A Computer Model of the Exploration of Western Oceania

by

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Abstract

The initial discovery and settlement of the islands of Oceania is an important issue in Pacific anthropology. I test two methods by which new island groups might be discovered: drift voyages and downwind sailing. I focus on the region of the initial eastward expansion into Remote Oceania by the Lapita people. Simulations are driven by high resolution surface wind and current data from atmosphere and ocean models forced by real observations and which capture the high degree of seasonal and interannual variability in the region.

Both drift and sailing voyages can account for the discovery of all the islands in the Lapita region based on initial starting points in the Bismarck and Solomon archipelagos. Eastward crossings are most probable in the Austral summer and fall when the probability of occurence of westerly winds is highest. Contact with islands in the arc from Santa Cruz to New Caledonia is viable in all years and is particularly probable in the Austral summer. Pathways further to the east as far as Tonga and

Samoa are plausible when considering anomalous westerlies which occur in certain years. Other key crossings in Polynesia are also possible when considering this interannual variability, much of which is associated with El Niño events. Many of my findings differ from an important, earlier modelling study performed by *Levison et al.* (1973).

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Chapter 1

The Colonization of Oceania

1.1 Introduction

The settlement of the islands of Oceania required that thousands of kilometers of open ocean be crossed in stone-age vessels and must surely rank amongst the most impressive achievements of mankind, but exactly how it occurred is unclear since nothing definite is known about navigation skills nor vessels used during periods of colonization (*McGrail* (2001)).

Oceania is here defined as the islands of the central and south Pacific Ocean, excluding island South-East Asia and Australia. Traditionally, the region is sub-divided into *Melanesia*, *Micronesia* and *Polynesia* (Figure 1.1). Melanesia includes islands in the western Pacific, south of the equator, from New Guinea to Fiji; Micronesia encompasses the islands north of the equator and east of the Philippines extending west to the Line Islands and Polynesia is roughly defined as the islands within the triangle defined by New Zealand, Hawai'i and Easter Island.

The dates of initial settlement of many Pacific island groups are still debated owing to differing interpretations of the radiocarbon and environmental record from these regions (*Spriggs and Anderson* (1993)). As such, some of the settlement dates presented in this work may be subject to revision. All dates in this document are presented as calendar years before present (cal BP). These dates should be recognized

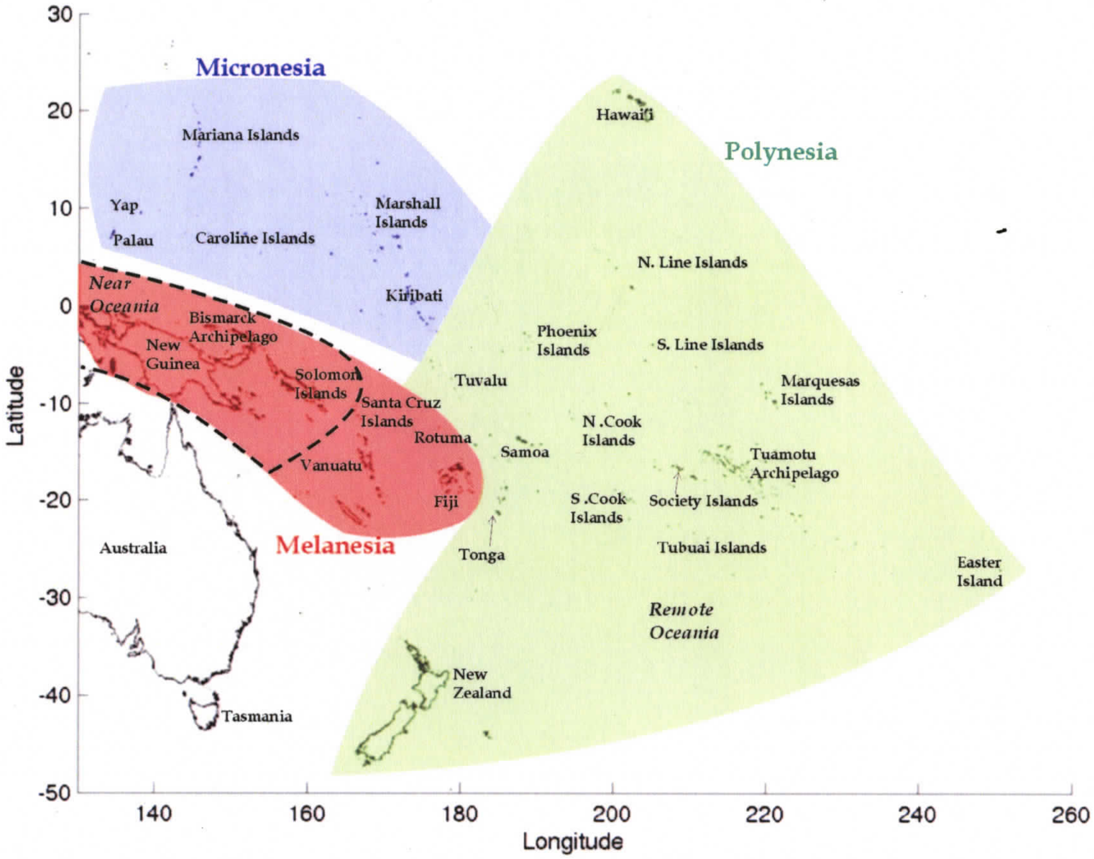

Figure 1.1: A map of Oceania. The colored regions show the traditional division of the region into Melanesia, Micronesia and Polynesia. The dashed black line shows the division between Near Oceania and Remote Oceania. Major islands and island groups are identified. The coastlines of Pacific landmasses are identified from the GLOBE 30" DEM dataset.

as estimates based on the synthesis of dating results from specific sites and artifacts (each of which has associated uncertainty) and not definite settlement times.

Presently, the settlement of the Pacific is seen as an episodic process with periods of rapid dispersal interspersed by long pauses. Humans first arrived in Australia, Tasmania and New Guinea between 60,000 - 40,000 cal BP (*Stringer* (2000)), during the Pleistocene epoch when sea levels were lower and these three landmasses were connected, forming a continent called Sahul. Sahul was never directly connected to South-East Asia during the Pleistocene, but was separated by an island-filled waterway called Wallacea, indicating that the initial settlers of this region must have had at least rudimentary maritime technology.

New Britain and New Ireland, the large islands of the Bismarck Archipelago, lying to the north-east of New Guinea and separated from Sahul by a narrow deep water trench, were reached by at least 35,000 cal BP (*Kirch* (2000)). The Solomon Islands, extending to the south-east of the Bismarcks, were also reached from Sahul or the Bismarcks during the Pleistocene. Buka, one of the most northerly islands in this chain, had human occupation by about 29,000 cal BP (*Spriggs* (1997)). There is a paucity of archaeological sites dating to this epoch in the Solomons and it is unclear exactly how far down the chain the initial settlements extended. However, during the last glacial maximum, sea levels were approximately 120 m lower than at present and Buka formed part of a large island which encompassed much of the present-day Solomon group (*Nunn* (1998)) and would have allowed early Melanesians to reach additional sites to the south-east by land. The remainder of Oceania, including the Santa Cruz and Vanuatu island groups, lying to the east and south-east, respectively, of the Solomons, was not settled until much later. The Oceanic island groups which began to be occupied beginning in the Pleistocene define a region called *Near Oceania* which extends from New Guinea to the southern tip of the Solomons (Figure 1.1), while the remaining Pacific Islands make up *Remote Oceania*.

It is unclear why the 350 km crossing from the southern Solomons east into the Santa Cruz Islands presented such a formidable barrier to the early explorers and settlers of this region. One possible explanation is that early explorers could have reached from mainland South-East Asia to the Solomon Islands by means of a series of *intervisible* water crossings wherein the destination island became visible before the departure island had sunk below the horizon (*Irwin* (1992)). Thus, the main island groups of Near Oceania could have been discovered as a result of cautious exploration by early seafarers who always remained within sight of land. In contrast, the islands of the Santa Cruz and Vanuatu groups were never connected to the Solomons via intervisible crossings, even at times of greatly reduced sea level.

The settlement of Remote Oceania began about 3,600 cal BP with a dispersal from the west into the Mariana Islands in Micronesia. At about the same time, the archaeological record of Near Oceania reveals the appearance of a new culture occupying coastal areas of the region (*Hurles et al.* (2003), *Kirch* (2000)) with the earliest sites found in the islands of the Bismarck Archipelago. This new, likely alien culture is characterized by a distinctive style of stamped pottery and is called the *Lapita* culture. Beginning about 3,200 cal BP, the Lapita peoples rapidly expanded into Remote Oceania, establishing settlements in the proximal Santa Cruz Islands and to the south in Vanuatu, New Caledonia and the Loyalty Islands (*Sand* (2000)). Another branch of the expansion moved eastward, colonizing the islands of Fiji and Tonga and Samoa, in marginal western Polynesia. Most major archipelagos in both branches of the expansion were likely settled by 2,750 cal BP at the latest (*Sand* (2000), *Sand et al.* (2002)).

Following the Lapita dispersal, eastward expansion into Remote Oceania appears to have stalled for somewhere between 500-1,700 years (*Irwin* (1998), *Anderson* (2003)), with recent evidence supporting a longer pause (*Hunt and Lipo* (2006)). During this pause, Lapita descendants dispersed into central-eastern Micronesia (likely

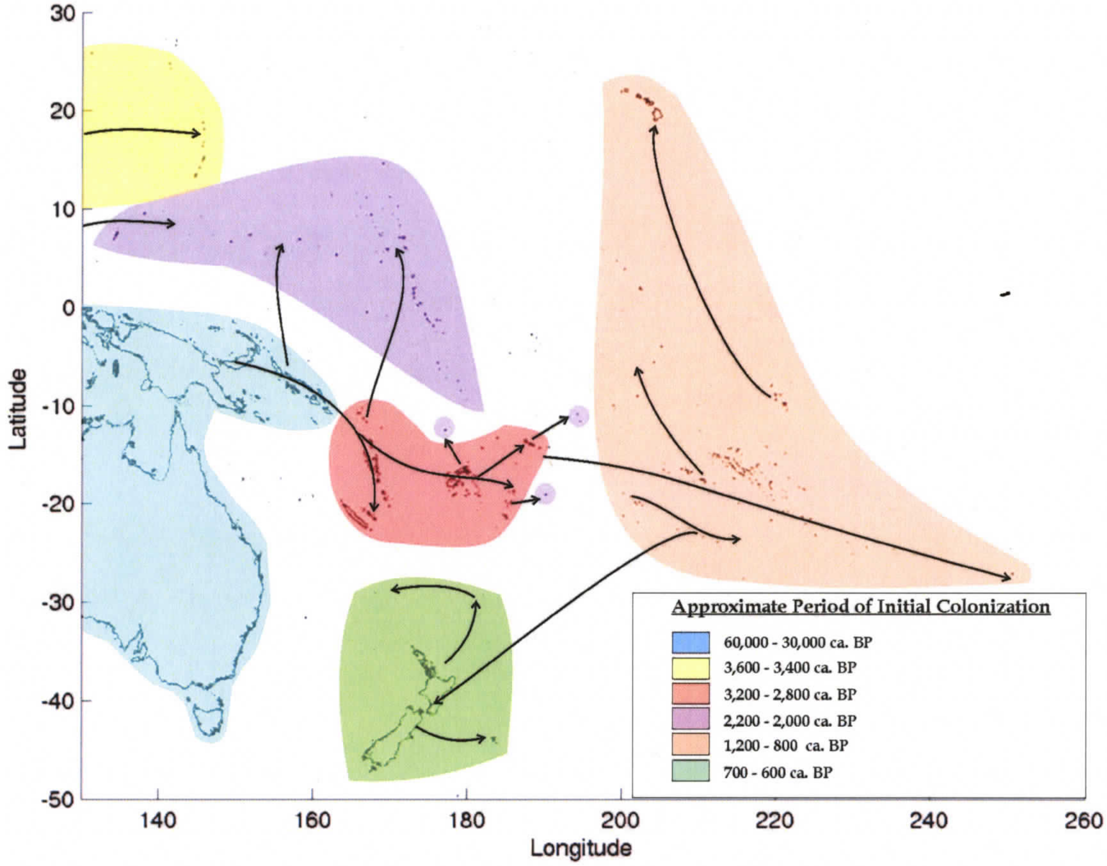

Figure 1.2: The settlement of the Pacific. Colonization occurred as the result of episodic waves of colonization separated by relatively long pauses. The colored regions of the plot show each of the waves of colonization and suspected directions of movement. The dates presented in this figure assume a long pause in western Polynesia with eastern and southern Polynesia colonized relatively recently. This figure is based on maps and information from *Anderson et al.* (2006), *Intoh* (1997)

from the Solomon and Vanuatu groups) and into Pukapuka (in the Northern Cooks), Niue and Rotuma (*Intoh* (1997), *Anderson* (2003)). Additional migrations from Asia into western and central Micronesia also likely occurred during this time period.

The colonization pattern of the rest of Oceania, east of the Lapita region, remains hazy, though it is generally accepted that the archipelagos in Central Polynesia were settled in advance of the marginal northern, southern and eastern archipelagos from a dispersal point in western Polynesia. *Kirch* (2000) suggests colonization might have proceeded along a south-eastern arc from western Polynesia towards the northern Cooks, Society and western Tuamotu groups with a second arc passing through the Southern Cooks and Austral Islands thence upwards to the Eastern Tuamotus and the Marquesas islands. Both *Anderson* (2003) and *Kirch* (2000) agree that Hawai'i was likely reached from the Marquesas islands, and southern Polynesia, including New Zealand and surrounding island groups, was reached from the Southern Cooks or the Australs. The colonization of southern Polynesia was the last phase of Oceanic colonization and likely occurred beginning about 700 cal BP (*Anderson et al.* (2006)).

1.2 Navigation and Maritime Technology

Prehistoric remains of Oceanic boats are extremely scarce and those that have been found are very fragmentary (*McGrail* (2001)). Linguistic reconstructions reveal Proto-Oceanic terms for sails, outriggers and planks, hinting at the type of vessels that might have been used by the earliest seafarers (*Kirch* (1997)). European explorers who visited the region beginning in the 16th Century observed the use of log rafts, single-hulled canoes (with and without outriggers) and double-hulled canoes. Of these, the double-hulled canoes seem best suited for lengthy sea voyages as they could be quite large, more than capable of carrying enough cargo to survive a long sea voyage or to establish a founding settlement on a new island (*McGrail* (2001), *Sharp* (1963)). However, *Anderson et al.* (2006) argue on the basis of linguistic evidence that double hulled canoes were developed only after the colonization of western Polynesia had been accomplished and that early stages of colonization were accomplished using outrigger canoes and rafts.

The navigational skills of Pacific peoples have been extensively debated and there seems to be little doubt that repeated contacts occurred between widely separated island groups in Melanesia and Polynesia at some point in prehistory, within so-called *interaction spheres*. Europeans at the time of contact reported that mariners knew directions to distant islands and in some cases had sophisticated traditional navigation methods based on celestial observations. Further, x-ray fluorescence analysis has demonstrated the transfer of basaltic adze material over thousands of kilometers (*Weisler* (1998)), helping to quantify the extent of interaction spheres [1]. Presumably settlement of newly discovered islands would also have required some form of navigation or at least directed sailing for colonists to arrive at their destination. But all of this behaviour would haved occurred after islands had been discovered and says nothing about the means by which they were first discovered.

At present, the favored view of Pacific exploration (best stated by *Irwin* (1992)) is that explorers were competent mariners who systematically explored the Pacific. These mariners might have refined their voyaging skills in the safe 'voyaging nursery' of the intervisible islands of Near Oceania where there are predictable seasonal reversals of wind and current. Voyages of exploration into Remote Oceania would then initially proceed against the direction of the prevailing winds so that explorers could rely on a rapid return voyage home by sailing downwind, thus minimizing losses at sea. Outbound voyages could be made by tacking against the winds, or by astute navigators who exploited sustained periods of winds from other directions (*Finney et al.* (1989)). *Anderson et al.* (2006) have argued that maritime technology at the

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[1] *Weisler* (1998) makes the case that one large interaction sphere extended from Santa Cruz through Fiji, Tonga and Samoa, north to Tuvalu and Tokelau in Micronesia and east to the Cook islands. There is also good evidence for extensive exchange networks within the Bismarck and Solomon archipelagos, beginning in the Pleistocene.

time of colonization was not sufficiently advanced to allow crews to make any significant progress against the winds, supporting the latter suggestion. Voyages down the direction of the dominant winds would be considerably riskier since the return trip home could not be assured. Part of the appeal of this theory is that the first waves of Oceanic expansion, through Melanesia and from western to central-eastern Polynesia, were eastward and against the easterly trade winds. Later, when technology and sailing abilities improved, explorers would sail across and then down the winds on their outbound voyages, allowing them to settle the most distant islands of Oceania.

