UNIVERSITY OF CALIFORNIA SCRIPPS INSTITUTION OF OCEANOGRAPHY INSTITUTE OF MARINE RESOURCES

PROGRESS REPORT

Scripps Tuna Oceanography Research (STOR) Program
Report for the Year

July 1, 1970 – June 30, 1971

National Marine Fisheries Service,
National Oceanic and Atmospheric Administration,
Department of Commerce
Contract 14-17-0001-2311

and

National Science Foundation
Grants GB-8618, GA-27320 and GA-27545.

IMR Reference 72-6
SIO Reference 71-28

November 1, 1971

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Prepared by
Maurice Blackburn, Program Director

Approved for Distribution:

John D. Isaacs, Director IMR

William A. Nierenberg, Director SIO

This progress report is not intended to represent a scientific publication and should not be cited as one. Results will be published in appropriate journals when they are suitable for that purpose. Inquiries or comments about sections of the report may be sent to the investigators named there.

CONTENTS

1. GENERAL REMARKS ON THE PROGRAM

Tunas are large, active, carnivorous fish that inhabit the upper layers of the ocean in tropical and temperate regions both near and far from land. Their distribution, abundance, and behavior depend upon physical, chemical, and biological properties of the water and its contents. Tunas support a major fishery of the United States in the Pacific, to which two tropical species, yellowfin and skipjack, are the major contributors. The fishery for those species extends from California to Chile and several hundred miles off the coast of the American continent. In recent years the fishery has operated more than a thousand miles from the coast. Other species of tuna fished by the United States in the Pacific, namely albacore and bluefin, are taken along the coast from northern Mexico to British Columbia. The range of bluefin significantly overlaps the range of yellowfin and skipjack, and the same principal fishing method, purse seining, is used for those three species. The albacore fishery is relatively distinct from the other tuna fisheries in area and method.

There is need to improve the effectiveness of the tuna fisheries in their present region, and to identify other regions into which the fisheries can expand. Investigations in physical, chemical, and biological oceanography of the eastern tropical Pacific and adjacent waters are therefore being conducted as a basis for understanding, explaining, and possibly forecasting changes in abundance, distribution, and amenability to capture of the skipjack, yellowfin, and bluefin tunas in the present fishery regions, and for identifying possible new fishery regions for those species. Some aspects of the investigations involve fundamental studies of the circulation, primary productivity, and food-chain relationships in the eastern tropical Pacific.

The Scripps Tuna Oceanography Research (STOR) Program has done these kinds of work since 1957/58, and continued them in 1970/71. Its principal financial support came from the National Marine Fisheries Service (Contract 14-17-0001-2311, $95,000 for 1 year commencing July 1, 1970; Dr. Maurice Blackburn, Principal Investigator). The Service also provided working space in its Southwest Fisheries Center without charge, as in previous years, and it provided the research vessel DAVID STARR JORDAN with staff and equipment for the cruises described in Section 2.3. Additional support also continued from the National Science Foundation (Grant GB-8618, $61,000 for 2 years commencing March 1, 1969; Grant GA-27320, $20,400 for 1 year

commencing January 1, 1971; Grant GA-27545, $29,300 for 1 year commencing March 1, 1971; Dr. William H. Thomas, Principal Investigator). There was also some support with regular University funds from the Institute of Marine Resources.

Investigations

The Program's work in the year ended June 30, 1971, had the following parts:

1. An oceanographic investigation of the eastern tropical Pacific and adjacent waters, with special reference to properties, features, and processes affecting the availability of skipjack, yellowfin, and bluefin tuna (mostly skipjack tuna in 1970/71). Most of this work was supported by the National Marine Fisheries Service (NMFS) contract. One part of the work, namely on nutrient chemistry of the eastern tropical Pacific, was also supported by National Science Foundation (NSF) Grant GA-27320.

2. Effects of nutrients on the growth of marine phytoplankton. This was supported by NSF Grants GB-8618 and GA-27545.

The connection between parts 1 and 2 is that nutrients and phytoplankton are among the properties that indirectly affect the availability of tuna, since they are links in the tunas' food chain. Parts 1 and 2 are discussed in Sections 2 and 3 respectively of this report.

Staff

The following persons worked in the STOR Program in 1970/71:

Dr. M. Blackburn, Research Biologist, Program Leader
Dr. F. Williams, Associate Research Biologist
Dr. W. H. Thomas, Associate Research Biologist
Dr. M. Tsuchiya, Assistant Research Oceanographer
Mrs. A. N. Dodson, Laboratory Technician II
Mr. D. L. Seibert, Laboratory Technician II
Miss A. Johnston, Senior Typist Clerk A
Miss Carol Linden, Student Assistant

Special Activities

Dr. Blackburn participated in the annual Tuna Conference and Eastern Pacific Oceanic Conference held at Lake Arrowhead, California, in October 1970. In the same month he visited Mexico at the invitation of the FAO Fisheries Project in that country to advise them on fishery oceanography. He continued as a member of the Ocean-Wide Surveys Panel of the National Academy of Sciences' Committee on Oceanography until the panel was discharged. Dr. Blackburn attended the La Jolla, California, meeting of the Pacific Division of the American Society of Limnology and Oceanography in June 1971. Other special activities not mentioned elsewhere included preparation of a symposium paper on Pacific micronekton for the 12th Pacific Science Congress, which Dr. Blackburn attended in August 1971; preparation of a chart of the living pelagic resources of the southwest Pacific at the request of FAO; and planning future research on coastal upwelling in the California Current region.

Dr. Williams visited the NMFS Laboratory in Honolulu, Hawaii, in July 1970, in connection with investigations on skipjack tuna. He attended the Tuna Conference and Eastern Pacific Oceanic Conference at Lake Arrowhead, California, in October 1970, and was elected Chairman of the next Tuna Conference. He reported on STOR activities at the annual meeting of the Institute of Marine Resources held at Davis, California, in March 1971, on behalf of Dr. Blackburn who was away on a cruise. Dr. Williams participated by invitation in a NMFS Workshop on billfish held at Tiburon, California, in March 1971.

Dr. William H. Thomas delivered a paper at the American Society of Limnology and Oceanography annual meeting in Kingston, Rhode Island, in August 1970. He also attended the CalCOFI meeting in Palm Desert, California, in November and the Gordon Research Conference on Chemical Oceanography in Santa Barbara, California, in January.

Dr. B. Zeitzschel, Institut für Meereskunde, Universität Kiel, who was a visiting investigator on EASTROPAC phytoplankton in the STOR group from 1968 to 1970, delivered a paper on his EASTROPAC studies at the Joint Oceanographic Assembly in Tokyo in September 1970.

2. OCEANOGRAPHY AND TUNA ECOLOGY IN THE EASTERN TROPICAL PACIFIC

2.1. Preparation of the EASTROPAC Atlas
(M. Tsuchiya; W. H. Thomas and D. L. Seibert)

In previous STOR annual reports we described the EASTROPAC oceanographic expedition of 1967/68 in the eastern tropical Pacific and progress being made in the preparation of the 11-volume EASTROPAC Atlas. The Atlas is a cooperative project by investigators in several of the research groups that participated in the expedition. STOR was the largest contributor to the Atlas among the groups.

