assessment of intensity of upwelling, although both serve to indicate the offshore extent of upwelling influence.

The nearshore distribution of salinity is relatively uninfluenced by processes other than diffusion and upwelling in the nearshore province, except where dilution occurs near coastal sources of fresh water. The water of the offshore halocline is displaced upward within upwelling areas and usually reaches the surface layers. The inshore occurrence near the sea surface of water of the same salinity (33.8°/₀₀) as that at the bottom of the offshore halocline (fig. 8) indicates upward transport of water from depths below the permanent halocline. Diffusion and transport across surfaces of constant salinity near shore apparently are important; the near-surface horizontal gradient of salinity in this province is about three orders of magnitude less than the corresponding vertical gradient in the halocline offshore.

Distribution of mass in the nearshore province follows the pattern characteristic of coastal upwelling in general: large horizontal gradients of density are normal to the coastline in the upper layer (fig. 5), and vertical gradients of density are weak. Mass transport probably takes place across surfaces of constant density within the near-surface layers, however, because density is decreased locally there by net heat gain from insolation.

Oxygen concentration may exhibit significant local increase in upwelled water due to photosynthetic processes and to rapid exchange with atmospheric oxygen (fig. 6). These local changes are not sufficiently rapid, however, to obscure the effect of upwelling on oxygen concentration; low oxygen values that denote deep offshore origin are consistently present in surface layers of the nearshore province.

Water in the surface layers of the nearshore province is of deep offshore origin. Water of $\sigma_t \geq 26$, corresponding in density to water near the bottom of the offshore halocline (fig. 9), is common in the nearshore surface layers (fig. 5). The density of some of this water must have been decreased, however, by mixing in transit and by local heating; therefore, it must have come from depths in excess of that of the offshore halocline.

Plume Province.—The second subdivision, plume province, is characterized by near-surface water of low salinity, the result of dilution by coastal fresh water. The Oregon-Washington coast represents a variable line source of fresh water. The Columbia River, however, with a mean annual discharge of 7.3 x 10^3m.^{3} sec.$^{-1}$ and a maximum discharge (in June) of about 16.0 x 10^3m.^{3} sec.$^{-1}$, contributes more than 73 percent of the average

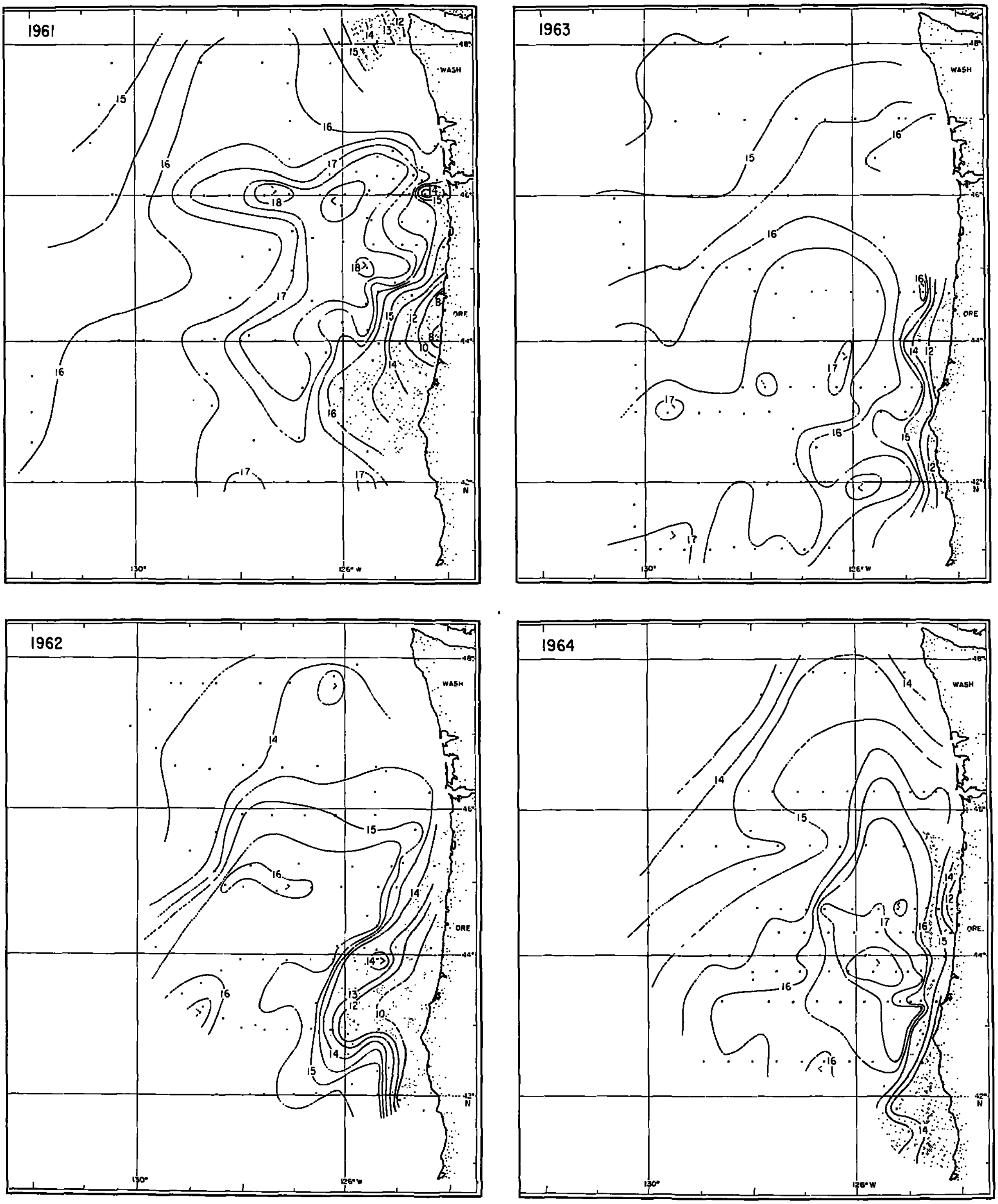

FIGURE 3.—July distribution of temperature at the sea surface, 1961–64. Contour interval is 0.5° C. except where shaded.

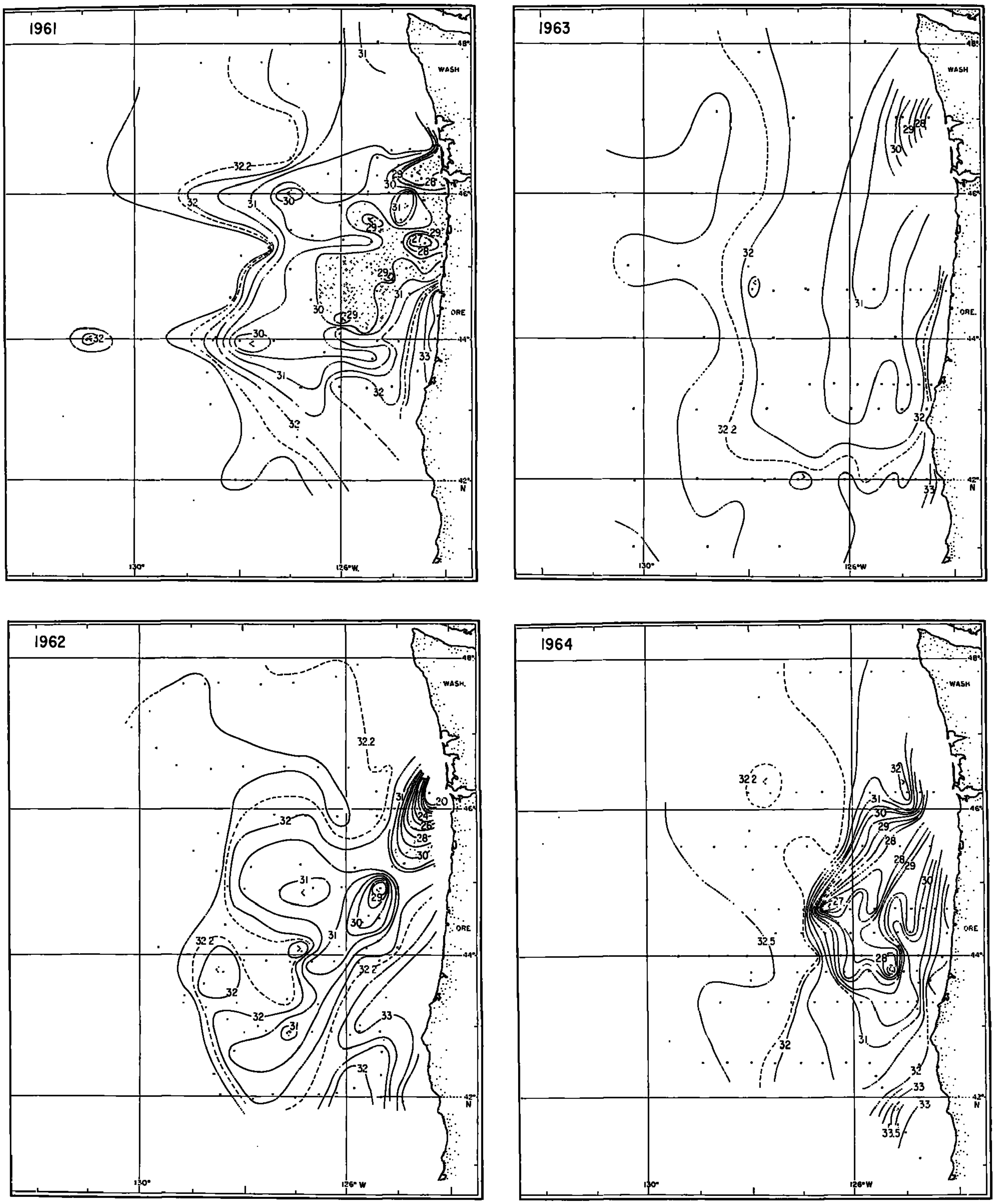

FIGURE 4.—July distribution of salinity at the sea surface, 1961–64. Contour interval is 0.5°/oo except where shaded.

