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University of Southampton

Faculty of Physical Sciences and Engineering

Maritime Engineering

Uncertainty in Marine Weather Routing: An Investigation into Polynesian Seafaring

by

Thomas Dickson

ORCID ID 0000-0002-3338-9716

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UNIVERSITY OF SOUTHAMPTON

ABSTRACT

FACULTY OF PHYSICAL SCIENCES AND ENGINEERING

MARITIME ENGINEERING

Thesis for the degree of Doctor of Philosophy

UNCERTAINTY IN MARINE WEATHER ROUTING: AN INVESTIGATION INTO POLYNESIAN SEAFARING

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The aim of this thesis is to quantify how Polynesian seafaring technology, climate and season may have influenced the length of the “long pause” between the settlement of West and Central East Polynesia. Current literature has not investigated the performance of Polynesian seafaring technology at the time of the long pause and how this could influence colonisation, or how uncertainty propagates through the marine weather routing process. Of interest is how Polynesian seafaring technology could have contributed towards the length of the long pause and how competing factors and sources of uncertainty could have influenced the result.

A review of Polynesian seafaring technology has allowed the performance of the earliest recorded voyaging canoe, the *Tongiaki* to be predicted. A novel methodology was developed to quantify the influence of weather, performance and numerical uncertainty on the minimum time taken to complete a specific voyage. The ability to use Bayesian Belief Networks (BBNs) to model the reliability within the routing algorithm was shown to improve the chances of completing a voyage using an autonomous sailing craft, a modern naval architectural problem. By applying the novel methodology it was found that the *Tongiaki* was only able to complete voyages between Samoa and Aituitaki, the voyage bridging West and East Polynesia, under El Niño conditions. The windward ability of a canoe was found to be more influential than speed increases from simulations generated by using a parametric voyaging canoe model. The trend in simulated Polynesian canoe performance mirrors that seen in the spatial development in Polynesian seafaring technology.

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Declaration of Authorship

I, Thomas Dickson, declare that this thesis entitled *Uncertainty in Marine Weather Routing: An Investigation into Polynesian Seafaring* and the work presented in it are my own and have been generated by me as the result of my own original research.

I confirm that:

1. This work was done wholly or mainly while in candidature for a research degree at this University;
2. Where any part of this thesis has previously been submitted for a degree or any other qualification at this University or any other institution, this has been clearly stated;
3. Where I have consulted the published work of others, this is always clearly attributed;
4. Where I have quoted from the work of others, the source is always given. With the exception of such quotations, this thesis is entirely my own work;
5. I have acknowledged all main sources of help;
6. Where the thesis is based on work done by myself jointly with others, I have made clear exactly what was done by others and what I have contributed myself;
7. Either none of this work has been published before submission, or parts of this work have been published as:
    - Thomas Dickson, James Blake and David Sear, *Reliability informed routing for Autonomous Sailing Craft*, Robotic Sailing (2018) 71-78 (Dickson et al., 2018)
    - Thomas Dickson, Helen Farr, David Sear and James Blake, *Uncertainty in marine weather routing*, Applied Ocean Engineering, 2019, Vol 88, p138-146 (Dickson et al., 2019)

Signed:

Date:

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Acknowledgements

This thesis would not have been possible without very many people. First of all, I would like to thank my supervisors; Dr James Blake, Professor David Sear and Dr Helen Farr. I admit that I found the combination of engineering, geography and marine archaeology confusing at times, and it was their patience which helped me through. I'm afraid I tested their patience more at the thesis writing stage where my literary idiosyncracies were laid bare.

I acknowledge my academic fairy godmother, Dr Gabriel Weymouth, for sprinkling copious amounts of fairy dust over my research throughout my time at Southampton. It's his fault that I discovered my interest in coding. I want to recognise the IRIDIS 5 supercomputer. It would not have been possible otherwise to perform the quantity of simulations that I required for this investigation.

I would like to thank my examiners, Professor Dominic Hudson of the University of Southampton and Professor Alvaro Montenegro of Ohio State University. Their good humoured critism and thoughtful suggestions have significantly improved this thesis.

Thanks to the DFUs, the DFLs the Spaniard, the Italian and Jack. Crews of Jitterbug and Helen. I must thank my family for keeping me going through the final phases of my PhD. Thanks to my Grandfather, Ken, for sparking my interest in engineering and to my parents for supporting me.

Finally, I want to recognise the achievement of those Polynesian sailors who undertook the successful and unsuccessful voyages which enabled the settlement of Polynesia must be remembered. It is the intention of this thesis to treat the heritage of all Polynesians with respect. Any disregard of the human side of the problem is a result of my curiosity in the technical challenge.

All mistakes were provided by myself.

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Chapter 1

Introduction

1.1 The Colonisation of Polynesia

The migration across Polynesia in the Pacific over three thousand years was the last and arguably most hazardous migration across Earth by humans. The chronology of settlement across Polynesia indicates there were two final phases: between West and Central East Polynesia (CEP) and then from CEP to the edges of the Polynesian Triangle (Wilmshurst et al., 2011a), Figure 1.1. Other potential barriers to colonisation include the increasing isolation and sparseness of land from East to West (Irwin, 2008), prevailing wind conditions and high energy climate events such as tsunamis or volcanic eruptions (Margalef et al., 2018). Understanding how this migration occurred answers questions about how humans used technology to overcome environmental barriers, adapted to climate change and managed resources to sustain exploration efforts.

The chronological gap between the colonisation of West and CEP is known as the "long pause" and lasted between $600 - 1000$ years. The eastern archipelagos of West Polynesia (Fiji, Tonga and Samoa) were colonised between $3111 - 2960$ B.P.

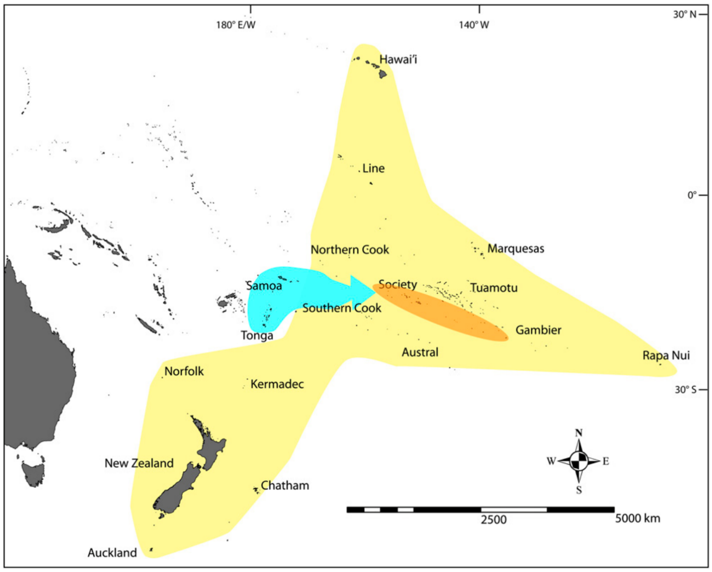

Figure 1.1: Map of the two key phases of movement from West Polynesia, first to CEP between A.D. 1025-1121 (in orange) and then from CEP to Outer East Polynesia (OEP) between A.D. 1200-1290 (in yellow) (Wilmshurst et al., 2011a).

(Clark et al., 2016; Nunn and Petchey, 2013) likely from the Bismark Islands, settled in 3360 – 3430 B.P. (Denham et al., 2012). The island of Aitutaki, on the Western edge of CEP, is thought to have acted as a stopping point between West and CEP. Aitutaki was colonised in 622.5 B.P. (Allen, 2007), although more recent analysis indicates it was settled in 1020 – 1070 B.C. (Sear et al., 2019). There is strong evidence for a significant length in time between the arrival of humans in West Polynesia and then the spread to CEP but there has yet to be clear agreement in the academic discourse as to the precise length of time. Although there is substantial evidence establishing the existence of the "long pause" it is unclear how different factors may have contributed to the precise length of the "long pause".

Identifying the influence of contributing factors to the length of the long pause is of interest in the field of Polynesian archaeology (Anderson et al., 2006; Avis et al., 2008; Di Piazza, 2014; Lilley and ICOMOS, 2010; Montenegro et al., 2014; Wilmshurst et al., 2011a). However, the paucity of archaeological evidence has led to a debate on numerous areas such as seafaring technology, environmental conditions and voyaging strategy (Anderson, 2008a, 2017).

This thesis is taking a scientific perspective to quantify the influence of competing factors on the challenge of voyaging. It describes an attempt to quantify the technical difficulty in overcoming this challenge, which was originally solved by people with a different culture and perspective on seafaring. Artefacts are considered from the perspective of a modern engineer and there is no judgement on the value of the culture which created them.

The environmental conditions in the Pacific hinder any seafaring to the East. The surface currents in the latitudes of interest, 0^o to 20^o S, have a mean flow from East to West (Bonjean and Lagerloef, 2002). The direction of wind and wave conditions is from East to West with the strength and direction varying as a function of El Niño Southern Oscillation (ENSO). ENSO is a $3 - 7$ year oscillation in the difference in temperature between the East and West Pacific Ocean and has been linked to phases in the colonisation of Polynesia (Anderson et al., 2014).

Seafaring technology is universally agreed to have played a central role in the colonisation process (Finney, 1977; Irwin, 2008). The term “seafaring technology” is used to describe technology such as canoes or construction tools that enable seafaring to occur, where seafaring is used as a term for general oceanic sailing rather than intentional voyaging (Anderson, 2014). Polynesian seafaring technology is described in Subsection 1.3.

Marine archaeology in the Pacific is challenging as seafaring is transient by nature and boats are rarely preserved due to being constructed out of organic material.