Most of the Atlas pages on biological oceanography, including all for which STOR was responsible, were completed over a year ago. The pages on physical oceanography and nutrient chemistry from the principal participating ships, for which STOR was responsible, have now been almost completed. Dr. Tsuchiya produced the pages on physical oceanography and Dr. Thomas and Mr. Seibert produced those on nutrient chemistry. Virtually all of STOR's promised contributions to the Atlas have thus been made.

The National Marine Fisheries Service is publishing the EASTROPAC Atlas as their Circular 330. Volumes 2 and 4 were produced in November 1970, and April 1971, respectively. Drs. Blackburn, Thomas and Zeitzschel of STOR contributed to each of those volumes. Volume 3, to which Dr. Tsuchiya contributed, is in press.

2.2. Research Projects with EASTROPAC Data
(M. Tsuchiya and Others)

STOR investigators previously published eight research papers based on EASTROPAC data and have three others in press. These papers are identified in Section 4 of this report. They all refer to biological or chemical oceanography, on which additional papers are expected later. Research on the physical oceanographic data was delayed until recently, because the processing, editing, and charting of those data was a very large task, but it has now been commenced by Dr. Tsuchiya who reports as follows.

As mentioned in the last annual report (SIO Ref. 70-32), an eastward subsurface flow is indicated at 3°-5° N, just to the south of the shallower North Equatorial Countercurrent, by a sharp gradient of the isotherms for 10°-13° C. In contrast to the shallower countercurrent, which lies in the layers above the thermocline and varies greatly in response to the variation of the atmospheric circulation, the subsurface countercurrent is remarkably stable. For instance, in April-May 1967, no countercurrent was observed at the sea surface of the EASTROPAC area, but the subsurface countercurrent was clearly indicated at 3°-5° N on all the four meridional sections occupied in this period.

Table 1 summarizes the results of geostrophic calculations of the subsurface countercurrent at 119° W, where seven sets of data are available at intervals of 2 months. The maximum eastward speed is about 30 cm/sec and always occurs at 170-180 cl/t of thermosteric anomaly. However, the actual depth of the maximum varies from 100 m to 200 m. The eastward flow sometimes reaches the sea surface, but the overlying surface current is usually westward and the upper boundary of the eastward current is usually deeper than 20 m. Although the southern boundary of the current is not always well defined, the band of strong current is limited to 60-90 miles. The average total eastward flux above 500 db is estimated to be 32 km^3/hour (8.9 X $10^6 m^3$/sec).

The subsurface countercurrent is also evident on the maps of acceleration potential for the 160- and 200-cl/t isanosteric surfaces. It continues to flow eastward at 3°-5° N as far as 98° W; farther east it appears to shift northward. The distribution of salinity clearly reflects the eastward transport of the countercurrent. Figure 1 shows the salinity distribution on the 200-cl/t isanosteric surface, which lies slightly above the maximum speed of the subsurface countercurrent. In the figure a narrow tongue of low salinity (<34.7‰) is seen extending as far east as 92° W just at the latitude of the countercurrent.

Additional data that confirm these findings from EASTROPAC data were obtained during the two skipjack resource assessment cruises, mentioned in Section 2.3 of this report, in 1970/71. These data are being processed.

A similar subsurface countercurrent is found at the same or a little higher latitude in the southern hemisphere and may be identified as the South Equatorial Countercurrent. This current is weaker than its northern counterpart but is clearly revealed on almost all meridional sections from the EASTROPAC cruises. The maximum eastward speed is estimated to be 20 cm/sec and is found at 160-170 cl/t of thermosteric anomaly. A preliminary analysis of EASTROPAC data suggests that this subsurface countercurrent transports water with salinity slightly higher than that to the north and south.

Table 1. Subsurface North Equatorial Countercurrent at 119° W

Ship and cruise number	Month and year	Stations used for geostrophic calculations	Maximum speed	Depth and δ_T at the maximum speed		Depth of the upper boundary	Total eastward flux	Surface-current speed*
			(cm/sec)	(m)	(cl/t)	(m)	(km^3/hr)	(cm/sec)
ARGO 11	February 1967	Stn. 78 3°29' N 72 4°42'	30	138	180	0	35	+1
JORDAN 20	April 1967	56 2°56' 52 4°19'	38	106	180	20	47	-12
JORDAN 30	June 1967	54 4°02' 51 5°04'	30	134	170	28	28	-3
WASHINGTON 45	August 1967	71 4°06' 65 5°23'	28	196	170	134	29	-28
JORDAN 50	October 1967	57 3°11' 51 4°38'	25	174	170	121	24	-47
JORDAN 60	December 1967	58 3°25' 50 4°48'	29	154	180	16	31	-2
WASHINGTON 75	February 1968	50 3°10' 44 4°13'	35	140	170	78	30	-32

*Positive eastward, negative westward.