In an earlier view, best advanced by *Sharp* (1963), Oceanic explorers lacked the navigational knowledge to complete two-way voyages of exploration. A vessel's course could have been crudely estimated by observing its motion relative to the wind. This 'dead-reckoning' technique could not account for the effects of ocean currents and lateral drift, which might introduce significant errors. Latitude could have been gauged from the stars, but no measurement of longitude was possible and, lacking this, voyagers would have no means of accounting for longitudinal errors in course [2]. With a sufficient understanding of regional waters, the reckoning system might be revised to counter such errors, but such knowledge would not be available to those who dared explore uncharted waters, making accurate navigation home impossible. For these reasons, *Sharp* (1963) argues that one-way voyages, either intentional or accidental, must have played an important role in the settlement of Oceania. Motivation is another issue with *Irwin* (1992)'s model; it is unclear why explorers would make difficult voyages of exploration seeking islands whose existence was unknown, especially since some have argued that the archaeological record of initial settlements in Remote Oceania implies a low population density (*Irwin* (1998)). Had new islands been discovered by accident, then this could serve to motivate later voyages of

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[2] *Irwin* (1992) argues that any longitudinal errors in course could be overcome through the use of the 'latitude sailing' technique wherein crews would sail to the latitude of their destination and then sail along that latitude to reach their destination. However, there is no evidence to suggest that this technique was ever used in pre-historic Oceania

exploration and settlement to return to the new discoveries.

1.3 Scope of Work

In this work I use a computer model to test two aspects of these different hypotheses: discovery of new islands by drifting vessels and downwind sailing. The former is one method by which the one-way voyaging proposed by *Sharp* (1963) may have occurred. Downwind sailing is a simple model of deliberate exploration in which crews intentionally orient their boats to move with the wind for ease of sailing. Such crossings can be either with or against the prevailing winds depending on the orientation of the winds experienced locally by the ship. I focus on the area of the Lapita expansion: a clearly defined geographic region whose initial colonists have a well-defined point of origin in the islands of Near Oceania (Figure 1.3). The area also presents an interesting case study as it is subject to strong seasonal and interannual variability in weather conditions.

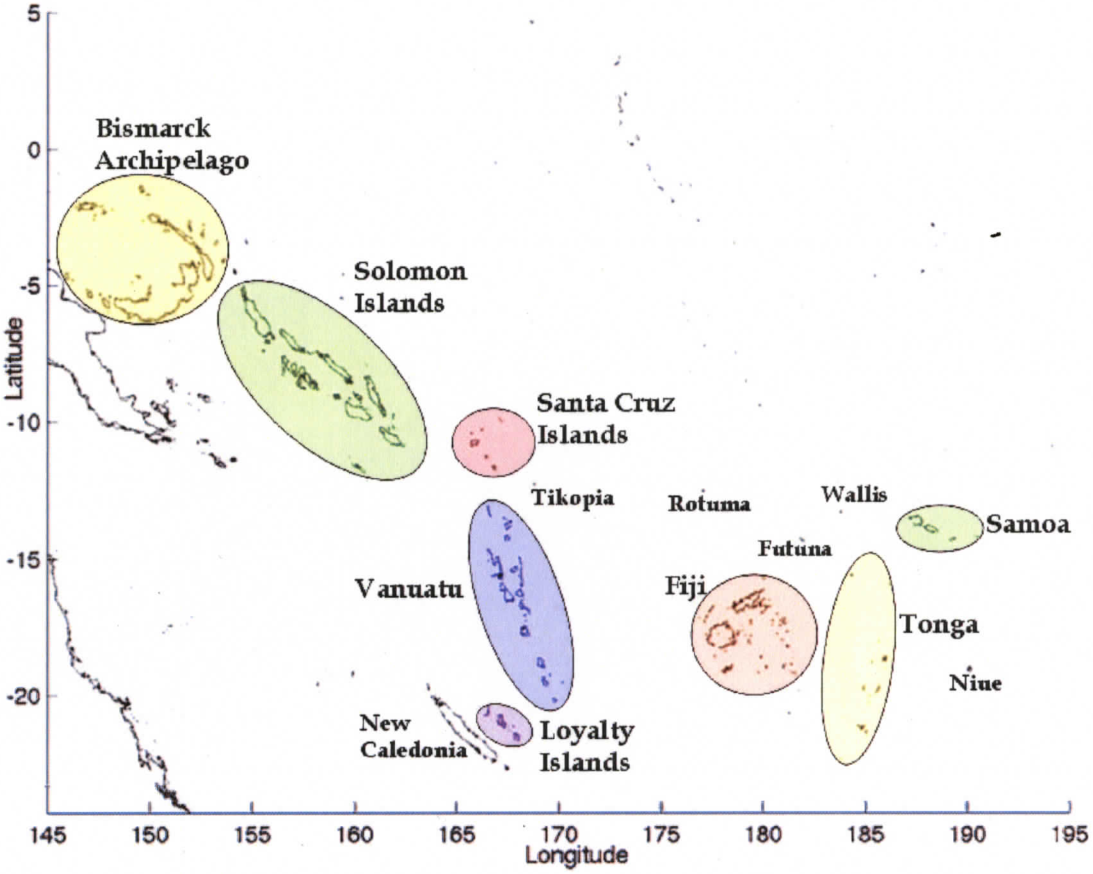

Figure 1.3: The islands of Near Oceania and the Lapita expansion. Islands are arranged according to conventional geographic groupings. The coastlines are identified from the GLOBE 30" DEM dataset.

Chapter 2

Climate of the Study Area

2.1 Climate at the Time of Colonization

Surface wind and current data which accurately reflect conditions at the time of initial colonization are needed to drive the simulations devised in this work. *Markgraf et al.* (1992) produced paleovegetation maps for the major landmasses of the southern Pacific based on pollen records from Australia, New Zealand and South America. Pollen records reflect the dominant vegetation in a region at a particular time, by recording the varying abundances of plant species dispersed by pollen transported by the wind. Such plant abundance records are in turn indicative of past precipitation and temperature conditions. Using these vegetation records in tandem with other available paleoproxies, *Markgraf et al.* (1992) estimated the state of the climate across the southern Pacific at five time periods between 18,000 and 3,000 cal BP. They concluded that the Australian monsoon circulation had been established and at its present strength by 6,000 cal BP and that the atmospheric circulation across the Pacific was essentially the same as in the present day climate by 3,000 cal BP. Since the Lapita expansion began just prior to this time, I make the assumption that the present day climate is a reasonable approximation to that at the time of colonization.

2.2 Surface Winds

The surface winds in the study area show distinct annual fluctuations. During the Austral winter, the wind field is dominated by the strong south-east trade winds (Figure 2.1). The Inter-Tropical Convergence Zone (ITCZ), a region of persistent convection and cloud formation associated with the intersection of the south-east and north-east trade wind belts (*Vincent* (1994)), lies to the north of the Lapita region.

The circulation is more complicated during the Austral summer (Figure 2.3). During this time, the north-east trades strengthen, the south-east trades weaken and the ITCZ shifts south, generally extending from New Guinea south-east towards Tonga and Samoa. In addition, the surface winds reveal the influence of the Australian monsoon circulation associated with a low pressure centre which extends from northern Australia eastward into Melanesia as a result of heating of southern hemisphere land masses during the summer months. This complicated circulation results in a band of north-westerly surface winds which generally extends into the Lapita region from the south-east coast of New Guinea through the Santa Cruz islands and partway to Fiji.

2.3 Surface Currents

Mean surface currents in the equatorial Pacific are largely driven by wind-stress. In the study area, the dominant current is the broad, westward flowing South Equatorial Current (SEC). During the Austral winter, this current extends from the equator to about 15° S (Figure 2.2). As it encounters the Australian continent, the SEC deflects to the south, forming the East Australia Current. In this season, the North Equatorial Counter Current (NECC), a narrow continuity current, flows eastward in a band from the equator to about 5° N.

In Austral summer (Figure 2.4), the NECC shifts to higher latitudes and another east-ward flowing current, the South Equatorial Counter Current (SECC), forms in response to the surface winds of the summer monsoon. The SECC typically forms in a narrow band from 5° S to 10° S and extends from the northern coast of New Guinea through the Solomon Islands to the north-east of Samoa.

2.4 Interannual Variability

Wind reversals associated with the Australian monsoon occur predictably within the western Lapita region, from New Guinea to the Santa Cruz region, where they dominate the summer wind field, and occur progressively more intermittently east of Santa Cruz. These winds occur in Fiji and further east, but they are much more episodic and occur in shorter bursts. For example, *Finney et al.* (1989) cite historic records of monsoon winds which extended as far east as the Societies and Southern Cooks and state that, on rare occasions, such winds may even reach as far east as the Marquesas. Thus, while the mean winter wind field provides an indication of the region where there are reliable monsoon winds, the actual eastward extent of such winds in a particular year may be much greater.

A larger-scale phenomenon which can also cause extended periods of anomalous westerlies within Melanesia and Polynesia is El Niño / the Southern Oscillation (ENSO), the dominant source of interannual variability in the equatorial Pacific. In the mean state, the easterly trade winds make up the bottom arm of the zonal Walker circulation cell which spans the tropical Pacific. Accumulation of warm surface water in the western Pacific by these winds warms the air and results in a region of rising air and low surface air pressure; in the east, cold, upwelling water from depth cools the surface air and leads to a region of subsidence and high surface air pressure. Westerly winds aloft form the remaining branch of the circulation. The zonal sea level pressure (SLP) gradient reinforces the easterly trades, demonstrating the coupling between atmosphere and ocean that is a key aspect of this circulation.

El Niño events are identified by a strong and sustained increase in the sea surface temperature (SST) of the eastern equatorial Pacific. This influences the surface air temperature across the basin and results in a reduction of the zonal SLP gradient, in turn reducing the strength of the easterly trade winds. During very strong El Niño events, the surface winds of the western-central Pacific may reverse as the pool of warm surface water sloshes eastward. La Niña episodes are associated with negative SST anomalies in the eastern Pacific resulting in an increase in the zonal SLP gradient and the strength of the Walker circulation and the trade winds.

In the present climate, ENSO is irregular, displaying variation in the amplitude and frequency of El Niño / La Niña episodes. Successive events of the same phase generally occur every 3-5 years, setting a timescale for ENSO-related climatic variability. Analysis of paleoproxies from regions of the world strongly affected by this phenomenon indicates enhanced environmental variability starting about 5,000 cal BP (*Markgraf and Diaz* (2000)). This suggests that around this time, ENSO had begun to behave as it does in the present climate, although the frequency of occurrence of El Niño conditions seems to have varied since the mid-Holocene (*Moy et al.* (2002)).

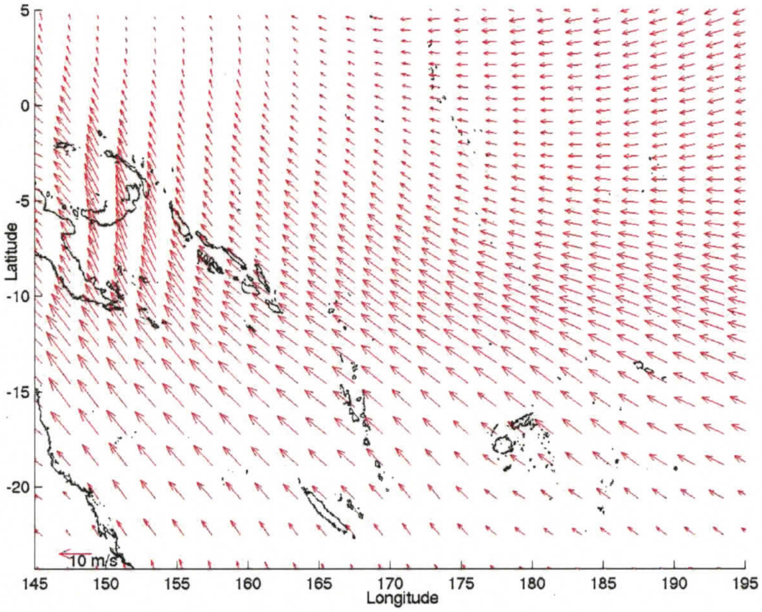

Figure 2.1: Surface winds in the Austral winter. The data come from monthly long-term means from the NCEP/NCAR reanalysis project (*Kistler et al.* (2001)). A reference 10 m/s vector is included in the bottom left corner.

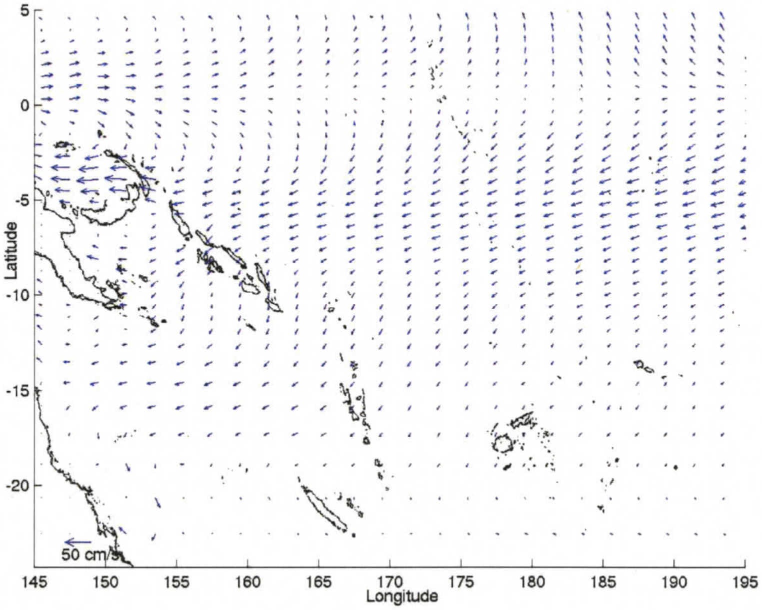

Figure 2.2: Surface currents in the Austral winter. The data come from MITgcm ECCO experiment (*Stammer et al.* (2002)) runs for 1993-2005. A reference 50 cm/s vector is included in the bottom left corner.

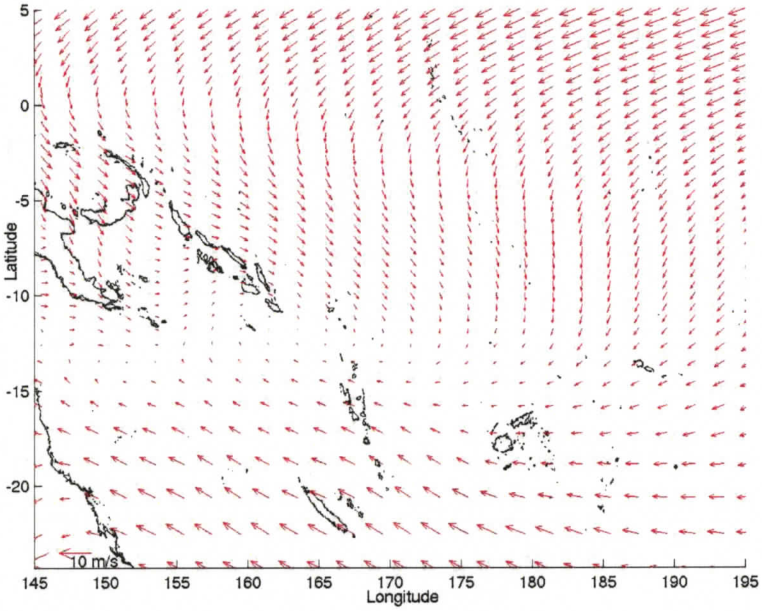

Figure 2.3: Surface winds in the Austral summer. The data come from monthly long-term means from the NCEP/NCAR reanalysis project (*Kistler et al.* (2001)). A reference 10 m/s vector is included in the bottom left corner.

