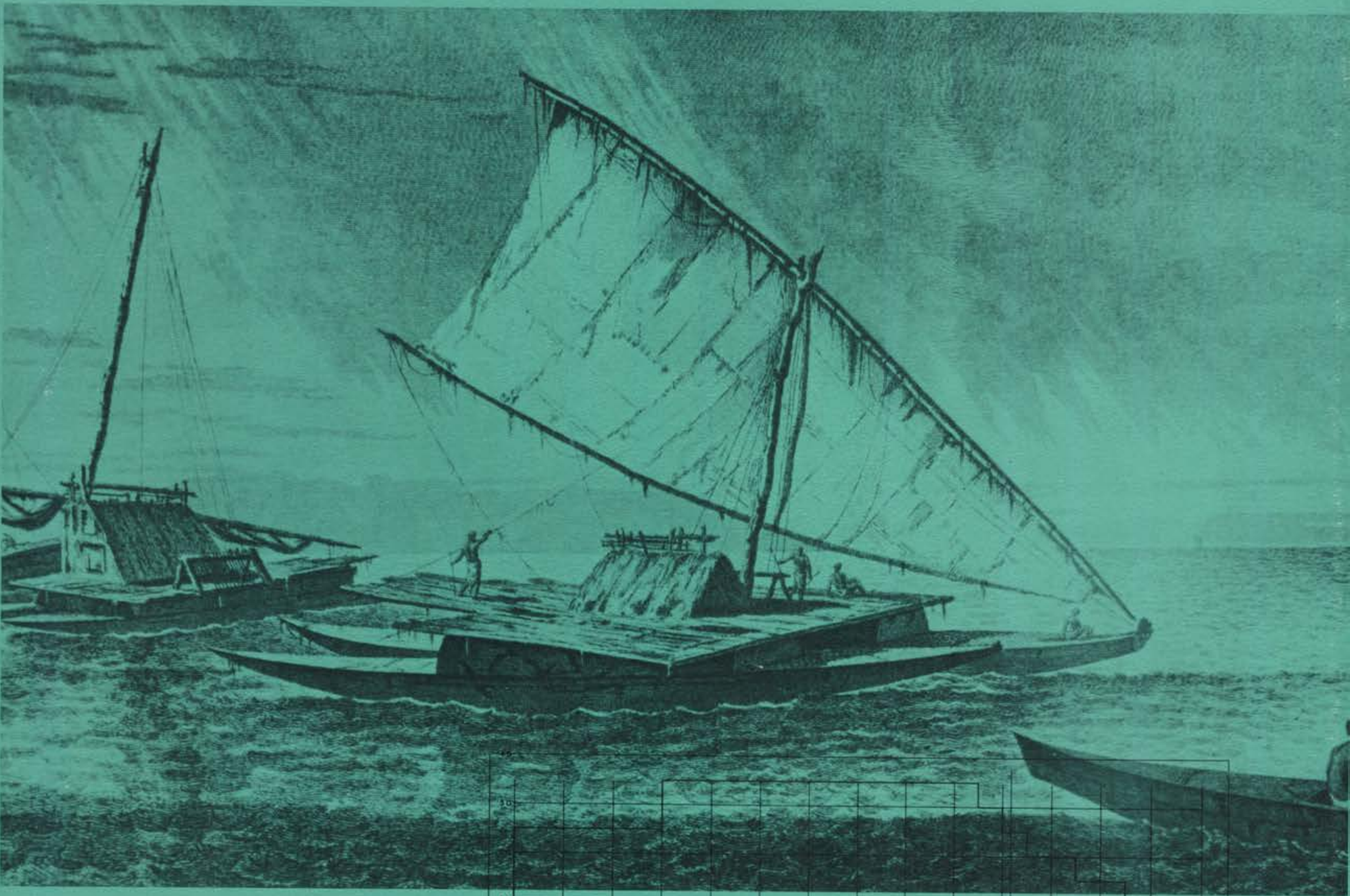
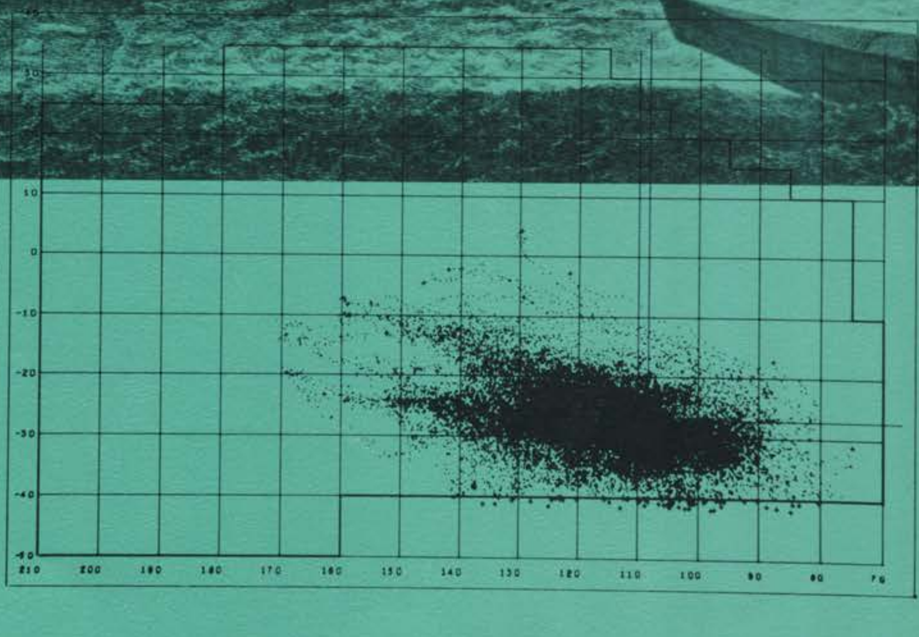
THE SETTLEMENT OF POLYNESIA





A Computer Simulation

MICHAEL LEVISON ■ R. GERARD WARD ■ JOHN W. WEBB

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The Settlement of Polynesia
A Computer Simulation

by **Michael Levison, R. Gerard Ward,** and **John W. Webb,** with the assistance of **Trevor I. Fenner** and **W. Alan Sentance**

For two centuries people have argued about how the multitudinous islands of Polynesia, flung over some twelve million square miles of ocean and separated by hundreds of miles from the nearest continental coasts, came to be discovered and settled by a single people at a time when navigators of the "civilized" world scarcely ventured willingly beyond the sight of land. Much writing and research have focused attention on the subject in recent years. Now, in a new approach to the question, the authors of this volume report on their use of computer techniques to provide new answers to some of the problems that are central to the controversy.

The research project they report upon is of two-fold interest—first, for the light it throws on the riddle of the settlement of Polynesia, and, second, as an innovative

SEE BACK FLAP

Illustration from *A Voyage Towards the South Pole and Round the World* by James Cook, London, 1777
From a painting by W. Hodges
Courtesy of the James Ford Bell Library
University of Minnesota

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MICHAEL LEVISON □ R. GERARD WARD □ JOHN W. WEBB

with the assistance of Trevor I. Fenner and W. Alan Sentance

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PREFACE

For two centuries people have talked, written, and argued about how the multitudinous islands of Polynesia, flung over some twelve million square miles of ocean and separated by hundreds of miles from the nearest continental coasts, came to be discovered and settled by a single people at a time when navigators of the "civilized" world scarcely ventured willingly beyond the sight of land.

Two books published in 1963 demonstrated the continuing interdisciplinary interest in this question. The first, *Polynesian Navigation* (ed. Jack Golson), was in the words of its subtitle *A Symposium on Andrew Sharp's Theory of Accidental Voyages.* The second, by Andrew Sharp, restated the basic argument he had published in 1956 under the title *Ancient Voyagers in the Pacific.* In the intervening years his theory had been criticized by many writers but as often as not the criticisms were based on misreadings of his text. In publishing *Ancient Voyagers in Polynesia* in 1963 Sharp sought to express his ideas more precisely and to make clear that he believed Polynesia had been settled by one-way voyages of exiles or by people blown off course while at sea. Neither of the 1963 volumes produced a final answer to the question of how the Polynesians' ocean crossings were made. An incontrovertible answer can never be provided, for the motives of men and the means they used to achieve them in the prehistoric past can only be inferred with different levels of uncertainty.

In 1964 two of us who were working in the Department of Geography, University College London (R. G. W. on the staff and J. W. W. visiting from the University of Minnesota) discussed the possibility of applying simulation techniques to the problem of Polynesian settlement in the hope that if a satisfactory model of Pacific voyaging could be devised, the area over which speculation was based on very limited empirical data might be reduced.[1] A simple model of the Pacific Ocean was designed quite quickly, incorporating winds, currents, islands, and drifting vessels. It was refined in the course of riding on London buses and during a field trip at Aberystwyth. At this and later stages the comments of our colleagues at University College were most helpful.

It soon became clear that a large computer and much programming skill were needed to implement the model, and so Michael Levison of the Department of Computer Science, Birkbeck College, London, joined the project. W. Alan Sentance and Trevor I. Fenner of the same department also assisted in various stages of the computation.

During 1965 and 1966 the basic data were collected. Through G. M. Rattray, Marine Division, United Kingdom Meteorological Office, and the staff of the Office's archives, we were able to use the tabulations prepared for wind and current charts of the Pacific and over five thousand tables of wind and current observations were transcribed on specially printed file cards. In this task R. G. W. was helped by his father, R. H. Ward. Information on survival at sea was sought from the Admiralty and the advice and guidance of E. C. B. Lee, secretary of the Naval Life Saving Committee, Bath, was especially valuable. Information on island locations and characteristics was obtained from Admiralty charts and other standard sources. Helpful comments, data for various parts of the model, or the opportunity to see prepublication versions of their work were provided by

1. To be more specific, J. W. W. talked about the value of simulation methods over coffee one morning, and a little later R. G. W., while sitting in the bath, thought of applying them to the "Polynesia problem."

C. R. Edwards, B. Finney, T. Heyerdahl, H. H. Lamb, and D. Lewis.

Once the wind and current tables had been transcribed, the mammoth task of keypunching, assembling on to magnetic tape, and checking began. The organization and programming involved in this task was undertaken by Alan Sentance, to whom the authors are deeply indebted.

Simultaneously with these operations M. L., with the assistance of Trevor Fenner, started writing and testing the programs for the model. At this time many refinements were incorporated; for example, a spherical earth replaced the earlier flat earth. Other improvements substantially reduced the amount of computing time, bringing it within practical limits. In this regard, the many suggestions of Trevor Fenner were invaluable. These were often made during the evening rush hour on the London Underground, and London Transport should perhaps be congratulated on providing such productive seminar facilities in their trains and buses.

At a later stage Mrs. Lorna Moore, chief programming advisor of the University of London Institute of Computer Science, was very helpful in smoothing the course of the work through the University of London Atlas computer. Her staff and the machine operators have also incurred our gratitude.

The first experiments on the computer were run in 1967. A preliminary paper on the method had been read at the Institute of British Geographers meeting in Sheffield in January 1967 and the first results, together with some details of the program, were presented at the International Federation for Information Processing Congress in Edinburgh in 1968. Other reports were made to the Australian and New Zealand Association for the Advancement of Science Congress in Christchurch, New Zealand, in 1968 and the International Geographical Union Commission on Quantitative Methods meeting in London in 1969.

In August 1967 R. G. W. moved to the University of Papua and New Guinea, but M. L. continued work in London, being joined there by J. W. W. for some months in late 1968. The design and computing of variations of the model were completed in mid-1970, shortly before M. L. moved to Queen's University at Kingston, Ontario. The original draft of this text was prepared in the first three months of 1971 at University College London by R. G. W. and J. W. W., and at Queen's University where the three of us were able to work together in one place for the first time. We are grateful to the departments of geography in both institutions for allowing us to use their facilities.

We have received financial assistance from a number of sources and wish to ackowledge our indebtedness to the Central Research Fund, University of London; the Graduate School, the Office of International Programs, and the College of Liberal Arts, University of Minnesota; the University of Papua and New Guinea; and the Interim Research Committee, Queen's University. The computations were carried out on the Atlas computer of the University of London Atlas Computing Service and the Science Research Council Atlas Computing Laboratory, Chilton, England, without whose help the project could not have been undertaken.

We are most grateful for the assistance received from the individuals and institutions named above and also to those, too numerous to name, who have answered our inquiries, given freely of their knowledge, and asked the awkward questions which have forced us to incorporate improvements in the model system and recognize its weaknesses. For these we alone remain responsible.

Michael Levison
R. Gerard Ward
John W. Webb

Kingston, Ontario
March 26, 1971

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THE SETTLEMENT OF POLYNESIA

A COMPUTER SIMULATION

Chapter One

PROBLEM

European navigators did not cross the Pacific Ocean until the sixteenth century. Another two centuries passed before Cook and his contemporaries removed *Terra Australis Incognita* from European world maps and revealed the Polynesians' *Te Moananui a Kiwa* — the Great Ocean of Kiwa — and its many islands. They found that most of the habitable islands were, or had been, occupied. First the navigators, and later the scholars, debated in their Eurocentric way how peoples, whom they called savage and primitive, could have crossed this largest ocean when they themselves with an advanced technology had only recently found the power to make such voyages. The continuing debate has focused on the Polynesians, who occupied the triangle between Hawaii, New Zealand, and Easter Island (Fig. 1), together with a scatter of small islands to the west, deep in Melanesia, and along the southern border of the island realm of Micronesia.

Polynesia,[1] virtually unknown until the late 1760s despite two centuries of Spanish and Dutch voyaging to the north and west, was revealed to European eyes at just that time when the idealization of natural man by the French *philosophes* enabled a myth of native bliss to be most easily established. The partial evidence of the navigators indicated that the Polynesians enjoyed a carefree life in which sexual liberality was the norm and a generous Nature provided a bountiful supply of food. This image, fulfilling the idea of the noble savage, has wrapped the Polynesian of literature and legend in a cocoon of romantic unreality to the present day. And so, despite the equal applicability of questions of origins, motives, and means to the settlement of Melanesia and Micronesia, the question of whence and how came the Pacific islanders became the "Polynesian problem."[2]

The theories were numerous and ranged from a claim that the Polynesians were the survivors of a lost continent living on the land fragments that had survived disaster to proposals that the Polynesians had come from the Middle East, or India, or Southeast Asia, or the Americas.[3] A more recent thesis argues that Polynesian society did not emerge until the peoples who formed it had already entered the triangle. Before this notion is discussed, however, we must examine briefly the alternative theories of ultimate origin; those arguing for settlement from the west and an Asian origin, and those favoring an eastern (i.e., American) origin.

Sir Peter Buck (Te Rangi Hiroa) is representative of those who favored an Asian origin. He thought a southerly route through Melanesia unlikely as it would have led to the adoption of certain customs and artifacts and to racial mixing with the consequent appearance of "Negroid characteristics" among the Polynesians. A northerly route through a Micronesia as yet uninfluenced by "Mongoloid elements" was more likely.[4]

Thor Heyerdahl, the strongest proponent of an eastern origin, argued in 1941 that there had been two

1. In this monograph we use the terms *Polynesia*, *Melanesia*, and *Micronesia* in an areal rather than a cultural sense. These areas are shown in Figure 1. The Polynesian "Outliers" in and near Melanesia are also shown on this map. The terms *Polynesian*, *Melanesian*, and *Micronesian* do have a cultural context and may be applied to people living outside Polynesia, Melanesia, and Micronesia, respectively. Ontong Java, for example, is part of Melanesia, but occupied by Polynesians, in the terminology adopted here.

2. The subsequent paragraphs do not attempt to give a full summary of past and present theories relating to this problem. For recent, detailed, and extensive reviews the reader is referred to Green, 1967; Howard, 1967; Lewthwaite, 1967; Sharp, 1963; and the various papers of Golson, 1963. Other useful sources are referred to later in this chapter.

3. Howard, 1967:46–60.

4. Buck, 1938:45–49.

migrations into Polynesia from the Americas. The first, from the Peruvian coast, entered by way of Easter Island; the second and more numerous group of migrants came from what is now British Columbia by way of Hawaii. By the *Kon-Tiki* voyage in 1947, Heyerdahl showed that American-Polynesian contact was possible, although, as he himself noted, the voyage did not prove his migration theory.[5] But recent archaeological and botanical research indicates that there was indeed contact between America and some parts of eastern Polynesia.[6] However, as Howard points out, the same type of evidence, together with that of linguistics,[7] physical anthropology,[8] and ethnology, leads most scholars to accept a western origin for a majority of the forebears of the Polynesians and for most of their culture.

In most of the early theories, the Polynesians are considered a distinct ethnic and cultural group, quite unlike the Melanesians and Micronesians to the west. As noted above, the very visible differences between the wavy-haired and light-brown Polynesians and the often crinkly-haired and darker-skinned Melanesians were used as evidence that the Polynesians could not have migrated through Melanesia, which was already occupied. Recently, however, the concept of a distinct people and culture area has been modified.[9] Green suggests that "the theory of a distinctive Polynesian migration or route" may be "replaced with the concept of development within Polynesia itself of the Polynesian racial, linguistic, and cultural patterns which were based on ancestral forms found in eastern Melanesia and in particular in Fiji."[10] Linguistic evidence also can be used to argue that eastern Micronesia was settled by people from the New Hebrides and that central Melanesia was settled from the east later.[11] Emory, who has contributed as much as anyone in recent decades to the restatement and clarification of questions of Polynesian origins, wrote a classic paragraph in 1959:

What now appears most likely is that people of somewhat diverse origins came together in a western archipelago in the Polynesian area about BC 1500, and, in comparative isolation, their descendants, their language, and their culture took on the features which the Polynesians now share in common and which give them their distinctive characteristics. These early Polynesians then moved eastward to the Tahitian archipelago where again, in isolation except for the occasional stray seagoing canoe from the west or a drifting raft from Peru, language and culture took on shapes which were later dispersed by migrant groups eastward as far as Easter Island, southward to New Zealand, and northward to Hawaii, arriving at these terminal points after the beginning of the Christian era.[12]

Population estimates are available for the main Polynesian island groups at the time of first European contact.[13] These figures can be derived from very small initial prehistoric populations at quite low rates of natural increase. Even if there were only one hundred people in New Zealand by A.D. 1000, a rate of growth of 1 percent a year would mean a population of 120,000 by 1770. Lower rates over a longer time span easily give the numbers living in other groups by the late eighteenth century. There is no need, therefore, to envisage large-scale migrations following a steady progression from Asia or America to the scattered islands of Polynesia. Sporadic movements of small numbers of people, perhaps quite unrepresentative of the community from which they came, would be adequate to provide the stock necessary for the emergence of the people of Polynesia and the Polynesian culture.

But even if the question of whence came the Polynesians' ancestors is answered for the moment in general terms, the problem of how and for what reasons they sought and reached the far-flung islands of Polynesia remains open to debate. In the first and second millennia B.C. the ocean to the east, north, and south of eastern Melanesia was a space frontier as the solar system is today. In some respects it was even more remote and unknown, for, to the watcher on the shore, the signs of undiscovered lands beyond the horizon were fewer than those of the visible moon and planets which daily reveal their orderly progression to modern man.

In the past, opinion on where the Polynesians' forebears came from has been influenced by current beliefs about how they came. For example, the widely accepted view, as firmly stated by Lothrop, that the balsa craft of the west coast of South America could only be used for short coastal voyages effectively blocked serious consideration of an American origin for some (or all) of the Polynesians' ancestors. This forced Dixon to postulate a successful canoe voyage from Polynesia to Peru and back to explain the presence of the sweet potato in the Pacific islands before the Spanish incursion. If this two-way journey were possible, then almost any two-way route might have been followed by Poly-

5. Heyerdahl, 1952:601, n. 1; 1950A: 230.
6. Heyerdahl and Ferdon, 1961; Green, 1967:221–228.
7. Biggs, 1967.
8. Green, 1967:219–220.
9. Golson, 1972.
10. Green, 1967:236. See also Groube, 1971, for an important review of early settlement in Tonga.
11. Grace, 1964:367.
12. Emory, 1959:34.
13. Emory, 1963; Green, 1967.

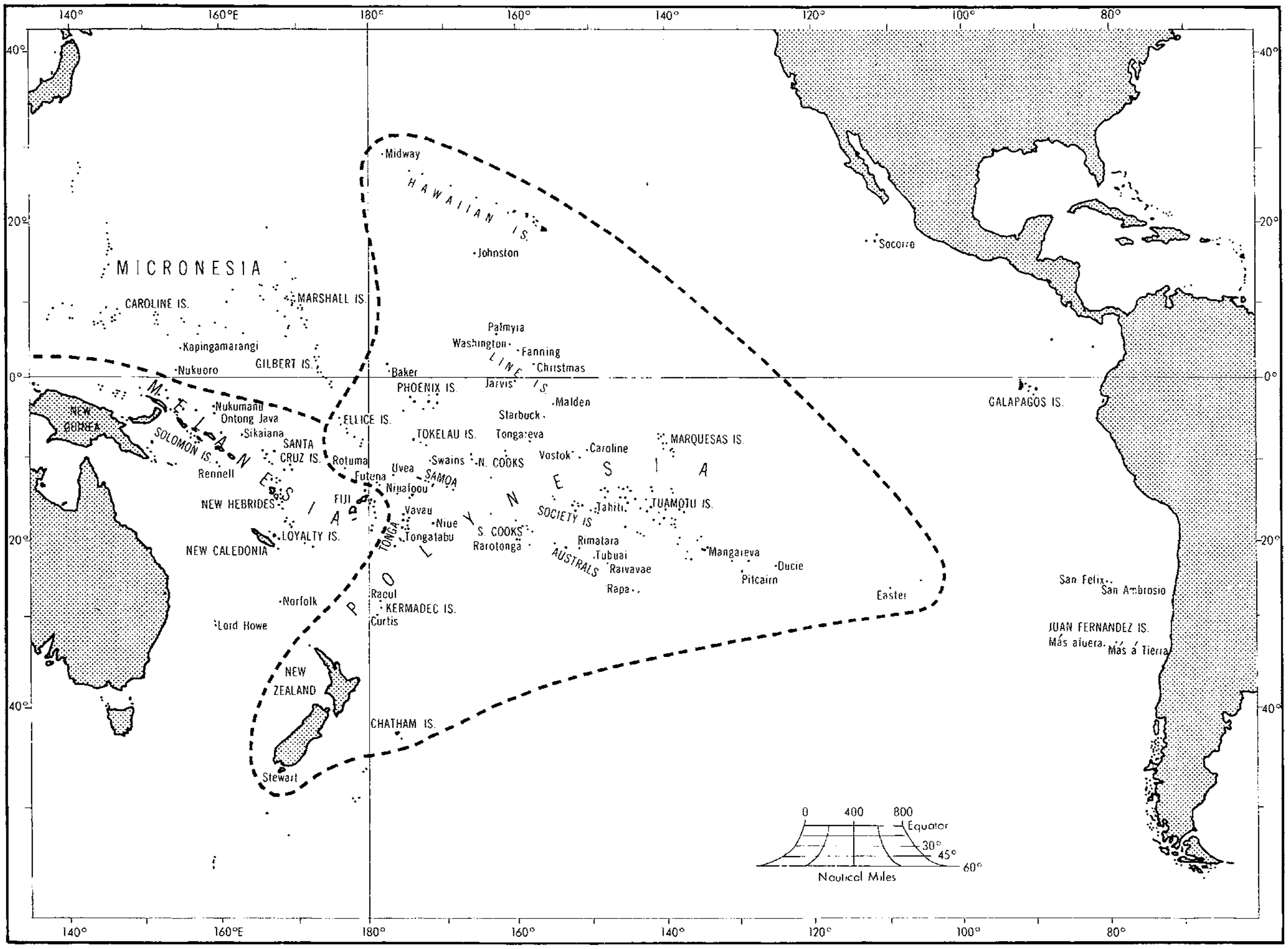


Figure 1. Polynesia: Location map

nesian seamen. Not until 1947, when Heyerdahl proved that the balsa raft was capable of reaching Polynesia, did the possibility of an American origin become a matter for serious consideration.[14] Furthermore, the fact that theories of Polynesian voyaging could, if desired, be formulated without the need to allow two-way navigation over long distances reopened the topic of the means of transoceanic movement by preindustrial peoples. Stated in extremes, the argument is between those who believe that purposefully navigated two-way voyages were made between island groups lying as much as two thousand miles apart and those who maintain that the islanders did not possess the navigational technology necessary for such return journeys. In this latter circumstance the settlement of Polynesia must have resulted from one-way voyages either by navigators deliberately searching for new islands or by people who had accidentally lost their bearings at sea and drifted to a chance landfall.

This question, which has implications for the wider discussion of transpacific contacts and the diffusionist-isolationist dispute, has received much attention since 1956. The publication of Sharp's *Ancient Voyagers in the Pacific* rekindled interest in this set of problems and since then the controversy has generated much heat, some light, and innumerable papers, monographs, and books.[15]

The debate on how men first reached the Pacific islands began soon after the European navigators realized the extent of the area occupied by the Polynesians. Cook, recognizing the essential unity of the

14. Lothrop, 1932:238. Dixon, 1934:174. Heyerdahl, 1952: 513–620.

15. For example, Åkerblom, 1968; Finney, 1967; Frankel, 1962; Golson, 1963; Heyerdahl, 1968; Lewis, 1964A, 1966, 1970; Sharp, 1956, 1963.

Polynesian "nation," apparently came to believe that "the inhabited islands in this Sea have been at first peopled" by castaways.[16] During the nineteenth century a large body of legends concerning their origins was collected from the islanders. Interwoven with old myths and laced with newer, post-European additions were tales of purposeful voyages to seek new lands or search for lost canoeists. According to these stories, the ancestors had, on occasion, set out from their homelands, discovered new island groups, and returned home to pass on the necessary sailing directions to their kinfolk. Either immediately or at some later time their descendants followed the guiding stars, sun, swells, and winds to settle the new lands. For those who accepted this theory, the traditional evidence sufficed to show that two-way voyages took place.[17] Given that this was so, the Polynesians must have had navigational techniques sufficiently accurate to give them a reasonable chance of a safe and predicted landfall after long periods at sea. Most writers noted that swell direction, stars at night and the rising and setting sun during the day, migrating birds, fish, reefs, and a multitude of signs of land were all used as guides.[18]

Although some indicated that "accidental drifting" probably played an important role in the settlement process[19] and others[20] expressed doubts about the reliability of traditions as datable evidence, few queried the underlying assumptions implicit in an acceptance of the traditional view of settlement over long distances by two-way voyaging. Sharp, however, attacked these assumptions. In brief, he argued in 1956 and again in 1963 that there was no reliable evidence[21] of intentional two-way voyaging over distances greater than 300 or 350 miles. Furthermore, over distances greater than this, it is virtually impossible to maintain an accurate course by use of guiding stars and dead reckoning because of the risk of obscured skies, changes in the direction of wind and swell, and particularly, the inability to record and counter lateral drift. On the other hand, there is sufficient evidence in the historical record of one-way voyages without precise navigation to allow "accidental settlement," or "one-way settlement" as he later termed it, to account for the occupation of all of Polynesia. Such voyages might result either from voluntary or forced exile from a home island or from vessels being blown off course by storms and becoming lost.[22]

Sharp's thesis attracted immediate attention with acceptance by some and rejection by others. It is, however, a thesis which is difficult to test, in part because of the very nature of drift or "one-way" voyaging. The evidence provided by voyages recorded in the last two centuries is inevitably incomplete. Most failures are unrecorded. We know little about the frequency of voyages in total or in relation to the population of particular groups. There is little comparative data on the varying propensity of different peoples to put to sea and thus to be exposed to the risk of loss or drift. And a basic question always remains — is the evidence of the last two centuries applicable to the last three millennia?

Most of the argument to date consists of varying assessments of the relative difficulties posed by the problems of navigation over long distances, the sailing qualities of Pacific craft, the wind and current conditions in the Pacific, and the interpretation of the record of known voyages.

The navigation issue has drawn the most response. In the absence of convincing documentation many observers mix supposition with firmer evidence to form a rather unstable mortar. Suggs points out that the techniques of navigation used by the Polynesians are "not known to us in any detail" and criticizes those who, on this basis, "hypothesize that precise methods never existed."[23] But if the techniques are "not known to us in any detail," one cannot argue convincingly that in fact "precise methods" did exist. And although all would accept that stars were used for bearings, such a guide is of strictly limited value over long distances in the absence of any measure of longitude.[24] Indeed the same is true in the absence of a measure of latitude, and though some argue that the zenith star method provides such a measure,[25] Frankel concludes after careful analysis that it would be "too inaccurate for midcourse guidance" and that, except when sailing east or west on the equator, it is too inaccurate for steering when close to a destination. Latitude sailing might be used, provided the zenith stars of the destination were known in advance — but of course such foreknowledge implies earlier two-way voyaging and thus leads us into circular

16. In Beaglehole, 1967A:87.

17. Howard, 1967, and Lewthwaite, 1967, provide recent and thorough reviews of the varied positions of different scholars and there is no need to provide a detailed summary here. Readers are also referred to the bibliographies of these two papers.

18. Dening, 1963:116.

19. Hardy, 1930:23.

20. Buck, 1938:23–25.

21. The traditional evidence of legends was unacceptable due to their late recording with the consequent risk of contamination, and the tendency for people to provide origin myths to account for events whose real history they did not know (Sharp, 1963:75–92).

22. Sharp, 1963:32; 1957:32–56; 1963:33–53; 1957:30; 1963:16; 1957:30–31; 1963:62–74.

23. Suggs, 1960:78–79.

24. Åkerblom, 1968:32–34; Hilder, 1963A:95–96.

25. For example, Gatty, 1958:40.

argument. Lewis shows that latitude sailing could be used successfully when seeking a large target, but Hilder considers it impractical for Polynesians, and Åkerblom contends that Makemson's evidence on the use of zenith stars and latitude sailing by Polynesians cannot be accepted. Åkerblom concludes that navigation by the zenith star method was not used and that "there is a complete absence of proof" for latitude sailing.[26]

Most writers accept that the Pacific islanders were skilled in the art of reading the signs of imminent landfall.[27] Some, however, tend to extrapolate from these skills, which are appropriate for relatively short voyages, to the quite different scale and problems of maintaining a course over long distances.[28] Parsonson apparently feels that "common sense" suggests that "navigational skills which suffice over shorter distances" also might work over distances of up to one thousand miles and that navigational skills "might seem to be founded on that almost uncanny sense of direction which early man perhaps shared with birds and other animals whose existence depends on their capacity to traverse long distances to and fro, winter and summer, across apparently featureless wastes of forest, desert or ocean and which civilized man has so largely lost."[29] Such extrapolation and imaginative conjecture are unwarranted: we must conclude that the verdict on long-distance, two-way navigation remains "not proven,"[30] although Lewis's practical experiments show that accurate landfalls can be made after voyages of several hundred miles.[31]

The way in which winds and currents hinder or assist navigators or drifters is discussed by many writers. Most restrict their consideration to the average or predominant monthly, quarterly, or yearly conditions revealed in various meteorological atlases or navigation charts. Interpretations of this information vary with the author's viewpoint.

Heyerdahl, in arguing that voyages may be made from the Americas to Polynesia with relative ease, likens the wind and current pattern of the east-central Pacific to a "perpetually moving escalator" in which "wind and water constantly travel from one coast to another." Similarly, the currents of the northern Pacific provide "the natural road from southeast Asia to Polynesia" via the waters off the northwest American coast, whereas the route through Micronesia is "against all the prevailing winds and currents."[32] Giving evidence in this general way obscures the variability in winds and surface drifts. Shallow draught vessels are influenced by the surface drift rather than by the more regular movements of water at greater depth. "The primary cause of surface currents in the open ocean is the direct action of wind on the sea surface,"[33] and wind and current atlases show that there is considerable variability in both wind and surface drift direction throughout the Pacific.[34] Practical experience indicates that the "escalators" do not always run in the "right" direction; for example, there was a strong likelihood of the *Kon-Tiki* being swept from a position off the Peruvian coast to the Galapagos Islands or the central American coast and not to Polynesia.[35] Willis also had to navigate his raft away from northward sweeping winds or currents.[36]

Those who argue for a western origin by one-way navigated or drift voyages note the existence in some latitudes of west to east moving currents, such as the equatorial counter current or that to the south of about 35°S.[37] In arguing for the drift hypothesis, Sharp pointed out that wind and current directions are seasonal and that westerlies occur in areas which have prevailing winds from the east.[38] Ferdon discusses how hurricanes and gales bring winds from unusual directions and considers the frequency with which such conditions might occur.[39] Most authors who note the likelihood of unseasonal or unusual conditions have not attempted to assess the statistical probabilities of such events occurring. One is left with the impression that those whose arguments depend on unusual winds or currents take it for granted that they occur often enough to substantiate their claims, while those whose case is supported by the

26. Frankel, 1962:44. Lewis, 1966:91–93. Hilder, 1963B:95. Makemson, 1941. Åkerblom, 1968:39–40, 47.

27. Åkerblom, 1968; Frankel, 1962; Gladwin, 1970; Lewis, 1970; Parsonson, 1963; Suggs, 1960.

28. For example, Suggs, 1960:79ff.

29. Parsonson, 1963:45, 40.

30. We feel that Åkerblom's review of the evidence is convincing and we agree with his conclusion that "from what we know of the navigational methods, however, it might seem justifiable to conclude that they were altogether too unreliable to permit regular contacts over distances, which required a long time at sea out of sight of land. . . . Polynesians and Micronesians accomplished their voyages, not thanks to, but in spite of their navigational methods. We must admire them for their daring, their enterprise and their first-rate seamanship" (1968: 156).

31. David Lewis has been collecting navigational information from Polynesians and Micronesians and testing it in a series of voyages without the aid of instruments or charts. The results to date indicate considerable success with voyages of up to perhaps 400 miles (Lewis, 1966, 1970, 1971B, and 1972).

32. Heyerdahl, 1950B:31; 1951:72.

33. Meteorological Office, 1956:189.

34. Marine Division, 1947, 1956, 1959, 1966, 1967.

35. Heyerdahl, 1950A:84–87.

36. Willis, 1957:77.

37. For example, Heyen, 1963:67; Suggs, 1960:15.

38. Sharp, 1963:105, 123.

39. Ferdon, 1963.

mean situation assume that maverick conditions are too infrequent to invalidate their case. In our research we have tried to cover this problem by taking acount of all the available observations of wind and surface drift direction for the study area.[40] Incorporating the known variability of wind and surface drift for each month for each part of the Pacific removes one element of subjectiveness (or prejudgment) from the argument.

In considering the sailing and endurance qualities of Pacific vessels, the evidence used is also insecure enough to allow disputants to argue that either the vessels were capable of staying at sea for long periods and making headway against contrary winds, or they were incapable of carrying sufficient supplies, tacking effectively or withstanding the strain this would impose on their lashings, and traveling at sufficient speed to cover the necessary distances. For example, Suggs argues (despite *Kon-Tiki*) that Peruvian Indians could not have reached Polynesia on a balsa raft since the prehistoric Indians did not use sails until they were introduced by the Spanish. Furthermore, he implies that they could not have carried sufficient supplies for a voyage to Polynesia.[41] Yet there is abundant proof both for the large cargo capacity of the early rafts and for the use of sail before the Spaniards could have introduced the Peruvians to the technique.[42]

Sharp accepts the evidence of some early observers that "Polynesian vessels could not work satisfactorily against the winds," yet Parsonson believes there is ample contrary evidence that they could do so. On the other hand, Parsonson takes Sharp to task for attributing a speed of only five knots to the Micronesian *prau* whereas they have been reported as being capable of twenty-two knots for sustained periods.[43] But Sharp is reporting the average speed on a specific voyage which would be likely to include periods of lying to with the sail furled (cf. McCoy, unpublished paper). Maximum observed speeds could rarely be maintained for long periods on long voyages, and nowhere in the literature is there an extensive and dispassionate analysis of likely speeds under different wind conditions. Once again the problem has been obscured, rather than clarified, and writers seem to have drawn their wished-for conclusions from the most amenable parts of the conflicting evidence. Recent experimental work by Bechtol and Finney shows that the types of canoes used by Polnesians could maintain speeds sufficient to carry them on long journeys in relatively short times, given reasonable wind conditions.[44] It is also clear that both Polynesian canoes and Peruvian rafts[45] could sail to windward, and the empirical evidence of known voyages[46] indicates that the vessels could survive for long periods at sea.

The accumulated evidence on techniques of navigation, the patterns of winds and curents, and the qualities of Pacific vessels has not yet been used to invalidate any of the conflicting hypotheses of intent or accident, drift or navigation. Where authors do claim such proof (or near proof) there is invariably sufficient conflicting evidence to invalidate their claim. It may be, of course, that the problem defies proof by its very nature. Proof that a drift hypothesis could account for the settlement of Polynesia does not thereby prove that intentional, navigated two-way voyages did not actually produce the same result. Alternatively, even if it were shown that a purely accidental drift hypothesis is untenable, there still remains a wide range of types of voyaging, from one-way drifts by exiles to two-way, navigated, long journeys, which might be responsible.

40. See below, Chap. 3.

41. Suggs, 1960:218, 219.

42. The sail question is discussed in some detail by Edwards (1965:66–80), who also provides evidence for the carrying capacity of these vessels. If the Peruvian Indians were not capable of carrying and storing food for a long voyage, one wonders how the Polynesians could have done so, yet Suggs does not allow this to interfere with his own view of Polynesian voyaging. See also Heyerdahl, 1952:526–527. Lanning, 1970: 176, states that the only vessels capable of making a Pacific crossing were those found along the Panama, Colombia, and Ecuador coasts.

43. Sharp, 1957:41; Parsonson, 1963:39; Sharp, 1957:207; Parsonson, 1963:27, 38. Parsonson seems to confuse the Micronesian *prau* with the Polynesian canoe on this point; at least he quotes the speed of the former (1963:27).

44. Bechtol, 1963; Finney, 1967.

45. Edwards, 1960; 1965:73.

46. For example, Dening, 1963:137–153; Heyerdahl, 1950A.

Chapter Two

METHOD

It is clear from the previous chapter that the main difficulty in assessing the worth of the various theories concerning the settlement of Polynesia is lack of direct evidence. The theories and viewpoints themselves are of varied provenance. Some are tentative and empirical in origin: that is, they come from scientifically acquired facts, and their proposers, relying more on their facts than their theories, will modify the latter when new evidence appears to warrant it.[1] A second approach may begin with the statement of a general theory, proceed to an examination of available facts, and then go on to a restatement or modification of the theory. The works of Heyerdahl and Sharp, dealing with the ideas of American origins and "accidental" discovery respectively, fall into this second category. The advantages and limitations of these two approaches in the context of the Polynesian problem need to be examined briefly to see if some other approach is possible.

Many accepted facts about Polynesian prehistory derive from the use of scientific methods and techniques which have proved useful in dealing with other problems in other parts of the world. Such methods and techniques are often quite neutral and can be applied dispassionately to a problem awaiting elucidation or solution. For example, the gradual acquisition of archaeological evidence from the use of the radiocarbon-14 dating method on prehistoric Polynesian materials is leading to the assembly of a series of facts about early settlements on a number of island groups.[2] As this information becomes more complete it is possible to draw generally accepted conclusions regarding the dates, directions, and stages of settlement in Polynesia. Work on Polynesian languages also gives an expanding body of material that, as empirical information, can be used to derive and modify general statements and theories concerning Polynesian prehistory.[3] Again, certain factual inferences are possible from a comparative examination of a wide range of cultural attributes—from plants and tools to methods and styles of house and boat building.[4] Some of these cultural comparisons fall within the domain of prehistory (though they may be made by workers in many disciplines) and the resulting empirical data can be laid alongside that of the archaeologist and the linguist.

In other instances, it can be useful to examine societies and their cultures as they presently exist, or as they have been in the recent past for which there is a historical record. The results can then be retrodicted or referred back to prehistoric times. This can be a dangerous procedure, and conclusions as to how empirical data from recent or present societies can be interpreted as representing societies of long ago must be hedged about with many limiting, if not negating, statements. Indeed such projections back into the distant past can result in an accumulation of false information which may result in erroneous theory, which in turn can contaminate other hypotheses.

This last problem has been of considerable significance in the long attempt to reach a solution of the question of Polynesian origins and dispersals. But, setting that thorny issue aside, there remains the catch that the assembly of empirical information about prehistoric Polynesia, despite its relative incontrovertability, may bypass the most significant issues and problems. Undoubtedly it is of great interest, given the current state of knowledge, to assemble, with the use of respectable

1. For example, Emory, 1963.
2. Emory, 1968; Golson, 1972; Yawata and Sinoto, 1968.
3. For example, Pawley, 1966, 1967.
4. For example, Finney, 1967.

research methods, information on the locations and dates of early Polynesian settlement. But the really important questions have to do with intent, motive, and thought, and how these relate to action. It is of great interest to know, for example, that the Hawaiian Islands were first settled about A.D. 600, perhaps from the Marquesas with a possibility of later arrivals about A.D. 1200, from the Society Islands. It is infinitely more interesting to know how these extraordinary events in the human occupance of the planet occurred, why the voyages were begun, what solutions were found to problems along the way, and why one course of action was taken as opposed to another. At the present time the small volume of empirical data allows few assays at these problems.

It is of course to solve these questions, or at least to provide partial answers to them, that other approaches have been used. Cases in point are the work of Sharp, who began his study of Polynesian discovery of the Pacific Ocean and its islands with a general statement about the nature of geographical discovery,[5] and Heyerdahl, who began his work with a general theory about the nature of transpacific contacts.[6] That both have modified their views as a result of their own and other's critical examination of their orginal theses does not reflect discredit on those theories but rather gives credit to the nature of their process of acquiring knowledge. But even these theories as now modified are untested by fact, and, like other statements, remain hypotheses only.

Another approach has been used to try to discover the intentions, motives, and beliefs of the early Polynesians. Ethnologists, historians, and gifted amateurs attempted to use the oral traditions of late Polynesian society to provide insights into the thoughts of the men and women who made the voyages.[7] It is fashionable today for social scientists to downgrade humanistic research of this kind (which might be relevant to their problems) because it does not conform to the canons of social scientific respectability. However, we can remind ourselves that work of this kind has the advantage that it does go directly to the real issue—the nature of human life and the people who lived it. The humanist could argue that he need not fritter his time away in attempting a scientific study in a situation where he cannot experiment and cannot make a useful assertion without his honesty being called into question in the learned journals.

5. Sharp, 1957.
6. See above, pp. 4–5.
7. For example, Smith, 1891, 1898, 1904; Buck, 1926, 1938.

To digress for a moment—the social scientist, with his armory of new methods and techniques, can add little to the study of European exploration in the "great age of discovery." The amount of literary and other evidence is so enormous that the problems relating to thought and action in that era have been gone into in enormous detail, and indeed books on the subject fill whole libraries.

In the case of Polynesia, however, the opposite is true. The main events of the discovery and settlement of Polynesia occurred between about 1500 B.C. and A.D. 1500 in a prehistoric situation. With no written sagas and no materials for historic interpretation it is as though we confront the Celtic civilization of the first millennium A.D. without its literature and without the written records of others who were in contact with it. That historical record is the key to a society of immense vitality and interest, yet how humble and even drab it might seem if all that remained were the archaeological record. The Polynesians' oral traditions hardly fill the gap, being full of pitfalls for the unwary, and they can be used to reconstruct the past only with the greatest circumspection. To use them as direct evidence to answer questions about the fundamentals of human existence at the time of the great colonization is highly questionable.[8]

And so the goal remains elusive. Neither the accumulation of empirical evidence, nor adequately tested theories, nor the interpretation of Polynesian traditions are yet able to give an adequate body of knowledge. Put another way, they ask the questions but do not answer them.

Can we escape from this dilemma and move beyond the collection of empirically derived events and the statement of untested theories? The answer is a partial and rather hesitant "yes." First, the continued accumulation of scientifically determined facts will help, because at the present rate of accretion, some theories or ideas about prehistoric Polynesia will be more adequately testable in the future. Some of these theories are actually descriptions of processes which can be enriched or modified as new evidence comes to light. The findings of the study of Polynesian languages provide a case in point. Careful comparison of the languages spoken in western Polynesia allows a partial reconstruction of the lost languages from which they derive. Consideration of these "proto-languages" and their more modern successors, joined to other ethnographical and archaeological facts, leads to the conclusion that "continuous two-way voyaging . . . took place within West Polynesia, probably throughout its prehistory. . . ."[9] This is an im-

8. But still defended; for example, see Parsonson, 1963.
9. Green, 1968:105.

portant statement with many implications about the nature of early or proto-Polynesian society as much as two millennia ago.

Similarly, the continued addition of archaeological materials will add new evidence against which old ideas may be tested and from which new theories may emerge. One might argue that there are already enough theories in the field; however, one can hardly doubt the stimulus to scholarly invention and to the sum of knowledge which has resulted from the work of a Heyerdahl or a Sharp. So we should be glad of new theories, especially those which survive rigorous comparison with the empirical evidence.

Another approach is to take the relevant known facts about the settlement and discovery of Polynesia and attempt to simulate a process which will account for, or help to account for, those facts. In the normal cases of geographic simulation, a spatial distribution of some kind, about which the locational facts are known, can be simulated to a greater or lesser degree of probability.[10] The greater the probability (i.e., the greater the congruence between the facts of reality and the pattern produced by simulation), the more confidence there will be that the processes built into the simulation model system can be used to describe how the distribution in question came about.

We assume a large number of initial starting locations for Polynesian peoples, since the facts concerning initial locations are not known and, as we have seen, there are differing and even rival theories regarding early locations. This makes this particular simulation difficult to manage operationally, and also less easy to interpret because the range of probabilities derived is very large, and ultimately results in a wish to undertake further simulations in an effort to obtain a clear-cut solution.

The process simulated is that of drift and navigated voyaging in the Pacific Ocean, and the distribution to be explained by the processes adopted is that of Polynesian peoples and culture.

The main advantage of a simulation model system is that it substitutes for a lack of direct evidence about the process needed to produce the distribution. True, it may take a considerable effort of will for those who wish for strongly identified empirical evidence to accept probabilities as knowledge. But even to some sceptics, successful simulations can be a remarkably convincing means of deducing processes or of providing information that can be used to infer processes. If a simulation is partly successful, it still has uses, and even if unsuccessful, the negative result can be used to expunge theories about the problem at hand. Whether or not this simulation has been successful in the sense of contributing to knowledge about the process of Polynesian colonization, the reader must judge for himself.

We assume that navigated voyages are not drifts and vice versa. Thus, drifts go with the wind and current, resulting in a track not influenced by consciously prescribed and enacted alternatives, which would be navigation. Navigation implies setting a course or sequence of courses and is a conscious activity directed to some goal, whether that goal is a known landfall or the search for possible homelands across a stretch of unknown ocean. In the drift situation the mariner is passive, being active only to keep the craft seaworthy, sustain himself in good heart and health, and act appropriately when landing becomes possible.

A drift may be involuntary or voluntary. The former is common in the historic record,[11] as when mariners became lost at sea. The latter type is also possible as with an exile who, after being set adrift, lets wind and current determine his track. We can assume, too, that navigated voyages could follow involuntary exile. However, we doubt it worthwhile, given the state of knowledge about prehistoric Polynesia, to speculate on the reasons for or reasoning behind voyages of colonization. For the moment at least we can set ourselves a more modest task and hope that some aspects of the process of Polynesian colonization will be illuminated. If there are further dividends well and good.

Could Polynesia have been discovered (and thus we presume, settled) by drift voyaging? Were navigated voyages responsible? The answer to these questions is unlikely to be an unqualified yes or no for the following reasons. The range of wind, weather, and water conditions in the Polynesian culture triangle Hawaii–Easter Island–New Zealand is enormous, and thus the possibilities of drift or navigated contact will differ from one part of the Pacific to another. Further, voyages from one island to others will occur with varying degrees of chance, or mishaps of different kinds may bring disaster. Put another way, voyages may have different probabilities of success depending on their points of origin, and voyages from the same location may result in landings at different groups of islands with varying degrees of probability. Thus the answer to the research question will be probabilistic, in the sense of relativity and frequency,[12] with varying probabilities for different Polynesian locations and a range of probabilities from each location.

10. A classic simulation study in geography is Hagerstrand's "Propagation of Innovation Waves" (1953).

11. Dening, 1963:138–153.

12. Harvey, 1969:231–239.

There is little need for a discussion of the philosophical or geographical worthiness of a probabilistic approach. These matters are dealt with in admirable fashion by Harvey, and Brown provides a review and bibliography of the literature on diffusion studies.[13] To test the probabilities of drifts and navigated voyages we need a model system consisting of components which pattern the factors bearing on voyages. Each of these factors (wind frequency, wind strength, current direction, survival, sighting distances, etc.) has great variety; for example, an adequate description of wind directions and strengths involves hundreds of thousands of bits of information. The only feasible way of solving the problem of finding the tracks and destinations of voyages on this sea of information is to use a Monte Carlo procedure. A precise mathematical solution is impossible, given the complexity of the model system's parts.

What we do in effect, then, is to construct a random sample of the set of all voyages which might take place under the conditions described by the data. To do this a random choice is made of variables such as the wind direction and speed, each possible choice being weighted in accordance with the observed data. If the random sample is large enough, it will be sufficiently representative to enable us to answer questions about the set of voyages as a whole.

The reader is cautioned to remember that the word *random* merely refers to the process of selection of the sample set of voyages, and not to the data. Nor does it necessarily imply randomness in the event the model hopes to simulate. The colonization of Polynesia could have been a highly structured exercise of organization and might have been carried out with full and complete knowledge as to how it progressed. Randomness is inherent in the research technique; it does not imply such in the events whose probabilities it seeks to discover.

The range and variation of the empirical observations, which are the data bases of the model components of the system, raise another issue. Generally speaking, the number of cases performed in a Monte Carlo situation affects the stability of the probabilities described by the operation of the model system.[14] As the number of cases increases, the probabilities become stabilized. But in our experiments the number of potential directions, speeds, and landings is very large. This matter is discussed below with examples; suffice it to say at this point that after a large number of cases has been run, the approach toward stability is slow; that is, a heavily increased number of cases results in only marginally more stabilized probabilities. This is because the wide range of wind, water, risk, and landing conditions is only brought partly into play in any operation. The enormous possibilities inherent in the model's data are reduced to a smaller nexus of probability by the regional location of the voyages in question.

In a series of landmark papers Curry pointed out the operational and theory building advantages of using the random approach to solve geographical problems, especially those which are concerned with the evolution or development of spatial patterns.[15] A probabilistic model system of the type developed in this study can simulate the environmental and operational conditions during colonization, and can be employed to test the validity of the theories put forward on the basis of fragmentary evidence at a second or third remove from the events they are used to illumine. Thus the real heart of this and other such research strategies is the building blocks of which the logic of the models is made. The results of the experiments have no validity other than that which is built into the model. For this reason considerable space below is devoted to its components.

Following the discussion of the model system, the results are described without considering their relevance to theories and ideas based on reasoning from ethnographic, linguistic, and other evidence. We should note that this model system is not an attempt to simulate the chronology of the settlement of Polynesia, but rather it tests theories concerning the settlement of Polynesia, especially the drift and navigated voyage theses. Following the description of the experimental results, these are related to the basic questions about Polynesian origins and settlement, and some light is shed on the validity of theories put forward about them.

13. Harvey, 1969:230–287; 1967:570–597. Brown, 1965.

14. Harvey, 1969:235.

15. Curry, 1962A, 1962B, 1964, 1966.

Chapter Three

MODEL

The simulation model system deals with as many as possible of the parameters which affect the course and survival of a small vessel and its crew when drifting at sea without motor power. The factors considered are as follows: temporal and spatial changes in wind direction and force; current (or surface drift) direction and speed; the course steered; the sailing qualities of the vessel; the location of reefs, islands, and coasts; the crew's survival chances; and the seaworthiness of the vessel. The problems of including these in the model, either to the extent that data are available or they are replaced by limiting assumptions, are discussed below.

The simulation of a single voyage involves the following steps: (1) Initialize the coordinates of the craft to those of the chosen starting island; assign the initial date; and select the voyage's maximum length at random, using the survival probability table. (2) Select at random the wind and current for the day using the wind and current probability tables for the date in question and the particular area of the Pacific. (3) Compute the resulting position of the craft at the end of that day's journey, by applying the relevant speeds and directions for the selected wind and current. (4) Determine whether the craft has sighted (passed close to) land during the day. If so, end the voyage; otherwise perform step 5. (5) If the maximum length of voyage has been exceeded, terminate the voyage; otherwise advance the date and continue from step 2.

Each voyage ultimately terminates either by sighting land, or by the expiration of its allotted time span, or (with probability 0.5) if a gale occurs (when the chosen wind is Force 9 or higher on the Beaufort scale), or if the vessel sails outside the study area.

The study area, outlined in Figure 2, extends from the west coast of the Americas, with the extreme boundary at 70°W, through 140° of longitude of 150°E. The north-south range is from 35°N to 50°S, with the exclusion of higher latitude areas devoid of islands to the north and west of 25°N, 180°E and to the south and east of 40°S, 100°W. Monthly wind data are available for each of the 392 5° "Marsden squares"[1] within the study area. Latitude and longitude form the basis of the coordinate system used in the model. Allowance is made, when plotting courses, for earth curvature and for the decrease in the length of a degree of longitude away from the equator.

Wind Data

The climatic information is from manuscript tabulations provided by the Marine Division of the Meteorological Office, Bracknell, England, for use in the preparation of the monthly meteorological charts of the Pacific Ocean.[2] The monthly summaries of observations from British naval and merchant vessels between 1855 and 1938[3] indicate, for 5° squares, the number of occurrences of winds from each of 16 compass points (plus calms and variable winds) for each of 13 forces of the Beaufort scale. In fact, summaries are not available for every 5° square. Where observations are few, records for adjacent squares were aggregated and applied to the whole area. In general, aggregations are east-west rather than north-south. As an example, Figure 3 shows that the data for January covering 135 5° squares condensed to form 61 composite areas. Despite this procedure the number of observations remains far fewer than is desirable for some regions, especially within Micronesia.

1. Areas bounded by lines of longitude and latitude at 5° intervals are not squares on the surface of the earth.
2. Marine Division, 1947, 1956.
3. Marine Division, 1956:1.

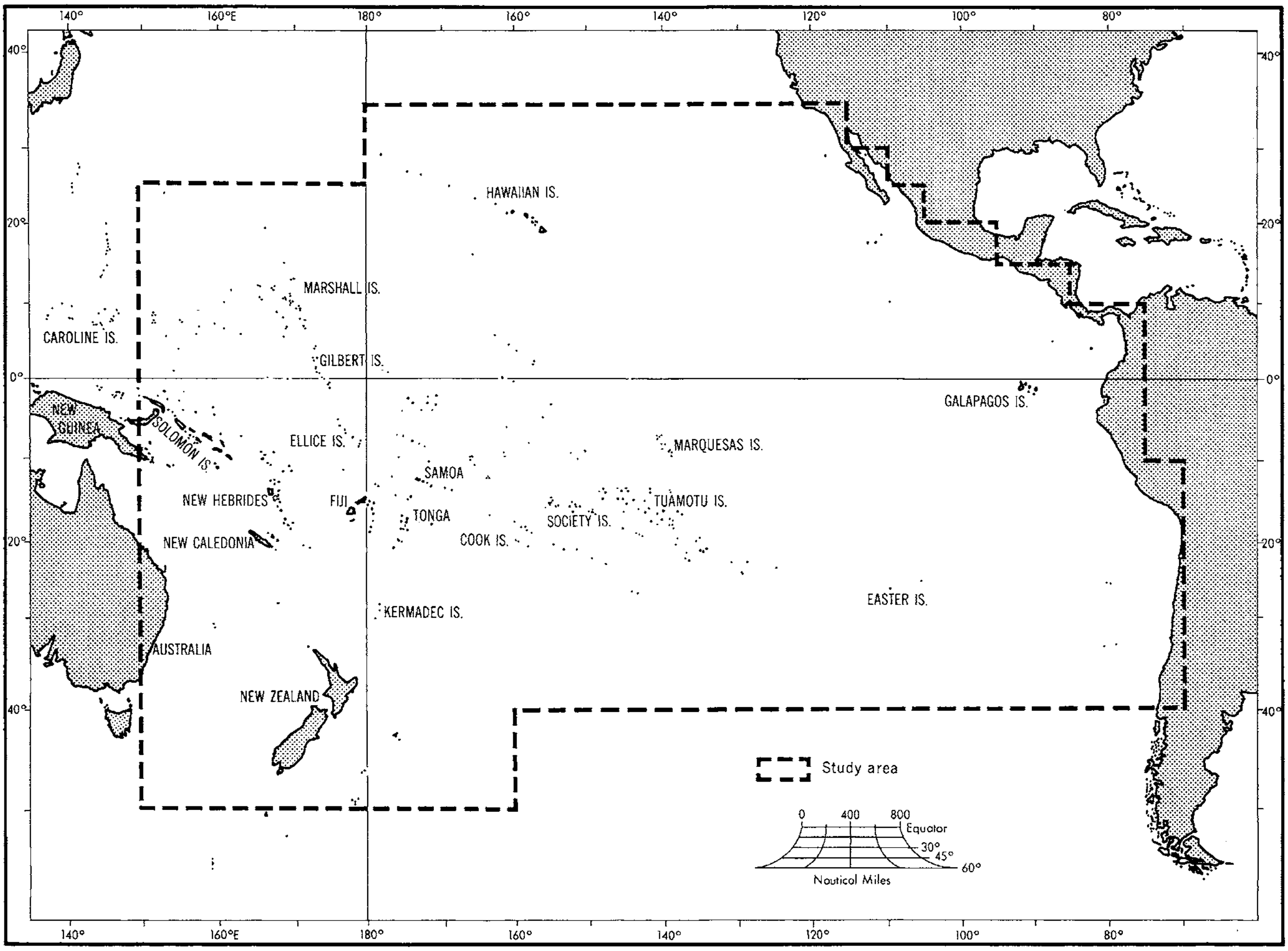


Figure 2. Polynesia: Study area

Some consideration was given to the possibility of statistically augmenting the data in some areas, but this was not done because it was thought that the variations in drift patterns which would result would be small and the difficulty of interpreting them greatly increased.

Even when an area has three hundred observations for one month, this is equivalent to only ten years continuous daily recording. When observations are few, a high proportion may originate from one ship on one voyage. The summary tabulations note extreme cases of this type and sometimes this is the reason for aggregation of squares. With observations of such varied number and temporal provenance it is difficult to test their reliability, and the best indication of their reasonableness lies in the apparent coherence of the spatial patterns revealed in the monthly charts.[4]

Fortunately, for the present project, data available for 5° squares over much of the South Pacific, and especially in tropical Polynesia, provide a reasonable set of wind probabilities. But it must be remembered that, like all climatological data, these probabilities are only an abstraction from reality which reflects in a general way the kind of conditions likely to be experienced by small vessels.

Figure 4 gives an example of one summary wind table. The summary for each month and 5° square has been abbreviated by grouping all occurrences of winds of Force 9 and above for each direction into one class. Transforming the number in each cell into a percentage of total observations provides the probability matrix for wind conditions for the particular month and 5° square. In all, there are 4,704 wind probability matrices for the study area, although some of these will be duplicates as a result of aggregations.

A question basic to the validity of the model is whether or not the wind and current data from 1855 to 1938

4. Marine Division, 1947, 1956.

give a fair indication of conditions likely to have been experienced by voyagers during the last two or three thousand years. The evidence for climatic change in the Pacific is limited but indicates that in some areas temperature variations have occurred of sufficient magnitude to influence, and be revealed in, vegetation patterns. Walker reviews this issue for the Australia-New Zealand region and concludes that local rather than wide regional environmental changes may account for known vegetational trends but that it is still too early to construct a climatic history of the area from botanical evidence.[5]

Within the last three thousand years, 100-year average temperatures (for A.D. 1000 to 1965) and 1,000-year average temperatures (for 1000 B.C. to A.D. 1965) for Western Europe have varied by little more than 1 °C.[6] Sawyer believes that major latitudinal shifts in the general circulation are unlikely to result from changes in the atmospheric heat budget of a few percent, though differences along particular longitudes may occur and be balanced out in the latitudinal means.[7] The annual latitudinal movement of the equatorial trough may be up to 25° in the western Pacific but is much less in the east,[8] and the poleward margins of the meridional Hadley cell (near the center of the subtropical anticyclones) are displaced by less than 10° between winter and summer.[9] In the last century latitudinal shifts in the general pressure pattern have been less than this. Between 1860 and 1959, the forty-year mean July position of the subtropical anticyclone belt over the Indian Ocean, Australia, and New Zealand moved northward by nearly

5. Walker, 1966:149–153.

6. Lamb, Lewis, and Woodroffe, 1966:176–177.

7. Sawyer, 1966:221–222.

8. Barry and Chorley, 1968:158.

9. Sawyer, 1966:220–222.

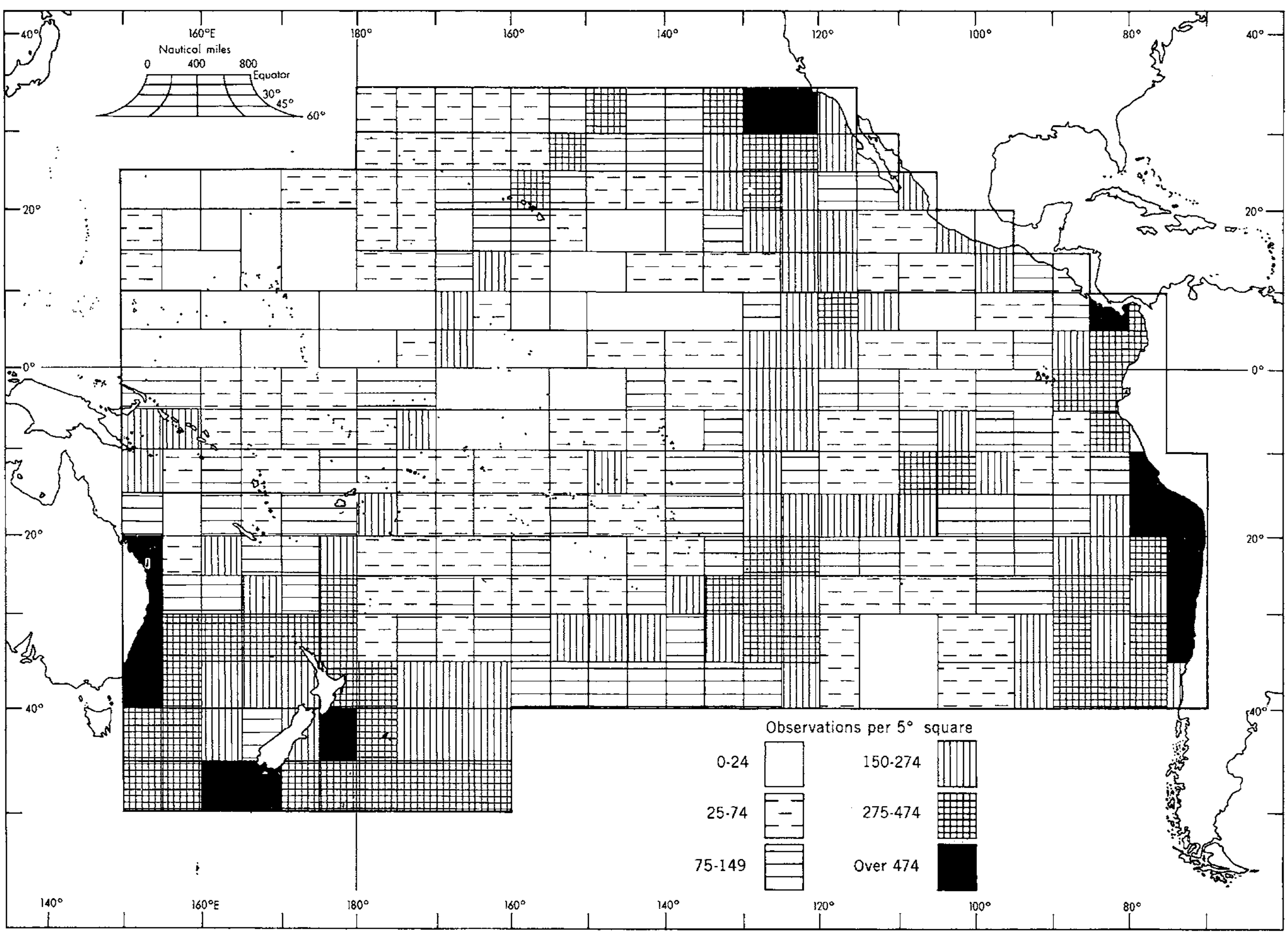


Figure 3. Wind observations for January

3°, though there was little shift in the subtropical pressure maximum in 70°W.[10] Over the same period there has been a southward shift of almost 5° in the forty-year mean January position of the inter-tropical trough over Australia but the position of the subtropical ridge has varied by only about 1.5°.[11]

Although there would seem to be little reason to believe that long period variations of the circulation in lower latitudes during the period since 1000 B.C. have been any greater than those associated with seasonal change, or noted in the last century,[12] a series of experiments were made with wind and current data latitudinally shifted 5° north and south. In the case of the northerly shift, the data for the most northerly row of 5° squares were eliminated and the most southerly row duplicated. All other rows were moved 5° to the north. A comparable procedure was followed in the case of the southerly shift. The results of these experiments are discussed in Chapter 4.

Longitudinal changes in wind and current patterns occur seasonally and also in conjunction with the longer term variations in pressure regime as described by Lamb and Johnson.[13] These seem to have greater influence in higher latitudes than in our study area but in periods when blocking anticyclones occur in the usual zones of subpolar cyclonic activity, the effects may be experienced in the area of Hawaii or southeast of New Zealand.[14] This could bring periods when winds with larger northerly or southerly components than normal were more common but the records are not sufficient to allow us to include this in the model. Therefore, no attempt has been made to simulate any longitudinal changes in circulation other than those which result automatically from the simulated latitudinal shifts.

The wind observations for the ocean areas give no information on weather sequences within any month. Such data are only available for a small number of land stations. To model the drift of vessels, the wind sequence experienced on a voyage is randomly selected from the direction-force probability matrices. This procedure may be questioned on the grounds that in reality the temporal autocorrelation of meteorological processes produces a sequence which is not random from day to day. Table 1 gives examples of sequences produced by the random process for two voyages. Inspection of voyage logs suggests that the random process does tend to produce wind sequences which simulate quite closely the type of wind patterns one might expect in reality.

Some allowance for correlation is implicit in the choice of a day, rather than some shorter period, as the model's unit of time. Such correlation could be increased by increasing this period (for, if we extend each leg of the voyage to two days, then, in effect, we obtain perfect correlation of winds, and of currents, for two days at a time), but at the expense of exaggerating unduly the influence of exceptional winds and currents on the outcome of a voyage. Furthermore, the correlation which occurs in reality is not necessarily among winds from

DIRECTION	WIND FORCE									Aug	386 c
	0	1	2	3	4	5	6	7	8	9+	DIR
CALM/ VARIABLE		2	1								C/V
NNE				1	3		1				NNE
NE			1		3						NE
ENE			1	1	3	1					ENE
E				2							E
ESE			1	3			1				ESE
SE		1		2	1	2					SE
SSE			3	2	1	3					SSE
S			5				3	1			S
SSW			1	3	1		1	1			SSW
SW			1	1				2			SW
WSW			1	3	2	6	1				WSW
W				1	3	3	2				W
WNW		2		1	3	2					WNW
NW		1	1	2	6	4	1				NW
NNW		1	1	3	4	5	1				NNW
N				2	1	2		1			N
								TOTAL		126	

Figure 4. Wind observations for August, Marsden square 386c

Table 1. Examples of Randomly Selected Wind Sequences

Experiment 1, Voyage 52[a]			Experiment 6, Voyage 56[b]		
Voyage Day	Direction	Force	Voyage Day	Direction	Force
1	WSW	3	54	SE	2
2	ESE	4	55	ESE	3
3	SW	4	56	E	3
4	ENE	4	57	E	3
5	SSE	4	58	ESE	3
6	NNE	1	59	CALM	
7	WNW	3	60	ESE	3
8	WNW	3	61	E	3
9	ESE	2	62	E	1
10	ESE	5	63	E	3
11	SSE	6	64	ESE	2
12	SE	5	65	ENE	4
13	SSE	7	66	NE	4
14	SE	5	67	CALM	
15	E	2	68	NNE	4

[a] Starting 21°14′S, 159°45′W. [b] Starting 8°42′S, 140°36′W.

10. Lamb and Johnson, 1961:377.

11. Lamb and Johnson, 1959:117.

12. Parsonson (1963:45) speaks of "that halcyon age of voyaging when meteorological conditions were probably far better than they are now," but there appears to be no good evidence to support his undocumented supposition.

13. Lamb and Johnson, 1959, 1961.

14. We are grateful to H. H. Lamb, Meteorological Office, Bracknell, England, for showing us and allowing us to use material from his forthcoming book *Climate: Present, Past and Future,* Vol. II. This paragraph is based on information from this book.

the same direction but among wind sequences from different directions. Finer control over correlation could be obtained by superimposing upon the probability weightings a "bias" matrix determined by the wind, or current, of the preceding day. Different bias matrices would be needed for different parts of the Pacific, for each month and for each major initial wind direction. Even if the data were available, the computer to manipulate such a vast amount of information is not.

We should note that as the output from separate voyages is aggregated into monthly classes and 5° squares and the experimental results are generalized, the precise sequencing of the daily courses of particular voyages assumes less significance than if the main conclusions were made from individual route patterns. Nevertheless, one result may be that our experimental results underrepresent the possible continuation of unusual wind sequences over many days.

Current Data

Data on surface currents also come from tabulations prepared by the Marine Division of the United Kingdom Meteorological Office. These consist of observations made from British ships from 1854 to 1952 aggregated into quarterly summaries,[15] and are used to prepare the current roses in the atlases of *Quarterly Surface Current Charts. . .* .[16] The summary tables give the number of observations of currents within six speed categories, plus zero, by sixteen directions, for areas of varying size, and thus indicate the degree of current variability in each area. For most of the tropical Pacific the summaries refer to rectangular areas usually spanning 6° of latitude and 8° of longitude, although sizes and shapes of areas vary "to separate the different current trends of the general circulation as far as possible."[17]

These data have been transformed for computer purposes to fit the 5° Marsden squares used for the wind information. This has been done by assigning to each square the data from that current area which covers its largest part. Over most of the Pacific this shift is in an east-west direction, though close to the coast of South America it is a north-south shift. These necessary modifications do not introduce undue inaccuracies since there are relatively consistent current patterns in these directions.

15. The quarters used are December–February, March–May, June–August, and September–November. The period of observations used for the western North Pacific is 1855 to 1939 (Marine Division, 1966:1).

16. Marine Division, 1959, 1966, 1967.

17. Marine Division, 1967:1.

Once again where the number of observations is very low the records for adjacent squares have been aggregated. Figure 5 shows the resultant pattern for the December–February quarter and indicates that the current data are generally poorer than the wind data.

Probability matrices were prepared for each Marsden square in a manner similar to those for winds, though each matrix applies for three months. The total of 1,568 matrices of surface currents includes duplicates arising from aggregations.

In reality the surface drift on any day with strong and persistent winds will be a partial resultant of that wind. There is thus a variable short-term correlation between wind and surface current, in addition to the larger scale correlation between the global circulation patterns of winds and currents. In the operation of this model the short-term wind and current correlation has been ignored in the selection of current sequences for a voyage. A process of random selection similar to that applied to the wind matrices is used. The random selection tends to add partial wind-current correlation to the voyage simulations. In any case, the output is used in such a way as to minimize the effect of ignoring the correlation, and the comments made above relating to the technical problems of incorporating the temporal autocorrelation of winds also apply here.

The Course and Speed of a Vessel

The course along which a vessel is steered at any stage of a voyage depends on the navigator's assessment of his position in relation to his planned intermediate or final destination (or his calculation of where that destination might lie). In the case of sailing vessels such assessment would take into account winds likely to be encountered during the remainder of the voyage. One of the basic reasons for constructing the present model was to test the validity of the theory which postulates that settlement of Polynesia was the result of one-way voyages in which the destination was not known.

In most experiments we assumed that there was no attempt at selecting and maintaining prescribed courses, and that, after the first day or two, vessels always sail with the wind. In a few experiments this assumption was relaxed to allow for crews trying to steer in a specified direction.

The limited empirical evidence of known drift voyages[18] suggests that the people involved usually conclude that they are lost fairly early in the voyage. Having no clear idea of their relative location, many islanders

18. Dening, 1963:138–153.

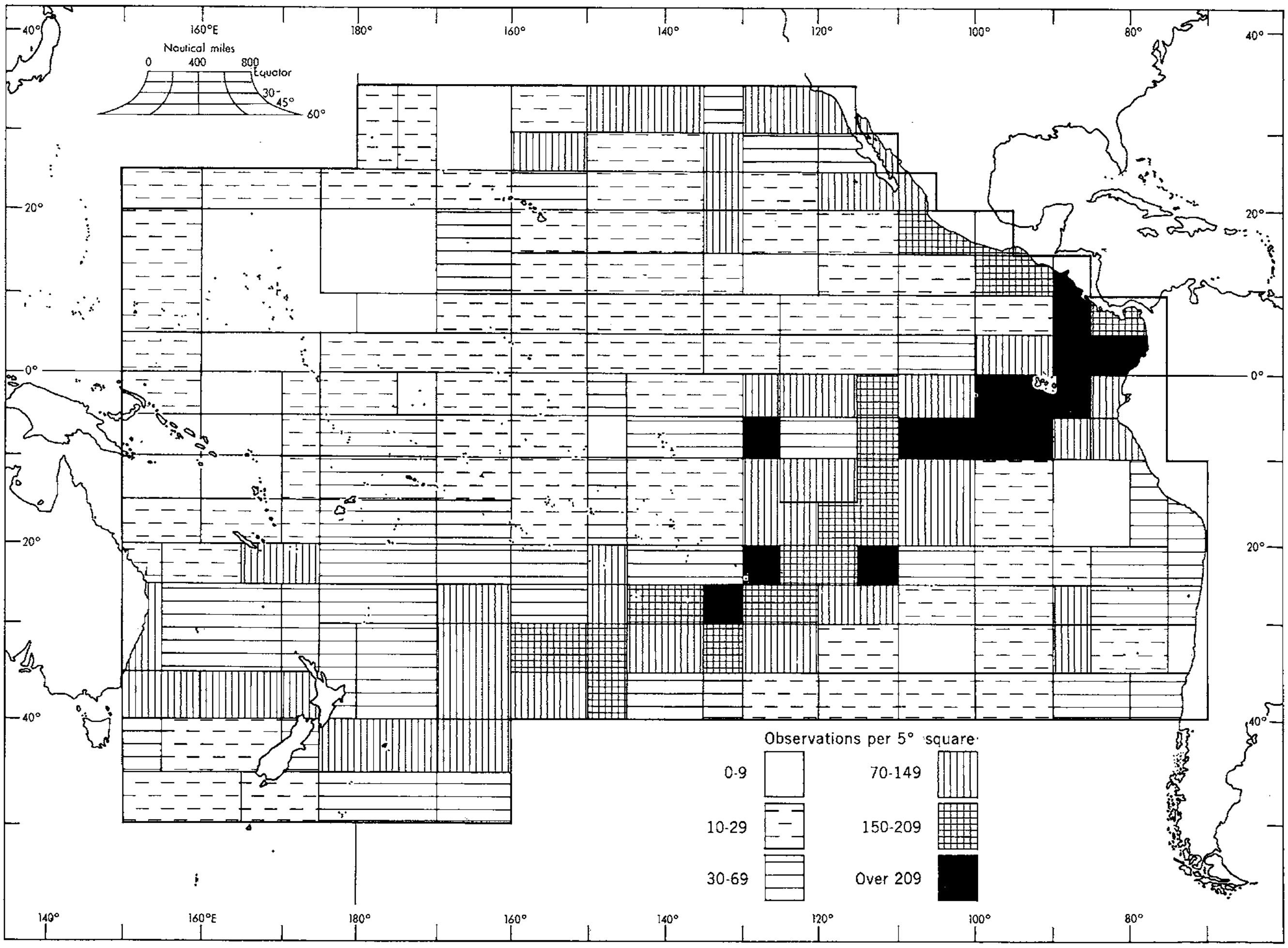


Figure 5. Current observations for December–February

in this situation apparently allow their vessel to drift, or run before the wind with little attempt at steering in specific directions.[19] For the voyager who is lost without a mental map of island locations, such a course would allow him to cover something close to the maximum distance in a given time, and thus increase his chance of finding an unknown island. Thus for most experiments random selection from the relevant probability matrices of wind and current determines the course for the day. Courses sailed on voyages with directional objectives are the resultant of randomly selected winds and currents, the crews' desire to sail in a specific direction, and their ability to hold their vessel on a course as close as possible to that direction.

The distance a vessel covers in a day when sailing or drifting will vary widely according to the qualities of the vessel and the amount and efficiency of sail carried. The types of vessels relevant to this study include outrigger and double canoes of varying rig and rafts of South American origin. For computing purposes it has been necessary to adopt a single set of distance values in relation to wind speeds.

