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Northern Hemisphere fish might tap the rich krill stocks of the Southern Ocean.

Salmon—Future Harvest from the Antarctic Ocean?

TIMOTHY JOYNER, CONRAD V. W. MAHNKEN, and ROBERT C. CLARK, JR.

INTRODUCTION

The ocean surrounding the Antarctic continent is an enormous reservoir of protein. A world increasingly beset with food shortages cannot for long afford to let it remain unharvested. The key to this untapped bounty is a little red crustacean, *Euphausia superba,* that looks like a small shrimp and is commonly called krill. A product of the immense fertility of the Southern Ocean, its food supply is assured by lush pastures of single-celled marine plants in the fertile zone of circumpolar upwelling (Figure 1). Second in the short Antarctic food chain, krill underlies the remaining links made up of squid, penguins, sea birds, seals, and whales.

Intensive study by Soviet scientists of data obtained by fishery research vessels, operating in Antarctic waters since the early 1960's, has produced evidence that exploitation of krill resources could at least double the present global production of aquatic animals. In late 1973, scientists of the All-Union Institute of Marine Fisheries and Oceanography (VNIRO) estimated the potential annual catch of krill to be 100 million tons.

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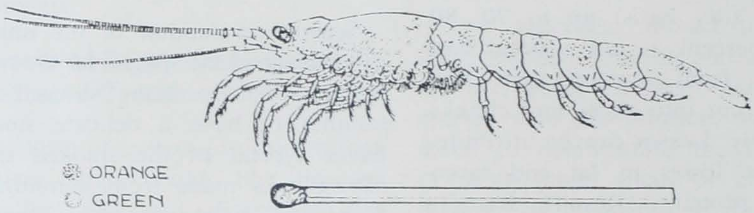


Krill, a small crustacean of the species *Euphausia superba*, forms a major part of the food supply of the whale population of the Southern Ocean.

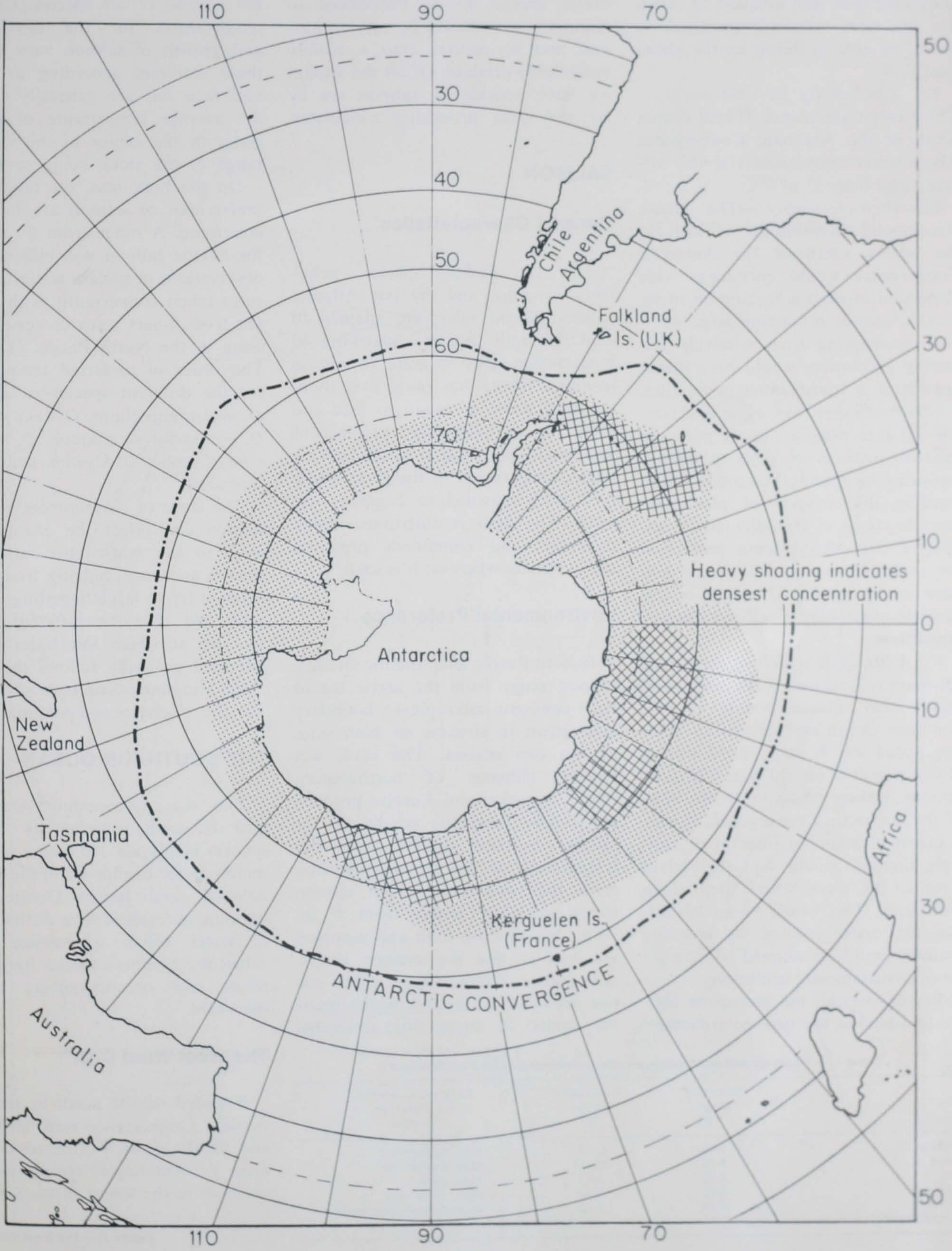
This enormous abundance of krill has been a source of fascination to fishing and food interests throughout the world. The Soviets and the Japanese are developing techniques for processing krill into a palatable food product. Harvesting it, though, is a difficult and expensive proposition, requiring large vessels operating for extended periods far from their home ports. With the skyrocketing prices of petroleum fuels brought on by the world-wide energy crisis, the prospects for a profitable high seas krill fishery now seem dim indeed.