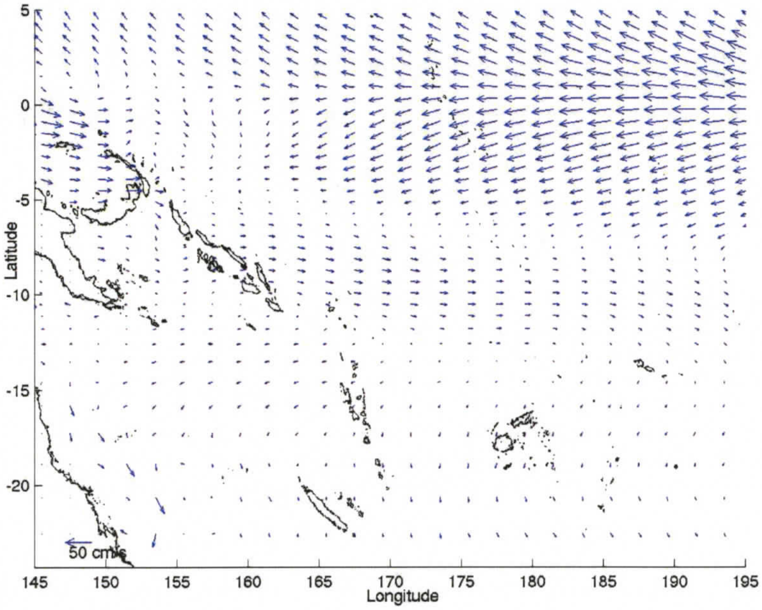

Figure 2.4: Surface currents in the Austral summer. The data come from MITgcm ECCO experiment (*Stammer et al.* (2002)) runs for 1993-2005. A reference 50 cm/s vector is included in the bottom left corner.

Chapter 3

Model Methodology

Drifting experiments were performed using a variant on a computer drift model developed by *Montenegro et al.* (2006). The model uses surface wind and current data derived from numerical models adjusted by observed weather data to generate vessel trajectories under the assumption that vessels are simply drifting at sea with no attempt by the crew to sail or navigate. It was originally designed to study prehistoric ocean crossings into the Americas and was subsequently used to investigate the introduction of the sweet potato into Polynesia (*Montenegro et al.* (2007)).

3.1 Wind and Current Data

The surface wind data used in the simulation are daily mean winds that came from the *National Center for Environmental Prediction / National Center for Atmospheric Research* (NCEP/NCAR) reanalysis product. These data were produced by combining empirical observations with a mathematical model of the atmosphere to generate a best estimate of the state of the atmosphere at a particular time (*Kistler et al.* (2001)). The NCEP/NCAR data have a horizontal resolution of approximately 1.9° x 1.875° [1] and were provided by the NOAA-CIRES Climate Diagnostics Center located in Boulder, Colorado.

Ocean current data were taken from the *Estimating the Circulation and Climate*

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[1] latitude x longitude

of the Ocean (ECCO) experiment, in which the MIT general circulation model is constrained by data from the World Oceanographic Circulation Experiment (WOCE) and forced with winds from the NCEP/NCAR reanalysis (*Stammer et al.* (2002)). As with the wind data, the result was a combination of modelled and measured data. The ECCO data utilized are 10-day velocity means. The horizontal resolution of the ECCO data is variable, ranging from 0.3° x 1.0° at the equator to 1° x 1° at high latitudes with each point representing the motion of the upper 5 m of the water column.

In total, 13 years' worth of wind and current data were selected from January, 1993 through to December, 2005. A 3-dimensional interpolation was performed on both data sets so that wind and current data had identical temporal and spatial resolution. The final data used in the simulation have a 1-day timestep with the same horizontal resolution as the ECCO data. The selected weather data extend from 40.5° N to 59.5° S and from 139.5° E to 290.5° E, encompassing all of Oceania and including marginal areas.

3.2 Modelling Drift

The velocity of a drifting object, $\mathbf{V}_{drift}$, is given by:

$$\mathbf{V}_{drift} = \mathbf{V}_{current} + \mathbf{V}_{winddrift} + \mathbf{V}_{wavedrift} \tag{3.1}$$

$\mathbf{V}_{current}$ is the current drift velocity due to the surface current. $\mathbf{V}_{winddrift}$ is the component of vessel drift caused by the direct effect of the wind on the vessel. The final term, $\mathbf{V}_{wavedrift}$, accounts for the wave force on the vessel and the Stokes' drift associated with the swell/wave currents. Studies have shown that wave forces are negligibly small for objects less than 50 m in length (*Hackett et al.* (2006)) and that the Stokes' drift is small compared with current- and wind-induced drift (*USCG* (2002)) so these are neglected in the simulation.

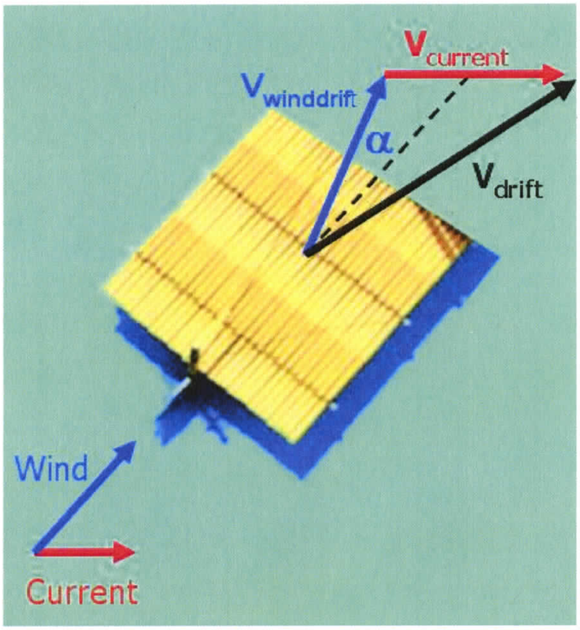

Figure 3.1: The velocity components of a drifting vessel. The net velocity may be decomposed into wind- and current-induced components. The wind-drift is generally not parallel to the surface wind, but deviates by a leeway angle, α.

Due to the asymmetry of floating objects, $\mathbf{V}_{winddrift}$ is not parallel to the local wind velocity but deviates by a leeway angle, α. Experimental work on different types of drifting vessels has shown that vessels of the same class will tend to drift to the right or to the left of the surface wind with roughly equal probabilities (*Hackett et al.* (2006)), and the exact direction is determined by small differences in the form of the vessel and the direction of the surface wind and waves. Figure 3.1, below, shows how the net drift velocity can be seen as the vector sum of wind- and current-induced drift components.

To assist in their marine search and rescue operations, the US Coast Guard (USCG) has developed a number of drift relations, based on empirical observations, for various classes of drifting vessels (henceforth, *drifters*). In these relations, $\mathbf{V}_{current}$ is equal to the surface current speed and $\mathbf{V}_{winddrift}$ is linearly proportional to the wind speed at 10 m and deviates from the wind by a constant leeway angle. *Montenegro et al.* (2006) simulated vessel trajectories for transoceanic voyages using the USCG parameters for a number of different types of small drifters and found that there were no statistically significant differences in the response of these craft over the long voyages simulated. In my simulations, I use the drift parameters for a type of vessel which resembles a large canoe with a basic canopy, similar to the type of craft which is thought may have been in use at the time of Oceanic settlement (*McGrail* (2001)).

The simulation's spatial grid is that of the ECCO data. Boats start from the centre of selected grid cells and move under constant wind and current conditions over a 1 day timestep. These weather conditions determine a drifter's daily velocity through the drift parameters and its displacement is the product of the daily velocity and the timestep. At the end of each timestep, the boat's position is then updated before the next iteration by adding its displacement to its previous position. A one-day timestep was selected for this project as it was found that, given the characteristic winds and currents in the study area and the USCG performance characteristics, vessels would generally cross no more than one or two grid cells per day.

3.3 Earlier Simulations

The role of drift voyages in Pacific colonization was addressed in a pioneering and influential computer simulation by *Levison et al.* (1973), who modelled drift contact between island groups in Polynesia. Ocean and atmosphere reanalysis and satellite data were unavailable at the time they conducted their simulation and they used wind and current data which had been collected sporadically between 1855 to 1938 and 1854 to 1952, respectively, by merchant and naval ships traversing their study area. Monthly wind observations and quarterly current readings were binned into a 5° by 5° grid, though the number of measurements per cell was highly variable across the study area, with cells lying along major shipping routes being much better sampled.

Lacking a sequential time series of data, *Levison et al.* (1973) adopted a stochastic approach to determine the weather conditions experienced by their drifters. Probability distributions for the speed and direction of winds and currents were constructed as a function of month and grid position and the conditions experienced by a drifter on a given day were randomly determined following these distributions. The group examined weather logs for real sailing vessels and claimed that the weather sequences generated by their model were similar to those experienced in reality. Nonetheless, a drawback of their simulation was that it did not capture the temporal autocorrelation of winds and current velocities[2] nor the correlation between wind and current. The nature of *Levison et al.* (1973)'s data did not allow for a study of the influence of interannual variability on their drift voyages. Furthermore, the coarse spatial resolution of *Levison et al.* (1973)'s data did not capture small-scale spatial variability which might have affected the trajectories and lengths of their simulated voyages.

Levison et al. (1973) estimated vessel movement parameters based on anecdotal reports of Oceanic watercraft since the time of European contact and from experiments sailing replica Polynesian canoes. In their scheme, wind- and current-induced drift speeds followed a step-function distribution: vessel drift speeds had constant values over ranges of wind and current values. Considering the *Levison et al.* (1973) parameters in the context of Equation 3.1, $\mathbf{V}_{winddrift}$ is in the same direction as the wind, neglecting any cross-wind drift, while $\mathbf{V}_{current}$ is parallel to the surface current.*Levison et al.* (1973)'s $\mathbf{V}_{winddrift}$ is generally between 0.15 and 0.3 of the surface wind speed, comparable to the performance of replica Polynesian canoes *sailing* with the wind (*Finney* (1977)). Figure 3.2 compares the wind- and current-induced drift response under the USCG and Levison movement schemes, demonstrating that vessels moving under the Coast Guard scheme, based on experimental drift observations, move considerably less efficiently under wind power that those moving under

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[2] Winds in the real world are not completely random: the direction that the wind blows on a particular day influences the following day's wind direction probability distribution. Winds can blow from the same direction for several days and these spells would not be accurately simulated by stochastic weather generation schemes.

Levison's scheme. Thus, while *Levison et al.* (1973) intended to model drift, the parameters they adopted are in fact more representative of a vessel sailing downwind.

Levison et al. (1973)'s findings, addressed in the discussion, are widely cited in the literature on Pacific settlement, but their work has not been repeated using higher quality weather data and this is one of the aims of this project. *Levison et al.* (1973)'s study is not the only numerical simulation of Pacific voyaging. Notably, *Irwin et al.* (1990) developed a simulation which compared the success of different intentional voyaging strategies in the exploration of the Pacific, utilizing the same weather data as the *Levison et al.* (1973) study. More recently, *Evans* (1999) developed a voyaging program which attempted to assess the influence of simulated weather and vessel performance characteristics on a navigated voyage to a known destination in Polynesia. Both of these works model decision-making by vessel crews and are difficult to directly compare with my experiments so they will not be further addressed.

3.4 Downwind Sailing Experiments

I conducted a second set of experiments testing downwind sailing as a means of discovering new islands. These simulations use the vessel movement parameters of *Levison et al.* (1973), allowing me to test my results against the earlier simulation and gauge how the different weather data affected results. These experiments will be referred to as the *Levison drifts* in contrast to those performed with the Coast Guard parameters which will be identified as the *USCG drifts*.

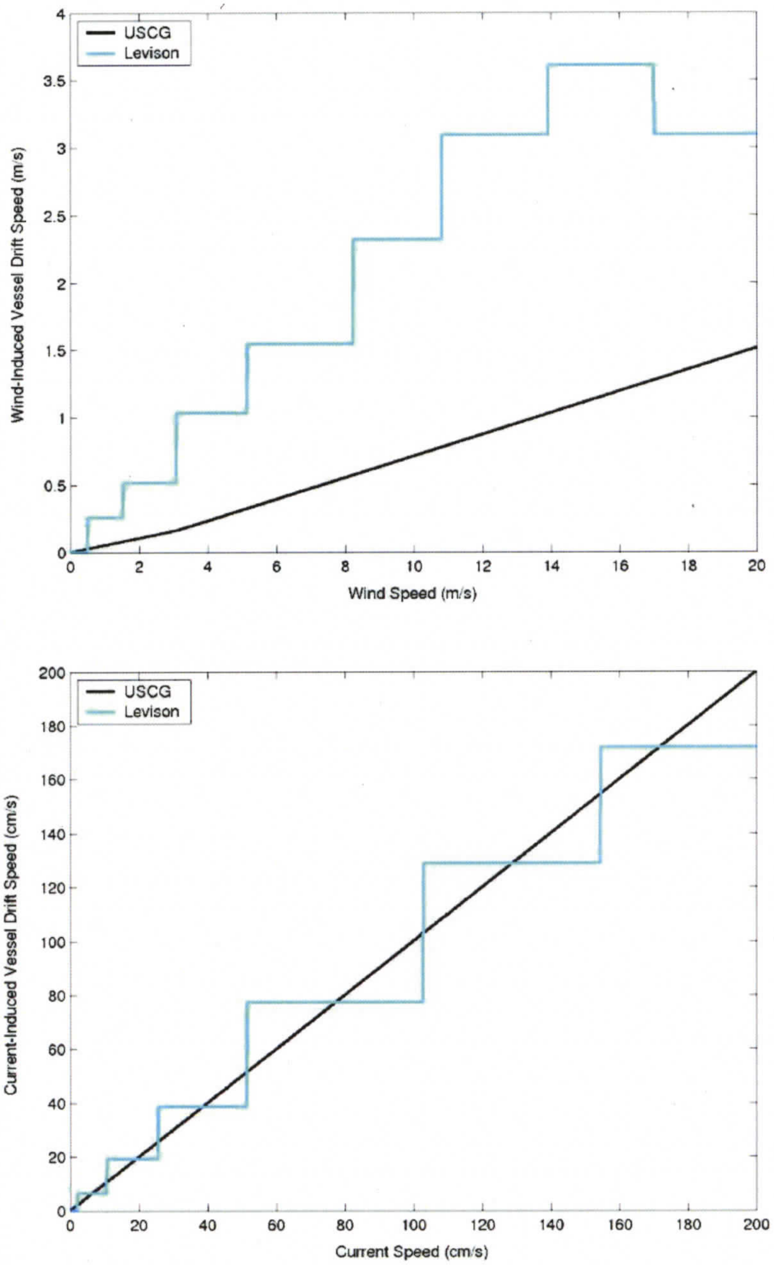

Figure 3.2: A comparison of the USCG and Levison parameterizations. The upper panel compares $\mathbf{V}_{winddrift}$ for the two models and the lower panel compares $\mathbf{V}_{current}$. Mean winds in the study area generally fall within the range of 0 - 10 m/s and mean currents in the range of 0 - 50 cm/s. The wind-induced vessel speed is significantly higher in the case of the Levison parameterization and is more properly representative of downwind sailing than drift. In the Levison scheme, wind-induced movement is parallel to the surface wind, while in the USCG scheme this drift component deviates from the wind by the leeway angle.

Chapter 4

Experiment Design

4.1 Definition of Island Groups

To identify island groups which would serve as launching and target sites for vessels, I generated a high resolution map of landmasses in the Pacific Ocean using the Global Land One-kilometer Base Elevation (GLOBE) Digital Elevation Map (DEM). The GLOBE model is an independently peer-reviewed DEM distributed by NOAA's National Geophysical Data Center with a latitude-longitude grid spacing of 30", which is roughly equivalent to a spacing of 1 kilometer at the equator (*Hastings and Dunbar* (1999)). Points lying between 55° S - 40° N and 140° E - 260° E having elevations between 0 and 50 m were selected to define coastlines of Pacific islands. This method is a rapid and quantitative means of identifying landmasses in the Pacific which takes into account the varying sizes of islands. As an example, Figure 4.1 shows the shorelines of islands in the Fiji group as identified from the GLOBE data.

Experienced mariners are able to deduce the presence of land by looking for signs such as the presence of island clouds, the deflection of swell, sea birds, logs and floating vegetation. 30 nautical miles is often taken as a conservative estimate of the distance from which a good Pacific seafarer could detect land, with tall islands visible from even further away (*Dodd* (1972)). I adopted 30 nautical miles as a measure of the detection distance, or sighting radius, for the shoreline of islands and extended

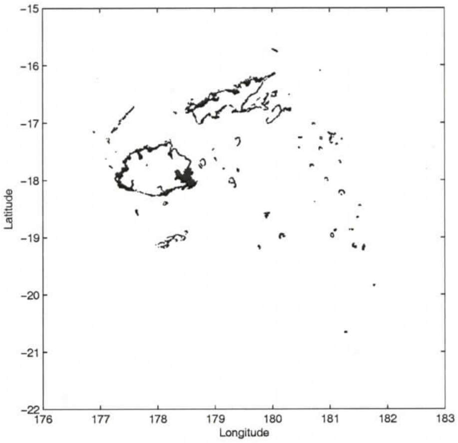

Figure 4.1: Shorelines of the islands of the Fiji group. Shorelines are datapoints with elevations between 0 and 50m in the GLOBE dataset.