The evidence of performance of Polynesian or Micronesian canoes and Amerindian rafts when sailing downwind (or indeed in any direction) in relation to specific wind speeds is limited. Anderson observed that large Tongan double canoes did seven knots in a "gentle breeze" in which the sloop *Resolution* did three, and in smooth water and a fresh breeze "it may easily be conceived they must go more than double that." Cook,

19. Though note that Heyen (1963:65) puts the alternative view that a crew captain, if lost, would be more likely to "sail on the wind, either to the north or south, direction being obtainable by heavenly bodies rising or setting." He further argues that if, in the southern Hemisphere, the captain sailed southward, cooler temperatures would soon encourage him to tack and stand back to the northward.

on board a Tongan canoe, found it did seven knots by the log when "close hauled in a gentle gale." In a "fresh breeze" double *orou* canoes of Mailu, Papua, "will travel at eight knots" according to Saville, and the *waga* canoes of the D'Entrecasteaux islanders can do six knots "with a good breeze on the quarter." Vason wrote of Tongan canoes maintaining six or seven knots over a period of perhaps ten hours, while Heyen noted that modern Gilbertese canoes "in racing trim" have been timed at over twenty knots in lagoon waters, and pelagic fishing canoes have been observed sailing at over ten knots. Parsonson reviews reports of vessels said to be capable of speeds of between twelve and twenty-two knots. In a return voyage of about 500 miles from Satawal to Saipan in May 1970 an outrigger canoe covered the first leg of fifty-two miles to West Fayu in ten hours, while the remaining 422 miles were covered in four days, including three periods when the sail was down because of strong winds or lack of wind. McCoy states that such a canoe close-hauled can "maintain a steady speed of approximately five knots under normal conditions." In 1966 Finney conducted sailing experiments with a double canoe of Hawaiian type and found that in moderate trade winds of fifteen to twenty knots (Beaufort forces 4–5) the canoe did up to eight knots downwind, six knots on a broad reach 90° to the wind, and four knots when making 75° to the wind.[20] Finney also suggests that ten to twelve knots might be reached downwind in the Beaufort scale range 5 to 7, provided sail could be carried. We should note, however, that many vessels will sail more slowly downwind than off the wind.

With the exception of Finney's observations none of the records above give any indication of variation in downwind speeds under winds of differing forces. The evidence for Amerindian rafts is similarly limited. Edwards reports that the fifteen- to twenty-foot balsa sailing rafts of Sechura, Peru, constructed of five to eight logs, will do four or five knots on the wind with a "good breeze" but states that this speed is reduced when running before the wind. Morrell saw larger Peruvian rafts sailing "six or eight miles an hour, on a wind," and Heyerdahl quotes a British naval officer who saw a raft close-hauled and "going at a rate of four or five knots" off the Peruvian coast. During the voyage of *Kon-Tiki* Heyerdahl did not make "any exact calculations as to the daily rates between wind and current propulsion." The average daily drift was forty-two and one-half nautical miles, with a maximum of seventy-one off the coast of Peru. This understates the potential of such a raft, for the crew were inexperienced with the *guaras* (center-boards), the splash boards on the bow were unnecessary and a hindrance, the individual logs were not pointed, and a larger sail could have been carried.[21] Modern twenty-man rubber naval rafts, not designed for sailing in any particular direction, will drift at 3.5 percent of wind speed in fair seas and 5.5 percent in rough seas with ten men on board, waterpockets up, and the drogue not streamed.[22]

This review is by no means exhaustive but sufficient examples have been quoted to indicate the order of speeds which might be considered. Many of the speeds quoted by observers are optimal rather than those normally attained or those maintained as daily averages. It is necessary to adopt one set of representative speeds and those used are given in Table 2. We believe that these speeds are within the capability of most Pacific craft and are moderately conservative.

Table 2. Speed of Vessels in Relation to Wind Speed

Beaufort Scale	Wind Speed (Knots per Hour)	Vessel Speed (Knots per Hour)	Daily Distance (Nautical Miles)
0	Less than 1	0	0
1	1–3	0.5	12
2	4–6	1	24
3	7–10	2	48
4	11–16	3	72
5	17–21	4.5	108
6	22–27	6	144
7	28–33	7	168
8	34–40	6	144
9 plus	Over 40	4.5	108

When winds are calm or variable we assume a zero value for the day's drift, for, although canoes might be paddled,[23] our basic assumption that the voyagers do not know their position gives such effort no meaning. In any case no direction could be assigned to any distance paddled. At higher wind speeds vessels must shorten sail or heave to. Hence we reduce speed values for winds of above Force 7. The greater risk of disaster which accompanies strong winds is discussed below.

The speed of drift in relation to surface currents is a simpler matter and it is assumed that the speed of a vessel's drift has a 1:1 relationship to the central value

20. Anderson, 1967:938. In Beaglehole, 1967A:164. Saville, 1926. Jeanness and Ballantyne, 1920:187. Vason, 1815. Heyen, 1963:64–65. Parsonson, 1963:37–38. McCoy, unpublished paper. Finney, personal communication, January 1, 1967. (See also Finney, 1967:148.)

21. Edwards, 1960:371. Edwards, personal communication, January 27, 1967. Morrell, 1832:223. Heyerdahl, 1955:257, as reported in Blaxland, unpublished. Heyerdahl, personal communication, January 7, 1967; 1952:606.

22. Lee, 1965:93.

23. Finney's test canoe could be paddled at slightly over three knots at a relaxed rate of paddling maintained for eight hours. Maximum speed at a racing pace was over six knots (1967: 150).

in the range of current speeds for each force category. Table 3 gives the values used.

Table 3. Surface Current Speeds and Vessel Speeds

Current Force Category	Range of Current Speeds (Nautical Miles per Day)	Vessel Speed (Nautical Miles per Day)
0	0	0
1	1–5	3
2	6–12	9
3	13–24	18
4	25–48	36
5	49–72	60
6	Over 72	85

Survival and the Length of Voyages

Any voyage will end with a landfall, the destruction of the vessel, or the death of the last crew member. We consider the problems of landfall later in this chapter. The probabilities of survival which must be included in the model can be no more than reasonable estimates, for although there are many records of successful voyages of considerable duration, there is no way of knowing what relationship these bear to total voyages, or how long unsuccessful voyagers survived. The undiscovered dead and the unrecorded living provide no evidence.

Tables of voyages in the South Pacific and another for those in Micronesia give the duration of many known voyages.[24] The longest recorded voyage by a Pacific islander was that of a Gilbertese named Nabetari who escaped with six companions in three canoes from Japanese-occupied Ocean Island on April 4, 1944. Two canoes were lost and Nabetari's remaining companion was eventually drowned. The canoe's sails were lost but rain provided water and some sharks were caught for food. Eventually Nabetari drifted to a landfall on Ninigo fifty miles west of Manus (north of New Guinea) in November 1944.[25]

Drift voyages of five months have been recorded, one of which, in 1869, included a woman,[26] and another, of 155 days from Maupiti, Society Islands, ended in Tau, American Samoa, on July 6, 1964.[27] Success in such voyages depends on the availability of water (usually from frequent rain) and food, either carried on board or caught en route. We cannot accurately predict, or allow for such luck or foresight, though clearly the chances of receiving rain varies greatly within the study area. The best we can do is provide an overall risk probability table which takes account of the fact that some vessels will carry provisions, water, or fishing equipment, and that some will have luck and others none.

The records of some 25,000 persons, mainly merchant seamen, who abandoned sinking ships in the Atlantic during World War II provide some data of relevance to the present study. Of those who abandoned ship, 18,406 reached lifecraft and 6 percent of these subsequently died. Only 23 percent of the boats and 10 percent of the rafts were adrift for more than a week.[28]

One of the main causes of death at sea is cold. Within the study area mean sea temperatures are above 10°C during all months in all areas, except to the south of New Zealand during midwinter. Within the tropics sea temperatures rarely fall below 20°C.[29] Wartime experience showed that when the sea temperature was between 10° and 19.9°C, death rates (for total voyages) were less than half those experienced when it was in the 5 to 9.9° range. On voyages of over fifteen days the death rate was 52 percent when the sea temperature was between 10° and 19.9°C, and 13 percent in the range from 20° to 31°C.[30] Thus cold is an important risk only in the most southerly parts of the study area.

The availability of water is probably the most significant single factor influencing survival within the study area. Lee states that in survival situations death is likely to occur within ten days in the absence of drinking water. But between the extremes of no water and ample water the whole range of unpredictable situations makes it impractical to construct a separate risk table for this factor. Lack of food is less immediately critical since "men at rest in a temperate climate can survive for at least 30 days without food" if there is sufficient drinking water.[31] And the records show that many of the Polynesian drift voyagers are quite successful in obtaining some food by catching fish and birds.

Another problem is that whereas the data sources give death rates in relation to persons at risk, in our model the unit must be the total crew rather than individuals. A voyage will continue until a 100 percent death rate is reached. Furthermore, the death of each crew member may increase the chances of the remainder surviving. Any rainwater or food caught thereafter is shared by fewer mouths, and the amount caught from any shower is determined by the size of boat rather than the number

24. Dening, 1963:137–153. Riesenberg, 1965.
25. Ellis, 1940:144–147; *P.I.M.*, December 1965:93.
26. Riesenberg, 1965:162, voyage 166.
27. *Auckland Star*, July 29, 1964. In 1970 the raft *La Balsa* sailed from Ecuador to Queensland, Australia, in 160 days (*Sunday Telegraph*, November 15, 1970).
28. McCance et al., 1956:6, 13.
29. Marine Division, 1947, 1956.
30. McCance et al., 1956:15–17.
31. Lee, 1965:96, 99.

of crew.[32] This helps explain why the table of risks may appear, at first sight, to be generous over the first two months.

The figures for survival chances are given in Table 4, and Figure 6 plots the cumulative percentage of losses by weeks. For computing purposes these were transformed into daily probabilities of survival for days 1, 2, 3, . . . , 183. The period for which any particular voyage survives is chosen randomly from this set of probabilities. If by the time the randomly chosen number of days has elapsed, and the voyage has not landed anywhere, the voyage ends.

Table 4. Survival Probabilities

Week	Percentage of Voyages Ending in Week	Week	Percentage of Voyages Ending in Week
1	1	14	6
2	2	15	4
3	2	16	2
4	3	17	2
5	4	18	1
6	5	19	1
7	6	20	1
8	7	21	1
9	8	22	1
10	10	23	1
11	11	24	1
12	10	25	1
13	8	26	1

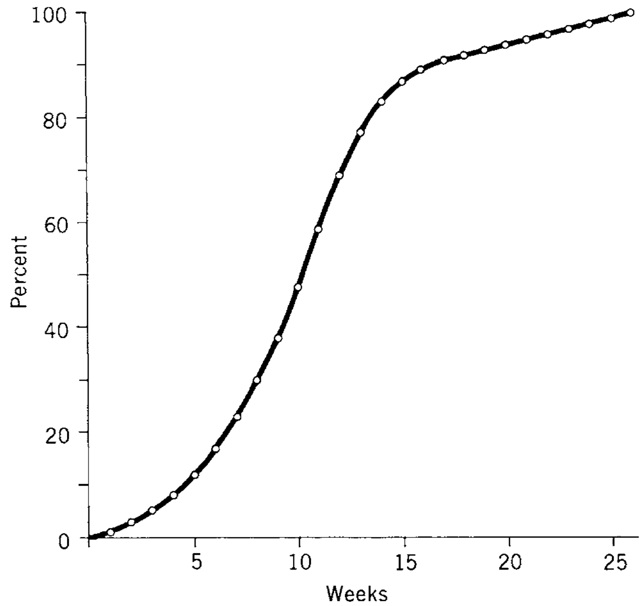


Figure 6. Probabilities against survival

Thus far we have not considered risks which affect, in the first instance, the vessel rather than the crew. Vessels of varied seaworthiness have made voyages in the Pacific, and in reading about these one is impressed by the long survival of many tiny and apparently unseaworthy craft. But of course we do not know about those which broke up and sank. The risks of swamping, in the case of canoes, or of breaking up, in the case of all vessels, increases greatly when strong winds occur. Therefore when a wind of Force 9 or greater occurs, we assume that the vessel has only a 50 percent chance of surviving to the next day. If the vessel does not survive, the voyage is ended.

Islands, Coasts, and Landfalls

To make a successful landfall the crew of a vessel must sight land, change course if necessary, and guide their craft to shore, avoiding reefs, cliffs, and other dangers. In the present model we assume these final hazards are always overcome. We do not distingish between habitable or inhabitable islands, and indeed a number of major reefs, which would spell disaster even to shallow draught vessels, are included as "islands."

Having made the assumptions above, we need to assign reasonable values to the sighting distances from which a mariner could locate an island and be able to reach it. A number of authors have considered this problem,[33] and there is no need to review it in detail. Where a number of islands lie close together they effectively enlarge the target and in some cases form "barriers" several hundred miles long.[34] We must note, however, that at night a vessel may pass through such a chain of islands without making a sighting.[35] The problem of reaching a small isolated island is much greater.

The distance from which an island may be seen from a small vessel varies with its height, but a man standing in a canoe might see an island three meters high from about seven miles away. Vegetation increases the height of most islands and refraction appears to make low islands visible from greater distances than is theoretically possible if only curvature is considered.[36] In contrast haze and clouds tend to reduce the visibility range of high islands below the theoretical figure.

Pacific islanders use a number of methods to expand their target. Birds known to roost ashore show the direction of land by their morning and evening flight,[37]

32. While discussing the survival problem, a naval person, who must remain anonymous, commented that people lacking food when adrift might resort to cannibalism. "But," he went on to say, "this would increase their protein intake and thus raise their water needs. If water were short they would be worse off than before, and so we don't recommend it for our chaps."

33. See Åkerblom, 1968; Frankel, 1962; Gatty, 1958; Gladwin, 1970; Hilder, 1963A; Lewis, 1964A, 1970.

34. Lewis, 1964A:368–371.

35. For example, Lewis, 1966:89.

36. Frankel, 1962:40.

37. Lewis, 1970.

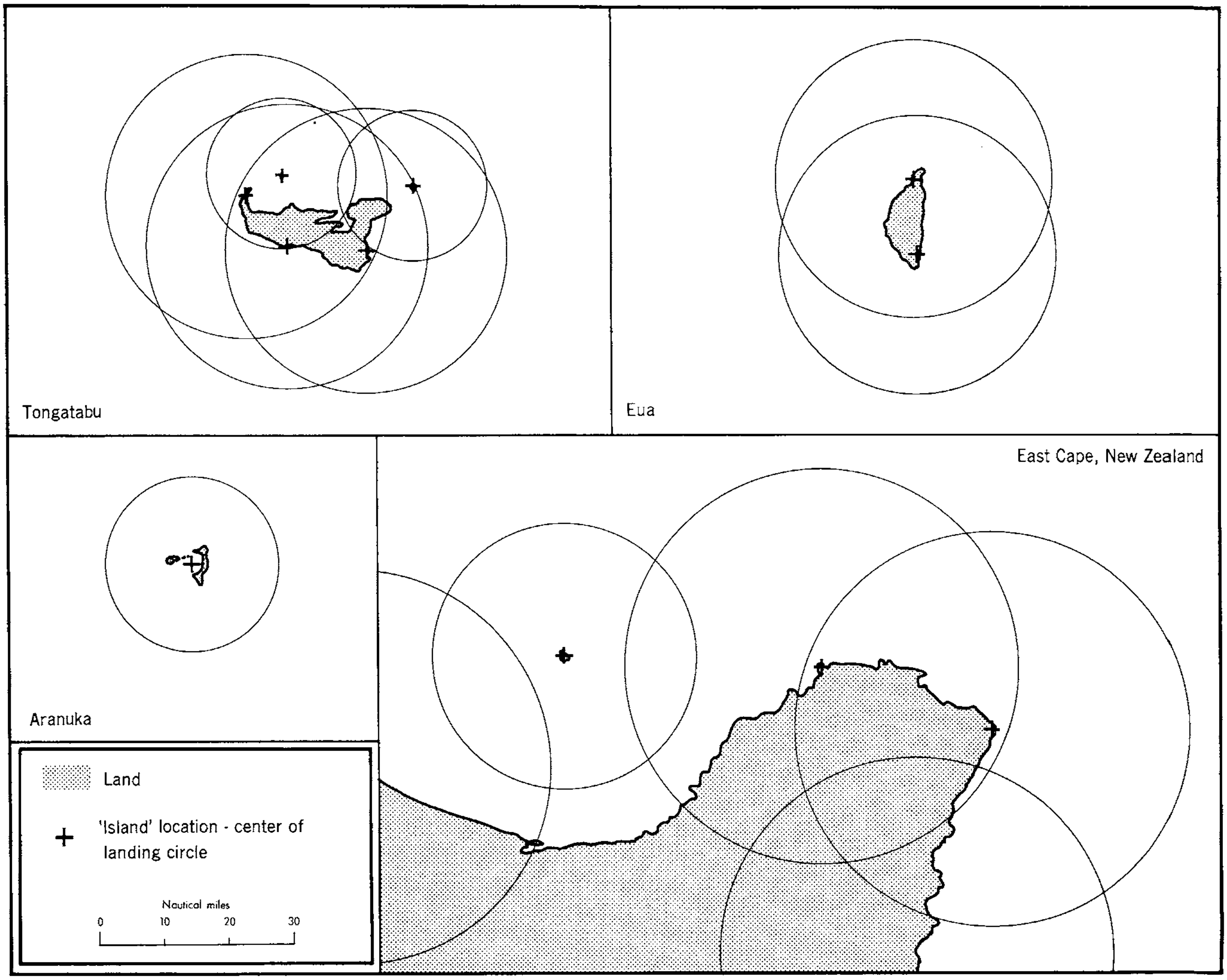


Figure 7. Sighting radii: Examples

and in relatively familiar seas distance from land may be estimated by the number of birds seen.[38] Lewis indicates that the bird zone of Pikelot, Caroline Islands, has a radius of twenty miles. Gatty suggests the technique can be used over much longer distances.[39] Clouds formed over high islands and over atolls may be used as markers,[40] while both the loom[41] of low islands and the reflection of a lagoon on a cloud above may extend the sighting radius. The deflection of swell and wave patterns by islands may also be read by the experienced mariner.[42]

38. Gatty, 1958.
39. Lewis, 1971B. Gatty, 1958.
40. Åkerblom, 1968:62.
41. The result of light reflected from the land.
42. Gatty, 1958:90. Grimble, 1924:128. Lewis, 1970:440–442.

These indications of land suggest that it would be reasonable to allow landing radii for low islands considerably in excess of the actual or theoretical sighting radii. Yet periods of reduced visability through haze, rain, darkness, or weakness of the crew, and the fact that an island might not be reached due to weather or wind conditions must also be taken into consideration. Therefore we have allowed a landing radius of ten nautical miles for low islands whose form or vegetation cover do not give them a maximum elevation of over about fifteen meters. Higher islands are allotted a landing radius of twenty nautical miles. Each small island is recorded by the coordinates of its central point and its assigned landing radius. Larger islands are represented by a series of points, each the center of a landing radius arc (Fig. 7).

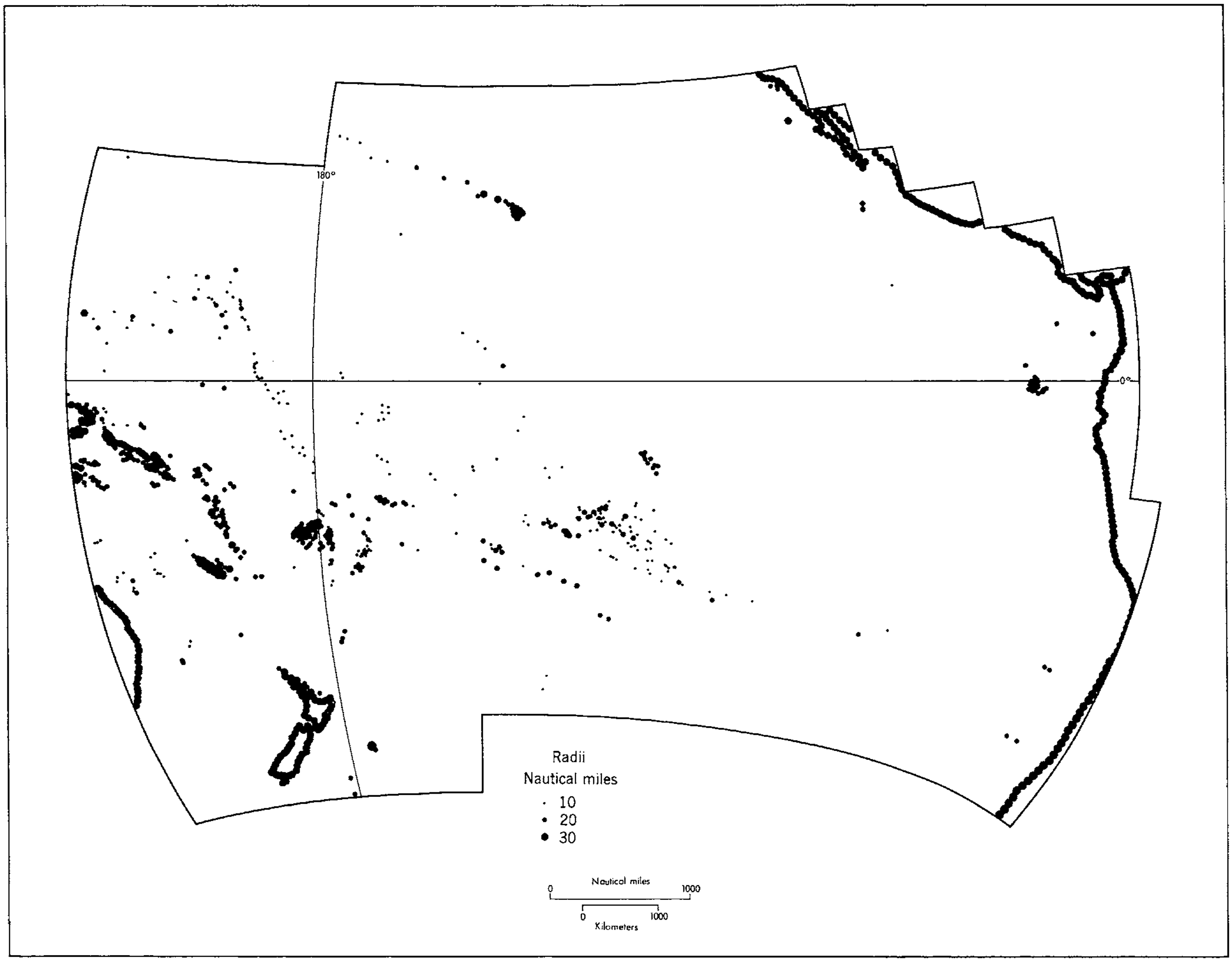


Figure 8. Study area: Sighting radii

When a vessel approaches a long stretch of coastline the problem of landing is less than in the case of a smaller island. Even if the crew do not succeed in reaching shore near their first sighting, they are likely to reach land further along the coast. Furthermore, the signs of a continental coast are likely to be perceived from a greater distance than are those of a small and isolated island. Such coasts are therefore allotted a landing distance of thirty nautical miles and the coast is represented by a series of locations or "islands" whose landing circles intersect to form a complete barrier (Fig. 8). If the day's course of a vessel intersects the landing circle of any island or coastal point, the voyage is considered to have terminated at that point.

The Timing of Voyages

A decision must be made about the date on which each voyage starts. Maritime activity in many of the Pacific islands is seasonal. In times of favorable winds more vessels set out on fishing trips or expeditions to adjacent islands. When gales or unfavorable conditions are more frequent, fewer islanders put to sea. Yet we would argue that the net result might be a relatively even spread or drift starts through the year, the lower risks in the favorable season being countered by the greater number of vessels at risk, while the high risks at other times operate on fewer vessels at sea. We therefore assume that there is an even spread and we begin two drifts on each day of the year.

The 732 drifts initiated from each starting point would represent the accumulated voyages from an island (accidental or intentional) for a very long period. But the period cannot be specified. The frequency with which vessels might be lost from an island varies with the size of population, the proportion who are coastal dwellers, and the amount of fishing and coastal navigation undertaken. The larger these are, the more frequent are losses at sea, and hence potential drifts, likely to be. Similarly, where people frequently travel between islands, such as Rakahanga and Manihiki, or Tikopia and Anuta, more accidental voyages are likely to result than from islands where people rarely venture out of sight of land. Variation in the predictability of weather and the occurrence of unseasonal storms will also influence the relative rates of voyages from different islands. It has not been possible to include all these variables in the present research design and therefore the model used here is essentially ergodic.[43]

Some Operational Considerations

The simulation of a single voyage has been outlined earlier in the chapter. When this is incorporated into a program to simulate a series of voyages, a number of practical considerations must be taken into account.

Foremost among these is that the entire wind and current data tables (comprising nearly 800,000 entries) cannot be stored in the main memory of the computer simultaneously, and must be brought from magnetic tape in sections as required. Sets of voyages must be simulated concurrently rather than consecutively in order to minimize the number of tape-to-store transfers. Each vessel of a concurrent set is assigned initial coordinates, a starting date, and a maximum period. The overall date is then initialized, and each vessel whose starting date has passed but whose voyage is not yet terminated has a wind and current selected, and so on, as in steps 2 to 5 of the outline described earlier. If any voyage remains unfinished, the overall date is then advanced and the operation repeated. For minimum transfers, the concurrent sets should be as large as possible, but a further consideration, that of restarting ("rescuing") the program in the event of computer malfunction, dictates that the size of sets should be limited. The voyages of an experiment are therefore organized into "cycles" of sixty or sixty-two concurrent voyages, each cycle consisting of all voyages starting in a particular month.[44] The resulting model is outlined by means of a "flow diagram" in Figure 9.

Another section of the program to which special attention has been paid is the landing search. Essentially, determining whether a craft has sighted a specific "island" on a particular day consists of deciding whether the line joining the day's starting and finishing points intersects the island circle. As this procedure is relatively time-consuming, steps are taken to apply it only to those islands not too far from the vicinity of the day's voyage. Also for reasons of time, the program reports as landing site the lowest-numbered island which the vessel has encountered that day, and no attempt is made to discover whether any other island might have been sighted earlier in the day's voyage. Since, however, landings on nearby islands are amalgamated in subsequent analysis, this does not affect the outcome.

The means of specifying islands impose some minor limitations on the choice of starting point. Obviously no starting point may fall within the sighting circle of an island (except the initial island, for which special provision is made), otherwise all voyages would land on that island the first day. Furthermore the "continental islands" which describe the coastline of large land masses cannot be chosen as starting points, since there would then be no way to prevent voyages inland. In these instances, offshore starting points are selected instead.

In the case of the initial island, the vessel is inhibited from landing there for the first three days of the voyage, thus ensuring that most of the voyages leave the starting point. This is appropriate since the model is concerned only with these voyages.

The coordinate system used in the model is the normal latitude and longitude system. The coordinates in the model, though not in this book, are expressed in degrees north of the Equator and degrees west of Greenwich, minutes and seconds being converted to decimal fractions of a degree.[45]

The assumption that this system as a whole is rectilinear would imply a flat earth. Instead, to allow for the earth's sphericity, we assume only that the area traversed in a day is rectilinear, and that the ratio of a degree of longitude to a degree of latitude is equal to

43. "The ergodic hypothesis amounts to assuming that the statistical properties of a time series are essentially the same as the statistical properties of a set of observations of the same phenomenon taken over a spatial ensemble. An ergodic process is thus a special type of stationary stochastic process. The assumption of ergodicity is often an act of faith, but is nevertheless an extremely useful and necessary assumption" (Harvey, 1969: 128).

44. A set of 732 voyages from a particular starting point is termed an "experiment." Two voyages are begun on each day of the year in which alternate months have thirty-one and thirty days (January having thirty-one).

45. Thus, for example, 20°S, 170°E is expressed as −20°N, 190°W.

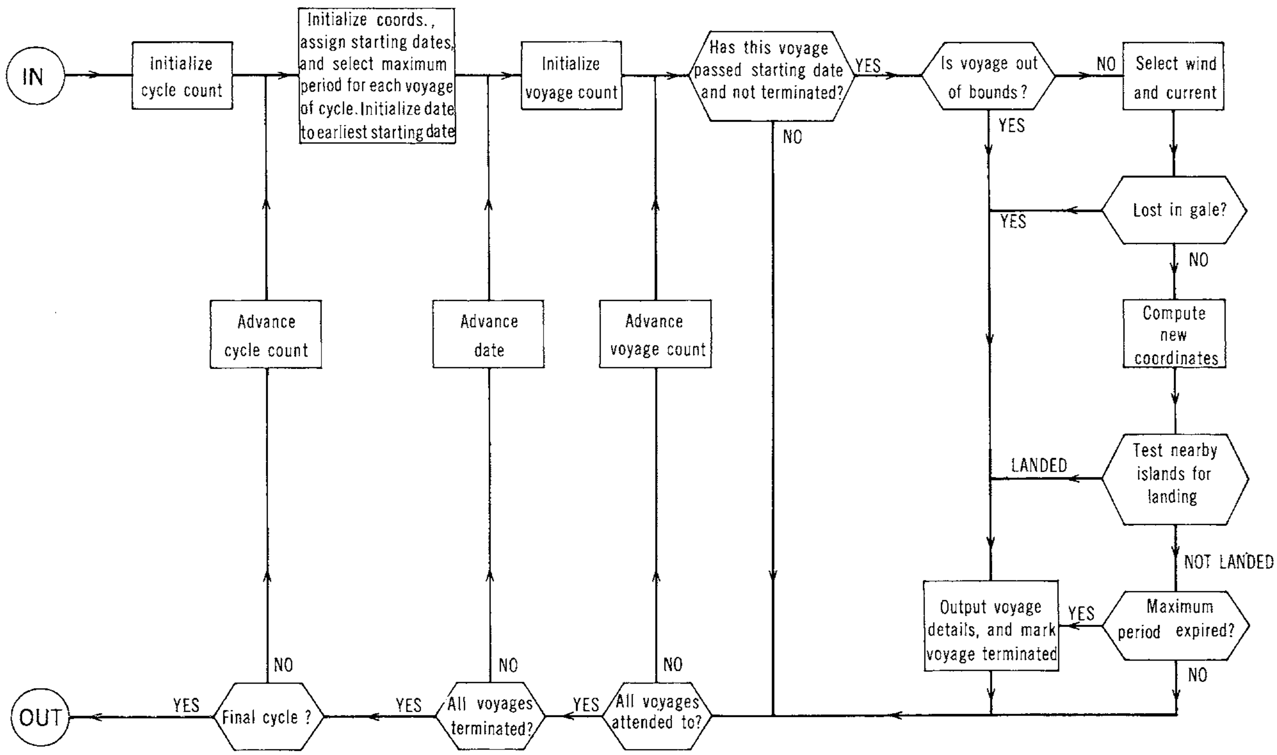


Figure 9. Outline of the model as programmed

the cosine of the latitude. In computing the new position of the vessel each day, the latitude used in this ratio is that of the vessel's initial position that day; in checking an island for a sighting, the latitude used is that of the island's center.

One final feature of the simulation program which should be mentioned is the "logging tape," which makes it possible to reconstruct a day-by-day log for any voyage, without further recourse to the wind and current selection or island checking procedures. For this purpose, it is arranged that, whenever a wind and current pair are chosen, the details are packed together with a voyage serial number and sent to a magnetic tape. A further entry is transmitted whenever a voyage is terminated indicating the reason for termination. These data have been used by subsequent programs to prepare the voyage-day cartograms, the microfilm maps, and several other analyses (see Chap. 4).

A complete listing and description of the program is given in Appendix 3.

A Sample Simulation

To indicate how the various elements of the model operate we may discuss the stages of a single simulated voyage, taking as our example a voyage started at Rapa on Day 222 (August 9).[46] The drift begins off the coast and the actual starting point for Rapa is to the northwest of the island at 27°33′ S, 144°20′ N. The maximum period for the voyage is selected randomly from the "risk probability table" (Table 4) and in this example, let us say, a maximum duration of thirty-seven days is given. If the vessel has not landed, or has been lost in a gale, the voyage will terminate with the expiry of the crew at the end of the thirty-seventh day. Using the August wind probability matrix for the 5° Marsden square 386c, which lies north and west of 30°S, 140°W (Fig. 4), the wind for Voyage Day 1 (August 9) is selected randomly and is a north wind of Force 5. As Figure 4 indicates there are two chances in 126 of such a wind occurring. From Table 2 we find that the vessel will sail 108 nautical miles to the south on the first day. The surface current for Day 1 is found by random selection from the current probability matrix for the same square and the quarter June–August (Fig. 10). The surface current, east-southeast at six–twelve knots a day, carries the vessel nine nautical miles to the west-northwest. The course for Day 1 is the resultant vector of these two forces and Figure 11 shows this course. The route is checked against the locations and landing circles of the islands in the vicinity and as none of these has been reached the voyage continues into Day 2. Wind and current for Day 2 are selected randomly, the values being WNW Force 5 and SE Force 1, respectively. The resultant course is plotted and checked for landfall. The

46. This is Voyage 17 of Cycle 5, Experiment 8.

DIRECTION	CURRENT 0	1	2	3	4	5	6			Rose No. 50 J-A 386C DIR.
	16									C/V
NNE		1	12	2						NNE
NE		8	3	4						NE
ENE		4	14	15	1					ENE
E		7	14	6						E
ESE		5	8	5						ESE
SE		11	4	1						SE
SSE		5	6	2						SSE
S		7	7							S
SSW		1	1	2						SSW
SW		4	3	2						SW
WSW		6	8	5	2					WSW
W		4	6	3						W
WNW			4							WNW
NW		6	7	2						NW
NNW		9	2	2						NNW
N		7	6	2						N
							TOTAL			262

Figure 10. Current observations: Marsden square 386c June–August

process is repeated for each day and Table 5 reproduces the output for the reconstruction of the whole of this voyage.

Table 5. Voyage 17, Cycle 5, Experiment 8, Start from Rapa on Day 222

Day	WD	WF	CD	CF	Position	
1	....N	5	ESE	2	−29.293	144.486
2	....WNW	5	SE	1	−29.946	142.620
3	....ESE	3	WSW	2	−29.583	143.313
4	....CALM		N	2	−29.733	143.313
5	....W	4	W	3	−29.733	141.586
6	....NW	3	WSW	2	−30.241	140.775
7	....W	2	ENE	1	−30.260	140.365
8	....WSW	7	ENE	1	−29.208	137.424
9	....SSE	5	CALM		−27.545	138.213
10	....WSW	4	E	2	−27.085	137.132
11	....W	3	E	1	−27.085	136.289
12	....N	1	NW	3	−27.497	136.051
13	....N	3	E	1	−28.297	136.107
14	....SSE	5	SE	1	−26.599	136.930
15	....S	2	N	1	−26.249	136.930
16	....S	2	CALM		−25.849	136.930
17	....SSW	5	ENE	2	−24.244	136.318
18	....WSW	3	WSW	1	−23.957	135.457
19	....SSW	6	WSW	2	−21.797	134.300
Landed on Island 161 (Mangareva)						

On Voyage Day 6 the vessel is carried south of 30°S and therefore moves out of Marsden square 386c. For Day 7 and Day 8 the wind and current probability matrices for Marsden square 422a are used. On the latter day the vessel moves into the area of Marsden square 385d and once again new wind and current probability matrices are brought into use. A further change is made at the end of Day 17. The voyage ends on Day 19 when the resultant course intersects the landing circle of Mangareva (island number 161). If the voyage had continued to Voyage Day 23 (September 1), the wind probability matrices for September and the current matrices for the September–November quarter would have been brought into use. If at any stage a Force 9+ wind had occurred, a test would have been applied in which there would be a 50 percent probability of the voyage ending due to the loss of the vessel in the gale.

In each experiment 732 voyages follow the process described in the preceding paragraphs. The end result of each voyage is recorded, the four possibilities being "landed on island number x," "lost in strong gale," "crew expire [day] x," or "out of bounds" when the vessel sails beyond the margin of the study area. In addition to the result a record is printed of the serial number of the voyage, the starting and ending days, the voyage's duration, and the coordinates at the beginning and end of the last day. In the case of a vessel "lost in strong gale" the maximum period for which the voyage might otherwise have continued (until the crew expired) is printed out.

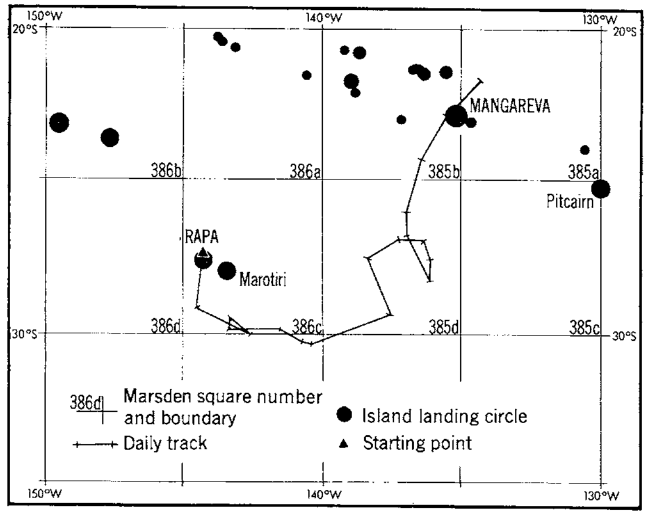


Figure 11. A simulated voyage

A further output provides a summary of the number of landings made at each island reached in the experiment and the number of voyages ending through other causes. Subsequently, using the logging tape two cartograms are constructed for each experiment, one giving the number of "voyage days" spent in each 5° square, and a second giving the number of landings recorded in each square. Finally, a microfilm map is produced for each experiment on which the locations of all 732 "vessels" at the end of each voyage day are plotted. Examples of these various forms of results are found in figures 21 to 24 and in Appendix 2.

Variations of the Model

The results of the main experiments show, as one would expect, considerable variation in monthly drift and landing patterns. For a number of starting points additional experiments were carried out for particular months, twenty-four voyages being started on each day. Results are in a form similar to that for the main experiments. In order to cover the question of possible latitudinal shift in pressure and wind systems in the prehistoric period, a series of "wind shift" experiments were carried out in which the wind and current data were moved 5° north and then 5° south of their normal position relative to the island locations.

A further variation of the model has been implemented in which the program remains basically the same as in the main experiments but the direction of movement relative to the wind or current is reversed (vessels are "pulled" rather than "pushed") and the date progresses backwards. The results may be interpreted as indicating where colonizers of an island x might have come from if colonization were by drift voyage. If all reverse voyages are found to have "started" in open ocean areas, then we can conclude that direct drift to island x would be impossible.

A final variation of the model involved substituting a preferred course for the pure drift course adopted in all other experiments. Literate Europeans, who saw Polynesian canoes and Amerindian sailing rafts during the early years of contact, often expressed admiration for the way in which vessels were handled and could be worked to windward. Finney and Bechtol have shown experimentally that Polynesian canoes could maintain a heading to within about 60° of the wind and make good a track within about 75° of the wind. Gladwin reports that the Micronesians of Palawat are able to hold their canoes on a bearing 62° off the wind and make good a track of about 77° at a speed of 3.9 knots in a wind of six knots.[47] In adapting these data to the model we assume that vessels can only sail on a reach, at 90° to the wind, and that speeds equivalent to those adopted for downwind sailing could be maintained. If the preferred course is due east, it can be maintained with any wind from north to south (inclusive) through west. If the wind is due easterly we assume the vessel makes no headway, but in other winds with an easterly component the vessel sails at 90° to that wind so as to make good some progress to the east. For example, in a southeast wind the vessel sails northeast and with an east-northeast wind it sails towards the south-southeast. The current parameters are unchanged. In theory any preferred course could be used in the model.

The model system as designed and operationalized could be modified in many ways to test various other hypotheses. In connection with the "Polynesian problem" we feel that further variations would produce results of diminishing value in view of the comments made in the last paragraph of Chapter 1. But there are theoretical problems, for example, concerned with the autocorrelation of wind and currents or the expansion of the wind and current probability matrices, which further work might illuminate. With different data the model might be used for evaluating theories concerned with migration over other oceans or the diffusion over ocean barriers of waterborne plants such as the coconut or bottle gourd. Modified versions of the model system might be used in sea rescue work, and the list of possible adaptations could easily be extended.

47. Finney, 1967. Bechtol, 1963:100. Gladwin, 1970.

Chapter Four

RESULTS

In the best of all possible worlds, where the use of computers is free of cost and unlimited in time, we would sample the model system with thousands of voyages from each Pacific Ocean island and coastal location. We did run 101,016 drifts, and 8,052 guided voyages taking a number of hours of computer time and involving a feat of considerable magnanimity and forbearance by the Atlas staff. The simulation experiments were run in different ways and the total can be divided into the following types:

A. *Main* experiments: 46,848 drift voyages from 62 different starting locations. From each starting point two drifts were begun on each day of a year of 366 days.

B. *Wind shift* experiments: 11,712 drifts from eight of the places used in the main experiments, giving 732 starts with the winds and currents moved north 5° and 732 starts with the winds and currents moved south 5°, again spread through a 366-day year of twelve months.

C. *Monthly* experiments: 31,940 drifts for forty-five specific months from twenty of the main experimental locations, giving twenty-four starts a day, or 720 drifts for thirty-day months and 744 drifts for thirty-one-day months.

D. *Reverse* experiments: 10,516 landings at eleven places, from each of which 732 voyages were run backwards to their points of origin, two drifts for each day of a twelve-month year of 366 days.

E. *Navigated* experiments: 8,052 navigated voyages from eleven starting points. For each experiment 732 voyages, or two each day for a year of 366 days.

Starting points chosen give broad coverage of islands and island groups in and near Polynesia (Fig. 12). Ideally the full roster of island groups would be represented by starting points but the missing groups seem relatively unimportant in the settlement of Polynesia.

We wished to test the drift settlement hypothesis comprehensively by creating drift probabilities to and from as many places as possible. To this end we used a number of marginal locations in advantageous positions to generate voyages to the far places of Polynesia. Many drifts were started in the eastern Pacific to test the probability of their reaching Polynesia, and some starting points were used to find the probabilities of drifting from western Polynesia to Melanesia.

For each experiment the computer produced the following: (1) A list of all voyages, giving for each its length in days, coordinates of the vessel at the start of the last day, and information on the way the voyage ended. (2) A summary giving the number of landings at each island and the mean duration of drifts to each island. The total numbers of landings, crews lost, out of bounds, and lost in gales were also given. (3) A cartogram of the Pacific Ocean in 5° squares, showing the number of days spent in each square by all voyages in the experiment. (4) A cartogram of the Pacific Ocean in 5° squares, showing the number of landings, crews lost, rafts out of bounds, and losses in gales for each square. (5) A single (35 mm) microfilm positive showing the position of all drifts at the end of each day throughout the experiment.

In addition, the computer provided a consolidated matrix of landings and starts (994 island and coastal locations × 149 starting points).

The Example of Motuiti

Motuiti, a small rocky island in the northwest Marquesas, was used as a starting point for all the different kinds of experiments; we use it to illustrate the materials provided. Figure 13 shows the drift-voyaging field from Motuiti, that is, the number of "voyage days" spent in each 5° square. Figure 14 shows landing probabilities for islands and coasts, aggregated for 5° squares. These

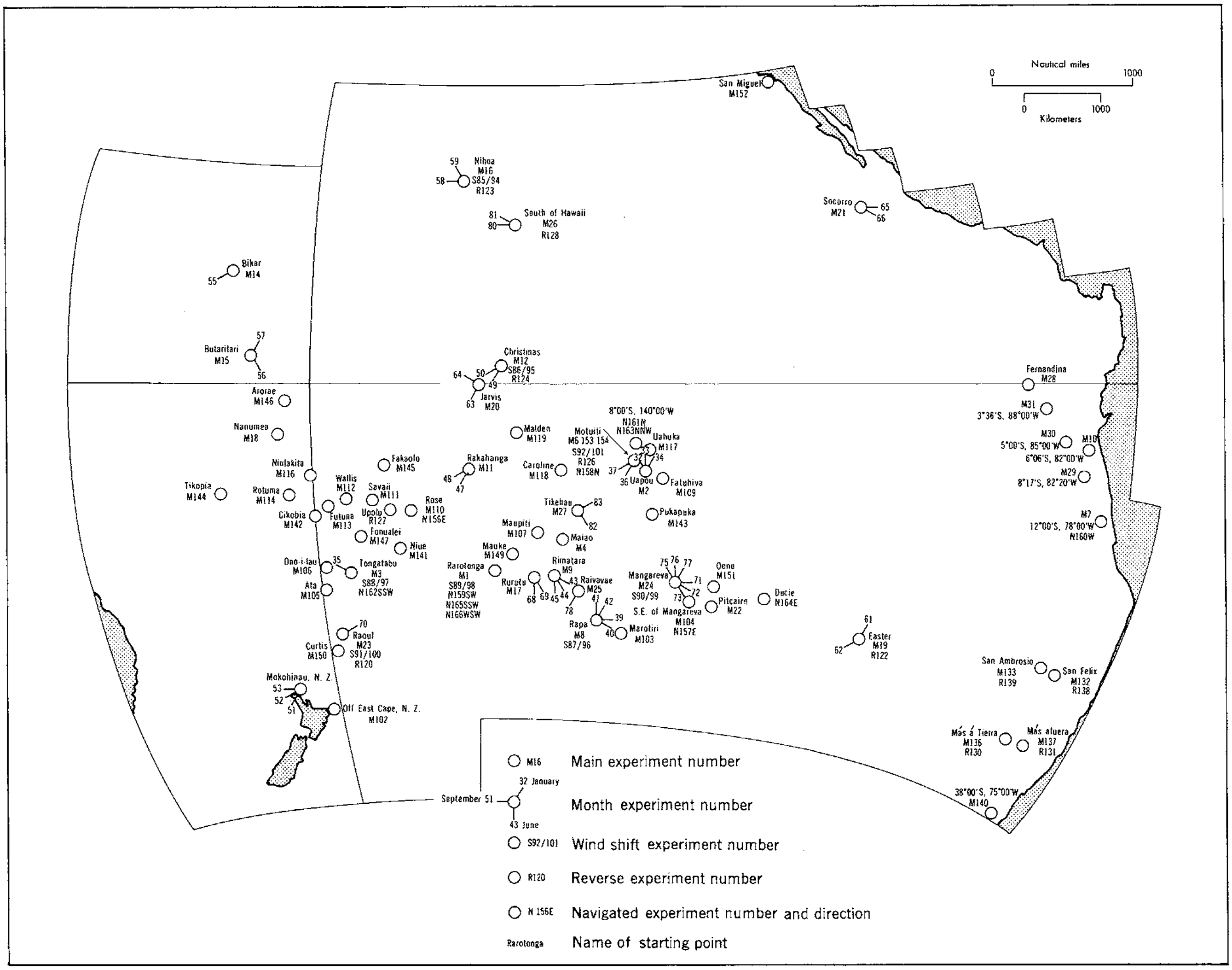


Figure 12. Starting locations for experiments

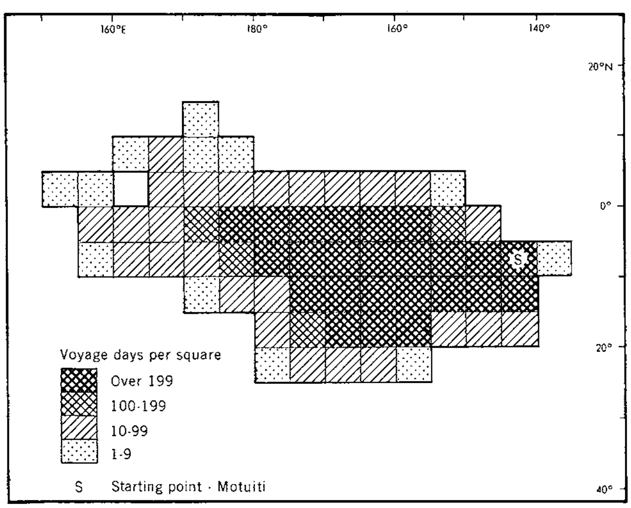


Figure 13. Motuiti (6): Drift-voyaging field by 5° squares

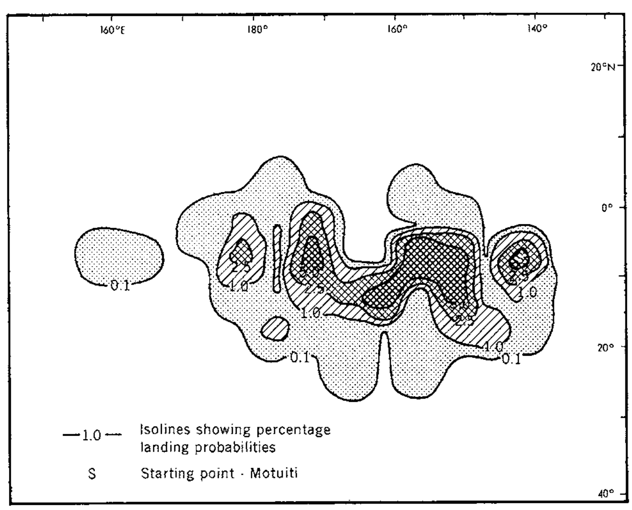


Figure 14. Motuiti (6): Landing probabilities by 5° squares

Table 6. Contact Probabilities from Motuiti

Percentage Probability	Experimental Results				
	Main	Sept.	Oct.	N. Shift	S. Shift
20.0 or over (very high)			N. Cooks		
10.0–19.9 (high)	N. Cooks Caroline	Phoenix N. Cooks Gilberts Malden	Tokelaus Phoenix Ellices Caroline	Phoenix Marquesas N. Cooks Caroline	Marquesas
5.0–9.9 (moderate)	Tokelaus Marquesas	Tokelaus	Gilberts	Malden	N. Cooks Malden
1.0–4.9 (low)	Phoenix Tuamotus Malden Ellices Gilberts Samoa Societies Niue	Ellices Marquesas Caroline Marshalls	Marquesas Malden	Gilberts Tuamotus Ellices	Carolines Samoa Phoenixes Tokelaus Jarvis Gilberts N. Lines Ellices S. Cooks Baker Niue
0.1–0.9 (very low)	S. Cooks Niue Baker Tonga Ontong Java Fiji N. Lines Marshalls Kapingar'i Sikaiana Solomons Rotuma Wallis	Sikaiana N. Lines Baker Ocean Jarvis Ontong Java Carolines Solomons	Santa Cruz Ocean Ontong Java	Marshalls Tokelaus Baker Samoa N. Lines Societies Ocean Carolines	Tonga Wallis Marshalls Societies Niuafoou Tuamotus Ocean Carolines Solomons
0.0 (zero)[a]	Jarvis	Niuafoou Tuamotus Samoa Societies S. Cooks Nuie	Samoa Tuamotus Societies Niuafoou Jarvis N. Lines S. Cooks Baker Niue	Niuafoou Niue	S. Cooks Niue

[a] No drifts from any of these experiments reached Hawaii, Easter, New Zealand, or South America. Thus, the entries are examples only.

cartograms demonstrate the cartographic output, which was used extensively in analyzing the results and their relationship to theories of Polynesian migration.

The voyaging field revealed by the main experiment (6)[1] ranges through 70° of longitude (4,100 miles) to the vicinity of the Solomon Islands, with many drifts reaching as far west as the Gilbert and Ellice islands (about 3,000 miles) and west-southwest to Niue (2,000 miles). Some craft picked up winds that drifted them south and southwest to the Societies and Tuamotus, but there was almost no sailing to the east or north of the Marquesas, with the result that no drifts even begin to look as though they could reach South America, the extreme east of Polynesia, or the Hawaiian Islands. The mass of drifts diverged immediately to the west of Motuiti and, in the longitude of the Northern and Southern Cooks (about 1,600 miles), had spread to cover 30° of latitude. The number of voyage-days dropped sharply in the vicinity of Tonga and Samoa, and the few voyages which continued west petered out in western Melanesia and the Marshall Islands.

The landing places contain few surprises, given the strongly westward nature of the drifts. Since Motuiti has a westerly location in its home group, there are relatively few contacts with other Marquesan islands, but many

1. The numbers in parentheses refer to serial numbers of experiments (Appendix 1) and the cartographic displays in Appendix 2 are indexed under these numbers.

with the scattered islands to the west, especially Caroline and Penrhyn. Many drifts ended in the Phoenixes and Tokelaus; some got to Fiji, the Gilberts, and the Ellices; a few as far as Ontong Java, a large coral atoll north of Melanesia; and one to Kapingamarangi, an isolated atoll to the south of the Caroline Islands.

The landings of drifts from Motuiti can be given in the form of contact probabilities, which are best defined as the propensity of drift voyages from an island or island group to result in landings at one or more island groups. They are chances (expressed in percentage or adjectival form) of drift connections between islands or island groups. Table 6 shows contact probabilities from Motuiti derived from the main experiment, additional experiments for July and August, and north and south wind shift experiments (see also Figs. 15, 16, 17, 18, and 19).

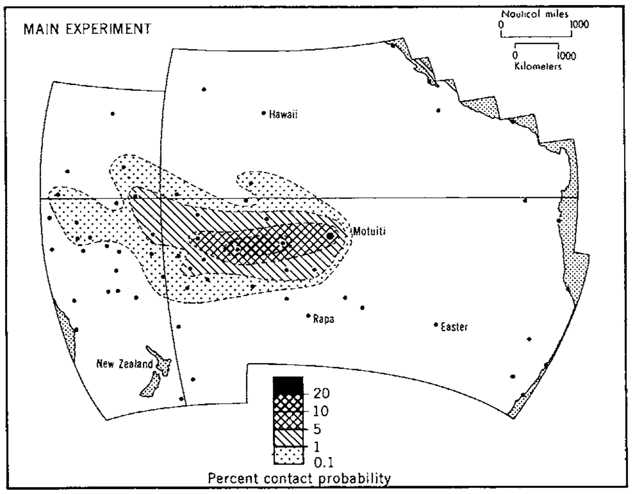


Figure 15. Motuiti (6): Drift contact probabilities, main experiment

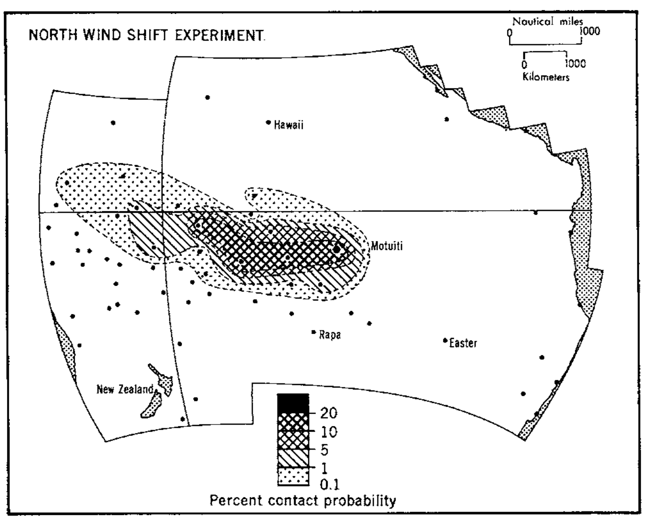


Figure 16. Motuiti (92): Drift contact probabilities, north wind shift experiment

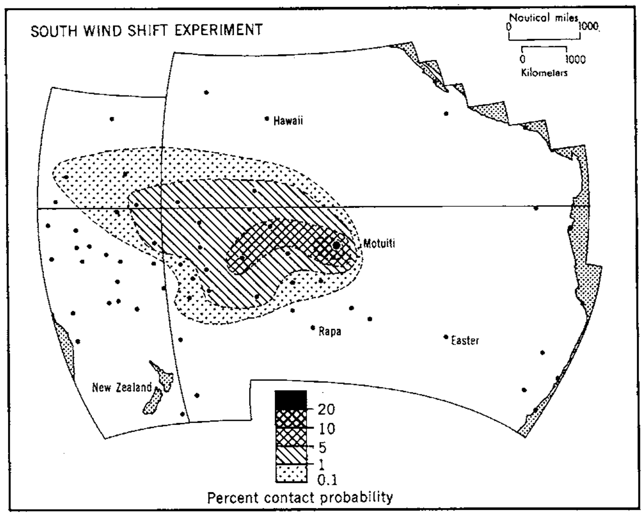


Figure 17. Motuiti (101): Drift contact probabilities, south wind shift experiment

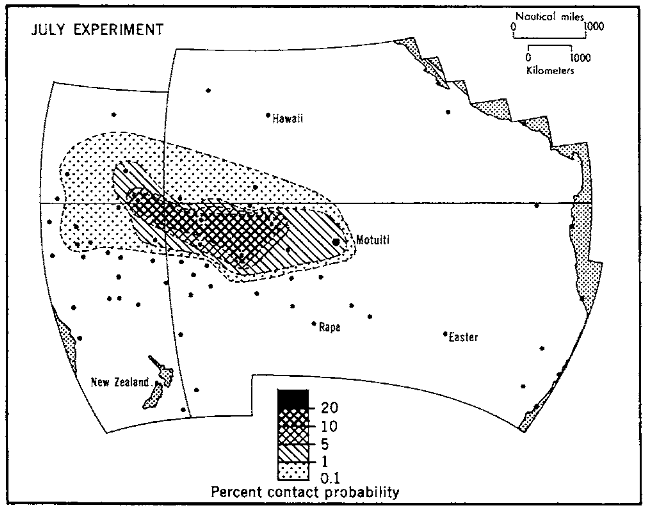


Figure 18. Motuiti (36): Drift contact probabilities, July experiment

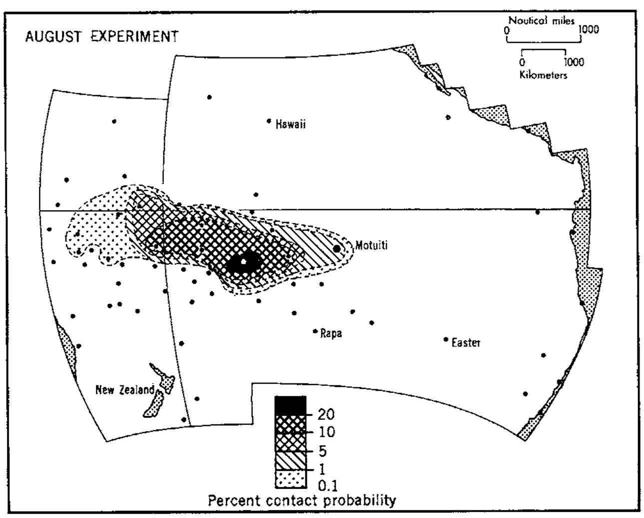


Figure 19. Motuiti (37): Drift contact probabilities, August experiment

The experiments for particular months indicate that drifting is seasonally more concentrated to the west than in the main experiment. In September, the westerly element is very strong for over 3,000 miles (to about 170°E), with minimal drifting to the southwest but many passages to the northwest, with some reaching the latitude of Hawaii, though at least 30° to the west of that island. Contact probabilities disappear to the south and southwest but increase to the west and northwest.

October sees westward sailings and landings intensified. Drifts cover a band only 15° of latitude in width and many reach places 3,500 miles to the west. The experiments for additional monthly voyages do not result in any appreciable additions to the voyaging field from Motuiti derived from the main twelve-month experiments. The absolute limits of the voyaging field of Motuiti, as delimited by the main experiment, encompass the voyaging fields of the additional month experiments.

Shifting the wind systems 5° to the north gives some different results. The voyage pattern has a west-northwesterly direction with many drifts reaching west of 180° in the neighborhood of the Ellice and Gilbert islands. Contact probabilities show much greater chances of landing in the Tuamotus than the main experiment, but less chance of contact with the far distant west. High probabilities extend west to the Phoenix Islands. There was high likelihood of landing at one of the Marquesas, but almost one-third of the vessels were lost at sea.

Shifting the winds 5° to the south gives quite different drifting and landing patterns. Many vessels move to the southwest, and some sail in the open ocean to the south of the Southern Cooks. Contact chances are relatively modest, however, due to the absence of islands in these waters; contact probabilities are moderate with the Northern Cooks and Malden.

An important question concerns the stability of probabilities obtained from simulations of 732 voyages. Ideally, checks should have been run on a fair sample of experiments, since probability stabilities very likely vary from one starting point to another. Nevertheless, the cost of additional experiments prohibited extensive checking, and we were able to make only one major check by running two additional experiments (153 and 154) from Motuiti. The results are given in Table 7. Chi-square tests demonstrate a close fit between the patterns of landings in individual experiments and the mean pattern. The higher probabilities show little variance from one experiment to another. As would be expected, the low probabilities show a greater variation from their individual means, but these are of much less significance in the analysis of the results.

Table 7. Probability Stability: Three Experiments from Motuiti

Island Groups	Number of Landings			
	Expt. 6	Expt. 153	Expt. 154	Mean[a]
Marquesas	56	63	71	63.3
Tonga	12	14	14	13.3
Societies	19	19	16	18.0
Samoa	24	24	29	25.7
Caroline	118	111	113	114.0
Southern Cooks	11	8	8	9.0
Northern Cooks	128	118	121	122.3
Ellices	39	41	38	39.3
Starbuck-Malden	27	24	24	25.0
Tokelaus	46	43	40	43.0
Phoenix	29	38	47	38.0
Gilberts	8	15	7	10.0
Number of landings	544	547	548	546.3
Crews lost	185	179	182	182.0
Out of bounds	0	0	0	0.0

[a] Contact probabilities with a mean of less than 1 percent are excluded.

Contact Probabilities between Island Groups

Extensive sampling within the model system gave contact probabilities from starting points to island and coastal locations of the study area. These contacts make up a drift probability matrix, with landings on the vertical axis and starting places on the horizontal axis. The table has 137 × 994 lines and is not reproduced here for reasons of space. Although details from it are used in subsequent discussion, the matrix needs to be generalized before it can be described and assimulated into the discussion of the colonization of Polynesia. It is more useful to describe a single contact probability from the Society Islands to Samoa than to list a complicated table with three starting places and eighteen landing places.

For this reason the 994 island and coastal places were collapsed into island and coastal groups. This operation was not performed on the basis of experimental results, but on the basis of cultural homogeneity and locational proximity. The results of the operation are shown in Figure 20. The South American coast was collapsed by the arbitrary method of dividing it into 10° latitudinal zones. The island groups which lie some distance off the coast were kept separate.

The advantages of combining the islands into groups to describe and interpret experimental contact probabilities are clear. It is easier to accept this for landings than for starts, however, and the need to generalize the starting points from individual islands to island groups needs further discussion.

Suppose we wish to consider contact probabilities

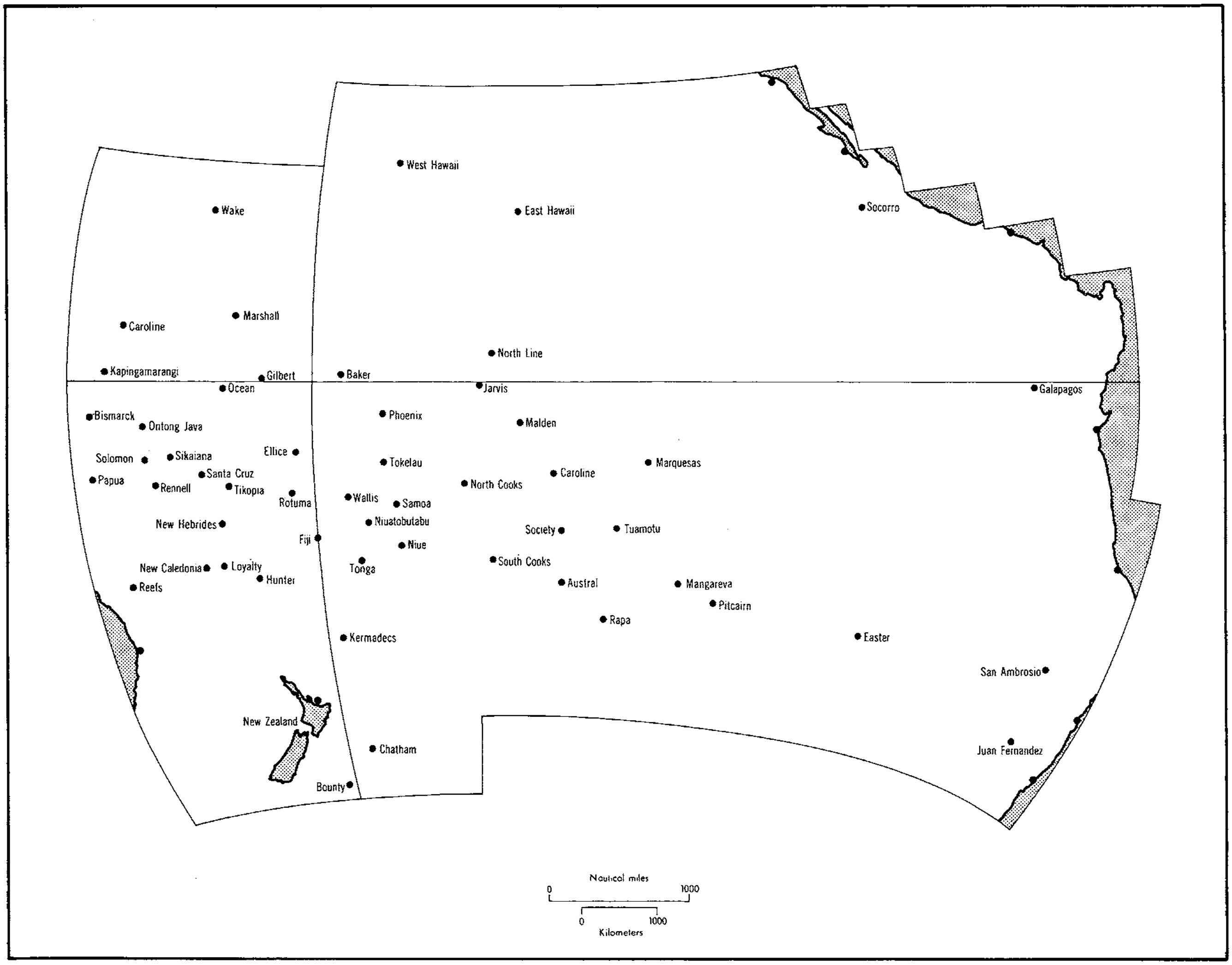


Figure 20. Study area: Island groups and coasts

from the Marquesas Islands to other island groups in the Pacific Ocean. The Marquesas stretch 250 miles from Eaio and Hatutu in the northwest to Fatuhiva in the southeast. Distances and directions from the Marquesas to potential landings are as follows: the Hawaiian Islands begin 2,500 miles to the north-northwest and end at Midway about 4,200 miles away; the Northern Line Islands face the Marquesas edge on at 1,100 miles to the west-northwest; Caroline Island lies 700 miles to the west and behind it Vostok and Flint a further 150 miles, with the Northern Cooks stretching out from Tongareva at 1,200 miles to Pukapuka at 1,800 miles; southwest lie the Societies from 800 to 1,000 miles and beyond them the Southern Cooks from 1,600 to 1,800 miles. The Societies are partly screened from the Marquesas by the Tuamotus, which lie in their scores across the ocean to the south, at distances ranging from 400 miles to 750 miles in a southwesterly direction. South-southeast lies the Pitcairn group at 1,300 miles; southeast is Easter at 2,200 miles; and finally, in the far distant east, the South American coast at 3,700 miles.

These distances and directions are roughly measured from the center of the Marquesas Islands. They will vary if measured from the specific islands. Further, if specific islands in the group are used to calculate contact probabilities, the individual islands of the home group begin to change probabilities drastically. Landings at other Marquesan islands are 6 percent from Motuiti, 20 percent from Uapou, 45 percent from Fatuhiva, and 99 percent from Uahuka. Because of the masking effects of other Marquesan islands, the spread, frequency, and direction of drifts to other areas will thus

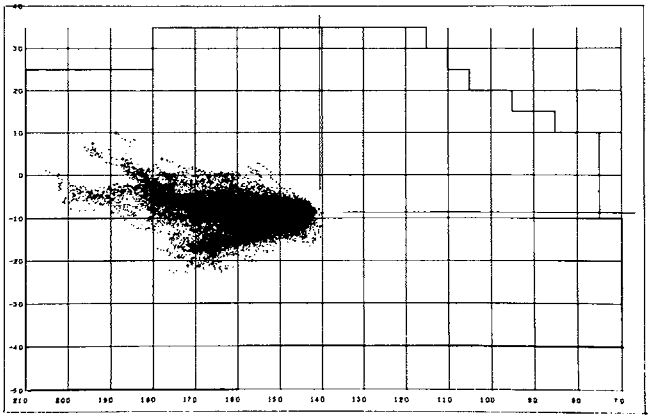


Figure 21. Motuiti (6): Voyage days computer map

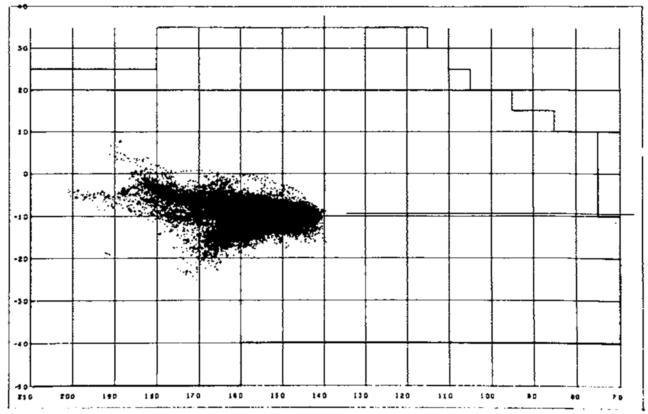


Figure 23. Uapou (2): Voyage days computer map

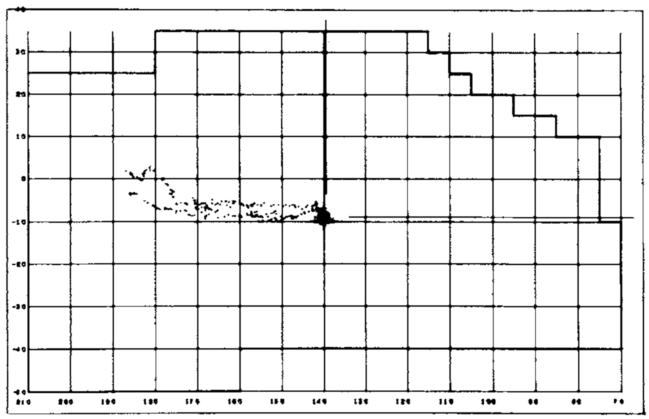


Figure 22. Uahuka (117): Voyage days computer map

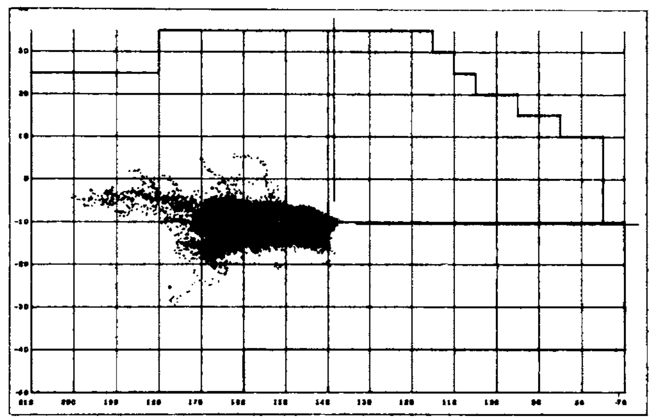


Figure 24. Fatuhiva (109): Voyage days computer map

vary considerably. Figures 21 to 24 show the positions of all drifts for each day from the four Marquesan locations.

For the purpose of constructing "contact" maps, we assume that the probability of reaching another island group from the Marquesas is best represented by the experimental location which gives the most chances of getting to that group. Using this assumption, the probabilities of reaching the island groups described above are as follows: Hawaii, 0 percent; Northern Line Islands, 0.3; Malden-Starbuck, 3.8; Caroline, 16.2; Northern Cooks, 19.0; Society Islands, 1.3; Tuamotus, 14.9; and Pitcairn, Easter, and the South American coast, 0. These probabilities do not total 100 percent, since they are based on the total number of starts from a group, including voyages which end within the group, those lost at sea, and those gone outside the study area.

A similar rule is used when describing contact probabilities from other island groups with more than one experimental starting point. At first sight this seems to weight the experimental evidence too heavily in favor

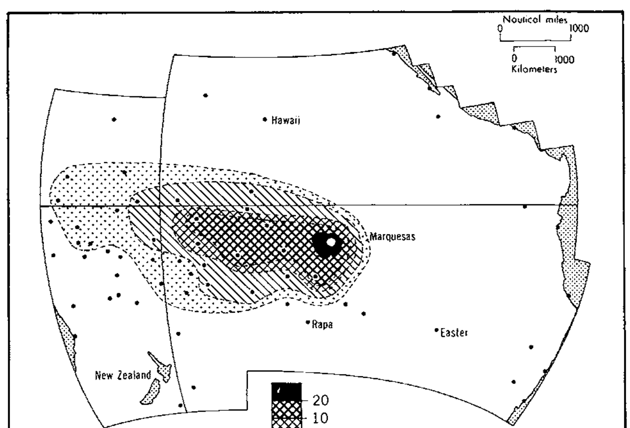


Figure 25. Marquesas Islands: Drift contact probabilities

of drift contact. As we shall see, however, the fundamental conclusions from this research are not materially affected.

Using this procedure we can calculate drift probabilities from the Marquesas as in Figure 25. On this map additional probabilities derived from wind shift experiments are added. A core of high contact chances stretches from the Tuamotus to the Phoenix Islands, surrounded by an arc of low probabilities from the Society Islands through Samoa to the Ellices and Gilberts round to the Northern Line Islands. Beyond this, very low probabilities extend from Tonga in the south past Ontong Java and the Solomons to Micronesia.

Throughout this and the following chapter contact probabilities have been grouped into the categories given in Table 8, and the adjectival descriptions "very high," "very low," and so on are used in the text synonymously with their numerical equivalents. It is hoped that the emotive value which might be placed on such words as "high" and "low" is reduced in this way.

Table 8. Contact Probabilities

Percentage Form	Descriptive Form
20.0 or more	Very high contact probability
10.0–19.9	High contact probability
5.0–9.9	Moderate contact probability
1.0–4.9	Low contact probability
Below 1.0	Very low contact probability
0	No contact probability

Contact Probabilities from Main Experiments

Very high contact probability (20.0 percent or more). Figure 26 shows where experimental results give very high contact probabilities between starting points and island groups and coasts. Within Polynesia there are five contact regions: Tonga to Fiji; Samoa to Wallis to El-

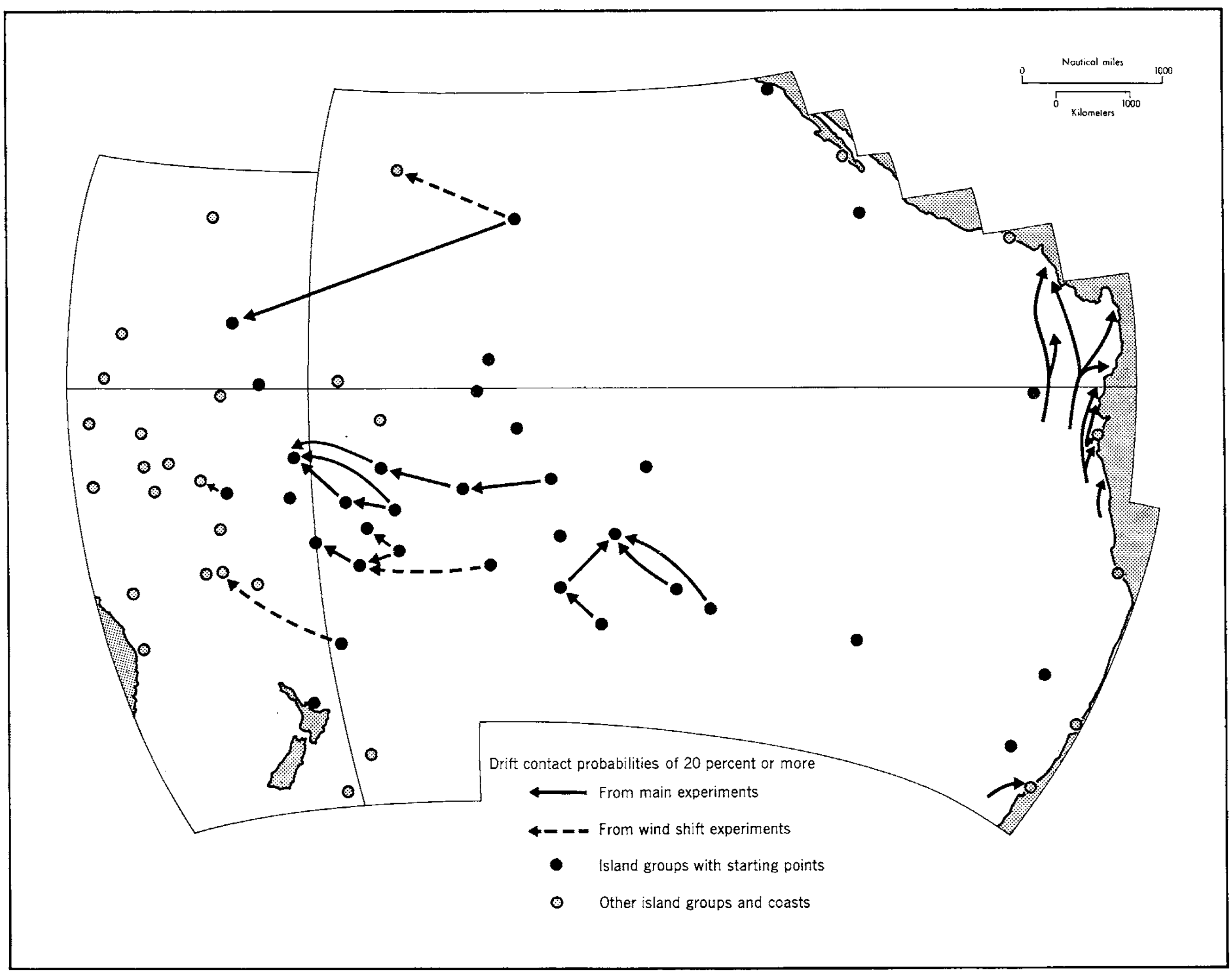


Figure 26. Very high drift contact probabilities

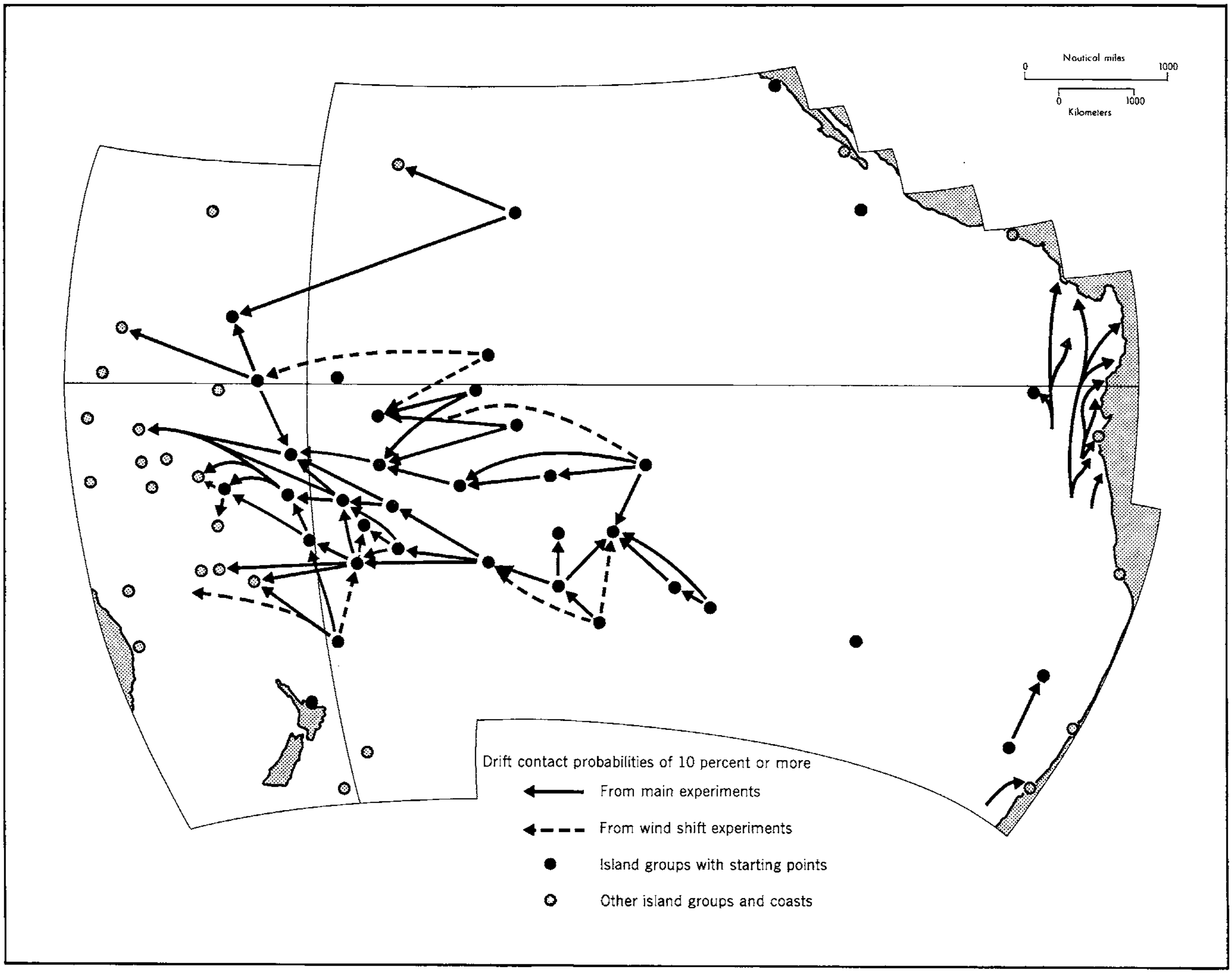


Figure 27. High drift contact probabilities

lice; Caroline to Northern Cooks to Tokelaus; Pitcairn to Mangareva to the eastern Tuamotus; and Rapa to Australs to Tuamotus and Southern Cooks. In each region contacts are from east to west with the exception of southwest to northeast contact from the Australs to the Tuamotus.