A seafaring craft leaves no trace as it passes through the water. Consequently, computer modelling has had a long history of application to modelling Polynesian seafaring and migration (Levison et al., 1973). Recent efforts have simulated island discovery (Avis et al., 2008) or investigated the influence of climate variation (Montenegro et al., 2016a). Yet these studies were not undertaken with the same level of accuracy as seen in modern marine weather routing analysis and did not consider the influence of different sources of uncertainty.

1.2 Marine weather routing

Marine weather routing is the process of identifying the optimal route to take between two points over the sea. Environmental factors such as the wind, wave and current often act to impede the progression of a marine vessel. Various optimisation algorithms have been implemented to identify routes which reduce exposure to environmental variables to optimise specific parameters (Walther et al., 2016). Common optimisation goals include the minimisation of voyaging time, V_t (Philpott and Mason, 2002), risk of losing to an opponent (Tagliaferri and Viola, 2017), the avoidance of structural failure (Decò and Frangopol, 2013) or fuel-efficiency (Lin et al., 2013).

An example of a route which was actually sailed can be seen in Figure 1.2. This voyage was sailed using a reconstructed Polynesian voyaging canoe, the Hokule'a. It is a record of the location of the craft as the navigator attempts to sail the fastest route between two points as they experienced the weather. Marine weather routing can be used to model how voyages such as these may have been completed in the past with different vessels and weather conditions.

Marine weather routing can be used to model routes which are going to take place in the future (Skoglund et al., 2015) or to reconstruct possible voyaging routes

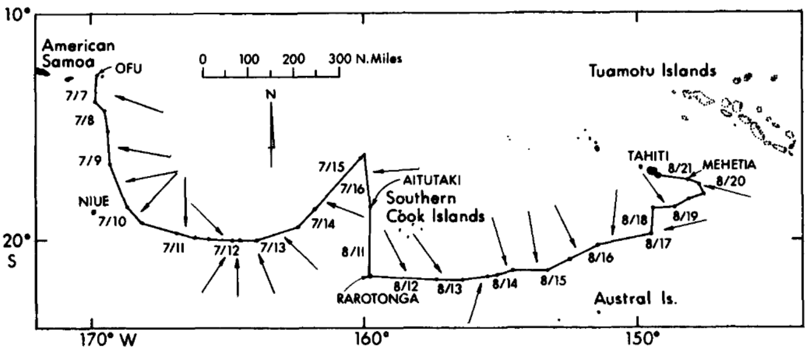

Figure 1.2: Voyage between Samoa, Aituitaki and Tahiti in the Hokolu'a (Finney, 1991).

undertaken in the past (Montenegro et al., 2016a). Modelling routes in the future occurs when a modeller has a known vessel design and seeks to understand how to optimally deploy it. Historical route modelling occurs when modellers want to evaluate the performance of different vessel designs (Oliver, 2006) or investigate how historical crossings may have occurred (Irwin et al., 1990).

The weather data used for future marine weather routing has a much shorter time span than historical routing. Weather forecasts are often only accurate to $5 - 7$ days (ECMWF, 2019a) which introduces an almost unquantifiable level of uncertainty in voyage modelling conducted for future trips. Reanalysis weather data is produced by analysing recorded weather conditions and predicting what conditions occurred, (Dee et al., 2011), for example. Reanalysis weather data is often used to model conditions which might have been seen in the past. Weather routing using weather forecasts takes place over a shorter length of time than that used in historical voyage modelling. It is likely that uncertainties associated with non-environmental sources dominate in modelling which uses reanalysis weather data which has a known level of uncertainty. These sources of uncertainty could include the performance model used to describe the behaviour of the craft.

Both applications of marine weather routing share similar problems. The influence of weather uncertainty, numerical error and influence of uncertainty within the performance model must be quantified in order to give credibility to the results of any routing analysis. The literature review in Chapter 5 shows that the contributions of each of these factors to optimal voyaging time has not yet been studied. A methodology for integrating different sources on the reliability of a sailing craft is applied to modelling trans Atlantic voyages by an autonomous voyaging craft, demonstrating the relevance of the methods developed in this thesis.

This thesis develops a novel methodology for investigating an archaeological marine weather routing problem; the peopling of Polynesia. The peopling of Polynesia was undertaken via voyaging canoe, a challenging process involving settling and then supporting settlements on disparate islands. It is only possible to investigate the challenge of settlement by modelling relevant voyaging canoe performance models over different routes and different weather conditions.

1.3 Polynesian seafaring technology

Perhaps the most iconic image of Polynesia seafaring technology is the voyaging canoe. The earliest recorded voyaging canoe is known as the Tongiaki and can be seen in Figure 1.3. There is debate surrounding the evolution of Polynesian canoe designs due to the spatial variation of hull and sail designs (Beheim and Bell, 2011). Different Polynesian canoe designs were used for different purposes such as inshore fishing or ocean voyaging (Haddon and Hornell, 1936). It is also probable that some changes in design, such as from the Tongiaki to the drua represented the adoption of better seafaring technology (Nuttall et al., 2014a). The drua design is based around a large hull attached to an outrigger and was known to have superior windward abilities relative to the Tongiaki. The difference in

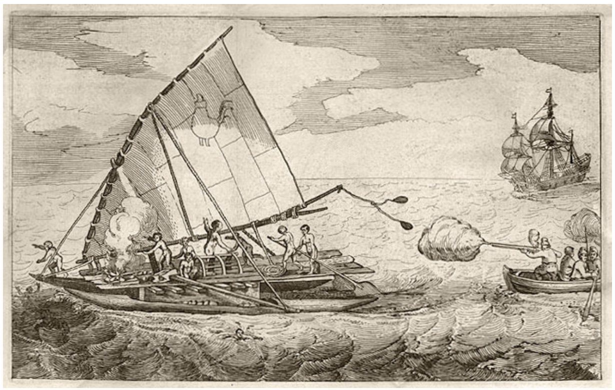

Figure 1.3: A double hulled Polynesian voyaging canoe recorded by Schouten in 1616 A.D. (Koch, 1971). Note the iconography on the sail, the tell-tails flying off the boom and the cooking fire.

performance is thought it have lead to the complete replacement of the Tongiaki after it was recorded by early European explorers (Nuttall et al., 2014a).

The central challenge in the study of how Polynesian seafaring technology influenced migration is the virtual absence of the remains of early voyaging canoes (Anderson, 2008b). This absence of evidence has spawned a debate on the design of Polynesian voyaging canoes between the "traditionalist" and the "historicist" perspectives. The "traditionalist" perspective is associated with sailing canoes which were fast and could sail to windwards, enabling voyages of discovery and colonisation (Finney, 1977). The "historicist" position argues for a slower less able design based on the archaeological evidence, which enabled colonisation given the right combination of weather conditions and skill (Anderson, 2008a). Both of these perspectives have require making different assumptions on how Polynesian seafaring technology developed over time. Consequently it is challenging to identify the point at which the canoe performance would have evolved to enable settlement voyages, and hence bring to an end the "long pause". This thesis models a range of different Polynesian voyaging canoe performance models to provide evidence on how each design behaves over ocean voyages.

This thesis takes an alternative approach to investigate the influence of Polynesian seafaring. The design of the earliest example of Polynesian seafaring technology, the Tongiaki (A.D. 1616), is reconstructed based on historical and archaeological evidence. It is possible to predict the performance of this design using a Velocity Prediction Program (VPP). Voyage modelling in then possible to quantify the time taken for this design to complete key voyages within the colonisation of Polynesia. This investigation will then shed insight into how different perspectives on Polynesian seafaring technology relate to the actual behaviour of these voyaging craft on settlement voyages.

To date, marine weather routing analysis of the Polynesian migration has utilised traditionalist performance models of Polynesian seafaring technology (Di Piazza et al., 2007). Although link has been drawn between inter annual weather variation and colonisation studies (Levison et al., 1973), there has been no investigation of how temporally relevant Polynesian voyaging canoe performance models could perform in varied weather conditions for the key colonisation voyages.

1.4 Overview of this study

This thesis aims to model the contribution of Polynesian seafaring technology towards the length of the "long pause" between the colonisation of West Polynesia and CEP. The Pacific has a varied climate with a high frequency of high energy environmental events such as tsunamis and cyclones that would have negatively impacted any people dependent on the sea. The prevailing weather conditions in the Pacific hinder any smooth sailing to the East. It is not known how Polynesian seafarers were able to overcome or avoid these conditions to successfully settle Polynesia.

Research has modelled the influence of voyaging strategy and weather but has been limited through debates on the accuracy of Polynesian voyaging canoe performance models. Furthermore, the accuracy of the marine weather routing models used have not been quantified. This study introduces predictions of the performance of a Polynesian voyaging canoe used in deep history. A parametric performance model is then developed to model uncertainty in the performance of Polynesian seafaring technology.

Marine weather routing simulations are performed to quantify the voyaging time required to complete different voyages throughout the Pacific. Current marine weather routing methodologies do not consider the role of numerical or performance uncertainty. Therefore, novel developments are implemented in a marine weather routing methodology to model numerical error, reliability, weather uncertainty and performance model uncertainty. These developments are essential for understanding archaeological problems but also for improving the accuracy of modelling modern marine weather routing problems.

1.4.1 Research Questions and Objectives

A series of research questions arise from the research problem discussed in Section 1.4:

1. What are the factors that influenced seafaring in Polynesia throughout the long pause?
2. How might seafaring technology and weather have influenced Polynesian voyaging into Eastern Polynesia?
3. Can contemporary engineering methodologies be developed to address the challenges of Polynesian voyaging uncertainty?
4. What are the performance envelopes of later Polynesian voyaging canoe designs post arrival in the Western Pacific?

