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# Biology, Oceanography, and Fisheries of the North Pacific Transition Zone and Subarctic Frontal Zone

Jerry A. Wetherall (editor)

U.S. Department of Commerce

# *NOAA Technical Report NMFS*

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# Biology, Oceanography, and Fisheries of the North Pacific Transition Zone and Subarctic Frontal Zone

*Papers from the North Pacific*
*Transition Zone Workshop*
*Honolulu, Hawaii*
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Jerry A. Wetherall (editor)

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# *Contents*

# Preface

In the past few years, large-scale, high-seas driftnet fishing has sparked intense debate and political conflict in many oceanic regions. In the Pacific Ocean the driftnet controversy first emerged in the North Pacific transition zone and subarctic frontal zone, where driftnet vessels from Japan, the Republic of Korea, and Taiwan pursue their target species of neon flying squid. Other North Pacific driftnet fleets from Japan and Taiwan target stocks of tunas and billfishes. Both types of driftnet fishing incidentally kill valued non-target species of marine life, including fish, mammals, birds, and turtles.

In response to public concerns about driftnet fishing, government scientists began early on to assemble available information and consider what new data were required to assess impacts on North Pacific marine resources and the broader pelagic ecosystem. Accordingly, a workshop was convened at the NMFS Honolulu Laboratory in May 1988 to review current information on the biology, oceanography, and fisheries of the North Pacific transition zone and subarctic frontal zone. The workshop participants, from the United States and Canada, also developed a strategic plan to guide NMFS in developing a program of driftnet fishery research and impact assessment.

This volume contains a selection of scientific review papers presented at the 1988 Honolulu workshop. The papers represent part of the small kernel of information available then, prior to the expansion of cooperative international scientific programs. Subsequent driftnet fishery monitoring and research by the United States, Canada, Japan, Korea, and Taiwan have added much new data. Nevertheless, this collection of papers provides a historical perspective and contains useful information not readily available elsewhere.

Jerry A. Wetherall
Honolulu, August 1991

# Subarctic-Subtropical Transition Zone of the North Pacific: Large-Scale Aspects and Mesoscale Structure

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## ABSTRACT

The subarctic-subtropical transition zone of the North Pacific is investigated on the basis of high resolution hydrographic data. The transition zone is an oceanwide feature associated with the oceanic and atmospheric gyre scale circulations. It is bounded in the north and south by frontal zones, in which one or several meandering fronts and frontal eddies occur. The positions of the transition and frontal zones do not vary by more than 150–200 km from their climatological mean positions. Individual fronts are highly variable in time and space. The northern boundary of the transition zone is marked by the disappearance of the subarctic halocline and the overlying shallow temperature minimum, and by large changes in the hydrostatic stability structure. A seasonal stability gap develops there in winter. The interannual variability of the subarctic front depends upon the flow dynamics at the particular geographical location. Over the Emperor Seamounts, the front appears to be topographically trapped, varying by not more than 50 km from its mean position at 43° N during 1981–1986; elsewhere, the displacements from the mean are about 150 km. The southern boundary of the transition zone is best described by the disappearance of the subtropical halocline and by large changes in the structure of the thermocline. A pervasive mesoscale eddy field is always present within the transition zone. The amplitudes of these eddies are three times larger west than east of the Emperor Seamounts.

## Introduction

The subarctic-subtropical transition zone is one of the main oceanic features of the North Pacific. It lies between the subarctic and subtropical gyres and extends from Japan to North America, a distance of nearly 9000 km (Fig. 1). Its average meridional extent in mid-ocean is about 1000 km. The northern and southern boundaries of the transition zone have the character of frontal zones, in which there are rapid changes in thermohaline structure, hydrostatic stability structure, and biological species composition. The climatological mean positions of the transition zone boundaries are at latitudes 32° N and 42° N. In the central North Pacific, the typical subarctic domain with its cool and low salinity surface water disappears within less than 150 km of 42° N (Dodimead et al. 1963; Uda 1963; Roden 1970). As one proceeds southward across the transition zone, temperatures and salinities gradually increase. Then, within 150 km of 32°N, there is a rapid change to the subtropical domain with its warm and salty top layer (Sverdrup et al. 1942; Seckel 1968; Roden 1970, 1980).

The frontal zones are of biological interest also, because they delineate species distributions. Thus, the copepods *Euphausia pacifica* and *longipes* occur only north of the subarctic boundary, *Euphausia brevis* is found only south of the subtropical boundary, while *Thysanoessa gregaria* is encountered almost exclusively in the transition zone between the subarctic and subtropical domains (Brinton 1962). Fishermen, too, are attracted to frontal zones because of improved fishing there.

The transition zone is the result of the large scale ocean circulation and air-sea energy exchange and some progress has been made in understanding the dynamics and structure of this zone and the associated frontal zones (Roden 1975, 1977a, 1981; Roden and Paskausky 1978; Camerlengo 1982; Cushman-Roisin 1981; Niiler and Reynolds 1984; Rhines 1986; Roden and Robinson 1988). The picture that emerges is one of subtle balances among mixing, advection, diffusion, and atmospherically induced surface heat, salt, and momentum fluxes which lead to thermohaline structures that occur in geographically preferred regions.

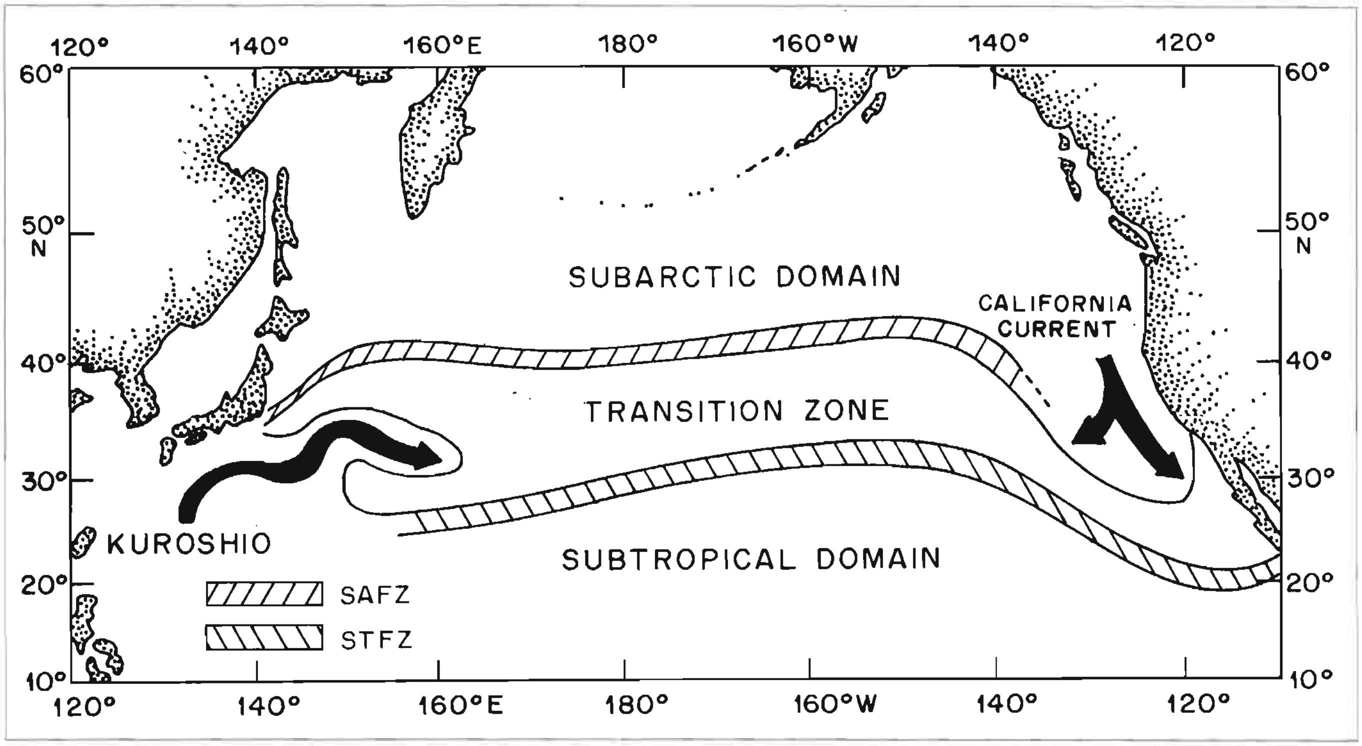


Figure 1

Schematic diagram showing the locations of the subarctic and subtropical domains, the transition zone and the associated subarctic frontal zone (SAFZ) and the subtropical frontal zone (STFZ). Black arrows indicate boundary current intrusions.

While the transition zone and associated subarctic and subtropical frontal zones are large scale and semi-permanent, there are mesoscale perturbations embedded in them that are highly time variable. They reflect the combined effects of intrusive boundary current instability (Holland et al. 1983; Watts 1983), weather disturbances (Frankignoul and Müller 1979; Müller and Frankignoul 1981), Rossby waves (Kang and Magaard 1980, 1982), mixing (Rudnick and Davis 1988), and topography, such as seamounts and seamount chains (Roden 1987). Chief among the observed mesoscale features are meandering fronts (Roden 1981; Van Woert 1982; Lynn 1986), jets (Kawai 1972; Woods 1988), propagating eddies (Kitano 1975; Kirwan et al. 1978; Bernstein 1983), trapped vortices (Roden and Taft 1985), and topographic boundary current deflections (Vastano et al. 1985; Roden 1987).

On synoptic time scales, these mesoscale perturbations often dominate the transition zone and the subarctic and subtropical frontal zones. This is seen in satellite infrared images (Legeckis 1978), satellite altimeter records (Cheney et al. 1983), high resolution dynamic height sections (Roden 1977b), and direct current measurements (Schmitz 1987). The findings indicate that the mesoscale variability in the transition zone varies strongly with longitude in a nonuniform manner: west of the Emperor Seamounts the amplitudes of the mesoscale perturbations are 3 to 6 times larger than east of it. This variability can be related to the presence of the Kuroshio extension and rugged topography in the western North Pacific basin and to the absence of strong boundary currents and high amplitude topography in the mid-latitudes of the eastern basin.

The above features indicate that to understand the synoptic thermohaline structure in the transition zone, both the large scale flow and the mesoscale perturbations need to be known. The purpose of the present paper is to discuss the large and mesoscale aspects of the transition zone and the accompanying subarctic and subtropical frontal zones based on recent observations and to elucidate the salient features.

## Transition and Frontal Zone Terminology

In discussing the oceanography of the North Pacific, it is useful to distinguish among water source domains, transition zones, frontal zones, individual fronts, and climatological mean fronts. A schematic vertical section through the subarctic-subtropical transition zone is shown in Figure 2.

The **subarctic domain** extends northward of about 43° N to Alaska and is characterized by a cool, low salinity surface layer, about 120 m deep in winter and 30 m deep in summer. A well defined permanent halocline occurs between about 120 and 180 m, which is usually

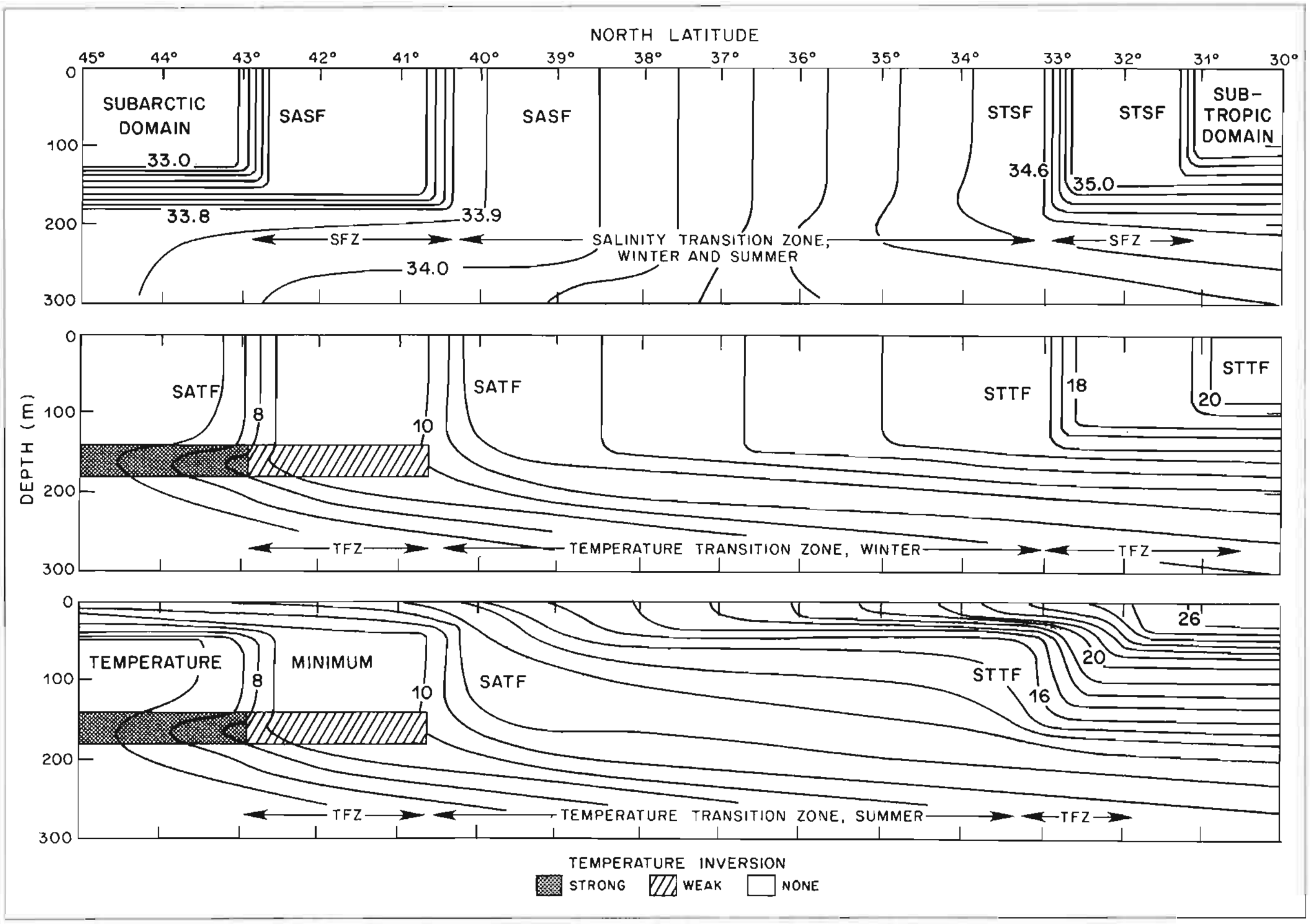


Figure 2

Schematic vertical section through the subarctic-subtropical zone in mid-ocean. Note the occurrence of temperature inversions in the halocline. SASF=subarctic salinity front; SATF=subarctic temperature front; STSF=subtropical salinity front, STTF=subtropical temperature front, TFZ=temperature frontal zone; and SFZ=salinity frontal zone.

bounded by the 33.0 and 33.8‰ isohalines. A persistent temperature inversion is often found in the permanent halocline. During summer, a distinct temperature minimum is encountered between the bottom of the shallow thermocline and the underlying temperature inversion. This minimum can be traced over long distances in the central and western parts of the domain (Uda 1963; Roden 1964). The subarctic temperature-salinity relation ($\theta/S$) is noted for a rather constant temperature in the salinity range from 33.0–33.8‰ (Fig. 3, left).

The **subtropical domain** extends southward from 31°N to about 20°N and is characterized by a warm, saline surface layer, about 125 m deep in winter and 60 m deep in summer. The 34.6 and 35.3‰ isohalines are usually embedded in the sharp upper halocline. In the eastern part of the domain, a shallow salinity minimum occurs beneath the salty top layer, containing modified subarctic and California current water (Reid 1973; Talley 1985). The subtropical $\theta/S$ relationship has a distinctive C-shaped curve, with a well developed intermediate depth salinity minimum of 34.0‰ near 600 m (Fig. 3, right).

The region between the subarctic and subtropical domains is occupied by the **transition zone,** where temperatures and salinities gradually increase southward. In this zone, waters of both subarctic and subtropical origin are present in various proportions, depending upon distance from the source regions. Near the center of the transition zone in mid-ocean, the $\theta/S$ relationship indicates an equal mixture of subarctic and subtropical waters (Fig. 3, middle). A closer look at the thermohaline structure reveals, however, that the change from purely subarctic to mixed subarctic-subtropical water and from this water to purely subtropical water is not uniform, but occurs rather abruptly near the northern and southern limits of the transition zone, which have the character of frontal zones.

The **subarctic frontal zone** in the mid-Pacific extends from about 40° N to 43° N. The southern limit is best

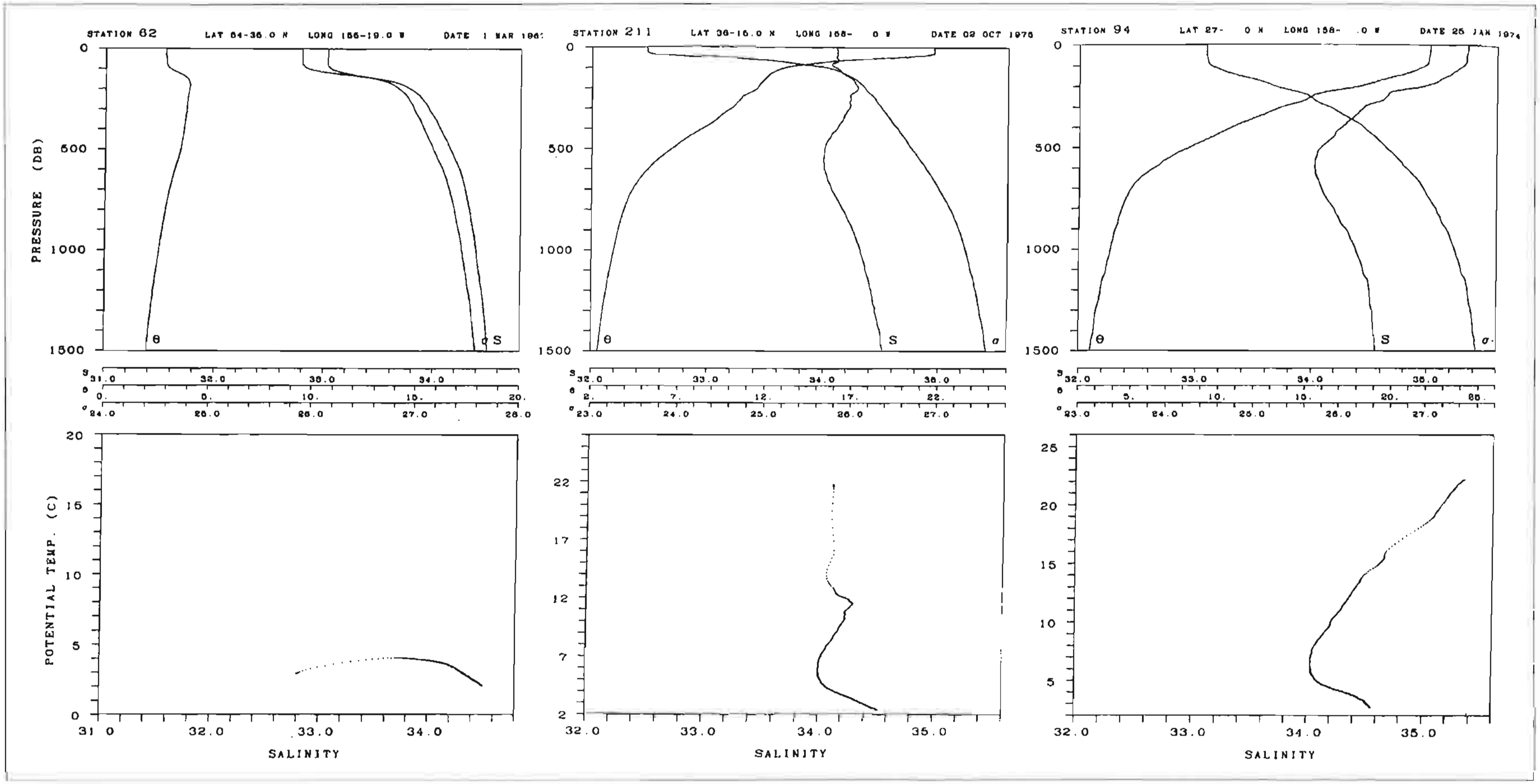


**Figure 3**

Characteristic vertical profiles of potential temperature, θ (c), salinity, *S* (‰), density, σ (kgm$^{-3}$), and characteristic potential temperature-salinity curves in the subarctic domain (**left**), in the subactic-subtropical transition zone (**middle**), and in the subtropical domain (**right**) in the central North Pacific.

defined by the outcrop of the 33.8‰ isohaline, which forms the bottom of the halocline in the subarctic domain (Fig. 2). The northern limit can be defined similarly by the outcrop of the 33.0‰ isohaline, which lies near the top of the subarctic halocline. It is also possible to define the southern limit of the subarctic frontal zone by the vanishing of large temperature inversions (>0.25° C), which can exist only within the subarctic halocline, for reasons of hydrostatic stability (Roden 1964, 1977a), and by the rapid increase in the depth of the 9° C and 10° C isotherms below the shallow seasonal thermocline.

The **subtropical frontal zone** in the mid-Pacific extends from about 31° N to 34° N. In winter, the northern limit is best described by a thermohaline front, in which the 34.8‰ isohaline and the 18° C isotherm are embedded (Roden 1980). In summer, only a salinity front is seen at the surface. Below the shallow seasonal thermocline, the temperature front can sometimes be located by the rapid change in depth of the 18° C and 20° C isotherms. The southern limit of the subtropical frontal zone can be described by the outcrop of the 35.2‰ isohaline, which lies near the top of the subtropical halocline.

One or several **individual fronts** occur in each of the frontal zones. The individual fronts at any given time are convoluted in shape, meander and shed eddies that retain their frontal characteristics. These individual fronts and eddies are in various stages of formation and decay (Roden 1981) and are of prime importance in understanding mesoscale physical processes and biological patchiness (Woods 1988).

When the individual fronts and eddies are averaged over time and space, the irregularities disappear and a single **climatological mean front appears.** In mid-ocean, the climatological mean position of the subarctic front is near 42° N and that of the subtropical front is near 32° N. Such climatological mean fronts are rarely seen in synoptic and quasisynoptic surveys.

For understanding processes of transition and frontal zone formation, it is important to distinguish also between

**Confluence,** which is related to the deformation field of flow, denotes the sidewise approach of currents from different directions and does not entail vertical velocity, and

**Convergence,** which basically expresses the decrease of current speed in the direction of flow. It can occur in unidirectional flow and is associated with a vertical velocity component.

While frontal zones occur in geographically preferred regions in response to the gyre-scale circulation and large-scale atmospheric and topographic forcing, individual fronts can occur anywhere in the ocean whenever confluent or convergent flow interacts with the ambient stratification. A clear distinction must be made, therefore, between upper ocean frontal zones, which are source water domain boundaries, and individual fronts, which do not always separate water masses of different origin (Roden 1980; Fedorov 1986).

Oceanic temperature, salinity, and density fronts do not always coexist nor penetrate to the same depth. For this reason, it is always necessary to specify the variable, in order to avoid ambiguities. For example, upper ocean temperature and salinity fronts are strong in the subarctic region of the western and central North Pacific, yet the subarctic surface density fronts are weak or nonexistent, because of a near balance of the horizontal temperature and salinity gradients. Likewise, in the subtropical frontal zone, the well-defined upper ocean salinity fronts are not accompanied by any temperature fronts during summer, because intense solar radiation has obliterated the wintertime horizontal temperature gradients.

## Large Scale Aspects of the Transition and Frontal Zones

### Basic Processes of Formation

The transition and associated frontal zones are features of the oceanic and atmospheric general circulation and represent regions of enhanced horizontal temperature and salinity gradients. To understand the formation of these zones, it is necessary to investigate processes that determine the intensities of these gradients. In the absence of molecular fluxes, horizontal temperature and salinity gradients will intensify when (Roden 1975)

$$\frac{\partial}{\partial t}|\nabla_H\theta| = -\frac{\partial}{\partial n}(\bar{v}_{n\theta}|\nabla_H\theta|) - \frac{\partial}{\partial n}\left(\bar{w}\frac{\partial\bar{\theta}}{\partial_z}\right) - \frac{\partial}{\partial n}\left(\frac{1}{\rho\bar{c}_{vs}}\frac{\partial\bar{q}_z}{\partial z}\right) - \frac{\partial}{\partial n}\frac{\partial\langle w'\theta'\rangle}{\partial z} > 0 \qquad (1)$$

and

$$\frac{\partial}{\partial t}|\nabla_{-H}S| = -\frac{\partial}{\partial n}(\bar{v}_{ns}|\nabla_{-H}\theta|) - \frac{\partial}{\partial n}\left(\bar{w}\frac{\partial S}{\partial z}\right) - \frac{\partial}{\partial n}\left(\frac{1}{\rho}\frac{\partial s_z}{\partial z}\right) - \frac{\partial}{\partial n}\frac{\partial\langle w'S'\rangle}{\partial z} > 0 \qquad (2)$$

where the bars represent the mean values and the primes the turbulent fluctuations, $|\nabla_H\theta|$ and $|\nabla_H S|$ the magnitudes of the horizontal temperature and salinity gradients, $\rho$ is density, $c_{vs}$ is the specific heat at constant volume and salinity, $t$ is time, $z$ is depth, $v_{n\theta}$ is the horizontal velocity component normal to the temperature front, $v_{ns}$ is the horizontal velocity component normal to the salinity front (the normals n are taken in the direction of increasing values of $\theta$ and $S$), $q_z$ is the vertical component of net radiative heat flux, $s_z$ is the vertical component of freshwater (precipitation) flux, and $\langle w'\theta' \rangle$ and $\langle w'S' \rangle$ are the turbulent heat and salt fluxes.

The dynamics of transition and frontal zone formation are contained in the four right hand terms of Equations 1 and 2. They depend upon the joint effects of velocity shear, thermohaline stratification, and geographically varying heat and salt fluxes. The relevant physical processes can be summarized as follows:

1) Differential horizontal advection of temperature and salinity. These processes will increase the intensity of horizontal gradients in regions of current confluence and convergence.

2) Differential vertical advection of temperature and salinity. These processes will increase the intensity of horizontal gradients in regions where large horizontal shear of the vertical velocity component occurs in the thermocline or halocline. Differential Ekman pumping atop the thermocline is an example.

3) Differential radiative heat and freshwater fluxes. These processes will increase the intensity of horizontal gradients in the vicinity of large scale cloudiness and precipitation fronts and are important only in the upper layer of the ocean. The doldrum salinity fronts are an example (Roden 1975).

4) Differential turbulent heat and salt fluxes. These processes act on both large and small scales increasing the intensity of horizontal gradients near climatic transition zones which, in turn, lead to buoyancy flux and double diffusion fronts (Rostov and Zhabin 1987).

Terms 1), 2), and 4) involve the configuration of the wind field. In regions away from boundary currents, the wind field configuration often plays the dominant role, where frontal zones are formed (Roden 1980, 1981; Camerlengo 1982). Equations 1 and 2 imply that the intensification of horizontal gradients depends upon the sum of the four terms being positive; it is not necessary that each individual term is positive.

Horizontal density gradients are linked to horizontal temperature and salinity gradients by the equation of state for seawater (Gill 1982). to first approximation, the horizontal density gradients will intensify when

$$\frac{1}{\rho}\frac{\partial}{\partial t}|\nabla_H \rho| = -\frac{\partial}{\partial t}\left|\left(\frac{1}{\rho}\frac{\partial \rho}{\partial \theta}\right)\nabla_H \theta + \left(\frac{1}{\rho}\frac{\partial \rho}{\partial S}\right)\nabla_H S\right| > 0 \qquad (3)$$

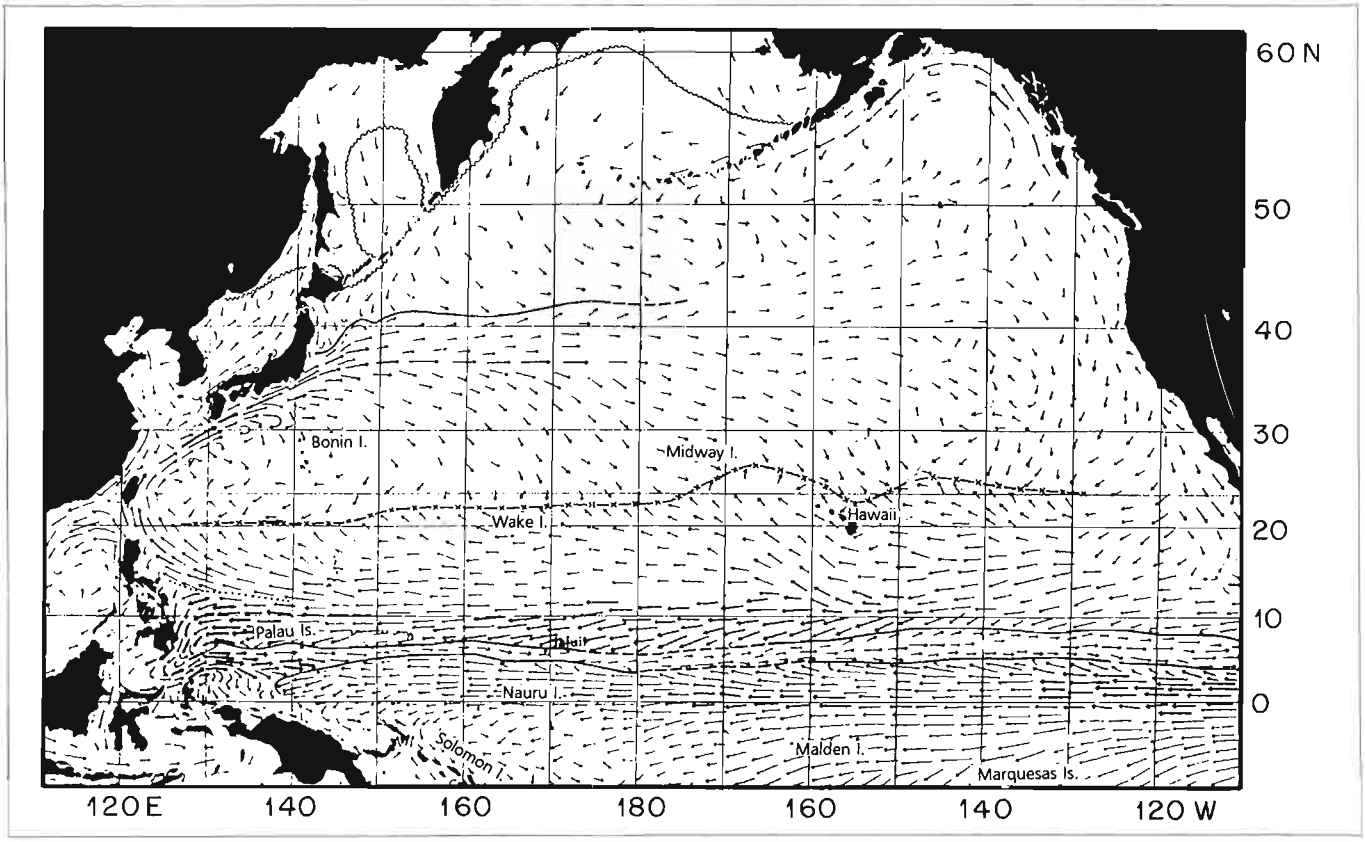


**Figure 4**

Surface currents in the North Pacific during winter. Solid black lines indicate clearly defined current boundaries, dashed lines less clearly defined ones. After Schott (1943).

The coefficient $\frac{1}{\rho}\frac{\partial\rho}{\partial\theta}$ varies from $-1 \bullet 10^{-4}$ °$C^{-1}$ at 0° C to $-3 \bullet 10^{-4}$ °$C^{-1}$ at 26° C, while $\frac{1}{\rho}\frac{\partial\rho}{\partial S}$ varies from $7.8 \bullet 10^{-4}$ $(‰)^{-1}$ at 0° C to $7.3 \bullet 10^{-4}$ $(‰)^{-1}$ at 26° C under oceanic conditions. Typical cross-frontal temperature and salinity differences vary between 2 and 10° C and 0.3–1.2‰, respectively. Because the thermodynamic coefficients are of opposite signs, while large scale horizontal temperature and salinity gradients in the transition and frontal zones are of the same sign (both $\theta$ and $S$ increase southward), the two right-hand terms in Equation 3 oppose each other. When these two terms are equal, the horizontal density gradients vanish. This is often observed in the subarctic frontal zone, where the intense temperature and salinity fronts in the upper layer are not accompanied by any density fronts (Roden 1972; Joyce 1987).

The above discussion indicates that a variety of physical processes are responsible for the formation of transition and frontal zones and that no single process can account for all of the observed features. Nevertheless, in specific regions or the North Pacific, it is possible to identify the dominant processes controlling the formation of these zones and to relate many of the observed features to them.

## Relation to Subarctic and Subtropical Gyre Confluence

The large scale ocean circulation of the mid-latitude Pacific is characterized by a cyclonic subarctic gyre and an anticyclonic subtropical gyre, as indicated in Figure 4, based on Schott (1943). Two current confluence lines stand out, one in the transition between the sub-

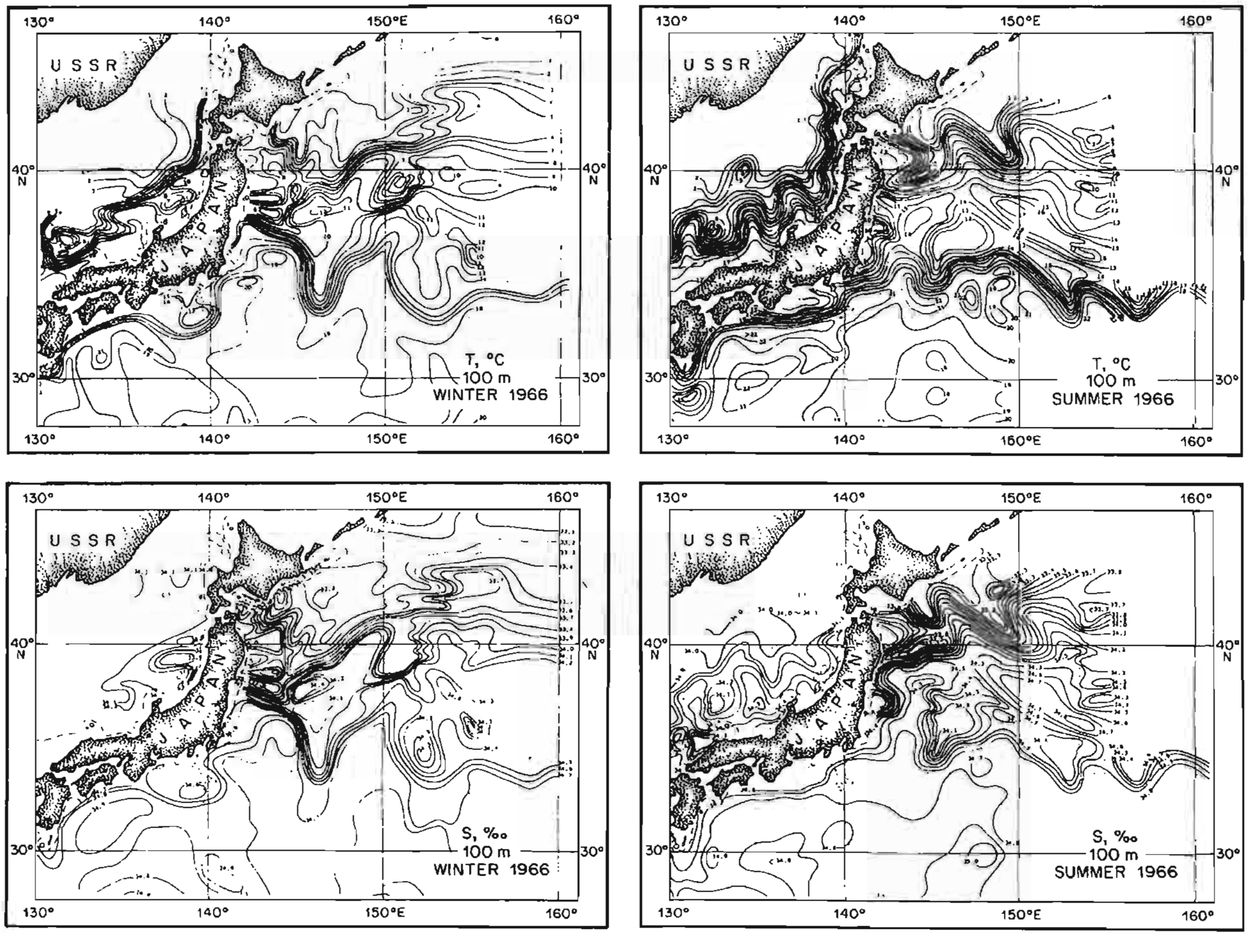


**Figure 5**
Subarctic-subtropical transition zone in the western Pacific. Note the occurrence of two sharp fronts at the boundaries of this zone. After Japan Oceanographic Data Center (1968, 1969).

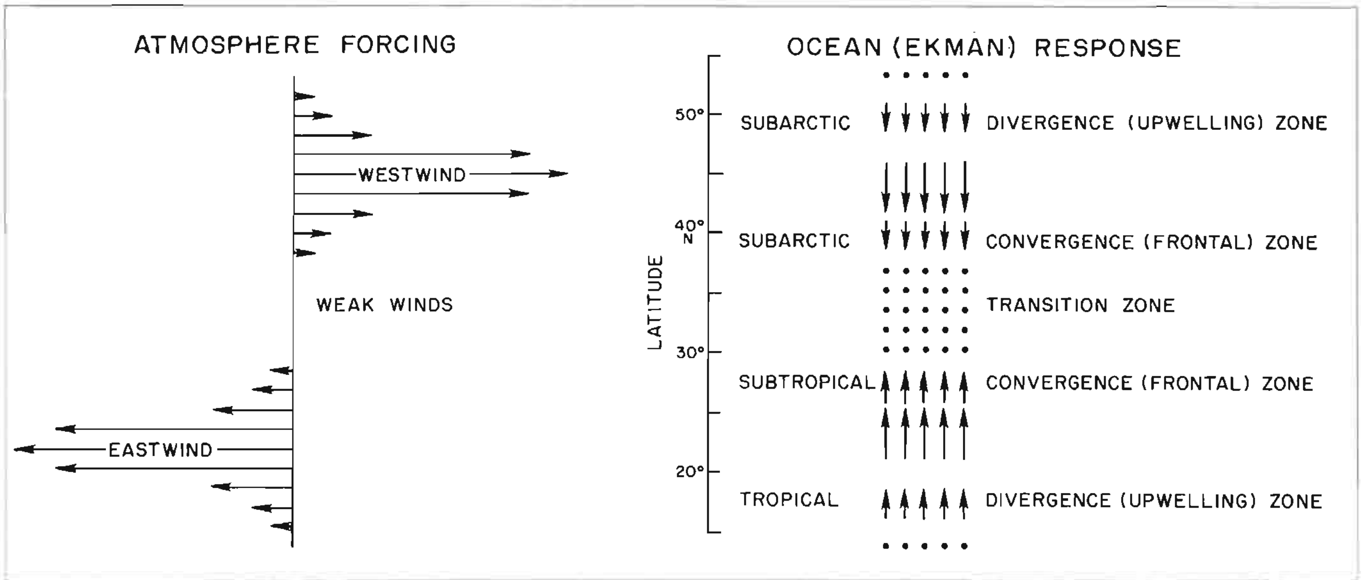


**Figure 6**

Schematic diagram showing the main wind belts in the central North Pacific and the upper layer Ekman response to them. Note the Ekman transport convergence zones to the right of the planetary west and eastwind maxima.

arctic and subtropical gyres, centered near 42° N, and the other within the center of the subtropical gyre near 23° N. It is tempting to associate these current confluences with thermohaline transition and frontal zones. This does not always lead to correct interpretations, however, because frontal zone formation does not depend upon confluence alone, but upon both the intensity of the initial thermohaline gradients and a favorable flow field configuration (which includes both confluence and convergence). The confluence between the subarctic and subtropical gyres leads to a transition zone at the boundaries of which two thermohaline frontal zones are located (Fig. 5), owing to convergence of flow within the Kuroshio and Oyashio currents. On the other hand, the confluence within the subtropical gyre is not associated with any thermohaline transition zone, because the upper ocean temperature and salinity differences of the meeting currents (North Equatorial Current and Kuroshio recirculation) are small.

## Relation to the Configuration of the Surface Ekman Transport Field

The planetary-scale atmospheric circulation in the North Pacific is characterized by westerlies in the north and easterly tradewinds in the south, separated by a zone of weak and variable winds, as shown schematically in Figure 6. The net effect of these winds is to move the surface layer of the ocean at right angles to the wind direction. This leads to a general confluence of Ekman transports and to the formation of two convergence zones (where the decrease in transport in the flow direction reaches a maximum), one on the equatorward side of the westwind peak and one on the poleward side of the eastwind peak. If the initial horizontal thermohaline gradients were zonal and uniform, the surface transition zone would coincide with the zone of Ekman transport confluence and the surface subarctic and subtropical frontal zones would form where the Ekman transports converge most strongly.

These idealized conditions are observed at times in the central North Pacific, where the baroclinic flow is weak and wind forcing dominates. In Figure 7 are shown the Ekman transports for April 1968, computed from the stress of the geostrophic wind on a 1° by 1° latitude-longitude grid (Roden 1970). There is a general confluence of Ekman transports between about 31° N and 43° N. Southward transports decrease most rapidly between 43° N and 40° N and northward transports decrease most sharply between 31° N and 34° N, forming two convergence zones. A concurrent vertical salinity section taken along longitude 158° W in April 1968 is shown in Figure 8. It is seen that the low salinity subarctic water terminates with a front at 39° N and that the high salinity subtropical water effectively terminates at the front near 34° N. Several secondary fronts occur in conjunction with these water mass limits, showing the existence of a subarctic frontal zone between 39° N and 45° N and a subtropical frontal zone between 31° N and 34° N. The location of these frontal zones agrees closely with the location of the Ekman transport convergence zones, in this case.

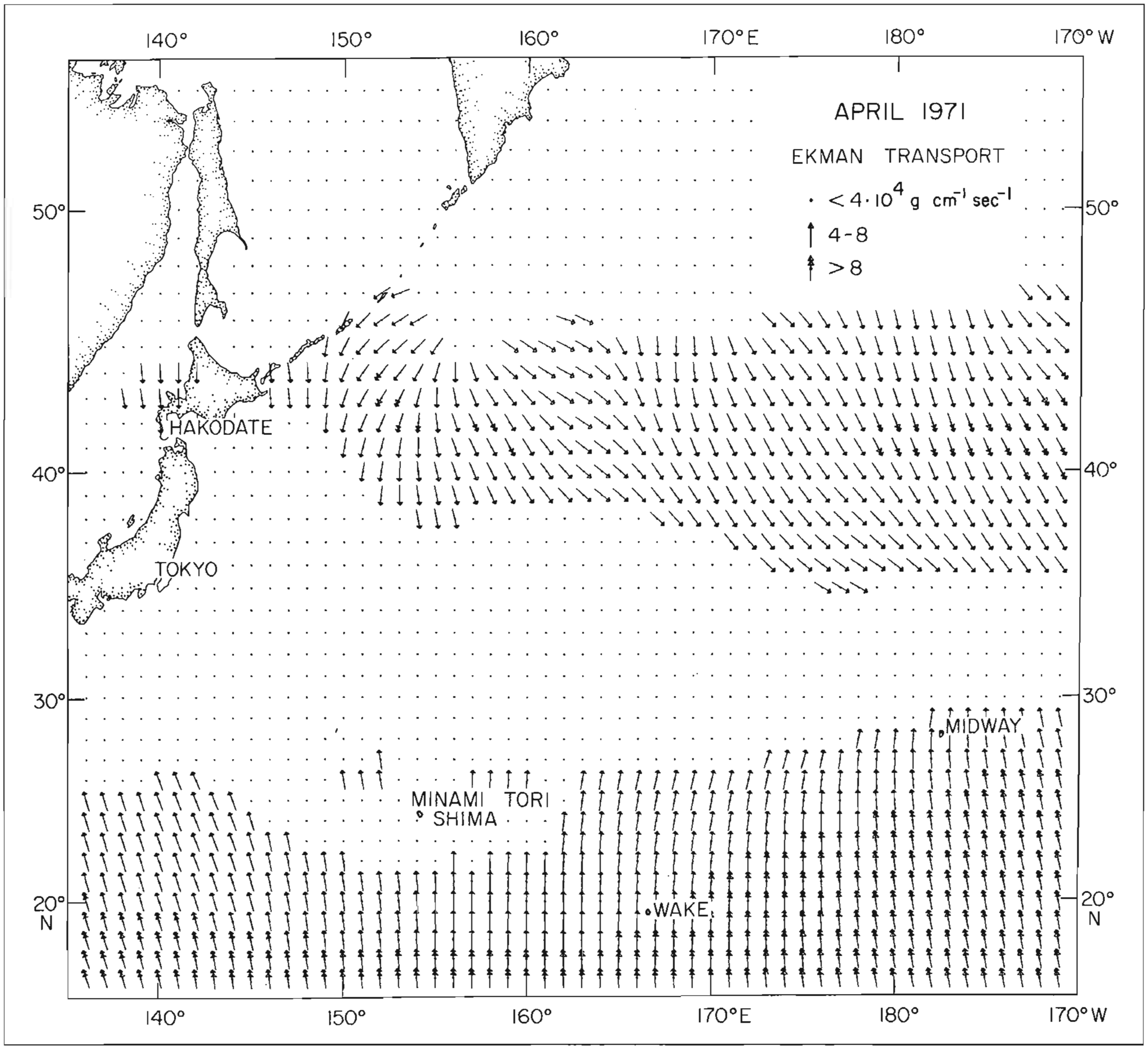


**Figure 7**
Ekman transport (gmc$^{-1}$s$^{-1}$) computed from the stress of the geostrophic wind on a 1° by 1° latitude-longitude grid. After Roden (1970).

Such good agreement as discussed above cannot be expected in regions of strong and dominating baroclinic flow, such as near the Kuroshio-Oyashio confluence, or in regions influenced by the Kuroshio extension and other boundary currents. Even in regions of weak baroclinic flow, the relationship between Ekman flow patterns and frontal zones is not simple, because it depends upon the existing thermohaline stratification and the duration of and intensity of atmospheric forcing. Firstly, a *given* favorable configuration of the Ekman transport field will lead to the formation of strong frontal zones in some geographic regions, but only weak ones in others, depending upon the intensity of the initial horizontal thermohaline gradients. Secondly, a favorable configuration of such a field must persist over a certain length of time before measurable frontal zone formation occurs. Thirdly, frontal zones do not disappear instantly after wind forcing ceases, but take time to decay. The exact formation and dissipation times of frontal zones are not known.

## Relation to the Configuration of the Wind-induced Vertical Velocity Field

The large scale winds in the subarctic are predominantly cyclonic and those in the subtropics are pre-

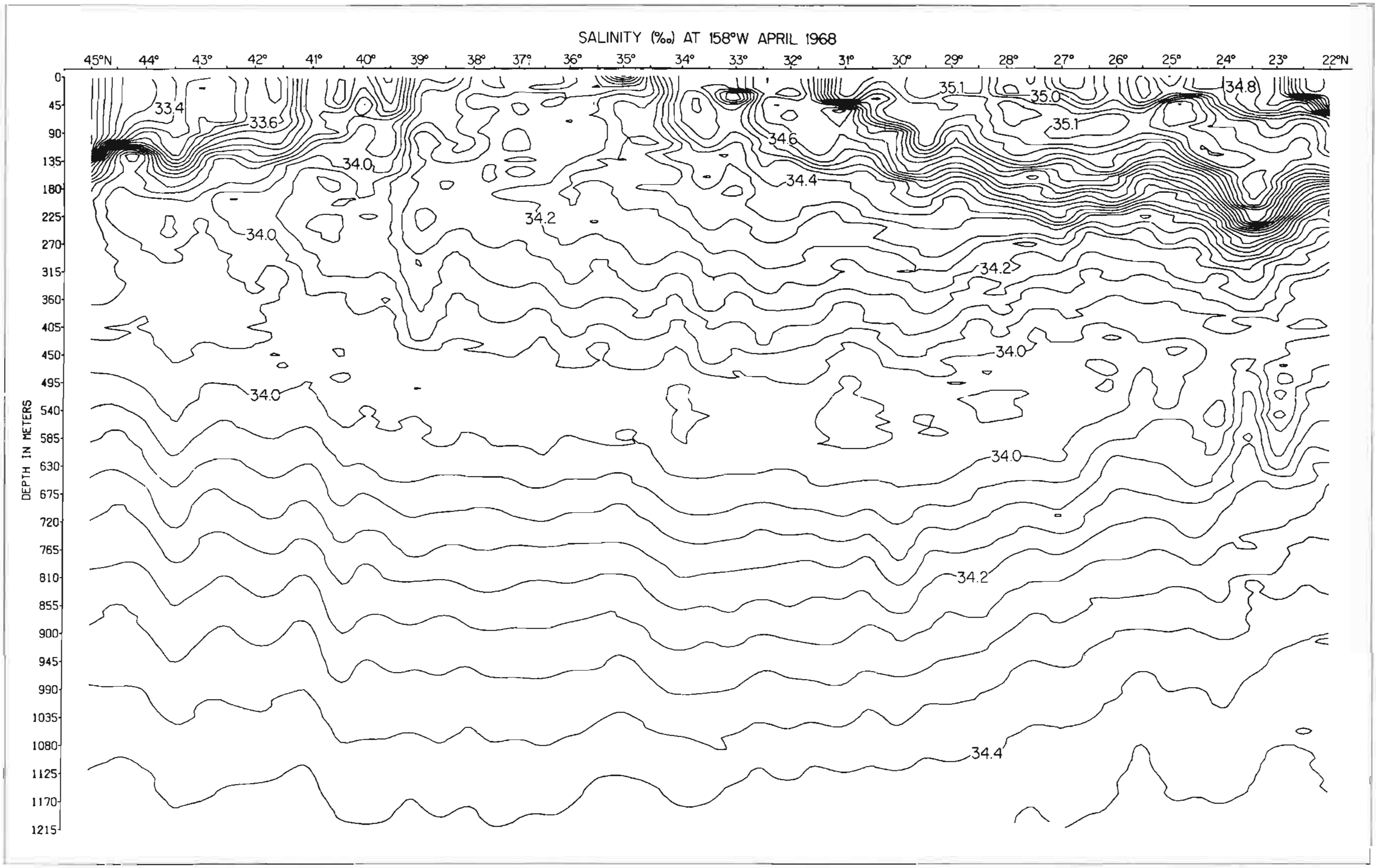


Figure 8

Meridional salinity section along 158° W in April 1968. Note the occurrence of multiple salinity fronts in the subarctic frontal zone (39°–45° N) and the subtropical frontal zone (31°–34° N). After Roden (1970).

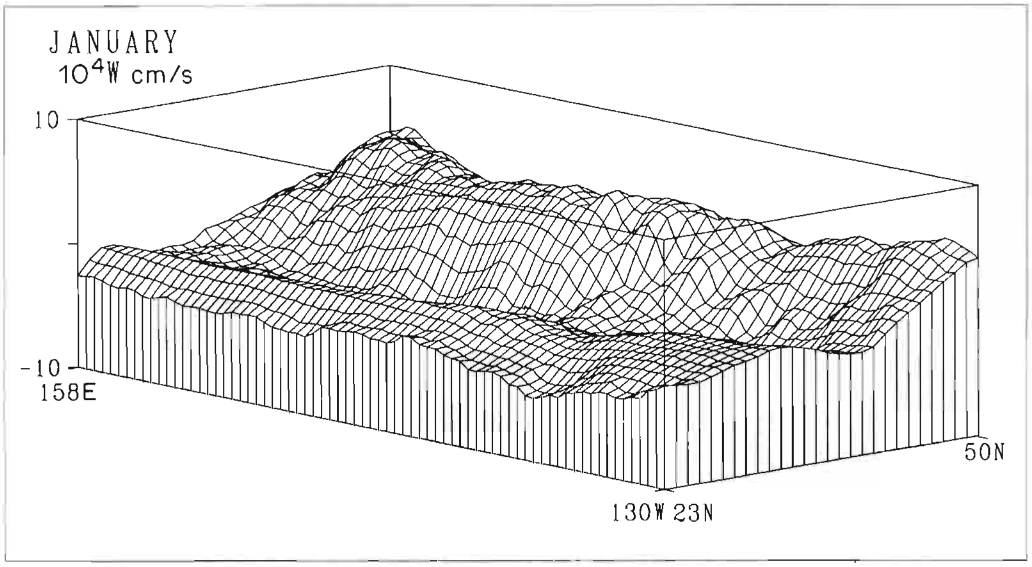


**Figure 9**
Three-dimensional plot of the wind induced vertical velocity at the bottom of the upper mixed layer. Note the sharp slope of the contours between latitudes 42° N and 48° N.

dominantly anticyclonic This induces upwelling in the former and downwelling in the latter region, while in the transition zone there are enhanced horizontal gradients of the vertical velocity component. The differential vertical motion leads to differential vertical advection of heat and salt, which is an important process in transition zone formation at depths below the upper mixed layer. A three-dimensional plot of the 30-year mean wind induced vertical velocity in winter is shown in Figure 9, on a 1° by 1° latitude-longitude grid. The vertical velocity is derived from the curl of the stress of the quasigeostrophic wind (geostrophic wind with a small frictional term included to allow for cross-isobar flow of about 15°). Clearly, the geographical variability of the vertical velocity component is large and nonuniform. Upwelling predominates north of 40° N and downwelling south of it. It is noteworthy that the strongest horizontal gradients of the vertical velocity occur between 42° N and 48° N, and not where $W = 0$. For this reason, the expected position of the subsurface transition zone is in the same latitude belt and not near the line where the curl of the wind stress vanishes. This is borne out in the meridional temperature section along 155° W (Fig. 10), where the largest horizontal thermal gradients occur between 42° N and 48° N below the upper mixed layer.

