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Annual Physical and Chemical Oceanographic Cycles of Auke Bay, Southeastern Alask

Herbert E. Bruce, Douglas R. McLain,
and Bruce L. Wing

May 1977

U.S. DEPARTMENT OF COMMERCE
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Annual Physical and Chemical Oceanographic Cycles of Auke Bay, Southeastern Alaska

HERBERT E. BRUCE, DOUGLAS R. McLAIN, and BRUCE L. WING[1]

ABSTRACT

The annual cycles of physical and chemical oceanographic conditions in Auke Bay, a small estuary in southeastern Alaska, showed a consistent pattern over an 8-yr period (1961-68). The cycles closely followed seasonal climatological and atmospheric events. Increased insolation in the spring caused general warming of the surface water and the air, which in turn increased the freshwater input into Auke Bay from melting snow and ice. The fresh water lowered surface salinities and together with warming of the surface waters caused a density stratification of the water column, which increased as the spring-summer season progressed. Maximum stratification occurred in August, followed by a general decay of stratification in September. Vertical mixing of the top 20 m of the water column by fall storms in September and cooling of surface water resulting from decreased insolation set up a thermohaline circulation that continued through the fall and early winter. The water column became homogeneous by January and remained thoroughly mixed from January through March or early April.

Auke Bay was rich in the inorganic nutrients phosphate, silicate, and nitrate. Spring phytoplankton blooms followed the onset of stratification and drastically reduced the concentration of all three nutrients in the surface water. Nitrate was essentially depleted and remained so throughout the summer. Low nitrate availability was undoubtedly one of the important factors limiting primary production in Auke Bay.

INTRODUCTION

Auke Bay is one of the many small bays along the major straits and passages of the inside waters of southeastern Alaska. Although these bays represent a small percentage of the total water mass of the area, they are important as spawning and nursery grounds for several species of fish and shellfish. Streams tributary to Auke Bay are spawning grounds for four species of salmon: pink, *Oncorhynchus gorbuscha*; chum, *O. keta*; coho, *O. kisutch*; and sockeye, *O. nerka*. Herring, *Clupea harengus pallasi*; king crabs, *Paralithodes camtschatica* and *P. platypus*; snow crab, *Chionoecetes bairdi*; and other species of commercial and recreational value spawn in the bay itself.

Several reports describe aspects of physical and chemical oceanography of small bays and estuaries in southeastern Alaska. Barnes et al. (1956) made an intensive survey (including some biological observations) of Silver Bay on Baranof Island near Sitka before construction of a pulp mill. Powers (1963) examined Little Port Walter at the southern end of Baranof Island. The U.S. Federal Water Pollution Control Administration (1966) made surveys of Gastineau Channel and Fritz Cove near Juneau and of Silver Bay and Ward Cove near Ketchikan in the summer of 1965. McLain (1968) surveyed Traitors Cove on Revillagigedo Island. McLain (1969) described seasonal changes in oceanographic conditions in Lynn Canal. Nebert and Matthews (1972) described the circulation of Endicott Arm. Most of these studies were less than 2-yr duration, not long enough to separate short-term and protracted hydrographic disturbances known to occur in natural environments.

Therefore, in our study of Auke Bay, the objective was to describe the annual cycles of oceanographic conditions in the bay over several years. In this way the complete annual cycle and the range of natural environmental variability could be identified. From this information the biological consequences of normal cycles and anomalous oceanographic conditions could be assessed.

DESCRIPTION OF STUDY AREA

Physiography and Geology

Auke Bay is one of a large number of small embayments off a system of large fiords connecting with the open ocean (Fig. 1). It is located at lat. 58°22′N and long. 134°40′W, 19.3 km northwest of Juneau, Alaska, and about 130 km inland from the open Gulf of Alaska. The bay covers an area of about 11 km^2 and contains several small islands and reefs.

The bottom topography of the bay is irregular, and submarine gulleys and mounts are quite common (Fig.

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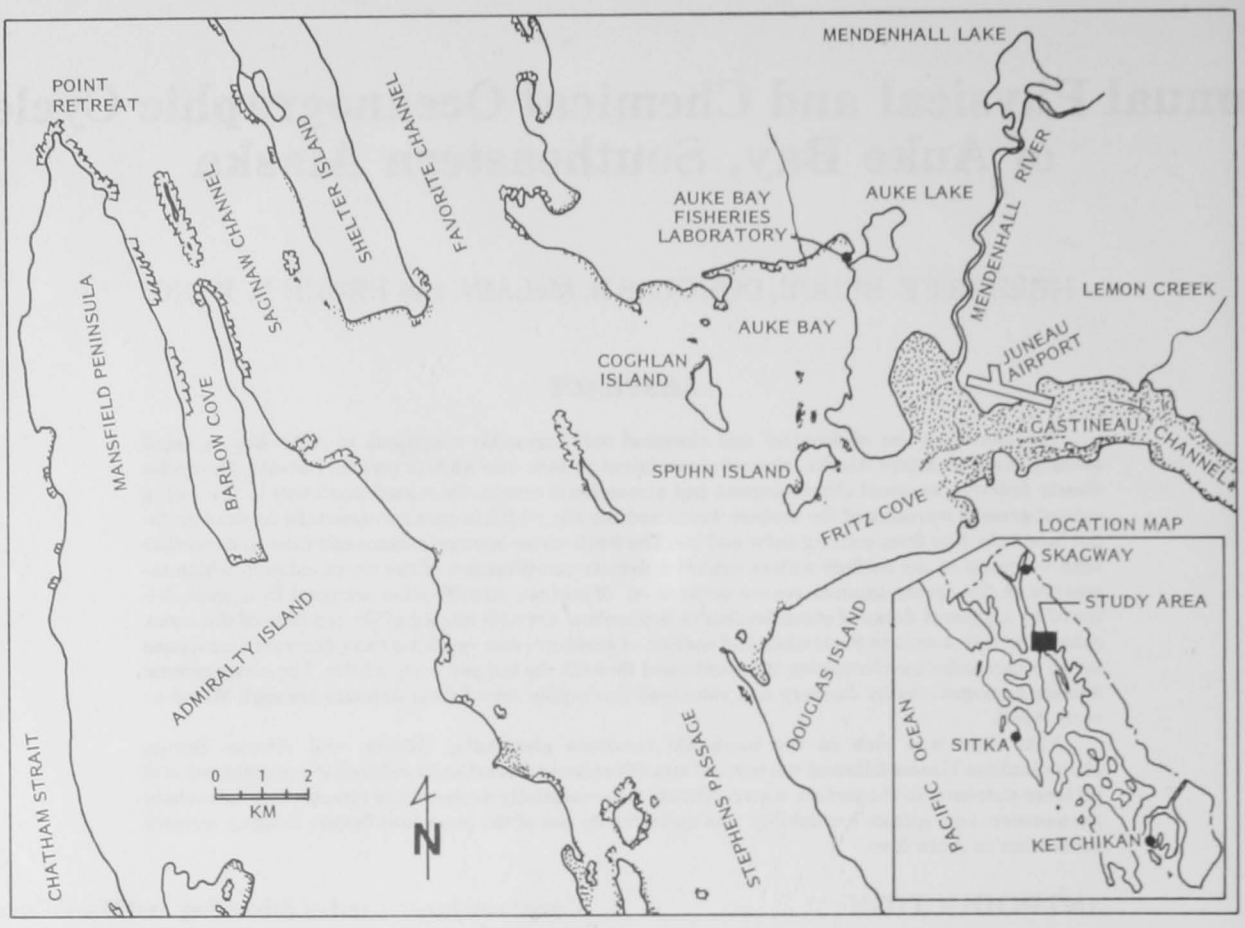

Figure 1.—Auke Bay, Alaska, and surrounding area.

