AN ABSTRACT OF THE THESIS OF

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Title: PHYSICAL HYDROGRAPHY AND NUTRIENT NITROGEN
BUDGET OF AUKE BAY, ALASKA

Abstract approved: Redacted for Privacy
Herbert C. Curl, Jr.

Physical sources of nutrient nitrogen for the Auke Bay, Alaska estuarine ecosystem were investigated. These sources included vertical dispersion, advection, and fresh water sources. Hydrographic circulation patterns for the bay, and a nutrient budget for the surface mixed layer were developed.

Measurements of temperature, salinity, currents, wind velocity, rainfall and runoff from the major streams and river influencing Auke Bay were made during the spring and summer of 1971. Initial hydrographic and nutrient data (total available nitrogen and nitrate) from early spring were taken during a cruise of R/V Cayuse. Nutrient concentration of nitrate and ammonia in Auke Bay and the fresh water sources entering Auke Bay were measured on a weekly basis from July to September. Vertical mixing rates of 0.42 cubic meters per day were calculated for those times wind

mixing did not occur. Mixing rates of 1.2 cubic meters/day were calculated for wind mixed conditions. Vertical dispersion through the pycnocline provided the major source of nutrients for summer phytoplankton production. Fresh water sources provided negligible amounts of nutrients.

Average vertical transport of nitrate and ammonia when wind mixing did not occur were 0.5 mg-at/m^2/day and 0.3 mg-at/m^2/day respectively. During wind mixing, 3.0 mg-at/m^2/day for nitrate and 2.0 mg-at/m^2/day for ammonia were supplied to the mixed layer. Estimate productivity based on these calculations ranges from an average 100 mgC/m^2/day during non wind mixed conditions to 600 mgC/m^2/day during wind mixed conditions.

Physical Hydrography and Nutrient Nitrogen Budget of Auke Bay, Alaska

by

Deborah Kathleen Kirk

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Professor of Oceanography
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Typed by Opal Grossnicklaus for Deborah Kathleen Kirk

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My special gratitude to all of the personnel at the Auke Bay Laboratory for their help last summer. Special thanks go to Mauri Pelto, Bruce Wing, Mel Bony and Fred (in the shed) Salter for their invaluable aid and considerable patience.

I acknowledge and thank Subdistrict Chief Vernon K. Berwick (USGS, Water Resources Division, Juneau, Ak.) for his cooperation in allowing me to monitor the stream gauges and for immediately processing the data which I needed. The easy access to their records and to their knowledge of local conditions provided by Pat Poole and the other meteorologists at the Juneau weather station is much appreciated.

Data analysis at OSU could not have been completed without the aid of Dale Pillsbury and Joe Bottero (Coastal Currents, OSU) for analysing my current meter data and Dave Bella (Civil Engineering, OSU) for helping with the mixing analysis. To these people a very large thank you.

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PHYSICAL HYDROGRAPHY AND NUTRIENT NITROGEN BUDGET OF AUKE BAY, ALASKA

INTRODUCTION

A study of the sources, sinks and forms of nutrient-nitrogen, available for phytoplankton growth, in an estuarine environment was undertaken during the spring and summer of 1971 at Auke Bay, Alaska. Auke Bay is a small eleven sq. Km. embayment, near Juneau, in the larger estuarine system of the Inside Passage of Southeastern Alaska (Fig. 1). Previous studies (Bruce, 1967; Curl, Iverson and O'Connors, 1971) indicate that the bay has high thermal and halal stability during the summer months. A shallow pycnocline (5 to 11 meters) is established by June, and frequently much earlier, and is maintained by high runoff and precipitation until fall. High winds and storms in the fall mix the bay until it is nearly isohalal and isothermal.

The project design for 1971 was based on information obtained in previous studies in this bay. Regular sampling in the 1960's under the auspices of the NMFS laboratory located at Auke Bay indicated definite successional blooms occurring in the absence of measureable nitrate-nitrogen. Bruce (1967) investigated amino acids as possible sources of nutrients for these blooms. Curl *et al.* (1971) carried out an intensive sampling plan at the Bay during the summer

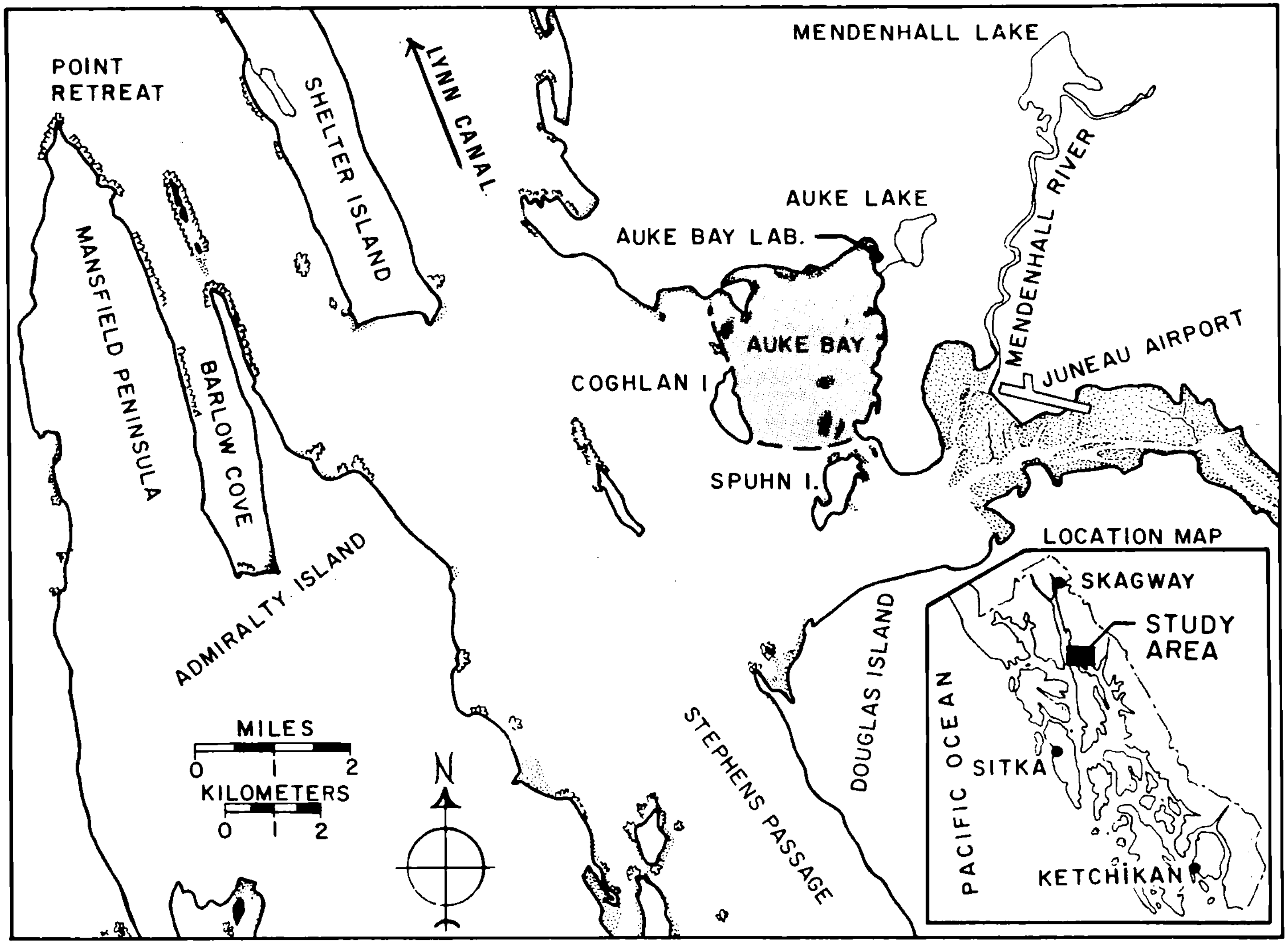


Figure 1. Location of Auke Bay in relation to major straits and passages in Southeastern Alaska. (From Bruce, 1967.)

of 1969 to further investigate the cause of phytoplankton blooms under low nutrient, high stability conditions. Iverson (1971) in a computer simulation model, identified wind as a primary forcing function for these blooms. High winds deepened the pycnocline into the lower nutrient rich zones, thus providing a pulsed source of nutrient for the blooms.

Both of these studies investigated specific phenomena related to the observed succession of blooms. However, forms and sources of nitrogen other than nitrate and amino acids were not investigated in any detail, or not at all. Identifying and quantifying some of these other sources of nitrogen for initial spring conditions and throughout the summer formed the basis of this present research. Forms of nitrogen which possibly could be investigated are nitrate, nitrite, ammonia, urea and amino acids. Our technical capabilities limited us to measurement of nitrate and total available nitrogen, TAN (TAN includes nitrate, ammonia, nitrite and organic forms of nitrogen; Coughenower, 1972) during the spring, and nitrate and ammonia during the summer. The following physical forces were thought to have the most effect on a nutrient budget for Auke Bay: rainfall, freshwater runoff, horizontal advection and vertical dispersion. Biological processes such as excretion, uptake and bacterial regeneration are considered indirectly in this essentially physical model of nutrient nitrogen.

METHODS

Data for initial conditions were taken during the cruise C7104A in April, 1971. Salinity and temperature with depth on the cruise were obtained by a Bissett-Berman ^{R} Model 6040 STD sensor (Becker and Curl, 1971). A pumping system attached to the STD sensor provided water samples for nutrient and chlorophyll analysis. Mr. D. Coughenower analyzed nitrate on an automated sampling system (Hager *et al.*, 1968) and total available nitrogen by ultra-violet oxidation (Coughenower, 1972). Thirty stations were monitored in the bay and its immediate vicinity. A twenty-four hour anchor station to the west of Spuhn Island was monitored on an hourly basis in conjunction with research being done aboard the University of Alaska's ship, R/V *Ursa Minor*, anchored nearby.

From mid June to mid September, Ms Karen Zakar and myself operated from a twenty-four foot open skiff, equipped with a gas powered winch, from which we could sample physical and biological factors within the bay. The boat, laboratory space, and various other forms of logistic support were provided by the NMFS laboratory at Auke Bay.

Salinity and temperature with depth were taken with an *in situ* Model Rs5-3 Beckman electrodless induction salinometer down to twenty-four meters. The instrument was calibrated against standard sea water and had a precision of ±0.3‰ and 0.5° C. Sigma-t values were obtained from tables (Keala, 1965).

Bottle casts to 45 meters for nutrient samples were taken at a mid bay station known as Auke Bay Monitor (ABM) (Fig. 2) on a weekly basis. Occasionally, meteorological events dictated a more closely spaced sampling time. Surface nutrient samples from Auke Creek, Wadleigh Creek, Auke Nu Creek, several unnamed creeks entering the bay, Lake Creek, Montana Creek and Mendenhall River were also taken on a weekly basis. Ms Karen Zakar analyzed nitrate by the method of Wood, Armstrong and Richards (1967) and ammonia by the method of Solorzano (1969). Rainfall was monitored on a daily basis at the laboratory.

Runoff data for Auke Creek, Lake Creek, Mendenhall River and Montana Creek were available from the Dept. Interior, Geologic Survey (Water Resources Data for Alaska, 1971). Wind data were supplied by the Juneau Airport Weather station.

Braincon Type 381 Savonius rotor current meters supplied by the NMFS laboratory were moored at strategic locations in Auke Bay (Fig. 2) for a period of 21 days, August 21 to September 10, 1971. The precision of the speed readout is ±2 cm/second for a 20 minute cycle. Precision for direction readout is ±3° (Mooers *et al.*, 1968). Data from these meters were analysed by the Coastal Current group at Oregon State University.

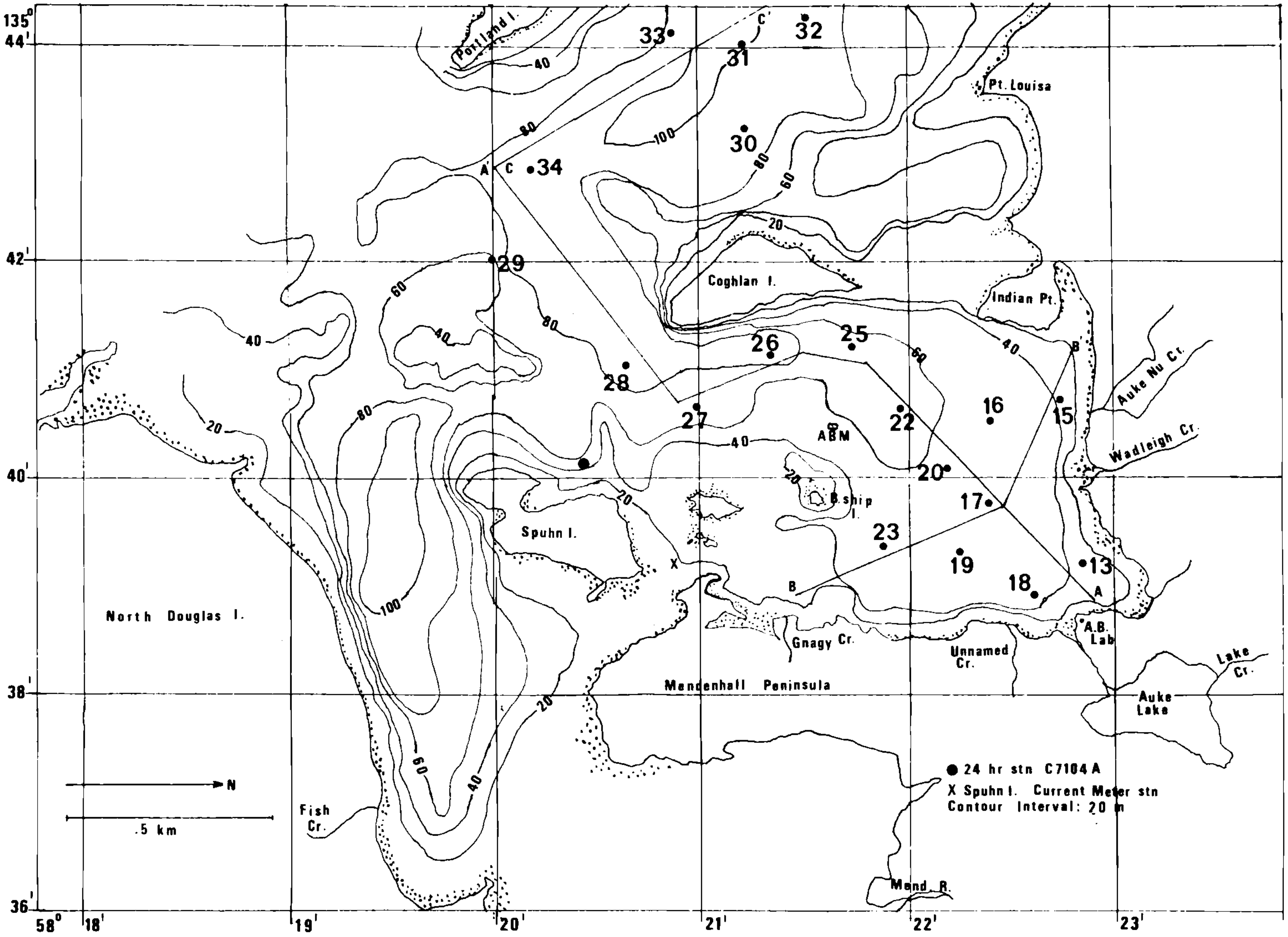


Figure 2. Location of Auke Bay stations and fresh water sources entering Auke Bay.

RESULTS

The spring cruise was timed to occur before the onset of spring production to obtain initial pre-bloom hydrographic and nutrient conditions, however we arrived during one of the early blooms. The stations occupied on this cruise are shown in Fig. 2. Hydrographic conditions at this time were fairly uniform throughout the Auke Bay region, with the exception of the stations along the north edge of the bay (Figs. 3, 4, 5). Temperature, salinity and sigma-t showed little stratification while nitrate and TAN both have a maximum concentration between 25 meters and 35 meters. Chlorophyll maxima and nitrate minima occur not only in the surface 10 to 20 meters but also at depth (Figs. 3, 4).

During the time the sampling was being carried out, a storm front from the southeast moved through the area. Winds were from the east-southeast at 8 to 12 meters/second for two days, with gusts to 22 meters/second recorded on the R/V Ursa Minor. A 24 hour anchor station in which both vessels participated was occupied during the latter half of the storm. Temperature, salinity, sigma-t and TAN data were taken on an hourly basis on R/V Cayuse. PCO_2 was monitored on a half hourly basis aboard R/V Ursa Minor during this same time period (Fig. 6). The storm system, and its high winds, had passed through this area by the time the last samples of the 24 hour

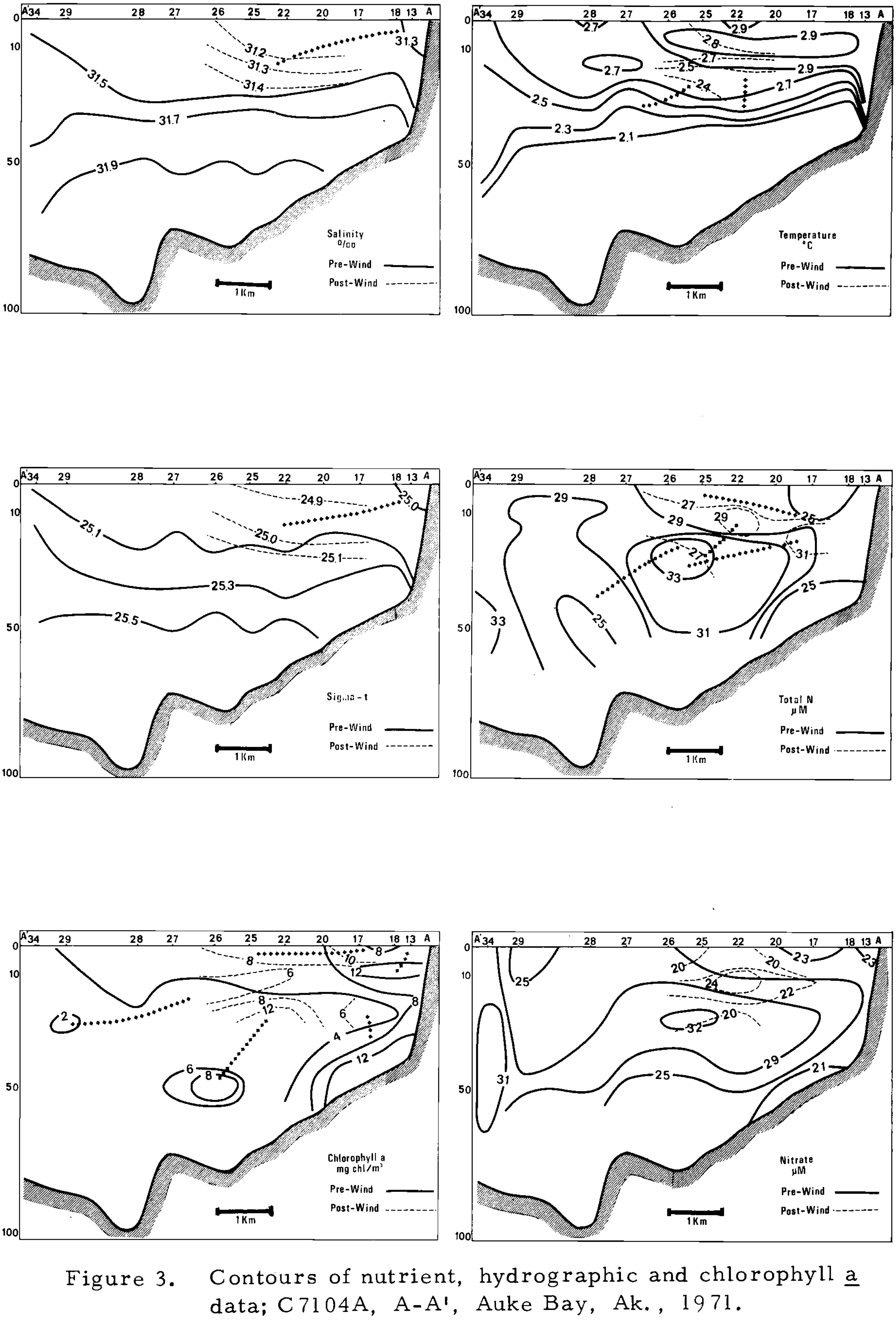


Figure 3. Contours of nutrient, hydrographic and chlorophyll a data; C7104A, A-A', Auke Bay, Ak., 1971.