A very high contact probability exists from Hawaii (Nihoa) to the Marshalls; in fact there is a 37 percent chance of making the voyage of three thousand miles.

Experiments from the offshore islands and coasts of South America show very high chances of contact with South American coasts to the north of the starting points.

High contact probability (10.0 percent or more). Figure 27 shows both high and very high contact probabilities. Most of Polynesia can be divided into three zones within which there is a high probability of contact between island groups: (A) Pitcairn-Tuamotus; (B) Marquesas-Tokelaus; (C) Rapa-Tonga and Ellices. In the main experiments these three regions are connected by southerly drifts from the Marquesas to the Tuamotus and northerly drifts from the Australs to the Tuamotus. Additional experiments might provide some further cross links between B and C, and certainly would provide additional north and south linkages at the western margins of Polynesia.

Other directions of high contact probability can be easily identified; for example, Marquesas–Caroline group–Northern Cooks, Tonga–Fiji–Central Melanesia, and Rapa–Australs–Southern Cooks.

The margins of Polynesia and the South American coasts are still isolated from the main contact regions identified above. Neither New Zealand nor Easter Island have high contacts with any other island group or coast,

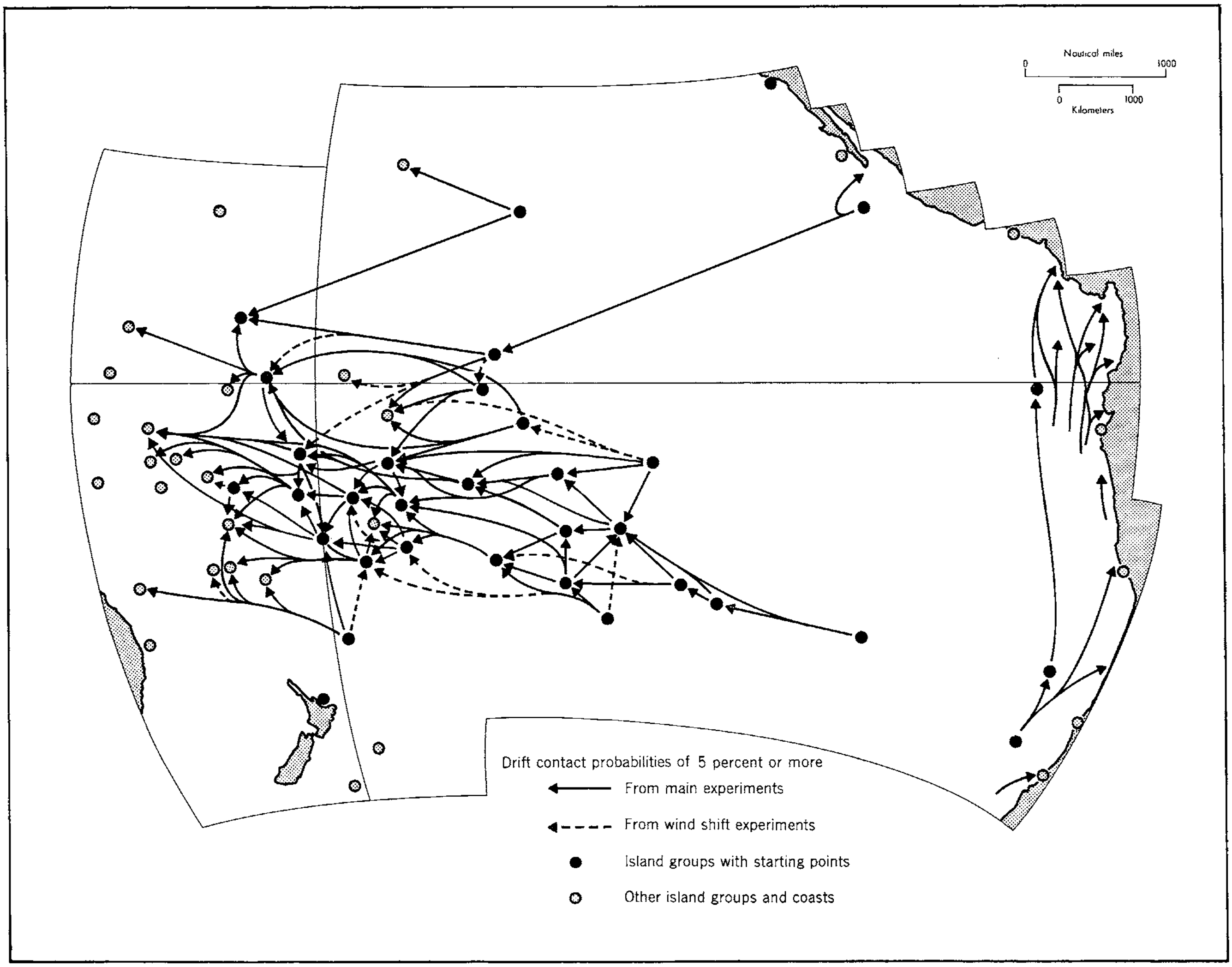


Figure 28. Moderate drift contact probabilities

and Hawaii has high chances of contact only with the Marshalls. Micronesia has high internal contacts from east to west only. Starting points off the South American coasts show high contact probabilities with nearby coasts and islands but no linkages with Polynesia.

Moderate and high contact probability (5 percent or more). By moderate contact probability we mean a chance of one in twenty of reaching an island group from a starting point. This may seem a tenuous link, but moderate seems a reasonable term when one considers the large range of low and very low chances of contact available to would-be voyagers.

The map (Fig. 28) shows an intensification of the patterns already described on the high and very high contact probability maps and east to west contacts still dominate the results. Many island groups previously isolated now have links to other regions.

Hawaii, with only a connection to the Marshalls, and New Zealand remain adrift from the many contact probabilities of other Polynesian areas. There are still no west to east connections. The small number of south to north and north to south contacts is remarkable, considering the closeness of some island groups and the probabilities of airstreams from directions other than the east.

The continued lack of contact probabilities from the eastern coasts of the Pacific Ocean to the islands of the central and western Pacific is surprising, given the wind data employed and the survival parameters built into the drift model. All that appears in this instance are moderate chances for drifts to reach the Northern Line Islands from Socorro and to reach the Marquesas from the Juan Fernandez Islands. The magnetism of the South American and Central American coasts and islands remains paramount for voyages initiated anywhere in tropical locations near those coasts.

Low Contact Probabilities (1.0 to 4.9 percent). In the central part of Polynesia, between the Societies and Tonga, contact possibilities of 1 percent or more are strongly east to west. In eastern Polynesia some divergences from the strongly westward pattern appear, especially northerly chances from the Austral Islands and Rapa, and southerly chances from the Marquesas and Caroline Island. On the border between Polynesia and the Melanesia westward links become less characteristic, and tend northwesterly rather than westerly. They are supplemented by north and south contacts. In the region between Fiji and the Ellices easterly probabilities appear for the first time, though not for any great distance.

From the Hawaiian Islands there are low probabilities to the Gilberts. From New Zealand low chances reach the various island groups to the north and the Chathams to the southeast but there are no links to New Zealand. The lack of contact probabilities between the South American coasts and Polynesia is maintained as is the continued hugging of the South American coast over long distances by drifts begun at locations south of the Tropic of Capricorn.

Additional Month Experiments

The strongly east to west direction of drift voyages became evident in the research after a few computer runs had been made. Further experiments for specific months were run to see if some of the more obvious gaps in inter-island sailing probabilities could be filled. A second reason for these experiments was to determine whether new contact probabilities would call into question the validity of the contact probabilities derived from the main experiments.

The additional months provided negative evidence on both counts. Despite the fact that each experiment launched over seven hundred drifts in a single month from a starting point, no new contact probabilities of any importance or significance emerged. In some instances voyages in westerly directions were strongly intensified due to the seasonal weather conditions, and landing chances increased (over the annual figures) to some island groups both near and far. In other cases, especially in months whose wind conditions were more variable than the prevailing annual norms, a more spread out effect was obtained. This, however, did not upset the landing probabilities derived from the main experiments, despite longer voyages to more unlikely quarters. From this we conclude that the main experiments provide enough drifts to give valid probabilities for all times of the year.

Using the experiments from Mangareva as an example, the voyaging and landing patterns disclosed by the main experiment were as follows. Drifts concentrated within 15° of longitude to the west of Mangareva with some voyaging as far as 30 or 40° to the west. A subsidiary voyaging pattern to the south gives a low number of voyage days as far as the southern boundary of the study area. Landings concentrated heavily in the Tuamotus (92.5 percent), and low contact showed with the Society Islands. Otherwise contact chances within the rather limited voyaging range were very low or nonexistent.

Additional experiments were run for January, February, March, July, August, and September. Sailing patterns are most different from the main experiment in September and February.

Table 9. Mangareva: Landing Probabilities

Island Group	Main Expt. 12 months	Addl. Expt. September	Addl. Expt. February
Mangareva, Teruse	3.7%	27.0%	5.1%
Pitcairn group	0.1	2.4	0.0
Tuamotus	92.5	36.3	58.6
Rapa/Marotiri	0.1	0.9	4.0
Austral group	0.6	0.7	8.5
Society group	1.8	0.7	2.5
Northern Cooks	0.1	0.3	0.0
Southern Cooks	0.4	0.4	2.4
Caroline	0.1	0.0	0.0
Samoan group	0.1	0.0	0.3
Tonga group	0.0	0.0	2.8
Tokelau group	0.0	0.1	0.0
Maria Theresa Reefs	0.0	0.0	0.1
Niue, Beveridge	0.3	0.0	1.7
Nuiatobutabu group	0.0	0.0	0.6
Fiji group	0.0	0.0	0.4

There are, as Table 9 shows, substantial changes in contact probabilities to nearby island groups; for example, to the Tuamotus and the Australs. Beyond these, however, landing chances are not changed materially, except perhaps to Nuie, the Southern Cooks, and Tonga, which the February experiment raises to low probability status.

Wind Shift Experiments

Sixteen experiments simulated 732 drifts from eight locations with the wind data moved first 5° north and then 5° south. The reasons for assuming that these modifications simulate possible past climates are described above (Chap. 3, pp. 14–16). The eight starting points form an arc around the northern, eastern, and southern margins of Polynesia stretching from Nihoa, Hawaiian Islands, to Raoul, Kermadecs (see Fig. 12). Since the main experiments did not give significant drift probabilities to and from many of the outlying islands of Polynesia, this modification of the model was undertaken to see if new contact probabilities could be generated.

The results are varied. In most cases voyaging fields are considerably different from those in the main experiments. As with the additional month experiments, however, altered voyaging fields are no guarantee of significantly different contact probabilities. The detailed discussion of these experiments below indicates some new low or very low probabilities, a few of which indicate the possibility of drift voyage contact of outlying areas isolated in the main experiments.

Nihoa, Hawaiian group. The north shift experiment gives strong voyaging patterns to the west and southwest, in contrast to the more concentrated pattern of the main experiment. Contact probabilities remain much the same, however, the only island group with higher ratings than the main experiment being the Ellice Islands (0.9 percent) and the Carolines (now 2.4 percent). In the Nihoa south shift experiment the voyaging field concentrates more to the southwest and the contact patterns are much reduced in the Marshalls but are increased in both eastern and western islands of the Hawaiian group. The far ranging drifts to the southwest netted only single landings in Fiji and the Bismarck Archipelago.

Christmas Island. The contact probabilities in the north shift experiment increased to the southwest in the Gilbert, Tokelau, and Phoenix islands, and low probabilities appeared for the Northern Cooks and the Samoan group. These were balanced by slightly lower chances of contact with the Marshalls and much lower chances to the other Line Islands. The south shift experiment gives only one-tenth of the Line Island contacts as the main experiment and much increased chances of drifting to the Gilbert and Ellice islands and to Western Melanesia.

Motuiti. (See pp. 28–32.)

Mangareva. The north shift experiment for Mangareva doubled the area of the voyaging field but contact probabilities remained much the same. Landings in the home Gambier group and the nearby Tuamotus add up to 82 percent as against 96 percent in the main experiment, and very low probabilities were recorded in the Pitcairn group and others to the northwest. The south shift gave much more westward drifting, lower contact chances (68 percent) with the home islands, and increased or new chances of contact with Rapa, the Australs, the Southern Cooks, and a few islands further west.

Rapa. The north shift simulation for Rapa gave more sailing to the south and east and less to the west and north than the main experiment. Landing probabilities to the Tuamotus reached 11 percent, but chances from the Australs to Tonga were much reduced. The south shift gave longer voyages to the west and northwest and higher contact chances to the west, especially to the Southern Cooks, the Tonga group, and Fiji.

Rarotonga: Southern Cook Islands. The north shift experiment from Rarotonga gives much sailing in the open ocean south of the Cook Islands, but contact probabilities remain much the same except for increased chances of reaching Niue or Tonga. The south shift gives much more voyaging to the west and results in high contact chances for Niue, Tonga, and the Nuiatobutabu group.

Tongatabu. The main experiment for Tongatabu showed a drift pattern highly concentrated in the Tonga–Fiji–Central Melanesia area with 90 percent of landings in Tonga and Fiji groups and the remainder in the New Hebrides (6.4 percent) and nearby Melanesia. The north shift experiment gives similar patterns, except for additional sailings to the distant west and northwest. The south shift of the wind data constricts the sailing and landing patterns, reducing the chance of reaching the New Hebrides.

Raoul (Kermadecs). Moving the wind systems 5° to the north results in substantially more drifting from Raoul to the south and east and less to the north and west. A result is greater chance of contact with Polynesian island groups (Tonga, Niue, Australs) than in the main experiment, which gave high chances of contact with central Melanesia. The south shift experiment gives more voyaging to the northwest than the main simulation; landfall probabilities are thus higher in the Loyalty Islands, the New Hebrides, New Caledonia, and other central Melanesian groups, but not in New Zealand.

Although these wind shift experiments do present some results different from those from the main experiments, the situation regarding the main problem areas—New Zealand, Hawaii, Easter, West to East Polynesia—remains much the same.

Reverse Experiments

Reverse experiments simulating drifts backward from a single landfall toward their starting points were mounted for eleven places. The intent of these experiments was to generate voyages in large numbers to marginal areas of Polynesia and so perhaps identify possible sources for marginal Polynesian populations. The results are helpful in a negative sense, for almost all the contact probabilities derived from these experiments are low or very low.

Contact probabilities determined from ordinary forward experiments and those obtained from reverse experiments are not the same. The former estimate the fraction of those voyages starting at island i which arrive at island j; the latter, the proportion of those voyages arriving at island j which have come from island i. If these are denoted by p_{ij} and q_{ij} respectively, then

$$p_{ij} = (\text{voyages from i to j})/(\text{total voyages leaving i})$$

$$q_{ij} = (\text{voyages from i to j})/(\text{total voyages arriving at j}).$$

Consider, for example, voyages to Christmas Island. We know, from the main and other experiments, that the chances of reaching Christmas Island from anywhere else are low. What the reverse experiment does in effect is increase ad infinitum the number of starts from all over the study area until the required number of landings are made. For example, the chances of reaching Christmas from the Marquesas according to the main experiments are 0.3 percent. From the reverse voyage experiment 1.4 percent of those landing at Christmas originate in the Marquesas; in other words, the number of voyages from Motuiti would have to be multiplied fourfold to achieve the same result. Conversely 1.5 percent of the voyages from Socorro end at Christmas, but only 0.1 percent of those ending at Christmas begin at Socorro. Forward experiments assume the universe of islands and coasts for landing, and reverse experiments assume the universe for launching.

The forward and reverse contact probabilities for any single island pair are not directly related. If, however, i, j, m, and n are four islands (not necessarily all different) of which i and j have been used as starting points for forward voyages and m and n as finishing points for reverse voyages, then[2]

$$(p_{im}p_{jn})/(p_{in}p_{jm}) = (q_{im}q_{jn})/(q_{in}q_{jn}).$$

This result follows trivially by substitution of the previous formulas for the p's and q's.

Paths in Polynesia

Using the experimentally derived drift contact probabilities between island groups, we can identify possible paths of contact from any island group to other island groups and then onward from these to other parts of Polynesia and beyond. The procedure used to find such paths of contact was as follows: (1) Select a starting point, for example, Easter Island or Hawaii. (2) Identify moderate or high contact probabilities from the starting point to other island groups, using the results of the main experiments, and draw these contacts on a cartogram which shows island groups as dots (see Fig. 20), distinguishing between moderate and high probabilities. (3) Use contacted island groups identified in step 2 as starting points: repeat step 2 continuing until no new contacts can be added. (4) Repeat steps 2 and 3 using the results of the north and south wind shift experiments.

The selection of starting points for this procedure is limited only by the number of places from which experiments were run. In practice it was necessary to use only a few starting points to achieve the maximum possible contacts between island groups in Polynesia. The preponderance of east to west contacts indicated in the simulation of drift voyages means that a group of starting locations in eastern Polynesia will incorporate most of Polynesia in these paths of contact. Conversely starting points on the western margins of Polynesia will result in only rare paths of contact into Polynesia, with contacts to Melanesia in the west added.

The question of which range or ranges of contact probabilities should be used cannot be finally resolved. We think it reasonable to use the level of one in twenty (5 percent) as a minimum of contact probability, but can, of course, give no quantitative reasoning to support it. A subsidiary set of cartograms shows paths of contact at the 1 percent level of probability. As the cartograms show, paths from certain gates contain contact chances of differing magnitude, and the reader will undoubtedly have his own intuitions of the proper level of probability relevant to the situation he is considering.

Figures 29 and 30 show paths of contact, at moderate or better probability, from the Marquesas, Easter, Rapa, Juan Fernandez, and Christmas; and from Hawaii, the Kermadecs, Rotuma, and New Zealand. The greatest degree of penetration and coverage of Polynesia is achieved by entering at the Marquesas or Easter Island.

From the Marquesas, only the Hawaiian group and the equatorial islands (including Christmas) to the north and the Australs, Rapa, Mangareva, the Pitcairn group, Easter, the Kermadecs, and New Zealand cannot be contacted. From Easter paths of contact reach all of Polynesia with the exception of Rapa, the Kermadecs, and New Zealand to the south, and the Marquesas, Caroline, the equatorial and Hawaiian islands to the north. The westward paths from Easter remain the same if Pitcairn, Mangareva, or the Australs are used for starting points. Contacts from Rapa (Fig. 29) are also

2. Note, however, that some care must be taken in applying the formula, since the forward main experiments estimate the p's based on voyages *starting* uniformly through the year; the reverse experiments estimate the q's based on voyages *terminated* uniformly through the year.

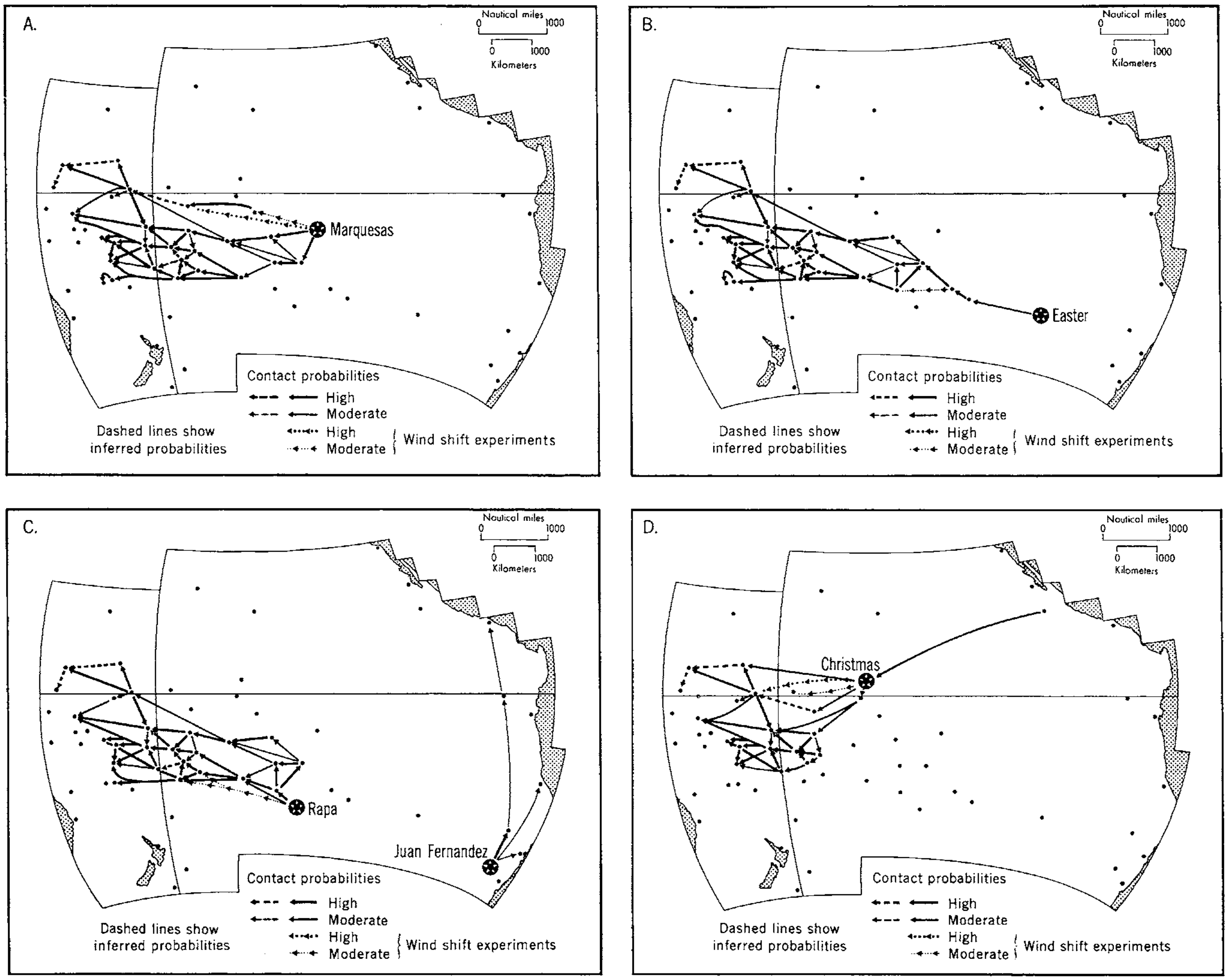


Figure 29. Paths of drift contact: Selected starting points

very extensive, although they exclude Mangareva and the islands further east.

These maps show that the chances of progressively greater inter-island contact decrease westward in Polynesia. An important characteristic common to these patterns is the lack of contact probability between the Gilbert and Ellice islands. Despite the westward contact pattern which pervades these results, it is necessary to have a starting point as far east as the Northern Cooks to reach both.

Contact paths from Christmas Island (Fig. 29) come only from moderate probabilities or from considering the wind shift experiments. Once at the Gilberts or Ellices, however, greater probabilities ensue to Micronesia and Melanesia. As with all the paths from locations previously discussed, the divergence into a northerly group of paths by way of the Gilberts and southerly groups by way of the Ellices converge in the ocean north of Melanesia and reach Ontong Java, a frequent termination for drift voyages begun in central and western Polynesia.

From Hawaii (Fig. 30) a high contact path reaches the Marshalls and thence drifts are likely to other parts of Micronesia. At the other end of the Polynesian world, New Zealand has no contact paths to other islands, while the Kermadecs can only reach Tonga by way of a wind shift experiment. The west coasts of South America and the island groups nearby remain isolated from Polynesia. The west coasts of North America and nearby island groups, however, do provide drift entry paths of moderate probability to Hawaii and Christmas Island and from those places onward to the west.

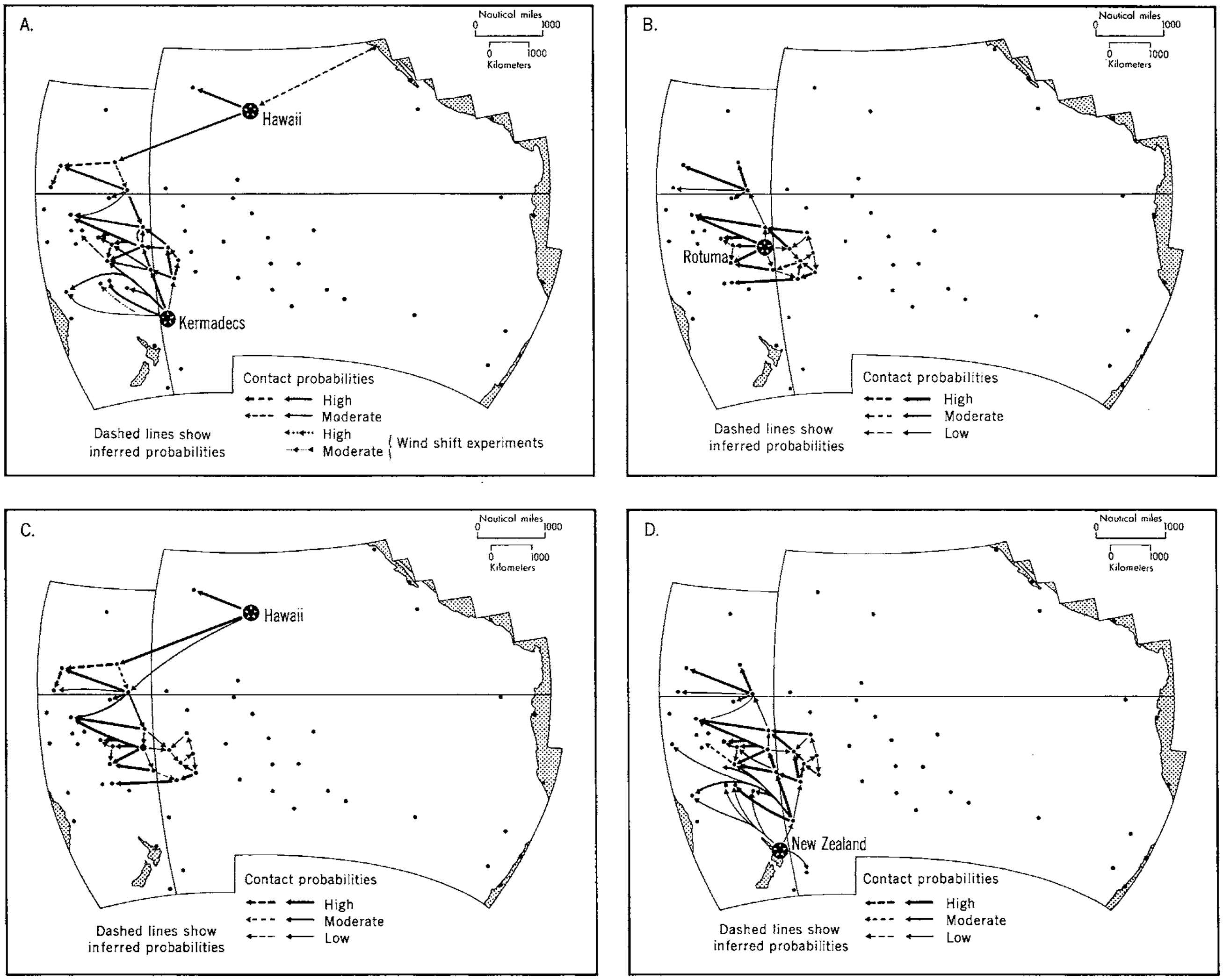


Figure 30. Paths of drift contact: Selected starting points

Three places, New Zealand, Hawaii, and Rotuma (Fig. 30), were chosen to investigate paths of contact using probabilities of 1 percent or more. From Rotuma, which is at the western margin of Polynesia proper, high probabilities exist to the west from the New Hebrides to Ontong Java. In other directions, apart from a chance of 6 percent to the Ellice Islands and then higher probabilities further west, drifts have only low chances of penetration even to such nearby groups as Fiji or Wallis. Low probabilities may eventually lead to the Tokelaus, Samoa, and Niue, but no further east.

This system can be entered from the northern extremity of Polynesia at Hawaii with low probabilities by way of the Gilbert and Ellice islands. Again, also, the difficulties of drifting east contrast with the ease of westward passages.

The nature of the results of the simulation experiments are clear; entry into the Polynesian island systems from the east central Pacific islands gives paths of contact of generally high probability through to the western margins of Polynesia and on to central Melanesia. From the northern and southern extremities and from the west part of Polynesia probabilities do not lead to extensive paths of contact except into Melanesia (Fig. 31). There are only low possibilities of reaching central Polynesia from the west, and, according to our experiments, less than one in seven hundred chances of drifting from Samoa to the Cook or Society islands. There is no chance of reaching Hawaii, Easter Island, and New Zealand from other parts of Polynesia.

In the final chapter we will relate these experimental results to evidence of the settlement process from eth-

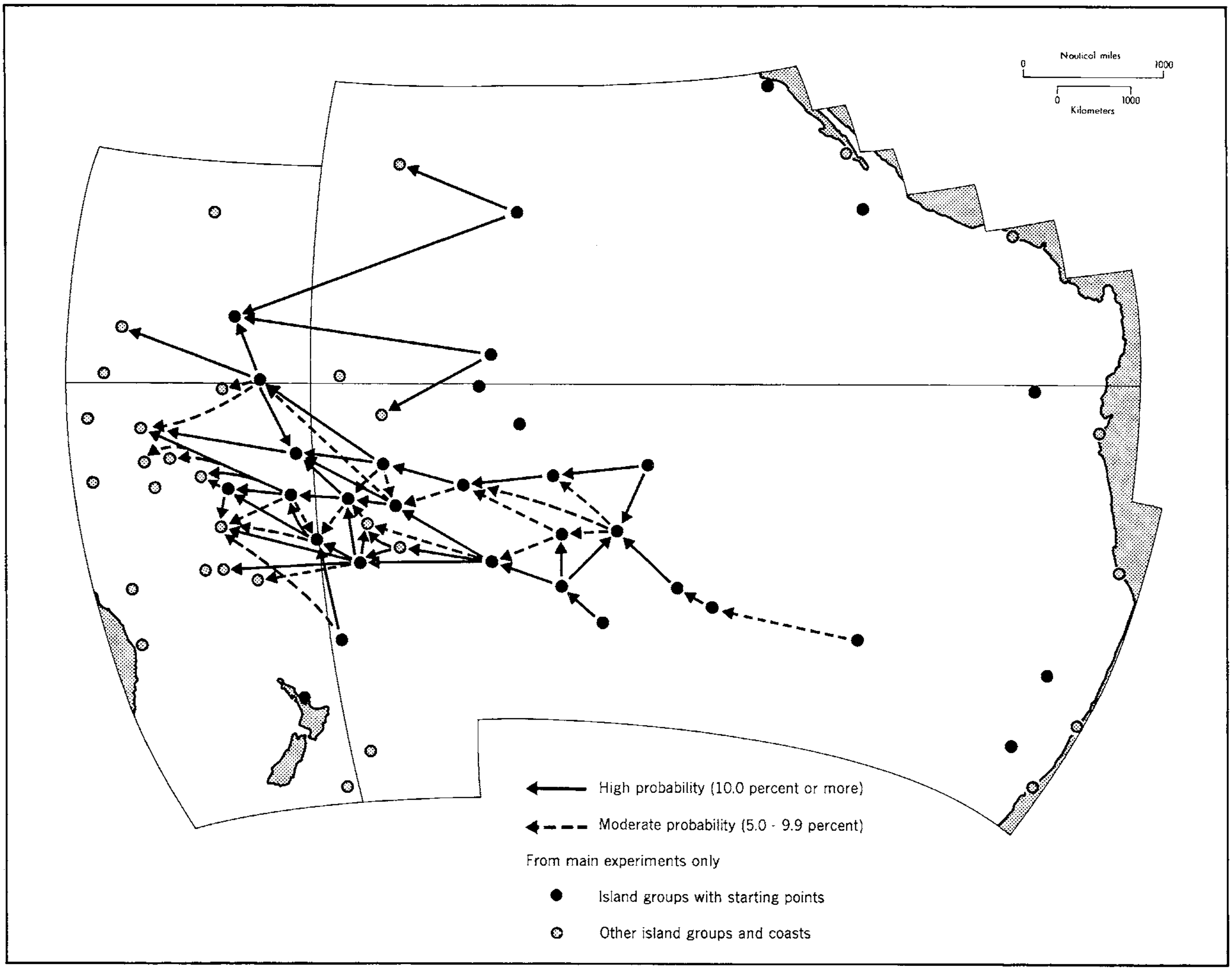


Figure 31. Study area: Paths of drift contact

nography, archaeology, history, and other disciplines, and to the various theories that have been proposed to account for the Polynesian diaspora.

The problem of validating any simulation model is difficult.[3] We have already discussed the values assigned to the several parts of the model, and the fact that the values used, in the table of vessel speeds, for example, are based on empirical observations and produce results consistent with these observations leads us toward one element of validation. But we should go beyond this in considering the model system as a whole and in interpreting the results it produces.

3. Harvey, 1967:586.

The model has simulated all the firmly documented drift voyages recorded by Dening.[4] Unfortunately the historical record is too fragmentary and too uncertain to draw valid statistical conclusions from a comparison with the results of the model. Perhaps the best validation is provided by the rather unexpected correspondence between "drift barriers" revealed by the model and some of the major cultural divides in the Pacific. Similarly Polynesian Outliers occur in locations which the model show to be unusually frequent destinations for drifts from Polynesia.[5]

4. Dening, 1963:138–149.

5. The authors recognize that there is a hint of circularity in this argument.

Chapter Five

CONCLUSIONS

In this chapter we examine the experimental results outlined above and illustrated in Appendix 2, and relate them to various theories of Polynesian origins and migrations.[1] We first consider the alternative routes which have been proposed for entry into Polynesia; then movements within central Polynesia; possible links between central Polynesia and Hawaii, New Zealand, and Easter Island; and the relationships between Polynesia and the Polynesian Outliers in Melanesia.

The protagonists of different theories suggest four main gateways to Polynesia — through Micronesia; through Melanesia and Fiji; from South America via the Marquesas or Easter Island; and from North America via Hawaii. A further suggestion brings people from Asia to Hawaii and thence to Polynesia. In the following discussion we examine whether or not, on the basis of the experimental evidence obtained from the model, drift voyages might have resulted in the peopling of Polynesia through any of the four main gateways. For data and data storage reasons the study was not extended west to the Asian coast and therefore the fifth alternative noted above has not been tested.

Western Approaches

Those who argue for a western gateway into Polynesia find support in the multitude of similarities between languages, physical characteristics, and cultural traits (and more recently the archaeological evidence of these) on both sides of the Melanesian (or Micronesian)-Polynesian divide.[2] Sharp accepts the view that Polynesia was probably settled from the west and argues that "one-way settlement" would be possible from Melanesia or Micronesia.[3] There may be two stages in reaching Polynesia from the west. The first takes settlers into the Fiji group and the second from there into Polynesia. But a direct route might bypass Fiji. To test the likelihood of drift voyages towards Polynesia from the western gateways, experiments were run from Arorae (146), the southernmost of the Gilberts; Niulakita (116), the southernmost of the Ellice Islands; Rotuma (114), viewed as an intermediate gateway; and Tikopia (144). Of the many islands of west Melanesia which might have served as starting points, Tikopia was chosen as more likely to experience northwesterly winds than islands to the south and hence to provide a favorable starting point for drifts to the eastwards.

If we are correct in this assumption about Tikopia's location, then the chances of drifting vessels reaching Fiji or Polynesia from west Melanesia are very low as only one voyage from Tikopia reached Polynesia (Rotuma) while one other ended in Fiji. If experiments had been conducted from starting points in the southern New Hebrides, then higher probabilities might have been obtained although the monthly wind and quarterly current patterns suggest this is unlikely.[4] It appears that the four hundred-mile expanse of ocean between the Solomons and New Hebrides to the west and Fiji in the east presents a formidable barrier to eastward drifts.

The drift hypothesis would be more acceptable if the route were from Micronesia into Fiji and Polynesia, for almost 22 percent of voyages from Arorae ended in Polynesia (excluding the Polynesian Outliers) and 1.3 percent in Fiji. Of these, most ended in the Ellices but

1. Readers should note that terms specifying degrees of probability of contact (e.g., "very high," "moderate," "low," etc.) are used as defined in Table 8 and refer to voyages as defined in the model system (see Chap. 3).

2. For example, see Buck, 1938; Green, 1967; Heine-Geldern, 1950.

3. Sharp, 1957:79–100.

4. Marine Division, 1947, 1967.

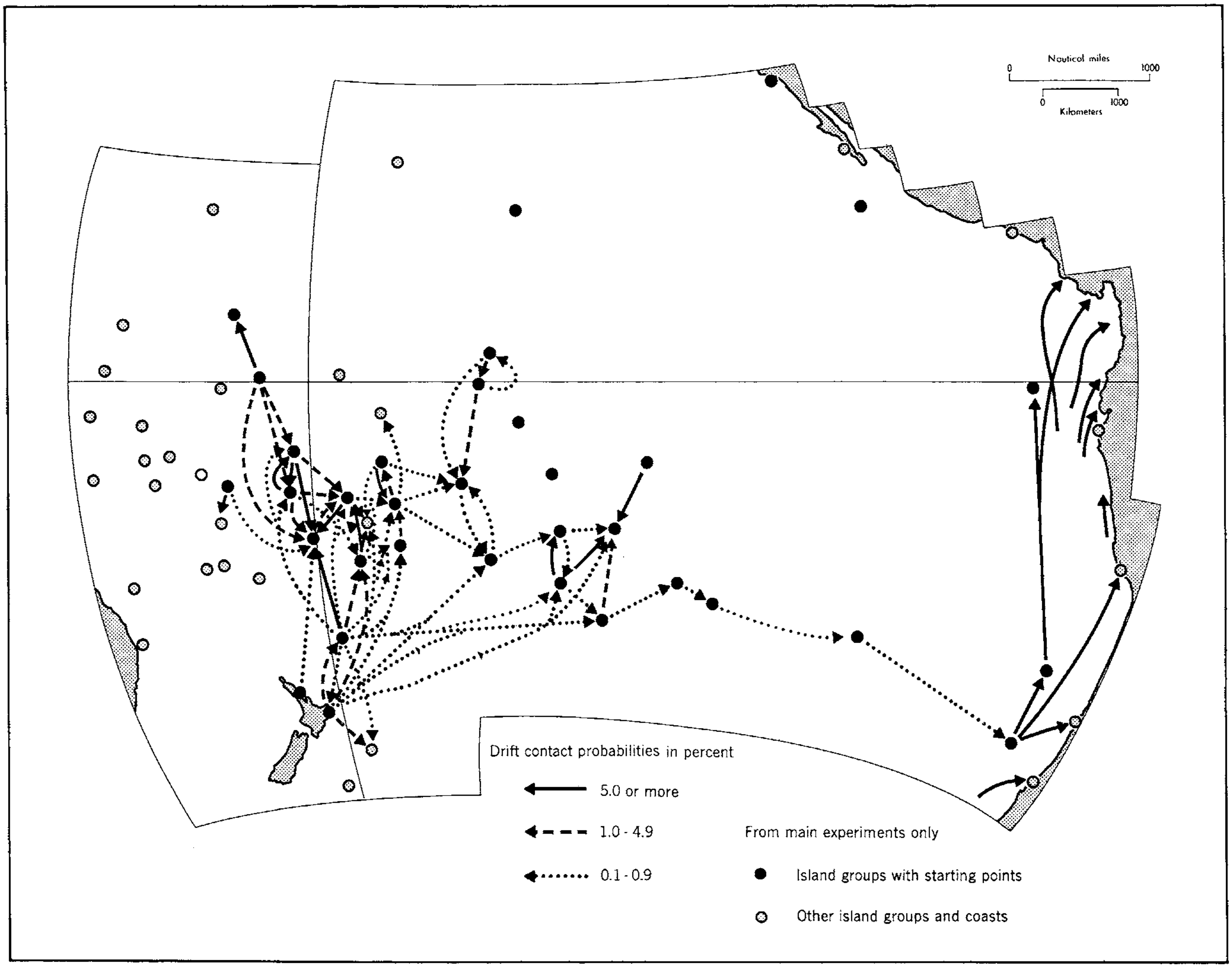


Figure 32. Drift contact probabilities to East, North, and South

from here (Niulakita) there is a high probability (15.6 percent) of reaching southeast to Rotuma, Wallis and Futuna, and Fiji — groups which provide some opportunity for further eastward links (Fig. 32).

The better chance (revealed by the experiments) of drift voyages reaching Polynesia by the Micronesian route finds some support in the evidence provided by Dening as his compilation includes no voyage from west Melanesia to Fiji or Polynesia, though it does record the drift of a party of twenty men, women, and children from the Gilberts to Rotuma in 1845.[5] But archaeology, linguistics, and other evidence suggest that of the two routes the Micronesian is less likely to have been the actual path taken by the progenitors of the Polynesians. Given the probable demographic need for sizable numbers to have made the crossing to Fiji within a fairly restricted time span, it seems unlikely that one-way accidental drift voyages would have provided the means of settlement. We might note, however, that the journey from west Melanesia to Fiji is the first major ocean crossing required along a route stretching back to the Asian mainland. The people who reached Fiji would have been familiar with island strewn seas, not with ocean expanses devoid of islands. The sea may have been perceived as a road, not as a barrier. We might conjecture therefore that with such a concept of their environment, the more adventurous might readily sail east confident that islands were sure to appear before them. In this case, a voyage of four hundred miles need not be considered as a major undertaking.[6]

5. Dening, 1963:140.

6. Cf. McCoy, unpublished paper.

Eastern Approaches from North America

The journey from North America to Polynesia requires a traverse of at least two thousand miles to reach the islands of the Hawaiian chain. From South America a similar distance must be covered to reach Easter Island and double the distance to get to the Marquesas. Direct drift voyages into the core of central or eastern Polynesia would have to cover longer distances. We must note, however, that the fastest drift tracks may not follow great circle routes and may cover greater distances following favorable currents and winds.[7] Experiments to test the chances of drifts crossing the northeast Pacific Ocean were started from San Miguel (152) and Socorro (21; monthly 65 and 66). The study area does not extend far enough north to start an experiment off the British Columbian coast but reverse experiments with end points at Nihoa (123) and south of Hawaii (128) provide some evidence for possible links from that direction. From the Socorro experiment (21) it appears that drifts from the coast of tropical Mexico have zero probability of reaching the Hawaiian Islands and very low probability of landing anywhere away from the Pacific coast except in the Northern Line Islands (Christmas Island to Palmyra) which have an 8.8 percent probability. The majority of drifts are lost in the empty ocean south of Hawaii. The poor resources of the Northern Line Islands would scarcely provide a satisfactory base for effective onward voyaging, though an experiment from Christmas Island (12) suggests a low probability of drifts from there to the Tokelau and Ellice islands. A low probability route into Polynesia is thus established, but the fact that the Mexican coast is a most unlikely starting point for voyages by crews carrying "Polynesian" traits reduces the significance of such a path.

Climatic data are weak for the vicinity of the Line Islands and better information might produce a wider voyaging field. Nevertheless, since the relatively good data between 115°W and 130°W do not produce any significant widening of the voyaging field, it seems unlikely that very different results would arise from more satisfactory wind information.

The chances of reaching the Hawaiian group from further north on the Pacific Coast are no doubt higher. Some evidence for this is provided by logs from the northwest American coasts which are not infrequently washed ashore in the Hawaiian Islands.[8] The limits of our study area did not allow us to start voyages far enough north to simulate these "driftwood voyages" and from the vicinity of San Miguel (152) only one voyage reached the Hawaiian chain. The Line Islands provided the destination for 3.3 percent of the drifts while two voyages reached the Gilberts and one the Marshalls. These figures are not of great value since, if drifts were made from North America, the British Columbia area would be the most likely starting point. Our reverse experiments to Nihoa (123) and to off Hawaii (128) show some voyages coming into the study area from the area to the northeast of the Hawaiian group. We cannot say whether these might have come right across the northeast Pacific from the continent and thus we are unable to state probabilities for such drift voyages.

7. See Heyerdahl, 1963:484.
8. Heyerdahl, 1952:162–164.

Eastern Approaches from South America

Since the *Kon-Tiki* raft sailed from off the Peruvian coast to Raroia in the Tuamotu Archipelago, seven more rafts have voyaged westward from the coast of Peru. Six reached Polynesia (two going on to Australia) and one the Galapagos.[9] There is no doubt that large sailing rafts were being used along the South American coast at the beginning of the sixteenth century.[10] A sophisticated system of steering with centerboards[11] and their seaworthiness made them capable of sailing from South America to eastern Polynesia. Whether or not they actually did is another question which we cannot answer here. But we are concerned with whether or not they could have done so by "accidental" drift.

Ten experiments were run from starting points off the South American coast, at the two islands of the Juan Fernandez group (136, 137) and at San Felix (139) and San Ambrosio (138). A further experiment was run from the Galapagos group, while reverse voyage experiments to Motuiti (126) and near Uahuka (129) in the Marquesas, San Felix (133), San Ambrosio (132), and the Juan Fernandez Islands (130, 131) tested further probabilities of drifts crossing the southeast Pacific (Fig. 12).

The results of these experiments are considered in two groups, those originating off the coast of Peru (7, 10, 29, 30, 31) and at the Galapagos (28) and those from off the Chilean coast (140) and the islands to the

9. Heyerdahl, 1968:85; Alsar, 1971.
10. Edwards, 1965:66–80. See also Lanning, 1970.
11. A technique not previously known to Europeans (Edwards, 1965:73). There is some archaeological evidence which may be interpreted as indicating the use of sailing rafts on the Peruvian coast about A.D. 1000 (Edwards, 1960:390).

west (136, 137, 138, 139). Of 4,392 drifts in the first group, none reached Polynesia. A solitary vessel from the Galapagos drifted almost due westward to 127°11′W at which point the crew expired after 182 days of drifting. All the remainder landed on the American coast, in the Galapagos, or were lost at sea. The maps (for experiments 7, 10, 28, 29, 30, 31) in Appendix 2 show how concentrated were the voyaging fields and demonstrate the power of the whirls of the eastern end of the equatorial counter current.

The result above is, at first sight, surprising in view of the successful voyages from off the Peruvian coast to Polynesia in the last twenty-five years. This prompted us to begin experiments (29, 30, 31) at considerable distances off the coast, at points representing positions reached in the first few weeks of the voyage of the *Seven Sisters* raft.[12] The solution to the puzzle seems to be that, at certain critical early stages of all the modern voyages, as much westing as possible was made by the crews specifically to avoid being swept to the Galapagos or back to the mainland coast.[13] These voyages were not drifts under the definition used in this model. And in all cases, though to varying degrees, they were intentional, navigated voyages with a known (if rather generally defined) destination. They were all trying to sail westward.

Edwards demonstrates that the use of sailing rafts in pre-Columbian times may have extended from 4°S in Ecuador to about 14° or 15°S in Peru.[14] From this area there appears to be a zero probability of rafts drifting to Polynesia. Furthermore, we argue that it would be extremely improbable for manned rafts from this stretch of coast to reach Polynesia by accident.[15] Whereas a vessel might be blown from an isolated island and the crew might lose all idea of the direction in which home lay, such disorientation would be most unlikely in the case of people blown off the continental coast. They would know its general north-south trend and its apparently endless form. Any generally eastward course would inevitably, it seems, bring them back to a landfall. And it is difficult for us to envisage a situation in which a crew might steer westward, to the setting sun and stars, imagining they were heading eastward toward the rising sun. We conclude therefore that if voyages were made directly to Polynesia from the Ecuador-Peruvian coast, they would not have been drifts or accidental voyages. They would in all probability have been intentional voyages of exploration, and, perchance, discovery.

12. Willis, 1957.

13. For example, Alsar, 1971:7; Heyerdahl, 1950A:84–85; Willis, 1957:77.

14. Edwards, 1965:107, 110–112.

15. When "accident" means as a result of being blown off course and thereby losing one's bearings.

A second group of experiments was conducted from starting points further south between latitudes 26° and 38°S and longitudes 75° to 80°W. Drifts begun close to the coast in 38°S, 75°W (140) have a 1.2 percent probability of contact with the Galapagos, a 0 probability of reaching Polynesia, and very high probability (83 percent) of terminating somewhere on the mainland from Chile to El Salvador. However, drifts begun in the vicinity of 80°W, some four hundred nautical miles off the coast, show a different pattern (136–139), and all four experiments show a low probability of making a landfall in Polynesia or the Line Islands. The voyage maps (Appendix 2) show that although the chances of landfall in Polynesia are not great, a significant proportion of the drifts are swept well to the westward by the inner margins of the Humboldt Current and the southeasterlies. The Juan Fernandez Islands and San Felix and San Ambrosio were apparently unoccupied in pre-Columbian times and were not discovered by the Spanish until between 1563 and 1574.[16] There is no evidence available to suggest that they were visited for fishing or other reasons by Amerindians before this. They lie well to the south of the area in which large sailing rafts were habitually used and distant from (though opposite) coasts where aboriginal vessels were small and less seaworthy.[17] It appears that in pre-Columbian times it would be extremely unlikely for vessels to be in the area except on rare intentional voyages, perhaps of exploration. If sailing rafts had come as far south as this regularly, one would expect some evidence of landings on the islands. We would suggest that although drifts from this area to Polynesia are possible (with low contact probability), the chances of them actually occurring would have been very slight as vessels probably would not be in this "starting area."

In general we conclude that it is most unlikely for drift voyages, as defined in the model, to reach Polynesia from the South American coast unless they begin some three or four hundred miles off the coast. This in itself seems an improbable eventuality since vessels trading north or south or on fishing expeditions would not venture as far as this. Even if they did they would be unlikely to sail (or drift) further west except by intent. Given the sailing qualities of the balsa rafts there is little reason to believe they could not have regained the coast from this distance had the crew so wished.

16. N.I.D., 1944, 2:54–58; Brand, 1967:127.

17. Edwards, 1965:107.

The drift patterns from the southern group of experiments provide a further interesting result. Even from these points no drifts reached Easter Island, and the voyage maps reveal that Easter Island lies over four hundred nautical miles outside the total voyaging field of all the experiments except that from Más afuera (137) in which a few drifts just reach the vicinity of Easter Island. But the Marquesas lie within the voyaging field of all four experiments (136–139) and the reverse experiments ending in the Marquesas (126, 129) show that the only feasible origin for drift voyages to the Marquesas is the vicinity of the Juan Fernandez and San Felix. This seems to support Emory's view that the Marquesas are likely to have experienced contact from South America earlier than Easter Island. If such contact were the result of drifts, this is especially likely, and even if it were the result of intentional westward sailing, the drift patterns also suggest that the Marquesas would be the more probable landfall, as it proved to be in the case of Mendana's second voyage in 1595. Heyerdahl implies that the early Spanish evidence, particularly that provided by Sarmiento de Gamboa, indicates that intentional two-way voyages were made by Amerindians in pre-Columbian times;[18] if this is so then the Marquesas would be the most likely point of contact.

We conclude from our experiments that it is highly improbable that men entered the Polynesian triangle (including Fiji) as a result of drift voyages. If this were the process, however, then entry from the west, perhaps from the vicinity of the northern New Hebrides, would be the most likely route. If drift voyages were not the means of first entry, then it seems that technically any of the postulated routes could have been used for navigated voyages. If the idea that the Polynesian cultural group emerged as an entity inside the Polynesian triangle is accepted,[19] then the number of first settlers probably would be quite small, and the fact that intentional voyages were involved should not lead us to believe in the need for large planned expeditions. We now turn to the question of movements within Polynesia.

Within West Polynesia

The archaeological, linguistic, and enthnographic evidence all points to West Polynesia as the earliest settled part of the triangle. Groube has suggested recently that it was in Tonga, in the first millennium B.C., that the Polynesian complex of physical and cultural traits developed.[20] Once the Fiji/Wallis area had been reached and settled, by whatever means, we may accept that a drift process could account for the subsequent expansion into the Tongan and Samoan groups. Within a group, sailing between intervisible islands or across quite narrow stretches of open water would allow a rapid latitudinal and longitudinal spread of settlement. Between Samoa and Tonga there are only very low probabilities of direct drift contact but the chain of links which are possible through the Samoa-Wallis-Futuna-Fiji-Tonga arc might be sufficient to establish initial drift contacts, to be developed later into the inter-group trading patterns of the early historic period.

From West to East Polynesia

A key event or series of events in the settlement of Polynesia was the movement eastward from the western margins of Polynesia. The ocean stretches one thousand miles before the Society Islands are reached, with only the widely spaced Northern and Southern Cooks intervening. Beyond, to the north and east of the Societies, lie the Marquesas, fully two thousand miles from eastern Samoa.

Scholars generally agree that eastern Polynesia was settled from the west. A Marquesan entry, perhaps from Samoa, has been postulated, with later diffusion to Easter Island, the Societies and other nearby groups, Hawaii, and New Zealand.[21] But Bellwood argues that "we do not yet have the earliest sites in East Polynesia" and "no island group has yet an unchallengeable claim to recognition as the earliest dispersal centre in East Polynesia." He further suggests that "the chances of sailing to the Cook or Society Islands directly from West Polynesia are higher than those of reaching the Marquesas Islands by a direct route." Although archaeological and other evidence has been used to support the idea of two successful voyages to Hawaii and New Zealand, none has been recently used to argue for continuous contacts between western and eastern Polynesia. According to Green, "continuous two-way voyaging . . . took place within West Polynesia, probably throughout its prehistory, in contrast to the lack of similar continuity of contact between West and East Polynesia after the settlement of the latter."[22]

The linguistic evidence shows a firm division of Polynesian languages between those of the east and those of

18. Emory, 1968:166. Heyerdahl, 1966.
19. Emory, 1963; Green, 1967.
20. Groube, 1971.
21. For example, Sinoto, 1970:130; Suggs, 1960:111–116.
22. Bellwood, 1970:93, 99. Green, 1968:105.

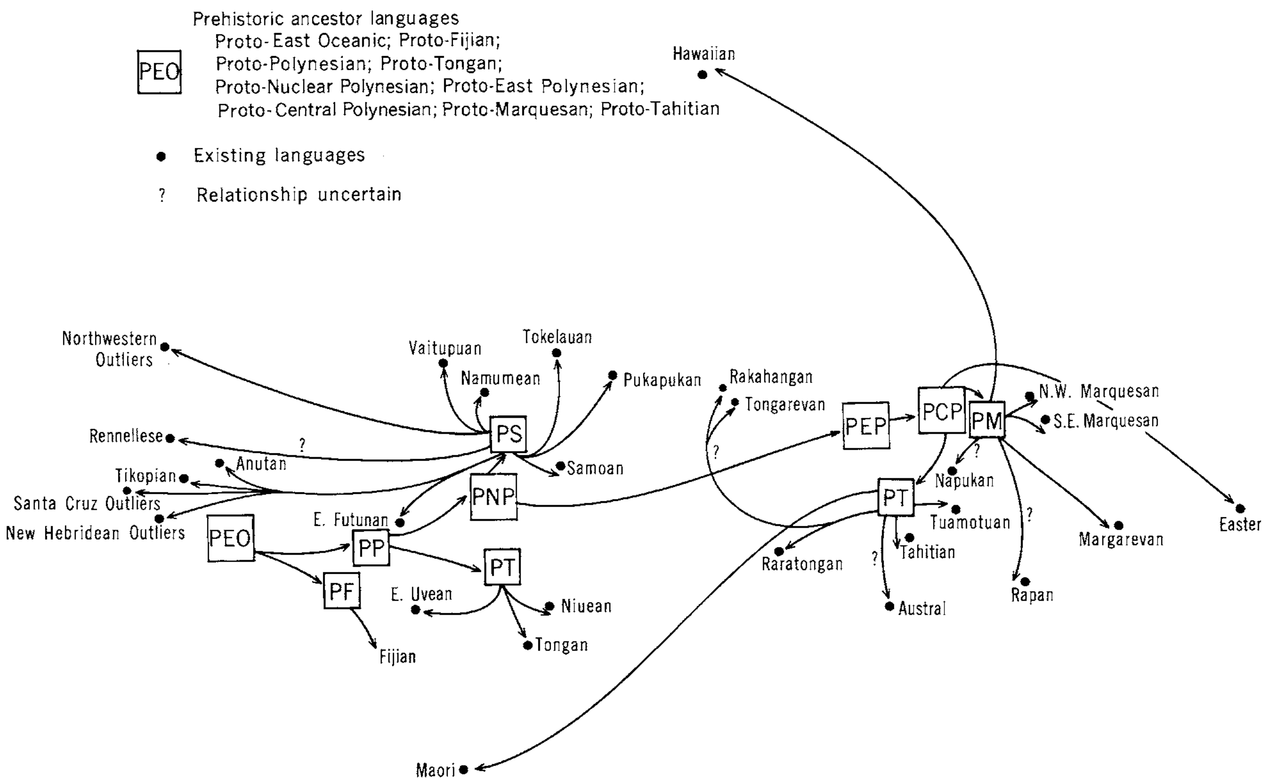


Figure 33. Polynesian linguistic relationships

the west.[23] Differences of opinion as to the genetic relationships within both groups need not mask the strong agreement on the themes of the initial divergence of the two and their subsequent development in isolation.

Elbert maintains that the separation of the Proto-Samoan (called Proto Samoic-Outlier by Pawley) and Marquesan (or, better, Proto-East Polynesian) languages occurred in 100 B.C. A first settlement at about that time in the Marquesas fits Suggs's radiocarbon date for his earliest archaeological evidence from the Marquesas, but Green and Sinoto have disputed this date and the latter suggests initial Marquesan settlement around A.D. 300.[24] The development of the East Polynesian languages from an initial center somewhere in central East Polynesia with subsequent dispersals to other parts of East Polynesia would seem fairly common ground among linguistic scholars (Fig. 33).

Until recently Tahiti was thought to be the center of dispersion in East Polynesia, and this was the basis of Emory's argument using linguistic and archaeological work. In a postscript to this important paper Emory acknowledged the possibility of earlier settlement in the Marquesas. We need not go into the reasons for the persistence of the idea of Tahiti as the center for East Polynesian dispersion, except to note that it fitted well with accepted theories of culture areas and peripheries. For example, Green thought that Tahiti, as a central location, would be better suited to receive and transmit innovations and cultural features than other places in East Polynesia.[25] But this could only apply in a situation which saw frequent two-way voyages connecting "Hawaiki" with its distant and nearer daughter settlements. But if, as Sharp argues, two-way voyaging was the exception rather than the rule, and most places in East Polynesia were settled by one-way voyage, then the culture center idea loses its meaning. There is no point in advocating a central location if there is no coming and going to give worth to the centrality of the place. The Marquesas could have been as effective a dispersal point but, as noted above, although some have advocated that these rather peripheral islands were the first settled in eastern Polynesia, with the Societies as a later

23. Biggs, 1967; Dyer, 1965; Elbert, 1953; Green, 1966; Pawley, 1966, 1967.
24. Elbert, 1953:167. Suggs, 1960:112. Green, 1967:223. Sinoto, 1970:106.
25. Emory, 1963:99. Green, 1966.

and subsidiary dispersal point, the primacy of the Marquesas is not yet proven.

Our experiments give no support to the possibility of drift voyages from Samoa to the Marquesas. The immense distance is reinforced by the dominance of the prevailing winds from the southeast, and it seems that such a voyage could only result from a sustained attempt to maintain an easterly course. For the time being at least there is no proof of contemporary settlement in any of the scattered intervening islands, although a short stay at Rakahanga, Manihiki, Caroline, or any of the others might not have left enough evidence to be recognized at this late date. Even if intervening islands are used as way stations, the possibility of drifts over that cultural and ocean divide is minimal or nonexistent (Fig. 32). Thus we think it unlikely that drift voyages played any part in the colonization move from west to east in Polynesia.

Scholarship based on Polynesian traditions advocates two-way voyaging as the means to the acquisition of information by the Polynesians, and the subsequent recolonization or reinforcement of daughter settlements. Although the weight of modern scholarship argues against this idea and tends to support Sharp's thesis of one-way discovery and colonization, Lewthwaite thinks the question is still open, after reexamining the evidence on Polynesian geographical knowledge at the time of European contact. The low drift probabilities from west to east further shade the decision against two-way contact, despite the high chances from east to west. Sharp's proposition of a single colonizing voyage from Samoa to the Marquesas carries the mark of a reasonable reconstruction, except that it seems the drift element should be eliminated and a navigated voyage of search allowed.[26]

Within East-Central Polynesia

From their probable first landfall and settlement, perhaps in the Marquesas, the Polynesians of the east sailed, by drift or design, to many islands and groups of islands in the central Pacific. The extent of this dispersal is truly astonishing, making it one of the major achievements in the human occupance of the planet. The sequences and dates of the migrations are not yet fully known, but the increased tempo of researches into linguistic history and archaeology is providing a more solid basis than the older study of oral traditions which are difficult to interpret locationally and are suspect because of possible European contamination.[27]

A tentative sequence postulates relatively early voyages to and settlement of Easter Island and the Societies from the Marquesas, and then later voyages to the northern Tuamotus, Mangareva, Rapa, and Hawaii, and perhaps New Zealand.[28] The Societies formed a secondary dispersal region, with voyages to the Southern Cooks, the Tuamotus, the Australs, Hawaii, and New Zealand. Rarotonga in the Southern Cooks may have been a way station for the New Zealand voyage begun from Tahiti. The prodigious journeys to Easter Island, Hawaii, and New Zealand merit separate treatment, as do possible voyages to the presently uninhabited Line Islands.

Before turning to the relationships within east-central Polynesia, however, one issue of general significance needs discussion. Most of the evidence now points to a temporal concentration of voyages of discovery and settlement in East Polynesia. Beginning with the arrival at Easter Island in about A.D. 300, most of the longer voyages had been accomplished by A.D. 900. This narrow time span tends to decrease the likelihood of a purely accidental drift provenance for the voyages, unless we are willing to advocate distinctive climatic conditions at that time, which seems very unlikely (see above, pp. 14–16). A more likely explanation, disregarding for a moment the drift contact probabilities discussed below, concerns a change within East Polynesian culture and society. This change may have stemmed from one of, or a compound of two elements: a recognition of the problems of overpopulation; and, the adoption of exploratory voyages for colonization perhaps based on folk memories of the voyage eastward from West Polynesia. But it must be acknowledged that the former would be unlikely to cause much intentional emigration in the first centuries after settlement as populations would still be small in relation to the resource base of most islands. The second alternative may seem more plausible though less easy to prove.

Sharp and other authorities accept the existence, over a long period, of two-way contacts between the Society Islands and the Tuamotus.[29] Although there is general agreement regarding that raiding and trading relationship, opinions differ as to the degree of inter-island contact prior to European entry. The preponderance of evidence indicates a considerable accretion of geographical knowledge of nearby islands among the Tahitians, but much less knowledge among the inhabitants of other

26. See above, Chap. 1, pp. 6–8. Lewthwaite, 1967. Sharp, 1963:133–134.

27. Dening, 1963:111.

28. Emory, 1963; Green, 1966:33.

29. Lewthwaite, 1967:85.

island groups, especially those with eastern locations like the Marquesas and Mangareva. In his list of Polynesian voyages compiled from historical sources, Dening cites evidence for deliberate voyages within a number of island groups, including the Marquesas, Societies, Tuamotus, Southern Cooks, and Australs. In the case of most groups, however, there is evidence that knowledge was quite local in extent, and sometimes did not include many islands in the home group.[30]

Discussions about eighteenth-century Polynesian geographical knowledge may not have much relevance to the elucidation of the process of prehistoric colonization. The variable nature of that knowledge, however, may be linked to the arrival of occasional drift voyagers, and its general increase westward from the Marquesas and Mangareva would be explainable by drift probabilities. These show a marked east to west majority for East Polynesia, as do the sum of those collected by Dening.[31]

How much of the original settlement of the East Polynesian island groups resulted from drifts is another question. Figure 34 shows contact probabilities between island groups in east-central Polynesia for our main experiments. Since the number of starting points was limited, readers are cautioned that the experimental results on drifts between groups with many islands in relatively close proximity are inadequate. Thus we can infer and add to the map high contact probabilities between the Tuamotus and the Societies, and moderate chances from the Societies and the Tuamotus to the Australs, and perhaps low probabilities from the Tuamotus to the Marquesas and Mangareva. The Marquesas group, Mangareva, Rapa, and the Australs are adequately represented in the experiments, and these show a network of mostly one-way contacts. The lack of appreciable west to east probabilities, except where island groups are in close proximity, is notable.

The main question centers around probabilities from the Marquesas and the Societies. Drift chances from the former are high to the nearby Tuamotus but fall off rapidly to the Societies and beyond, and there are zero drift probabilities to the Australs, Rapa, and Mangareva. From the Societies there are moderate probabilities to both groups of the Cook Islands but very low or zero chances to the more easterly islands, except the Tuamotus. From these contact probabilities we might infer drift voyages as a means to settlement from the Marquesas and the Societies to some parts of east-central Polynesia; to others, however, voyages must have been by some method other than drift. Even with the use

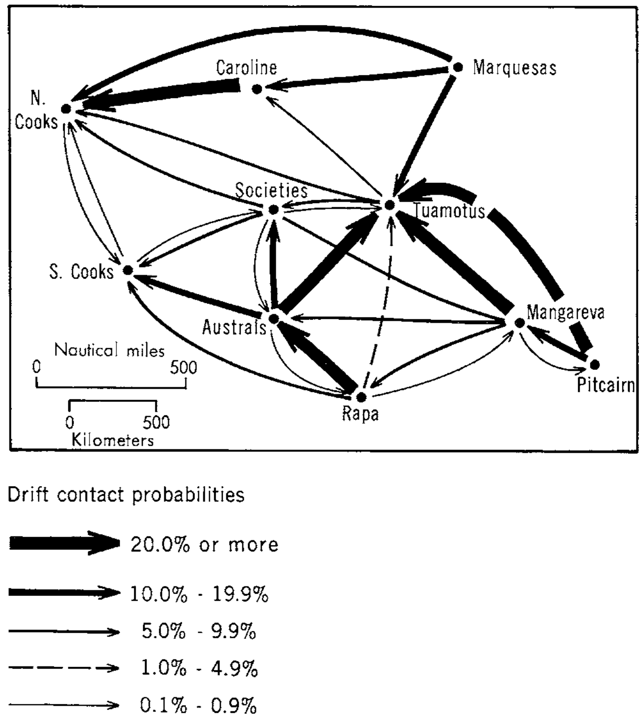


Figure 34. East-central Polynesia:
Drift contact probabilities

of way stations, as might have been the case with voyages from the Marquesas to the Societies and from the Societies to Rarotonga, drifting from either group to Mangareva and Rapa is very difficult. As for the Northern Cooks, they lie in the way of drifts from the Marquesas; however, they are very difficult to reach from Rarotonga or from other islands in the Southern Cooks, whence some of their early inhabitants may have come.

From these drift probabilities it seems that we must continue to accept the notion of navigated voyages of search and colonization for some islands of east-central Polynesia, but retain the possibility of drifts along the route from the Marquesas to the Tuamotus and on to the Societies, Australs, and Southern Cooks.

Apart from Easter Island, the widely spaced islands of the Pitcairn group form the eastern point of Polynesia. Pitcairn Island, like its lonely companions Oeno, Henderson, and Ducie, was uninhabited at the time of the arrival of the *Bounty* mutineers and their Tahitian friends. Stone structures and artifacts including adzes and fishhooks, found on Pitcairn, indicate prehistoric Polynesian settlement, and it has been usual to attribute these to colonists from Mangareva. Sharp, however, dismisses the evidence from Mangarevan oral traditions as being European inspired and argues in favor of occupation by drifting voyages from various Polynesian island

30. Dening, 1963:110, 137–153, 107–108.

31. Dening, 1963:129.

groups to explain the different types of artifacts found on the island.[32]

Drift contacts with Pitcairn from a starting point southeast of Mangareva have only 0.8 percent probability, and zero probability to Oeno, Henderson, and Ducie. From Easter Island probabilities are 2.1 percent to Pitcairn, 3.1 to Ducie, 2.4 to Henderson, and 1.7 to Oeno, making a net probability of 9.3 percent for reaching one of the four islands. Although we must certainly support the theory of a navigated voyage from east-central Polynesia resulting in the settlement of Easter Island, an accidental drift from Easter to Pitcairn is obviously within these bounds of probability, and it may have been from such a voyage that the stone fishhooks of Easter Island origin discovered on Pitcairn derive.[33]

Uninhabited Equatorial Polynesia

North and west of the Marquesas lie a score of islands uninhabited at the time of European discovery. The Line Islands stretch from Flint (12°S) to Palmyra (6°N) and include five with remnants of prehistoric Polynesian occupation — Caroline, Malden, Christmas, Fanning, and Washington. Of the Phoenix Islands, a relatively compact group just south of the equator, Canton, Hull, and Sydney have evidences of Polynesian settlement. So too does Howland, paired with Baker Island, and lying just north of the equator.

Preliminary archaeological investigation[34] and subsequent and more detailed work at Fanning and Washington have not revealed any distinctive relationships between the the temporarily inhabited islands and other Polynesian groups, with the exception of Finney's proposal that materials from Fanning relate that island's temporary occupants to Tonga.[35]

Except for the Southern Line Islands, drift contact probabilities from inhabited parts of Polynesia are low or very low. Indeed, some of the Northern Line Islands are almost inaccessible by drift from elsewhere in Polynesia, according to our experiments.

Caroline, Vostok, and Flint lie directly in the path of winds and currents from the Marquesas, and drift probabilities to the group are high. Caroline, the one of the three with known prehistoric settlement, can be reached by about one in ten drifts from the Marquesas. Probabilities to Vostok and Flint are much lower at 4 and 3 percent, respectively. Caroline, with the highest drift probabilities, has the evidence of former settlement, and the possibility that it was settled by drift voyages from the Marquesas remains open. It might be argued, by those who advocate massive island searches with full locational knowledge by the early Polynesians, that a colonizing party aware of all three islands would choose Caroline, since it is considerably more suitable for settlement than the other two.

Malden and Starbuck lie about one thousand miles west-northwest of the Marquesas, which are the only inhabited Polynesian islands from which they have drift contact probabilities. The signs of prehistoric settlement at Malden are quite extensive, indicating occupation for some generations.[36] Drift probabilities to Malden from the Marquesas are very low in the main experiments, being less than 1 percent, but they rise to 4 percent in the north wind shift experiment (92) and to over 3 percent in the additional month experiment for drifts beginning in 36. Starbuck lies about ninety miles south of Malden but has no signs of temporary settlement, despite the fact that its contact probabilities from the Marquesas are two or three times those to Malden. If the Malden settlement is eventually dated and is found to correspond in time to the settlements on Hawaii, the voyage which led to it could, in theory at least, be added to the list of voyages from east-central Polynesia.

Of the Northern Line Islands, Christmas, Fanning, and Washington show evidences of temporary Polynesian occupation; Palmyra and Jarvis do not. Evidence from Fanning has been used by Finney to advocate a landing by Tongans, and Sharp has reconstructed a history of the brief occupation of the island.[37] The main experiment yielded very low contact probabilities with the Marquesas, and chances of 1.5 percent to Christmas and 3.4 percent to Jarvis were reached in the south wind shift experiments from Motuiti. If the Polynesians came from the Marquesas it is just possible they drifted to these islands; if from elsewhere it is highly likely they were on a purposefully navigated voyage of exploration.

The eight islands of the Phoenix group lie south of the equator in 160°W. The three once inhabited islands are Hull and Sydney, which face open ocean to the south and east, and Canton, the most northerly of the group. If we assume a reasonable amount of initiative and seamanship among Polynesians coming to the Phoenix group, we can argue that the remains may have resulted from occupation following a single landing. Canton Island, unattractive in its aridity, has the lowest contact probability of all the islands from the Marquesas, the

32. Sharp, 1963:108.
33. Green, 1959:21–22.
34. Emory, 1934.
35. Finney, 1958:70–72.
36. Emory, 1934.
37. Finney, 1958. Sharp, 1963:102.

main source of drifters to the Phoenix Islands in our experiments. Hull and Sydney, which are merely semi-arid in climate and vegetation, have the highest and third highest drift probabilities in the group, receiving voyages from the Societies and Northern Cooks, as well as from the Marquesas.

To Hawaii from the South

A series of eight experiments were conducted from starting points along the northern margins of central and eastern Polynesia, together with two reverse experiments to Hawaii, wind shift experiments from Christmas Island and Motuiti, and nine additional month experiments from the Marquesas and Line Islands. Over sixteen thousand drifts were generated in these experiments. None reached the Hawaiian Islands.

The linguistic, archaeological, and traditional evidence relating to the settlement of Hawaii has been interpreted as indicating two main phases of contact from eastern Polynesia. Emory and Green have both argued for early settlement from the Marquesas with later migrants bringing Tahitian influences between the twelfth and fourteenth centuries A.D. More recently Kirch has pointed out that the "widespread cultural uniformity which seems to be appearing in early East Polynesian sites" requires a reexamination of this hypothesis as it may be unwise to assign the early migrants specifically to a Marquesan source. Green has also stressed that as yet the hypothesis of a Marquesan origin cannot be fully tested in the absence of early dated assemblages of artifacts from possible alternative sources in East Polynesia.[38]

In 1957 Sharp stated that "Hawaii was favourably placed for accidental voyages from Eastern Polynesia," since canoes carried north from eastern Polynesia in a storm might be carried across the equator and then be picked up by a southwest gale and borne towards Hawaii.[39] The evidence provided by our experiments suggests that drift voyages to Hawaii would be extremely unlikely, as few drifts originating in eastern Polynesia cross the equator to the east of 180° longitude. Even in the case of drifts from Christmas Island (12) no voyages reach north of 10°N until west of 180°. The likelihood of vessels then being carried northeast to Hawaii appears infinitesimal.

In his later book Sharp asserts that his "preferred view" is "that the effective settlers of Hawaii . . . were Marquesan one-way voyagers who set out in the hope of finding traditional islands." Heyen felt that voyages from Savaii to Hawaii would be "barely possible" and "highly improbable" for Polynesian vessels, though conditions for journeys from the Marquesas and Tahiti would be favorable. Having tested the sailing qualities of a replica of a Hawaiian double canoe, Finney also concludes that voyages from the Marquesas and Tahiti to Hawaii would be quite possible.[40]

In view of our experimental results we are led to the conclusion that voyages from the Marquesas and Tahiti areas would have to be made by crews who intended to follow a northerly course, which implies a motive such as seeking new lands. This is in accord with Sharp's later view and with the conclusions of Heyen and Finney.