2). The maximum depth, 100 m, is near the south end of Coghlan Island; depths of 40 to 60 m are common over much of the bay.

Auke Bay is not a fiord-type estuary of the form described by Pritchard (1952), but is a small tributary embayment to a system of large fiords. Lynn Canal-Icy Strait-Chatham Strait and Stephens Passage-Frederick Sound-Chatham Strait are major interconnected passages in southeastern Alaska and provide communication between Auke Bay and the Gulf of Alaska. The entire region was heavily glaciated during the Pleistocene Epoch. Martin and Williams (1924) concluded that glacial deepening of a preexisting river valley was the primary process in the formation of the Chatham Strait-Lynn Canal fiord. Auke Bay may have formed as a side valley of the larger fiord system.

Climatology

Auke Bay lies within that part of the maritime province extending along the northwest coast of North America. Winds in this area are predominantly southerly off the Pacific Ocean. These warm, moisture-laden winds strike the high coastal ranges and result in abundant precipitation, little sunshine, and moderate air temperatures. Observations by the National Weather Service at the Juneau Airport 3 km east of Auke Bay are that precipitation in the area is lightest in the spring and heaviest in the fall (Fig. 3). Between February and May the average monthly precipitation rate is fairly constant (the monthly average for 1931-60 was 6.6 cm). Precipitation increases rapidly in June and reaches a maximum in October (the 30-yr average for October 1931-60 was 21.3 cm).[2] After the October maximum, precipitation decreases until February.

The average monthly insolation for the Auke Bay area from 1959 to 1962 is shown in Figure 4. Insolation, which we estimated from cloud cover data, is a predominant factor in controlling seasonal cycles of air and sea surface temperature. Data from Roden (1959) on the total amount of radiation received at sea level under cloudless skies were converted to insolation under cloud cover according to the equation of Sverdrup et al. (1942):

$$Q_i = Q_0(1\text{-}0.071\ C)$$

where Q_i = radiation received at sea level adjusted for cloud cover

Q_0 = total incoming radiation under cloudless skies

C = amount of clouds (in tenths of sky covered).

[2]The average was calculated from data in the U.S. Weather Bureau's annual publication Climatological Data, vols. 17-46, Alaska section (No. 13).

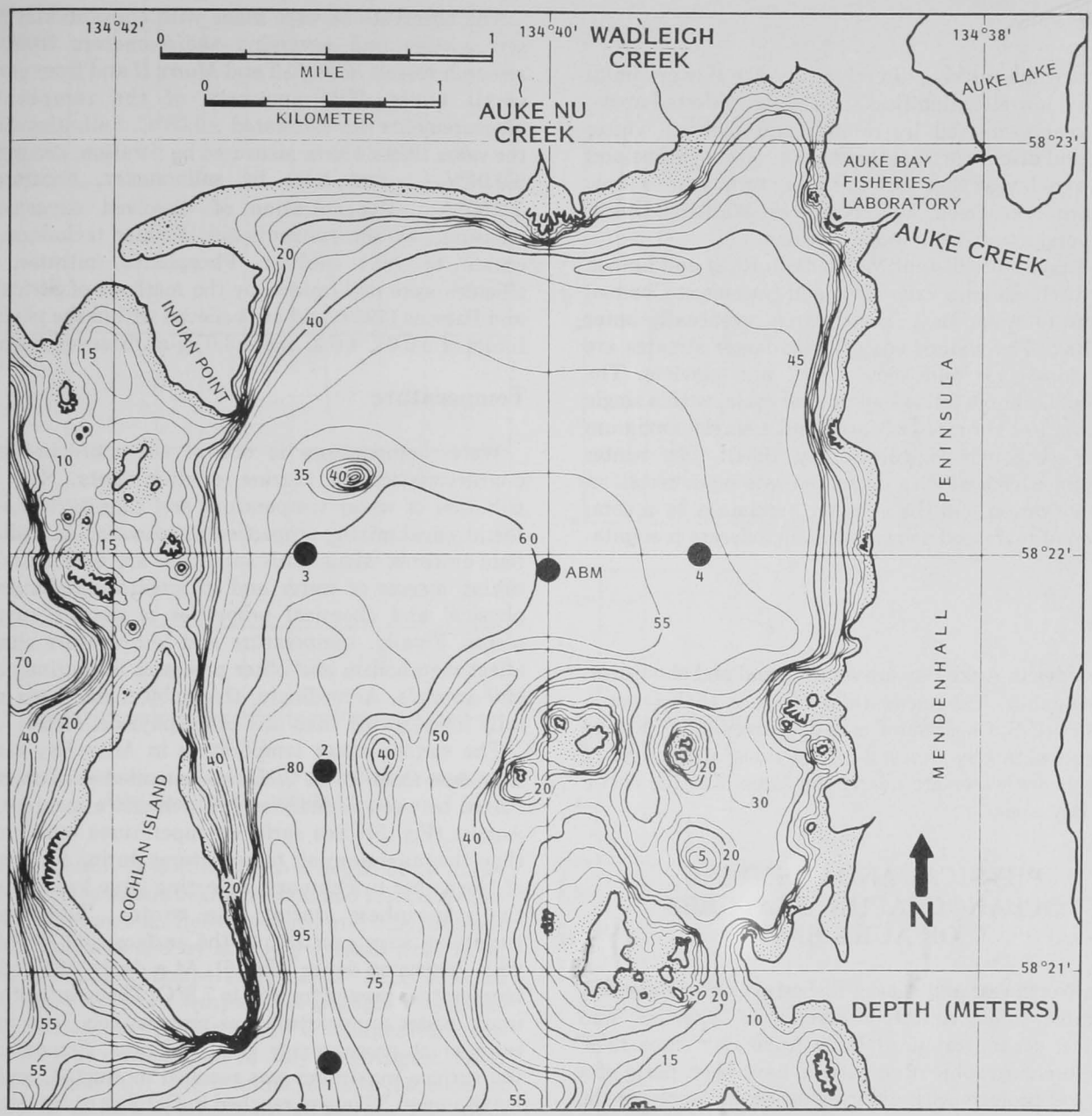

Figure 2.—Bathymetry of Auke Bay, Alaska, and locations of oceanographic stations.

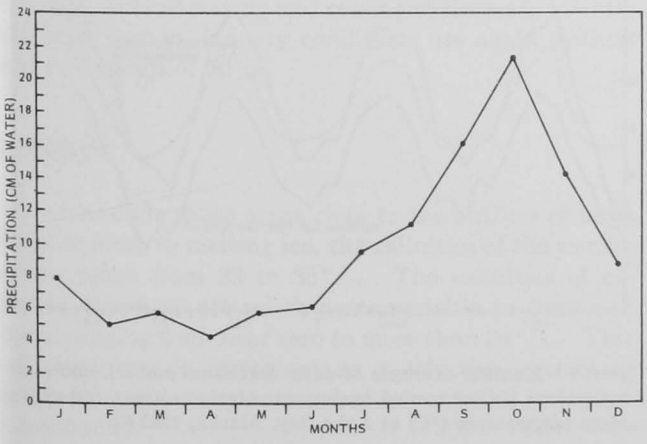

Figure 3.—Average monthly precipitation (cm of water) at Juneau airport, 1931-60. (See text footnote 2.)