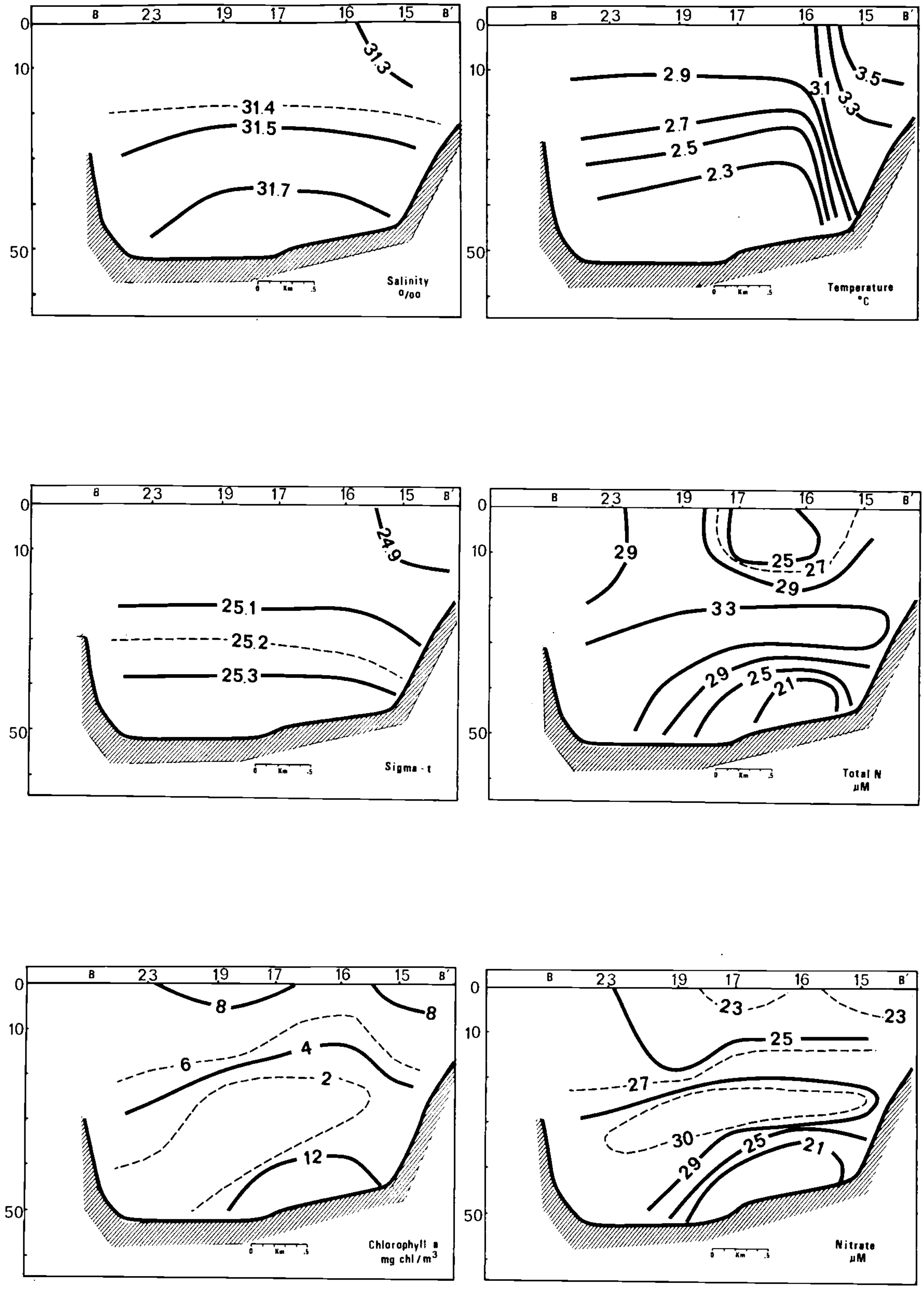


Figure 4. Contours of nutrient, hydrographic and chlorophyll a data; C7104A, B-B', Auke Bay, Ak., 1971.

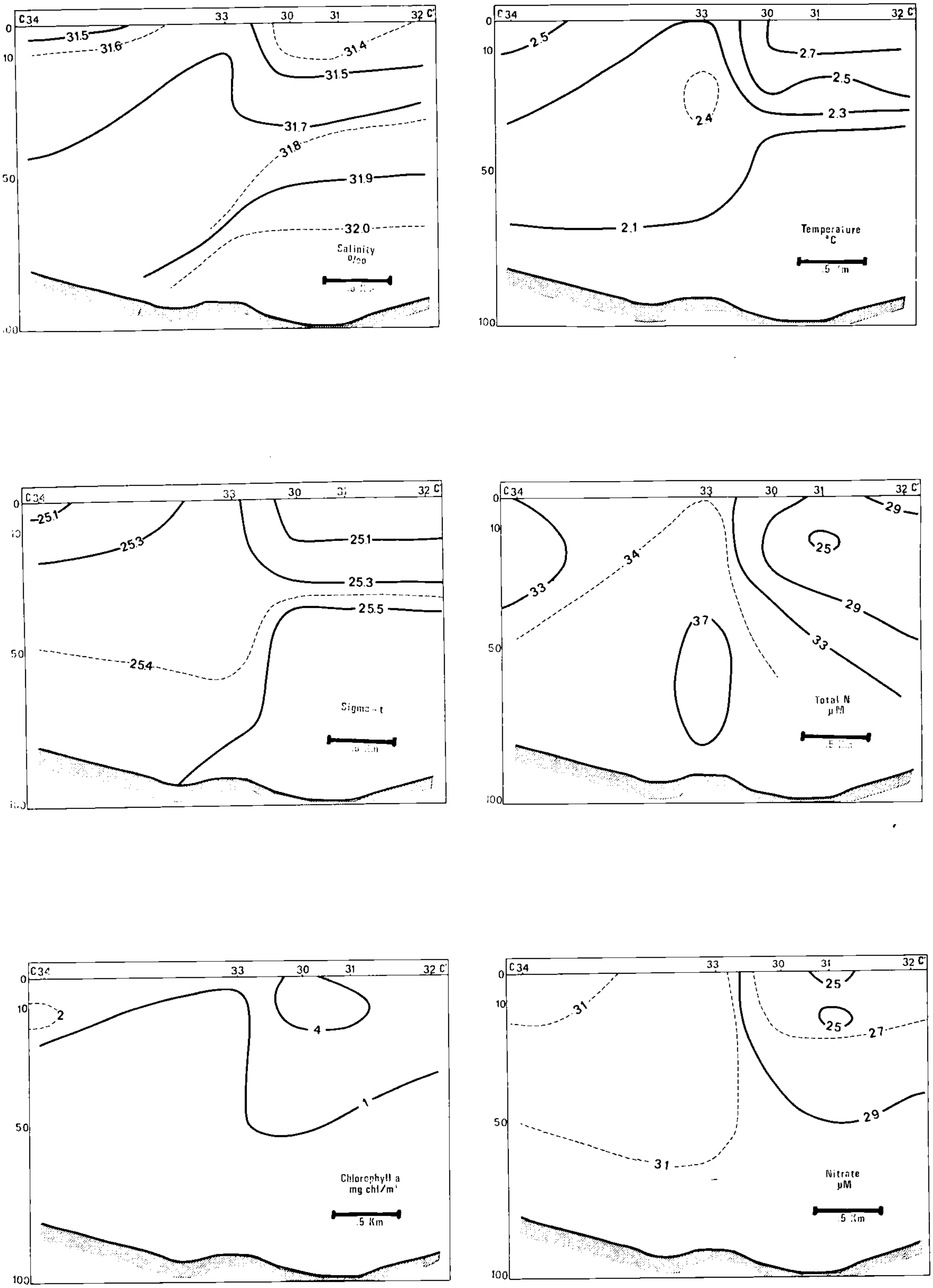
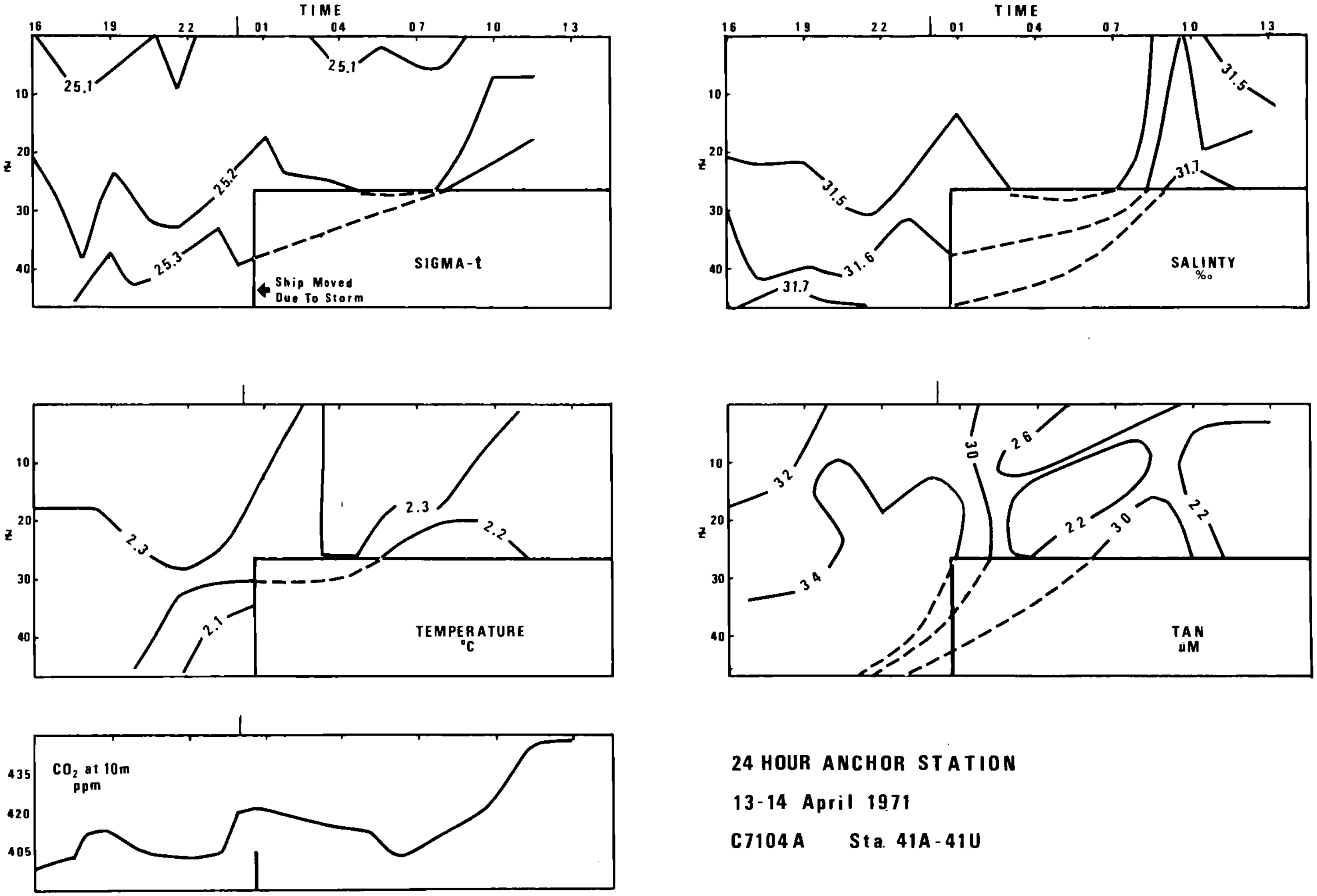


Figure 5. Contours of nutrient, hydrographic and chlorophyll a data; C7104A, C-C', Auke Bay, Ak., 1971.



24 HOUR ANCHOR STATION

13-14 April 1971

C7104A Sta. 41A-41U

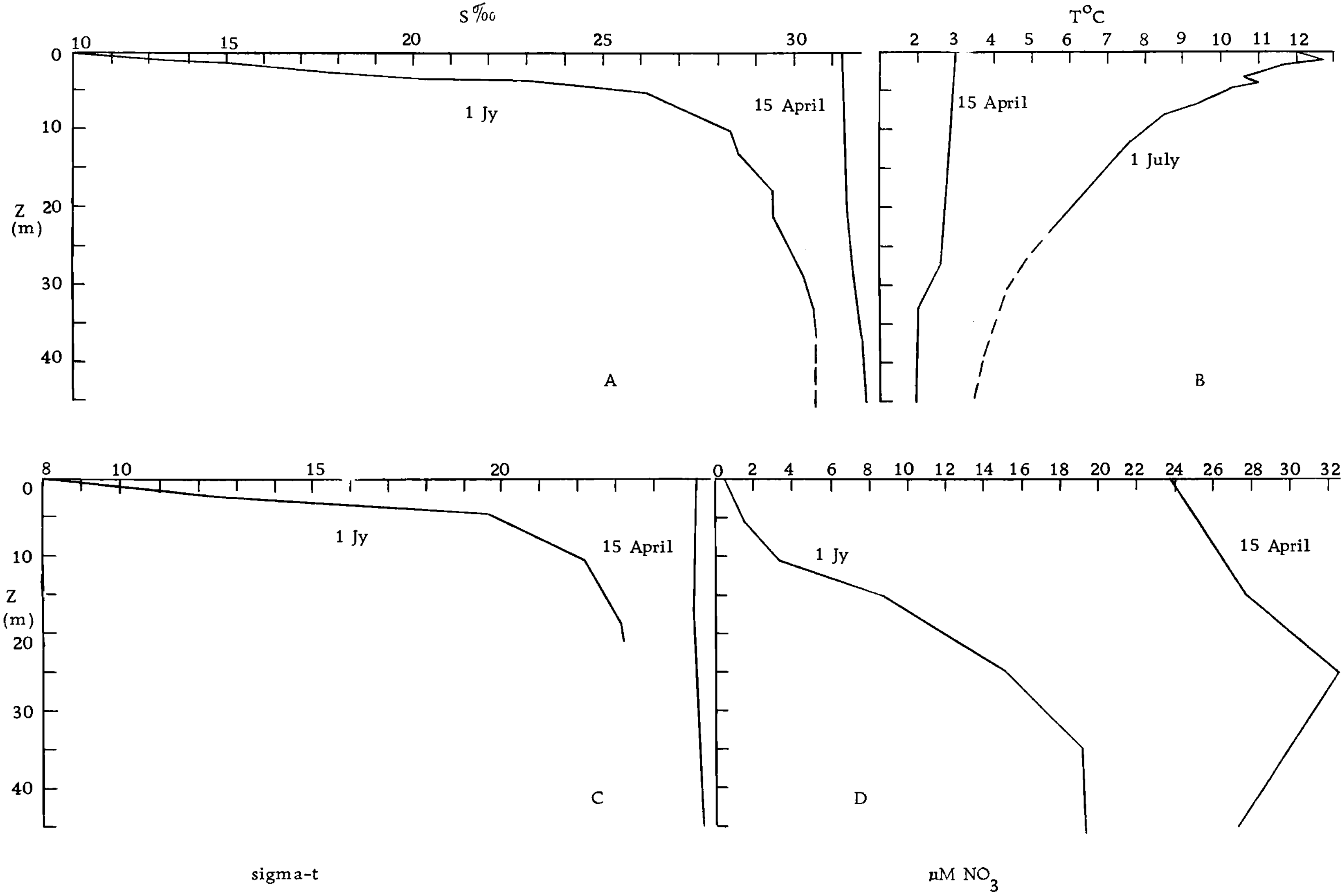
Figure 6. Physical and nutrient properties observed during the 24 hour anchor station; C7104A, Auke Bay, Ak., 1971.