PROSPECTS FOR AN ALTERNATIVE HARVEST

Is there another way of tapping this vast Antarctic reservoir of protein? Since we cannot yet harvest krill economically by ourselves, ought we not to try to get help from some other creature better equipped by nature to do it? To a limited extent baleen whales once did this. However, as they breed slowly and produce few offspring, the stocks were so decimated by intensive whale fishing that they are now threatened with extinction. Since none of the other links of the short Antarctic food chain that depend on krill could withstand intensive harvesting either, it would seem logical to examine the prospects for introduction of species from the great diversity of arctic and subarctic fauna. Success in introducing exotic species to Antarctic waters would be favored by:

(1) *Adaptability to life at sea and a propensity to feed on marine plankton.*—Except for the barren, ice-covered Antarctic continent, there is little land in the Southern Ocean.

Figure 1.—Krill resources in the Southern Ocean—summer distribution.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Argentina
Falkland Is. (U.K.)
Heavy shading indicates densest concentration
Antarctica
New Zealand
Tasmania
Africa
Kerguelen Is. (France)
ANTARCTIC CONVERGENCE
Australia

Only creatures well adapted to ocean life and able to feed on plankton would be able to thrive on the abundant krill.

(2) *Adaptability to cold water.*—The greatest abundance of krill occurs south of the Antarctic Convergence where water temperatures at the surface range from 5° to 0°C.

(3) *High fecundity.*—The broad, circumpolar distribution of krill in the waters south of the Antarctic Convergence would encourage wide dispersion of species feeding on them. Prolific species producing large numbers of offspring from relatively few mating encounters would help insure growth of a transplanted population.

(4) *Protection for eggs and larvae.*—Large populations of potential predators such as sea birds and plankton-straining marine mammals would threaten the survival of planktonic juvenile stages of transplanted stocks. Species that afford some protection for their vulnerable offspring would have an important advantage in the struggle to establish a self-reproducing population.

(5) *A life cycle matching the period of ocean circulation.*—The west wind drives the surface waters of the Southern Ocean eastward at an average speed of 1 knot, producing a global circuit at lat. 50°S in 690 days. Species feeding randomly in the zone of the Antarctic Convergence, if they matured in a similar interval or multiple thereof, would find themselves close to the place where they began their lives. This would be an advantage for many species, as breeding patterns could be adapted to a single set of environmental conditions.

Beyond having the biological ability to adapt to the new environment, exotic species to be introduced to Antarctic seas should be easy to harvest and to process into a readily marketable product. Of all the species we have considered, salmon are by far the most promising candidates.