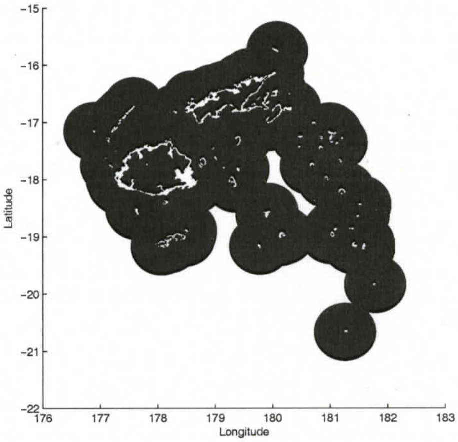

Figure 4.2: Islands of Fiji surrounded by sighting circles with a radius of 30 nautical miles.

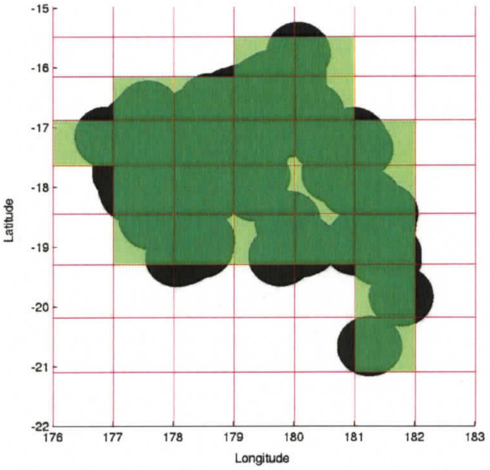

Figure 4.3: Grid cells corresponding to the Fiji group.

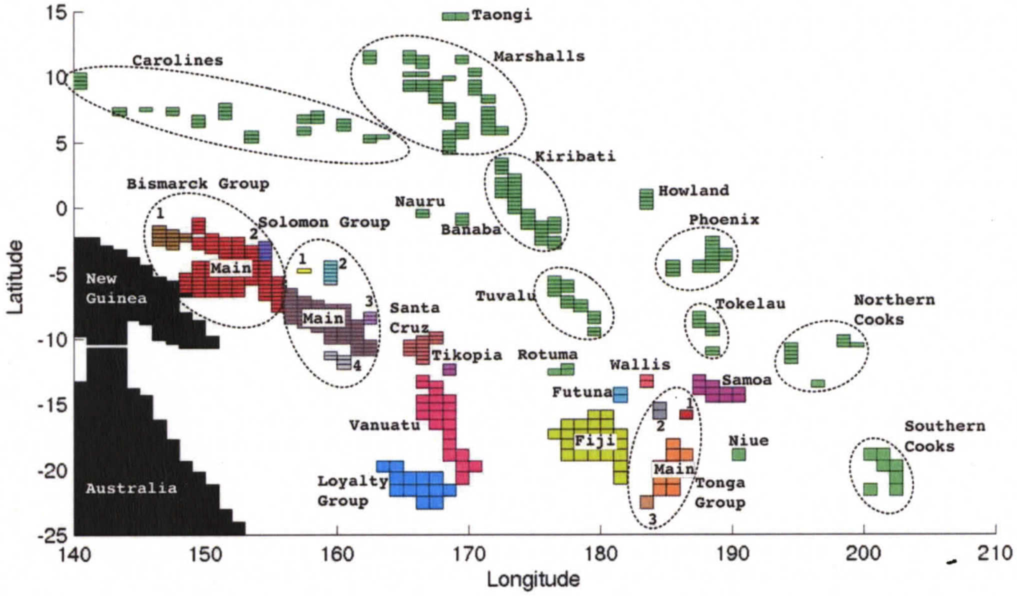

Figure 4.4: The islands of the Lapita region in terms of simulation grid cells. Cells with the same colour represent single, interconnected island screens. Green cells are Oceanic islands which are thought to have been settled after the Lapita expansion. Black grid cells represent Australia and New Guinea, which served as target sites but not launching sites.

sighting circles having this radius around each shoreline point. Closely spaced groups of islands then form extensive island screens as sighting circles from adjacent islands intersect, as Figure 4.2 shows in the case of the Fiji group.

The resolution of the simulation is ultimately set by that of the weather data, so I chose to represent island groups using cells from the weather grid. Grid cells whose centres lay within the sighting circles of an island were selected to represent an island or island group. Figure 4.3 shows the grid cells corresponding to Fiji. As the figure demonstrates, clusters of grid cells are a good approximation of overlapping island screens and this method eliminates the need to model hundreds of Pacific islands individually.

Figure 4.4 shows the islands and archipelagos of the Lapita region and nearby sites in Micronesia and Melanesia as represented by grid cells. The Bismarck, Solomon and Tonga groups all consist of one large 'main' island screen and several smaller, numbered screens representing outlying islands in the group. Some of the clusters in Figure 4.4 encompass multiple islands and archipelagos. The sites that fall within such groups are as follows:

- **Bismarck - Main**: Bougainville, Buka, New Britain, New Ireland
- **Bismarck - 1**: Manus Island
- **Bismarck - 2**: Nuguria Islands
- **Fiji**: Fiji & Lau archipelagos
- **Loyalty**: New Caledonia & the Loyalty Islands
- **Samoa**: Savai'i, Tutuila, Upolu & the Manu'a Islands
- **Santa Cruz**: Nendo, Utupua, Vanikolo, Duff Islands & the Reef Islands
- **Solomon - Main**: Islands in the chain from Choiseul to San Cristóbal
- **Solomon - 1**: Takuu Islands
- **Solomon - 2**: Nukumanu Islands
- **Solomon - 3**: Sikaiana Islands
- **Solomon - 4**: Rennell Island
- **Tonga - Main**: Ha'apai, Tongatapu & Vava'u Groups
- **Tonga - 1**: Niuatoputapu & Tafahi
- **Tonga - 2**: Niuafo'ou Island
- **Tonga - 3**: 'Ata Island
- **Vanuatu** : Islands in the chain from the Torres Islands to Anatom Island

The centres of the selected grid boxes are the starting points for the simulated boats. These cells also serve as target boxes for islands or island groups. Voyages end when a vessel's trajectory intersects cells of an island group other than the departure group or if it intersects the departure group after 6 or more days at sea. I invoke these criteria because it may take a few days for vessels to cross the larger island groups; during this time the boats would be within sight of land and not lost at sea or out exploring. It is assumed the crew of drifting vessels would attempt to make landfall upon sighting land after being lost. Likewise, explorers stop when they reach land, to investigate a new island or to return to populated areas after an unsuccessful exploration outing. I also included targets for the eastern portion of New Guinea and Australia. Voyages can also end if the boats move out of the study area, and to quantify the number of such vessels, I created an 'out of bounds' target box.

Drifting and sailing boats were launched starting every 7 days from January 1993 to December 2004[1]. This value was selected based on the computational efficiency of the simulation code in order to produce a set of results in a reasonable length of time. Based on sample drifts from a subset of the full set of launching sites, it was found that simulation results were not significantly different when a higher frequency of vessel launches was employed, thus validating the selected launch frequency. Voyages were allowed to last for up to 90 days, which was taken as a conservative estimate of the length of time that a vessel and crew could survive at sea and is significantly shorter than the length of the longest historical drift voyages with survivors (*Montenegro et al.* (2006)).

4.2 Contact Probabilities

The main parameter I use to describe contact between island groups is the *contact probability*. To understand how this quantity is calculated consider the following example. Suppose one considers crossings *from* group A *to* group B where A consists of 10 grid cells and B consists of 5 grid cells. On a given launch day, 10 voyages start from A and are tracked by the simulation. Each of these 10 trajectories is then checked to see if they intersect *any* of the 5 target cells from group B. If a boat's trajectory intersects a target cell, a 'hit' is registered and the boat is stopped. There can be a maximum of 10 hits in group B from this set of launches. The code then moves on to the next launch day under consideration and adds the number of hits in group B for this launch day to the total number of hits and so forth. In general, the contact probability from A to B is then calculated as follows:

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[1] Experiments starting in the latter half of 2004 could last into the following year which is why data from 2005 were needed.

$$\frac{Total\ \#\ of\ Hits\ to\ B}{(\#\ of\ Launch\ Sites\ in\ A)(\#\ of\ Launch\ Days)} * 100\% \tag{4.1}$$

Crossing probabilities do not reflect the differing size of the launch groups and this is important to recognize when considering the results. For example, crossings to a target from cells representing an individual, isolated island and a large archipelago might have the same contact probability, but over time one would expect a greater number of total launches (and thus successful crossings) from the larger group.

In this work, I consider overall probabilities, which were determined based on launches which occurred in all months and in all 12 launch years. As well, I calculated mean seasonal probabilities and seasonal probabilities for launches which began in specific years. Separate contact parameters were determined for the drifting and sailing schemes. The seasons were defined based on conditions in the southern hemisphere as follows: summer (December, January, February), fall (March, April, May), winter (June, July, August) and spring (September, October, November). In addition to contact probabilities, I also quantified crossings by calculating the minimum and mean crossing times.

Chapter 5

Results

5.1 Simulation Length

In my simulations, any vessels which did not encounter land before the maximum voyage length were identified as being 'lost at sea'[1]. Previous experiments with the drift model allowed voyages to last for 180 days. I experimented with the maximum voyage length, initially starting with a value of 180 days, and found that the percentage of vessels lost at sea after half a year from most of the launching sites was quite low, on the order of 5% or less, and mean crossing times for key crossings were generally much lower than half-year limit. I found that decreasing the maximum voyage length to 90 days did not significantly impact my results. I therefore adopted this new set of crossing parameters, excluding a few, very lengthy crossings, as I felt that survival at sea for 3 months was much more plausible than for 6 months.

5.2 Overall and Summer Results

I present my crossing results in terms of island groups that can be reached from a given departure site. I chose to individually identify crossings which occurred with probabilities greater than 5 % in either the drift or sailing schemes; this is consistent with *Levison et al.* (1973) who considered this probability to be a reasonable threshold

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[1] This does not imply that crews couldn't survive beyond this time, it simply means the vessels hadn't reached land by the end of the simulation.

	USCG Parameters			Levison Parameters		
Launch Site Target Site	**Hit %**	**Min Time**	**Mean Time**	**Hit %**	**Min Time**	**Mean Time**
Bismarck - Main						
Bismarck - 1	9.1 %	2	7.7	9.5 %	2	5.1
Bismarck - 2	3.1 %	2	10.2	5.9 %	2	5.2
Bismarck - Main	70.5 %	7	8.2	43.5 %	7	8.0
Other	8.7 %	-	-	31.8 %	-	-
Lost at Sea	8.6 %	-	-	9.3 %	-	-
Fiji						
Fiji	59.0 %	7	7.6	16.0 %	7	9.7
Santa Cruz	2.0 %	18	29.2	12.9 %	6	12.2
Solomon - Main	0.2 %	25	38.1	5.6 %	7	15.8
Tikopia	2.5 %	15	26.4	6.3 %	5	11.5
Vanuatu	32.7 %	11	30.4	40.5 %	5	14.3
Other	2.5 %	-	-	17.1 %	-	-
Lost at Sea	1.1 %	-	-	1.6 %	-	-
Loyalty						
Australia	15.5 %	23	48.8	24.8 %	7	21.8
Bismarck - Main	0.3 %	32	43.6	10.9 %	9	17.1
Loyalty	54.5 %	7	7.7	8.5 %	7	8.8
New Guinea	3.0 %	27	45.5	27.9 %	7	17.4
Other	0.2 %	-	-	6.1 %	-	-
Lost at Sea	26.5 %	-	-	21.8 %	-	-
Samoa						
Fiji	2.4 %	14	36.8	5.3 %	6	17.9
Futuna	7.1 %	9	20.1	5.2 %	4	11.3
Rotuma	3.7 %	16	27.6	5.5 %	6	13.7
Samoa	34.0 %	7	7.7	5.7 %	7	10.5
Santa Cruz	3.3 %	31	49.1	6.6 %	12	21.4
Solomon - 2	0.8 %	55	71.2	6.6 %	20	31.7
Tonga - 1	7.5 %	4	16.0	4.6 %	2	7.5
Tonga - 2	9.2 %	6	16.6	6.6 %	3	9.7
Tonga - Main	4.0 %	10	36.2	6.5 %	4	16.4
Wallis	22 %	7	13.5	17.9 %	3	7.4
Other	4.2 %	-	-	26.7 %	-	-
Lost at Sea	1.8 %	-	-	2.8 %	-	-
Santa Cruz						
Santa Cruz	31.2 %	7	9.7	6.8 %	7	11.6
Solomon - 3	7.3 %	6	13.4	10.5 %	3	6.0
Solomon - 4	5.2 %	8	18.7	3.1 %	5	13.2
Solomon - Main	36.4 %	4	12.4	40.2 %	3	6.5
Vanuatu	7.2 %	3	28.0	12.0 %	2	11.8
Other	8.1 %	-	-	25.4 %	-	-
Lost at Sea	4.6 %	-	-	2.0 %	-	-
Solomon - Main						
Bismarck - Main	12.9 %	2	13.8	31.8 %	2	6.8
Santa Cruz	1.5 %	5	24.6	5.1 %	2	11.1
Solomon - Main	73.1 %	7	7.8	36.1 %	7	8.0
Other	8.8 %	-	-	23.8 %	-	-
Lost at Sea	3.7 %	-	-	3.2 %	-	-
Tonga - Main						
Fiji	60.5 %	4	10.8	64.8 %	2	5.0
Tonga - 3	6.1 %	2	8.6	4.1 %	2	5.6
Tonga - Main	25.2 %	7	8.3	5.9 %	7	9.3
Vanuatu	3.8 %	24	49.9	7.9 %	7	20.6
Other	3.2 %	-	-	16.1 %	-	-
Lost at Sea	1.2 %	-	-	1.2 %	-	-
Vanuatu						
Australia	9.9 %	35	57.6	8.8 %	14	31.0
Bismarck - Main	4.8 %	24	42.6	19.5 %	7	16.5
Loyalty	7.8 %	2	12.8	6.0 %	2	9.4
New Guinea	9.8 %	25	45.4	13.4 %	8	20.4
Solomon - 4	7.6 %	9	17.5	12.9 %	4	8.4
Solomon - Main	3.4 %	7	17.7	16.5 %	3	10.1
Vanuatu	23.8 %	7	7.9	8.5 %	7	11.1
Other	0.3 %	-	-	3.3 %	-	-
Lost at Sea	32.6 %	-	-	11.1 %	-	-

Table 5.1: Overall crossing parameters for major island groups under the USCG and Levison parameterizations. Crossing probability, minimum and mean crossing time (in days) are all presented. Crossing parameters are based on all simulated voyages and the selected launching groups are the largest groups in the study area. Crossings to targets which which have a probability of 5 % or greater in either scheme are singled out, crossings with less than this percentage fall into the *other* category. The *lost at sea* category represents the percentage of vessels that have not encountered land after 90 days.