## Mesoscale Aspects of the Transition and Frontal Zones

On the planetary scale, the subarctic-subtropical transition and associated frontal zones are semipermanent features of the general circulation, slightly fluctuating about their mean positions. On the mesoscale, the dominating features in these zones are individual fronts, eddies, and jetlike flows that are highly variable in both time and space. In addition, there are quasiregular long wave disturbances (Roden 1977b; Kang and Magaard 1980; White 1982) and topographically induced perturbations (Roden 1987). These mesoscale features are important in understanding the synoptic variability within the transition and frontal zones. In the following an overview will be given of the salient observed mesoscale structures.

## Mesoscale variability of dynamic height and baroclinic flow

The mid-latitude North Pacific can be divided into two basins, separated from each other by the Emperor Seamount Chain that extends in a nearly north-south direction in the vicinity of 170° E for a distance of 2500 km. In the western basin, the dynamic height perturbations are three to six times larger than in the eastern one (Fig. 11). Maximum perturbations in the western basin reach 8 J $kg^{-1}$, equivalent to about 0.8 m in sea surface elevation. The large variability of sea surface height in the western Pacific is seen also in records derived from satellite altimetry (Cheney et al. 1983). The reason for the large perturbations in this region is generally attributed to the instabilities and eddy shedding of the Kuroshio extension, which meanders eastward along this longitude (Kawai 1972; Roden et al. 1982).

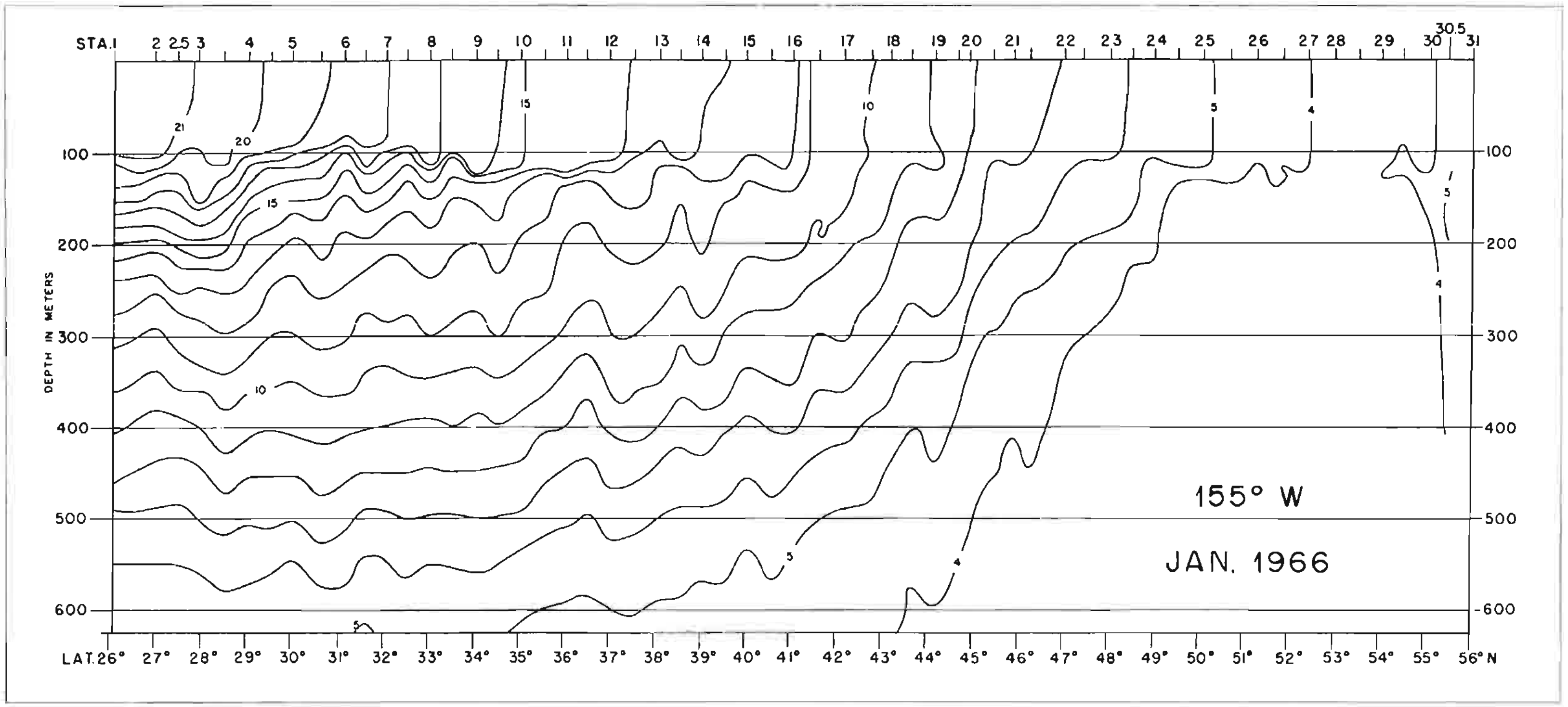


Figure 10
Meridional temperature section along 155° W in January 1966 taken during the Zetes Expedition. (Scripps Institution of Oceanography, 1970)

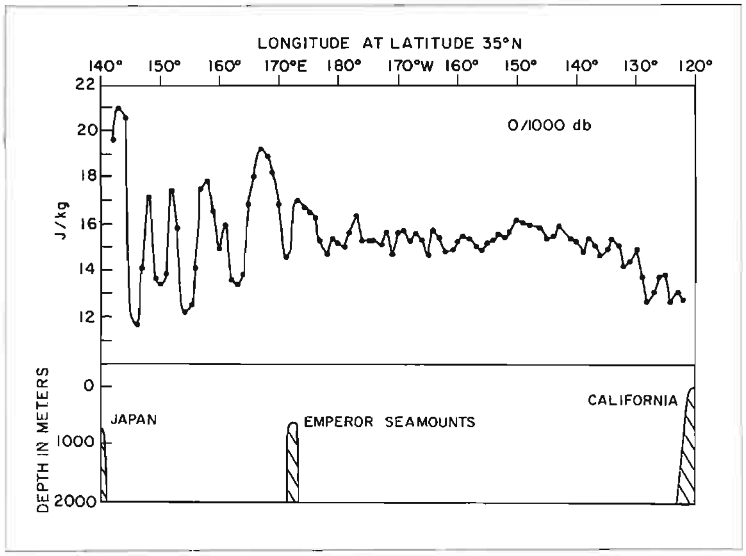


**Figure 11**
Relative dynamic height between Japan and California in a section along 35° N near the center for the subarctic-subtropical transition zone. Note the large amplitude perturbations west of the Emperor Seamounts. Based on Kenyon (1978) and Roden et al. (1982).

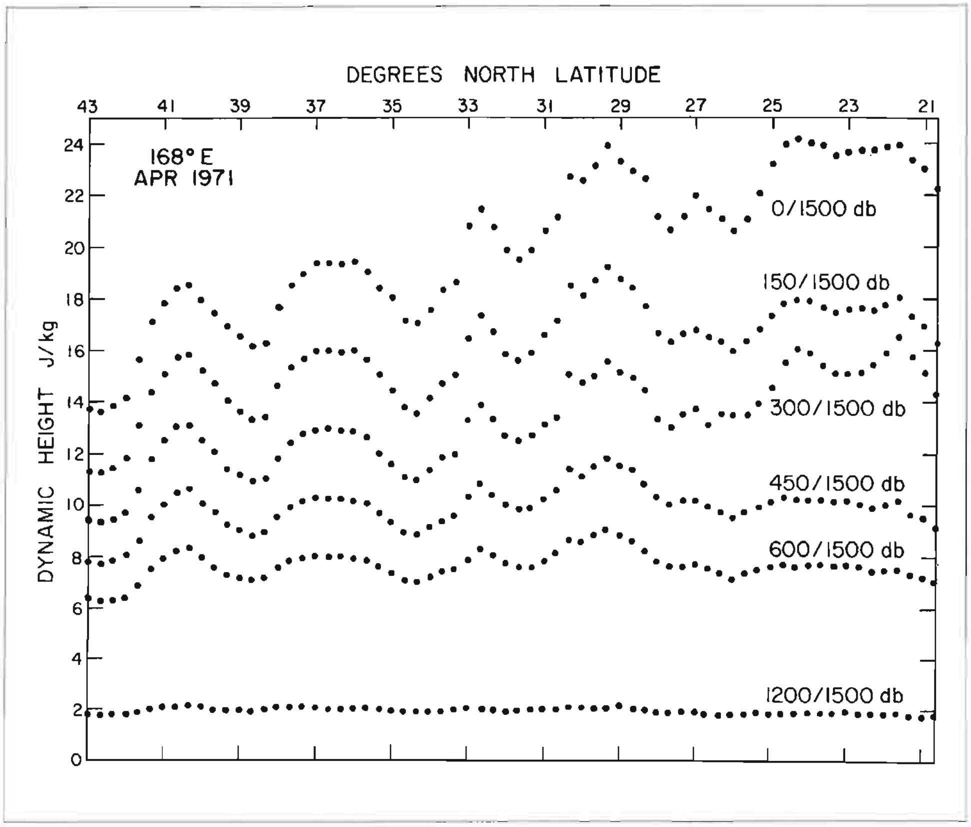


**Figure 12**
Relative dynamic height across the transition zone in the western North Pacific at various pressures (depths). After Roden (1979).

**Western Basin**—Mesoscale dynamic height perturbations are apparent not only in zonal sections, but occur in meridional ones as well. In Figure 12 are shown the relative dynamic heights across the transition zone in the western basin at 168° E, about 250 km west of the Emperor Seamounts. Two features stand out: the perturbations between 25° N and 43° N are vertically coherent and they have dominant wavelengths of about 400 km (Roden 1979). There is no sign that the amplitudes of the perturbations decrease with distance from the Kuroshio extension (here located near 33° N); the trough to crest equivalent sea surface elevation differences are of the order of 0.4 m throughout the region. This implies that there are sources other than the Kuroshio extension that contribute to the sea surface height variability. A possible source is the subarctic current which occurs in the vicinity of the subarctic front; it, too, is meandering and eddy shedding (Kawai 1972). The transition zone of the western Pacific thus appears to receive eddy injections from both the north and the

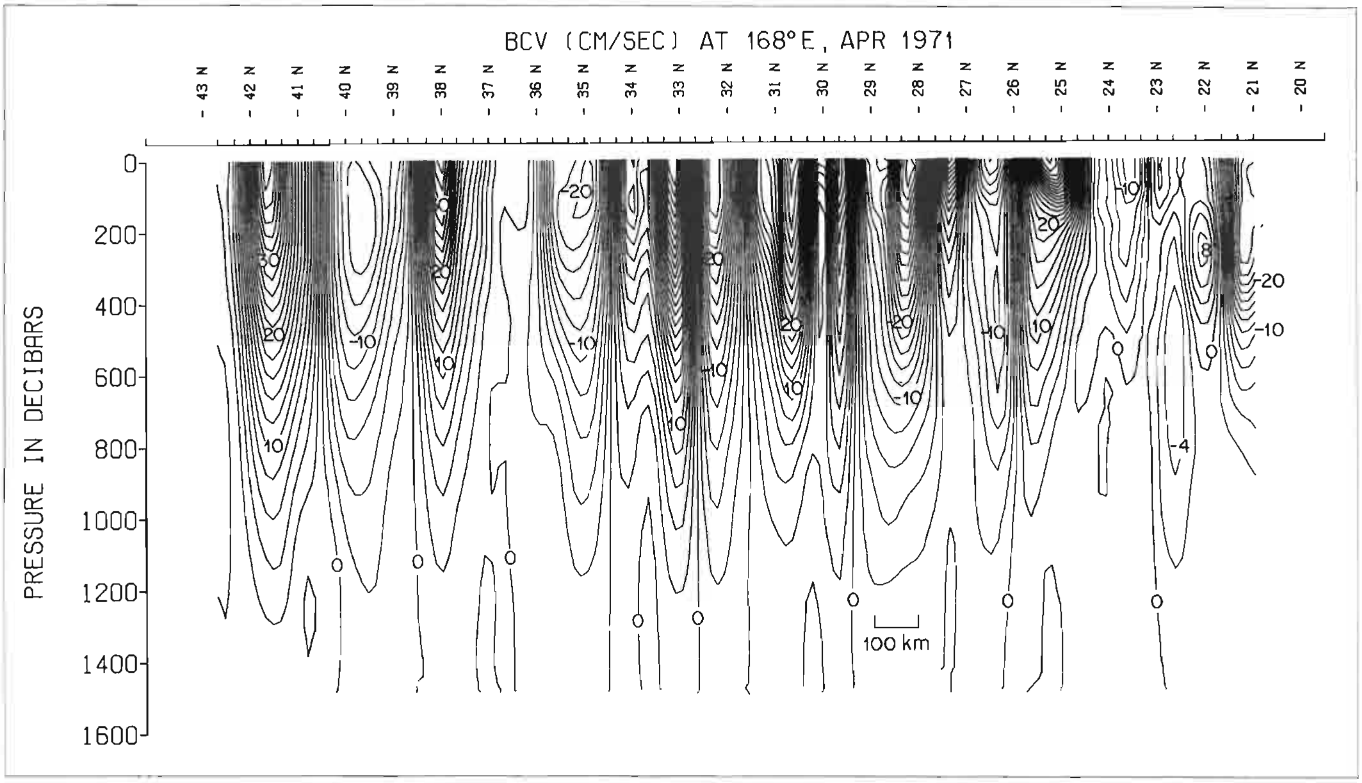


**Figure 13**

Mesoscale variability of the zonal component of baroclinic flow across the subarctic-subtropical transition zone in the western Pacific at 168° E, after the end of the 1971 winter. Speeds are in cm $s^{-1}$. After Roden (1984).

south, which may account for the semiconstant perturbation amplitudes throughout the zone.

Associated with the dynamic height perturbations are those of baroclinic flow. The latitudinal variation of the zonal flow component along 168° E is shown in Figure 13; the 2442-km long section was taken between 3 and 11 April 1971 after the end of the winter season and has a 37-km station spacing and a 3-m vertical sampling interval (Roden 1972; Roden and Fredericks 1987a). The pattern consists of alternating eastward (positive) and westward (negative) flows, spaced at quasiregular intervals of a few hundred kilometers. Maximum speeds are of the order of 0.5 $ms^{-1}$ and the depth penetration of the flow, as measured by the 0.02 $ms^{-1}$ isotach, is about 1000 m. There is strong vertical coherence of the flow. The subarctic current is centered near 41°40' N and the Kuroshio is near 33° N, with surface baroclinic speeds of 0.38 $ms^{-1}$ and 0.48 $ms^{-1}$, respectively.

How representative are the above findings taken shortly after the end of the winter season in 1971? Indications are that the pattern of alternating flows persist, while the location of the cores of the subarctic and Kuroshio currents shift with time. In Figure 14 is shown the latitudinal variation of the zonal flow component along 167° E during the summer of 1982 (Roden and Taft 1984) using the same 37-km horizontal and 3-m vertical sampling intervals. The subarctic current is centered near 41° N and has a surface speed of about 0.26 $ms^{-1}$ (Roden 1984). The Kuroshio is encountered near 35°30' N, with a surface speed of 0.54 $ms^{-1}$ (Roden and Taft 1985). In November 1983, using a coarser horizontal sampling grid along 165° E, Joyce (1987) found the subarctic current to be located near 41° N with a surface speed of 0.2 $ms^{-1}$ and the Kuroshio near 34°30' N, with a speed of 0.85 $ms^{-1}$. He also found the 0.02 $ms^{-1}$ isotach to penetrate to 1000 m under the subarctic current and to about 2500 m under the Kuroshio Current.

Direct current measurements at an array placed along 165° E (Schmitz 1987) and 167° E (Hamann and Taft 1987) confirm the strong vertical coherence suggested by the baroclinic currents computed from the distribution of mass. Below 2000 m, however, the barotropic flow components dominate and near the bottom they exceed the baroclinic components by an order to two orders of magnitude. At 41° N, the abyssal flow is surprisingly stable and almost unidirectional, for reasons unknown (Schmitz 1987).

**Eastern Basin**—In contrast to the large mesoscale perturbations observed in the western Pacific, those en-

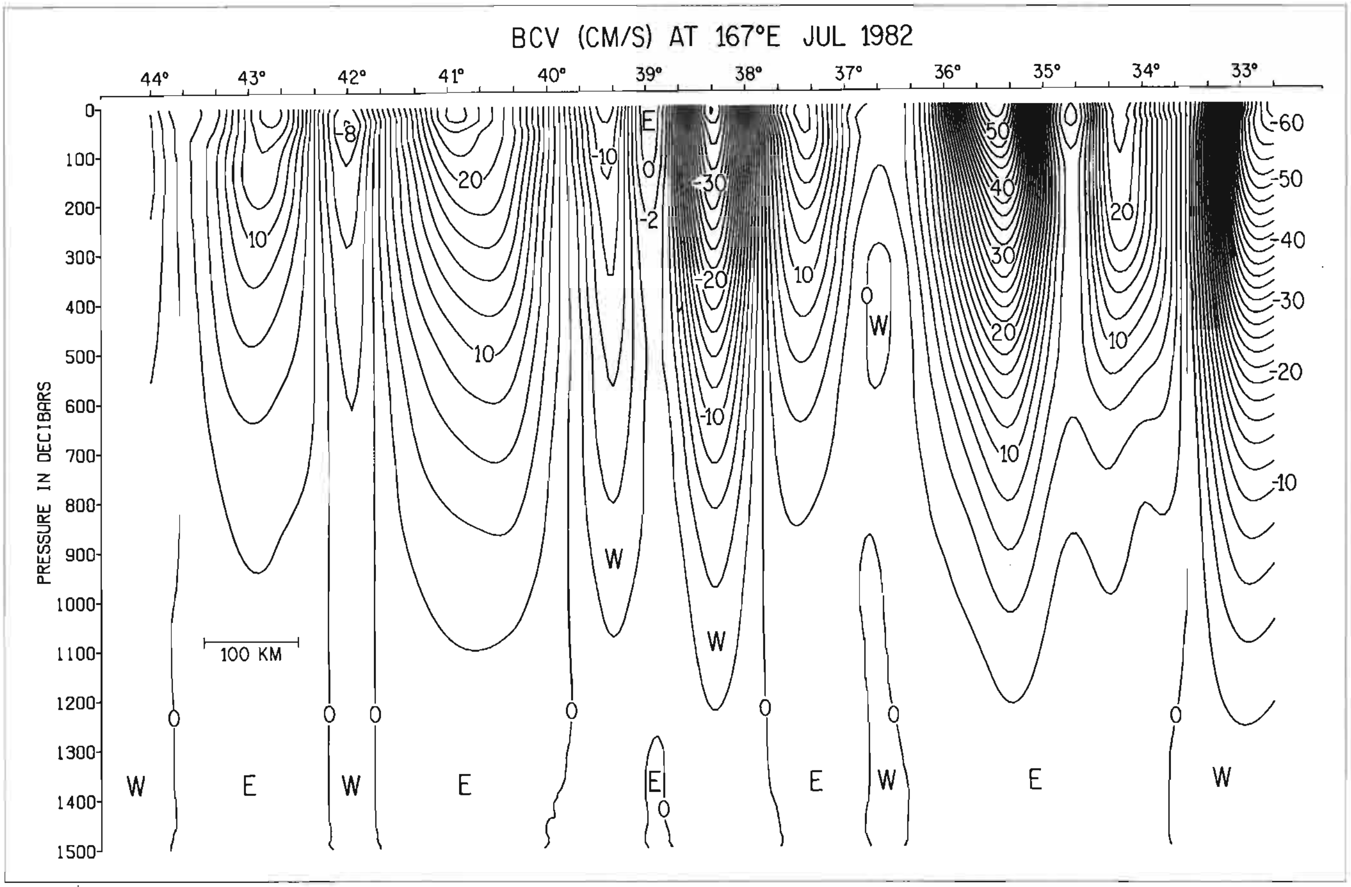


Figure 14
Mesoscale variability of the zonal component of baroclinic flow across the subarctic-subtropical transition zone in the western Pacific at 167° E, in the summer of 1982. Speeds are in cm s$^{-1}$. After Roden (1979).

countered in the mid-latitude eastern Pacific are small. The main distinguishing characteristics of the eastern basin are the absence of strong boundary currents that penetrate into the ocean interior and the smooth bottom topography between 30° N and 50° N. Thus, two major sources of eddy variability are lacking in the region. Nevertheless, a low amplitude mesoscale perturbation field is common in the mid-latitudes, dominating the flow on synoptic time scales.

A representative dynamic height section extending from the subarctic domain across the transition zone into the subtropical domain is shown in Figure 15. The 2781-km long section along 158° W is based on 27-km station spacing and was occupied between 27 September and 8 October 1975 (Roden 1977b; Roden and Fredericks 1987b). The noteworthy features are the northward decrease of the perturbation amplitudes and their rapid attenuation with depth, particularly north of 34° N (the southern limit of the transition zone). The perturbation heights vary from 2.5 J kg$^{-1}$ near Oahu to less than 1.0 J kg$^{-1}$ in the subarctic domain (equivalent to 0.25 m and less than 0.1 m of sea-surface elevation, respectively). Similar results were obtained by Talley and DeSzoeke (1986) when analyzing a high re-solution dynamic height section along 152° W in May 1984.

The temporal variation of the zonal baroclinic flow component along 158° W is shown in Figures 16 and 17 for spring and fall based on data by Roden and Fredericks (1987, b and c). In both seasons the basic current structure is similar. Throughout the transition zone and in the subarctic domain, the mean flow is eastward with a sluggish speed of 0.02– 0.03 ms$^{-1}$. The amplitude of the superposed eastward and westward perturbations rarely exceeds 0.1 ms$^{-1}$. The depth penetration of the flow, as measured by the 0.02 ms$^{-1}$ isotach, is about 600 m. In the subtropical domain, the character of the flow changes. The mesoscale perturbations extend deeper (to 1000 m) and the perturbation speeds become stronger (0.2–0.4 ms$^{-1}$), especially near the Hawaiian Ridge. The amplification of the mesoscale perturbations and their banded structure near this ridge is believed to result from topography-flow interaction (Mysak and Magaard 1983; Oh and Magaard 1984; Sun et al. 1988).

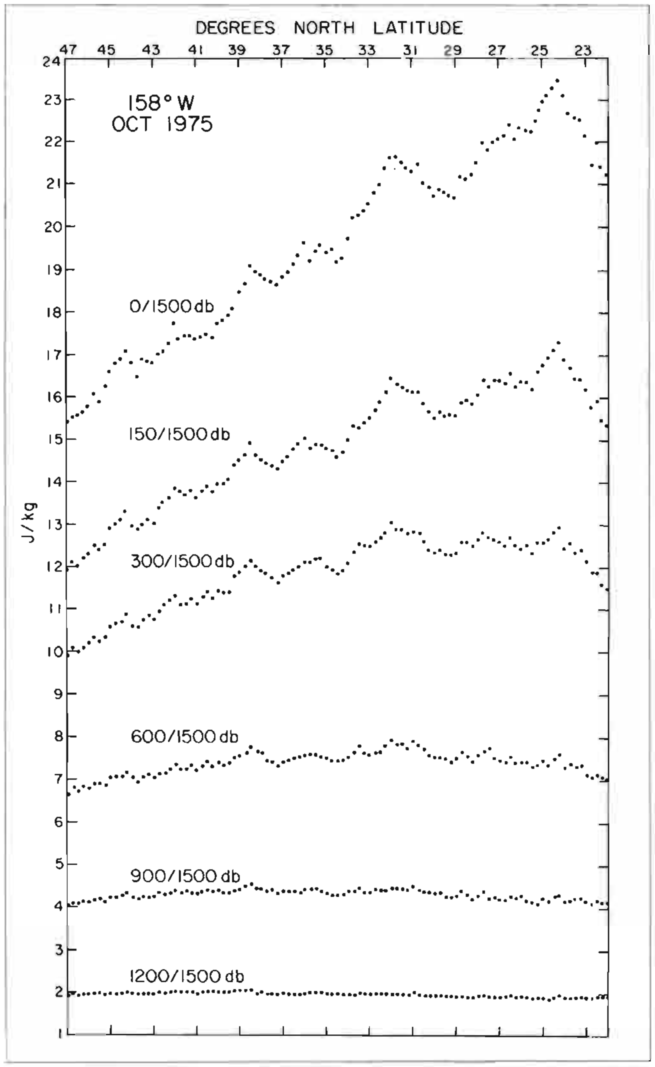


**Figure 15**

Relative dynamic height in the transition zone in the central North Pacific at various pressures (depths). After Roden (1977b).

**Mesoscale Variability of Hydrostatic Stability in the Upper Ocean**—Hydrostatic stability is a fundamental oceanic parameter affecting the depth of wind mixing, thermohaline convection, and potential vorticity dynamics (Rhines 1986). It can be expressed by the Väisälä stability frequency

$$N^2 = -g\left(\frac{1}{\rho}\frac{\partial\rho}{\partial z} + \frac{g}{c^2}\right) \qquad (4)$$

where $g$ is the acceleration of gravity and $c$ is the speed of sound. In the pycnocline, the first right-hand term dominates; elsewhere, the two right-hand terms are of the same order of magnitude, but of opposite sign. Stability exists when $N^2 > 0$ or, in terms of the vertical density gradient, when $\frac{\partial\rho}{\partial z} < -\rho g c^{-2} = -4.5 \bullet 10^{-3}$ kgm$^{-4}$, approximately.

**North Pacific Low Stability Gap**—The meridional distribution of $N^2$ from the subarctic domain across the transition zone into the subtropical domain is shown in Figure 18. The section is along 158° W and illustrates conditions in early spring and early fall, based on high resolution sampling (Roden and Fredericks 1987, b and c). Only frequencies larger than 0.01 rad s$^{-1}$ have been contoured to bring out the main points. The outstanding feature is the seasonal low stability gap between 43° N and 37° N, which has important consequences for the depth penetration of wind mixing and thermohaline convection.

In winter and early spring, wind mixing and convection in the subarctic domain to the north of 43° N is limited to the upper 150 m by a hydrostatic stability maximum related to the permanent subarctic halocline. To the south of 37° N, a developing shallow spring thermocline limits these processes to the upper 50 m. In the low stability gap, where the subarctic halocline is absent and spring warming has not progressed far enough north, wind mixing and thermohaline convection can penetrate deeper than elsewhere in the region (*see* Fig. 28 below).

As the season advances, the low stability gap narrows until it completely disappears in summer and early fall. At this time an intense, shallow, high-stability layer related to solar heating covers the entire transition zone, restricting wind mixing and convection effects to the upper 30–50 m. As winter approaches, cooling destroys the upper high stability layer in the northern part of the transition zone and the gap opens again.

**Three-Dimensional Variability of the Väisälä Frequency**—The three-dimensional variability of the hydrostatic stability is shown in Figure 19 in a series of meridional sections through the subarctic domain and adjacent subarctic frontal zone. The sections cover the region between 150° W and 158° W and were obtained in the early fall of 1975 (Roden 1977a). There are two layers of high stability separated from each other by a 70-m thick layer of minimal stability. The upper high-stability layer occurs between 30 and 50 m and increases in strength southward; there is little variation with longitude. The lower high-stability layer is encountered between 120 and 150 m. Its southward limit depends strongly upon longitude, varying from 45° N at 158° W to 41° N at 150° W. On the other hand, the intensity of this layer does not vary much with geographical position.

**Mesoscale Variability of the Thermohaline Structure in the Upper Ocean**—The mesoscale thermohaline structure in the mid-latitude North Pacific is complex. The complexity arises from the interaction of currents of different origin among themselves as well as with the

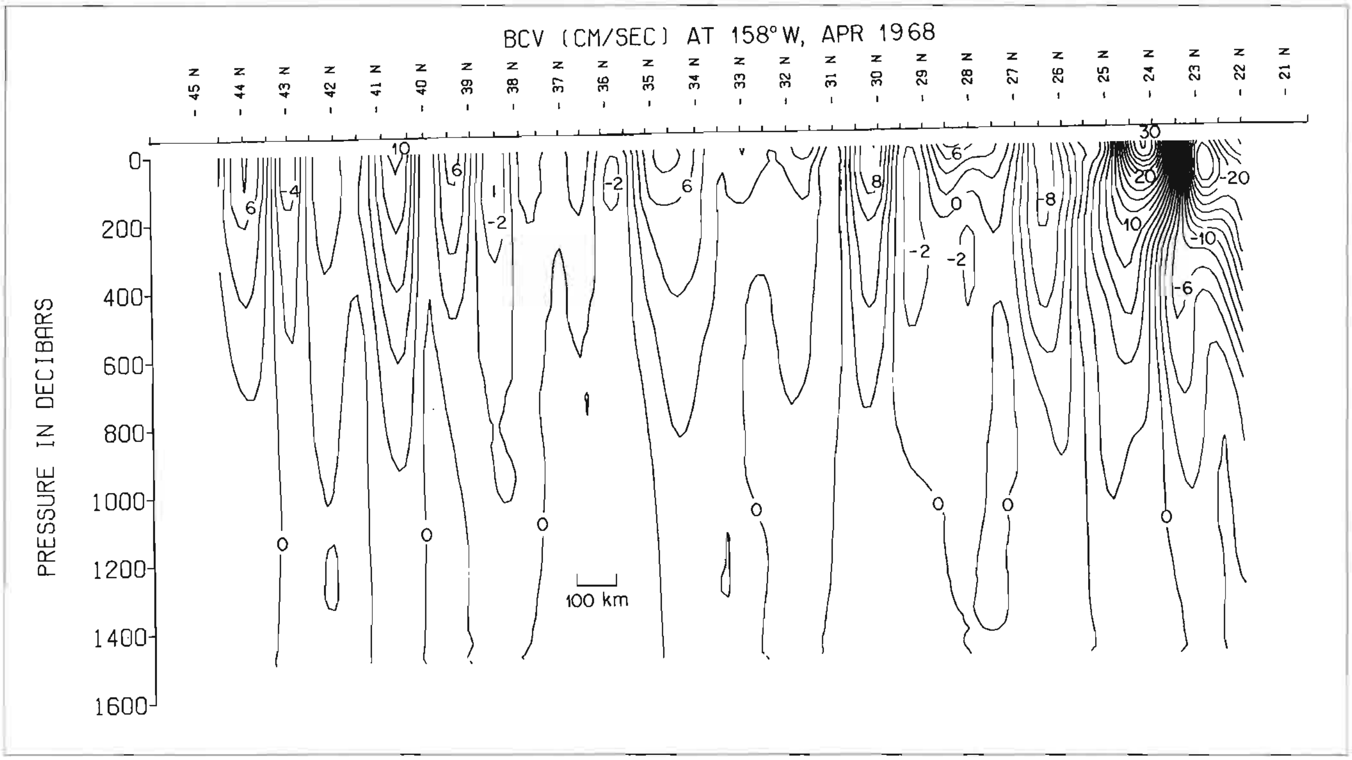


Figure 16
Mesoscale variability of the zonal component of baroclinic flow across the subarctic-subtropical transition zone in the eastern Pacific at 158° W, in the spring of 1968. Speeds are in cm $s^{-1}$. The station spacing is 54 km.

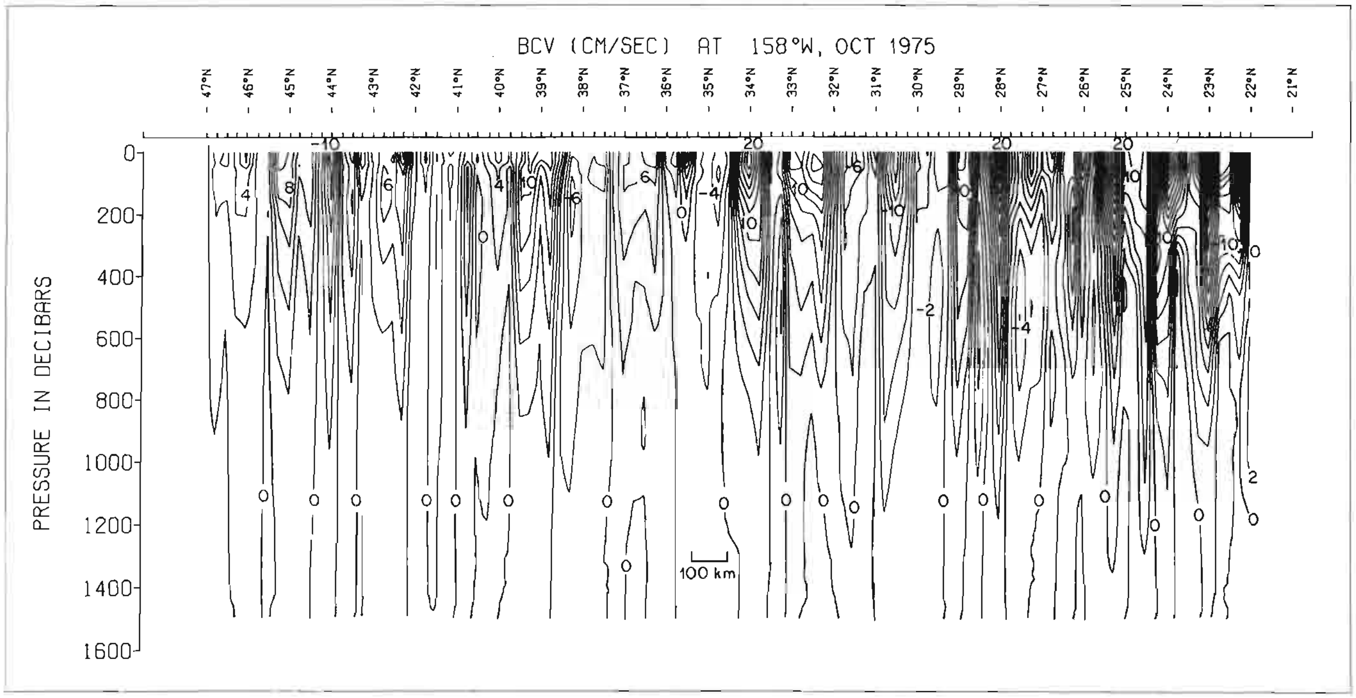


Figure 17
Mesoscale variability of the zonal component of baroclinic flow across the subarctic-subtropical transition zone in the eastern Pacific at 158° W, in the early fall of 1975. Speeds are in cm $s^{-1}$. The station spacing is 27 km.

atmosphere above and the bottom topography below. This produces a great variety of observable thermohaline structures ranging from isolated eddies and convoluted fronts to more organized eddy and wave-like perturbations, all of which change with time. It is, in general, quite difficult to obtain representative synoptic thermohaline structures from a slow moving ship (3–5 ms$^{-1}$). Only those mesoscale structures that move and evolve slowly compared to the ship's speed can be described and understood adequately. Fast evolving structures are better studied by remote sensing, provided they have a clear surface signature (Stewart 1985).

**Basic Mid-Latitude Frontal Structures**—Three main frontal zones occur in the mid-latitude North Pacific: the subarctic frontal zone, the frontal zone associated with the Kuroshio extension (western basin only) and the subtropical frontal zone. The thermohaline fronts occurring in these zones and the thermohaline eddies encountered in them have distinguishing characteristics, as shown in Figure 20. The subarctic front (*top*) has well-defined horizontal temperature and salinity gradients in the upper layer which balance each other in such a way that the resulting horizontal density gradients are small. The Kuroshio front (*middle*) has strong temperature, salinity, and density signatures from the surface to great depths. The subtropical front is primarily a salinity front in the upper layer, with only weak horizontal temperature and density gradients.

**Interannual Variability of Thermohaline Fronts**—Only a few repeat hydrographic sections exist that permit one to illustrate the mesoscale interannual variability of both temperature and salinity fronts in the open ocean. In Figures 21 to 24 are shown the frontal changes over a six-year period (1981–1986) in the western and eastern North Pacific basins. The sections along 170° E and 175°30' E cover the latitude belt between 38° N and 48° N and were occupied regularly by the Japanese RV *Hokusei Maru* during the third and fourth weeks of July (Hokkaido University, 1982–1987).

In the western basin at 170° E the outstanding features are the constancy of the position of the subarctic temperature and salinity fronts. Over the six-year period, these fronts occurred within 50 km of latitude 43° N. The thermal fronts are strongest between the bottom of the seasonal thermocline and 600 m and the salinity fronts between the sea surface and 300 m. The intensity of these thermohaline fronts varies from year to year, but the most notable changes occur between 1985 and 1986. The temperature section illustrates also the interannual variability of the intensity of the shallow temperature minimum: while it is always present north of the subarctic front between about 80 and 180 m, temperatures of less than 2° C were encountered in only two of the six years.

In the eastern basin at 175°30' E, the intensity of the thermohaline fronts is not only weaker, but the interannual variability of the position of these fronts is larger, varying between about 45° N in 1981 and about 43° N in 1986, when judged by the positions of the 4° C isotherms and the 33.8‰ isohalines. The shallow temperature minimum to the north of the front also is more time variable: well-developed in 1985 and 1986, it was not encountered at all in 1982 in the latitude range investigated.

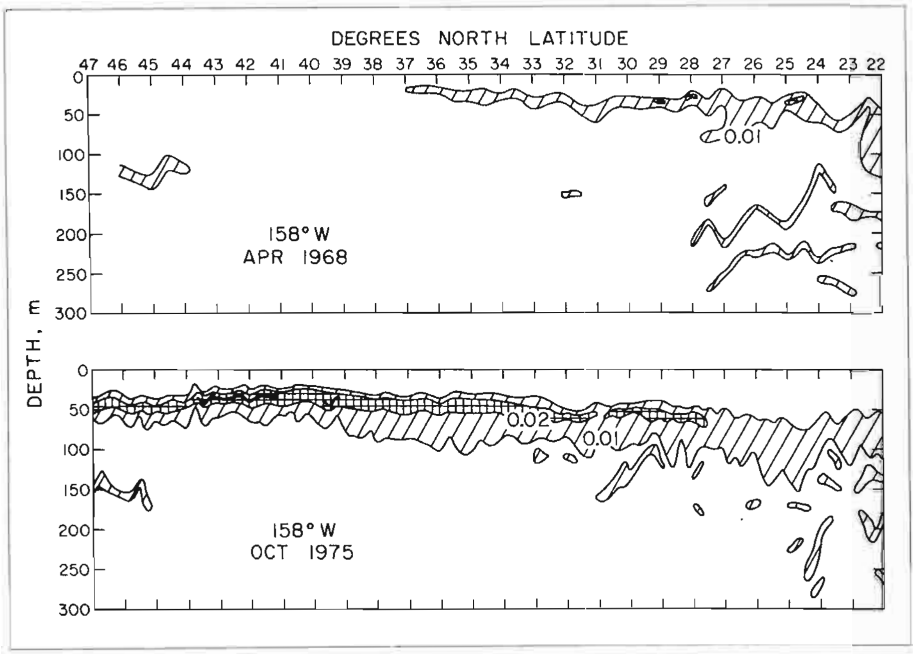


**Figure 18**

Mesoscale variability of the Väisälä stability frequency across the subarctic-subtropical transition zone in early spring and early fall. Units are in rad s$^{-1}$. Shading has been added for emphasis. Note the low stability gap in early spring.

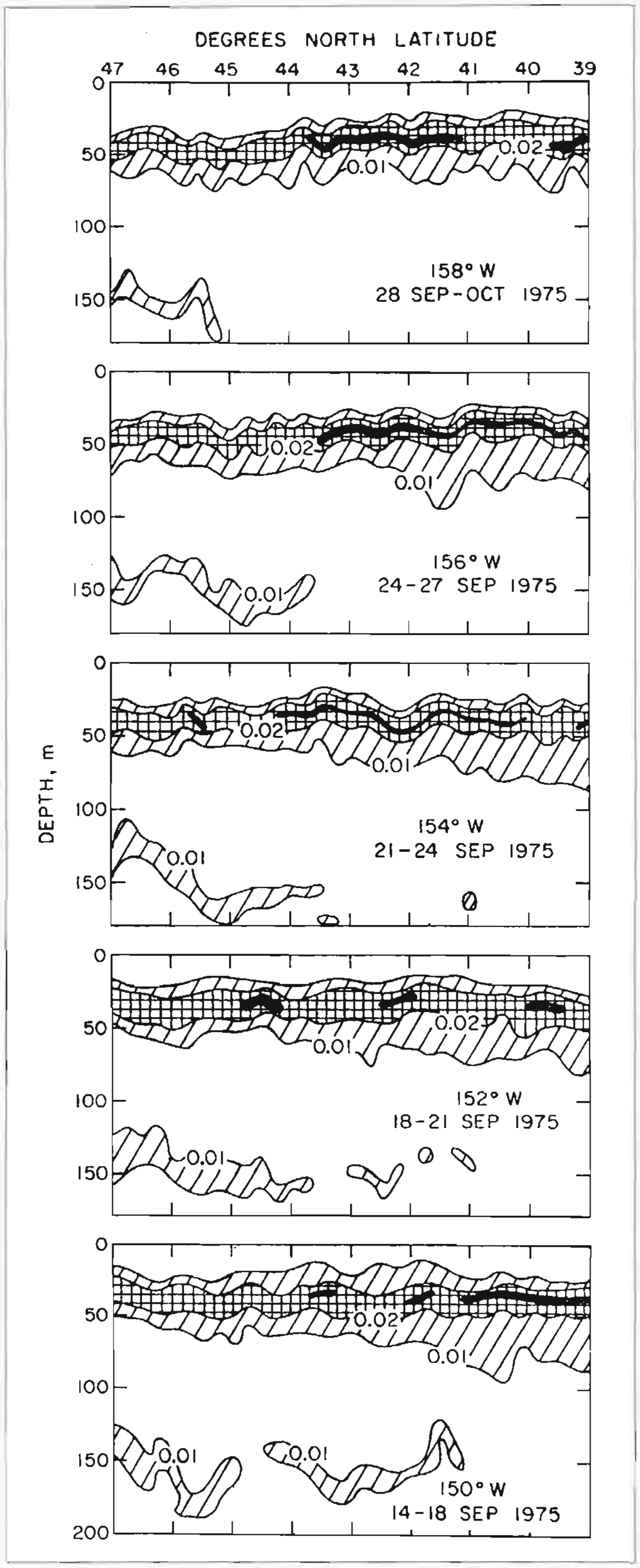


**Figure 19**
Mesoscale variability of the Väisälä stability frequency in the subarctic domain of the central North Pacific. Units are in rad $s^{-1}$. Shading has been added for emphasis. After Roden (1977a).

The above examples indicate that the interannual variability of the subarctic front depends upon longitude and that findings from location cannot be extrapolated to other nearby locations necessarily.

The interannual variability of the Kuroshio was investigated by Mizuno and White (1983). The authors contoured the temperature field at 300 m, obtained by expendable bathythermographs (XBT) dropped from ships-of-opportunity. They found that the variability was dominated by large amplitude, quasistationary meanders, confined to the latitude interval between 32° and 38° N, indicating Kuroshio excursions of about 300 km from its mean position near 35° N.

**Eddy and Wavelike Perturbations in the Western Basin**—The western North Pacific is dominated by the meandering and eddy-shedding Kuroshio and Oyashio currents and their seaward extensions. In the sea area off northeastern Japan, where branches of the cold and low salinity Oyashio intermingle with offshoots from the warm and saline Kuroshio, numerous fronts and frontal eddies are found (Kitano 1975; Roden 1975; Vastano and Bernstein 1984). Figure 25 shows the thermohaline structure in the upper 300 m. In the 400-km long section, taken along 40° N in April 1971 (Roden and Fredericks 1987a), six thermohaline fronts spaced about 60–70 km apart are encountered. Temperature gradients of up to 9° C/30 km and salinity gradients exceeding 1‰/30 km occur in this region. There are numerous temperature inversions, mostly in the cold Oyashio water mass.

Large mesoscale thermohaline perturbations occur not only in the vicinity of Japan, but also in the interior of the western basin. Typical temperature, salinity, and density perturbations across the transition zone at 168° E are shown in Figures 26–28. The sections are based on a 37-km station spacing and were occupied in early April 1971. Several interesting features stand out. The prominent feature near 42° N is the subarctic front, which has deep, vertically coherent signatures. Just south of it, between 40° N and 42° N, there is an area of very uniform temperatures, salinities, and densities between about 30 and 300 m. This is the low stability gap, where thermohaline convection and wind mixing can penetrate deeper than elsewhere in the region during winter. The convection is initiated by the cooling of high salinity water of Kuroshio origin; presumably, this is an episodic event occurring during outbreaks of arctic air.

Beneath the upper atmospherically influenced layer, large amplitude quasiregularly spaced oscillations are encountered, which are indicative of wavelike differential vertical motion or an organized eddy field of preferred wavelengths. A spectral analysis of these oscillations (Roden 1979) showed a well-defined peak at a wavelength of 400 km and most of the spectral energy concentrated between the wavelengths of 300 and

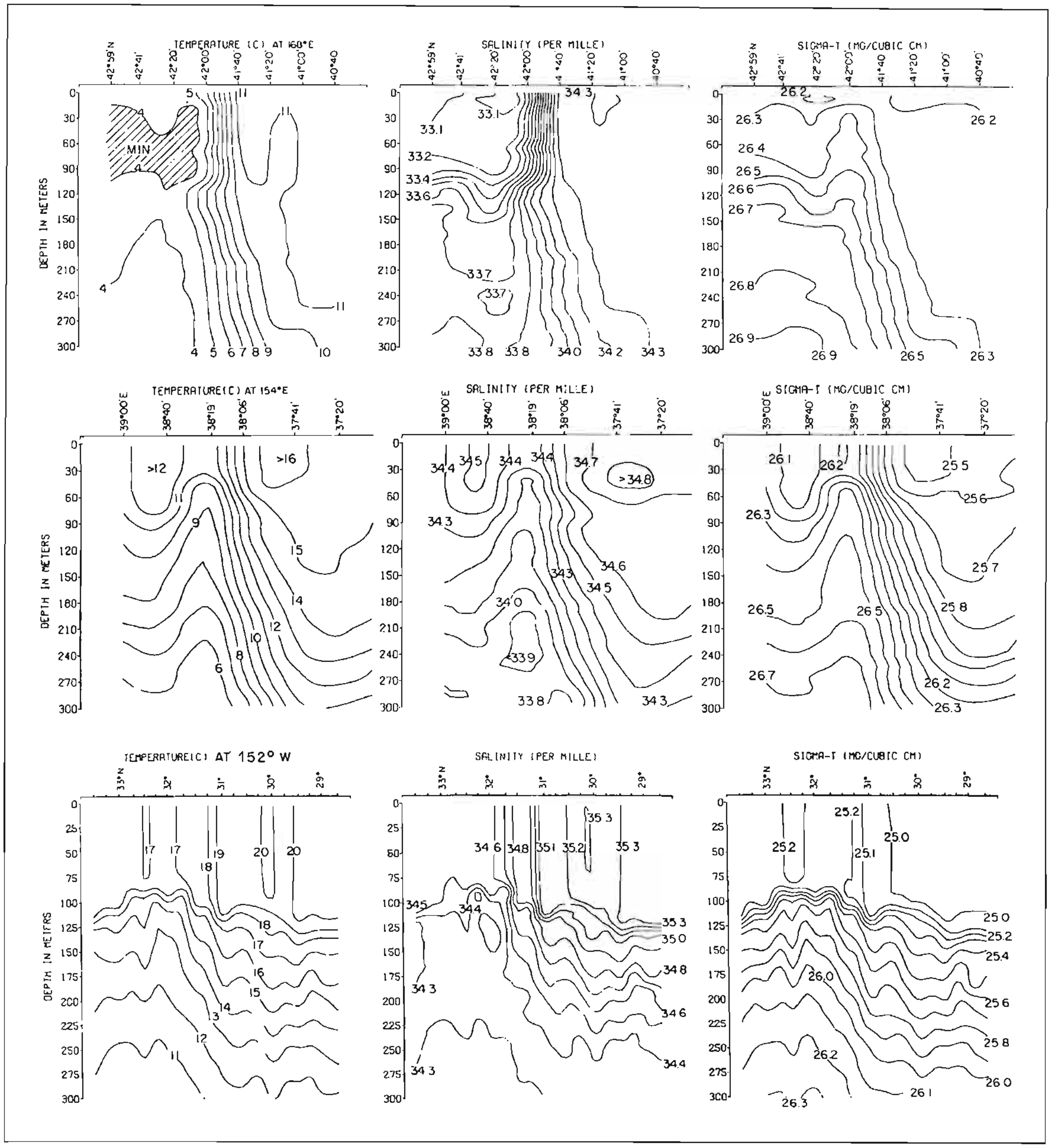


**Figure 20**

Main types of upper ocean temperature, salinity, and density fronts in the mid-latitude North Pacific. (**Top**) Subarctic front in early April 1971; (**middle**) Kuroshio front in April 1971; (**bottom**) subtropical front in February 1974.

600 km. Good vertical coherence of the oscillations was found between 150 and 600 m. Associated with these oscillations are quasiregularly spaced thermohaline fronts, which occur at half wavelength intervals (about 200 km). These fronts are strongest between 150 and 600 m and then weaken rapidly with increasing depth.

The origin of these quasiregularly spaced oscillations is obscure; both Rossby wave generated by the annual oscillation of the wind stress and instabilities in baroclinic shear flow are capable of generating the observed wavelengths (Kang and Magaard 1982).

The amplitude of the mesoscale thermohaline perturbations in the western basin does not appear to depend significantly upon season. In Figure 29 is shown the thermal structure along 167° E in the summer of 1982 (Roden and Taft 1984, 1985). The subarctic front is located near 42°50' N. A remnant of the winter mixed isothermal area to the south of this front is visible between about 200 and 300 m. In the main thermocline there are quasiregularly spaced oscillations with amplitudes of about 200–300 m and dominant wavelengths of 300 to 500 km.

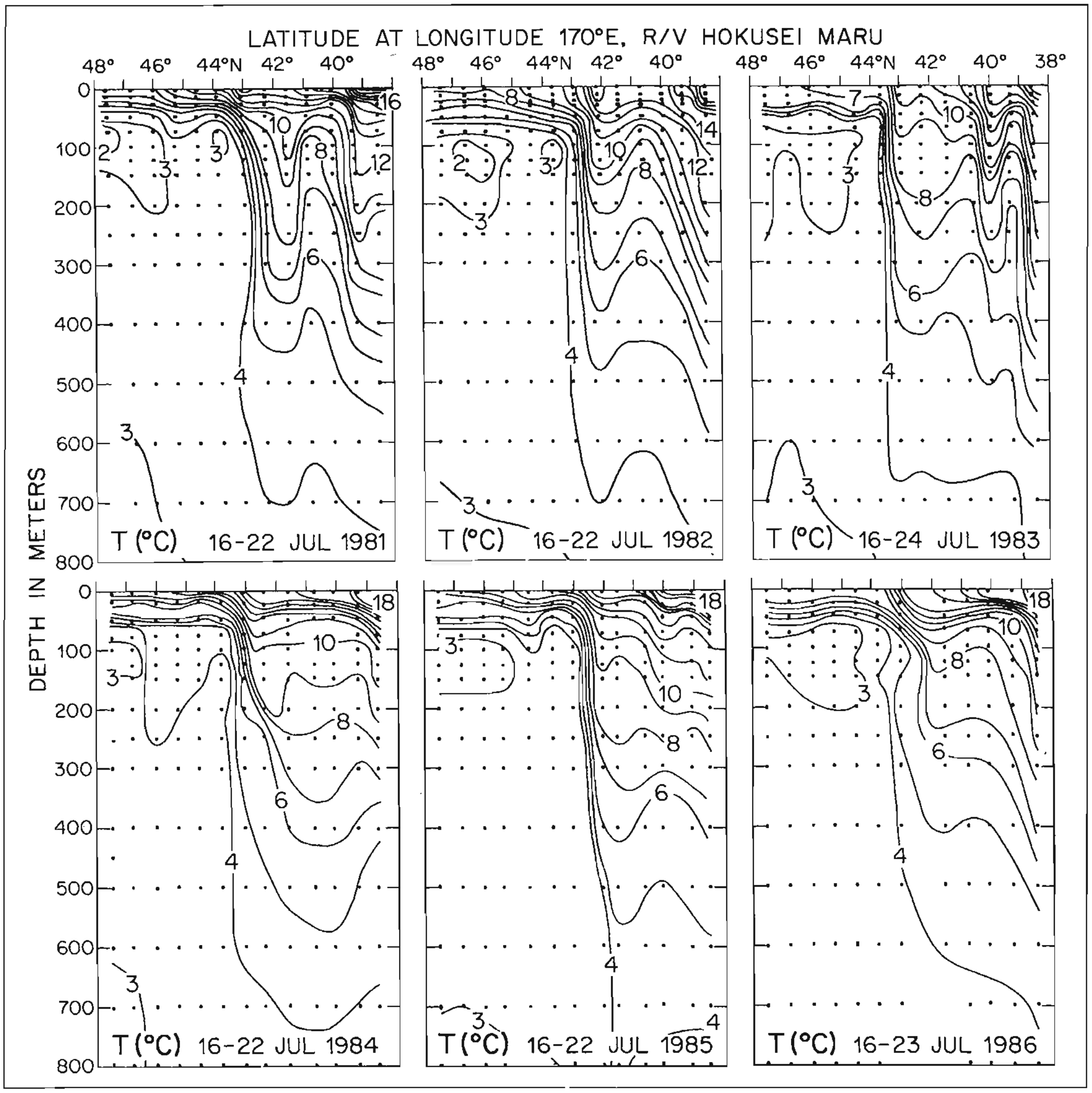


Figure 21

Interannual variations of the subarctic temperature front in the western Pacific basin. Based on Hokkaido University (1982–1987) data reports.