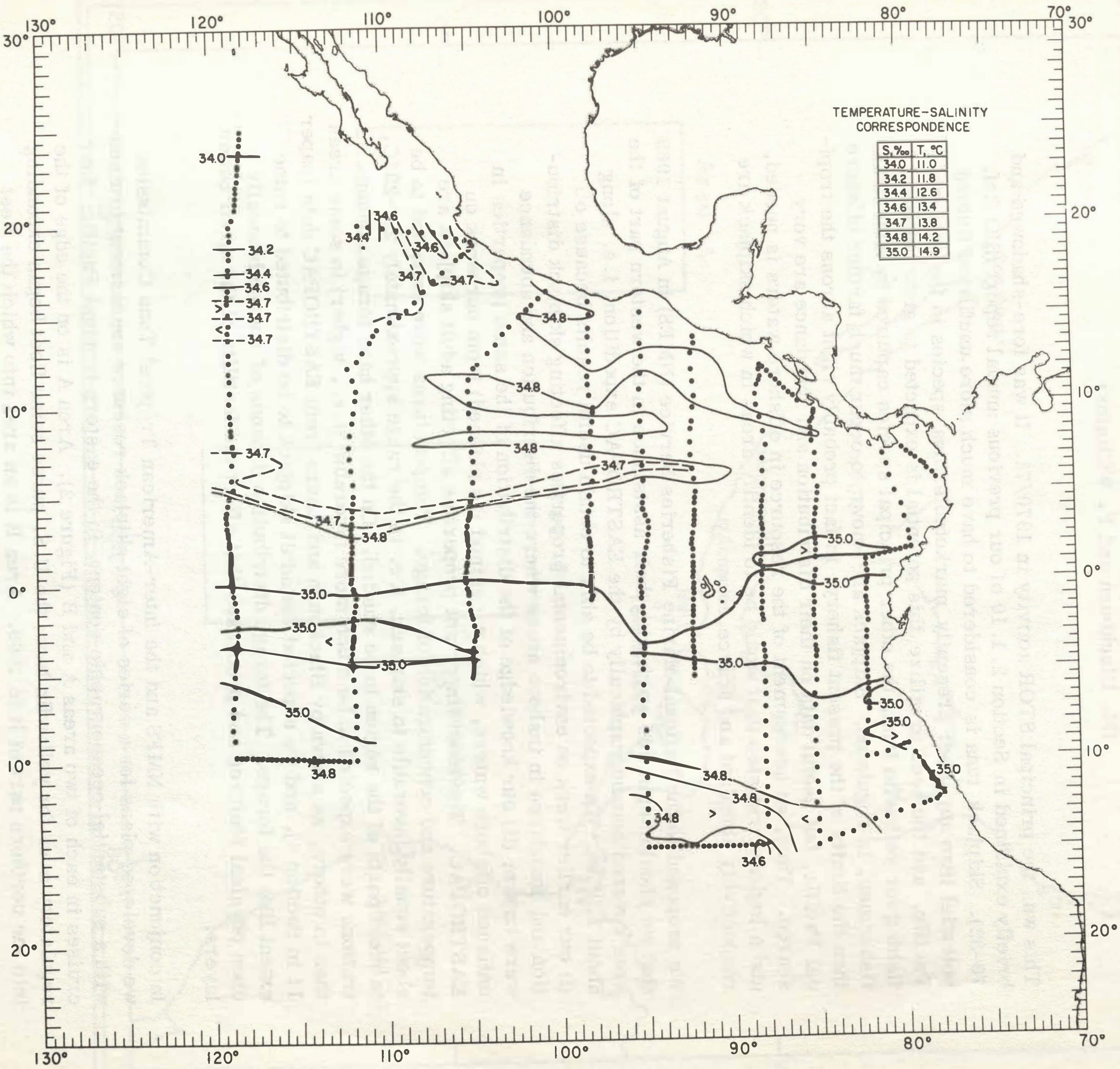

Figure 1. Salinity, in per mil, at 200 cl/t of thermosteric anomaly in August-September, 1967

2.3. Skipjack Resource Assessment in the Offshore Eastern Pacific (M. Blackburn and F. Williams)

This was the principal STOR activity in 1970/71. It was fore-shadowed and briefly explained in Section 2.1.10 of our previous annual report (SIO Ref. 70-32). Skipjack tuna is considered to have much more unutilized fishing potential than any other presently marketable tuna species in the eastern Pacific, and the need to utilize this potential is expected to grow because fishing for yellowfin tuna, the other principal species captured by American fishermen, is regulated. Skipjack are known to occur much farther offshore than the limits of the present fishery, in fact probably right across the tropical Pacific, but useful data on their distribution and abundance are very scarce. Thus, an assessment of the resource in offshore waters is needed, and a logical first step in it would be to identify areas in which skipjack are respectively abundant and scarce.

We proposed to the National Marine Fisheries Service (NMFS) in August 1969 that we should begin this work with their assistance in the western part of the area covered oceanographically by the EASTROPAC expedition, i.e. along about 119° W. We expected to be able to obtain useful results because of: (i) our earlier work on environmental properties affecting skipjack distribution and abundance in inshore areas where the distribution and abundance were known; (ii) our knowledge of the distribution of the same properties in unfished offshore waters, which we gained (as planned) from our work on EASTROPAC. The most important properties affecting adult skipjack are temperature and concentration of forage. Temperatures were expected to be about equally favorable to skipjack, i.e. in the range approximately 20°-29°C, in most parts of the region to be studied. On the other hand forage concentrations were expected to be much more favorable (i.e., higher) in some areas than in others, as shown by Blackburn and Laurs from EASTROPAC data (paper 11 in Section 4), and we expected the adult skipjack to be distributed to some extent like the forage. The forage distribution depends of course basically upon physical features and processes that affect the fertility of the upper ocean layers.

In conjunction with NMFS and the Inter-American Tropical Tuna Commission we developed plans for a series of eight skipjack resource assessment cruises with a substantial oceanographic content, in the eastern tropical Pacific: four cruises in each of two areas A and B (Figure 2). Area A is on the edge of the regulatory area for yellowfin tuna; the U.S. purse seine fleet began expanding into the northern part of it in 1969. Area B is an area into which the fleet

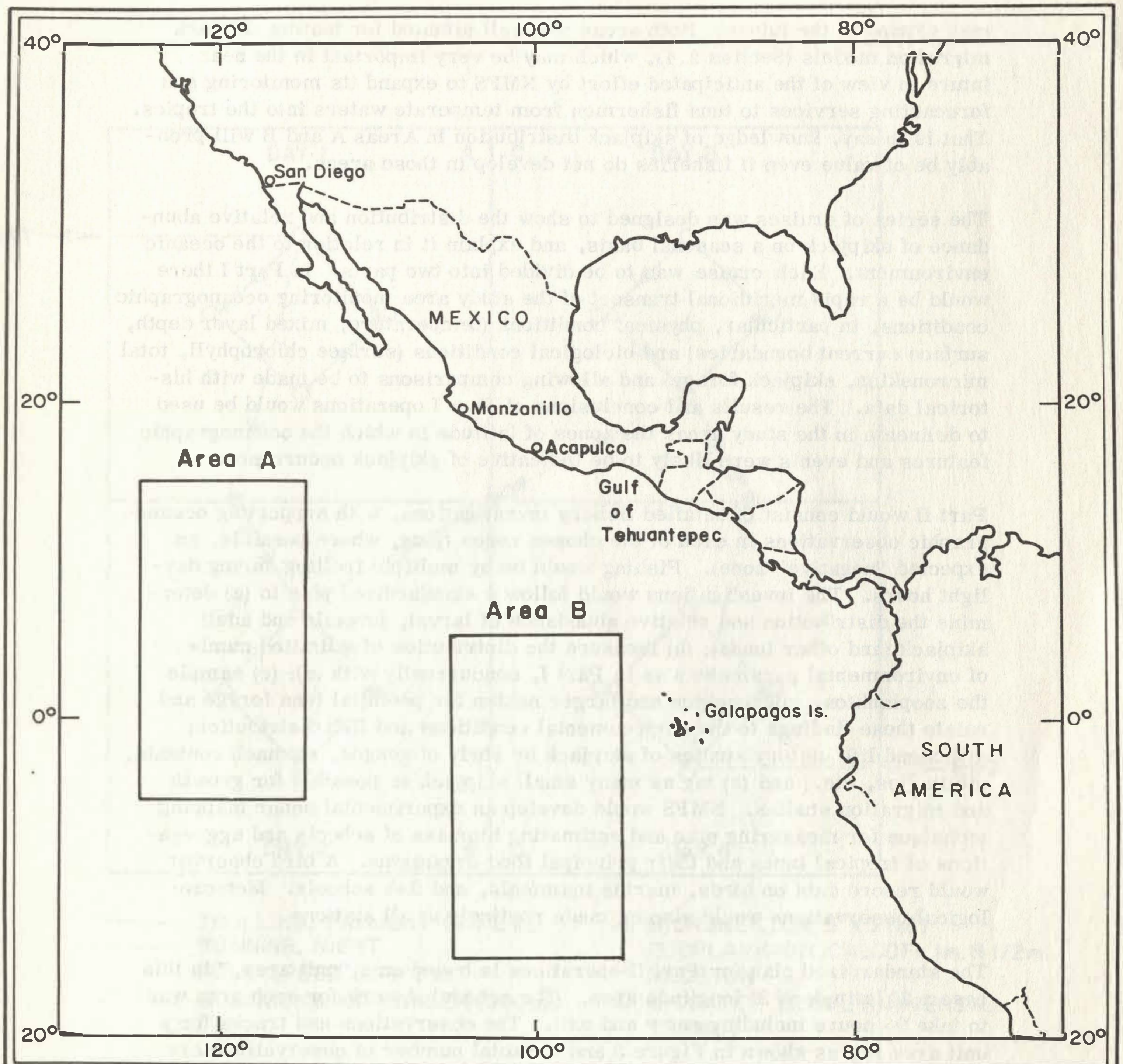

Figure 2. Areas of eastern tropical Pacific Ocean under investigation in skipjack oceanography and resource assessment cruises