5. How might seafaring technology have influenced the challenge of the settlement of CEP at the time of the long pause?

The first question establishes the background of the process of how Polynesia was settled. Identifying how multiple factors would have influenced the choice to explore or voyage to new islands is critical for putting the performance of Polynesian seafaring technology in context. The second question investigates how state of the art in engineering methods, more specifically marine weather routing methodologies, need to be improved to model the archaeological problem and quantify the influence of uncertainty. The third question seeks to develop existing marine weather routing methodologies to cope with the significant uncertainties within archaeological problems. The fourth question focuses on quantifying the performance of Polynesian seafaring technology, a necessary step to be able to model Polynesian seafaring. The fifth question specifies the problem of interest, to model how seafaring technology might have influenced the challenge of voyaging compared to other competing factors.

The following objectives reflect the steps that are required to answer the research questions:

1. Establish the evidence for Polynesian seafaring technology, inter-annual variability and climate at the time of the long pause (Chapter 3).
2. Investigate the performance of Polynesian seafaring technology (Chapter 4).
3. Development of marine weather routing methodologies to quantify uncertainty (Chapter 6).
4. Using marine weather routing models to model the voyaging time between key islands for Polynesian seafaring performance models under different wind and wave climates (Chapter 7).
5. Statistical evaluation of the contribution of the variation of performance,

season and climate to voyaging time, V_t, for the voyage from Samoa to Aituitaki (Chapter 8).

1.4.2 Academic contribution

This thesis presents the development of a novel methodology in marine weather routing and applies it to develop new insights into a complex archaeological problem. The key idea of this thesis is that the process of quantifying uncertainty at all levels of the marine weather routing process is necessary in order to contextualise the results, whether for archaeological research or modern day routing. The novel contributions of this thesis are;

1. Production of a model to describe the performance of the earliest recorded example of a Polynesian voyaging canoe, the "Tongiaki". Chapter 4 provides new insight into the influence of the variation of sail type and size for double-hulled sailing canoes.
2. Implementation of a failure model within a routing algorithm which allows dangerous areas to be avoided, this is described in Chapter 6 and (Dickson et al., 2018).
3. Implementation of a new methodology for quantifying uncertainty in marine weather routing. This methodology introduces the ability to compare sources of uncertainty in marine weather routing to quantify the accuracy of a result. The methodology is described in Chapter 6 and (Dickson et al., 2019). It was identified that low levels of uncertainty in the performance model significantly alter the estimate of V_t and associated uncertainty for a specific route.
4. The first study comparing the performance of Polynesian seafaring technology over colonisation voyages in Polynesia. Chapter 7 shows how the change of seafaring technology improved the ease of voyaging between islands. This

analysis identified a significant improvement in V_t between the performance of the Tongiaki and a later voyaging craft.

5. The first study into how assumptions on the performance of Polynesian seafaring technology influence the challenge of voyaging. These results allow clarification, for the first time, on how the "historicist" or "traditionalist" perspectives on seafaring technology influence the challenge of seafaring. Statistical analysis shows that seasonality was more influential than interannual variability. The analysis also confirms that improvements in windward ability would have significantly improved the chances of successful colonisation voyaging. This analysis correlates with improved windward sail performance found from travelling West to East in Polynesia (Di Piazza et al., 2014).

1.4.3 Thesis outline

An introduction to the different engineering methodologies used in this thesis is provided in Chapter 2, including marine weather routing and sailing craft performance prediction. The background to the colonisation of Polynesia is then established in Chapter 3. Chapter 3 provides a review of the evidence for the "long pause" between the colonisation of West and East Polynesia is presented and the geography and climate of Polynesia is described. Note unfamiliar terms have been included in a glossary to be found at the end of this thesis.

Chapter 4 focuses using the evidence of Polynesian seafaring technology to create a performance model for the Tongiaki. The Tongiaki is the most likely craft which enabled the passage between West and East Polynesia to be undertaken. This performance model allows more accurate voyage modelling to be performed with a design which is more relevant than those models used previously. The influence of the assumptions used in the production of the performance model are discussed.

The literature on Polynesian voyage modelling and modern marine weather routing is reviewed in Chapter 5. Both of these areas of literature are unified in the lack of consideration of different aspects of uncertainty in the voyaging modelling process. Given the uncertainty in the production of Polynesian voyaging canoe models there is a requirement to model performance uncertainty and uncertainty associated with different aspects of Polynesian voyaging canoe design.

Novel methodologies for modelling the influence of uncertainty in marine weather routing technology are implemented in Chapter 6. These methods quantify the influence of numerical error, performance model uncertainty and reliability. Modern and archaeological problems are used to demonstrate the significance of these areas of uncertainty.

The ability for two different Polynesian voyaging canoes to complete three different voyages is evaluated in Chapter 7. This Chapter evaluates the significance of climate and season variation on V_t as a function of two different performance models, one developed specifically for this research.

A new investigation modelling the uncertainty in Polynesian voyaging canoe performance and the subsequent significance of climate and season variation is described in Chapter 8. This analysis statistically evaluates the relative significance of aspects of canoe performance against the variation in season and climate for a specific route. Chapter 9 concludes this thesis.

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Chapter 2

Sailing craft routing and performance

2.1 Theory of marine weather routing

Marine weather routing methodologies consider three key areas: 1. the optimisation algorithm, 2. the marine craft performance model and 3. the environmental data used. This section will introduce the fundamentals of how the optimisation algorithm models and then solves over the marine environment. Section 2 describes how the performance of sailing craft can be described, analysed and predicted. There is also a brief discussion on what the significant environmental variables are.

The marine weather routing algorithm is solved over a domain on the Earth's surface over which the modelled sailing craft could sail. The algorithm used in this study discretises the environment between the start and finish locations into several points perpendicular to the Great Circle drawn between the start and finish locations. A review of marine weather routing methods is provided in Section 5.3. The distance between each location is determined by setting the maximum distance between nodes, d_n. d_n can be controlled separately as the grid height or grid width, as seen in Figure 2.1. For this research, the grid height and grid width are being set as equal. This algorithm generates a grid of nodes with equal numbers of ranks as well as nodes within each rank.

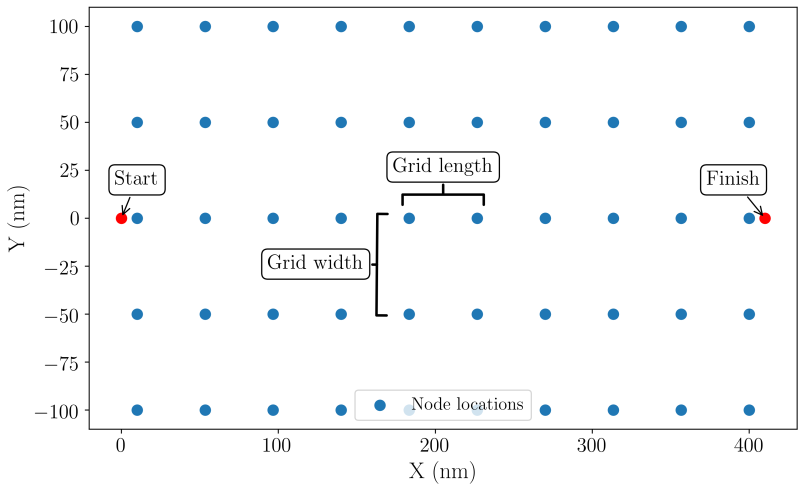


Figure 2.1: Discretized domain along great circle line between voyage start and finish.

For the position at any given node i the travel time between nodes i and a node on the next rank j along the arc (i, j) starting at time t is $c_{arc}(i, j, t)$. The cost function, $c_{arc}(i, j, t)$, provides an estimate of the time taken for a sailing craft to sail between two points given the environmental conditions at time t. An initial speed estimate is taken from interpolating the results of a performance prediction analysis for the specific wind condition. This speed is modified to account for the wave conditions experienced. A final optimisation takes place to identify the optimum heading to sail between the two points considering the current. If it is not possible to achieve a positive speed towards location j from location i, then the speed will be set to 0 returning an infinite travel time for that particular arc. It is possible to penalise areas of the domain in this manner and identify combinations of initial conditions which are unable to return valid results.

The minimum time path is identified using a forward-looking recursive algorithm, described in Equation 2.1. $f^*(i,t)$ is the time taken for the optimal sequence of decisions from the node-time pair (i,t) to the finish node and $j^*(i,t)$ is the successor of i on the optimal path when in state t. Through solving $j^*(i,t)$ within $f^*(i,t)$, it is possible to solve for the minimum time path. Γ_i is the set of all nodes on the graph. The algorithm identifies the shortest path by iterating from the start node to the finish node and updating each node in between with the earliest time that it is reached.

$$f^*(i,t) = \begin{cases} 0, & i = n_{finish} \\ \min_{j \in \Gamma_i}[c_{arc}(i,j,t) + f^*(j, t + c_{arc}(i,j,t))], & \text{otherwise} \end{cases} \tag{2.1}$$

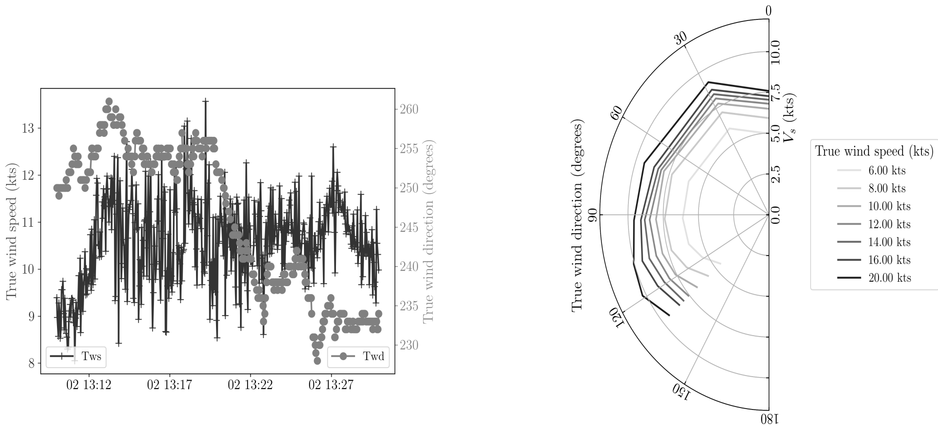
$$j^*(i,j) = \arg\min_{j \in \Gamma_i}[c_{arc}(i,j,t) + f^*(j, t + c_{arc}(i,j,t))], i \neq n_{finish}$$

2.2 Sailing craft performance prediction

The performance of a sailing craft is a function of the balance of the driving force generated by the wind passing over the sail set against the resistance of the hull and appendages. The wind passing over the sail set also generates a heeling moment which acts against the righting moment of the hull. The interaction of these force balances and the additional moments primarily determines the speed and heel angle of the sailing craft (Philpott et al., 1993).