**Eddy and Wavelike Perturbations in the Eastern Basin**—The eastern North Pacific between 30° N and 50° N is dominated by a low-amplitude eddy field superposed upon a weak mean flow (Wyrtki et al. 1976). The thermohaline perturbations in this region are lower by factors between 3 and 6 compared with those observed at comparable latitudes in the western Pacific. Typical temperature, salinity, and density sections across the transition zone at 158° W are shown in Figures 30–32. The sections are based on a 27-km station spacing and were occupied in early fall 1975. Several noteworthy features stand out. The transition zone is most clearly defined in the salinity field and is located between about 34° N and 39° N. On its northern side, between 39° and 43° N, lies the subarctic frontal zone in which several salinity fronts are located. On its southern side, between 32° and 34° N, lies the subtropical frontal zone, in which two haline fronts are encountered. The salinity fronts are most pronounced in the upper 200 m and have strong surface signatures. Beneath 200 m, the isohalines undergo low amplitude (up to 50 m) oscillations of variable wavelength and show few frontal features except in the vicinity of the Hawaiian Ridge at the southern end of the section.

The frontal zones and fronts are much less defined in the corresponding temperature and density sections. Summer heating has led to the formation of an intense shallow thermocline between 30 and 60 m that

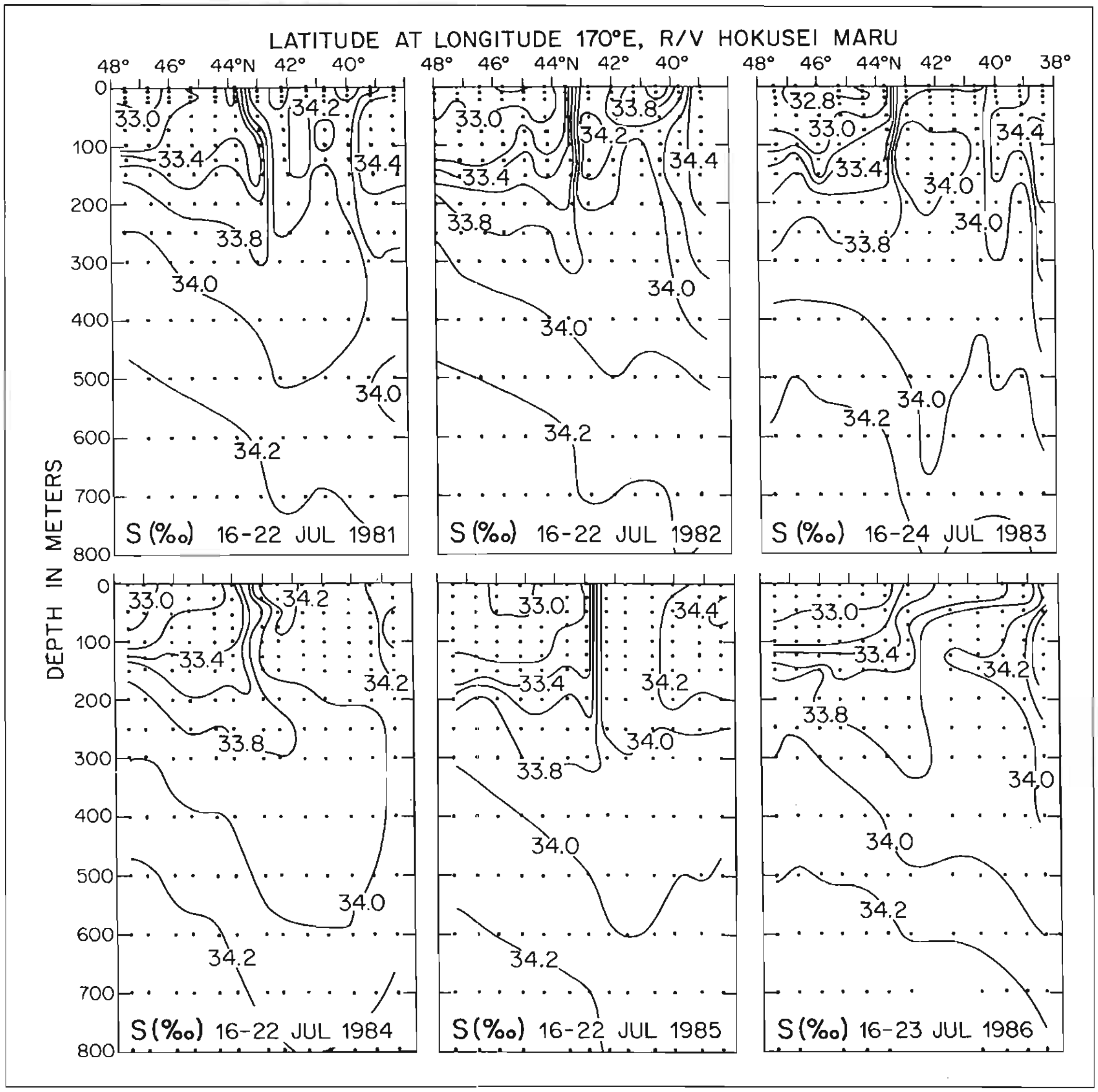


**Figure 22**

Interannual variations of the subarctic salinity front in the western Pacific basin. Based on Hokkaido University (1982–1987) data reports.

stretches as an unbroken band from 47° N to 27° N and only begins to weaken in the tradewind region to the south. In the heated surface layer, horizontal temperature gradients are weak, rarely exceeding 1–2° C/ 30 km. These weak gradients nearly balance the existing horizontal salinity gradients such that density fronts rarely form. Beneath the intense seasonal thermocline and a depth of 200 m, the subarctic frontal zone is outlined by weak thermal fronts in which the 8° C and 10° C isotherms are embedded. The subtropical frontal zone is characterized by the rapid deepening of the 14–18° C isotherms, from about 60 m to about 200 m at 32° N. Below 200 m, the isotherms and isopycnals undergo low amplitude oscillations. The amplitudes are fairly uniform throughout the transition zone, then increase southward to the Hawaiian Ridge.

The positions of the transition and frontal zones do not vary much, when judged from the salinity distributions. In the spring of 1968, the transition zone was at the same location as in the fall of 1975. The subarctic frontal zone in the spring of 1968 (Fig. 8) was slightly wider than in the fall of 1975, extending from 39° N to 45° N. This was also the case for the subtropical frontal zone, which extended from 31°–34° N in the spring of 1968 as compared to 32°–34° N in the fall of 1975. Investigations of the subtropical frontal zone in the winter of 1974 also showed it to lie between 31° at 158° W (Roden 1980).

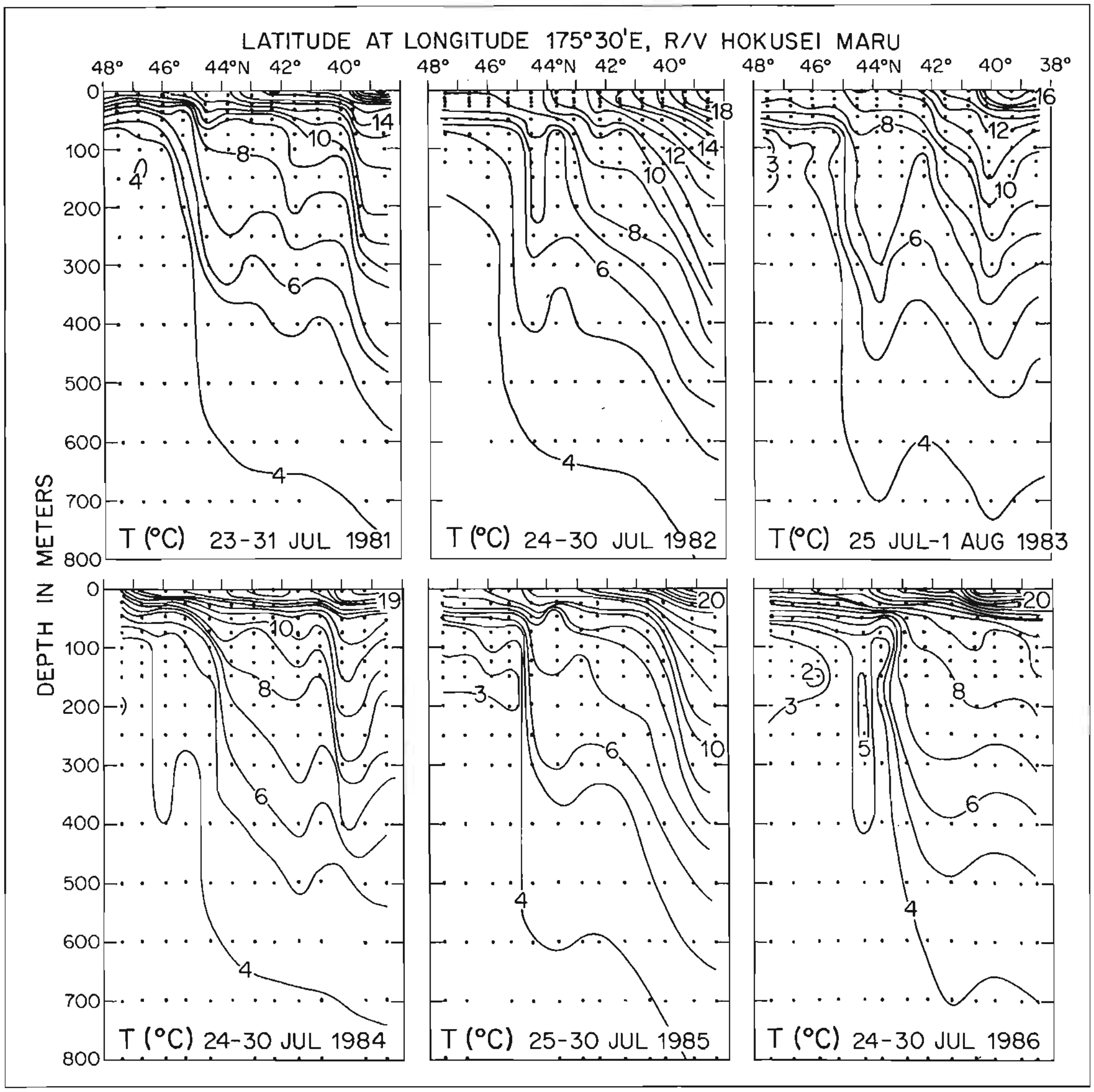


**Figure 23**

Interannual variations of the subarctic temperature front in the eastern Pacific basin. Based on Hokkaido University (1982–1987) data reports.

Inside the frontal zones, convoluted fronts are found. A three-dimensional study of the subtropical front in the winter of 1980 (Roden 1981; Van Woert 1982; Niiler and Reynolds 1984) revealed a persistent cold meander centered near 30° N 153° W. The meander was identifiable by satellite infrared images, shipboard derived sea surface temperatures, surface dynamic topography relative to 1500 decibars (db) and satellite tracked drifter trajectories (Fig. 33). A coldcore cyclonic eddy was observed to the north and a warmcore anticyclonic eddy was observed to the south of the front. Drifters released north of the front tended to stay north and those released south tended to stay south. The front changed slowly with time, as indicated by salinity (Fig. 34). While the frontal position and shape remained relatively constant, its intensity increased by the advection of low salinity water from the north.

**Topographically induced mesoscale variability**—The ocean floor in the region of the subarctic-subtropical transition zone is not flat, but contains topographic features of various shapes and sizes. Some of these are minor abyssal hills and valleys, but others rise abruptly from the deep ocean floor to a height of 4 to 5 km. These large amplitude seamounts can occur singly, in clusters, or arranged along planetary scale seamount chains.

The tall seamounts reach into the stratified part of the ocean and interact with the impinging flow which,

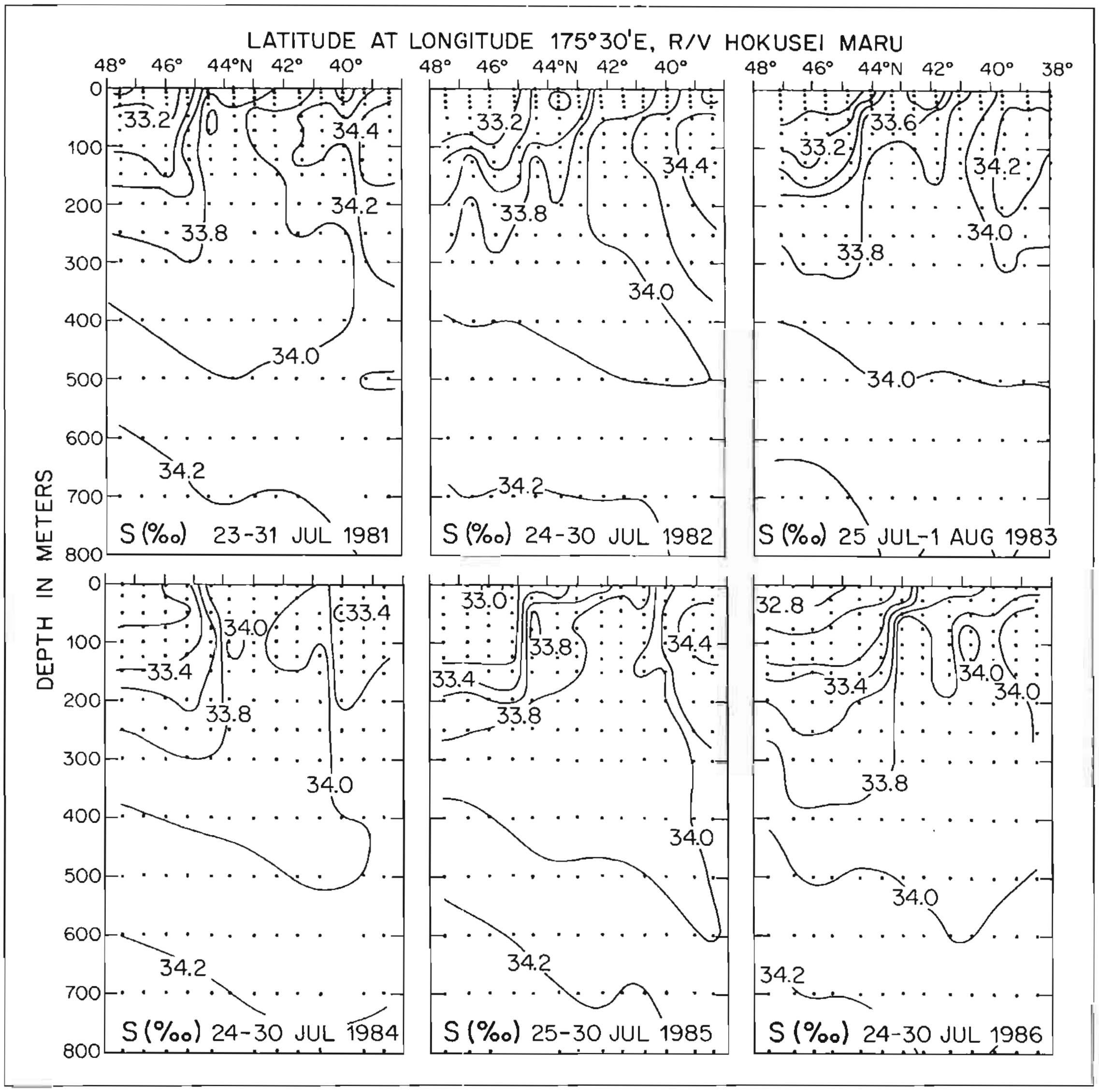


**Figure 24**

Interannual variations of the subarctic salinity front in the eastern Pacific basin. Based on Hokkaido University (1982–1987) data reports.

in general, is both time variable and spatially nonuniform. The results of these interactions are highly complex. They affect the ocean circulation on all scales and are known to enhance boundary mixing (Armi and Millard 1976; Eriksen 1985), amplify tidal flow (Meincke 1971), generate internal wavetrains (Eriksen 1982), give rise to eddies and Taylor columns (Owens and Hogg 1980; Roden 1987), trap drifting buoys and advected eddies (Cheney et al. 1980), cause mesoscale perturbations of sea surface height (Roden and Taft 1985) and deflect boundary currents such as the Kuroshio (Roden et al. 1982; Vastano et al. 1985). These physical processes have biochemical and biological consequences, ranging from nutrient enrichment and enhanced primary productivity to concentrations of demersal fish on and around seamounts (Boehlert and Genin 1987).

Many of the above processes are amplified in the vicinity of the Emperor Seamount Chain, which connects the Aleutian and Hawaiian island arcs in the neighborhood of 170° E. In Figure 35 are shown the deflections of the Kuroshio and subarctic currents and thermohaline fronts by the seamount chain, at a depth of 150 m. This depth was selected to bring out more clearly the various fronts and eddies. The Kuroshio extension, located near 35°30' N at 167° E, approaches the seamounts in a southeastward direction. About 50 km to the west of Kinmei Seamount (33°43' N,

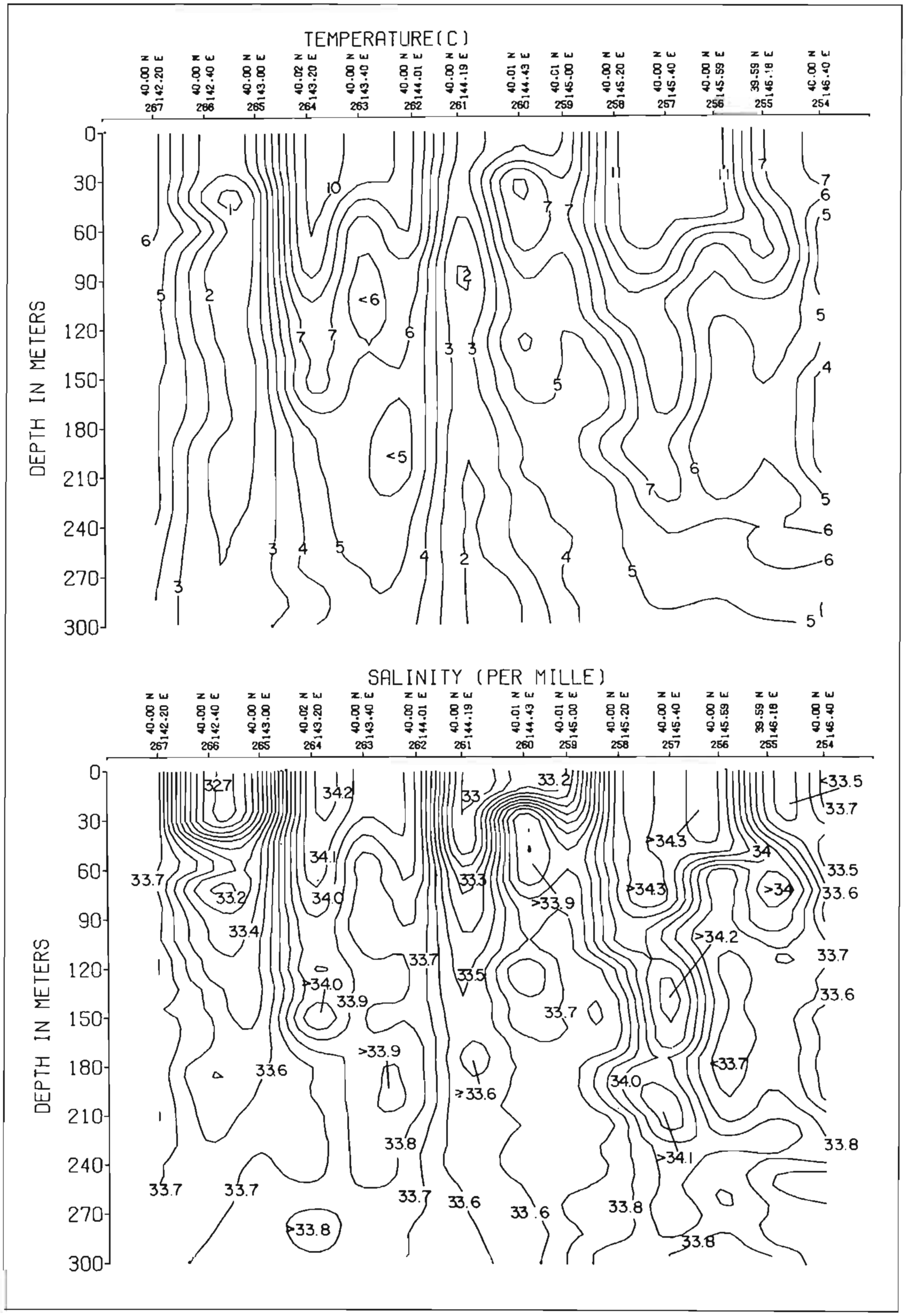


**Figure 25**
Mesoscale thermohaline structure in a zonal section along 40° N off Cape Ma Saki, Japan. After Roden (1975).

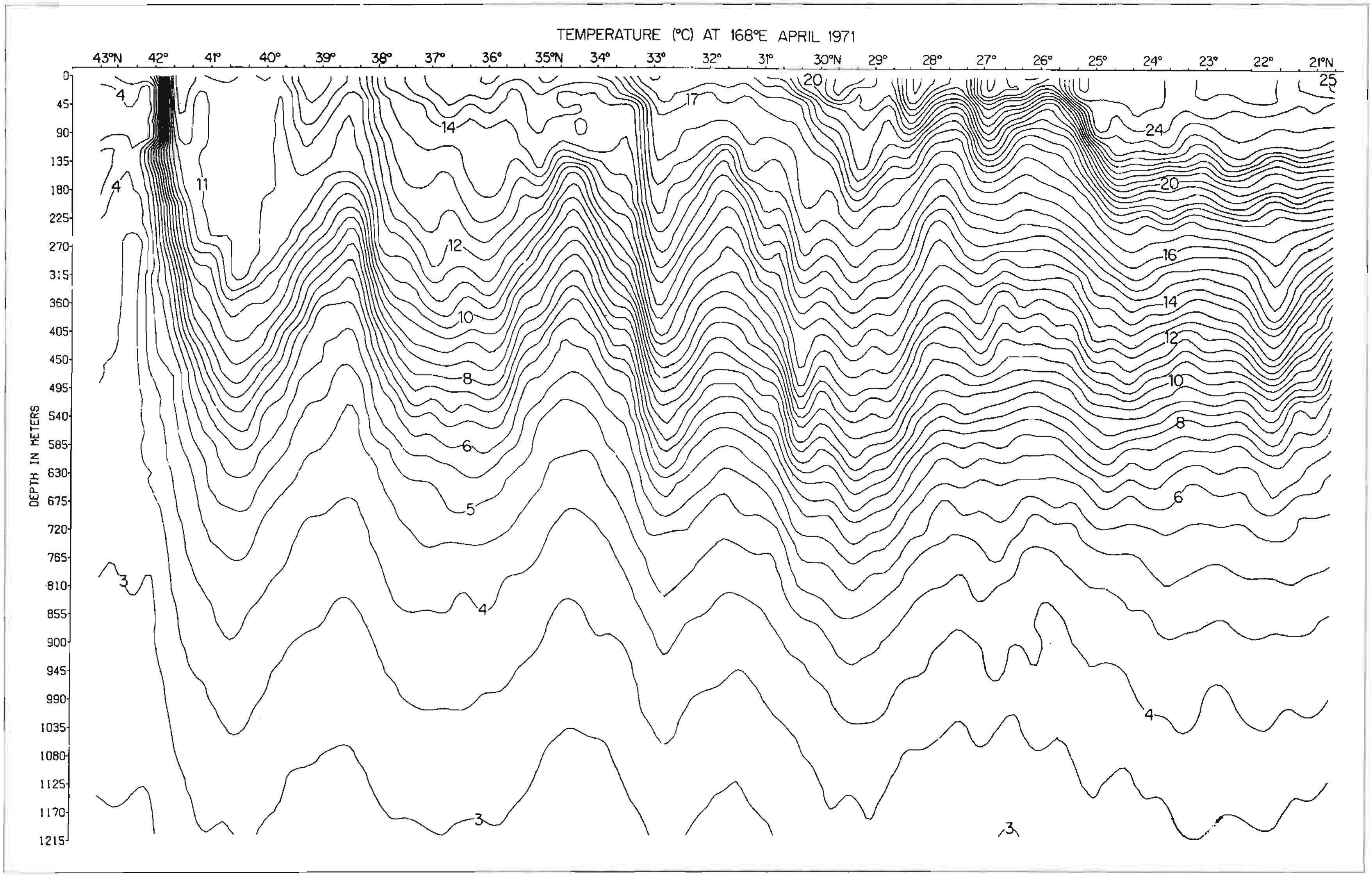


Figure 26
Meridional thermal structure across the transition zone at 168° E in April 1971.

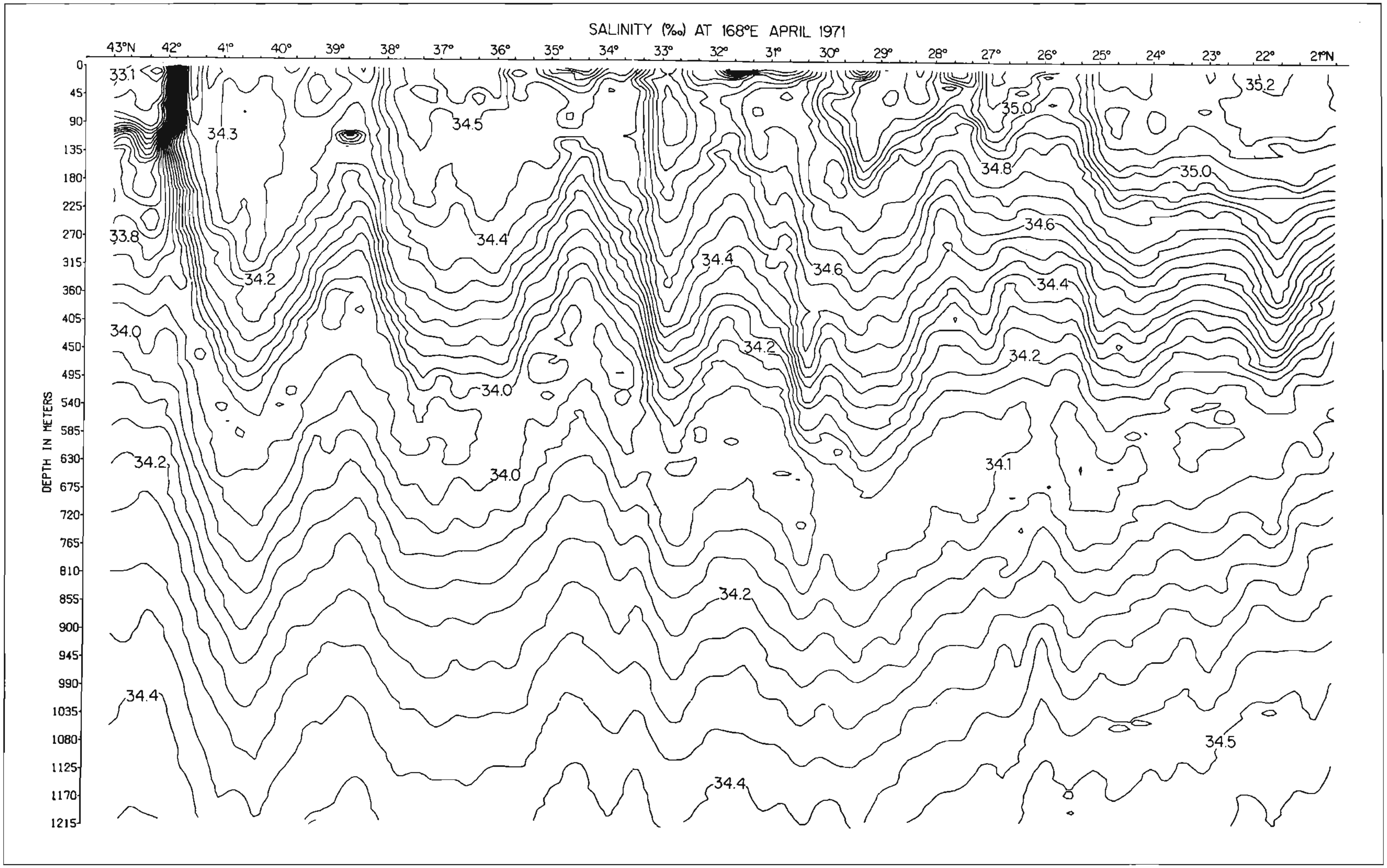


**Figure 27**
Meridional salinity structure across the transition zone at 168° E in April 1971.

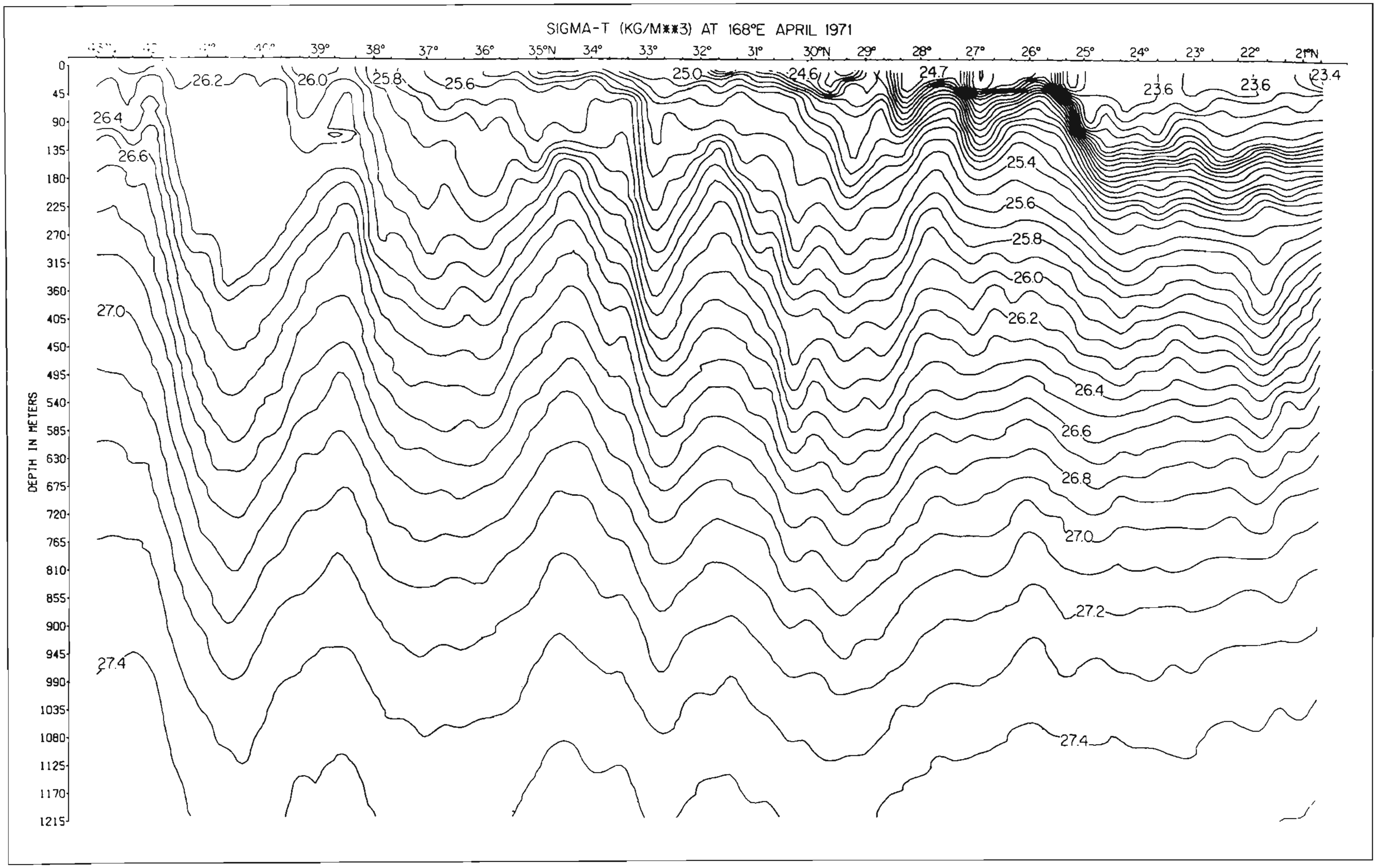


**Figure 28**
Meridional density structure across the transition zone at 168° E in April 1971.

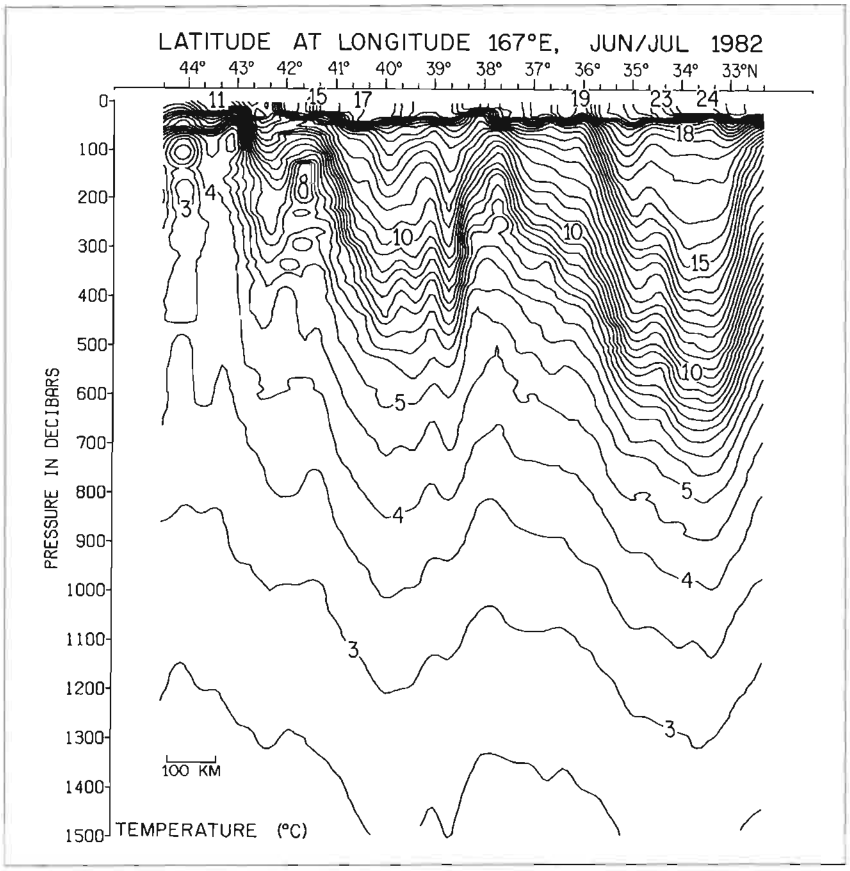


**Figure 29**
Meridional thermal structure across the transition zone at 167° E in June/July 1982.

171°30' E), the Kuroshio extension is deflected to the northward. Over this seamount the current performs an omega-shaped loop and weakens in the process. Downstream of the seamount, the Kuroshio extension intensifies again, though not to its upstream strength. The temperature and salinity fronts associated with this current undergo the same large amplitude anticyclonic deflections over the seamount. Similar deflections have been observed by satellite tracked drifters (Vastano et al. 1985).

The subarctic current also gets deflected by the Emperor Seamounts. This current, located near 41° N at 167° E, first flows toward the southeast, then turns northward over the southern part of Nintoku Seamount (41° N, 170°40' E) and continues in that direction until about 42°30' N, whence it turns eastward and splits. The southern branch of this current forms a large omega-shaped loop returning to the southeast, while the northern branch continues eastward. A strong thermohaline front is located over this seamount in the vicinity of 43° N. The position of this front is remarkably constant from year to year (Fig. 22), indicating that it may be topographically trapped.

The flow topography interaction along the Emperor Seamount Chain results not only in the deflection of large scale flows, but also in the generation of large amplitude mesoscale eddies, with roots that extend deep. This is shown in Figure 36, which illustrates a pronounced eddy 40 km west of Jingu Seamount. The eddy is strongly asymmetric, has stronger gradients on the seamount side; which are indicative of enhanced baroclinic flow there. The core of the eddy is about 60 km wide. The largest vertical displacements of the isopycnals are about 300 m and occur between 200 and 500 m. The amplitudes of these displacements decrease rapidly on approaching the underside of the intense seasonal pycnocline and somewhat more slowly on approaching the level of the seamount top.

Drifter trapping by the Jenkins Seamount group, located just south of the Emperor Seamounts, is shown in Figure 37, based on data by Cheney et al. (1980). The drifter, originally released in the Kuroshio near Japan, arrived in the vicinity of this group on 30 March 1977. It then performed numerous anticyclonic loops among the seamounts of this group and departed the region on 25 May 1977. The loop diameters ranged from 5 to 65 km. Peripheral speeds depended on loop size, reaching 0.7 ms$^{-1}$ in the large loops. The drifter trajectories are suggestive of transient eddies generated by the seamount group.

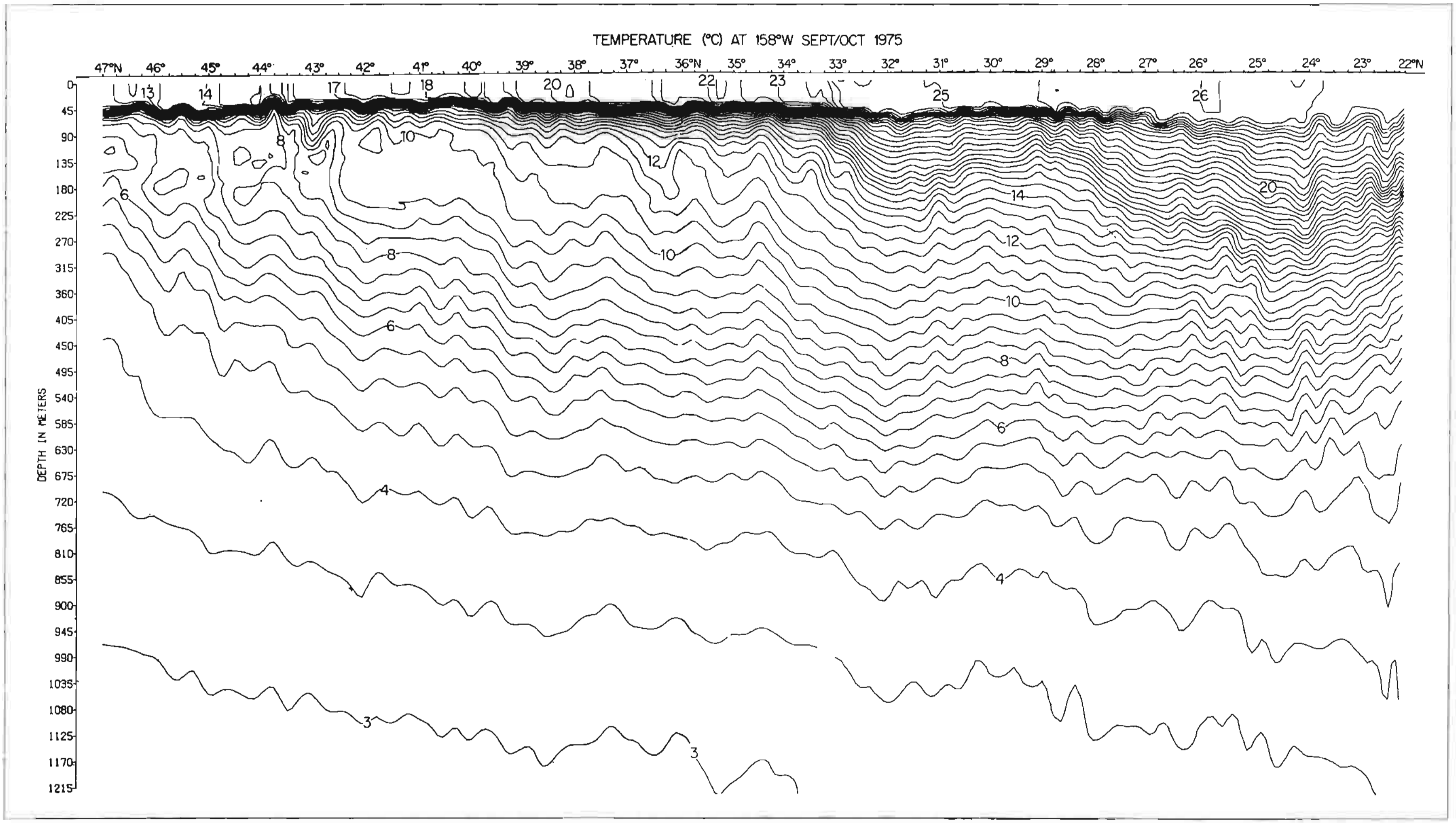

TEMPERATURE (°C) AT 158°W SEPT/OCT 1975

**Figure 30**
Meridional thermal structure across the transition zone at 158° W in early fall 1975.

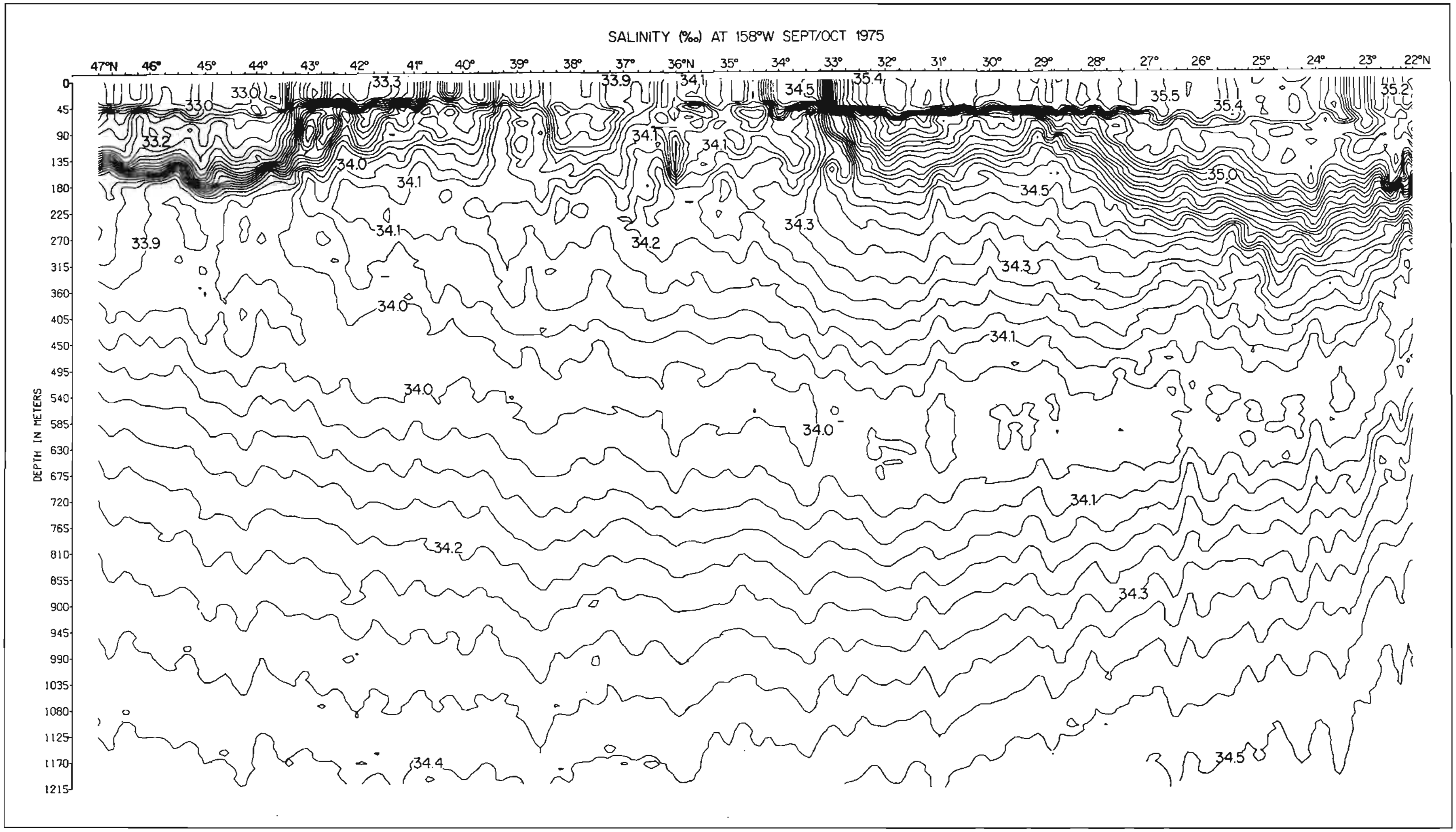
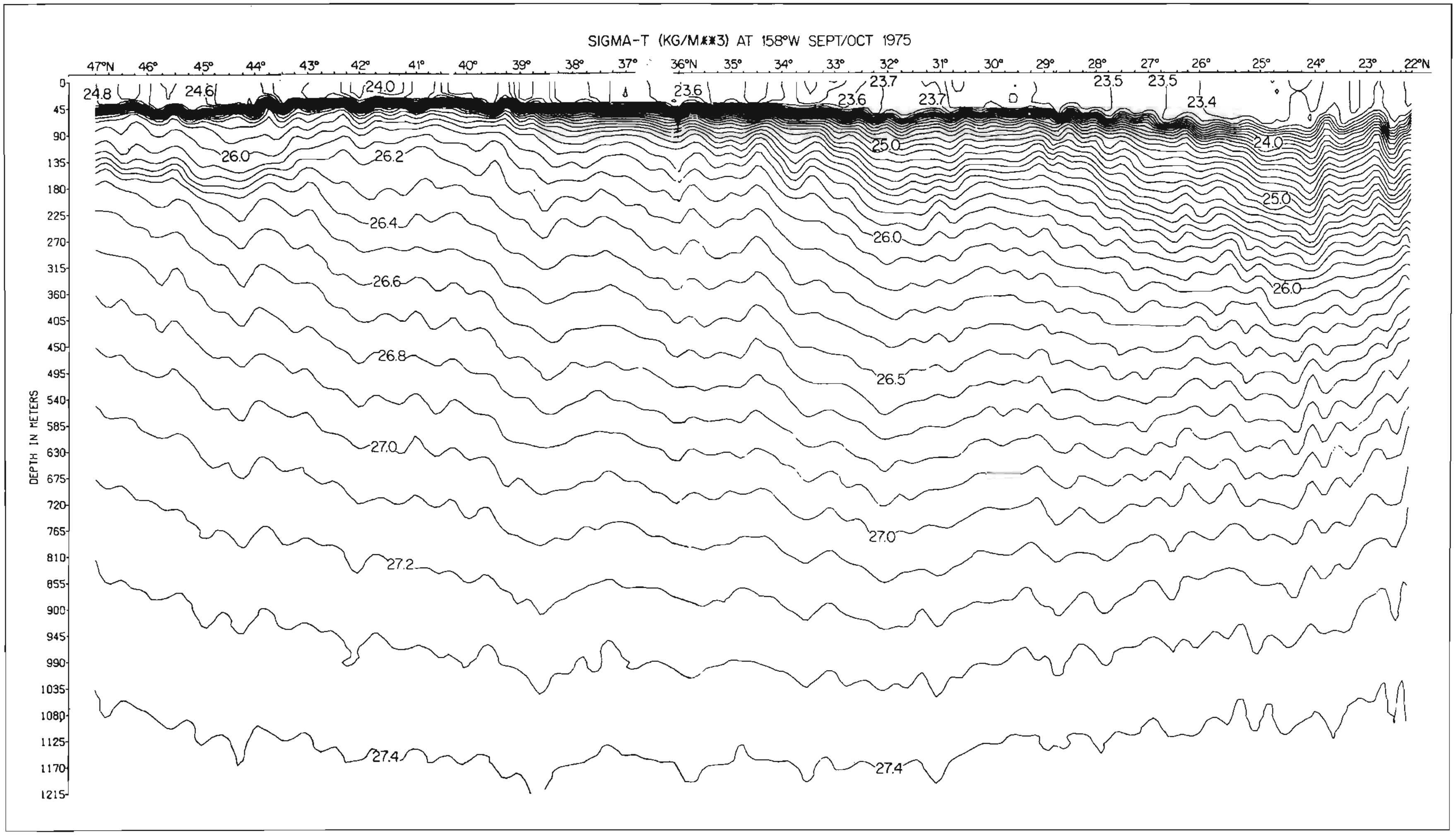


**Figure 31**
Meridional salinity structure across the transition zone at 158° W in early fall 1975.



## Figure 32

Meridional density structure across the transition zone at 158° W in early fall 1975.

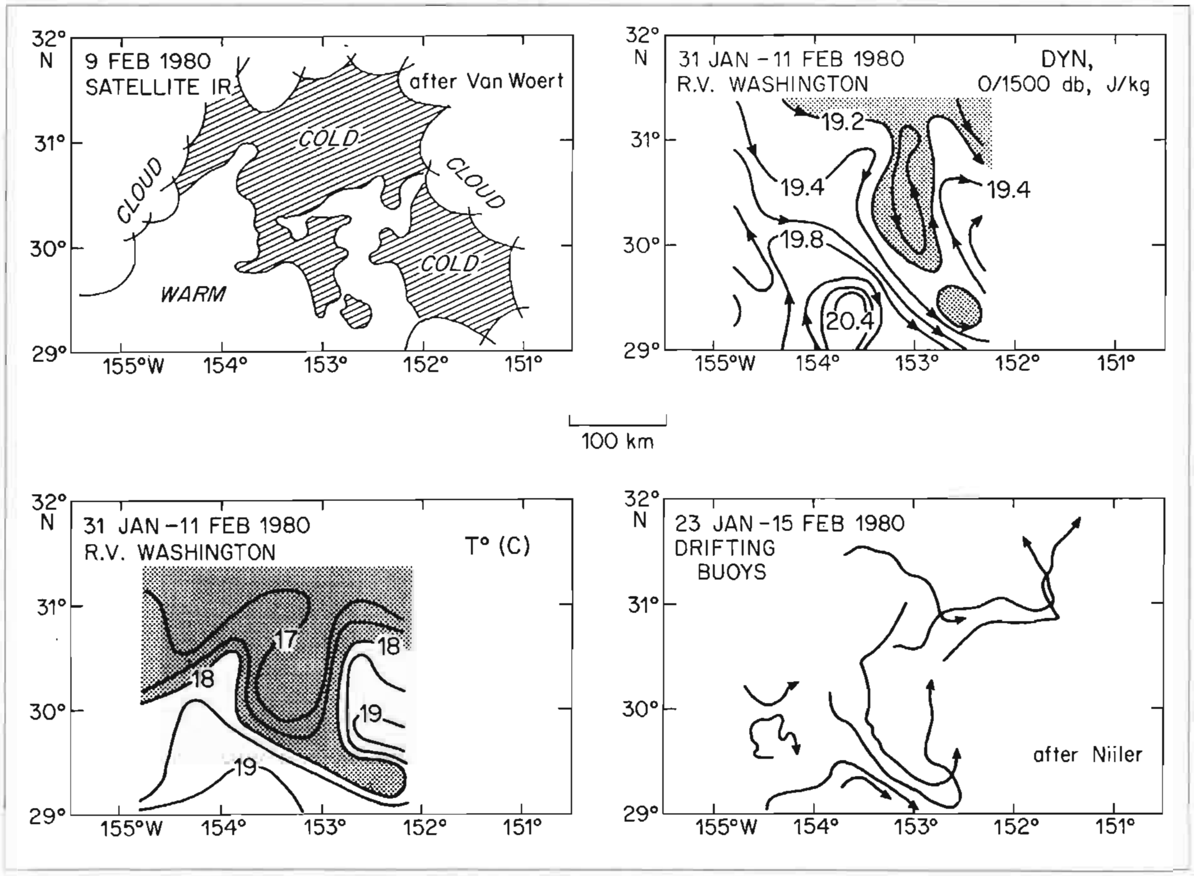


**Figure 33**

The subtropical front north of Hawaii during the winter of 1980 as seen by satellite infrared image (**top left**), ship-derived sea surface temperature (**bottom left**), surface dynamic typography relative to 1500 db (**top right**), and satellite tracked drifting buoy (**bottom right**). After Roden (1981), Van Voert (1982), and Niiler and Reynolds (1984).

## Conclusions and Discussion

In the classical view, the subarctic-subtropical transition zone is a region between the subarctic and subtropical gyres in which the flow is orderly to the eastward and across which the thermohaline properties change smoothly (Sverdrup et al. 1942). The view is reinforced by the large scale distribution of plankton species, many of which show a distinct zonation of subarctic, transition zone, and subtropical types (Brinton 1962).

The classical view changed when high resolution physical and biological sampling techniques replaced the low resolution hydrographic casts at widely spaced stations. In the modern view, the subarctic-subtropical transition zone appears as a complex region in which mesoscale flow structures and biological patchiness dominate at any instant of time. This is evident in both shipboard and remote sensing investigations. Fronts, jets, eddies, current meanders, and wavelike perturbations dominate the physical field (Kawai 1972; Roden 1975, 1977a, 1981; Cheney et al. 1980; Vastano and Bernstein 1984). Plankton populations respond to these temporally varying flow structures, partly following and partly migrating across them (Lobel and Robinson 1986; Woods 1988). Seamounts and seamount chains add to the mesoscale variability by entrapping, generating, and shedding eddies and maintaining resident demersal populations (Boehlert and Genin 1987; Roden 1987).