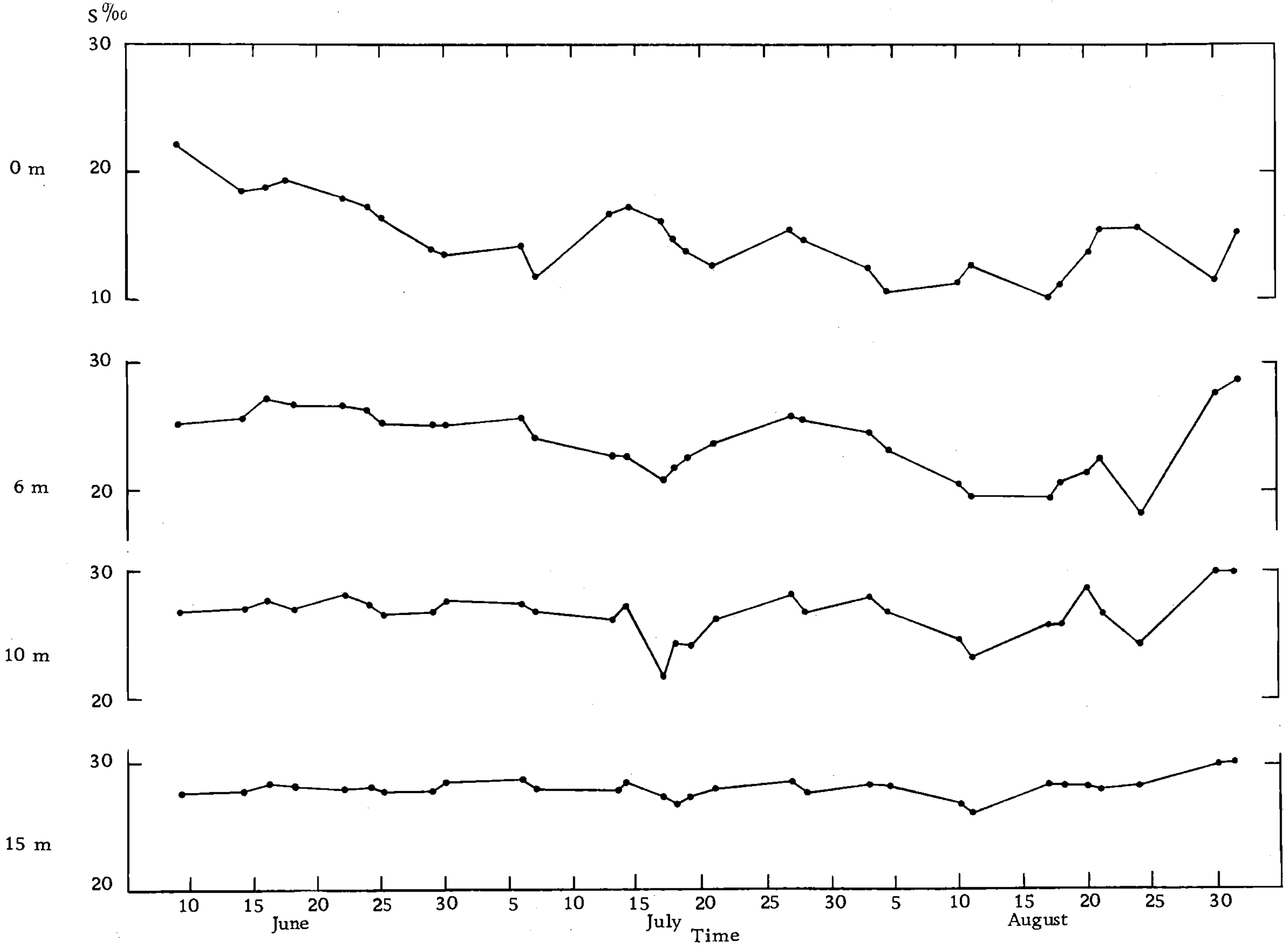
station were taken.

Numerous changes in properties occurred between the initial stations taken during the storm and those stations taken after the storm had passed 48 hours later (Figs. 3, 5). The unusual contours on transect C-C' result from plotting pre- and post-wind stations on the same graph. Stations 30, 31, and 32 were sampled during the storm and show stratification similar to that of the rest of the bay. Stations 33 and 34 were taken after the storm.

Between the April cruise and the first complete station taken in July, numerous changes in nutrient and hydrographic properties had occurred (Fig. 7). Salinity integrated over 45 meters decreased by 9%; 4.5 cubic meters per square meter of fresh water would be required to affect this change. Rainfall, Auke Creek runoff and the runoff from the rest of the Auke Bay watershed accounted for 1.1 cubic meters per meter square (Fig. 16); the Mendenhall River must supply the remainder. Nutrients under a square meter to 45 meters on July 1 had decreased by 58.5% of that present under a square meter to 45 meters at station 25 on the spring cruise.

Over the summer, salinity down to 18 meters is observed to decrease; temperature shows a gradual warming (Figs. 8, 9). Below this depth, the trend is partially obscured due to scatter in the data. As had been found earlier by Iverson (1971), perturbations in the trend occurred only when storms from the southeast with winds greater than


S ‰
T°C
15 April
1 Jy
1 July
Z (m)
A
B
C
D
sigma-t
µM NO_3


S ‰
30
20
10
0 m
30
20
6 m
30
20
10 m
30
20
15 m
10
15
June
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August
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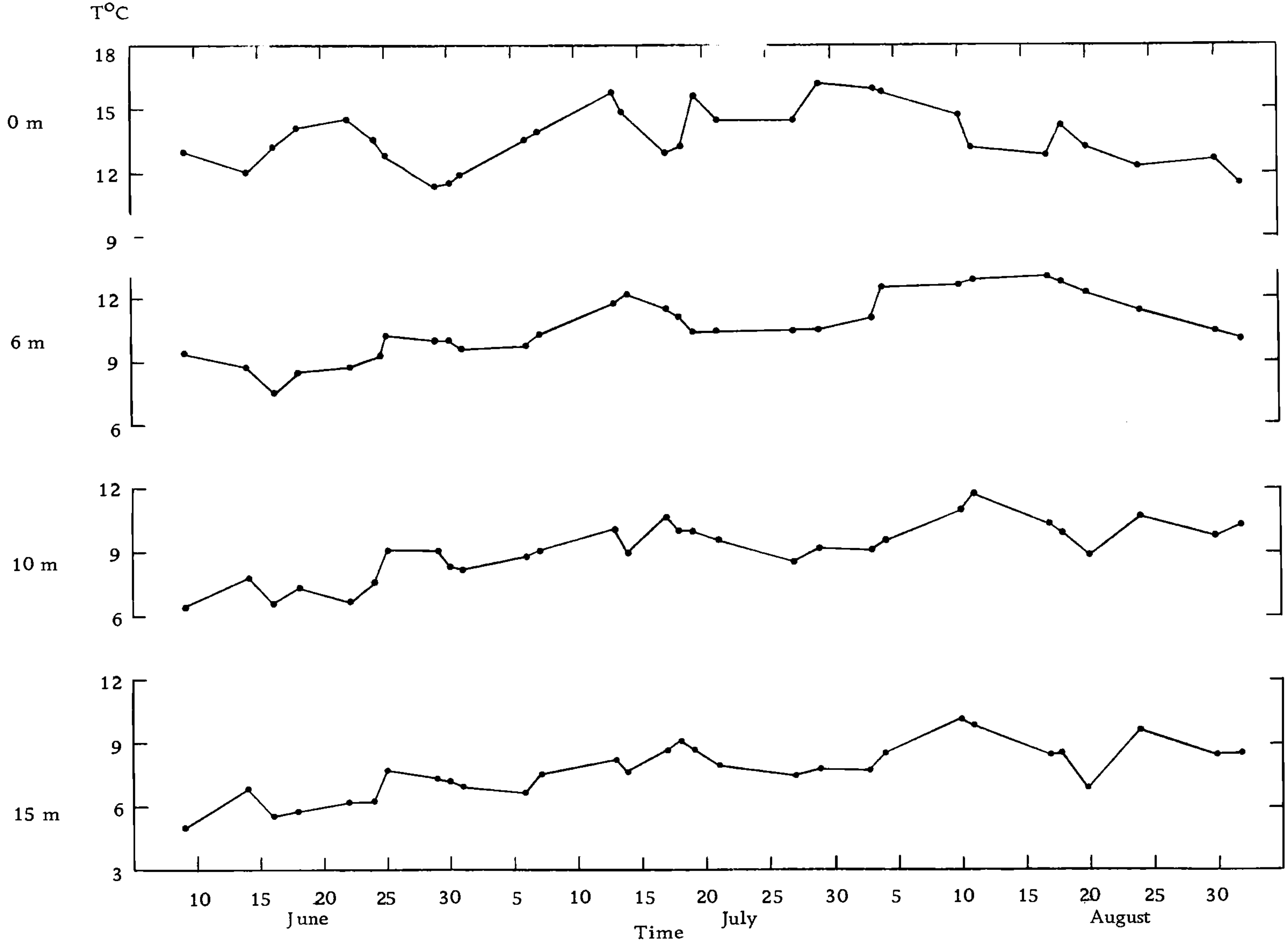
25
30
Time


T°C
0 m
18
15
12
9
6 m
12
9
6
10 m
12
9
6
15 m
12
9
6
3
10
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20
25
30
5
10
15
20
25
30
5
10
15
20
25
30
June
July
August
Time

4 meters/second pass through the area. During the passage of these storms, the mixed layer increases in depth, salinity decreases and heat is mixed down into the water column (Fig. 10 A, B).

Several time series temperature-salinity surveys, with depth, over parts of the tidal cycle were carried out during the summer (Fig. 11). These surveys indicated the presence of some type of internal wave or seiche which did not correlate with the tidal cycle. These oscillations greatly affected the upper layer of the water column, changing the position and shape of the pycnocline and sigma-t profile respectively (Fig. 11). Given their similarity to seiches, I will hereafter refer to them by this name.

Stability values, calculated from Sverdrup's (1941) formulae:

$$E = 10^5 \frac{d\sigma_t}{dz} \qquad (1)$$

indicated that the upper 11 meters of the bay were highly stable during the summer months (Fig. 12). These stability values were used in designating layers of the bay: The "surface layer" had stability values of less than 1×10^5, a "pycnocline zone" was defined by stability values greater than 10^5, and a "lower layer" where stability values were again less than 10^5 and decrease with depth. Generally, the base of the pycnocline zone was fairly well defined, while the distinction between the upper layer and the pycnocline zone was often obscure or non existent. The latter effect can be attributed to either

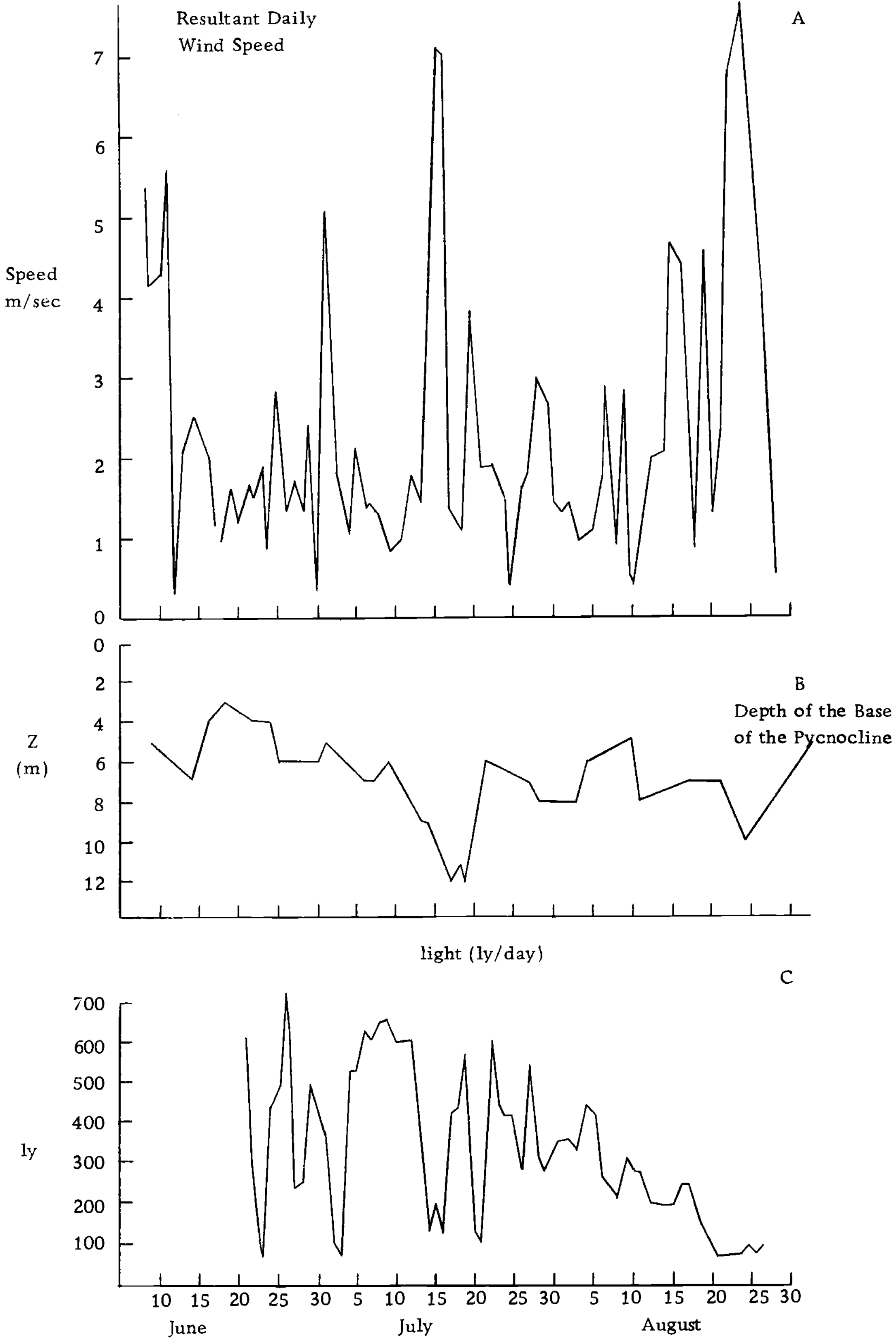


Figure 10. The resultant wind speed (A), depth of the base of the pycnocline (B) and light (C); June-August, 1971.

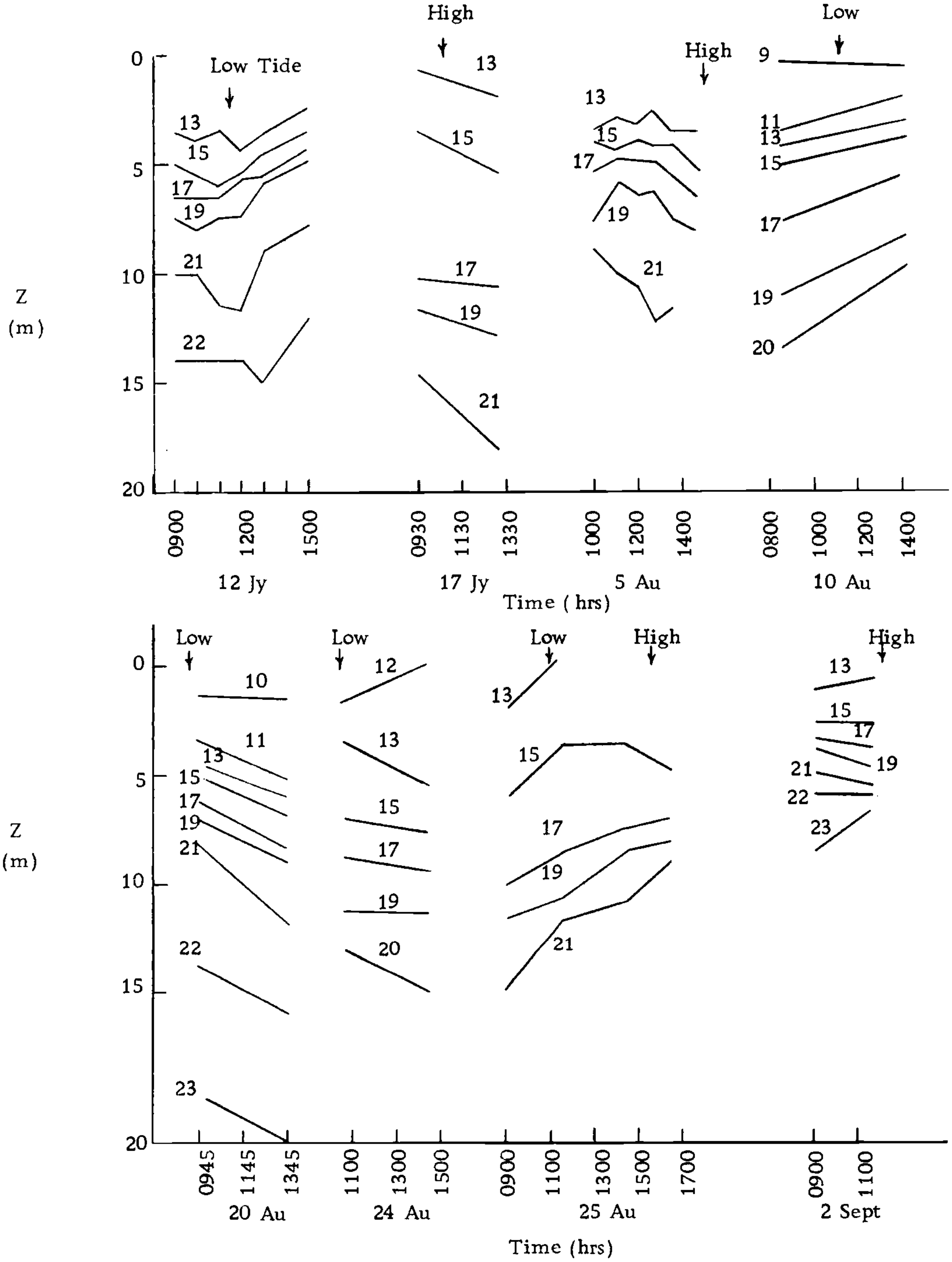


Figure 11. Changes in density contours over several tidal cycles.