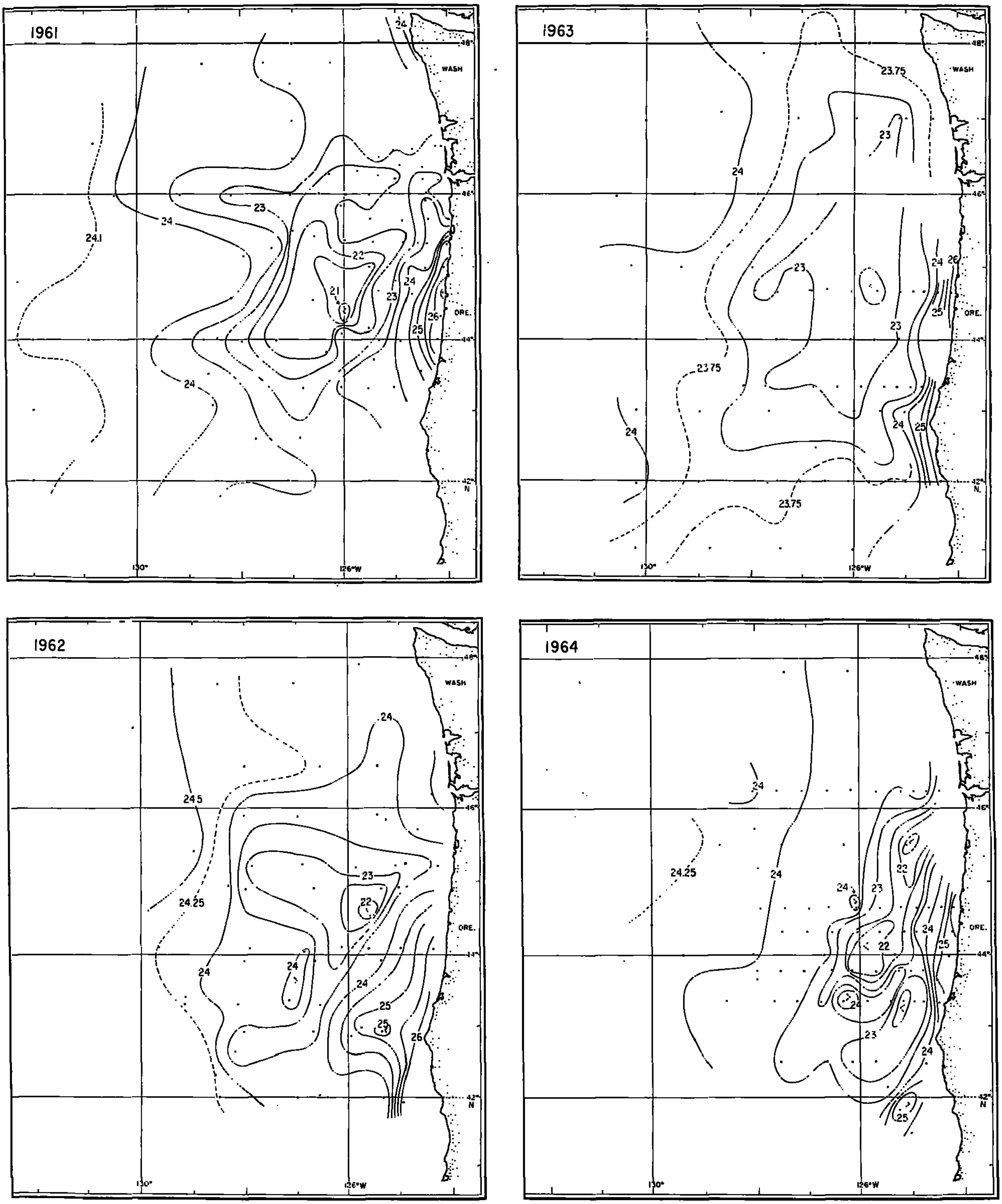

FIGURE 5.—July distribution of density at 10 m. depth, 1961–64. Contour interval is 0.5σ_t unit.

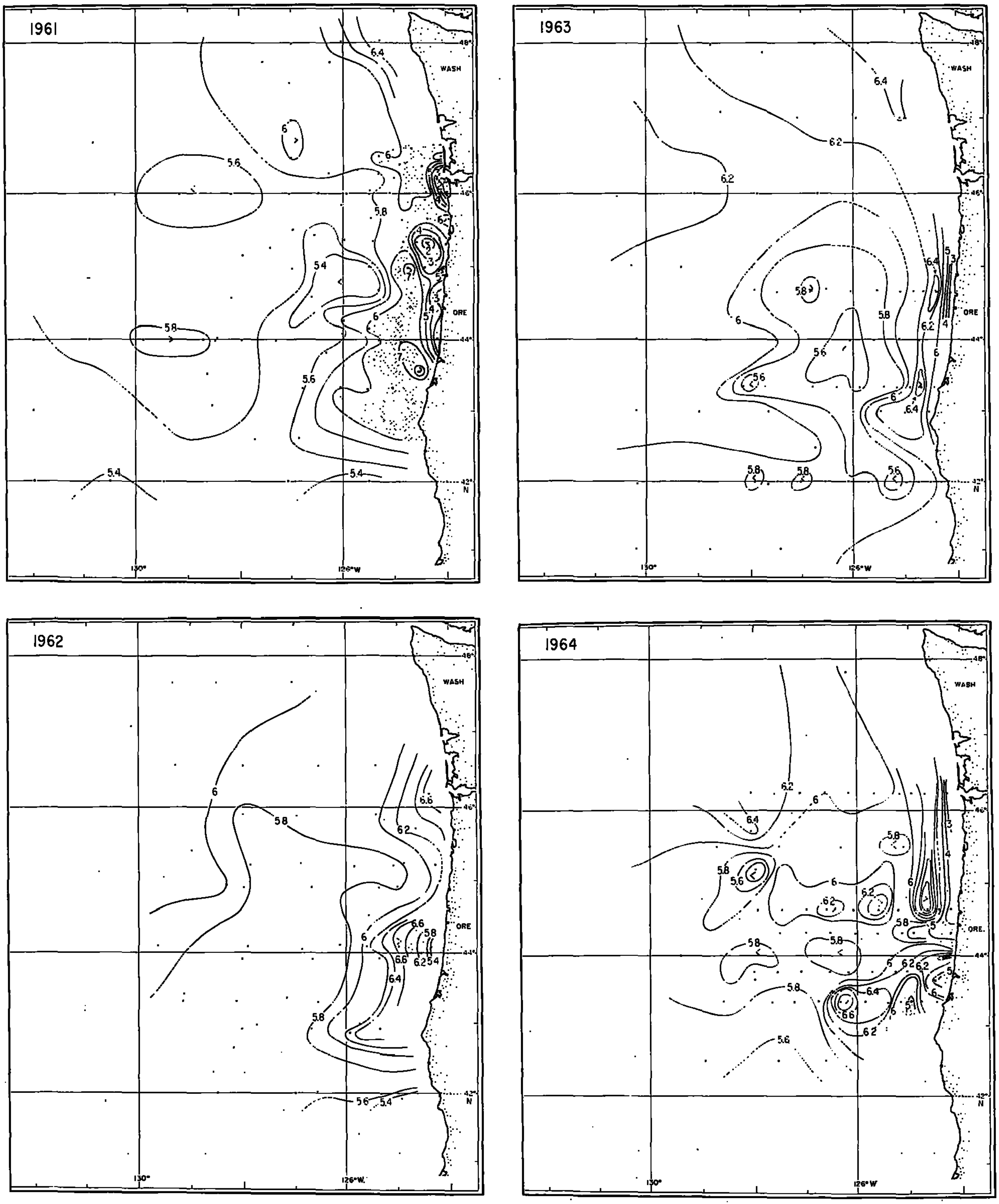

FIGURE 6.—July distribution of oxygen concentration at 10 m. depth, 1961–64. Contour interval is 0.2 ml./l. except where shaded.

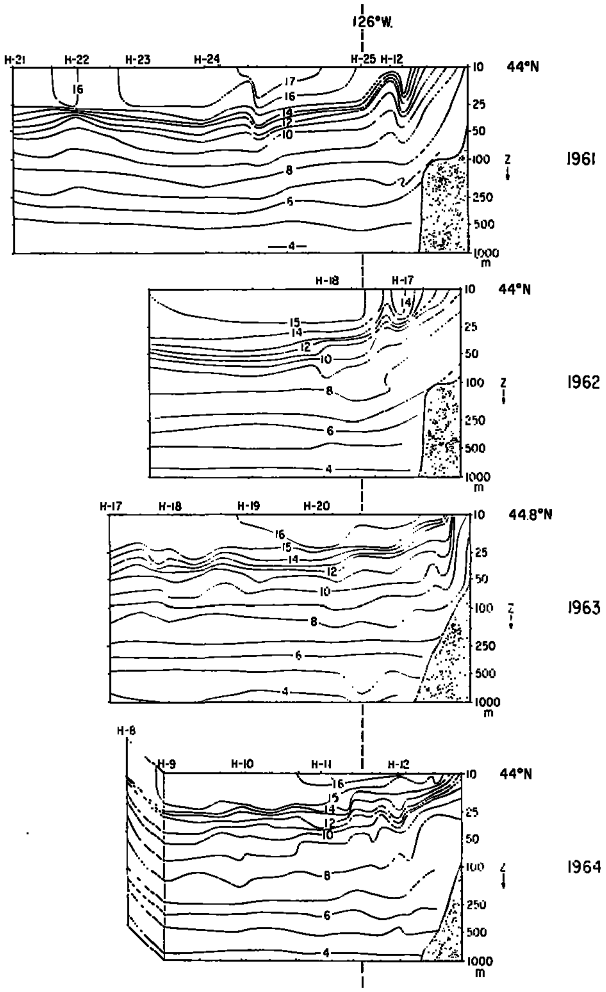

FIGURE 7.—Vertical profiles of July temperature along lat. 44° N. (approximately). Longitudinal relations between profiles are preserved. Sea floor is stippled. Contour interval is 1° C. Depth scale is logarithmic. *Cobb* hydrographic stations are identified along the top of each profile. The letter Z refers to depth.