The observed mesoscale structures are the result of interactions on all scales. Large scale flows such as the Kuroshio extension and the subarctic current grow unstable, and shed eddies. Mesoscale eddies are generated also directly by traveling and stationary atmospheric disturbances and the irregular bottom topography. Once formed, the mesoscale eddies interact among themselves and with the mean flow. Transient jets are developed between the eddies and on the

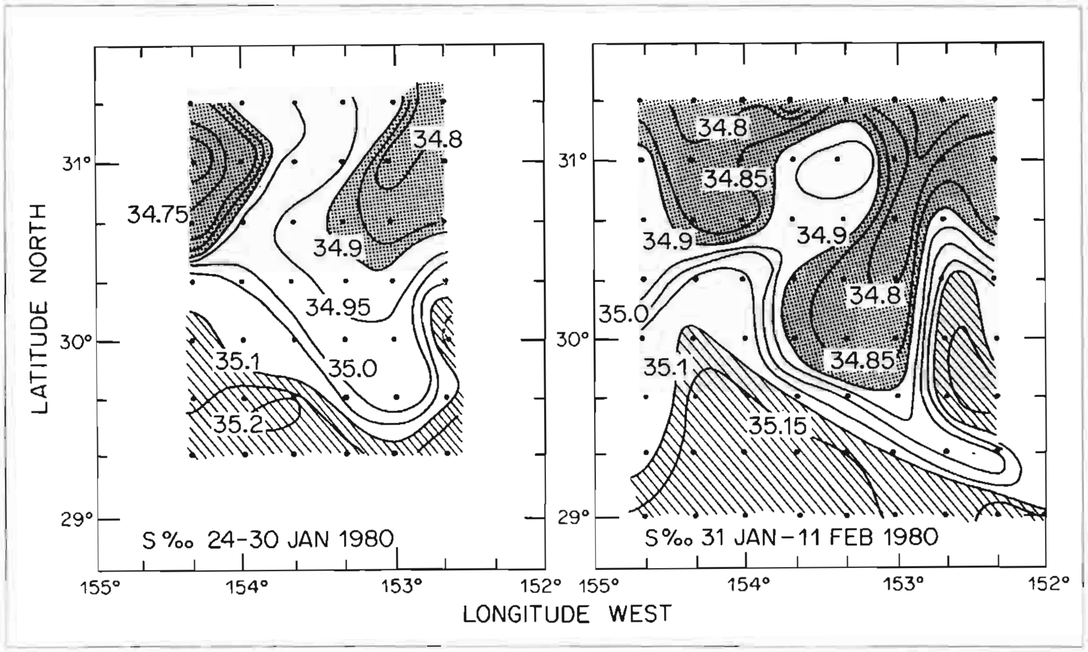


**Figure 34**
Temporal changes of the subtropical salinity front north of Hawaii during the winter of 1980. Dotted pattern indicates cold, low salinity water, striped pattern warm, high salinity water. After Roden (1981).

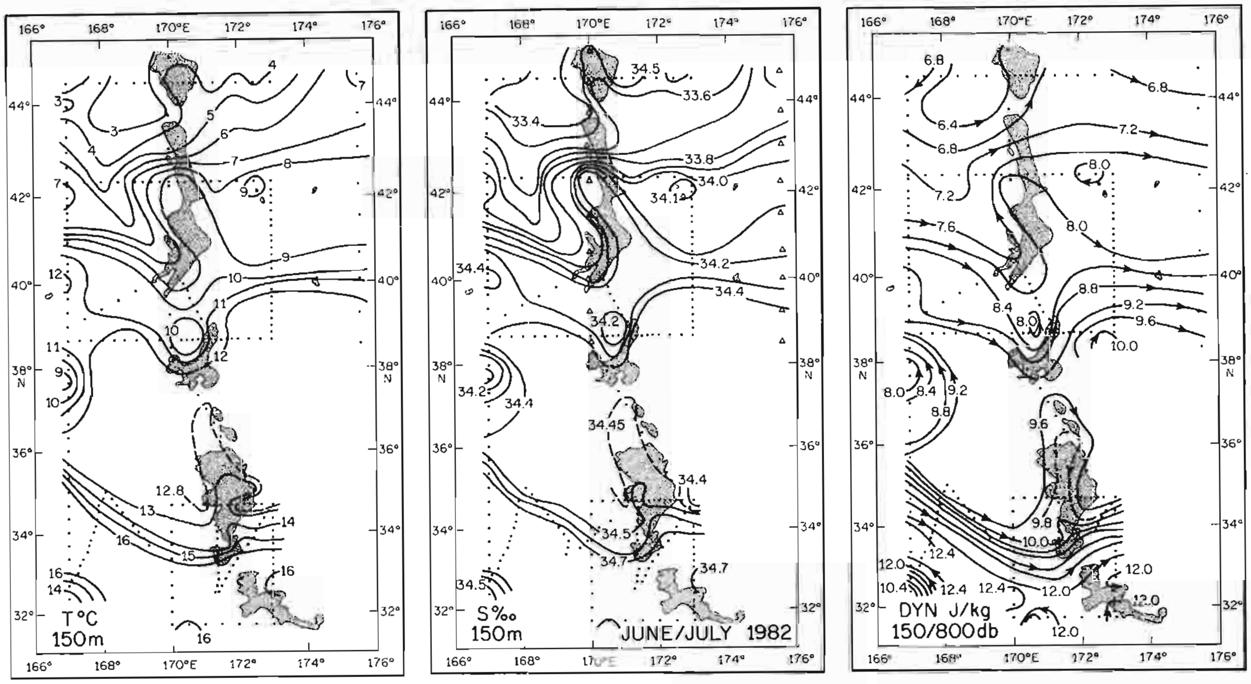


**Figure 35**
Deflection of the Kuroshio and subarctic thermohaline fronts and baroclinic currents by the Emperor Seamounts. Dots refer to stations taken by the RV *Thomas G. Thomas* and triangles by the RV *Oshoro Maru,* both in the summer of 1982. After Roden (1987), based on data by Roden and Taft (1984) and Hokkaido University (1983).

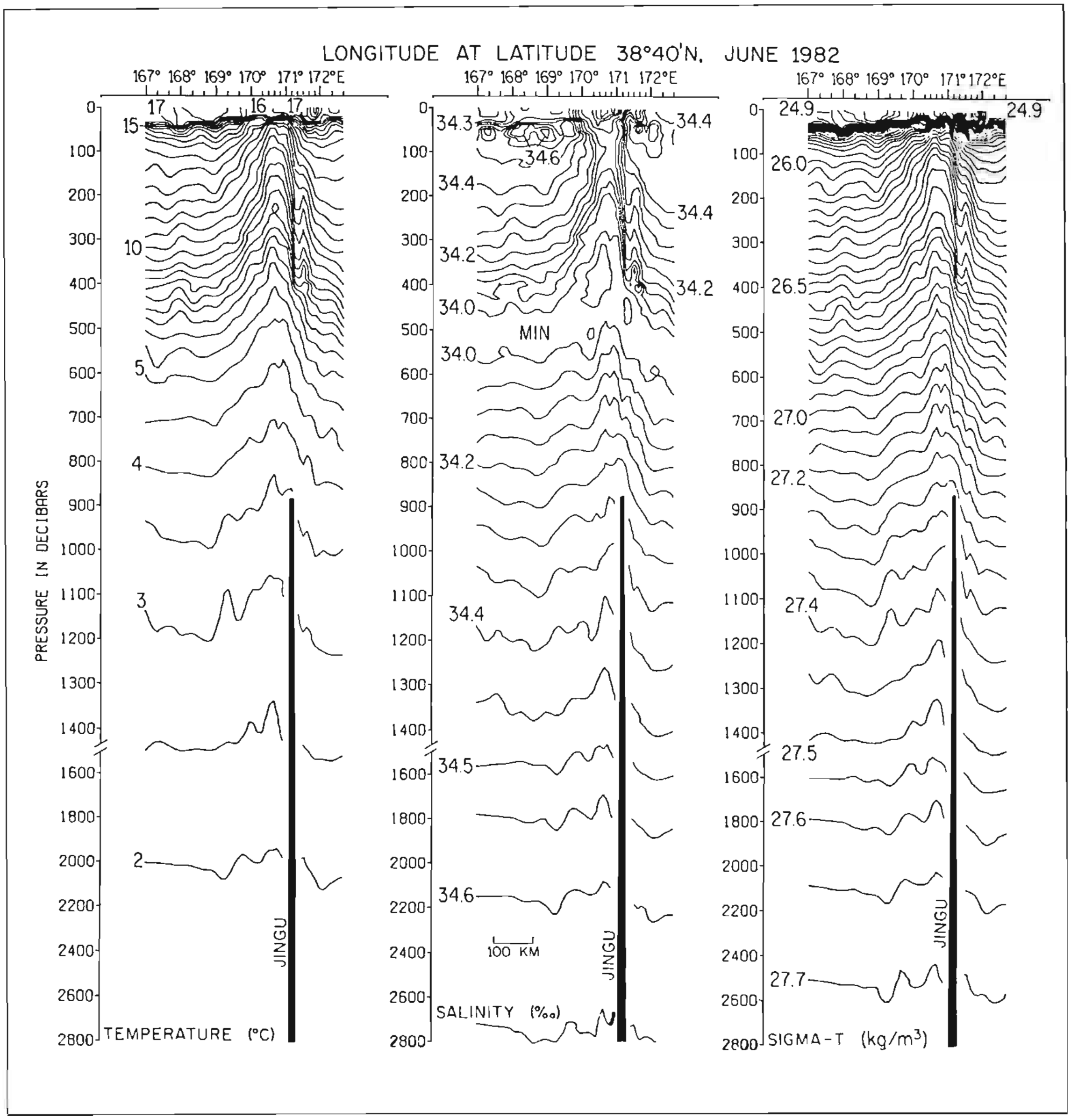


**Figure 36**
Mesoscale disturbances induced by Jingu Seamount. Note the sharp uplift of the isotherms, isohalines, and isopycnals beneath the pycnocline.

flanks of these jets are concentrated submesoscale vortices, which are accompanied by upwelling and downwelling patches a few kilometers across. The upwelling patches may include nutrient enhancement with increase in primary productivity, i.e., represent biological patchiness (Woods 1988).

Analysis of recent and historical data permits one to draw the following conclusions:

- The subarctic-subtropical transition zone is an oceanwide feature associated with the oceanic and atmospheric gyre scale circulations and air-sea energy exchange processes.
- The transition zone is bounded in the north by the subarctic frontal zone and in the south by the subtropical frontal zone. In each, one or several meandering fronts and frontal eddies are found. In the upper layer of the ocean, temperature, salinity, and density fronts do not always coexist.
- In mid-ocean, the positions of the transition and associated frontal zones are relatively fixed in time and space, varying not more than 150–200 km from their climatological mean positions. Individual fronts within these zones are highly time variable, however.
- The northern boundary of the transition zone is marked by the disappearances of the subarctic halo-

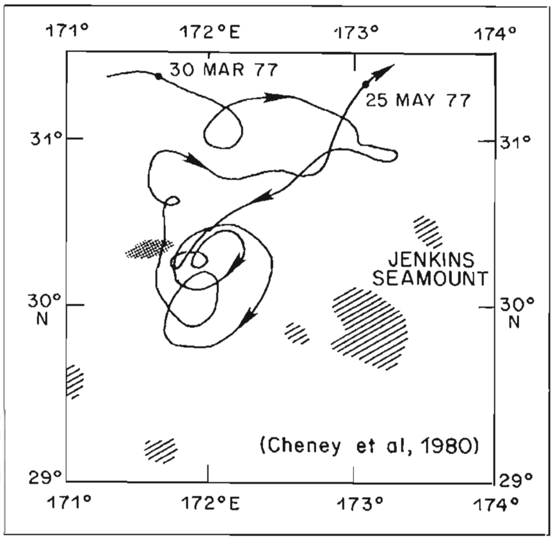


**Figure 37**
Path of satellite tracked drifters in the vicinity of the Jenkins Seamount group. After Cheney et al. (1980).

cline and the overlying shallow temperature minimum. Large changes occur in the hydrostatic stability structure. A seasonal stability gap develops near the northern boundary of the transition zone, allowing atmospheric influences to penetrate deeper than elsewhere in the region during winter.

- The southern boundary of the transition zone is marked by the disappearance of the subtropical halocline and by large changes in the vertical structure of the thermocline and pycnocline, which deepen toward the south.
- Mesoscale perturbations of the flow and thermohaline structure are the dominant features on synoptic time scales, greatly overshadowing the weak mean flow and the climatological mean structure. The mesoscale perturbations west of the Emperor Seamount Chain are three to six times larger than those to the east.
- Mesoscale perturbations in the western basin are characterized by alternating bands of eastward and westward flows 150–300 km wide and vertically coherent in the upper 1500 m. The corresponding variations in sea surface height are of the order of 0.4 m throughout the transition zone. The mesoscale flow perturbations are accompanied by quasiregularly spaced temperature and salinity fronts in the thermocline and halocline.
- Mesoscale perturbations in the eastern basin are characterized by alternating bands of weak eastward and westward flow that does not penetrate much below 600 m. The corresponding variations in sea surface height are of the order of 0.1 m in the transition zone. Because the mesoscale flow perturbations are weak, quasiregularly spaced temperature and salinity fronts in the thermocline and halocline are not evident.
- Large amplitude topography has a measurable effect on flow and thermohaline structure in the transition zone. The interaction of the Kuroshio and subarctic currents with the Emperor Seamount Chain not only results in deflection and weakening of these currents as they cross the chain, but also results in the generation of intense mesoscale eddies. Thermohaline fronts accompany these current deflections and eddies and extend to depths of 1 km or more. The fronts are strongest beneath the seasonal thermocline and are not always detectable at the sea surface (in case of temperature).
- The interannual variability of fronts depends on the flow dynamics at the particular geographic location. The subarctic front over Nintoku Seamount (43° N, 170° E) appears to be topographically trapped. Over the six-year period 1981–1986, the position of the front varied by less than 50 km from its mean position at 43° N. About 400 km to the east, over a flat seafloor, the position of the same front varied by more than 150 km during these years.

## Acknowledgments

The high resolution hydrographic data used in this study were mostly collected by the RV *Thomas G. Thompson* during the years 1968–1982 under Office of Naval Research contract N00014-84C-0111 (Roden and Fredericks 1987, a through c) and National Science Foundation grant OCE 81-17047 (Roden and Taft 1984, 1985). Data collected in the Emperor Seamounts region by the RV *Hokusei Maru* (University of Hokkaido, 1982–1987) made it possible to investigate the interannual variability of the subarctic front. The writing of this paper was supported by Joint Institute of Marine Research (JIMAR) of the University of Hawaii. Special thanks are due J. Wetherall of the Honolulu Laboratory of the National Marine Fisheries Service for organizing the NMFS/JIMAR Workshop on the Biology, Oceanography, and Fisheries of the North Pacific Transition Zone and Subarctic Frontal Zone in May 1988 and for inviting the author. This is contribution No. 1871 from the School of Oceanography, University of Washington, Seattle WA 98195.

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# Biology of the Transition Region

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## ABSTRACT

The transition region of the North Pacific Ocean includes the Transitional Domain of the Subarctic Water Mass and the transition zone south of the subarctic boundary. It is therefore located between two different epipelagic ecosystems, each with characteristic nutrient regimes, productivity cycles, and faunal compositions. The transition region has distinct endemic species of zooplankton and micronekton. Common species of epipelagic nekton caught in gill nets both north and south of the subarctic boundary in this region during the summer include Pacific saury, Pacific pomfret, albacore, blue shark, flying squid, and boreal clubhook squid. Albacore, skipjack tuna, and dolphin are common south of the subarctic boundary in the transition zone. Most of the large nektonic animals of this region undertake north-south seasonal migrations that capitalize on the high productivity of the subarctic waters in the spring and summer and the availability of large, nutritious prey such as gonatid squids. During the winter, migrants retreat south of the subarctic boundary where water temperatures are warmer, the seasonal changes in productivity are less pronounced and frontal structure may concentrate prey. In addition to preying on the endemic fauna of the subarctic region in the summer, the large migratory fishes and squids also consume small migratory fishes, such as saury and sardine, that precede them in northward movements.

## Transition Region

Two predominant gyres exist in the North Pacific Ocean: The cyclonic subarctic gyre north of 45°N and the anticyclonic North Pacific central gyre in subtropical latitudes. Distinct water masses and biota are associated with these gyral systems. The subarctic boundary, often denoted by the vertical 34‰ isohaline (Dodimead et al. 1963; Favorite et al. 1976), usually forms a sharp front along the southern boundary of subarctic waters between 40–45°N across the Pacific Ocean (Fig. 1). Cool, low salinity waters with a permanent halocline between 100–200 m and large seasonal variations in temperature in the upper mixed layer characterize subarctic waters north of this front. South of the subarctic boundary, between 42° and 32°N, lies the transition zone, a zone of mixing between subarctic and central waters where the halocline is weak and stability is low (Roden 1970, 1980). The subtropical front is a region of rapid, southward increases in temperature and salinity in the winter and in salinity in the summer along the southern margin of the transition zone, between the prevailing westerlies and easterly trades at 28°–35°N (Roden 1975). North Pacific Central Water south of this front is characterized by warm, high salinity (35‰ at the surface) water with a persistent thermocline, high stability, no halocline below low-salinity surface waters, but a salinity minimum at about 500 m (Roden 1970, 1980).

The Subarctic Water Mass has been divided into several domains (Dodimead et al. 1963; Favorite et al. 1976). The transitional domain is located between the subarctic boundary and the central subarctic domain (Fig. 1). Here the flow is principally zonal. The northern boundary of the transitional domain has been defined by several physical features: where the 7° isotherm intersects the upper halocline (Dodimead et al. 1963), the surface isohaline is 33‰ or the 4°C isotherm plunges below 100 m (Favorite et al. 1976; Shimazaki 1986), or where dichothermal or temperature minimum layer of the more northern central subarctic waters disappears (Dodimead et al. 1963). The transitional domain is latitudinally narrow in the western Pacific and broad in the eastern Pacific where it expands into the Cali-

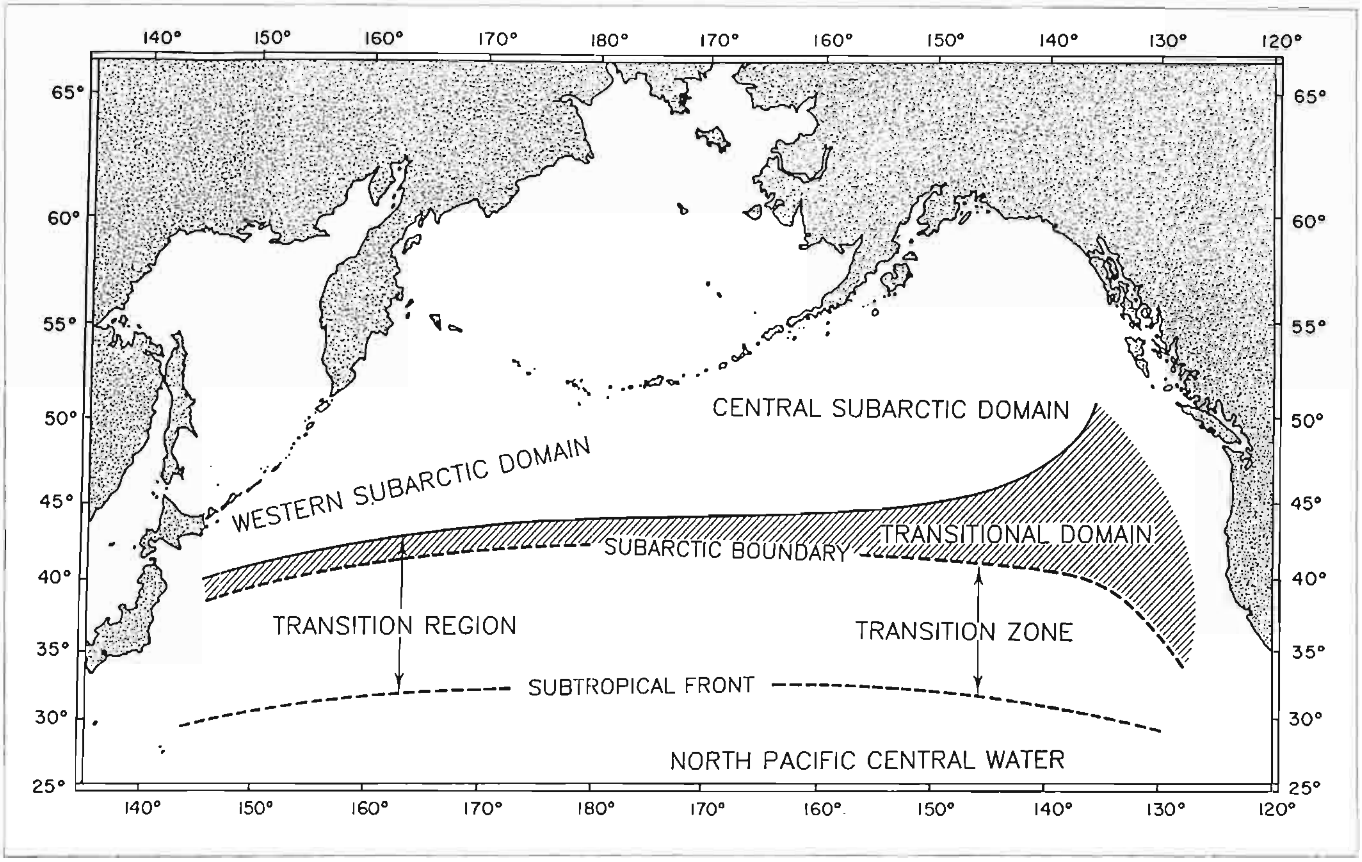

**Figure 1**
Oceanographic regions of the North Pacific Ocean.

fornia Current and Alaska Current. The ridge domain, with doming of isopycnals indicative of massive divergence, is found to the north of the transitional domain in central subarctic waters.

Because many of the nektonic animals associated with this region between waters of the central subarctic and central North Pacific are broadly distributed and migrate between the boundaries of these two gyres, this review includes both the transition zone and the transitional domain. I will call both regions combined the "transition region" (*see* Fig. 1).

## Biology of the Transition Region and Adjacent Waters

Since the transition region is an area of mixing between Subarctic and Subtropical Central Water Masses, our understanding of this region is facilitated by comparison of the basic features of these two different gyral ecosystems that border the transition region (Table 1).

## Primary Production and Plankton Dynamics

Concentrations of nutrients, such as $PO_4$–P, are generally high in subarctic waters and low in the subtropical waters (Reid 1962; McGowan and Williams 1973). Strong north-south gradients in nitrate, phosphate, and silicate are found in the region of the subarctic front between these water masses (Park 1967; McGowan and Williams 1973). Phytoplankton standing stocks, as measured by chlorophyll *a*, and productivity also decrease markedly from eutrophic subarctic waters across the transition region into the subtropical regions (Koblenz-Mishke 1965), McGowan and Williams (1973) found that mean concentrations of chlorophyll *a* were significantly lower in the transitional domain than in central subarctic waters during both summer and winter seasons.

Phytoplankton production in oligotrophic central waters is limited by lack of major nutrients resulting from the weak mixing and strong vertical stability of the water column throughout the year (Eppley et al. 1973; Hayward et al. 1983). There is little evidence

**Table 1**

Features of the structure and function of plankton in three geographic regions of the North Pacific Ocean.

| | Central subarctic | Transition region | North Pacific central | References |
|---|---|---|---|---|
| **Phytoplankton** | | | | |
| Limiting Factors | Light, Fe<br>Grazers | N | N and P | 1, 2, 3, 4<br>5, 6, 7 |
| Chlorophyll *a* | High | Mod. | Low | 8, 9 |
| Seasonality in chlorophyll | No | No | No | 1, 9, 10 |
| Primary productivity (g/m$^2$/yr) | 100–150 | 80–100 | <50 | 11 |
| Productivity peak | Spring | Late Spring? | Winter? | 5, 9 |
| Summer/winter ratios in prod. | >10 | 2–6 | 2 | 11 |
| **Zooplankton** | | | | |
| Seasonal variability | High | Low | None | 5, 9, 10, 12 |
| Standing stock | High | Mod. | Low | 9, 11 |
| Summer/winter (g wet/1000m$^3$) | 200–500/<50 | 100–200/50–100 | 10–50/10–50 | 11 |
| Carnivore: total zooplankton | Low | ? | High | 11, 13 |
| Body size of macrozooplankton | Large | ? | Small | 8, 14 |
| Lipid content | High | ? | Low | 14 |
| Seasonal vertical migrations | Yes | | No | 10, 11, 15 |
| Species richness | Low | Mod. | High | 13, 14, 16, 17 |
| Percent endemic species | High | Mod. | Low | 16 |

1 Parsons and LeBrasseur 1968
2 Anderson et al. 1969
3 Eppley et al. 1973
4 Martin and Fitzwater 1988
5 Frost 1983
6 Miller and SUPER group 1988
7 Miller et al. in press
8 Reid 1962
9 McGowan and Williams 1973
10 Hayward et al. 1983
11 Taniguchi 1981
12 McAllister 1960
13 Reid et al. 1978
14 Motoda et al. 1974
15 Miller et al. 1984
16 McGowan 1974
17 McGowan and Walker 1985

for seasonal cycles of chlorophyll concentrations of primary productivity (McGowan and Williams 1973; Taniguchi 1981; Hayward et al. 1983). A deep chlorophyll maximum is present above the nutricline in the region of the upper thermocline during all seasons (McGowan and Williams 1973; Venrick et al. 1973).

In the subarctic Pacific, on the other hand, where deep water is upwelled and intense winter mixing above the halocline alternates with thermal stratification in the euphotic zone, major nutrients are not depleted, even during the spring and summer (Anderson et al. 1969). Large seasonal fluctuations exist in primary productivity. Production is high in the spring when nutrients exist in high concentrations above the shallow thermocline. But this region, including the transitional domain, is characterized by a lack of phytoplankton blooms (Parsons and LeBrasseur 1968; McAllister 1969; Parslow 1981; Taniguchi 1981; Frost 1983).

Phytoplankton standing stocks in the subarctic Pacific, which are dominated by nanoplankton (Parsons and Lalli 1988), are limited by low temperature and light intensities, by grazing of herbivores in the spring, (McAllister 1960; Venrick 1971; Taniguchi 1981; Frost et al. 1983; Miller and SUPER group 1988; Parsons and Lalli 1988), and by low availability of iron (Martin and Fitzwater 1988; Martin et al. 1989). The absence of a spring bloom in the subarctic Pacific had been attributed to intense grazing by the large copepods, particularly the endemic *Neocalanus* spp. which reproduce without feeding in the spring, using lipid stores accumulated from the previous growing season (Heinrich 1962; Frost et al. 1983; Miller et al. 1984). Recently, the role of microzooplankton in this ecosystem has been emphasized, and now heterotrophic protozoans, not large calanoid copepods, are thought to be major consumers of nanoplankton in subarctic waters

(LeBrasseur and Kennedy 1972; Frost 1987; Miller and SUPER group 1988). The absence of a typical phytoplankton bloom in the subarctic Pacific may therefore be due to iron limitation, which establishes a phytoplankton community dominated by small cells, intense grazing by microzooplankton during the spring, and the reduced mixing of the water column by the strong halocline which retains both phytoplankton and grazers in upper waters during the winter (Miller et al., in press). The southern extent of the "balance" phenomenon is not known, but nanoplankton and microzooplankton are presumably the predominant producers and grazers throughout the transition region.

The geographic pattern of zooplankton biomass in the North Pacific is very similar to that of phosphates (Reid 1962) with high standing stocks in subarctic, low standing stocks in central waters, and a pronounced gradient across the transition region (Hayward et al. 1983). A region of lower than average standing stocks of zooplankton noted by Reid (1962) in the central subarctic domain is attributed to rates of surface divergence that exceed the population growth rates of zooplankton.

McGowan and Williams (1973) reported higher standing stocks of zooplankton (0–300 m) in the central subarctic domain than in the transitional domain during summer and winter. Seasonal cycles of zooplankton biomass are weak in central waters (Hayward et al. 1983) but pronounced in subarctic waters. Taniguchi (1981) estimated that the summer: winter ratio of zooplankton in the upper 150 m was 4–10 in subarctic waters compared to 1.0 in central waters. McAllister (1960) and Frost (1983) also reported large seasonal variations in the standing stocks of zooplankton at Station "P" in the subarctic Pacific.

The ratio of carnivores to total zooplankton also differs between these two gyral ecosystems, with carnivores composing a larger fraction of the total in subtropical areas (Reid et al. 1978; Taniguchi 1981). The average body size of zooplankters is larger in subarctic than in subtropical waters, and their lipid content is higher in northern areas (Motoda et al. 1974). Seasonal or ontogenetic migrations of zooplankton are pronounced in the .subarctic Pacific. *Neocalanus* copepods enter a diapause state and descend into deep water in the summer (Miller et al. 1984; Miller and Clemons 1988). Such ontogenetic migrations of common zooplankton are not well documented from the transition or subtropical regions. Diel vertical migrations of zooplankton and micronekton are probably more pronounced in central waters where transparency is high and day-night cycles of sunlight are more equal (Hayward et al. 1983).

Less is known about the plankton dynamics of the transition region than for either of the adjoining gyres (McGowan and Williams 1973). McGary et al. (1958) concluded that the transition zone was a region of low vertical stability where optimum conditions for a phytoplankton bloom and increased zooplankton abundance would advance to the north in the spring.

## Micronekton

Micronekton also increases from central to subarctic waters. Average volumes of small fishes, squids and crustaceans in Isaacs-Kidd midwater trawls were higher from 35° to 50°N in the Subarctic Current-transitional domain than between 28° and 35°N in the transition zone north of Hawaii (King and Iversen 1962). Pearcy et al. (1988) found that the biomass per $m^3$ of taxa collected in a 4.5 $m^2$-midwater trawl was larger in subarctic than in subtropic waters with large catches of medusae and ctenophores in the central subarctic domain. Donaldson and Pearcy (1972) also reported large variations in the biomass of plankton and micronekton captured in a 3-m Isaacs-Kidd midwater trawl in the mid-Pacific between Hawaii and Adak, Alaska. They found that zooplankton biomass was largest in subarctic waters, intermediate in the transition region and lowest in central waters. The biomass of fishes, shrimps and squids, however, was largest in the transition region at 42°35.5' N.

These trends in catches were not always reflected by measurements of sound scattering at 38.5 kHz. Subarctic waters had almost no scattering but high biomass of most groups including euphausiids. Transitional waters had extensive scattering and a large biomass of all groups. Central waters had extensive scattering but low biomass of plankton and micronekton (Donaldson and Pearcy 1972). Pearcy (Fig. 2) noted that the number, intensity and maximum depth of 24-kHz scattering increased from the central subarctic domain to the subarctic boundary along 155°W during July. Increased scattering south of the subarctic boundary may be explained by the increased occurrence of good acoustical scatterers, such as mesopelagic fishes with gas-filled swim bladders (Johnson 1977; Pearcy 1977).

## Summary

The subarctic ecosystem, in contrast to the subtropic ecosystem, is a cold, eutrophic region with large bio-

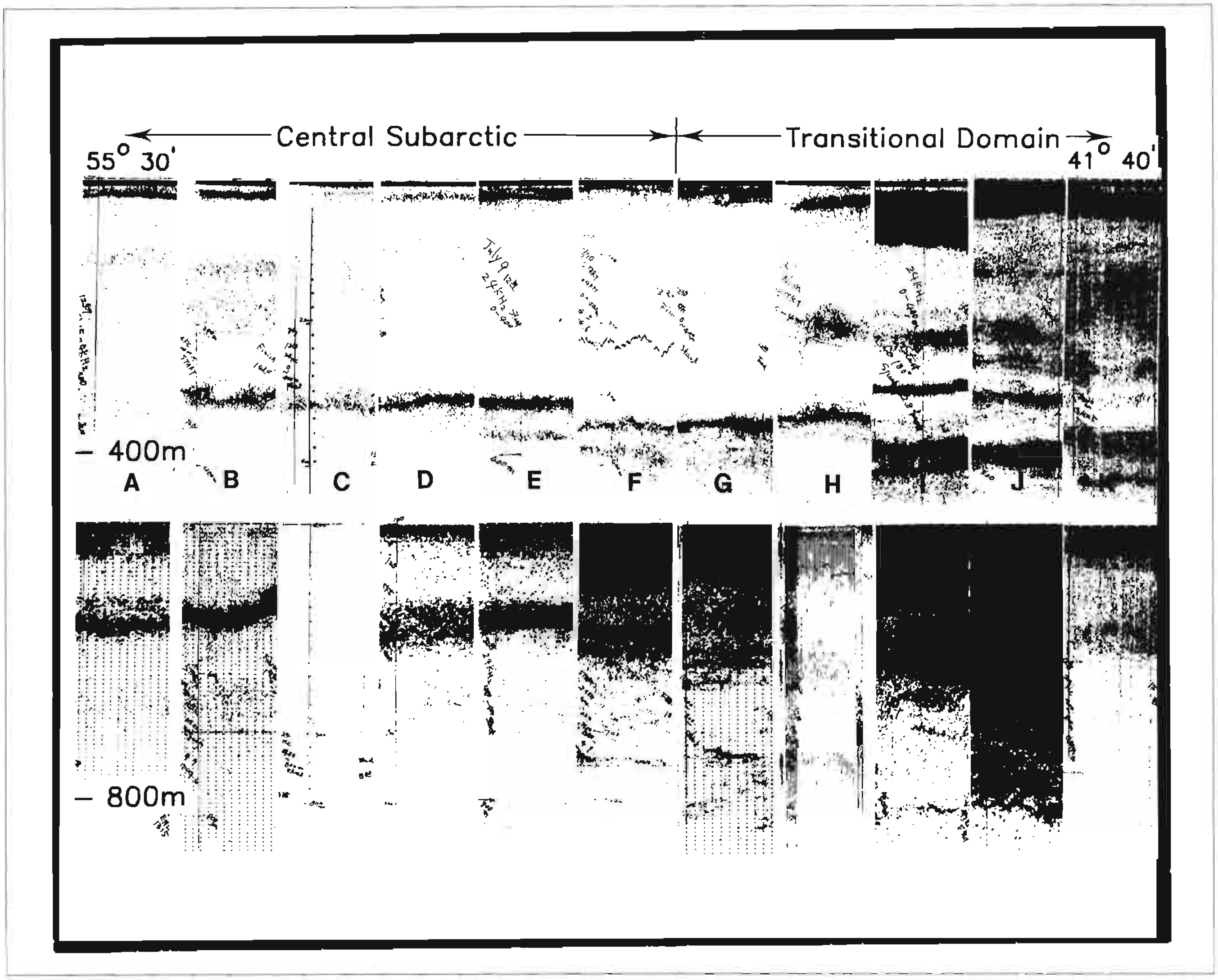

Figure 2
24 kHz Echograms recorded at mid-day from 55°30' N to 41°40' N along 155°W during July 1985, 0–400 m, 400–800 m.

mass of zooplankton and micronekton. Seasonal fluctuations in production of phytoplankton and standing stocks of zooplankton are large compared to the warm, oligotrophic, southern waters where species richness is high and seasonal variations are low (McGowan 1974; Reid et al. 1978). According to Hayward et al. (1983) and McGowan and Walker (1985), the plankton of the central gyre has low heterogeneity in community structure in both time and space compared to regions like the California Current that are influenced more by advection, possibly because a stable environment may create conditions favoring strong regulation of species structure.

The transition region is poorly studied in comparison to the central and subarctic waters proper. Gradients exist in physical and biological properties across this region from the "end member" gyres to the north and south. Fishes, squids, and shrimps appear more abundant there than in central waters. We have little knowledge of the processes regulating the productivity of this region (McGowan 1974) but can assume the large-scale and mesoscale circulation interact with the biology to produce a unique environment (Olson 1986). This environment may also experience large interannual changes. For example, large-scale shifts in the subarctic boundary in the eastern Pacific associated with El Niños may affect the species and size composition of zooplankton in this region (Fulton and LeBrasseur 1985).

Taniguchi (1981) concluded that the subarctic region, with its high primary and secondary production and its large and nutritious zooplankton, is a good foraging ground for fishes and other nektonic animals during the spring and summer, but not during the winter when temperatures are cool and prey organisms less available. The transition zone south of the subarctic boundary is more favorable in the winter than summer because of moderate temperatures and peaks in production during winter and spring season. These may be major reasons for the pronounced seasonal latitudinal migrations of transition region fishes and squids that will be discussed later in this review.

## The Transition Biogeographic Province

Distributional patterns and species-associations of oceanic plants and animals often have boundaries that conform to water masses and their distinct physical, chemical, and biological properties. In the North Pacific four major biogeographic provinces are usually recognized: subarctic, transition, central, and equatorial (Fager and McGowan 1963; McGowan 1971, 1974; Reid et al. 1978).

The transition region is delimited by the northern and southern ranges of planktonic organisms (McGowan 1971, 1974), the copepod *Eucalanus californicus,* and the euphausiid *Thysanoessa gregaria* (Reid et al. 1978). All of these distributions extend hundreds of miles both north and south of 40°N, and usually include both the transitional domain of the subarctic waters as well as the transition zone south of the subarctic boundary. In the eastern Pacific, the ranges of transition species often extend as far south as Baja California in the California Current.

Maintenance of endemic planktonic or even micronektonic populations within the transition region with its easterly meridional flow is enigmatic. Several hypotheses have been proposed to explain the persistence of this unique zoogeographic pattern (Willis et al. 1988):

1 a reproductive center of species in the western Pacific with eastward dispersal of individuals in the Subarctic Current;
2 return circulation in a counter current south of 40°N (McGowan 1971); and
3 reproduction throughout the transition region permitting self-sustaining populations despite net transport out of the area.

If the first hypothesis is true, youngest individuals of a species would be found in the western Pacific, and minimum sizes would increase to the west. This was not observed'for mesopelagic fishes of this region. In most·cases, smallest individuals were found in the east and the minimum size increased to the west (Willis et al. 1988). The pronounced mesoscale eddies often associated with the transition zone (Roden 1991), lend support to the third hypothesis for this zoogeographic pattern.

Recent reviews of the oceanic zoogeography of micronekton (mesopelagic fishes, shrimps and squids) provide useful information on the fauna of the transition region and its relationship to water masses and other faunal regions:

### Mesopelagic Fishes

Willis et al. (1988) found two basic patterns for mesopelagic fishes captured with small midwater trawls north of 40° N in the subarctic Pacific: 1) those found in the subarctic proper, and 2) those found in the transitional domain. Within each of these general regions, some species were mainly distributed a) in a pan-Pacific zone across the Pacific, b) in a western, or c) an eastern subarea of the region. Other species, such as the abundant lanternfish *Stenobrachius leucopsarus,* were found throughout the entire subarctic and transition region. Similarity in the species composition among regions was higher for fishes sampled in deep (>500 m) than in shallow (<500 m) strata, indicating that the shallow mesopelagic fish faunas are more provincial than the deep faunas, probably because of the semiclosed gyres in the upper ocean.

In another study, Willis (1984) identified three faunal groups of mesopelagic fishes in the Northeast Pacific: a) subarctic (north of the subarctic front), b) central (south of the subarctic front and north of the north equatorial front where salinity increased rapidly), and c) southern (near the Hawaiian Islands south of the north equatorial front). The subtropical front was not detected as a boundary for vertically migrating mesopelagic fishes, probably because it is a feature of the upper 200 m.

### Shrimps

Seven distinct zoogeographic distributions were recognized for pelagic shrimps in the North Pacific, including (singly or in combination) subarctic, transition, central, and equatorial (Krygier and Wasmer 1988). The distributions of many species appeared to be centered in gyres but overlapped water mass boundaries. Thirteen species were classified as transitional. The common *Sergestes similis* occupied both subarctic and transitional zone waters.

### Cephalopods

Jefferts (1988) identified zoogeographical patterns of pelagic cephalopods that often corresponded to basic water masses in the northeastern Pacific Ocean.

Transitional endemics ranging both offshore and in the California Current region were identified. Most of the 14 offshore transitional species were in the family Enoploteuthidae, whereas 90% of the subarctic species were Gonatidae. Species diversity and richness were highest in central waters, but were higher in subarctic than transition waters because of the large number of endemic species of gonatids in the subarctic region (Okutani et al. 1988).

## Epipelagic Nekton

Because of extensive fishing for salmonids and squid by research vessels with surface gill nets, data are available on the distributions and species associations of large epipelagic animals in the North Pacific, especially during the summer season.

Mishima (1981) reported on the catches in research gill nets from about lat. 39°N to 50°N, between long. 165°E and 175°E during the summers of 1978 and 1979. Based on the catches of nektonic animals in each set, these species assemblages were identified: 1) subarctic animals which were found almost exclusively north of the subarctic boundary, including six salmonids (*Oncorhynchus* spp.), eight-armed squid (*Gonatopsis borealis*), boreal clubhook squid (*Onychoteuthis borealijaponica*) and salmon shark (*Lamna ditropis*); 2)subarctic-transitional zone species that were caught in waters both north and south of the subarctic boundary, e.g. Pacific saury (*Cololobis saira*), Pacific pomfret (*Brama japonica*), neon flying squid (*Ommastrephes bartrami*), blue shark (*Prionace glauca*) and Pacific mackerel (*Scomber japonicus*); and 3) transition zone species usually caught south of the subarctic boundary, such as albacore (*Thunnus alalunga*), skipjack tuna (*Katsuwonus pelamis*) and dolphin (*Coryphaena hippurus*). Mishima noted that the subarctic-transitional group comprises species that migrate north- ward across the subarctic boundary in the summer and retreat to the south across the boundary in the autumn when water temperatures decline.

Shimazaki (1986) determined the similarity of species composition of nekton caught in gill nets in subarctic and subtropic areas west of 180° long. during the summer. He concluded that the communities were related to oceanographic features. The subtropic region included an association of skipjack tuna, small flying squid, sardine (*Sardinops melanostictus*) (and in some years immature albacore and large blue shark). In the subarctic region, north of the subarctic boundary, larger Pacific saury, sardine, large flying squid, large pomfret, and boreal clubhook squid were included in two species associations. The central subarctic and transitional domains had many of the same species. Shimazaki observed that small planktivorous fishes, such as saury and sardine, migrated across the subarctic boundary into subarctic waters earliest in the year, followed by the large sizes of carnivores, such as pomfret and flying squid.

A demonstration of a similar latitudinal trend in the catch composition of gill nets in the eastern Pacific (55°N to 36°30′ N along 155°W) was provided by the Japanese Training Vessel *Oshoro Maru* (Table 2). Again, three species assemblages are recognized. The first group of subarctic species included six salmonids, salmon shark, spiny dogfish (*Squalus acanthias*), and the eight-armed squid. All of these species were confined to subarctic waters north of the transitional domain as denoted by the intersection of the 7°C isotherm with the top of the halocline (33‰ isohaline). The second group of transitional-subarctic species included Pacific pomfret, boreal clubhook squid, smalleye squaretail (*Tetragonurus cuvieri*), saury, blue shark, albacore, and flying squid. All these species, except albacore and flying squid, extended northward beyond the transitional domain into the central subarctic domain, but only pomfret and boreal clubhook squid penetrated far north into the ridge domain by mid-July. Most of these species were also caught south of the subarctic boundary in subtropic waters. The third group of species were skipjack tuna, bigeye tuna (*Thunnus obesus*), billfishes, frigate mackerel (*Auxis thazard*), dolphin, and yellowtail (*Seriola dorsalis*). These species were found only south of the subarctic boundary with the exception of skipjack and yellowtail.

### Catches in Gill Nets Fished for Squid[1]

These meridional comparisons, and reports (Larkins 1964; Robinson and Jamieson 1984; Murata and Shingu 1985; Bernard 1986; Murata 1986, 1987; Jamieson and Heritage 1987), suggest the Pacific pomfret, Pacific saury, and blue shark are the most common species caught in association with flying squid in surface gill nets in transition waters during the summer. Few data exist on the incidental catches of fishes in drift gill nets set for squid in the winter season, but Risher (1988) observed that saury, blue shark, pomfret, and bonito (*Sarda chiliensis*) were captured along with flying squid during November, 175° E and 160° E when all flying squid were caught south of the subarctic boundary.

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[1] Incidental catches of seabirds and marine mammals are considered elsewhere in this report.

**Table 2**
Catches of fishes and squids in gill nets along 155° W by *Oshoro Maru*, 15–30 July 1984. (Only total catches of five or more individuals of identified species are included unless indicated.[a]

|  | Subarctic Ridge Domain |  |  |  |  |  |  |  |  | Transition Domain Subarctic Current |  |  |  |  | Sub-Tropic |  |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Latitude ° N: | 55 | 54 | 53 | 52 | 51 | 50 | 49 | 48 | 47 | 45–30 | 44 | 42–30 | 41 | 39–29 | 38 | 36–30 |
| Sockeye | 263 | 357 | 171 | 169 | 88 | 52 | 33 | 50 |  |  |  |  |  |  |  |  |
| Chum | 294 | 316 | 209 | 183 | 42 | 121 | 117 | 38 | 2 |  |  |  |  |  |  |  |
| Pink | 313 | 110 | 134 | 105 | 104 | 158 | 118 | 5 |  |  |  |  |  |  |  |  |
| Coho | 146 | 27 | 16 | 15 | 31 | 33 | 16 | 5 | 2 |  |  |  |  |  |  |  |
| Chinook | 3 | 1 | 1 | 1 | 1 |  | 1 | 1 |  |  |  |  |  |  |  |  |
| Steelhead | 42 | 24 | 33 | 16 | 11 | 9 | 10 | 6 | 4 | 2 |  |  |  |  |  |  |
| Salmon shark | 1 | 1 |  |  |  |  |  |  | 1 | 2 |  |  |  |  |  |  |
| Spiny dogfish | 1 | 1 | 2 | 1 |  | 1 |  |  |  |  |  |  |  |  |  |  |
| Eight-armed squid | 4 | 10 | 2 | 7 | 9 | 5 | 6 | 6 |  | 36 |  |  |  |  |  |  |
| Pacific pomfret |  |  |  |  | 9 | 12 | 14 | 177 | 1040 | 1444 | 72 | 56 | 94 |  | 2 |  |
| Boreal clubhook squid |  |  |  |  |  | 8 | 12 | 24 | 15 | 3 |  | 4 |  |  |  | 1 |
| Smalleye squaretail |  |  |  |  |  |  |  |  | 5 | 18 |  | 98 |  | 174 | 2 |  |
| Saury |  |  |  |  |  |  |  |  |  | 6626 | 1 | 625 | 349 | 4241 | 6 |  |
| Blue shark |  |  |  |  |  |  |  |  |  | 1 | 4 | 29 | 128 |  |  |  |
| Albacore |  |  |  |  |  |  |  |  |  |  | 23 | 3 | 3 | 39 | 6 |  |
| Flying squid |  |  |  |  |  |  |  |  |  |  | 26 | 57 | 167 | 27 | 48 | 64 |
| Skipjack tuna |  |  |  |  |  |  |  |  |  |  |  |  |  | 6 | 104 | 4 |
| Bigeye tuna |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 6 | 1 |
| Striped marlin[a] |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 1 | 1 |
| Shortbill spearfish[a] |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3 |
| Frigate mackerel |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 6 |  |
| Dolphin[a] |  |  |  |  |  |  |  |  |  |  |  |  |  |  |  | 3 |
| Yellowtail |  |  |  |  |  |  |  |  |  |  |  | 3 |  |  | 1 | 63 |

Although maximal catches of skipjack tuna commonly occur south of the latitude of maximal flying squid catches (Murata 1986), Dahlberg and Sigler (1987) reported that catches of skipjack tuna exceeded catches of flying squid in gill nets at some stations in the western Pacific. Skipjack tuna were also common in catches west of 180° long. where they were second by weight only to flying squid (National Fisheries Research and Development Agency 1987). Other epipelagic species are sometimes caught in large numbers along with flying squid. Murata (1986) reported very high catches of sardine (*Sardinops melanostictus*) north of the area of peak catches of flying squid, and high catches of Pacific mackerel and skipjack tuna south of the region of high squid catches along 175° E. Sometimes albacore is common in surface gill nets fished for pomfret and squid. Albacore ranked second in weight to Pacific pomfret in catches from April to June from 171° W to 131° W (Fisheries Agency of Japan 1983). In the eastern Pacific, large numbers of jack mackerel (*Trachurus symmetricus*) were taken while gill netting for flying squid (Jamieson and Heritage 1987) or albacore (Powell 1957).

The incidental catches of several fishes are substantial in the gillnet fishery for flying squid. LeBrasseur et al. (1987) and Robinson and Jamieson (1984) found that Pacific pomfret often were more numerous than flying squid in their gill net survey in the eastern North Pacific (38°–45° N, 150°–180° W). LeBrasseur et al. (1987) estimated that 100–300 × $10^6$ pomfret may be discarded annually by the drift net fishery for squid. Sloan (1984) also observed that pomfret was a major bycatch in gill nets used for flying squid off the coast of British Columbia, and Light (1986) reported that pomfret were the most abundant fish caught in gill nets and longlines from a research vessel in the western Pacific (43°30′ N–50°30′ N).

## Temperature and Catches of Nekton

Several authors have examined the relationships between sea surface temperatures and catches of epipelagic fishes and squids in the North Pacific. Most species occur over a broad range of temperatures, but highest catch rates usually are within a relatively narrow "optimal" range. Generally the ma-

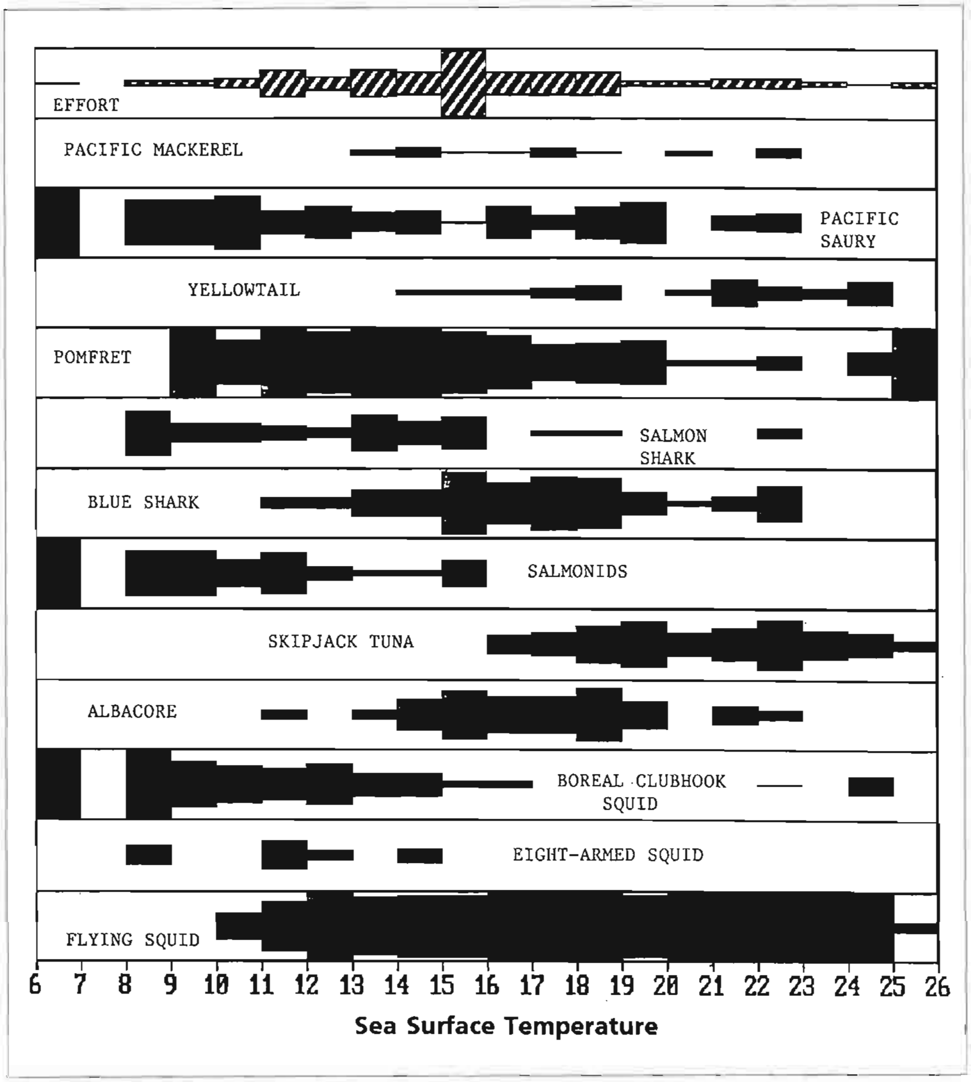

**Figure 3**
Relative occurrence of common nekton in gillnet catches of Japanese, Taiwanese, Korean, and Canadian research vessels vs. sea surface temperature (data compiled by J. Wetherall).

jor species found in the transition region, such as Pacific pomfret, Pacific saury, blue shark, jack mackerel, Pacific mackerel, albacore, and flying squid, are found in warmer waters than salmon, steelhead, salmon shark and eight-armed squid (Neave and Hanavan 1960; Manzer et al. 1965; Naito et al. 1977; Macy et al. 1978; Brodeur 1988). The temperature that delimits these two groups is about 12° C, a temperature that often marks the boundary between subarctic proper and transitional domain (Mishima 1981; Brodeur 1988).