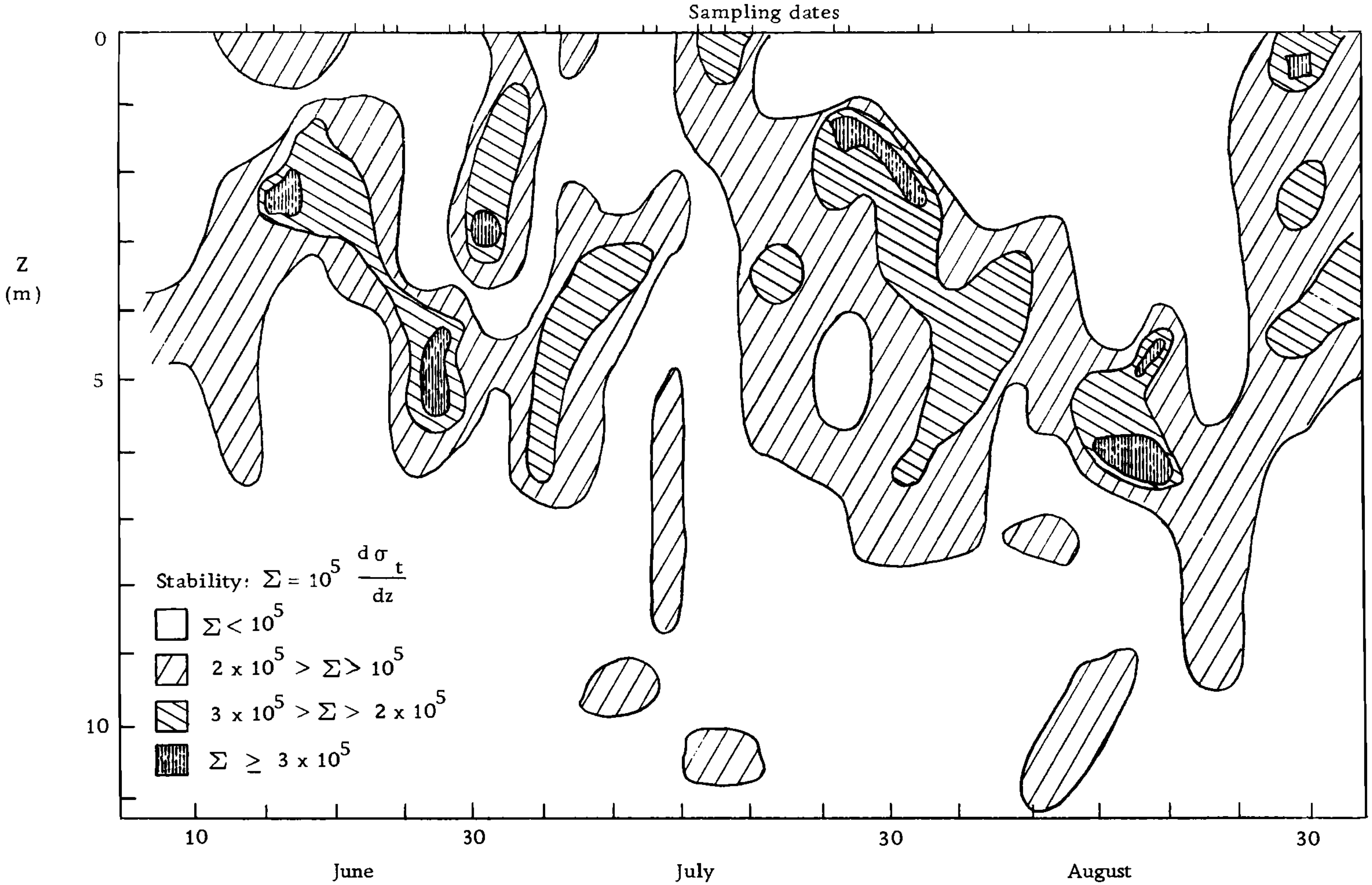


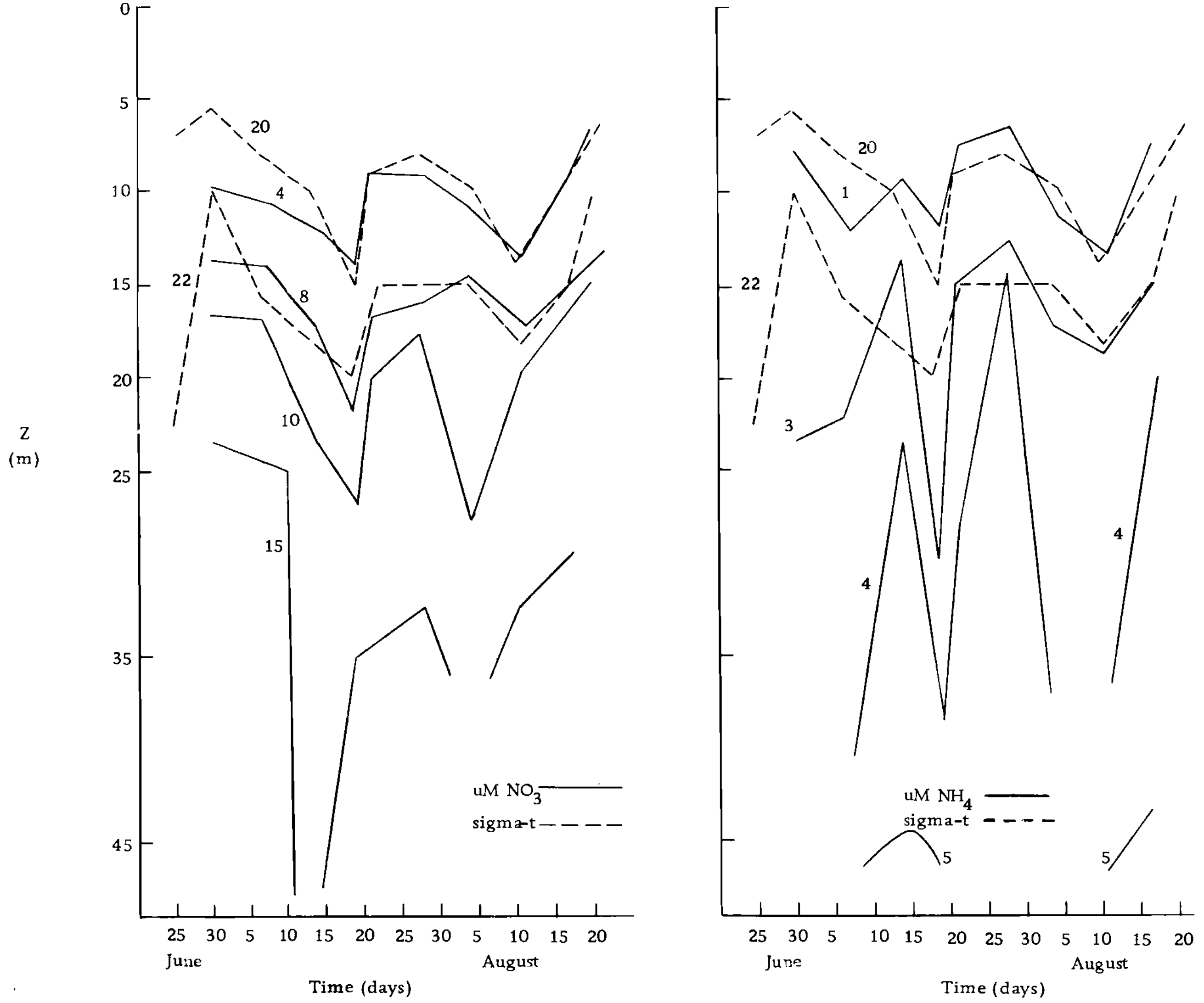
Figure 12. Stability per meter; lower boundary delimiting $\Sigma < 10^5$ is the base of the pycnocline zone, defined p. 16.

seiche or tidal movement.

No trends are observed at any depth in ammonia concentration over the summer (Fig. 13). Nitrate concentrations show a trend over the summer only at 25 and 35 meters where they decrease slightly with time (Fig. 13). Nutrient samples taken on one station close to the Auke Bay Laboratory dock over a tidal cycle indicate the nutrient concentrations are positively correlated with sigma-t values (Fig. 14).

The measured concentration of ammonia and nitrate in a given stream did not correlate with the volume flow of that stream, thus indicating an erratic source of nutrients (Table 1). Samples taken above houses on one unnamed stream entering Auke Bay contained less than 0.05 μM nitrate, while the concentration below the houses was always one to two orders of magnitude greater.

Winds in the Juneau area were of two types during the summer: less than three meters/sec from a northerly direction and greater than 4 meters/sec from a southeasterly direction (Fig. 10A). Winds from the southeast are a result of storm fronts moving from west to east and are accompanied by heavy rainfall. While wind velocities in Lynn Canal are more from the south, the particular topography of the Gastineau Channel, a narrow channel with mountains on either side, acts as a funnel, forcing the winds to be from a more easterly direction (native tradition). This is reflected in the energy spectra


Z
(m)
0
5
10
15
20
25
35
45
20
4
22
8
10
15
uM NO$_3^-$
sigma-t
25
30
5
10
15
20
25
30
5
10
15
20
June
August
Time (days)
20
1
22
3
4
4
uM NH$_4$
sigma-t
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25
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20
June
August
Time (days)

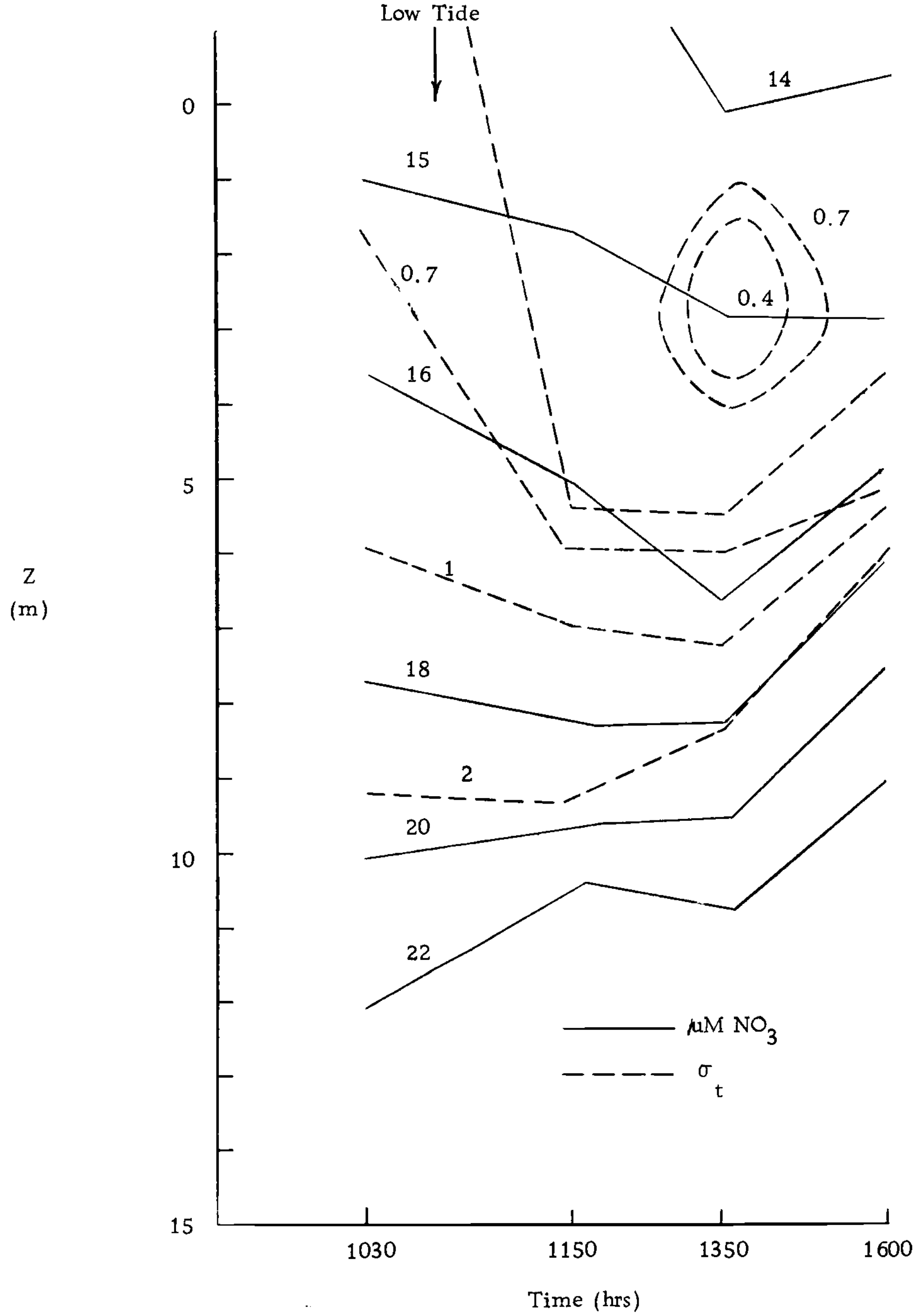


Figure 14. Tidal cycle survey near laboratory; 25 August, 1971.

Table 1. Nutrients in fresh water sources of Auke Bay. See Fig. 2 for locations.

Location	2 Jy	12 Jy	19 Jy	29 Jy	4 Aug	12 Aug	20 Aug	27 Aug
				uM NO_3 - N				
Auke Creek	1.60	1.11	0.71	0.12		0.31	2.00	0.44
Mendenhall R.	3.50	1.95	1.13		0.14	0.19		3.58
Wadleigh Cr.			17.00	0.97	0.72	4.86	0.55	0.35
Auke Nu Cr.			14.60	0.83	0.32	0.19	2.92	6.35
Montana Cr.	4.70	3.24	2.56	3.10	3.32	2.96	4.59	6.66
Lake Cr.							3.67	2.19
Gnagy Cr.		5.40		5.94	5.76	3.65	2.96	3.59
Unnamed 1						0.04		
				uM NH_3				
Auke Cr.		3.56	0.64	0.00		0.64		
Mendenhall R.		4.48	0.53			1.38		
Wadleigh Cr.			0.41	0.00		0.33		
Auke Nu Cr.			0.61	0.07		0.47		
Montana Cr.		1.04	0.9	0.97		1.14		
Gnagy Cr.				0.10		1.47		
Unnamed 1						0.36		

of winds from late August and early September: most of the energy is located in the U (east) component of the winds (Fig. 15). These spectral analyses also show a peak of energy at the semi-diurnal frequency, due to land/sea breezes. Two periods of very high winds occurred during the summer: 14-17 July and 20-24 August.

Heavy rains in short periods of time generally occur with southeast storms, however rain is by no means restricted to these times (Fig. 16B). Runoff increases over the summer as a function of increasing glacial melt and precipitation (Fig. 16 A, C).

Current meters were moored at two locations in Auke Bay: at 2 meters and 20 meters at ABM and at 2 meters in the channel between Spuhn Island and Mendenhall Peninsula (Fig. 2). Spectral analysis of the current meters show the energy to be located at the semidiurnal (0.08 cycles/hour) and diurnal (0.04 cycles/hour) frequencies, with larger amounts of energy in the V (north) component than in the U (east) component (Figs. 17, 18).

Progressive Vector Diagrams (PVD) for the surface current meters were prepared (Fig. 19) along with the PVD for wind velocities during the time the current meters were moored. PVD's give an impression of the vector mean flow and an estimate of the slow changes. They are constructed by vector addition, beginning with the initial observation at each current meter and adding successively a vector representing each ensuing observation of velocity. Such a

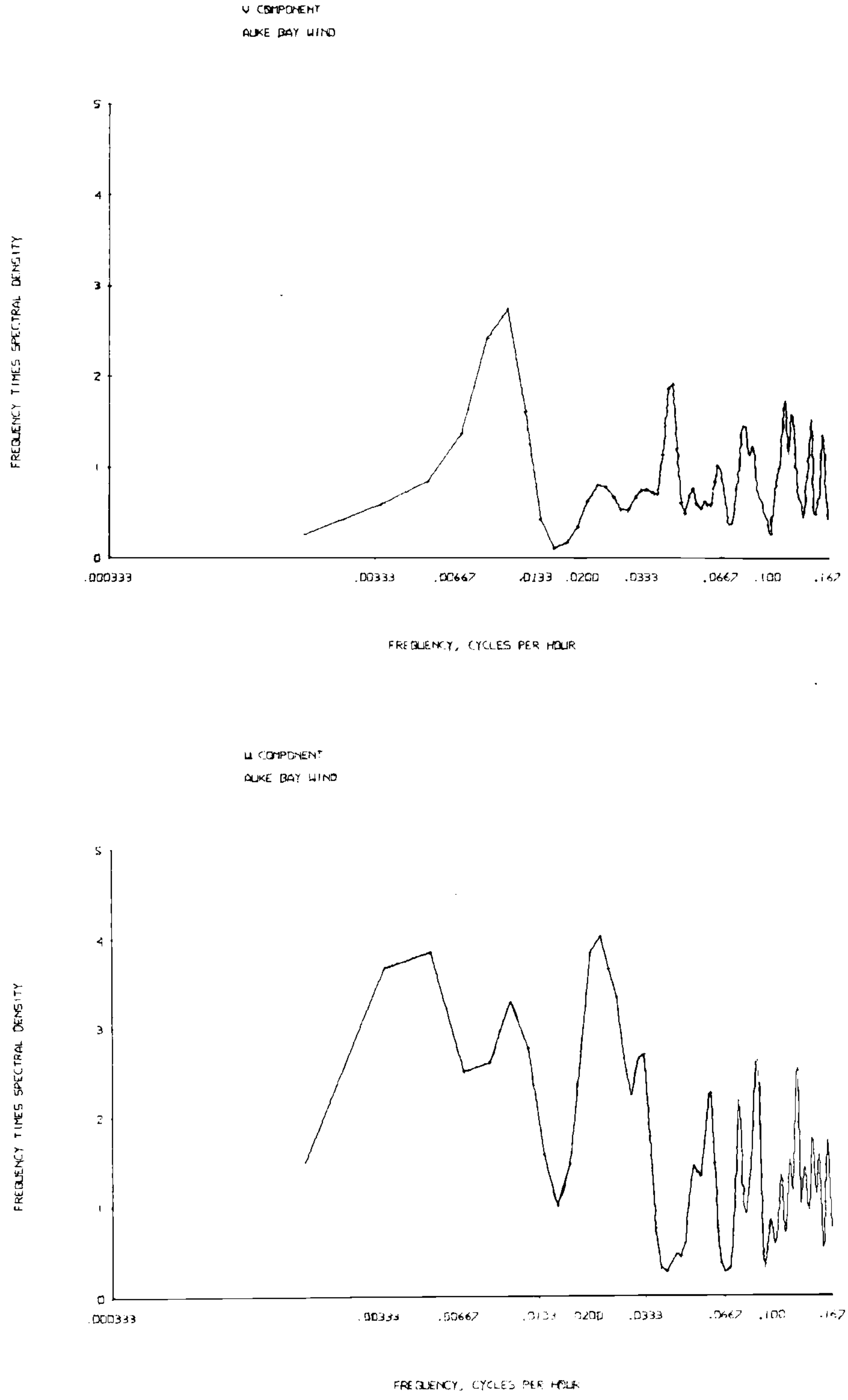


Figure 15. Energy spectra for wind velocity, V (north-south) and U (east-west) components; 21 August-10 September, 1971.