We come to similar conclusions about voyages from Hawaii southwards to the core of Polynesia. As noted in Chapter 4, the only part of Polynesia which has any significant chance of receiving drifts from Hawaii would be the Ellice Islands and even here the probability is only 0.8 percent (experiment 26). Chances of reaching the Marshalls are very high from Nihoa (16) and high from near Hawaii (26). A northward wind shift (85) makes little difference to these chances but a southerly shift (94) decreases the contact probabilities.

It is most unlikely that vessels would drift from Hawaii to other parts of Polynesia. Finney suggests that attempts to sail south to Tahiti could be successful though the traverse from Hawaii to the Marquesas would be much more difficult.[41] We feel that if links were made from Hawaii to either of these groups or, say, to Samoa, they must have been the result of intentional southward sailing.

To Easter Island from the West

Easter Island has the distinction of being the most isolated inhabited island in the Pacific. The nearest island which was inhabited for a significant period in the pre-European era was Pitcairn, some 1,200 miles to the west, and early writers believed that beyond vague memories, the Easter islanders knew of no other islands except Sala y Gomez, 200 miles to the east.[42] For those who think the Polynesians performed long, navigated

38. Emory, 1963:96; 1968:116–167. Green, 1966:29–30. Kirch, 1970:234. Green, 1971A:175.

39. Sharp, 1957:75, 76. Sharp is here using "accidental" to mean voyages "arising either from storms or exile" (1957:31).

40. Sharp, 1963:135. Heyen, 1963:75, 73. Finney, 1967:152–160.

41. Finney, 1967:156.

42. Lewthwaite, 1967:86.

two-way voyages, the origin of the Easter islanders poses no new problem. The fact that it was occupied by Polynesians simply indicated their great skill as seamen. Similarly, those who consider cultural traits, archaeological materials, and plant species found on Easter Island to be of American origin assume that these demonstrate the Amerindians' navigational ability. We need not recapitulate all the bitterness and partiality in the debates which have ensued since Heyerdahl published his two books after the *Kon-Tiki* voyage. Later he has argued for early (about A.D. 400) settlement of Easter Island from the Peruvian area and the later arrival of a second group from elsewhere in Polynesia. Golson has reinterpreted the archaeological evidence from the Norwegian expedition and asserts that it is consistent with settlement by a single population from somewhere in eastern Polynesia. This view seems to be accepted by Emory and Green.[43] Linguistic evidence suggests that the Easter Island language split from proto-East Polynesian relatively early following the settlement of the Marquesas, much earlier in fact than the other East Polynesian languages.[44] There is nothing, however, which suggests whether the journey to Easter Island was direct or indirect.

As Emory says, "the chance of Easter Island being reached even once was extremely limited."[45] We have already shown that the likelihood of Easter Island being reached by a drift or accidental voyage from South America is virtually nil. The question which remains is whether the island is likely to have been reached by drift from elsewhere in Polynesia.

Experiments were begun at Pitcairn (22), Mangareva (24), Oeno (151), Marotiri (103), Pukapuka (Tuamotus — 143), and southeast of Mangareva (104), and a reverse voyage experiment (122) to Easter Island was also carried out. No drifts from any of the inhabited starting points in Polynesia (including those from the Marquesas) reached Easter Island and none of the reverse voyages terminating at Easter Island began anywhere in Polynesia. One drift from uninhabited Oeno did reach Easter. The voyage maps (Appendix 2) show that the only other voyages to reach the vicinity of Easter Island were two from Pitcairn (22) whose tracks passed to the south of Easter Island in June and July and in the extreme case ended in 30°48'S, 96°40'W. The model provides a near zero probability of reaching Easter Island by drift from anywhere else in Polynesia. That the chances would be extremely slight is confirmed by experiments 71–73 in which twenty-four drifts were begun from Mangareva on each day of May, June, and July, the most favorable months for drifting eastward. Of the total 2,208 drifts none reached Easter Island, and only three came within 200 miles of the island. It seems, therefore, that the inhabitants of Easter Island either stem from spontaneous creation on that island or reached there from elsewhere in Polynesia having intentionally followed an easterly course. We prefer the latter hypothesis, though we cannot say whether they sailed east seeking unknown islands or hoping to regain a home island after disorientation by storm or other cause.

South to New Zealand

There is a greater volume of writing on the settlement of New Zealand than on any other part of Polynesia. We need not provide a full review in this work, and in the next few paragraphs we give only a representative sample of differing opinions. For many years the popularly accepted view of the Maori discovery and settlement of New Zealand was that for which Buck provides the fullest recent account. In about 925 A.D. Kupe, while chasing an octopus, came upon New Zealand, then apparently uninhabited, and returned home to "Hawaiki." Later several canoes (with women abroad) were driven to sea by westerly gales, and swept to New Zealand. Their crews were the ancestors of the first settlers but they did not carry tropical food plants to New Zealand. In the twelfth century Toi, seeking his grandsons who had disappeared at sea from "Hawaiki," arrived in New Zealand and settled amongst the earlier occupants and was later joined by one of the grandsons who was, in turn, searching for Toi. At intervals others arrived, among them castaways who brought news of the sweet potato; a vessel was dispatched to "Hawaiki" to find this plant. Finally, following disputes, and using known sailing directions, a number of canoes (often called "the Fleet") set out for New Zealand and arrived in about 1350, according to genealogical dating by S. Percy Smith. Those who had gone to seek the sweet potato returned with "the Fleet," and this and other root crops were thus introduced.[46]

This traditional account includes castaways and purposeful seamen, chance first discoveries and navigated

43. Heyerdahl, 1950A, 1952. An example may be found in Suggs (1960:212–224) where the use of evidence to refute Heyerdahl's thesis appears to us to be just as partial and cavalier as that which Heyerdahl is himself accused of. Heyerdahl and Ferdon, 1961. Golson, 1965:78–80. Emory, 1968:167. Green, 1967:221–228.

44. Green, 1966.

45. Emory, 1968:165.

46. Buck, 1949:5–7, 10–11, 22–27, 33, 36–57, 61–64.

settlement expeditions, and both one-way and two-way voyages. The dating and the outline have become accepted dogma. More recently the legends on which the account is based have been subjected to critical evaluation. It is evident that inconsistencies and embellishments abound, and Simmons concludes that what he terms the "New Zealand myth" does not represent Maori tradition. Sharp discussed (albeit in an understandably partisan manner) the varied provenance and partial use of legends by some of Buck's predecessors and concluded that the Maoris "were the descendants of a long succession of one-way voyagers."[47]

Many writers have supported other reconstructions of New Zealand's prehistoric settlement. Keyes has recently reviewed evidence for an older theory of Melanesian influences existing as a "subculture" in pre-European New Zealand following early links from the Fiji–West Polynesia area. Golson and Gathercole discussed the rapidly growing corpus of archaeological evidence and suggested that it could be interpreted as indicating initial settlement from East Polynesia and subsequent internal cultural elaboration. Green believes that there is a case to be considered for two separate settlement events stemming from the Marquesan and Tahitian areas in a period before the coming of "the Fleet." He follows other archaeologists in accepting the later development of Maori culture from the early settlement "without any recourse to the concept of the fleet."[48]

The dating of the settlement of New Zealand has been attempted using genealogical, linguistic, and carbon-14 techniques. The first has been discussed above. Emory suggests a date of about 1000 A.D. for the separation of New Zealand Maori from other East Polynesian languages, and the cluster of C14 dates around the twelfth century for widely dispersed sites has been interpreted by Groube as indicating a relatively dense settlement by that time. Shawcross has proposed as an alternative hypothesis that these sites represent "a significant proportion of the original, major settlement of the country." He also points out that (especially if a correction factor for New Zealand C14 dates of about 200 years is applied to make these fourteenth-century dates) they overlap with the date range for traditions of "a number of perhaps contemporary canoe-loads of voyagers, genealogically dated, . . . to between the eleventh and fourteenth centuries A.D."[49]

47. Simmons, 1969:29. See also Lewthwaite, 1967:85, and references. Sharp, 1957:166–175; 1963:121.

48. Keyes, 1967. Golson and Gathercole, 1962:272–273. Green, 1966:31–33.

49. Emory, 1963:83. Groube, 1968:144. Shawcross, 1969:197, 198.

As has been found in other cases, there are firmly expressed but diametrically opposed views on the likelihood of "accidental" voyages reaching New Zealand from tropical Polynesia and on whether the Polynesians' navigational skills would be sufficient to enable them to make such two-way voyages. Hilder contends that the navigational and geographical knowledge necessary for an intentional voyage over this stretch of ocean was beyond that available to the Polynesians and therefore he would "firmly conclude that the voyages to New Zealand were accidental." On the other hand Heyen feels that a canoe captain would not continue to sail southward into colder latitudes except by intent, and for climatological reasons he believes that drift voyages to New Zealand would be unlikely. He also concludes that "direct voyages from Tahiti to New Zealand, although theoretically possible, would be beyond the capabilities of the old native navigators," but that the passage from Tongatabu (and back) might be accomplished relatively easily. Åkerblom appears to agree that the navigational methods of the Polynesians would not permit intentional (two-way) contacts betwen Rarotonga and New Zealand.[50]

In 1965 David Lewis successfully carried out an experimental voyage without instruments from Rarotonga to New Zealand;[51] we must note that this presupposes prior knowledge of the relative location of New Zealand from the Cook Islands which could only be obtained by earlier successful two-way voyaging. This has not yet been proved either to have occurred or to be possible.

Of the several thousand simulated drifts performed from islands along the southern margin of tropical Polynesia, none reached New Zealand.[52] The reverse experiment to New Zealand (120) produced one voyage from Rapa to New Zealand.[53] We must accept that a drift voyage to New Zealand is possible, but the likelihood of it occurring directly is extremely small.

The only area from which voyages reached New Zealand in the main experiments was the Kermadec group, and even in this case only seven drifts came to New Zealand from Raoul (23). There are very low probabilities that drifts from Rapa (8) and the Society

50. Hilder, 1963A:97. Heyen, 1963:65, 74–75. Åkerblom, 1968:85.

51. Lewis, 1966.

52. This result surprised at least one of the authors (R. G. W.). In December 1957 or early January 1958 he had seen the trunks of coconut palms washed up on the beach near Opotiki in the Bay of Plenty, North Island, New Zealand. Sharp also reports palms washed up further north in 1957 (1963:116).

53. It should be noted again that this represents 0.1 percent of a very low probability produced by the main experiments.

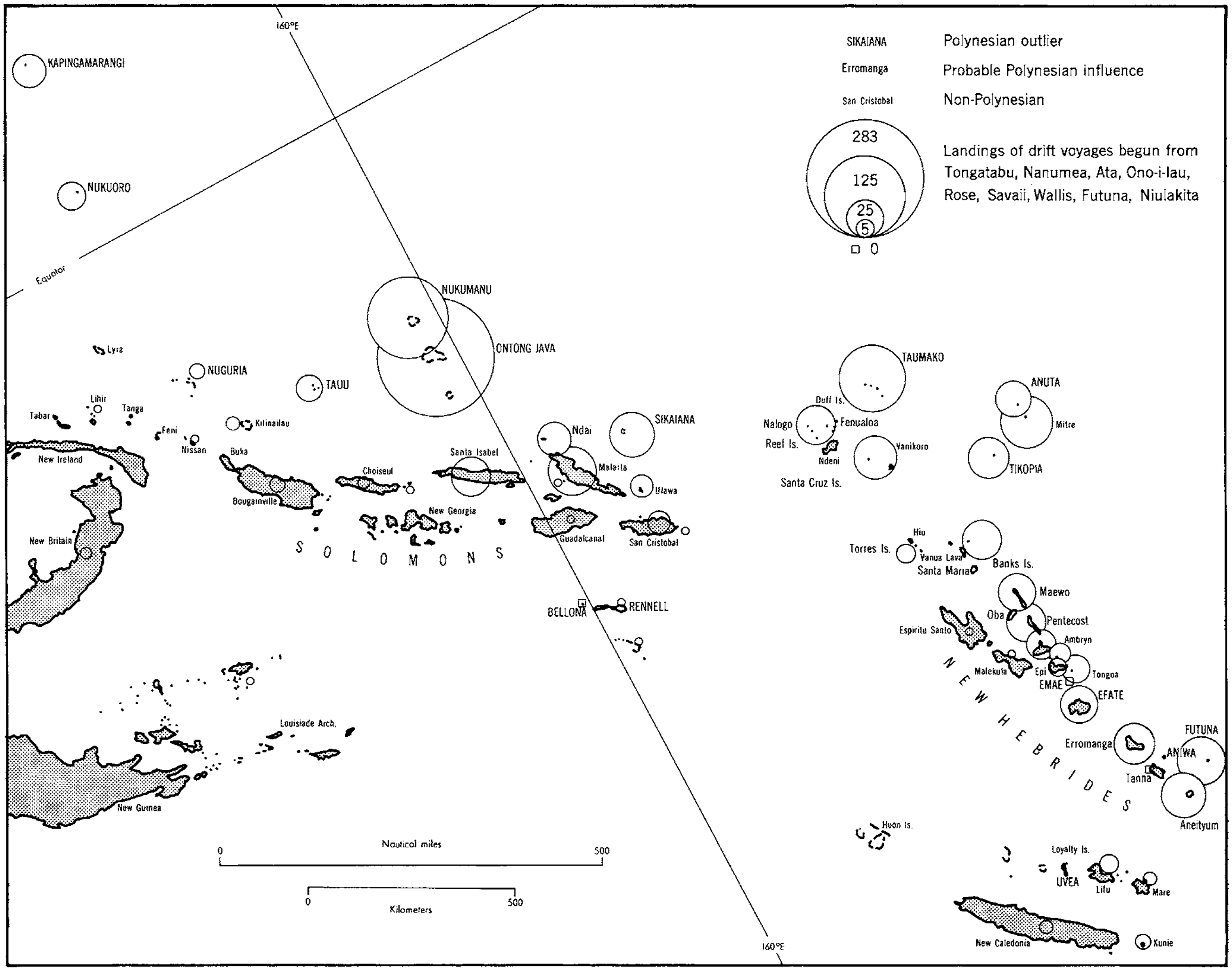


Figure 35. Polynesian Outliers in Melanesia

Islands (4) will reach the Kermadecs, and hence two-stage drift journeys to New Zealand are just possible, though very unlikely. We feel that this very slender chance of a drift connection and the even more remote possibility of drifting directly to New Zealand as revealed by the reverse experiments do not provide sufficient evidence to support a hypothesis that New Zealand was settled by drift voyages.[54] It seems that as in the case of voyages to Easter Island and Hawaii an element of intent and deliberate course setting would have been necessary.

Drift voyages from New Zealand to Polynesia are more likely to occur. From off East Cape (102) 2.4 percent of voyages reached islands in tropical Polynesia and 0.8 percent ended in Fiji. From Mokohinau (13), just off the New Zealand coast, 2.0 percent of the voyages reached tropical Polynesia and Fiji. These are low probabilities, but they suggest that drifts to tropical Polynesia from New Zealand are much more likely than the reverse route. One might surmise that after the initial settlement of New Zealand such drift voyages could have been the means by which knowledge of these southern islands and their zenith stars and perhaps the greenstone artifacts reported in the Cook Islands[55] might have been carried to tropical Polynesia. If so the information necessary for later navigated voyages would have been made available in "Hawaiki."

54. In experiment 87 from Rapa, in which the winds were shifted north 5°, one voyage reached New Zealand.

55. Lewthwaite, 1967:84.

Polynesian Outliers in Melanesia

To the west of Polynesia lie the many islands of Melanesia (Fig. 1).[56] There language, custom, and physique are woven into a human fabric of such complexity that, despite much work already done, its unraveling will be a lengthy task. But imbedded deep within Melanesia are a number of islands whose people exhibit strong cultural and (especially) linguistic affinities with Polynesia. Pawley identifies "some 14 or 15 Outlier languages" and the places where they are spoken are shown on Figure 35. This map also shows, with lesser certainty, some other peoples with Polynesian cultural or physiognomic characteristics.[57]

Views of the origins of Polynesian peoples and traits in the Outliers cluster around two opposed theories. Churchill argued that the Polynesian languages spoken in the Outliers and the retention of some Polynesian lexical items in Melanesian languages were relics of the prehistoric migration of Polynesians through Melanesia to the western and central Pacific Ocean. More recently Capell has echoed this view, calling the Outlier tongues "archaic forms of Polynesian" coming from the time when Polynesians were moving eastward through Melanesia.[58]

Most scholars, however, now believe that the Outlier peoples derive from westward migrations.[59] A commonly held view connects them with established Polynesian subcultures in the region from the Ellice Islands to Tonga, near the western edge of the Polynesian triangle.[60] Bayard, after reviewing linguistic and other cultural evidence, concluded "all outliers do not derive from a single source, but are examples of east to west voyaging from numerous sources," especially the Ellices, Fatuna, and Tonga. Pawley agreed with this conclusion and examined in detail the relationships of Outlier languages to the historical development of Ellicean and Futunan.[61]

An acceptable thesis is that Polynesian culture took on its distinctive linguistic and other features in eastern Melanesia or Tonga, and did not become "set" and indeed did not exist before the triangle had been breached in the west. If this theory is true, then the view that the Outlier populations derived from relics of a Polynesian migration through Melanesia is untenable and the only acceptable thesis is that the Outliers result from east to west voyages from Polynesia.

Experiments were run from nine places in west central Polynesia: Nanumea (18) and Niulakita (116) in the Ellice Islands; Futuna (Hoorn Island) and Wallis (Uvea) (112); Savaii (111) and Rose (110) in Samoa; Ono-i-lau (106); and Ata (105) and Tongatabu (3) in the Tongan archipelago. We deal first with probabili-

Table 10. Contact Probabilities to Polynesian Outliers in Melanesia[a]

Destination	From Ellice Islands[b]	From Futuna (Hoorn) and Wallis (Uvea)[b]	From Samoa[b]	From Tonga[b]
Northwest Outliers	1.4%	0.5%	0.2%	0.0%
Kapingamarangi	0.9	0.4	0.0	0.0
Nukuoro	0.5	0.1	0.2	0.0
Central Outliers	16.8	10.7	4.5	0.1
Ontong Java	10.7	5.7	2.8	0.1
Nukumanu	4.6	3.2	1.1	0.0
Sikaiana	1.0	1.3	0.5	0.0
Ta'uu	0.2	0.4	0.1	0.0
Nukuria	0.1	0.1	0.0	0.0
Santa Cruz Outliers	5.2	5.4	0.7	0.4
Duff Islands	3.1	2.5	0.4	0.0
Reef Islands	0.6	1.1	0.2	0.1
Tikopia	0.7	1.0	0.1	0.2
Anuta	0.8	0.8	0.0	0.1
New Hebrides Outliers	0.1	0.2	0.1	4.2
Emae	0.0	0.0	0.0	0.0
Efate	0.1	0.2	0.1	1.6
Futuna	0.0	0.0	0.0	2.0
Aniwa	0.0	0.0	0.0	0.6
Uvea (Loyalty Islands)	0.0	0.0	0.0	0.1
Rennell & Bellona	0.1	0.0	0.0	0.0
Total	23.4	16.8	5.5	4.8
Other Melanesian Islands	8.0	5.6	1.1	11.6
Solomon Islands	5.2	3.0	0.5	0.0
Santa Cruz Island	1.0	0.6	0.3	0.0
New Hebrides	1.8	2.0	0.3	10.6
New Caledonia, etc.	0.0	0.0	0.0	1.0

[a] Figures are percent probability of contact by drift voyage, including lost at sea, out of bounds, and landings outside Melanesia.

[b] Starts were from Nanumea and Niulakita (Ellices); Futuna and Wallis; Savaii and Rose (Samoa); Ata and Tongatabu (Tonga); and Ono-i-lau.

56. Scholars usually refer to Polynesian-settled islands in Melanesia as the "Outliers." We use this term to mean islands to the west of the Ellices, Rotuna, and Fiji with populations of apparently total or partial Polynesian origin. For our purposes we also include the Polynesian-occupied atolls of Kapingamarangi and Nukuoro, which lie south of the Caroline Islands. Ward, Webb, Levison, in press.

57. Pawley, 1966, 1967. N.I.D., 1944: Vol. 3.

58. Churchill, 1911. Capell, 1962.

59. Green, 1966.

60. Elbert, 1953; Green, 1966; Pawley, 1966, 1967.

61. Bayard, 1966:88. Pawley, 1967.

ties aggregated to all Outliers, then with results to and from individual islands and groups.

Almost a quarter of all drifts from the Ellices landed at Outliers, giving a higher contact probability than between many Polynesian island groups. By contrast, landings at all other Melanesian islands, including the Solomons, totaled only 8 percent of all starts (Table 10). The probabilities of drift from Futuna, Wallis, and Samoa for the Outliers and the rest of Melanesia have similar proportionality. Thus the chances of reaching one of the Outliers as opposed to a non-Polynesian island in Melanesia are three to one or better from the Samoa-Ellices area.

Voyages from Tonga fare differently. Contact probabilities to the Outliers are much lower than to other Melanesian islands (excluding Fiji). In fact, most drifts from Tonga end at one of the islands of the Fiji group, which lie across the seaways from Tonga to Melanesia, except in the direction of the southern New Hebrides and some uninhabited reefs like Conway. Most drifts from Tonga which reach Fiji terminate in the eastern Lau group, where there are strong "Polynesian" elements.

Table 11. Drift Voyage Destinations in Melanesia[a]

Destination	No. of Landings	Comments
Ontong Java	283	Polynesian language Outlier
Nukumanu	130	Polynesian language Outlier
Taumako	88	Polynesian language Outlier
Mitre	59	Used for gardens by Anuta people
Malaita	43	Melanesian language, large island, Solomons
Futuna	42	Polynesian language Outlier
Sikaiana	38	Polynesian language Outlier
Aneityum	36	S. New Hebrides, Melanesian language, Polynesian influences?
Santa Cruz Islands	35	Some Polynesian features?
Eromanga	33	S. New Hebrides, Melanesian language, Polynesian influences
Tikopia	31	Polynesian language Outlier
Conway	29	Uninhabited, southeast of New Hebrides
Outer Reef Islands	29	Polynesian language Outlier
Pentecost	28	N. New Hebrides, Polynesian characteristics, Melanesian language
Banks Islands	28	Polynesian characteristics
S. Ysabel	27	Melanesian language, large island, Solomons
Maewo	26	N. New Hebrides, Melanesian language, perhaps some Polynesian features
Efate	25	Polynesian language Outlier
Anuta	24	Polynesian language Outlier
Hunter	20	Uninhabited island, south of New Hebrides

[a] Drifts from Ellices, Futuna, Wallis (Uvea), Samoa, and Tonga.

These aggregated probabilities mask immense differences in contact chances between Polynesia and individual Outliers. In Table 11 the islands of Melanesia are ranked by their total of landings from the nine starting points in western Polynesia. From this ranking it is clear that there is a prima facie case that some Outlier populations derive from drift voyages. Nine of the Outliers fall in the top twenty destinations, six of the other fourteen have some evidence of Polynesian features in the ethnic character of their populations, and two are large islands in the Solomons with firmly Melanesian inhabitants.

The other end of the ranking (not included in the table) also has its interest. Outliers with two, one, or zero landings are West Uvea, Emae in the New Hebrides, and Rennell and Bellona. Oba in the New Hebrides and Tana in the Loyalties, both said to have inhabitants with Polynesian characteristics, had no landings at all.

The linguistic and ethnographical materials used by Bayard and Pawley are difficult to interpret and do not show simple and clear relationships between each Outlier and triangle Polynesia.[62] Apart from difficulties due to fragmentary evidence, it appears that some Outliers have had a long history of relationships of some kind with Polynesia, and there has also been contact between some of the Outliers themselves.

The linguistic evidence shows a relationship between the languages of the Ellices and those of the central and northwestern Outliers. Our experiments indicate a considerable likelihood of drifts from the Ellices to these islands, especially to Ontong Java. Bayard's thesis of inter-island contact subsequent to initial settlement seems reasonable, since our probabilities to the more distant Outliers, such as Nukuria and Nukuoro, are negligible, but would probably be high or very high if voyages were started from Ontong Java or Sikaiana.

At the present the Duff Islands (Taumako) and the Outer Reef Islands (Pileni) cannot be related linguistically to the Ellices or Futuna. Since drift probabilities to the Duffs are roughly even from the Ellices and Futuna-Wallis,[63] it will be interesting to see if the linguistic relationships that emerge after further study support a hypothesis of settlement from both sources.

62. Bayard, 1966; Pawley, 1967.

63. Successful drifts to the Duff Islands were 2.9 percent from Nanumea, 3.3 from Niulakita, 2.9 from East Futuna, and 2.4 from Wallis (East Uvea).

The Reef Islands, since they are only one hundred miles to the west, can be reached easily from Taumako.

Tikopia has the strongest drift contacts from East Futuna, with whose language it is probably associated, according to Pawley. Bayard suggests Tikopian origins lie in the Ellices or East Futuna, and drift chances, though highest from East Futuna, are next highest from the Ellices. It has been claimed that Anuta is related linguistically to Tonga from which there are minimal drift probabilities, but Green shows that it is a Nuclear Polynesian language of the Samoic-Outlier subgroups with a possible close relationship to Tikopian.[64] There is evidence for some linguistic borrowing from Tongan. There is a moderate probability of drifts from Tikopia reaching Anuta or Mitre.

The Outliers in the New Hebrides are related linguistically to East Futuna, but there is effectively zero probability of reaching them by drift directly from that island. Similarly West Uvea in the Loyalty Islands, which has similar language relationships, cannot be reached by drift from East Futuna. Once in the New Hebrides (at Emae, for example) drifts to Efate or West Uvea could be very probable, but not to Aniwa or West Futuna.

Rennellese is related to languages in West Polynesia, and although the details are uncertain at present, there is evidence to suggest a very close link with Tikopian.[65] It is virtually impossible to drift directly to Rennell or Bellona from our Polynesian starting points, and we doubt that drifting to them is possible from the other Outliers, except Tikopia from which there is a very low contact probability.

Our experimental data thus support the idea that some of the Outliers could have been settled by direct drifts from the Polynesian islands with which they have linguistic relationships. Using the eye of faith we might jump the gap between caution and certainty and claim that they *were* settled by drift. But a reasonable scepticism requires that we do not convert a positive probability into a dogmatic certainty. On the other hand, since negative experimentation can more easily be used to state strong conclusions, we can say there is zero probability that the southern Outliers were settled by direct drift voyages from their linguistically related islands in western Polynesia.

Vayda develops the argument that the success of new arrivals in establishing themselves and their culture at a new location will depend in part on the size of the island and its population.[66] A small group arriving by sea might strongly influence the culture and genetic makeup of a small population; on a large island, however, they might have little or no influence on cultural evolution. In the case under consideration most Outliers are small islands or, in the case of large atolls like Ontong Java, places with relatively small land areas. There is little evidence as to previous settlement on them, but we surmise that most were uninhabited or had small populations before their occupation by peoples of Polynesian origin. The ranking of drift arrivals from Polynesian islands in Melanesia (Table 11) includes a number of small islands (Ontong Java, Nukumanu, Taumako, West Futuna, Sikaiana, Tikopia, Outer Reef Islands, and Anuta) in which peoples of apparently Polynesian origin are solely resident; medium-sized islands (Aneityum, Santa Cruz Island,[67] Banks Island, Eromanga, Maewo, and Efate) with some evidence of Polynesian influences, especially in the last named, which has some Polynesian language speakers; and large islands (Malaita and Santa Ysabel) which have strongly indicated Melanesian inhabitants. At first sight these correspondences seem a cast-iron support of Vayda's thesis and they are indeed corroborative evidence. There are also Polynesian populations on Rennell, West Uvea, and Emae which are small or medium in size.

Drift Voyaging — Summary

In summary we would divide the Polynesian triangle into three distinct regions defined in terms of the process required for their discovery and settlement. Once entry into the triangle has been affected from the west, West Polynesia could be occupied by a process of island hopping and drift voyages. The second region, the core area of East Polynesia, is unlikely to have been reached by drift voyages from the west, but once the Marquesas had been settled a drift process could account for the occupation of almost all the tropical islands of the region. The position of the Pitcairn group is unresolved: it is very difficult to reach from east-central Polynesia unless by a purposefully navigated voyage; on the other hand it can be reached quite easily by drift from Easter Island. The third region is the outer arc from Hawaii through Easter Island to New Zealand, and here a drift hypothesis cannot be sustained; intentionally navigated, though perhaps only one-way, voy-

64. Pawley, 1967:264. Bayard, 1966:88. Green, 1971B:360–361.

65. Green, personal communication, August 1971.

66. Vayda, 1959.

67. The Polynesian influence in Santa Cruz stems from the Outer Reef Islands. Green, personal communication, August 1971.

ages must have been necessary. The only islands currently occupied by Polynesians which fall outside these three regions are the Polynesian Outliers within Melanesia and at least some of these could have been settled by direct drifts from within the Polynesian triangle.

Voyaging with Intent

Having concluded that a drift process as defined in our model system was unlikely to result in the settlement of East Polynesia (from either the west or the east) or of Hawaii, New Zealand, or Easter Island from East Polynesia, we modified part of the model system to allow for sailing on a preferred course. Initially an experimental voyage was calculated (without the aid of a computer) in which a flat earth with degrees of longitude and latitude of sixty-six nautical miles was assumed. It was also assumed that vessels could only maintain a course of 90° to the wind. Speed values were the same as those adopted in the main experiments. The voyage was started on July 1 in the vicinity of the Marquesas, with a heading of north until latitude 20°N, then a heading due west (thus following a navigational procedure similar to that postulated by Finney for voyages from the Marquesas to Hawaii);[68] a crossing was successfully accomplished in forty-one days.

Computer experiments were then carried out in which it was assumed that vessels could hold a track at 90° to the wind and would steer as close as possible to a specified direction. All other elements in the model system, including the sphericity of the earth, remained unchanged (see Chap. 3). Experiments 156 to 166 inclusive (see Appendix 1) were designed to test the feasibility of making those major crossings which were not made under drift conditions (see Fig. 36).

An experiment was begun from Rose (156), the easternmost of the Samoan islands, in which an eastward course was maintained whenever winds permitted. Despite the constraint that vessels could not sail closer than 90° to the wind, there was a moderate probability of craft reaching each of the Marquesas (6.8 percent), Tuamotu (6.0 percent) and Society (8.3 percent) groups. The Northern Cooks provided landing places for 31.3 percent of the voyages, while the Southern Line Islands (Malden, Starbuck, Caroline, Vostok, and Flint) were the landing places of a further 11.6 percent. It is interesting to note that the dominance of the southeasterlies forces vessels seeking an easterly course towards the northeast so that of those craft which reached islands to the east of Samoa, 76 percent landed to the north of their starting point. The Northern Cook Islands and the Southern Line Islands act as a screen to the west of the Marquesas. One might surmise that voyagers reaching these relatively inhospitable atolls might push on eastward seeking high islands like those of Samoa, and thus increase the landings in the Marquesas. Six voyages reached the coast of Panama or Colombia. Taken in toto, these results suggest that vessels seeking to hold an easterly course from Samoa might well reach the Marquesas rather than the nearer islands of the Societies or Tuamotus, and also that the crossing eastward from Samoa to part of eastern Polynesia might be made quite readily with limited navigational skills. The time necessary ranged from an average of five days to reach Pukapuka or Nassau in the Northern Cooks to fifty-two days to cross to the Marquesas.

The crossing from the Marquesas to Hawaii was attempted in three experiments. One beginning from Motuiti (158) was unsuccessful as a preferred northerly course resulted in virtually all voyages ending on other Marquesan islands just north of Motuiti. One voyage did reach the island of Hawaii in thirty-five days. A second experiment (161), with a northerly course setting but beginning at 8°S, 140°W in order to clear the Marquesas islands, resulted in no landings in Hawaii: most craft sailed out of the study area in 35°N between 142°W and 156°W. With a course of north-northwest (163) there was a moderate (8.5 percent) chance of landing in the Hawaiian islands with an average passage of thirty-six days. The majority of drifts still passed to the east of the group. These results suggest that the crossing to Hawaii could well be made by using the techniques of latitude sailing postulated by Finney once vessels reached the vicinity of the Tropic of Cancer. Alternatively a direct course between north-northwest and northwest would seem likely to give high landing probabilities, though this could not be tested directly as only the sixteen main compass directions could be used as courses in the model.

The voyage from East Polynesia to New Zealand was simulated by three experiments from Rarotonga, using courses of southwest (159), south-southwest (165), and west-southwest (166). In experiment 159 no less than 453 of the 732 voyages (61.7 percent) reached New Zealand. With a west-southwest course there was a moderate (6.7 percent) probability of reaching New Zealand in an average of twenty-nine days and a very high probability (27.9 percent) of landing in Australia. The south-southwest course (165) resulted in virtually all vessels passing east of New Zealand. A course of south-southwest from Tongatabu (162) carried 12.1

68. Finney, 1967.

percent of the vessels to New Zealand to indicate a high contact probability of a successful crossing from West Polynesia. This figure was obtained despite the fact that 72.4 percent of the voyages ended on Ata, less than two days' journey to the southwest of Tongatabu, and we might assume that voyagers proceeding with intent would have pressed on beyond this island.

The remaining barrier to drift voyages, the ocean expanse to the east of the Tuamotus and the Pitcairn group, can also be spanned by voyages of intent. From Timoe (157) an easterly course carried 14.3 percent of craft to the American coast and 19.1 percent to the Galapagos. Although only ten craft reached Easter Island or Sala y Gomez in this experiment, fifty-nine (8.1 percent) of those sailing east from Ducie (164) completed this link after a mean voyage of twenty-four days. Many reached the American coast in a little over two months.

If navigators were to set off from the coast of Peru in the vicinity of Callao (160) and keep a course as close to west as possible, the probability of their reaching Polynesia would be very high. Just over one-third of the craft in our experiment from off Callao landed on Polynesian islands, usually within three months of starting. Seven vessels reached Polynesian Outliers in the vicinity of Tikopia and the Santa Cruz group. Fifteen were carried back to the American coast and the remainder were "lost at sea." In view of comments made earlier on the greater likelihood of the Marquesas, rather than other Polynesian groups, being a point of contact from South America, we might note that of the 254 vessels in this experiment which landed in the Pacific

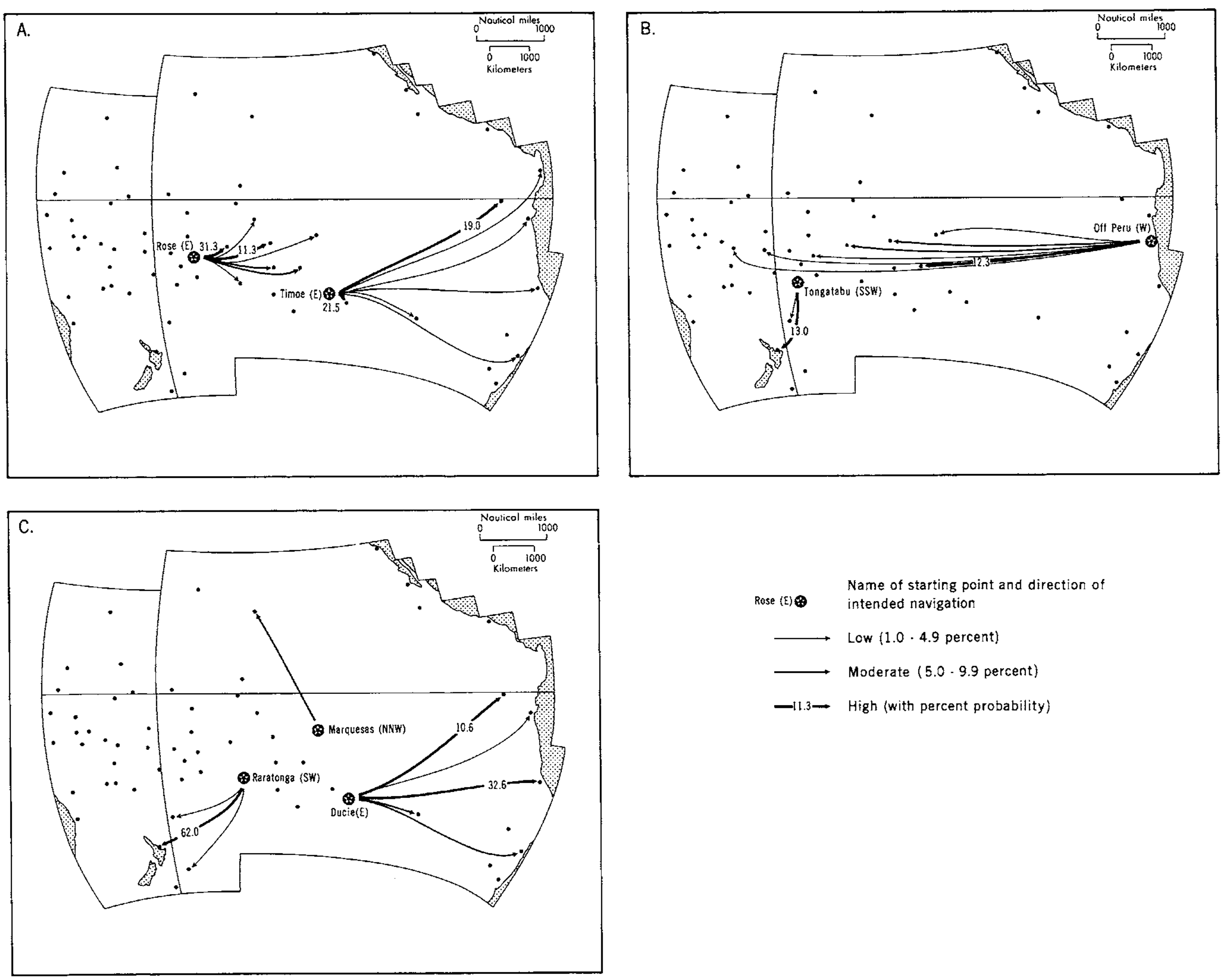


Figure 36. Navigated voyages experiments: Contact probabilities

islands 38.5 percent reached the Marquesas compared with only 5.5 percent landing in the Tuamotu archipelago. The Southern Line Islands and the Northern Cooks received 15.7 and 16.9 percent respectively of the successful voyages. These figures suggest that a passage across the northern face of central and eastern Polynesia would be the most likely route followed by craft sailing westward from the Peruvian coast, and in fact this corresponds to the tracks followed by *Kon-Tiki* and the rafts which have made subsequent passages from Peru to Polynesia.

In view of the long debate on the navigational skills required to make long sea crossings in prehistoric times, we feel that the most significant inference to be drawn from the results of our "navigated" experiments is that there are good chances of successfully crossing all the major ocean stretches within and around the Polynesian triangle, with a very limited degree of navigational skill, within a reasonable survival period, and in craft which have poor capabilities of sailing to windward. The only navigational skill assumed in our model is the ability to hold approximately to a course, and in general the directions chosen (east, west, north, or southwest in the main) are relatively easy bearings to recognize by sun or stars. Precise landfalls on specific islands are of limited significance to people seeking land—any land, provided it can support life, will suffice for initial occupation in an island group. Whether accurately navigated two-way voyages occurred later is another matter beyond the scope of the present work.

We believe that the experiments made with our model system suggest that a drift process would not have resulted in the initial settlement of the extremes of the Polynesian triangle though it may well have been the principal mechanism within some regions. Some element of purposeful voyaging was necessary for prehistoric man to reach the outer groups. Yet the skills and technology required to complete the settlement process were not of a high order. Endurance and determination may have been vital, but we believe that it was not essential for the Polynesians to be skilled in navigation over long distances. Provided they were prepared to set off, their chances of success were not unreasonable and not significantly lower than those risked by later European voyagers with a more highly developed technology.

EPILOGUE

The debate on the "Polynesian problem" will no doubt continue for many years. Certainly we do not expect this volume to stem the rush of words, any more than steamships and outboard motors have stopped the voyaging and drifting of island navigators. For just as the technology of motorized voyaging and modern navigation increasingly separates the sailor from the vagaries of wind and water, the technology of the computer and the rules of a model system separate us from the motivation of the individual navigator and the personal skills of his eye, his hand, and his navigational lore. Furthermore, we acknowledge that we are neither islanders nor navigators, and being separated by centuries from the Polynesians' forebears we cannot hope to know with any certainty what led them to set off on purposeful long-distance voyages. Firth and others have recorded how islanders in different parts of the Pacific at different times have engaged in bouts of voyaging for a variety of reasons.[69] Some motives may appear trivial to a modern nonislander but they should be viewed as far as possible in the context of the islanders' own culture and beliefs.

A vital and often missing element in discussions of the "Polynesian problem" is the difference in attitudes to the sea, sailing, and survival which separated the Pacific islander from continental man. Early islanders may have perceived the Pacific as a sea of islands. To continental man it is often envisaged as an empty expanse of ocean. Perhaps this contrast arose from differing oceanic experiences. It was the expanses of the empty Atlantic and eastern Pacific which formed the ocean images of Europeans, but people entering the Pacific from its western margins might well expect the seas to the east to be as island-studded as the margins they knew. If one believes that island-studded seas are the norm and has not had experience of the empty ocean wastes, then one may well sail forth with confidence. And failure to find land or survive landing is unlikely to be reported back to alter the images of the home community.[70]

69. Firth, 1961:150–152. See also Morrell, 1832.

70. The unpublished journal of Edward Robarts provides an interesting example of this. In the first decade of the nineteenth century Robarts was at Tahuata in the Marquesas Islands and he records that following quarrels "their prophets pretend to tell them of fine Islands, uninhabited, with all Kinds of food in great plenty, that they have nothing to do but make a canoe and go and take possession. Great numbers have gone, led by these uncertain tales." Later, when at Tahiti, Robarts recorded how canoes landed with forty or fifty men, women, and children on board who were fugitives from the Tuamotus. One of the women told Robarts how when people from the Marquesas had landed at her island they had been killed by the Tuamotans. Since the real fate of the voyagers was not reported back to the home islanders, the assumption that they had found a favorable landing remained intact. Robart's journal is now being prepared for publication by G. M. Dening. We are grateful to Mr. H. E. Maude for bringing this journal to our attention.

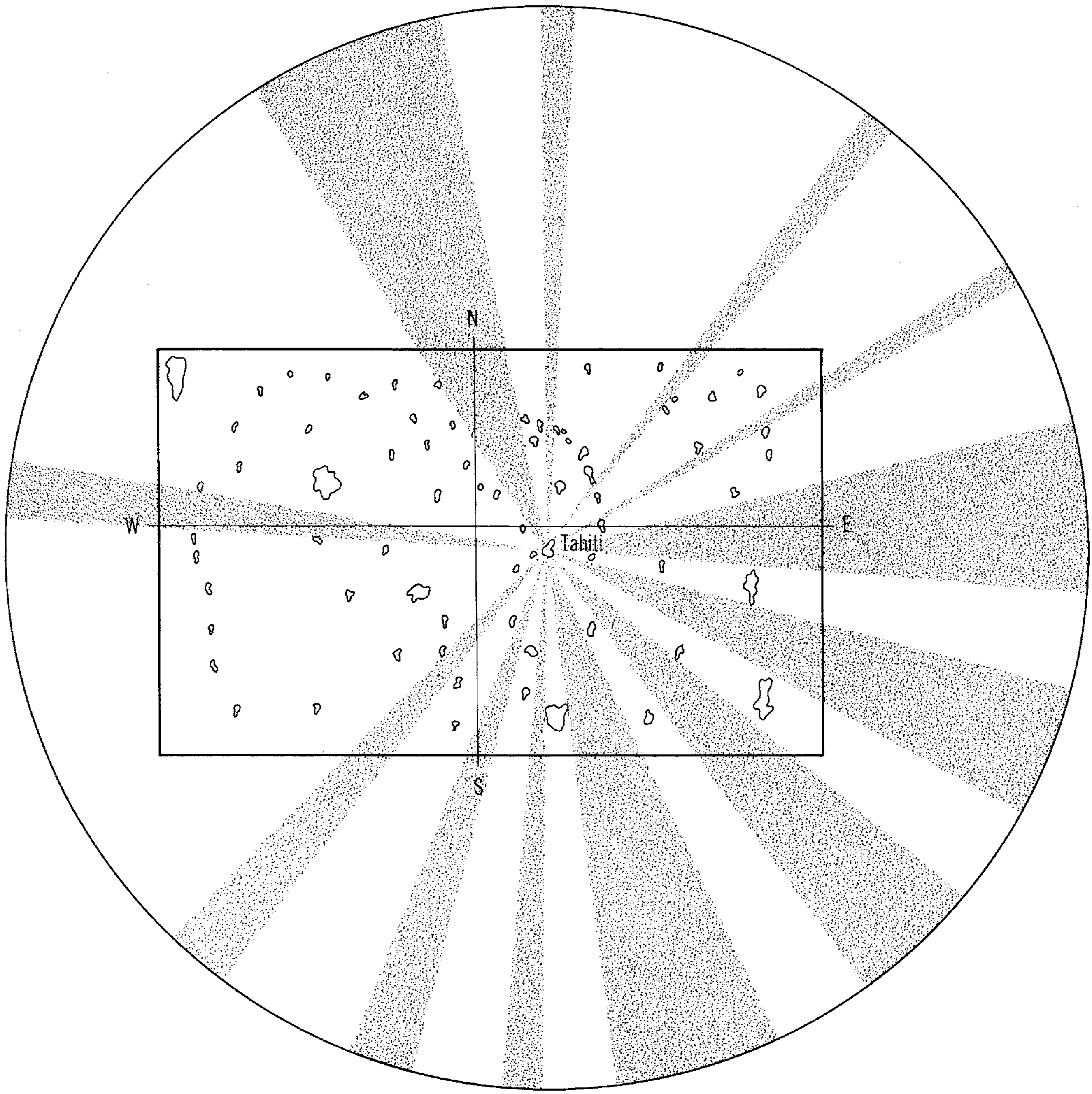


Figure 37. Tupaia's map and island screens

Early attempts by Polynesians to portray their island world for cartographically minded explorers provide some insight into their vision of their environment. The greatest significance of Tupaia's map may be that it shows that his image of his own world was of Tahiti surrounded on all sides by a screen of islands. Whether they existed in reality or not may be less important than the fact that they existed in the minds of persons likely to be sailing in Tahitian waters. The security of believing that islands lay just out of sight and that if one landfall were missed another would be made could materially alter the voyaging behavior of islanders.[71] Figure 37

71. Lewthwaite, 1920. We are grateful to R. C. Green for suggesting this interpretation of the map to us.

gives a representation of the effectiveness of this island screen. Viewed from the Tahiti of Tupaia's map, over 55 percent of the circumference of the surrounding sea was masked by islands and the Tahitian sailor may well have felt secure, insulated from the dangers of open oceans.

Further evidence of the security which some Pacific islanders feel when at sea and far from land in small vessels is provided by Gladwin, Lewis, McCoy, and others in their recent studies of Polynesian and Micronesian navigation and need not be reviewed at this stage. We would, however, point out one aspect of the way in which Micronesian navigators conceptualized their navigational environment which highlights the confidence with which they work. The European, at sea in a small vessel, tends to envisage his situation as one in which his craft moves towards, passes by, and then away from fixed islands. The islands are secure and he is in motion. But Gladwin describes how the Puluwat navigator, once on course, inverts the concept and in his navigational system considers the canoe to be stationary and the islands to move towards and past him.[72] Such a vision seems to reflect a high level of security and confidence in the self-contained little world of craft, crew, and navigational lore.

We accept that the risks and dangers of the sea which seem to weigh heavily in the minds of continental men are not given such emphasis by island navigators today. And we may surmise that a western Pacific islander in the past might well sail east or south or north in search of new land, confident in the belief that, as usual, islands would rise over the horizon to meet him.

72. Gladwin, 1970; Lewis, 1970, 1971A, 1971B; McCoy, unpublished paper. Gladwin, 1970:181–184.

Appendixes

APPENDIX 1

The following list gives the starting point and program variation used in each of the experiments. The omission of certain numbers arises not from any desire on the part of the authors to suppress evidence but from the means used by the programs to bring computer runs to a conclusion. In one case, experiment 5, the cause was an inappropriate choice of starting point (see Chap. 3), and the voyagers of that experiment are still marooned somewhere in central Peru.

Expt. No.	Island No.	Island	Notes
1	185	Rarotonga (S. Cooks)	12 months
2	595	Uapou (Marquesas)	12 months
3	208	Tongatabu (Tonga)	12 months
4	342	Maiao (Societies)	12 months
6	597	Motuiti (Marquesas)	12 months
7	....	12.00s:78.00w (off Peru)	12 months
8	136	Rapa	12 months
9	180	Rimatara (Australs)	12 months
10	....	6.06s:82.00w (off Sechura Point)	12 months
11	495	Rakahanga (N. Cooks)	12 months
12	784	Christmas (Line)	12 months
13	77	Mokohinau (New Zealand)	12 months
14	880	Bikar (Marshalls)	12 months
15	797	Butaritari (Gilberts)	12 months
16	952	Nihoa (Hawaii)	12 months
17	179	Rurutu (Australs)	12 months
18	613	Nanumea (Ellices)	12 months
19	133	Easter	12 months
20	722	Jarvis (Line)	12 months
21	915	Socorro	12 months
22	134	Pitcairn	12 months
23	137	Raoul (Kermadecs)	12 months
24	161	Mangareva (Gambier)	12 months
25	177	Raivavae (Australs)	12 months
26	....	19.00n:154.30w (south of Hawaii)	12 months
27	674	Tikehau (Tuamotus)	12 months
28	720	Fernandina (Galapagos)	12 months
29	....	8.17s:82.20w ("Seven Sisters")	12 months
30	....	5.00s:85.00w ("Seven Sisters")	12 months
31	....	3.36s:88.00w ("Seven Sisters")	12 months
32	595	Uapou (Marquesas)	November
33	595	Uapou (Marquesas)	December
34	595	Uapou (Marquesas)	January
35	208	Tongatabu (Tonga)	October
36	597	Motuiti (Marquesas)	July
37	597	Motuiti (Marquesas)	August
39	136	Rapa	March
40	136	Rapa	April
41	136	Rapa	December
42	136	Rapa	January
43	180	Rimatara (Australs)	April
44	180	Rimatara (Australs)	May
45	180	Rimatara (Australs)	June
47	495	Rakahanga (N. Cooks)	July
48	495	Rakahanga (N. Cooks)	August
49	784	Christmas (Line)	July
50	784	Christmas (Line)	August
51	77	Mokohinau (New Zealand)	July
52	77	Mokohinau (New Zealand)	August
53	77	Mokohinau (New Zealand)	September

Expt. No.	Island No.	Island	Notes
55	880	Bikar (Marshalls)	August
56	797	Butaritari (Gilberts)	May
57	797	Butaritari (Gilberts)	January
58	952	Nihoa (Hawaii)	September
59	952	Nihoa (Hawaii)	November
61	133	Easter	March
62	133	Easter	August
63	722	Jarvis (Line)	July
64	722	Jarvis (Line)	October
65	915	Socorro	March
66	915	Socorro	April
68	179	Rurutu (Australs)	May
69	179	Rurutu (Australs)	June
70	137	Raoul (Kermadecs)	February
71	161	Mangareva (Gambier)	May
72	161	Mangareva (Gambier)	June
73	161	Mangareva (Gambier)	July
75	161	Mangareva (Gambier)	November
76	161	Mangareva (Gambier)	December
77	161	Mangareva (Gambier)	January
78	177	Raivavae (Australs)	July
80		19.00n:154.30w (south of Hawaii)	September
81		19.00n:154.30w (south of Hawaii)	October
82	336	Tikehau (Tuamotus)	May
83	336	Tikehau (Tuamotus)	February
85	952	Nihoa (Hawaii)	12 months north shift
86	784	Christmas (Line)	12 months north shift
87	136	Rapa	12 months north shift
88	208	Tongatabu (Tonga)	12 months north shift
89	185	Rarotonga (S. Cooks)	12 months north shift
90	161	Mangareva (Gambier)	12 months north shift
91	137	Raoul (Kermadecs)	12 months north shift
92	597	Motuiti (Marquesas)	12 months north shift
94	952	Nihoa (Hawaii)	12 months south shift
95	784	Christmas (Line)	12 months south shift
96	136	Rapa	12 months south shift
97	208	Tongatabu (Tonga)	12 months south shift
98	185	Rarotonga (S. Cooks)	12 months south shift
99	161	Mangareva (Gambier)	12 months south shift
100	137	Raoul (Kermadecs)	12 months south shift
101	597	Motuiti (Marquesas)	12 months south shift
102		37.00s:179.00e (off East Cape, New Zealand)	12 months
103	135	Marotiri (Rapa)	12 months
104		25.00s:35.00w (south-east of Mangareva)	12 months
105	214	Ata (Tonga)	12 months
106	215	Ono-i-lau (Fiji)	12 months
107	348	Maupiti (Societies)	12 months
109	483	Fatuhiva (Marquesas)	12 months
110	499	Rose (Samoa)	12 months
111	514	Savai'i (Samoa)	12 months

Expt. No.	Island No.	Island	Notes
112	518	Wallis (East Uvea)	12 months
113	520	Futuna (East Futuna)	12 months
114	522	Rotuma	12 months
116	521	Niulakita (Ellices)	12 months
117	594	Uahuka (Marquesas)	12 months
118	600	Caroline (S. Line)	12 months
119	721	Malden (Line)	12 months
120	77	Mokohinau (New Zealand)	Reverse 12 months
121	137	Raoul (Kermadecs)	Reverse 12 months
122	133	Easter	Reverse 12 months
123	952	Nihoa (Hawaii)	Reverse 12 months
124	784	Christmas (Line)	Reverse 12 months
126	597	Motuiti (Marquesas)	Reverse 12 months
127	506	Upolu (Samoa)	Reverse 12 months
128		19.00n:154.30w (south of Hawaii)	Reverse 12 months
129		Off Nukuhiva (Marquesas)	Reverse 12 months
130	105	Más á Tierra (Juan Fernandez)	Reverse 12 months
131	106	Más afuera (Juan Fernandez)	Reverse 12 months
132	130	San Ambrosio	Reverse 12 months
133	131	San Felix	Reverse 12 months
136	105	Más á Tierra (Juan Fernandez)	12 months
137	106	Más afuera (Juan Fernandez)	12 months
138	130	San Ambrosio	12 months
139	131	San Felix	12 months
140		38s:75w (near Chile 3)	12 months
141	358	Niue	12 months
142	414	Cikobia (Fiji)	12 months
143	481	Pukapuka (Tuamotus)	12 months
144	525	Tikopia	12 months
145	603	Fakaofo (Tokelaus)	12 months
146	731	Arorae (Gilberts)	12 months
147	366	Fonualei (Tonga)	12 months
149	182	Mauke (Societies)	12 months
150	108	Curtis (Kermadecs)	12 months
151	157	Oeno (near Pitcairn)	12 months
152		33.15n:120.30w (near San Miguel)	12 months
153	597	Motuiti (Marquesas)	12 months (stability test)
154	597	Motuiti (Marquesas)	12 months (stability test)
156	499	Rose (Samoa)	12 months navigated East
157	160	Timoe (Gambier)	12 months navigated East
158	597	Motuiti (Marquesas)	12 months navigated North
159	185	Rarotonga (S. Cooks)	12 months navigated SW

APPENDIX 1

Expt. No.	Island No.	Island	Notes
160	....	12.00s:78.00w (off Peru)	12 months navigated West
161	....	8.00s:140.00w (off Marquesas)	12 months navigated North
162	 208	Tongatabu (Tonga)	12 months navigated SSW
163	....	8.00s:140.00w (off Marquesas)	12 months navigated NNW
164	 157	Ducie (near Pitcairn)	12 months navigated East
165	 185	Rarotonga (S. Cooks)	12 months navigated SSW
166	 185	Rarotonga (S. Cooks)	12 months navigated WSW

APPENDIX 2

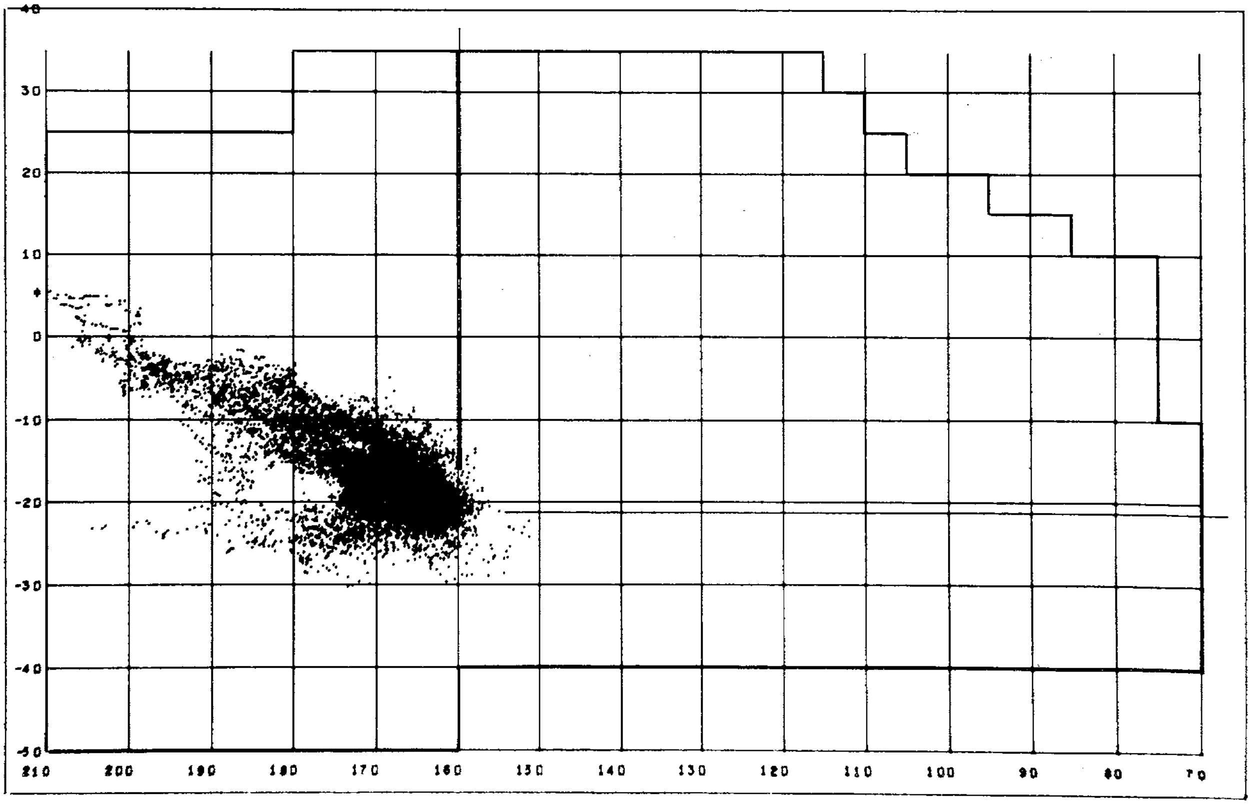
The microfilm maps reproduced in this appendix were constructed by computer using an off-line Stromberg Carlson SC4020 microfilm plotter, the information needed to produce them being extracted from the "logging tapes" (p. 25). Each microfilm frame illustrates a single experiment, and is built up from points giving the position of each vessel at the end of every day (days 1 to 3 omitted). The symbol + indicates where voyages terminated other than by landing. Up to 50,000 points appear on each frame, the points being plotted at rates up to 17,000 per second.

The points are plotted on a 10° grid, a square projection being employed since only the topography is of interest. Two extra axes indicate the starting point. To avoid confusion, no islands are shown in the maps, but a separate transparency is provided showing the islands drawn on an identical grid, and this may be overlaid on the maps. The resulting diagrams provide a good illustration of the drift fields from various starting points.

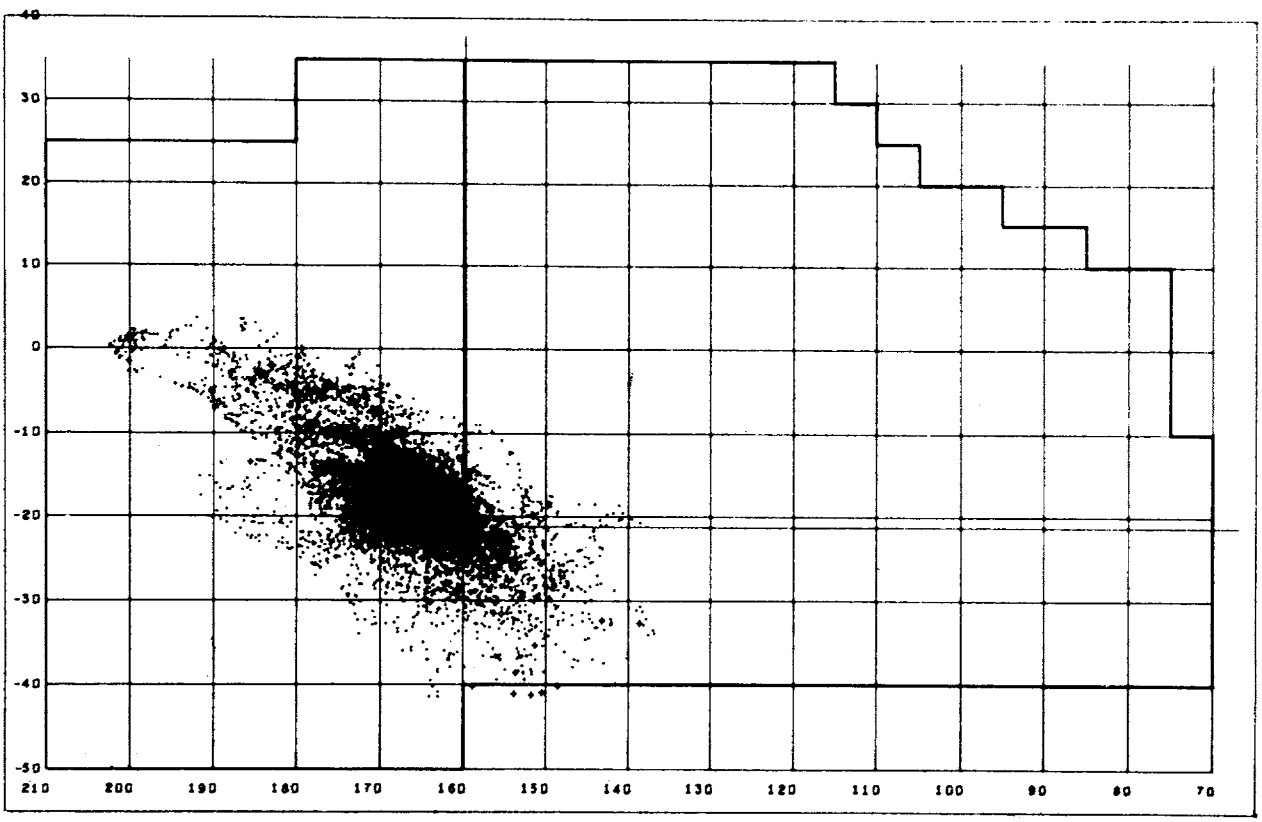
One matter on which a comment should be made is the tendency of voyages near the Equator to adhere to one of the 5° lines of latitude (see, for example, experiment 138). This effect is due to the model itself and arises because the 5° squares are slightly too coarse in a region where sharp changes of prevailing wind direction occur within a few degrees. In particular, at certain times of the year, the line of separation between the NE and SE Trades coincides with a 5° line of latitude. At such a time, a vessel just south of this line will very probably receive a SE wind and will move across it to the north; whereupon it will very probably receive a northeast wind and will move back south again, and so on. In year-round experiments in this region three bands can sometimes be noted. If suitable data were available, this phenomenon could be eliminated by refining the size of squares near the Equator. Its effect on the overall results, however, is negligible since there are almost no islands in the area, and one may imagine true voyages to be spread out between the bands.

The microfilm computer maps for certain of the twelve months experiments are included in the body of the monograph. These are Figure 21, Motuiti (8); Figure 22, Uahuka (117); Figure 23, Uapou (2); and Figure 24, Fatuhiva (109).

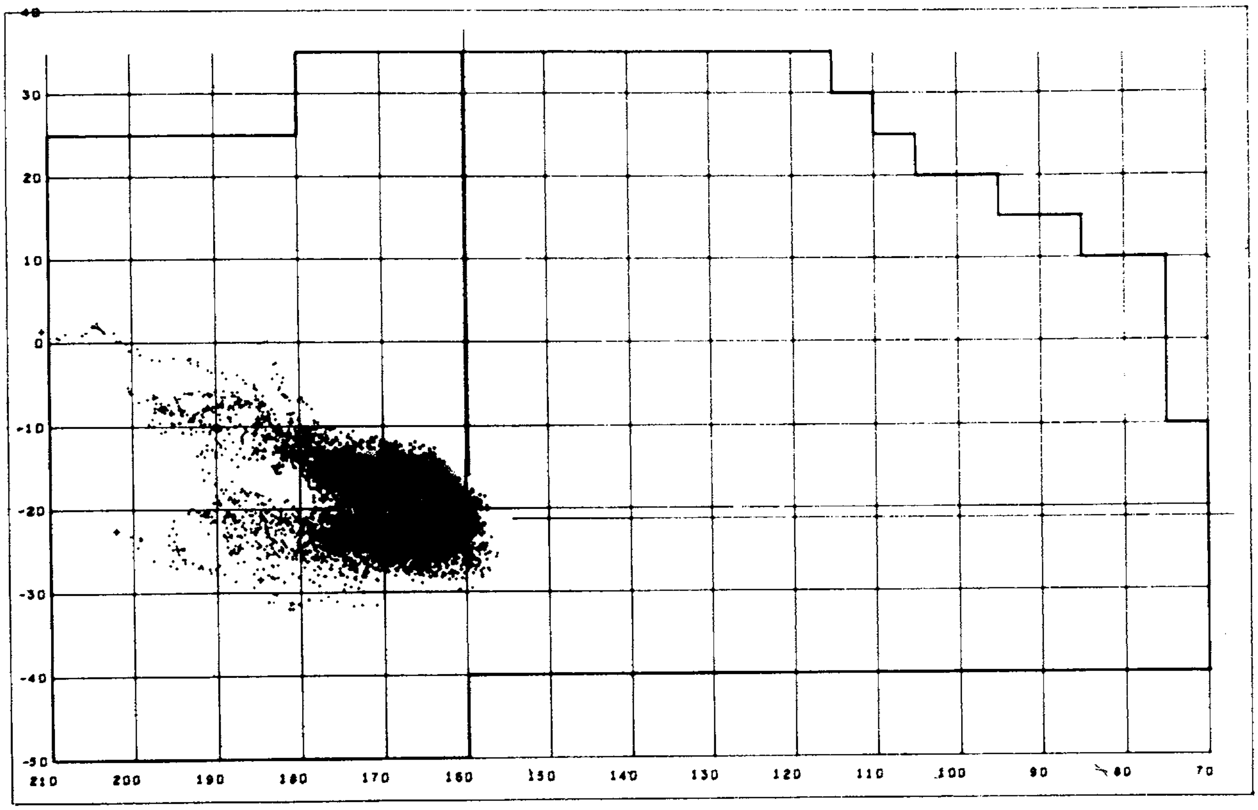
NOTE: Variations in the resolution of the computer maps result from the fact that some of the maps were produced on paper whereas others were produced on microfilm. The photographic and printers' procedures could not altogether remove these variations.