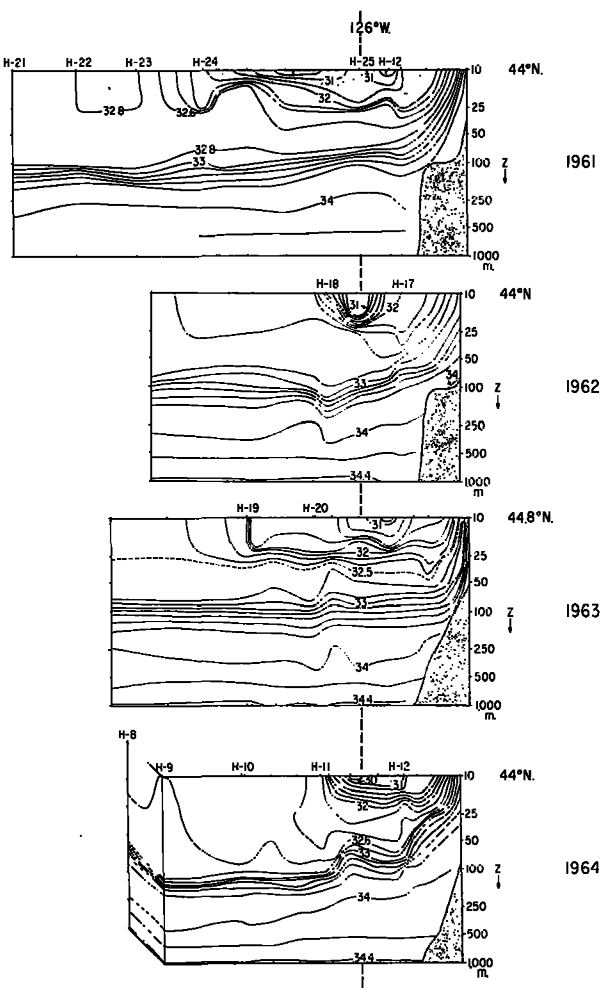

FIGURE 8.—Vertical profiles of July salinity along lat. 44° N. (approximately). Longitudinal relations between profiles are preserved. Sea floor is stippled. Contour interval is 0.2°/₀₀ except where shaded. Depth scale is logarithmic.

annual discharge from all rivers along the Oregon-Washington coast (Budinger et al., 1964); probably it is the sole contributor of fresh water to the plume province in summer. For this reason, salt distribution in the surface layers of the plume province is predominantly influenced by Columbia River effluent at all times of the year. This effluent now enters the ocean at approximately the ambient offshore temperature, although its average temperature may increase in future summers as the number of Columbia River Basin impoundments increases and the June discharge pulse decreases.[1]

This discharge creates a plume of low-salinity water which in summer extends southwest from its source, in response to currents and to wind stress. Studies of the effluent by Budinger et al. (1964) indicated that estuarine mixing introduces into the open sea a mixture that consists approximately of one part river water with two parts sea water. Once a parcel of this mixture is at sea,

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[1] This temperature increase may or may not be reflected in plume temperatures in future years.

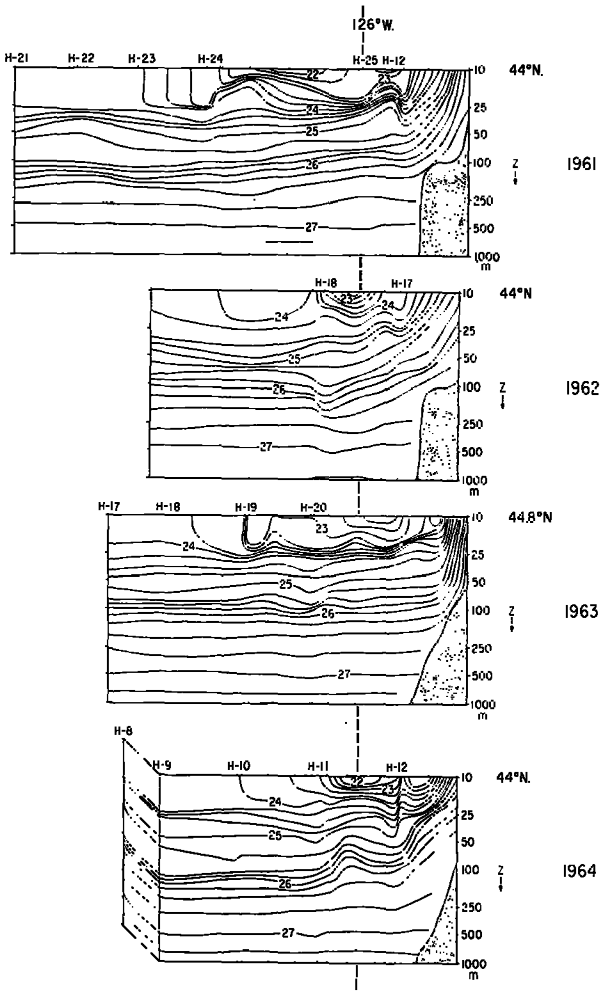

FIGURE 9.—Vertical profiles of July density along lat. 44° N. (approximately). Longitudinal relations between profiles are preserved. Sea floor is stippled. Contour interval is 0.25 σ_t unit except where shaded. Depth scale is logarithmic.

entrainment and diffusion produce lateral and vertical flux of salt into the plume so that the moving parcel loses its dilute character with time and distance from its source until it is indistinguishable from water of offshore origin.

In the present treatment, the 32.2‰ isohaline is the criterion of the plume limit. This value was chosen because 32.2‰ conservatively specifies the largest value of salinity in the salinity gradient at the interface between the plume and surrounding water (figs. 4 and 8), beyond which the immediate physical influence of the plume is much diminished. The plume province thus may be defined as the portion of the area over which surface salinity is less than 32.2‰. Geographic limits of the plume, as defined by Budinger et al. (1964) for examining the fresh-water budget, were given by the location of the 32.5‰ isohaline. By this criterion, plume in summer has been detectable south of lat. 42° N. and as far as 300 nautical miles (560 km.) offshore (fig. 4), although the plume province itself does not extend so far.

The secondary halocline between plume and underlying water partly coincides with the summer thermocline (compare figs. 7 and 8 above 50 m. depth). This superposition notably increases the vertical density gradient $\partial\rho/\partial z$ over the extent of the plume province. Stability, related to the density gradient approximately by $\frac{-1}{\rho}\frac{\partial\rho}{\partial z}$ is also high; in July 1964, for example, average plume stability at 14.2 x 10^{-7} cm.$^{-1}$ was about 80 percent greater than average stability in the corresponding pycnocline beyond the plume.

Offshore Province.—The third subdivision, which lies seaward of the plume province, is termed the offshore province. Its character is identical with the eastern extreme of the subarctic region termed "Transitional Domain" by Dodimead et al. (1963), in that it is subarctic water with temperatures in excess of 7° C. at the top of the halocline. The offshore province may also be considered to be part of the upstream source of the California Current, since at least some of the water flows southward off the coast of California. The offshore province exhibits the vertical salinity and temperature structure characteristic of the eastern subarctic as a whole (fig. 2)—a deep, permanent halocline through which temperatures are nearly constant, and a separate, overlying summer thermocline. No strong secondary halocline is present, and salinity increases gradually and continuously with increasing depth through the layer between the summer thermocline and permanent halocline (fig. 8).

Lower Zone

Below the main halocline, coastal runoff has no direct physical influence so that only two provinces, nearshore and offshore, are distinguishable.

The nearshore lower zone is defined here as the region where the field of motion and bottom topography produce significant onshore ascent[2] of

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[2] Ascent is here considered significant if the slope of isopleths monotonically exceeds 10^{-3} over more than two sampling locations. The term "monotonic" refers in this paper to slopes with no maxima or minima, i.e., $\partial^2/\partial z^2=0$.

surfaces of constant density. The seaward limit of the nearshore province is not often well defined but appears to lie farther from the coast than its upper-zone analogue (figs. 7, 8, and 9). This displacement is presumed to occur because upward deflection of coastward flow occurs farther offshore with increasing depth in response to proximity of the sloping sea floor.

Coastal upwelling in the area is largely seasonal and is caused principally by response of surface waters to the spring shift in prevailing wind direction from southwest to northwest (Lane, 1962). Because characteristics of the water in the lower-zone nearshore province are affected by this seasonal process, this province stands in contrast to that of the offshore, where seasonal changes are difficult to distinguish from nonseasonal changes (Tully, Dodimead, and Tabata, 1960).

Depth to which upwelling affects distribution of heat, salt, mass, and oxygen concentration is presumed usually to be less than about 200 m. (Sverdrup, 1938; Doe, 1955). Portions of many of the vertical sections that lie within the nearshore province, however, exhibit significant onshore ascension of isopleths of these variables at depths in excess of 250 m. (figs. 7, 8, 9, and 10).

Located beyond direct influence of bottom topography and seasonal processes, the lower-zone offshore province exhibits the horizontal uniformity of property distributions that is typical of the lower-zone subarctic. Small slopes of surfaces of constant salinity, temperature, and density indicate sluggish circulation, except where deep eddies occur. The recurrent nature of some of the closed-curve patterns that suggest eddylike motion has been noted by Budinger et al. (1964). That these patterns are recurrent implies that they do not result from internal-wave distortion of the mass field or from failure of the assumption that measurements were synoptic—possibilities suggested by Defant (1950).

Currents

The study area is largely shoreward of the region where the West-Wind Drift diverges to feed the California Current to the south and the Alaska gyre system to the north (see Dodimead et al., 1963). Previous works that included the study area (Doe, 1955; Barnes and Paquette, 1957) show weak, variable geostrophic currents that are sensitive to the influence of wind and bottom topography.