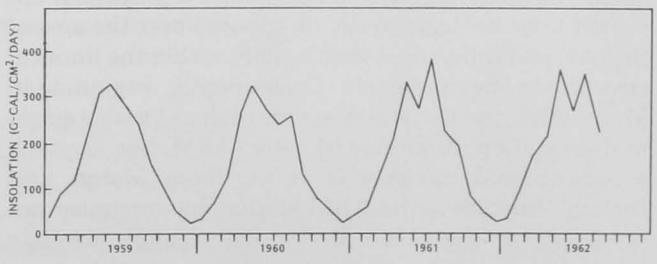

Figure 4.—Monthly averages of daily insolation (g-cal/cm²/day) in Auke Bay area, 1959-62. (See text for calculation of insolation.)

Runoff

The streams entering directly into Auke Bay are small and drain low-elevation (less than 900 m) forested areas. The streams are fed by rainfall and melting winter snows, and discharge from them has several maxima and minima each year that vary in timing from year to year. These are Auke Creek, Auke Nu Creek, Wadleigh Creek, and several smaller unnamed streams.

The larger more distant Mendenhall River and Lemon Creek discharge into Fritz Cove and Gastineau Channel adjacent to Auke Bay. Their waters eventually enter Auke Bay. The watersheds of these larger streams are rocky slopes, ice and snow fields, and glaciers. The monthly discharge follows an annual cycle, with a single minimum in February or March and a single maximum in July (U.S. Geological Survey 1964). The winter minimum is caused by a decreased rate of snowmelt at higher elevation and the summer maximum by a combination of increased snowmelt and moderate precipitation.

Tides

The tides in Auke Bay are semidiurnal and show diurnal inequality. The mean tidal range is slightly more than 4 m (U.S. Coast and Geodetic Survey 1962). Spring tides exceed this by almost 2 m. The times and heights of high and low water are nearly the same over the entire Auke Bay area.

PHYSICAL AND CHEMICAL OCEANOGRAPHIC FEATURES OF AUKE BAY

The Northwest and Alaska Fisheries Center Auke Bay Laboratory has collected descriptive physical and chemical oceanographic data in Auke Bay since 1959. These oceanographic observations have been parts of a variety of projects with differing needs and goals, so the schedules and types of observations have varied over the years. The seasonal cycles described in this report are derived primarily from data collected from 1961 to 1967, supplemented by some earlier and later observations.

Five oceanographic stations (Fig. 2) were occupied monthly during 1961-63. The local variations within the bay were relatively small when compared with the frequent transient vagaries. Oceanographic properties appeared to be homogeneously distributed over the area of the bay, and differences were usually within the limits of error in our measurements. Consequently, beginning in March 1963, the five stations were replaced with a single midbay station, Auke Bay Monitor (ABM, Fig. 2) which was monitored monthly for 1 yr. From March 1964 through July 1967, the ABM station was occupied approximately weekly in order to define more precisely short-term variations in oceanographic conditions associated with use of amino acids as a nitrogen source by the phytoplankton (Bruce 1969).

The observations were made with conventional Nansen bottles and reversing thermometers from the research vessels *Sablefish* and *Murre II* and from various small boats. The accuracy of the temperature measurements was estimated ±0.05°C. Salinities during the years 1959-64 were measured by titration, accurate to ±0.01°/$_{oo}$, and later by salinometer, accurate to ±0.05°/$_{oo}$. Concentration of dissolved oxygen was measured by the conventional Winkler technique, accurate to ±0.1 ml/liter. Phosphates, nitrates, and silicates were determined by the methods of Strickland and Parsons (1960) and are believed within the precision limits of ±0.05, ±0.3, and ±3.0 μg-at./liter respectively.

Temperature

Water temperature is one of the most important characteristics of marine environments. The distribution of water temperature and salinity influences the physical mixing properties of the water. In addition, temperatures, along with salinities, are useful in identifying masses of water and in monitoring changes in physical and chemical properties of marine environments. Finally, temperature and temperature changes affect metabolism and other processes in marine plants and animals. Accordingly, this subject has been more fully investigated than any other physical factor.

The surface water temperature in Auke Bay ranged from less than 2° to 17°C; an extended minimum occurred between January and March and a maximum in August (Fig. 5). Sea surface temperatures were greater than the maximum air temperatures during the months of November to February, reflecting large heat losses to the atmosphere during the winter. Temperature variations were greatest at the surface and decreased with increasing depth (Fig. 6). At a depth of 50 m, the temperature ranged from 2° to 7.8°C. The month of maximum water temperature was progressively later in the summer at progressively greater depths. For example, the surface maximum was reached in August, and the maximum at 50 m was reached in October or November.

During the year vertical temperature profiles change from well mixed to strongly stratified (Fig. 7). In January

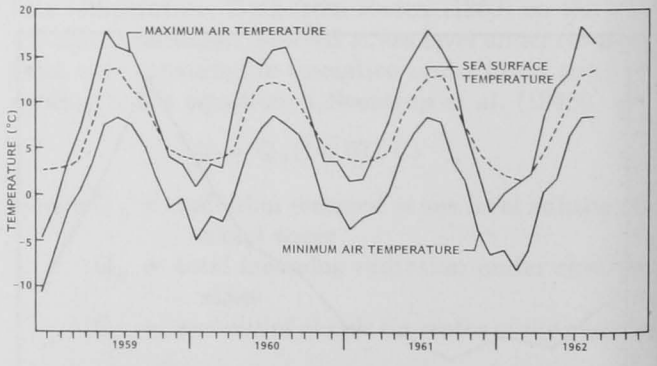

Figure 5.—Monthly averages of daily maximum and minimum air temperatures (°C) recorded at Juneau, Alaska, airport and of sea surface temperature (°C) at Auke Bay, Alaska, 1959-62.

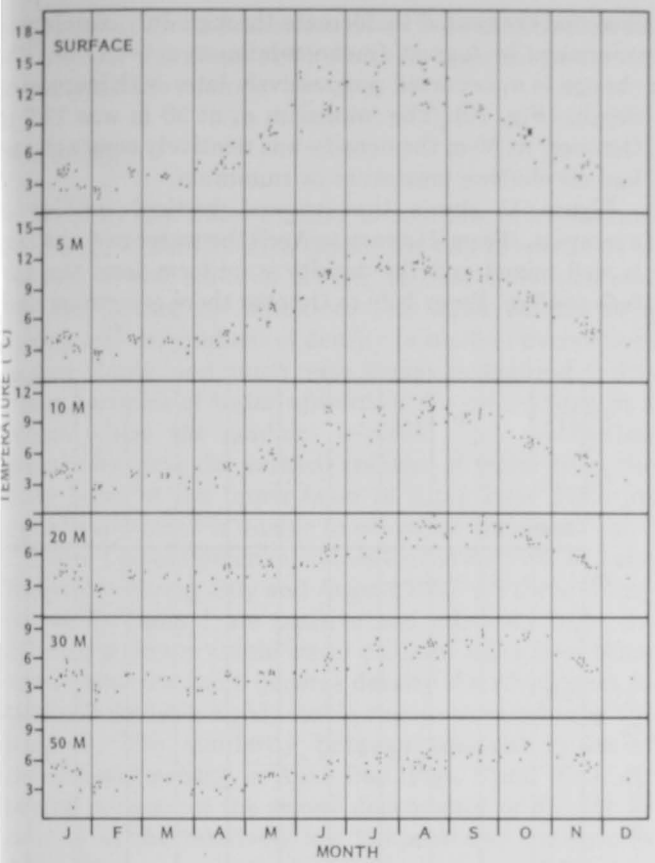

Figure 6.—Observed water temperatures (°C) at selected depths in Auke Bay, Alaska, 1960-68.

the water column is isothermal to a depth of 50 m. In April the surface waters begin to warm and start development of a thermocline. Between April and July, surface warming continues and by late July extends from 10 m. A lesser gradient in temperature exists from 10 to 30 m, and below 30 m the temperature changes very little. In the thermocline proper, a 10°C temperature difference may be encountered in July and August. After mid-September, the thermocline decays because of radiant heat losses and mixing by fall storms. The effect of storms is to change the distribution of heat, as illustrated by the decrease in the temperature of the surface waters to a depth of 10 m and a warming of the water below 10 m by vertical mixing. Between October and January, vertical mixing and cooling of the surface water continue, and in January conditions are again isothermal to a depth of 50 m.