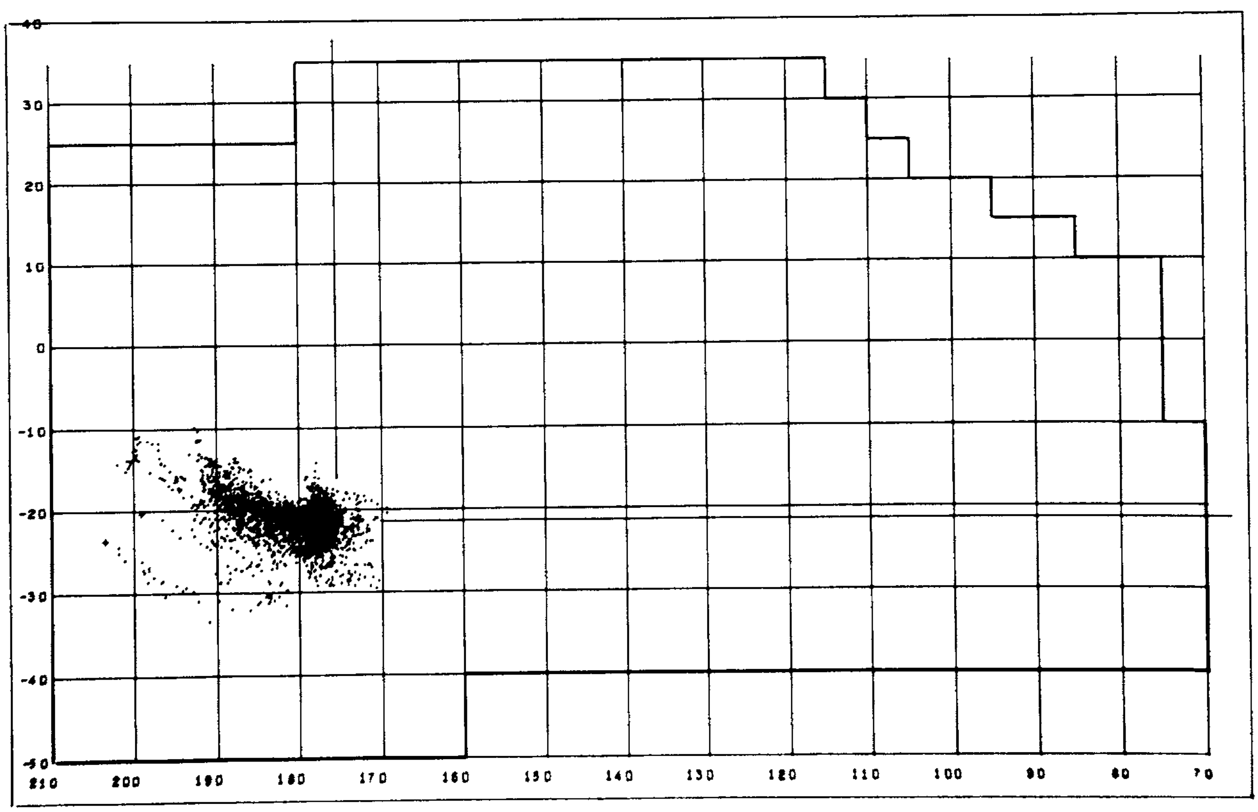
Rarotonga (Southern Cooks) twelve months experiment 1



Rarotonga (Southern Cooks) north wind shift experiment 89

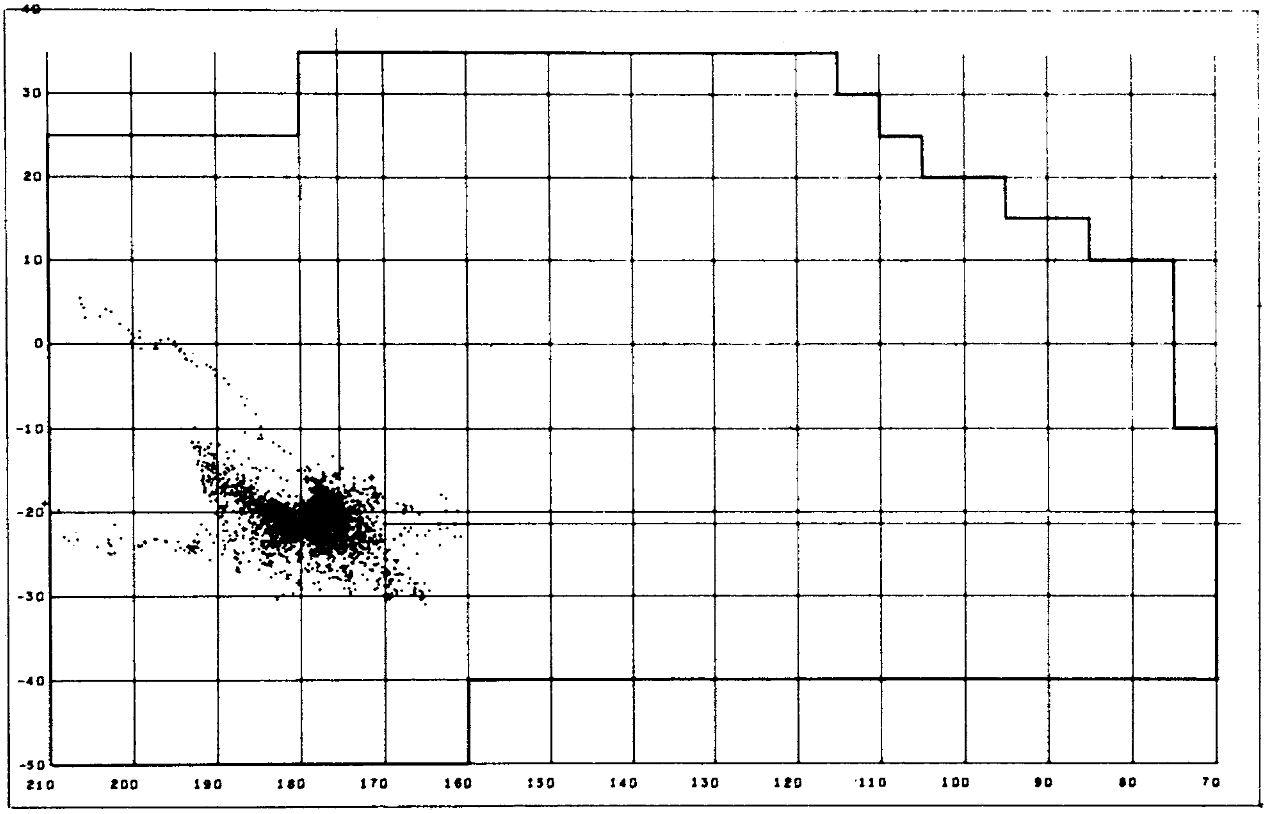


Rarotonga (Southern Cooks) south wind shift experiment 98

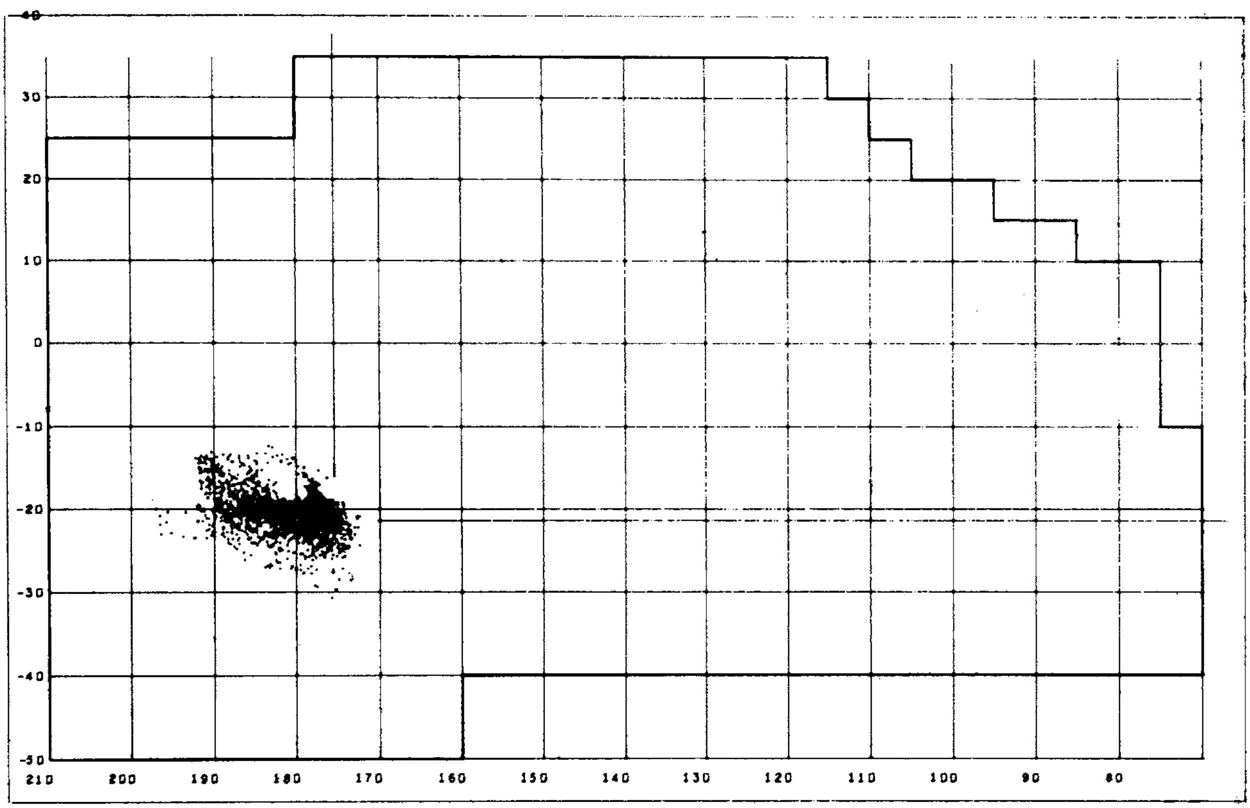


Tongatabu (Tonga) twelve months experiment 3

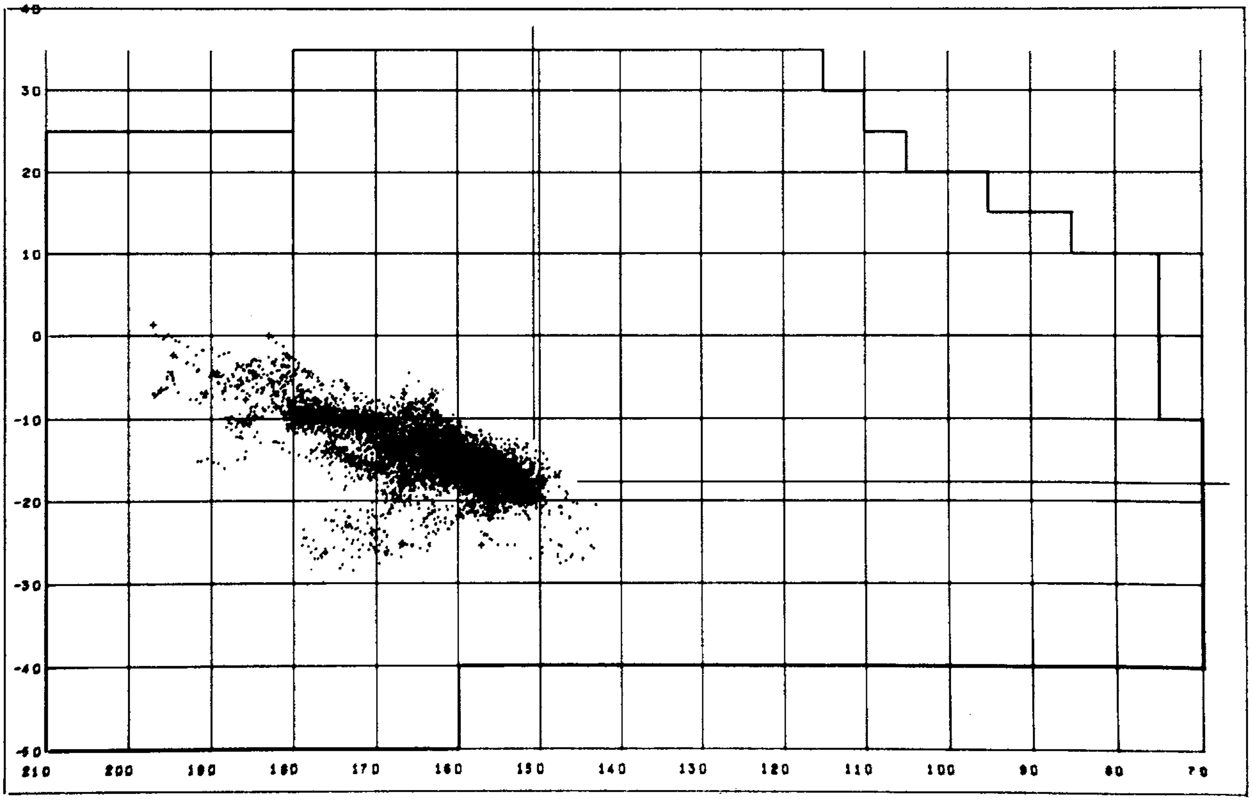
APPENDIX 2



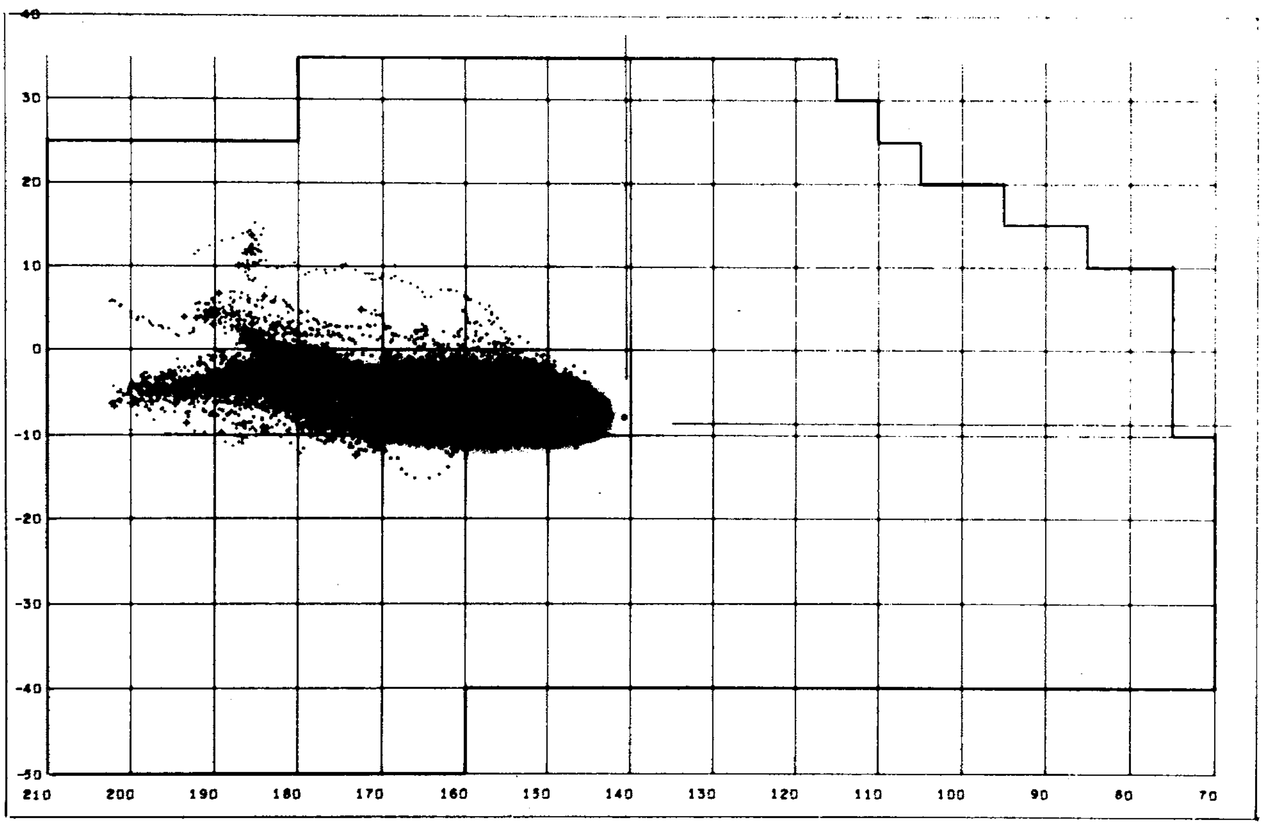
Tongatabu (Tonga) north wind shift experiment 88



Tongatabu (Tonga) south wind shift experiment 97

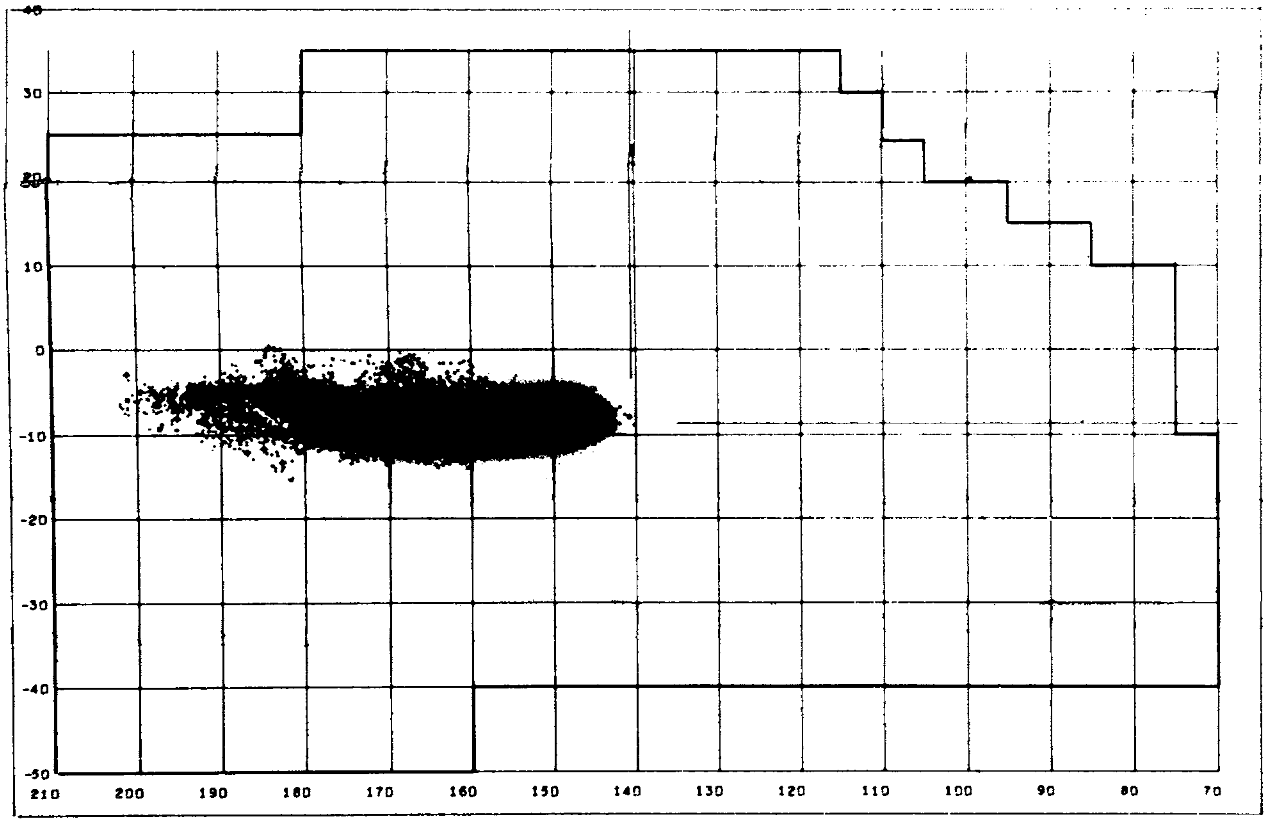


Maiao (Societies) twelve months experiment 4

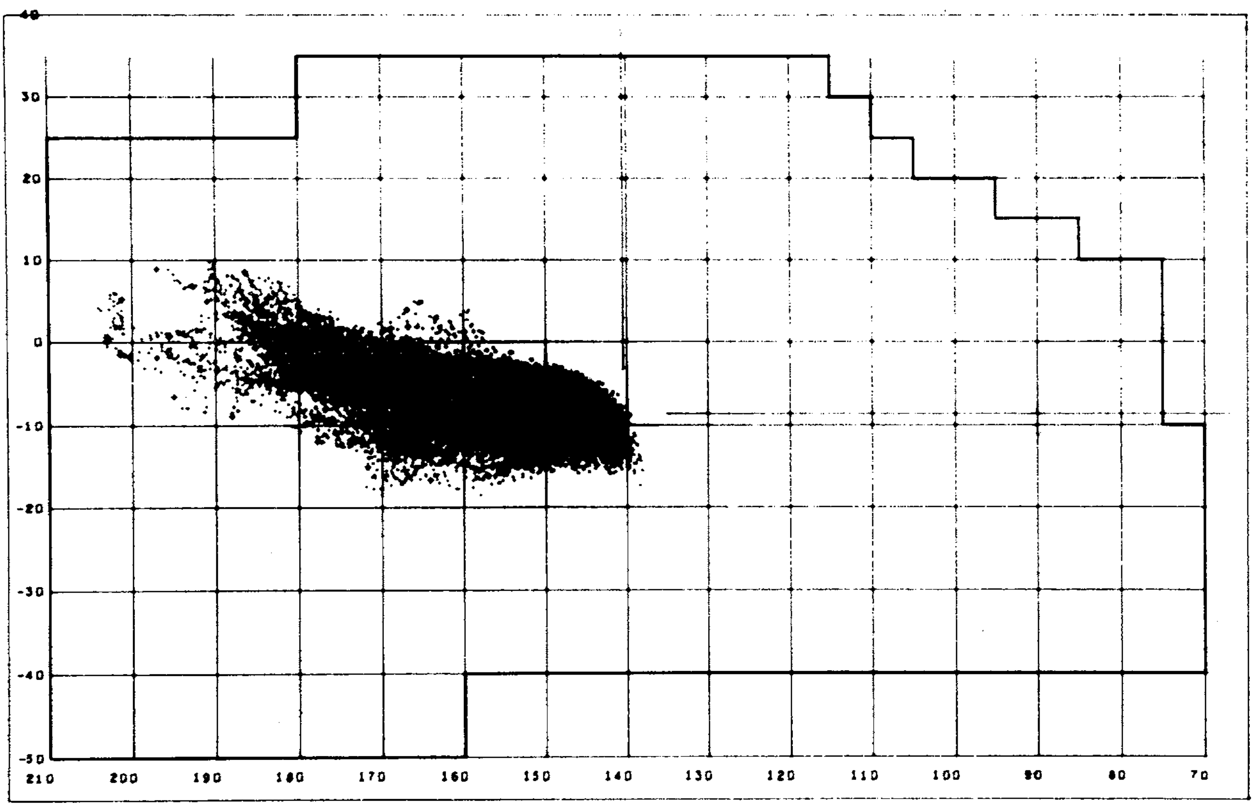


Motuiti (Marquesas) July experiment 36

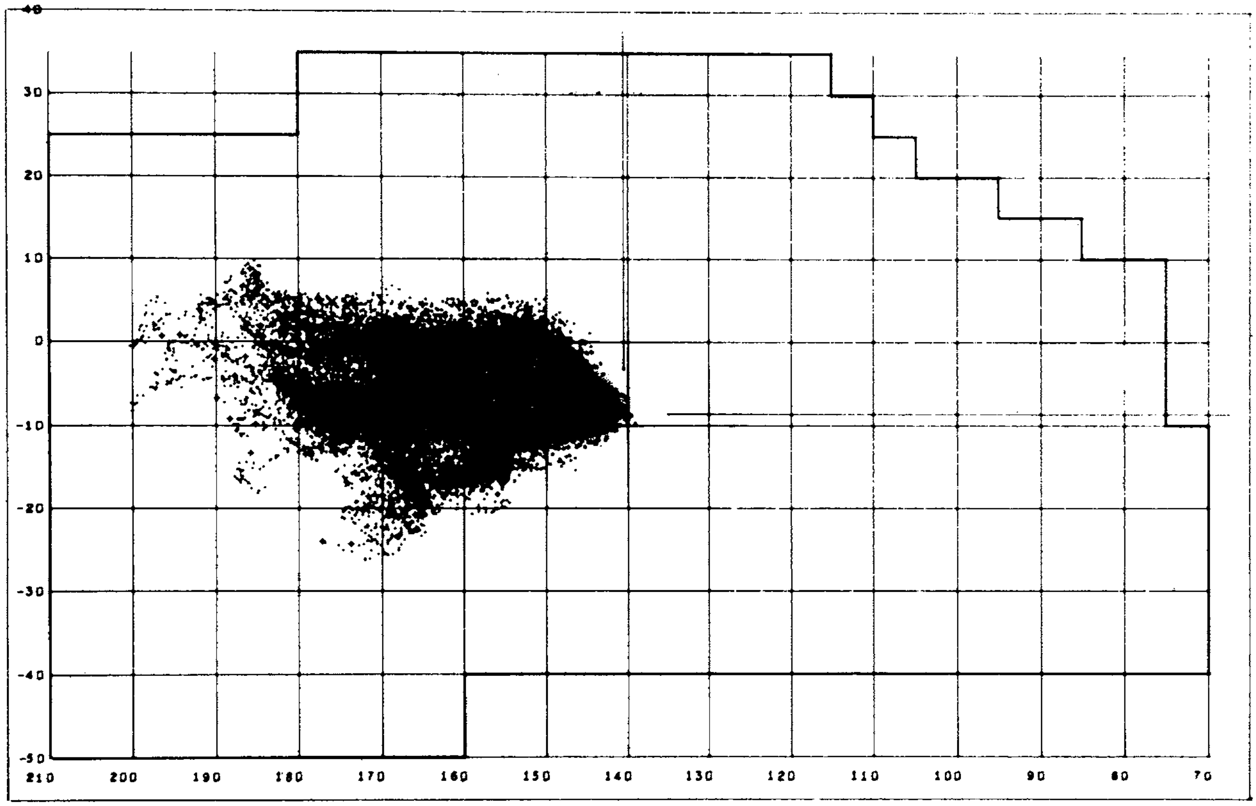
APPENDIX 2



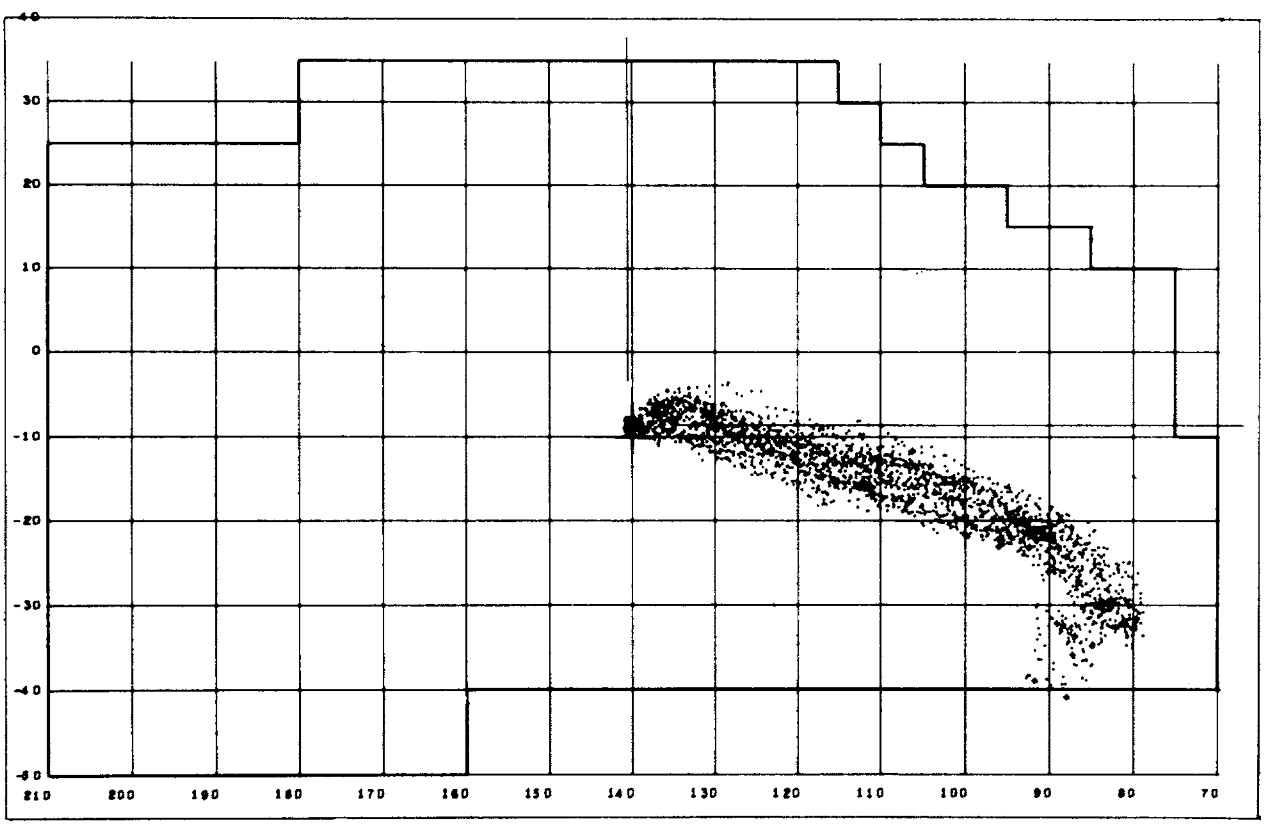
Motuiti (Marquesas) August experiment 37



Motuiti (Marquesas) north wind shift experiment 92

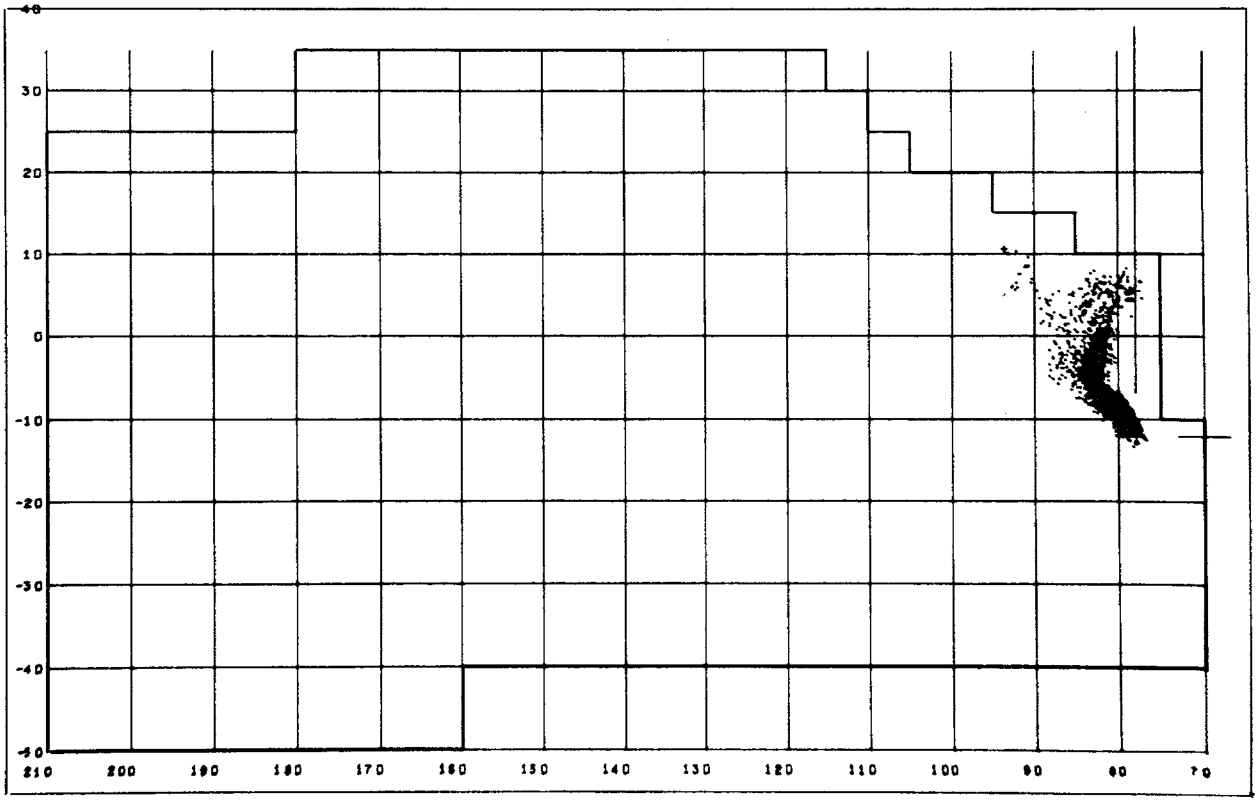


Motuiti (Marquesas) south wind shift experiment 101

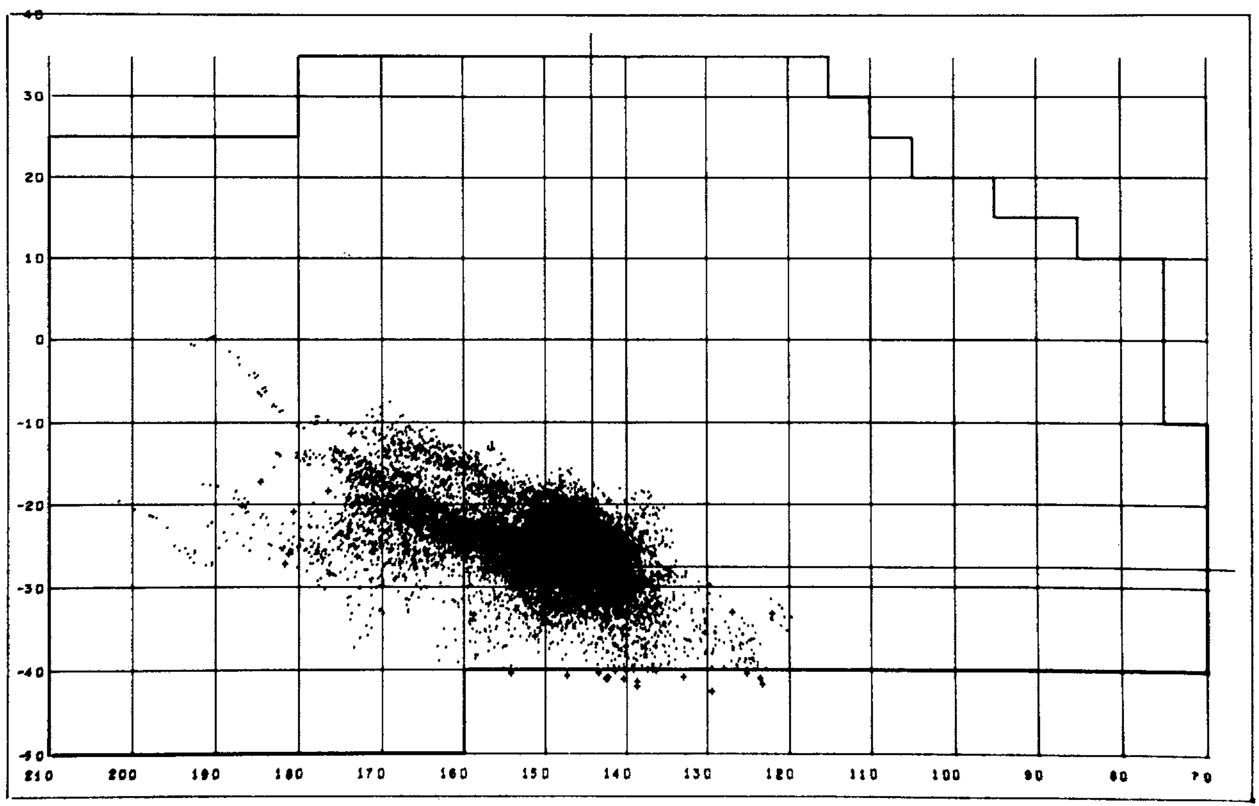


Motuiti (Marquesas) reverse experiment 126

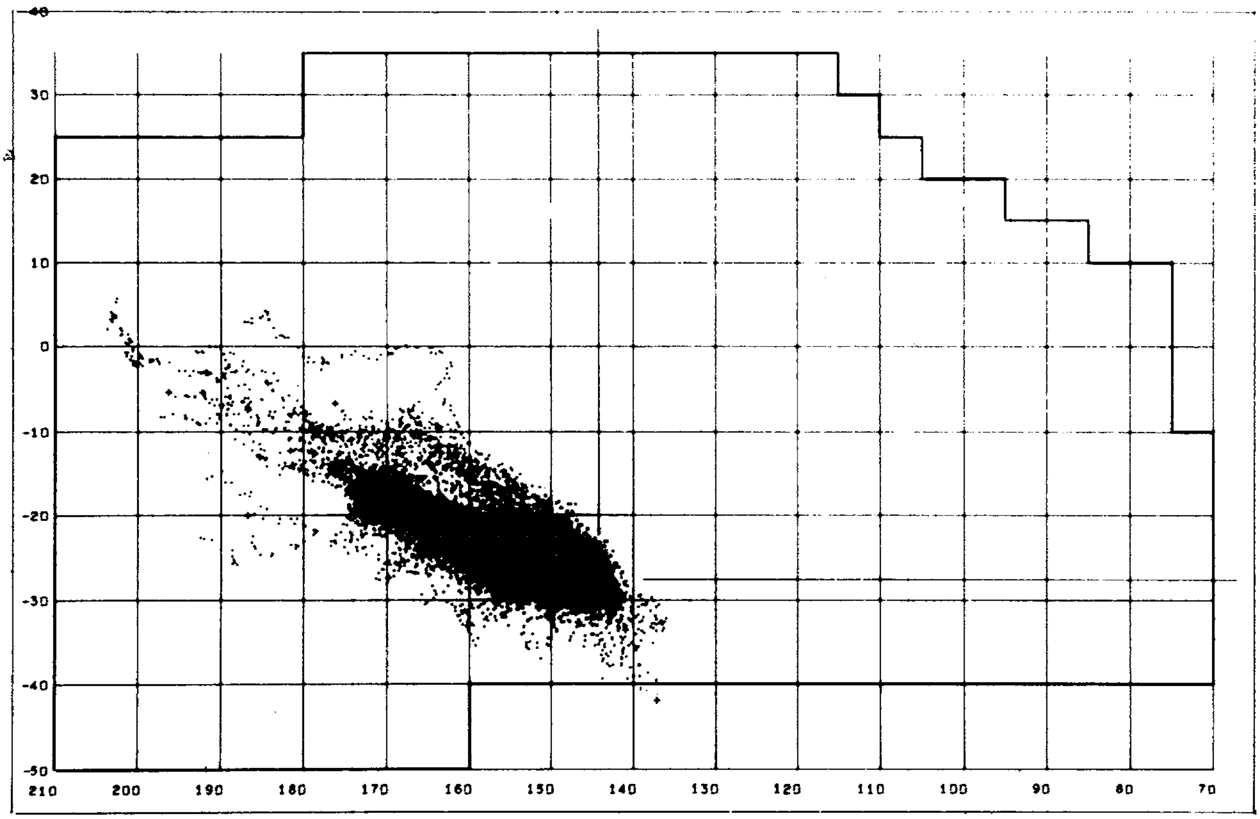
APPENDIX 2



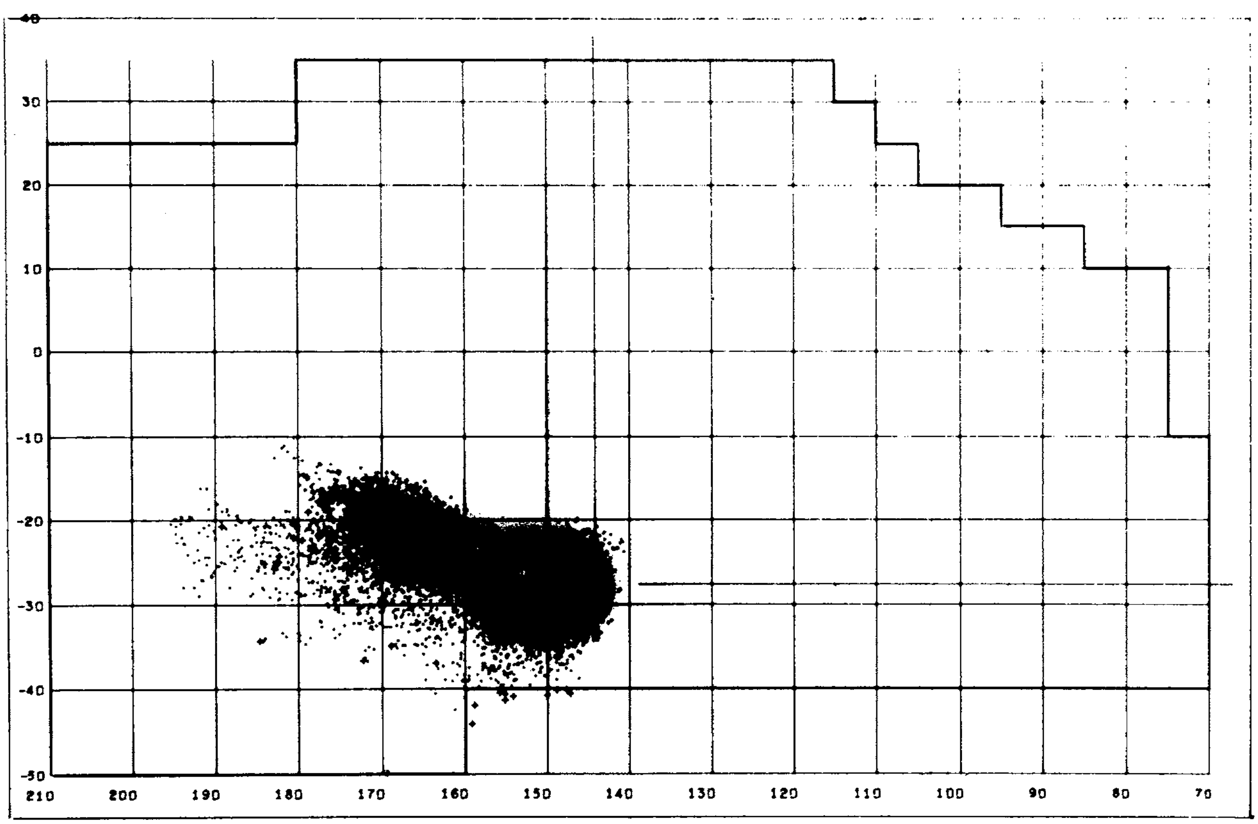
12s:78w twelve months experiment 7



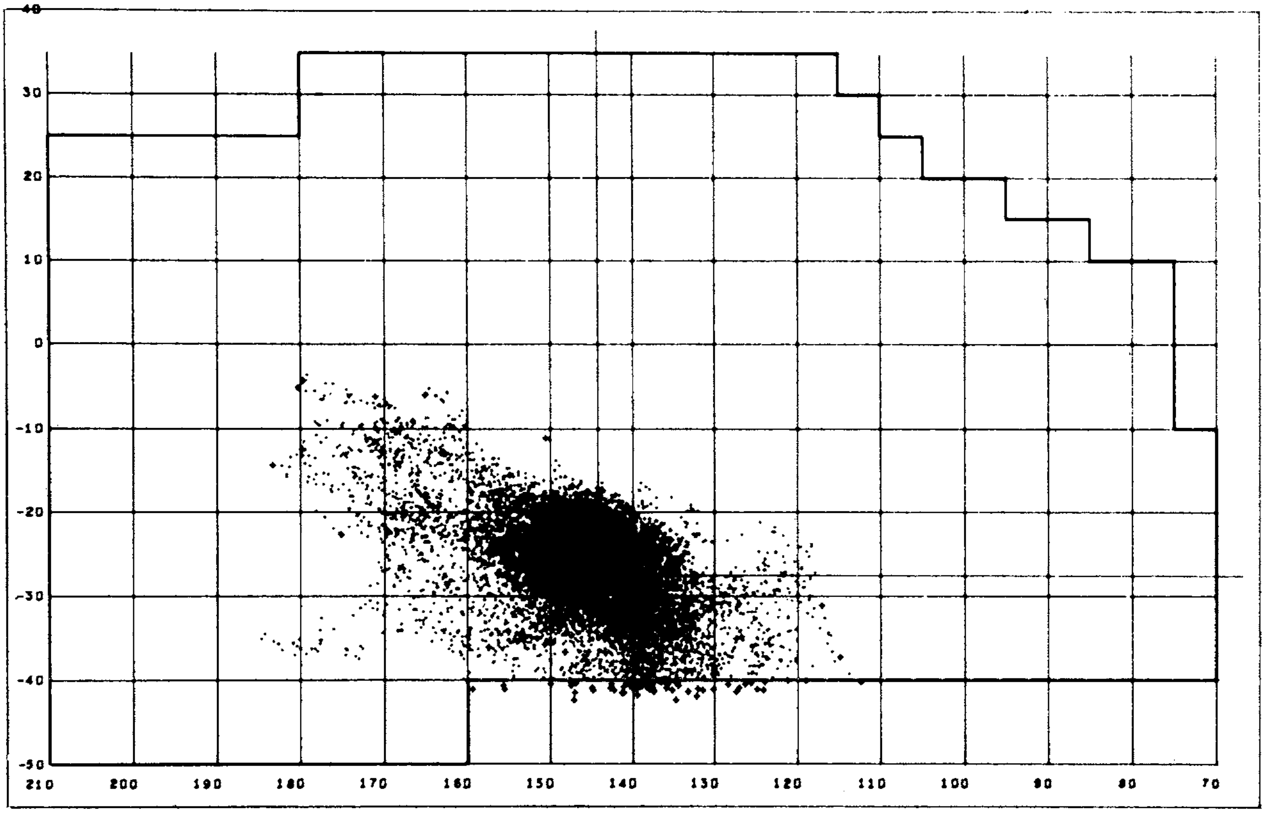
Rapa twelve months experiment 8



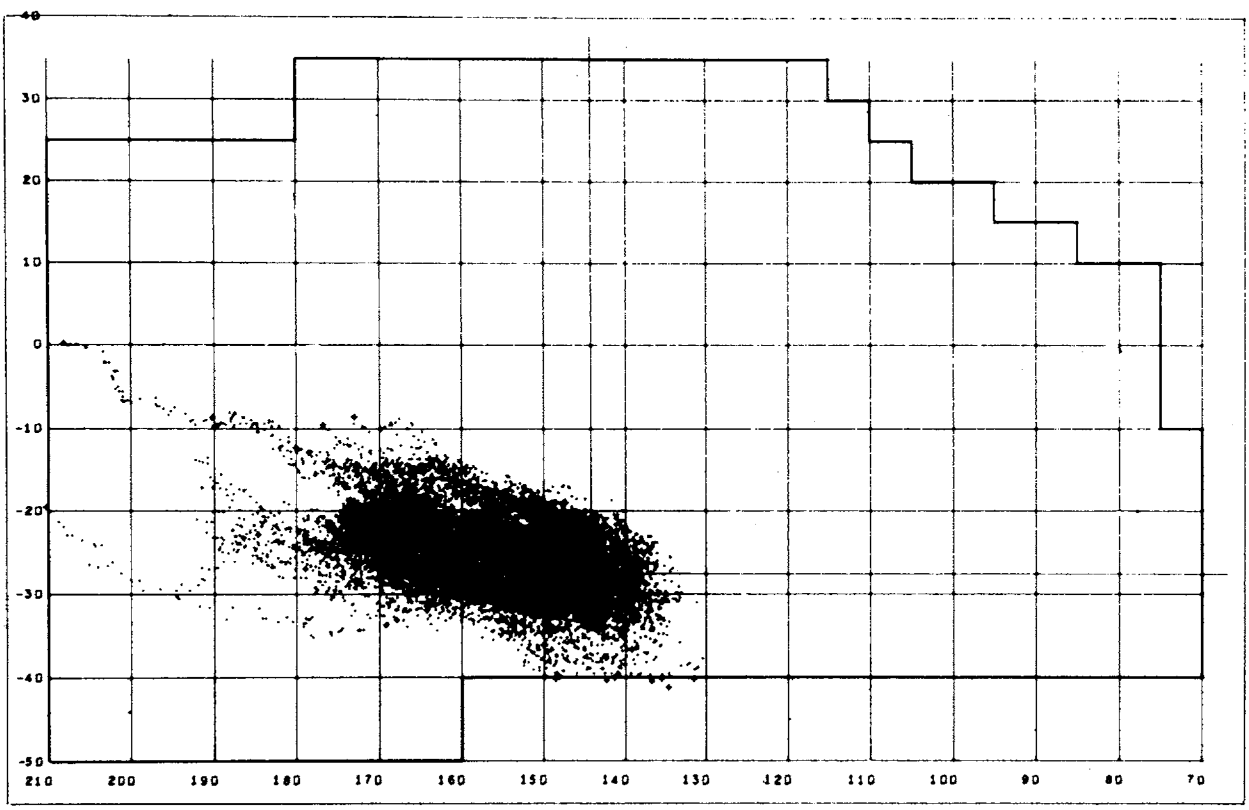
Rapa March experiment 39



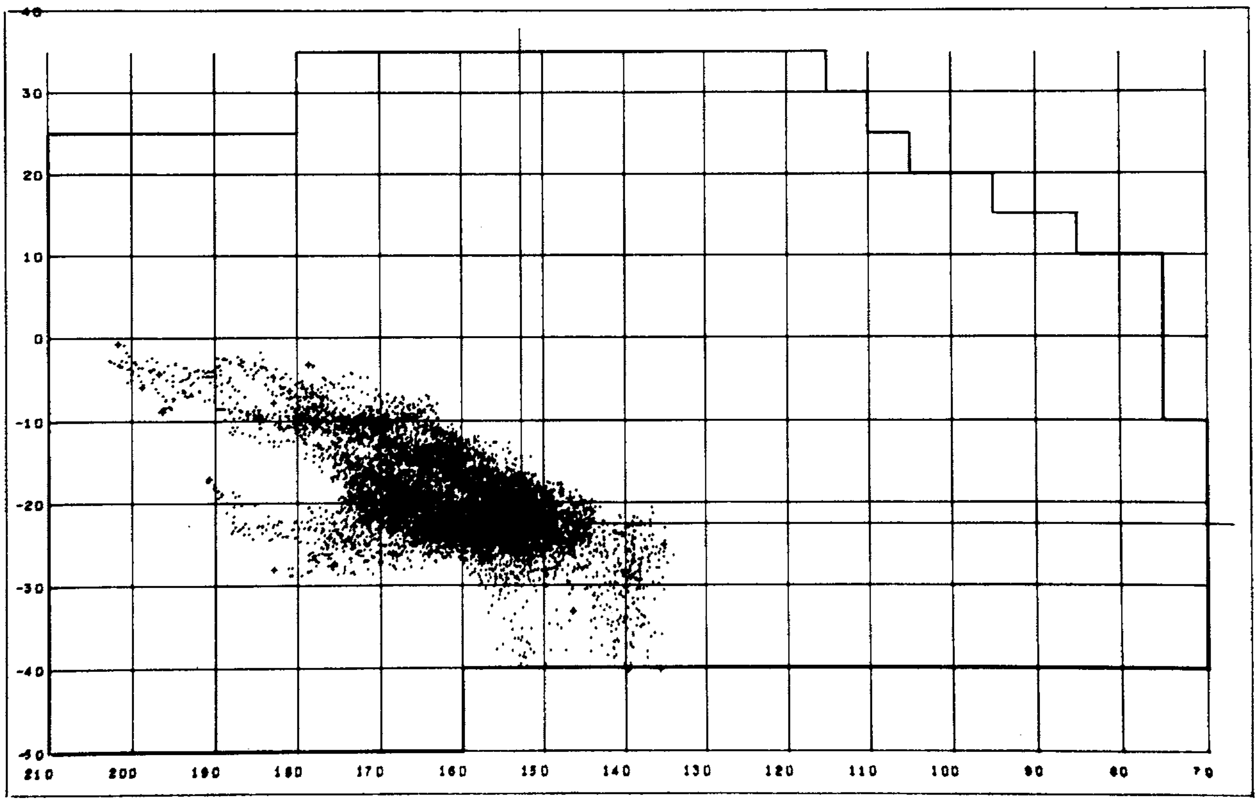
Rapa January experiment 42



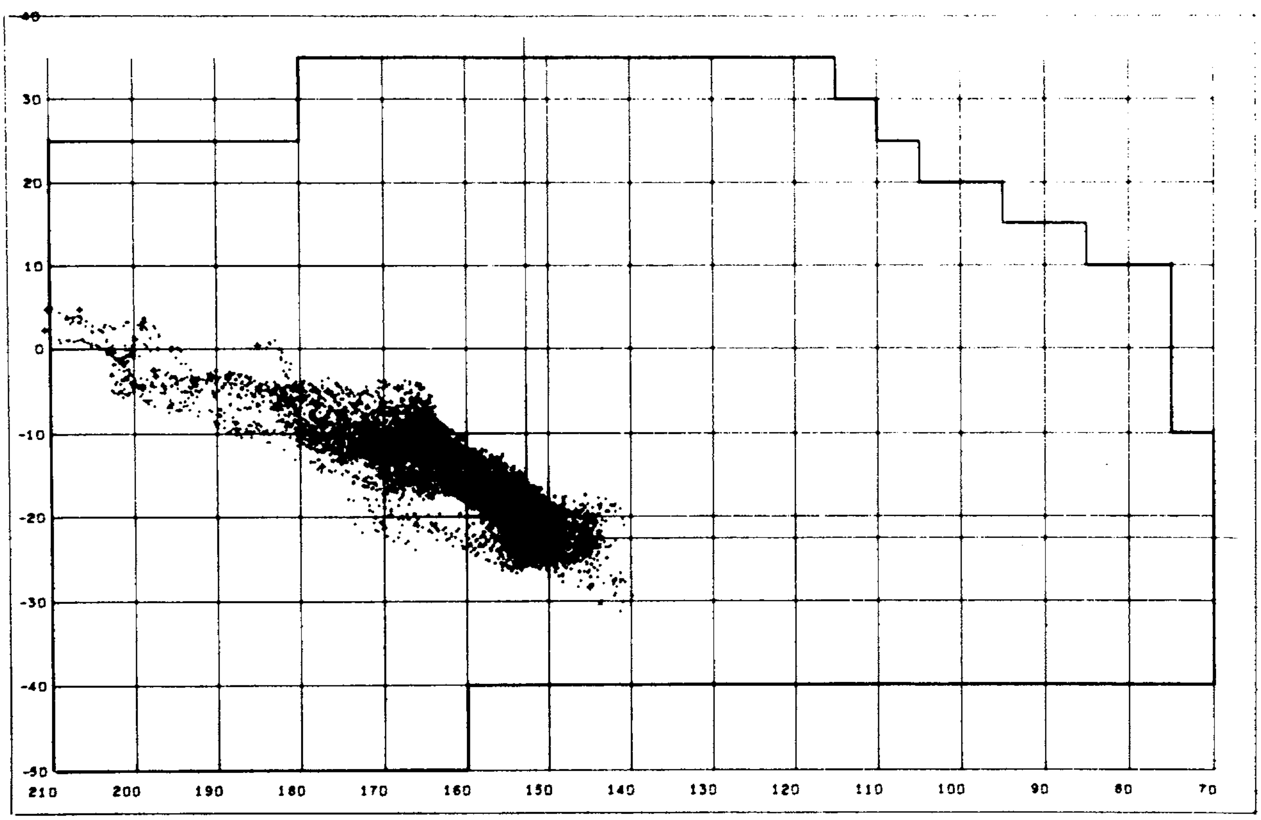
Rapa north wind shift experiment 87



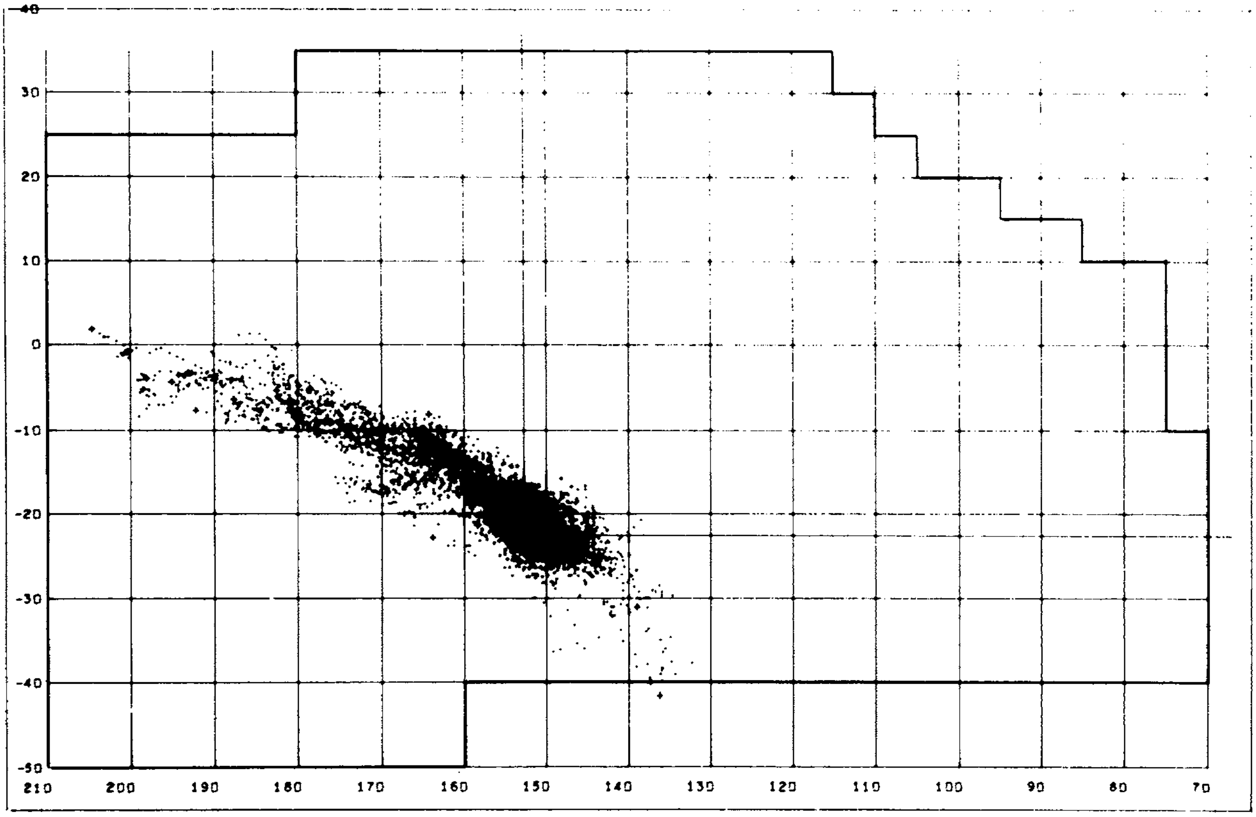
Rapa south wind shift experiment 96



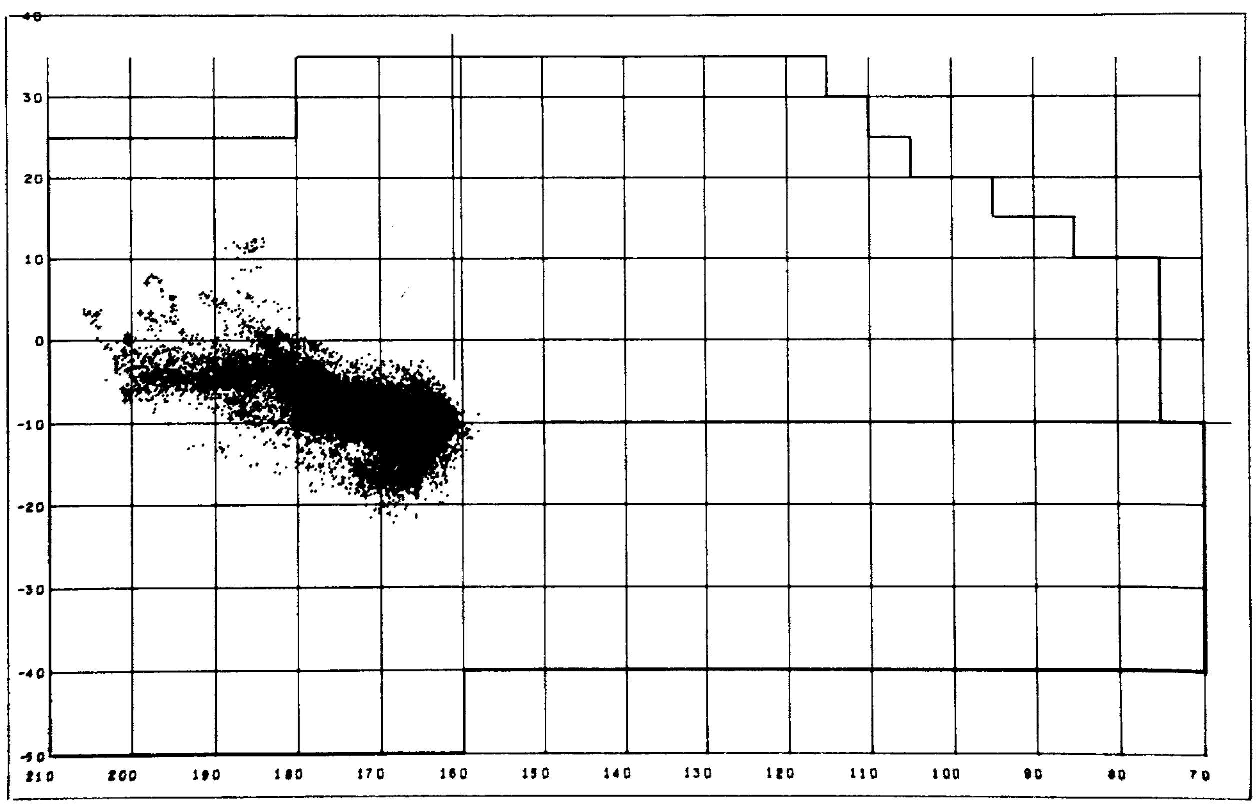
Rimatara (Australs) twelve months experiment 9



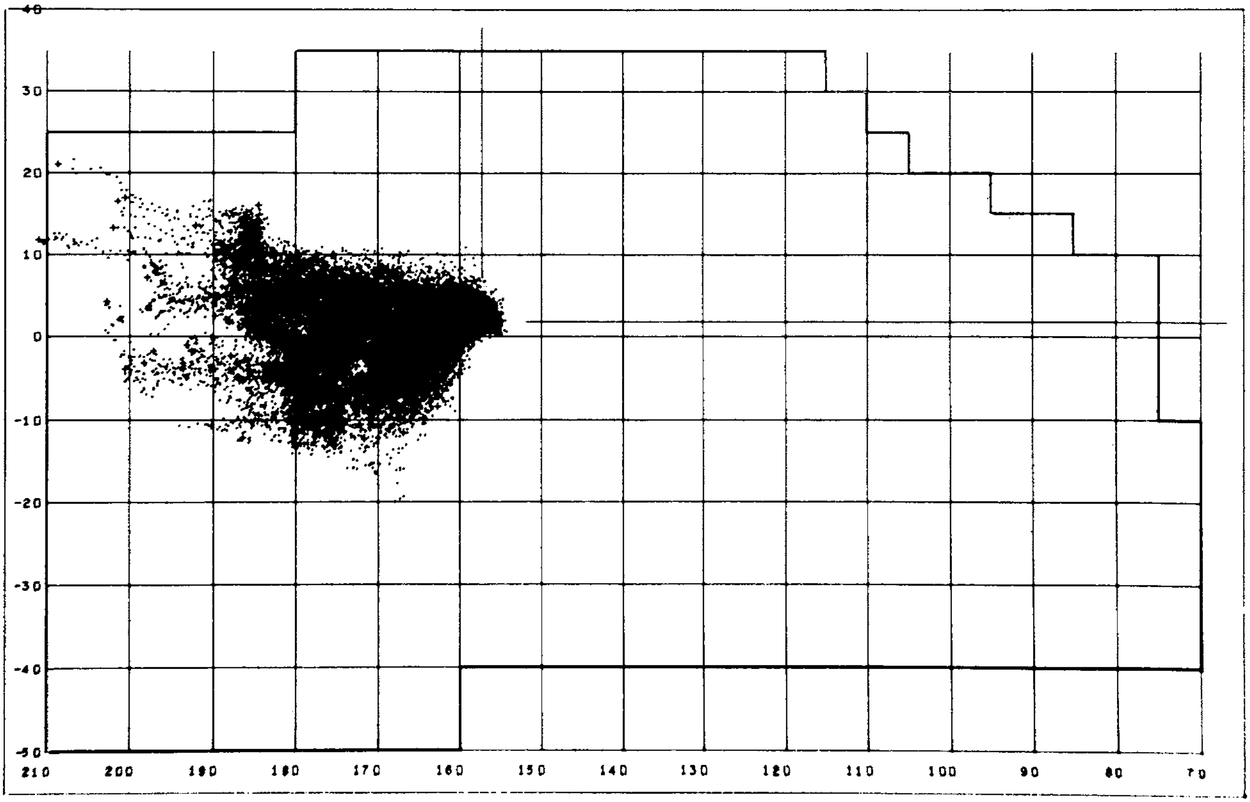
Rimatara (Australs) April experiment 43



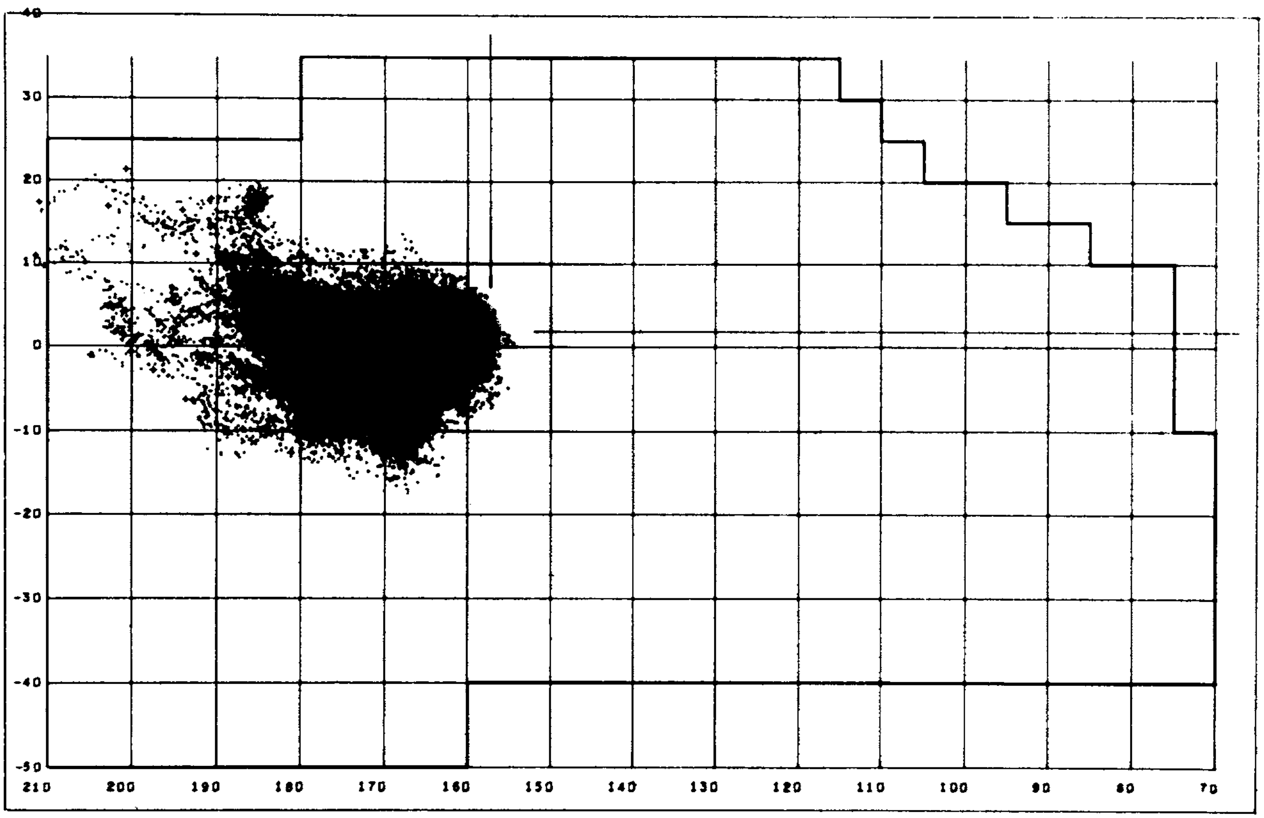
Rimatara (Australs) May experiment 44



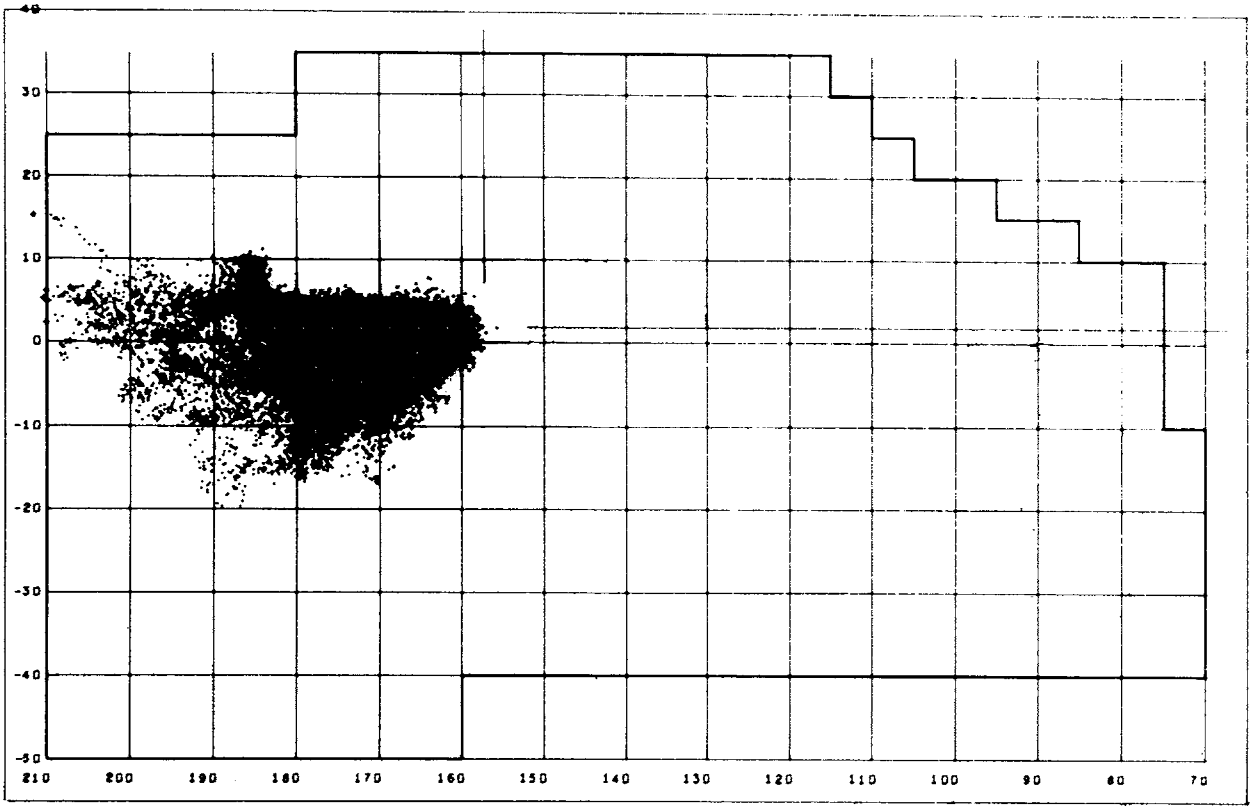
Rakahanga (Northern Cooks) twelve months experiment 11



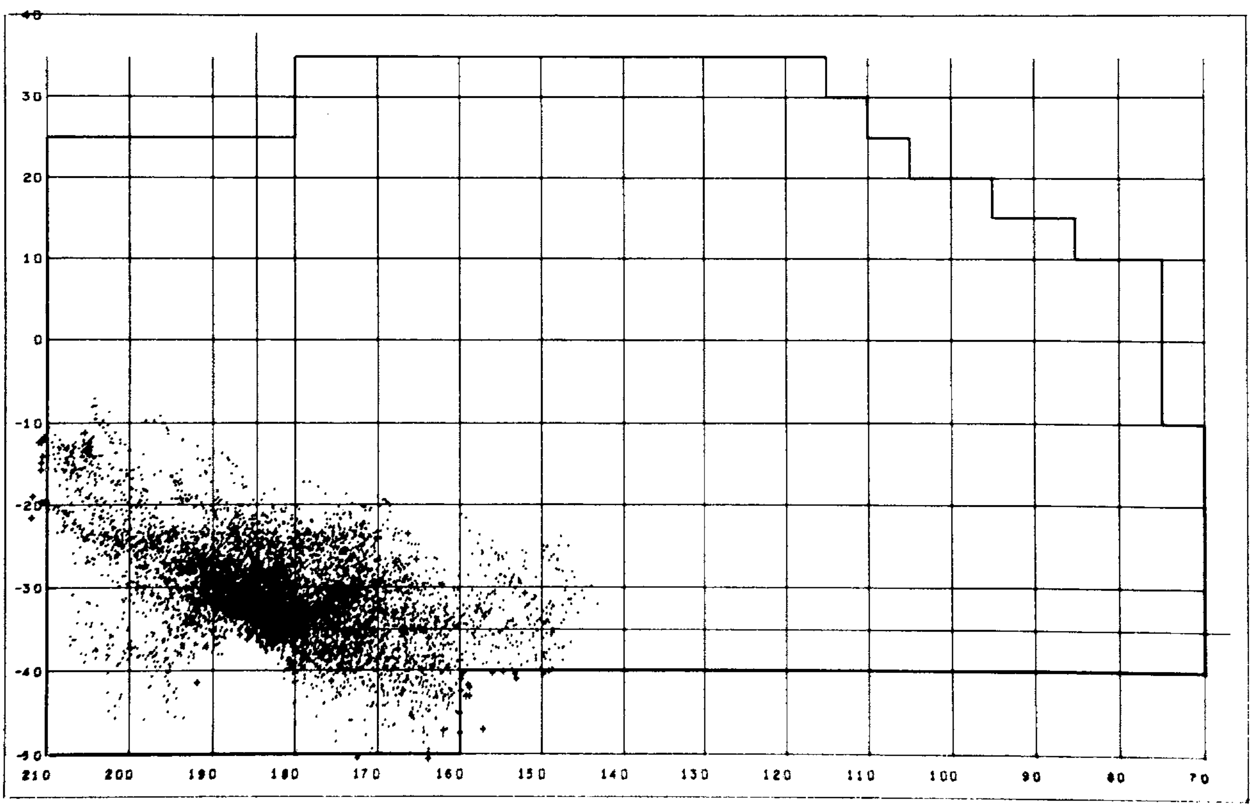
Christmas (Line) twelve months experiment 12



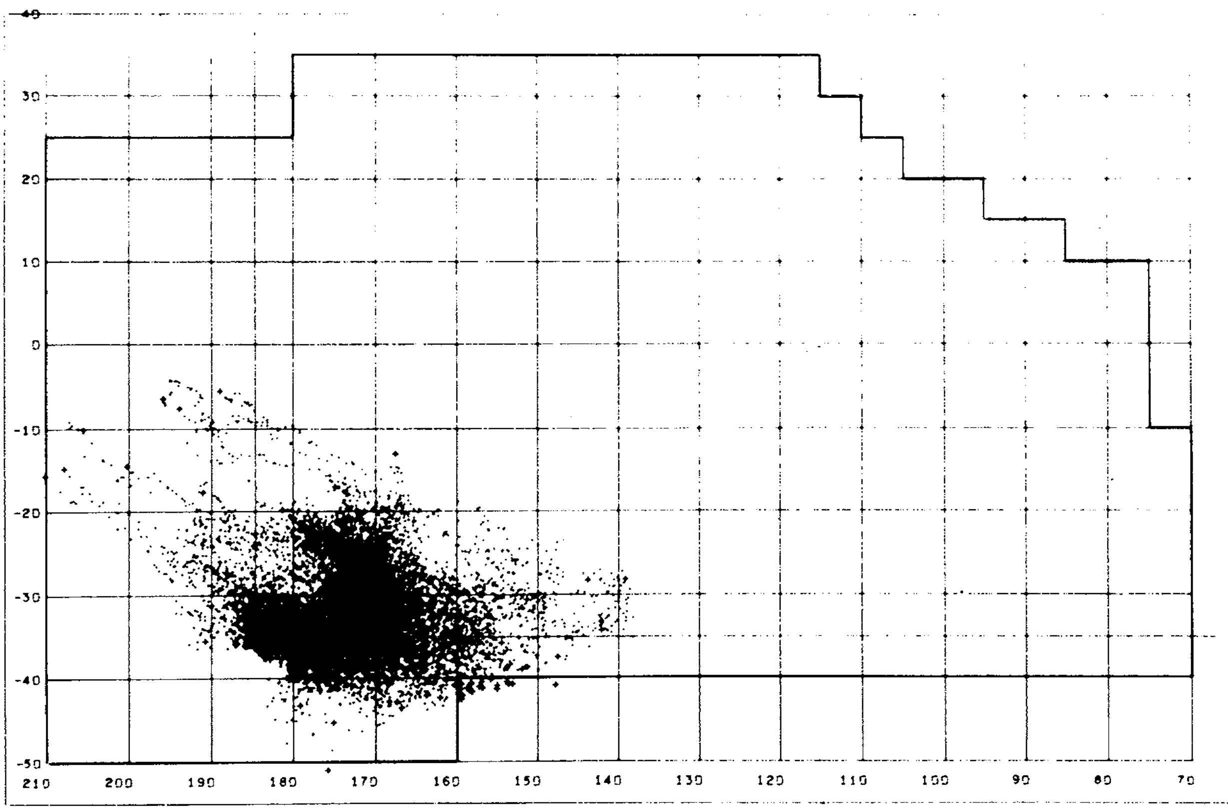
Christmas (Line) north wind shift experiment 86



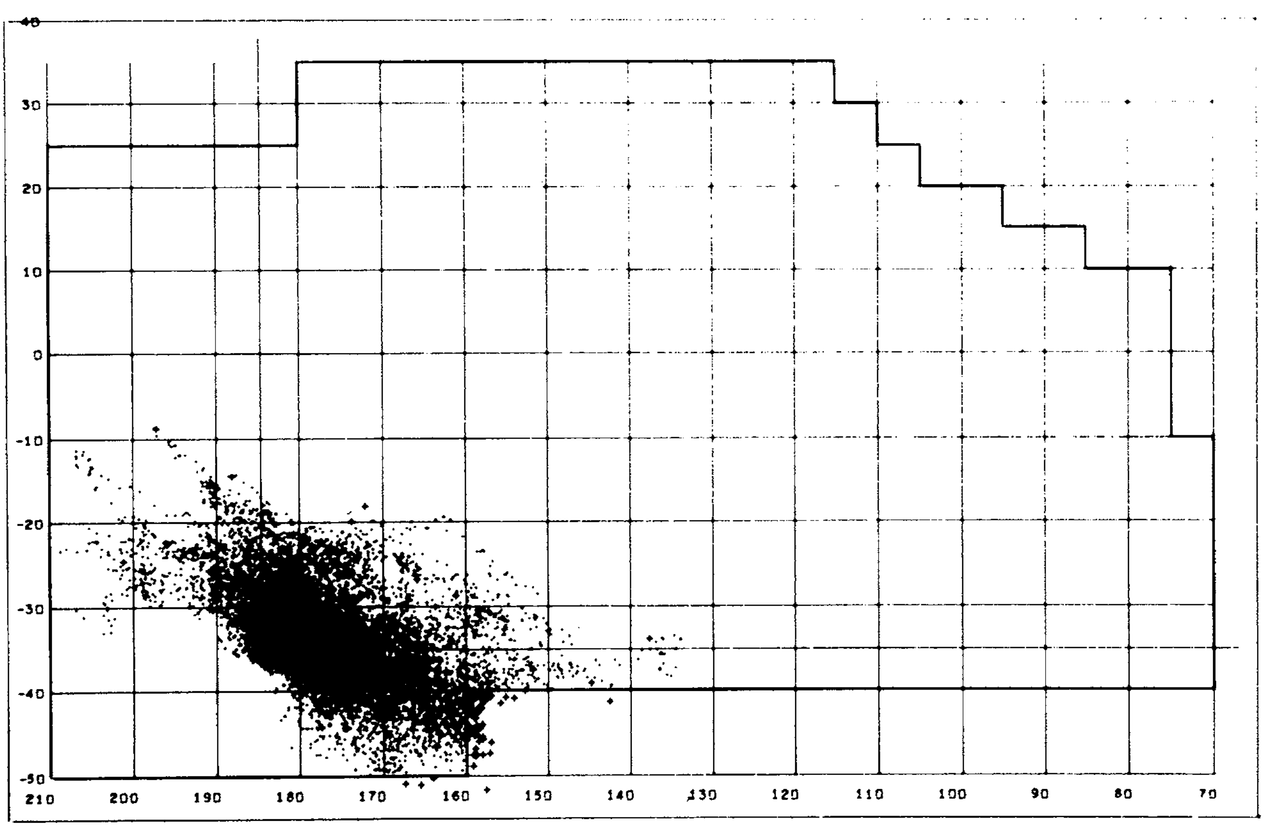
Christmas (Line) south wind shift experiment 95



Mokohinau (New Zealand) twelve months experiment 13

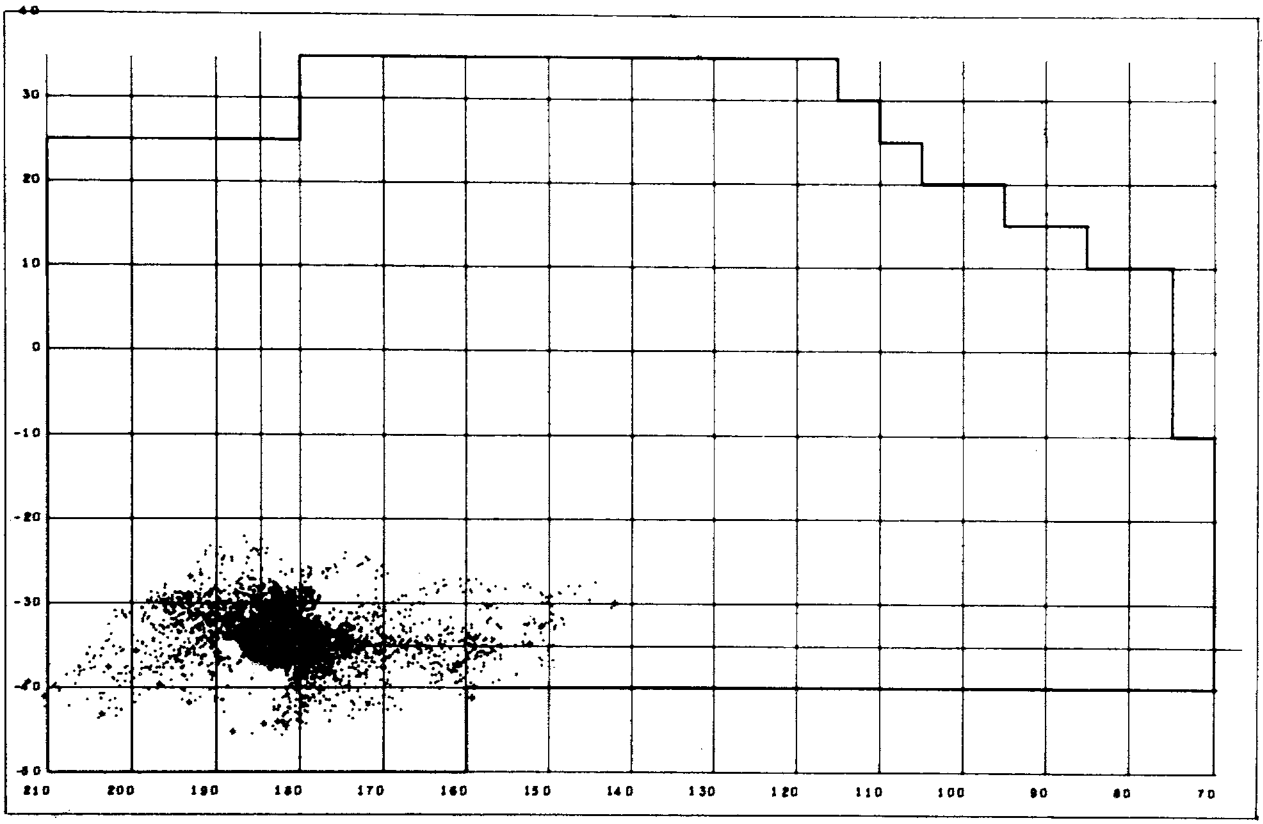


Mokohinau (New Zealand) July experiment 51

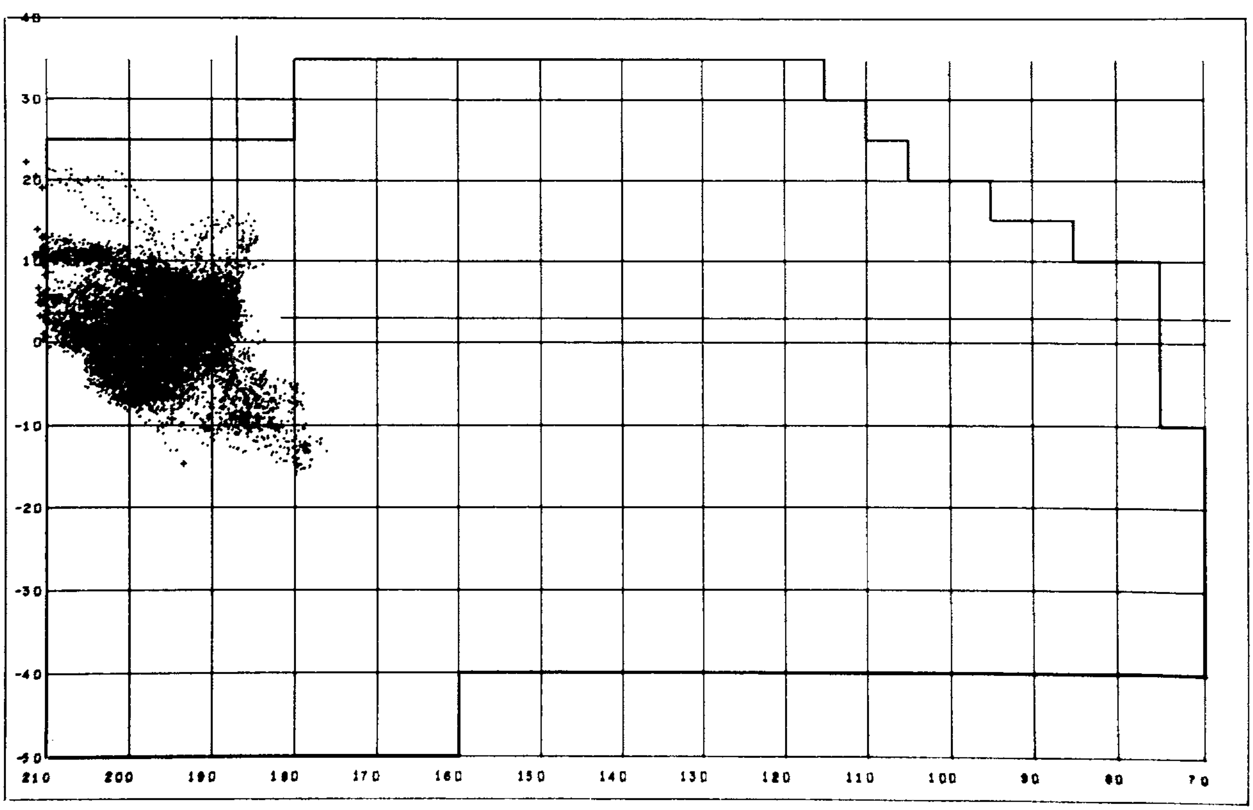


Mokohinau (New Zealand) September experiment 53

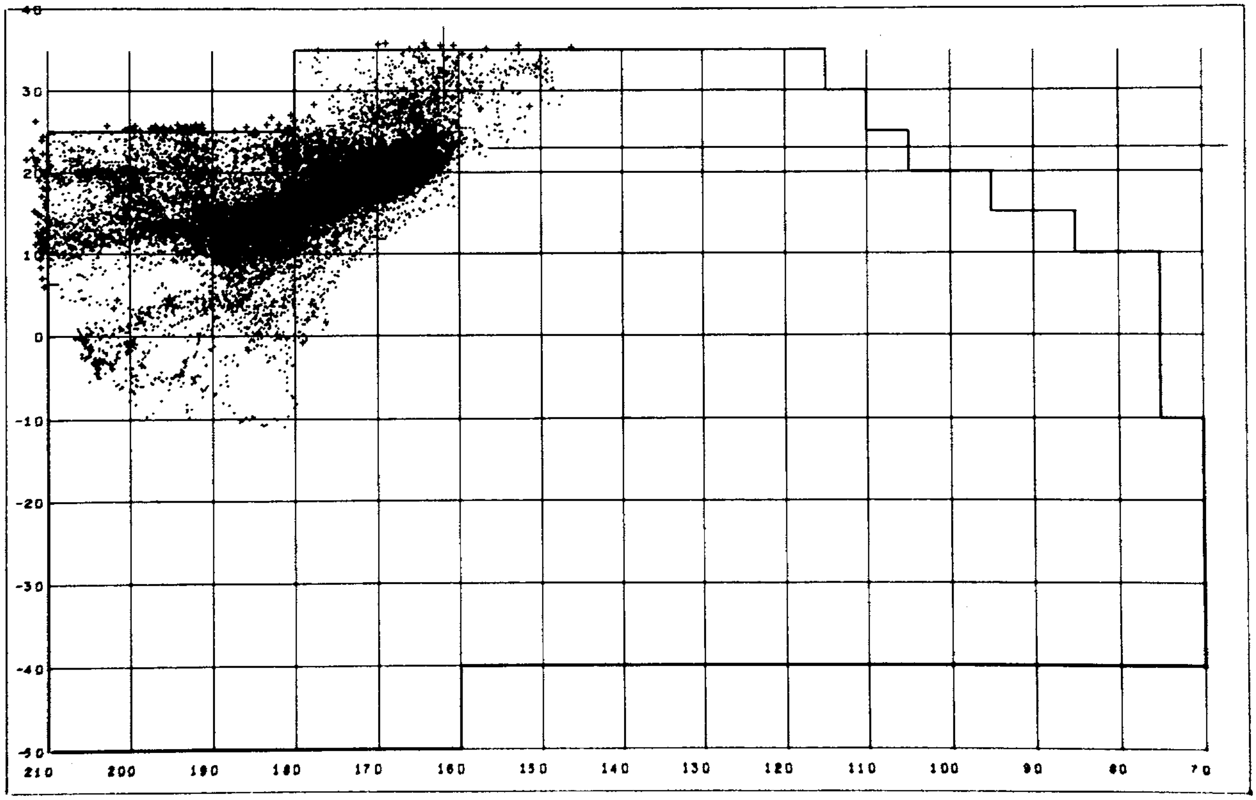
APPENDIX 2



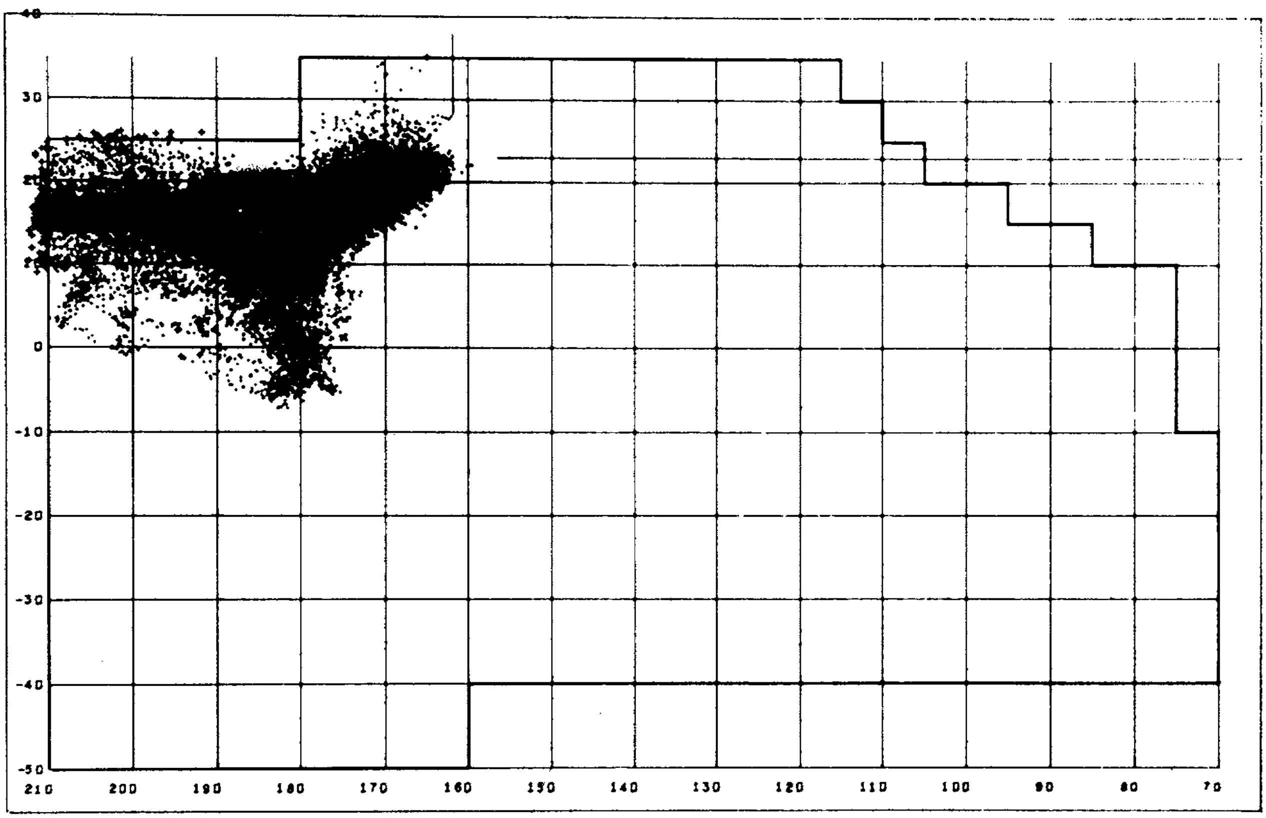
Mokohinau (New Zealand) reverse experiment 120