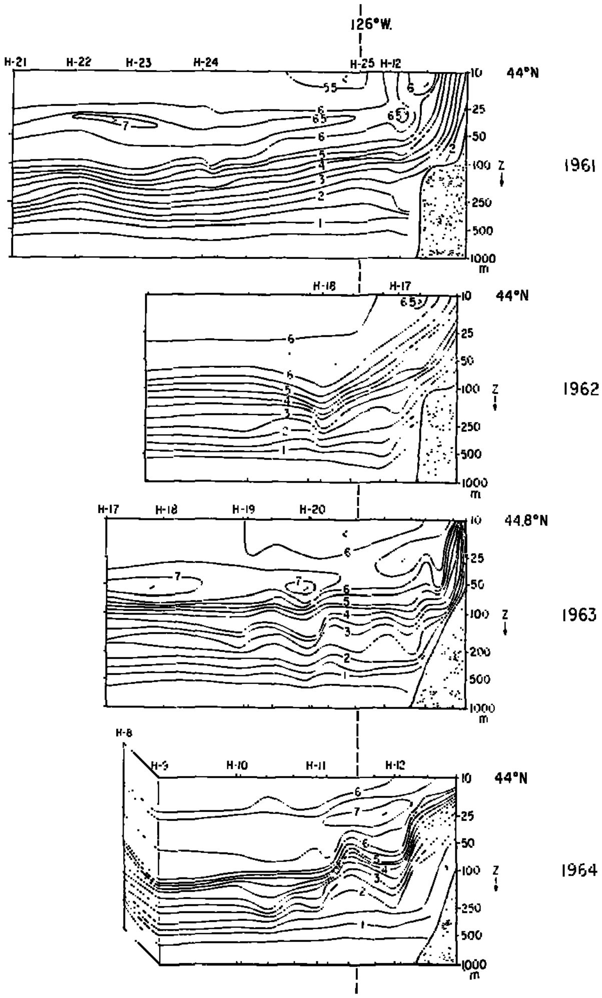

FIGURE 10.—Vertical profiles of July oxygen concentration along lat. 44° N. (approximately). Longitudinal relations between profiles are preserved. Sea floor is stippled. Contour interval is 0.5 ml./l. Depth scale is logarithmic.

The reference level of 500 dbar. (decibars) is used in the present work; this value was selected because data were insufficient below the corresponding geometric depth. Agreement in speed and direction of geostrophic flow referred to the 500 dbar. surface with flow referred to 1,000 dbar., previously accepted as adequate for direction (Dodimead, 1961, and others), is sufficient to warrant use of the 500 dbar. level. Dodimead et al. (1963) presented flow at 500 dbar. with respect to 1,000 dbar. for summers of 1955–59. Their charts, which include the study area, indicate current speeds on the 500-dbar. surface that generally do not exceed 0.8 cm. sec.$^{-1}$; i.e., they are insignificant. Also, average flow direction referred to 1,000 dbar., and to 500 dbar. by the extension above, has been shown to agree with independent observations of ship drift over large parts of the North Pacific (Reid, 1961). No single level, however, is strictly appropriate for use as a "level of no net motion" in the subarctic. Drogue measurements in the study area (Budinger et al., 1964) indicated a weak current at 1,000 m. depth, so that slight error from this source is expected in charts of geopotential referred either to surfaces of 500 dbar. or of 1,000 dbar.

Current direction denoted by dynamic topography varies from year to year, particularly in the offshore and plume provinces (fig. 11). Geostrophic speeds, proportional to geopotential gradients, are slow and generally uniform beyond the nearshore province; values of 3 to 8 cm. sec.$^{-1}$ are typical.

Redistribution of mass due to nearshore upwelling results in a dynamic topography that consistently suggests intensified southerly flow (30–50 cm. sec.$^{-1}$) near the coast, and an eddy or loop with even greater velocities at about lat. 43° N. It is unlikely, however, that geopotential gradients reflect current velocities in nearshore areas as accurately as in the offshore and plume provinces. Time lags in the response of distribution of mass to changes in wind-driven transport probably negate the assumption of a steady state in the nearshore provinces.

The wind-induced component of flow, the Ekman transport, is superimposed on geostrophic flow in the upper layer of the sea. Ekman transport by blocks of 1° latitude, averaged zonally from longs. 130.5° W. to 124.5° W. in June and July, was calculated from the source and by the method given later in this paper. These averages demonstrate that wind-induced flow is generally to the west or southwest and that the flow—in particular its zonal component—intensifies with decreasing latitude (fig. 12). No such marked tendencies are apparent from analogous meridional averages, except that of direction.

Average current speeds computed from Ekman transport, presumed to extend to 30 m. depth, generally are lower, often by a factor of 10, than geostrophic speeds. The effect of Ekman transport on distribution of variables is probably very important, however, where Ekman transport is not parallel to geostrophic transport—in the nearshore province, parts of the offshore province, and near the plume boundaries.

Tongue Structures

Recurved, tonguelike isopleths are apparent in distributions of temperature, salinity, density, and oxygen concentration over the upper-zone waters. Along any approach to the coast from the offshore province, one thus encounters a maximum in temperature (fig. 3), minimums in salinity and density (figs. 4 and 5), and both a minimum and a maximum in oxygen concentration (fig. 6). These large-scale extremes are mainly confined to the surface layers but occur occasionally at greater depths. Each large-scale extreme, except the oxygen maximum, occurs within the area here defined as the plume province.

The salinity minimum is due simply to the presence of the low-salinity plume. In the absence of runoff, salinity at the sea surface would presumably decrease monotonically from about 33.5°/oo in the upwelling areas to about 32.5°/oo with increasing distance offshore.

The tonguelike ridge of higher temperatures is ascribable to two effects of the plume itself. Because the secondary halocline at the plume-sea water interface partly coincides with the thermocline, stability is augmented in this interface layer; consequently, downward heat flux through the thermocline is less than that across the unaugmented thermocline of the offshore province. Retention above the thermocline of heat gained in surface layers thus tends to be greater in the plume province than beyond. Second, this greater stability in the plume may be considered to dictate a preferred site for development of the summer thermocline at depths generally less than 20 m.[3] Wind-mixing in the offshore province, in the absence of the effect of the plume on stability, is effective to greater depths. The offshore thermocline accordingly develops at greater depths in the manner described by Tully and Giovando (1963). By this difference in mixed-layer depth (depth to the top of the summer thermocline), heat gained in the surface layer is constrained to a smaller volume in the plume than offshore, and hence the plume province has higher summer temperatures. The shoreward decrease of temperature in the nearshore province results simply from upwelling of cold water.

A measure of the extent to which the plume

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[3] With the partial exception of July 1963, the offshore limit of the plume province is in fact approximated by the 20-m. isopleth of thermal mixed layer depth (fig. 13).

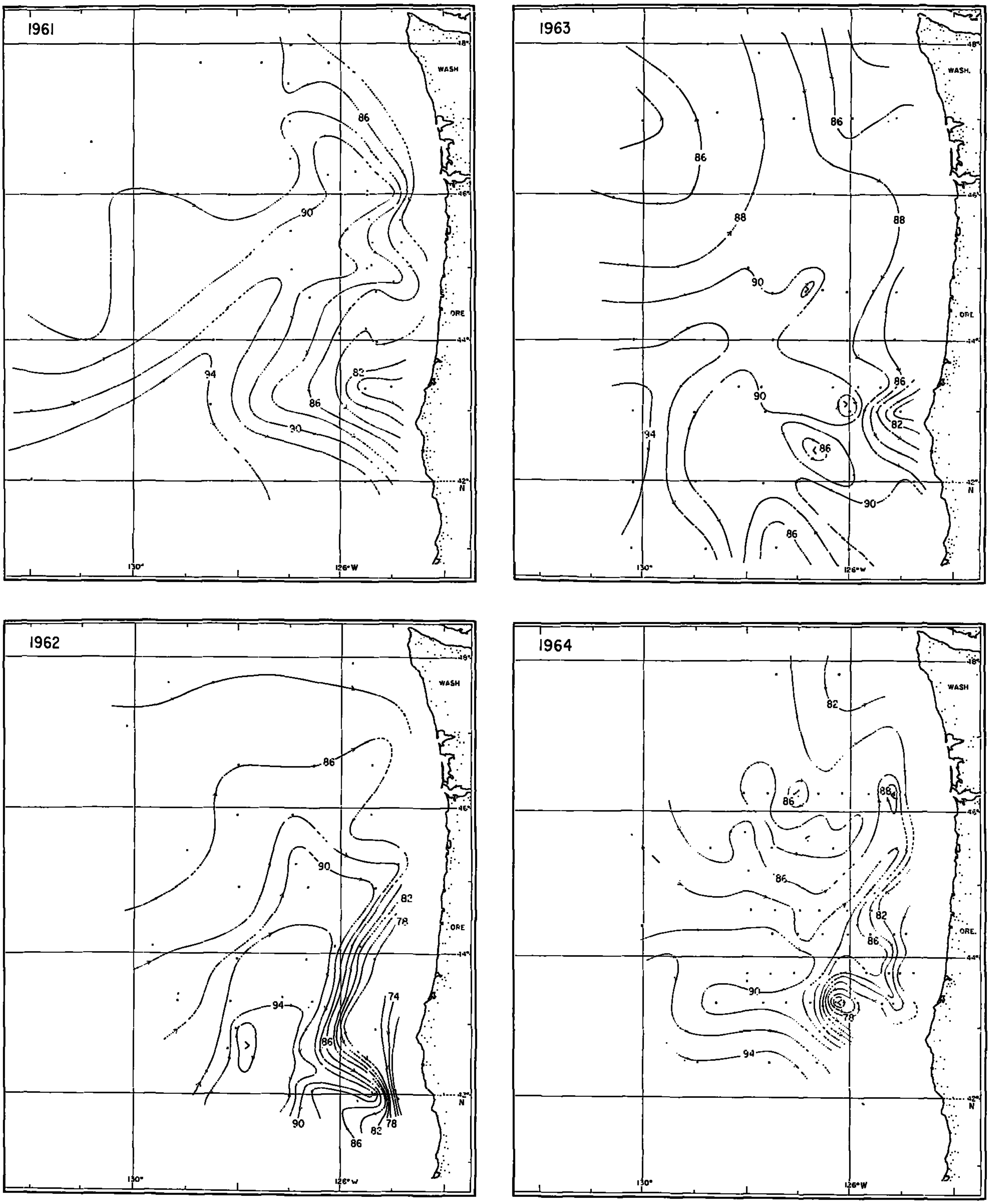

FIGURE 11.—Geopotential topography of the July sea surface relative to 500 dbar., 1961–64. Contour interval is 2 dynamic cm.