Salinity

If we exclude those areas close to the outflow of large rivers or close to melting ice, the salinities of the world's oceans range from 32 to 38°/₀₀. The salinities of estuaries, however, are much more variable in time and space, ranging from near zero to more than 30°/₀₀. This wide variation is important as a selective agency in determining the composition and structure of biological communities.

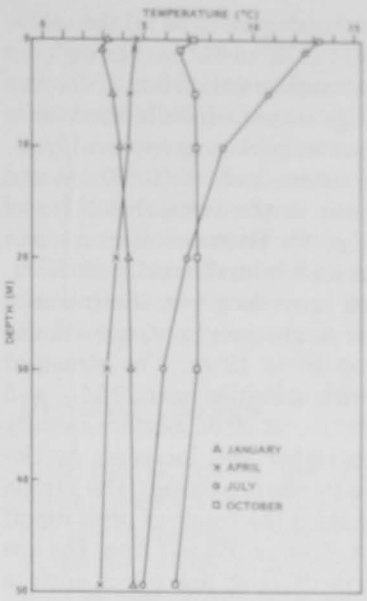

Figure 7.—Typical profiles of temperature (°C) in Auke Bay, Alaska, for January, April, July, and October; data are averages for 1960-68.

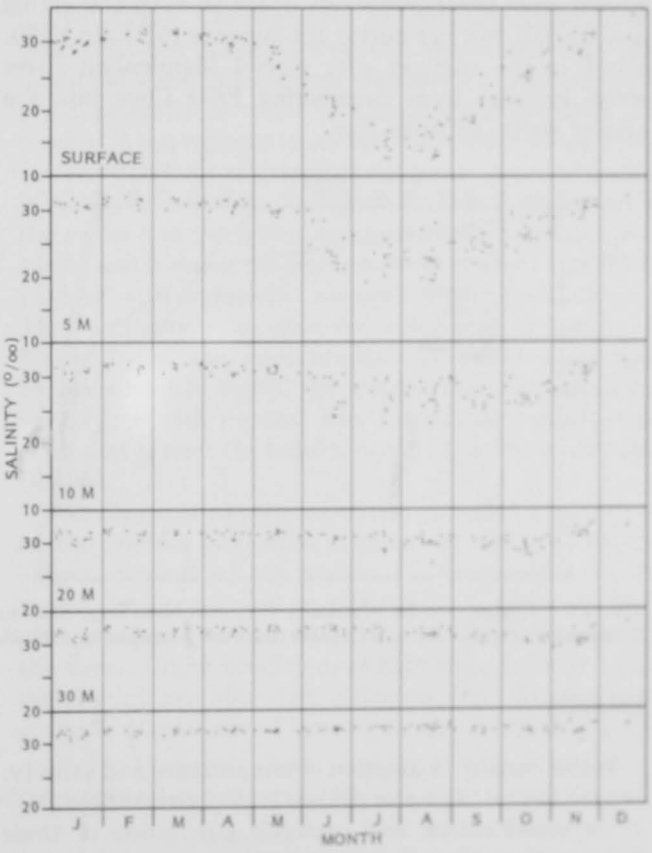

Figure 8.—Observed salinities (°/₀₀) at selected depths in Auke Bay, Alaska, 1960-68.

Variation of salinity at selected depths in Auke Bay from 1960 to 1968 is shown in Figure 8. In general, the annual cycle of salinity in the top 10 m was characterized by 1) a period from January to April when salinity remained between 29 and 31°/₀₀, 2) a period between May and July-August when salinity decreased to a minimum of about 17°/₀₀, and 3) a recovery period (September-December) when salinity increased again to

the winter values. In deeper water (20 to 50 m) the salinity remained rather constant at 30 to 31 °/₀₀ through the year. The salinity of surface waters varied 3 to 5 °/₀₀ in a few days during the spring-fall period while short-term variations in the deeper water seldom exceeded 1 °/₀₀.

Two distinct layers of water—surface (to 30 m) and deep (below 30 m)—appear in the vertical profiles of salinity in Auke Bay (Fig. 9). Between January and April, isohaline conditions exist from the surface to 50 m. The salinity of the surface layer decreases continuously from April through July or August, and a strong salinity gradient forms in the top 10 to 12 m. The strongest halocline occurs in July with salinities near 20 °/₀₀ at 5 m, 27 °/₀₀ at 10 m, and 31 °/₀₀ at 30 m. Surface salinity remains low through September and increases in October as a result of autumn storm mixing. The strong halocline of July and August is the result of peak runoff from the large, glacial-fed streams. Runoff from the low elevation, forested watersheds does not affect surface salinities as much as runoff from the glacial streams. Runoff from lower elevations peaks in both the spring and the fall, but not during the summer (McLain 1969). Often in the summer silty glacial Mendenhall River water intrudes from neighboring Fritz Cove into the clearer waters of Auke Bay.

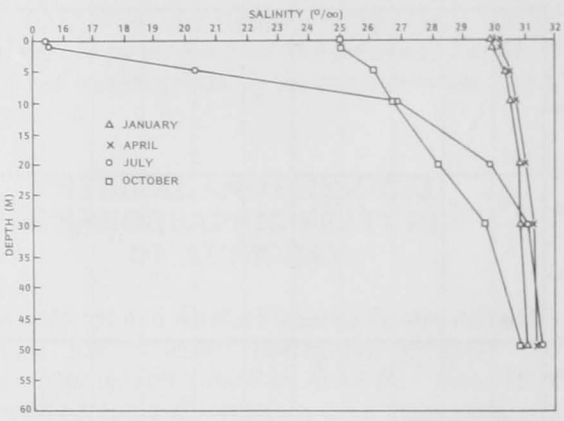

Figure 9.—Typical profiles of salinity (°/₀₀) in Auke Bay, Alaska, for January, April, July, and October; data are averages for 1960-68.

Density

Water density, a function of temperature and salinity, is used to identify water masses and to assess the stability or stratification and probable circulation of these water masses. Over the range of values observed in Auke Bay density is affected more by salinity variation than by temperature variation.

The annual cycle of water density of Auke Bay from 1960 to 1968 expressed in terms of σ_t[3] is shown in Figure 10. The density of the surface water in Auke Bay varied over a range of σ_t values between 9 and 24. Density was greatest and varied little with depth from December to April. In late April, density began to decrease at the surface and continued to decrease through July, reaching a minimum in August (mean minimum σ_t = 11.0). The change in σ_t occurred progressively later with increasing depths (Fig. 10). The minimum σ_t at 30 m was 22.2 in October. At 50 m the density was relatively constant and had no obvious maximum or minimum.