The relationship between catch per effort in surface gill nets and ocean features was examined for three common epipelagic squids in the subarctic Pacific by Kubodera et al. (1983) and Kubodera (1986). They found that flying squid, boreal clubhook squid, and eight-armed squid sometimes had overlapping temperature distributions, with flying squid at the warmest and eight-armed squid at the coolest temperatures. Water temperatures where these species were caught generally increased between May and August, probably as a result of seasonal warming of waters above the thermocline. These authors also stressed the importance of vertical features of temperature and salinity in the distribution of squids. They suggested that high catches of flying squid were associated with the region of the subarctic boundary and the thermohaline convergence zone between transitional and western subarctic domains, perhaps because northward migration of this squid is impeded along these barriers.

Latitudinal movements of flying squid may also affect the relationship between catches and sea surface temperatures. Seasonal changes in the surface water temperatures where jigging boats operated for flying squid decreased from about 20° C in early summer to less than 15° C in autumn (Murata et al. 1983), suggesting that squid migrated northward into cooler water as the summer progresses. Gong (1985) and Gong et al. (1985) showed that surface temperatures where peak gillnet catches occurred varied among months and with latitude during the year, but peak catches were most often at about 15° C.

Data on the occurrence of epipelagic nekton in gill nets fished by Japanese, Korean, Taiwanese, and Canadian research vessels for flying squid again emphasize the broad range of temperatures occupied by most species (Fig. 3). Salmonids, boreal clubhook squid and eight-armed squid occurred mainly in the cooler range of temperatures, and yellowtail and skipjack tuna occurred in catches at warmer temperatures. Flying squid, pomfret, saury were present in gillnet sets over a temperature range of 15° C or more.

The relationships between sea surface temperatures and the catches of salmonids in the region of the Japanese drift gillnet fishery for flying squid indi-

**Table 3**

Prey identified from stomachs of transition-region nekton caught in gill nets set by the TV *Oshoro Maru* along 155° W, 3–18 July 1985.

| Species | ° N Latitude | No Examined | Stomach contents |
|---|---|---|---|
| Flying squid | 44 | 16 | almost exclusively *Berryteuths anonychus*, few fish scales |
| | 42–30 | 44 | fishes (scales/otoliths), squid |
| | 41 | 63 | fish remains, pteropods, heteropods, amphipods |
| | 39–30 | 28 | pteropods, crustaceans, squids, fishes |
| | 38 | 33 | fishes, isopod, squid |
| | 36–30 | 25 | fishes, crustaceans |
| Pomfret | 48 | 38 | 100% *Berryteuthis anonychus*, many full stomachs |
| | 47 | 24 | 100% *B. anonychus*, many full stomachs |
| | 45–30 | 27 | 100% *B. anonychus* |
| | 44 | 6 | 100% squids (*B. anonychus?*) |
| | 42–30 | 1 | squid (*Chiroteuthis?*) |
| | 41 | 25 | heteropods, squids, amphipods |
| Albacore | 44 | 5 | almost all squid (*B. anonychus?*) |
| | 42–30 | 3 | squids, fishes |
| | 41 | 13 | heteropods, squids, isopod |
| | 39–30 | 6 | squid beaks |
| | 38 | 43 | hyperiid amphipods, squids, fishes (*Alepisaurus*) |
| Blue shark | 41 | 2 | large squid, beaks |
| | 39–30 | 2 | large cranchiid squid |
| | 36–30 | 1 | Alloposid octopod |
| Saury | 45–30 | | pteropods (*Clio* and *Limacina*), amphipods, polychaetes |
| | 38 | | euphausiids. crustaceans |
| Yellowtail | 42–30 | 4 | squids, heteropods, fish |
| | 41 | 18 | squids, pteropods, heteropods, isopods, hyperiids |
| Smalleye squaretail | 48 | 5 | salps |
| | 41 | 4 | salps, gelatinous zooplankton |
| Salmon shark | 47 | 1 | squid beaks, 1 *Anotopterus?* |
| | 45–30 | 4 | squid beaks, 1 *Gonatopsis borealis* |
| | 44 | 4 | saury?, squid beaks |
| Skipjack tuna | 36–30 | 5 | squids, crustaceans |

cate that the incidental catch of salmonids has been low within the regulated squid fishing area but could increase north of the northern boundary or during late summer or fall months (Burgner et al. 1982; Burgner and Meyer 1983; Walker and Burgner 1985; Harris and Kautsky 1987). Ogura and Takagi (1987) reported that salmonids were caught in water temperatures between 1° and 15° C while squid were caught between 9° and 15° C, but they concluded that the catches of salmonids were negligible in waters of 14° C, which was the lower limit of optimal water temperature for squid.

## Common Epipelagic Fishes

This section briefly reviews the distribution, migration, and food habits of common epipelagic fishes of the transition region. Catches of blue shark, Pacific saury, Pacific pomfret and albacore are often large in gill nets fished in the mid-Pacific transition region. Pacific mackerel and jack mackerel are also taken closer to the coasts in the western or eastern Pacific. Hart (1973) and Brodeur (1988) provided more detailed descriptions of the biology of these species.

### Blue Shark (*Prionace glauca*)

The blue shark is found in warm temperate, subtropical and tropical oceans of the world (Hart 1973). It is common in the North Pacific between 20° and 50° N and makes pronounced migrations northward into subarctic waters during the summer and southward into the transitional zone and subtropical waters during the winter (Strasburg 1958; Neave and Hanavan 1960; Larkins 1964; Parin 1968). Most of the blue shark caught north of 40° N are females which apparently migrate north to feed. Females with embryos were only found south of 35° N (Strasburg 1958).

Food of blue shark caught in gill nets in the Gulf of Alaska consisted of salmon, pomfret, saury, lanternfishes, and daggertooths (*Anotopterus pharao*), squids, shrimps and salps; chunks of salmon were apparently taken from salmon caught in the gill net (LeBrasseur 1964). Strasburg (1958) found mostly fishes and cephalopods in the stomachs of blue shark caught on longlines and concluded that they are opportunistic feeders. Blue shark examined from *Oshoro Maru* gillnet catches contained mainly remains of large cephalopods, including beaks. Exclusive of fresh fish that were common in gillnet catches, only one macrourid fish was identified (Table 3).

### Pacific Saury (*Cololabis saira*)

The Pacific saury is widely distributed in epipelagic waters of the North Pacific between 19° N and 58° N (Kobayashi et al. 1968; Odate 1977). Three centers of distribution are reported in the North Pacific (eastern, central, and western) which may represent genetically distinct stocks (Inoue and Hughes 1971; Macy et al. 1978). Seasonal migrations related to feeding and spawning occur in all three subpopulations. During the summer, saury are common in subarctic waters and even enter the Bering Sea (Kobayashi et al. 1968; Trumble 1973; Macy et al. 1978). According to Odate (1977) and Shimazaki (1986), large saury migrate the farthest north across the subarctic boundary during the summer to feed. Spawning apparently occurs after migration south of the subarctic boundary in the western Pacific (Sato 1981). Saury feed on zooplankton, largely copepods, euphausiids, and amphipods (Hotta and Odate 1956).

### Pacific Pomfret (*Brama japonica*)

Pacific pomfret are abundant in the North Pacific Ocean. They perform pronounced northerly migrations from the transition zone across the subarctic boundary into subarctic waters during the summer and retreat to the southern part of their range into subtropical/transition zone waters in the winter (Neave and Hanavan 1960; Machidori and Nakamura 1971; Shimazaki and Nakamura 1981; Shimazaki 1989). The northward movements clearly correspond to the latitudinal advance of the 9–10° C isotherm (Trumble 1973; Shimazaki 1989) but distributions may also be influenced by the vertical thermohaline structure (Shimazaki and Nakamura 1981). Large pomfret migrate the farthest north during the summer, whereas small pomfret are most common in the vicinity of the subarctic boundary. During the summer pomfret increase their body weight and fatness substantially (Shimazaki and Nakamura 1981).

Gonatid squids and fishes (including saury, sardine and Atka mackerel, *Pleurogrammus monopterygius*) compose most of the stomach contents of pomfret, but crustaceans may be important prey for small pomfret (Pinckard 1957; Machidori and Nakamura 1971; Wada and Murata 1985; Kubodera and Shimazaki 1989). Sometimes the pteropod *Clio pyramidata* is important (C. B. Miller, College of Oceanography, Oregon State Univ., Corvallis, OR 97331 pers. commun. June 1989). Stomachs of pomfret taken by the *Oshoro Maru* in the Gulf of Alaska frequently contained only squid (mainly *Berryteuthis anonychus*) (Table 3).

### Albacore (*Thunnus alalunga*)

Albacore is cosmopolitan in warm, temperate waters of the world and common in the transition region of the North Pacific. Laurs and Lynn (1977) recognized two populations of albacore in the North Pacific: a northern group that undertakes trans-Pacific migrations from waters off Japan to North America, usually north of 40° N, and migrates into the transitional and dilute domains of the Northeast Pacific Ocean, and a southern group that is found off California during the summer that has migrational patterns differing from the northern group. Both types of albacore spawn in subtropical waters presumably in the western Pacific (Laurs and Lynn 1977; Sund et al. 1981; Laurs, 1991).

The food of albacore consists mainly of fishes and squids. Saury, lanternfishes, lancetfish (*Alepisaurus*), sergestid shrimps, and heteropods are sometimes important prey (Iverson 1962, Iversen 1971; Pearcy 1973; Table 3).

### Pacific Mackerel (*Scomber japonicus*)

Pacific mackerel or chub mackerel is a transition-zone species that inhabits warmer water of the eastern and western boundary currents but migrates into the Gulf of Alaska and waters south of the Aleutians during the summer (Larkins 1964; Macy et al. 1978; Mishima 1981; Brodeur 1988). During warm years, such as the strong 1982–1983 El Niño years, Pacific mackerel were abundant from Oregon into British Columbia (Ashton et al. 1985; Brodeur and Pearcy 1986; Pearcy and Schoener 1987).

Spawning occurs during the winter mainly close to shore off southern and Baja California and off Japan (Kashahara 1961; Macy et al. 1978; Belyayev 1984).

Pacific mackerel feed on a variety of prey including copepods, euphausiids, shrimps, larval and juvenile fishes and cephalopods (Fry 1936; Fitch 1956: Hart 1973; Ashton et al. 1985; Brodeur et al. 1987).

### Jack Mackerel (*Trachurus symmetricus*)

Jack mackerel are a transition-zone species found along the west coast of North America but not in the western Pacific. They are sometimes common in gillnet catches (Jamieson and Heritage 1987) or in purse seine catches (Brodeur and Pearcy 1986; Pearcy and Schoener 1987) in the northeastern Pacific. They migrate north as water temperatures increase during the summer and range into the Gulf of Alaska (Neave and Hanavan 1960; Brodeur and Pearcy 1986). They occur hundreds of miles offshore. Jack mackerel form large schools at the surface, occasionally mixed with Pacific mackerel (Trumble 1973; Brodeur 1988).

Eggs and larvae of jack mackerel are found as far as 1,100 miles offshore but have not been reported in the central Pacific (Macy et al. 1978).

Jack mackerel feed on zooplankton and small nekton. Copepods, euphausiids and pteropods were the main prey off California (Carlisle 1971), and euphausiids were the main prey off Oregon, followed by pteropods (Brodeur et al. 1987).

## The Pelagic Food Web

Several interesting trends can be derived from the observations on food habits of epipelagic nekton caught in gill nets along long. 155° W from lat. 44° N to 36°30′ N (Table 3). In both the southern portion of the subarctic domain proper and the northern portion of the transitional domain, the gonatid squid *Berryteuthis anonychus* was the major prey species for pomfret, flying squid, and albacore. Pomfret preyed almost exclusively on *B. anonychus* at stations from 48° N to 44° N. Coho, sockeye, and pink salmon, as well as steelhead, caught in gill nets at 48° and 47° N also preyed intensively on this squid (Pearcy et al. 1988). Gonatid squids appear to be a key prey for epipelagic nekton in the Subarctic Current region of the Gulf of Alaska during the summer.

The diets of different species show similar changes with latitude. For example, pteropods and heteropods were well represented in the stomach contents of flying squid, pomfret, and albacore at 41° N. Crustaceans (hyperiid, amphipods, and isopods) appeared more frequently in the diets of these species caught at the lower than at the higher latitude stations. In general, the stomach fullness of the pomfret and flying squid was highest at northern stations where squids were the principal prey.

Gonatid squid apparently are not a major prey for flying squid in the western Pacific. Naito et al. (1977) reported that small fishes (the lanternfish *Diaphus coerulens,* and *Engraulis japonica*) and squids (*Watasenia scintillans* and small *O. bartrami*) occurred most frequently in the stomachs of large flying squid off northeastern Japan. Small flying squid consumed large zooplankton such as euphausiids, large copepods, and amphipods.

A food web diagram for common epipelagic nekton of the transition region (Fig. 4) is based on the previous references on the food habitats of common

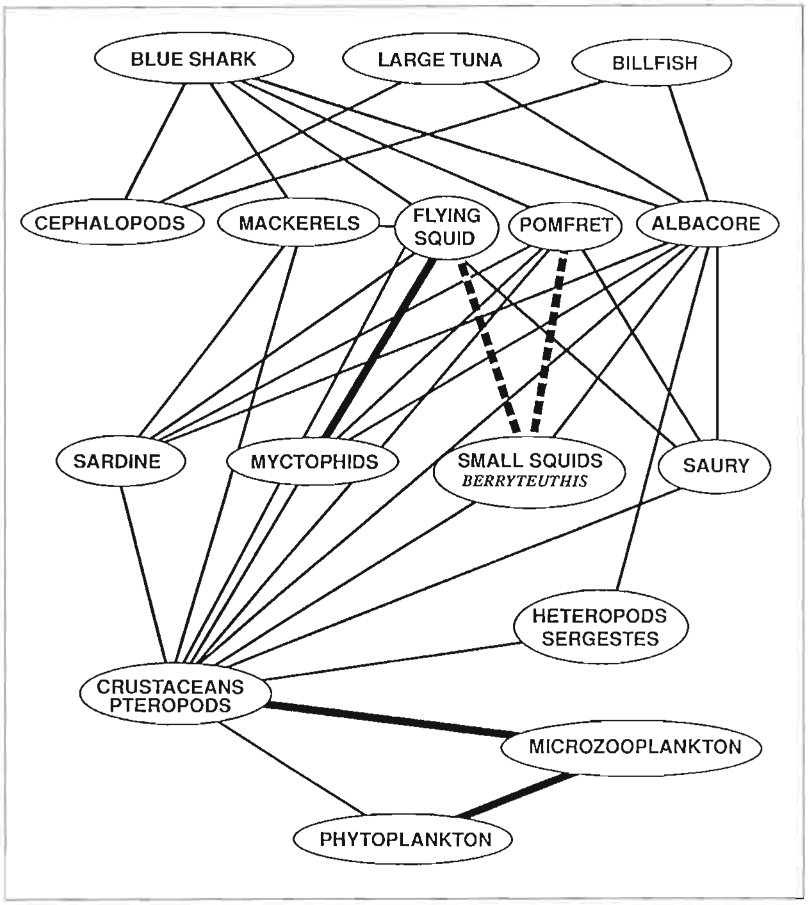

**Figure 4**
Generalized food web for common nekton of the transition region, eastern and western Pacific combined, except for dashed lines that pertain to eastern Pacific.

fishes, the results of stomach analyses aboard the *Oshoro Maru* (Table 2), and general reviews of the diet of epipelagic fishes (Kohno 1983; Shimazaki 1986; Brodeur et al. 1987) and squids (Naito et al. 1977). A generalized food web for the subarctic and transitional zones is also given by Brodeur (1988).

Assuming that most of the primary production is consumed by microzooplankton which in turn is ingested by crustaceans and pteropods, the main species caught in gill nets in the transition region, such as large flying squid, pomfret and albacore, probably occupy trophic level 5. Large blue shark, tunas, and billfishes are the next higher trophic level, whereas saury and small squids, myctophids and sardine are about trophic level 4. Most large fishes and squids are opportunistic feeders and the potential for competition exists between common species such as pomfret, flying squid, and albacore that consume similar prey (Table 3). Small gonatid squids appear to be particularly important in the northern part of the transition domain in the eastern Pacific during the summer. Sardine and myctophids appear to be more important as forage species in the western Pacific than in the eastern Pacific.

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# Review of the Biology and Distribution of the Neon Flying Squid (*Ommastrephes bartrami*) in the North Pacific Ocean

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## ABSTRACT

This review is the first attempt to compile published and unpublished data from American, Canadian, Japanese, Korean, and Taiwanese researchers on the life history of *Ommastrephes bartrami*. Much of the available information in the literature is conflicting, in part because of the complex and dynamic nature of the biology and distribution of this species. Given the intense pressure on *Ommastrephes bartrami* and other squid species by high seas gillnet fisheries, timely analysis and comprehensive review of forthcoming data is critical to the conservation of the North Pacific ecosystem.

## General Distribution

*Ommastrephes bartrami* (family Ommastrephidae) is a transition zone species occurring worldwide in oceanic, near surface waters of temperate and subtropical regions (Fig. 1). Distribution in the North Pacific is from Japan to North America, between approximately 25° N and 50° N latitude (Naito et al. 1977a; Murakami et al. 1981; Murata 1990). The northern limit of distribution in the northwest and central Pacific, is the transitional domain of the subarctic water mass (Kubodera et al. 1983; for description of oceanographic terms, *see* Favorite et al. 1976, and Roden or Pearcy 1991). In the northeast Pacific, *Ommastrephes bartrami* has been reported from the broad transitional domain off British Columbia as far north as 53° N (Jamieson and Heritage 1987), however, no collections have been reported from the Gulf of Alaska. *Ommastrephes bartrami* does not occur in the Bering Sea (Kubodera et al. 1983).

### Stocks in the North Pacific

Based on indications of separate spawning grounds and on distributional patterns from jigging and tagging surveys, more than one stock of *Ommastrephes bartrami* may exist in the North Pacific (Naito et al. 1977b; Murata 1987). However, no genetic studies of stock discreteness have been conducted. Low densities reportedly occur between 165° E and 170° E longitude relative to high densities west of 165° E and east of 170° E, suggesting little intermixing, and reproductive isolation of at least two stocks (Araya 1983). Maximum body size and rate of growth may vary between the two regions and *Ommastrephes bartrami* may reach a larger size at sexual maturity in the central and northeast Pacific than in the northwest region (Araya 1983; Murata 1987). Features that separate groups in these two regions include the Emperor Seamounts (33°30′ N to 45° N 170° E), and the shifting southern extent of the transition zone (Roden 1991).

Two to four size classes of *Ommastrephes bartrami* have been described from the North Pacific, based on monthly mantle length distributions and maturity states (Murata and Ishii 1977; Murakami et al. 1981; Murata 1987). The different size classes and maturity states may be due to extended or disjunct hatching periods in winter (January–February) and spring (April–May) (Murata and Ishii 1977; Naito et al. 1977a; Araya 1983). Disjunct spawning periods are common among the Ommastrephidae (Roper et al. 1984), giving rise to two or more growth groups. But, lifespan is variable between the different growth groups of *Ommastrephes bartrami*, and the possibility of distinct populations (Murata 1987) has not been eliminated.

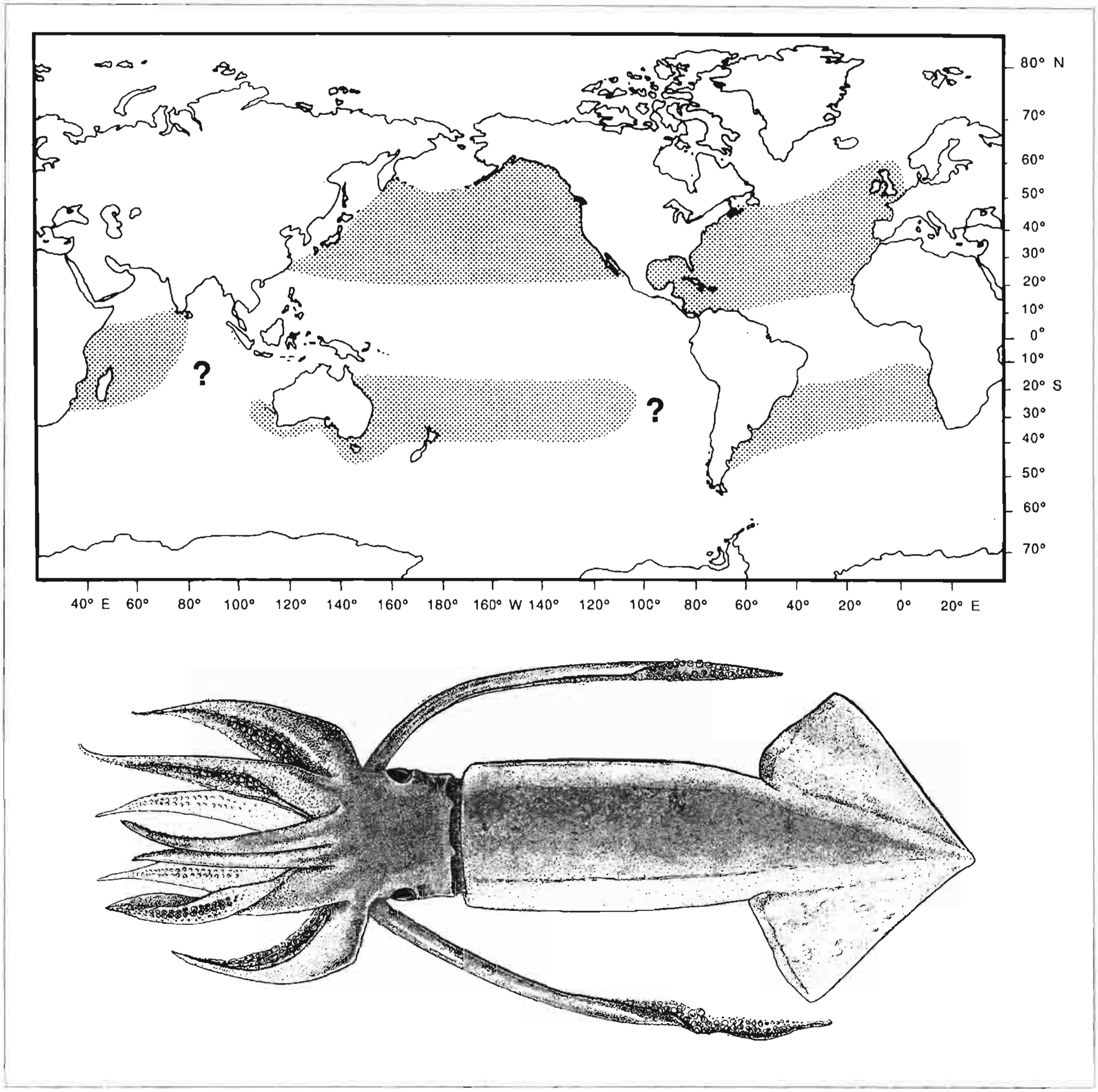


**Figure 1**
Worldwide distribution of *Ommastrephes bartrami.* (Adapted from Roper et al. 1984.)

The long or disjunct spawning period of *Ommastrephes bartrami* produces what has been generally interpreted as large and small cohorts, or winter and spring brood stock (Murakami et al. 1981), or early and late migrants (Murata and Ishii 1977). The described growth categories are extra large sized (LL), large (L), small (S), and very small (SS) (Murata and Ishii 1977; Murakami et al. 1981). The ranges in dorsal mantle lengths given below are based on squid caught both by jigging and gillnetting (research and commercial size nets):

**LL** This group consists of females only. They are thought to live for two years and mature and spawn in their second winter in January and February. The LL females reach a maximum dorsal mantle length (DML) of 48–53 cm (Tung 1981; Kubodera et al. 1983).

**L** This group, also known as the winter brood stock, consists of males and females that live for one year. Breeding takes place in October through December, and females spawn in January and February. The dorsal mantle length range for a combined sample of males and females collected in October, 1984 was 31–40 cm (Murata and Shingu 1985).

**S** This group, also known as the spring brood stock, consists of both males and females. Lifespan is one year with breeding and spawning in March and April. The DML range for a combined sample of males and females collected in October, 1984, was 25–31 cm (Murata and Shingu 1985).

**SS** This group is composed of both males and females. Males first appear in the fishing ground in autumn and winter and are mature by winter and spring at a mantle length of 30 cm. Males die after mating in spring and are probably part of the S group. The SS females do not mature their first winter and probably correspond to the LL type. The maximum mantle length recorded for a combined sample of males and females of the SS group in October, 1984, was 25 cm (Murata and Shingu 1985).

Length frequencies described for the four growth groups are sometimes inconsistent between researchers and years sampled, owing in part to variable sampling methods and the definition of size categories. However, comparison of early (Naito et al. 1977a; Murata and Ishii 1977) and more recent reports (Araya 1983; Murata et al. 1988; Murata 1990)

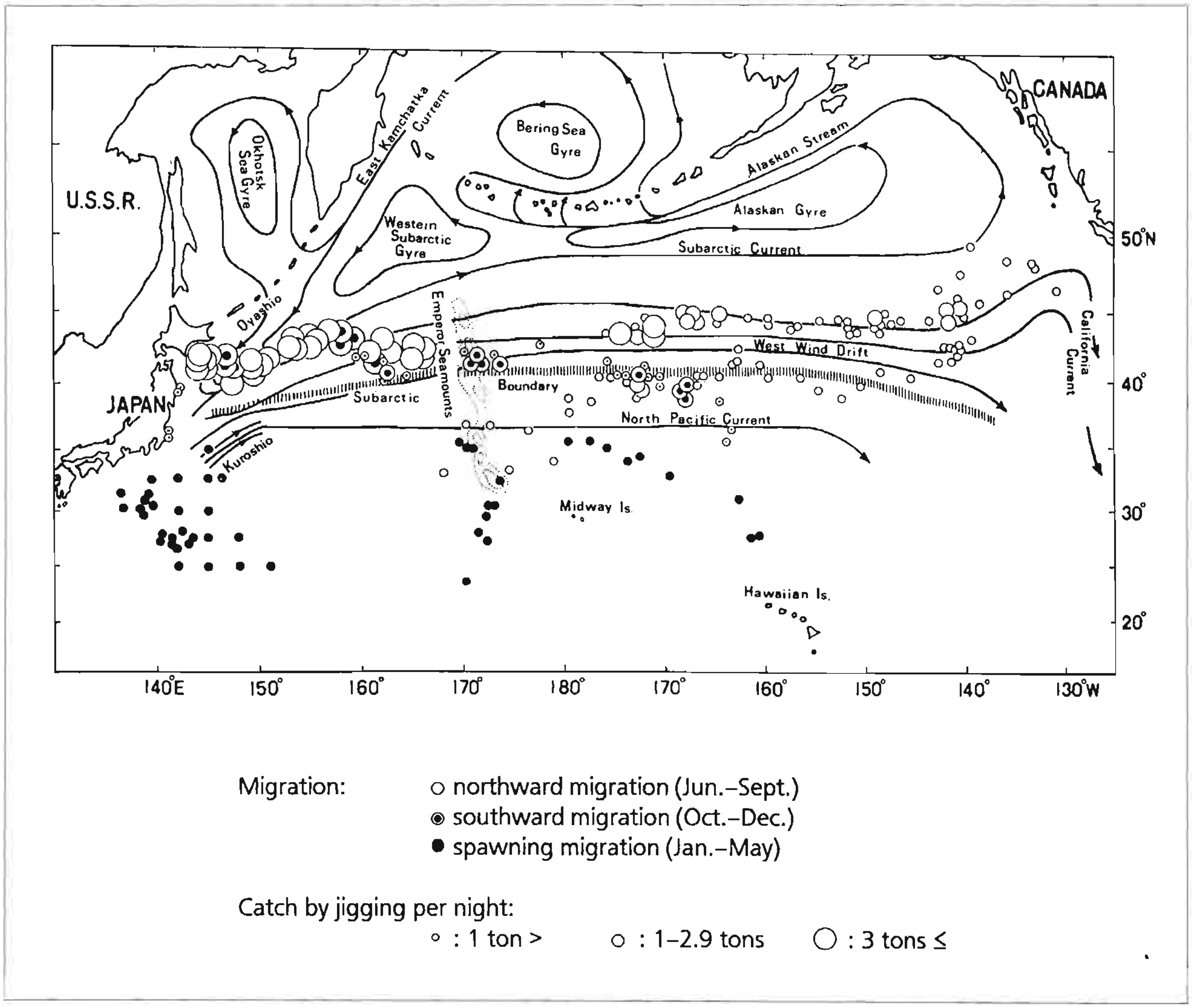


**Figure 2**

Distribution of *Ommastrephes bartrami* in the North Pacific from June, 1978 to February, 1980. A schematic diagram of surface currents after Dodimead et al. (1963). (Reprinted from Murakami et al. 1981.)

of length frequencies, suggests that the sizes of *O. bartrami* caught in both the jigging and gillnet fishery are decreasing.

*Ommastrephes bartrami*, like other Ommastrephidae, is a thick-mantled, powerful swimmer and undergoes extensive seasonal migrations. Seasonal movements have been best described for this squid in the northwest Pacific (west of 165° E), but limited data from the central and northeast Pacific are available as well.

## Seasonal Distribution

Spring migrants from subtropical waters (south of 34° N) reach the region of the subarctic boundary and transitional domain in early summer and return to subtropical waters by the following spring. Seasonal movements have been verified by tagging experiments in the western Pacific (Araya 1983) and commercial catch data across the Pacific (Jerry Wetherall, NMFS, Honolulu, HI 96822, pers. commun. May 1988). Araya (1983) reported squid tagged and recaptured west of 165° E (*N*=28, 15–39 cm mantle length) averaged a travel speed of 8 km/day during northbound movements May to August, 1.6 km per day from August to October, and 16 km per day during the southbound phase from October to December.

Seasonal movements apparently occur in a clockwise fashion in the northwest Pacific. Late spring through early fall (May through September), flying squid travel north, then northeast, following the movement of the Kuroshio Current and its frontal zone (Murata et al. 1976; Araya 1983; Murata et al. 1983) (Fig. 2). The primary migration route is thought to be in relation to the flow of the northern warm-water branches of the Kuroshio Current at longitudes 144°–146° E, 148°–151° E, and 154°–156° E (Araya 1983). The densest concentration in May and June in the northwest Pacific is found at 36°–38° N and 144°–156° E. Northward migrating squid arrive and concentrate along the subarctic boundary (42°–43° N and 173°–175° E) by July. Between July and November, the densest concentrations are along the subarctic boundary between 39°–46° N west of 165° E and between 170° E and 177° W. Commercial and research data show that only large females penetrate the subarctic boundary to move northward into the transitional domain (Kubodera et al. 1983), where they are found at 40° N between 180° and 160° W and up to 50° N between 165° W and 130° W, June through September.

During the fall through early winter (October–December), the population moves south and southwest ahead of the expanding cold Oyashio Current in the northwest Pacific (Murata et al. 1976; Araya 1983). Exact locations, January through May, are unknown, but northwest, central, and northeast Pacific groups all spawn in the subtropical region at this time (Murakami et al. 1981) (Fig. 2). Spawning concentrations in the northwest subtropical Pacific occur at 27°–32° N and west of 156° E, in the region of the Kuroshio Counter-Current (Murata et al. 1976; Araya 1983). Dense concentrations in early winter have also been found off the Boso Peninsula in Japan (35°30′ N 140° E) (Murata et al. 1976). Paralarvae have been described from the Hawaiian Archipelago, between the islands of Midway and Oahu (Young and Hirota 1990).

Ommastrephidae generally produce large numbers of small eggs which hatch within a few days to a few weeks (Roper et al. 1984). Spawning behavior, parental investment after spawning, and movement and growth of eggs and larvae have not been described for *Ommastrephes bartrami.* Young-of-the-year in the western Pacific presumably remain in the hatching area until they reach juvenile growth stages, at which time they move north with the Kuroshio extension, growing to the subadult stage by May–August.

Based on research vessel data (Jerry Wetherall, NMFS, Honolulu, HI 96822, pers. commun. May 1988), similar seasonal patterns of movement occur at approximately the same time and to the same extent in the central and northeast Pacific. However, little is known regarding association of these squid with current systems or winter distribution of the supposed east Pacific stock.

## Seasonal Movement Relative to Temperature and Salinity

*Ommastrephes bartrami* occurs in greatest abundance where surface water temperatures are warmer than 10° C, with highest catches in surface temperatures of 15°–20° C (Fig. 3) (Murata et al. 1976; Naito et al. 1977b; Kubodera et al. 1983; Murata et al. 1983; Gong et al. 1985a; Murata 1987). Distribution in summer through early winter is primarily in upper surface layers at night, and correlates strongly with a surface layer temperature range of 15°–24° C in July and August, and 10°–22° C, September through December (Roper et al. 1984). This is confirmed by data collected from commercial and research vessels between 1983 and 1986 which showed catches of *O. bartrami* between 10°–26° C across the Pacific (Jerry Wetherall, NMFS, Honolulu, HI 96822, pers. commun. May 1988). Flying squid have been caught in water as low as 6° C, however, this seems to be uncharacteristic of the species (Naito et al. 1977b; Kubodera et al. 1983).

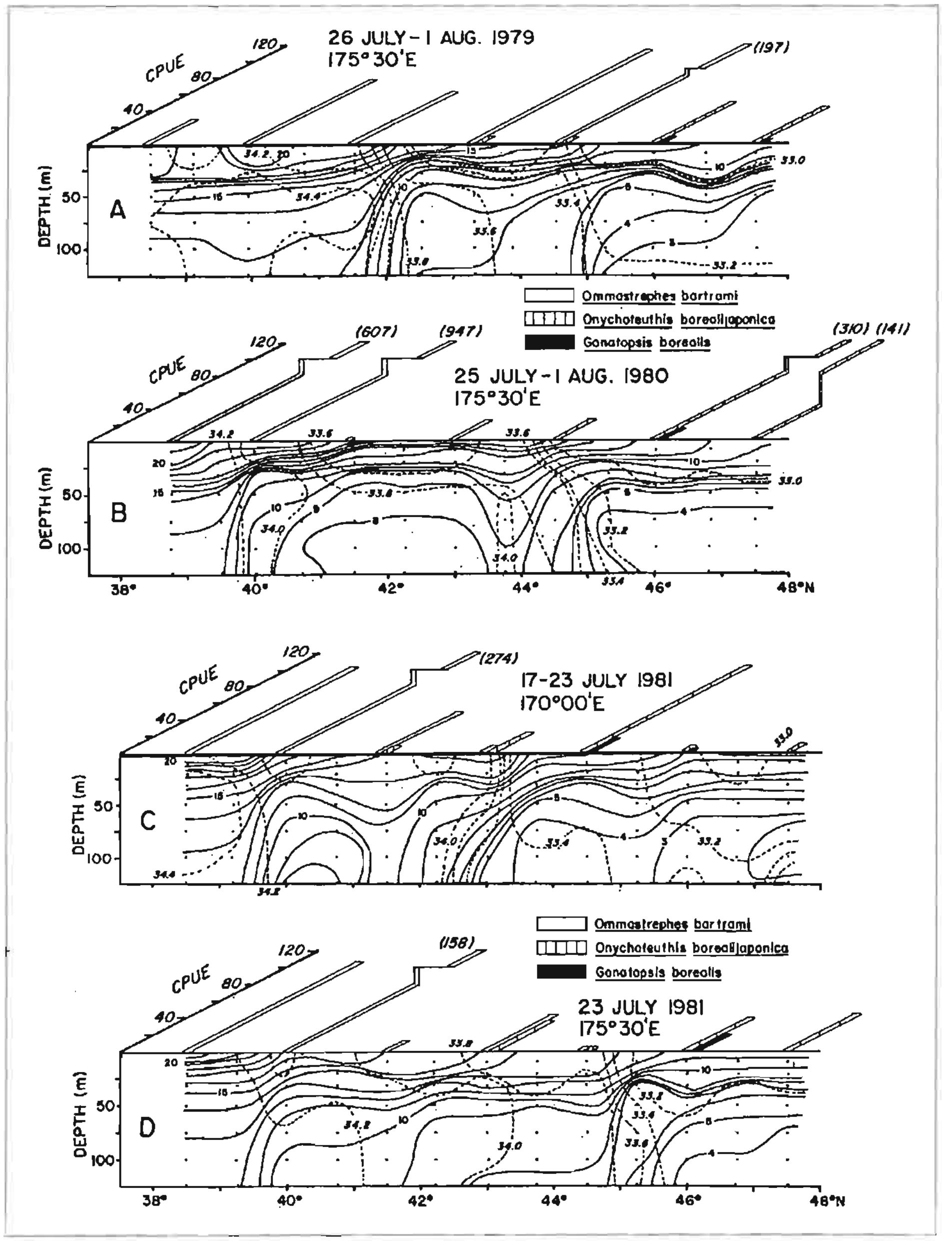


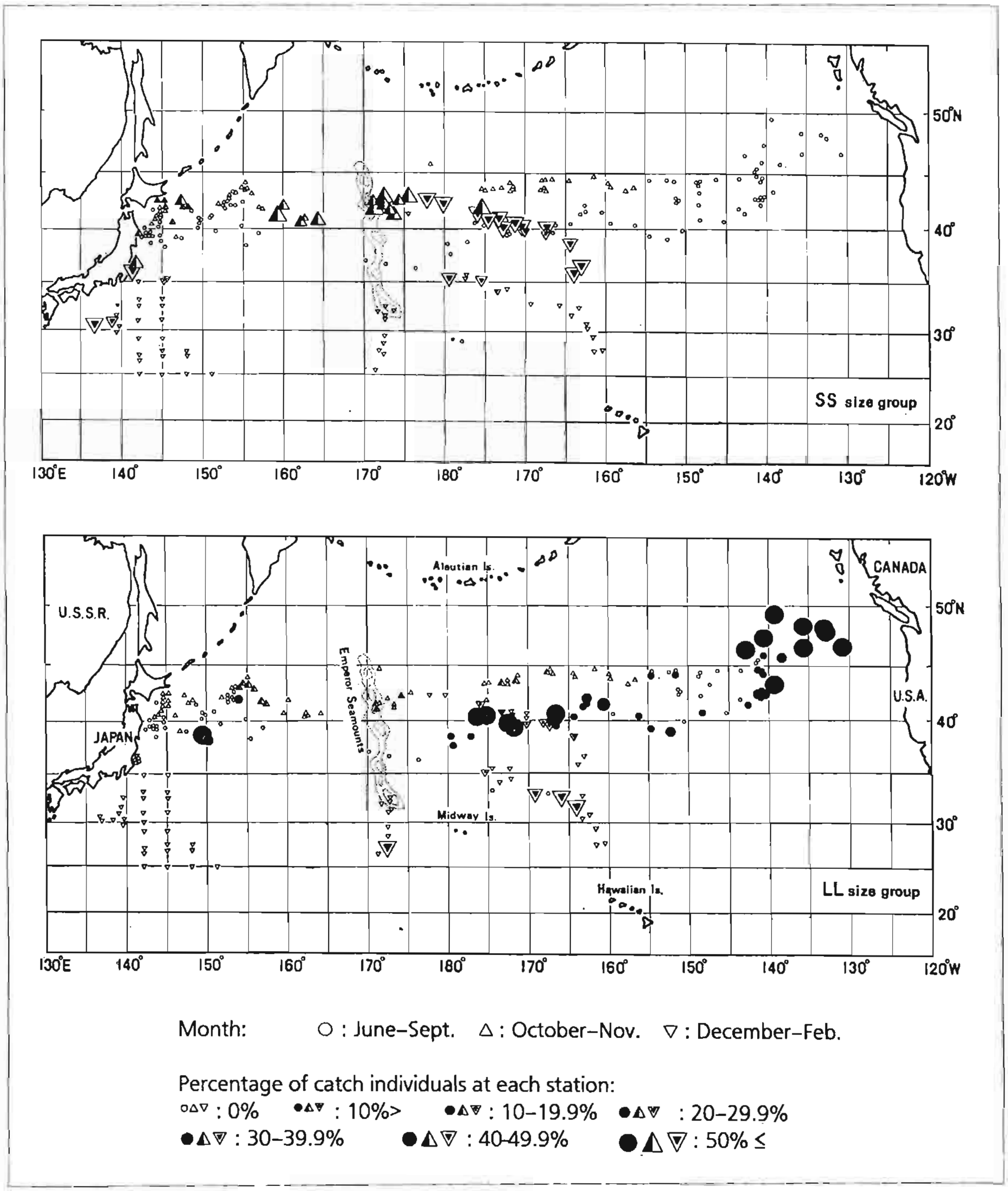
**Figure 3**
Vertical features of temperature and salinity from the surface to 125 m depth, along with CPUE of *Gonatopsis borealis*, *Onychoteuthis borealijaponica*, and *Ommastrephes bartrami* in late July 1979–1981. (Reprinted from Kubodera et al. 1983.)

The avoidance of water temperatures below 10° C may restrict *Ommastrephes bartrami* to surface layers above the summer and fall thermocline (less than 50 m depth) in the transitional domain and along the subarctic boundary (Kubodera et al. 1983). Salinity tolerances are less well defined but, the thermohaline structure of convergence zones formed by the warm Kuroshio and cold Oyashio Currents, by the subarctic boundary, and by the boundary between the transitional and subarctic domains may act as barriers to further northward movement and result in large concentrations of squid along these boundaries (Kubodera et al. 1983). These boundaries may be more of a barrier to squid prey than to squid, and thus serve as a preferred feeding area for *O. bartrami.*

Based on the behavior of other ommastrephids (Roper et al. 1984), *Ommastrephes bartrami* probably undergoes diel vertical migrations. The presence of a ventral silver stripe that is a distinguishing characteristic of the species suggests a predominantly meso- to epi-pelagic lifestyle. Nighttime distribution, as indicated by gillnet catches, extends into the upper 10 m of the water column. Small (<18 cm DML) flying squid have been observed at the sea surface day and night (Murata 1988). Adult *Ommastrephes bartrami* may reach depths of 1500 m during the winter and spring spawning seasons in subtropical waters (Roper et al. 1984), but are more typically in the top 100 m of the water column during the summer and fall feeding period in northern waters (Murata 1988).

## Seasonal Movement Relative to Sex and Size

Patterns of seasonal migration in the northwest Pacific are different between sexes, and between large and small females (Fig. 4). Young-of-the-year squid are in juvenile growth stages during the northward migration. The oldest of this age group migrate north first (Naito et al. 1977b; Murakami et al. 1981) and are generally located farther offshore in the northwest Pacific than younger individuals (Murakami et al. 1981; Gong et al. 1985a). Thus, body size measurements increase predictably with latitude during the summer (Tung 1981; Murata 1987) (Fig. 5). Large females that penetrate the sub-



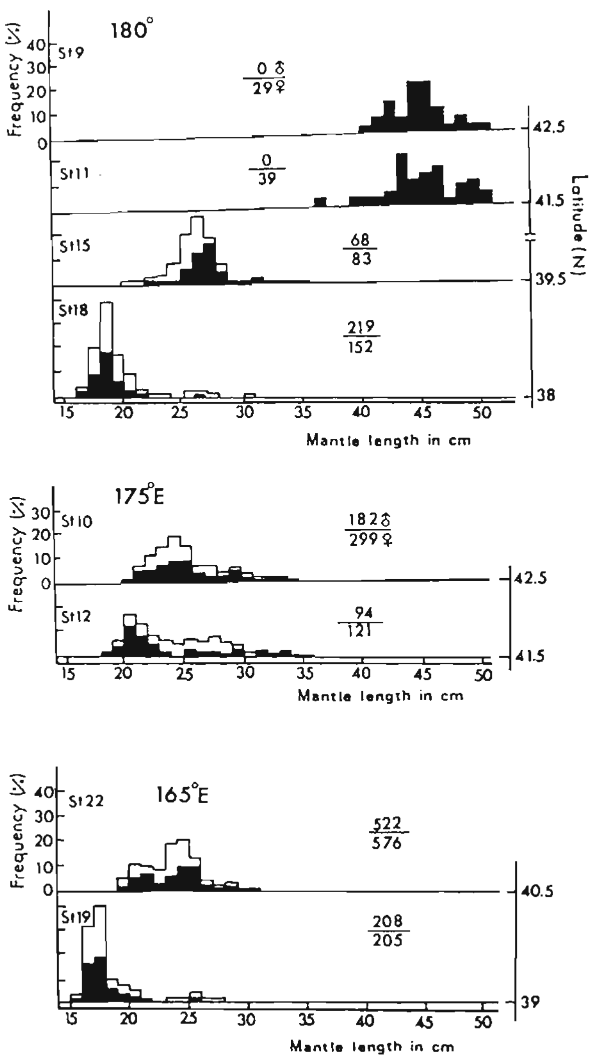


**Figure 4 (facing page)**

Distribution of SS and LL mantle-size groups of *Ommastrephes bartrami* expressed as percentage of catch at stations in the North Pacific Ocean from June, 1978 to February, 1980. ○ = June–September; Δ = October–November; ∇ = December–February. (Reprinted from Murakami et al. 1981.)

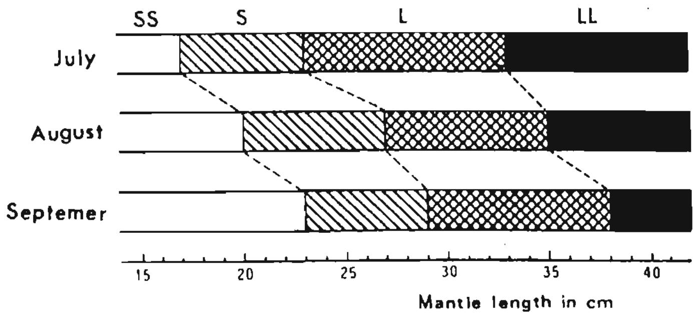


**Figure 5**

Classification of the four size groups of flying squid based on monthly mantle length ranges. SS = very small; S = small; L = large; LL = very large. (Reprinted from Murata 1987.)

arctic boundary into the transitional domain are less abundant in both inshore waters of Japan (Murakami et al. 1981) and in Japanese waters of the transitional domain than they are farther east (Murakami et al. 1981; Murata 1987). This distribution may be related to the narrowness of the transitional domain (Favorite et al. 1976) in the western Pacific relative to the central and eastern zones.

Catches of both immature males and females throughout the North Pacific are typically highest along the subarctic boundary (Kubodera et al. 1983). The most densely concentrated shoals are found in the western Pacific boundary region (Gong et al. 1985a). High concentrations of squid at the subarctic boundary of the western Pacific may be related to the steeper horizontal gradients of temperature and salinity in this area than in the subarctic boundary region of the eastern Pacific (Gong et al. 1985a). Immature males and females (15–25 cm DML) are caught in equal numbers at the subarctic boundary of the western Pacific in July (Kubodera et al. 1983). Catches within the transitional domain of the Subarctic Water Mass are high during late summer. Kubodera et al. (1983) and Murata (1987) reported entirely large (LL, 34–48 cm DML) immature females north of the subarctic boundary (denoted by 34‰ at the surface). Thus, both the average size and proportion of female flying squid increase with latitude (Murata and Ishii 1977). *Ommastrephes bartrami* are not caught north of the transitional domain in the northwest or central Pacific (Kubodera et al. 1983).

Males begin southerly migrations first (Naito et al. 1977b; Murakami et al. 1981; Tung 1981). Males mature before females (Murata and Ishii 1977; Murakami et al. 1981) and southbound migration is triggered by the onset of sexual maturity (Murata et al. 1976). Large females lead or overtake the small females in northerly migrations in the northwest and central Pacific (Murata 1987) and overtake both small females and males in their southward movement (Tung 1981; Gong et al. 1985a).

In summary, males migrate north, mature, return to subtropical waters, copulate, then die in their first winter and spring. With the exception of the LL and SS type females, all individuals are thought to migrate, mature, and spawn after one year. The SS females presumably make an abbreviated, round trip migration in their first year, pass a full year without spawning, and grow to become the very large females that migrate farthest north in their second year, when they mature, return south, copulate, then die after spawning in their second winter and spring. Perhaps the SS females skip the northward migration altogether their first spring, and travel north only during their second spring as LL females. The northern migration is a time of feeding and growth. The southern migration is initiated with the onset of sexual maturity and punctuated by spawning.

## Biology and Growth

The average body size of *Ommastrephes bartrami* caught in jigs and gillnets across the Pacific is about 27 cm, within a range of 14–50 cm. Maximum mantle length reported for females is 53 cm and over 2 kg body weight. Males reach a maximum length of 41 cm and 1+kg body weight (Tung 1981).

Body weight to mantle length relationship, according to Tung (1981), is

$$BW = 6.16335 \times 10^{-6}\, ML^{3.2716} \quad (R = 0.9884;\ n=247) \qquad (1)$$

while body weight to mantle length relationship, according to Murata and Ishii (1977), and Gong et al. (1985b), is

$$BW = 1.2799 \times 10^{-5}\, ML^{3.1437}. \qquad (2)$$

Estimated growth curves for flying squid in the northwest Pacific are sigmoid, and the total growth attained in any given month varies between groups of large and small body size (Murata and Ishii 1977) (Fig. 5). Preliminary tagging and capture studies indicate highly variable growth rates (Araya 1983).

Growth rates are intensive during the spring and summer period of northward migration and decrease as sexual maturity is approached in late fall and winter (Murata and Ishii 1977). In June–October and October–December, growth of the early migrants (males and females combined) is 3–4 cm/mo and 1 cm/mo, respectively. Growth of the small-sized group (males and females combined) is 2–3 cm/mo throughout this period. In the central Pacific, Tung (1981) reported rates of 1 cm/mo growth for early migrant males in August through October. Late migrant males from late July to mid-September averaged 3 cm/mo. Growth rates of the late migrating females appears similar to the males in July and August, although the trends are less clear owing to combined measurements of large and small sized females (Tung 1981; Araya 1983). December through February, growth of the large group slows to 0.5–1 cm/mo, while the small size group averages 1–2 cm/mo (Murata and Ishii 1977).

Wide deviations from these median growth rates (up to 8 cm/month) have been documented for some individuals tagged in May through July and recaptured July to October (Araya 1983). The rapid rate of growth may be correlated with population size or density, or environmental conditions, particularly temperature and food availability.

## Size at Sexual Maturity

In the northwest Pacific, males show first signs of spermatogenesis at 28.5 cm DML and 670 g body weight (Tung 1981). Almost all northwest Pacific males examined are fully mature by November or December, at a mantle length of 32.5 cm, testis weight of 15–20 g, and approximate body weight of 1 kg (Murata and Ishii 1977; Tung 1981). Females with spermatophores in January–February are 40 cm DML and have 20–50 g ovary weights (Murata and Ishii 1977). Females are slower to mature and larger at maturity than males in all Pacific groups (Murata and Ishii 1977).

In a 1986 study conducted June through September across the Pacific, using commercal and scientific gillnets and jigs, Murata (1987) reported that nearly all females caught were immature and unmated, and nearly all males were immature and lacked spermatophores. Individuals caught in commercial salmon gillnets (110–115 mm mesh) were primarily female (Murata 1987).

## Food Habits

Stomach samples examined from *Ommastrephes bartrami* collected by gillnet in the northwest Pacific, south of the subarctic boundary, primarily contained fishes and secondarily squids (Naito et al. 1977a; Tung 1981). Planktonic crustaceans (primarily Euphausiacea and *Parathemisto* sp.) were present in low numbers (Tung 1981) and found in greatest proportions in immature squid (Naito et al. 1977a). Identified fishes include lanternfishes, anchovy, sardines, mackerel larvae, and saury. Squids eaten were *Watasenia scintillans, Onychoteuthis borealijaponica*, and *Ommastrephes bartrami* (Naito et al. 1977a).

Pearcy (1991) found remains of fishes, squids, other mollusks, and crustaceans in the stomachs of *O. bartrami* caught in gillnets along 155° W from 36° N 30′ and 44° N in the eastern Pacific in July, 1985. Diet was composed almost exclusively of *Berryteuthis anonychus* at 44° N.

## Other Squids

Gillnet and jigging research surveys indicate the frequency of occurrence of three other squid species (*Gonatopsis borealis, Berryteuthis magister*, and *Onychoteuthis borealijaponica*) within the North Pacific driftnet fishing zone is higher than that of *Ommastrephes bartrami* (Kubodera et al. 1983). However, *O. bartrami* forms dense concentrations compared to the other species, and as a result, the total numbers of flying squid caught in gill nets is higher (Kubodera et al. 1983). Naito et al. (1977b) reported that in gill nets with mesh sizes ranging from 24–157 mm, the peak catch for all four species occurred in 48 mm mesh. Murata (1987) reported that within a range of 33–157 mm mesh, maximum catches of *Ommastrephes bartrami* were in 48 mm and 63 mm mesh, while maximum numbers of *Onychoteuthis borealijaponica* and *G. borealis* were caught in 37 mm and 55 mm mesh, and in 55–82 mm mesh respectively. Summer research vessel surveys conducted in the subarctic domain, transition zone, and south of the subarctic boundary found *Ommastrephes bartrami* to be the most abundant squid (46% catch), *Onychoteuthis borealijaponica* the second most abundant, and *Gonatopsis borealis* the third most abundant, however the frequency of occurrence of the three species was reversed (Kubodera et al. 1983). Of the four species, *Ommastrephes bartrami* attains the largest maximum mantle length (Naito et al. 1977a).