SALMON

General Characteristics

The six Pacific species, genus *Oncorhynchus*, and the one Atlantic species, *Salmo salar*, are adapted to cold subarctic waters. Spawning in fresh water, they migrate to sea as juveniles. There they range over thousands of miles of ocean to feed and grow fat on planktonic crustaceans and small fish. Several years later as adults, they return to the river where they were spawned to complete the cycle. The flesh is nutritious, highly palatable, and commands premium market prices wherever it is sold.

Environmental Preference

In both Pacific and Atlantic Oceans, salmon range from the arctic ice to the subarctic-subtropical boundary and spawn in streams on both sides of the two oceans. The cool, wet marine climates of northwestern North America and Europe produce particularly favorable conditions for salmon. In these climatic zones the temperature of the groundwater that feeds the streams in which salmon spawn generally ranges from 3° to 10°C. Winters are mild and summers are cool so that the streams, rivers, and lakes seldom freeze solid nor rise above 20°C, a range which spans the limits of temperature tolerable for salmon of all species. Optimum temperatures for the development and growth of salmon vary between these extremes according to species and race but are generally close to the average temperature of groundwater in the center of the spawning range of the stock being considered.

Table 1.—Tolerable and preferred sea-surface temperature for Pacific salmon.

Species	Tolerable range °C	Preferred range °C	Reference months for preferred range
Sockeye	1-15	2,3-9	May, September
Chum	1-15	2,3-11	May, September
Pink	3-15	4-11	May, June
Coho	5-15	7-12	May, June, July
Chinook	2-13	7-10	July, August, September
Cherry (masou)	5-15	7-12	March, April, May

On the high seas, the temperature preferences of salmon are harder to determine. A range from 2° to 12°C for Pacific salmon was inferred from observations of surface water temperatures taken concurrently with gill net sets from fishery research vessels operating in the North Pacific (Table 1). The order of preferred temperatures for the different species is: sockeye, *O. nerka*, and chum, *O. keta* < pink, *O. gorbuscha* < chinook, *O. tshawytscha* < coho, *O. kisutch*, and cherry, *O. masou*.

The stage of development at which salmon can effect the change from fresh to salt water also varies with species and race, ranging from newly hatched fry to large fingerlings several years old. For the different species the size at which salt water can be tolerated generally follows the order: chum and pink < sockeye < chinook < coho < cherry and Atlantic.