Launch Site	USCG Parameters			Levison Parameters		
Target Site	Hit %	Min Time	Mean Time	Hit %	Min Time	Mean Time
Bismarck - Main						
Bismarck - 2	6.0 %	2	9.5	11.2 %	2	4.8
Bismarck - Main	75.8 %	7	7.9	53.9 %	7	7.6
Solomon - 2	1.8 %	9	32.4	5.0 %	4	13.5
Solomon - Main	6.1 %	2	19.2	11.7 %	2	7.7
Other	4.6 %	-	-	15.5 %	-	-
Lost at Sea	5.7 %	-	-	2.7%	-	-
Fiji						
Fiji	68.3 %	7	8.0	27.1 %	7	11.4
Loyalty	3.8 %	26	54.6	6.6 %	9	21.3
Vanuatu	23.9 %	15	41.1	42.0 %	6	18.4
Other	1.4 %	-	-	22.1 %	-	-
Lost at Sea	2.6 %	-	-	2.2 %	-	-
Loyalty						
Australia	15.9 %	24	50.6	42.6 %	7	24.2
Loyalty	56.6 %	7	7.7	11.3 %	7	10.2
New Guinea	0.4 %	44	59.5	7.8 %	13	32.0
Other	0.2 %	-	-	10.56 %	-	-
Lost at Sea	26.9 %	-	-	27.8 %	-	-
Samoa						
Fiji	4.7%	14	38.9	12.0 %	6	16.3
Futuna	3.2 %	13	24.1	5.5 %	5	11.6
Niue	2.9 %	11	24.1	5.2 %	3	12.1
Samoa	38.9 %	7	8.1	10.4 %	7	10.8
Tonga - 1	15.6 %	4	16.7	9.5 %	3	7.6
Tonga - 2	12.4 %	8	18.3	11.7 %	4	9.3
Tonga - Main	12.6 %	10	37.7	16.8 %	6	15.6
Wallis	6.4 %	7	16.9	12.4 %	3	8.9
Other	1.3 %	-	-	15.4 %	-	-
Lost at Sea	2.0 %	-	-	1.1 %	-	-
Santa Cruz						
Fiji	0.3 %	59	74.7	9.0 %	7	22.0
Santa Cruz	48.1 %	7	9.5	11.4 %	7	11.6
Solomon - Main	6.5 %	6	15.0	13.8 %	3	9.5
Tikopia	10.6 %	3	16.5	8.5 %	2	6.6
Vanuatu	20.6 %	3	31.2	30.0 %	2	13.3
Other	5.0 %	-	-	24.6 %	-	-
Lost at Sea	8.9 %	-	-	2.7 %	-	-
Solomon - Main						
Bismarck - Main	1.7 %	3	16.0	8.3 %	2	10.3
Santa Cruz	4.1 %	5	23.9	13.6 %	2	10.4
Solomon - 3	5.0 %	2	9.2	7.5 %	2	5.4
Solomon - 4	4.0 %	2	15.5	8.4 %	2	9.2
Solomon - Main	80.6 %	7	8.1	40.0 %	7	8.5
Vanuatu	0.9 %	13	36.6	7.2 %	3	14.9
Other	1.2 %	-	-	12.8 %	-	-
Lost at Sea	2.5 %	-	-	2.2 %	-	-
Tonga - Main						
Fiji	44.8 %	5	11.1	58.6 %	2	5.3
Tonga - 3	10.0 %	3	10.1	6.1 %	2	5.9
Tonga - Main	34.1 %	7	8.8	9.7 %	7	9.2
Vanuatu	3.5 %	27	56.0	13.1 %	9	23.1
Other	4.9 %	-	-	10.0 %	-	-
Lost at Sea	2.7 %	-	-	2.5 %	-	-
Vanuatu						
Australia	9.3 %	40	70.2	17.3 %	16	35.4
Loyalty	12.4 %	3	16.4	14.0 %	2	11.8
New Guinea	2.2 %	48	73.1	5.1 %	12	38.2
Solomon - 4	3.0 %	12	25.2	8.1 %	5	14.9
Solomon - Main	1.3 %	11	37.4	12.5 %	4	18.0
Vanuatu	42.7 %	7	8.4	19.1 %	7	12.6
Other	0.6 %	-	-	9.6 %	-	-
Lost at Sea	28.5 %	-	-	14.3 %	-	-

Table 5.2: Crossing parameters for major island groups which occur in the Austral summer (December, January, February) in all years. Crossing parameters and categories are as per Table 5.1.

for crossings to be likely to occur[2]. In this way, I focus my analysis on the more probable crossings. Considering only crossings which exceeded this threshold did not decrease the overall area that was reached in either movement scheme. However, certain key crossings exceed the probability threshold only in certain seasons or years, reflecting the influence of seasonal and interannual variability on the experiments.

To give a sense of the major crossing pathways within the study region, I begin by presenting overall crossing probabilities from the large launch sites. These crossing parameters are based on launches which occurred in all years and all months and are shown for both the USCG and Levison parameterizations in Table 5.1. Two categories in these results warrant explanation. The *other* category encompasses all crossings from a launch site which, individually, had probabilities less than the 5 % threshold. The *lost at sea* category records the percentage of launches which did not reach land after 90 days.

A similar set of parameters for voyages which began in December, January and February - in the Austral summer - is shown in Table 5.2. Winds having a westerly component are most probable in this season and I generated this table to demonstrate the degree to which seasonal crossing parameters differ from the mean annual parameters.

I now focus on three key eastward crossings to Santa Cruz, Fiji/Rotuma and Tonga/Samoa to identify launch sites from which these groups can be reached and the conditions under which these crossings are probable. My experiments indicate that crossings from the west to Futuna and Wallis are also possible but these islands do not offer critical connections to other island groups and so are omitted to maintain focus on the larger groups. In this exercise, the possible crossing pathways under the USCG and Levison parameterizations proved to be sufficiently different that separate tables were warranted.

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[2] Crossing probabilities were categorized as follows in the 1973 work: Very high: > 20 %, High: 10.0 - 19.9 %, Moderate: 5.0 - 9.9 %, Low: 1.0 - 4.9 %, Very low: < 1.0 %

		USCG Parameters		
Launch Site Target Site	**Season**	**Hit %**	**Min Time**	**Mean Time**
Solomon-1				
Santa Cruz	Summer	6.6 %	25	50.0
Solomon-2				
Santa Cruz	Summer	12.4 %	23	48.5
Solomon-3				
Santa Cruz	Overall	17.6 %	5	20.8
Santa Cruz	Summer	46.9 %	5	20.4
Santa Cruz	Fall	20.3 %	5	20.5

Table 5.3: Crossings into the Santa Cruz island group from sites in Near Oceania under the USCG (drift) parameters. Crossings have a higher probability in the summer months when the frequency of occurrence of winds having a westerly component is higher.

		Levison Parameters		
Launch Site Target Site	**Season**	**Hit %**	**Min Time**	**Mean Time**
Solomon-1				
Santa Cruz	Summer	7.8 %	7	19.5
Solomon-2				
Santa Cruz	Overall	7.6 %	5	23.0
Santa Cruz	Summer	18.4 %	5	16.9
Santa Cruz	Fall	7.3 %	6	24.2
Solomon-3				
Santa Cruz	Overall	11.3 %	3	10.0
Santa Cruz	Summer	30.5 %	3	9.3
Santa Cruz	Fall	11.5 %	3	9.8
Solomon-Main				
Santa Cruz	Overall	5.1 %	2	11.1
Santa Cruz	Summer	13.6 %	2	10.4
Santa Cruz	Fall	5.8 %	4	9.8

Table 5.4: Crossings into the Santa Cruz island group from sites in Near Oceania under the Levison (sailing) parameters.

5.3 Crossings to Santa Cruz

Crossings from the Bismarcks and the Solomons to Santa Cruz easily exceed the threshold crossing probability when considering the mean seasonal results for summer and fall both in the USCG (Table 5.3) and Levison (Table 5.4) schemes. Tikopia, Vanuatu and the Loyalty group may be easily reached starting from Santa Cruz (Table 5.2) and I next consider crossings from these sites as well as the Bismarcks and the Solomons into the eastern Lapita region.

5.4 Crossings to Fiji and Rotuma

Drift crossings to Fiji and Rotuma do not exceed the 5 % probability cutoff in the overall and mean seasonal results. However, drift crossing probabilities are significantly higher when considering drifts which occur in the summer months of specific years (Table 5.5). Conditions in summer 2002 and 2003 are particularly favorable for reaching this area from the Solomons and Santa Cruz, though mean crossing times are on the order of 60-70 days, significantly longer than the drifts to the Santa Cruz group from Near Oceania.

In the downwind sailing experiments, Fiji can be reached from the western Lapita region under mean summer conditions with probabilities as high as about 9 % (Table 5.6). The crossing probabilities in summer months vary from year to year and additional crossings are possible when considering specific years. For instance, Rotuma can be reached in the sailing scheme from Santa Cruz, Solomon-1, Solomon-2, Solomon-3 and Tikopia if we consider launches that occur in the summer months of particular years (Table 5.8). Crossing probabilities to Fiji are also significantly higher than the average summer values in specific years. For instance, the crossings from Santa Cruz and Tikopia occur with a probability of 28 % and 25 %, respectively, in summer 2002. In the case of both drift and sailing, Fiji can be easily reached from Rotuma in the summer months.

Launch Site		**USCG Parameters**		
Target Site	**Year**	**Hit %**	**Min Time**	**Mean Time**
Santa Cruz				
Rotuma	2003	5.6 %	42	62.7
Solomon - 1				
Rotuma	2002	14.3 %	64	66.0
Solomon - 2				
Fiji	2002	10.7 %	80	84.2
Rotuma	2002	17.9 %	55	65.3
	2003	8.3 %	64	69.3

Table 5.5: Crossings into Fiji and Rotuma - USCG scheme. Drift pathways into these groups are probable when considering crossings that take place in the summer months of particular years.

Launch Site		**Levison Parameters**		
Target Site	**Season**	**Hit %**	**Min Time**	**Mean Time**
Santa Cruz				
Fiji	Summer	9.0 %	7	22.0
Solomon-2				
Fiji	Summer	5.4 %	16	31.7
Solomon-3				
Fiji	Summer	8.0 %	9	22.7
Tikopia				
Fiji	Summer	6.6 %	8	18.3

Table 5.6: Crossings into Fiji - Levison scheme. Crossings are viable under mean summer conditions and occur with mean crossing times that are 1/3-1/2 of those of the drifters.

Launch Site		**USCG Parameters**		
Target Site	**Year**	**Hit %**	**Min Time**	**Mean Time**
Rotuma				
Tonga - 1	1993	12.5 %	44	49.3
Tonga - 2	1993	16.7 %	33	47.3
Tonga - 2				
Samoa	1993	6.3 %	48	48.0

Table 5.7: Crossings to Tonga and Samoa - USCG scheme. Crossings are probable in particular summers, though all pathways from the west require Rotuma as an intermediate stepping stone. Additional crossings to Tonga and Samoa are possible using Wallis and Futuna as stepping stones but these must be reached via Rotuma.

		Levison Parameters		
Launch Site Target Site	**Year**	**Hit %**	**Min Time**	**Mean Time**
Fiji				
Samoa	1993	6.8 %	16	20.5
Tonga - 3	2002	6.0 %	3	13.9
Tonga - Main	1997	5.1 %	4	5.1
	1999	8.6 %	3	8.3
	2001	6.3 %	5	9.5
Rotuma				
Samoa	1993	12.5 %	12	16.3
	2004	7.1 %	15	20.7
Tonga - 2	1993	8.3 %	10	16.0
	1994	7.1 %	8	15.0
	2003	7.1 %	37	39.7
Tonga - Main	1993	8.3 %	21	29.0
	1996	7.1 %	9	10.3
	1999	19.0 %	5	8.5
	2000	9.5 %	8	16.0
	2002	9.5 %	9	12.3
Santa Cruz				
Rotuma	1995	9.7 %	24	33.1
	2003	12.8 %	11	24.6
Samoa	1995	5.1 %	33	47.8
Tonga - 1	2003	5.1 %	39	50.5
Tonga - 2	2003	5.1 %	28	31.3
Tonga - Main	2002	6.1 %	26	32.9
Solomon - 1				
Rotuma	1998	7.1 %	21	21.0
Tonga - 1	1993	12.5 %	32	32.0
Tonga - Main	2002	7.1 %	34	34.0
Solomon - 2				
Rotuma	1996	7.1 %	24	24.5
	2002	7.1 %	18	27.8
	2003	10.7 %	28	35.9
Samoa	1995	6.0 %	47	52.6
Tonga - 2	1993	8.3 %	28	32.5
Tonga - Main	1993	6.3 %	39	39.3
Solomon - 3				
Rotuma	1993	12.5 %	16	19.0
Tonga - Main	2002	7.1 %	30	39.0
Tikopia				
Rotuma	2003	17.9 %	17	20.6
Tonga - 3	2002	7.1 %	24	24.0
Tonga - 1				
Samoa	1996	7.1 %	25	25.0
	2003	14.3 %	3	4.0
	2004	7.1 %	26	26.0
Tonga - 2				
Samoa	1993	18.8 %	10	15.0
	1996	7.1 %	16	21.0
	2003	10.7 %	6	17.7
	2004	10.7 %	22	24.0

Table 5.8: Crossings to Rotuma, Tonga and Samoa - Levison scheme. Crossings are probable in particular summers. A number of pathways to the easternmost groups are possible, including some direct connections from the western Lapita region.

5.5 Crossings to Tonga and Samoa

Crossings to Tonga and Samoa from the west are not viable under the mean annual or mean seasonal conditions in either scheme, so I again consider launches in specific summers from Fiji, Rotuma and western sites to reveal connections which are possible under these conditions. In the case of drift, these eastern targets can be reached only from Rotuma (Table 5.7), while downwind sailing experiments allow for crossings from the western Lapita sites as well as Fiji and Rotuma (Table 5.8). The overall contact probability table (Table 5.1) demonstrates that Tonga can be readily reached from Samoa, but the reverse crossing requires specific conditions.

5.6 Crossings to Central Polynesia

The above results show that interannual variability is clearly important in facilitating crossings within the Lapita region. Eastward drifting and sailing crossings from the eastern Lapita sites do not occur with probabilities in excess of 5 % under any conditions, restricting the area reached in these experiments to the Lapita region given the chosen probability cutoff. To see if interannual fluctuations had a similar influence on crossings elsewhere in Polynesia, I examined launches from the Northern and Southern Cook groups, the closest groups to the east of the study area, to see if additional eastward crossings within Polynesia were possible under specific conditions.

No major eastward connections were possible based on mean annual and seasonal conditions, but again, the situation was different when I considered certain summers. Table 5.9 shows eastward drift crossings from the Cooks and Table 5.10 is the equivalent table for downwind sailing. A detailed investigation of crossings within Polynesia is beyond the scope of this paper, but these results suggest that anomalous conditions that occur in certain years may also play a role in further expansion into Polynesia.

The islands which are represented by the groups in Tables 5.9 and 5.10 are as follows:

- **Australs - 4**: Rimatara Island, the westernmost Austral island
- **Northern Cooks - 1**: Manihiki and Rakahanga Islands
- **Northern Cooks - 2**: Suwarrow Island
- **Northern Cooks - 3**: Tongareva Island
- **Society - 1**: Motu One, Manuae and Maupihaa Islands
- **Society - Main**: Islands in the Society group other than those in Society - 1
- **Southern Cooks - Main**: Aitutaki, Atiu, Manuae, Mauke, Mitiaro and Takutea Islands
- **Tuamotu - Main**: Broad island screen encompassing the majority of the islands in the Tuamotu archipelago (and 35 model grid cells)

Launch Site		USCG Parameters		
Target Site	Year	Hit %	Min Time	Mean Time
Northern Cooks - 3				
Society - 1	1993	12.5 %	53	53.0
	2002	7.1 %	17	17.5
Tuamotu - Main	1998	25.0 %	72	81.1

Table 5.9: Sample eastward crossings from the Cook islands - USCG scheme.

Launch Site		Levison Parameters		
Target Site	Year	Hit %	Min Time	Mean Time
Northern Cooks - 1				
Society - 1	1993	12.5 %	10	11.0
	1996	8.9 %	9	14.0
Society - Main	1996	8.9 %	9	12.4
Tuamotu - Main	1998	35.7 %	13	25.5
Northern Cooks - 2				
Australs - 4	2001	7.1 %	9	9.0
Northern Cooks - 3				
Society - 1	1993	37.5 %	8	15.0
	1995	7.1 %	5	5.5
	2002	14.3 %	7	8.3
Society - Main	1993	25.0 %	9	14.8
	1996	17.9 %	10	12.6
	2001	10.7 %	10	10.3
Tuamotu - Main	1998	39.3 %	13	22.5
	2004	7.1 %	19	19.5
Southern Cooks - Main				
Australs - 4	2000	5.7 %	9	13.3

Table 5.10: Sample eastward crossings from the Cook Islands - Levison scheme.

Chapter 6

Discussion

6.1 Crossings in the Lapita Region

As with the tabular presentation of my results, I restrict my discussion to those crossings which occur with probabilities greater than 5 %. As demonstrated, the entire Lapita region can be reached by drift and sail from Near Oceania under this restriction. A crossing probability of 5 % implies that, on average, 1 out of 20 vessels launched will accomplish the crossing under the conditions for which the probability was generated.

As anticipated, given the direction of mean winds and currents, westward crossings are most probable overall and have enhanced probabilities in the Austral winter and spring, when the trades are strongest and most consistent. The ease of such westward journeys would allow those who had found new land to easily drift or sail to populated areas in the west with news of their discovery. Whether they could return to their departure site would depend on the navigational skill of the voyagers.

Since westward movement can be achieved with apparent ease, I focus my discussion on the case of crossings to the east. Figure 6.1 summarizes the key results presented in the preceding chapter, demonstrating the sections of the Lapita region reached under particular conditions, assuming that all discoverers ultimately originated in the Bismarcks or the Solomons.