Although there is distributional overlap among the four species, different temperature tolerances segregate them spatially (Naito et al. 1977b; Kubodera et al. 1983) (Fig. 3). *Onychoteuthis borealijaponica* is distributed in subtropical and subarctic waters, primarily in temperatures of 11°–15° C and depths of 20–30 m. *Gonatopsis borealis* is considered a subarctic species and is found most abundantly at 5°–10° C, at depths greater than 40 m. *Berryteuthis magister* is distributed in the subarctic domain and appears to overlap least with *Ommastrephes bartrami.*

Three of the four squid species frequently caught in the gill nets are known to be important prey of marine mammals (Fiscus et al. 1964; Kajimura 1984; Sinclair 1988). Sperm whales reportedly prey on adult flying squid (Okutani 1977), while juvenile *O. bartrami* may be an important resource for other toothed cetaceans, seabirds, and large predatory fishes such as tunas. There is justifiable concern about the degree of incidental take of non-target species of marine mammals, birds, and fish but the most dramatic effect of extensive gillnetting for *O. bartrami* may be the indirect impact of the removal of these and other squids as an important food resource. The number of non-target squid species caught in the commercial gillnet fishery was not consistently monitored prior to 1990.

## Trends in Recruitment Success of *Ommastrephes bartrami*

In a review of studies based on data collected from the northwest Pacific in 1976 through 1979, Araya (1983) described a trend of decreasing mantle length beginning in 1977, and considered this the result of overexploitation of winter hatched or large squid. From gillnet and jigging research data in the northwest and central Pacific, Murata (1987) reported a decreasing trend in squid densities of large sized individuals between 1984 and 1986. Fishing effort in August and September is concentrated within the transition zone and along the subarctic boundary. An overemphasis in fishing effort on the large pre-spawning females within the transitional domain could severely reduce the spawning success of the winter brood group.

A trend of decreasing catch (CPUE) is apparent between 1977 and 1979 (Tung 1981; Araya 1983), and 1980–1983 (Gong et al. 1985b). Increased numbers of squid were caught during the initial expansion of the fishing gounds and addition of boats; however catch-per-unit-effort values reportedly leveled off or decreased among Taiwanese vessels by 1979, and the actual catch by Korean vessels in 1986 (59,000 tons) was lower than 1979 levels (71,000 tons) (Gong et al. 1985b; Natl. Fish. Administration 1987). Fishing effort among Korean vessels in the northwest and central Pacific more than doubled between 1980 and 1983, and quadrupled by 1986, yet the catch per unit net (96–115 mm mesh) declined sharply from 22 kg/net in 1980 to 7 kg/net in 1983, 4 kg/net in 1984, and 3.4 kg/net by 1986 (Gong et al. 1985b; Natl. Fish. Administration 1987).

Efforts to calculate an accurate population size and status for *Ommastrephes bartrami* in the North Pacific are complicated by variable research and commercial fishing methods, inconsistent availability of catch records, discrepancies in the interpretation of cohort size categories, and a lack of detailed knowledge regarding the biology and distribution of the population. Despite these complicating factors, a general trend towards a decrease in dorsal mantle length, body weight, and squid densities since the late 1970's is indicated by the most conservative estimates. Strong concern for the status of *Ommastrephes bartrami* in the North Pacific has been expressed by scientific representatives from each nation commercially fishing for this species in the North Pacific (Tung 1981; Gong et al. 1985b; Murata 1990).

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# North Pacific Albacore Ecology and Oceanography

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## ABSTRACT

Albacore, *Thunnus alalunga,* is a wide-ranging tuna species occurring between latitudes 10° and 50° N in the North Pacific Ocean. Albacore are a resource which supports important U.S. and Pacific-nation commerical fisheries and U.S. recreational fisheries. There is a growing body of evidence that there are two subgroups of albacore that have different migratory patterns, modal sizes, growth rates, and spawning periods, although they do not appear to be genetically distinct. Pre-spawning albacore, two to five years old, are highly migratory and conduct well-defined, trans-Pacific migrations. The spawning adults are generally confined within the subtropical and tropical zones of the central North Pacific. Their distribution and migration are markedly influenced by the marine environmental conditions associated with the waters of the North Pacific transition zone and its frontal boundaries. The subarctic and subtropical fronts are regions of large gradients in temperature and salinity which lie in bands across much of the North Pacific. The dynamic processes that maintain these gradients influence the nutrient and biomass distribution. The major centers of albacore catch are found about these fronts and within the transition zone waters that lie between them.

## Introduction

Albacore, *Thunnus alalunga,* is a wide-ranging tuna species occurring between latitudes 10° and 50° N in the North Pacific Ocean. There is a general geographical separation by age, spawning adults occurring mostly in the central waters between latitudes 10° and 20° N and pre-spawning juveniles making extensive migrations between latitudes 30° and 50° N. The resource supports important U.S. commercial and recreational fisheries and several foreign fisheries. The distribution, availability, and migration of the albacore, as well as its vulnerability to capture, are markedly influenced by marine environmental conditions. A general review of the ecology, biology, and fisheries operating on the resource are discussed in this report with emphasis on the physical oceanographic regimes associated with the North Pacific transition zone.

North of the subarctic front the waters are cold and have low salinity. South of the subtropical front waters are warm and have high salinity. The waters between these large water masses are transitional in characteristics and are termed the North Pacific transition zone. The narrow zones where the changes in properties are abrupt are termed fronts. The schematic representation of ocean fronts presented in Figure 1 is a simplification of the complex features found.

## Fisheries Harvesting North Pacific Albacore

Japan and the United States account for the majority of the catches of North Pacific albacore, catching approximately 72% and 26%, respectively, from 1965 through 1985. Canada, Korea, and Taiwan each land about 0.5% to 1% of the total catch. Historically, the Japanese have had two fisheries that harvest North Pacific albacore, a pole-and-line surface fishery operating during spring and summer and a longline subsurface fishery operating during winter. In 1978, a third Japanese fishery gained importance with the

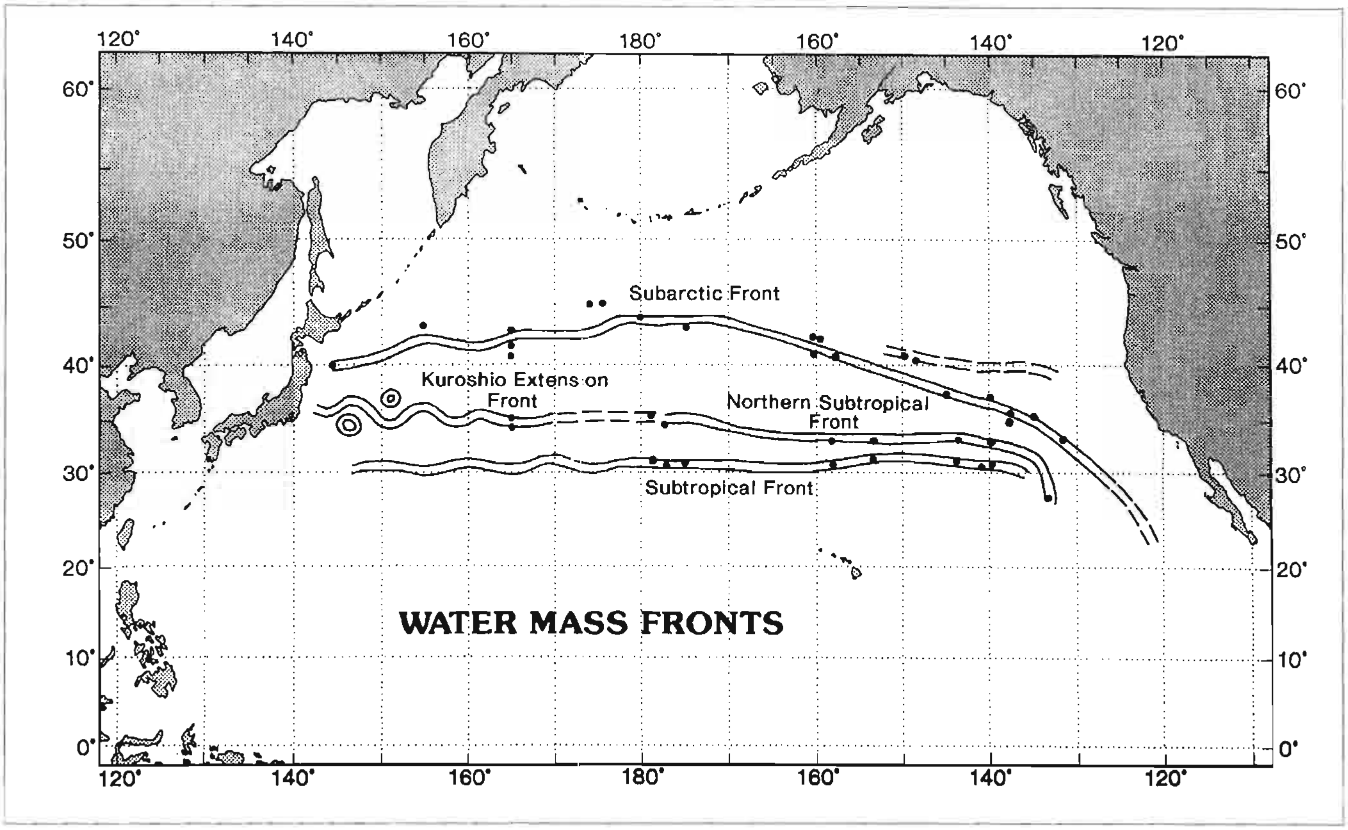

Figure 1
Schematic representation of the major fronts in the temperate zone of the North Pacific based upon numerous individual observations (dots). The transition zone lies between the fronts.

dramatic expansion of summer gillnet fishing targeting albacore.

For several decades the pole-and-line (bait boat) fishery extended from near the coast of Japan eastward to about 150° E. In the early 1970's, the fishery was expanded further eastward within the Kuroshio extension waters to near the dateline. However in the mid-1980's, it was contracted back to about the same distribution as earlier. The Japanese longline fishery is conducted across much of the North Pacific, and by 1981, gillnet fishing operations had also spread almost entirely across the North Pacific, mostly within the North Pacific transition zone waters. The major centers of catches of the Japanese pole-and-line and longline fisheries are shown in Figure 2A and the distribution of the gillnet fishery in 1981 in Figure 2B.

The U.S. North Pacific albacore fishery, which began in the early 1900's, uses surface trolling and pole-and-line fishing gear (Dotson 1980). The fishery takes place during summer and autumn, and for many decades has operated in waters within a few hundred miles of the coast between northern Baja California, Mexico, and British Columbia, Canada. In 1975, the U.S. troll fleet began a broad westward extension of its operating range (Laurs and Nishimoto 1979). Beginning by the late 1970's, 35 to 50 vessels would start to fish near the date line in about May, and progress eastward across the mid-North Pacific in transition zone waters, ending the fishing season in autumn in California Current waters off the west coast of the United States. The main centers of catches of the U.S. fishery are shown in Figure 2A.

Major geographical variations in the location of the U.S. coastal fishery occur; during some periods it is centered in waters off the Pacific Northwest, during others, off southern-central California (Laurs et al. 1976). These geographical shifts in the location of the fishery have been linked to variations in large-scale environmental conditions (Clark et al. 1975).

The U.S. albacore industry through the cooperation of American Fishermen's Research Foundation[1] and NOAA/NMFS scientists has conducted numer-

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[1] The American Fishermen's Research Foundation is an albacore fishing industry non-profit organization funded by assessments imposed by the industry on landings of albacore caught by U.S. fishermen. The funds are used for research and education purposes.

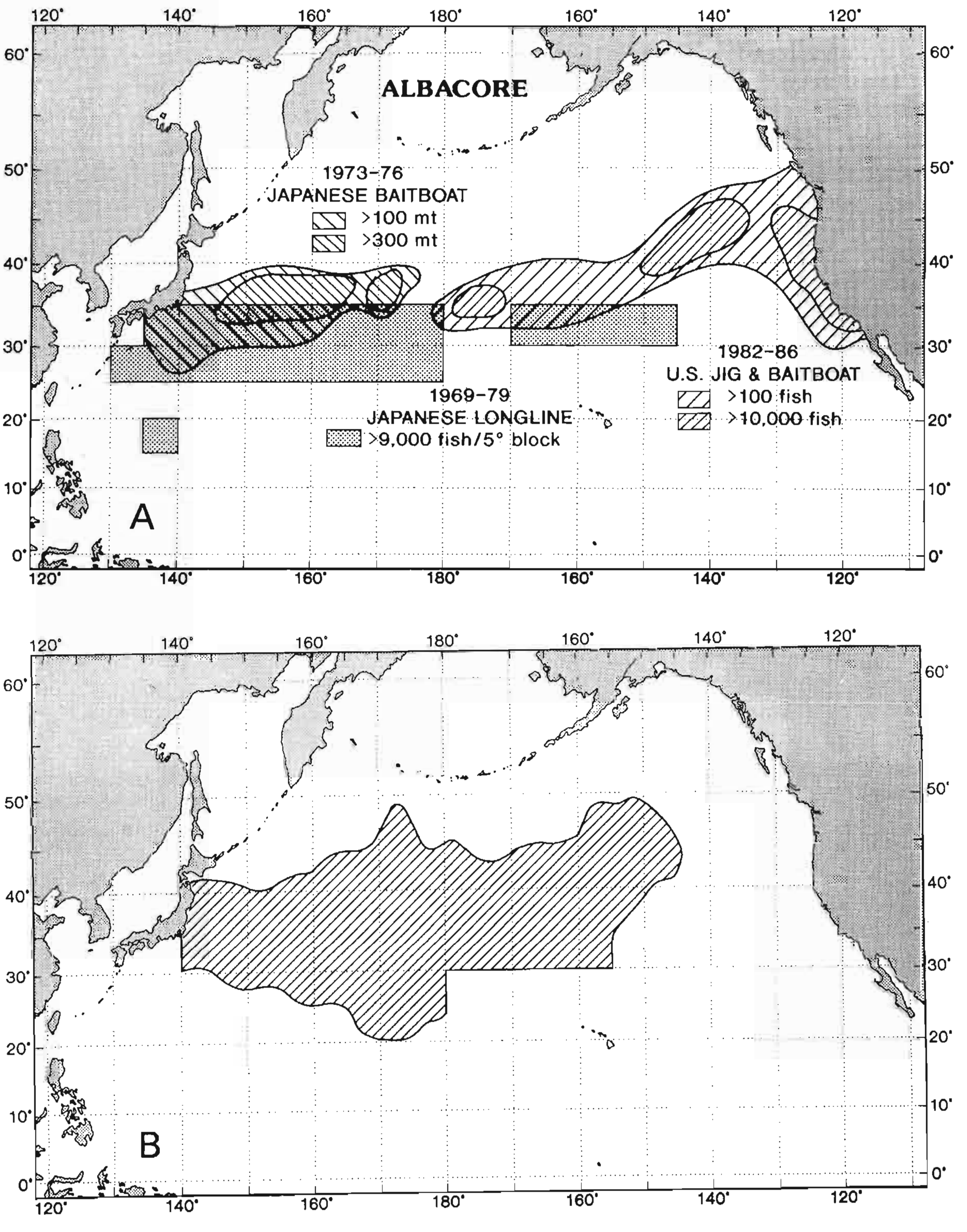

Figure 2

(**A**) Major centers of catch for Japanese Pole-and-line, longline, and U.S. jigboat fisheries. The contoured and shaded regions represent approximately 75% of total annual average for the years indicated for each fishery. The contoured regions having finer hatching (Japanese baitboat and U.S. jig and baitboat only) indicate areas of highest concentrations of catch. (**B**) Distribution of the Japanese drift gill-net fishery for North Pacific albacore in 1981, indicated by the shaded area.

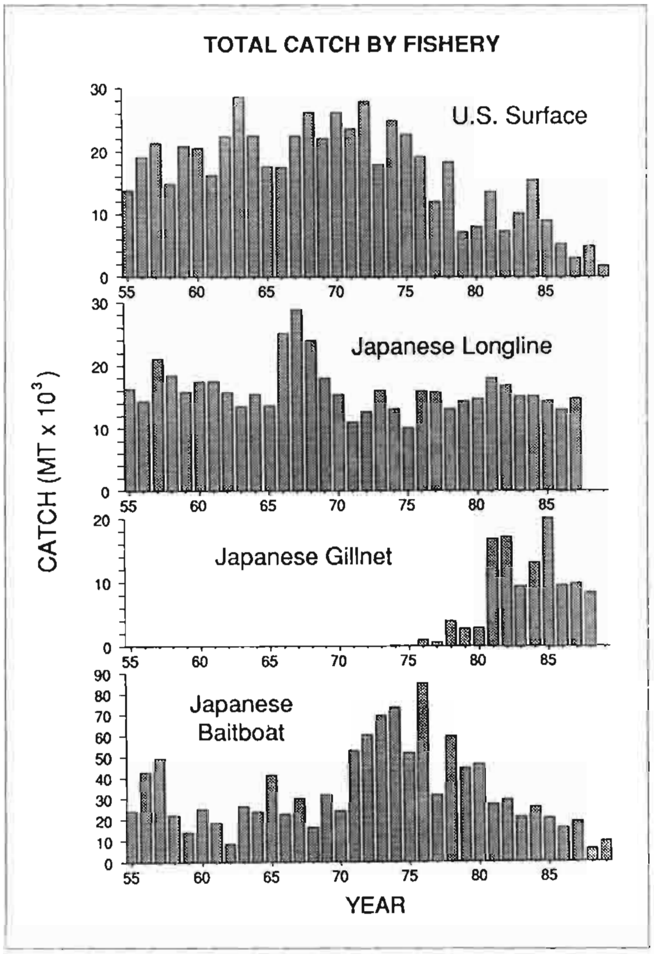

**Figure 3**
Annual catches of North Pacific albacore by country and year for 1955–1983 (from A. Coan, G. Rensink, C. Perrin, and F. Miller, NMFS SWFSC Adm. Rep. LJ-90-21, "Summary of the 1989 North and South Pacific albacore fisheries data" 1990).

ous research operations, including a series of exploratory fishing and research operations to evaluate the feasibility of establishing a winter U.S. longline fishery for albacore in the eastern Pacific (Laurs and Dotson 1983). The results of the experiments are encouraging, and while a number of fishermen have expressed an interest in participating in this winter expansion of the U.S. albacore fishery, none are doing so at this time.

Annual catches of North Pacific albacore by country and gear type are given in Figure 3 for years 1955–1989 and in Table 1 for years 1952–1988. Fishing effort and catch in both the Japanese baitboat and U.S. surface fisheries have declined beginning in the early 1980's. In contrast, recent landings and effort in the Japanese longline fishery have been relatively constant and there has been a rapid development of Asian gillnet fisheries that take large numbers of albacore in the North Pacific.

There are a number of factors which are associated with the decline in the traditional North Pacific albacore surface fisheries, but the relative importance of these factors is unknown. Parrish et al. (1989) discuss trends and status of the fisheries and the North Pacific albacore population.

## Stock Structure

There is a growing body of evidence (Brock 1943; Laurs and Lynn 1977; and Laurs and Wetherall 1981) that the population of North Pacific albacore is not as homogeneous as has been assumed (Clemens 1961; Otsu and Uchida 1963). Results from tagging studies suggest that there are two subgroups of albacore which have different migratory patterns (Laurs 1983), modal sizes (Brock 1943; Laurs and Lynn 1977; Laurs and Wetherall 1981), growth rates (Laurs and Wetherall 1981), and peak spawning periods (Wetherall et al. 1987). Off the coast of North America, the boundary between the two subgroups appears to be situated near 40° N. Although the proposed subgroups are differentiated by geographic dissimilarities in biological or fishery statistic criteria, they do not appear to be genetically distinct (Graves and Dizon 1989).

## Migration

North Pacific albacore are one of the most highly migratory species of tuna. The extent and degree of migration are most expansive in pre-adult ages between about 2 and 5 years. Fish of these ages may conduct trans-oceanic migrations or migrations across broad regions of the North Pacific, mostly within transition zone waters. The migration habits of the spawning adults, six years of age and older, are much more limited and are confined mostly within the subtropical and tropical zones of the central North Pacific.

Tagging results show that albacore that had been tagged and released in coastal waters off North America north of lat. 40° N have a different migration pattern than those tagged south of 40° N. For example, for fish that had been tagged and released in the northern area and had been at liberty for up to 5 years, 28 percent were recovered in the same general area as release, 54 percent west of long. 180°, 13 percent in coastal waters off North America south of 40° N and about 5 percent in the central eastern Pacific or unknown area of recovery (Fig. 4A). In contrast, for fish that had been tagged and released

**Table 1**

Catches of North Pacific albacore in metric tons by fisheries, 1952–1988 (from N. Bartoo and Y. Watanabe, NMFS SWFSC Adm. Rep., "Report of the eleventh North Pacific albacore workshop, May 18–19, 1989" 1989).

| | Japan | | | | | Taiwan | | | Korea | | | United States | | | | | Canada | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | Pole and line[a] | Long-line[b] | Gill net[c] | Other gear | Total | Long-line | Gill net[d] | Total | Long-line[e] | Gill net[d] | Total | Pole and line | Troll[f] | Sport | Gill net | Total | Troll | Grand Total |
| 1952 | 41,786 | 26,687 | | 237 | 68,710 | | | | | | | | 23,843 | 1,373 | | 25,216 | 71 | 93,997 |
| 1953 | 32,921 | 27,777 | | 132 | 60,830 | | | | | | | | 15,740 | 171 | | 15,911 | 5 | 76,746 |
| 1954 | 28,069 | 20,958 | | 38 | 49,065 | | | | | | | | 12,246 | 147 | | 12,393 | | 61,458 |
| 1955 | 24,236 | 16,277 | | 136 | 40,649 | | | | | | | | 13,264 | 577 | | 13,841 | | 54,490 |
| 1956 | 42,810 | 14,341 | | 57 | 57,208 | | | | | | | | 18,751 | 482 | | 19,233 | 17 | 76,458 |
| 1957 | 49,500 | 21,053 | | 151 | 70,704 | | | | | | | | 21,165 | 304 | | 21,469 | 8 | 92,181 |
| 1958 | 22,175 | 18,432 | | 124 | 40,731 | | | | | | | | 14,855 | 48 | | 14,903 | 74 | 55,708 |
| 1959 | 14,252 | 15,802 | | 67 | 30,121 | | | | | | | | 20,990 | 0 | | 20,990 | 212 | 51,323 |
| 1960 | 25,156 | 17,369 | | 76 | 42,601 | | | | | | | | 20,100 | 557 | | 20,657 | 5 | 63,263 |
| 1961 | 18,636 | 17,437 | | 268 | 36,341 | | | | | | | 2,837 | 12,061 | 1,355 | | 16,253 | 4 | 52,598 |
| 1962 | 8,729 | 15,764 | | 191 | 24,684 | | | | | | | 1,085 | 19,760 | 1,681 | | 22,526 | 1 | 47,211 |
| 1963 | 26,420 | 13,464 | | 218 | 40,102 | | | | | | | 2,432 | 25,147 | 1,161 | | 28,740 | 5 | 68,847 |
| 1964 | 23,858 | 15,458 | | 319 | 39,635 | 26 | | 26 | | | | 3,411 | 18,392 | 824 | | 22,627 | 3 | 62,291 |
| 1965 | 41,491 | 13,701 | | 121 | 55,313 | 16 | | 16 | | | | 417 | 16,545 | 731 | | 17,693 | 15 | 73,037 |
| 1966 | 22,830 | 25,050 | | 585 | 48,465 | 16 | | 16 | | | | 1,600 | 15,342 | 588 | | 17,530 | 44 | 66,055 |
| 1967 | 30,481 | 28,869 | | 520 | 59,870 | 17 | | 17 | | | | 4,113 | 17,826 | 707 | | 22,646 | 161 | 82,694 |
| 1968 | 16,597 | 23,961 | | 1,109 | 41,667 | 15 | | 15 | | | | 4,906 | 20,444 | 951 | | 26,301 | 1,028 | 69,011 |
| 1969 | 32,107 | 18,006 | | 1,480 | 51,593 | 21 | | 21 | | | | 2,996 | 18,839 | 358 | | 22,193 | 1,365 | 75,172 |
| 1970 | 24,376 | 15,372 | | 956 | 40,704 | 23 | | 23 | | | | 4,416 | 21,041 | 822 | | 26,279 | 354 | 67,360 |
| 1971 | 53,198 | 11,035 | | 1,262 | 65,495 | 24 | | 24 | | | | 2,071 | 20,537 | 1,175 | | 23,783 | 1,587 | 90,889 |
| 1972 | 60,762 | 12,649 | 1 | 921 | 74,333 | 25 | | 25 | | | | 3,750 | 23,608 | 637 | | 27,995 | 3,558 | 105,911 |
| 1973 | 69,811 | 16,059 | 39 | 1,883 | 87,792 | 35 | | 35 | | | | 2,236 | 15,667 | 84 | | 17,987 | 1,270 | 107,084 |
| 1974 | 73,576 | 13,053 | 224 | 1,065 | 87,918 | 40 | | 40 | | | | 4,777 | 20,187 | 94 | | 25,058 | 1,207 | 114,223 |
| 1975 | 52,157 | 10,060 | 166 | 402 | 62,785 | 28 | | 28 | 319 | | 319 | 3,243 | 18,975 | 640 | | 22,858 | 101 | 86,091 |
| 1976 | 85,336 | 15,896 | 1,070 | 1,394 | 103,696 | 37 | | 37 | 971 | | 971 | 2,700 | 15,932 | 713 | | 19,345 | 252 | 124,301 |
| 1977 | 31,934 | 15,737 | 688 | 1,039 | 49,398 | 61 | | 61 | 65 | | 65 | 1,497 | 10,005 | 537 | | 12,039 | 53 | 61,616 |
| 1978 | 59,877 | 13,061 | 4,029 | 3,209 | 80,176 | 53 | | 53 | 174 | | 174 | 950 | 16,682 | 810 | | 18,442 | 23 | 98,868 |
| 1979 | 44,662 | 14,249 | 2,856 | 1,280 | 63,047 | 81 | | 81 | 27 | | 27 | 303 | 6,801 | 74 | | 7,178 | 521 | 70,854 |
| 1980 | 46,743 | 14,743 | 2,986 | 1,516 | 65,988 | | | | 15 | | 15 | 382 | 7,574 | 168 | | 8,124 | 212 | 74,339 |
| 1981 | 27,426 | 18,020 | 10,348 | 959 | 56,753 | | | | 600 | | 600 | 748 | 12,694 | 195 | | 13,637 | 200 | 71,190 |
| 1982 | 29,615 | 16,762 | 12,511 | 1,054 | 59,942 | | | | 1,070 | | 1,070 | 425 | 6,661 | 257 | | 7,343 | 104 | 68,459 |
| 1983 | 21,098 | 15,103 | 6,884 | 471 | 43,556 | | | | 1,233 | | 1,233 | 607 | 9,512 | 87 | | 10,206 | 225 | 55,220 |
| 1984 | 26,015 | 15,111 | 10,569 | 3,898 | 55,593 | | | | 2,708 | | 2,708 | 1,030 | 9,378 | 1,427 | | 15,563[g] | 50 | 73,914 |
| 1985 | 20,714 | 14,320 | 13,132 | 1,940 | 50,106 | | | | 5,447 | | 5,447 | 1,498 | 6,431 | 1,176 | 2 | 9,109 | 56 | 64,718 |
| 1986 | 16,096 | 12,945 | 9,749 | 2,192 | 40,982 | | | | | | | 432 | 4,708 | 196 | 3 | 5,339 | 30 | 46,351 |
| 1987[h] | 19,091 | 14,642 | 7,617 | 1,394 | 42,744 | | | | | | | 158 | 2,766 | 74 | 5 | 3,003 | 104 | 45,851 |
| 1988[h] | 7,000 | | | | 12,000 | | 11,000 | 11,000 | | | | 598 | 4,212 | 64 | 15 | 4,889 | 85 | 27,974 |

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[a] Japanese pole-and-line catches include fish caught by research vessels.

[b] Japanese longline catches for 1952–60 exclude minor amounts taken by vessels under 20 tons. Japanese longline catches from 1958–68 were readjusted in 1988. Longline catches in weight are estimated by multiplying annual number of fish caught by average weight statistics.

[c] Japan gillnet catches include south Pacific catches.

[d] Taiwanese and Korean gillnet catches are missing or incomplete.

[e] Korean longline catches calculated from FAO statistics and Korean catch/effort data.

[f] U.S. troll catches from 1952–60 include fish caught by baitboats, from 1961–85 include fish landed in Hawaii. U.S. jig (troll) catches (1984–88) include gillnet catches.

[g] U.S. total for 1984 includes 3,728 mt caught by purse seines.

[h] Figures for 1987–88 are preliminary.

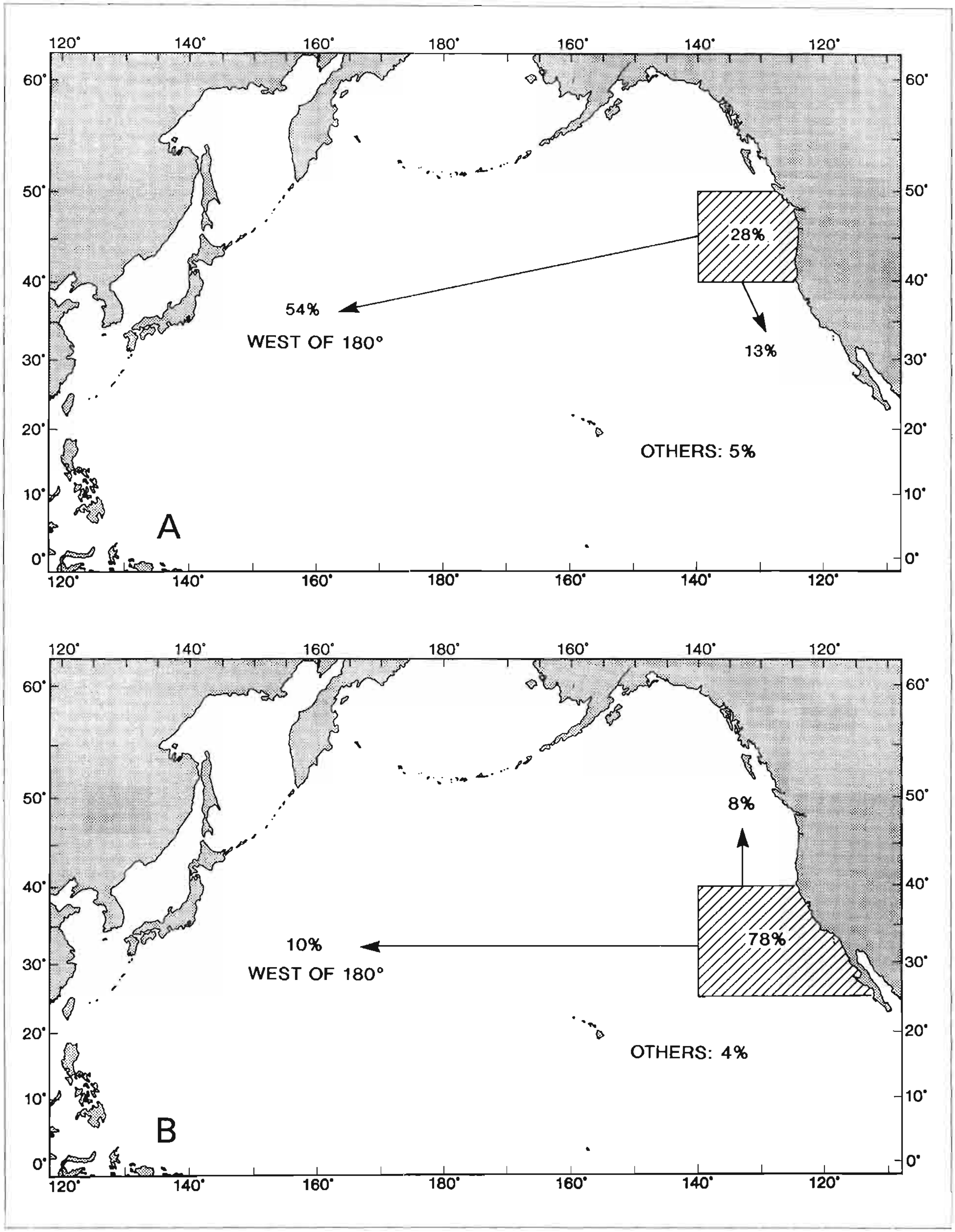

Figure 4

(A) Percent of total recoveries of tagged albacore for fish released in coastal waters off North America north of 40° N. Release area is indicated by hatching. (B) Percent of total recoveries of tagged albacore for fish released in coastal waters off North America south of 40° N. Release area is indicated by hatching.

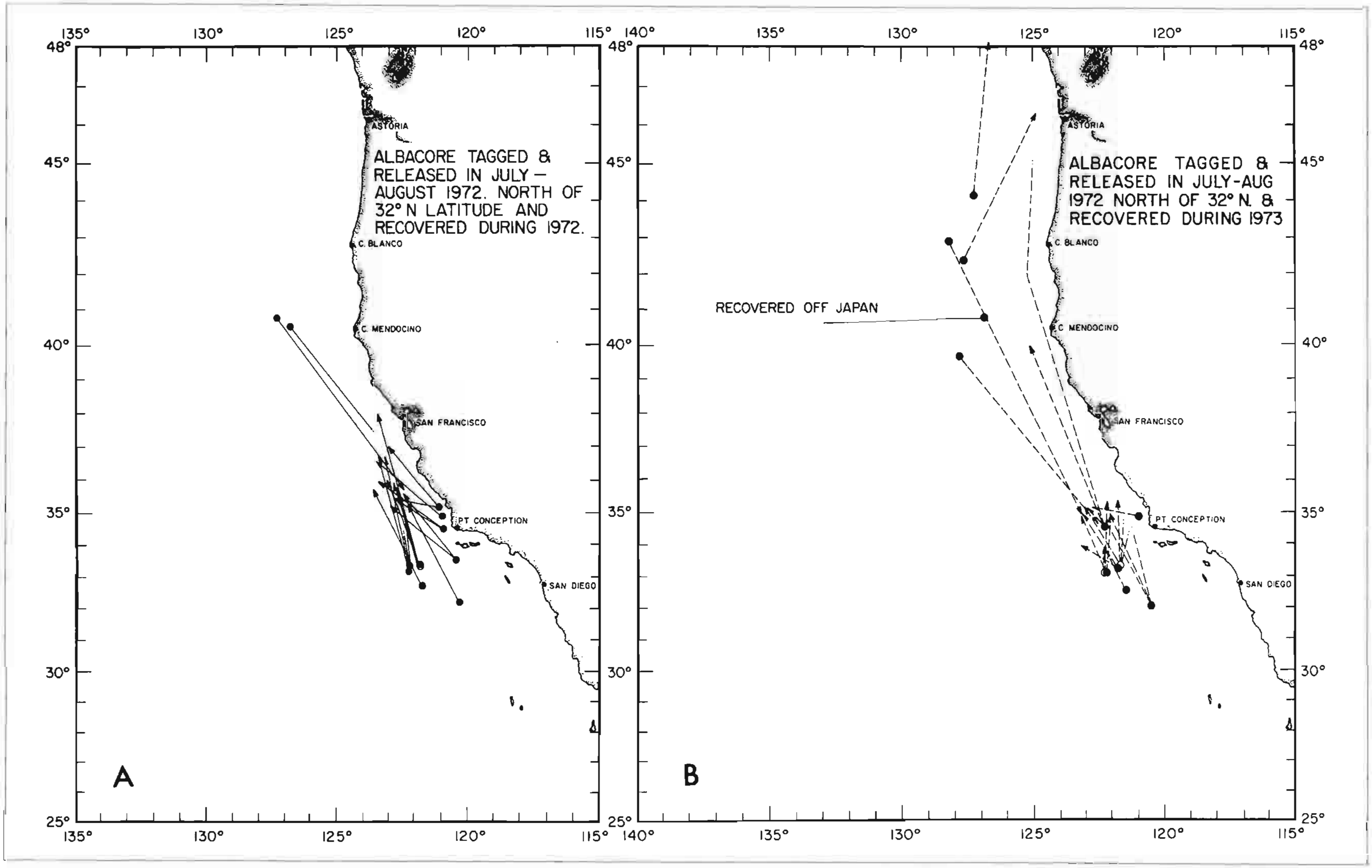

**Figure 5**

(**A**) Positions of release (dots) and recovery (arrowheads) of tagged albacore which were recovered within the season of release during 1972. (**B**) The same as A except for recoveries in the subsequent fishing season, 1973.

in the southern area, 78 percent were recovered in the same general area as release, 10 percent west of 180°, 8 percent in coastal waters off North America north of 40° N, and about 4 percent in the central eastern Pacific or unknown area of recovery (Figure 4B).

The tagging results suggest that the northern subgroup of albacore is primarily exploited by the Japanese surface fishery in the western Pacific, the Asian longline fishery and the portion of the North American fishery operating north of about 40° N. The southern subgroup appears to be harvested mainly by the North American surface fishery operating south of about 40° N and the Asian longline fishery, and only limitedly by the Japanese pole-and-line fishery.

Release and recovery locations for tagged albacore that were recovered by U.S. fishermen within the same fishing season as release and the fishing season following release are shown in Figure 5, A and B, respectively. These results reveal that the movement patterns of albacore are highly directed, that the fish follow well-defined routes during intra- and inter-fishery migrations. Further evidence for this is indicated by the relatively high proportion of tagged fish that have been recovered within 150 miles of where they were released off the coast of North America after being at liberty for one to three fishing seasons (Laurs and Nishimoto 1974). Presumably these fish had migrated seasonally between coastal waters off North America and the central or western Pacific. For example, one tagged fish was recovered only 39 miles from where it had been tagged nearly two years earlier. Tagged albacore recoveries made by the Japanese pole-and-line fishery also show a pattern indicative of a directed, well-defined migration route (Laurs and Nishimoto 1974).

## Physiological Ecology and Habitat Definition

Most of the present understanding of albacore habitat has been gained through studies at sea following multi-disciplinary approaches including physical and biological oceanography, satellite oceanography, acoustic tracking, and physiological ecology research. The latter investigations have shown that the albacore is a highly advanced teleost with many specialized adaptations. It is a thermo-regulating endotherm (Graham and Dickson 1981), has a high metabolic rate (Graham and Laurs 1982), an advanced cardio-vascular system (Breich et al. 1983; Lai et al. 1987), specializations in the circulatory system and blood/gas exchange system (Laurs et al. 1978; Alexander et al. 1980; Cech et al. 1984; Graham et al. 1989), distinctive enzyme and complement systems (Morrison et al. 1978; Giclas et al. 1981; Dyke et al. 1987; Dickson 1988), and high energetic costs for migration (Sharp and Dotson 1977), which may be partly met by utilization of stored fat (Dotson 1978).

Recent research refutes earlier published information on temperature preference, which was based on the belief that albacore were confined to the upper mixed layer and that the thermocline formed a barrier to their vertical distribution (Clemens 1961). Based on these assumptions, modal sea surface temperatures (SST) measured where highest troll catches were made, generally between 16° and 19° C (e.g., Clemens 1961), were thought to represent the temperature preference for pre-adult albacore in the eastern Pacific. However, acoustic tracking of free-swimming albacore and concurrent measurement of ocean vertical thermal structure (Laurs et al. 1980; Laurs and Dotson, in prep.) have demonstrated that 3 to 5 year-old albacore spend most of their time swimming in or near the thermocline. The fish spend small amounts of time in the upper mixed layer, presumably only when enticed there to feed. The tracked fish moved through waters with a temperature range of about 10° to 19° C and spent most of the time in waters with temperatures much cooler than those originally thought to be their optimal range.

The tracked fish also exhibited marked vertical excursions in depth; the range generally was larger during the day than at night when in California Current waters (Fig. 6). However, two fish tracked in offsore waters, which are believed to have been actively migrating, showed larger depth excursions during the night, which often brought them up into the lower portion of the mixed layer. When making vertical excursions, albacore pass through large temperature gradients, routinely 4° to 6° C and up to 10° C, within about twenty-minute periods.

Based on the acoustic tracking results that albacore seldom enter into waters cooler than 10° C and the finding of Graham and Dickson (1981) that thermoregulation processes begin to fail at temperatures below 10° C, it appears that this temperature is the lower limit of the preferred temperature range. At this point of our understanding, we believe that the normal habitat of albacore is within a temperature range of about 10° to 20° C, in waters with a dissolved oxygen saturation greater than 60 percent (Graham and Laurs 1982). However, the SST range of 16° to 19° C still has value in fishing operations.

There is ample evidence that the migration, distribution, availability, and vulnerability of albacore are markedly influenced by oceanographic conditions in the North Pacific Ocean, notably fronts. Albacore

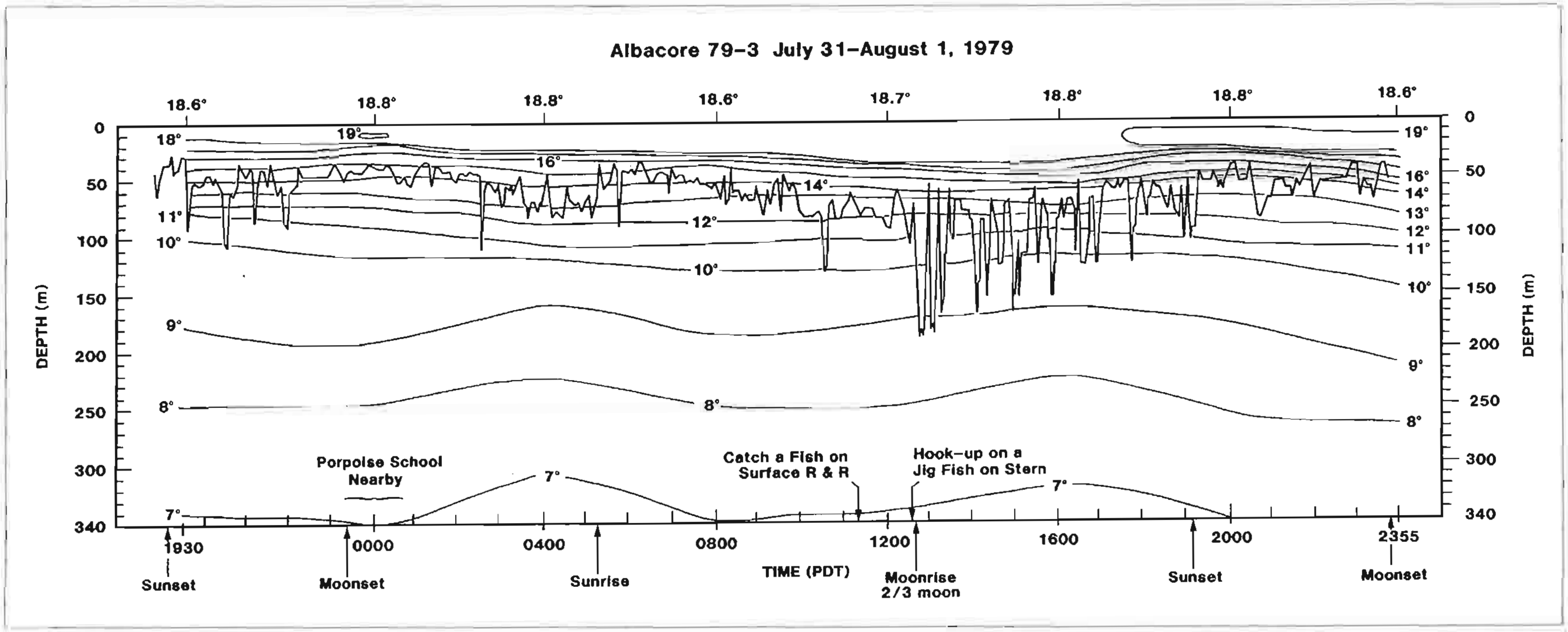

Figure 6
A time plot of the vertical movements of an acoustically tracked albacore in California Current waters. Vertical temperature field is based upon concurrent XBT casts.

fishing grounds in the western Pacific have been linked to oceanic fronts (Uda 1973). Also, the seasonal migration of albacore into North American coastal waters has been found to be associated with the North Pacific transition zone waters and its frontal zone boundaries (Laurs and Lynn 1977). Oceanographic conditions also play important roles in the local concentrations and movements of albacore in coastal waters off North America. Albacore tend to aggregate on the warm side of upwelling fronts and to move away from the locations where the fronts occurred when upwelling breaks down (Laurs et al. 1977). Satellite images of ocean color and SST and concurrent albacore catch data also clearly show that the distribution and availability of albacore in nearshore waters off California are related to coastal upwelling fronts. Albacore are most abundant in warm, clear, blue oceanic waters adjacent to the temperature and color fronts which form the seaward boundary of the relatively cool, turbid coastal water masses (Laurs et al. 1984). Laurs et al. (1984) found that, in waters beyond about 500 miles from the coast, fishing success was related to the productivity of the waters. Ocean boundaries associated with the Columbia River plume also appear to be important in the aggregation of albacore (Pearcy and Mueller 1970).

It is presumed that albacore aggregate in the vicinity of upwelling fronts to feed on forage organisms that are plentiful in these areas (Blackburn 1969; Laurs et al. 1977). Yet, it remains unclear what physical factors prevent albacore from penetrating these fronts in order to reach what would likely be the highest potential forage biomass (Blackburn 1969). Because tuna can perceive temperature gradients as small as 0.1° C (Steffel et al. 1976), thermal-physiological mechanisms have been thought to be the main limitation to tunas crossing sea surface·temperature gradients into cooler waters. Neill (1976) postulated that tunas utilize frontal gradients for behavioral thermoregulation. Past studies have also stressed confinement to physiological optimal temperature range (Thompson 1917; Clemens 1961; Sund et al. 1981). However, the findings that albacore can regulate their body temperatures over a relatively broad range and that they may routinely pass through vertical temperature gradients of up to 10° C, clearly substantiate that the aggregation of albacore on the warm, clear side of SST fronts is not related to thermal-physiological mechanisms.

Recent research involving acoustic telemetry of free-swimming albacore, satellite measurements, and oceanographic sampling indicate that water clarity as it affects the ability of albacore to detect prey may be the causal mechanism underlying the aggregation of albacore on the warm, clear sides of upwelling fronts (Laurs, in prep.). In offshore regions, the distribution of albacore in relatively productive waters of the transition zone is believed to occur because relatively higher amounts of food organisms are present than in the Central Pacific gyre waters, yet the waters are clear enough for the albacore to see their prey.

## Food Habits of Albacore in Transition Zone Waters

Information is very limited about the food habits of albacore in the central North Pacific. However, they appear to be opportunistic carnivores, as they are in other areas (e.g., McHugh 1952).

Iverson (1962) reported on the stomach contents of 79 albacore caught by trolling and 87 caught by gill net in the area bounded by longitudes 140° W and 180° and latitudes 32° and 47° N. The fish ranged in fork length from 51 to 85 cm and were caught on research cruises conducted between 1950 and 1957. The average displacement volume of food per stomach in troll-caught fish was 15.1 mL and in gillnet-caught fish was 9.8 mL. The author speculated that there was less food in the stomachs of the gillnet-caught fish because the fishing was done at night and albacore are not known to feed at night, and because the fish may have vomited excessively while struggling in the net. Laurs and Nishimoto (1973) and Nishimoto and Laurs (1974) reported on the stomach contents of 33 and 75 albacore caught in the transition zone area between 130° and 140° W during May of 1973 and 1974, respectively. Stomachs were examined in both years from fish ranging in size from 50 to 85 cm FL. Food was found in all stomachs and averaged 16.3 mL displacement volume for fish examined in 1973, and was found in 88 percent of the stomachs and averaged 13.3 mL for fish examined in 1974.

Variations are apparent in the frequency of occurrence and percent volume of the major food groups found in the albacore stomachs in the studies reported above (Table 2). Cephalopods had the greatest biomass in two of the analyses and saury the greatest in the other two. For all the analyses combined, cephalopods occurred in nearly 57 percent of the stomachs examined and comprised approximately 38 percent of the food by volume. Fishes (other than saury) and crustaceans were found in nearly the same number of stomachs, about 48 and 42 percent, respectively, but contributed only about 14 and 11 percent of the volume of food, respectively.

**Table 2**

Summary of albacore feeding habits in transition zone waters. (Displacement volumes in mL.)

| Food Group | Gillnet caught[a] % occur | Gillnet caught[a] vol. | Gillnet caught[b] % occur | Gillnet caught[b] vol. | Gillnet caught[c] % occur | Gillnet caught[c] vol. | Gillnet caught[d] % occur | Gillnet caught[d] vol. | All studies combined % occur | All studies combined vol. |
|---|---|---|---|---|---|---|---|---|---|---|
| Saury | 11.5 | 26.5 | 25.3 | 61.5 | 10 | 38.2 | 10 | 0.3 | 14.2 | 31.6 |
| Other fish | 10.3 | 8.0 | 31.6 | 16.9 | 80 | 18.0 | 65 | 14.8 | 46.7 | 14.4 |
| Cephalopods | 28.7 | 62.1 | 53.1 | 11.3 | 70 | 20.1 | 75 | 59.1 | 56.7 | 38.2 |
| Crustacea | 5.7 | 1.2 | 41.7 | 6.5 | 60 | 16.7 | 60 | 19.5 | 41.8 | 11.0 |
| Others and Unidentifed | — | 2.1 | — | 3.8 | 35 | 7.0 | 25 | 6.3 | — | 4.8 |

[a] Iverson (1962) $n = 87$; mean volume = 9.8 mL.
[b] Iverson (1962) $n = 79$; mean volume = 15.1 mL.
[c] Laurs and Nishimoto (1973) $n = 33$; mean volume = 16.3 mL.
[d] Nishimoto and Laurs (1974) $n = 75$; mean volume = 13.3 mL.

Because of their large size, saury, which occurred in only about 14 percent of the stomachs examined, composed nearly 32 percent of the biomass of food found in the stomachs.

The number of albacore stomachs that were examined in the investigations discussed above was relatively small, and care must be exercised in drawing conclusions concerning the feeding habits of albacore in the transition zone waters. However, some trends are evident and it is possible to make tentative comparisons with the results of investigations of feeding habits of albacore caught in waters closer to shore in the California Current (McHugh, 1952; Pinkas et al. 1971; Bernard et al. 1985). Larval fishes from several families, juvenile lanternfishes, and often times small-eye squaretail (*Tetragonurus cuvieri*), carangid fishes, and amphipods are more important in the diet of albacore in the offshore transition zone waters than in those caught closer to shore in the California Current. In the latter region, saury or anchovy (or both) and euphausiids or sergestid shrimps are generally more important. Squids are important in both regions, but the species composition is different. While the composition of the food in the stomachs is different between inshore and offshore, the average volume of food in stomachs from the two regions is similar. For example, in an examination of 262 stomachs of albacore caught by trolling in waters along the Pacific coast of the United States within a few hundred miles of shore, the volume of food averaged 15.0 mL displacement volume per stomach (Laurs and Nishimoto, in prep.). This compares with displacement volumes ranging between 13.3 mL and 16.3 mL for albacore caught by trolling in the Transition Zone (Table 2).

## North Pacific Albacore in Relation to Transition Zone Oceanography

North Pacific transition zone waters lie between the cool, low salinity Pacific Subarctic waters to the north and the warm, saline North Pacific Central waters to the south and have temperatures and salinities characteristic of a mixture of these two water masses (Sverdrup et al. 1942). Transition zone waters are found in a band across the North Pacific middle latitudes within the North Pacific Current and are bounded by sharp discontinuities in temperature and salinity at the surface, extending to depths of about the halocline (McGary and Stroup 1956; Roden 1975; and Lynn 1986). These bounding gradient regions are often times referred to as the subarctic front at the north and the subtropical front at the south (Fig. 1), and each may comprise a complex series of fronts. The dynamic processes which produce and maintain these gradients also enrich these waters (McGary and Stroup 1956).

The association of albacore with transition zone waters in the central North Pacific was initially suggested by Shomura and Otsu (1956), Graham (1957) and McGary et al. (1961). These authors reported on the results of a two-year program, 1954 and 1955, in which a series of eight exploratory fishing surveys in various seasons and three oceanographic surveys were conducted in the central temperate North Pacific. The fishing methods used were longlining, trolling, and a brief experiment with gill netting. Although catches were small, there was a clear association with the oceanographic regime of the transition zone and a significant latitudinal shift with season.