Figure 11 shows the seasonal vertical profiles of average σ_t. From January to April the water in Auke Bay is well mixed and the density is uniform from the surface to 50 m. From July to October there is a strong den-

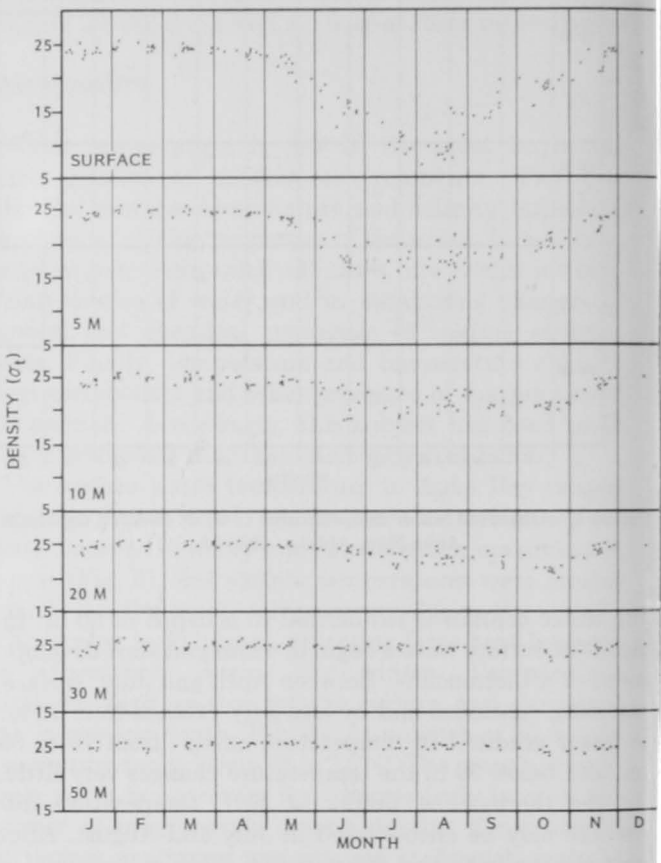

Figure 10.—Observed densities (as σ_t) at selected depths in Auke Bay, Alaska, 1960-68.

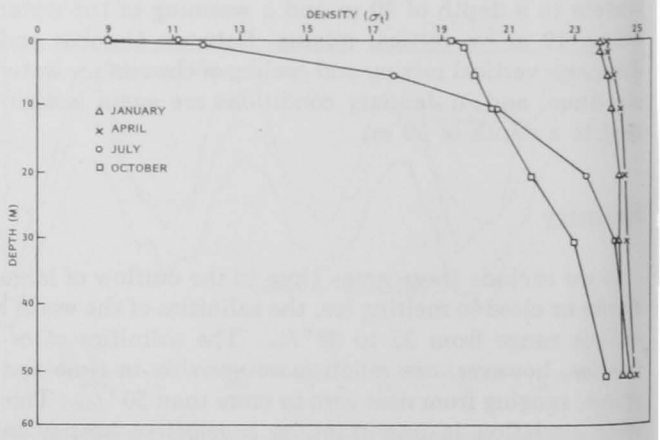

Figure 11.—Typical profiles of density (as σ_t) in Auke Bay, Alaska, for January, April, July, and October; data are averages for 1960-68.

[3]Sigma-t (σ_t) = 1,000 (ρ-1) where ρ is the density of the water.

sity gradient from the surface down to 30 m. The data for all years of this study show the same seasonal pattern of density distribution.

Stability

Stability of a water column[4] is determined by the rate of change of density with depth, the vertical gradient of density. Where stability is high, vertical movement and vertical mixing are inhibited. The water column in a strong vertical gradient of density (a marked pycnocline) is very stable, and much more energy is required to displace particles of water upward or downward than in a region where the gradient is weak. This mechanism greatly restricts the vertical transfer of water from the deep layer to the upper layer in Auke Bay. Tidal-induced turbulence is unable to penetrate the pycnocline.

Table 1 gives numerical values for the stability of Auke Bay water during July and August 1965. All the stability values in Table 1 are positive and relatively high, indicating a highly stable water column. Data from other years show the same general density distribution as in 1965; all depict a highly stable water column during the summer. The similarity between seasonal cycles of salinity and density in Auke Bay (Figs. 8 and 10) is expected because of the strong dependency of density on salinity at the relatively low temperatures common in Auke Bay.

The development of a stable water column is one of the most ecologically significant features of the oceanography of Auke Bay because stability of the water column is a prerequisite for the onset of spring phytoplankton bloom (Riley 1942; Sverdrup 1953; Steele 1966). Gilmartin (1964) found that seasonal variability in the stability of the water column in a British Columbia fiord was the primary factor controlling phytoplankton growth. We observed a strong burst of phytoplankton growth each year in April or early May as solar radiation increased and a stable water column began to form. It is clear that stratification has a pronounced effect on the basic productivity of Auke Bay throughout the spring-summer growing season.

Dissolved Oxygen

Oxygen is one of the common gases dissolved in natural waters and is critically important because of its key role in biological energy transfers. Although aquatic organisms respire efficiently at oxygen concentrations considerably below saturation values, metabolic rates and efficiencies are dependent on the availability of dissolved oxygen. Consequently, the dissolved oxygen concentration is a major determinant of the environmental quality of water. The oxygen requirement of organisms is given generally in terms of absolute concentration expressed in appropriate units such as ml/liter or mg/liter.

Concentrations of dissolved oxygen at selected depths in Auke Bay are shown in Figure 12. Dissolved oxygen in the upper 5 m generally remained above 6 ml/liter, and spring and summer concentrations were above 8 ml/liter. Highest concentrations occurred from April through June and maximum observed value was 11.4 ml/liter. Below 10 m the concentration of dissolved oxygen decreased with depth. In winter the concentrations varied less with depths. The lowest concentrations of oxygen at or near the bottom occurred in September and October.

The degree of oxygen saturation provides information on the relative intensities of processes which affect the oxygen content of the water. Supersaturation is observed frequently and is essentially a result of high photosynthetic activity by plants in the upper layer of the water. Under conditions of high solar radiation during the day and abundant nutrients, the rate of oxygen production may exceed the rate at which oxygen is given

[4]For depths to 100 m, stability (E) can be expressed by

$$E = 10^{-3} \frac{d\sigma_t}{dZ}$$ (Sverdrup et al. 1942, p. 417),

or in different form

$$E = 10^{-3} \left(\frac{\sigma_{t_2} - \sigma_{t_1}}{Z_2 - Z_1} \right)$$

where Z = depth
$dZ \cong Z_2 - Z_1$ = change in depth
$d\sigma_t \cong (\sigma_{t_2} - \sigma_{t_1})$ = change in σ_t
σ_t = $1{,}000\,(\rho - 1)$ where ρ = density of the water.

Table 1.—Stability (E)[4] at Auke Bay monitor station in July and August 1965.

	21 July 1965				10 August 1965			
Depth (m)	Temp. (°C)	Salinity (°/₀₀)	σ_t	10^6E	Temp. (°C)	Salinity (°/₀₀)	σ_t	10^6E
0	13.48	16.30	11.94		16.55	16.30	11.37	
				1,107				1,189
10	7.84	29.50	23.01		7.98	29.85	23.26	
				151				101
20	5.82	31.10	24.52		6.21	30.85	24.27	
				49				43
30	4.76	31.57	25.01		5.66	31.30	24.70	
				16				22
50	4.28	31.90	25.32		4.70	31.72	25.13	

[4]See text footnote 4.