There are terms for the points of the sail of a sailing craft when it is sailing at different True Wind Angles (TWAs). When the sailing craft is at a TWA of between $30 - 50°$ it is known as being close hauled. Figure 2.2b shows that for conventional monohull sailing craft, the best upwind speed is attained at a TWA of around $30 - 40°$. At a TWA of around $90°$ the sailing craft is reaching. At angles greater than $120°$ the sailing craft is described as sailing downwind.

The aerodynamic driving force of the sail set of a sailing craft depends on the wind speed, V_t, and TWA, β_t relative to the sailing yacht, where $V_t, \beta_t \in \mathbb{R}$. Figure 2.2a is an example of a wind trace for a moving location, showing that the wind varies in both speed and direction in a stochastic manner.



(a) 20 minute wind trace.

(b) First 40 sailing yacht performance polar plot.

Figure 2.2: Wind plot recording the True Wind Speed (TWS) and True Wind Direction (TWD) for 20 minutes recorded in the middle of Palma Bay. Also included is a polar plot of the performance of a First 40 sailing yacht.

The models used to predict the performance of sailing craft are known as Velocity Prediction Programs (VPPs). Figure 2.2b was generated using a VPP and shows that the relationship between wind condition and boat speed is non linear. “Static” VPPs assume that the forces acting on the sailing craft are steady (Philpott et al., 1993), whereas “dynamic” velocity prediction programs solve for the acceleration of the sailing craft given the unsteady forces acting on the craft (Philpott et al.,

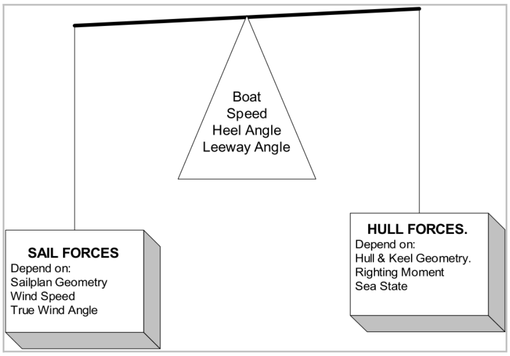


Figure 2.3: VPP as a force balance (Milgram, 1993).

2004).

VPPs estimate the forces which are acting on a sailing craft and use these to predict its performance. It is possible to conceptualise this process as a process of balancing opposing forces, as shown in Figure 2.3.

The performance at each point of sail is a function of crew activity, sail and hull design. The forces acting on the sailing craft must be analysed in order to predict the performance. Figure 2.4 shows the fundamental forces acting on a sailing craft.

The first static velocity prediction program implemented is described in (Kerwin and Newman, 1979). This research integrated force prediction models based on empirical performance data into an optimisation routine to identify different equilibrium sailing conditions based on environmental conditions. Other examples of static velocity prediction programs include (Inukai et al., 2001; Oliver, 1989; ORC, 2011; Philpott et al., 1993; van Oossanen, 1993).

Dynamic velocity prediction techniques use differential equations to describe the motion of a sailing craft which was first applied on a sailing cruiser (Masuyama et al., 1993). This method has been developed to improve the accuracy of predictions through integrating new data sources or mathematical descriptions

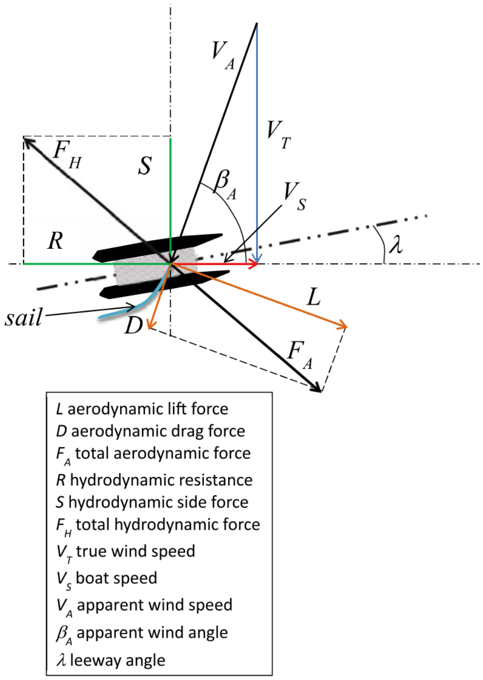


Figure 2.4: The balance of forces acting on a sailing craft (Irwin and Flay, 2015).

(Angelou and Spyrou, 2016; Böhm, 2010; Korpus, 2007; Ridder et al., 2004).

Static velocity prediction programs are less complicated than dynamic velocity prediction program and require less information on the design of a sailing craft to produce estimates of its performance. However, this means that there is more uncertainty associated with the predictions of a static velocity prediction program. The magnitude of this uncertainty is quantified through conducting experiments in real life or comparison with the predictions of a dynamic velocity prediction program.

Some static VPPs are developed to compare different sailing craft designs and use the static method with semi-empirical performance models (Claughton et al., 2006; ORC, 2013). These methods are computationally efficient while retain enough accuracy to effectively compare different sailing craft designs.

Dynamic VPPs have been used to investigate tacking manoeuvres of a range of craft designs (Giovannetti et al., 2014; Masuyama and Fukasawa, 2011; Ridder et al., 2004) in order to identify the performance of a given sailing craft design throughout a tack and to investigate how human factors influence the sailing craft. Other research has identified how to quantify the tactical advantage a yacht might have in races with other sailing craft factoring the influence of wind (Philpott et al., 2004; Spenkuch et al., 2010). In all these applications, there is a requirement to simulate the behaviour over a short period for an extremely well-defined sailing craft design. However, the lack of knowledge of the hydrodynamic derivatives of a given sailing craft would require expensive and time-consuming experimental or computational experiments to evaluate a range of experimental designs.

2.3 Design information

Various sources of information are combined in a VPP to predict the performance of a sailing craft. Initial design work is completed using pre-existing information on hull and sail performance for similar designs of craft; some sources include (Claughton and Fossati, 2008; van Oossanen, 1993). More detailed information on the behaviour of sail and hull performance is required to improve the accuracy of the velocity prediction program.

The Delft Systematic Yacht hull series provides a significant amount of information on the hydrodynamics of parametrically varied sailing craft hull forms (Gerritsma and Keuning, 1992; Keuning and Sonnenberg, 1998). However, these hulls were designed for Western monohull sailing craft which do not have parallel midsections, a significant feature of Polynesian seafaring technology.

Experimental information on high speed catamaran hull forms was gathered from testing the NPL Series 64 model series. The NPL Series 64 model series have been tested with the Southampton Round Bilged Catamaran series (Insel and Molland, 1992; Molland et al., 2011). These hull forms are slender, round bilged and possessed transom sterns. They bear more similarity to those used in Polynesian voyaging canoes.

More detailed investigations require either physical testing of hull or sail designs or the integration of computational design tools into the design process to direct the process such as CFD Böhm (2010). The computational resources and detail of the design definition must be considered when identifying the sources of data which should be used. For example, a poorly defined archaeological sailing craft design would require a range of modelling assumptions to be made before any real design analysis could take place.

A program named 'WaveSTL' is an in-house tool developed at the University of Southampton to estimate ship resistance based on thin ship theory (Gadd, 1968). It allows the contribution of wave resistance on the total ship resistance to be estimated. 'WaveSTL' has been extensively validated against experimental measurements, (Molland et al., 2004) for example.

Semi-empirical relationships based on experimental data are not the most accurate methods of performance prediction compared to specific model tests or computational experiments such as CFD. However, archaeological uncertainty in the identification of how a particular design is defined means that these relationships offer both initial performance estimates but also what the likely trend in performance might be.

2.4 Race Modelling Programs (RMPs)

The process of integrating the design and evaluation of sailing craft performance is completed using RMPs. These programs integrate the evaluation of the performance of a sailing craft into a routine which also includes the environmental conditions on a racecourse, sailor decision making and the influence of other sailing craft on wind speed. The first RMP implemented was for the use of the 1987 Americas Cup Campaign (Oliver et al., 1987), modelling the likelihood of a design winning or losing based on the wind conditions for a given race or series of races. They were able to link key design parameters such was waterline length to the success or failure of a given race and environmental conditions. Another formulation of a RMP was also given in (Philpott et al., 1993) which applied optimisation techniques on empirical evidence to produce a comparison between two designs.

One RMP integrated a more accurate wind model with a dynamic velocity prediction program to model the performance of a sailing yacht (Philpott and Mason, 2002). When sailing craft are in close proximity, the effect of the upwind craft on the wind experienced by the downwind craft is essential to model. This interaction between sailing craft was studied in detail by (Spenkuch et al., 2010), providing a methodology for estimating the impact of altering the wind on the downwind yacht. Race modelling programs have focused on developing methodologies to compare different sailing craft design performance over a specific racecourse. So far, they have only considered short racing problems incorporating simple route plans.