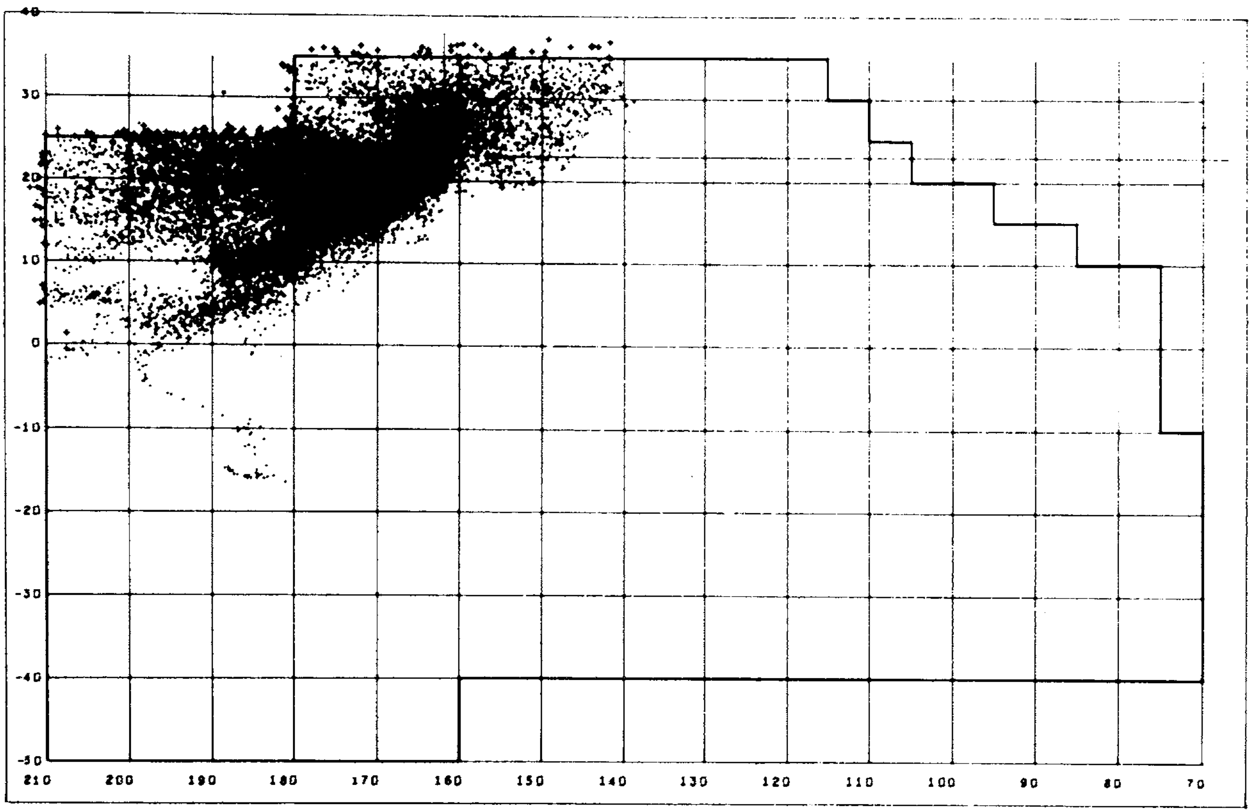
Butaritari (Gilberts) twelve months experiment 15



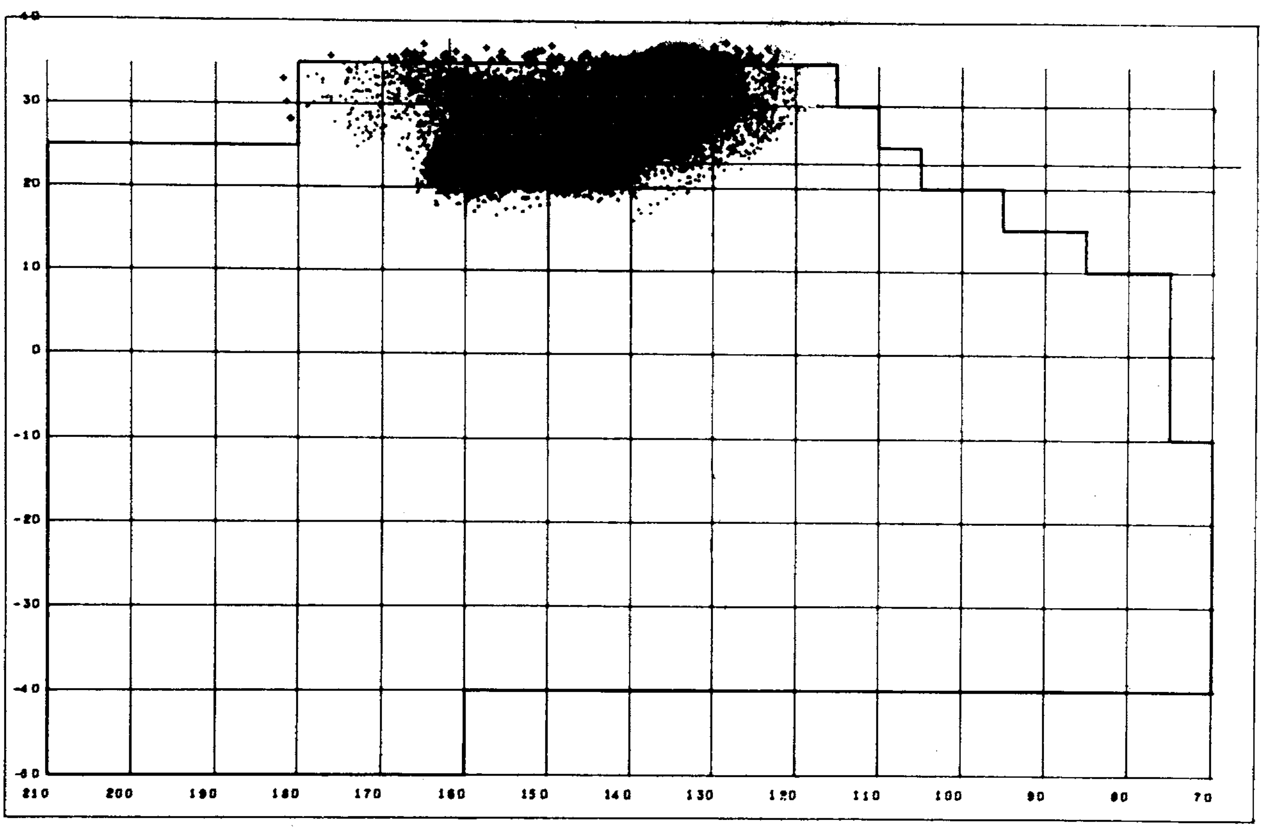
Nihoa (Hawaii) twelve months experiment 16



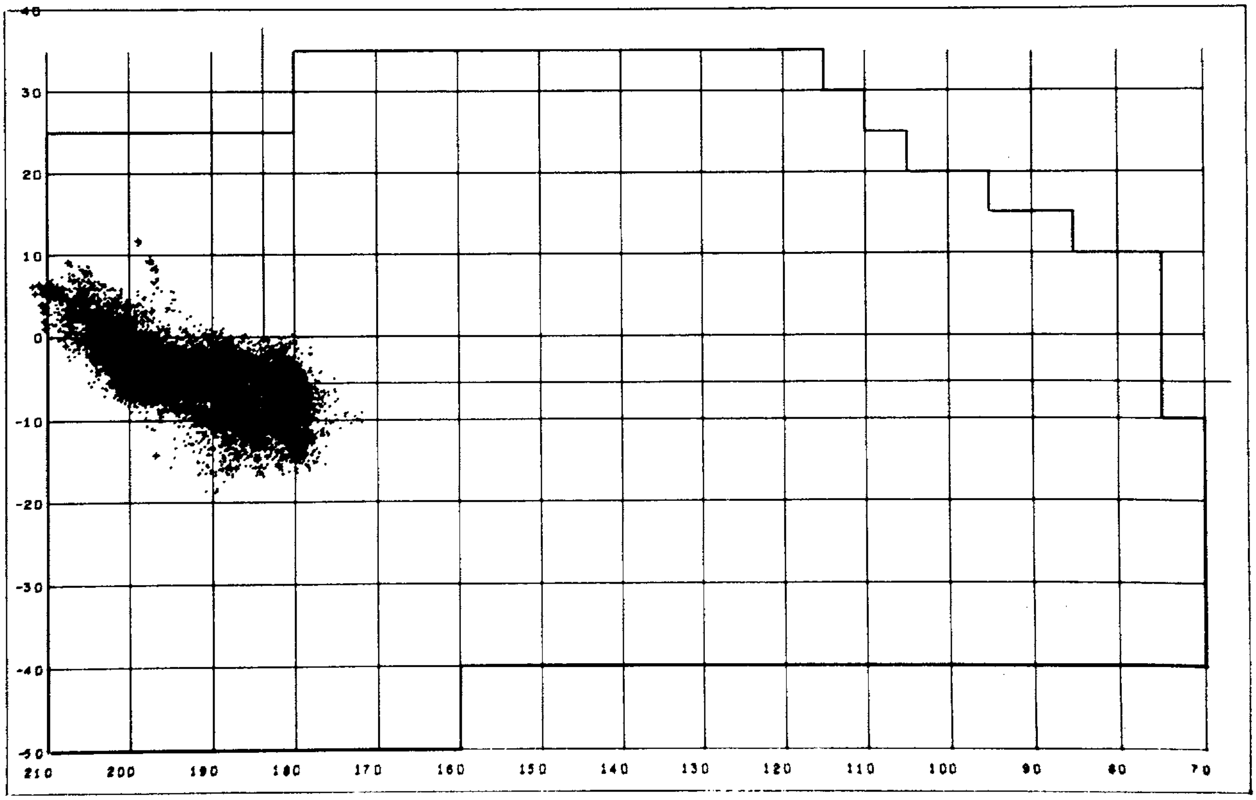
Nihoa (Hawaii) north wind shift experiment 85



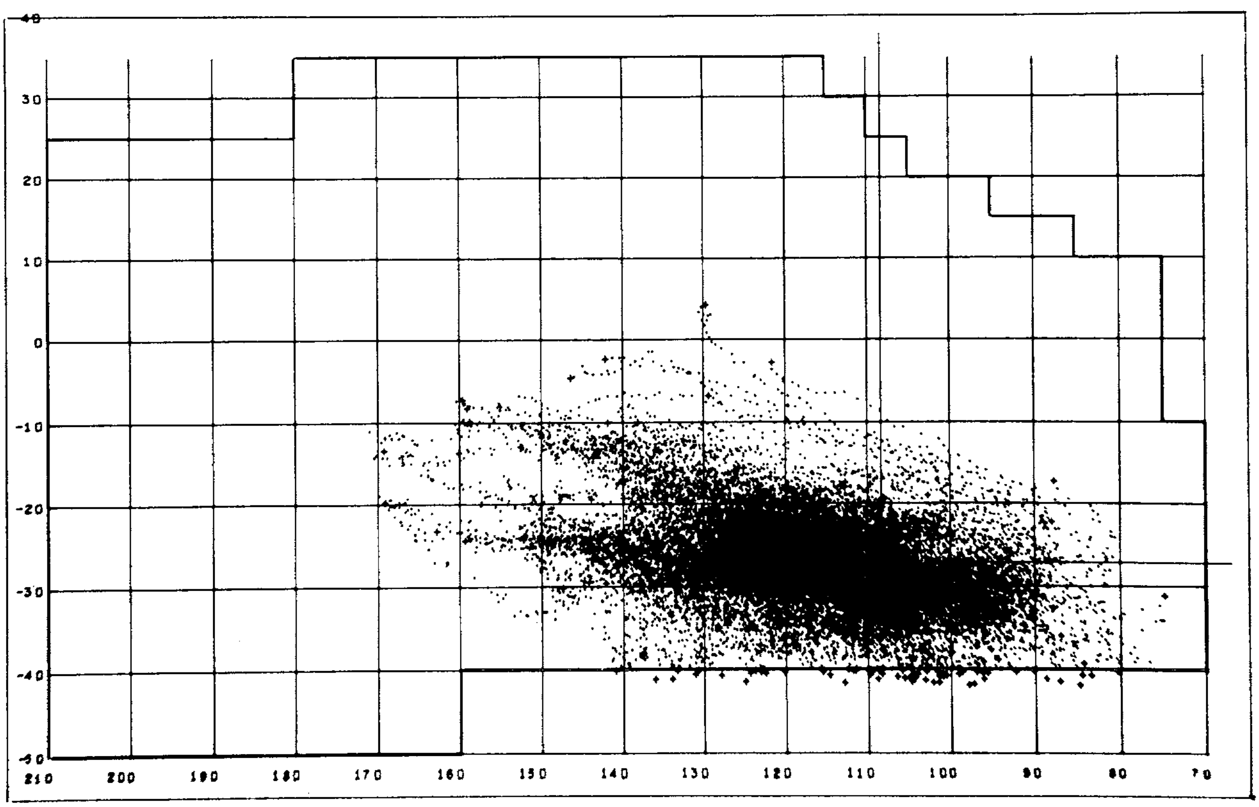
Nihoa (Hawaii) south wind shift experiment 94



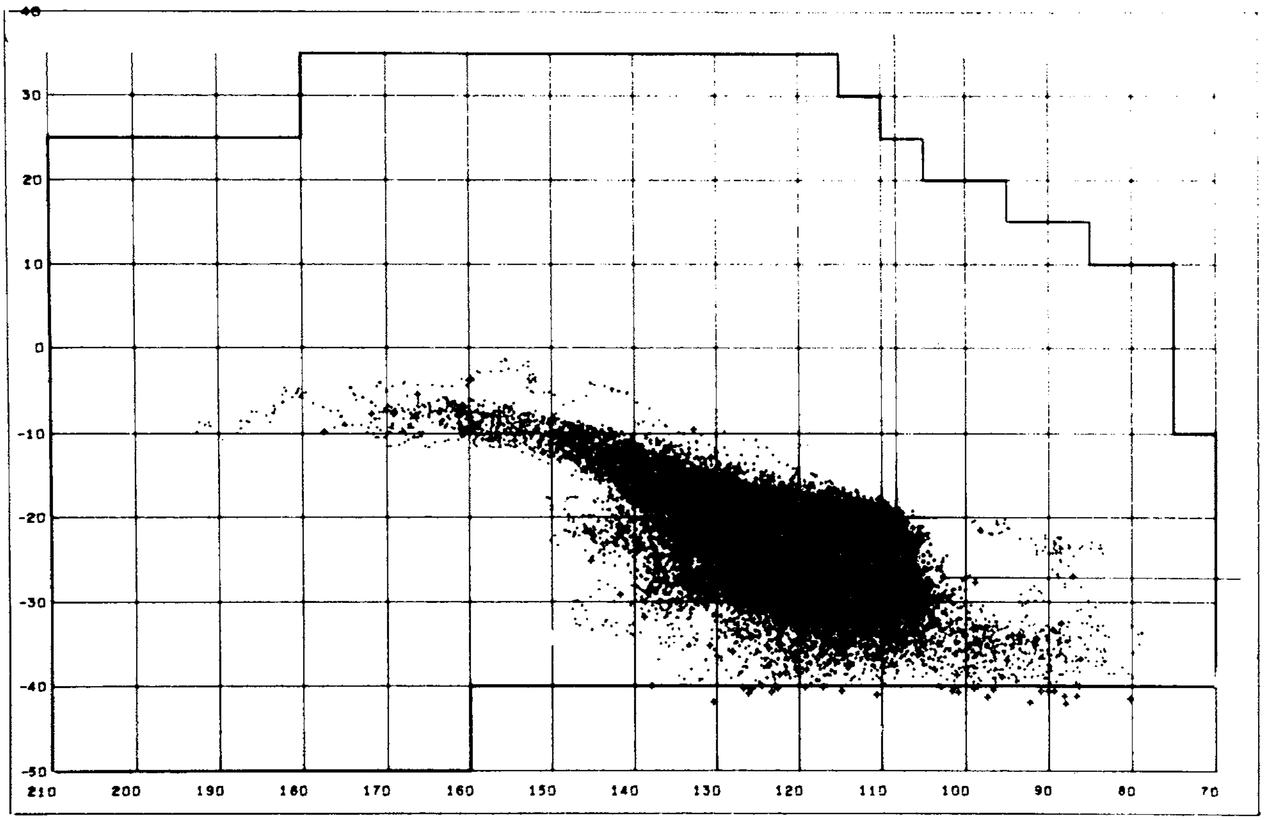
Nihoa (Hawaii) reverse experiment 123



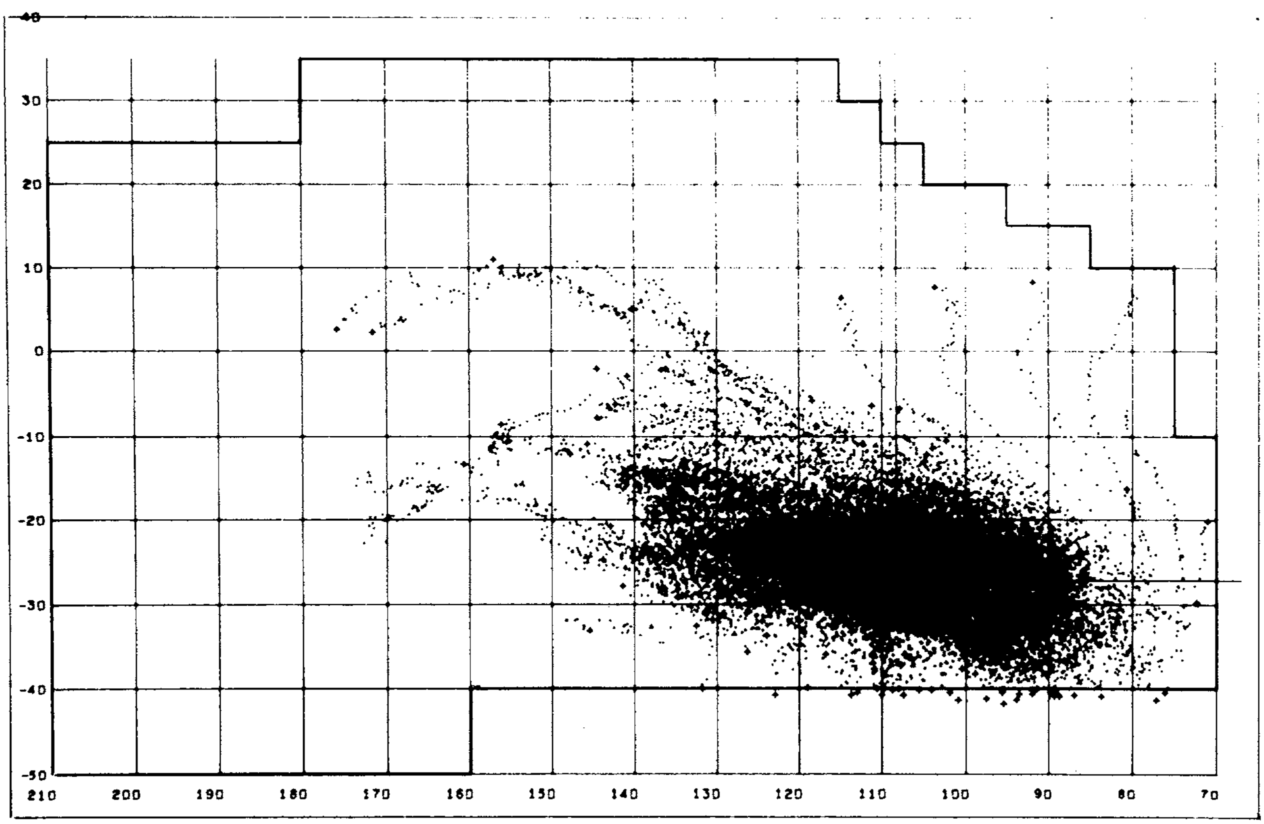
Nanumea (Ellices) twelve months experiment 18



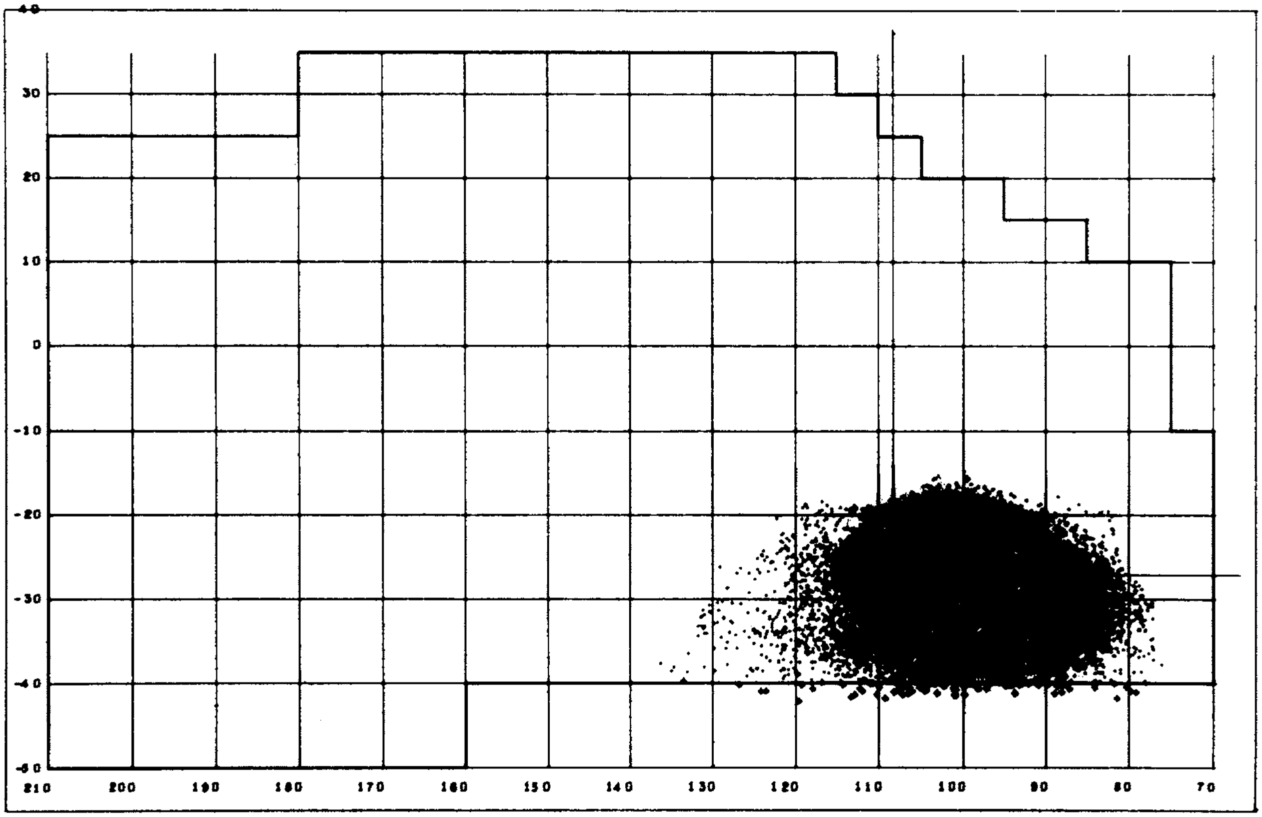
Easter twelve months experiment 19



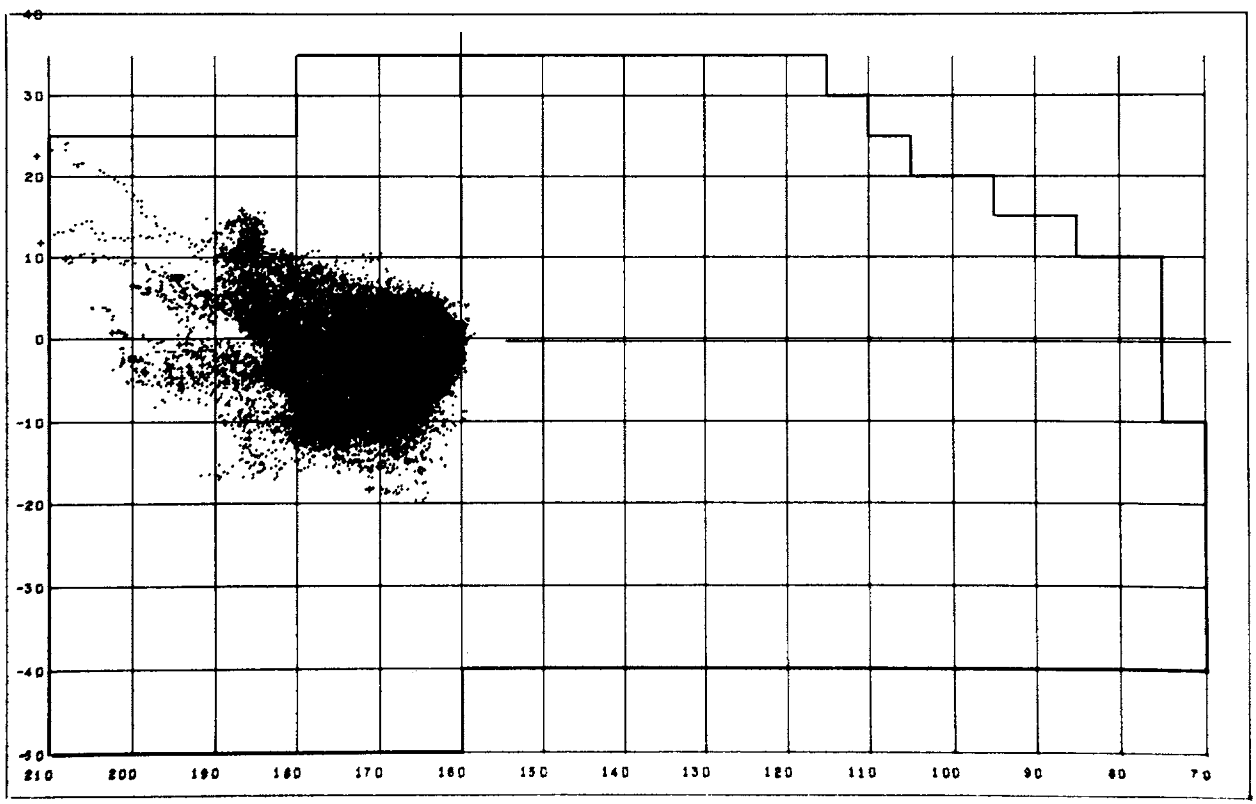
Easter March experiment 61



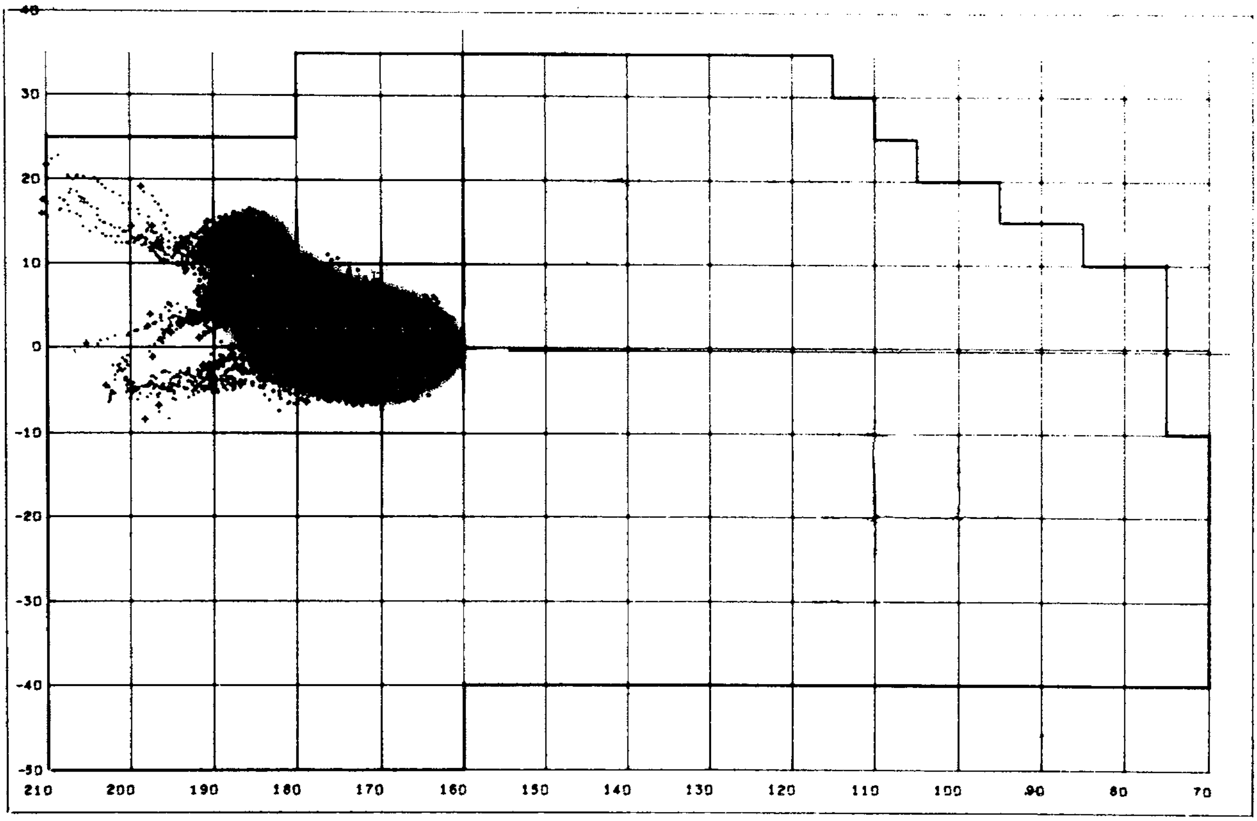
Easter August experiment 62



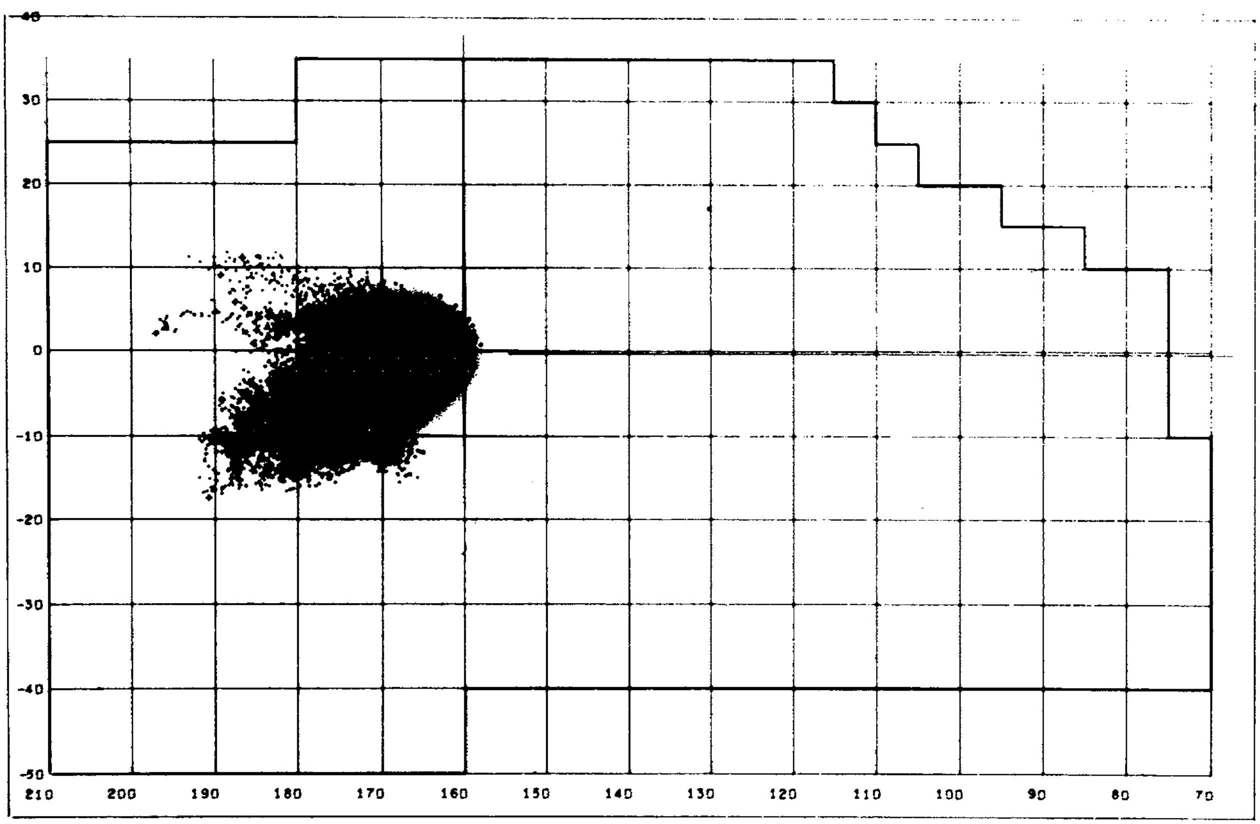
Easter reverse experiment 122



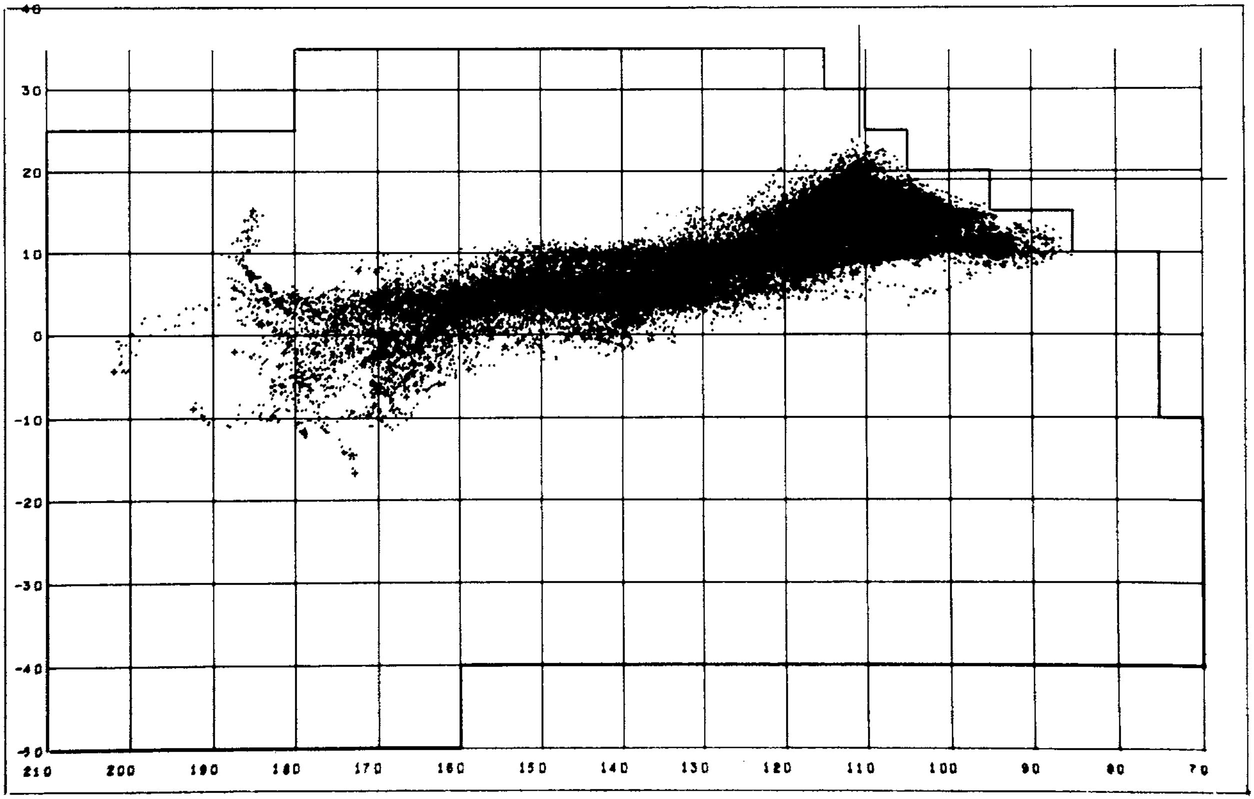
Jarvis (Line) twelve months experiment 20



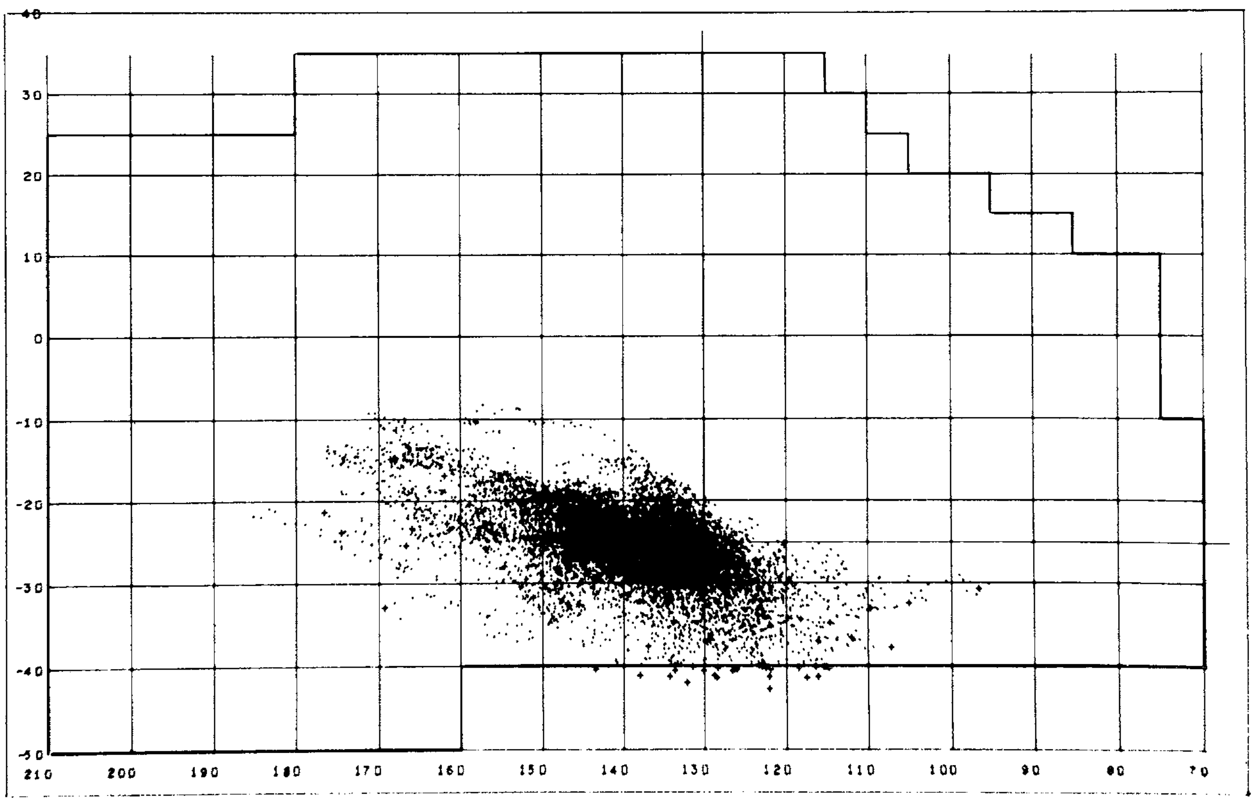
Jarvis (Line) July experiment 63



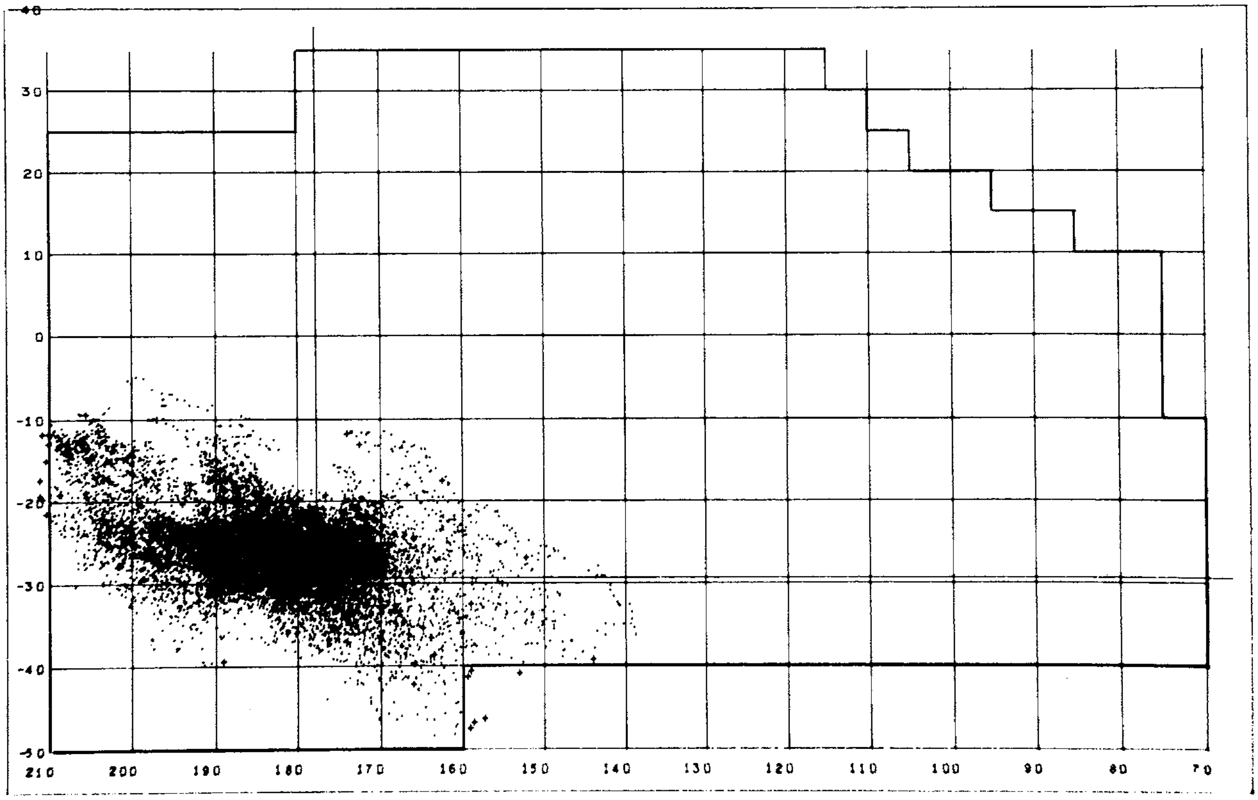
Jarvis (Line) October experiment 64



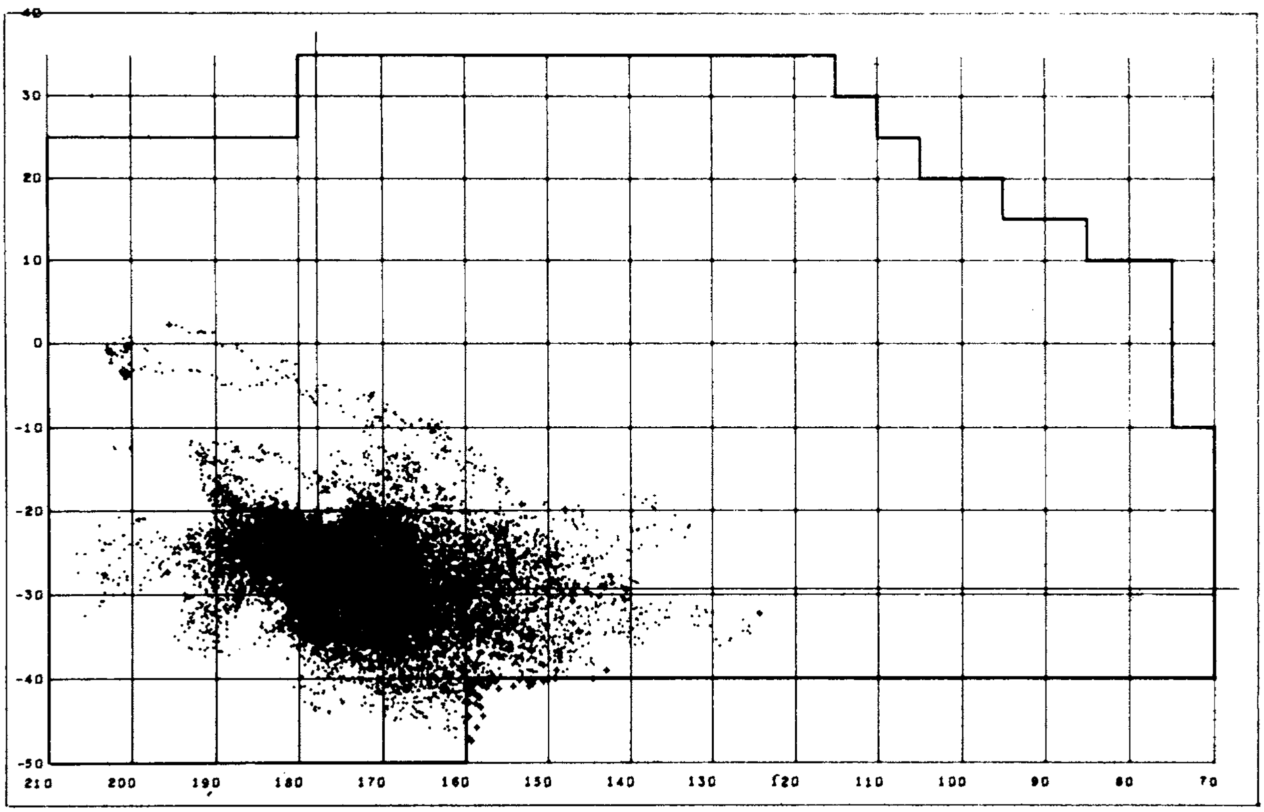
Socorro twelve months experiment 21



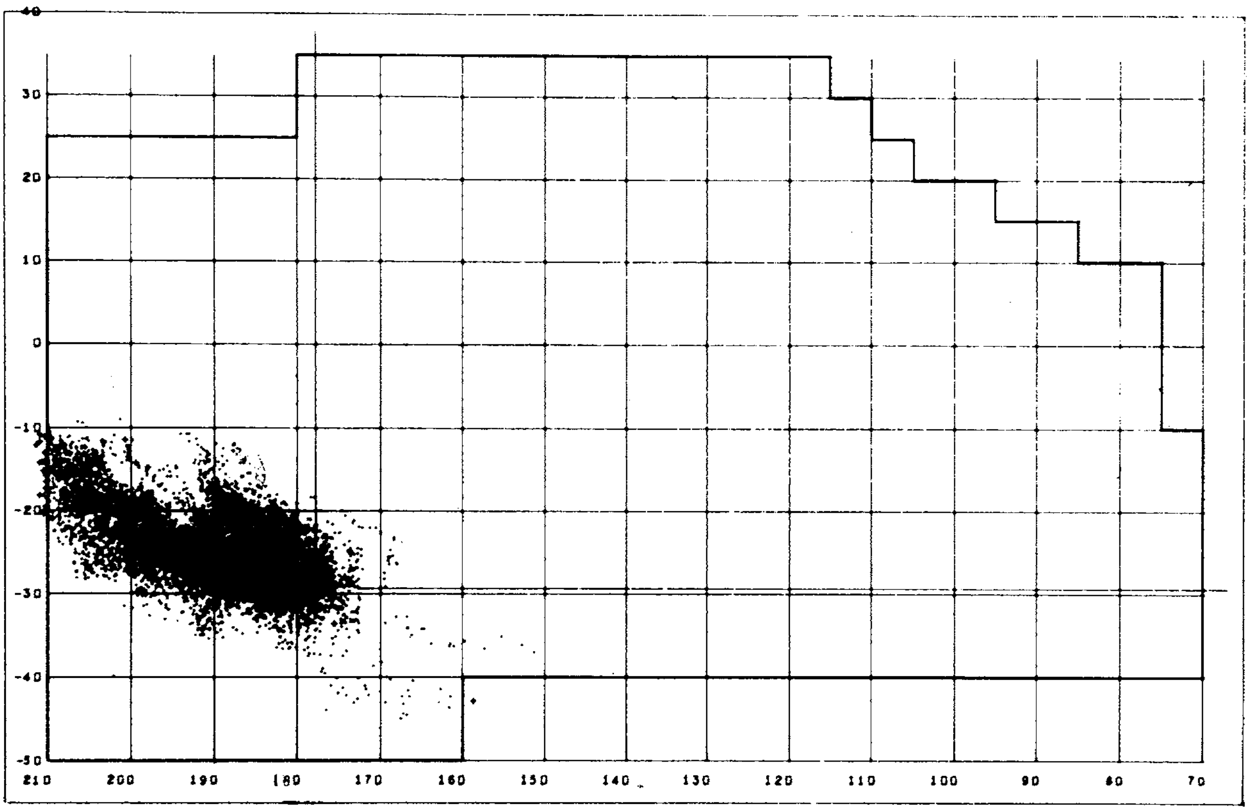
Pitcairn twelve months experiment 22



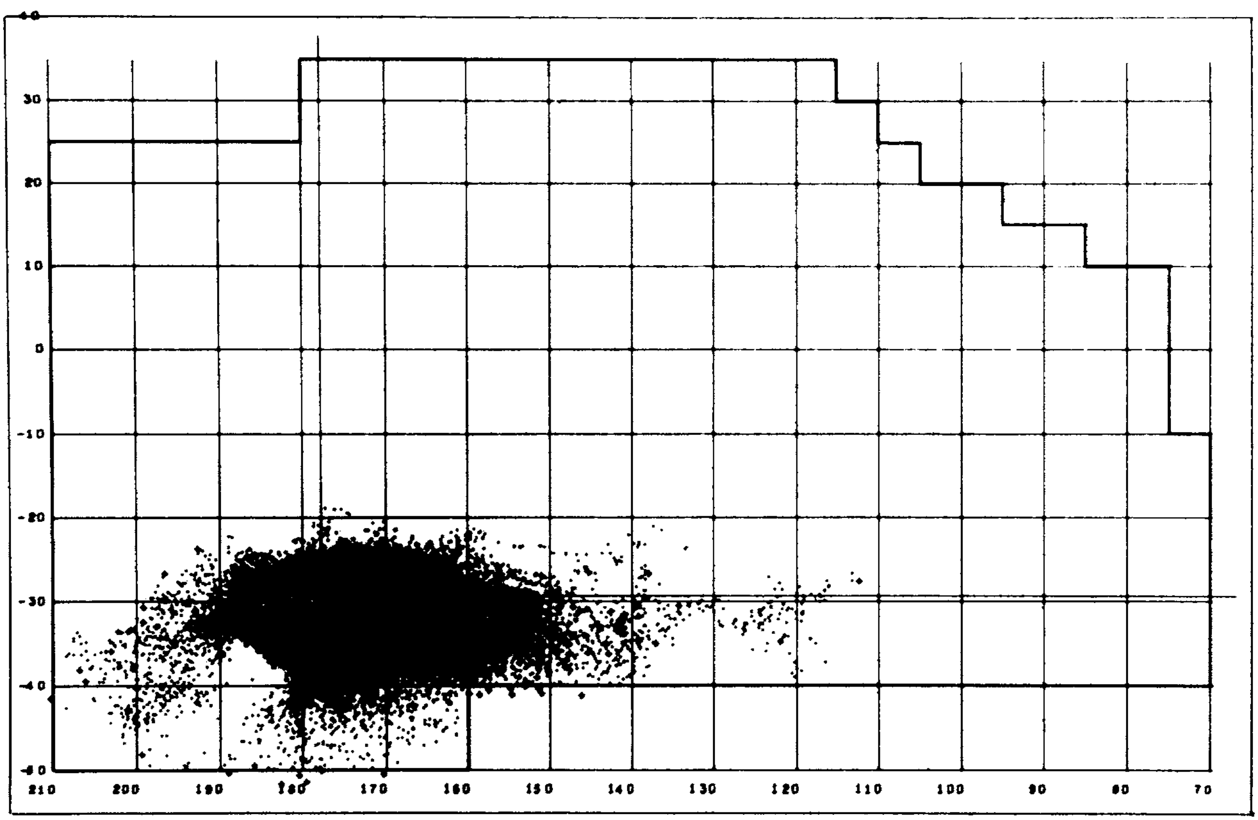
Raoul (Kermadecs) twelve months experiment 23



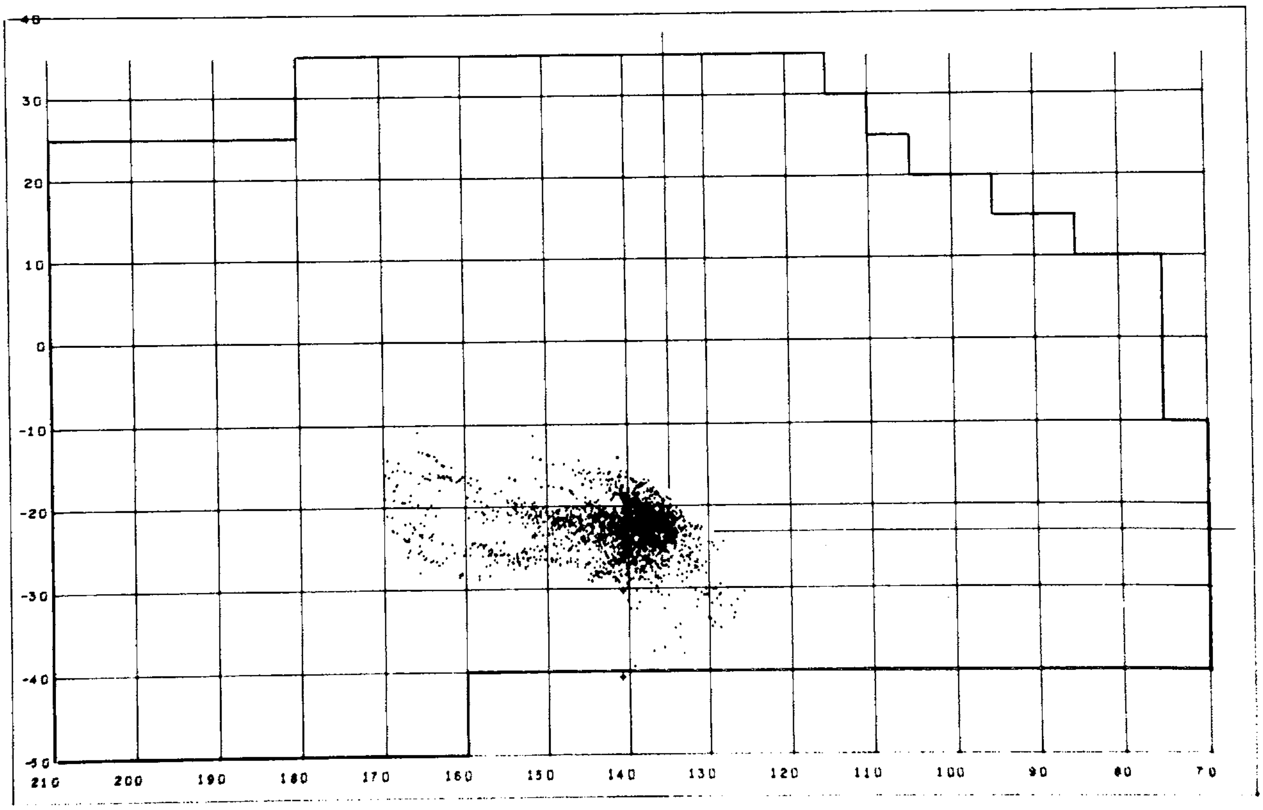
Raoul (Kermadecs) north wind shift experiment 91



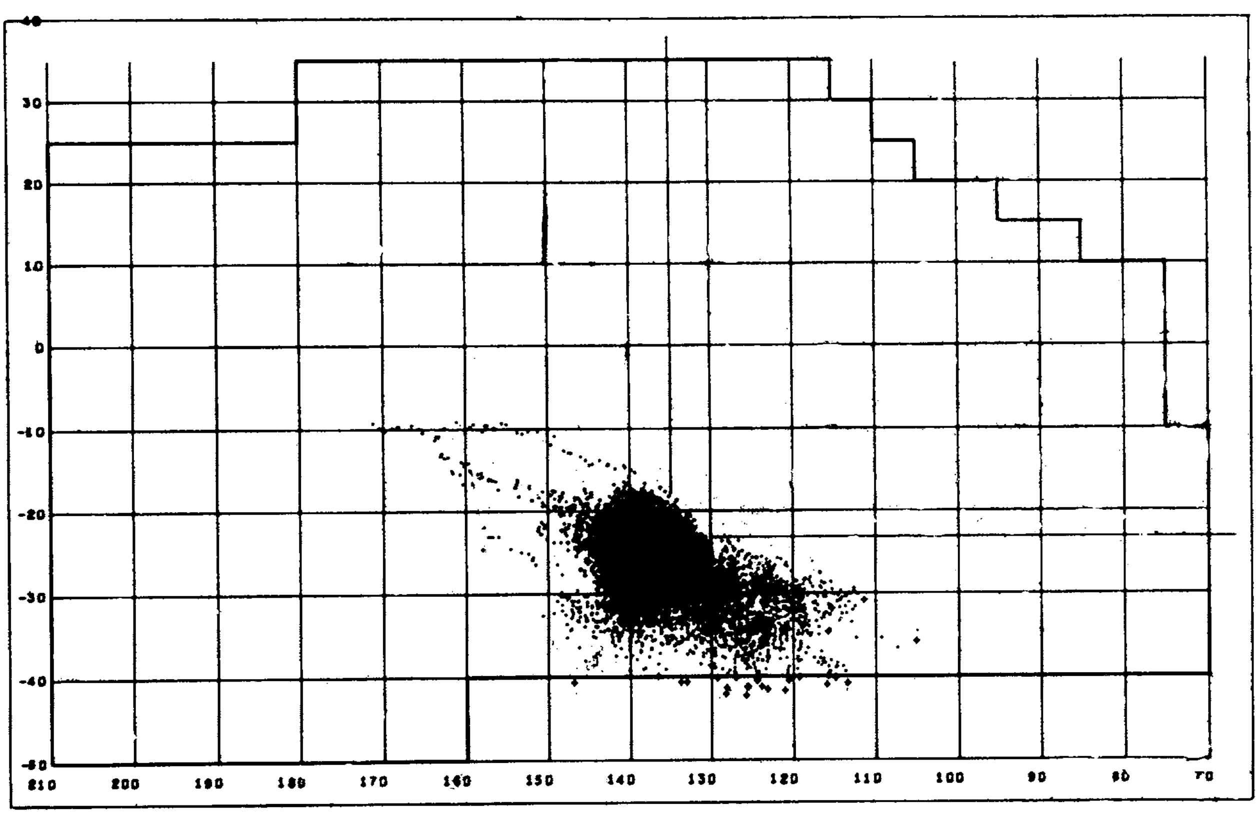
Raoul (Kermadecs) south wind shift experiment 100



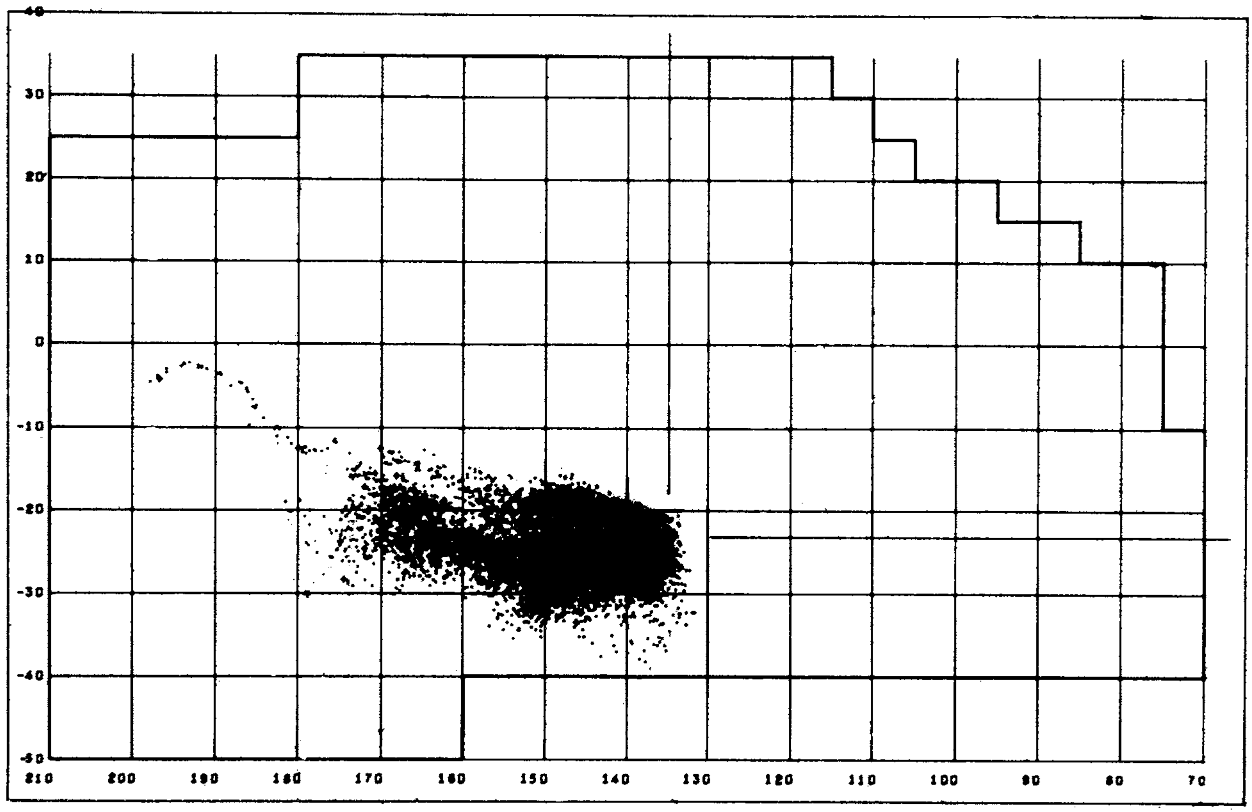
Raoul (Kermadecs) reverse experiment 121



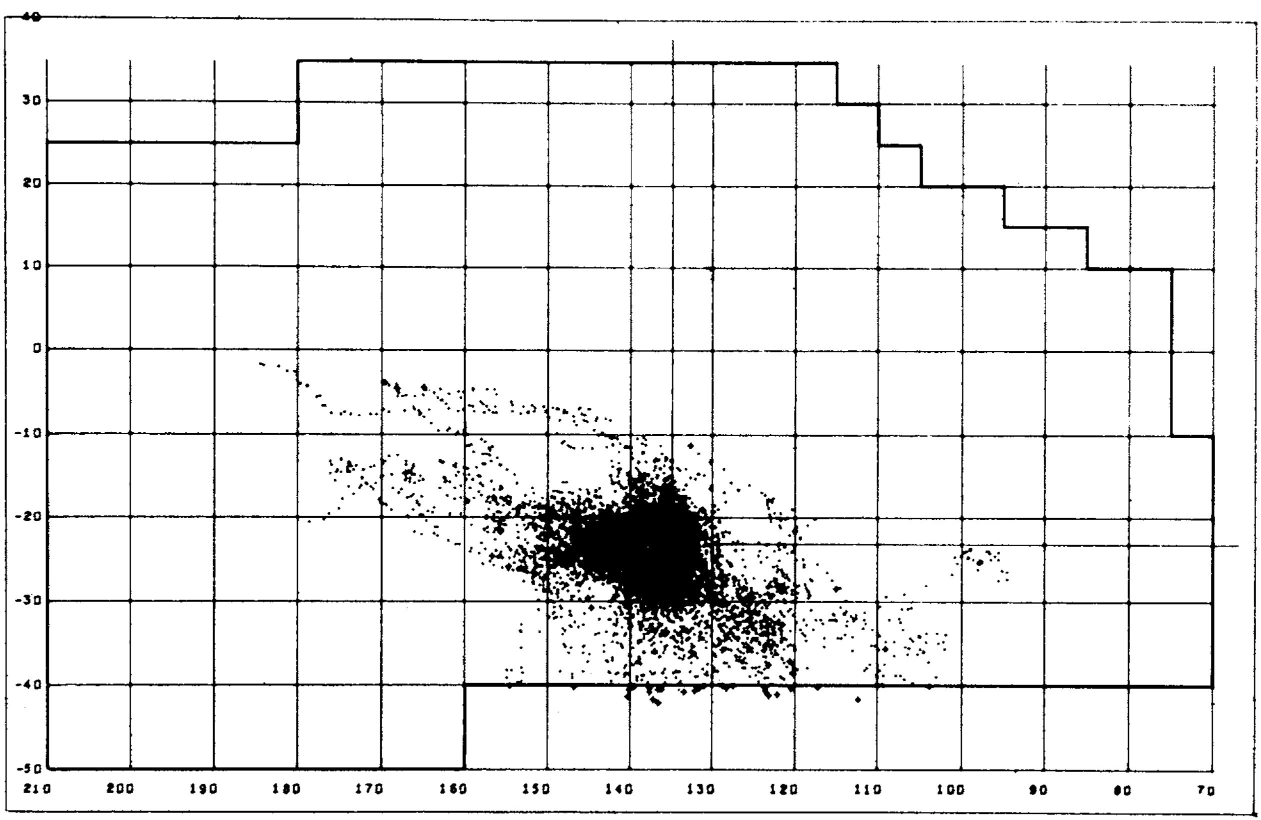
Mangareva (Gambier) twelve months experiment 24



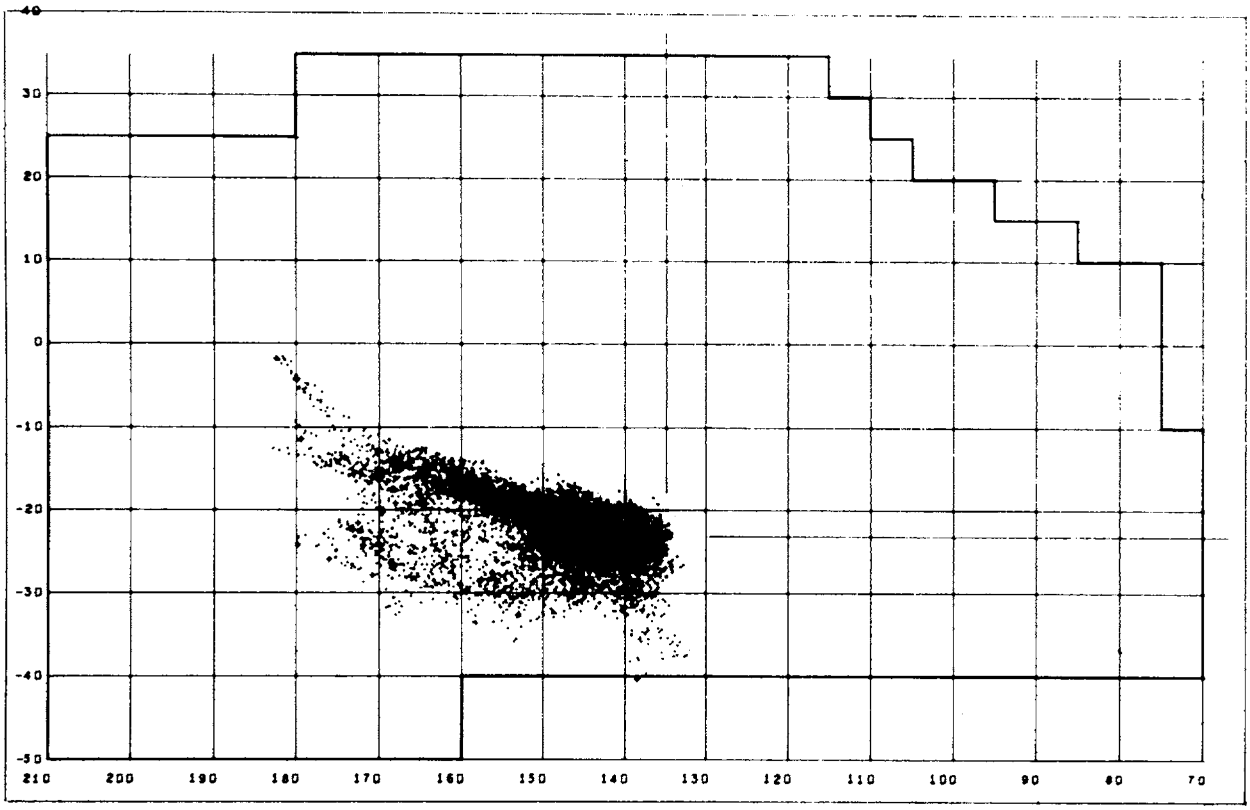
Mangareva (Gambier) July experiment 73



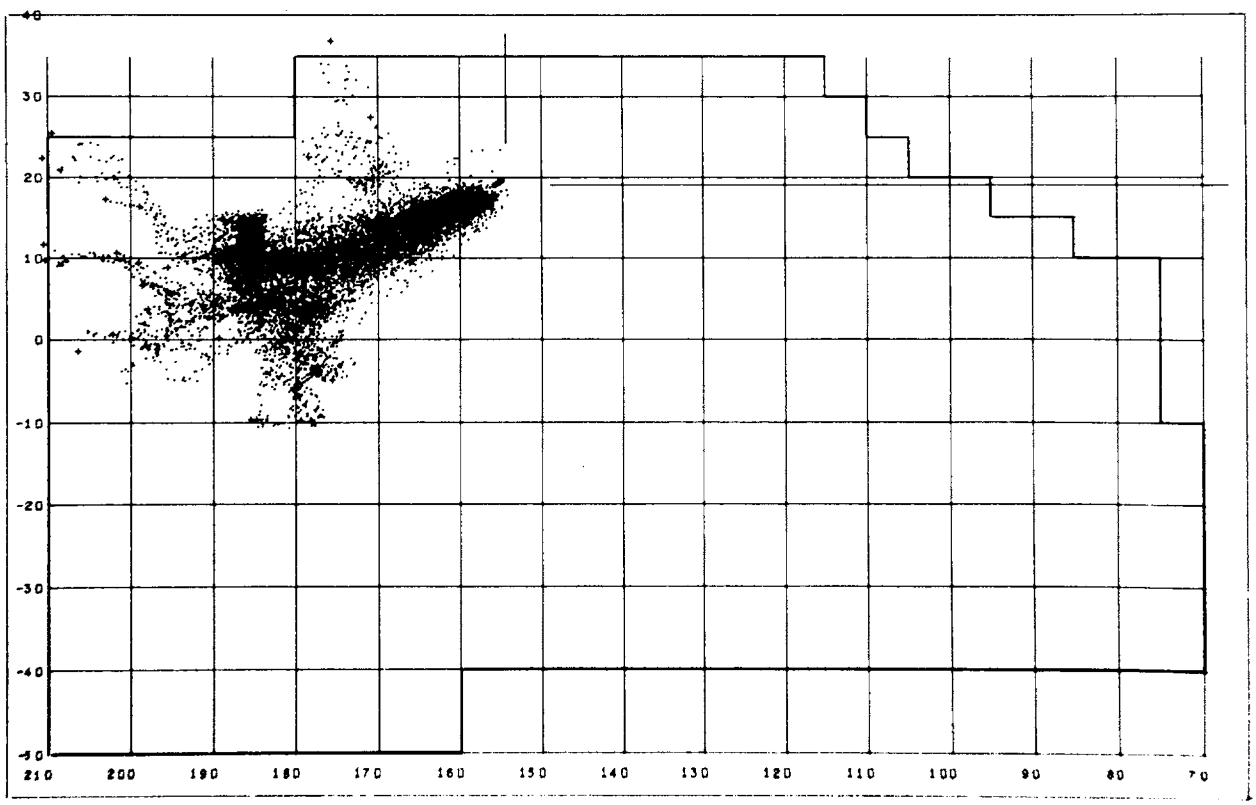
Mangareva (Gambier) December experiment 76