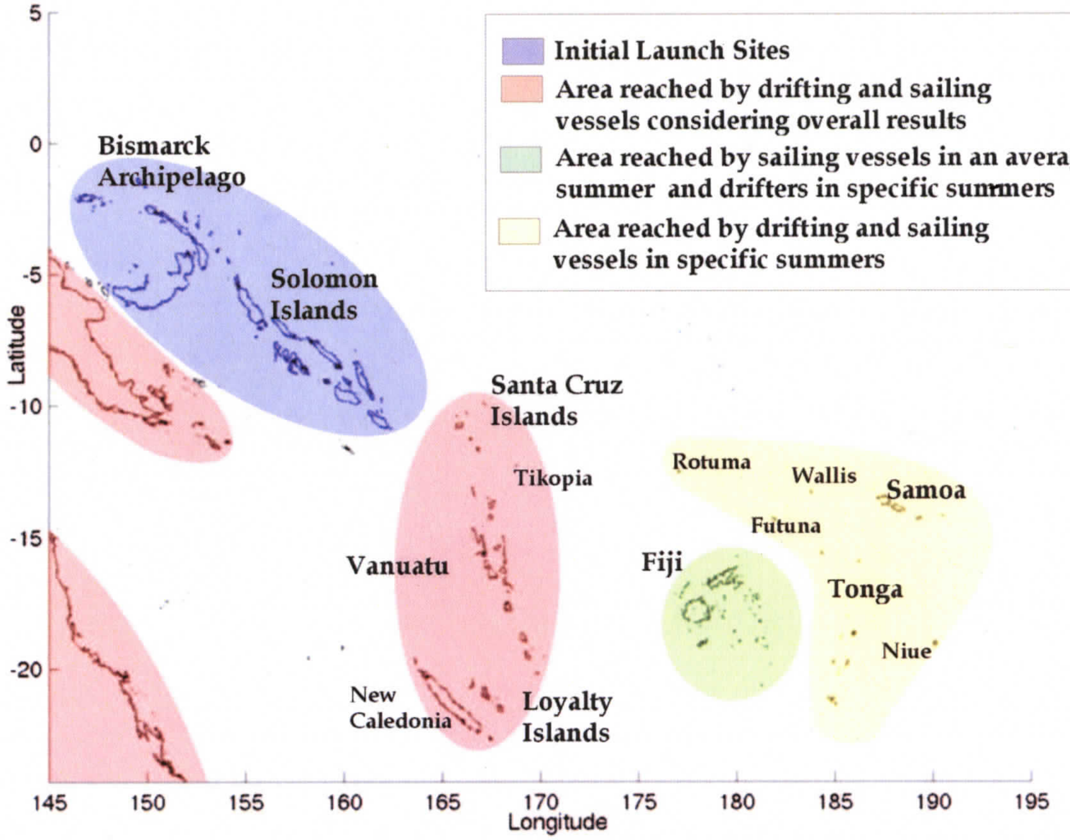

Figure 6.1: Summary of simulation results. The shaded areas indicate the different areas which are reached by drift and downwind sailing under the specified conditions.

6.1.1 Santa Cruz to the Loyalty Group

Crossings to Santa Cruz from the Solomon Islands are probable in an overall sense, but probabilities are heightened in the summer and fall under the influence of the Australian monsoon (Tables 5.3, 5.4). Arrivals in this group are most likely from the outlying Solomon groups (Solomon - 3, in particular) since these are separated from the large island screens of the main Solomon and Bismarck groups. Vessels starting from these larger groups generally return there, even after allowing for a week at sea, such is the influence of the broad island screens. I argue that this is a sensible result, since vessels lost at sea would no doubt stop upon reaching land and exploring sailors would also stop, if they found no new land and the winds pushed them home.

The great increase in the likelihood of crossings to Santa Cruz in the summer months is reflective of the strong and predictable seasonality of the winds in this part of Melanesia. Figure 6.2 shows a time series of the monthly crossing probabilities from Solomon - 3 to Santa Cruz, revealing a distinct seasonal signal. Probabilities peak around January-February, reaching values as high as 80 - 100 % in the drift model and 60 - 75 % in the sailing model. Figure 6.3 shows a time series for the westward crossing from Santa Cruz to the main Solomon group and shows the opposite seasonal signal with this crossing most probable in the winter and spring. While the influence of the monsoon winds becomes more limited further to the east, these winds occur in a predictable manner in the vicinity of this crossing. These figures demonstrate how this strong seasonality could be exploited in facilitating interaction between islands in Near Oceania and those further east, once their presence was recognized.

From the Santa Cruz group, vessels can drift or sail to Vanuatu and from there reach the Loyalty Islands and New Caledonia; these crossings appear in the overall table but, again, are more probable in the summer and fall. In my experiments, Vanuatu and the Loyalty group were 'dead ends' in terms of eastward exploration as launches from these sites reach no new islands under any conditions.

An interesting set of results from this western portion of the study area are pathways between Remote Oceania and Australia. Australia is reached with relatively high overall contact probabilities from Vanuatu (USCG: 9.9 %, Levison: 8.8 %) and the Loyalty group (USCG: 15.5 %, Levison: 24.8 %). Remote Oceania was peopled beginning about 3,500 years ago, and it is curious that there appears to be little evidence for pre-historic interactions between Remote Oceania and Australia given the apparent ease with which such crossings could occur.

6.1.2 Fiji and Rotuma

Fiji is reached by sailing boats from Santa Cruz, Solomon - 2, Solomon - 3 and Tikopia with probabilities ranging from 5.4 % to 8.9 % in the sailing experiments when mean summer results are considered (Table 5.6) and with significantly higher probabilties in particular summers. Fiji is nearly 1,500 kilometers from the nearest western launch point, yet these crossings have a mean time of a month or less. These crossings are not possible by drift in mean summer conditions, the first indication of the more limited set of contact pathways open to drifters. Sailing crossings further east are also not probable under mean summer conditions. Drifts directly to Fiji occur only in summer, 2002 from Solomon - 2, but here the mean crossing time is nearly three months, significantly longer than in the sailing experiments.

Sailing boats reach Rotuma from Solomon - 1 in 1998, Solomon - 2 in 1996, 2002 and 2003, Solomon - 3 in 1993 and Tikopia in 2003 (Table 5.8), while drifters can reach the island from Santa Cruz in 2003, Solomon - 1 in 2002 and Solomon - 2 in 2002 and 2003 (Table 5.5). Again, the number of probable crossings in the drift scheme is greatly reduced over the sailing connections. Fiji can be easily reached from Rotuma in both sets of simulations, presenting another pathway by which it could have been discovered. I have included Rotuma as a launching site in these simulations since it is the only point from which Tonga and Samoa may be reached by drift. Its inclusion is, however, problematic since Rotuma is thought to have been

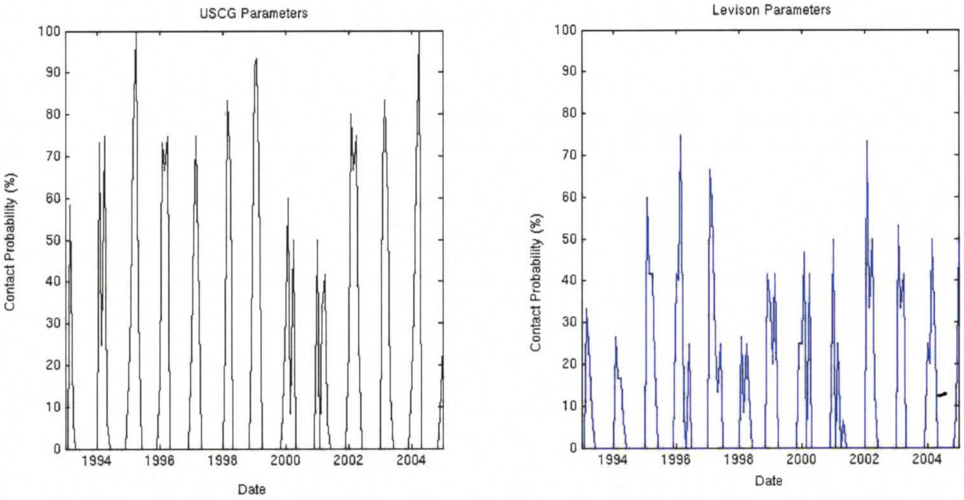

Figure 6.2: Time series of monthly crossing probabilities from the Solomon - 3 launch group to the Santa Cruz group. Probabilities for the USCG parameters are shown in the left panel and for the Levison parameters in the right panel. These plots show a distinct seasonal signal: crossings occur with high probabilities in the Austral summer and not at all in the winter.

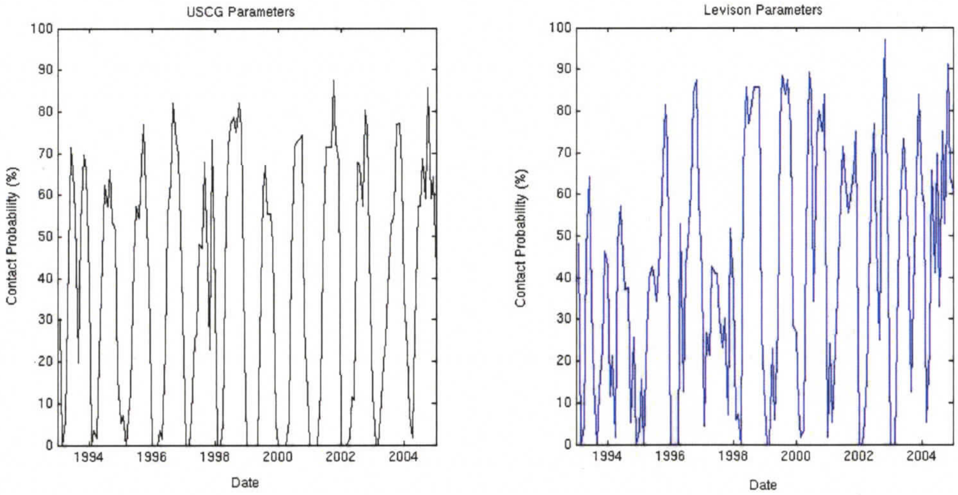

Figure 6.3: Time series of monthly crossing probabilities from Santa Cruz to the main Solomon target. The plots show a seasonal signal opposite to that in Figure 6.2 with crossings most probable in the Austral winter.

first settled after the initial Lapita expansion (*Anderson* (2003)). Thus, the role of this island in the actual expansion is questionable.

6.1.3 Tonga and Samoa

To allow for pathways to Tonga and Samoa in marginal western Polynesia, I must again consider crossings that occur in particular summers as voyages to this group from the west are not probable under mean summer conditions, even from Tonga and Rotuma and even allowing Futuna and Wallis as intermediate launching points. Under specific conditions, sailing boats from Fiji, Rotuma, Santa Cruz and the Solomons reach Samoa; Tonga is reached from all preceding sites as well as from Tikopia (Table 5.8). Sailing crossings from Samoa to Tonga occur with high overall probabilities. The reverse crossing is possible, too, but only in particular years.

Drifting vessels reach Tonga only from Rotuma (Table 5.7). Drifts directly to Samoa from western sites are not probable, but the group can be reached from Tonga in summer, 1993. Thus, while a number of sailing pathways to western Polynesia are possible, there is a single drift path to Tonga and Samoa, one which must necessarily include Rotuma as an intermediate point. My experiments demonstrate pathways to all the island groups in the Lapita region by drift and by sail from initial launches in the Solomons and Bismarcks. The region of influence of the mean monsoonal winds allows for drifts as far as the Loyalty group and sailing connections as far as Fiji. Further movement eastward is possible in certain years but not in the general case.

6.2 Beyond the Lapita Expansion

From Samoa, sailing boats reach Niue[1], to the south-east, under mean summer conditions. While sites in Micronesia can be hit by boats from the northern reaches of the study area in certain years, no crossings further to the east exceed the 5 % probability threshold under any conditions. There is a 3.5 % chance of sailing from

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[1] Like Rotuma, Niue is thought to have been settled post-Lapita.

Samoa to the Southern Cooks in 2001, a crossing which occurs with a mean time of 13 days, and an additional crossing to this group is possible in 2003 with a probability of 1.5 %. Similarly, sailing crossings from Tonga - 2 to the Northern Cooks occur with a probability of 3.6 % and mean crossing time of 18 days in 1998. All other eastward crossings occur with probabilities less than 1 %, and this includes any drift crossings. Thus, if a lower probability cutoff is acceptable, the region reached in these simulations may be extended.

The islands of Polynesia lie outside of the average zone of influence of the Australian monsoon, and reliable and predictable seasonal crossings to the east, such as those in the western Lapita region, are absent. A detailed study of the settlement of Polynesia is beyond the scope of this work, but the sample results for drifts and sailing voyages from the Cooks suggest that interannual variations in the surface wind field are important when considering the exploration of this region. Boats sailing downwind reach the Society and Tuamotu groups from the Northern Cooks and the Australs from the Southern Cooks. Significantly, these crossings align with the two Polynesian settlement paths favored by *Kirch* (2000). *Kirch* (2000)'s model was based on linguistic relationships between Polynesian islands and evidence for interaction spheres between islands and it is interesting that these paths are supported by my simulations, especially if the geographic pattern of modern climate variability reflects that during the colonization period.

Of particular note are the results from summer 1998, which suggest that sailing vessels can reach the Tuamotus from the Northern Cooks with a probability of nearly 40 % and a mean sailing time of 22.5 days, over a distance on the order of 2,000 km. Drifts too can complete this crossing and stand a 25 % chance of doing so with a significantly longer mean time of 81 days. This is an important result since this voyage accounts for the longest crossing needed to account for the settlement of central-eastern Polynesia, aside from the voyage to Easter Island. While this pathway may seem implausible when considering that the trades generally blow steadily across this area, it is again unusual conditions which allow otherwise untenable movements. Launches from the Tuamotus can easily reach the Australs and the Societies to the west and reach Mangareva, Rapa and Pitcairn in certain years. This adds to the significance of the result, since the Tuamotus represent an area from which the majority of islands in central Polynesia can be reached.

6.3 Drift and Sailing Results

The number of possible crossings into the eastern Lapita region is much greater for the downwind sailing experiments than for the drifters. In general, such crossings, when they do occur, also have higher probabilities and shorter mean crossing times in the downwind sailing results. Both the USCG and Levison parameterizations have a very similar response to surface currents (whose effects are generally much less important than the wind), so differences are almost entirely due to differing response to surface winds. Simply put, the sailing vessels move directly down wind and have much better performance than do the drifters.

Figure 6.4 shows sample trajectories for the same launch day from Solomon - 3 with sailing trajectories in blue and drifters in black. The mean step size for the sailing boats is considerably greater than for the drifters, indicating that these vessels move much further in an average 24-hour timestep. The drift trajectories appear somewhat jagged as a result of the the drifters changing their orientation with respect to the driving wind [2]. Both types of vessels initially follow a track due east. North of Santa Cruz, the sailing ships move southeast, eventually reaching Fiji. The drifters veer more sharply to the south, arriving in Santa Cruz. The different tracks taken reflect the relative speeds of the vessels; by the time the drifters had reached the vicinity of the Santa Cruz group, the winds had a more southerly component than those

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[2] Recall the drift direction is randomly assigned to the right or left of the wind on a given day, always deviating by the constant leeway angle.

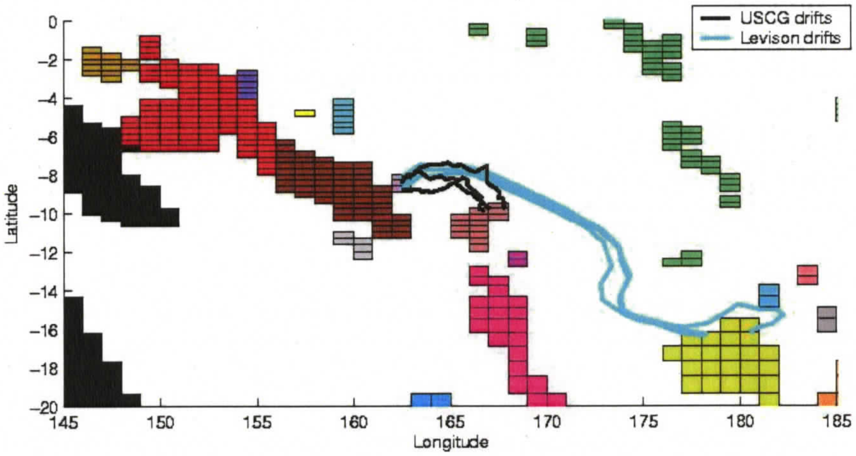

Figure 6.4: Sample trajectories for vessels using the USCG (black) and Levison (blue) parameters. Drifts start from the centre of the three grid cells making up the Solomon - 3 launch area. The selected drifts come from the summer 1993 set of launches. USCG vessels all arrive in the Santa Cruz group after 22-24 days; Levison vessels all reach the Fiji group after 19-28 days.

experienced by the sailors.