A commercial program which includes an RMP as well as a VPP is “WinDesign4”. This program was developed by the Wolfson Unit, based in the University of Southampton, and has been used for commercial yacht design and research

(WUMTIA, 2019). It is flexible and can accept different sources of information for aerodynamic and hydrodynamic forces. Consequently, WinDesign4 is a suitable choice of VPP to use for this research.

Chapter 3

Polynesian seafaring and the "long pause"

The colonisation of the islands of East Polynesia from the western archipelagos of Remote Oceania, or West Polynesia, represents the last significant migration of people into unoccupied territory in deep history (Kirch, 2000). Movement into Remote Oceania was unlikely to have to started before 3000 B.P. (Sheppard et al., 2015) and was completed approximately 2000 years later with a 3000 km journey from tropical East Polynesia to the temperate waters of New Zealand (Walter et al., 2017). The voyaging canoe is the "primary artefact of colonisation" (Irwin and Flay, 2015). Thus the colonisation of Polynesia cannot be understood without quantifying the performance of Polynesian voyaging canoes.

The performance and voyaging capability of Polynesian seafaring technology must be viewed within the context of the competing factors which influenced the colonisation process. Figure 3.1 shows how the colonisation process can be divided into different phases of associated factors. It can be seen that seafaring technology influences each stage of the colonisation: the discovery, settlement and establishment of new colonies.

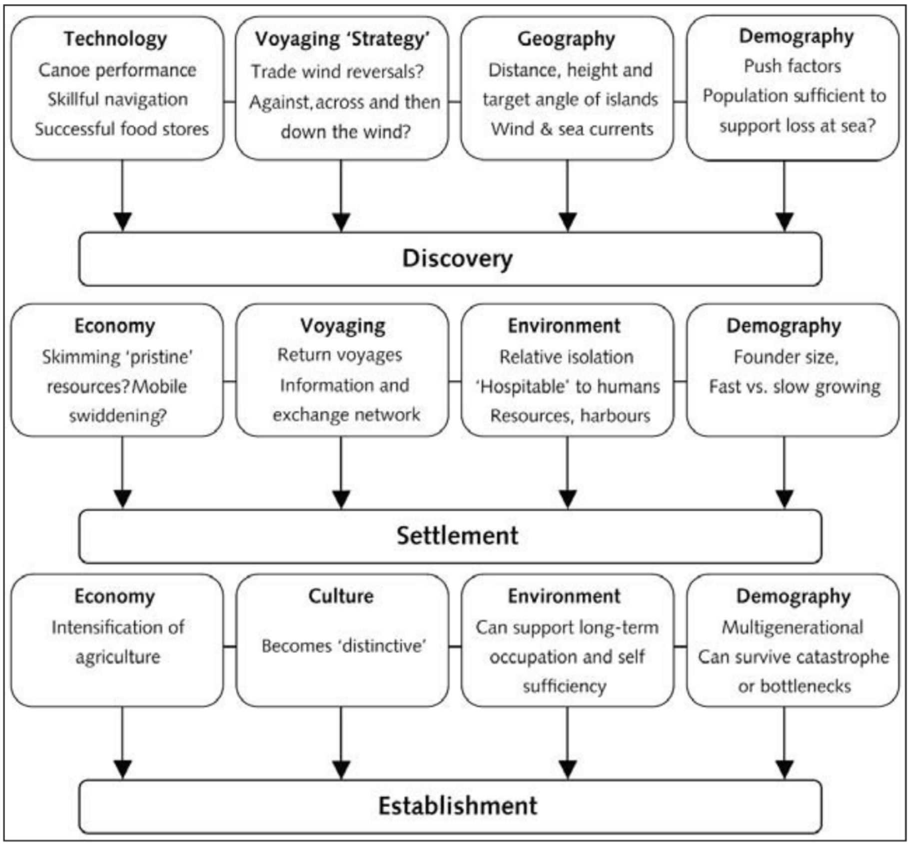


Figure 3.1: The colonisation process broken down into different factors (Thomas, 2008). Seafaring technology significantly contributes towards the discovery and settlement phases of colonisation.

This Chapter will review the evidence on Polynesian seafaring technology and associated investigations. The geography of Polynesia is described first, in Section 3.1. To provide temporal context, Section 3.2 will establish the chronology of colonisation. The climate and environmental factors are described in Section 3.3. Human factors and evidence for human settlement are reviewed in Sections 3.4 and 3.5.

3.1 Geography

East Polynesia is a triangular region covering 20 million km^2 spanning between Hawaii, New Zealand and Easter Island with only 0.29 million km^2 of land mass (Anderson and Spriggs, 1993). From West to East, the distance between islands increases and the ratio of land area to sea area decreases indicating an increase in navigational difficulty (Irwin, 2008). A 'friction model'[1] of colonisation identified that a maritime reach of 741 km would be sufficient to reach Fiji and Tonga (Clark and Bedford, 2008), however, there are gaps of 1852 km between Samoa and the islands of Central East Polynesia. This is a significant increase in the distance between islands and the area which would have had to have been searched to discover them. This section will describe the geography of Polynesia, with a focus on the islands on either side of the gap between West and Central Eastern Polynesia.

The archipelagos on the eastern fringe of West Polynesia are Fiji, Samoa and Tonga. Fiji consists of 330 islands and 500 islets with a total land area of approximately 18300 km^2. Samoa consists of two main islands with an area of 2,842 km^2. Tonga consists of 169 islands with a land area of 748 km^2 stretching across approximately 500 nm of latitude.

The Southern Cook islands are the closest islands to the East of Samoa, with the larger Society islands lying another 900 km to the West (Niespolo et al., 2019). Aitutaki has been identified as the gateway to East Polynesia as it is the closest island to Samoa which has evidence of a settled population (Allen, 2007).

The resources available across different islands determined their role in the local trading sphere. For example, the island of Kabara in Fiji had sparse groundwater

[1] A friction zone is a landscape which is "hostile, fragmented, unfamiliar or difficult to reach" (Clark and Bedford, 2008). In this case, an analysis of different geographic statistics of Polynesian islands is used to approximate what is termed a 'friction model' of colonisation.

and poor soil but was the centre of canoe manufacture in the region due to the range of useful tree species it possesses (Banack and Cox, 1987).

One study identified the relationship between canoe design traits and the sizes of different islands (Beheim and Bell, 2011). This research drew a link between the quantity of resources available for canoe production and the level of innovation seen in canoe design. Islands which have an wide elevation profile (mountains), called "high", have a wider range of vegetation, hence resources, than "low" islands. This larger range of resources could also cause design innovation. For example, canoe builders in New Zealand could use the larger trees to manufacture larger canoes which could make outriggers and double hulled canoes redundant (Beheim and Bell, 2011).

The landscape of Polynesia changes dramatically from West to East (Irwin, 1998, 2008). There is a reduction in island area and an increase in the distance between islands. Smaller islands have a reduced amount of resources which could have driven canoe builders to innovate solutions such as double hulls or outriggers to improve performance. The geographic location of the "long pause" occurred at the first significant land gap between West and East Polynesia.

3.2 Colonisation chronology

Accurate knowledge of the chronology of the settlement of Polynesia is essential in order to understand the process of human dispersal (Kirch and Green, 1987). Conflicting dating of archaeological evidence has produced alternate chronologies that date the colonisation of Polynesia with differences of between $400-1000$ years (Wilmshurst et al., 2008). An analysis of shortlived pollen and plant fragments has revised forward the dates of colonisation of East Polynesia (Wilmshurst et al., 2011a). These dates are contested on the basis that the criteria for inclusion is too stringent (Mulrooney et al., 2011), although it has been argued that these stringent criteria are precisely what it required for accurate dating (Wilmshurst et al., 2011b).

Metaphors such as "express train" or "slow boat" have been used to describe the strategies by which humans may have migrated throughout the Pacific (Montenegro et al., 2016a). The approach of invoking metaphors to explain the colonisation process has been criticised; an alternative approach is to look at the baseline physical probabilities associated with events that occurred in the colonisation process (Terrell, 2014). As the focus of this research is on a specific geographic and temporal gap, the evidence on the chronology of colonisation will be reviewed without attempting to describe it via metaphor.

The challenge of dating colonisation starts with establishing what colonisation exactly means. Colonisation has heavy political and ideological connotations surrounding the exploitation of land areas and subjugation of peoples in the European colonial era (Sommer, 2011). In this research the use of the word colonisation refers to the establishment of outpost colonies established on land which has previously been unsettled.

Figure 3.2 shows the location and age of the evidence found at different sites, summarised in Table 3.1. It can be seen that there is a clear spatial and temporal gap between the colonisation of West and Central Eastern Polynesia. Although there is clear evidence for the long pause, there are several sources of uncertainty surrounding the process of dating the initial settlement of a location. The dating process involves identifying a site on a given island which might be archaeologically relevant. Artefacts may be discovered in the site assemblage which are then dated using specific techniques to determine age. A judgement is formed on whether the artefacts provide proof of the site being the location of earliest settlement on that given island.