may expand in the future. Both areas are well situated for testing skipjack migration models (Section 2.4), which may be very important in the near future in view of the anticipated effort by NMFS to expand its monitoring and forecasting services to tuna fishermen from temperate waters into the tropics. That is to say, knowledge of skipjack distribution in Areas A and B will probably be of value even if fisheries do not develop in those areas.

The series of cruises was designed to show the distribution and relative abundance of skipjack on a seasonal basis, and explain it in relation to the oceanic environment. Each cruise was to be divided into two parts. In Part I there would be a rapid meridional transect of the study area monitoring oceanographic conditions, in particular, physical conditions (temperature, mixed layer depth, surface current boundaries) and biological conditions (surface chlorophyll, total micronekton, skipjack forage) and allowing comparisons to be made with historical data. The results and conclusions of Part I operations would be used to delineate in the study areas the zones of latitude in which the oceanographic features and events were likely to be indicative of skipjack occurrence.

Part II would consist of detailed fishery investigations, with supporting oceanographic observations in each of the chosen zones (plus, where possible, an expected "negative" zone). Fishing would be by multiple trolling during daylight hours. The investigations would follow a standardized plan to (a) determine the distribution and relative abundance of larval, juvenile and adult skipjack (and other tunas); (b) measure the distribution of a limited number of environmental parameters as in Part I, concurrently with (a); (c) sample the zooplankton, micronekton and larger nekton for potential tuna forage and relate these findings to the environmental conditions and fish distribution; (d) extend life history studies of skipjack by study of gonads, stomach contents, pituitaries, etc.; and (e) tag as many small skipjack as possible for growth and migration studies. NMFS would develop an experimental sonar mapping technique for measuring size and estimating biomass of schools and aggregations of tropical tunas and their principal food organisms. A bird observer would record data on birds, marine mammals, and fish schools. Meteorological observations would also be made routinely at all stations.

The standardized plan for Part II operations is based on a "unit area," in this case a 2° latitude X 2° longitude area. The scheduled work for each area was to take 96 hours including entry and exit. The observations and tracks for a unit area are as shown in Figure 3 and the total number of observations are given in Table 2. Coverage in any zone could consist of any number of unit areas, or fractions of a unit area (quadrants or 1° X 1° areas).

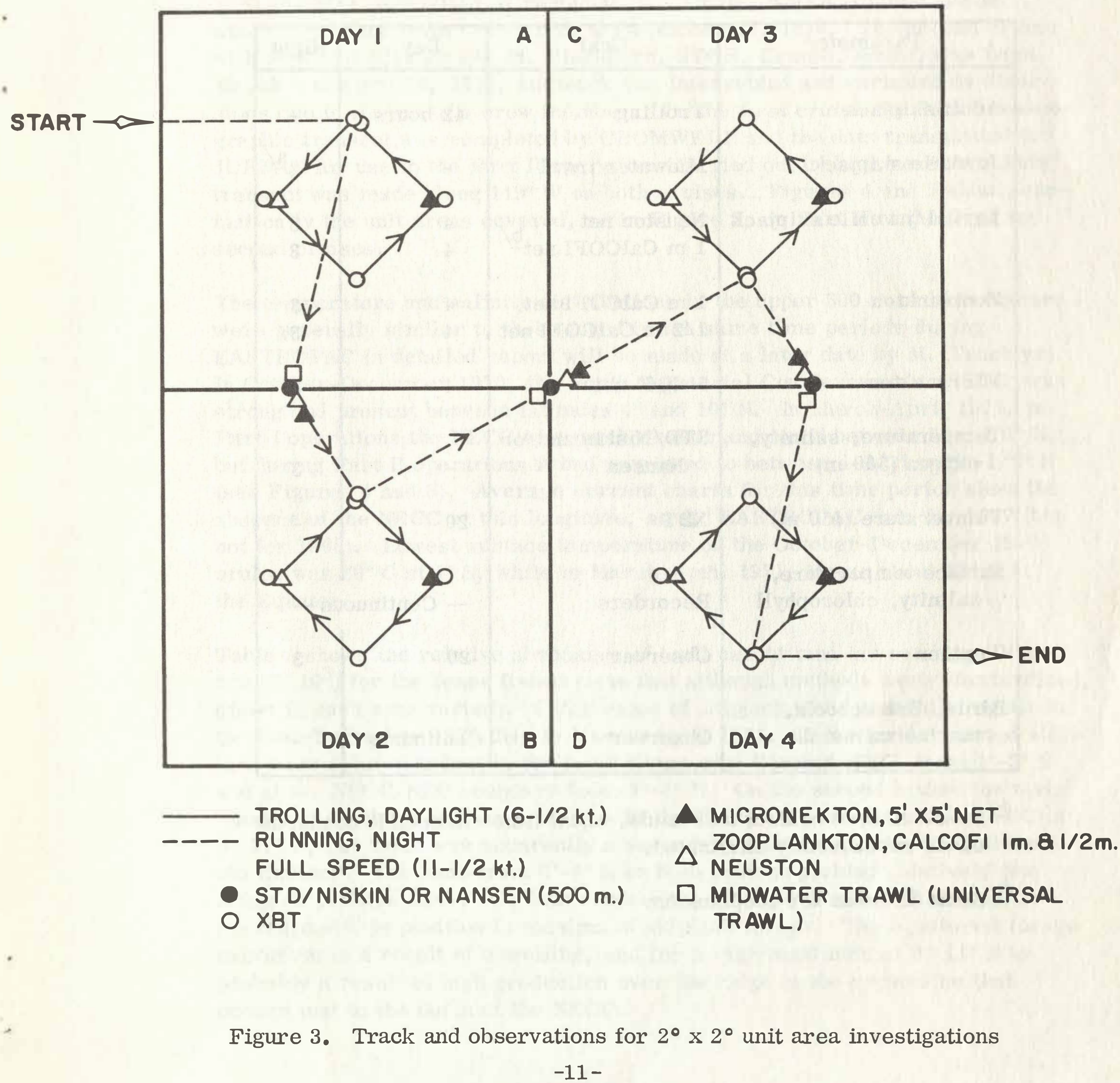

Figure 3. Track and observations for 2° x 2° unit area investigations

Table 2. Number of observations scheduled for each unit area (2° X 2° area) - Part II operations

Parameter	Gear	Day	Night
Adult skipjack	Trolling	42 hours	-
Juvenile skipjack	Midwater trawl	-	3[a/]
Larval/juvenile skipjack	Neuston net	4	3
	1 m CalCOFI net[b/]	4	3
Zooplankton	1 m CalCOFI net	4	3
	1/2 m CalCOFI net	4	3
Micronekton	5' X 5' net	4	3
Temperature, salinity, oxygen (500 m)	STD/Niskin and/or Nansen	-	3
Temperature (450 m)	XBT	20	-
Surface temperature, salinity, chlorophyll	Recorders	-- Continuous --	
Weather	Observer	20	3
Birds, fish schools, marine mammals	Observer	Continuous	-

a/ Seven on first cruise; four hauls, equal time either side of marine dawn, subsequently eliminated.

b/ Same hauls as for zooplankton.