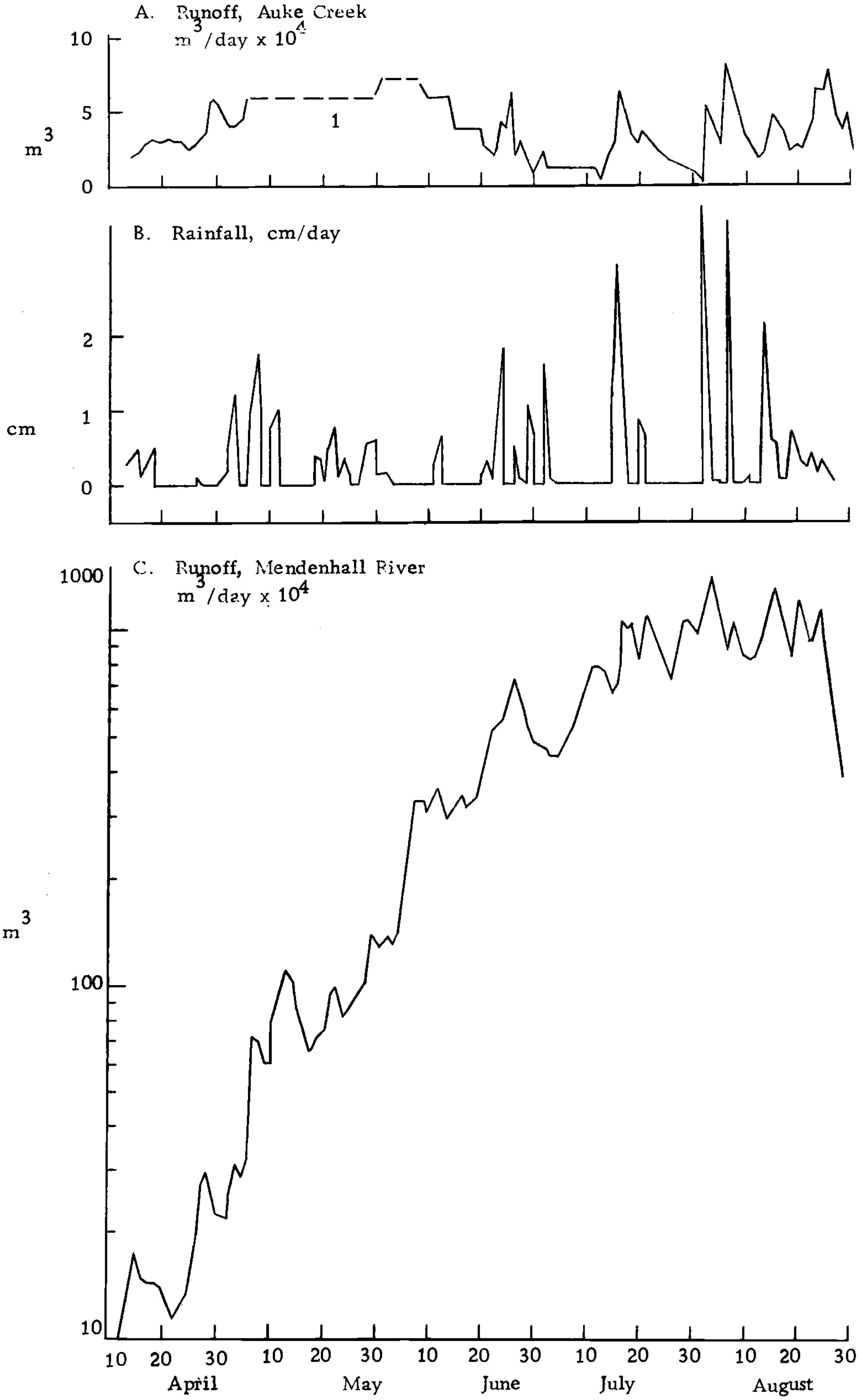
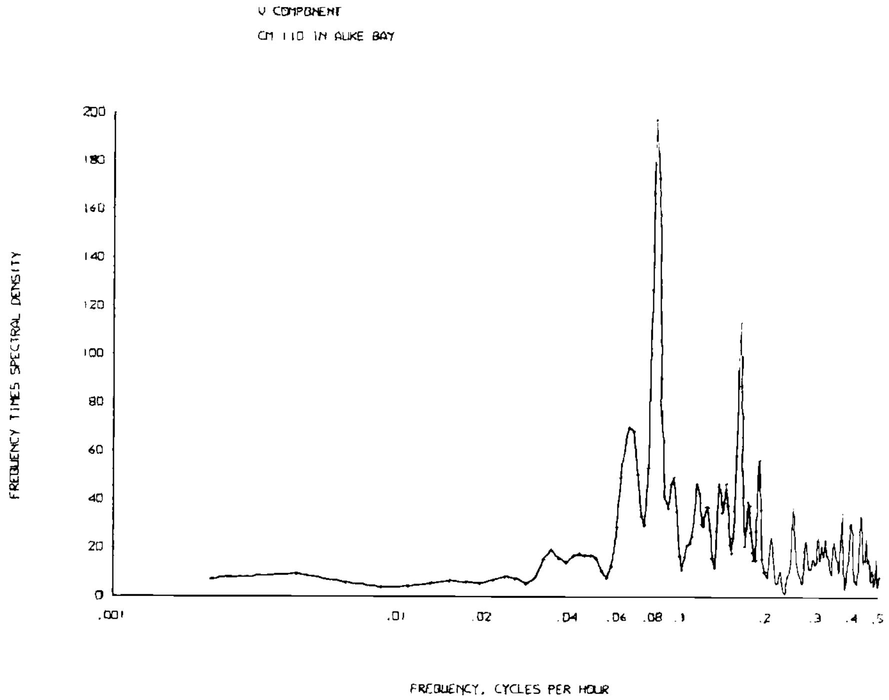


Figure 16. Auke Creek runoff, Mendenhall River runoff, and Rainfall; April-August, 1971. [1]Data based on previous year's analysis.



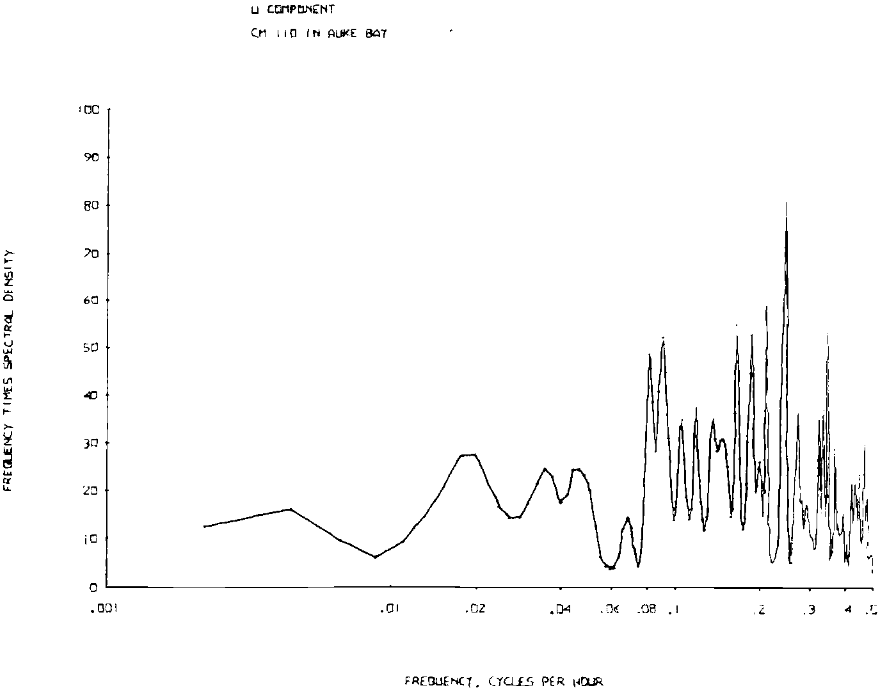


Figure 17. Energy spectra for surface current meter, ABM, V (north-south) and U (east-west) components, 21 August-10 September, 1971.

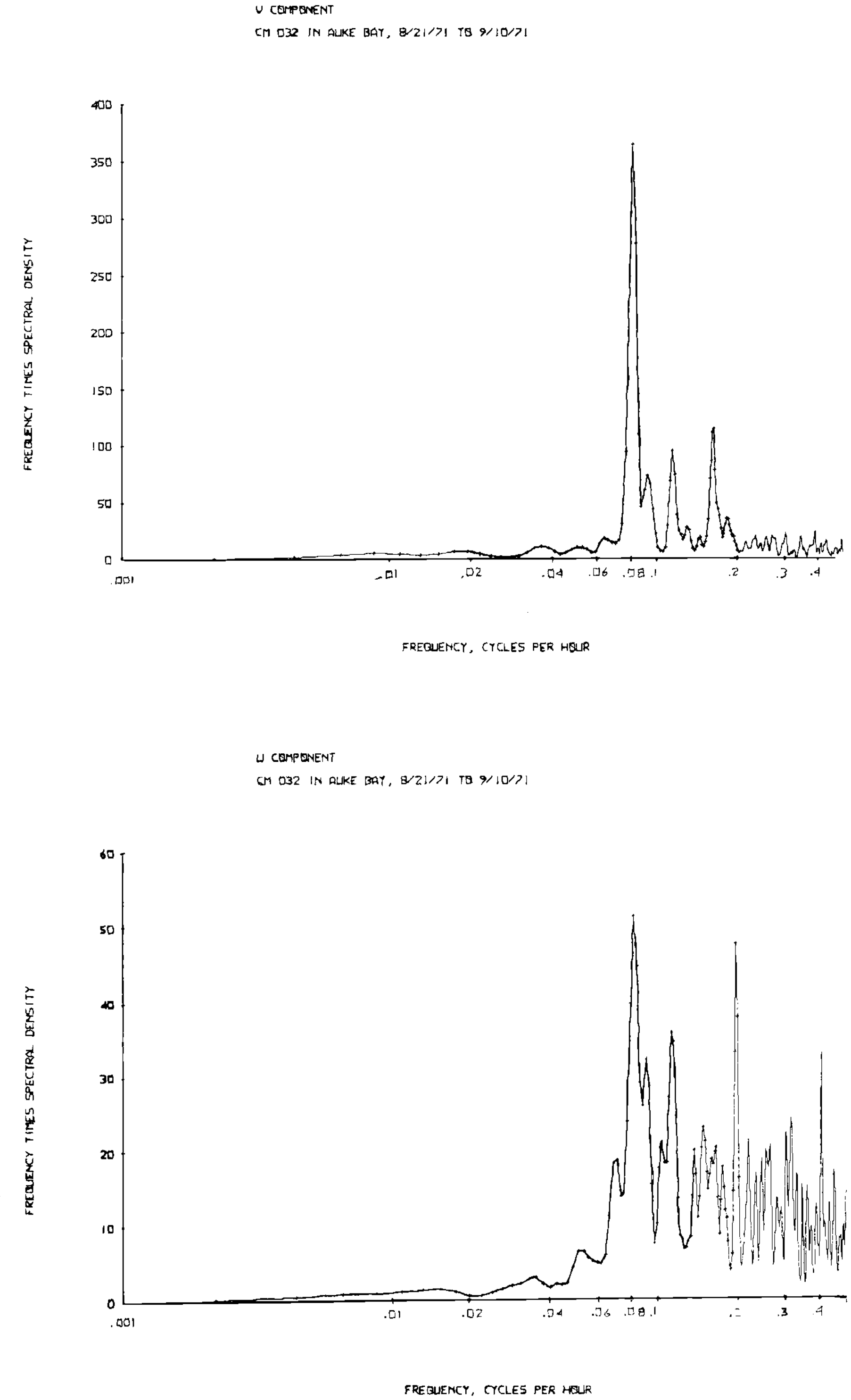
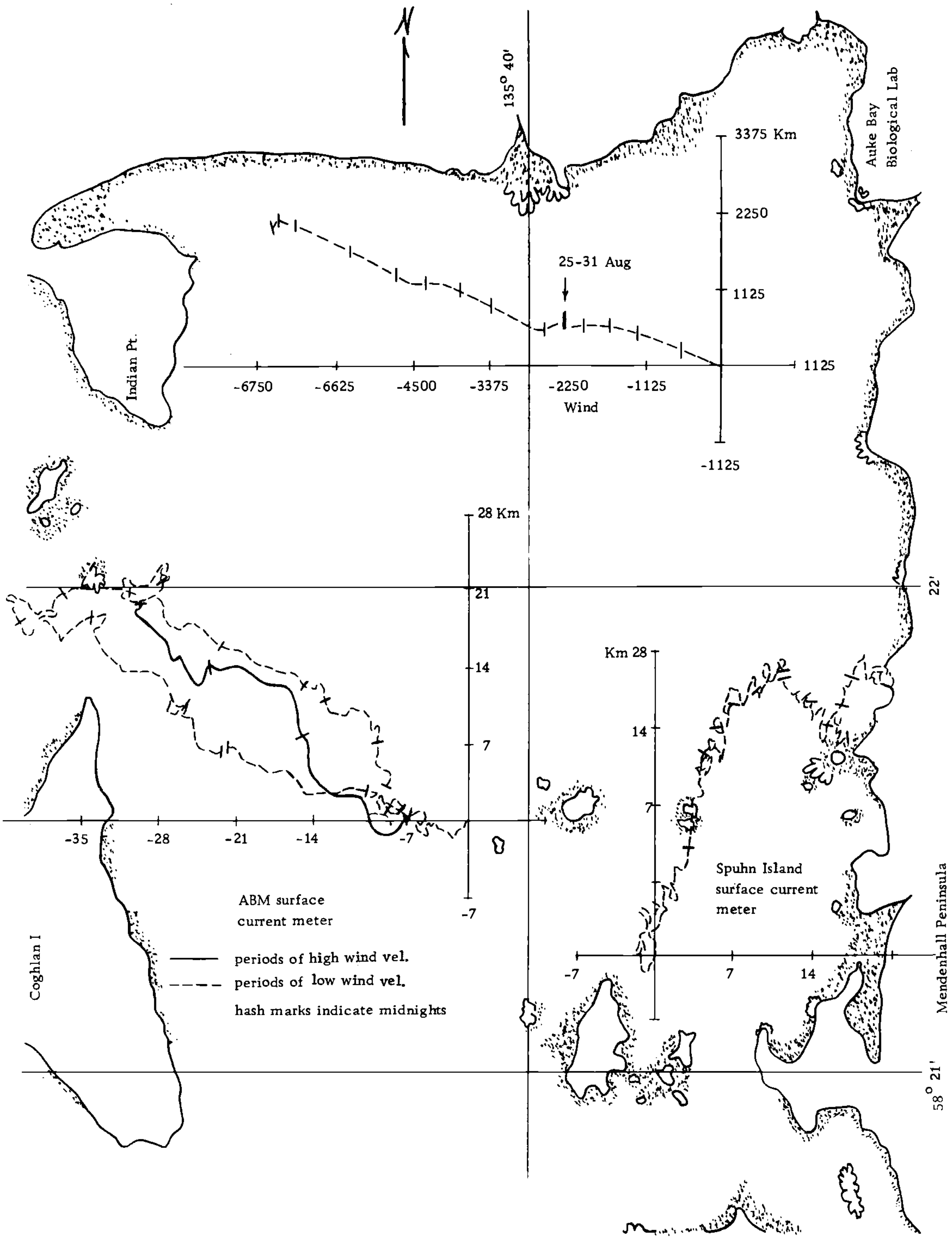


Figure 18. Energy spectra for surface current meter, Spuhn Island, V (north-south) and U (east-west) components, 21 August-10 September, 1971.


N
135° 40'
3375 Km
2250
1125
1125
-1125
25-31 Aug
-6750
-6625
-4500
-3375
-2250
-1125
Wind
Auke Bay Biological Lab
Indian Pt.
28 Km
21
14
7
-7
-35
-28
-21
-14
-7
22'
Km 28
14
7
-7
7
14
Spuhn Island surface current meter
ABM surface current meter
periods of high wind vel.
periods of low wind vel.
hash marks indicate midnights
Coghlan I
Mendenhall Peninsula
58° 21'

PVD does not represent the actual path of the particle unless there is homogeneous horizontal flow (Pillsbury, 1972).

The PVD for Spuhn Island shows well defined tidal ellipses. Although spectral analysis for surface currents at ABM indicate the energy was located at the semidiurnal and diurnal frequencies, tidal ellipses are not observed in the PVD. Surface currents at Spuhn Island show considerable variation in direction under high southeast winds, but show a uniform north-flowing direction when the wind is at low speeds from the north.

The surface currents at ABM show a definite correlation with wind velocity. Under high winds from the southeast, the currents at ABM are consistently to the northwest; when the wind decreases in speed and changes direction, the currents reverse and flow to the southeast. Measured currents at 20 meters ABM (Fig. 20) were slow, at the limit of resolution for the current meter, but did show a consistent northerly flow into the bay.

Mean measured speeds at the three current meter locations were 12 cm/sec at Spuhn Island; 16 cm/sec at 2 meters ABM and 5 cm/sec at 20 meters ABM. The mean measured speeds are, however, largely, a function of tidal motion.