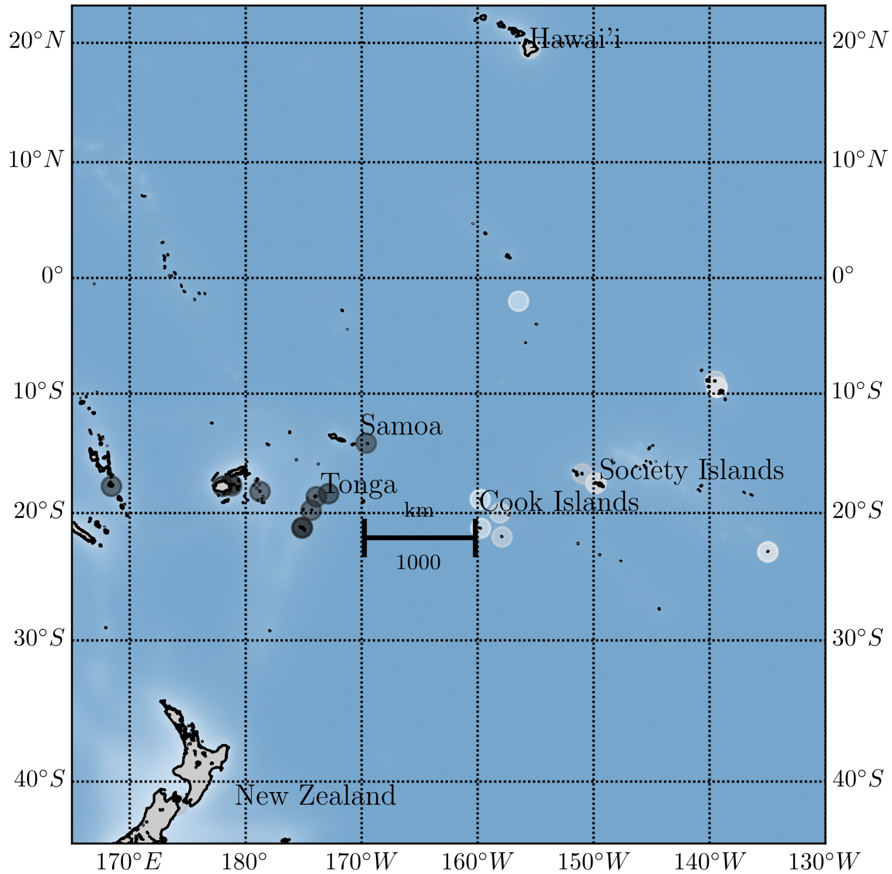


Figure 3.2: Settlement dates on different islands across Polynesia. Dark points indicate islands which were settled before the long pause and the light points indicate those settled afterwards. Data is summarised in Table 3.1.

Table 3.1: Dates of arrival across West Polynesia and the Southern Cook Islands. The uncertainty is half the interval of the reported arrival date estimates.

Location	**Latitude (^{o})**	**Longitude (^{o})**	**Date start (B.P.)**	**Uncertainty (± years)**	**Dating technique**	**Reference**
Viti Levu, Fiji	-17.8	178	3111	466	14C	Nunn and Petchey (2013)
Naigani, Fiji	-17.58	178.68	2941	78	14C	Nunn and Petchey (2013)
Beqa, Fiji	-18.4	187.13	2932	101	14C	Nunn and Petchey (2013)
Teoma, Vanuatu	-17.7856	168.3862	2895	25	14C	Petchey et al. (2015)
Tongatapu, Tonga	-21.21	-175.15	2863		U/Th	Burley et al. (2015)
Lakeba, Fiji	-18.2167	-178.783	2840	65	14C	Nunn and Petchey (2013)
Nukuleka, Tonga	-21.15	-175.13	2838	8	U/Th	Burley et al. (2012)
Vava'u, Tonga	-18.65	-173.93	2805		U/Th	Burley et al. (2015)
Ha'apia, Tonga	-19.75	-174.37	2772		U/Th	Burley et al. (2015)
Moturiki, Fiji	-17.75	178.75	2768	84	14C	Nunn and Petchey (2013)
Ofu, Samoa	-14.175	-169.618	2690	26	14C and U/Th	Clark et al. (2016)
Southern Cook Islands	-21.2333	-159.767	1265.5	15.5	14C	Wilmshurst et al. (2011a)
Taravai, Mangareva	-23.1367	-135.026	950	25	14C and Th	Kirch et al. (2010)
Mangaia, Southern Cook Islands	-21.9214	-157.923	939	8	U/Th	Niespolo et al. (2019)
Aitutaki, Southern Cook Islands	-18.85	-159.79	622.5	102.5	14C	Allen (2007)

There are a series of challenges associated with dating of settlement at a specific archaeological site. These include: 1. Whether the dating technique uses Carbon (^{14}C) or Thorium (U/Th). There is a high level of variability in the ^{14}C curve used for dating (Taylor, 1997) and low variation associated with U/Th (Niespolo et al., 2019). 2. Post depositional disturbance by animals at the site. 3. The use of materials such as driftwood or marine shells that predate their inclusion or use in the archaeological site. 4. The complexity associated with animals inhabiting multiple locations with different sources of carbon (Nunn and Petchey, 2013).

A desire for improved "chronometric hygiene" argues for higher levels of confidence in the dating method, laboratory and physical evidence in order to provide credible evidence for human settlement (Anderson and Spriggs, 1993). The most recent example of a study of improved "chronometric hygiene" has classified ^{14}C dates across Polynesia to provide dates of likely human arrival across archipelagos in Polynesia (Wilmshurst et al., 2011a). Varying the criteria on whether evidence is acceptable leads to elongated chronologies (Mulrooney et al., 2011; Wilmshurst et al., 2011b).

The dating of U/Th samples can provide more accurate dating of Polynesian sites, yielding uncertainties of $5-10$ years for coral approximately 1000 years old (Cobb et al., 2003). It is possible to date coral samples using the U/Th method, and it is known that Polynesians used coral for a range of purposes (Niespolo et al., 2019). It can be seen from Table 3.1 that the divide in time and space exists for U/Th samples as well as ^{14}C samples. Ultimately, an uncertainty of 250 years does not disprove the existence of a long pause which lasted approximately 1800 years.

Evidence of island discovery would likely be absent from the archaeological record (Mulrooney et al., 2011). For example, it would be impossible to date the first human sighting for a given island from the sea. However, defining colonisation as being invisible from the archaeological record abandons the scientific principle of falsifiability (Wilmshurst et al., 2011a). For this investigation, the dates of settlement recorded in Table 3.1 are deemed sufficient proxy for dating the human discovery and settlement on islands in Polynesia.

3.3 Climate

Changing environmental conditions could have enabled colonisation efforts through favourable wind conditions for sailing, but also through influencing access to resources (Bridgman, 1983). The weather conditions are driven on an inter-annual basis by the ENSO phenomenon. It has been suggested that ENSO influences the levels of conflict that are recorded (Hsiang et al., 2011). It is likely that environmental disasters such as tsunamis or cyclones occurred periodically, which would have negatively impacted seafaring peoples (Goff et al., 2011). Furthermore, there was a global increase in temperature around the time of the initial settlement of Central East Polynesia, known as the Medieval Climate Anomaly (MCA). The MCA would have improved the chances of successful Eastwards voyaging due to the reversal in the prevailing wind conditions associated with the rise in temperature (Goodwin et al., 2014b).

The ENSO phenomenon varies between two main phases: El Niño and La Niña. El Niño is characterised by a warmer ocean surface temperature with La Niña being the corresponding cold phase. During El Niño the prevailing Easterly winds are weakened or reversed entirely, with La Niña strengthening the prevailing wind conditions (L'Heureux, 2014). Figure 3.3 shows the mean environmental conditions for both phases of ENSO.

The difference between sea surface temperatures in different locations of the Pacific has been the most popular method of quantifying the strength of El

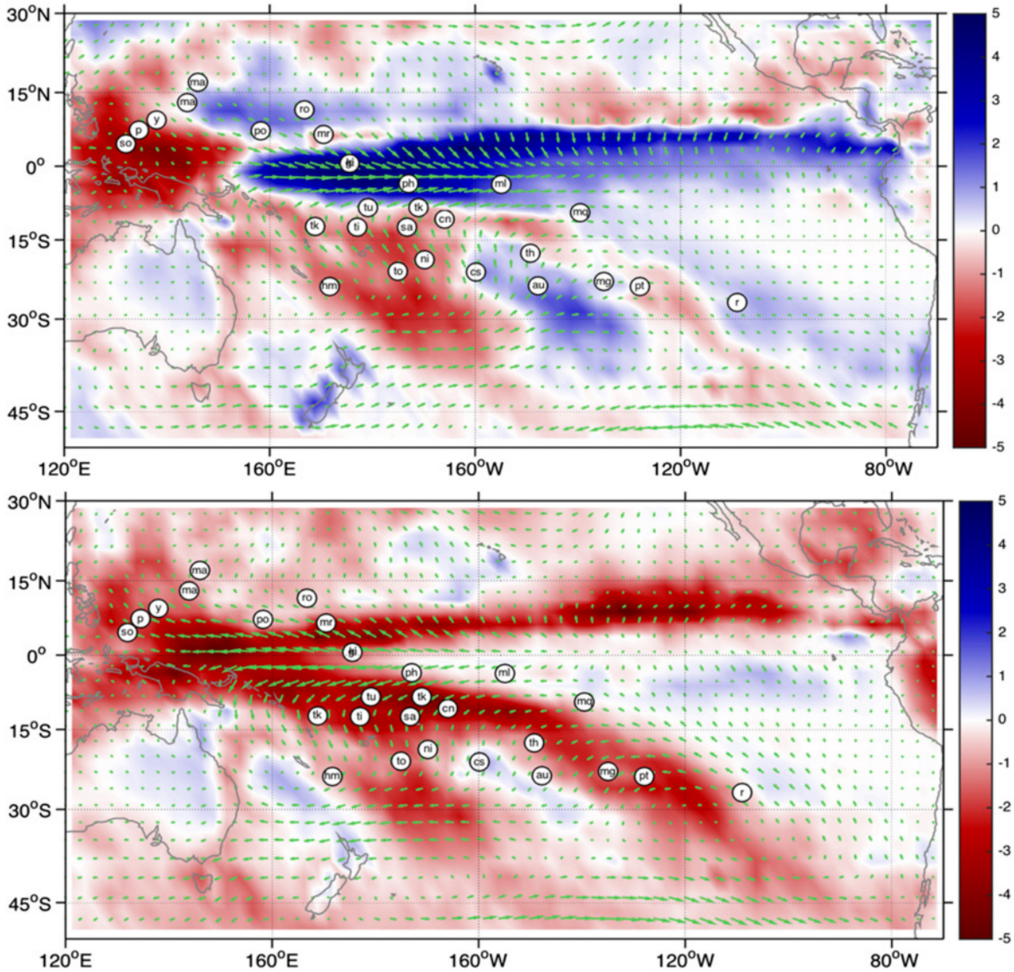


Figure 3.3: Mean El Niño (upper) and La Niña (lower) wind (green vectors) and precipitation (colors, mm/d) anomalies (Montenegro et al., 2016a). These are the difference between mean annual precipitation and El-Niño or La Niña average conditions between 1979-2009.