Two cruises took place in 1970/71, both to Area A (Figure 2). The first cruise was a two-vessel operation with the NMFS R/V DAVID STARR JORDAN (Cruise 57: F. Williams, STOR, Cruise Leader) and the NMFS R/V TOWNSEND CROMWELL (Cruise 51: R. Uchida, NMFS, Cruise Leader), which took place from October 28 to December 17, 1970. The second cruise with JORDAN (Cruise 60: M. Blackburn, STOR, Cruise Leader) was from March 1 to April 16, 1971, but work was interrupted and curtailed by diversions due to illness of a crew member. On the first cruise the Part I oceanographic transect was completed by CROMWELL and the data transmitted to JORDAN for use in the Part II operations carried out by both vessels. This transect was made along 119° W on both cruises. Figures 4 and 5 show schematically the unit areas covered, as in Figure 3, on Part II of the first and second cruises.

The temperature and salinity distributions in the upper 500 m on both cruises were generally similar to those found in the same time periods during EASTROPAC (a detailed report will be made at a later date by M. Tsuchiya). In October-December 1970, the North Equatorial Countercurrent (NECC) was strong and present between latitudes 4° and 10° N. In March-April 1971, in Part I operations the NECC was much weaker and found between 5° and 8° N, but during Part II operations it had narrowed to between 4-1/2° and 6-1/2° N (see Figures 4 and 5). Average current charts for this time period show the absence of the NECC at this longitude, as did EASTROPAC data for 1967 (but not for 1968). Lowest surface temperature on the October-December 1970 cruise was 20° C at 1° S, while in March-April 1971, it was about 25° C at the Equator.

Table 3 shows the relative abundance of troll caught tuna (as catch per line-hour X 10^3) for the zones fished (note that although methods were standardized, effort in each zone varied). Catch rates of skipjack were generally higher in October-December 1970 than in March-April 1971. In the former period skipjack were most abundant in the South Equatorial Current (SEC) from 1°-3° N and at the NECC/SEC boundary from 3°-5° N. On the second cruise the main maximum of skipjack abundance was in the North Equatorial Current (NEC) at 9°-11° N, but there was apparently a secondary maximum in the SEC close to the Equator. The zone from 6°-8° N on both cruises yielded relatively few skipjack per line-hour. On both cruises the maxima of skipjack abundance corresponded in position to maxima of skipjack forage. The equatorial forage maximum is a result of upwelling, and the forage maximum at 9°-11° N is probably a result of high production over the ridge in the pycnocline that occurs just to the north of the NECC.

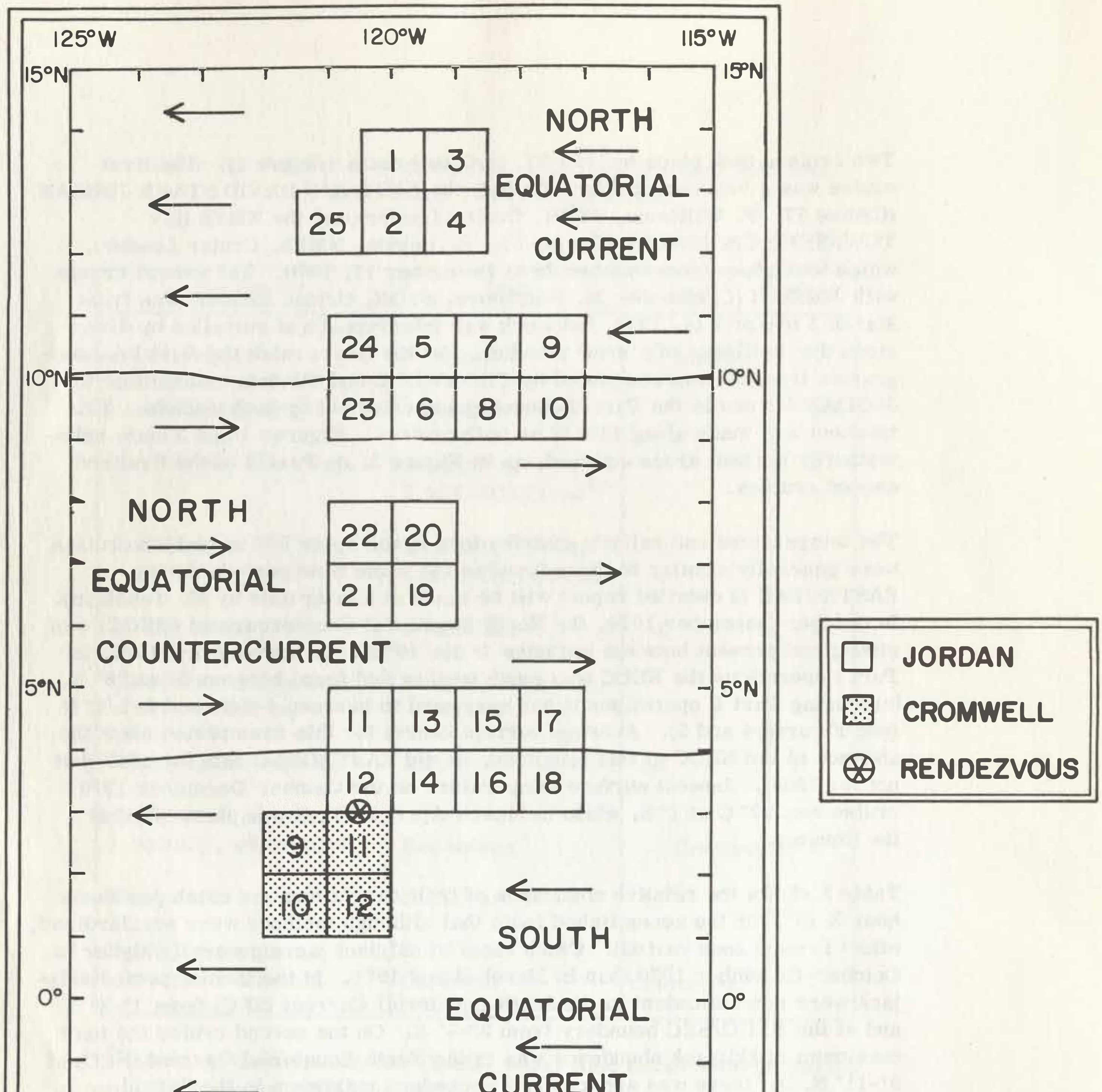

Figure 4. Unit areas investigated in Part II operations, CROMWELL 61–JORDAN 57, November–December, 1970 and relation to surface current systems. Numbers in fishing quadrants of unit areas denote order of occupation by vessels