The term, residual current, as used in this thesis, is defined as: the current remaining after tidal flow has been algebraically subtracted. This procedure gives the net distance travelled by a

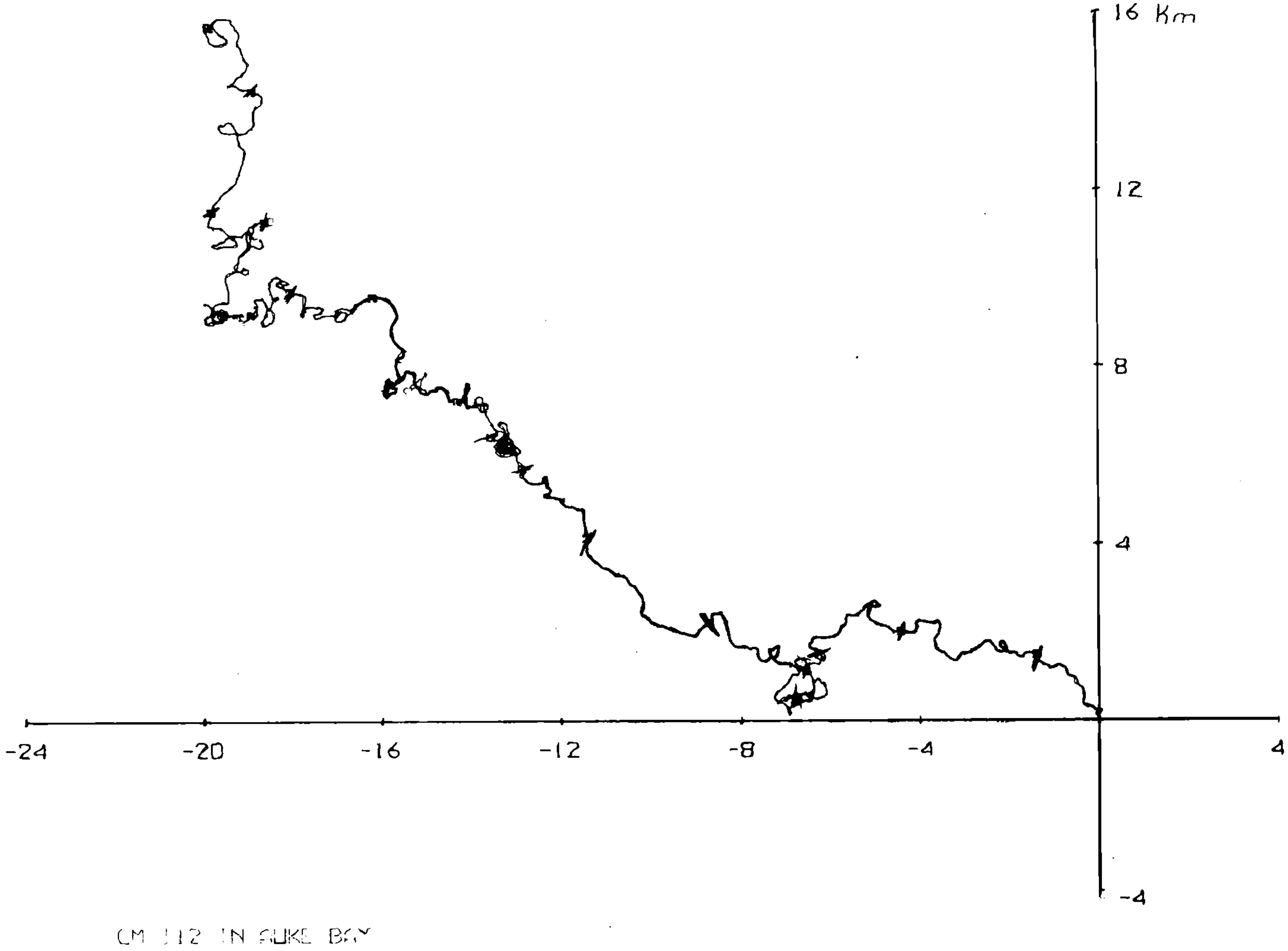


Figure 20. Progressive vector diagram at 20 meters, ABM, 21 August-10 September, 1971.

particle of water in a given time and direction. The residual currents for the individual V (north), U (east) components and the resultant V-U vector were calculated for the three current meters and the wind for periods of 24 hours (Table 2). Midnight to midnight times were chosen to simplify correlation with the PVD's since midnight positions are marked on the latter.

Calculation of Vertical Transport

Vertical transport in the water column was calculated on the assumption that Auke Bay is a two-layered system: the surface wind mixed layer plus the pycnocline zone, and the lower layer. The pycnocline zone had an average base depth of six meters during those times when wind mixing was absent and is considered part of the surface layer.

Analysis of the Mixing Coefficient

Steele (1958) suggested the use of thermal structure as a means to determine vertical transport. The assumptions in this method are:

1) The temperature gradient can be treated as a step function and the depth of the thermocline is assumed constant.
2) Mass will be transported in the same manner as heat.
3) Observed changes in the temperature structure below the

Table 2. Computed residual currents given as vectors.

Date	Spuhn Island surface cm Resultant speed, cm/sec	Direction	ABM Deep current meter	Direction	ABM surface c. m.	Direction	Wind	Direction
18 Aug								
19							4.65	NW
20							1.12	NW
21							2.80	NW
22	3.54	NE	3.51	NW	14.10	NW	6.60	NW
23	3.24	SW	2.48	SW	12.30	NW	7.70	NW
24	4.05	NE	1.53	SW	9.80	NW	5.70	NW
25	4.20	NE	2.38	NE	3.30	NE	4.50	NW
26	7.20	NE	3.10	NW	4.02	SW	3.00	NW
27	3.32	NE	3.68	NW	1.61	SE	0.61	NE
28	1.70	SW	2.54	NW	9.34	SE	0.51	NW
29	3.90	NE	1.00	NW	9.80	SE	0.24	NE
30	2.83	NE	0.50	NW	3.40	SE	0.51	NW
31	2.90	NE	1.22	NW	6.56	SE	0.24	SE
1 Sep	3.10	NE	1.70	NW	7.30	SE	3.80	SW
2	0.66	SE	2.20	NW	1.51	SE	2.02	SW
3	3.26	SE	2.10	NW	2.28	NW	7.00	NW
4	3.18	SE	1.10	NW	2.78	NW	5.76	NW
5	3.45	NE	1.00	NE	15.50	NW	5.90	NW
6	4.40	NE	2.86	NE	6.20	NW	5.02	NW
7	1.87	SW	1.60	SW	12.90	NW	8.76	NW
8	3.80	SW	3.58	NE	7.90	SW	10.20	NW
9	3.13	SE	2.02	NW	5.80	NE	3.52	NW

depth of the upper layer are due only to mixing and are independent of solar heating.

4) Lateral advection does not effect vertical heat transport.

The formulae given by Steele (1958) is based on the downward flux of heat:

$$U = \frac{1}{Z_u \triangle t (T - T_o)} \int_{Z_b}^{Z_u} (T_2 - T_1) dz \qquad (2)$$

where:

U = fraction of surface water mixed per unit time

t = time, in days

Z_u = depth of surface mixed layer

Z_b = depth of deepest observation

T = average temperature Z_u over $\triangle t$

T_o = average temperature Z_b over $\triangle t$

T_1 = average temperature Z_b at beginning $\triangle t$

T_2 = average temperature Z_b at end $\triangle t$

The choice of depth for Z_u and Z_b is at the discretion of the investigator; Z_u is generally taken as the depth of the surface mixed layer, while Z_b is taken as the depth of the layer beneath this surface layer. The mixing coefficient, U, has dimensions of per unit time and represents that fraction of the upper layer exchanged with the lower layer. U is multiplied by the depth of the upper layer to obtain the actual volume of water exchanged. The mass of nutrient transported with this volume is obtained by multiplying the volume exchanged by the differences in concentration between the upper and lower layers: $[(U)(Z_u)](N-N_o)$ where N is the nutrient concentration in the lower layer, and N_o is the nutrient concentration in the surface layer. In order to dampen seiche and tidal effects, T_1 and T_2 were calculated by averaging the temperatures of Z_b for two days at the beginning and end, respectively, of the time period, t.

Calculation of U Under No Wind Conditions

It was not possible to calculate U continuously throughout the summer because the data frequently show advection of colder water at depth; this results in very low or negative values of U. The actual calculation of U was made for two eight-day periods when no wind mixing or advection occurred, July 6 to July 14 and July 27 to August 4. In both cases, Z_u equals six meters and Z_b equals 18 meters. A U of 0.1 per day was calculated for July 6 to July 14. In this instance, part of the measured increase in temperature below six meters may have been due to high solar radiation at this time (Fig. 10C), therefore the calculated value of U may be an overestimate. The calculated value of U for July 27 to August 4 is 0.04 per day; solar radiation would not have caused an overestimate of U.

The average of these two values, 0.07 per day, is chosen as the estimate of U for all periods of non-wind mixing. This value will give a volume exchange rate of 0.42 cubic meters per day through a square meter at the density interface at six meters.

Calculation of U During Wind Mixing

U was calculated for the two times during the summer when wind mixing occurred on a large scale, July 14-July 17 and August 20 to August 24. Under these conditions, calculation of U is complicated by a changing depth of the surface mixed layer. Wind mixing erodes the assumed six meter thermocline to eleven meters. No suitable manipulation of the formulae was found which would correct for this effect, therefore, the mixed layer, Z_u, was assumed to be constant at a depth intermediate between 6 meters and 11 meters. Seven meters was chosen as Z_u because the amount of heat lost from above this interface is equal to the amount of heat gained below this interface over the time wind mixing occurred. Z_b is chosen as 18 meters. A calculated U of 0.157 per day for July 14 through 17 results in a volume transport vertically of 1.1 cubic meters per day through a square meter at seven meters. Over the period of wind mixing from August 20 to August 24, U is calculated as 0.174 per day, giving a volume transport of 1.2 cubic meters vertically per day through a square meter at seven meters.

Evaluation of the Method

There are several disadvantages in using this general approach to determine a vertical mixing rate. These disadvantages arise from the previously mentioned assumptions made in calculating U. The major inadequacies are:

1) Solar radiation may be responsible for part of the measured increase in temperature.

2) Treating the thermal gradient between the upper and lower layers as a step function may result in overestimation of U.

3) Assuming a constant average value for U under non wind conditions can result in an underestimate of mixing since smaller wind mixing episodes were observed during these times. Inadequate data or insufficient magnitude of these occurrences prevented them from being included in wind mixing, however they would have resulted in higher mixing rates when they occurred.

4) It may be argued that the observed density structure would have prevented any vertical mixing. The occurrence of vertical mixing is supported by the following arguments: a) Qualitative evidence of increased turbulence in the area of the pycocline was observed on several occasions during *in situ* salinometer measurements; b) Tidal and seiche motions are known to cause turbulence between layers (Phillips, 1966); c) The deep current meter at ABM

indicated slow net transport at depth into the bay; any water advected into the bay must be transported into the surface layer to be removed.

Despite the disadvantages, the method is used because no better method of estimating vertical transport was found and because the calculated values of U are the same order of magnitude as those found by Steele (1958) and Iverson (1971).

Calculation of Vertical Transport from Current Meter

One might consider estimating vertical transport rate from the current meter data at depth at ABM. The channel between Coghlan Island and Spuhn Island is the only deep entrance to the bay. Since this channel has a north-south orientation, only the north-south component of velocity was used in calculating the flow rate. The assumption is made that this current meter is representative of the entire lower layer for both speed and direction. Currents consistently flowed north, into the bay, therefore the volume of water which enters through the cross section Coghlan Island - Battleship Island must be transported through the interface into the surface layer of the bay to be removed from the bay. Under the assumptions just given, and a calculated average daily residual velocity of 0.5 cm/sec at 20 meters ABM, a vertical rate of 3.37 meters/day through a square meter would be required. Since the measured velocity approached the limits of sensitivity of the instrument, the estimated values must be regarded as maxima. It is questionable whether such a vertical rate occurs; the vertical rate given by Steele's method is an order of magnitude less. Furthermore, with the high stability of the Auke Bay water column, it does not intuitively seem reasonable that fifty percent of the surface layer would be replaced from below on a daily basis.

The assumption in the above calculation which is most questionable is that concerning uniform velocity over the entire cross section. Possibly, the current meter is not representative of the entire cross section.

DISCUSSION

Definition of the Model

The objective of this research was to identify and quantify nutrient nitrogen sources and sinks for spring and summer production in the surface layer. Evaluation of these sources and sinks from a physical approach requires a knowledge of water mass transport within the bay. Conceptually, each of the factors involved in mass transport can be considered an element of a model. Each element must then be quantified with respect to both water volume flow and nutrient concentration. The model, in its final form, will then define the nutrient changes with time in the surface layer as a result of the nutrient input from the model elements. From this, an estimate of production in the surface mixed layer over the summer can be made.

The elements of the model can also be analysed to elucidate more general phenomena effecting the entire bay. These will be dealt with subsequently.

Elements of the Model

Runoff, rainfall and vertical transport were identified as the primary sources of nutrients for the surface layer. The elements of the model are the individual components of these major sources. For purposes of calculation, the elements of the Auke Bay watershed, other than Auke Creek watershed, are lumped into one term, and referred to as the north shore sources. The Mendenhall River provides most of the fresh water required for the observed changes in salinity over the summer. The nutrients supplied by these elements will be discussed as vertical transport under non-wind and wind conditions and as fresh water input over the summer.

Period of Calculation

The periods of calculation were logically determined by meteorological events. The summer was divided into four parts: two long periods of assumed non-wind mixing divided by a short period of wind mixing, plus a week of high winds which occurred at the end of the summer. Calculation of nutrient input was made on a weekly basis as this was the most usual sampling period. The two periods of wind mixing are discussed separately.

Model Assumptions

1) Auke Bay is assumed to be a two-layered system consisting of an upper surface layer and a lower layer. The upper surface layer is defined as the mixed layer plus the pycnocline zone; the base of the pycnocline zone is taken to be six meters during those

times when wind mixing is not observed.

2) Fresh water runoff from the Auke Bay watershed occurs primarily along the north shore. This runoff is at all times assumed to spread evenly over the eleven square kilometer area of the bay. Rainfall is also assumed to be uniform over this area.

3) The single mid-bay station monitored on a regular weekly basis, ABM, is assumed to be representative of hydrographic and nutrient conditions in a horizontal plane throughout the bay. The corollary of this assumption is that nutrients in the surface layer are distributed uniformly in the horizontal plane. This assumption is supported by the surveys of Bruce (1967), and Curl, Iverson and O'Connors (1971).

4) Another critical assumption concerns horizontal transport of nutrients in the upper layer. Since horizontal homogeneity of nutrients in the surface layer is assumed, surface input into Auke Bay is assumed to equal surface output and is neglected.

5) The production estimated from nutrient input into the surface mixed layer is assumed to occur with essentially no time lag.

Vertical Mass Transport of Nutrients

The vertical exchange rates calculated by Steele's method are used to determine the concentrations of nitrate and ammonia being mixed into the surface layer. Theoretically, one should calculate the concentration of tracer being mixed through the interface using the same system of averaging that is used for calculating heat flux, i.e., the average nitrate concentration in the lower layer, Z_b. This, however, gives unacceptably high concentrations of nutrient being mixed into the surface layer. For example, in Figure 21 the average measured temperature per meter (a gradient) is plotted with the temperature structure assumed in calculating U (a step function), and the average measured nitrate concentration per meter for the period July 27 to August 4. The average concentration of nitrate from six to eighteen meters is higher than the concentration which persists at the interface at six meters. Since the gradient of nutrient concentration is maintained with respect to time, the assumption is made that the concentration of nutrient persisting just below the interface is the concentration which will be mixed through the interface. The average of the nutrient concentrations measured for the beginning and end of any given week were the values used in calculating the mass exchanged during that week.

Vertical Transport, No Wind Mixing

Under conditions of light winds, N_o, the nutrient concentration in the surface layer, was taken as the average nutrient concentration per cubic meter in the upper layer; N was taken as the average

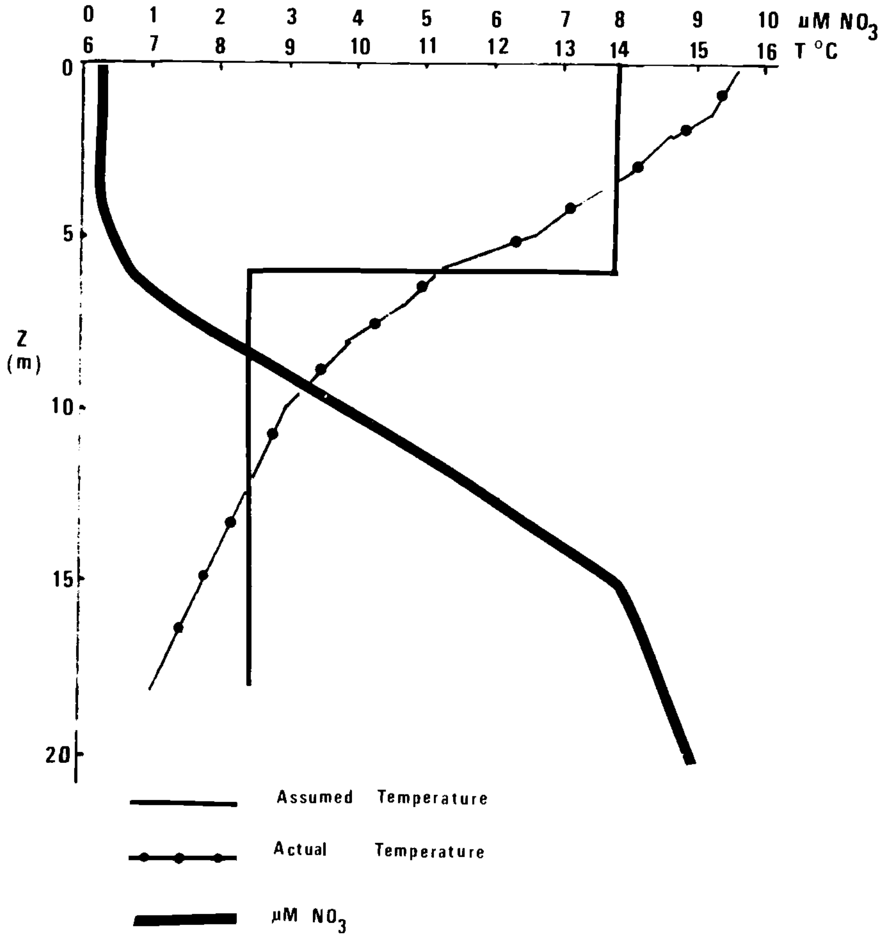


Figure 21. Profiles of temperature, assumed temperature and nitrate concentration at ABM, July 27-August 4, 1971.

nutrient concentration per cubic meter from six to eight meters. The mass of nutrient nitrate and ammonia added to the surface layer by this method are tabulated by week in Table 4.