Niño. The El Niño 3.4 index has been deemed the "most representative" index to describe ENSO (Bamston et al., 1997). The variability of ENSO 3.4 index can be seen in Figure 3.4.

Research has identified different "flavours" for each phase of ENSO, something that is challenging to quantify with an index measuring a single quantity (Johnson,

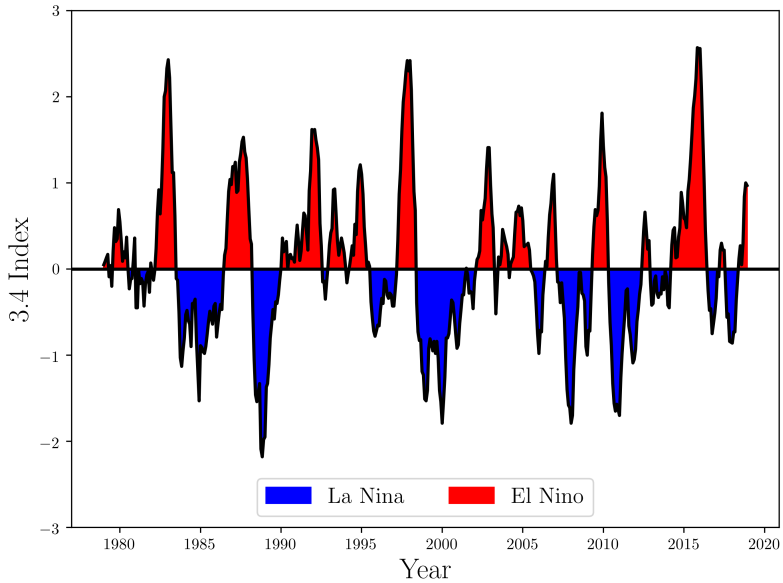


Figure 3.4: Fluctuations in the ENSO 3.4 index over the previous 40 years (Trenberth and National Center for Atmospheric Research Staff, 2019).

2013). One analysis identified the presence of East Polynesian and Central Polynesian events (Kao and Yu, 2009). The E.P. event is associated with heating and cooling closer to the South American coast. Another analysis identified the existence of nine different ENSO "flavours" (Johnson, 2012). Clearly ENSO is a complex phenomenon which requires consideration in Polynesian voyage modelling.

Climate modelling has predicted that there were significant and lengthy wind reversals over East Polynesia during the Medieval Climate Anomaly, a time period lasting between 1150 - 650 B.P. (Goodwin et al., 2014b). However, this model is based on peripheral data, with no records from within Polynesia, which would directly validate the climate prediction. Nevertheless, this research has been used to identify suitable weather conditions for colonisation in Polynesia

(Montenegro et al., 2016a). This study identified that easterly flow dominates the annually-averaged mean wind over West Polynesia, but between December to February westerly winds dominate.

Another factor influencing early colonisation could have been changing sea levels changing the available land for settlement (Dickinson and Burley, 2007). Sea levels have dropped over a metre since 5000 - 3000 B.P. leaving areas of flat land exposed as well as navigational hazards such as reefs. The increase in the exposed area would increase the probability that explorers would have found land. This may have prompted the emergence of the Lapita[2] culture and the initialisation of the colonisation process.

Evidence for stronger Westerly winds between $2000 - 1000$ B.P. has been gathered from the stunted growth of trees in the Campbell and Auckland islands (Turney et al., 2016). These islands lie between $50 - 52^o$ S and are much further South than Central Polynesia, however these findings correlate with the general pattern found across the Pacific at this time.

High energy events such as tsunamis, volcanic eruptions and cyclones regularly occur in the Pacific, any of which could have allowed the initiation or cessation of conditions allowing voyaging. There was a higher level of cyclonic activity between the periods of $5000 - 3800$ and $2900 - 500$ years B.P. (Toomey et al., 2013). A link has been made between Paleotsunamis c. $2800, 1860 - 2000$ B.P. and 600 B.P. and the advent of the long pause and the cessation of long-distance voyaging (Goff et al., 2011). One analysis suggested that the Medieval Climate Anomaly (MCA) could have been the result of a volcanic event (Margalef et al., 2018).

[2] Lapita is the term used to describe a particular type of pottery found throughout West Polynesia. It has been linked to initial settlement of West Polynesia but is not found in CEP (Irwin, 1998).

The MCA was a period of warm temperatures across the Pacific Basin, lasting between 1000 – 600 B.P., followed by the 600 B.P. event which precipitated the Little Ice Age (Nunn, 2007). Between 1150-1050 B.P. and 950-850 B.P., the mean climate pattern appears to shift to the Central Pacific (Modoki) El Niño pattern, which has anomalous westerly wind fields over the Central Pacific (Goodwin et al., 2014a). Between B.P. 810-690, there was a shift in mean climate to the Central Pacific (Modoki) La Niña pattern (Goodwin et al., 2014a).

The climate in Polynesia throughout the colonisation likely changed to enable rapid colonisation with the appearance of favourable wind patterns in the advent of the MCA. The occurrence of high energy events could have caused the MCA, but also could have destroyed settlements and technology lying close to the sea. The high energy events could have destroyed or shifted evidence of early settlement. The tropical climate would have caused rapid decay of any material which would have been used in the construction of seafaring technology, reducing the likelihood of discovery for seafaring technology used in deep history.

3.4 Human factors

An understanding of the culture and motivation of the people undertaking ocean voyaging is essential to contextualise the scientific modelling undertaken in this thesis. Although this thesis is predominantly analysing the quantifiable factors which can be simulated within an engineering methodology. Factors such as belief systems, identity and religion would have influenced how voyaging canoes were used, and evidence on settlement provides information on the boundary conditions of the model.

It has been proposed that Polynesian seafarers were undertaking a process of self-development to achieve god-like status through participating in ocean voyaging (Richards, 2008). Seafarers might also have had a strong motivation to succeed given push and pull factors such as religion or resource scarcity and overpopulation.

There is evidence for seafaring traditions which are interwoven into contemporary Polynesian society. A 9 day pause in voyaging to other islands marked the death of Mau Piailug, a master navigator, on Satawal in 2010 (Tribune, 2010). The heritage of great navigators and their findings is often recorded through legend. The poem 'Nga-Iwi-o-Aotea' is named after the canoe which brought the Polynesian chief Ui-te-Rangiora to Antarctic waters. This poem was dated to 1300 B.P., and hard evidence of Polynesian settlement has been found as far south as the Auckland islands (Anderson, 2005). These finds provide archaeological evidence that Polynesians possessed the capability to voyage in sub antarctic waters, although at the slightly later time of the 6/5th centuries B.P.

An association may be made between the settlement of West Polynesia and a particular type of pottery, known as Lapita. This pottery was found throughout the southwestern Pacific and the archipelagos of Tonga and Samoa. Although, calling Lapita a "cultural phenomenon" has been argued to be unhelpful concerning understanding the historical issues which surround this material (Terrell, 2014). It is also impossible to associate the pottery of a culture and the design of any seafaring craft which could have carried it.

The Polynesian culture was hierarchical, any opportunities to enhance position were restricted, meaning that voyaging to new islands and starting new settlements was one method of gaining recognition (Adds, 2012). Another plausible motive could have been the act of fleeing warfare, which was endemic across Polynesian societies (Kirch, 1984).

The manufacture of a voyaging canoe and the production of necessary supplies requires an estimated 6500 person-hours, 2.27% of the total working time in a year for a community of 300 people (Sheerin and Cunio, 2016). These estimates demonstrate the feasibility of manufacturing and operating voyaging canoes over the course of a few years. Consequently, it can be argued that canoe manufacture did not present a significant barrier to colonisation.

Evidence of ecological change throughout the Polynesian islands settled by humans demonstrates the existence of a "transported landscape" (Anderson, 2009a). A "transported landscape" consists of those animals or fauna which replicate the environment of the settlers previous island (Kirch, 1982). The introduction of pigs, dogs, fowl and rats are linked with three phases of human movement, the last two being the settlement of West Polynesia and then the expansion to East Polynesia (Anderson, 2009b).

Evidence on the ability of seafaring capability is inferred from tracking the movement of commensal species throughout Polynesia. For example, the voyaging canoes must have had the capability to hold animals and their food reliably in order to complete the voyages between West and East Polynesia (Anderson, 2009b).

Some have suggested that the sweet potato was transported to the West from South America, which requires considerable seafaring expertise and the ability to undertake two-way voyaging (Denham, 2013). However, a more recent study has provided evidence which suggests that the sweet potato spread to Polynesia by long distance dispersal in pre-human times (Muñoz-Rodríguez et al., 2018). Although the sweet potato played a significant role in the Polynesian diet, identifying when and where it entered their diet remains open to investigation.

Freshwater is necessary to support the growth of animals and plants for human consumption. El Niño conditions are linked to humidity in the East Pacific and drought to the West (Anderson, 2014). Low populations on small islands are particularly susceptible to periods of drought (Weisler, 1995). The variable nature of rainfall as a function of climate could have contributed towards the decision of voyagers to leave an island suffering drought.