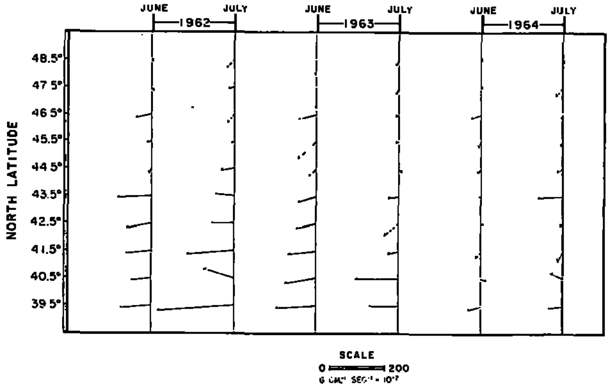

FIGURE 12.—Wind-driven (Ekman) transport vectors by 1° increments of latitude, averaged between longs. 124° W. and 130° W. Length of vectors gives transport in g. cm.$^{-1}$ sec.$^{-1}$ according to the scale below figure.

influences heat constraint, and therefore temperature distribution, is provided by figure 14. As implied by figure 2, the permanent halocline is the lower limit of winter mixing; consequently temperature near the top of the permanent halocline is nearly identical to that of the mixed layer in the previous winter (Dodimead et al., 1963). Hence the July difference between temperature at the sea surface and the temperature where salinity equals 33‰, located within the halocline, is a measure of mixed-layer temperature change, $\Delta\theta$, from the previous winter. The area of greater temperature change substantially corresponds to the plume province as defined by surface salinity distributions (fig. 4).

The summer tongue of lower density in the plume province (fig. 5) is produced by the coincidence of tongues of low salinity and high temperature described above.

Distribution of oxygen concentration in the near-surface layers is more complicated than that of the preceding variables. Shoreward of the minimum (5.4–6.5 ml./l.) in the plume province are a maximum (6.6–8.0 ml./l.) in the seaward portion of the nearshore province and a minimum (2.0–5.0 ml./l.) nearest the coast. These extremes combine to produce the trough-and-ridge oxygen distribution that was characteristic of the area in each summer in 1961–64, except the last (fig. 6).

The oxygen minimum in the plume is the result of the larger influence of reduced oxygen solubility at higher temperatures over the opposite influence of higher oxygen solubility at reduced salinities. Since the degree to which waters of the surface layer are saturated with oxygen is the same in the offshore as in the plume province (about 104 percent), this variation is not attributable to differences in biological processes.

In the horizontal distribution of oxygen, the presence of both the minimum and maximum concentrations in the surface layer of the nearshore province is the product of one or both of two effects of upwelling. Upwelling transports nutrient-rich water that is undersaturated with oxygen into the photic zone, where algal photosynthesis increases the oxygen concentration sufficiently to produce supersaturation. If the transfer of oxygen from the air to the sea proceeds faster than the transfer of heat, supersaturation can result independently from this purely physical process. The oxygen minimum along the coastal portion of the nearshore province may thus represent that part of the upwelling system where the residence time of low-oxygen water in the surface layer has been too short to exhibit effects of local oxygen gain by photosynthesis and atmospheric exchange. Conversely, the maximum in the outer part of the nearshore province represents the area where one or both processes have been operating for sufficient time to effect supersaturation. Large standing stocks of phytoplankton, indicated by higher chlorophyll concentrations (Owen, 1967b) and larger rates of carbon assimilation nearshore (Anderson, 1963), support the hypothesis of greater oxygen production by photosynthesis in the fertile nearshore province than beyond. That local processes of oxygen gain are effective in this province is evident from the decreased slopes of near-surface oxygen isopleths (fig. 10) relative to isohaline slopes (fig. 8). In the absence of local oxygen gain, these slopes would be identical.

The nearshore maximum in the horizontal distribution of oxygen may also be ascribed to a more direct effect of upwelling. Seaward of the nearshore province, a maximum value (5–7 ml./l.) in the vertical distribution of oxygen concentration occurs in summer at depths of 30 to 70 m. (fig. 10). This maximum is not confined to the present area, but is present over large parts of the North Pacific, where it has been ascribed to summer loss of oxygen above the layer in which the maximum occurs (Reid, 1962; Pytkowicz, 1964). Summer upwelling in the nearshore province would displace the layer of this oxygen maximum upward to form the horizontal maximum in the

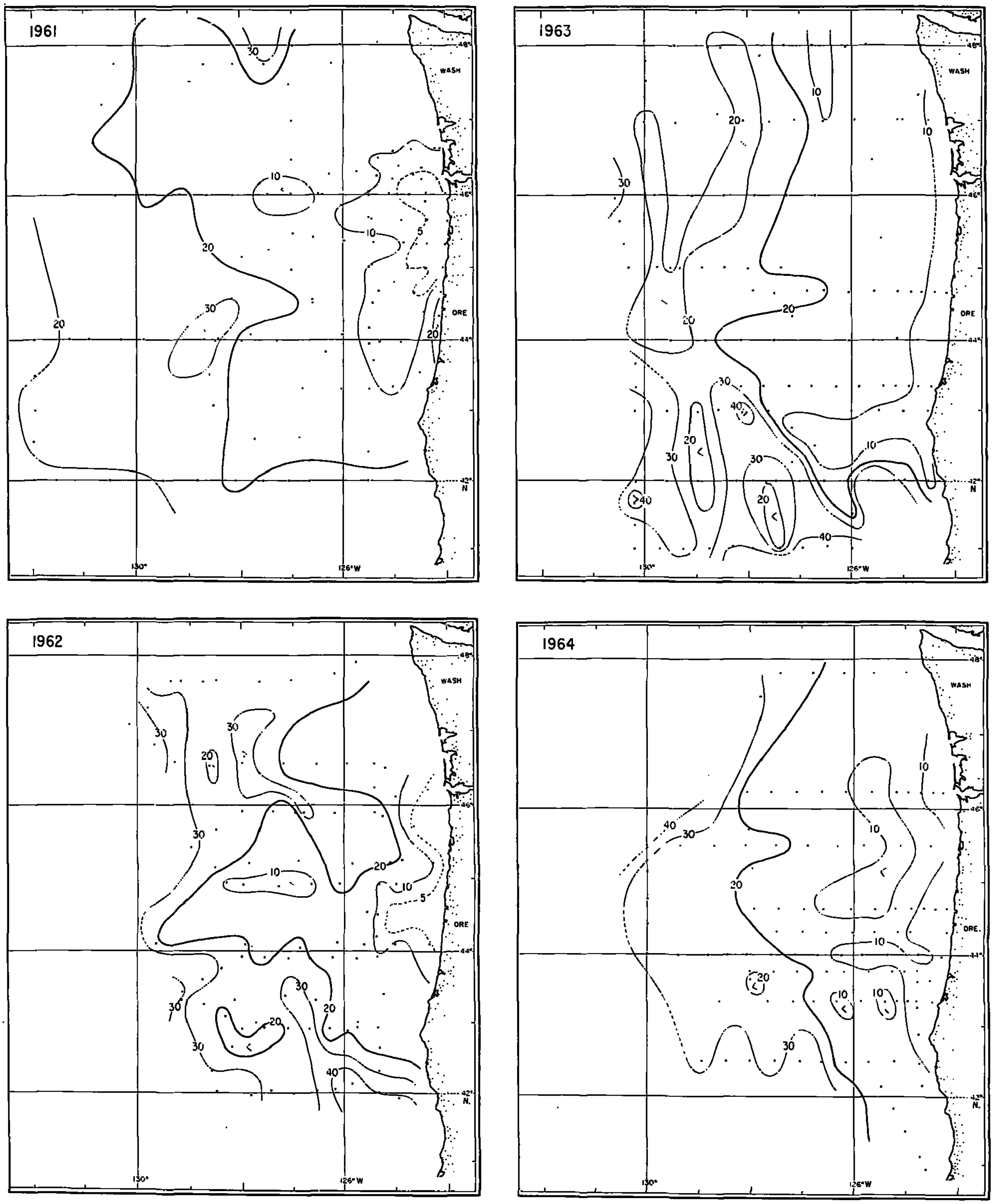

FIGURE 13.—Depth of the upper mixed layer in July 1961–64. Contour interval is 10 m.