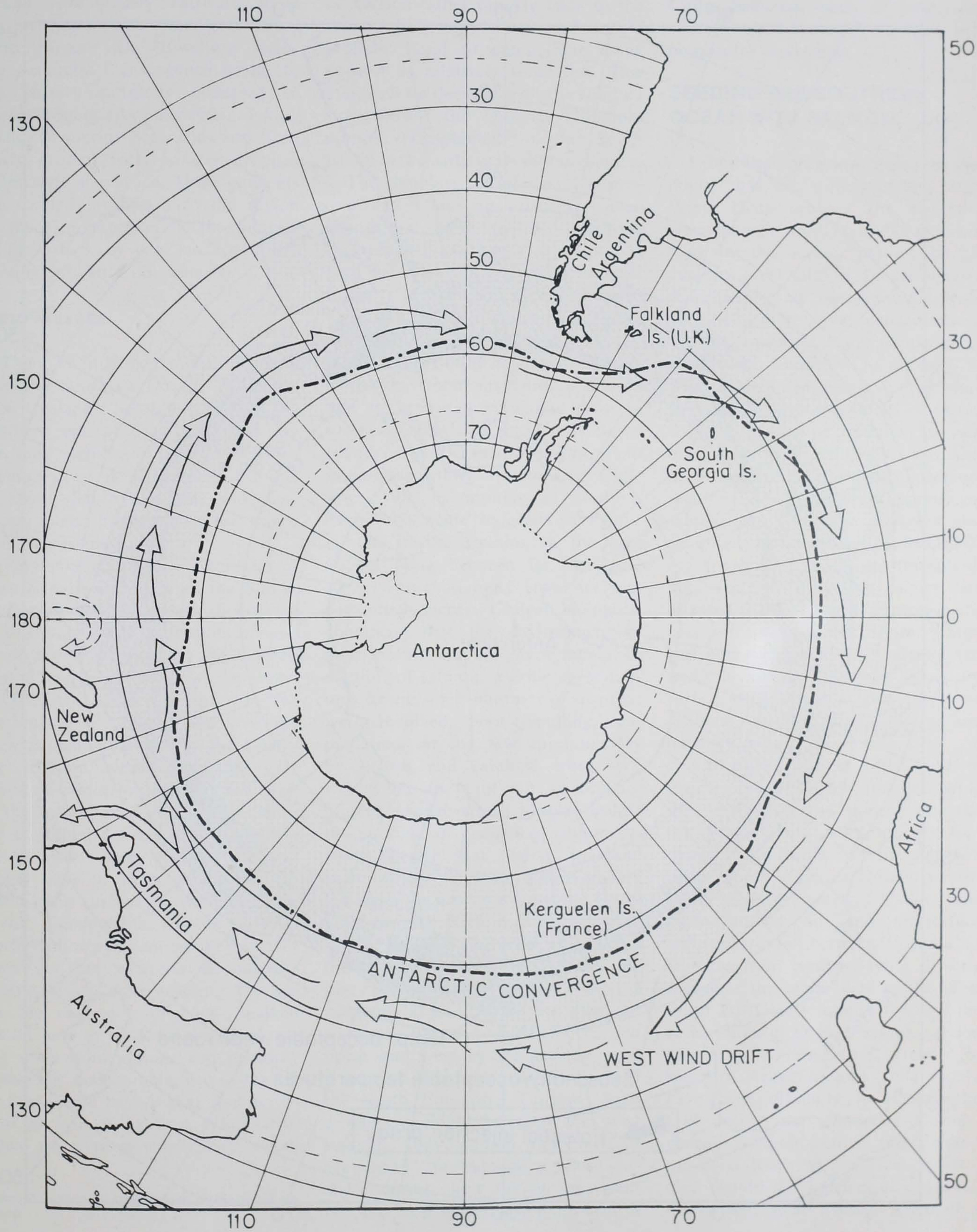
THE SOUTHERN OCEAN

The seas surrounding Antarctica gird the earth unbroken by any significant land mass. No longer regarded merely as the confluence of the Pacific, Atlantic, and Indian Oceans, they are now recognized as a distinct body of water which is coming to be called the Southern Ocean by geographers and oceanographers around the world.

The West Wind Drift

Bounded on the north by the Subtropical Convergence near lat. 40° S and on the south by the ice-covered mass of Antarctica, strong westerly winds drive the waters of the Southern

Figure 2.—The West Wind Drift.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ANTARCTIC CONVERGENCE
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WEST WIND DRIFT
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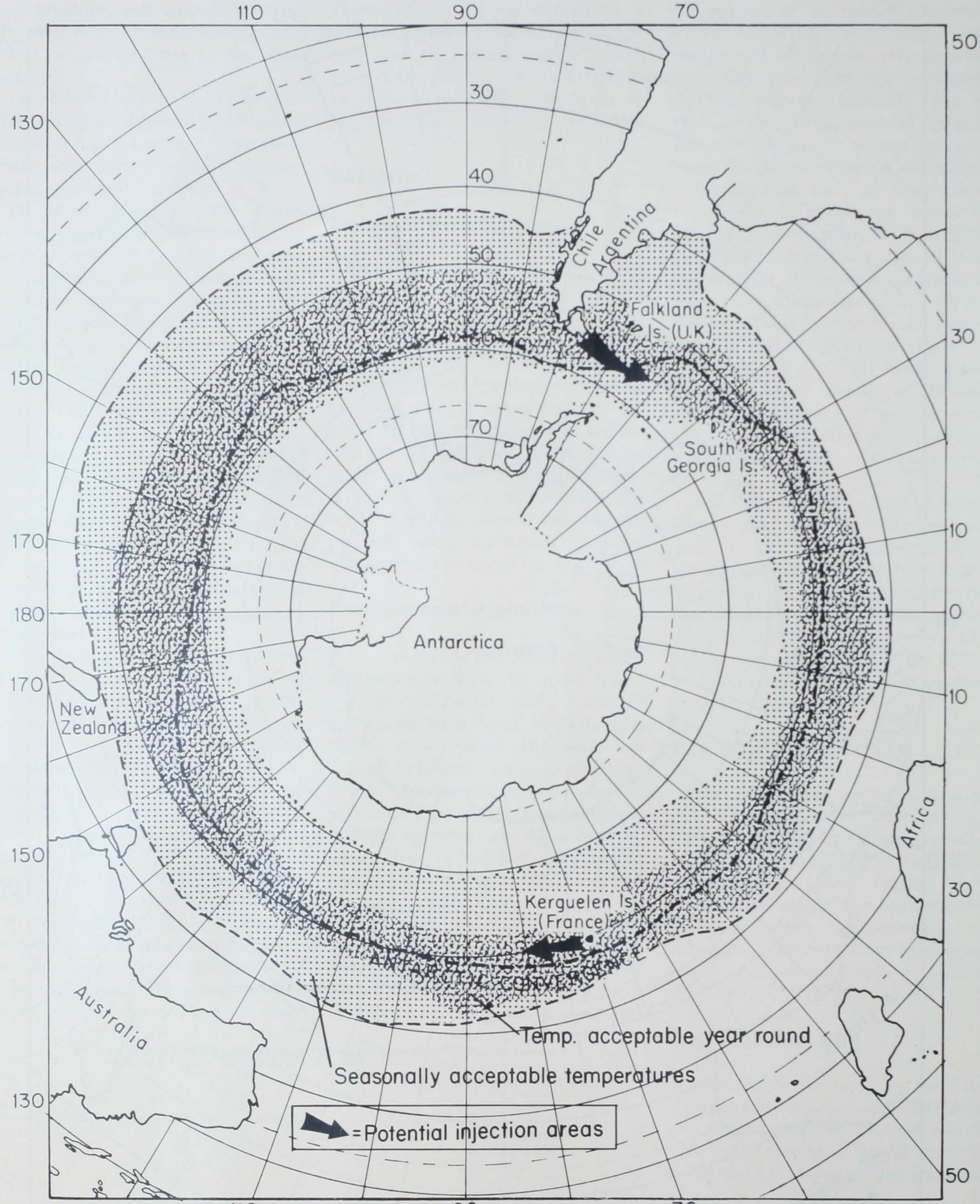