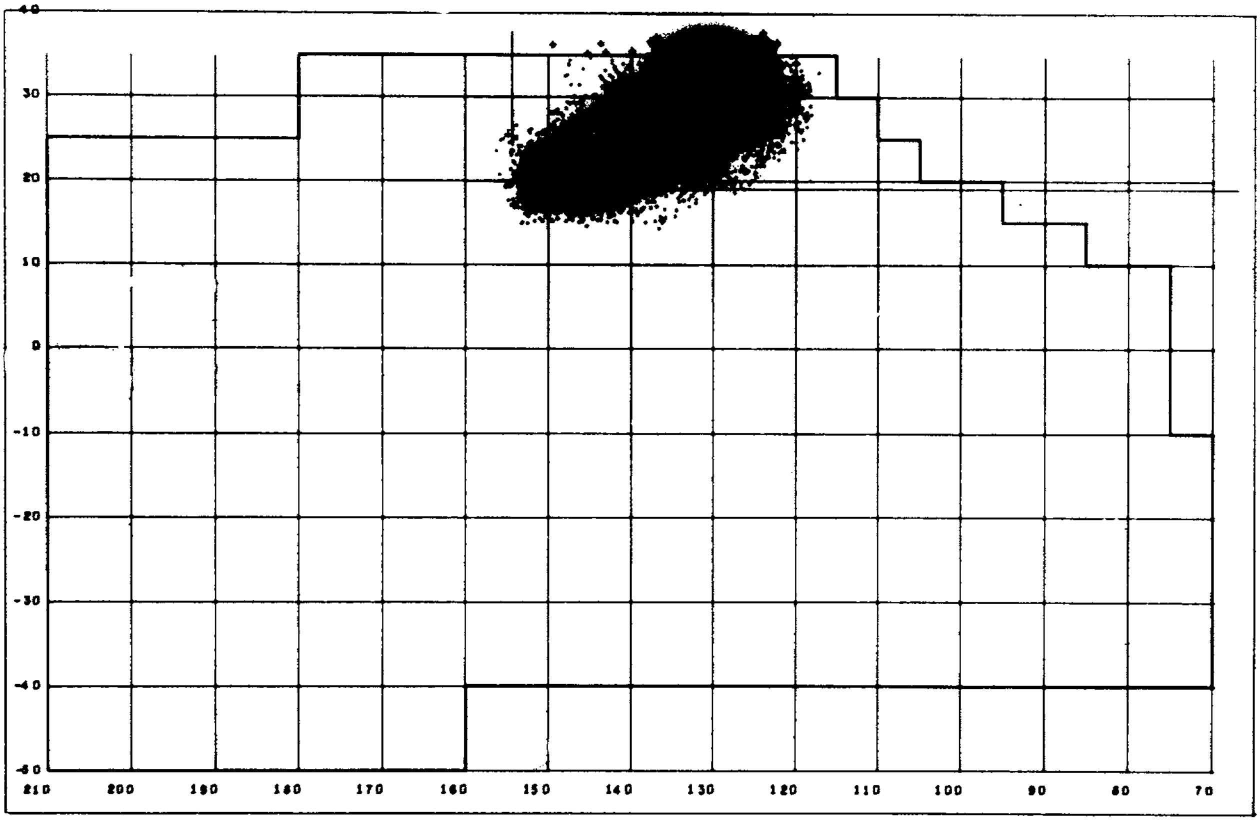
Mangareva (Gambier) north wind shift experiment 90



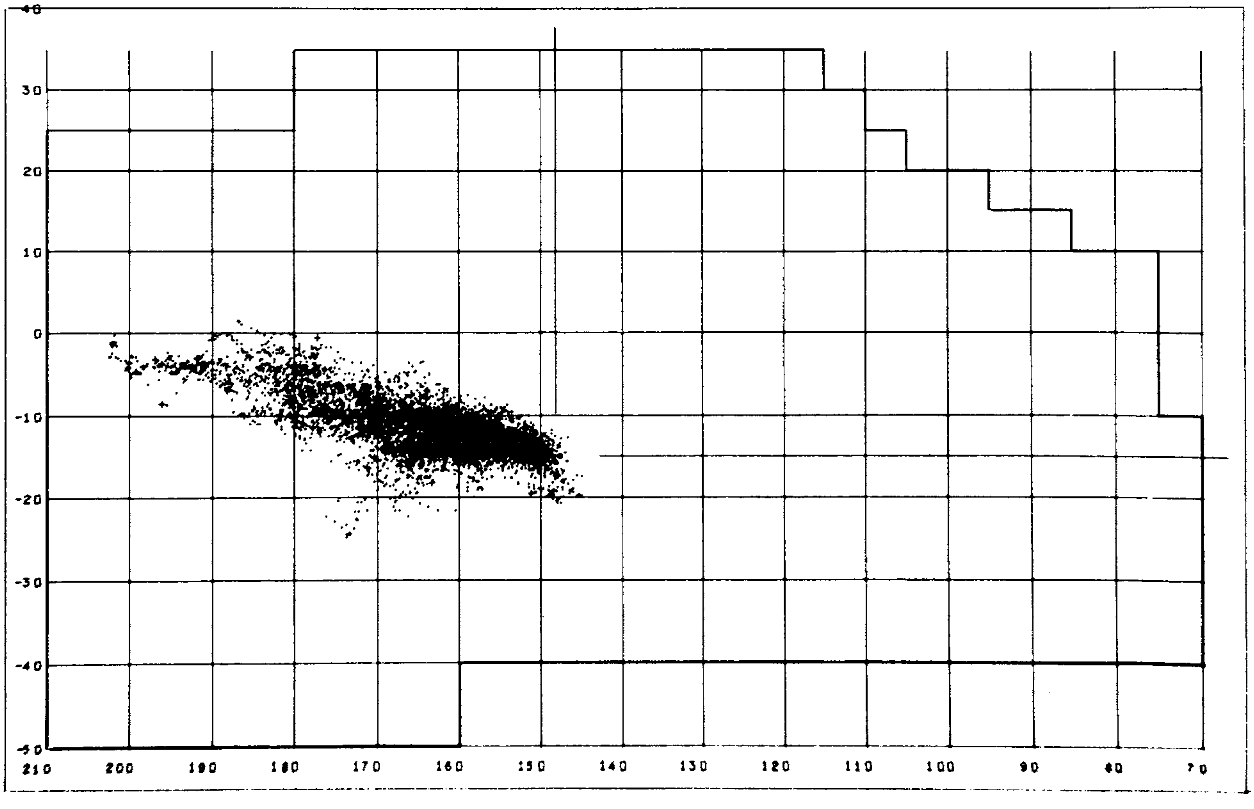
Mangareva (Gambier) south wind shift experiment 99



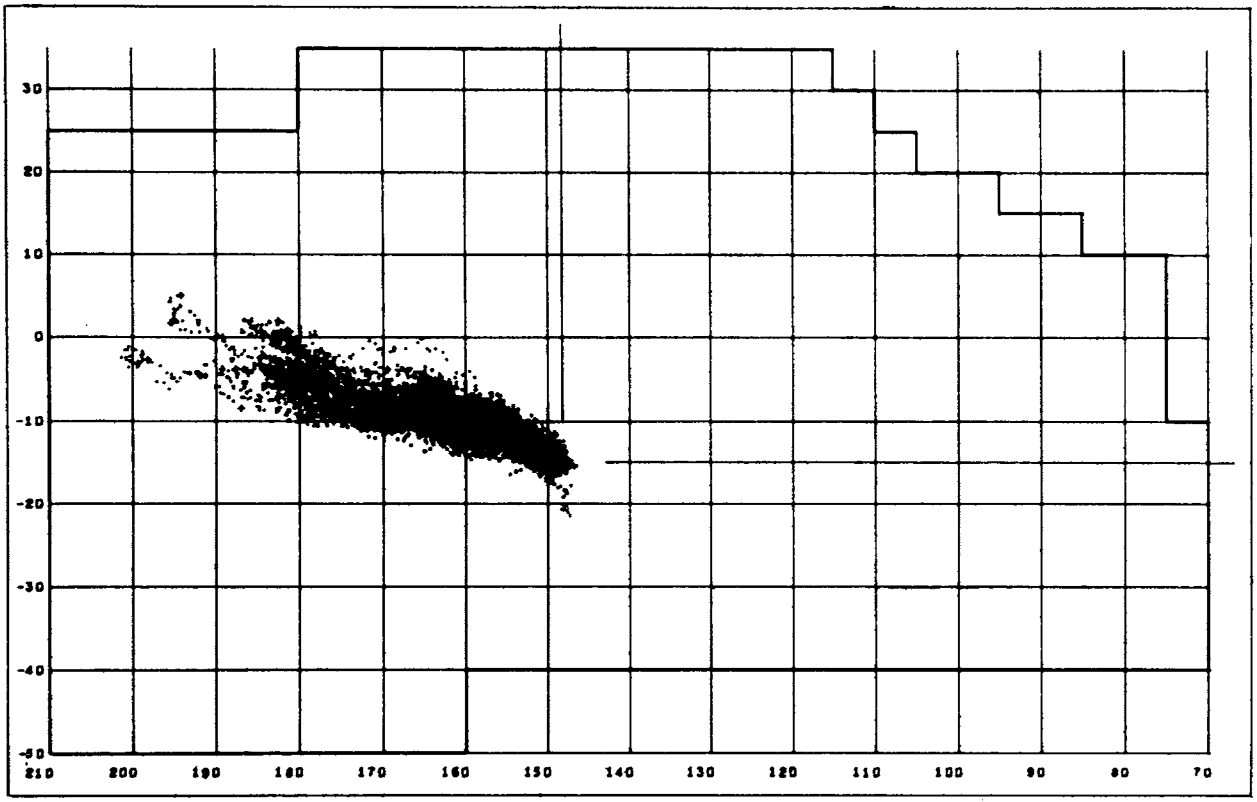
19n:154.30w (South of Hawaii) twelve months experiment 26



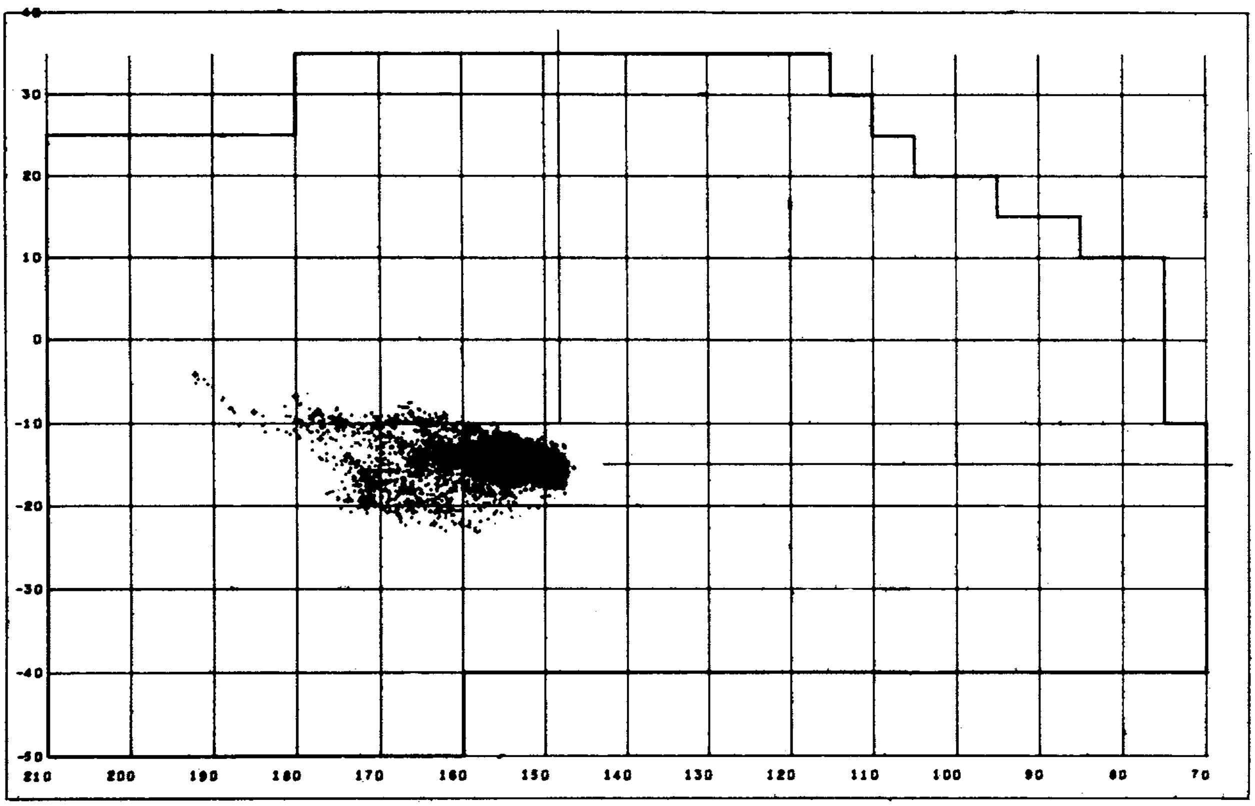
19n:154.30w (South of Hawaii) reverse experiment 128



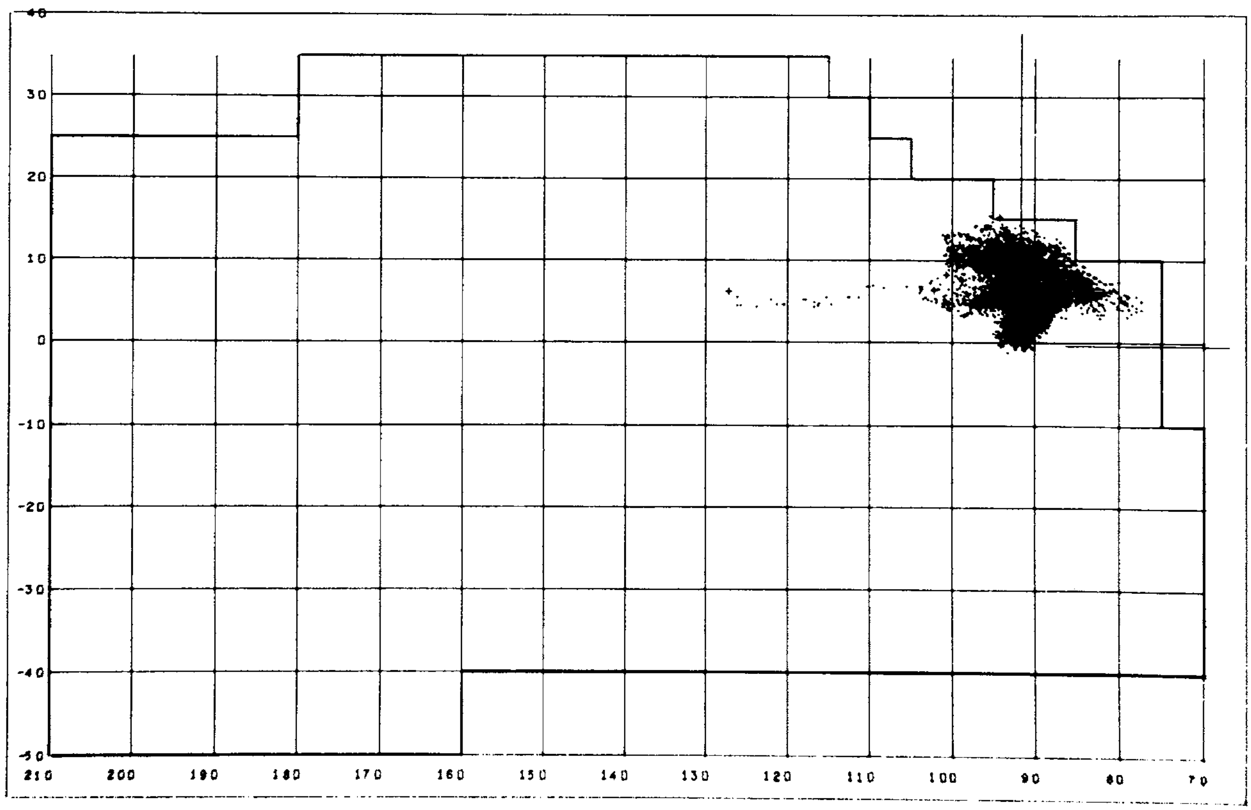
Tikehau (Tuamotus) twelve months experiment 27



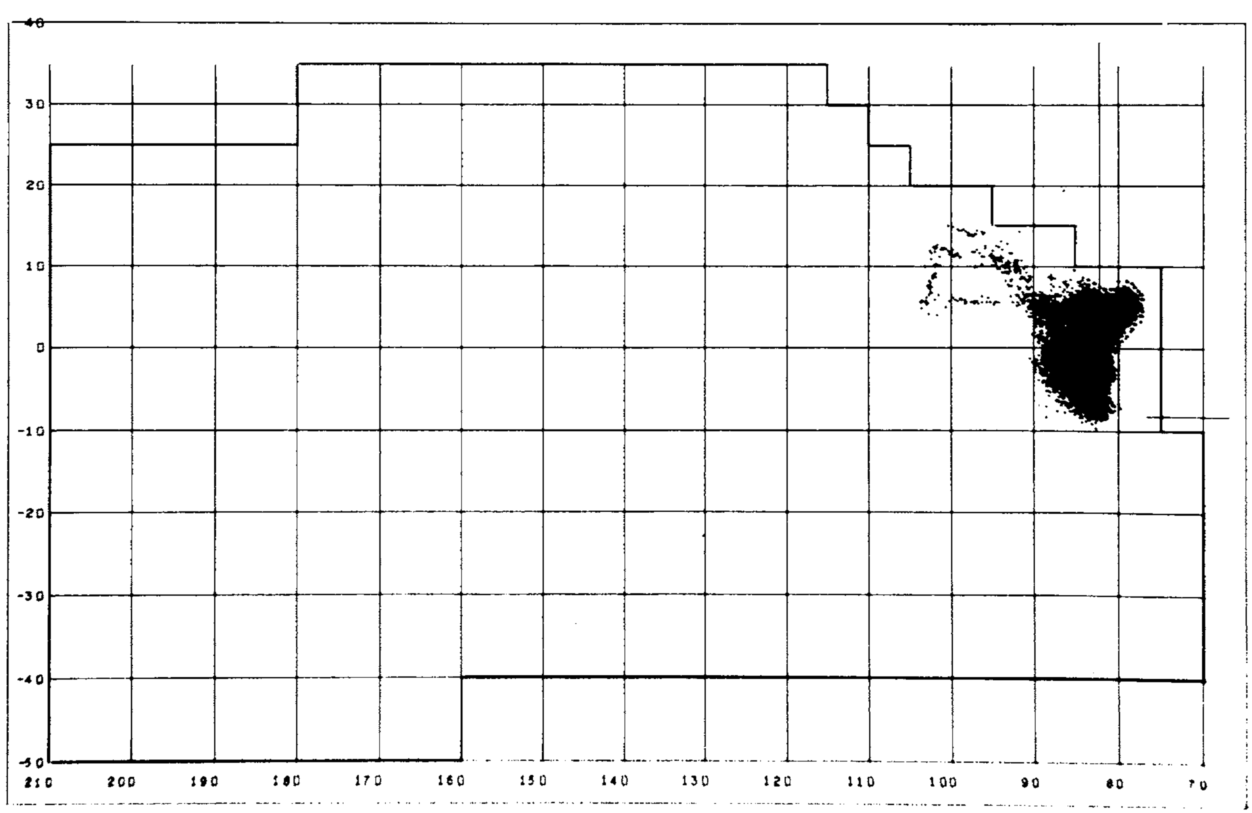
Tikehau (Tuamotus) May experiment 82



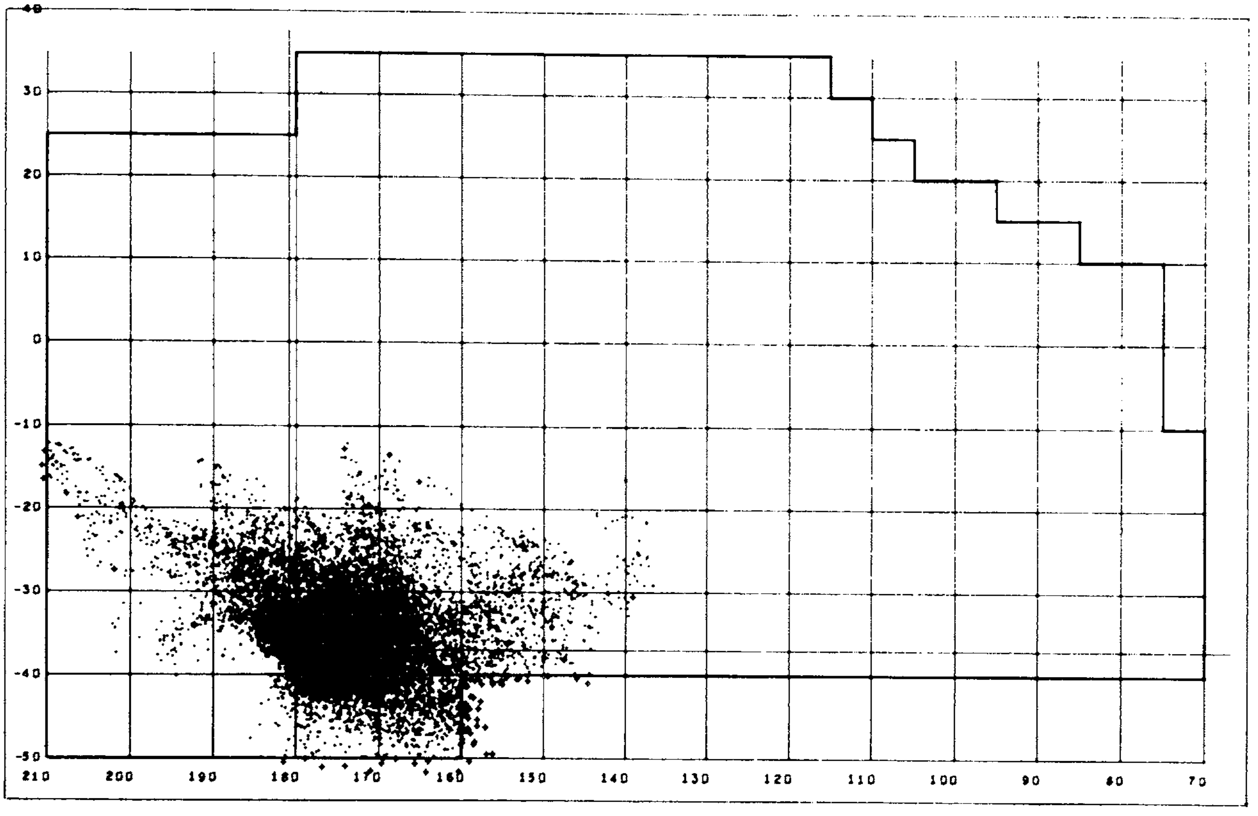
Tikehau (Tuamotus) February experiment 83



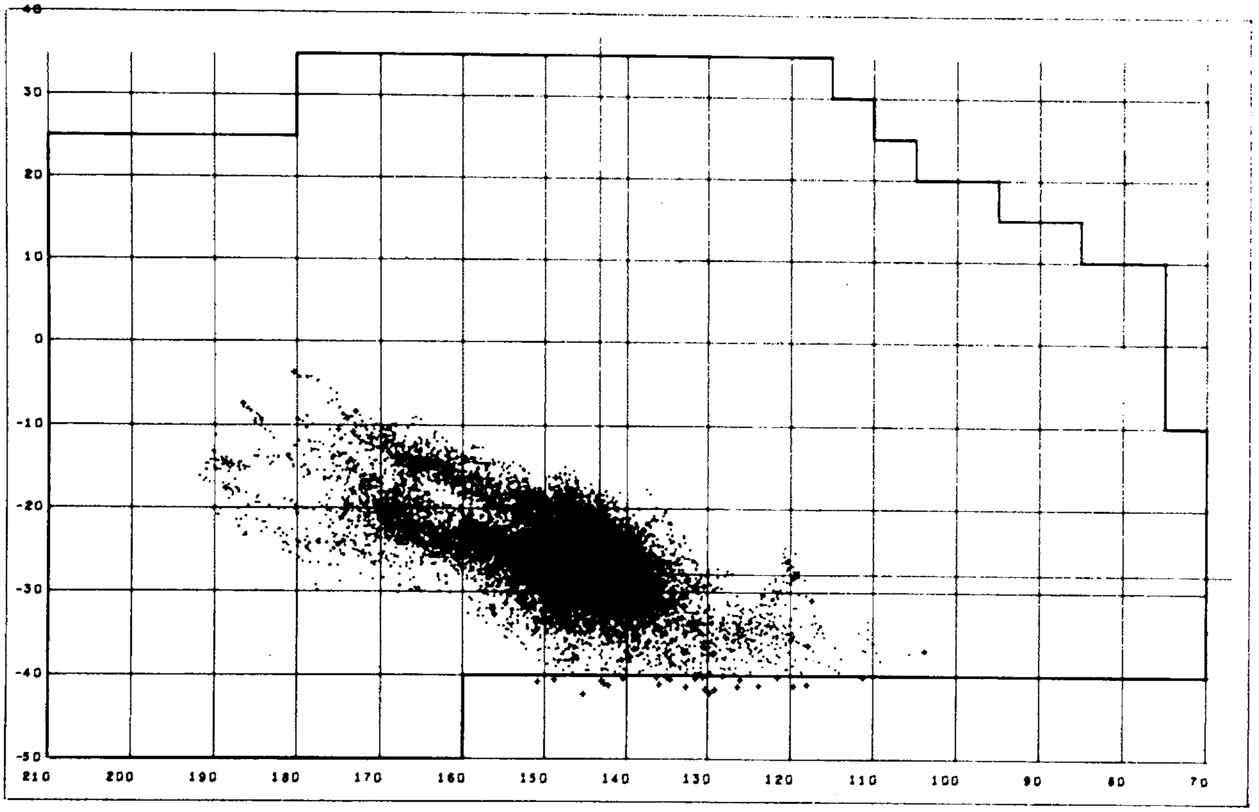
Fernandina (Galapagos) twelve months experiment 28



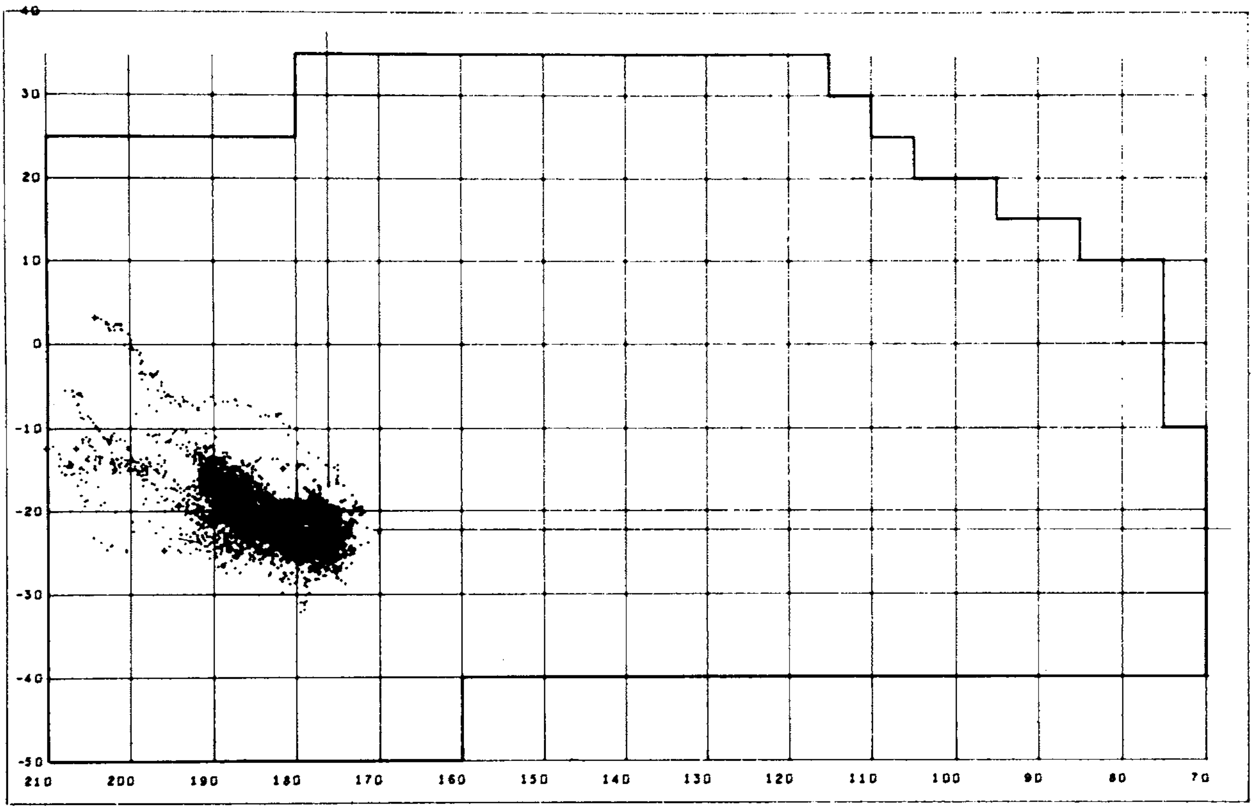
8.17s:82.20w twelve months experiment 29



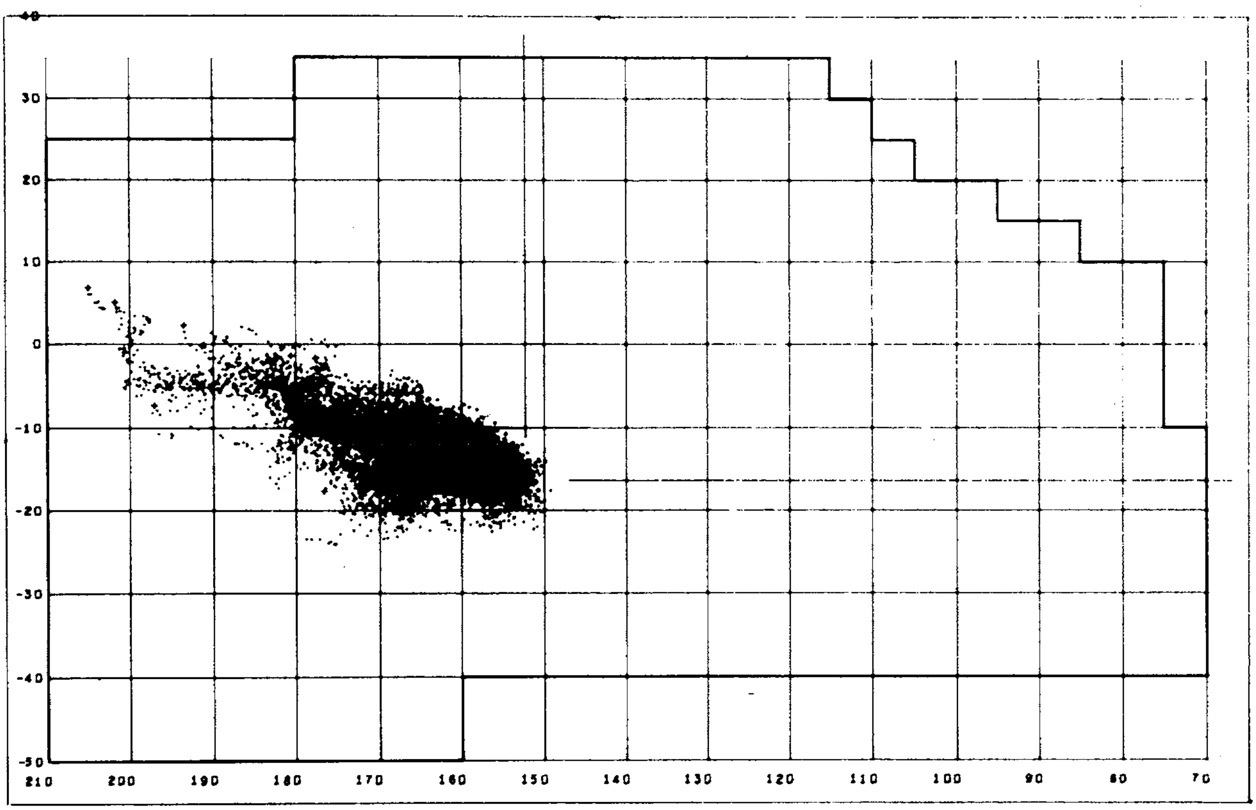
37s:179e (off East Cape, New Zealand) twelve months experiment 102



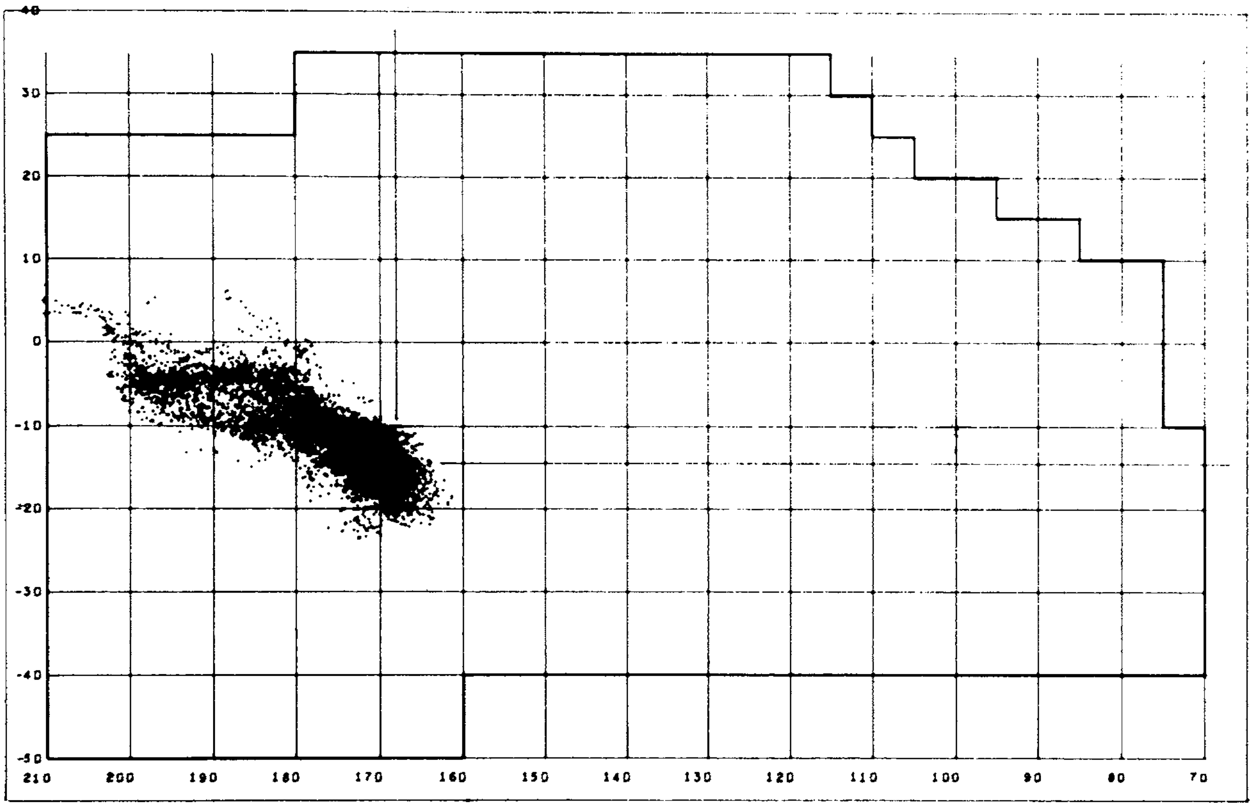
Marotiri (Rapa) twelve months experiment 103



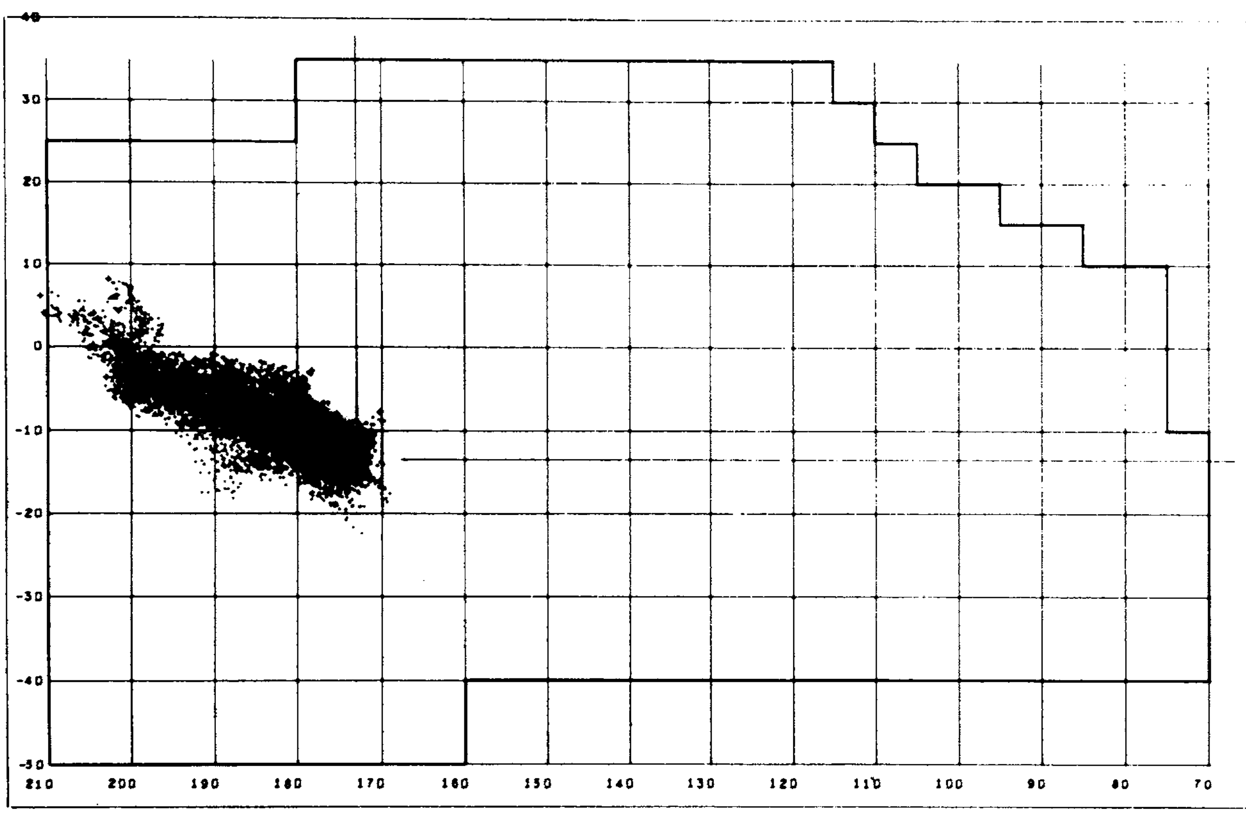
Ata (Tonga) twelve months experiment 105



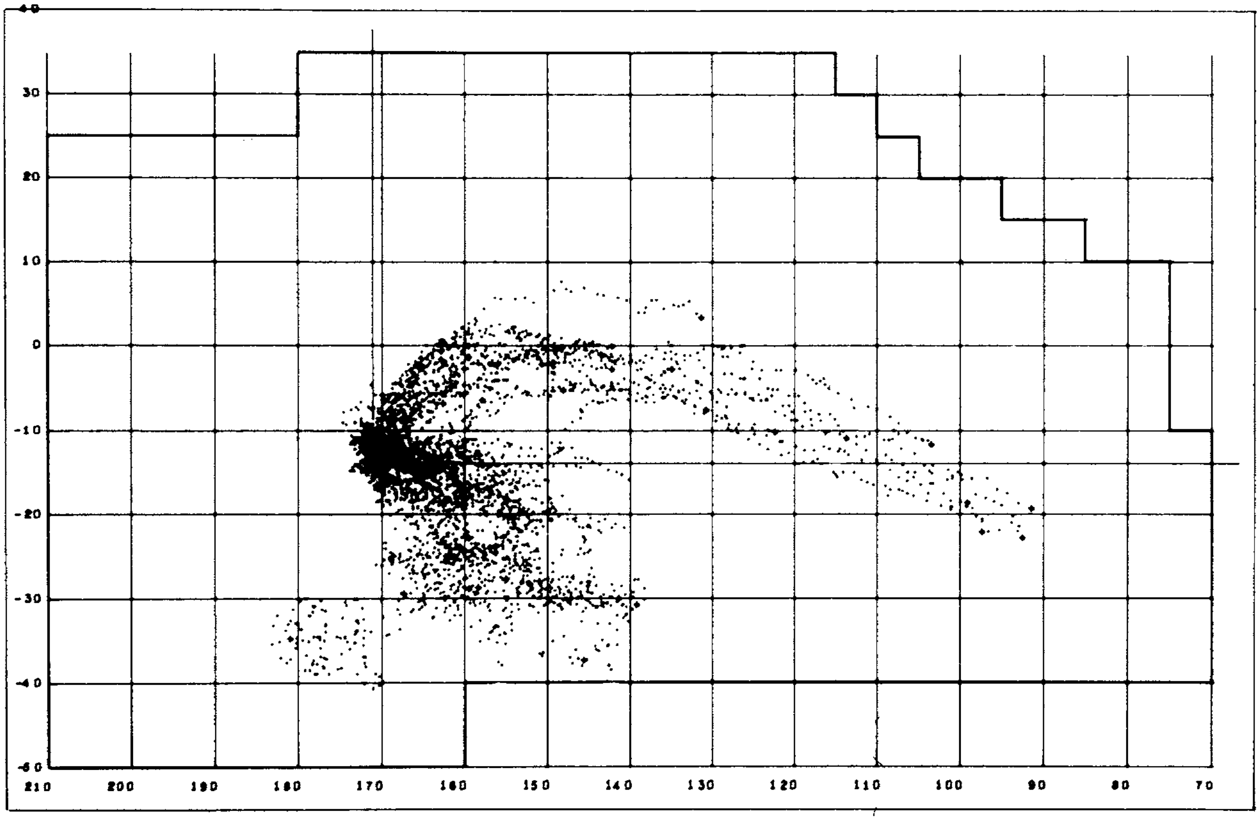
Maupiti (Societies) twelve months experiment 107



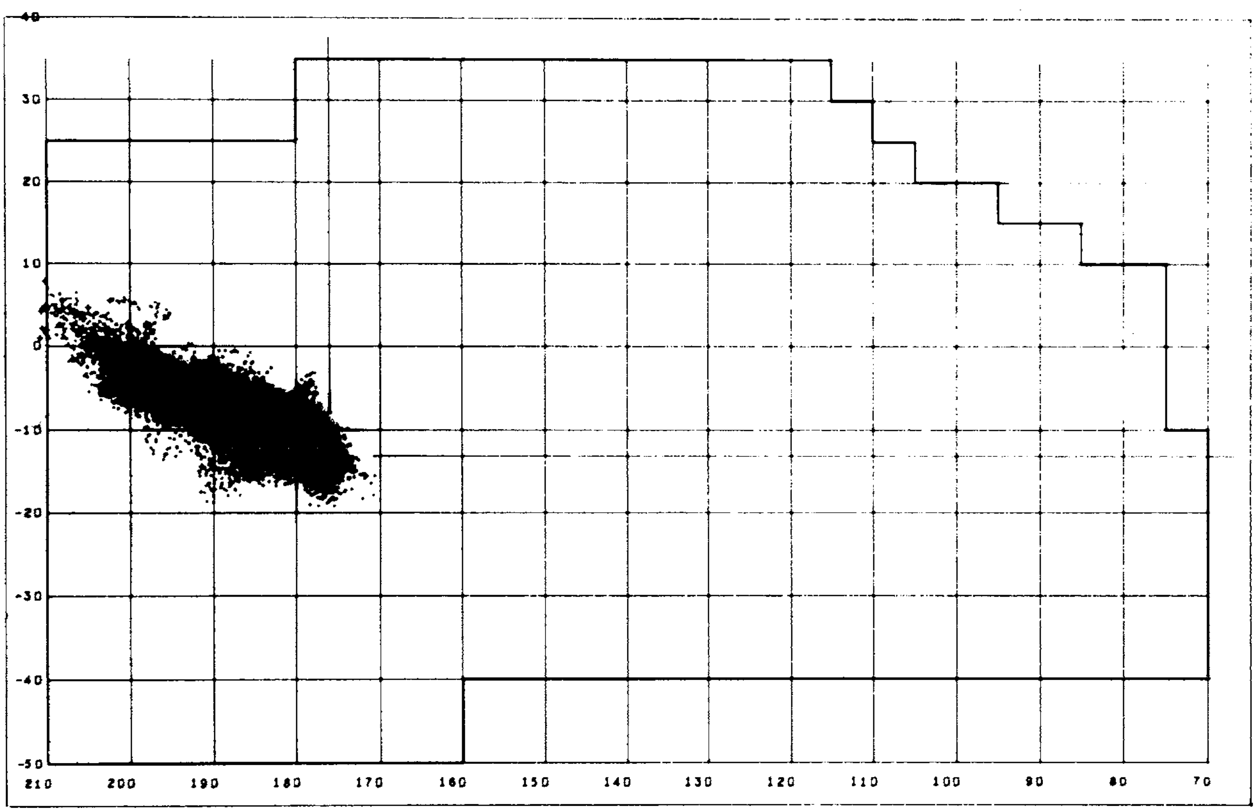
Rose (Samoa) twelve months experiment 110



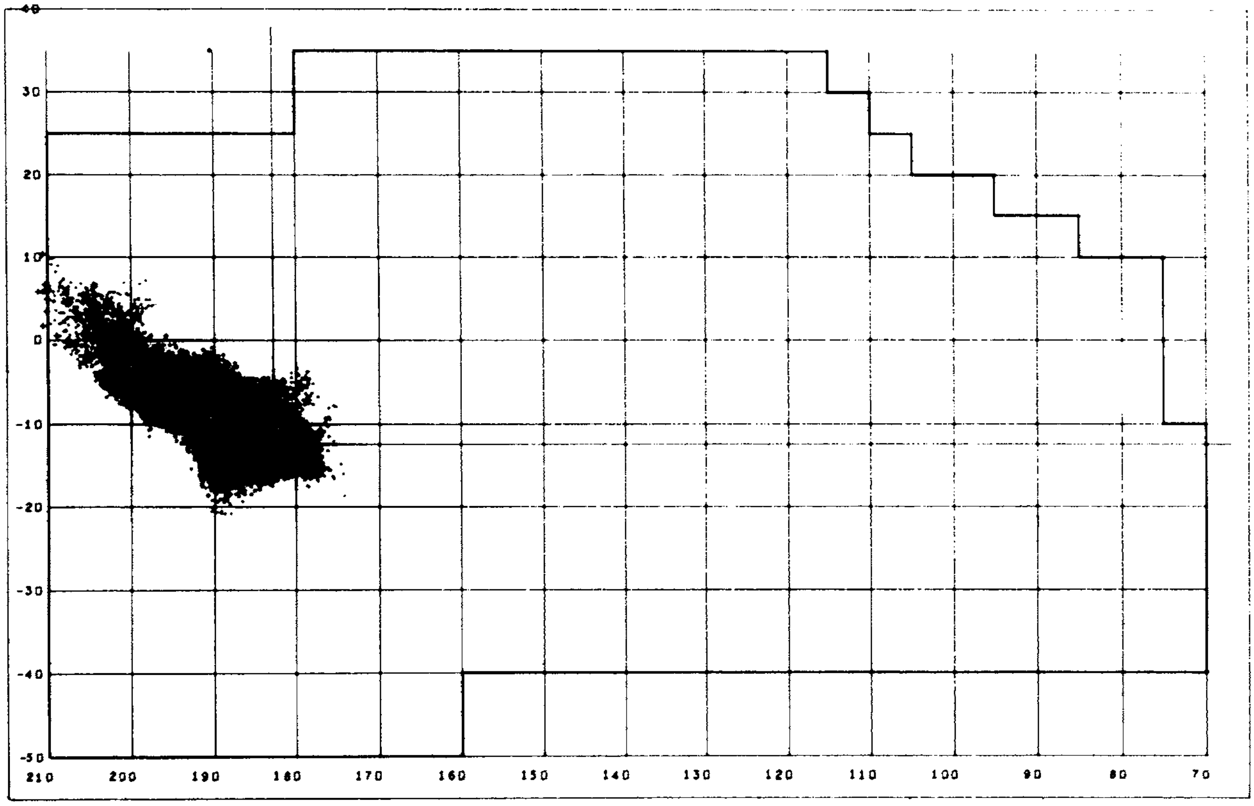
Savai'i (Samoa) twelve months experiment 111



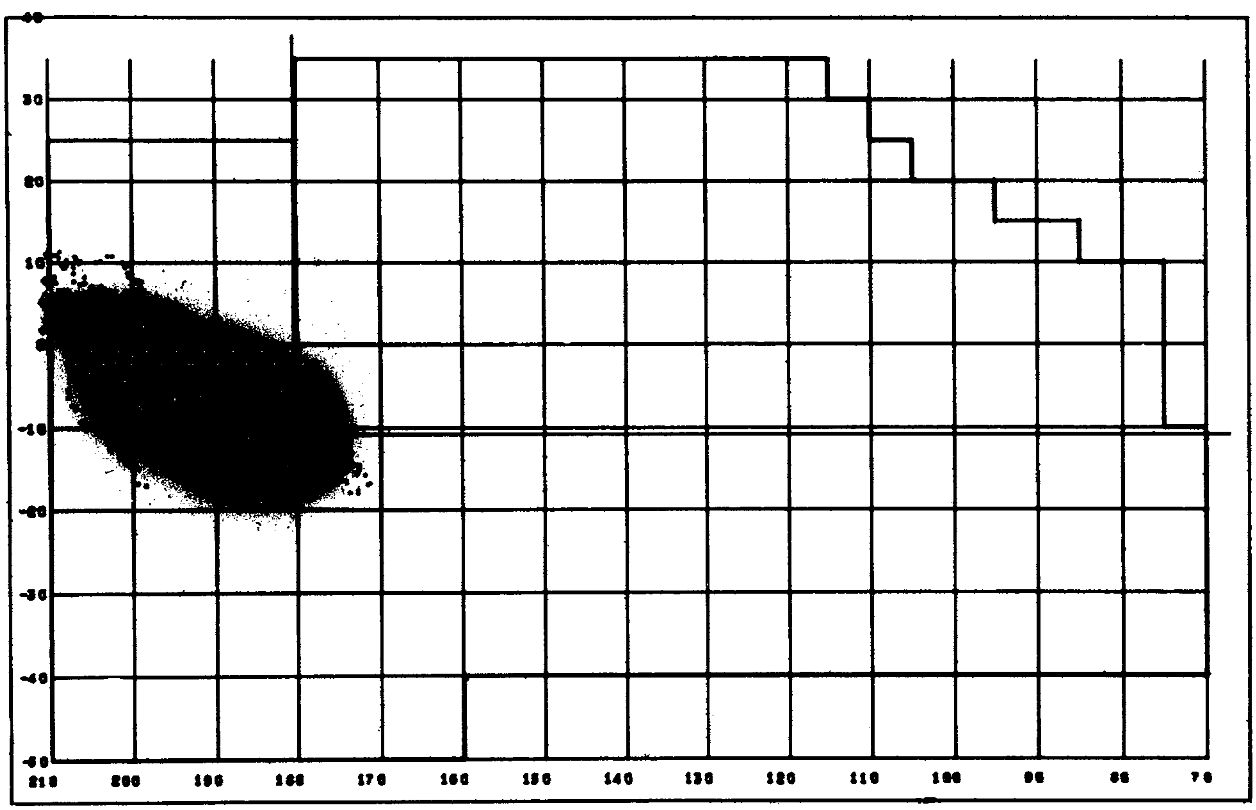
Upolu (Samoa) reverse experiment 127



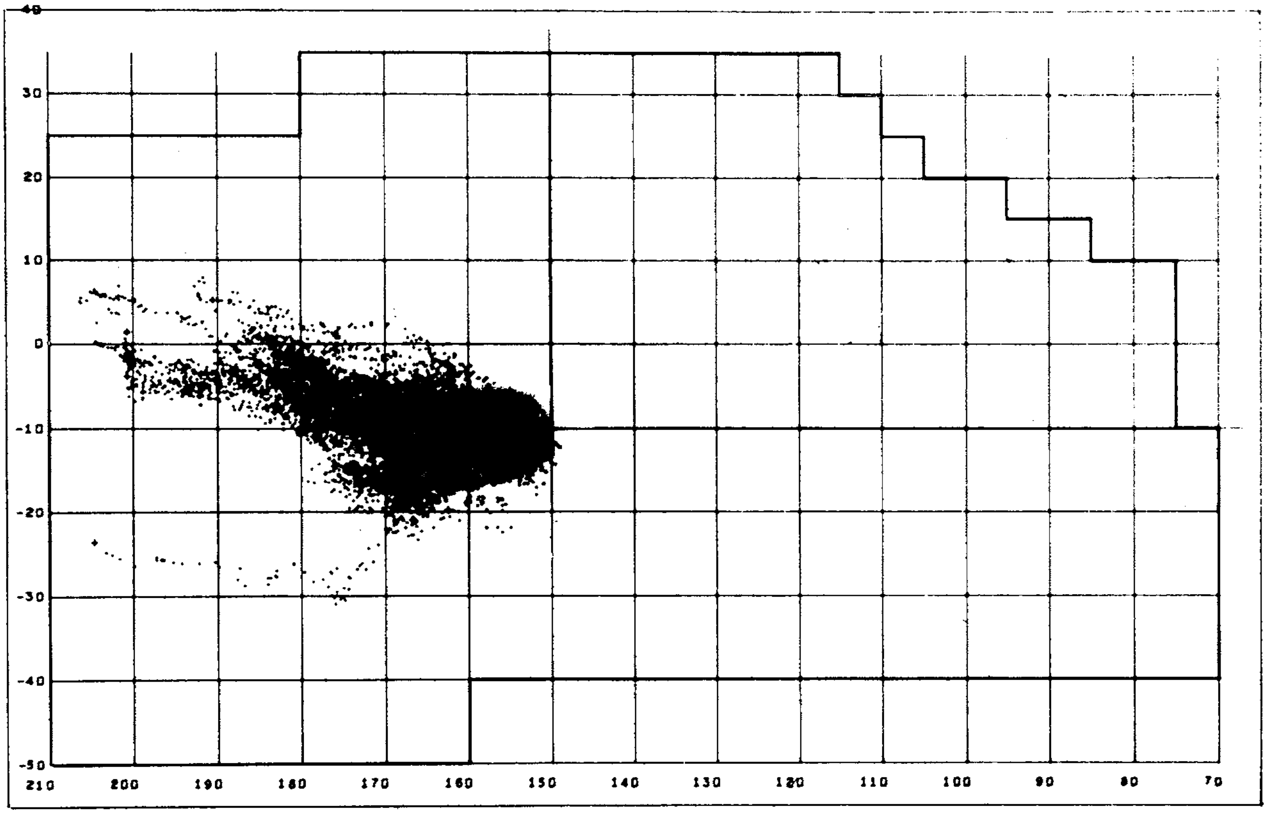
Wallis (East Uvea) twelve months experiment 112



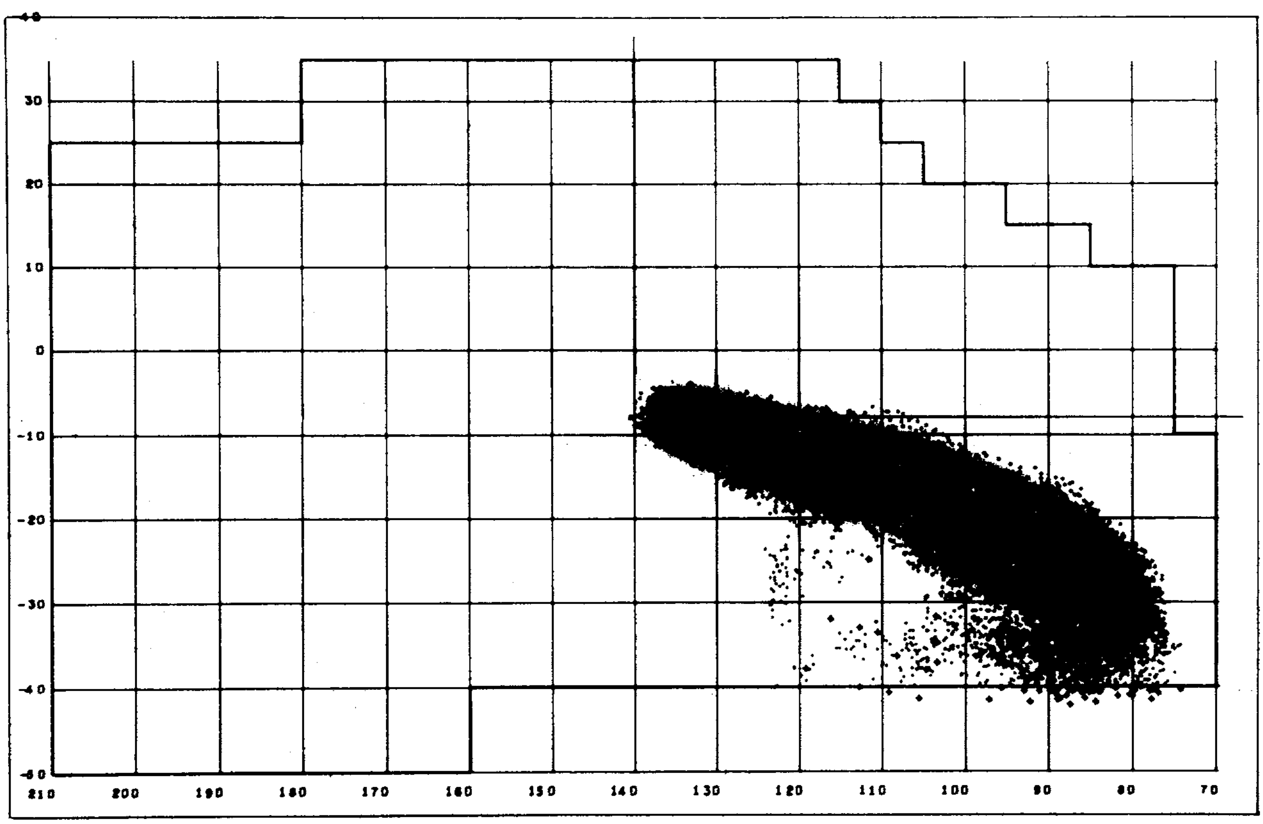
Rotuma twelve months experiment 114



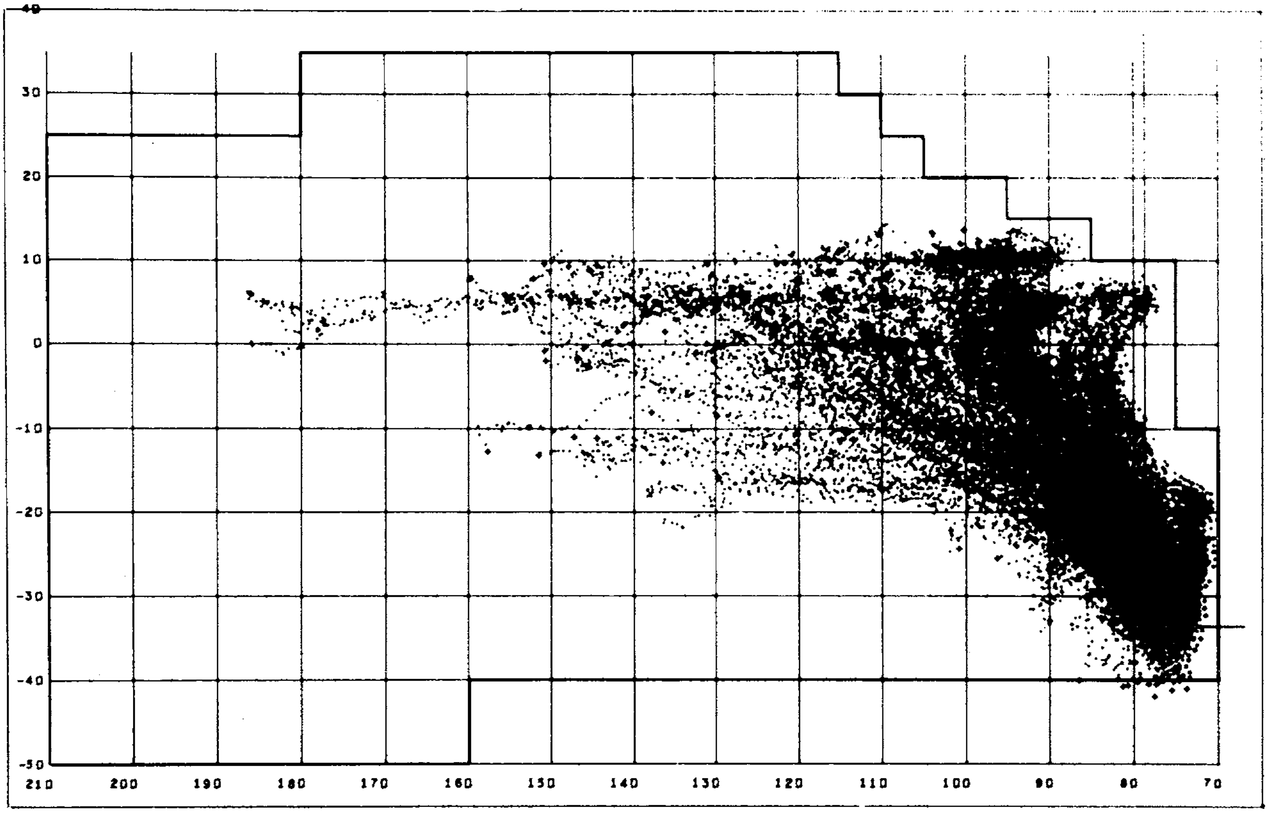
Niulakita (Ellices) twelve months experiment 116



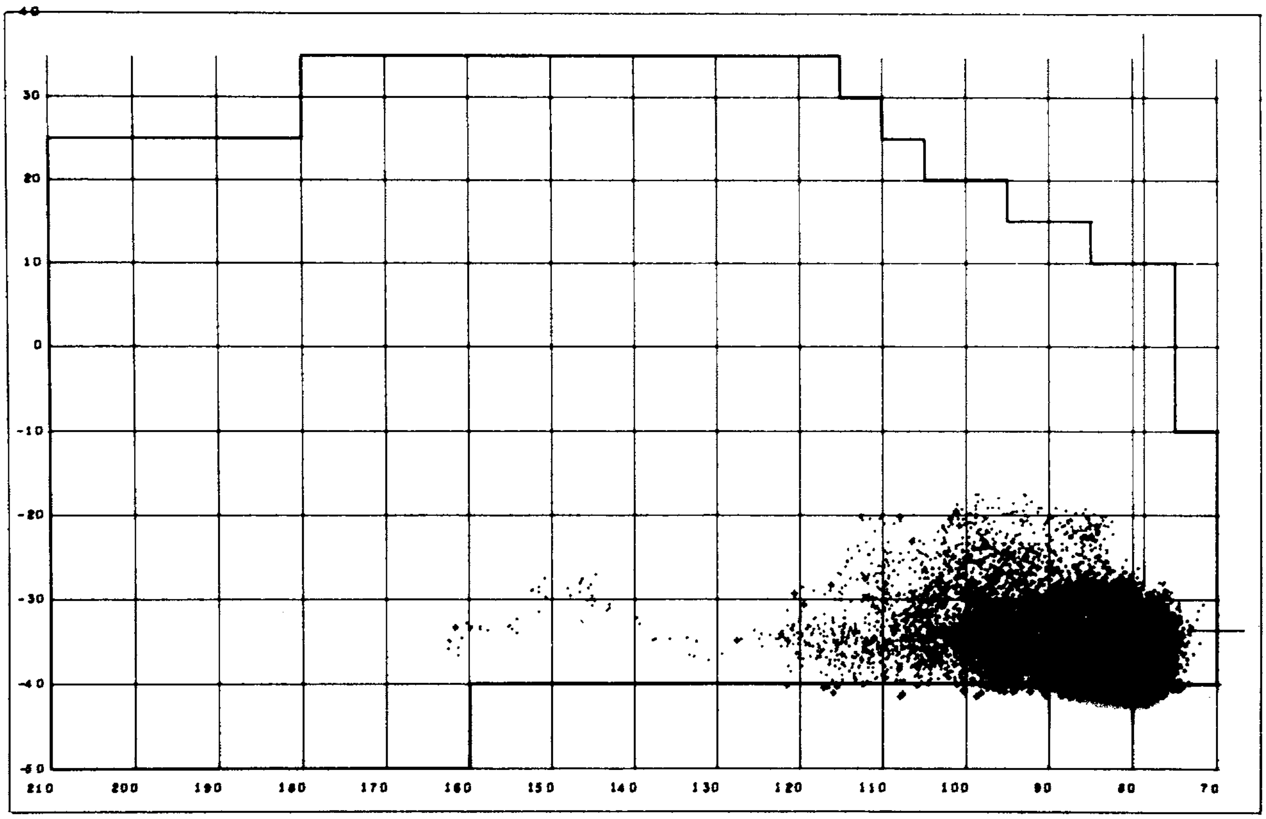
Caroline (Line) twelve months experiment 118



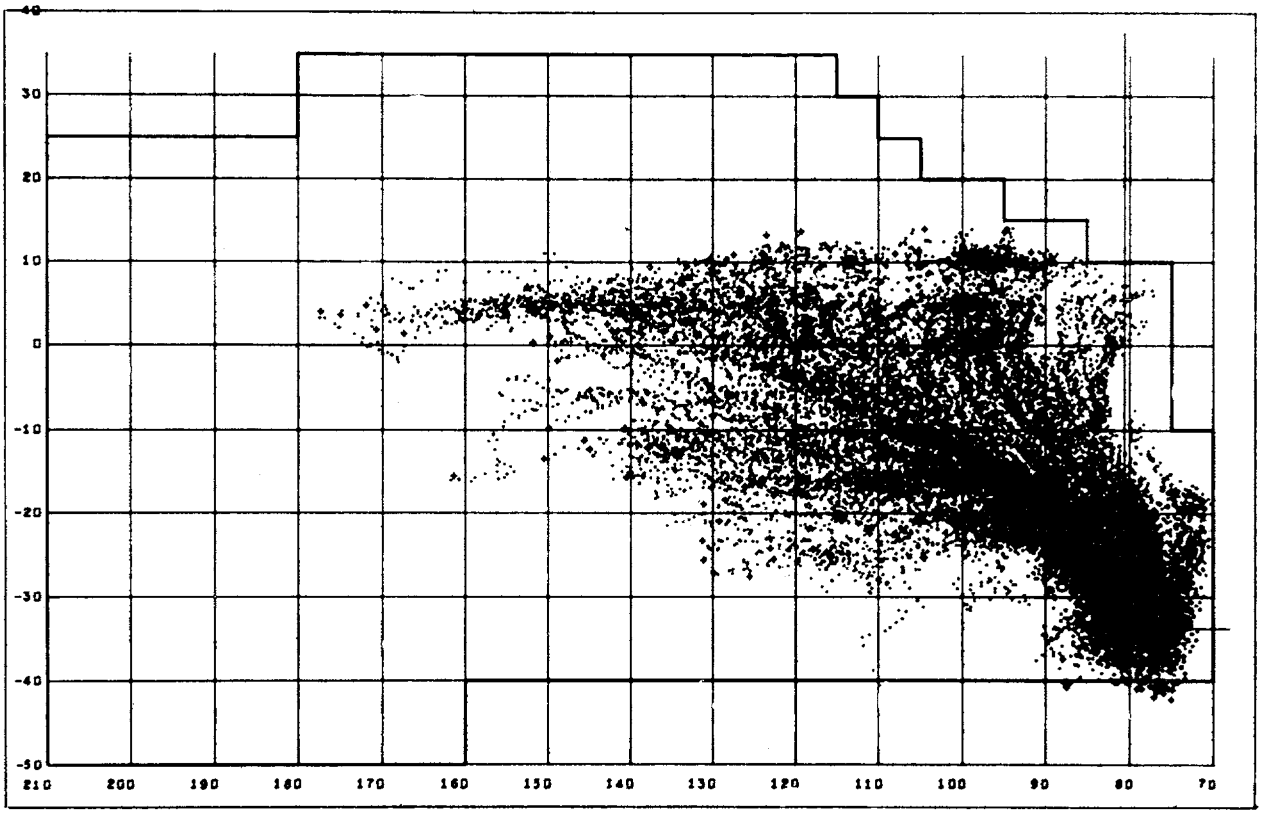
Off Nukuhiva (Marquesas) reverse experiment 129



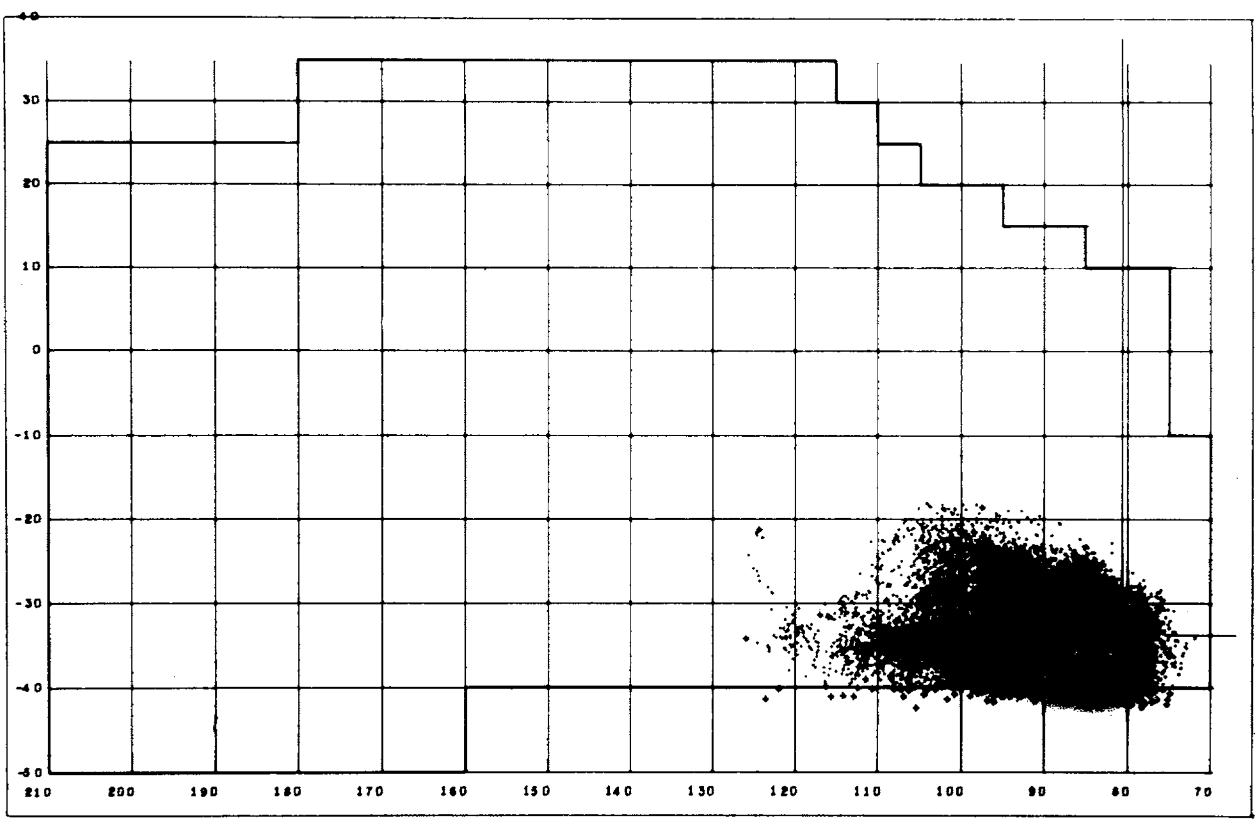
Más á Tierra (Juan Fernandez) twelve months experiment 136



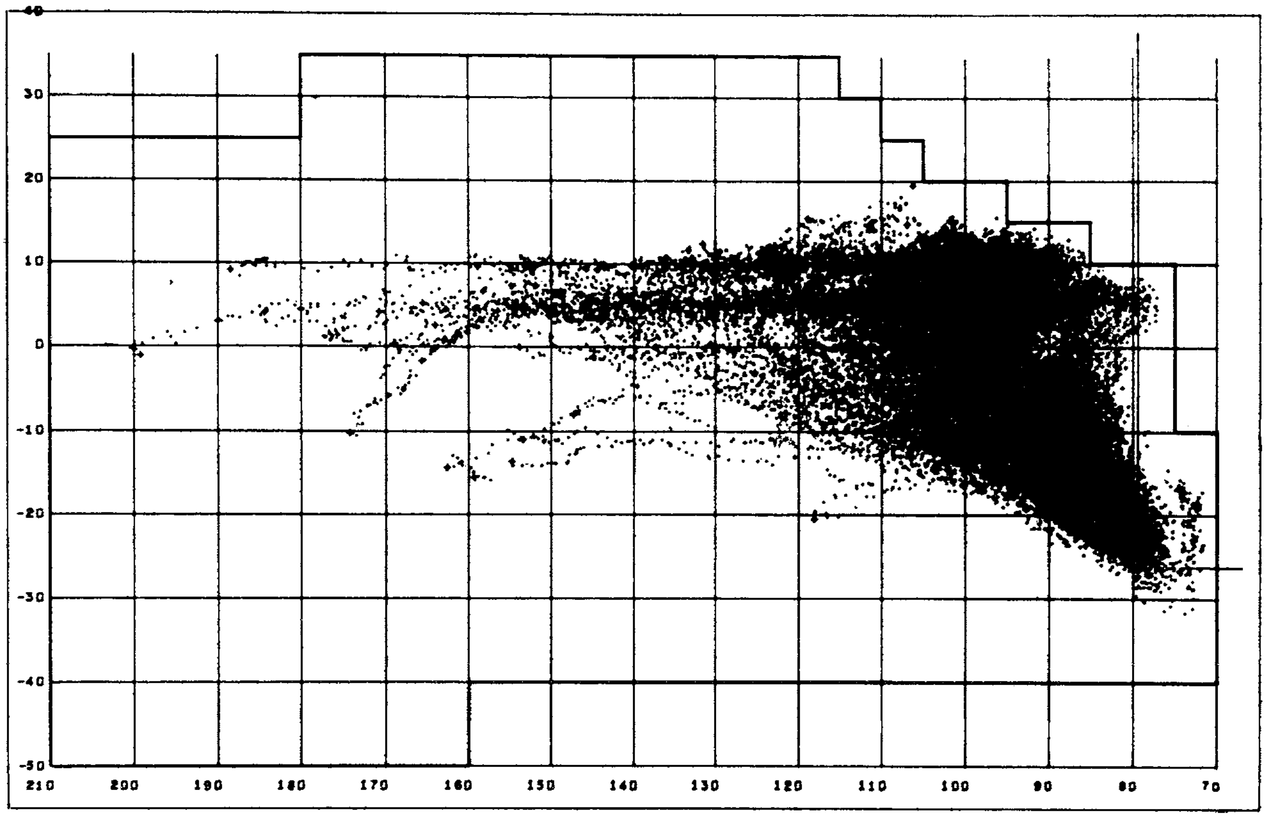
Más á Tierra (Juan Fernandez) reverse experiment 130



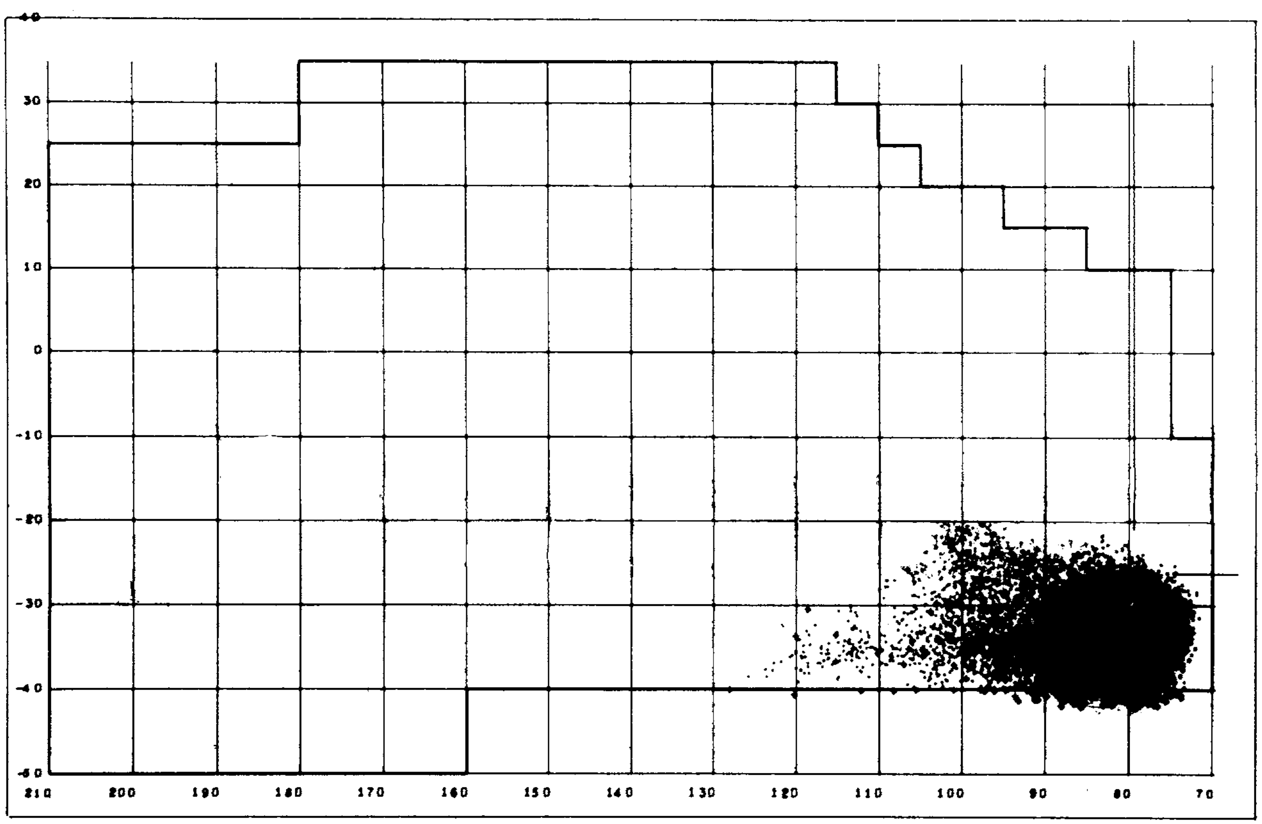
Más afuera (Juan Fernandez) twelve months experiment 137