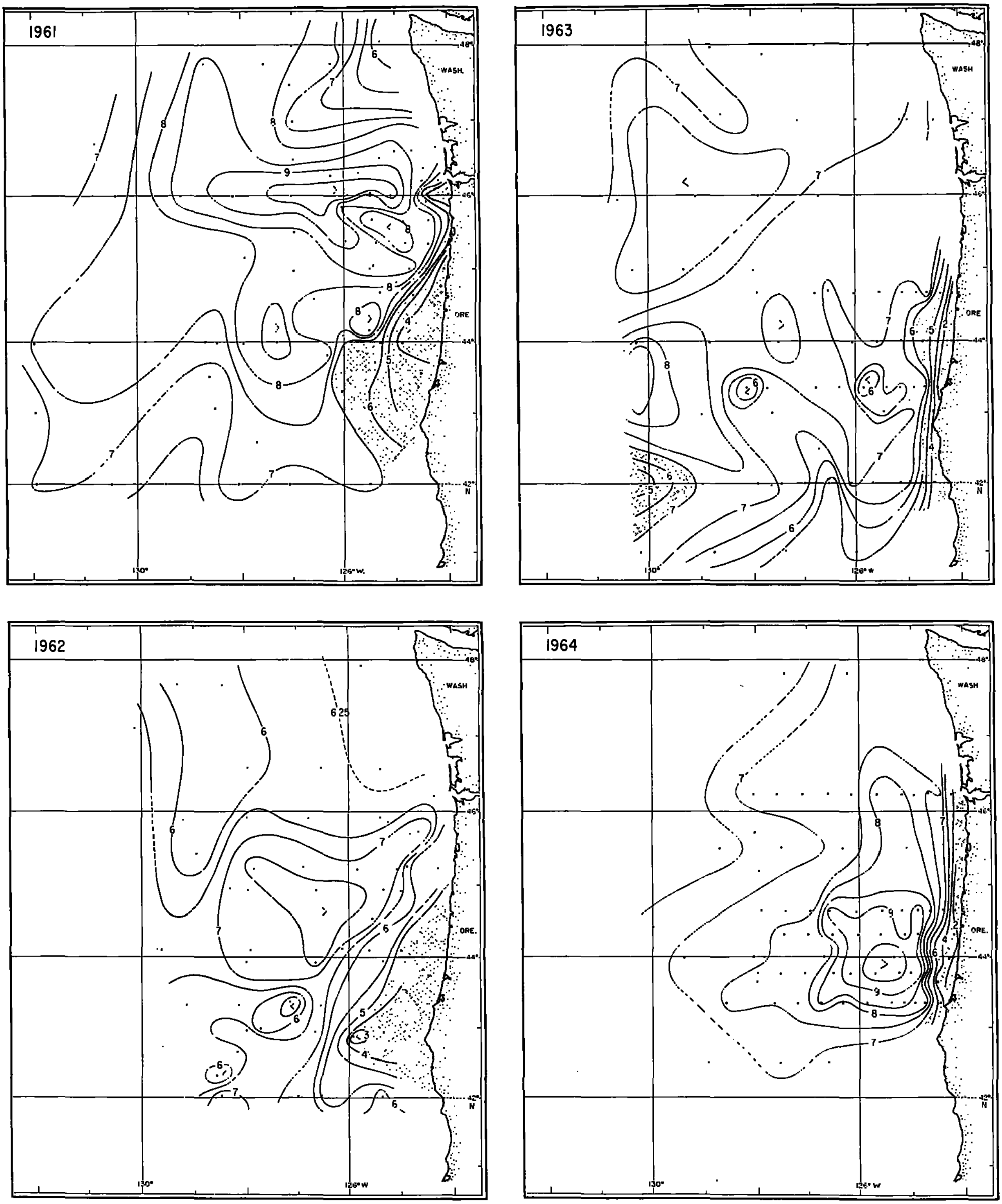

FIGURE 14.—Difference between surface-layer temperature and temperature at the depth where salinity equals 33°/oo, 1961–64. Contour interval is 0.5° C.

near-surface layer (fig. 6). Stefánsson and Richards (1964, p. 374), on the other hand, have suggested that offshore movement and subsequent sinking (along isentropic surfaces) of upwelled water which has gained oxygen from photosynthesis would "largely contribute to the formation of the (offshore vertical) maximum." If so, then the near-surface horizontal maximum would presumably result. It seems unlikely, however, that this process alone could generate the vertical maximum that occurs widely over the North Pacific; definitive measurements—e.g., apparent phosphate uptake (APU) in the layer of the offshore oxygen maximum—are not yet available to indicate whether the vertical oxygen maximum of the plume and offshore provinces is derived from the nearshore, near-surface horizontal maximum, or, conversely, whether it produces the nearshore maximum by upward displacement.

Oxygen distribution in the near-surface layer apparently was atypical in the summer of 1964 (fig. 6). The basic pattern described above was altered in the plume by the presence of well-developed pockets of high concentrations of oxygen. Production of some pockets by phytoplankton photosynthesis is indicated from their high degree of supersaturation (106–110 percent) and from generally large concentrations of chlorophyll *a* in the plume and offshore province in 1964. High-oxygen pockets were associated with low temperatures (13–14.5° C. at 10 m.). Heterogeneity of their mode of generation is indicated, however, by the large corresponding range of salinity (30.5–32°/oo at 10 m.), and one pocket, centered at lat. 43.3° N. and long. 126.2° W., clearly was produced as part of a dome formed by the motion of a cyclonic eddy (fig. 11).

Tonguelike patterns occur occasionally at greater depths (100 m. or more) but not with sufficient frequency to be considered recurrent or characteristic. It is difficult to see how these tongues could arise from the same mechanisms that produce near-surface tongues. Because of the nearly uniform temperature-salinity relation beneath the near-surface layer, the tongues at the greater depths appear to be produced by the distribution of mass associated with geostrophic flow.

ANNUAL VARIATIONS

Differences from year to year in extent and character of provinces are generated by changes in the dominant processes. The basic patterns discussed in the previous section are not obscured, however, but are altered only in degree. Effects of these differences upon heating in the surface layers are discernible.

Extent and Character of Provinces

The state of development of the nearshore province is determined principally by the intensity and duration of upwelling, which in turn depends upon the nature of the coastal wind field and upon local bathymetry. Because bathymetry is fixed, between-year differences in the extent of the nearshore province should be assignable to differences between years in the June and July wind fields. A means of assessing the effect of wind field on upwelling is provided by estimation of average zonal components of Ekman transport across the near-coast meridian 124.5° W. Wind data for the study area in June and July 1962–64 were obtained from monthly summaries of marine weather observations for the Pacific Ocean prepared by the Tuna Resources Laboratory, Bureau of Commercial Fisheries, La Jolla, Calif., in the form of average zonal and meridional components of wind velocity by 1° squares. Average wind stress, $\bar{\tau}$ (g. cm.$^{-1}$ sec.$^{-2}$), was computed from average wind velocity, $\overline{U}$ (assumed to have been measured at 10 m. above sea surface), by the basic equation

$$\bar{\tau}=\rho C_D U^2$$

where air density, ρ, is taken to be constant at 1.2×10^{-3} g. cm.$^{-3}$ and $C_D=(1+0.07U) \times 10^{-3}$ (Deacon and Webb, 1962, p. 61). The computing equation, with constants adjusted for the use of U in knots, is

$$\bar{\tau}=0.318\overline{U}^2(1+0.036\overline{U}) \times 10^{-2} \qquad (1)$$

Because instantaneous values of wind velocity were not available from the summary described above, equation (1) was entered with averaged values of wind speed ($\overline{U}$). Because $(\overline{U})^2<\overline{U^2}$, values of $\bar{\tau}$ used here underestimate the true averages of wind stress.

Ekman transport, which is assumed not to extend beyond the bottom of the pycnocline produced by the thermocline and plume halocline, is given by integration of equations of motion with appropriate boundary conditions:

$$M_x=\tau_y/f$$
$$M_y=\tau_x/f$$

where f, the Coriolis parameter, is evaluated for present purposes at lat. 45° N. The zonal component was computed for each degree of latitude from 39.5° N. to 48.5° N. along long. 124.5° W., and then averaged to give mean zonal transport in g. $cm.^{-1}$ $sec.^{-1}$ for June and July 1962–64. The results indicated that the intensity of upwelling was highest in June and July of 1962, when the offshore transport across 124.5° W. was largest, and lowest in June and July of 1964, when offshore transport was least (table 1). Wind data are not available for June and July of 1961.

TABLE 1.—*Average zonal component of Ekman transport, M_x(g. $cm.^{-1}$ $sec.^{-1} \times 10^{-3}$), westward across long. 124.5° W. from lat. 39.5° N. to 48.5° N., for June and July 1962–64*

Year	June	July	Average
1962	6.77	8.75	7.76
1963	3.67	5.89	4.78
1964	3.34	0.72	2.03
Average	4.59	5.12	4.86

Correspondingly, oceanographic evidence indicates greater upwelling in 1962 than in 1963 or 1964. Local heating of upwelled water, as pointed out previously, precludes use of near-surface temperature and density for assessment of upwelling. Salinity, however, is little changed by processes other than diffusion and upwelling, and thus provides the best available estimator of upwelling effects. The extent of the nearshore province and, therefore, July development of upwelling may be compared between years by noting the distance from the coast at which the 32.5 °/₀₀ isohaline is first encountered at the sea surface. The mean distance of this isohaline from the coast was about 50 nautical miles (90 km.) in 1962, but less than 20 nautical miles (35 km.) in 1961, 1963, and 1964. These distances indicate a significant seaward extension of the nearshore province in 1962. The rather precise nearshore coincidence of the 32.5 °/₀₀ isohalines in 1961, 1963, and 1964 suggests close similarity of upwelling in these years and further heightens the contrast of 1962 conditions. Similar checks on the near-surface distributions of other less conservative properties (temperature, density, oxygen concentration) confirm qualitatively that upwelling effects were markedly pronounced in July 1962. Secondary effects of differences were not apparent; extremes were observed in the plume in years when intensity of upwelling in the nearshore province was similar.

Closer correspondence of June transport than of July transport to the July distributions of properties suggests an appreciable time lag in the response of the nearshore province to changes in wind field. Prediction of upwelling conditions by computations from coastal wind field of the previous month may thus be possible.

The extent and character of the plume province have exhibited the greatest variation from year to year. Differences in size and intensity of the plume itself, shown by comparison of values and gradients in near-surface salinity distributions (fig. 4), suggest large year-to-year differences in the balance of processes that determine plume distribution—volume of discharge from land, diffusion, and advection.[4] For the period 1961–64, summer conditions in 1963 and 1964 displayed maximum contrast. The plume in July 1963 showed the weakest development; though the area was large the salinity was high and the horizontal gradients were exceedingly small. In spite of less than normal June discharge of fresh water into the province, the depth of the secondary halocline in the plume was not notably less in 1963 than in other years (fig. 8). The small horizontal gradients and large values of salinity in the upper layers of the plume thus show that lateral diffusion and zonal advection were relatively more effective than meridional advection in distributing plume water. Indeed, the smaller zonal gradients of dynamic height of July 1963 (fig. 11) indicate diminished southward transport by the geostrophic component of motion, whereas wind-velocity fields in June and July 1963 indicate large offshore displacements by the Ekman component of motion (fig. 12), particularly to the south of lat. 44° N.

The July 1964 plume, at the other extreme, was highly constrained and was characterized by low salinities (< 27 °/₀₀ at one offshore station) and by large horizontal gradients of salinity. The meridional constraint of the 1964 plume, together with the observation that the discharge in June 1964 from the Columbia River was largest of the years considered (table 2, last column), indicates dominance of meridional advection over zonal advection

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[4] The effects of time-dependent hydraulic mixing near fresh-water sources, which presumably would determine the characteristics of water in the plume province, are here considered to have been "averaged out" in the time required for water to transit the nearshore province and enter the plume province.

and diffusion in plume dispersion. In contrast to flow conditions in 1963, southward transport by the geostrophic component of motion in July 1964 is indicated to be larger (fig. 11) and to predominate over transport by the much diminished Ekman component of June and July 1964 (fig. 12).