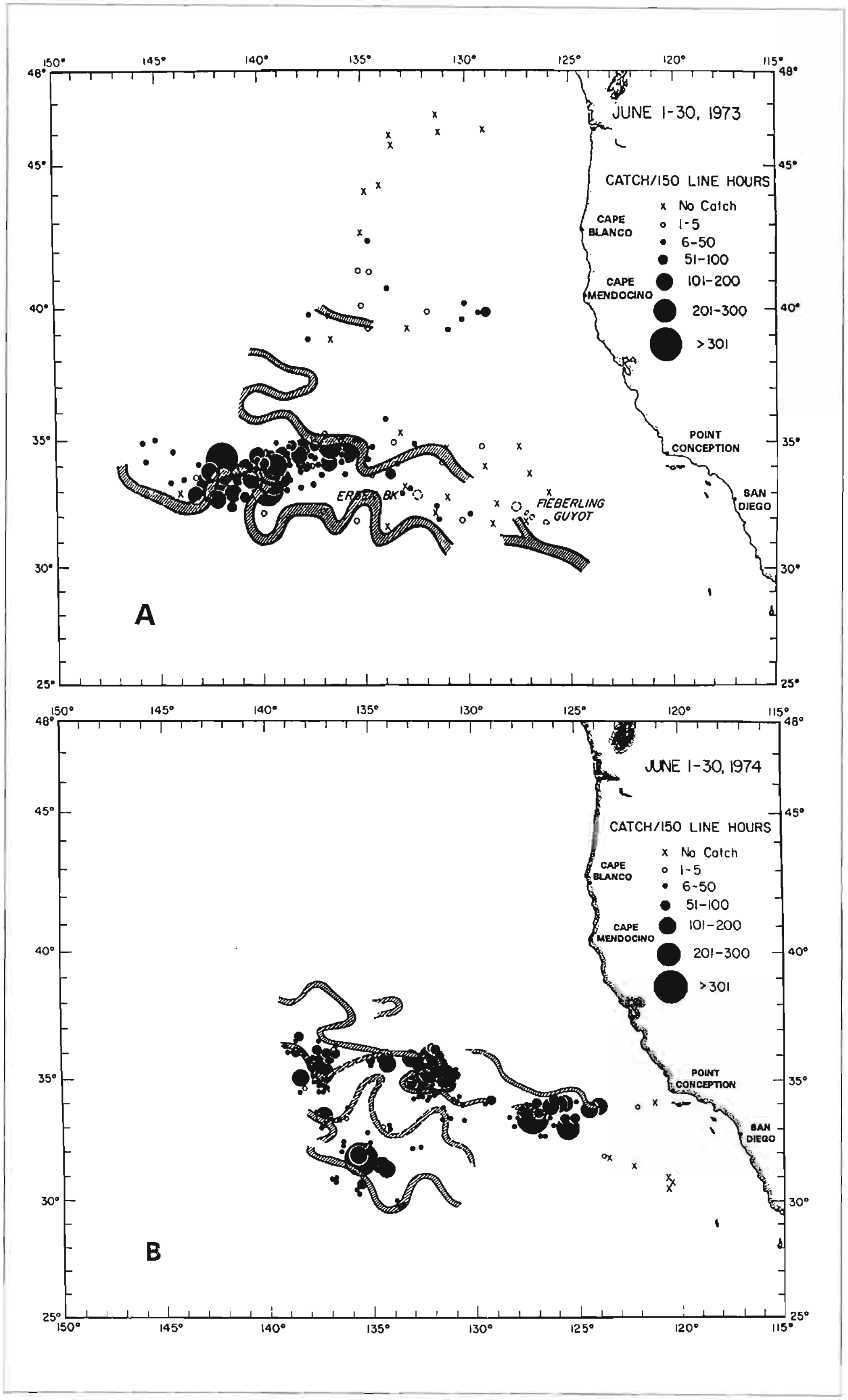

**Figure 7**

**(A)** Jig-boat catches of albacore and oceanic fronts for June 1973 (from Laurs and Lynn 1977). **(B)** Jig-boat catches of albacore and oceanic fronts for June 1974 (from Laurs and Lynn 1977).

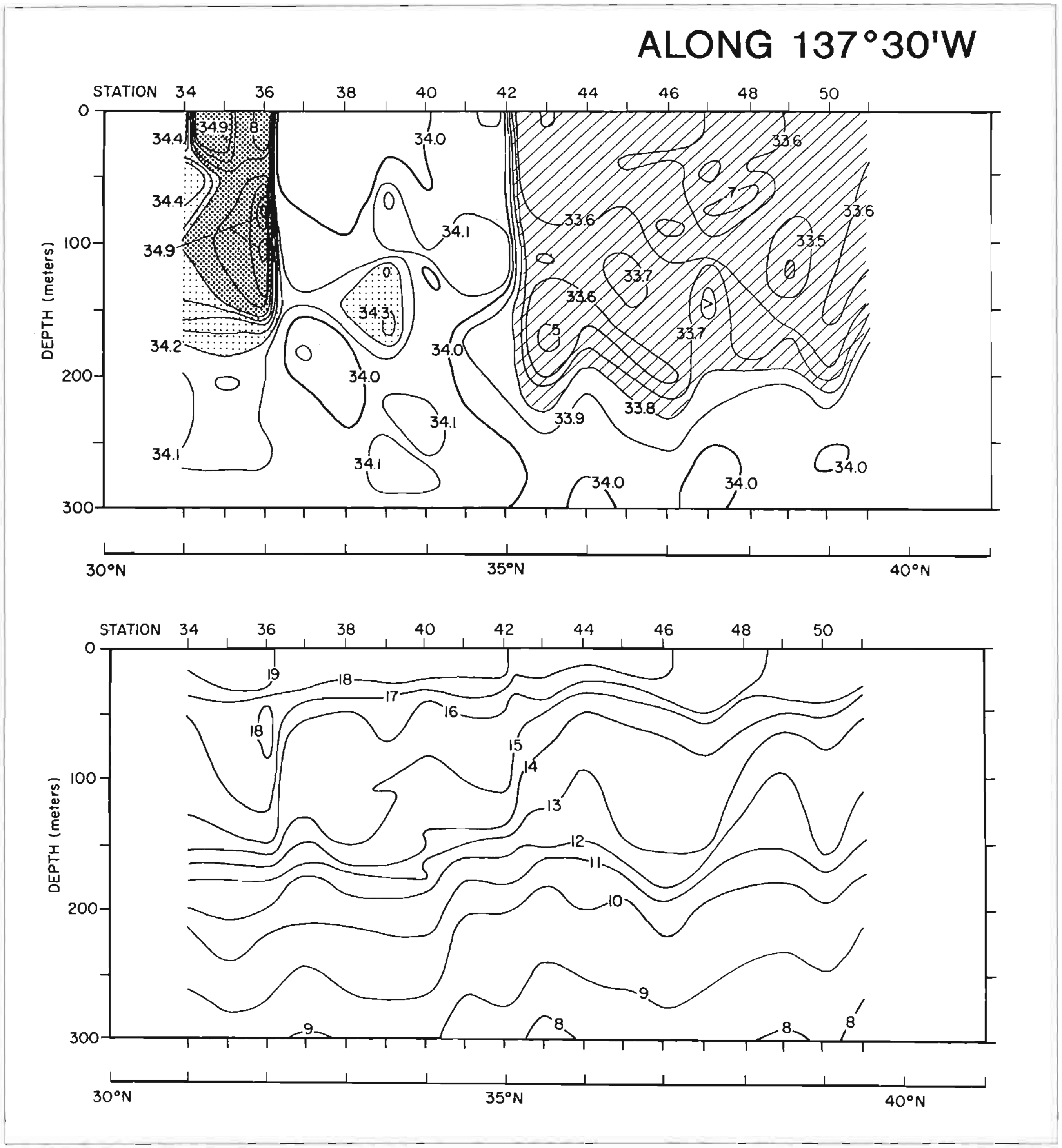

Figure 8
Vertical sections of temperature and salinity along 137°30' W for June 1973 (from Lynn 1986).

Based on extensive oceanographic sampling and concurrent albacore fishery data in the eastern North Pacific, Laurs and Lynn (1977) demonstrated that the distribution, relative abundance, and seasonal migration of albacore in the eastern Pacific are related to the transition zone waters. In a series of late spring surveys conducted in 1972 through 1976, albacore were caught by chartered commercial fishing boats, while a research vessel made detailed oceanographic measurements. The summaries of re-

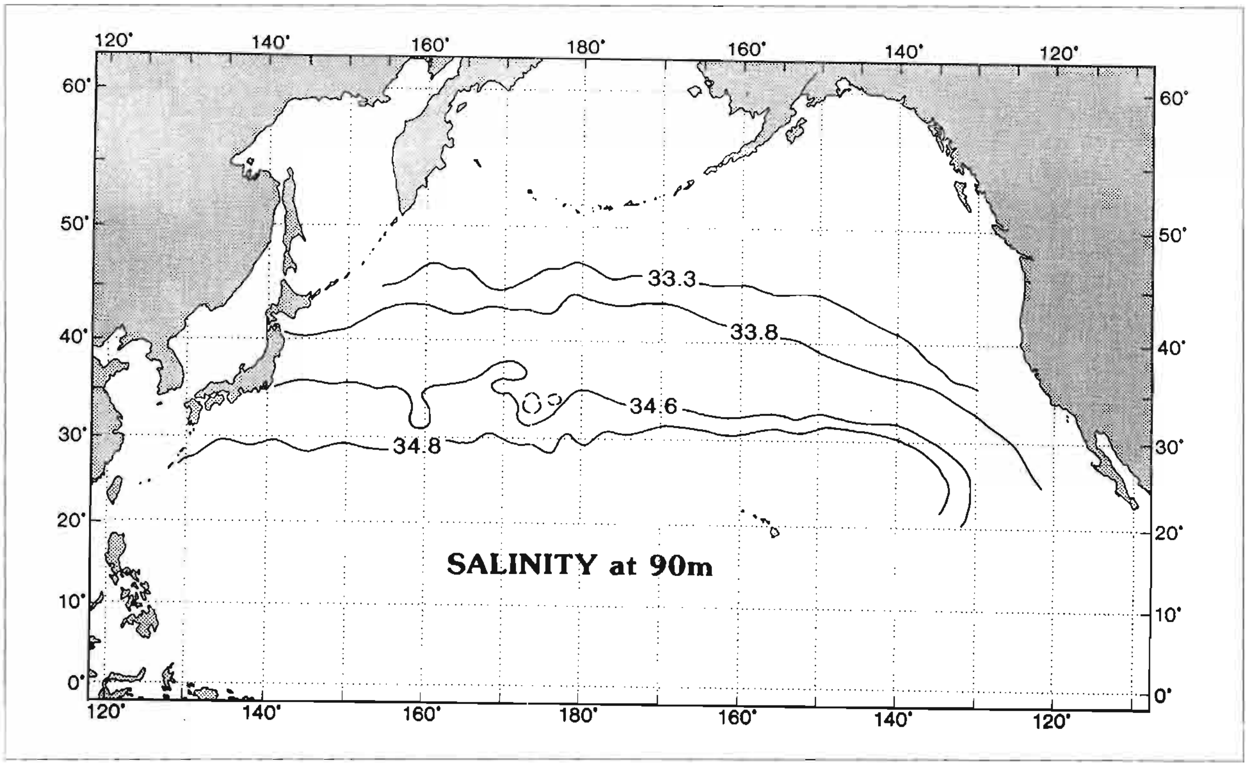

**Figure 9**
Selected isolines of the salinity distribution at 300 feet (90 meters) (from Robinson 1976).

sults for June 1973 and June 1974 are given in Figure 7, A and B. The shaded bands indicate oceanic fronts in plan view, at which there were strong horizontal gradients of temperature and salinity. The solid circles show albacore daily catch rates, using a scale given in the legend. There was a well-defined relationship between high albacore catch rates and fronts. In 1973 the fronts were strong and catches were confined between them. In 1974 the fronts were weak and diffuse, and catches were spread over a greater region and showed considerable movement over short periods during the month. Despite the weaker development of the ocean fronts, there was still a clear association of albacore with the fronts.

Vertical sections of salinity and temperature along a meridian for 1973 show the water masses and the fronts that define their boundaries (Fig. 8). The definition is clearest in the salinity structure. Water having its source in the subarctic is low in salinity (hatched) and that from the subtropics is high in salinity (shaded). Although there is a great deal of variability, these fronts are semi-permanent and quasi-continuous across the North Pacific. Specific isohalines are traditionally associated with each front (e.g., Roden 1980; Lynn 1986). The average salinity: contours at 90 m (Robinson 1976) for the North Pacific are roughly zonal (Fig. 9) and show some curvature similar to the large-scale pattern of the North Pacific current field. The 33.8 isohaline is found in the subarctic front. The 34.6 isohaline is located in the Kuroshio Extension front and in the northern subtropical front in the eastern North Pacific. The 34.8 isohaline is situated in the subtropical front. The meanders in the 34.6 isohaline coincide with major bathymetric features, the Shatsky Rise, the Emperor Seamounts, and the Hess Rise (Fig. 10), showing the strong influence that these major features have upon surface currents and distributions (*see* Roden and Taft 1985). The schematic of the frontal system in the temperate zone (Fig. 1) was drawn using this smoothed version of salinity and a large number of specific observations of fronts from research cruises (most conducted by the International North Pacific Fisheries Commission, the University of Washington [G. Roden] and the Southwest Fisheries Center). This is not unlike a similar schematic developed by Roden (1975). It does, however, add the northern subtropical front first identified by Lynn (1986). For a major portion of the year, these fronts apparently are an important mechanism for increasing biological productivity in the central portions of the North Pacific Ocean, which lead to higher levels of forage organisms for albacore.

At any particular time and place, the fronts associated with the transition zone may have large

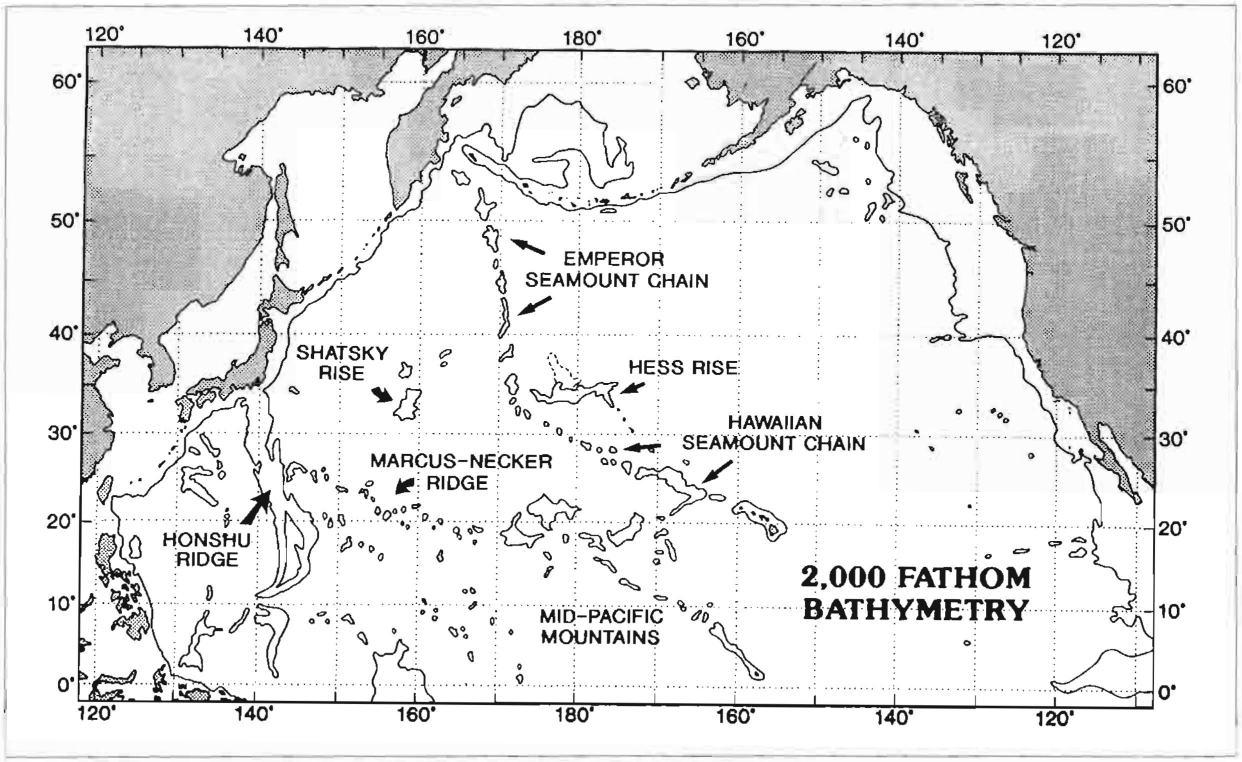

Figure 10
Bathymetric features of the North Pacific as given by the 2000 fathom isobath.

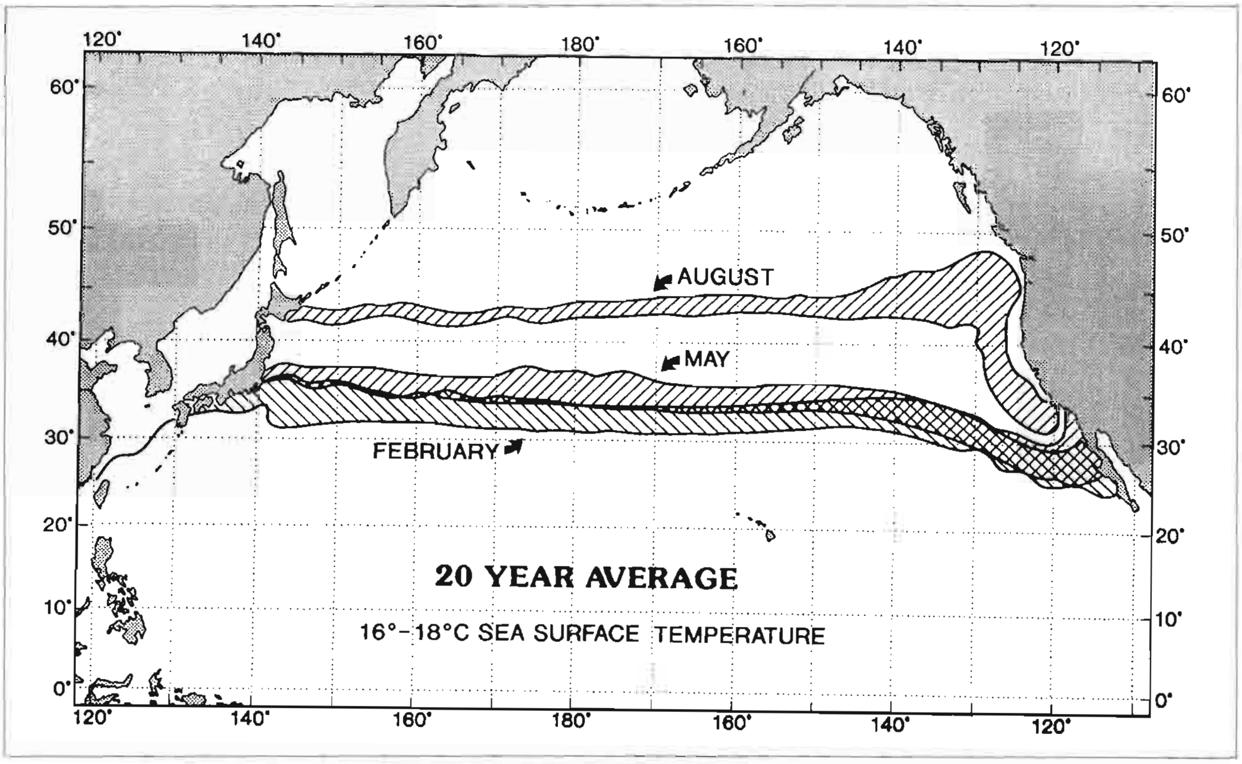

Figure 11
Distribution of the 20-year average sea surface bands of temperature between 16 and 18° C for February, May, and August.

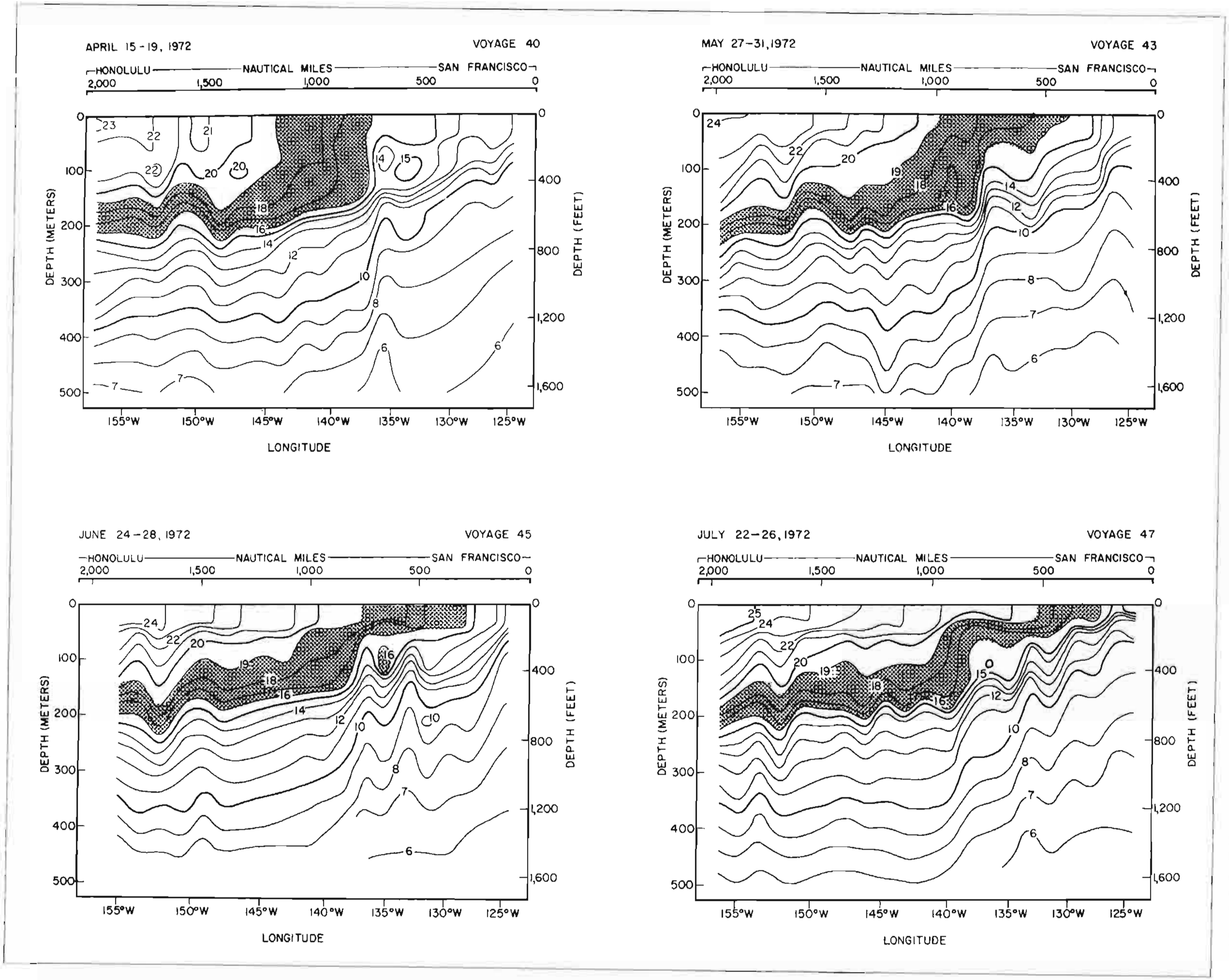

**Figure 12**

Vertical sections of temperature for a great circle path between Honolulu and San Francisco for four periods between April and July 1972.

meanders, be split into multiple fronts, or be dissipated. The schematic in Figure 1 is meant to describe a base pattern that may not be evident at the surface at all times, but likely can be found in the upper 100 or so meters. The surface mixed layer undergoes strong seasonal changes in temperature. In particular, during late summer and fall the surface may not reflect the deeper frontal structure. During winter, cooling and deep mixing reestablish the fronts in the surface layer.

Peak catches of albacore in the U.S. surface fisheries generally occur where SSTs are between 16° and 19° C (Clemens 1961). Plots of surface temperatures within this latter temperature range for February, May, and August show the seasonal progression of warming (Fig. 11). In some seasons and some regions this temperature range coincides with the oceanic fronts; in other seasons and regions they are greatly separated. For instance, in the western Pacific in May, the temperature range coincides with the Kuroshio Extension front and, in the eastern Pacific during summer, it falls well to the north and east of the fronts associated with the transition zone.

The seasonal warming of the surface layer and the development of the summer thermocline is shown in a series of panels of temperature versus depth along a great circle route between Honolulu and San Francisco for April through July, 1972 (Fig. 12); temperatures between 16° and 19° C are shaded. In April there is a deep mixed layer and winter thermocline. The surface warming indicated in the subsequent panels, forms a shallow surface layer in which the waters characteristic of albacore surface fisheries advance toward the California coast. This development is coincident with the local development of the U. S. troll fishery.

## Catches and Ocean Features

The center of the largest catches by the Japanese longline fishery based on 5° square data summaries falls in a band of latitude between 25° and 35° N, and extends from Japan to the dateline (Fig. 2A). A second band is found north of Hawaii between 30° and 35° N. The largest catches are coincident with the estimated mean position of the subtropical front, 30° to 31° N (Fig. 1). Winter surface temperatures at these locations are higher than 15° C; hence, a layer of water that has temperatures that include the upper end of the "favored" range lies above the deep winter themocline (Fig. 12). The zonal division in longline catches in the area located at 170°W to 180°, appears well documented in the data records. It appears to be related to a downstream effect of major bathymetric features (Fig. 10) upon the current field and oceanic structure. This division in catches may offer an explanation for the development of subgroups of North Pacific albacore. If large-scale oceanic structure divides the wintering habitat, separate migration paths and related consequences may be the result.

The center of the largest catches of the Japanese pole and line fishery progresses from near the coast of Japan during April to 175° E by June (Fig. 2A). The large catch nucleus is found within the Kurshio extension front (Fig. 1) and follows the northward advance of warming, which forms a shallow surface layer over the transition zone waters north of the Kuroshio front (Fig. 11). The core of high catches near 170° E is probably related to events controlled by the bathymetry of the rises and seamounts.

The U.S. jig surface fishery starts in May near the Hess Rise, centered at about 180° and 35° N (Fig 2A). The appropriate surface temperatures coincide with the northern subtropical front, or eastward continuation of the Kuroshio extension front. Subsequently, the surface warming and the fishery shift northward as the migration of albacore continues eastward. By July the seasonal warming creates favorable temperatures north and east of the subarctic front. A fishery subsequently develops offshore of coastal upwelling regions off the coast of North America.

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# Zonal Variability in Salmonid Driftnet Catch Rates in the Central North Pacific Ocean

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## ABSTRACT

Data from 17 Canadian, Japanese, Taiwanese, and Republic of Korea research vessel cruises conducted between 1983 and 1987 were examined for salmonid catches along the northernmost one-half degree latitude of the Japanese squid-driftnet fishing area. A total of 325 salmon (*Oncorhynchus* spp.) and 2 steelhead trout *(O. mykiss)* were caught in 11 of 30 driftnet operations, resulting in an overall catch of 0.127 salmonids per 50 m (tan) of driftnet. Chum *(O. keta)* and coho *(O. kisutch)* salmon composed 60% and 34%, respectively, of the total salmonid catch. The proportion of sets west of 175° W encountering salmon was 53%, compared to 9% east of 175° W longitude. Catch per tan in the western and eastern regions was 0.168 and 0.006, respectively, a 28-fold difference between regions. When the data were stratified further by sea surface temperature interval, the zonal cline in salmonid catch rates persisted.

## Introduction

In the early 1980s, the Government of Japan established regulatory measures for their flying squid *(Ommastrephes bartrami)* driftnet fishery in the central North Pacific Ocean. These measures provided a fishing season extending from June through December and restricted vessel operations between 145° W and 170° E longitude, north of 20° N latitude and, depending upon the month, south of 40°, 42°, 44°, or 46° N latitude (Fisheries Agency of Japan 1982). The monthly moving northern boundary was set to approximately coincide with the mean monthly position of the 15° C sea surface temperature (SST) isotherm. Such a provision was believed to restrict fishing to areas where salmonid abundance (*Oncorhynchus* spp.) is low, thereby minimizing the impact of this fishery on salmonid stocks. (Takagi 1983).

Several studies have been conducted in recent years to assess the effectiveness of these regulations in minimizing impacts to salmonids. Of primary interest has been the relationship of salmonid catch per unit effort (CPUE) with respect to SST and the distributional overlap of flying squid and salmonids (Takagi 1983; Dahlberg and Sigler 1987; Harris and Kautsky 1987; and Ogura and Takagi 1987). In general, these studies have shown some overlap in salmonid and flying squid distribution, negligible salmonid CPUE in SSTs above 14–15° C, low squid CPUE in SSTs below 12° C, and an encounter rate of flying squid north of the northern boundary of the squid driftnet fishery that is higher than the encounter rate of salmonids south of the boundary. The studies have also included analyses of data from a small number of driftnet operations that have shown salmonid harvest within the squid area to be infrequent and low in magnitude, especially during years when SSTs are warmer than average. Despite the paucity of oservations from the regulatory area, most authors have concluded that the northern boundary is an effective management measure for limiting incidental catches of salmonids (Takagi 1983; Harris and Kautsky 1987; and Ogura and Takagi 1987).

Other studies have analyzed how the oceanographic features characteristic of the northern boundary of the squid regulatory area are potentially associated with salmonid harvest. Burgner et al.

(1982) and Burgner and Meyer (1983) showed that temperatures below 15° C are often found within the squid fishing area during each month of the fishing season. They also noted that the 12° C isotherm extends into the zone during most months of the fishery in cooler years and, more generally, that salmonid interceptions are potentially significant owing to the large variability in SSTs. Ignell (1987) documented the repeated occurrence of cold water incident to the fishing area during recent years and identified the importance of mesoscale variability in SST for introducing cold water (11° C) several degrees south of the northern boundary during some years. Because of interannual variability in oceanographic conditions in this region (Davis 1976), Ignell (1987) concluded that the use of climatological values in the establishment of a squid driftnet regulatory regime should be reexamined and an in-season management system explored.

Additional data from driftnet operations located within the squid regulatory area have been collected in recent years, allowing a direct assessment of the potential for salmonid harvest by driftnet fishermen operating near the northern boundary of the fishery. In this paper, encounter and catch rates are calculated for salmonids from research vessel operations located near the northernmost one-half degree latitude of the northern border. Also, differences between catch rates in the eastern and western portions of the regulatory area are evaluated as a function of SST.

## Methods

Data from 17 research cruises (vessels from Canada, Japan, Taiwan, and the Republic of Korea (ROK) ) conducted between 1983 and 87 were used for the analyses (Table 1). Twenty-seven driftnet operations from the 17 cruises were located within the study area—defined as the northernmost one-half degree latitude of the 1987 Japanese squid regulatory area—and used for the analyses. Three additional operations were included in the analyses because of their close proximity (within 2 minutes of latitude) to the study area.

Most of the research vessels deployed a combination of commercial and research drift net. Commercial drift net was monofilament with stretched mesh sizes of 110–130 mm on the Japanese vessels, 60–120 mm on the Taiwanese vessel, and 115 mm on the Canadian vessel. Research drift net was either monofilament or multifilament, consisting of mesh sizes designed to provide non-selective (i.e., constant catchability) sampling for the target species (Takagi 1975). When catch and effort data from either very small (33 mm) or very large (197 mm) mesh were recorded separately, these data were excluded from analyses because of the greatly reduced catchability of salmonids. Therefore, the stretched mesh sizes of research drift net included in the analyses were 48–157 mm on Japanese vessels, 120–180 mm on the Taiwanese vessel, and 33–115 mm on the ROK vessel. Although length of net per set varied among operations (0.45–7.7 km), most of the 30 sets used about 5 km of drift net for a total deployment of 128.3 km of drift net.

Data were divided into two geographical regions (170° E to 175° W and 145 W to 175° W, hereafter called the western and eastern region, respectively) according to similarity of oceanographic characteristics. Within these two areas, the data were further divided into three SST intervals (<13° C, 13–15° C, and ≥15° C).

**Table 1**

The Canadian, Japanese, Taiwanese, and Republic of Korea (ROK) research vessel cruises that provided data for analyses of salmonid catch as a function of sea surface temperature and geographical area.

| | | Year of cruise | | | | |
|---|---|---|---|---|---|---|
| Nation | Vessel name | 1983 | 1984 | 1985 | 1986 | 1987 |
| Taiwan | *Hai Kung* | | | | x | x |
| ROK | *Pusan 851* | | | | x | x |
| Canada | *Ricker* | | | | | x |
| Japan | *Oshoro Maru* | | x | | x | x |
| Japan | *Hokusei Maru* | x | x | x | x | x |
| Japan | *Iwaki Maru* | | | x | | |
| Japan | *Shoyo Maru* | | | | x | x |
| Japan | *Kuromori Maru 38* | | | | x | |

Average catch rates were computed for each of the six strata. Catch rates were calculated by dividing total number of salmonids caught by total length of drift net deployed.

For each strata, salmonid encounter rates were computed as the proportion of driftnet operations encountering salmonids (hereafter called the uncorrected method). Because this estimate assumes that the probability of salmonid incidence is unrelated to length of drift net deployed, two alternative section-based estimates were developed. 1) Assume that $r$ fish are randomly distributed in a drift net consisting of $n$ driftnet sections (50-m segment) and the probability of finding exactly $m$ cells empty is $p_m(r,n)$. This is a variation of the classical occupancy problem in probability theory (Feller 1968). The expected number of empty cells is (Hamming 1991):

$$E(m) = \Sigma m \cdot p_m (r, n) = \frac{(m-1)^n}{m^{n-1}}$$

where the probability of salmon incidence per net section (hereafter called salmonid incidence) is computed as $1 - E(m) / n$. 2) Let $q$ be the probability that no salmonids are caught in a net section and $x_n$ the total catch in $n$ net sections. If catches in sections are independent,

$$P[X_n = 0] = q^n, \quad P[X_n > 0] = 1 - q^n.$$

Let $x_{n1}{}^{(1)}, x_{n2}{}^{(2)}, \ldots x_{nk}{}^{(K)}$, be the results of $K$ operations in a stratum. Define $Y_k$ as 0 if $X_{nk} = 0$, or 1 if $X_{nk} > 0$; $Z_k$ as 0 if $X_{nk} > 0$, or 1 if $X_{nk} = 0$. Then the likelihood function of $y_1, y_2, \ldots, y_k$ and $z_1, z_2, \ldots, z_k$ is

$$L = \Pi^{K}_{k+1} \, q^{n_k z_k} [1 - q^{n_k}]^{y_k}.$$

The two terms in the likelihood function identify the probability of no catch and positive catch, respectively, in the $k^{\text{th}}$ driftnet operation. Setting the partial derivative of the log-likelihood with respect to $q$ equal to 0, gives

$$\Sigma^{K}_{k=1} n_k z_k - \Sigma^{K}_{k=1} n_k z_k \cdot \frac{q^{n_k}}{1-q^{n_k}} = 0.$$

Solving for $q$ provides a maximum likelihood-based measure of salmonid incidence ($p = 1 - q$) that accounts for differential net lengths between driftnet operations. Computations of maximum likelihood estimates are restricted to three strata as they require both zero and non-zero values of salmonid incidence within a stratum.

For each of the section-based methods, salmonid encounter rate for a 5-km length of net can be computed from the incidence rate as

$$\textit{Encounter Rate} = 1 - (1 - \hat{p})^{100}.$$

## Results

Three hundred twenty-seven salmonids were encountered in 11 of 30 driftnet operations, resulting in an overall catch rate of 0.127 salmonids per 50 m of drift net (*see* Appendix Table). Most of the operations (84%) occurred in sea surface temperatures of 15° C or less. Chum salmon (*O. keta*) and coho salmon (*O. kisutch*) were the predominant species caught, comprising 60% and 34%, respectively, of the total salmonid catch. The remaining salmonid catch consisted of chinook salmon (*O. tshawytscha*), pink salmon (*O. gorbuscha*), and steelhead trout (*O. mykiss*). In the area west of 175° W, almost 88% of the chum were caught during August and September although over 67% of the fishing effort (km) occurred in June and July. Conversely, 99% of the coho were caught during June and July.

Ten of 19 (53%) gillnet operations in the northwestern portion of the squid fishing area encountered salmonids compared to 1 of 11 (9%) operations (uncorrected rates) in the northeastern area. This 5.8-fold difference was only partially explained by a 1.7-fold difference in the average length of drift net deployed between areas (5.06 km per operation in the western area versus 2.92 km per operation in the eastern). Regional differences in uncorrected encounter rates were still prevalent when the data were stratified further by SST interval (Table 2). Encounter rates were consistently higher in the western region: 100% versus 25% in the western and eastern regions, respectively, for driftnet operations in SSTs <13° C; 40% versus 0% in SSTs of 13–15° C; and 25% versus 0% in SSTs ≥15° C.

Encounter rates computed from maximum likelihood-based incidence rates applied to the average length of drift net deployed per strata were similar to those of unweighted operation-based method (Table 2). Encounter rates standardized to a 5-km length drift net were estimated at 38% and 26% for the western region SSTs of 13–15° C and ≥15° C respectively, and 36% for eastern region SSTs of <13° C.

Salmonid encounter rates estimated by the occupancy-based measure, however, were too high in two of four strata. This overage was apparently caused by the effect of heterogeneous incidence rates within a strata, or non-random distribution of catch within a driftnet operation, or both. Occupancy-based encounter rates were independently estimated for each driftnet operation, then averaged across driftnet operations within each strata. Estimates of encounter

**Table 2**

Driftnet catch and effort stratified by region and sea surface temperature (SST) interval. Three estimates of salmonid encounter rates are also presented (*see* text for description of estimates). Data are from research driftnet operations located in the northernmost one-half degree latitude of the Japanese squid driftnet fishing area, 1983–1987.

| | 170° E to 175° W | | | 145° W to 175° W | | |
|---|---|---|---|---|---|---|
| | SST interval (°C) | | | SST interval (°C) | | |
| | <13 | 13–15 | >15 | <13 | 13–15 | >15 |
| **Catch (no.)** | | | | | | |
| Coho | 43 | 171 | 1 | 0 | 0 | 0 |
| Chum | 14 | 67 | 0 | 3 | 0 | 0 |
| All salmonids | 74 | 248 | 1 | 4 | 0 | 0 |
| **Fishing effort** | | | | | | |
| Number of operations | 5 | 10 | 4 | 4 | 5 | 2 |
| Total effort (km) | 22.8 | 54.2 | 19.2 | 12.7 | 17.8 | 1.6 |
| Average effort (km) | 4.6 | 5.4 | 4.6 | 3.2 | 3.6 | 0.8 |
| **Encounter rate (%)** | | | | | | |
| Uncorrected | 100 | 40 | 25 | 25 | 0 | 0 |
| Maximum likelihood | | | | | | |
| (strata average) | | 41 | 25 | 24 | | |
| (standardized—5 km) | | 38 | 26 | 36 | | |
| Occupancy (5 km) | 100 | 100 | 24 | 84 | | |

rates for each strata, therefore, did not minimize between operation error variability (which the maximum likelihood method did minimize). Simulations of alternative occupancy patterns showed this overage could be reduced if fish were distributed contagiously. Such a distribution would mean that the assumption of random occupancy of net sections was not met by the data, and that salmonid incidence estimates based on the occupancy method would be high.

The regional differences in salmonid incidence were reflected in catch rate differences. Catch per tan (50-m panel of drift net) of salmonids, hereafter called CPUE, in the western and eastern regions was 0.168 and 0.006, respectively, representing a 28-fold difference between regions. Salmonid CPUE stratified by SST interval (<13° C, 13–15° C, and >15° C) was 0.162, 0.229, and 0.003 for the western region, and 0.016, 0.0, and 0.0 for the eastern region. In the western region, coho were the dominant species caught when SST was <13° C (CPUE of 0.094 for coho versus 0.031 for chum), whereas chum were the dominant species from 13 to 15° C (CPUE of 0.164 for chum versus 0.062 for coho).

## Discussion

Analyses of 1983–87 Japanese, Taiwanese, Canadian, and ROK research vessel data show a zonal cline in salmonid incidence and catch rates when the data are stratified by SST interval and limited to the northernmost portion of the squid fishing area. Here, at the southernmost limit of salmonid habitat, driftnet operations within a given range of SSTs are more likely to encounter salmonids in the western than in the eastern portion of the fishing area.

Regional differences in salmonid abundance may contribute to the observed geographical variation in catch rates. An analysis of 1955–1960 U.S. research vessel data showed that the abundance of salmon was greatest in the western North Pacific and in the Bering Sea (Manzer et al. 1965). Recent data, although extensive for the western subarctic waters, cover very little of the eastern waters, thereby limiting comparisons of salmonid abundance between these areas.

Because the magnitude of regional differences in catch rates is so great, the small number of driftnet operations used in these analyses (and possible sampling biases) add variability to the 1983–87 data but do not likely affect the conclusions. Any sampling bias in the data probably reduces, rather than increases, catch rate differences. Sampling dates in the western region occurred mostly towards the end of the month. This sampling bias, however, is not apparent in the eastern region. Because salmonid harvest within the squid fishing area is most probable during the first several days of each summer month (Ignell 1987), catch rates for the western region are likely biased downwards when compared to eastern catch rates.

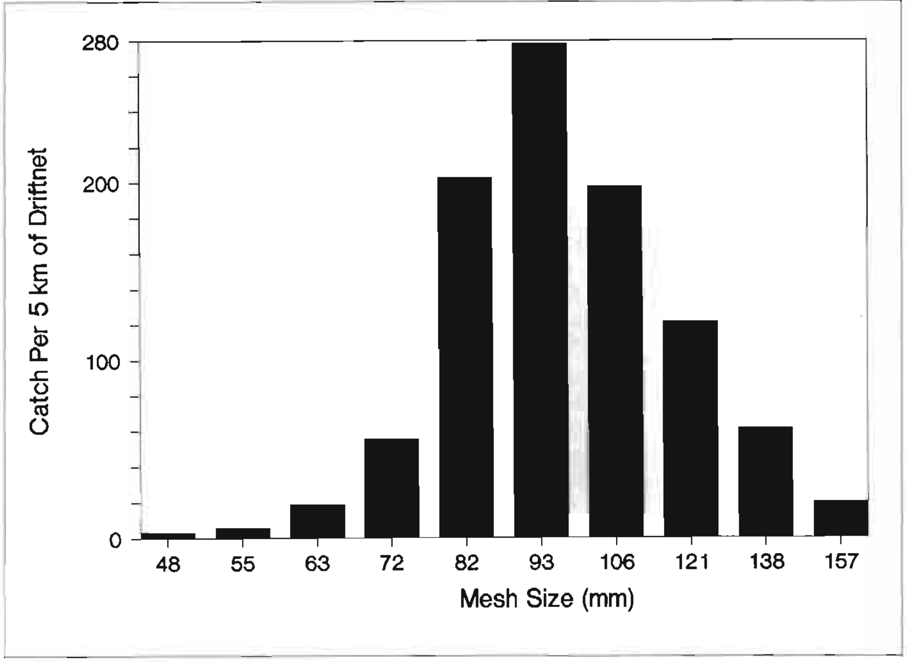

**Figure 1**
Frequency distribution of the number of salmonids caught per 5 km of driftnet effort, stratified by the stretched mesh size of the drift net. Data from the Japanese RV *Hokusei Maru,* 1983–1987 cruises.

Differences in average mesh size between research vessel cruises also cannot explain geographical differences in catch rates. Vessels operating in the western area with mesh sizes ≥105 mm encountered salmonids much more frequently than vessels operating in the eastern area with smaller mesh sizes <105 mm. The opposite would be expected based on Japanese research vessel data that show CPUE is largest for mesh sizes of 93 mm (Fig. 1).

Geographical differences in the CPUE/SST relationship may be explained by physical oceanographic differences between the two regions because water-mass structure is an important factor affecting the ocean distribution of salmonids (Favorite and Hanavan 1963; Murata 1987). Although SST isotherms are almost strictly zonal across the North Pacific Ocean, the subarctic frontal zone angles northward 4° to 6° of latitude to the east (Levine and White 1981). Because of this northward angling, subarctic water intrusions, as defined by the subsurface thermohaline structure, are less likely to occur in the eastern portion. As a result, salmonid catch rates in the eastern region are reduced compared to the western region where intrusions of subarctic water are more frequent.

The salmonid incidence data show that there is a high probability of salmonid harvest (primarily chum and coho salmon) when SSTs are <13° C, and very low incidence when SSTs are ≥15° C. These results generally reflect those of Ogura and Takagi (1987): waters inhabited by chum and coho salmon usually have SSTs <13° C; however, their catch rates were several times that of data from the western region and approximately an order of magnitude greater than the eastern region. For instance, catch per tan of chum salmon in the western squid regulatory area was 0.03 and 0.14 (for SSTs of 10.5–13° C and 13–15° C), respectively, as compared to Ogura and Takagi's (1987) estimate of about 0.5 for driftnet operations in SSTs of 11–12.9° C. Catch per tan for coho salmon were less disparate between the two data sets, ranging between 0.2 to 0.4 for SSTs of 11–12.9° C (Ogura and Takagi 1987) as compared to 0.12 in my analysis.

Although catch rates presented in this paper are imprecise owing to a limited number of observations, the large differences in catch rates between the two data sets are likely real and may stem from geographical differences. Ogura and Takagi's (1987) data were obtained throughout a broad portion of the North Pacific Ocean, whereas data used in the present study were constrained to operations within the Japanese squid regulatory area. Thus, although neither data set associated catch data with water-mass type (subarctic domain versus subarctic frontal zone), the proportion of driftnet operations in subarctic water is probably highest for Ogura and Takagi's (1987) data.

The above sampling differences are important because marine organisms are distributed according to environmental conditions needed for successful development (Uda 1961). In the epipelagic marine community of the North Pacific Ocean, these environmental conditions are characterized in terms of water-mass properties (rather than SST) which reflect the oceanographic characteristics important to the species complex of a particular region (Shimazaki 1986). Salmon are part of the fish community associated with subarctic water; they are seldom found south of subarctic waters and then only within the northern portion of the subarctic frontal zone (Shimazaki 1986; Murata 1987). Thus, catch rates from driftnet operations located in subarctic waters should exceed those from driftnet operations located within the subarctic frontal zone, even if SSTs are similar between areas.

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## Appendix Table

Salmonid catch data from 30 research vessel operations located near the northernmost one-half degree latitude of the Japanese squid driftnet regulatory area, 1983–87.[a]

| Vessel | Date | Lat. | Long. | SST | Tans of net | | Avg. mesh size (mm) | Net lgth. (km) | Catch in numbers | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Comm.[b] | Res.[c] | | | Chum | Coho | Pink | Chinook | Trout | Total |
| *Hokusei Maru* | 7-22-83 | 41°31′N | 170°01′E | 11.0 | 80 | 30 | 110 | 5.5 | 5 | 6 | | | | 11 |
| | 7-29-83 | 41°32′N | 175°33′E | 13.5 | 80 | 30 | 110 | 5.5 | | | | | | |
| | 7-21-84 | 41°30′N | 170°00′E | 15.0 | 80 | 30 | 110 | 5.5 | | | | | | |
| | 7-27-84 | 41°29′N | 175°45′E | 14.4 | 80 | 30 | 110 | 5.5 | | | | | | |
| | 7-21-85 | 41°31′N | 170°02′E | 15.0 | 80 | 30 | 110 | 5.5 | | 1 | | | | 1 |
| | 7-27-85 | 41°29′N | 175°27′E | 15.7 | 80 | 30 | 110 | 5.5 | | | | | | |
| | 7-28-86 | 41°30′N | 175°55′E | 16.0 | 70 | 30 | 110 | 5.0 | | | | | | |
| | 7-28-87 | 41°31′N | 174°59′E | 14.5 | 50 | 30 | 108 | 4.0 | | | | | | |
| *Oshoro Maru* | 6-13-84 | 39°30′N | 180°00′ | 11.1 | 48 | 30 | 107 | 3.9 | | 14 | | | | 14 |
| | 6-16-86 | 40°00′N | 179°59′W | 14.8 | 60 | 40 | 111 | 5.0 | 14 | 65 | | | | 79 |
| | 6-14-87 | 40°02′N | 180°00′ | 16.7 | 50 | 40 | 108 | 4.5 | | 1 | | | | 1 |
| *Iwaki Maru* | 7-13-85 | 41°58′N | 172°10′E | 10.7 | 102 | 30 | 108 | 6.6 | 1 | 23 | 17 | | | 41 |
| *Kuromori Maru 38* | 7-20-86 | 41°30′N | 180°00′ | 13.0[d] | 34 | 50 | 100 | 4.2 | | | | | | |
| | 8-27-86 | 43°30′N | 175°00′E | 16.0[d] | 34 | 50 | 100 | 4.2 | | | | | | |
| *Shoyo Maru* | 7-15-86 | 42°00′N | 150°00′W | 14.5[d] | 34 | 50 | 100 | 4.2 | | | | | | |
| | 8-14-86 | 44°00′N | 165°00′W | 14.0[d] | 34 | 50 | 100 | 4.2 | | | | | | |
| | 7-11-87 | 42°00′N | 150°00′W | 11.7 | 34 | 50 | 100 | 4.2 | | | | | | |
| *Hai Kung* | 8-05-86 | 44°00′N | 173°00′E | 14.6 | 171 | | 99 | 5.6 | 40 | 1 | | | | 41 |
| | 8-13-86 | 44°00′N | 177°00′W | 14.8 | 172 | | 97 | 5.7 | | | | | | |
| | 9-14-86 | 46°00′N | 175°00′W | 13.1 | 198 | 36 | 107 | 7.7 | | | | | | |
| | 9-18-86 | 46°00′N | 171°00′E | 13.2 | 198 | 36 | 107 | 7.7 | 124 | | | 2 | 1 | 127 |
| | 8-14-87 | 43°59′N | 176°46′W | 11.7 | 150 | | 102 | 5.4 | 5 | | | | | 5 |
| *Pusan 851* | 7-26-86 | 41°58′N | 170°00′W | 14.9 | | 10 | 96 | 0.5 | | | | | | |
| | 7-28-86 | 41°30′N | 172°00′W | 16.0 | | 16 | 94 | 0.8 | | | | | | |
| | 7-31-86 | 42°00′N | 175°00′W | 17.5 | | 16 | 94 | 0.8 | | | | | | |
| | 7-28-87 | 42°00′N | 170°00′W | 14.0 | | 23 | 79 | 1.2 | | | | | | |
| | 8-06-87 | 44°00′N | 178°40′E | 11.9 | | 27 | 74 | 1.4 | 3 | | | | | 3 |
| *Ricker* | 6-04-87 | 39°38′N | 161°04′W | 11.9 | 54 | | 115 | 2.6 | 3 | | | | 1 | 4 |
| | 6-23-87 | 39°41′N | 160°37′W | 11.7 | 62 | | 115 | 3.0 | | | | | | |
| | 6-25-87 | 39°48′N | 157°25′W | 11.7 | 60 | | 115 | 2.9 | | | | | | |
| | | | | | | | | Total: | 195 | 111 | 17 | 2 | 2 | 327 |

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[a] Source: Data record of Oceanographic Observations and Exploratory Fishing, The Faculty of Fisheries, Hokkaido University, Nos. 27, 28, 29, 30, and 31; Murata (1987); Technical Report of National Fisheries Research and Development Agency, Pusan, Republic of Korea (ROK), Nos. 68, 76; Cruise Report of the RV *Hai Kung*, HK-1986, HK-1987, Taiwan Fisheries Research Institute, Keelung, Taiwan, Republic of China; Lebrasseur et al., (1987); Cruise Report of the *Shoyo Maru* in the central North Pacific Ocean, 26 June through 28 August 1987 by Michael Johnson, U.S. Dep. of Commerce, National Marine Fisheries Service, National Marine Mammal Laboratory, Seattle, Washington.

[b] Mesh sizes varied by research vessel; Japanese commercial mesh sizes were 110–130 mm, Taiwanese commercial mesh sizes were 60–135 mm, and Canadian commercial mesh sizes were 115 mm.

[c] Only includes "C" type net for Japanese operations (48–157 mm). Mesh sizes for Taiwanese research drift net ranged from 120–180 mm, and for ROK research drift net, from 33–115 mm.

[d] SST data interpolated from contour plot.

# The Fisheries for Neon Flying Squid (*Ommastrephes Bartrami*) in the Central North Pacific Ocean

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## ABSTRACT

During the 1970s, the increased exploitation of squid stocks near Japan and reduced harvest opportunities or poor market conditions affecting other distant-water fisheries led Japan, Taiwan, and the Republic of Korea to fish the neon flying squid *(Ommastrephes bartrami),* an under-utilized food species abundant across the North Pacific Ocean. Japanese jigging vessels pioneered the fishery in 1974, but were displaced by the more efficient driftnet vessels of Japan in 1978, the Republic of Korea in 1979, and Taiwan in 1980. Each year, over 750 driftnet vessels fish from April to December. Each vessel deploys up to 60 km of drift net nightly. Vessels fish independently or within a multi-vessel array where nets are set along an east-west direction and are spaced 2–4 km apart along a north-south axis. Total catch ranges from 200,000 to 300,000 t. In recent years, vessel numbers have stabilized or, in the case of the Japanese fleet, have decreased. Annual effort (i.e., the total amount of drift net deployed annually), however, has increased owing to increased vessel sizes, length of drift net deployed, and fishing season. As a result, catch per vessel day has remained constant or increased in recent years, while catch per unit length of net has decreased in the Taiwanese and Republic of Korea fisheries. The squid are processed by separating the mantle from the head; mantles are frozen. Some incidentally caught species (such as tuna, billfish, yellowtail, and pomfret) are also retained and processed. Japanese vessels fish under a complex set of fishery regulations designed to, *inter alia,* limit competition with jigging vessels in the western Pacific, limit total fishing effort, and minimize the incidental (and prohibited) catch of salmonids. Korean and Taiwanese vessels are less regulated and primarily fish west of the Japanese driftnet fleet.

## Introduction

The neon flying squid *(Ommastrephes bartrami)* driftnet fisheries of Japan, Taiwan, and the Republic of Korea (ROK) in the North Pacific Ocean are in combination the largest of the pelagic driftnet fisheries. Each year, over 750 driftnet vessels fish from April to December. Each of these vessels deploys up to 60 km of drift net nightly at speeds of about 10 knots, retrieving the gear at speeds up to 5 knots. Their efficiency has created financial difficulties for vessels using more traditional and less efficient harvesting methods such as jigging (Araya 1983); however, it has enabled the profitable exploitation of an important and previously under-utilized food species.