Vertical Transport, Wind Mixing

Wind mixing occurred twice during the summer, July 14 through July 17, and August 20 through August 24. During the passage of such storms, the temperature structure destratifies, salinity decreases and the pycnocline deepens (Figs. 22, 23). To estimate mixing under these conditions, three methods of analysis were used; transport rate varied both for the method used and the time period over which it was calculated (Table 3).

1) Steele's Method. Calculation of a mixing coefficient by Steele's method, assuming Z_u constant at seven meters, gives values of 0.157 per day and 0.174 per day respectively for the July and August episodes of wind mixing. N_o is taken as the average concentration per cubic meter in the surface seven meters at the beginning of the time period and N as the average concentration per cubic meter from seven to nine meters at the beginning of the time period. The value for ammonia in August is an estimated value based on the approximate ratios of nitrate to ammonia at eight meters during the

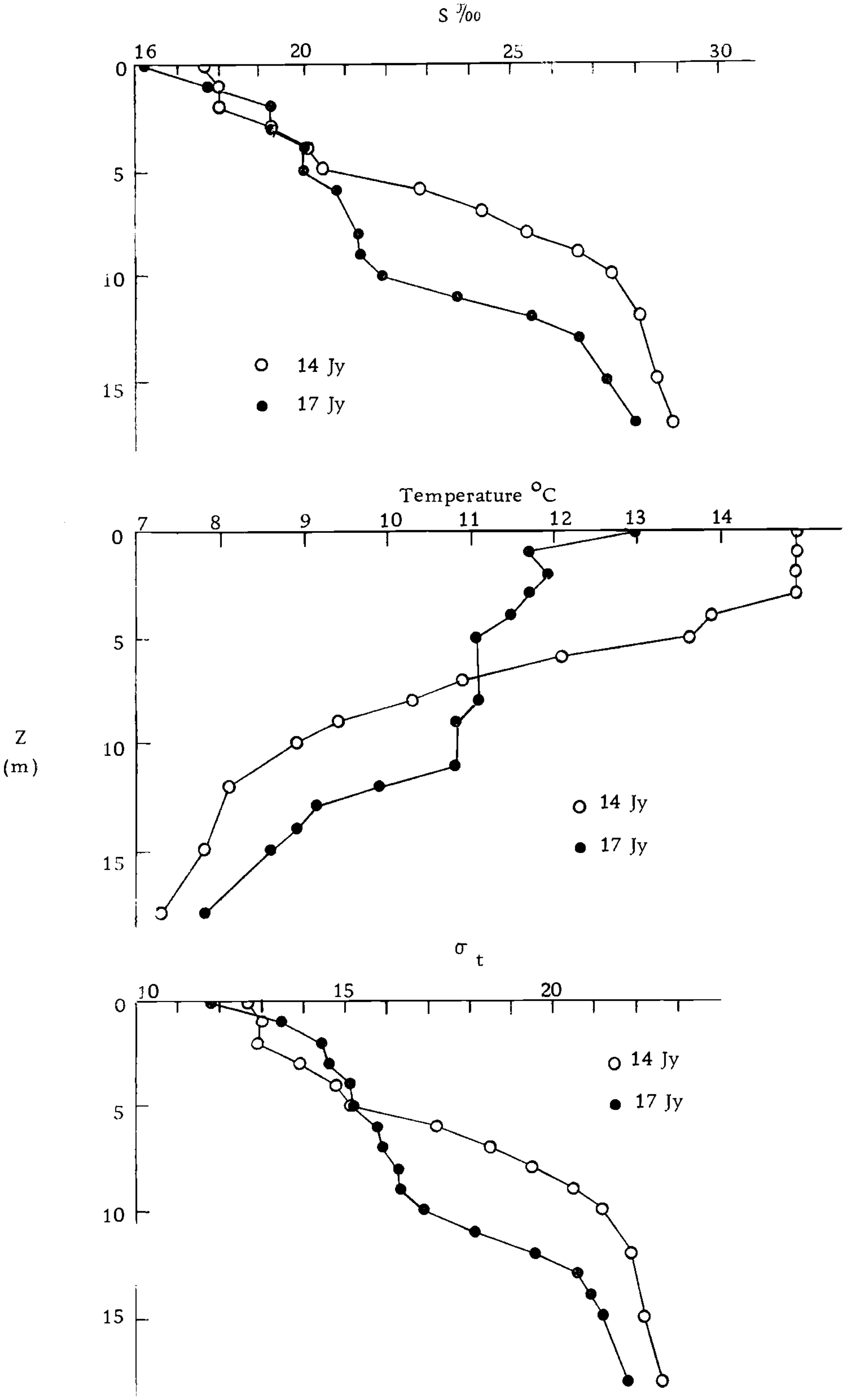


Figure 22. Pre- and post-wind hydrographic characteristics, ABM: 14 July and 17 July, 1971.

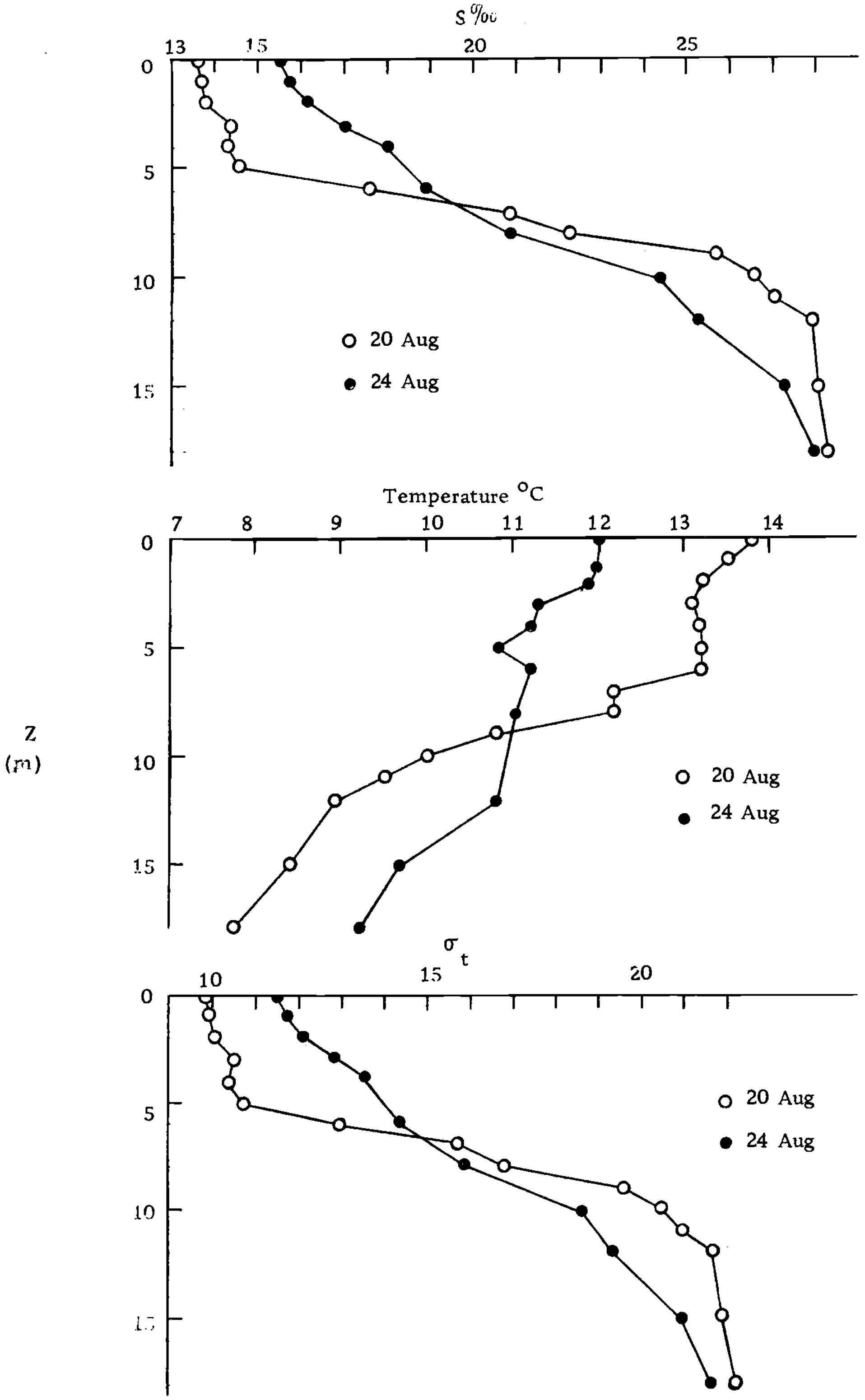


Figure 23. Pre- and post-wind hydrographic characteristics, ABM; 20 August, and 24 August, 1971.

Table 3. Mass transport of NO_3 and NH_4 per square meter into the surface mixed layer during wind mixing. Calculated according to three different methods.

	Steele's method	Heat exchange method	Thermocline deepening method
		$\mu M\ NO_3 - N$	
14-17 July	2.04 μM/day	0.57 μM/day	2.5 μM/day
20-24 Aug	6.70 μM/day	1.90 μM/day	6.00 μM/day
		$\mu M\ NH_3 - N$	
14-17 July	0.68 μM/day	0.24 μM/day	1.50 μM/day
20-24 Aug	3.40 μM/day	0.90 μM/day	3.00 μM/day

summer.

2) Heat Exchange. In both cases, the total heat in the water column remained the same before and after wind mixing; the amount of heat lost above seven meters equalled the amount of heat gained below seven meters. In July, it would require a volume exchange of 1.08 cubic meters of water from below seven meters to affect this change; 1.36 cubic meters would be required for the August wind mixing episode. This method assumes no other mixing occurs and linear transport with time.

3) Deeping of the Thermocline. A third estimate of nutrients added during wind mixing requires the assumption that all nutrients existing in the water column between six and eleven meters before the storm passed through the area were incorporated into the mixed layer. Eleven meters is the depth to which the pycnocline deepened during wind mixing.

The method using heat exchange is a minimum estimate since it assumes linear transport with time and no other mixing. Steele's method of calculating mass transport and the method using the assumption of total incorporation of nutrients give approximately the same values for mass transport per day. Steel's method has the disadvantage of assuming a constant depth of the pycnocline when in fact it isn't. For this reason the rates inferred from assuming the total incorporation of nutrients into the mixed layer will be used in determining nutrients supplied to the surface mixed layer.

Mass Transport of Nutrients in Fresh Water

Integrated salinity to fifteen meters in the Auke Bay water column decreased throughout the summer by 20%. The minimum volume of fresh water required to affect this change was calculated by summing salinity over depth with time. This is a minimum estimate because no correction is made for salt being mixed up. Since the fresh water input could not be determined on a weekly basis due to tidal or seiche induced scatter in the data, the calculation was made for the two longer time periods of assumed non wind mixing. This value was then averaged over the time period to give an estimated volume entry per week. Salinities were averaged for two to four days at the beginning and end of the periods to reduce the effect of tides and seiche. The volume of fresh water added to the water column was calculated for both surface to six meters and surface to ten meters. The value obtained for six meters was the same as that for ten meters indicating either a) fresh water is added only to the top six meters, or b) whatever fresh water is added below six meters is balanced by the salt being mixed up. The calculation of fresh water input during periods of high winds is easier as the volume is larger.

Rainfall, runoff from the Mendenhall River, runoff from Auke

Creek watershed and runoff from the rest of the north shore of Auke Bay are the sources for this fresh water. The former three are gauged while the latter is not. To calculate the volume flow of the north shore watershed, it is first assumed that the volume flow for Auke Creek is representative of the entire Auke Bay watershed. The area of Auke Creek watershed times the factor 1.45 gives the area of the north shore watershed, therefore the volume flow of Auke Creek is multiplied by 1.45 to give the approximate volume flow from the north shore watershed. Rainfall, Auke Creek and north shore runoff are assumed to spread uniformly across the bay; the volume of fresh water added by these three sources over a square meter is subtracted from the calculated volume of fresh water added; the remainder is attributed to the Mendenhall River.

Nutrient concentrations for these fresh water inputs, with the exception of rain, were measured on a weekly basis; they varied randomly with respect to time and did not correlate with volume flow. Thus the average concentration measured at the beginning and end of any week was used as the concentration for that week. In the case of north shore runoff, the weekly average nutrient concentrations of Wadleigh Creek and Auke Nu Creek were averaged to give an estimate of nutrient concentration for this area. Using the above methods, the mass of nutrient added to Auke Bay from fresh water sources was calculated using the formulae:

(mg A nutrient/volume) (volume flow) = mgA nutrient added (3)

Problems with contamination during the summer prevented the measurement of nutrient concentrations in rainfall samples, therefore values for nitrate and ammonia were taken from the literature. The concentration of nitrate in rainfall was taken as 4.0 μM and that of ammonia as 2.0 μM (Junge, 1963; Jones, 1970). However, measured nitrate and ammonia in rainwater collected during R/V Cayuse cruise C7204I, April, 1972, in the vicinity of Ketchikan, Southeast, Alaska, were 2-3 μM nitrate and 9-11 μM ammonia. This indicates the amount of nitrogen contributed by rainwater in the form of nitrate and ammonia may be double the value used in this analysis. Nevertheless, the total rainfall during the year, 1.37 meters, is an insignificant proportion of the fresh water which enters the bay. The nutrients supplied to the surface layer from these fresh water sources are tabulated in Table 4.

Loss of Nutrient Between Spring and Summer

The observed decrease in nitrate under a square meter down to 45 meters between the April cruise and July 1 could be due to errors in analyses, advection of a low nutrient water mass or biological activity. There is no reason to suspect the accuracy of the analyses. No source of low nutrient water was sampled during the spring cruise. The decrease in nitrate is assumed to be a function of biological activity and to be equal to that incorporated into production. The latter assumption may be inaccurate as there is another possible explanation for the decrease (pg. 59). Assuming that all of the nitrate is consumed in biological production, and using a C/N ratio of 7 in particulate matter, based on the ratios measured during the summer (Zakar, 1972), the total biological production as grams carbon fixed per square meter from April to July is 62 grams. This total production has been converted to an average daily biological production (Fig. 24) for the April to July period of time.

Calculated Production in the Surface Mixed Layer

Two of the calculated values (Table 4) are believed to be in error. The calculated vertical mass transport of nutrient from June 25 to June 30 is believed to be too low. Within this time period, wind velocities and thermal structure indicate some wind mixing occurred, however the vertical transport is calculated under assumed non wind mixing conditions. As discussed previously (pg. 37) this situation would lead to an underestimate of vertical transport.

The calculation made for August 11 to August 19 for vertical transport may also be too low. At that time, the surface mixed layer included the top five to seven meters (Fig. 12). The nutrient concentration used for N may have been indicative of the surface

Table 4. Rates of nutrient addition per square meter to the surface 6 meters of Auke Bay, and the primary production calculated from these rates.

Period	Addition of Nutrient-N to upper 6 meters per @ time period										6		7[a]		8[b]	9[c]	10[d]
	1 Rainfall mg-at $\times 10^{-2}$		2 Auke Cr. mg-at $\times 10^{-2}$		3 North Shore mg-at $\times 10^{-2}$		4 Mendenhall River mg-at		5 Vertical Transport mg-at		Sum of Sources mg-at		Δ N mg-at		Available N	Calc. prod. mg C	Calc. prod. mg C/ day
	NO_3	NH_3	NO_3	NH_3	NO_3	NH_3	NO_3	NH_3	NO_3	NH_3	NO_3	NH_3	NO_3	NH_3			
25 Ju-30 Ju	7.90	3.96	2.40	2.89	3.85	1.08	0.56	0.43	2.52	1.40	3.22	1.94	-4.60	-1.3	0.60	55	88
1 Jy- 6 Jy	6.55	3.26	1.29	1.55	1.88	0.52	0.63	0.49	3.10	3.53	3.83	4.07	+4.60	+1.3	13.79	1155	192
7 Jy-13 Jy	0	0	4.93	7.17	7.15	2.43	0.57	0.44	4.70	3.38	5.39	3.91	-0.30	-1.7	5.29	613	97
14 Jy-17 Jy	23.2	11.6	0.82	1.87	26.40	0.63	1.31	2.46	11.0	6.20	12.81	8.74	+1.60	+0.4	22.54	1891	573
18 Jy-20 Jy	3.64	1.82	0.77	1.75	24.80	0.59	0.15	0.28	2.64	1.08	3.08	1.40	+0.03	-0.3	4.21	353	118
21 Jy-27 Jy	2.75	1.38	0.67	2.66	36.90	0.90	0.39	0.74	3.50	2.10	4.29	2.88	+4.29	+0.4	7.57	636	91
28 Jy- 3 Aug	20.88	10.44	0.11	1.64	1.04	0.56	0.04	0.67	3.00	1.50	3.26	2.29	-0.1	+1.0	6.45	544	78
4 Au -10 Au	15.05	7.52	1.07	5.62	6.30	1.91	0.04	0.58	0.90	0.60	1.17	1.33	-0.2	+0.6	2.92	246	35
11 Au -19 Au	17.28	8.64	3.24	4.54	7.35	1.53	0.07	0.84	1.13	0.76	1.48	1.74	-0.4	-1.7	1.08	92	10
20 Au -24 Au	7.18	3.59	2.41	3.26	7.43	1.10	3.24	1.92	30.00	15.00	33.40	17.00	-3.6	0	47.40	3988	797

[a] Δ N: difference in standing stock of nutrient between beginning and end of @ time period in upper 6 meters. See Table 1 and p. 23 for data.

[b] Available N: net mas (mg-at) nutrient (NO_3 + NH_3) available for phytoplankton per @ time period.

[c] Calc. prod., mg C: Primary production calculated from net nutrient available: (mg-at nutrient N) (C/N) (mg C/g mol wt. C)
where: C/N ratio = 7, mg C/g mol wt C = 12.

[d] Calculated primary production as mg C/day.