The plumes of 1962 and 1963 would be expected to be similar on the basis of the similarity of June-July wind-induced transports (fig. 12) and of June discharge rates from the Columbia River. They differed markedly, however, in salinity. Although the 1962 plume was nearly as broad as that of 1963, it displayed larger gradients and smaller values of salinity; these differences imply reduced importance of diffusion processes during 1962. Because wind effects were about equal in the 2 years, differences in the geostrophic component of flow must have caused this difference in the relative importance of diffusion, and (together with variation in river discharge volume) the differences in salinity characteristics of the plume. Comparison of dynamic height patterns of the 2 years (fig. 11) reveals two significant differences in the nature of geostrophic flow: greater current speeds and a pronounced northward component in the outer plume province and offshore province in 1962. The apparent reduction of diffusion effects relative to advective effects in 1962 was accomplished by faster geostrophic transport of the plume. Further, the breadth of the 1962 plume and the lateral disposition of pockets of less saline water could have been the consequence of transport of the plume from southwest to northeast, indicated by geostrophic flow in the offshore part of the study area.

Geostrophic flow in 1961 was similar to that of 1962 in current speeds and in the presence of the offshore northward component; probably the plumes of the two years were produced by the same balance of forces. The principal difference between the two plumes was in salinity—the 1961 plume was less saline than that of 1962. This difference appears to have resulted from high runoff in 1961: average discharge rate of the Columbia River for June 1961 was about 1.7 x 10^4 m.^{3} sec.$^{-1}$ or 1.5 times greater than the discharge for June 1962 (estimated from Budinger et al., 1964, fig. 34, p. 51).

Differences between years in near-surface salinity of the offshore province were insignificant.

Heating

The general effect of the fresh-water plume on temperature was described above. Briefly, heat is constrained to a smaller volume in the plume than beyond so that, by July, plume temperatures exceed offshore temperatures. Because the degree of plume development varied widely from summer to summer during 1961–64, one may reasonably expect to see variations among the respective temperature distributions.

Temperature of the mixed layer in July at any location in the study area may be considered to be the net expression of the following factors: temperature at the start of the heating season (about March); heat gain, principally across the sea surface, between March and July; heat loss by advection and diffusion; and depth over which heat changes are distributed (thickness of the mixed layer and thermocline). If it is assumed for present purposes that advective heat change is important only in the nearshore regime (as upwelling), and that the meridional gradient of heat-exchange across the sea surface is constant while the zonal gradient is zero over the study area, then one must only consider variation of initial temperature, lateral and vertical diffusion, and free-mixing depth to explain the mixed-layer temperature patterns of figure 3.

July temperature near the top of the permanent

TABLE 2.—*Maximum temperature changes and salinity gradients in the plume province and average discharge rates of the Columbia River, 1961–64*

[Ranks are provided to facilitate comparisons]

Year	Mid-plume temperature change from previous winter to July		Average vertical salinity gradient at plume boundary, lat. 44° N. in July		Average horizontal salinity gradient normal to plume boundary in July		Average of the Columbia River discharge rate in June	
	$\Delta\Theta$ (°*C.*)	*Rank*	$\partial S/\partial z$ ($^{\circ}/_{\circ\circ}$ *m.*$^{-1}$)	*Rank*	$\partial S/\partial n$ ($^{\circ}/_{\circ\circ}$ *km.*$^{-1}$)	*Rank*	$\partial V/\partial t$ (10^3 *m.*^{3} *sec.*$^{-1}$)	*Rank*
1961	8.5	2	0.6	2	0.041	2	17.0	2
1962	7.5	3	.4	3	.022	3	11.9	3
1963	7.0	4	.2	4	.006	4	11.7	4
1964	9.5	1	1.0	1	.092	1	17.5	1

halocline, as noted above, is a measure of the minimum mixed-layer temperature of the previous winter. By definition, minimum temperature occurs at the beginning of the heating season. Seaward of upwelling influence, distribution of July temperature at 100 m. thus approximates the initial field of temperature. Temperature variation at this depth did not generally exceed 1° C. over the plume and offshore provinces, either spatially or from year to year (Owen, 1967b). Compared with spatial and temporal temperature changes in the near-surface layer, this variation was small enough to permit the assumption that none of the variation of July mixed-layer temperature was due to initial temperature differences.

Two sources of variation remain: thermal diffusion and mixing depth. Both may be expected to be substantially affected by salinity gradients at plume-sea interfaces, so that their effects on temperature distribution may be treated collectively as the "plume effect." It is this influence to which the recurrent ridge of higher temperatures was ascribed in the previous section.

On this basis, the validity of the proposed plume effect can be examined by comparing the pattern of plume disposition with the pattern of near-surface temperature change from the respective winters. Average values of salinity gradients normal to the plume edges were estimated from figure 4 (horizontal gradient estimates) and figure 8 (vertical gradient estimates along lat. 44° N.) and entered with values of maximum within-plume temperature change in table 2. The association of larger temperature change within the plume with large plume-edge gradients is clear from this table as well as from the figures themselves.

To examine the plume effect further, mixed-layer temperature change, $\Delta\Theta$, was plotted as a function of surface salinity for each July of the 4 years on the basis that surface salinity inversely represents the degree of "presence" of the plume and hence the magnitude of its interface gradients. Sets of paired data from each hydrographic station for each year were subjected to Spearman's rank-difference correlation test (Tate and Clelland, 1957); testing showed significant inverse relation at levels of $p<0.001$ for 1961, $p<0.001$ for 1962, $0.1<p<0.2$ for 1963, and $p\ll0.001$ for 1964. Differences between these levels of significance appear to depend on the degree of plume development and salinity gradients.

Validity of the assumed sea surface heat-exchange field must remain an open question. It is difficult, however, to see how the particular field of heat exchange could arise to produce the closed curves of $\Delta\Theta$ in the plume regime in the absence of oceanographic mechanisms discussed previously. The lack of advective heat change in the plume and offshore provinces is certain to be an approximation: ridgelike dynamic topography indicates possible advective transport of warmer offshore waters of more southern origin in 1961 and 1962. That this approximation is sufficiently good for showing the plume effect, however, is indicated by the differential heating in the plume in 1964, in spite of a flow pattern that suggests advective transport of colder water from the northwest. Advective effects thus appear to be masked by local change.

SUMMARY OF OCEANIC PROCESSES AND VARIATIONS OFF OREGON AND WASHINGTON

The region studied off the coast of Oregon and Washington is divisible in summer into three oceanographic provinces above and two provinces below the main halocline. This division is based on discontinuities in the distributions of variables that denote discontinuities in the influence of physical mechanisms, so that the oceanographic processes may be considered similar within and dissimilar between provinces. These processes—upwelling in the nearshore province, modification by land runoff in the plume province, and net dilution of surface layers in the offshore province—produce recurrent distributions of heat, salt, mass and, together with biological processes, oxygen.

Annual variations in the distribution of variables are attributable to changes in wind field, in fresh-water discharge from the land, and in advection. The variations are not sufficiently large, however, to obscure the basic patterns generated by dominant processes.

The balance of processes off Oregon and Washington is atypical in one respect. Whereas advection strongly influences recurrent patterns of near-surface distributions in oceanic regions lacking large fresh-water sources, its role in the study area is limited to disposition of land runoff. The low-salinity plume itself establishes the conditions for differences in local processes that generate the recurrent distribution patterns described here.

RELATION OF PHYSICAL PROCESSES TO THE ALBACORE FISHERY

It is particularly desirable to attempt to correlate the environmental conditions encountered each year by albacore when they first enter the region off Oregon and Washington with the subsequent distribution and numbers of fish available to the fishery. Suggested relations of environmental mechanisms to potential success of the fishery (that rarely extends seaward of the plume province) may then be tested in a preliminary fashion.

It appeared early in the analysis that the Oregon-Washington fishery for albacore might owe its degree of success to effects of the plume rather than despite them—i.e., that the limit of the area which contains commercial quantities of albacore might be locally extended to the north by these effects. Larger catches and catch rates of the *John N. Cobb* at and within the lateral limits of the plume than beyond it support the proposal that numbers of available albacore generally are higher in the plume than beyond (table 3, fig. 15).

TABLE 3.—*Summary of albacore trolling in July by M/V "John N. Cobb" off the Oregon-Washington coast, 1961–64*

[Effort is summed from day of first catch]

Year	Area of catch				Ratio of catch/effort (within/beyond)	
	Within plume [1]		Beyond plume [2]			
	Effort	Catch/effort	Effort	Catch/effort	Value	Rank
	Line-hours	*No./100 line-hours*	*Line-hours*	*No./100 line-hours*		
1961	602	7.5	647	1.4	5.4	3
1962	705	33.3	<10	(3)	(2)	(2)
1963	568	24.8	234	0.4	62.0	1
1964	202	16.3	183	22.4	0.7	4

[1] Where $S<32.2$‰.

[2] Where $S>32.2$‰.

[3] Catch per unit of effort was not measured because effort was insufficient outside the plume province after the day of first catch within it. On the basis of 316 line-hours expended outside the plume before the day of first catch, however, it can be said that the availability of albacore was far greater within the plume than outside it.

One physical mechanism to which these concentration effects may be related is the greater retention of heat within the surface layer of the plume province. This retention, coupled with wind-induced upwelling in the nearshore provinces, produces the temperature ridge discussed earlier. By extension of previous examples of albacore-temperature relation (e.g. Alverson, 1961; Johnson, 1962) we may assume that, at any instant of the fishery period, albacore will tend to concentrate in the region where temperature is most nearly optimal and will be absent from regions where surface-layer temperatures are less than 13° C. From smoothed plots of albacore catch frequency as a function of sea surface temperature for the fishery off California (Glenn Flittner, personal communication), 18° C. appears to be the optimal temperature. This temperature is seldom exceeded in the study area in July and is only barely exceeded in August and September. Consequently, after the albacore had moved into the region, we would expect the largest concentrations of fish to develop in the areas with the highest water temperatures or in the plume province rather than in the colder waters of the nearshore or offshore provinces.