Chile
Argentina
Falkland Is. (U.K.)
South Georgia Is.
Antarctica
New Zealand
Australia
Africa
Kerguelen Is. (France)
ANTARCTIC CONVERGENCE
Temp. acceptable year round
Seasonally acceptable temperatures
=Potential injection areas

Ocean continuously eastward in a current known as the West Wind Drift (Figure 2). Upwelling inside the Antarctic Convergence brings to the surface nutrients dissolved in deeper waters from decayed, sinking bodies of marine organisms and from finely ground rock powder dropped by melting glacial ice. These nutrients are carried northward to the region of the Convergence, in the vicinity of lat. 50° S, by cold surface waters flowing outward from Antarctica.

Land Masses

There is little penetration by land into the Southern Ocean. Tasmania, New Zealand's South Island, and the southern end of South America are the only significant land masses impinging upon it. There are also the Falkland, South Georgia, and Kerguelen Island groups and a few minor Antarctic islands.

Tasmania and South Island lie at the northern extremity of the Southern Ocean where the major divergence of the West Wind Drift splits off and heads northward through the Tasman Sea to merge with the warm waters of the Australian Current. On the eastern side of South Island, over the New Zealand Plateau and the Chatham Rise, a weak, clockwise gyre sends water northward along the coast to the Subtropical Convergence. Salmon migrating to sea from Tasmania or the west coast of New Zealand would have to swim great distances against the current to reach the Antarctic Convergence. Those drifting north with the current would probably perish as they were carried into the subtropics. Salmon entering the sea on the east side of New Zealand would tend to circle in the gyre over the sea-bottom plateau and probably would not find suitable feed as readily as they would have if they had gotten into the krill of the West Wind Drift. Since the gyre is small, they would be carried rather quickly back to the coast of South Island and would probably tend to enter their home streams as relatively small fish. This may well be the case with the residual stocks from the Quinnat (chinook) salmon transplanted to the South Island in the early years of this century.

Figure 3.—Salmon environment in the Southern Ocean.

The southern extremities of Argentina and Chile and the Kerguelen Islands lie close to the Antarctic Convergence and krill-rich waters. In both areas a cool, wet Marine West Coast Climate prevails. Combined with the deeply indented coastlines rising to hilly or mountainous terrain—which typifies these two regions—environments are produced that are strikingly similar to those of southeastern Alaska and the Aleutian Islands, which contain some excellent salmon spawning streams. In Chile since 1905, a number of attempts have been made to establish Pacific salmon in the streams of the lake district lying between lat. 38° and 42°S. These attempts have not met with much success. Chilean biologists, convinced that the environment in their country should favor the introduction of salmon, ascribe these failures to the small numbers of ova that were involved, poor handling, and predation on the few surviving fry by brown and rainbow trout. We would like to point out an oceanographic feature which weighs against the survival of sea-going salmon introduced into that region. In those latitudes, the dominant oceanographic feature is the northward-moving Humboldt Current. Rich in feed and cooled by the upwelling of deep water along the coast, it would be an attractive lure to sea-going salmon. Moving randomly as they fed on the abundant small sea life, they would be carried north and west by the current until it merged with the warm waters of the South Equatorial Current. Such a journey would be fatal for most salmon. Only salmon that have a propensity for remaining close inshore during their life at sea could become established in south-central Chile. Selected races of coho and cherry salmon would be the best choices for this region.