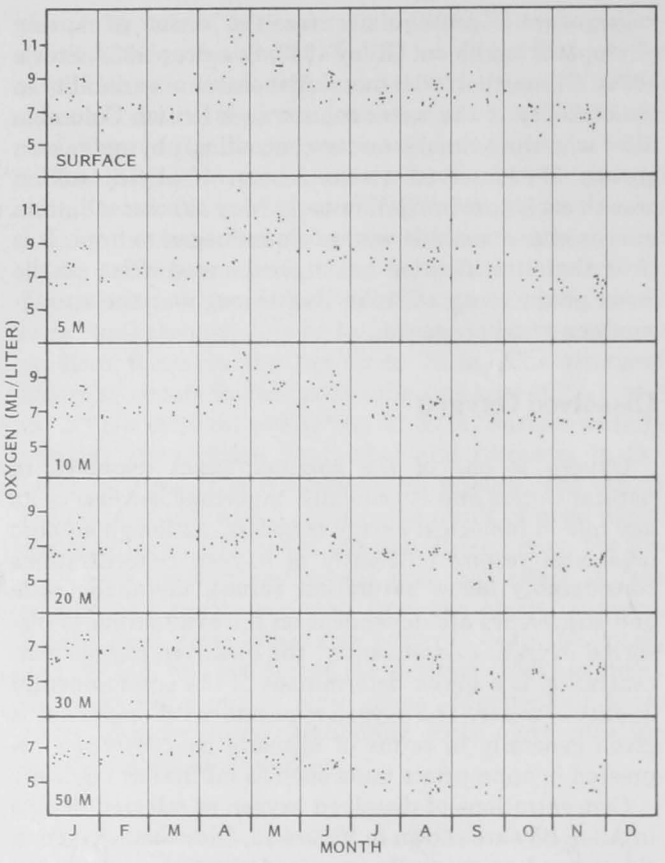

Figure 12.—Observed concentrations of dissolved oxygen (ml/liter) at selected depths in Auke Bay, Alaska, 1960-68; data are observed concentrations.

off at the surface, and supersaturation will occur. Appreciable supersaturation occurs in Auke Bay during the spring and summer, even down to 10 to 20 m (Fig. 13). This coincides with spring and summer phytoplankton blooms. Lowest concentrations of oxygen occur during the fall and winter when photosynthetic activity is reduced and bacterial decomposition and chemical oxidation of detritus lower the oxygen content.

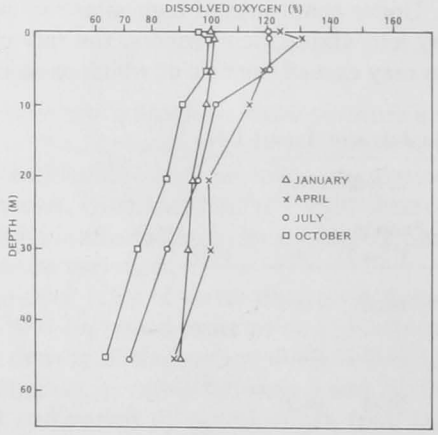

Figure 13.—Typical vertical profiles of percent saturation of dissolved oxygen in Auke Bay, Alaska, for January, April, July, and October; data are averages for 1960-68.

Inorganic Nutrients

The circulation of biologically active materials such as phosphate, silicate, and nitrate, as well as their distribution in the water column, depends on biological and physical processes and differs in detail from the circulation and distribution of water and its conservative properties. Because these materials are dissolved components of water, they are affected by advective and eddy diffusion processes. In addition, they are exchanged between the water and the biomass in a cyclic process. During periods of high biological activity, changes in the distribution and abundance of biologically active components of the water column may occur rapidly relative to changes due to physical processes alone. Thus, their study may add significantly to the physical description of an area.

During our study in Auke Bay, there was a regular seasonal cycle in concentrations of inorganic phosphate, silicate, and nitrate (Figs. 14, 15, 16). Maximum concentrations of all three nutrients occurred in winter (January-April), and all were uniformly distributed throughout the water column in this period. A rapid reduction of the three nutrients above 20 m in April was associated with the outburst of phytoplankton growth. In each year of our study, we noticed a marked rise in numbers of diatoms and chlorophyll concentrations and a corresponding drop in concentrations of phosphate, silicate, and nitrate (unpublished data on file Northwest and Alaska Fisheries Center Auke Bay Laboratory). Once stability is established in spring, high levels of photosynthetic activity rapidly deplete the available nutrients because vertical advection of nutrients into the surface is inhibited by the stability of the water column.

Raymont (1963) reviewed the distribution and amounts of phosphate, silicate, and nitrogen throughout the world oceans, including many of the important coastal and inshore areas. In comparison with other nutrient-rich coastal and inshore environments, the amounts of these materials in Auke Bay water were relatively high. Friday Harbor in western Washington had some of the highest observed concentrations of both phosphate and nitrate—about 1.8 μg-at./liter of phosphate and 21.0 μg-at./liter of nitrate (Raymont 1963). Riley and Conover (1956) found maximum phosphate and nitrate concentrations in Long Island Sound of 1.9 and 17.0 μg-at./liter, respectively. Maximum concentrations in Auke Bay were 3.5 μg-at./liter of phosphate and 26.0 μg-at./liter of nitrate. Maximum silicate concentrations in Auke Bay were also comparatively high—70.0 μg-at./liter. This is significantly greater than the maximum values reported for the English Channel, 5.0 μg-at./liter, or for Friday Harbor, 53 μg-at./liter (Raymont 1963). The highest silicate concentration reported anywhere was 160 μg-at./liter in the deep water of the North Pacific Ocean (Raymont 1963).

In general, throughout the summer, phosphate values in Auke Bay in the upper 5 m tended to remain low, although there were some fluctuations. Minimum concentrations of phosphate observed in surface water were

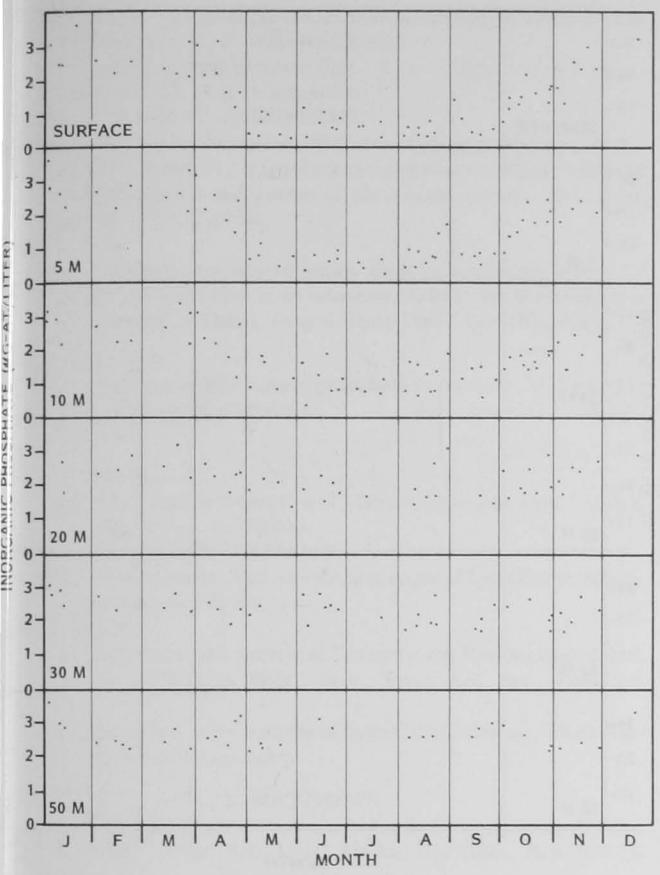

Figure 14.—Observed concentrations of inorganic phosphate (μg-at./liter) at selected depths in Auke Bay, Alaska, 1963-67.