Drift nets, although highly efficient harvesting devices, do not discriminate well between species. Most non-target species too large to pass through the mesh are entangled and killed or drop out before being brought aboard, creating waste and potential economic loss (Major 1982). Though of little commercial value, some of these species are major components in the North Pacific Transition Zone ecosystem (Shimazaki 1986), and/or have cultural value (e.g. marine mammals, seabirds, and some fishes).

These factors have led in recent years to increased concern about the possible impact of incidental catches by squid driftnet fisheries on North Pacific Ocean marine resources (Eisenbud 1985). Incomplete information about fishery impacts has increased this concern. Although 11 years have passed since the inception of the fisheries, estimates of the magnitude of incidental take are still difficult to obtain. The dynamics of the fisheries (e.g., amount of gear deployed) are also not well known.

In particular, there is difficulty in defining a unit of fishing effort. Fishing effort is reported three ways: number of vessels fishing, days fished, or the number of units of gear fished. These three effort measures, however, have not been available for each fishery, and may not be reported consistently within a fishery or among fisheries (e.g., one unit of effort may be 50 m of drift net for the ROK fishery, but 42 to 105 m for the Japanese fishery [Ignell et al. 1986]). As a result, calculations of catch per unit effort (CPUE) depend upon the type of effort measure used, and may not be comparable between fisheries.

This paper provides a summary of the North Pacific squid driftnet fisheries of Japan, the ROK, and Taiwan as of 1989. The following sections on each of these national fisheries cover fishery development, characteristics, and regulations; gear and vessel characteristics; and fishing methods. The last section is devoted to an overview of the fisheries, including a discussion of recommended catch levels for flying squid given historic catch and effort.

## Japanese Squid Driftnet Fishery

Squid have long been important to the economy and diet of the Japanese. Dried squid was a major trade item as early as the 1600s, becoming even more important in 1864 when Chinese markets opened to this product (Osako and Murata 1983).

After World War II, high unemployment, low labor cost (due to Japanese troops returning home), and a food supply shortage resulted in a great expansion of the fishery for the Japanese common squid (*Todarodes pacificus*); little capital was needed for its growth compared with other industries (Court 1980; Osako and Murata 1983). Catches of common squid rose rapidly, from about 100,000 t in 1945 to over 500,000 t in 1951. The catches were of the winter group (common squid are divided into three groups according to spawning time: winter, summer, and autumn), which had the largest biomass and was primarily caught along the Pacific coast of Japan.

Until the late 1950s, most squid were caught by hand with jigging gear. With the development of automatic jigging machines and fishing lamps, fishing power increased dramatically (Osako and Murata 1983). After a record catch of 670,000 t in 1968, winter group catches fell to below 10,000 t by 1976. This decrease prompted the exploitation of the autumn group on new, offshore, fishing grounds during the early 1970s (Chikuni 1985). These grounds, primarily in the Sea of Japan, immediately suffered heavy exploitation, and catches decreased after only a few years of fishing (Okutani 1977).

As fishing grounds shifted offshore, fishing vessels became motorized and the number of large vessels increased. The emergence of large jigging vessels and the subsequent decline in common squid prompted fishermen in 1974 to target neon flying squid (hereafter called flying squid) in the northwest Pacific Ocean east of Hokkaido and northeast of Honshu (Osaka and Murata 1983).

Driftnet vessels first began fishing for flying squid in September 1978. Over 170 Japanese salmon driftnet vessels (displaced from their traditional salmon fishing grounds owing to reduced harvest quotas in 1978) were the first to use drift nets for flying squid (Herrfurth 1988), but were soon followed by many squid boats (Court 1980). A classic example of gear conflict developed. Jigging proponents argued that their established, economically-dependent fishery gave them a historic right to the flying squid resource. Furthermore, they opposed driftnetting because it was too efficient (2–4 times more than jigging [Araya 1983]), was wasteful because of dropouts, created conservation problems, and was often used as a cover for illegal salmon (*Oncorhynchus* spp.) fishing (Court 1980).

### Fishing Regulations

On 1 January 1979, the Fisheries Agency of Japan (FAJ) addressed this conflict by prohibiting driftnets west of 170°E, south of 20°N (the area fished by jigging vessels). Continued financial losses by jigging vessels—in part due to competition from the large number (up to 1000) of Japanese driftnet vessels (Court 1981)—resulted in the 1981 limited-entry program. This program established regulatory measures to minimize the incidental catch of salmonids (Court 1981). These regulations as outlined in FAJ (1982) set a 7-month fishing season from June through December, a northern boundary designed to avoid the incidental catch of salmonids, and an eastern boundary at 145°W (Fig. 1). The northern boundary was set to coincide approximately with the long-term monthly average of the 15°C surface isotherm (INPFC 1982), and to change monthly.

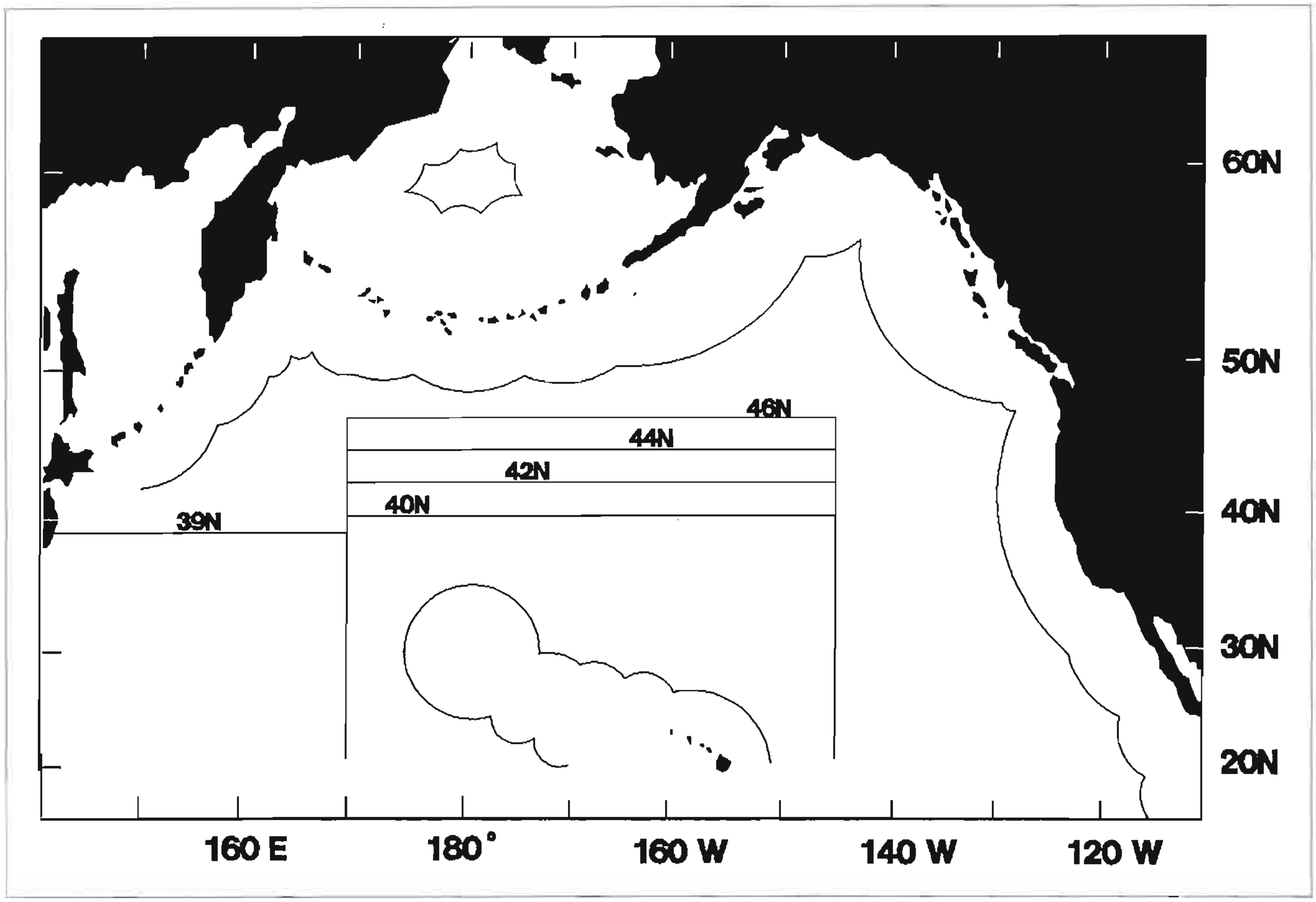

Figure 1
Time and area regulations for the Japanese and Taiwanese squid driftnet fisheries in the north Pacific Ocean (Fisheries Agency of Japan 1985b). For both fleets, fishing is prohibited east of 145°W, and north of 40°N in June and December, 42°N in July and November, 44°N in August and October, and 46°N in September. For Japanese vessels, fishing is prohibited west of 170°E, and for Taiwanese vessels, north of 39°N and west of 170°E.

Japanese scientists felt this regulation would enable the squid driftnet fishery to avoid incidentally catching salmon (Takagi 1983).

Under the limited entry established by the FAJ, two types of permits for vessels between 50 and 500 gt are issued, one allowing 7 months of operation (1 June to 31 December), the other, 4 months (1 August to 30 November). Other regulations require net mesh sizes between 100 and 135 mm to conserve squid resources, submission of a catch-and-operation report by vessel operators after a fishing trip, special identification coloring and permit display on the vessels, non-retention of salmonids, and a limit of three ports per vessel for landing catch. Fishing vessels are also required to notify the FAJ when approaching and leaving the fishing grounds at 170°E. When navigation beyond the northern and eastern boundary is unavoidable, fishermen are required to report the estimated course and itinerary one day in advance.

## Fishery Characteristics

Japan's annual catch of flying squid by the driftnet fishery increased from 46,308 t in 1978 to a peak of 216,000 t in 1983, then decreased slightly to about 208,000 t in 1987 (Table 1). Since the early to mid-1980s, there has been a steady decrease in vessel numbers, but an increase in permitted fishing time and in vessel size (Table 2). Because larger vessels fish 2.67 times more gear than smaller vessels (M. Nakamura, FAJ, Tokyo, Japan 100, pers. commun., 10 March 1989), the increase in fishing time and vessel size has likely offset the decrease in vessel numbers in terms of the total amount of drift net deployed annually.

The Japanese squid driftnet fishing season begins in June and lasts through December. More than 42% of the average annual fishing effort (vessel days) and 50% of the average annual catch since 1983 has oc-

**Table 1**

Catch and fishing effort statistics of the Taiwanese (Republic of China—ROC)[a], Japanese[b], and Republic of Korea[c] (ROK) squid driftnet fisheries in the North Pacific Ocean, 1977–88. Korean data from sampled vessels are given in parentheses. NA = not available.

| | Driftnet vessels | | | | Vessel days | | | | Driftnet catch (t) | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Year | ROC | Japan | ROK | | ROC | Japan | ROK | | ROC | Japan | ROK | |
| 1977 | | | | | | | | | | | | |
| 1978 | | NA | | | | NA | | | | 46308 | | |
| 1979 | | NA | 3 | (1) | | NA | 108 | (36) | | 47652 | 360 | (120) |
| 1980 | 12 | NA | 14 | (9) | NA | NA | 1064 | (684) | 908 | 119000 | 4693 | (3017) |
| 1981 | 44 | 534 | 34 | (9) | NA | NA | 5190 | (1374) | 10719 | 104000 | 22901 | (6062) |
| 1982 | 88 | 529 | 60 | (56) | 5636 | 33085 | 6825 | (6374) | 21868 | 158722 | 23738 | (21364) |
| 1983 | 101 | 515 | 99 | (77) | 6505 | 32685 | 12862 | (10004) | 14257 | 215778 | 48513 | (37732) |
| 1984 | 146 | 505 | 111 | (105) | 11389 | 32555 | 17297 | (16362) | 27553 | 123719 | 52266 | (49441) |
| 1985 | 124 | 502 | 125 | (104) | NA | 35132 | 19799 | (16473) | 21807 | 197795 | 85495 | (71132) |
| 1986 | 110 | 492 | 117 | (107) | NA | 35549 | 20518 | (18764) | 13887 | 152226 | 64539 | (59023) |
| 1987 | 87 | 478 | 140 | NA | 6635 | 29613 | NA | | 18578 | 208319 | NA | |
| 1988 | 166 | 463 | 150 | NA | NA | 31998 | NA | | NA | 157773 | NA | NA |

[a] 1980–81 data from Liu (1984); 1982, 1983, and 1984 data from 1982–1984 editions of Statistics of Deep Sea Jigging and Gill Net Fishery of Squid in Northwest Pacific Ocean, Institute of Fishery Biology of Ministry of Economic Affairs and National Taiwan University; 1986 data from Report of the November 1988 U.S.-Taiwan Bilateral Meeting on Assessment of North Pacific Fisheries Resources, 5–6 November 1988, at Institute of Oceanography, National Taiwan University, Taipei, Taiwan; 1983–87 data from Tung (1988); and 1981–88 data from CCNAA (unpublished data, previously cited).

[b] Catch and effort data from Masayuki Komatsu, Fishery Agency of Japan, Tokyo, pers. commun., Sept. 1986; Fishery Agency of Japan (1982, 1984, 1985a, 1986, 1987, 1988, 1989); and Fisheries Yearbook, 1986, Ministry of Agriculture, Forestry, and Fisheries, Japan.

[c] Data from NFRDA (1988). The catch and fishing effort statistics for the entire fleet are computed by using sample data divided by the sampling fraction.

**Table 2**

Number of Japanese driftnet vessels categorized by vessel size and permit type that are authorized to harvest squid in the North Pacific Ocean 1981–1988[a].

| | Vessel class (gt)[b] | | Permit type[a] | | |
|---|---|---|---|---|---|
| Year | 59–100 | 100–500 | 4–month | 7–month | Total Vessels |
| 1981 | 371 | 163 | | | 534 |
| 1982 | 326 | 203 | | | 529 |
| 1983 | 285 | 230 | | | 515 |
| 1984 | 265 | 240 | | | 505 |
| 1985 | 259 | 243 | 84[c] | 418 | 502 |
| 1986 | 237 | 255 | 66[d] | 426 | 492 |
| 1987 | 209 | 269 | 41 | 478 | 478 |
| 1988 | 202 | 261 | 24 | 439 | 463 |

[a] Data from Snead et al. (1988), Herrfurth (1988), and the Regional Fisheries Attaché, American Embassy, Tokyo.

[b] gt = gross tons.

[c] All but three permits used by 59–100 gt vessels.

[d] All but one permit used by 59–100 gt vessels.

curred in July and August (Table 3). About 85% of the mean monthly fishing effort (vessel days) in July and August takes place in the northern 2° latitude of the permitted fishing area, producing about the same mean percentage of the monthly catch each year (Table 4).

Five different vessel classes operate in the Japanese squid driftnet fishery (Table 5). Entry time to the fishery and fishing season length vary by vessel class because most vessels are committed to other fisheries (such as salmon, squid jigging, or groundfish) during part of the year. Vessels from the mothership and

**Table 3**

Fishing effort and catch per unit effort stratified by month for Taiwanese[a], Japanese[b], and ROK[c] squid driftnet fisheries operating in the North Pacific Ocean, 1983–1987. Fishing effort is given in vessel days for the Taiwanese and Japanese fisheries, and in pieces (50 m) of drift net for the ROK fishery.

| | Fishing effort (vessel days) | | | | | Catch (t)/vessel day | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Month | 1983 | 1984 | 1985 | 1986 | 1987 | 1983 | 1984 | 1985 | 1986 | 1987 |
| **JAPAN** | | | | | | | | | | |
| Jun | 4348 | 4124 | 3664 | 4832 | 5001 | 6.98 | 4.47 | 6.57 | 5.75 | 7.80 |
| Jul | 5410 | 6580 | 5802 | 7599 | 6896 | 8.84 | 5.42 | 7.94 | 5.23 | 10.31 |
| Aug | 8137 | 7923 | 8072 | 8721 | 5697 | 7.65 | 3.60 | 6.20 | 4.50 | 7.72 |
| Sep | 5825 | 5895 | 6326 | 6049 | 5261 | 6.47 | 2.79 | 4.88 | 3.20 | 5.22 |
| Oct | 5100 | 4124 | 5956 | 3847 | 4207 | 4.08 | 2.86 | 4.02 | 3.14 | 3.65 |
| Nov | 2917 | 2940 | 4013 | 3396 | 1892 | 4.18 | 3.31 | 4.46 | 2.95 | 4.63 |
| Dec | 948 | 969 | 1299 | 1105 | 659 | 4.85 | 2.95 | 3.82 | 3.61 | 3.97 |
| Total: | 32685 | 32555 | 35132 | 35549 | 29613 | $\bar{X}$: 6.60 | 3.79 | 5.63 | 4.28 | 7.03 |
| **TAIWAN** | | | | | | | | | | |
| Apr | 9 | 208 | | | | 0.69 | 1.38 | | | |
| May | 284 | 734 | | | 125 | 0.92 | 1.53 | | | 1.46 |
| Jun | 633 | 1123 | | | 705 | 1.67 | 1.95 | | | 1.94 |
| Jul | 865 | 2393 | | | 1453 | 2.54 | 1.80 | | | 2.76 |
| Aug | 1499 | 2642 | | | 1743 | 2.47 | 2.14 | | | 2.43 |
| Sep | 1839 | 2714 | | | 1704 | 1.97 | 3.28 | | | 3.36 |
| Oct | 952 | 1559 | | | 881 | 1.17 | 3.25 | | | 3.38 |
| Nov | 424 | 16 | | | 24 | | 0.49 | | | 3.75 |
| Total: | 6505 | 11389 | | | 6635 | $\bar{X}$: 2.19 | 2.42 | | | 2.77 |

| | Fishing effort (pieces of net) | | | | | Catch (t)/net | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| Month | 1983 | 1984 | 1985 | 1986 | 1987 | 1983 | 1984 | 1985 | 1986 | 1987 |
| **ROK** | | | | | | | | | | |
| Apr | | | 66 | 247 | | | | 2.00 | 0.87 | |
| May | | | 1147 | 2266 | | | | 2.14 | 2.09 | |
| Jun | | | 1981 | 2888 | | | | 4.89 | 3.02 | |
| Jul | | | 1954 | 2217 | | | | 6.81 | 3.31 | |
| Aug | | | 2266 | 2603 | | | | 6.30 | 2.80 | |
| Sep | | | 2614 | 2569 | | | | 6.07 | 5.22 | |
| Oct | | | 1860 | 2326 | | | | 4.89 | 4.71 | |
| Nov | | | 1346 | 1714 | | | | 3.75 | 3.04 | |
| Dec | | | 743 | 744 | | | | 1.69 | 1.50 | |
| Jan | | | 12 | 13 | | | | 2.33 | 0.85 | |
| Total: | | | 13989 | 17587 | | $\bar{X}$: | | 5.08 | 3.36 | |

[a] Data from 1983 and 1984 editions of Statistics of Deep Sea Jigging and Gill Net Fishery of Squid in Northwest Pacific Ocean. Institute of Fishery Biology of Ministry of Economic Affairs and National Taiwan University. Data (1987) from CCNAA (unpublished data, previously cited).

[b] Data from Fisheries Agency of Japan (1984, 1985a, 1986, 1987, 1988).

[c] Data (1985) from NMFS (1986). Data (1986) from NFRDA (1987b).

land-based salmon driftnet fisheries are the smallest, and fish primarily during late summer and fall in western waters. Vessels dedicated to squid driftnet fishing are the only class that fish an entire season (June through December).

Vessels fish independently or within multi-vessel arrays. Array fishing is a group of vessels coordinating net deployment, usually in an east-west direction, with vessels spaced at least 3.5 km apart along a north-south axis (Tsunoda 1989). The organization is

**Table 4**

Catch (t), effort (vessel days), and the percentage of total monthly catch and effort within 2° of the northern boundary of the Japanese squid driftnet fishery for July and August (the months of peak effort) and for the entire season (FAJ 1984, 1985a, 1986, 1987, 1988)

| | July | | | | August | | | |
|---|---|---|---|---|---|---|---|---|
| Year | Catch | (%) | Effort | (%) | Catch | (%) | Effort | (%) |
| 1983 | 34515 | (72) | 3959 | (73) | 51448 | (83) | 6404 | (79) |
| 1984 | 33741 | (95) | 6195 | (94) | 24675 | (87) | 6926 | (87) |
| 1985 | 43339 | (94) | 5431 | (94) | 41210 | (82) | 6625 | (82) |
| 1986 | 37850 | (95) | 7184 | (95) | 36359 | (93) | 7931 | (91) |
| 1987 | 59786 | (84) | 5677 | (82) | 34358 | (78) | 4039 | (71) |
| Average | 41846 | (87) | 5688 | (88) | 37610 | (84) | 6385 | (83) |

**Table 5**

Characteristics[a] of vessel classes participating in the Japanese squid driftnet fishery in the North Pacific Ocean, 1987.

| | | | Fishing Grounds | | | | |
|---|---|---|---|---|---|---|---|
| Vessel class | Avg. (t) | No. of vessels | 170°E | 175°W | 160°W | 145°W | Main season |
| Mothership salmon | 96 | 42 | <-------- | -------- | --> | | Aug–Nov |
| Landbased salmon | 80 | 80 | <-------- | -------- | --> | | Aug–Nov |
| Trawler/longliner | 350 | 49 | | <-------- | -------- | --> | Jun–Sep |
| Jigging | 345 | 39 | | <-------- | -------- | --> | Jul–Oct |
| Dedicated | 300 | 172 | <-------- | -------- | -------- | --> | Jun–Nov |

[a] Data from the Fisheries Agency of Japan, Tokyo, Japan (unpubl. data).

not predetermined; it develops on the fishing grounds. Arrays usually consist of vessels of similar class, because information is rarely exchanged between vessel classes on the fishing grounds.

### Gear and Vessel Characteristics

The number of single panels (tans) of net that are set nightly varies among vessels, and depends on weather and other factors (Tsunoda 1989). Amount of net fished is relative to vessel size; small vessels (<100 gross tons) set as few as 450 tans nightly, whereas large vessels typically set 1200 tans nightly (M. Nakamura, FAJ, Tokyo, Japan, pers. commun., 10 March 1989). Net dimensions are not standardized and may be changing over time. In 1985,. the FAJ (1986b) reported a tan to be 72–90 m long with a corkline and leadline shrinkage factor of 46.9% and 45%, respectively. Observations (by U.S. scientific observers and enforcement personnel in 1985 and 1986) indicated tans ranged from 40 to 105 m in length (Ignell et al. 1986; Tsunoda 1989) and 9 to 10 m in depth. More recent information from Japanese officials indicates that tans range in length from 36–50 m (Snead et al. 1988). All nets are of similar design—a corkline at the surface, monofilament mesh stretched horizontally, and a leadline at the bottom—with stretched mesh sizes typically ranging from 115 to 120 mm. Single tans are tied and laced together to construct "sections" of gear approximately 5.5 km long; two may be tied together to form double-length sections. Most large vessels deploy at least 8–10 net sections per night.

## The Republic of Korea Squid Driftnet Fishery

### Fishery Characteristics

The Republic of Korea (ROK) high-seas, driftnet flying squid fishery began in 1979 as an exploratory fishery (Gong 1985); three vessels fished from August through October off the coast of Japan (Table 1)

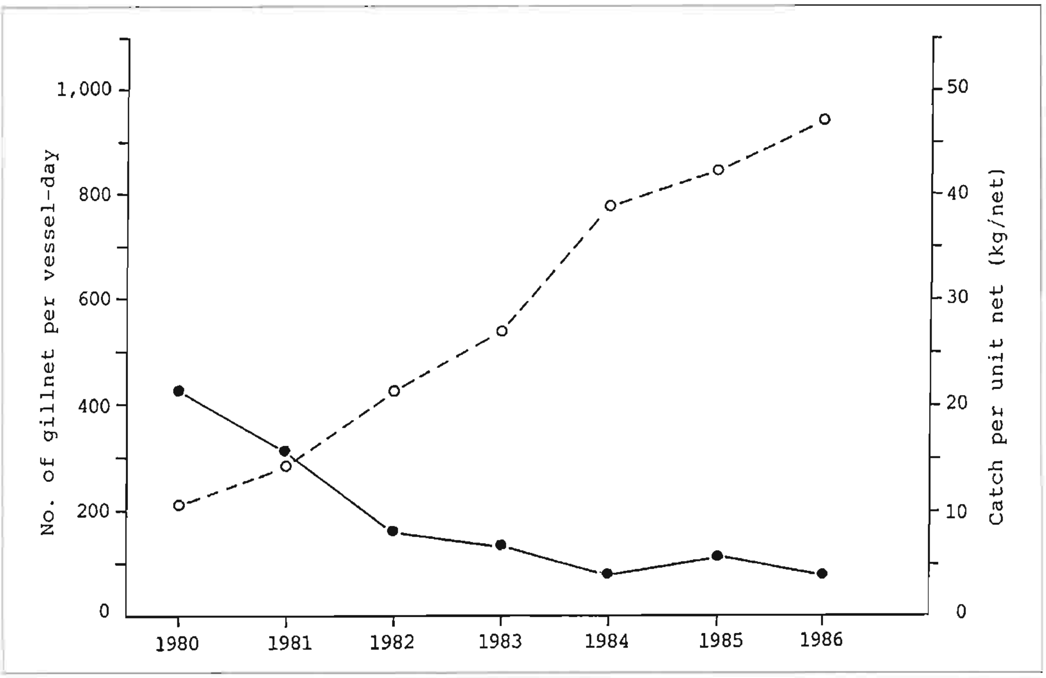

**Figure 2**
Annual fluctuation of fishing effort (open circle) and catch per unit effort (dark circle) for the Korean flying squid driftnet fishery in the north Pacific Ocean, 1980–1986 (NFRDA 1988).

(NFRDA 1988). The fishery expanded the following year when 14 vessels fished March through December, from the Japanese coast to 180° longitude. Since then, the number of registered vessels has continued to increase yearly: National Fisheries Research and Development Agency (NFRDA) records show 99 licensed vessels in 1983 and 150 in 1988. Since 1980, the fishing grounds have expanded eastward (NFRDA 1988), reaching 155°W in 1986.

Korea's annual driftnet catch of flying squid increased from 360 t in 1979 to a peak of 85,495 t in 1985, then decreased to 64,539 t in 1986 (Table 1). Although the catch increase generally parallels the increase in vessel numbers, CPUE (per 50 m of drift net) has steadily decreased since the early 1980s to the point where increased number of vessel days in recent years has been offset by the decline in catch rates (Table 1; Fig. 2).

The ROK fishing season begins in late April near 35°N, 165°E. By May, most of the vessels have moved eastward (NFRDA 1988), fishing from 170°E to 155°W. Approximately half the fleet moves back westward (west of 170°E) in July, the rest in August. The westward movement continues during the year, with a few vessels fishing near Japan's coast at season's end in January.

Fishing is concentrated along a 4° band in latitude that varies latitudinally by month (NFRDA 1988). East of 170°E during the summer, ROK vessels are generally located slightly south of the Japanese fleet (FAJ 1987). About one-fourth of the total catch came from east of 170°E in 1985 (NFRDA 1987a), but that proportion is undoubtedly greater in recent years owing to a gradual eastward shift in fishing location (NFRDA 1988).

The vessel movements reflect the two distinct seasons and fishing grounds of the ROK fleet. "Western grounds" are primarily between 160°W and 170°E, and are fished late spring and summer. "Eastern grounds" are between 143°E and 169°E, and are fished from mid-August through December; squid here are smaller but more abundant than those in western grounds (Gooder 1989).

Vessels are organized into 16 fleets to ensure orderly conduct of the fishery (K.Y. Kim, Fishery Attaché, Republic of Korea, Embassy of the Republic of Korea, Washington, DC, pers. commun., 17 February 1989); fishing groups typically consist of 7–10 vessels whose captains attended the same fishing college (Gooder 1989). Within each fleet, one vessel is selected to establish communication links among vessels themselves and with the Korean Deep Sea Fishery Association (KDSFA). Observations from a U.S. scientist aboard a ROK driftnet vessel in 1988 indicate that vessels of a fleet fish in an array pattern and exchange information regarding fishing success (Gooder 1989). The arrays consist of nets set in an east-west orientation, spaced approximately 3.5 km apart along a north-south axis, similar to those of the Japanese fleet. Some vessels fish up to nine months before returning to port; off-loading catch, replenishing supplies, and refueling are done at sea.

## Fishing Regulations

In an overview of ROK fishing regulations, Kim (pers. commun. already cited) stated that ROK squid driftnet vessels are jointly managed by the KDSFA (an industry group representing most Korean fishing companies) and by the government. Vessels are not subject to time or area regulations, and there is no limited-entry system established for the fishery. All vessels must be licensed. Directives concerning the non-retention of salmonids, the accounting for all driftnets and vinyl products before and after each cruise, and the proper disposal of vinyl products and waste drift net are provided through licensing conditions or by KDSFA and governmental instruction. Each year before vessels embark for the fishing grounds, vessel captains must participate in an instruction program conducted by the NFRDA where

**Table 6**
Composition of vessels according to gross tonnage for ROK[a] and Taiwanese[b] squid driftnet fisheries.

| Vessel Tonnage | Proportion of Fishing Vessels | | | |
|---|---|---|---|---|
| | ROK | Taiwan | | |
| | 1988 | 1983 | 1984 | 1987 |
| 100–200 | 0.05 | 0.08 | 0.04 | 0.05 |
| 201–300 | 0.61 | 0.47 | 0.31 | 0.48 |
| 301–400 | 0.21 | 0.35 | 0.44 | 0.34 |
| 401–500 | 0.13 | 0. 07 | 0.15 | 0.05 |
| 501–600 | | 0.03 | 0.04 | 0.00 |
| 601–800 | | | 0.02 | 0.08 |

[a] National Fisheries Research and Development Agency (NFRDA), Republic of Korea, 1988 (unpubl. data).

[b] Data from 1983 and 1984 editions of Statistics of Deep Sea Jigging and Gill Net Fishery of Squid in Northwest Pacific Ocean, and Tung (1988).

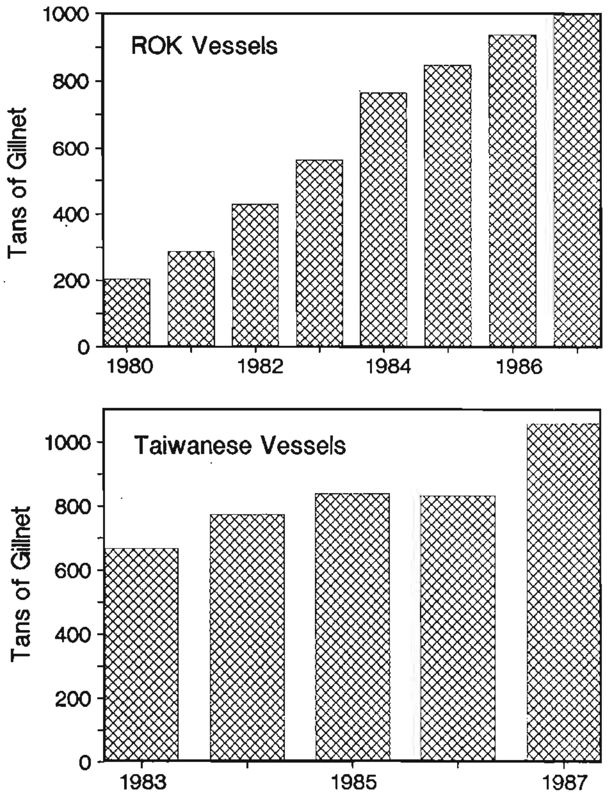

**Figure 3**
Trends in the amount (tans) of drift net set nightly by ROK **(upper graph)** and in the amount of drift net loaded on Taiwanese **(lower graph)** squid driftnet vessels fishing in the North Pacific Ocean. Data from NFRDA (1988) and Tung (1988).

the foregoing directives are discussed. Production statistics are to be reported monthly to the KDSFA, and at season's end all squid vessels are to report catch and effort statistics to NFRDA.

### Gear and Vessel Characteristics

Most ROK driftnet vessels are converted tuna longliners, reflecting the economic difficulties faced by tuna longliners in past years (Gong 1985). Vessels range from 170 to 500 gt (Table 6); average displacement is approximately 290 gt, and about 90% of the converted vessels are at least 16 years old (NFRDA, unpubl. data on file with author).

Driftnet mesh sizes range from 86 to 155 mm (Y. Gong, NFRDA, Pusan, Republic of Korea, pers. commun., Nov. 1987); the most common sizes range from 96 to 115 mm (Gong 1985). Single panels of net (poks) are 50 m long and 9 m deep (Gooder 1989). Due to seasonal and geographical differences in the size of flying squid (Gong, Kim, and Kim 1985; Gooder 1989), mesh sizes are changed throughout the fishing season. In the western grounds, 105- and 115-mm mesh gear is most common, whereas 86- and 96-mm mesh gear is most common in the eastern grounds (Gooder 1989).

Since the start of the fishery, the average number of poks deployed nightly per vessel has risen steadily, from 200 in 1980 to almost 1000 in 1986 (Fig. 3). Little additional increase is expected, because most ROK vessels are operating at full capacity if 1000 poks are deployed (Y. Gong, NFRDA, Pusan, Republic of Korea, pers. commun., Nov. 1987).

## The Taiwanese Squid Driftnet Fishery

### Fishery Characteristics

The Taiwanese driftnet fishing grounds for flying squid in the North Pacific Ocean were first developed in 1977 by jigging vessels (Chen 1985; Tung 1988). Increased oil prices in the late 1970s prompted 12 vessels to switch to driftnet gear in 1980, thereby saving on the oil costs necessary to maintain lights for jigging (Tung 1988). The driftnet fishery grew to over 100 vessels by 1983, and 166 vessels by 1988 (Table 1). Annual catches increased from 908 t in 1980 to a peak of 27,553 t in 1984, and then declined to 18,578 t in 1987. Although catch per vessel per day increased slightly between 1983 and 1987 (Table 3), the number of nets deployed per vessel rose markedly (Table 7), resulting in a reduction over time of catch per net.

Although fishing grounds were located initially in the western North Pacific, the fishery extended eastward, reaching 160° W by 1983 (Liu 1984) and 145 by 1986 (Tung 1988). Fishing has generally occurred from May through October, with peak effort (vessel days) in August and September. About 30% of the total catch comes from fishing grounds east of 170°E (Tung 1988). In early fall, vessels return westward, fishing near Japan's coast at season's end in November.

**Table 7**

Amount[a] of drift net (each piece equals 50 m) loaded on Taiwanese squid driftnet vessels fishing in the North Pacific Ocean, 1983–87.

| | Number of vessels | | | | |
|---|---|---|---|---|---|
| Pieces of net | 1983 | 1984 | 1985 | 1986 | 1987 |
| 200–399 | 12 | 7 | 5 | 6 | 2 |
| 400–599 | 31 | 42 | 20 | 17 | 4 |
| 600–799 | 26 | 33 | 33 | 33 | 14 |
| 800–999 | 15 | 30 | 30 | 22 | 14 |
| 1000–1199 | 17 | 23 | 23 | 21 | 27 |
| 1200–1399 | | 11 | 12 | 8 | 12 |
| 1400–1599 | | | 1 | 1 | 10 |
| 1600–1800 | | | | 2 | 4 |
| Total vessels: | 101 | 146 | 124 | 110 | 87 |
| Total nets: | 69500 | 112800 | 104000 | 91600 | 92100 |

[a] Data from Tung (1988).

### Fishing Regulations

Because of U.S. concerns about the incidental harvest of salmonids, the Taiwanese adopted additional domestic regulations in 1986 for squid driftnetters. Under these regulations, fishing requires a permit from the Council of Agriculture (CCNAA [Coordination Council for North American Affairs] 1989, unpubl. data on file with author), and is prohibited north of 39°N west of 170°E (NMFS 1988). Regulations similar to Japanese domestic regulations were adopted for waters east of 170°E (Fig. 1). Since all Taiwanese squid driftnetters operate from the Port of Kaohsiung, Port authorities there are charged with enforcement of fishing regulations (CCNAA, unpubl. data on file with author).

### Gear and Vessel Characteristics

In 1982, three years after the start of the squid driftnet fishery, drift nets became the gear most commonly used by Taiwanese squid fishermen (Chen 1985). The overwhelming effectiveness and efficiency of drift nets quickly became apparent, and by 1984 over 95% of the squid fleet were driftnetters (Tung 1988).

Most Taiwanese driftnet vessels range from 200 to 500 gt (Table 6); average displacement in 1987 was 325 gt. In recent years, the number of vessels ≥700 gt has been increasing. Taiwanese driftnet vessels are typically converted longliners (Chen 1985).

Tung (1988) gives the following description of mesh sizes used. Driftnet vessels carry a variety of mesh sizes and may target both squid and tuna during a fishing season. Mesh sizes <120 mm are typically used to harvest oceanic squid; the primary mesh sizes in this range are 110 mm and 80–85 mm. The recent shift to smaller mesh sizes reportedly stems from management guidelines in the western fishing grounds that restrict fishing south of 39°N latitude, thereby forcing fishing operations into areas where squid are small. Although drift nets with mesh sizes up to 160 mm can be used to harvest flying squid, mesh sizes above 146 mm are used for harvesting other species such as tuna and billfish in the large-mesh driftnet fishery. Principal mesh sizes for the large-mesh fishery range from 196 to 220 mm.

Similar to the ROK fishery, total driftnet length used per vessel has increased yearly. At first, Taiwanese driftnetters were equipped with 250–500 tans of drift nets (Anonymous 1981). By 1987, an average of 1059 tans of drift nets were loaded on each vessel (Table 7; Fig. 3). About 50–75% of the nets (25–37 km) loaded aboard the vessel are fished nightly; this percentage varies according to weather conditions and the skipper's skill (I. Tung, National Taiwan University, Taipei, pers. commun., Jan. 1988).

## Overview of North Pacific Squid Driftnet Fisheries

### Characteristics of Fishing Area

The northern portion of the flying squid fishing area (where most of the fishing occurs) lies within what may be the most important major frontal zone in the North Pacific Ocean. Called the subarctic frontal zone (SFZ), this area is typified by multiple fronts (mesoscale fronts) within a general frontal zone ranging from 35° to 47°N (Roden 1977; Fig. 4). To the north, the SFZ is bounded by subarctic waters (cool, low salinity), with a permanent halocline between 100 and 200 m and a large seasonal temperature variation; to the south are the transitional region and subtropical waters (stable, warm, high salinity) with a permanent thermocline and no halocline (Roden and Robinson 1988).

The chemical and biological properties of the SFZ provide a unique environment to pelagic species. The high productivities resulting from frontal dynamics influence forage aggregations, thereby impacting species distributions in higher trophic levels (McGowan 1986). For example, when frontal structures are poorly developed and water-mass boundaries indistinct, catches of albacore decline (Laurs and Lynn 1977). This may explain why ROK squid driftnet fishermen select areas of sharp frontal gradients for net deployment (Gooder 1989). Japanese squid driftnet fishermen probably do likewise, since sea-surface temperatures may differ by 2–3°C from one end of a drift net to the other (Tsunoda 1989).

As an environmental barrier, the SFZ affects size and sexual dimorphism in flying squid distribution, thereby affecting fishing patterns. Four modes in the frequency distribution of mantle lengths have been identified by Murakami et al. (1981). Called the LL (extra-large), L (large), S (small), and SS (extra-small) groups, these modes presumably reflect differences in age structure, spawning period, or sex, and indicate possible differences in stocks or in life-history strategies.

The LL squid are found north of the SFZ, are primarily females, and are targeted by fishermen from all three countries. Abundances of the LL group are relatively high east of 170°E and low west of 170°E (Murata 1987). The L-, S-, and SS-group squid have

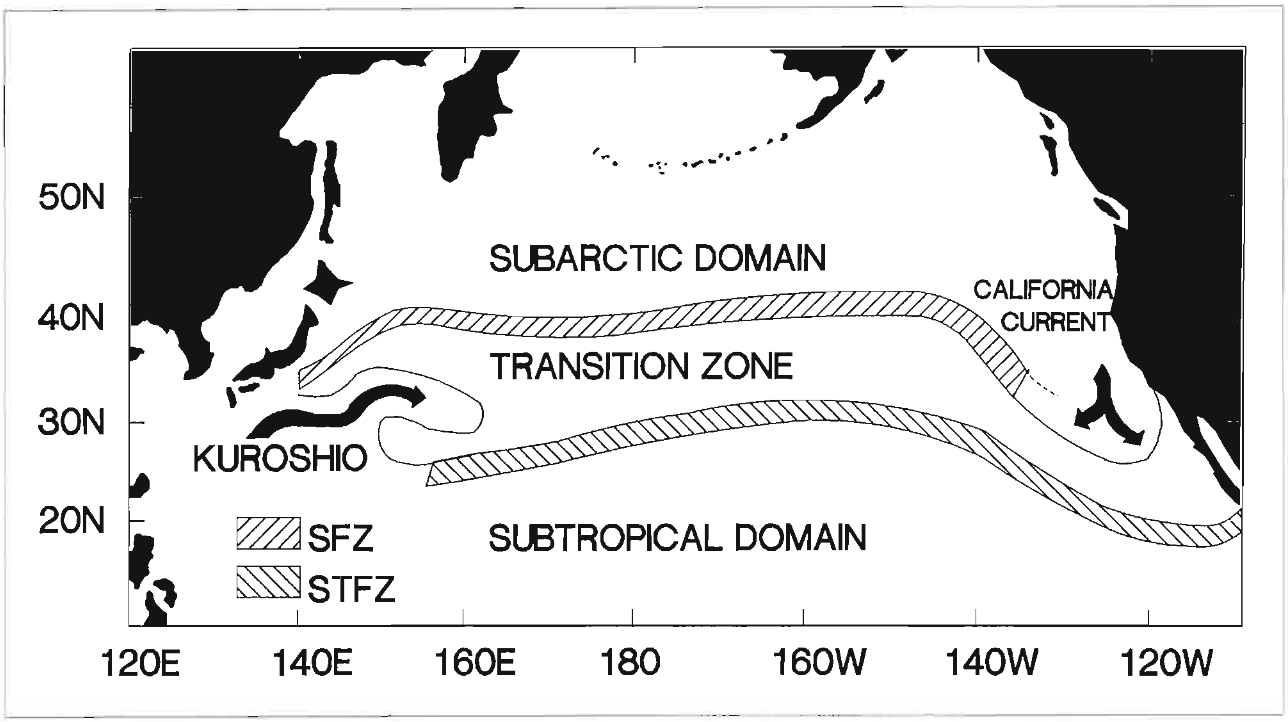

**Figure 4**

Schematic diagram showing the locations of the Subarctic and Subtropical Domains, the North Pacific Transition Zone, and the associated Subarctic and Subtropical Frontal Zones (SFZ and STFZ). Black arrows indicate intrusions of boundary currents.

sex ratios near 1:1 (Kubodera et al. 1983), and are sometimes targeted by ROK and Taiwanese fishermen. The L- and S-group squid are distributed in and south of the subarctic boundary but north of the SS-group (Murata 1987). Positive correlation between latitude and size is not restricted to the four squid groups; it also pertains to squid within a particular group (Kubodera et al. 1983), and to other fishes such as pomfret that migrate seasonally from subtropical to subarctic waters (Shimazaki 1986) and are incidentally harvested by driftnet fishermen.

## Fishing Methods

Japan, the ROK, and presumably Taiwan use similar fishing gear and methods to harvest flying squid in the North Pacific Ocean. The following paragraphs describe a typical squid driftnet fishing operation, summarized from Cary and Burgner (1983), Ignell et al. (1986), Gooder (1989), and Tsunoda (1989).

Driftnet vessels often fish in a coordinated fashion: nets are set along an east-west direction and set positions are spaced about 3.5 km apart (inter-vessel distance) on a north-south axis. Information is exchanged among vessels to locate fishing grounds with high squid abundance. Surface water temperatures are monitored to determine regions of abrupt temperature change. Satellite produced, 5-day summaries of sea-surface conditions and other cues, such as plankton and seabird densities, are also used to position the vessels.

Drift nets are typically deployed in the afternoon, usually 2–4 hours before sunset, along an east-west direction. The net is deployed from the stern net well over a horizontal roller at constant speed (near cruising speed). Sprayed water keeps the net from tangling, and two men use poles to separate the leadline and corkline. A combination of float, radio, and light buoys marks the end of net sections.

Net retrieval begins before sunrise; incandescent and halogen lights illuminate the deck, and a spotlight is directed at the net in the water. The net is retrieved and hauled aboard the port side at speeds from 1 to 5 knots. After the catch is removed, the net is pulled through a tube on the starboard side and back to the net well at the stern where it is stacked for subsequent deployment. Billfish, large sharks, and porpoise are often gaffed and pulled onto the deck manually or with an electric winch.

Besides flying squid, species that may be retained include albacore (*Thunnus alalunga*), skipjack (*Euthynnus pelamis*), other tunas (*Thunnus* spp.), swordfish (*Xiphias gladius*), striped marlin (*Tetrapturus audax*), dolphin fish (*Coryphaena* *hippurus*), and yellowtail (*Seriola* spp.). Others are usually discarded, although large Pacific pomfret (*Brama japonica*), ocean sunfish (*Mola mola*), and salmon shark (*Lamna ditropis*) are occasionally kept. During retrieval, approximately 8–10% of the squid drop out of the net alongside the vessel. Dropout rates for many of the non-commercial species caught in the gear are considerably higher since they are shaken out before they reach the deck.

Dorsal mantle lengths of commercially caught squid range from 20 to >50 cm; most are at least 35 cm. Mantle-length modes for the ROK fishery are 38–39 cm in the central North Pacific Ocean from June to July, and 30–31 cm in the northwestern Pacific Ocean from September to December (Gong, Kim, and Kim 1985). About 95% of the squid in the Taiwanese commercial catch exceed 35 cm (Tung 1988). The Japanese fishery is particularly selective towards large squid because their regulations prohibit use of nets with mesh sizes <100 mm, and because they prefer to fish north of the Taiwanese and ROK fleets where the largest squid are found. Squid are processed by separating the mantle from the head and by removing the arms, tentacles, and viscera. Mantles (and on some vessels the head, arms, and fins also) are placed in a pan and frozen.

## Total Fishing Effort

Since 1983, the total number of squid driftnet vessels licensed by Japan, Taiwan, and the ROK has ranged from 715 vessels in 1983 to 779 vessels in 1988 (Fig. 5). Although fishing effort (measured in terms

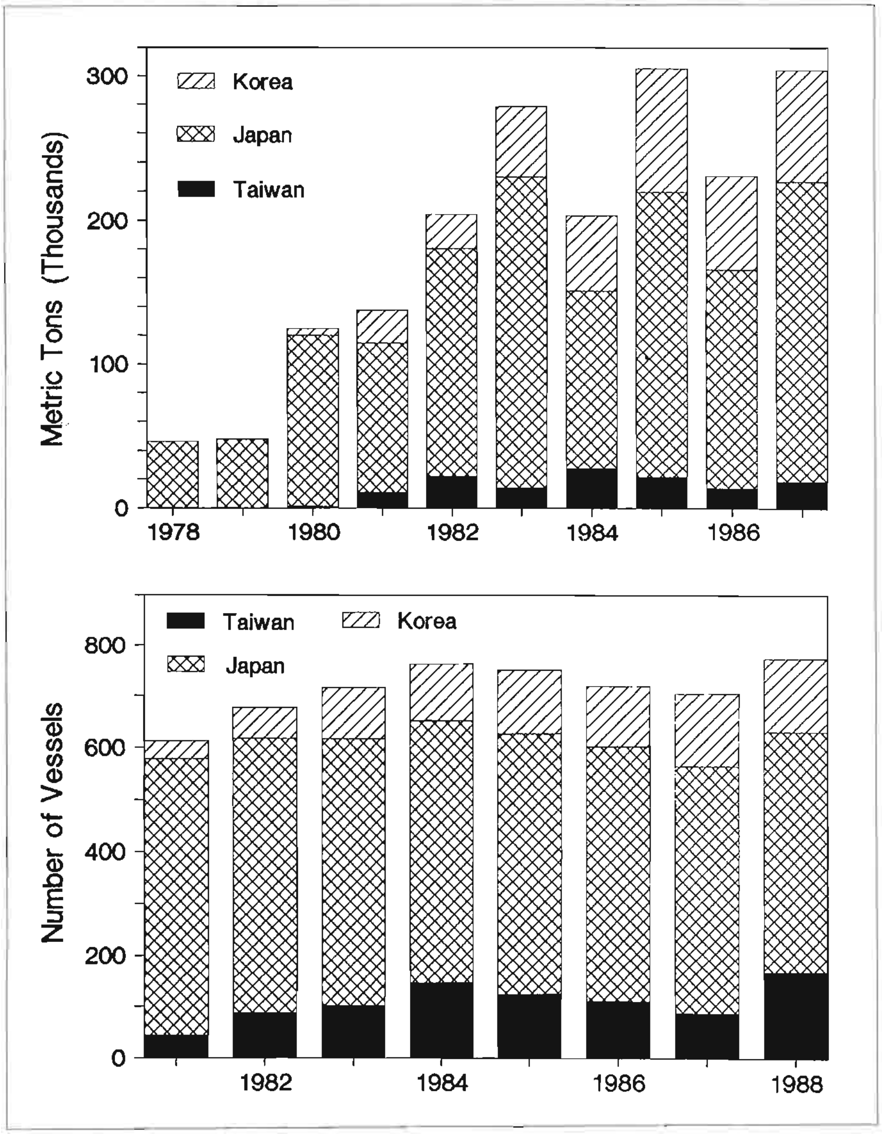

**Figure 5**
Catch (t) and fishing effort (number of vessels) for the squid driftnet fisheries of Japan, ROK, and Taiwan in the North Pacific Ocean. Fishing effort prior to 1981 is unavailable for the Japanese fleet.

of panels of drift net) is unavailable for the Taiwanese and Japanese fisheries, total fishing effort has probably increased in recent years, owing to longer fishing seasons and increased gear deployment. For instance, since 1982 the average number of days fishing per vessel has increased 19% in the Taiwanese fishery, 11% in the Japanese fishery, and 54% in the ROK fishery (Table 1). The increase in gear deployment is most evident in the ROK and Taiwanese driftnet fleets: since 1983, the average length of drift net used nightly has increased 85% and 54% (Gong 1985; Tung 1988; Fig. 3), respectively. Because small vessels fish 450 tans and large vessels fish 1200 tans nightly, length of drift net deployed nightly in the Japanese fleet has probably also increased because fewer small vessels participate in the fishery.

## Total Catch

Despite increased fishing effort and power, total catches of flying squid have remained relatively stable, ranging since 1982 from 200,000 to 300,000 t (Fig. 5), and averaging 258,404 t since 1984 (Table 1). All Japanese and approximately 30% of ROK and Taiwanese driftnet catches (about 75% of the total flying squid catch) have occurred east of 170°E. Estimated catches of other retained species are 7500–23,000 t of albacore and probably several thousand metric tons each of skipjack, yellowtail, and marlin (J. Wetherall, Natl. Mar. Fish. Serv., NOAA, Honolulu, HI 96822-2396, pers. commun.).

## Sustainable Yield

Total catch of flying squid in the North Pacific Ocean is near or below estimated sustainable-yield levels. The amount of flying squid caught by jigging vessels in recent years is unknown; however, 29,000 t were caught in 1984 (Anonymous 1986). Assuming that current jigging harvests approach 35,000 t and that 62,500 t (25% of 250,000 t) of squid are caught by driftnet vessels fishing west of 170°E, total catch of flying squid west of 170°E is about 100,000 t, or 110 million squid (conversion data from Gong, Lim, and Hur [1985]). This catch estimate is near Osako and Murata's (1983) recommended catch level of 80,000–100,000 t, but much less than Okutani's (1977) potential catch of 150,000–600,000 t. The catch estimate also yields a relatively low rate of exploitation (<0.5) based on Chikuni's (1985) estimate of 250,000–350,000 t (estimate includes 2 less abundant species: *Onychoteuthis borealijaponica* and *Gonatopsis borealis*) and Araya's (1983) estimate of 219–264 million individuals for the flying squid stock west of 170°E.

A yield estimate has not been calculated for the entire North Pacific Ocean flying squid resource; however, total catch is probably within recommended levels. The total catch of flying squid west of 160°W has averaged about 255,000 t from 1983 to 1985 (assuming all the ROK and Taiwanese, and 82% of the Japanese catch occurs here). This estimate is probably within sustainable yield levels, based on the estimate of Gong, Lim, and Hur (1985) of 322 and 469 million squid or 351,000–511,000 t for the flying squid resource west of 160°W.

Although recent harvests have apparently been within sustainable yield levels, CPUE (one unit equals one piece of net) has been declining. CPUE calculated from ROK commercial fishery logbook data has fallen 75% since 1980 (Fig. 2). Despite yearly increases in fishing power, catches have remained relatively stable (Table 1), suggesting that CPUE has declined in recent years.

This decline may reflect a reduction in the large-sized squid population in the western portion of the fishery. In the late 1970s and early 1980s, mantle lengths of squid caught by jigging vessels decreased (Osako and Murata 1983). This decrease occurred during a period of heavy exploitation (1978 jigging catch was 151,000 t [Araya 1983]), and led Araya (1983) to suggest that the winter spawning group was "in danger and susceptible to overfishing." This decline could also prompt a change in targeting from L- to S-sized squid, which would lead to additional reductions in a CPUE index based on weight if abundances among groups were similar. On the other hand, the decline may be indicative of gear competition in the fishery; gear competition occurs when each additional unit of drift net, above some threshold, competes with preceding driftnet units (Rothschild 1977). The data in Table 1 indicate that years with low CPUE are weakly associated with years of high driftnet effort, but more-detailed effort data are needed to further test this hypothesis.

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