SEEDING THE SOUTHERN OCEAN WITH SALMON

From the foregoing it can be deduced that the waters of the West Wind Drift provide the Southern Hemisphere's most favorable environment for the oceanic part of the life cycle of most salmon. In the zone of upwelling inside the Antarctic Convergence where great concentrations of krill are found, water temperatures range from about 7° to about 2°C. Such a regime would favor the more northerly distributed stocks of chum, sockeye, and pink salmon as candidates for transplanting to the Antarctic (Figure 3). The stage of development at which different species of salmon can enter salt water is also an important consideration for selecting appropriate stocks for transplanting. The earlier young salmon are released to go to sea, the lower is the cost of operating hatcheries. Chum and pink salmon fry can tolerate salt water as soon as the yolk sac is absorbed. If released at this stage, no artificial feeding is necessary and hatchery costs are minimal.

Although there is little land in the Southern Ocean for providing the freshwater environment essential for the early life of salmon, the topography and climate of the southern tip of South America closely parallel those of southeastern Alaska. The mean annual air and sea-surface temperatures fall between 7° and 8°C. Starting from a coast lying directly alongside the main body of the West Wind Drift as it funnels through the constriction of Drake Passage, salmon migrating to sea from streams in southern Argentina and Chile should have little difficulty in finding the krill inside the Antarctic Convergence. Assuming that they would move randomly as they fed on krill, they would be carried eastward in the current at an average speed of 1 knot. At lat. 50°S they would complete one circuit in about 2 years and two circuits in 4 years. Or, they might choose to stay in the rich krill concentrations of the Scotia Sea to the southeast of Cape Horn. In either event, the mingling of freshwater runoff from the Andes Mountains with the waters of the West Wind Drift should lead them readily back to the coastal area where they were spawned.

The Kerguelen Islands in the Indian Ocean sector, with mean annual air and sea-surface temperatures close to 5°C, lying directly in the zone of the Antarctic Convergence, could also possibly serve as a land base for transplanting salmon into the Southern Ocean.

Introduction of salmon on a scale sufficient to generate a significant fishery in the Southern Hemisphere will have to confront the basic problem of initially injecting large numbers of suitably adapted stocks from a strategically located land base into the West Wind Drift close to the Antarctic Convergence. The initial injection should be sufficiently massive that enough would survive the difficulties of inverted seasons and an alien geography to produce a growing population with each successive cycle. Stocks of chum and possibly sockeye or pink salmon adapted to Arctic waters released from southern Chile and Argentina or the Kerguelen Islands, should move across the temperature gradient until they passed the 5°C isotherm just inside the Antarctic Convergence. There they should find plenty of krill.

Soviet experiences with transplanting pink salmon to the Murmansk area of the European Arctic from Sakhalin Island in the Pacific Ocean provide us with some valuable insights regarding the problem of large-scale transplants. From 1956 to 1961, transfers of from 4 to 46 million roe were made between fish culture stations in Sakhalin and Murmansk. Ocean survival was good and the returns peaked in 1960 when 300,000 adult pink salmon entered streams in the Murmansk area, with smaller numbers showing up along the coasts of Norway, Iceland, and Great Britain. The runs subsequently dwindled, as the roe from the returning spawners perished during incubation, the winters being considerably colder around Murmansk than on Sakhalin, home of the parent stock. These Soviet experiences suggest strongly that plans for mass transplants to the Southern Ocean should involve initial releases of millions of fish. There should also be provisions for recapture of a significant fraction of the homing migration to take eggs for artificial incubation. It would be too risky to rely on natural stream spawning to maintain the transplanted population.