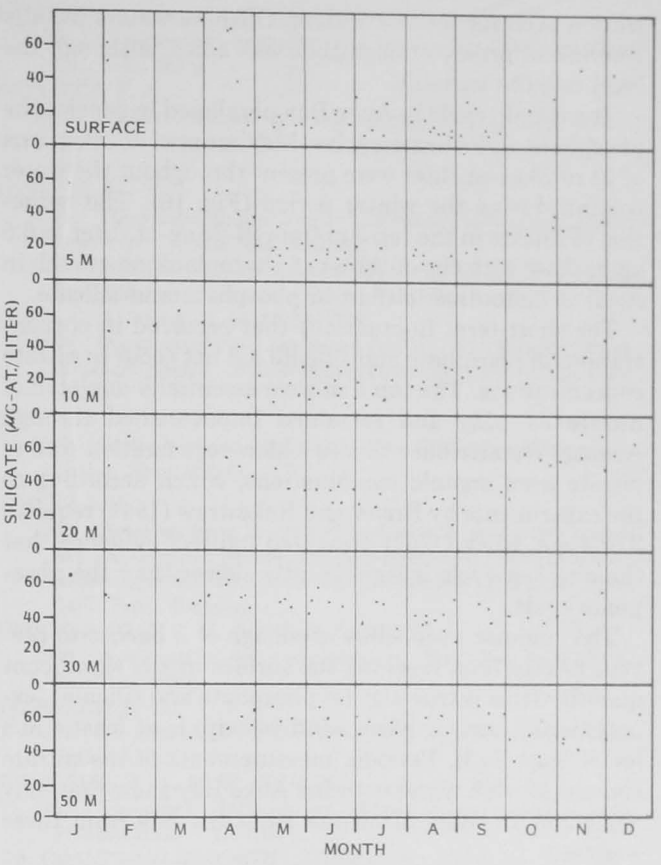

Figure 15.—Observed concentrations of dissolved silicate (μg-at./liter) at selected depths in Auke Bay, Alaska, 1963-67.

between 0.30 and 0.20 μg-at./liter, versus a winter high of 3.0 to 3.5 μg-at./liter (Fig. 14).

Short-term increases in phosphate concentrations in the top 5 m from May through August did not have a strong coincidence with periods of increased runoff. Hence, freshwater input was discounted as a significant cause of increases in nutrients, including phosphate, over short time periods (3 to 7 days). Studies by Curl, Iverson, and Conners[5] showed that tidal effects in Auke Bay were not sufficient to mix nutrient-rich water into the euphotic zone, but that wind-induced mixing through the pycnocline could be caused by winds of 4 m/s persisting for 24 h or longer.

Although the causes of fluctuation in phosphate levels are not clear, the most probable causes are regeneration of inorganic phosphate from organically bound phosphate and wind-induced vertical mixing of inorganic phosphate through the pycnocline. Laboratory measurements of the rate of phosphate regeneration (Cooper 1935) indicate that up to one-half of the total phosphorous content of decomposing plankton appears in soluble form within 24 h.

The silicate cycle in Auke Bay (Fig. 15) generally paralleled the phosphate cycle; this similarity was also demonstrated by Richards (1958) in the western Atlantic. Studies in the English Channel by Atkins (1930) showed that silicate was depleted and regenerated simultaneously with phosphate.

While phosphate and silicate in Auke Bay had the same general seasonal patterns of distribution, some differences appear when the data are examined in detail: short-term variation in concentration of phosphate occurred primarily in the upper 5 m of the water column (Fig. 14); the greatest variations in silicate occurred between 10 and 20 m (Fig. 15). Variability in the concentration of silicate throughout the water column in Auke Bay is generally greater than it is for phosphate.

Minimum silicate concentrations of 2 to 4 μg-at./liter occurred in the surface water of Auke Bay during July, August, and September (Fig. 15). Short-term increases occurred in late June and early July, when the proportion of dinoflagellates (phytoplankton which do not utilize silicate) to diatoms was quite high. We interpreted this increase as a reflection of the difference in rate of uptake by the relatively small number of diatoms present and the rate of in situ regeneration, plus advective input.

Maximum silicate concentration of about 60 μg-at./liter occurred throughout the water column from December through the middle of March—a high concen-

[5]Curl, H. C., Jr., R. L. Iverson, and H. B. O'Conners, Jr. 1971. Pelagic ecology of biological production in Auke Bay, Alaska. Final report to National Marine Fisheries Service, Auke Bay Fisheries Laboratory, Auke Bay, Alaska, Contract 14-17-0005-207.

tration even for inshore waters. Offshore waters usually contain an order of magnitude less silica, although the level is quite variable.

The nitrate cycle in Auke Bay paralleled in general the phosphate and silicate cycles. Maximum concentrations of 24 to 28 μg-at./liter were present throughout the water column during the winter period (Fig. 16). The reduction of nitrate in the top 5 m from 24-28 μg-at./liter to 0.5 μg-at./liter with the outburst of phytoplankton growth in April is more drastic than in phosphate and silicate.

The short-term fluctuations that occurred in concentrations of phosphate and silicate did not occur in nitrate concentrations. The top 5 m were essentially depleted of nitrate by May and remained impoverished through August. We attribute this to a slow regeneration rate of nitrate from organic combinations, which according to the experiments by Brand and Rakestraw (1941) requires 3 or 4 mo. Riley (1967) presented indirect evidence that the nitrogen cycle is significantly slower than the phosphate cycle.

The summer pycnocline is enough of a barrier to prevent nitrate from reaching the surface in any significant quantity (this is true also for phosphate and silicate), except during periods when wind velocity is at least 4 m/s for at least 24 h. Periodic measurements of the nitrate content of fresh water entering Auke Bay show that only negligible amounts of nitrate enter the bay from these sources.[6]

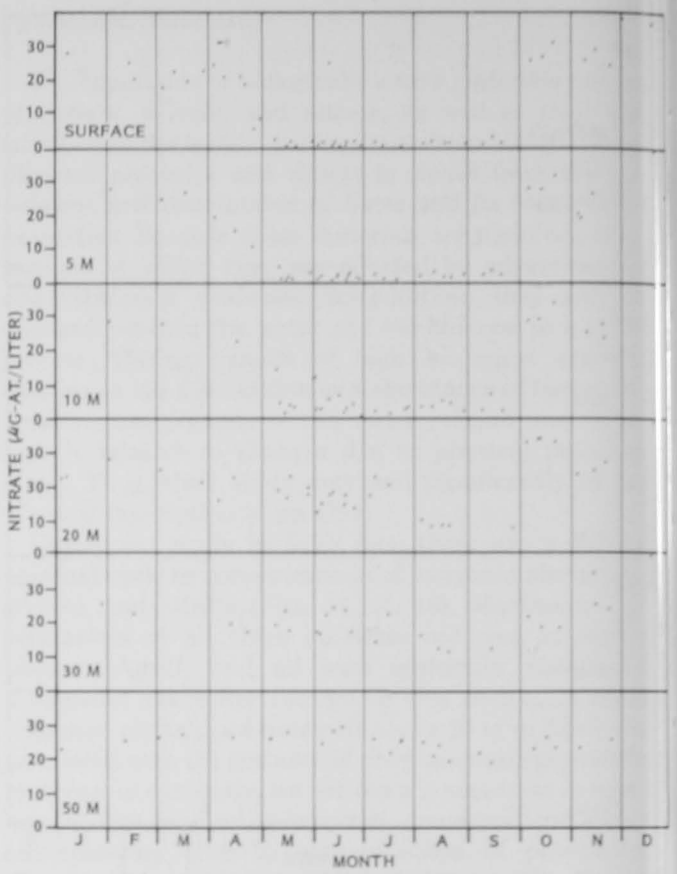

Figure 16.—Observed concentrations of dissolved nitrate (μg-at./liter) at selected depths in Auke Bay, Alaska, 1963-67.