Furthermore, in the absence of other environmental effects, relatively more albacore would be expected to be in the plume than outside it in years of greater temperature increase, when the plume is most sharply defined; then catch rates should be higher in the plume province than offshore. This expectation was not upheld, however: comparison of temperature change and plume intensity with average catch rates of fishing by the *John N. Cobb* within the plume province (table 3) and concurrent July–August averages of catch per unit of effort for the commercial fishery in the study area (fig. 16) showed that greater than average numbers of albacore were available in 1962 and 1963, when July temperatures were lower (fig. 3) and temperature changes (table 2, fig. 14) were smaller, than in 1961 and 1964. Furthermore, the ratio of catch rate within the plume to that beyond the plume (table 3) was largest in 1963. These differences in catch rates indicate that albacore concentrated in the plume to a greater degree when the difference in July temperatures in the plume and offshore provinces was least (fig. 3).

These results indicate that at least one variable other than temperature affects the distribution of albacore over the provinces. One factor is variation in catch rate and its relation to abundance of available albacore. If the catch rate for each province adequately represents the number of available albacore, then the ratio of catch rate within the plume to that beyond is free of influence by total abundance of albacore. The agreement of catch rates for exploratory fishing in the plume each year with respective July and August

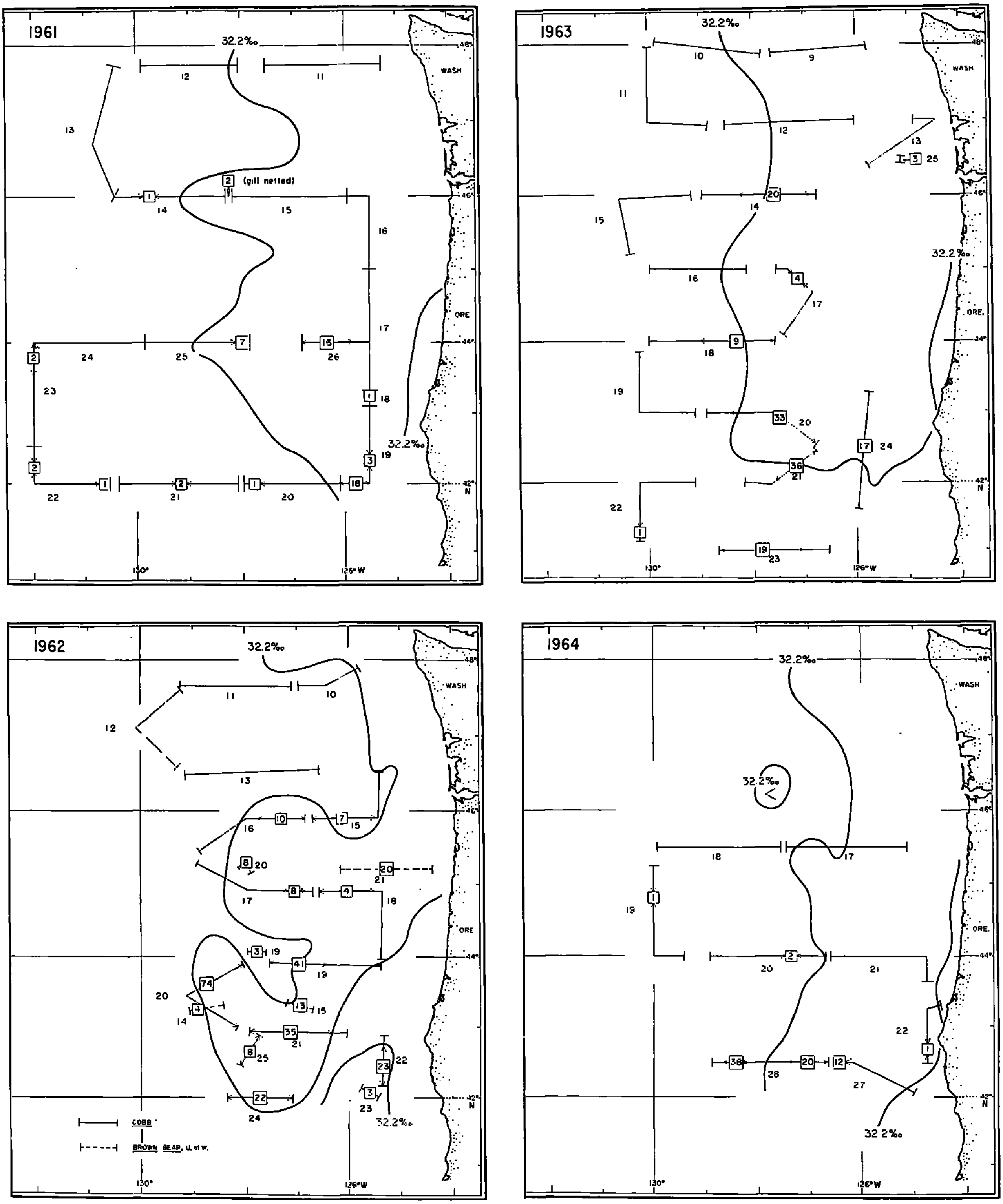

FIGURE 15.—Albacore catches (boxed numerals) by M/V *John N. Cobb* in July 1961–64, with corresponding lateral plume limits (32.2 °/₀₀ isohaline). July dates are given below or beside track line segments.

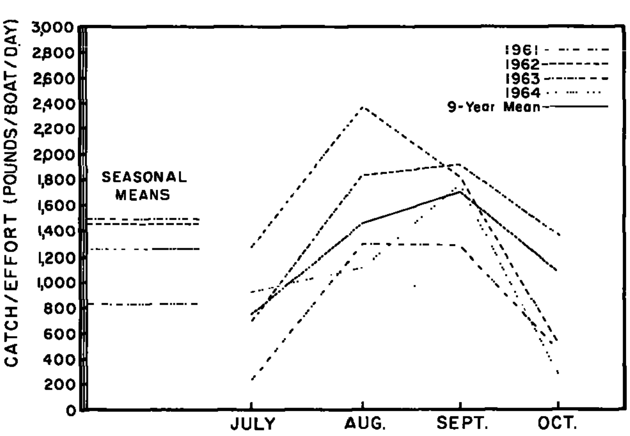

FIGURE 16.—Monthly averages of catch per unit of effort (pounds of albacore per boat-day of fishing) for the area north of lat. 40° N., east of long. 130° W. Data from Ayers and Meehan (1963) and James Meehan (personal communication) for effort exceeding 5 days per 1° square in the month.

catch rates for the commercial fishery in the plume province, although imperfect, indicates that the catch rates for exploratory fishing are adequate for use as ratios in the following discussion.

Still another factor is salinity. Nowhere over their known distribution do migrating albacore encounter a greater range of salinity than in the region off Oregon and Washington. Albacore thus may respond not only to temperature variation, as described above, but also to variation of salinity in the plume—for example through its effect upon balance of osmotic pressure. This balance, the difference between the organism's internal and environmental osmotic pressure (both referred to pure water at 0° C.), was studied by Sakamoto (1962) as a mechanism for determining movements of pelagic fishes and was applied to the Japanese fishery for yellowtail (*Seriola quinqueradiata*, Temminck and Schlegel).

Albacore, like other teleosts, must maintain their internal osmotic pressure at a nearly constant level so that pressure balance is a function only of environmental osmotic pressure. Rewritten from equations of Thompson (1932) and of Lyman and Fleming (1940) in terms of salinity and temperature, the unified expression for osmotic pressure of sea water, π, is (in millibars)

$$\pi(S^{\circ}/_{\circ\circ}, \theta) = (130.067\, S^{\circ}/_{\circ\circ} + 5.051)\,(0.018\,\theta + 5.051).$$

Salinity variation clearly dominates variation of environmental osmotic pressure in the surface layer, and hence the osmotic pressure balance experienced by albacore.

If albacore move so as to maintain a constant balance of osmotic pressure, the response of albacore to more favorable temperatures in the plume would be diminished or even canceled by their negative response to low salinity. Support for a salinity effect is gained by comparing ratios of average catch rates within the plume to rates outside the plume (table 3) with concurrent salinities (fig. 4) and salinity gradients (table 2) in the plume. Salinity and intensity of the plume are inversely ordered with catch-rate ratios (see rank columns in tables 2 and 3).

In summary, I suggest that higher temperatures within the plume, produced by relative constraint of heat, give rise to greater concentration of albacore within the plume province than beyond it once the fish move into the area off Oregon-Washington; plume salinity, to which temperature change is inversely related, qualifies the degree to which temperature difference can be effective (or even negates it during times of extremely low salinity, such as July 1964). Although the now unknown year-to-year differences in total abundance of albacore should be considered in this discussion, the degree to which the proposed mechanisms for differential distribution of albacore are supported by fishery data indicates that variation of albacore distribution over the study area may be as important as variation of total abundance in determining the yield of that fishery.

Results of this study indicate effects of variation of temperature and salinity on albacore distribution. At present experimental information is lacking on physiological and behavioral responses of albacore to such variations. Other factors may affect albacore and may themselves be related to variation of temperature and salinity: the role of forage in the plume province as an attractant to albacore may be worth investigating.

The commercial fishery for albacore off Oregon and Washington has extended infrequently to, and seldom beyond, the offshore limit of the plume province, in part because the range of Oregon-Washington fishing boats is generally short. Consequently, I believe that only a small fraction of the total albacore in the area considered has been exposed to fishing. Results of this work suggest that the fishery should be extended to the plume limits in most years and farther in years of high plume intensity. Confirmation of the hypothesis presented here will be necessary, as well as useful, by accumulation of more paired observations on plume and albacore distribution. Should the hypothesis be supported, areal differences in catch rate of albacore can be estimated from preseason geostrophic flow, wind field, and Columbia River discharge, because these factors largely determine the physical characteristics of the environment in this region.

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