In our opinion, a hatchery and suitable fish traps should be built on the southern coast of Chile or Argentina. As many eyed eggs of Arctic stocks of chum salmon as could be collected would be shipped to the hatchery for incubation and released as swim-up fry. The hatchery should be as close to the sea as possible so that the fry on their way downstream to the ocean would not be spotted easily by birds. The hatchery would consist of low-cost gravel type incubators (Figures 4, 5). Feeding would not be necessary as the fry would be released as soon as the yolk sacs were absorbed. Returning adults would be collected in Alaska-type salmon traps

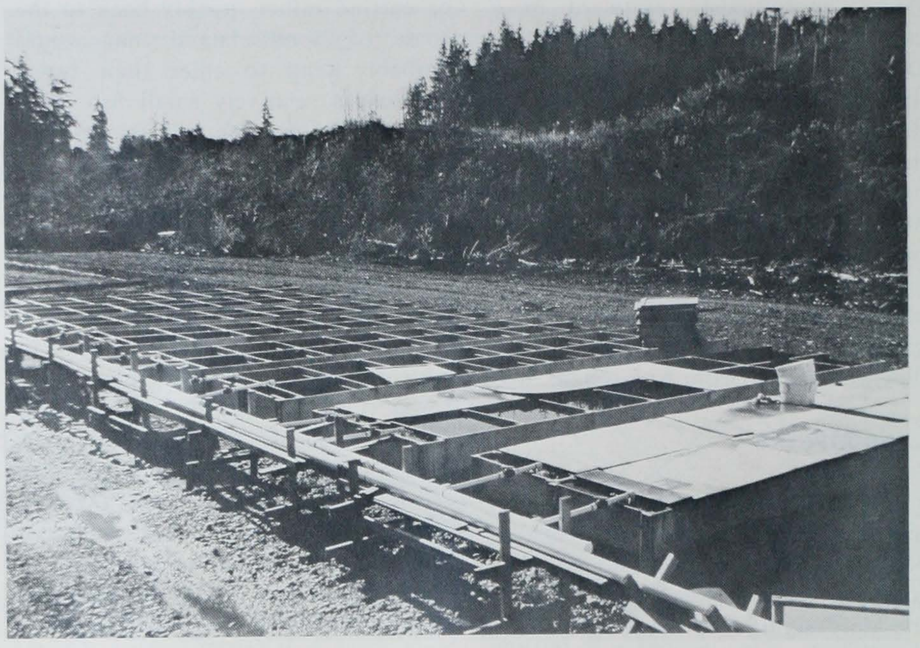

Figure 4.—Low-cost gravel incubators, Quinault Indian Reservation, Washington.

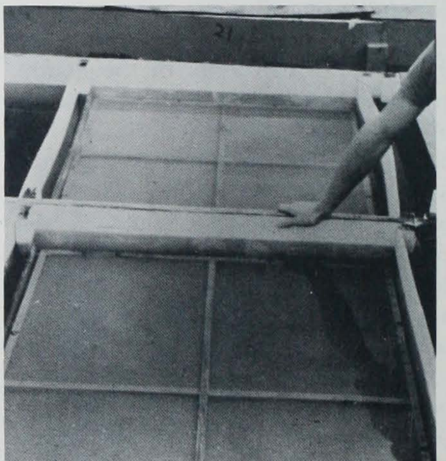

Figure 5.—Detail—gravel incubator.

Figure 6.—Aerial view of floating salmon trap, Alaska.