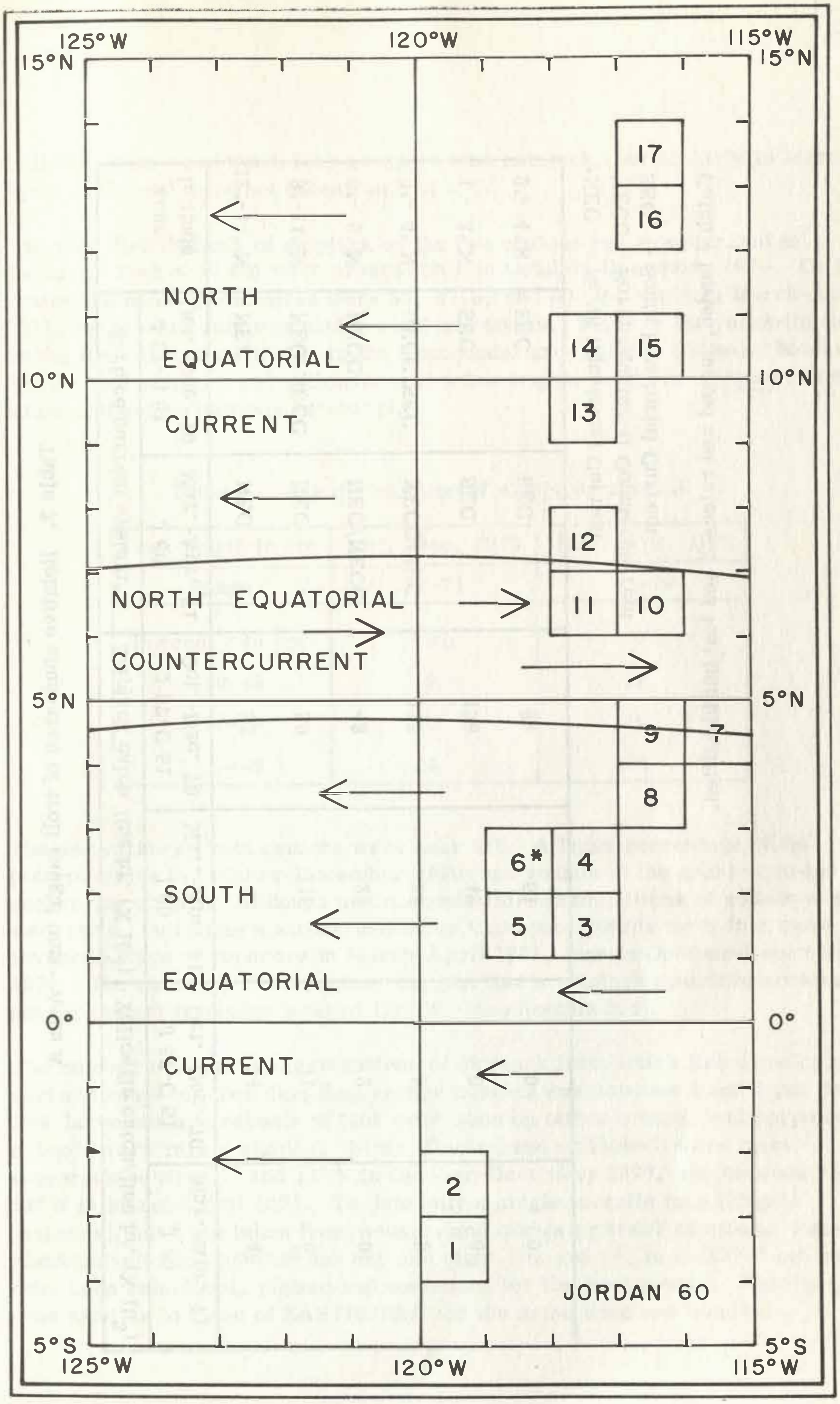

Figure 5. Unit areas investigated in Part II operations, JORDAN 60, March-April 1971, and relation to surface current systems. Numbers in fishing quadrants of unit areas denote order of occupation by vessel. *Indicates quadrant not completed

Table 3. Relative abundance of troll caught tuna—Area A

Zone latitude	Surface current system*		Skipjack catch/line hr. (X 10^3)		Yellowfin catch/line hr. (X 10^3)	
	J 57-C 51 Oct.-Dec. 70	J 60 Mar.-Apr. 71	J 57-C 51 Oct.-Dec. 70	J 60 Mar.-Apr. 71	J 57-C 51 Oct.-Dec. 70	J 60 Mar.-Apr. 71
12°-14° N	NEC	NEC	52	42	34	4
9°-11° N	NEC/NECC	NEC	39	116	11	0
6°- 8° N	NECC	NEC/NECC	43	21	2	0
3°- 5° N	NECC/SEC	NECC/SEC	115	28	8	3
1°- 3° N	SEC	SEC	196	49	0	0
2°- 4° S	SEC	SEC	82	51	0	0

*NEC - North Equatorial Current
NECC - North Equatorial Countercurrent
SEC - South Equatorial Current

Catch = landed, tagged and released and lost but identified.

Yellowfin tuna were much less abundant than skipjack, particularly in March-April 1971, and were not taken south of 3° N.

The size distributions of skipjack on the two cruises are summarized in Table 4. Fish < 40 cm were present only in October-December 1970. On that cruise the mean modal sizes were 35, 47.5, and 60 cm, while in March-April 1971, there were only two modes at 45 and 58 cm. Many of the yellowfin caught on the first cruise were also in the first modal group (mean 35 cm). Most of these small skipjack and yellowfin (and a few frigate mackerel - Auxis) were taken in the zone between 12°-14° N.

Table 4. Size distribution of skipjack—Area A

Fork length in cm	Oct.-Dec. 1970	Mar.-Apr. 1971
Range	32-71	41-70
Percent < 40 cm	13%	0%
40-49	9	12
50-59	54	46
> 59	24	42

The sex ratios on both cruises were near 1:1. A large percentage of fish (except males in October-December 1970) had gonads in the spent or spent-recovering stages. Although macroscopic field examinations of gonads were subjective, there was a strong indication that spent gonads were in a more advanced stage of recovery in March-April 1971, than in October-December 1970. The data from both cruises suggest that a skipjack spawning area was not far distant (probably west of 120° W - see Section 2.4).

The number of separate aggregations of skipjack from which fish were caught varied from 0 to 7 per day; the average number was between 1 and 2 per day. Few large surface schools of tuna were seen on either cruise, and porpoise schools were rarely sighted. Birds (flocked and unflocked) were most numerous between 7° and 11° N in October-December 1970, and between 9°-14° N in March-April 1971. To date only a single juvenile tuna (frigate mackerel) has been taken from neuston and midwater trawl samples. Zooplankton volumes/1000 m^3 for day and night 1 m and 1/2 m CalCOFI net hauls have been calculated, plotted and contoured for the first cruise. Results appear similar to those of EASTROPAC for the same time and longitude.