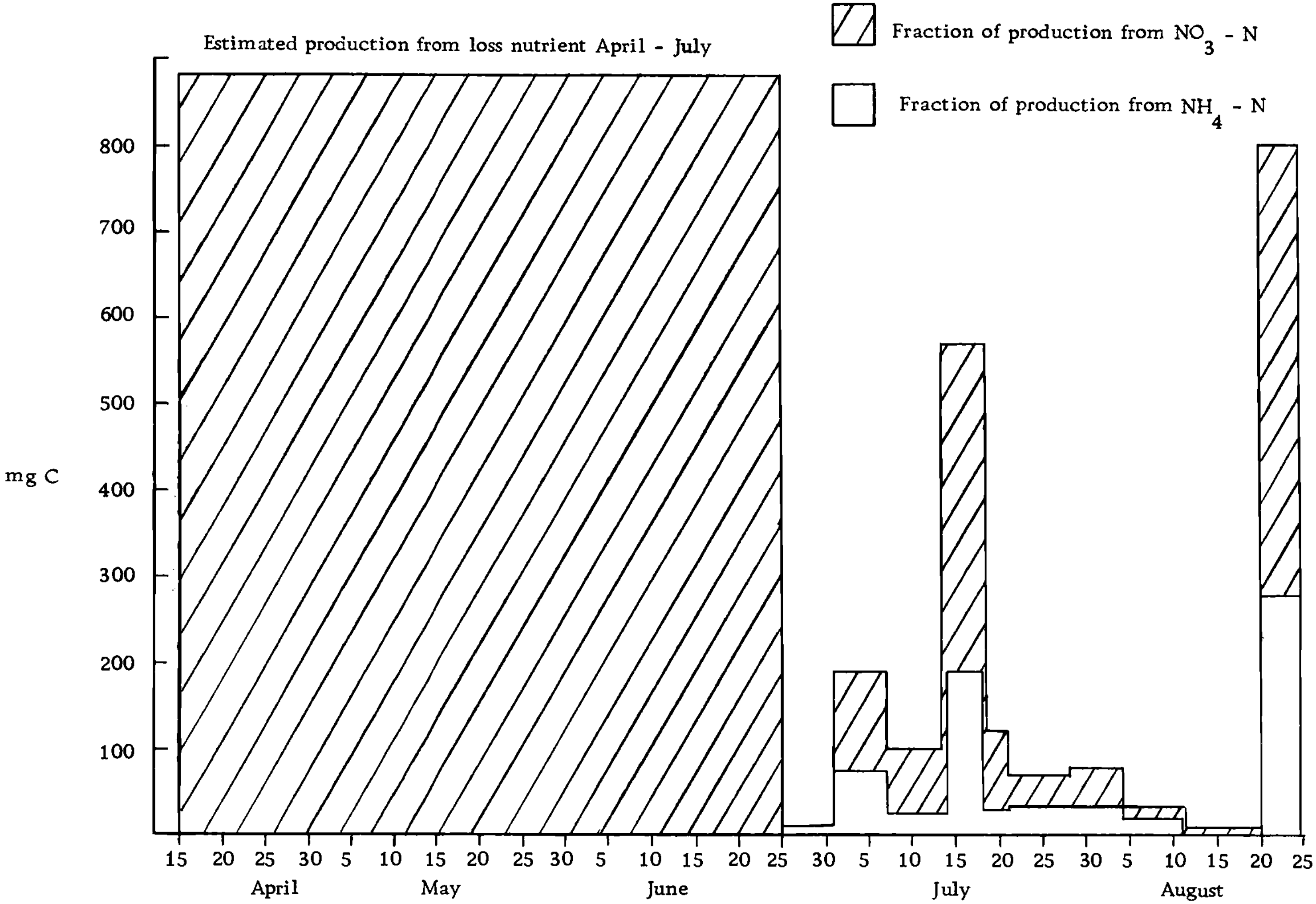


Figure 24. Estimated total production per square meter from nitrate and ammonia additions, April-August, 1971.

layer concentrations rather than the nutrient concentrations below the pycnocline.

Any discussion of the nutrient and hydrographic budgets of Auke Bay must include those phenomena which do not directly effect the surface mixed layer. These processes are separated into two overlapping categories: phenomena related to nutrient observations and phenomena related to water mass circulation under various meteorlogical conditions.

Nutrient Observations in the Upper 15 Meters

Perturbations in the nutrient data to 20 meters correlate with change in sigma-t (Fig. 13). The changes in these two properties are indicative of a) advection of a particular water mass into the bay, b) high winds from the southeast and c) tidal variation.

Advection

Advection of a particular water type at depth is indicated by the data from July 12, 13 and 14. Physical data taken on July 13 have some anomalous (with respect to July 12 and 14) characteristics: salinity increased above 5 meters, decreased between 5 meters and 11 meters from concentrations measured on July 12 and July 14; the density structure indicated pycnoclines at 3 and 11 meters; a current was noted at 9 meters on July 13. The differences in density structure between July 13 and July 12, 14 were not within the expected tidal or seiche range (Fig. 25). Continuous, high solar radiation values were recorded for the preceding week. Nutrient concentrations measured on July 14 correlate with sigma-t values on July 13. An explanation for these observations is that surface waters outside the bay, warmed and depleted of nutrients, flowed into the bay seeking its own density. This water could have been warmed in the bight between Point Louisa and Indian Point (Fig. 2). The frequency of this occurrence is unknown.

Effect of Southeast Winds

The decrease in sigma-t between July 14 and July 17 was caused by a southeast storm which passed through the area between July 14 and July 17. The volume of fresh water required to cause the decrease in salinity could not, by dilution, decrease the nutrient concentration to the measured levels; qualitative phytoplankton samples taken during this time indicated increased numbers and species during that week so this may have contributed to the observed decrease in nutrients.

Tidal Variation in Nutrients

The decrease observed in the upper 15 meters on August 11 is not, like those of July 14, directly attributable to any transient

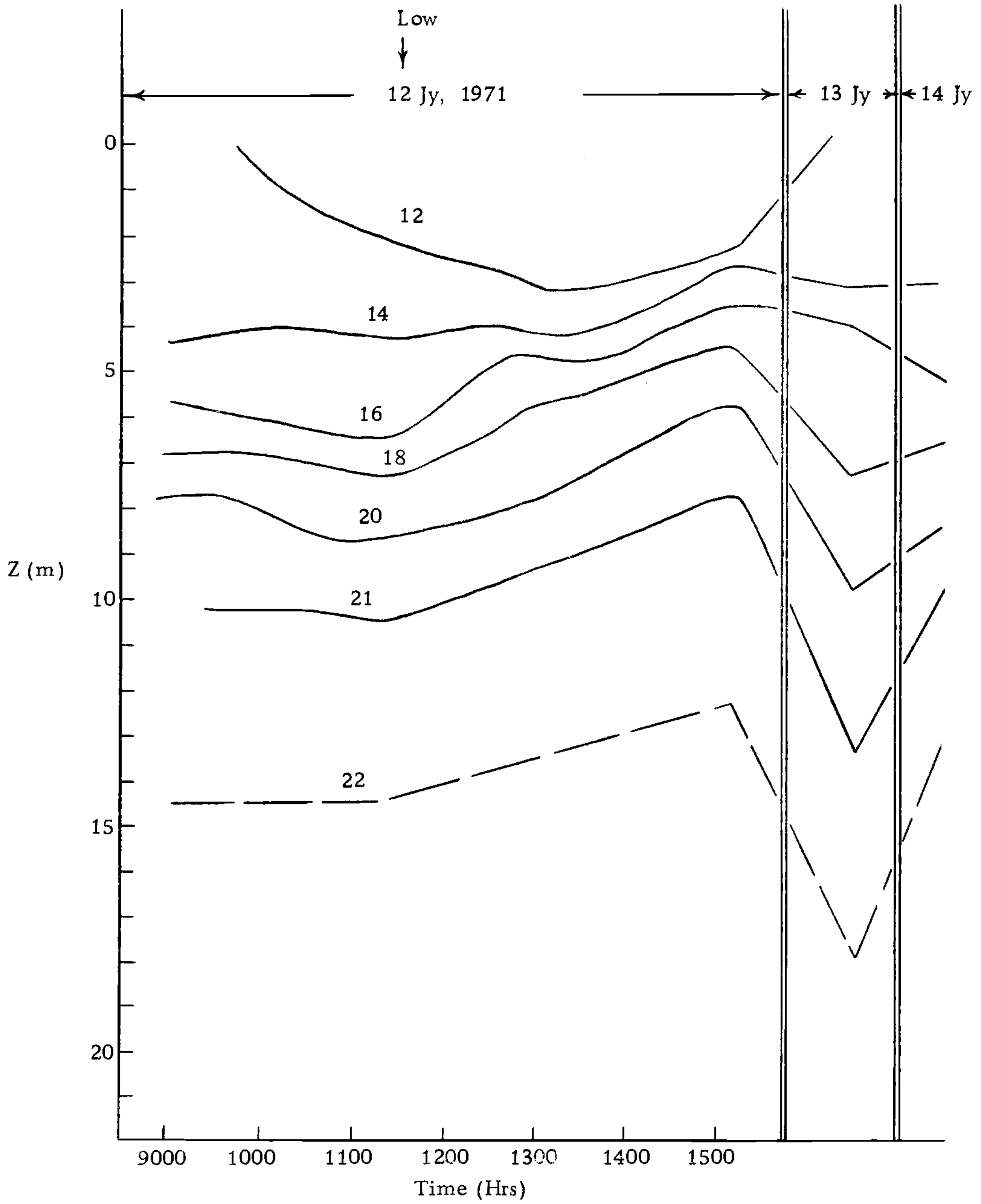


Figure 25. Tidal cycle density contours at ABM, 12 July and density profiles for 13 and 14 July.

water mass movement. The variation in sigma-t is within the extreme limits allowed by tidal variation on August 10, although the stability contours indicate a possible recurrence of an advective flow (Fig. 12). Runoff from Auke Creek and Mendenhall River had been decreasing for the preceding five days, thus this is an unlikely source of low nutrient water. Since nutrients can vary with sigma-t over tidal cycles (Fig. 14), this may be the explanation for the observed decrease.

Ammonia, with the exception of the first part of July, correlates with the variation in nitrate and sigma-t. Ammonia does not correlate with sigma-t and nitrate on July 13, when the advection of surface waters from outside the bay is thought to have occurred. Since zooplankton were abundant during this time, the surface waters would have contained higher concentrations of ammonia than might otherwise be expected.

Nutrient Observations Below 15 Meters

Hydrographic data could not be obtained for depths greater than 21 meters, therefore the fluctuations in nitrate and ammonia at 25, 35 and 45 meters could not be correlated with any specific hydrographic event. The total integral nutrient concentration under a square meter did not, however, show any marked decrease during the summer months. This is in sharp contrast to the 58% decrease in nutrients under a square meter between April and July. Several hypotheses could account for these observations:

1) Production is higher in the spring, thus there are more cells absorbing nutrients both in the photic zone and as the cells sink.

2) The nutrients absorbed by cells sinking in the summer is balanced by some form of recycling at lower depths.

3) The nutrients absorbed by cells sinking in the summer is balanced by the nutrient concentrations entering the bay at depth.

The most probable cause of large decrease in nutrients between spring and summer is the absorption of nutrient by sinking cells. This hypothesis is supported by the cruise data and by laboratory experiments (Dugdale and Goering, 1967). The cruise data indicated chlorophyll maxima and nitrate minima both at the surface and the bottom of the bay at the stations closest to the north shore (Figs. 3, 4). The phytoplankton species were the same in samples taken at the surface and near the bottom. Although we did not sample at depth for chlorophyll or cells, Schell (1971) found cells at the bottom in 50 meters of water in May. That the total nutrient per square meter does not decrease during the summer is probably due to a balance between cells sinking and absorbing nutrients, regeneration of nutrients and advection of nutrients.

Water Mass Circulation

Currents are referred to hereafter as Indian Point currents, Spuhn Island currents or ABM currents (Fig. 2). Surface currents measured at ABM are assumed representative of the cross section from Coghlan Island to Battleship Island to a depth of six meters. Surface currents at Indian Point are inferred from the directions at the ABM and Spuhn Island locations.

Under light winds from the northwest, flow is into the bay at Indian Point and Spuhn Island; flow is out of the bay, i.e. to the southeast, at ABM (Fig. 19). From the position of flotsam and jetsam in a calm, runoff from the north watershed of Auke Bay is observed to flow along the north shore towards the west; Under the above conditions, it would then be carried over the surface of Auke Bay towards ABM. Fresh water from the Mendenhall River is carried into Auke Bay at the Spuhn Island Passage.

Volume transports at the surface under light northerly winds were calculated from average daily residual velocities. Surface transport out of the bay at ABM was 5.5×10^2 cubic meters/sec to the southeast; transport into the bay at Spuhn Island was 0.32×10^2 cubic meters/sec to the north, leaving a deficit of 5.18×10^2 cubic meters/sec. Using the rate calculated from Steele's formula, 0.048×10^{-4} cubic meters/sec through a square meter, vertical transport was 0.48 and 10^2 cubic meters into the entire surface layer of Auke Bay. The difference, 4.6×10^2 cubic meters/sec is assumed to enter at Indian Point.

Under strong southeast winds, the surface layer at ABM and Spuhn Island are uniformly transported into the Bay (Fig. 19); transport is inferred to be out of the bay, i.e. to the west, at Indian Point. The spring cruise data indicate upwelling could occur along the east shore of Mendenhall Peninsula (Fig. 19). This type of upwelling results from wind pushing the surface waters away from the shore (as opposed to currents flowing at right angles to the wind as in upwelling off the Oregon Coast).

TAN decreases over the 24 hour station and is the only factor in Fig. 6 which may be questioned as an indicator of upwelling. The changes in TAN are not, however, inconsistent with the proposed upwelling since waters of the same density immediately west of the anchor station on transect A-A' (Fig. 3) have similar concentrations of TAN as those found in the upwelled waters. Although the upwelling phenomena could not be investigated during the summer, it is unlikely upwelling would occur to the same extent as in the spring. Rather than upwelling, the intense stratification and a source of large quantities of fresh water (Mendenhall River) in the summer may simply cause a continuous surface layer to flow across the bay, mixing and deepening the surface layer with time.

The strong winds from the southeast in Gastineau Channel are from the south in Lynn Canal and could temporarily reduce southward flow of surface water in the canal. When the wind ceases, the accumulated water could then flow south down the channel. The presumed effect of this "rebound" has been observed at Auke Bay forty hours or more after the wind ceases.

Evidence from the summer which supports this "rebound" occurred two days after the wind had ceased. Colder, more saline, higher nutrient water appears at ABM at depths greater than five meters between July 19 and July 21. This water displaces the 11 meters of fresher water present on July 17. The same phenomena occurs even more markedly after the high winds recorded at the end of the summer, August 20-24.

Further supporting evidence for the "rebound" is provided by the current meters. The daily residual speed at surface ABM is markedly higher on the 28th of August, two days after the winds change direction and decrease in speed. On the 28th, the twenty-four hour residual velocity for the surface current meter of Spuhn Island, after four days of flowing to the north, reverses and flows to the south for one day.

Data taken on the spring cruise indicated a change in water properties between stations taken during and after the storm. These changes (Figs. 3, 5) indicated water mass movement into the bay at depth. Transect C-C' (Fig. 5) showed a major change in water properties over this time. Stratification existing before and during the storm (Stations 30, 31, 32) was removed after the "rebound" (Stations 33, 34). Despite the magnitude of the change, the data is judged to be good as all factors responded in a like manner. There is no completely reliable data from the summer for deep currents at Auke Bay, although the residual V (north) component of the deep current meter at ABM does show increased velocities on August 28 (Table 2). The effect of upwelling and "rebound" on phytoplankton production during the summer could not be determined with our sampling methods.

SUGGESTIONS FOR FURTHER RESEARCH

The results and analyses discussed in this thesis suggest several areas for further investigation. A time series study of temperature and salinity with depth should be carried out on transects similar to those used during the cruise. This should be done over several tidal cycles throughout the summer to obtain a profile of physical factors in Auke Bay. This would provide a much better idea of both the distribution of physical properties in space and the tidal variations occurring in Auke Bay. A tide gauge should be installed to determine whether and how often seiches and internal waves occur. Surface and deep current meters should be arrayed across the Coghlan Island-Battleship Island entrance and at Indian Point to determine the actual current flows. The conditions and magnitude of upwelling during the summer should be investigated both as a physical phenomena and as a source of nutrients for phytoplankton.

Urea and amino acids should be monitored with nitrate and ammonia in Auke Bay and in the fresh water sources entering Auke Bay since they were not investigated in our study. Laboratory uptake experiments using these forms of nitrogen should be carried out in conjunction with the nutrient and cell sampling in Auke Bay. The interrelationships between zooplankton and phytoplankton have not been investigated in this system; the effect of zooplankton or phytoplankton as a source of nutrients and as grazers should be studied.

The phenomena of cell nutrient uptake in the dark should certainly be investigated with respect to cell viability. The phenomena of cell sinking should be studied not only as a mechanism which influences nutrient reserves in a water column, but also to determine what their eventual fate is, i. e. are they incorporated into the sediments or used by bottom feeders.

It is also advisable to monitor the fresh water streams and rivers in the Juneau area, particularly above and below populated areas. The data, and our observations of open drainage creeks entering Auke Bay, indicate that the human population is most likely responsible for any nutrient input from fresh water sources. Since the fresh water runoff controls the physical factors of the area nearly half of the year, it is important to know how much and what is being added.

No data concerning the concentration of nutrients in rainfall have been published for the Alaska area. Since the values taken during C7204I were so much higher than literature values, the concentration in rainfall needs to be studied on a long (seasonal) and short (during storms) term basis.

One last interesting area of investigation concerns the salmon runs in Alaska. The particular run in Auke Bay occurs in mid summer, with the salmon entering Auke Lake, and spawning in Lake Creek. It is of interest to know the fate of the organics and nutrients released from the decaying fish, does Auke Lake act as a nutrient trap, or are they eventually released to Auke Creek, thence to Auke Bay.

CONCLUSIONS

1. Analysis of the physical sources of nutrients indicate vertical transport provides the majority of nutrients supplied to the surface layer.

2. Mixing caused by high velocity winds from the southeast provide a pulsed source of nutrients for phytoplankton blooms during the summer months.

3. A "rebound" of water from Lynn Canal after southeast storms could provide a mechanism to replenish nutrients at depth in the bay.

4. Upwelling can occur along the east shore of Mendenhall Peninsula during southeast storms.

5. Transient advection of a particular water mass from outside the bay on a specific density boundary at depth occurs during the summer.

6. Cells sinking out of the water column absorb nutrients, and thus cause part of the observed decrease in nutrients at depth during the spring and summer.

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