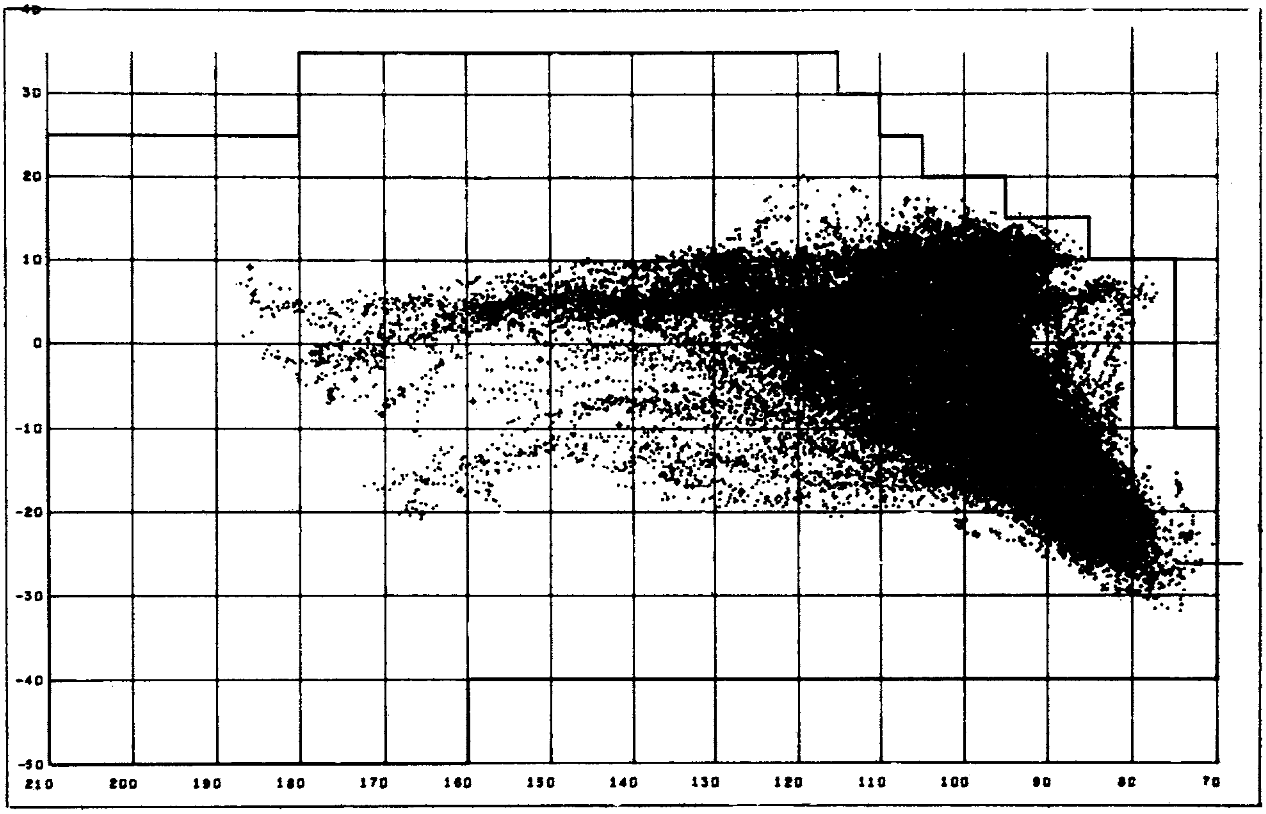
Más afuera (Juan Fernandez) reverse experiment 131



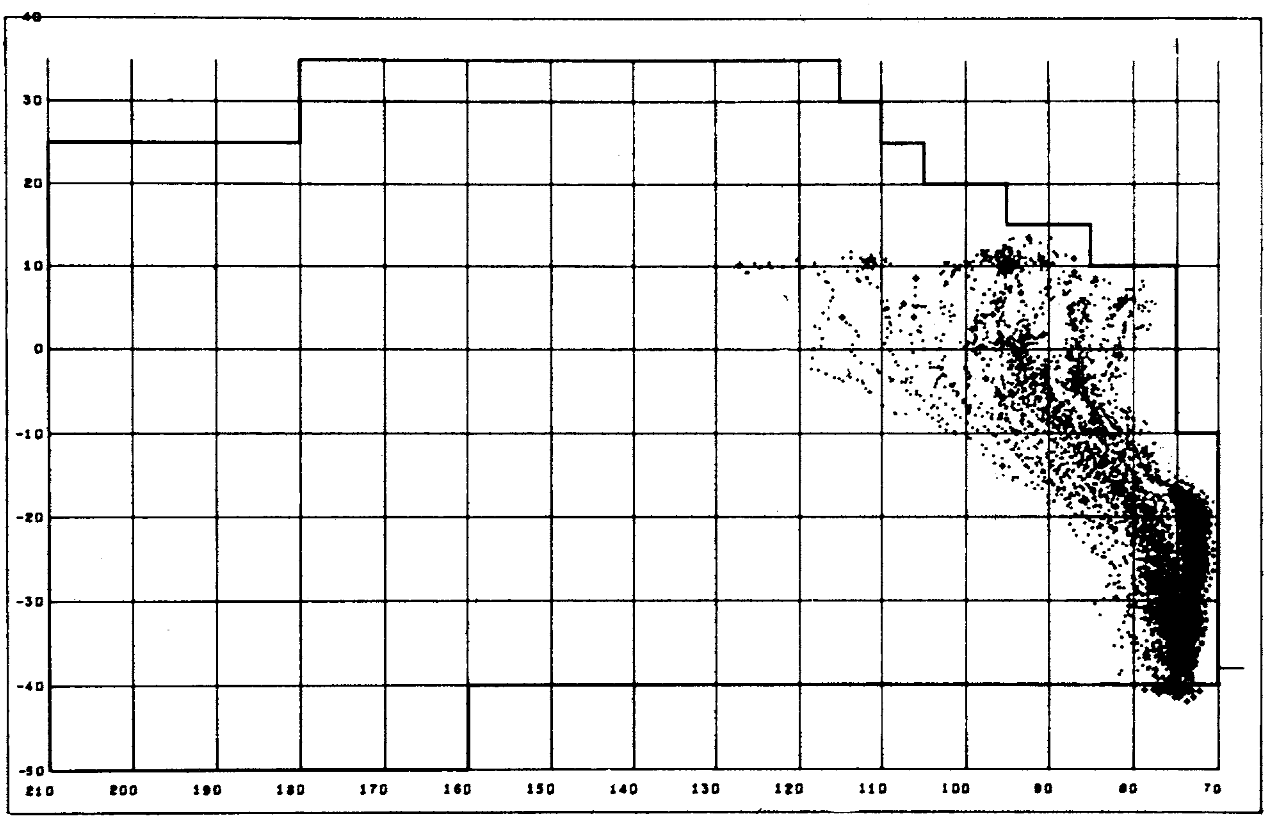
San Ambrosio twelve months experiment 138



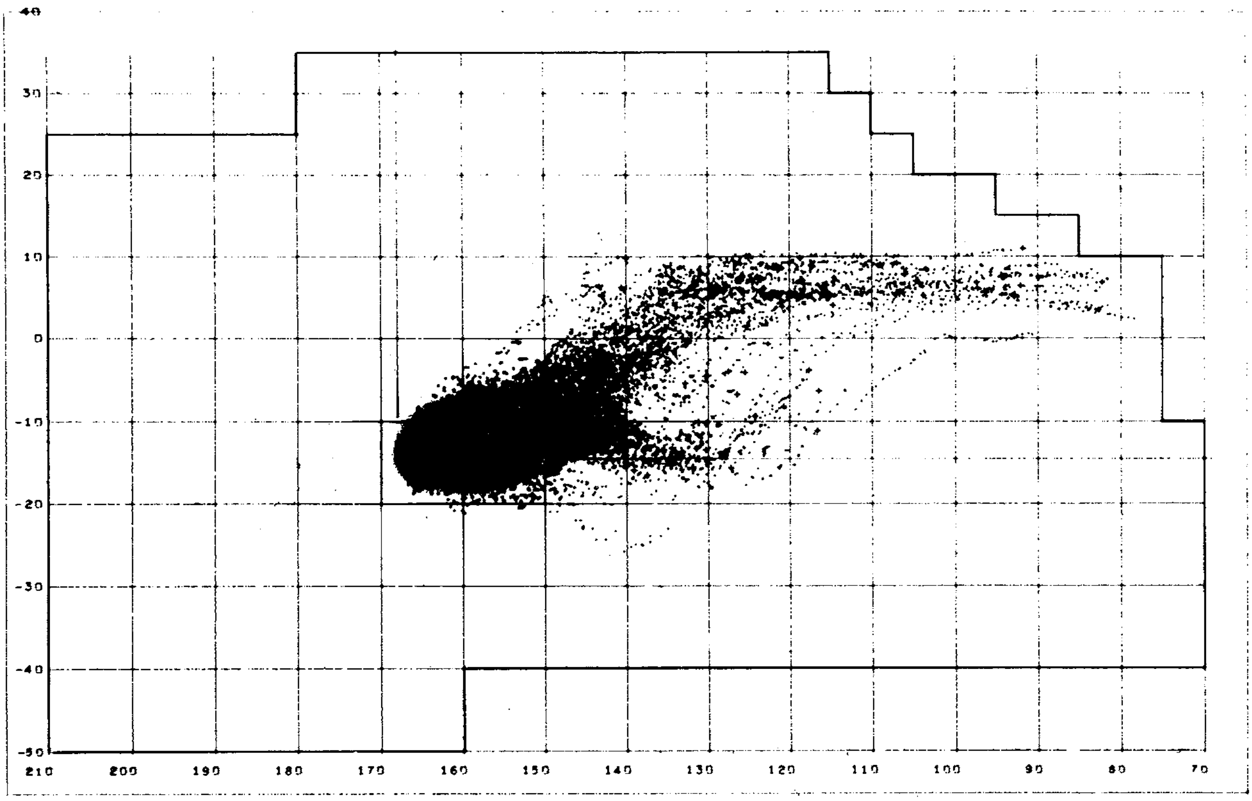
San Ambrosio reverse experiment 132



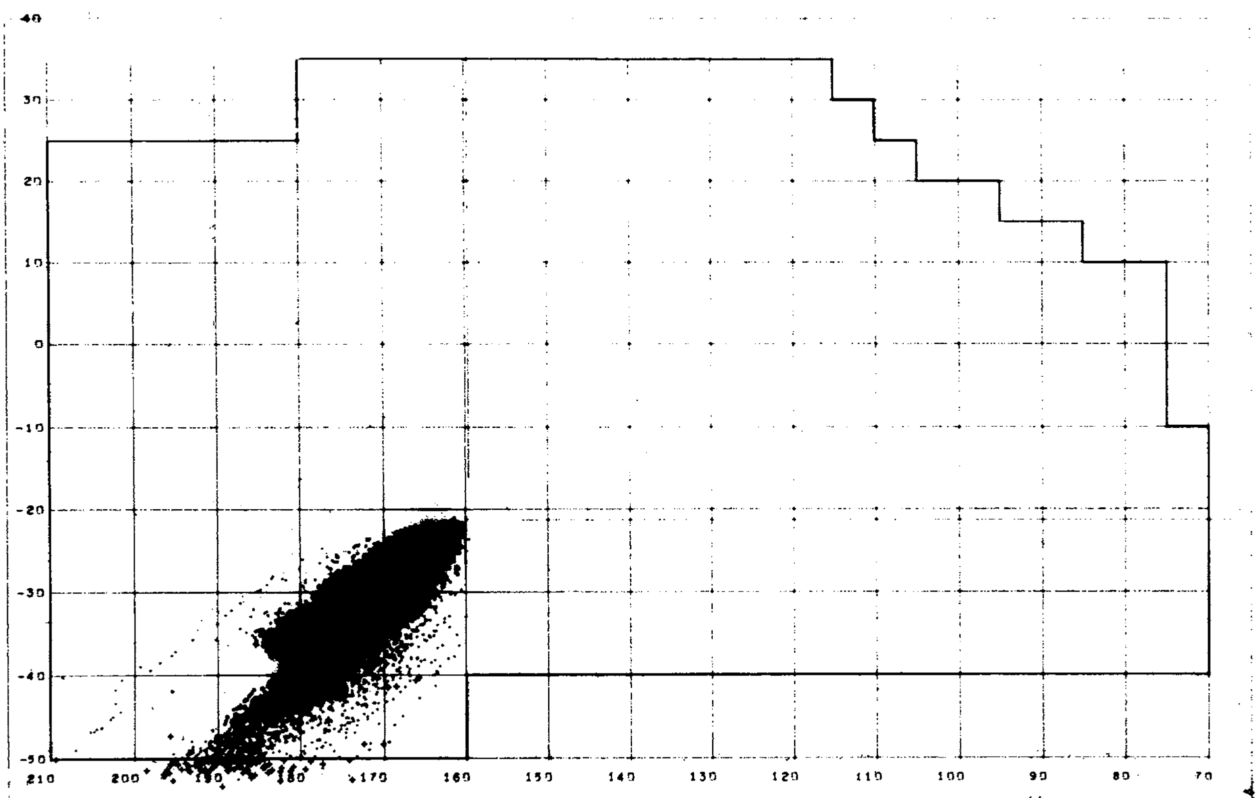
San Felix twelve months experiment 139



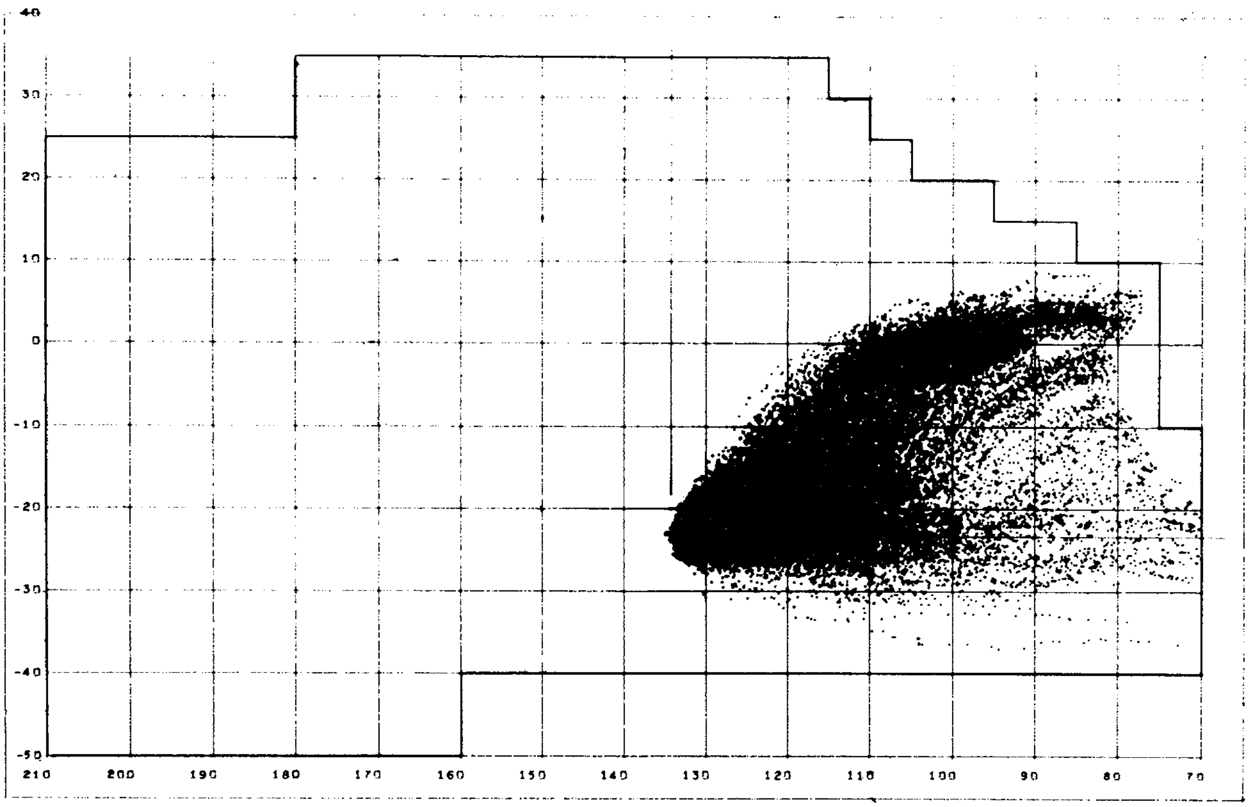
38s:75w twelve months experiment 140



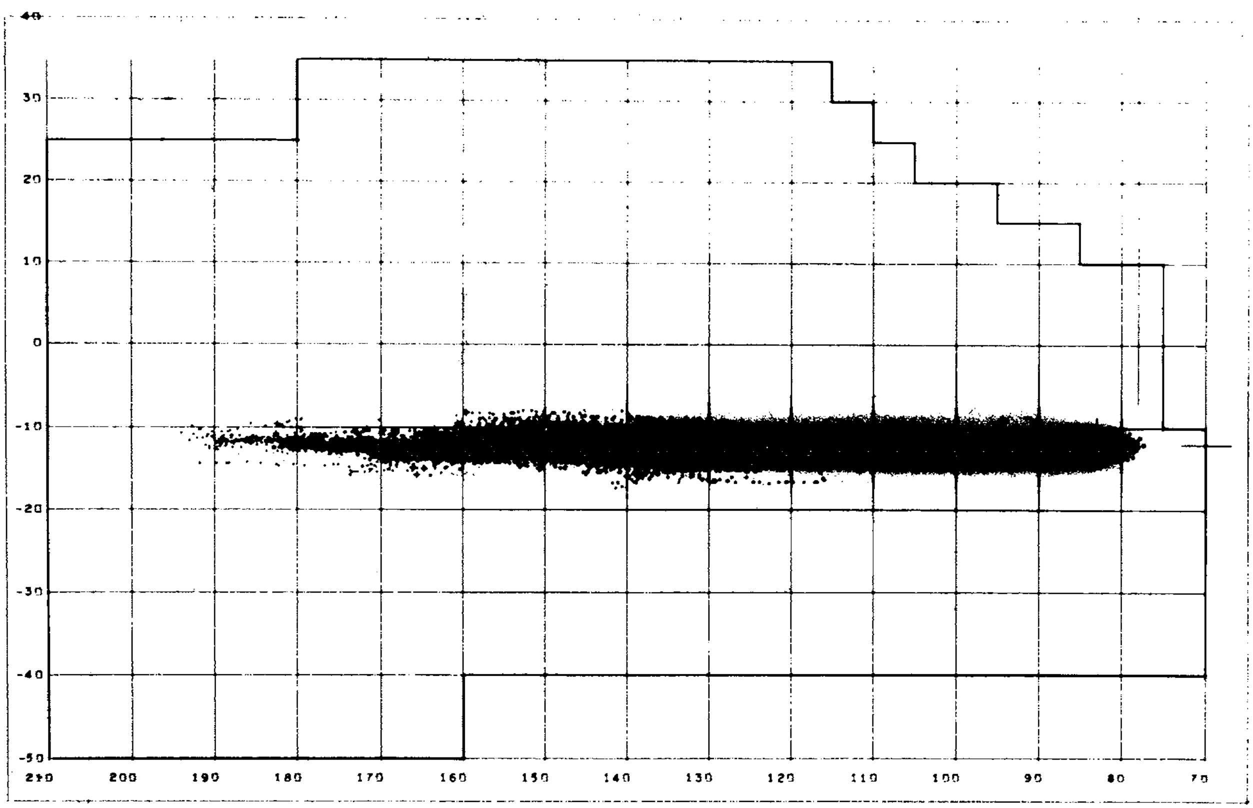
Rose (Samoa) eastward navigation experiment 156



Rarotonga (Southern Cooks) southwestward navigation experiment 159



Timoe (Gambier) eastward navigation experiment 157



12s:78w (off Peru) westward navigation experiment 160

APPENDIX 3

An outline of the model has been given in Chapter 3. This appendix contains a listing of and a detailed commentary on the program for the basic simulation model (POLYNESIA 2), and an outline of the variants and ancillary programs used in the study.

The programs are written in I.C.T. Atlas ALGOL which, in its use here, differs from ALGOL 60[1] only in the provision of input/output facilities, typically

y: = *read*;	(to input a number to *y*)
print (*y* + *z*, 2, 3);	(to print the value of $y+z$ in (2,3) format)
writetext ('*TEXT*');	(to print the text *TEXT*).

and in the hardware representation used, for example,

or for ∨
* for ×

In the listing given here, the bodies of procedures in Atlas machine code have been omitted.

The symbol § is used throughout this appendix to cross-reference the text with sections of the program.

The Program POLYNESIA 2

```
begin comment Polynesia 2 is a program to model the
    behavior of rafts on accidental drift voyages in the
    Pacific Ocean;

comment §1;
real n,w,nt,wt,initlat,initlong,pi,ang,rad;
integer experiment,firstcycle,landings,crewloss,bounds,
    galeloss,logblock,logcell,initial island, excyc,excyct,
    rmv,cycle,date,month,quarter,fd,ld,nv,v,fv,lv,i,q,j,k,
    logdt,wdt,cdt,logiii,wiii,ciii,wi,ci,lm,lq,dtape,c2,c4,c6;

real array islat,islong,ir2,coslat,coslat2 [1:994 ],wind [1:9 ],
    current [1:5 ],liferisk [1:183 ],raftlat,raftlong [1:62 ];
```

1. Naur, 1963.

```
integer array landfall,days [1:994 ],block [ -10:6,14:41 ],
    logarray [0:1022 ],startdate,maxdate [1:62 ],isrange
    [ -11:7,13:42,0:7 ],winddata [0:30206 ],currentdata
    [0:17918 ];

Boolean array dormant [1:62 ];

real procedure random;
comment the procedure chooses a number at random from
a uniform distribution in the range 0<r<1                 §2;

integer procedure pick(prob,m,n); value m,n;
integer array prob; integer m,n;
comment §3;
begin integer i,j,h,k,qtr,nbr;
    procedure split(p); value p; integer p;
    begin integer a;
    a:=p÷16777216;
    h:=p÷65536-256*a;
    i:=p÷256-65536*a-256*h;
    j:=p-16777216*a-65536*h-256*i;
    h:=a-h
    end;

pick:=0;
k:=entier(prob [m ]*random + 1)*16777216 - 1;
if k≥prob [n ] then goto finish;
i:=(n-m)÷4;
qtr:=m+i-1+i*(if k<prob [m+i ] then 0
    else if k<prob [m+2*i ] then 1
    else if k<prob  [m+3*i ] then 2 else 3);
for j:=qtr-i+2 step 1 until qtr do
    if k<prob [j] then begin nbr:=j; goto l end;
nbr:=qtr+1;
l:     k:=k÷16777216;
split(prob [nbr ]);
pick:=4*(nbr-m) - (if k≥h then 0
    else if k≥h-i then 1
    else if k≥h-i-j then 2 else 3);
finish:
end of pick;

integer procedure lifelength;
comment the procedure chooses a maximum crew-life for
a voyage in accordance with the probabilities stored
in the array liferisk                                      §36;
```

```
begin real s; integer k;
s:=random;
for k:=1 step 1 until 183 do
    begin
    s:=s-liferisk[k];
    if s<0 then goto out;
    end;
k:=183;
out: lifelength:=k;
end of lifelength;

procedure storelog(n); value n; integer n;
comment the procedure is used to record entries on the
logging tape                                         §4;
begin
logarray [logdt+logcell]:=n;
if logcell=511 then
    begin
    write(4,logblock,logiii);
    logblock:=logblock+1;
    for logcell:=0 step 1 until 511 do
    logarray[logdt+logcell]:=0;
    logcell:=0
    end
        else logcell:=logcell+1
end of storelog;

procedure terminate(vy,rs); value vy,rs; integer vy,rs;
comment the procedure takes all necessary steps to
bring to a conclusion the voyage vy. Parameter rs indi-
cates the reason for termination                     §5;
begin integer isle, termdate;
switch alternative:=crew perish, out of bounds, gale;

newline(1); print(experiment,2,0); writetext('/');
print(cycle,2,0); writetext('/'); print(vy,2,0);

storelog(excyct+65536*vy+(if rs<0 then -rs else
    4096*rs));
dormant[vy]:=true;
termdate:=if rs=2 then date-1 else date;
print(startdate[vy],4,0);
print(termdate-startdate[vy]+1,4,0);

if rs=1 then begin n:=nt; w:=wt end;
print(n,3,3); print(w,3,3);

if rs>0 then goto alternative[rs];

landed: landings:=landings+1; isle:=-rs;
    landfall [isle]:=landfall [isle]+1;
    days[isle]:=days[isle]+termdate
        -startdate[vy]+1;
    print(nt,5,3); print(wt,3,3);
    writetext('LANDED/ON/ISLAND');
    print(isle,1,0);
    goto date print;

crew perish: crewloss:=crewloss+1;
    writetext('`15s'CREW/EXPIRE');
    goto date print;

out of bounds: bounds:=bounds+1;
    writetext('`15s'RAFT/OUT/OF/BOUNDS');
    goto date print;

gale: galeloss:=galeloss+1;
    writetext('`8s'RAFT/LOST/IN/STRONG/
    GALE');

date print: print(termdate,4,0);
    if rs≥2 then
    begin writetext('(MAXD='); print(maxdate[vy],
        1,0); writetext(')') end
    end of terminate;

procedure switch ci;
comment the procedure switches the current data indi-
cator from one half of the current data array to the
other                                                §6;
ci:=3704-ci;

procedure switch wi;
comment the procedure switches the wind data indica-
tor from one half of the wind data array to the
other                                                §7;
wi:=14848-wi;

procedure set base points;
comment the procedure determines the machine address
of the first Atlas page in each of three arrays, and
the subscripts corresponding to these addresses      §8;

comment §9;
procedure readfwd(t,p,iii,n);
value t,p,iii,n; integer t,p,iii,n;
comment the procedure copies 4*n+1 blocks from
magnetic tape t starting at block p into the main
store starting at machine address iii;

procedure write(t,p,iii);
value t,p,iii; integer t,p,iii;
comment the procedure takes the 512 words from
machine address iii to iii+511 and writes them onto
block number p of magnetic tape number t;

procedure search(t,p);
value t,p; integer t,p;
comment the procedure winds magnetic tape number t
to the start of block number p;

procedure break output(n); value n; integer n;
comment the procedure permits the Atlas Supervisor
to begin printing any output already produced on
channel n without waiting for the end of the program;


START OF MAIN PROGRAM:
set base points;
experiment:=read;

comment bring down rescue block                      §10a;
readfwd(5,experiment,logiii,0);

comment bring down permanent data                    §11a;
readfwd(2,1,ciii,4); dtape:=3;

comment set permanent constants;
pi:=3.141592653; ang:=pi/8; rad:=pi/180;

writetext('`3c'THIS/IS/THE/START/RESTART/
    OF/EXPERIMENT');
print(experiment,3,0);

comment initialize rescue parameters, etc            §10b;
rmv:=logarray[logdt+1];
firstcycle:=logarray[logdt+2];
logblock:=logarray[logdt+3];
landings:=logarray[logdt+4];
crewloss:=logarray[logdt+5];
```

```
bounds:=logarray[logdt+6];
galeloss:=logarray[logdt+7];
initial island:=logarray[logdt+8];
initlat:=logarray[logdt+9]/100;
initlong:=logarray[logdt+10]/100;
for i:=11 step 1 until 507 do
      begin
      k:=logarray[logdt+i];
      landfall[2*i-21]:=q:=k÷1000;
      landfall[2*i-20]:=k-1000*q
      end;
writetext('2c'RESCUE|PARAMETERS|CALLED|DOWN|
ARE:');
for i:=0 step 1 until 7 do print(logarray[logdt+i],7,0);
writetext('2c'INITIAL|ISLAND');
print(initial island,1,0);
island,1,0);
print(initlat,4,2); print(initlong,4,2);
comment position the logging tape                 §12;
search(4,logblock);
comment call down initial wind and current data for
first cycle                                       §13;
readfwd(2,(firstcycle÷3)*104+20, ciii+8704,4);
readfwd(2,(firstcycle÷3)*17+29*firstcycle+37, wiii,7);
ci:=0; wi:=14848;
comment initialize permanent data                 §11b;
for i:=1 step 1 until 9 do
      wind[i]:=currentdata[cdt+i-1];
for i:=1 step 1 until 5 do
      current[i]:=currentdata[cdt+i + 8];
for i:=1 step 1 until 183 do
      liferisk[i]:=0.0014285714*currentdata[cdt+i+13];
c2:=cdt+512; c4:=cdt+1536; c6:=cdt+2560;
for i:=1 step 1 until 994 do
      begin
      islat[i]:=n:=0.01*currentdata[c2+i];
      coslat[i]:=n:=cos(rad*n);
      coslat2[i]:=n*n;
      islong[i]:=0.01*currentdata[c4+i];
      n:=currentdata[c6+i];
      ir2[i]:=0.0002777777*n*n
      end;
q:=cdt+3583;
for i:= -10 step 1 until 6 do
      for j:=14 step 1 until 41 do
            begin
            q:=q+1;
            block[i,j]:=currentdata[q]
            end;
q:=cdt+4095;
for i:= -11 step 1 until 7 do
      for j:=13 step 1 until 42 do
            for k:=0 step 1 until 7 do
                  begin
                  q:=q+1;
                  isrange[i,j,k]:=currentdata[q]
                  end;
comment §14;
for i:=1 step 1 until 994 do days[i]:=0;
```

```
START OF MAIN CYCLE:
for cycle:=first cycle step 1 until 11 do
      begin
      writetext('3c'EXPERIMENT');
      print(experiment,1,0);
      writetext('c'START|OF|CYCLE');
      print(cycle,1,0);
      comment §15;
      excyc:=8388608*(16*experiment+cycle);
      excyct:=excyc+32768;
      for logcell:=0 step 1 until 511 do
            logarray[logdt+logcell]:=0;
      logcell:=0; storelog(excyc);
      comment position the alternate data tape          §16;
      if cycle ≠ 11 then search(dtape,((cycle+1)÷3)*104
            +20);
      dtape:=5-dtape;
      comment §17;
      nv:=62-2*cycle+4*(cycle÷2);
      fd:=entier(30.5*cycle+61.6);
      comment initialize voyages for this cycle         §18;
      for v:=1 step 1 until nv do
            begin
            startdate[v]:=fd+(v-1)÷2;
            maxdate[v]:=startdate[v]+lifelength-1;
            dormant[v]:=true;
            raftlat[v]:=initlat;
            raftlong[v]:=initlong
            end;
      ld:=maxdate[1];
      for v:=2 step 1 until nv do if maxdate[v]>ld then
            ld:=maxdate[v];
      lm:=(ld*2)÷61+1;
      lq:=lm÷3;
      comment §19a;
      fv:=1; lv:=0;

      START OF DATE CYCLE:
      for date:=fd step 1 until ld do
            begin
            comment adjust the first and last voyage
            parameters if necessary             §19b;
            if lv≠nv then
                  begin comment add two new voyages;
                  lv:=lv+2;
                  dormant[lv-1]:=dormant[lv]:=false
                  end;
            advance fv:
            if dormant[fv] then
                  begin comment advance first voyage;
                  if fv=nv then
                        begin
                        if date≤entier(30.5*lm-29.9) and
                        cycle≠11 then
                              begin comment call down initial
                              wind/current data for next cycle,  §20;
                              q:=(cycle+1)÷3; k:=5-dtape;
                              readfwd(k,q*104+20,
                                    ciii+8704-ci,4);
                              readfwd(k,q*17+29*cycle+66,
                                    wiii+14848-wi,7)
```

```
            end;
        goto endcycle
        end;
    fv:=fv+1;
    goto advance fv
    end;
comment test for first day of month;
month:=(date*2)÷61+1;
if date≠entier(30.5*month−29.9) then
    goto sail voyages;
comment first day of month, §21;
quarter:=month÷3;
writetext('`2c'START|OF|MONTH');
print(month,1,0);
if month=quarter*3 or month=cycle+3 then
    switch ci;
if month=3*quarter+2 and quarter≠lq then
    readfwd(dtape,quarter*104+20,
        ciii−8704−ci,4);
if month≠lm then
    readfwd(dtape,((month+1)÷3)*17+29*
        month−38,wiii+wi,7)
        else
    if cycle≠11 then
        begin
        q:=(cycle+1)÷3; k:=5−dtape;
        readfwd(k,q*104+20,ciii+8704−ci,4);
        readfwd(k,q*17+29*cycle+66,
            wiii+wi,7)
        end;
switch wi;
sail voyages:
for v:=fv step 1 until lv do
    begin real blow, drift;
    integer b,wch,cch,wforce,cforce,wdir,cdir,s,e;
    if dormant[v] then goto next voyage;
    comment §23;
    n:=raftlat[v]; w:=raftlong[v];
    s:=entier(n/5); e:=entier(w/5);
    b:=if s<−10 or s>6 or e<14 or e>41 then
    0 else block[s,e];
    if b=0 then
        begin comment raft has sailed out of
        bounds previous day             §24;
        terminate(v,2);
        goto nextvoyage
        end;
    comment §25;
    select wind: k:=wdt+wi+(b−1)*37;
    wch:=pick(winddata,k,k+36);
    wdir:=(wch−1)÷9; wforce:=wch−9*wdir;
    blow:=if wch=0 then 0 else wind[wforce];
    select current: k:=cdt+ci+(b−1)*21;
    cch:=pick(currentdata,k,k+20);
    cdir:=(cch−1)÷5; cforce:=cch−5*cdir;
    drift:=if cch=0 then 0 else current[cforce];
    comment §26;
    storelog(excyc+cch+128*(wch+512*v));
```

```
if wforce≠9 then goto move raft;
comment §27;
if random>0.5 then
    begin comment crew lost in heavy gale;
    terminate(v,3);
    goto next voyage
    end;
comment §28;
move raft:
nt:=n−(blow*cos(ang*wdir)+
    drift*cos(ang*cdir))/60;
wt:=w+(blow*sin(ang*wdir)+
    drift*sin(ang*cdir))/(60*cos(rad*n));
comment §29a;
check islands:
begin integer ia,ib,range,smid,emid;
Boolean nfd;
real N,W,r2,f,D2,dn2,dw2,h,k,l,m,B2,p;
dn2:=(n−nt)*(n−nt);
dw2:=(w−wt)*(w−wt);
comment §29b;
if dn2 + dw2<0.000001 then
    goto none sighted;
comment §29c;
nfd:=date>startdate[v]+2;
comment §29d;
smid:=entier((n+nt)/10);
emid:=entier((w+wt)/10);
range:=−2;
nextrange: range:=range+2;
ia:=isrange[smid,emid,range];
if ia=0 then goto none sighted;
ib:=isrange[smid,emid,range+1];
for i:=ia step 1 until ib do
    begin
    comment test whether raft has sighted
    island i                          §29e;
    N:=islat[i];
    W:=islong[i];
    r2:=ir2[i];
    f:=coslat[i];
    h:=(w−W)*f; k:=n−N;
    l:=(wt−W)*f; m:=nt−N;
    D2:=dw2*coslat2[i]+dn2;
    p:=m*h−l*k;
    if D2*r2<p*p then goto next island;
    B2:=l*l+m*m;
    if B2>r2 and D2<abs(h*h+k*k−B2)
        then goto next island;
    comment §29f;
    if nfd or i≠initial island then
        goto island sighted;
    next island:
    end of island cycle;
comment §29g;
if range ≠6 then goto next range;
comment §30;
none sighted:
```

```
            if date=maxdate[v] then terminate(v,1) else
                begin
                raftlat[v]:=nt;
                raftlong[v]:=wt;
                end;
            goto next voyage;
            comment §31;
            island sighted: terminate(v,-i);
            goto next voyage;
            end of island check;
            next voyage:
            end of v cycle;
        end of date cycle;
    comment §33;
    endcycle:
    storelog(excyc+63*65536);
    if logcell≠0 then
        begin
        comment store partly used log block;
        write(4,logblock,logiii);
        logblock:=logblock+1;
        for logcell:=0 step 1 until 511 do
            logarray[logdt+logcell]:=0
        end;
    comment pack and store rescue parameters         §34;
    logarray[logdt]:=-1;
    logarray[logdt+1]:=rmv;
    logarray[logdt+2]:=cycle+1;
    logarray[logdt+3]:=logblock+1;
    logarray[logdt+4]:=landings;
    logarray[logdt+5]:=crewloss;
    logarray[logdt+6]:=bounds;
    logarray[logdt+7]:=galeloss;
    logarray[logdt+8]:=initial island;
    logarray[logdt+9]:=entier(100*initlat+0.1);
    logarray[logdt+10]:=entier(100*initlong+0.1);
    for i:=11 step 1 until 507 do
        logarray[logdt+i]:=1000*landfall[2*i-21]
            +landfall[2*i-20];
    write(5,experiment,logiii);
    write(4,logblock,logiii);
    logblock:=logblock+1;
    writetext(‘ ‘2c’RESCUE|OPERATION|
        PERFORMED ‘c’ PARAMETERS|SENT|UP|
        ARE:’);
    for i:=0 step 1 until 10 do
        print(logarray[logdt+i],1,0);
    for i:=0 step 1 until 511 do
        logarray[logdt+i]:=-2;
    readfwd(5,experiment,logiii,0);
    writetext(‘ ‘c’CHECK:||’);
    for i:=0 step 1 until 10 do
        print(logarray[logdt+i],1,0);
    newline(1);
    break output(0);
    end of main cycle;
comment §35;
    summary:
    writetext(‘ ‘3c’A|SUMMARY|OF|VOYAGES|IN|
        EXPERIMENT’);print(experiment,1,0);
    writetext(‘ ‘2c’ INITIAL|ISLAND’);
        print(initial island,1,0);
        print(initlat,4,2); print(initlong,4,2);
    writetext(‘ ‘c’NUMBER|OF|LANDINGS’);
        print(landings,4,0);
    writetext(‘ ‘c’NUMBER|OF|CREWS|LOST’);
        print(crewloss,4,0);
    writetext(‘ ‘c’NUMBER|OUT|OF|BOUNDS’);
        print(bounds,4,0);
    writetext(‘ ‘c’NUMBER|LOST|IN|GALES’);
        print(galeloss,4,0);
    writetext(‘ ‘c’TOTAL’);
        print(landings+crewloss+bounds+galeloss,4,0);
    writetext(‘ ‘3c’SUMMARY|OF|LANDINGS|ON|EACH|
        ISLAND
        ‘2c4s’(NOTE:||IN|EVENT|THAT|A
        ‘c6s’ RESTART|HAS|PROVED|NECESSARY,
        ‘c6s’ THE|THIRD|COLUMN|OF|THIS
        ‘c6s’ TABLE|SHOULD|BE|DISREGARDED)’);
    writetext(‘ ‘2c’ISLAND|||LANDINGS|||AVERAGE|
        JOURNEY(DAYS)’);
    for i:=1 step 1 until 994 do
        begin
        if landfall[i]=0 then goto no print;
        newline(1);
        print(i,4,0);
        print(landfall[i],6,0);
        print(days[i]/landfall[i],8,3);
        no print:
        end;
    writetext(‘ ‘3c’FINAL|VALUES|OF|PARAMETERS’);
    writetext(‘ ‘c’RMV’); print(rmv,12,0);
    writetext(‘ ‘c’LOGBLOCK’); print(logblock,3,0);
    terminate program: writetext(‘ ‘2’SO|ENDS|
        EXPERIMENT’); print(experiment,1,0)
    end
```

The Commentary

POLYNESIA 2 is a program which simulates 732 accidental drift voyages from a single starting point, two beginning each day of a 366-day year. The program is run in twelve "cycles," each comprising all voyages starting in a particular month; thus cycle 0 consists of voyages commencing in March, cycle 1 in April, and so on.

The coordinate system

The coordinate system used in the program is the ordinary latitude and longitude system. The position of any point is given in terms of degrees *north* of the equator and degrees *west* of Greenwich. The area of study is contained within the region ($-50 \leq$ north < 35; $70 \leq$ west < 210).

Dates

The year is taken to consist of 366 days, numbered 0 to 365, having alternate months of 31 and 30 days.

The **integer** *date* itself may actually take a value > 365. It will then be interpreted modulo 366.

The actual dates in each month are:

January	0–30	366–396
February	31–60	397–426
March	61–91	427–457
April	92–121	458–487
May	122–152	488–518
June	153–182	519–548
July	183–213	549–579
August	214–243	580–609
September	244–274	
October	275–304	
November	305–335	
December	336–365	

If the months are numbered January 1, February 2, . . . , and the quarters March/April/May 1, . . . , then

$month = (date * 2) \div 61 + 1$

$first\ day\ of\ month = entier\ (30.5 * month - 29.9)$

$quarter = month \div 3$

The initial month of any cycle is (*cycle* + 3).

Winds and currents

The wind and current directions are 16 in number, and are numbered clockwise starting at north, so that N = 0, NNE = 2, . . . , NNW = 15.

In each of these 16 directions, the wind may take 1 of 9 forces; the current, 1 of 5 strengths. Additionally, either may calm (i.e., force zero), which of course has no direction. There are therefore 145 wind and 81 current force-and-direction combinations, and these are numbered so that the wind of force f, direction d, is $9 * d + f$, and the current of strength s, direction d, is $5 * d + s$. Calm in each case is numbered 0.

The islands

The region of the ocean from which each island can be sighted is deemed to consist of one or more overlapping circles, each circle being specified by three parameters: the two coordinates of its center, and the sighting radius.

In the case of the larger ("continental") land masses, such as South America, Australia, and so on, considerable saving of space is effected by covering only the coastline. This leads to a minor restriction in the choice of starting points in order to prevent journeys passing into the interior.

In the region of Fiji, a sequence of island circles was noted forming a closed loop. This area was therefore taken as "continental," and the interior islands (none of whose areas protruded beyond the sequence) were eliminated.

The continuity of all coastlines was checked using ancillary program SEQ, and additions or alterations made where necessary. In one case a spurious island (929) was inserted to prevent voyages sailing inland via the Gulf of California.

Note that, where an island consists of overlapping circles, there is a "fringe" effect, whereby a landing could be missed if a voyage passed into and out of a cusp between two circles. This is mainly applicable to the long coastlines, where for reasons of economy the circles do not always have a substantial overlap. Any peculiar landings missed in this way, however, would be spotted on the microfilm output produced by program PV3.

§1 *Declarations*

(a) *Permanent data*

islat [1:994]	island latitude	*
islong [1:994]	island longitude	*
*ir*2 [1:994]	(island radius)²	*
coslat [1:994]	*cos* (*rad* * island latitude)	*
*coslat*2 [1:994]	*cos*²(*rad* * island latitude)	*
wind [1:9]	wind distances	
current [1:5]	current distances	
liferisk [1:183]	life probabilities	
block [−10:6,14:41]	base point within probability data for each 5 degree square	
isrange [−11:7, 13:42,0:7]	defines, for each 5 degree square, islands potentially sighted if the journey midpoint is in that square	

(b) *Constants*

pi	π
ang	$\pi/8$
rad	$\pi/180$
logdt, wdt, cdt *logiii, wiii, ciii*	give the subscripts and absolute machine addresses of the start of the first Atlas page in three arrays: *logarray*, *winddata*, and *currentdata*
c2, c4, c6	ancillary constants

(c) *Constants for the present experiment*

experiment	experiment number
first cycle	number of the first cycle in this experiment

* Island data.

initlat	the initial latitude of voyages in this experiment
initlong	the initial longitude of the voyages in this experiment
initial island	the number of the initial island (if any)

(d) *Summary data*

landfall[1:994]	number of landings on each island
landings	total landings
crewloss	number of crew losses
bounds	number out of bounds
galeloss	number of crew losses due to strong gale
days[1:994]	total number of days to reach each island

(e) *Data for the present voyages*

raftlat[1:62]	vessel latitude
raftlong[1:62]	vessel longitude
dormant[1:62]	**false** if voyage is active **true** before voyage starts and after it finishes
startdate[1:62]	initial date of voyage
maxdate[1:62]	date set for crew loss if voyage not previously terminated

(f) *Wind and current data*

winddata[0:30206]	wind probability data for the present and the following month (58 blocks + 511 cells)
currentdata[0:17918]	current probability data for the present and the following quarter (34 blocks + 511 cells)
wi	indicates which of the halves of **array** *winddata* is presently in use
ci	indicates which of the halves of **array** *currentdata* is presently in use
dtape	indicates which of the two magnetic tapes holding the data is presently in use

(g) *Logging data*

logarray[0:1022]	holds the present block of logging data
logblock	number of the next free block on logging tape
logcell	number of next free cell in logging block

(h) *Other parameters*

rmv	the random number procedure parameter
excyc,excyct	constants involving experiment and cycle numbers
cycle,date,month,quarter	give the present cycle, date,month,quarter
fd,ld,lq,lm	give the first day of first voyage, last (possible) day, last month and last quarter for voyages in the present cycle
fv,lv	give the numbers of the first and last voyages presently active in this cycle
v	gives the number of the voyage presently being moved
n,w,nt,wt	are the initial and final positions of the vessel on the present day for the present voyage
i,j,k,q	are workcells

§2 **procedure** *random*

This procedure generates random numbers in the range (0,1). A multiplicative congruential generator is used, and a global **integer** *rmv* is provided to preserve the most recent member of the underlying random integer sequence from one call to the next. This parameter is initialized and stored with the "rescue" data.

§3 **procedure** *pick*

procedure *pick* (*prob,m,n*), which is used for wind and current selection, chooses at random one of a set of k ($= 4(n - m) + 1$) alternatives, such that the i^{th} alternative occurs with relative probability $p[i]$ $(i = 0,1, \ldots ,k - 1)$. The relative probabilities are small integers and, for optimal storage, are packed in part of **array** *prob* four to a cell. Specifically, if

$$S[j] = \Sigma^{j}_{i=1}\, p[j] \text{ and } T = p[0] + S[k - 1]$$

then *prob* $[m]$ contains T, while for $j = 1, \ldots, n - m$, *prob* $[m + j]$ is in the form

S[4j]	p[4j]	p[4j − 1]	p[4j −
12	8	8	8

Essentially the procedure obtains a random number r in the interval (0,1) and determines w such that $S[w - 1] \leq T^* r < S[w]$, w being returned as the selected alternative. If $T * r \geq S[k - 1]$, w

is set to zero. The form of storage allows the procedure to search first for *nbr* such that

$$prob[nbr - 1] \leq 2^{24} * entier(T * r + 1) - 1 < prob[nbr]$$

after which it is necessary to unpack only *prob* [*nbr*] in order to find *w*. The search used is a mixed logarithmic and linear search chosen to be efficient in the specific cases $k = 81$ and $k = 145$ which arise in the program. **procedure** *split*, which is properly a code procedure employing shifts instructions, sets *a* to *S*[4**nbr*], *h* to *S*[4**nbr* − 1],*i* to *p*[4**nbr* − 1] and *j* to *p*[4**nbr* − 2].

§36 **procedure** *lifelength*

Data on the probability of crew loss are recorded in the **array** *liferisk*, in the form of a set of 183 values giving the relative probabilities that the crew will die on each of days 1, 2, 3, . . . , 183. On the basis of these probabilities, a survival time for the crew is selected before each voyage. **procedure** *lifelength* which carries out this operation ensures that the crew cannot survive beyond 183 days, thus giving a finite limit to the length of each voyage.

§8,9 *Atlas magnetic tape procedures*

On the Atlas computer, data are recorded on one-inch magnetic tapes in the form of addressed blocks each 512 cells long. The main store is divided into "pages" also containing 512 cells. Transfers necessitate moving a block of tape to a page of store, or vice versa.

Since, in general, an array will not begin at the start of a page, it is necessary that any array to or from which a tape transfer is to be made should be declared to have 511 extra cells. **procedure** *setbasepoints* (§8) is then called to determine for each such array the machine address of the first page wholly within the array and the array subscript corresponding to the first cell of this page. The other three procedures (§9) are self-explanatory. The somewhat unlikely choice for the fourth parameter of **procedure** *readfwd* is due to further properties of Atlas.

§11a,b *Initializing the permanent data*

The "permanent" data (see §1(a)) are prerecorded (using program UPPERMDATA 2) on blocks 1–17 of magnetic tape 2 (and also 3), and are brought to the permanent data arrays using **array** *currentdata* as a buffer. The tape transfers are initiated as early as possible (§11a), and take place simultaneously with some of the surrounding operations. The array initialization occurs subsequently (§11b).

The layout of the data on the magnetic tape is as follows (all data being stored in integer form):

blocks	*cells*	*data*	
1	 0–8	*wind*[1:9]	
	9–13	*current*[1:5]	
	14–196	700 * *liferisk*[1:183]	
2–3	. . . 1–994	100 * *islat*[1:994]	
4–5	. . . 1–994	100 * *islong*[1:994]	
6–7	. . . 1–994	island sighting radii (in nautical miles)	
8	 0–475	*block*[−10:6,14:41]	rightmost subscript varying most frequently
9–17	. . . 0–4559	*isrange*[−11:7,13:42,0:7]	rightmost subscript varying most frequently

§14

The **array** *days*, which are used to compute the average time taken to reach each island, are initialized to zero at the start of the experiment. Strictly speaking, they should have formed part of the rescue data, but this was precluded by the desirability of keeping the latter to a single block. If, therefore, a program restart is necessary, the average journey times printed in the summary must be disregarded. In §35, a warning to this effect is output.

§17

nv, the number of voyages in the present cycle, is set to 62 in even-numbered cycles, 60 in odd ones.

fd is set to the first day of the starting month of the present cycle.

§18 *Voyage initialization*

Each voyage is assigned a starting date (two start each day of the month), and a date on which the crew will expire if the voyage has not previously terminated (determined by **procedure** *lifelength* (§36)). The position coordinates of the vessel are initialized, and the voyage designated as "dormant." The last possible date for this cycle (*ld*) is determined as the maximum of the dates by which each crew will have expired; the last month (*lm*) and last quarter (*lq*) are respectively the month and quarter containing *ld*.

§19a,b

During the early stages of a cycle, the higher-numbered voyages will remain dormant because their starting dates have not yet been reached; at the later stages, there may well be a sequence of voyages starting at 1 which are dormant because they have terminated. In order to save each voyage from having to be tested for dormancy every day, **integers** *lv*, *fv* are used to delimit these sequences, *fv* denoting the first and *lv* the last currently active voyage.

These parameters are initialized to 1 (*fv*) and 0 (*lv*), §19a, and *lv* is increased by 2 each day (since two voyages start each day) until $lv = nv$, §19b. By testing whether any sequence of voyages starting at *fv* has become dormant, *fv* is updated daily. If $fv > nv$, the cycle may be terminated (and indeed most cycles end this way).

Once *lv* has reached *nv*, it would be possible to decrease it again if the voyage indicated by *lv* became dormant. Termination of the cycle would then occur if $fv > lv$, provided that all voyages had indeed become active.

§6,7,13,16,20,21 *Calling down wind and current probability data* (see Fig. 38)

The wind and current probability data for the complete year and the complete study area occupy 416 Atlas magnetic tape blocks. For use in this program they are written twice in succession on each of two magnetic tapes (logical numbers 2 and 3) starting at block 20 (the "permanent" data occupying blocks 1–17). Writing the data twice in succession (one-and-a-half times would have sufficed) saves the tape from having to be rewound during any cycle, since the latest possible date for any voyage to terminate is eighteen months after the start of the first voyage of the first cycle. By duplicating tapes, and using alternate tapes in successive cycles, delay due to waiting for tape rewind is avoided. (Theoretically, Atlas itself should utilize the delay time on other programs; in practice, this program occupies so much of the store that the sharing of time is impossible). The **integer** *dtape* indicates which tape is presently the one in use.

The wind data for each month occupy 29 blocks of tape, and the current data for each quarter 17. The layout of the tapes is as follows:

Blocks	*Data*	*Month*
20–36	current	March/April/May
37–65	wind	March
66–94	wind	April
95–123	wind	May
124–140	current	June/July/Aug
141–169	wind	June
170–198	wind	July
199–227	wind	August
228–244	current	Sept/Oct/Nov
245–273	wind	September
274–302	wind	October
303–331	wind	November
332–348	current	Dec/Jan/Feb
349–377	wind	December
378–406	wind	January
407–435	wind	February
436–851	repetition of blocks 20–435	

Thus the current data for any quarter begin on block

$$quarter * 104 - 84,$$

(taking March/April/May as quarter 1 [and 5]); while the wind data for month *m* begin on block

$$(m \div 3) * 17 + m * 29 - 67$$

(taking January as month 1 [and 13]).

The wind (current) data are brought to **array** *winddata* (**array** *currentdata*) in the main store a month (a quarter) at a time. In fact these arrays are large enough to hold the data for two complete months (quarters), and the transfers are initiated to one half of each array one month in advance of the data being needed. The transfer is thus able to take place while the program is utilizing the data in the other half of the array. **integer** *wi* (**integer** *ci*) indicates which half of the array is presently in use.

The data transfer algorithm consists of the following four parts, in which *W*(*a*), *W*(*b*), *C*(*a*), and *C*(*b*) denote the halves of the *winddata* and *currentdata* arrays, *C*(*ci*) denotes half of the *currentdata* array indicated by *ci*, *C*(∼*ci*) denotes the opposite half, and so on:

(a) At the start of the experiment, §13:
Bring the current data for the initial quarter of the first cycle to *C*(*b*), and the wind data for the initial month of the first cycle to *W*(*a*); set *ci* to *a*, *wi* to *b*, and *dtape* to 3 (this last is performed at §11a).

(b) At the start of each cycle, §16:
Unless this is the last cycle, position tape *dtape* for the start of the next cycle (i.e., at the current data block required for the first month of the next cycle); switch *dtape* (on all cycles). (Note: This rewinds the alternate tape on cycles 2–10, and advances it on cycle 1.)

(c) At the start of each day, §21:

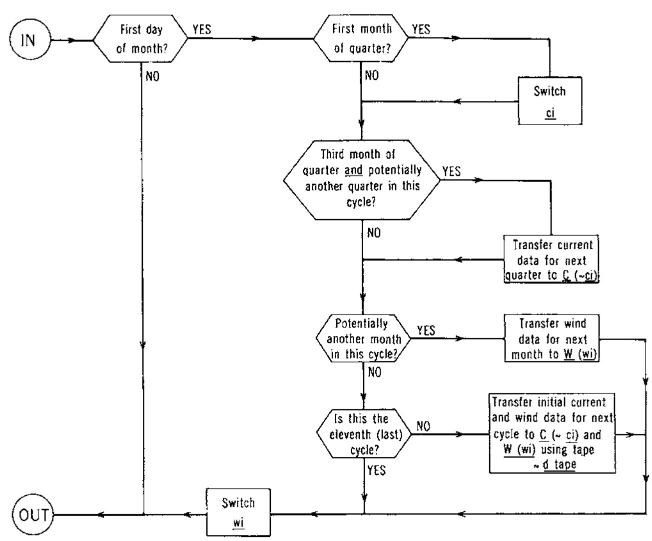


Figure 38. Wind and current data transfer test

(Note: Whether or not there is *potentially* another month or quarter in the present cycle is determined by considering *ld*, the latest date by which all crews on the cycle will have perished. If certain voyages terminate before their maximum permitted length, this month or quarter may not take place.)

(d) On premature exit from the present cycle, §20:
If, as in fact will usually occur, control exits from the date cycle before the date exceeds *ld* (i.e., because all voyages have terminated), *and if additionally* the start of the month containing *ld* has not yet taken place, then the program will have bypassed the section of §21 which brings down the data for the first month of the next cycle. Therefore we must:
bring the current data for the initial month of the next cycle to *C*(∼*ci*) and the wind data for the initial month of the next cycle to *W*(∼*wi*), using the alternate tape, i.e., ∼*dtape*.
This is, of course, omitted on the final cycle.

The **procedures** *switchci*, *switchwi* (§6, 7) are self-explanatory. The indicator *ci* takes one of the values 0(*a*) or 8704 (= 17 * 512, *b*); the indicator *wi* one of the values 0(*a*) or 14848 (= 29 * 512, *b*). The indicators merely serve as displacements for the base point of the data within the appropriate array.

§23,25 *Wind and current selection*

The small integers which give the relative wind (current) probabilities for a particular 5° square of the sea and a particular month (quarter) of the year are packed four to a cell (see §3), and occupy 37 (21) cells within the **array** *winddata* (*currentdata*). The exact position of the data in this array is deduced from the **array** *block*; more precisely, the data for the 5° square with southeast corner at (5**i*, 5**j*) are displaced (*b* − 1)*37 cells (for wind; (*b* − 1)*21 for current) from the start of the data for that month (quarter) where *b* = *block* [*i*,*j*].

Corresponding to any 5° square for which no data are provided, the *block* element is zero. A vessel drifting into such a square, or beyond the region ($-50 \leqslant$ north < 35; $70 \leqslant$ west < 210) is "out of bounds" (see §24).

The coordinates of the southeast corner of the square containing the vessel are found at §23, and wind and current selection take place at §25. The total displacement of the appropriate wind data from the base of the array is computed by summing the individual displacements for the Atlas magnetic tape system (*wdt*) for the half array in use (*wi*), and for the appropriate 5° square. A wind number (*wch*) is selected by calling **procedure** *pick*, and the direction (*wdir*), force (*wforce*), and distance moved under this force (*blow*) are computed. A similar sequence of operations is used to select the current.

§28 *Computing the new coordinates*

The position of the vessel at the end of the present day is computed in accordance with the wind and current selected. In the basic version of the model, the vessel travels with the wind and current, so that, for example, under a north wind the vessel moves south. Thus under a wind of direction *wdir* the direction of travel makes an angle $-(wdir * \pi/8)$ with the north-axis in the positive (i.e., anticlockwise) sense.

Each degree of latitude is 60 nautical miles, whereas a degree of longitude varies with the cosine of the latitude. The new west coordinate is computed using the cosine of the latitude of the day's starting point. The average distance covered in a single day for each wind force and current strength is given in nautical miles in **arrays** *wind* and *current* respectively.

§5,24,27,30,31 *Termination of voyage*

A voyage may terminate (a) if an island is sighted; that is to say, if any point on the line segment joining (*n*,*w*) and (*nt*,*wt*) falls within one of the sighting circles of an island, (b) if the crew exceeds its allotted lifespan (see §36), (c) if the vessel goes out of bounds; that is, if it goes outside the region $-50 \leqslant n < 35, 70 \leqslant w < 210$, or if it enters one of the 5° squares at the corners of the study area for which no data are provided, or (d) (with probability 0.5) if the vessel encounters a wind of Force 9. The total number of voyages terminating in each manner is recorded in the **integers** *landings*, *crewloss*, *bounds*, and *galeloss*, respectively.

If a vessel goes out of bounds during any day, the possibility of its having sighted an island is still checked (indeed, the "out of bounds" condition is not checked until the following day). The terminating conditions are tested in the following order:

out of bounds *on the previous day* (§24)
gale (§27)
landed (§29,31)
crew loss (§30)

If none of these conditions hold, the terminal coordinates for the present day are written back into the **arrays** *raftlat*, *raftlong* (§30). **procedure** *terminate* (*vy*, *rs*), §5, takes all the actions necessary when voyage *vy* comes to an end. It stores the terminator entry in the logging record, sets the appropriate element of **array** *dormant* to **true**, and prints a suitable output message. Parameter *rs* indicates which of the four possible reasons has caused termination as follows:

$rs < 0$ implies a landing, the island number being given by $-rs$
$rs = 1$ implies crew loss
$rs = 2$ implies out of bounds
$rs = 3$ implies gale

§29 *The island check*

The island check is the section of the program which determines whether a voyage has landed during the present day. Essentially this involves finding whether the line segment joining (n,w) to (nt,wt) intersects any of the island sighting circles. In order to prevent a high proportion of voyages terminating before they have got underway, there is a restriction against landing on the starting island during the first three days of voyaging.

Testing each individual island circle for an intersection on every day of every voyage would be prohibitively time-consuming (requiring as many as 20,000,000 executions of §29e for a single experiment), and is in fact unnecessary. Most of the islands are too far distant from any specific voyage.segment to merit consideration, and it is possible to arrange to test only those islands in the immediate vicinity of the journey. Specifically, we note that no day's journey can exceed 228 miles, and that no island circle has a radius greater than 38 miles; thus no voyage segment can intersect an island circle if its midpoint is distant more than 152 miles from the island center.

With this in mind, a preliminary program (PY 5) was used to list for each 5° square all islands whose centers fall within 152 miles of the square (actually, 180 miles was used). It was found that, by the addition of a few unnecessary islands in some of the squares, the lists could be summarized into at most four ranges (primarily due to the way in which the islands had been numbered —roughly east to west in each 5° band of latitude, with the bands from south to north). These ranges are stored in **array** *israngc*, those for the square having southeast corner at $(5*i,\ 5*j)$ occupying *israngc* $[i,jsr]$, $r = 1, \ldots, 8$. A zero lower bound indicates that there are no further ranges for this square. Since a half-day's journey may extend into one of the squares surrounding the initial position (but no further), the array includes ranges for a band of 5° squares surrounding the study area. It then suffices, for any given voyage segment, to apply the intersection test (§29e) to just those islands listed for the square containing the segment's midpoint. Selection of the appropriate islands is achieved by §29d,g.

If more than one island is sighted in a single daily journey, the program finds the lowest numbered, which is not necessarily the first encountered. Since it is not intended that the final results should attempt to differentiate nearby islands, this was considered to be adequate.

The central part of the island check is the individual island intersection test (§29e), which is based on the following:

Let $I\ (N,W)$ be the center of the island circle being tested, $S\ (n,w)$ and $F\ (nt,wt)$ the starting and finishing points of the day's voyage, and r the circle radius. Then (i) if angle IFS is obtuse (or right-angled), intersection occurs if and only if $IF \leqslant r$, (ii) if angle ISF is obtuse (or right-angled), intersection occurs if and only if $IS \leqslant r$, and (iii) if both angles are acute, intersection occurs if and only if the perpendicular distance (IE) from I to $FS \leqslant r$. Now IFS is acute if and only if $IS^2 < IF^2 + FS^2$ and ISF is acute if and only if $IF^2 < IS^2 + FS^2$. Therefore both angles are acute if $FS^2 > abs(IS^2 - IF^2)$. The sides of triangle IFS can be computed trivially from the coordinates, and IE can be found by considering the area of triangle IFS both directly and by subtracting right-angled triangles from the surrounding rectangle (see Fig. 39).

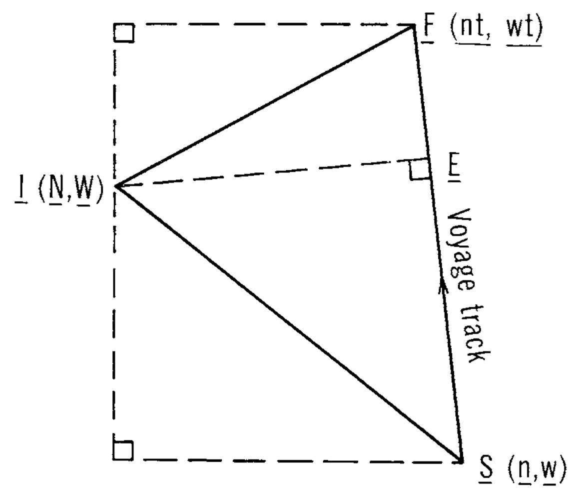


Figure 39. The intersection test

In practice, since §29e is the innermost loop of the program and is obeyed a great many times, some care has been taken to arrange the tests in an order expected to minimize the overall time of the program. In some cases assignments have been performed to avoid accessing the same element of an array twice in one iteration, since array access is considerably more time-consuming than simple-variable access; squares of distances have been compared to avoid taking square roots; and those components fixed for a given voyage are calculated outside the loop, at §29a. The comparison of IS with r is omitted altogether since IS is known to be greater than r. (Note: On any day after the first of a voyage, IS coincides with IF of the previous day, and so exceeds r, since otherwise the voyage would have ended the previous day. On the first day, S is the voyage starting point and is chosen to fall outside any island circle except the initial island. For if this were not so, and if the test $IS \leqslant r$ were included, all the voyages of the experiment would terminate on one island on the first day. The exceptional case, where I is the initial island, is dealt with below.)

As in the case of the coordinate computation (see §28), the ratio of distance to degrees in the East-West direction varies as the cosine of the latitude; and, in this case, the latitude of I (rather than S) is used in the calculations (otherwise the sighting circle of an island would vary from one voyage segment to another). Certain functions of the island parameters needed in the calculations are computed and stored in advance (see §11b).

The above remains valid if IF (or IS) is zero. If the length of the voyage segment (FS) is zero, then the island check is bypassed entirely (§29b). Note that the actual distance FS is $(dn2 + dw2cos^2\lambda)$, but the condition tested is equivalent, since no non-zero daily journey is less than 3 miles.

§29c,f *The initial island*

The point at which the voyages of an experiment begin is given by the coordinates (*initlat*, *initlong*). This point need not necessarily be an island, but if it is within an island circle then a high proportion of voyages might terminate on that island within the first few days (in fact, if the test $IS \leqslant r$ is included in §29e, *all* will do so on the first day). To avoid this, one of the islands may be designated the "initial island," and an arbitrary inhibition is imposed to prevent voyages landing on this island on the first three days (§29f). This is justifiable since the simulation is concerned only with voyages which actually leave the starting island. Note that only one island may be so designated, and no other landing circle should contain the starting point.

Actually the program as written does not fully implement the above intention; for example, if a voyage is within the initial island circle after three days and if its journey on the fourth day is zero, the inhibition continues. This makes no significant difference to the results.

Lastly it should be recalled that a "continental" landing circle must not be designated as "initial island" (and therefore a starting point cannot be directly on the coast of a "continent"), since otherwise there is nothing to prevent a voyage passing inland.

§4,12,15,26,33 *The logging record*

Throughout each experiment, whenever a (wind, current) pair is selected and whenever a voyage terminates, a 36-bit positive integer entry is made in the logging record. This enables all or any of the voyages to be reconstructed quickly and simply, if any subsequent analysis is required.

The structure of each entry is as follows:

9	4	7	1	8	7	
experiment	cycle	voyage	t	wind	current	wind/current entry (t = 0)
				reason	island	terminal entry (t = 1)
				3	12	

where experiment is the experiment number (1–511)

cycle — is the cycle number (0–11)
voyage — is the voyage number (1–62)
wind — is the wind selection (0–144)
current — is the current selection (0–80)
reason — is the reason for termination (0 if landing, 1–4 otherwise, see §5)
island — is the island number (if reason = 0)

The logging record is stored initially in **array** *logarray*, and is transferred to a magnetic tape (logical number 4) as each block is filled. Each cycle starts on a new block, the first entry being a "start of cycle marker" (voyage = t = wind = current = 0) and the last an "end of cycle marker" (voyage = 63, t = wind = current = 0). Following each cycle record is a copy of the rescue block at the end of that cycle. (Thus, in an emergency, an experiment can always be repeated starting at any cycle.)

At any time, the next free block on the tape is indicated by **integer** *logblock* (initialized with the rescue data), and the next free cell in *logarray* by **integer** *logcell*. Individual entries to the record are made by **procedure** *storelog(n)*, §4, which also carries out all the necessary housekeeping and transfers filled blocks to the magnetic tape. At the start of each cycle, §15, *logarray* is zeroed, the parts of the logging entries constant for that cycle are computed, and the "start of cycle marker" written.

Wind/current entries are written immediately after selection, §26, while terminal entries are written by **procedure** *terminate* (see §5). The "end of cycle marker" is written at §33, at which stage the partially filled block in *logarray* (if any) is sent to the magnetic tape. The tape is initially positioned as early as possible after the start of the experiment, §12, and the final value of *logblock* (indicating its final position) is printed during the summary output (see §35).

§10a,b,34 *Program rescue*

In order to avoid substantial loss of computer time in the event of machine failure, the program incorporates "rescue" facilities which enable it to be restarted from the beginning of the cycle being executed when the failure occurred. For this purpose one block (called the rescue block) is stored on a magnetic tape (logical number 5), and contains the values of all parameters needed to effect the restart. The layout is as follows:

cell 0	−1	cell 6	*bounds*
cell 1	*rmv*	cell 7	*galeloss*
cell 2	*firstcycle*	cell 8	*initial island*
cell 3	*logblock*	cell 9	100 * *initlat*
cell 4	*landings*	cell 10	100 * *initlong*
cell 5	*crewloss*		
cells 11–507	1000 * *landfall*[2*i−21] + *landfall*[2*i−20] in cell *i*		

Of these, 1, 2, 3, 8, 9, 10 are essential to resuming the program correctly; the others effect only the summary output and could if necessary be reconstructed from the logging tape. The factor 100 in parameter 9 and 10 makes these values integral for simplicity of tape storage.

The initial version of this block is prerecorded on the tape by a different program (UPRESCUE 4), and this is overwritten with an updated version at the end of every cycle. Whenever the program is entered, the parameters concerned are initialized from the data presently on the block. After failure, therefore, if the program is simply reentered from the start, the parameters are set back to the values current at the end of the last completed cycle.

To enable more than one experiment to be submitted to the computer center at one time, the rescue blocks for different experiments occupy different blocks on the tape, that for experiment *E* being on block *E*.

In detail, the operations are as follows: (a) at the start of the experiment: the rescue block is brought down as early as possible, **array** *logarray* being used as a buffer, §10a, so that some further operations can be performed while the transfer is taking place; it is subsequently unpacked, and items 0–10 are printed (§10b). (b) at the end of each cycle, §34: the rescue parameters are repacked, and the block is written to the rescue tape, a copy being sent also to the next free block on the logging tape; items 0–10 are then printed, and the buffer cleared to −2; the newly stored rescue block is then called back and items 0–10 printed again; **procedure** *breakoutput* is then called to enable the Atlas Supervisor Program to print the output from the cycle immediately, rather than hold it to the end of the program.

§35

The remaining section of the program prints a summary of the outcome of the experiment. The details are self-explanatory.

Variants and Ancillary Programs

POLYNESIA 3 (multiple experiment variant)

This program is the production variation of POLYNESIA 2 and runs several experiments in succession. The rescue blocks for each of these experiments are recorded on consecutive blocks of the rescue tape (the experiments must therefore be numbered consecutively), terminated by a dummy rescue block having the value of parameter *firstcycle* equal to −1. After completing each experiment, the program returns to §10a to call down the next rescue block. The value of the *firstcycle* is tested. If it is 12, then this experiment has already been completed and the program proceeds to the next; if −1, the program is terminated.

The rescue facilities of POLYNESIA 2 are thus preserved; in the event of a restart, the program will begin at the first rescue block, but will skip blocks until an incomplete experiment is found.

Wind shift experiments are also run by POLYNESIA 3, the only difference being in the data prerecorded in array block.

POLYNESIA 4 (repeat-month variant)

POLYNESIA 4, the "repeat-month" variation, is used to obtain additional voyages for any starting month of an experiment which seems of special interest. This is achieved by arranging that successive cycles begin in the same, rather than successive, months. In this way, 744 or 720 extra voyages are provided according to whether the starting month is odd or even; a lesser number can be obtained by arranging for the prerecorded rescue block to have its *firstcycle* parameter greater than 0.

In this variation an additional parameter, *stm*, is needed in the rescue block to store the required starting month. This is placed in cell 511, and the corresponding additions made to §10b, §34.

POLYNESIA 5 (reverse-voyage variant)

POLYNESIA 5, the "reverse-voyage" variation, causes voyages to be simulated from finish to start, by having the wind and the current pull the vessel and by having the date run backward. This is achieved simply by altering the signs in the expressions for computing *nt* and *wt* (§28), and by reordering the wind-current data tapes as follows:

block 20–36	current	Dec/Jan/Feb
37–65	wind	February
66–94	wind	January
and so on		

Internally, day 61 then comes to be regarded as the last (and day 62, the last but one) day of February rather than the first (and second) day of March. This is rectified on output by subtracting the date from 487 (and rendering the result modulo 366) prior to printing.

This actually has the effect of making February, December, October, . . . , 31-day months, and January, November, September, . . . , 30-day months—the opposite of the situation in forward simulation. In this and a number of other respects an antisymmetry exists between reverse and forward voyages.

POLYNESIA 6 (intentional voyage variant)

Once a daily wind/current combination has been chosen, intentional voyaging according to some specified strategy can be achieved by altering the coordinate computation to conform with the strategy. In the instance employed in this study, the strategy is to sail as close as the wind permits (that is, no closer than 90° to the wind) to some given "direction of intended sailing."

This is arranged by setting up an array which is used to translate the wind direction selected for the day into a "pseudo-wind-direction." For example, if the direction of intended sailing is east, then all winds from north through west to south have pseudo-wind-direction west, and so on. Current is unaffected.

As in POLYNESIA 4, an additional parameter is required in the rescue block to indicate the direction of intended sailing, and again this is placed in cell 511.

Other programs

Other programs were written to prerecord the rescue data (UPRESCUE 4, 5) and the "permanent" data (UPPERMDATA 2); to prepare and check the island and *isrange* data (SEQ, PY1–5); to assemble and check the wind and current probability data (UPPROB); to produce individual voyage logs (VT 4), cartograms (DCS 3,4) and microfilms (PV 3,4,5) from the logging tapes; to prepare summaries (ISLIST 2, POLYSUMMARY) from the rescue tape; and for several other purposes.

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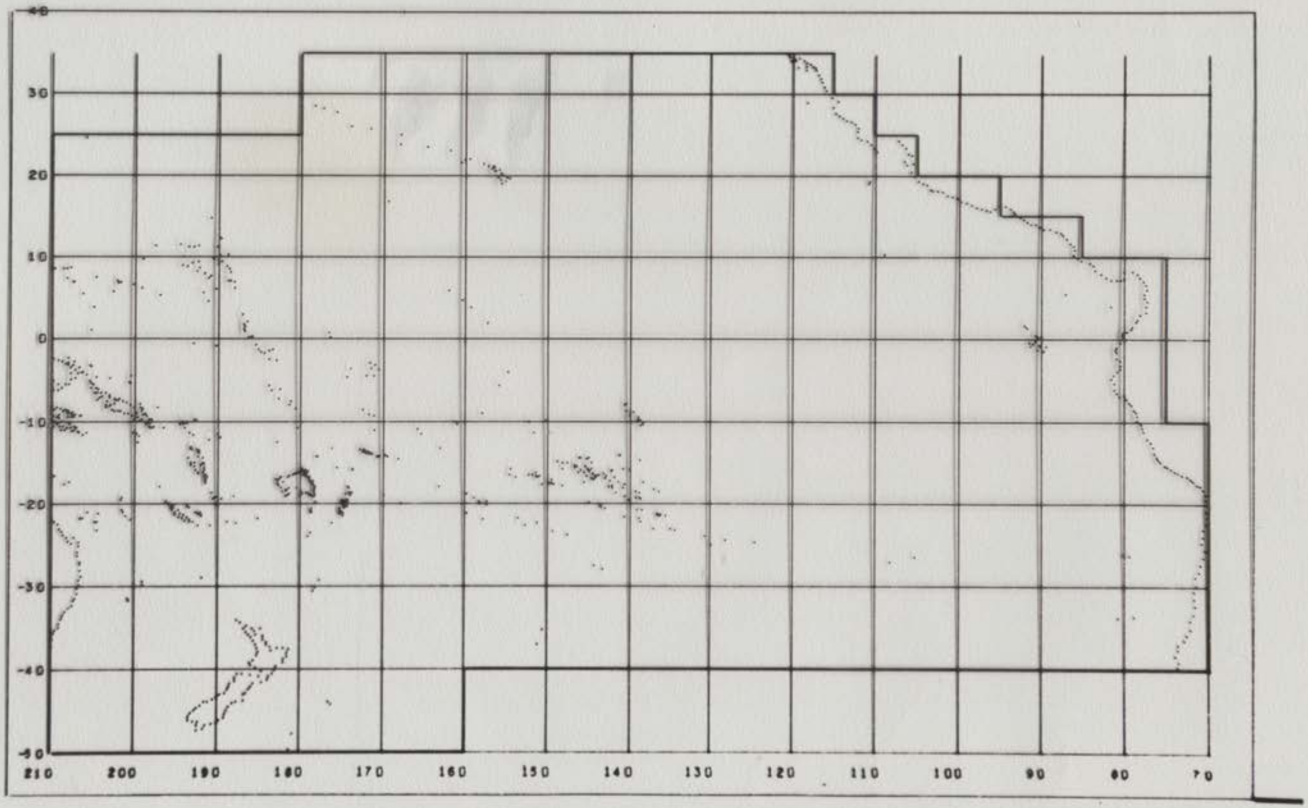
Overlay for Computer Maps



FROM FRONT FLAP

demonstration of how computer technology may be applied to a wide variety of research in the social and physical sciences.

The authors devised a computer program which simulated Pacific voyaging in its many aspects and variations. Data about winds, currents, islands, and many other pertinent matters were incorporated in the program. Using this model they conducted experiments which showed the outcomes of hypothetical voyages representing many possible variations which real voyages might embrace. The authors describe the experiments and discuss the results and conclusions, illustrating them with numerous maps and cartograms. Computer-drawn maps are included in an appendix.

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