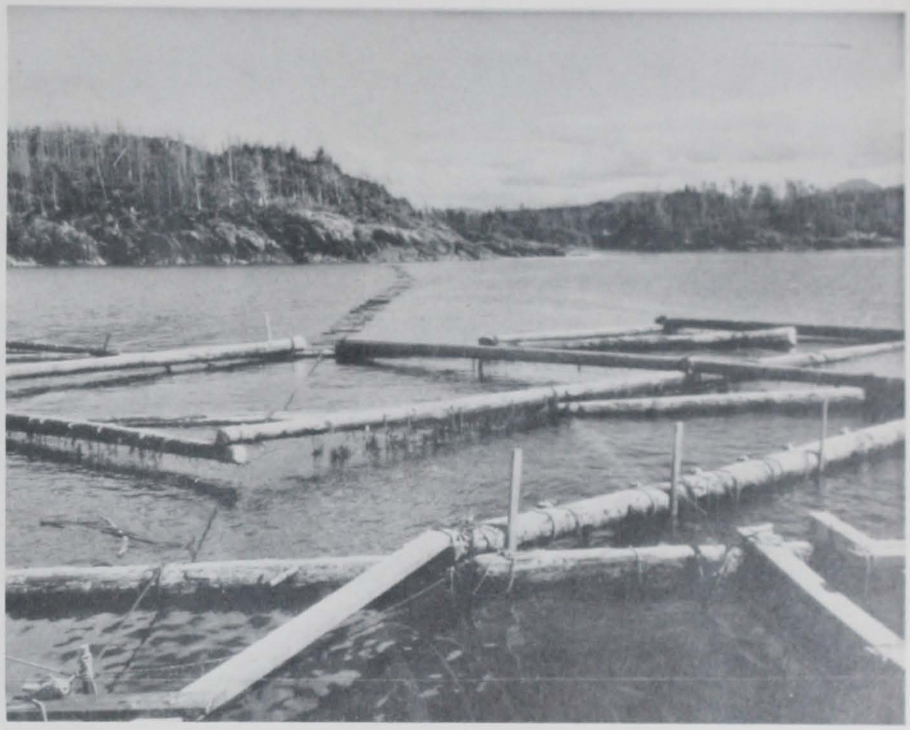

Figure 7.—Closeup view of floating salmon trap, Alaska. (Photograph courtesy of Fisheries Research Institute, University of Washington.)

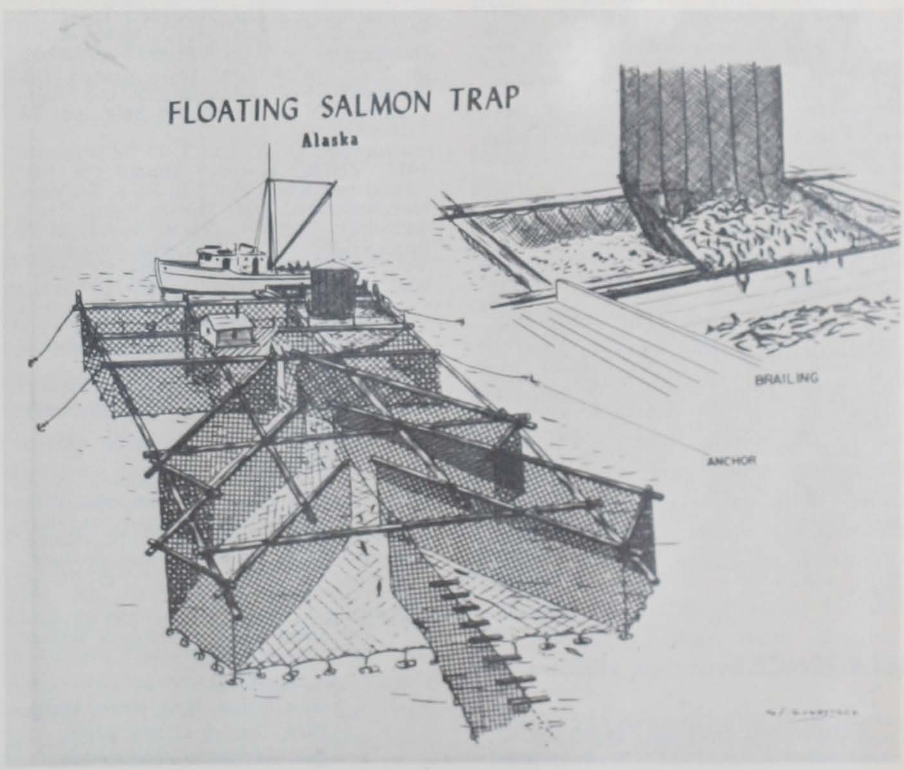

Figure 8.—Detail, floating salmon trap, Alaska. From Sundstrom, Gustaf T., 1957. Commercial Fishing Vessels and Gear. U.S. Fish and Wildlife Service Circular 48.

Icebergs of the Southern Ocean. (Photograph courtesy of Wm. H. Curtsinger, National Science Foundation.)

of proven efficiency (Figures 6-8). Eggs would be shipped by air in refrigerated containers for four successive years. By then the probable success or failure of the experiment should be discernible.

If successful, the experiment would point the way to a low cost hatchery-trap system for harvesting Antarctic krill resources as nutritious, highly marketable salmon. The efficiency and consequent low energy cost of such a system should make it not only an ecologically desirable alternative to the whale fishery, which is threatening these rare and unique animals with extinction, but also an economically viable alternative to a potentially expensive high-seas krill fishery.

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