SUMMARY

This study has described temporal variation in oceanographic conditions over an 8-yr period and provides background information on environmental variability for future detailed studies of the ecology of Auke Bay. Salient environmental features of an annual cycle in Auke Bay are summarized below.

Auke Bay is about 130 km from the open ocean and is relatively isolated from direct oceanic moderation and from major circulation patterns of the main passages and straits in southeastern Alaska. The bay is strongly influenced by land runoff and by the local climate. The annual oceanographic cycles closely follow local atmospheric cycles.

By the end of the second week in April, the water column began to stratify because of increased absorption of solar radiation in the upper 5 m and the accumulation of fresh water on the surface from increased runoff and precipitation. As the spring-summer season progressed, stratification increased until a strongly developed pycnocline essentially isolated the upper 12 to 20 m from the deeper water.

Full development of the brackish surface layer in Auke Bay occurred in late July or August. In September, cooling of surface water coupled with wind mixing due to fall storms broke the density stratification developed during the spring-summer period. Nutrient-rich water below the pycnocline was mixed into the euphotic zone to replenish the nutrient-impoverished surface water, and a fall phytoplankton bloom occurred.

As the season progressed into fall, decreasing temperatures and increasing salinities in the surface layer of water increased the density of the surface water, resulting in thermohaline circulation which thoroughly mixed the water column. Hence, during the winter, the water column was essentially homogeneous, and the concentrations of phosphate, silicate, and nitrate throughout the water column were high. A well-mixed water column and low solar radiation prevented any significant phytoplankton growth during the winter; consequently, the distribution of biologically active dissolved components depended almost totally on physical processes during the winter.

The seasonal pattern described was repeated each year during the 8-yr period that routine observations were made.

LITERATURE CITED

ATKINS, W. R. G.
1930. Seasonal variations in the phosphate and silicate content of sea-water in relation to the phytoplankton crop. Part V. November 1927 to April 1929, compared with earlier years from 1923. J. Mar. Biol. Assoc. U.K. 16:821-852.

[6]Unpublished data on file Northwest and Alaska Fisheries Center Auke Bay Laboratory, NMFS, NOAA, P.O. Box 155, Auke Bay, AK 99821.

RNES, C. A., T. F. BUDINGER, E. E. COLLIAS, W. B. McALISTER, . N. SUND, and M. P. WENNEKENS.
1956. Oceanography of Silver Bay. Univ. Wash. Dep. Oceanogr., Spec. Rep. 24, 85 p. + appendix.
AND, T., and N. W. RAKESTRAW.
1941. Decomposition and regeneration of nitrogenous organic matter in sea water. IV. Interrelationship of various stages; influence of concentration and nature of particulate matter. Biol. Bull. (Woods Hole) 81:63-69.
JCE, H. E.
1969. The role of dissolved amino acids as a nitrogen source for marine phytoplankton in an estuarine environment in southeastern Alaska. Ph.D. Thesis, Oregon State Univ., Corvallis, 124 p.
OPER, L. H. N.
1935. The rate of liberation of phosphate in sea water by the breakdown of plankton organisms. J. Mar. Biol. Assoc. U.K. 20:197-200.
LMARTIN, M.
1964. The primary production of a British Columbia fiord. J. Fish. Res. Board Can. 21:505-538.
RTIN, L., and F. E. WILLIAMS.
1924. An ice-eroded fiord, the mode of origin of Lynn Canal, Alaska. Geogr. Rev. 14:576-596.
LAIN, D. R.
1968. Oceanographic surveys of Traitors Cove, Revillagigedo Island, Alaska. U.S. Fish Wildl. Serv., Spec. Sci. Rep. Fish. 576, 15 p.
1969. Heat and water balance of Lynn Canal, Alaska. Ph.D. Thesis, Univ. Michigan, 143 p.
BERT, D. L., and J. B. MATTHEWS.
1972. A proposed circulation model for Endicott Arm, an Alaskan fjord. Inst. Mar. Sci., Univ. Alaska, Fairbanks, Rep. R72-10, 90 p.
WERS, C. F.
1963. Some aspects of the oceanography of Little Port Walter estuary, Baranof Island, Alaska. U.S. Fish Wildl. Serv., Fish. Bull. 63:143-164.
ITCHARD, D. W.
1952. Estuarine hydrography. *In* H. E. Landsberg (editor), Advances in geophysics, Vol. I, p. 243-280. Academic Press, N.Y.
RAYMONT, J. E. G.
1963. Plankton and productivity in the oceans. The MacMillan Co., N.Y., 660 p.
RICHARDS, F. A.
1958. Dissolved silicate and related properties of some western North Atlantic and Caribbean waters. J. Mar. Res. 17:449-465.
RILEY, G. A.
1942. The relationship of vertical turbulence and spring diatom flowerings. J. Mar. Res. 5:67-87.
1967. Mathematical model of nutrient conditions in coastal waters. Bull. Bingham Oceanogr. Collect., Yale Univ. 19(2):72-80.
RILEY, G. A., and S. A. M. CONOVER.
1956. Oceanography of Long Island Sound, 1952-1954. III. Chemical oceanography. Bull. Bingham Oceanogr. Collect., Yale Univ. 15:47-61.
RODEN, G. I.
1959. On the heat and salt balance of the California current region. J. Mar. Res. 18:36-61.
STEELE, J. H.
1966. Notes on some theoretical problems in production ecology *In* C. R. Goldman (editor), Promary productivity in aquatic environments, p. 383-398. Mem. Ist. Ital. Idrobiol., 18 Supple., Univ. Calif. Press, Berkeley.
STRICKLAND, J. D. H., and T. R. PARSONS.
1960. A manual of sea water analysis. Fish. Res. Board Can., Bull. 125, 185 p.
SVERDRUP, H. U.
1953. On conditions for the vernal blooming of phytoplankton. J. Cons. 18:287-295.
SVERDRUP, H. U., M. W. JOHNSON, and R. H. FLEMING.
1942. The oceans, their physics, chemistry, and general biology. Prentice-Hall, N.Y., 1087 p.
U.S. COAST AND GEODETIC SURVEY.
1962. Tide tables, west coast North and South America, 1964. U.S. Coast and Geodetic Survey, 224 p.
U.S. FEDERAL WATER POLLUTION CONTROL ADMINISTRATION.
1966. Oceanographic and related water quality studies in southeastern Alaska, August 1965. U.S. Water Pollut. Control Admin., Northwest Reg., 74 p.
U.S. GEOLOGICAL SURVEY.
1964. Surface water records of Alaska, 1963. U.S. Geol. Surv., Water Res. Branch, Juneau, 94 p.