The schedule of skipjack resource assessment cruises required the third cruise to be made in Area B (see Figure 2) in the period August-October 1971. This cruise was made under STOR leadership and will be discussed in the next annual STOR report.

2.4. Models of Skipjack Migration
(F. Williams)

A draft manuscript has been prepared which considers three proposed models of the migration of young skipjack into the eastern Pacific Ocean. Last year a brief description was made of a single migration model; since then further investigations have led to proposing two other models.

The fishery for skipjack in the eastern Pacific is divided into two parts, the northern one from Baja California to Acapulco and the southern one from the eastern part of the Gulf of Tehuantepec to Peru, each including the adjacent offshore area. The skipjack in the eastern Pacific are relatively small and generally sexually immature. It is believed that fish of both fisheries originate in spawning areas in the central Pacific, west of 130° W. After a short period in the eastern Pacific fishery, the fish leave the coastal areas and probably do not re-enter the fishery to any great extent.

Active Migration Model.—In this model it was assumed that larvae and early juveniles are maintained in the central Pacific by some passive migration system(s). Juveniles at a certain size (probably <30 cm) make an active migration eastwards ending in the neritic feeding grounds off the American continent. Subsequent departure of the fish from these areas is attributed to a reproductive drive to return to the central Pacific where final maturation of the gonad occurs. The model briefly considers the inter-related roles of external stimuli (environmental conditions), and internal stimuli (endocrine secretions), in inducing the eastward migration.

The juvenile skipjack are considered to be in those parts of the west-flowing North Equatorial Current (NEC) and the South Equatorial Current (SEC) where the two main forage maxima are located, respectively just north and south of the NECC boundaries (see Section 2.3 above). It is hypothesized that the juveniles move continuously eastward until nearing the coast where from about August to April they migrate into the southern fishery areas. However, when the NECC is interrupted or ceases east of 120° W, in January/February to April/May the orientation and movement of the juveniles is affected. This is either directly through the current systems or indirectly through changes in the forage distribution. It is at this time that the initial movement towards the northern fishery areas is started, and some ideas are advanced in the model regarding the mechanisms for the reorientation northeastwards of the juvenile skipjack.

In essence it is proposed that a gating or shunting mechanism operates in the region of 120° W across the migration routes of the skipjack juveniles. The continuity of the NECC is the oceanographic feature involved, which in turn is controlled by the annual southward migration, and return, of the Intertropical Convergence Zone (ITCZ ≡ meteorological equator) and the subsequent changes in dominant wind fields. Thus variability both in the temporal and spatial aspects of the ITCZ movement may influence the eventual north-south distribution of recruit skipjack in the eastern Pacific fisheries.

Passive Migration Model.—In this model it is considered that many of the larval or early juvenile skipjack, spawned in the central Pacific, originate in, or are involuntarily carried into, the NECC, and are carried eastwards with it. Such a passive eastward migration eliminates the difficult problem of orientation in juvenile skipjack in the active migration model. The dispersion of the young skipjack from the terminus of the NECC into the southern fishery can easily be accounted for by an active migration. However, for the recruits to the northern fishery the problem is more complex and depends on whether the migration occurs when the NECC flows through to the American coast or when it is intermittent or stopped east of 120° W. In the former case the juveniles on reaching the NECC terminus would continue to be carried passively northwest along the coast of central America until they reached the Cape Corrientes-Revillagigedo Islands region. From there they could make an active migration into the northern fishery areas.

As the size at entry, but not the time of entry, to the northern and southern fishery areas is similar, there are obviously problems with the model related to the distribution of juveniles in the eastbound current, i.e. the NECC. However, these problems might be resolved if the northern and southern fisheries represented two spawning groups (6 months apart) with spawning areas showing some longitudinal separation. Thus the NECC could be carrying recruits of both spawning groups into the eastern Pacific fisheries at the same time but at different sizes.

Gyral Migration Model.—This model involves all life history stages of skipjack and both active and passive migrations.

For the northern fishery group it is proposed that the fish are moving counter-clockwise in a zonally narrow equatorial gyre consisting of the NECC and the NEC with the western limit of the gyre west of 130° W (possibly as far as 170° W) and the eastern limit the American coast. Spawning takes place to the west of 130° W and the larvae and juveniles are then passively carried into and in the east-flowing NECC. The majority of the juveniles on reaching the NECC terminus are then transported northwestwards in the coastal current to the area of Cape Corrientes and the Revillagigedo Islands. During the whole of this time the movement of the adults probably parallels the juveniles but with a wider distribution and no restriction to the NECC. In the area of Cape Corrientes the coastal current turns west and offshore and is joined by the California Current Extension and the gyre is then completed towards the southwest (the NEC). On reaching the Cape Corrientes-Revillagigedo Islands area the juveniles migrate actively out of the gyre into the Baja California feeding grounds. At the end of the feeding season the sexually maturing young fish move southwest to rejoin the adults which remained mainly offshore in the gyre. Both groups then migrate southwest in the gyre to the spawning grounds.

The southern fishery stock is moving clockwise in a gyre formed by the NECC and the SEC, and spawning takes place in the equatorial central Pacific. The juveniles are carried eastwards in the NECC and on reaching the coast the young fish migrate actively into the areas of the southern fishery. Again adult movements would probably parallel those of the juveniles, but mainly in the SEC and remaining outside of the coastal fishery. After feeding, the young fish rejoin the adults for return to the spawning grounds in the SEC. There are considerable problems in the southern gyral model related to the recruitment into the eastbound NECC of larvae and early-juveniles spawned well south of the Equator. The role of a surface South Equatorial Countercurrent in resolving this and other problems in the model is considered.

The hypothetical nature of certain aspects of these three migration models is clear. However, a full presentation of existing data and ideas in the form of models serves a useful purpose at this time, because the skipjack assessment cruises (Section 2.3) provide a good opportunity to test the models.

3. EFFECTS OF NUTRIENTS AND POLLUTANTS ON THE GROWTH OF MARINE PHYTOPLANKTON

(W. H. Thomas and Anne N. Dodson)

Besides maintaining some 70 cultures of tropical oceanic and subtropical coastal species of phytoplankton, we are continuing experimental work on their nutritional, particularly nitrogenous, requirements. During this period we have completed work on chemostat cultures where we wanted to quantify nitrogen deficiency and on a new method of measuring phytoplankton growth using in vivo fluorescence.

During the final EASTROPAC cruise in 1968, water samples from a depth of 10 m were taken in both poor (nitrate-free) and rich (nitrate-containing) tropical Pacific water. Photosynthesis in such samples was expressed as rates at light saturation per amount of chlorophyll. This expression is called the assimilation ratio. Ratios in poor water were significantly lower than ratios in rich water, but the difference was not great. We concluded that cells in poor water were qualitatively not very nitrogen deficient.