The differences in crossing parameters between both sets of simulations can be understood in terms of the relative 'efficiency' of the different movement schemes. This also explains why a significantly higher percentage of drift voyages end up back in the departure group. Drifters have a lower chance of clearing their home group on favorable winds before the wind changes direction, pushing them back. This is especially true of departures from large island groups such as Fiji or the Solomons since they present a much larger area to intercept returning drifts. The results from these experiments demonstrate the importance of applying appropriate parameters to the problem at hand. *Levison et al.* (1973), while intending to model drift voyages, used the same parameters I used for my downwind sailing experiments, thus greatly exaggerating the performance of their vessels over true drifters.

6.4 Survival at Sea

The proper way to interpret the 'lost at sea' category in the results is not as a measurement of fatalities, but as representation of the percentage of vessels which did not reach land within 90 days. Drifts and sailing voyages which start from islands lying in the band stretching from the equator to 20° S, both within Melanesia and Polynesia, have low 'lost at sea' percentages of 25 % or less (considering overall results), with the majority having percentages of 10 % or lower. These low values show that a majority of simulated vessels encounter land within three months at sea, reflecting the influence of the extensive screens of islands in the equatorial Pacific which can 'catch' drifting or sailing vessels. So, these results imply that, if survival at sea for 3 months is accepted, the number of fatalities may not be large even in voyages of drift or undirected exploration.

A number of factors affect survival including availability of food and water, precipitation received en route (which supplies drinking water), the nature of wind and temperature extremes encountered and so on. In an attempt to address this issue, *Levison et al.* (1973) allowed for variable voyage lengths: individual voyages were randomly assigned maximum lengths following a survival probability table based on anecdotal reports of drifts [3]. Survival at sea is a complicated matter and to model it given the unknowns would require a number of additional and arbitrary assumptions, and I chose not to model it at all.

I acknowledge that mariners, especially drifters, could expire before three months was up though it should be noted that there are a number of historical accounts of drifts with survivors which lasted for at least half a year (*Montenegro et al.* (2006)). Furthermore, since the downwind sailing experiments represent intentional exploration, crews of such ships would surely bring stores of food and water to help them withstand lengthy voyages, so survival at sea for extended periods is much easier to accept in this case.

In the *Levison et al.* (1973) simulation, vessels stood a 50 % chance of capsizing

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[3] Following their survival probability distribution, roughly 25 % of the voyages ended within 7 weeks, 50 % within the first 10 weeks, 75 % within the first 13 weeks and all voyages ended within 26 weeks.

upon encountering winds of force 9 on the Beaufort scale or greater (> 20.6 m/s). I make no attempt to model the seaworthiness of vessels and assume that boats withstand all weather that they encounter. Since nothing firm is known about maritime technology at the time of Pacific settlement (*McGrail* (2001), there is no reason to choose any particular value as the maximum wind speed that could be withstood by boats, and doing so involves making further assumptions in the simulations. I do note however that force 9 winds and higher occur within the study area only infrequently.

Such intense winds are often associated with cyclones which typically originate east of the Solomons at around 8 ° S, generally between November and March (*Irwin* (1992)). Thus the summer months, when eastward movement is most probable, coincide with the cyclone season in the Lapita region. Tropical storms are cyclonic disturbances having peak sustained wind speeds between 17 m/s and 32 m/s and hurricanes or typhoons are systems having maximum sustained wind speeds in excess of 32 m/s. Since 1988, the number of tropical storms per year in the eastern Australia basin[4] has ranged between 3 and 14 and the number of hurricanes/typhoons per year has varied between 1 and 12 (*UKMet* (2007)). Frequencies generally increase in strong El Niño years, associated with positive anomalies in sea surface temperature in the western Pacific. Individual systems only affect a small portion of the basin, and *Irwin* (1992) argues that the frequency of occurrence of cyclones is sufficiently small that the odds of a particular canoe encountering one are low.

6.5 A Comparison with *Levison et al.* (1973)

Much of the present understanding of the Lapita peoples and their significance as the ancestors of those who settled Polynesia developed after *Levison et al.* (1973) performed their computer simulation, since many of the major Lapita sites were uncovered in the past 30 years (*Kirch* (2000)). In fact, their discussion indicates that,

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[4] The eastern Australian basin is defined as the area between the equator and 40° S and between 135° E and 225° E.

at the time, there was still considerable uncertainty as to whether marginal western Polynesia had been reached through Micronesia or via Melanesia. It is understandable, then, that they focused their work on Polynesia since a more solid point of origin for the settlement of this region, namely its western archipelagos, had been established.

Nonetheless, *Levison et al.* (1973) tested western gateways to Polynesia with Tikopia, Rotuma, Wallis, Futuna and islands in Fiji, Tonga and Samoa as starting points for drifts and additional sites in Melanesia included as targets[5]. As do I, the authors found that westward drifts were quite feasible with a large number of crossings having probabilities of 10 - 20 % or higher. Drifts to the east, north and south *did* occur, but generally with exceedingly low probabilities. It is also important to bear in mind that *Levison et al.* (1973)'s contact probabilities were derived using an extremely liberal estimate of drift performance; had more realistic drift parameters been used, these probabilities would almost certainly be significantly reduced.

In *Levison et al.* (1973)'s study, the only crossing having an eastward component and a probability in excess of 5 % was that from the Australs to the Tuamotus; additional paths to the east having probabilities between 1 % and 4.9 % were those from Rotuma to Fiji and Samoa, from Fiji to Samoa, from New Zealand to the Kermadec islands, from the Kermadecs to Tonga and from Rapa to the Tuamotus. Of these crossings, those from Rotuma, the Australs and Rapa could fit within the accepted model of eastward expansion but key crossings to Fiji and Rotuma and to central Polynesia occurred with negligible probabilities, if at all.

For example, out of 732 drifts from Tikopia, only one reached Fiji and another, Rotuma, leading the authors to conclude that "the four hundred-mile expanse of ocean between the Solomons and New Hebrides[6] to the west and Fiji to the east

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[5] The authors state they chose Tikopia over other potential sites in western Melanesia as it appeared most likely to experience north-westerly winds.

[6] Vanuatu

presents a formidable barrier to eastward drifts." *Levison et al.* (1973) felt, though, that once that crossing had been made, the remaining islands in marginal western Polynesia might be uncovered by drift, even though eastward connections between Fiji/Rotuma and Wallis/Futuna/Tonga/Samoa occurred with probabilities less than 5 %. Drifts from these western Polynesia islands to the central groups, even allowing the use of intermediate islands as stepping stones, occured with negligibly small probabilities and the authors concluded that it was "unlikely that drift voyages played any part in the colonization move from west to east in Polynesia."

My results differ significantly from those of *Levison et al.* (1973) especially with regards to crossings into Fiji/Tonga/Samoa[7] and from western Polynesia to central Polynesia. Such pathways are possible both using *Levison et al.* (1973)'s own "drift" parameters and more conservative estimates of drift from the US Coast Guard. The critical element needed to account for passages to the east of Fiji is interannual climate variability. *Levison et al.* (1973) never broke up their results based on specific annual conditions owing to the paucity of readings recorded in any given year in their dataset. So, effectively only crossings that occurred under mean conditions would be seen as plausible in these simulations.

Another issue with the earlier simulation is the stochastic weather creation method. Randomly generated wind sequences based on monthly probability tables do not well represent sustained periods of winds from a particular direction, unless such winds are dominant. For instance, westerlies might blow for 3 or 4 days in a particular region during the Austral winter but the odds of a probabilistic model producing such a weather sequence would be very low. However, some crossings in my simulations such as from the Solomons to Santa Cruz can occur as quickly as 3 days for sailors and 5 days for drifters. These pathways which make use of such short-term variability in conditions would not be well accounted for in the earlier simulation.

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[7] *Levison et al.* (1973) tested only a western crossing from Tikopia into this region.

Levison et al. (1973)'s work was an important early application of computer models to anthropology and its main results, demonstrating the apparent implausibility of eastward crossings against the trades, are similar to my 'overall results' for sites not strongly influenced by monsoonal winds, as is the recognition that westward drifts are highly probable. However, this model cannot account for the influence of any kind of interannual variability nor sustained periods of anomalous winds in particular months, both of which could be important aspects of a strategic exploration strategy which exploits such unique conditions.

6.6 The Influence of El Niño

El Niño is considered to be the major source of interannual variability in the equatorial Pacific, though the climate of the Lapita region is complicated and alterations in the strength and extent of the winter monsoon and other factors contribute to the overall climate variability. El Niño itself exhibits fluctuations in strength, duration and zone of influence from event to event.

One indicator of this phenomenon is the Southern Oscillation Index (SOI), which measures the deviation from the normal sea level pressure (SLP) gradient between Darwin, Australia and Tahiti in the Society Islands. The SLP is generally higher at Tahiti than at Darwin. During an El Niño event, there is warming of the surface waters in the central-eastern Pacific which serves to reduce the SLP gradient between the two measurement sites, causing negative SOI values. Prolonged periods of negative values are indicative of El Niño conditions; conversely, periods of extended positive SOI values are indicative of La Niña conditions. The SOI can also be regarded as an estimate of the strength of the trade winds: strongly positive SOI values are associated with unusually vigorous easterly winds while strongly negative values are associated with unusually weak easterlies and wind reversals in the western-central equatorial Pacific.

Figure 6.5 is a plot of the monthly SOI values from 1993-2005, covering the same time period as the simulations. There are five periods of sustained, negative SOI values and these correspond to the 1993, 1994-95, 1997-98, 2002-03 El Niños and the beginning of the 2004-05 El Niño. Of these, the most pronounced is the 1997-98 El Niño, well known as the most intense such event on record. While the majority of paths that are probable in specific years occur in El Niño years, a few eastward crossings occur in 1996 and 1999, under La Niña conditions when the SOI had strong positive values. Furthermore, the paths that are possible in one El Niño are different in another and there is no apparent correlation between the number of viable pathways in the Lapita region and the strength of the El Niño. For instance, the number of crossings possible in winter 1993 exceeds those in 1997-1998 despite the latter being a much more intense event.

Figure 6.6 shows why the 1993 Austral summer conditions were particularly favorable. During these months, there was a band of westerly winds extending from Near Oceania out to Samoa, explaining how voyages from the Solomons and Santa Cruz could rapidly and with high contact probabilities reach Fiji, Futuna and Tonga and, from there, Samoa. Figure 6.7 shows the surface wind field during summer, 1998. Here, as in 1993, there was a narrow band of westerly winds which extended westward from Near Oceania. In this case, however, the band of reversed winds was centered at a higher latitude, to the north of islands in the eastern Lapita region. The effects of this strong El Niño were, however, very pronounced east of the Lapita region and allowed the surprising crossings from the Northern Cooks to the Tuamotus. So, while the 1997-98 El Niño had a much broader region of influence, when considering the Pacific as a whole, its effects on the Lapita region were not as direct as the 1993 episode.

More simulations using a longer weather data set that captured additional intense El Niños might be used to look for a correlation between event strength and crossings

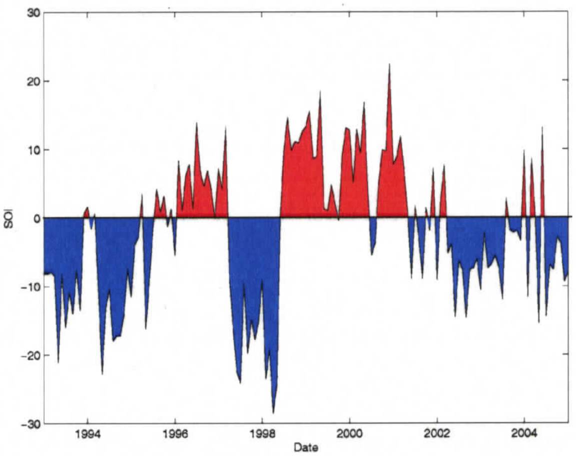

Figure 6.5: The Monthly Southern Oscillation Index for 1993-2004. Periods of sustained negative SOI values are indicative of El Niño conditions. Five such periods are recorded in the SOI values corresponding to the 1993, 1994-95, 1997-98, 2002-03 and 2004-05 El Niños. Data taken from *BOM* (2007).

within central Polynesia. Sampling the influence of additional El Niños might also reveal new crossings, possibly including a stronger connection between Tonga and Samoa and the Cooks than I was able to demonstrate. Overall, these results suggest that climate fluctuations associated with El Niño may play an important role in facilitating crossings to the east, though the stochastic nature of the phenomenon makes it difficult to predict which crossings are possible in a particular episode. That some eastward crossings also occur in La Niña years, when easterlies would generally be expected to be more intense, further reflects the complicated nature of the interannual variability in the Lapita region.

6.6.1 ENSO in the Holocene

There are a number of paleoproxy indicators (such as corals and tree rings, for example) which are sensitive to the influence of El Niño, some of which capture a long temporal record of the phenomenon. In contrast, continuous, proxy records sensitive to the Australian monsoon, another important form of variability in my results are rare (*Wyrwoll and Miller* (2001)), and I was unable to find any records describing changes in the monsoon circulation from the Holocene onwards.

The frequency of occurrence of anomalous conditions associated with the El Niño appears to have varied since the mid-Holocene, though a clear understanding of this variability requires long, continuous paleoproxy records with high temporal resolution. One promising record comes from sediment cores of Laguna Pallcacocha, a lake in the Ecuadorian Andes. This region experiences greatly enhanced precipitation during El Niño events; strong events can trigger clastic debris flows which result in distinct sediment laminae in the lake record (*Rodbell et al.* (1999)). *Moy et al.* (2002) analyzed a 12,000-year-long core record and produced a time series, reproduced in Figure 6.8, that shows the number of moderate-to-strong El Niño events per 100 years since 5,000 cal BP. The record shows a gradual, pulsing increase in the frequency of El Niño events beginning in the mid-Holocene and peaking between 1,000 and 2,000 years ago.

By comparison with the numerical modelling study of *Clement et al.* (2000), which showed a similar frequency time series to the lake record, *Moy et al.* (2002) argue the increase in frequency from the mid-Holocene to 1,000 cal BP is associated with orbitally-induced changes in insolation driven by the precession of the equinoxes which occurs on a 20,000 year period and affects ENSO through a complicated series of feedbacks. Additional, shorter period variability in the time series is attributed to internal ENSO dynamics. Though the lake core records do not describe variation in the intensity of El Niño events, the modelling results of *Clement et al.* (2000) quantify such variations by measuring the intensity of the anomaly in sea surface temperature in the NINO3 region. Their results suggest that the amplitude of El Niño events remained nearly constant until about 7,000 cal BP, followed by a steady increase to 2,000 cal BP and a gradual decline to present day.

Anderson et al. (2006) have proposed that prehistoric Pacific watercraft were not advanced enough to permit sailing against the trades and observe that El Niño-related wind reversals could facilitate eastward movement. The present view is that Oceanic colonization was highly episodic and the authors observe that colonization episodes either coincide with or slightly lag behind periods where there was an increase in the frequency of El Niño events. The black boxes at the bottom of Figure 6.8 represent the currently accepted range of dates for colonization. Speckled boxes represent a proposed earlier range of dates during which settlement might have occurred if El Niño forcing was significant.

As discussed above, my results indicate that important eastward crossings in the Lapita region and Polynesia have higher probabilities in El Niño years, and lend support to *Anderson et al.* (2006)'s hypothesis. However, caution must be exercised in reading too much from a single paleoproxy record from a single location and I argue that a similar signal needs to be demonstrated in a comparable, long, high-resolution El Niño record from another area of the Pacific strongly affected by this phenomenon in order to be certain that the implied variations in El Niño are real.

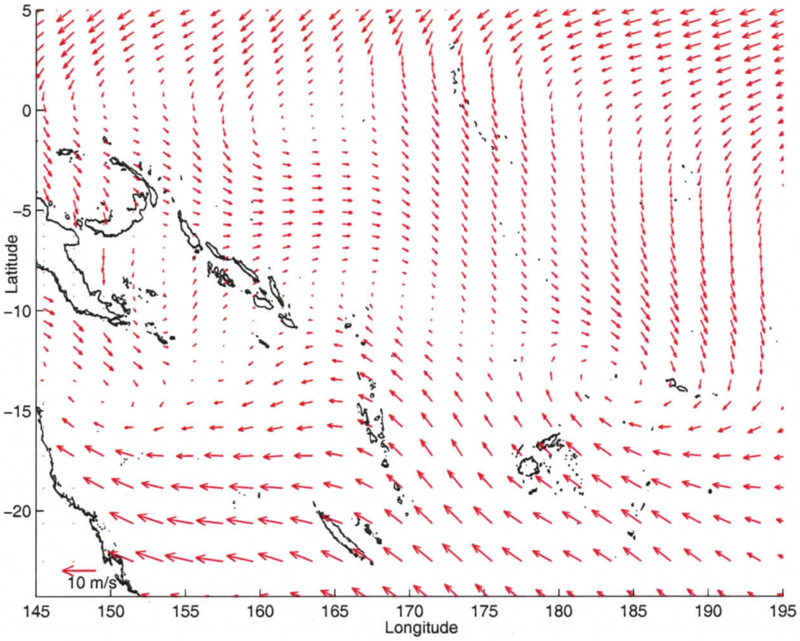

Figure 6.6: Austral summer 1993 wind field.