This was only a qualitative conclusion and we have made a quantitative study of deficiency by growing cells in a chemostat at precisely controlled growth rates. With such cells we measured assimilation ratios, pigment ratios, and cell carbon/nitrogen ratios and have related these to the growth rate which was expressed as a percentage of the maximum growth rate, μ_{max}. These studies have been completed and a manuscript entitled "On nitrogen deficiency in tropical Pacific oceanic phytoplankton. II. Photosynthetic and cellular characteristics of a chemostat-grown diatom" has been submitted to Limnology and Oceanography. An abstract follows:

"Cells of the tropical Pacific diatom, Chaetoceros gracilis, were grown in a nitrogen-limited chemostat at varying percentages of the maximum growth rate. At each rate, cells were harvested and photosynthetic and cellular parameters were measured. Assimilation ratio (photosynthesis at light saturation per unit chlorophyll) increased with increasing growth rate while dark uptake of ^{14}C decreased. Cellular C/chlorophyll ratios also decreased with increasing growth rate, but carotenoid/chlorophyll ratios showed no obvious trend. The C/N ratio decreased and chlorophyll/cell increased with increasing growth rate. Steady-state cell numbers were not constant at different growth rates, but decreased as the rates increased. Growth rates seemed to be controlled by internal supplies of nitrogen, and the apparent half-saturation constant, K_s', decreased with increasing growth rate. The results are discussed in relation to field measurements of some of these parameters and in relation to other work with algal chemostats."

For studies on the effects of light and temperature on nutrient requirements, a rapid means of assaying algal growth rates in small scale cultures was needed. Previously we had used in vivo fluorescence to measure growth in cultures of natural communities, so we made a critical study of the method for laboratory cultures grown under various conditions. The work was completed during this period and a manuscript entitled "Measuring growth rates of marine phytoplankton by in vivo fluorescence" was submitted to the Journal of Phycology for publication. An abstract is as follows:

"Growth rates of seven marine planktonic algae were measured under near-optimal conditions by successive daily in vivo fluorescence assays. These rates compared favorably with rates calculated from successive increases in cell numbers. With Asterionella japonica there was no statistically significant difference in rates measured by either method. The response of growth rates of this alga to varying temperatures was similar when rates were measured by both methods. Rates of A. japonica measured by fluorescence saturated at a lower light intensity than cell division rates. Using fluorescence to assess the effects of nitrate concentration on growth rates of A. japonica showed that K_s values similar to previous values could be obtained. K_s values from cell division rates were somewhat lower than the value obtained by in vivo fluorescence rates, but were within the confidence limits of previous values. In the experiment on nitrate effects, the maximum growth rate from fluorescence increase was not statistically different from μ_{max} calculated from cell number increases."

4. PUBLICATIONS, MANUSCRIPTS, AND REPORTS

The following 10 papers from the STOR Program were published during the year ended June 30, 1971:

1. Blackburn, M., R. M. Laurs, R. W. Owen, and B. Zeitzschel. (1970). Seasonal and areal changes in standing stocks of phytoplankton, zooplankton, and micronekton in the eastern tropical Pacific. Marine Biology 7(1): 14-31.

2. Blackburn, M., W. H. Thomas, and B. Zeitzschel. (1970). Micronekton (part); Nutrient chemistry; Phytoplankton (part); April-July 1967. In EASTROPAC Atlas, Vol. 4, National Marine Fisheries Service, Circular 330.

3. Blackburn, M., W. H. Thomas, and B. Zeitzschel. (1971). Micronekton (part); Nutrient chemistry; Phytoplankton (part); February-March 1967. In EASTROPAC Atlas, Vol. 2, National Marine Fisheries Service, Circular 330.

4. Jerde, C. W. (1970). Further notes on the distribution of Portunus xantusii affinis and Euphylax dovii (Decapoda Brachyura, Portunidae) in the eastern tropical Pacific. Crustaceana 19(1): 84-88.

5. Owen, R. W. and B. Zeitzschel. (1970). Phytoplankton production: seasonal change in the oceanic eastern tropical Pacific. Marine Biology 7(1): 32-36.

6. Thomas, W. H. and R. W. Owen. (1971). Estimating phytoplankton production from ammonium and chlorophyll concentrations in nutrient-poor water of the eastern tropical Pacific Ocean. National Marine Fisheries Service, Fishery Bulletin 69(1): 87-92.

7. Thomas, W. H., E. H. Renger, and A. N. Dodson. (1971). Near-surface organic nitrogen in the eastern tropical Pacific Ocean. Deep-Sea Research 18: 65-71.

8. Williams, F. (1970). Sea surface temperature and the distribution and apparent abundance of skipjack (Katsuwonus pelamis) in the eastern Pacific Ocean, 1951-1968. Inter-American Tropical Tuna Commission, Bulletin 15(2): 229-281.

9. Williams, F. (1971). Current skipjack oceanography cruises in eastern tropical Pacific Ocean. Commercial Fisheries Review 33(2): 29-38.

10. Zeitzschel, B. (1970). The quantity, composition and distribution of suspended particulate matter in the Gulf of California. Marine Biology 7(4): 305-318.

The following six papers from the STOR Program were in press or had been submitted on June 30, 1971:

11. Blackburn, M. and R. M. Laurs. Distribution of forage of skipjack tuna (*Euthynnus pelamis*) in the eastern tropical Pacific. National Marine Fisheries Service, Special Scientific Report Fisheries.

12. Longhurst, A. R. and D. L. Seibert. Oceanic distribution of *Evadne* in the eastern Pacific. Crustaceana.

13. Longhurst, A. R. and D. L. Seibert. Breeding in an oceanic population of *Pleuroncodes planipes* (Crustacea, Galatheidae). Pacific Science (published July 1971).

14. Thomas, W. H. and A. N. Dodson. On nitrogen deficiency in tropical Pacific oceanic phytoplankton. II. Photosynthetic and cellular characteristics of a chemostat-grown diatom. Limnology and Oceanography.

15. Thomas, W. H. and A. N. Dodson. Measuring growth rates of marine phytoplankton by *in vivo* fluorescence. Journal of Phycology.

16. Tsuchiya, M. Physical oceanography (part); April-July 1967. *In* EASTROPAC Atlas, Vol. 3.

The following reports from the STOR Program were distributed in mimeograph form:

IMR Ref. 71-3 (SIO Ref. 70-32). Progress report of the STOR Program for the year July 1969-June 1970. (M. Blackburn).

IMR Ref. 71-9. Final report. Effects of nutrients on growth of algae: tropical oceanic phytoplankton. (W. H. Thomas).

The cumulative list of STOR research papers arising from the EASTROPAC expedition, exclusive of the EASTROPAC Atlas itself, is as follows:

Numbers 1, 4, 5, 6, 7, 11, 12, 13, in list above, plus the following three earlier papers:

Thomas, W. H. (1969). Phytoplankton nutrient enrichment experiments off Baja California and in the eastern equatorial Pacific Ocean. Journal of the Fisheries Research Board of Canada 26: 1133-1145.

Thomas, W. H. (1970). On nitrogen deficiency in tropical Pacific oceanic phytoplankton: photosynthetic parameters in poor and rich water. Limnology and Oceanography 15(3): 380-385.

Thomas, W. H. (1970). Effect of ammonium and nitrate concentration on chlorophyll increases in natural tropical Pacific phytoplankton populations. Limnology and Oceanography 15(3): 386-394.

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