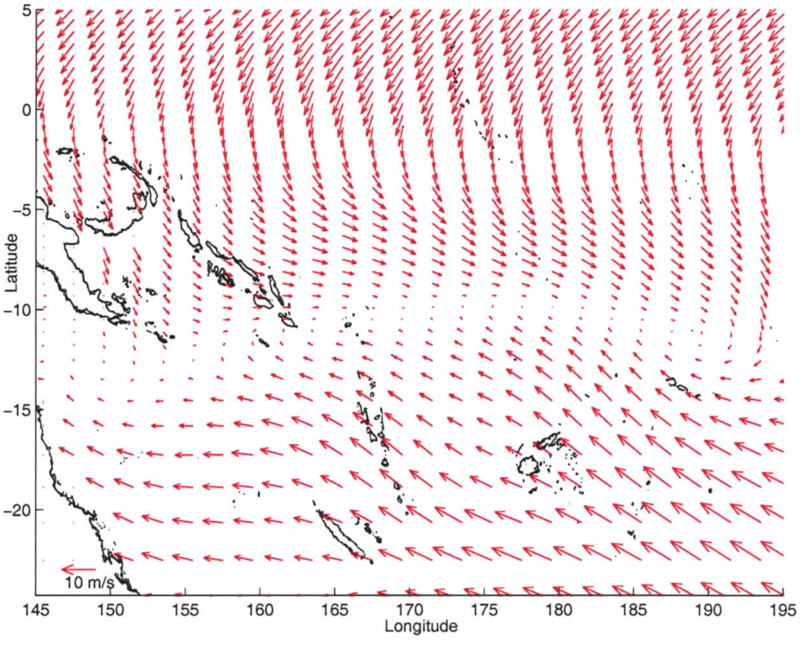

Figure 6.7: Austral summer 1998 wind field.

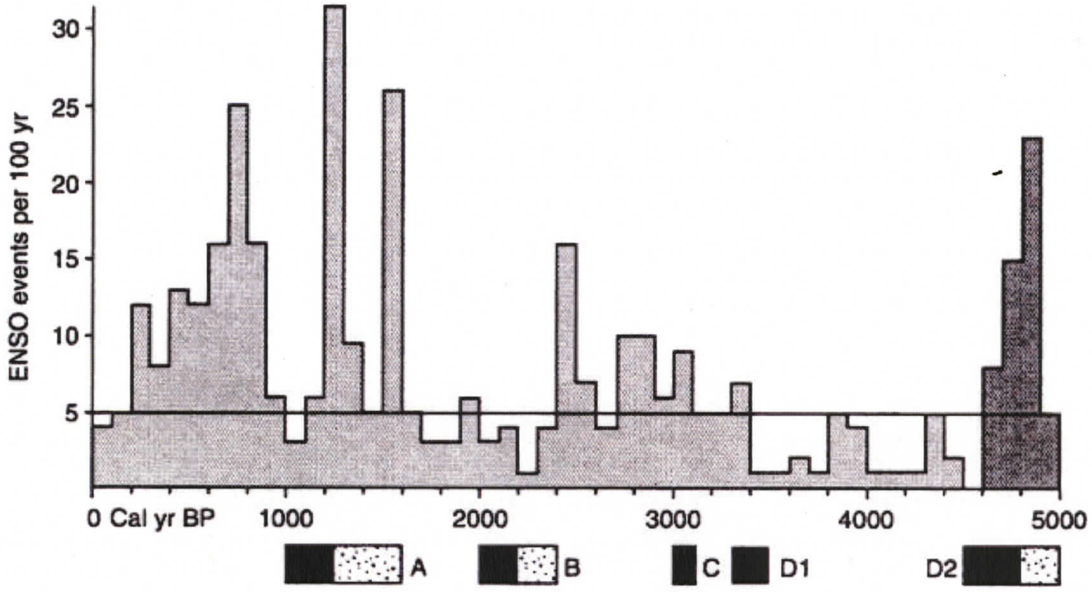

Figure 6.8: El Niño frequency variations since the mid-Holocene. This figure shows the inferred number of El Niño events per 100 years since 5,000 cal BP. Black shading represents the currently accepted date ranges for Pacific settlement episodes; speckled shading is a proposed early settlement date range if ENSO forcing was significant. Letters represent the different waves of colonization as follows: A - central/eastern Polynesia, B - central / eastern Micronesia, C - Lapita expansion, D1 / D2 - western Micronesia. The figure has been reproduced from *Anderson et al.* (2006).

Chapter 7

Conclusions

That the Lapita peoples and their descendants were capable seafarers is not in question. The extensive interaction spheres and exchange of artifacts between widely separated islands and archipelagos imply they could cross long stretches of open water with apparent ease, perhaps employing relatively sophisticated navigational skills. But sailing and navigating in a sea of known islands where mean currents and winds are understood is a different matter than exploring an unknown ocean for the first time. My simulation results suggest that no advanced exploration schemes need to be proposed to account for the discovery of islands in the Lapita region, since contact pathways from Near Oceania to Tonga and Samoa are possible both through drift and downwind sailing. This is not to say that more advanced exploration strategies were not employed, merely that they appear to be unnecessary under the assumptions of my model.

Even if the Lapita people were very skilled mariners, it is unreasonable to say that they never got blown off course or lost at sea. I take such unfortunate events to be one way by which my simulated drift voyages might occur. I do not hold that drifters can account for the settlement of new islands, but they could explain their discovery. From the drift 'lost at sea' results, such drifters stand a very good chance of reaching land, accepting that the crews can survive at sea for 3 months. The majority of drifters return back to the area from which they were lost but a sizable percentage move eastward. Having encountered new land, the crews of such boats could wait for easterly winds and attempt to sail or drift west to inform others of their discovery. The knowledge of land to the east could then serve as motivation for deliberate voyages of exploration and, later, settlement.

That many key drift crossings in the study region occur only in particular years when the wind field is different from the mean state fits well with this scenario since it seems more plausible for vessels to lose their way when faced with unusual weather. In the drift experiments, a specific pathway to marginal western Polynesia is implied: drifters must first reach Rotuma in order to encounter Tonga. From there, drifters can move northwest to Samoa. If Rotuma was indeed discovered and settled post-Lapita, then the role of drift discovery in that expansion would appear to be limited to Fiji.

Irwin (1992)'s safe exploration model suggests that the Lapita region and central-eastern Polynesia were probed by vessels sailing against the dominant trade winds. Downwind sailing is an element of this model, but in *Irwin* (1992)'s view, crews on outbound voyages would only use this strategy if progress to the east could be made. In my simulations, vessels sail downwind no matter which way the wind blows and since the simulation does not prevent boats from leaving when easterlies blow, it is not a pure test of this aspect of *Irwin* (1992)'s theory. However, a comparison of the Austral summer crossing probabilities with corresponding results from the overall table gives an indication of how strategic exploration that exploits westerlies could increase the frequency of contact to the east.

This downwind sailing experiment implies a greater number of pathways in the Lapita region, many of which occur with significantly higher probabilities than in the drift case. One would therefore anticipate a faster rate of island discovery of new islands in the sailing case because of these heightened probabilities.

Downwind sailing is the simplest exploration strategy to test and involves the fewest assumptions, requiring only that the crew opt to sail with the wind and are able to make landfall when islands are sighted. This is not to say that this strategy was that employed by the Lapita settlers nor that other exploration strategies were not possible. The boats used by explorers and settlers could almost certainly sail, not just downwind, but also at various angles to the wind. Indeed, this would be necessary if crews were to steer towards land once islands were sighted. This steering ability would increase the possible courses in the Lapita region over those represented by my simulations.

Modelling directed sailing makes simulations more difficult to interpret and to justify as decision-making must be modelled in order to choose a course to be sailed and the means by which the crew would attempt to maintain it. Thus, while eastward contact probabilities might increase (and crossing times decrease) under a more advanced exploration scheme, I opted not to test such models given the added complexity and assumptions that would be involved. I suspect, though, that the fundamental results of this simulation would also apply to models incorporating more advanced exploration strategies: eastward courses would be fastest and easiest to maintain in summer months and El Niño conditions when the frequency of occurrence of easterly winds decreased.

I feel the most important result to come out of my experiments is the importance of considering climate variability in models of Pacific exploration, a factor which could not be addressed in *Levison et al.* (1973)'s influential work. While my experiments are doubtless an oversimplification of the actual means by which the Pacific was explored, they are more sensitive to this variability than more advanced exploration models might be. It is sometimes said that the settlers of the Pacific perceived their world not as a barrier, but a highway. To extend this metaphor, I suggest that the ocean can indeed be seen as a highway, but one with an ever shifting roadmap.

Bibliography

Anderson, A. (2003), Initial human dispersal in Remote Oceania: pattern and explanantion, in *Pacific Archaeology: Assessments and Prospects, Les Cahiers de l'Archéologie en Nouvelle Calédonie*, vol. 15, edited by C. Sand, pp. 71–84, Service des Musées et du Patrimoine de Nouvelle-Calédonie, Nouméa.

Anderson, A., J. Chappell, M. Gagan, and R. Grove (2006), Prehistoric maritime migration in the Pacific islands: an hypothesis of ENSO forcing, *The Holocene*, *16*(1), 1–6.

BOM (2007), Australian Bureau of Meteorology: S.O.I. (Southern Oscillation Index) Archives, http://www.bom.gov.au/climate/current/soihtm1.shtml. Last accessed: February 2nd, 2007.

Clement, A., R. Seager, and M. Cane (2000), Suppression of El Niño during the mid-Holocene by changes in the Earth's orbit, *Paleoceanography*, *15*(6), 731–737.

Dodd, E. (1972), *Polynesian Seafaring*, Dodd, Mead, New York.

Evans, B. (1999), Simulating Polynesian double-hulled canoe voyaging: combining remotely-sensed and experimental data, M.A. thesis, University of Hawai'i.

Finney, B. (1977), Voyaging canoes and the settlement of Polynesia, *Science*, *196*(4296), 1277–1285.

Finney, B., P. Frost, R. Rhodes, and N. Thompson (1989), Wait for the west wind, *Journal of the Polynesian Society*, *98*(3), 261–302.

Hackett, B., O. Breivik, and C. Wettre (2006), Forecasting the drift of objects and substances in the ocean, in *Ocean Weather Forecasting*, edited by E. Chassignet and J. Verron, pp. 507–523, Springer, Berlin.

Hastings, D., and P. Dunbar (1999), The Global Land One-kilometer Base Elevation (GLOBE) Digital Elevation Model, version 1.0, *Tech. rep.*, National Oceanic and Atmospheric Administration, National Geophysical Data Center, Boulder, Colorado.

Hunt, T., and C. Lipo (2006), Late colonization of Easter Island, *Science*, *311*(5767), 1603–1606.

Hurles, M., E. Matisoo-Smith, R. Gray, and D. Penny (2003), Untangling Oceanic settlement: the edge of the knowable, *Trends in Ecology and Evolution*, *18*(10), 531–540.

Intoh, M. (1997), Human dispersals into Micronesia, *Anthropological Science*, *105*(1), 15–28.

Irwin, G. (1992), *The Prehistoric Exploration and Colonization of the Pacific*, Cambridge University Press, Cambridge.

Irwin, G. (1998), The colonisation of the Pacific plate: chronological, navigational and social issues, *Journal of the Polynesian Society*, *107*(2), 111–143.

Irwin, G., S. Bickler, and P. Quirke (1990), Voyaging by canoe and computer: experiments in the settlement of the Pacific Ocean, *Antiquity*, *64*(242), 34–50.

Kirch, P. (1997), *The Lapita Peoples: Ancestors of the Oceanic World*, Blackwell Publishers, Cambridge, Massachusetts.

Kirch, P. (2000), *On the Road of the Winds: An Archaeological History of the Pacific Islands before European Contact*, University of California Press, Berkeley.

Kistler, R., et al. (2001), The NCEP/NCAR 50-year Reanalysis: Monthly means CD-ROM and documentation, *Bulletin of the American Meteorological Society*, *82*(2), 247–267.

Levison, M., R. Ward, and J. Webb (1973), *The Settlement of Polynesia: a Computer Simulation*, The University of Minnesota Press, Minneapolis.

Markgraf, V., and H. Diaz (2000), The past ENSO record: a synthesis, in *El Niño and the Southern Oscillation: Multiscale Variability and Global and Regional Impacts*, edited by H. Diaz and V. Markgraf, pp. 465–488, Cambridge University Press, Cambridge.

Markgraf, V., J. Dodson, A. Kershaw, M. McGlone, and N. Nicholls (1992), Evolution of late Pleistocene and Holocene climates in the circum-South Pacific land areas, *Climate Dynamics*, *6*(3-4), 193–211.

McGrail, S. (2001), *Boats of the World: From the Stone Age to Medieval Times*, Oxford University Press, New York.

Montenegro, A., R. Hetherington, M. Eby, and A. Weaver (2006), Modelling pre-historic transoceanic crossings into the Americas, *Quaternary Science Reviews*, *25*(11-12), 1323–1338.

Montenegro, A., C. Avis, and A. Weaver (2007), Modelling the pre-historic arrival of the sweet potato in Polynesia, *Journal of Anthropological Science*, in press.

Moy, C., G. Seltzer, D. Rodbell, and D. Anderson (2002), Variability of El Niño / Southern Oscillation activity at millennial timescales during the Holocene epoch, *Nature*, *420*(6912), 162–165.

Nunn, P. (1998), *Pacific Island Landscapes*, Institute of Pacific Studies, The University of the South Pacific, Suva, Fiji.

Rodbell, D., G. Seltzer, D. Anderson, M. Abbott, D. Enfield, and J. Newman (1999), An $\sim$ 15,000-year record of El Niño-driven alluviation in Southwestern Ecuador, *Science*, *283*(5401), 516–520.

Sand, C. (2000), La datation du premier peuplement de Wallis et Futuna: contribution à la définition de la chronologie Lapita en Polynésie occidentale, *Journal de la Société des Océanistes*, *111*(2), 165–172.

Sand, C., J. Bolé, and A. Ouetcho (2002), Site LPO023 of Kurin: Characteristics of a Lapita settlement in the Loyalty Islands (New Caledonia), *Asian Perspectives*, *41*(1), 129–147.

Sharp, A. (1963), *Ancient Voyagers in Polynesia*, Angus & Robertson Ltd., London.

Spriggs, M. (1997), *The Island Melanesians*, Blackwell Publishers, Cambridge, Massachusetts.

Spriggs, M., and A. Anderson (1993), Late colonization of East Polynesia, *Antiquity*, *67*(255), 200–217.

Stammer, D., C. Wunsch, R. Giering, C. Eckert, P. Heimbach, J. Marotzke, A. Adcroft, C. Hill, and J. Marshall (2002), The global ocean circulation during 1992-1997 estimated from ocean observations and a general circulation model, *Journal of Geophysical Research*, *107*(C9), 3118–3146.

Stringer, C. (2000), Coasting out of Africa, *Nature*, *405*(6782), 24–26.

UKMet (2007), United Kingdom Meteorology Office: Eastern Australian Basin tropical cyclone activity, http://www.metoffice.gov.uk/weather/tropicalcyclone. Last accessed: February 2nd, 2007.

USCG (2002), U.S. Coast Guard addendum to the United States National Search and Rescue supplement to the International Aeronautical and Maritime Search and

Rescue manual, second edition, *Tech. rep.*, United States Coast Guard, comdtinst m16130.

Vincent, D. (1994), The South Pacific Convergence Zone (SPCZ): A review, *Monthly Weather Review, 122*(9), 1949–1970.

Weisler, M. (1998), Hard evidence for prehistoric interaction in Polynesia, *Current Anthropology, 39*(4), 521–532.

Wyrwoll, K., and G. Miller (2001), Initiation of the Australian summer monsoon 14,000 years ago, *Quaternary International, 83-85*(1), 119–128.