3.5 Voyaging evidence

The most unequivocal evidence of intentional voyaging is the dating of human arrival on each island across the Pacific, summarised in Section 3.2. Identifying the evidence on two-way voyaging provides the minimum capability for the seafaring technology to be quantified. For example, the minimum capability of the voyaging canoes used must have been good enough to sail between West and East Polynesia, as East Polynesia was settled and the voyaging canoe was the only means of transport.

Long Distance Exchange Networks (LDENs) provide evidence of intentional voyaging. Evidence for LDENs can be obtained through identifying the provenance of artefacts such as adzes (Weisler, 1998) or ceramics (Kirch and Kahn, 2007). Adzes are a popular method for establishing exchange networks within West Polynesia (Clark, 2002) and across Polynesia (Rolett et al., 2015). Other research has investigated the eastwards movement of snail shells from the Society islands, perhaps indicating the existence of intentional two way voyaging (Lee et al., 2007).

The spread of a "transported landscape" on islands where humans settled provides evidence on the capacity of voyaging canoes to carry vegetable crops and animal species. The transfer of culture was also enabled, evidenced by the appearance of "Hawaiian type" petroglyphs on an island in Tonga (Egan and Burley, 2009).

Studies recording the provenance of artefacts can be used to argue for the existence of long-distance exchange networks, but questions remain surrounding the purpose and significance of this contact (Clark et al., 2014). For example, it is argued that the movement of snail shells could have resulted from the European era voyaging (Anderson, 2008c). Some have argued that the evidence of LDENs require a *a priori* assumption of plausibility through using the oral tradition of Hawaii (Anderson, 2008c).

3.6 Summary

The colonisation of Polynesia took place over several thousand years, with a hiatus between the colonisation of the archipelagos of Fiji, Samoa and Tonga and the colonisation of islands further East. A temporal gap in the archaeological record and spatial gap in the geography is identified. A maritime reach of only 740 km is required to sail from mainland Asia to Tonga and Samoa. There is a gap of over 1000 km to the East of Samoa, before the Southern Cook Islands are reached.

Several factors would have influenced the challenge of bridging this spatial gap. The most influential factor would have been the use of seafaring technology, the study of which is the focus of Chapter 4. A contributing factor would have been the environmental conditions present, heavily influenced by the ENSO phenomenon and the global increase in temperature known as the Medieval Climatic Anomaly.

The agency of human settlers ultimately determines the decision on whether to voyage or not. Ethnographic records have identified the central role of the chieftain and navigator within Polynesian society. Motives for voyaging could include resource scarcity, perhaps influenced by drought, as well as power struggles and the desire to avoid conflict. The internal dynamics of society are challenging to model, but quantifying the challenge of voyaging gives insight into the difficulties of making voyaging decisions.

This chapter has reviewed the chronology, geography, climate and human factors associated with the colonisation of Polynesia. In order to model the contribution of these factors to the challenge of voyaging at the time of the "long pause" the performance of Polynesian seafaring technology must be quantified based on a review of the existing evidence.

Chapter 4

Quantifying the performance of Polynesian seafaring technology

4.1 Introduction

The ability for Polynesian voyaging canoes to sail in different weather conditions is a central topic of debate in the field of Pacific archaeology (Irwin and Flay, 2015). The performance of Polynesian seafaring technology determines the challenge of completing exploratory or colonisation voyages. Consequently, Polynesian voyaging canoe performance underpins the current understanding of the challenges experienced throughout the colonisation of Polynesia.

This chapter aims to quantify the performance of the earliest recorded Polynesian voyaging canoe, the “Tongiaki”. It is likely that the Tongiaki bears the most similarity to those used in deep history to cross from West and Central East

Polynesia at the end of the “long pause”. A review of Polynesian seafaring technology is completed to establish the design, and thus performance, of the earliest known voyaging canoe. This canoe is known as the *Tongiaki*. The design of the *Tongiaki* can be established based on specific measurements from sketches by early European explorers, with additional evidence supplied by archaeological finds. However, there remains uncertainty surrounding the sail performance and rigging, as well as more specific design details.

The considerable archaeological uncertainty surrounding the design of the *Tongiaki* contributes towards uncertainty in performance. Extensive spatial and temporal variation of Polynesian seafaring technology was recorded at the time of European contact. Quantifying the sensitivity of the performance of Polynesian seafaring technology to design variation is essential as it is challenging to identify the shape of various design elements, let alone the specific dimension.

A sailing craft must be sufficiently reliable in order to complete a voyage. The chapter concludes with an investigation into the reliability of Polynesian seafaring technology to identify what the limits of safe operation may have been. Through relating the limits of safe operation to prevailing weather conditions, it is possible to gain insight into the use of Polynesian seafaring technology for colonisation voyages.

4.2 Evidence of Polynesian seafaring technology

The design of a sailing craft must be established in order to predict its performance. This section reviews the evidence of Polynesian seafaring technology with a focus on what type of sailing craft may have been in use at the time of the “long pause”, approximately 800 – 2900 years ago. A range of different types of evidence exists such as excavated material, petroglyphs, linguistics and historical accounts by early European voyagers.

This section will focus on describing the limitations of each item of evidence concerning how it may be used to contribute towards constructing a design of a prehistoric voyaging craft. Within the academic discourse on Polynesian seafaring, there exists a range of perspectives on the performance of Polynesian seafaring technology. The "Historicist" position argues for canoes which were slow and had limited windward performance based on an analysis of historical records (Anderson, 2017). The opposing position is known as "Traditionalism" and bases their arguments for fast, weatherly vessels on ethnographic accounts of Polynesian seafaring (Finney, 2008). It is essential to analyse evidence in light of these positions so that it is possible to identify how this research contributes to the academic discourse.

In the literature on the colonisation of Polynesia, the terms "voyaging canoes" and "seafaring technology" are used interchangeably to describe the boats, sails and associated paraphernalia used by Polynesian sailors. This review prefers the term "seafaring technology" as seafaring is a more general term covering a variety of situations, rather than the more intentional "voyaging" (Anderson, 2014).

Pre metallurgic peoples constructed the majority of their artefacts out of organic material. Perishable material would disappear from the archaeological record after some time, certainly within the timescale of the initial settlement of East Polynesia. The conditions for the preservation of canoes are generally poor throughout the Pacific due to warm waters and climate, which promote the rapid decomposition of organic materials.

This absence of evidence adds to the challenge of Pacific archaeology, although some useful finds have been discovered. A collection of artefacts, initially dated to the 11/10th century B.P., was recovered from a series of excavations from the Society islands (Sinoto, 1983, 1988, 1979). Settlement in the Society islands has since been dated to 900 – 790 B.P. (Anderson et al., 2019). Other finds included manufacturing tools, rope samples and parts of voyaging canoes such as an unfinished paddle, an outrigger boom, a mast and plank fragments. It has been speculated that fixing the planks together would enable the construction of a canoe larger than the *Hōkūle'a* [1]. Regardless of the construction challenges, these finds provide evidence that people were constructing large canoes on or soon after arrival on a new island.

A section of a voyaging canoe hull, or *wa'ka*, was recovered from New Zealand, dating from 550 B.P. (Johns et al., 2014). This segment, seen in Figure 4.1, is an example of the technology which was used before European contact. The artefact has multiple holes which were used for sewing the planks together. The engraved sea turtle found on the hull indicates that Polynesians had a cultural, not only technological relationship with their voyaging craft.

Figure 4.1: An East Polynesian voyaging canoe from New Zealand dating from 550 B.P. (Johns et al., 2014). It is possible to see the transverse frames as well as the holes used to sew this section into connecting sections of the canoe. This artefact gives an indication of the construction techniques used and hull dimensions which were found to be robust. This artefact likely formed part of the main hull of an outrigger (Johns et al., 2014).

A collection of wooden artefacts were found deposited in a small swamp behind the seashore in Waitore, New Zealand (Cassels, 1979). These finds include what appears to be the remains of an outrigger canoe. The finds show decorative features similar to those predicted for the period of transition from New Zealand

[1] The *Hōkūle'a* is a reconstructed voyaging canoe, see Section 4.2.1 for a description.

East Polynesian to Classic Maori forms, dated to within 570-450 B.P.

A review of archaeological Maori canoes identified changes in the design and construction material (Irwin et al., 2017). There was a variation in the shape and dimensions of the hulls, and the authors conclude that the largest would not have had a length larger than $10 - 15$m. These finds help show how seafaring technology altered from outriggers used for ocean voyaging to monohulls more suitable for the transport of stone around New Zealand. The divergence between East Polynesian and Maori seafaring technology can be understood within the context of the likely isolation of Aotearoa (New Zealand) after initial settlement (Adds, 2012).

Linguistic studies provide another opportunity to identify how Polynesian seafaring technology could have evolved. One study has aimed at reconstructing the material culture of proto-Austronesian languages in order to identify what words describing aspects of seafaring craft are shared between different Austronesian languages (Pawley and Ross, 1993). It has been possible to identify words for ‘sail’, ‘mast’, ‘outrigger’ and ‘outrigger boom’ with suggested dates indicating these terms are perhaps 5000 years old.

Twenty terms for different aspects of seafaring and canoe design have been identified in proto Oceanic languages, those in Melanesia East of 138^o. Proto Oceanic speakers were likely constructing and sailing substantial voyaging canoes (Pawley, 2007).

It has been noted that it is linguistically challenging to distinguish between terms for outrigger and double canoe. Linguistic studies have been able to identify the essential parts of a voyaging craft, and these aspects must be recognised in a physical model.

Some petroglyphs of Tahitian sail types in Oceania have been recorded on the island of Maui in the Hawaiian island group (Lewis, 1994, p. 65,351), and of an entire craft on the central North Island, New Zealand (Scarre, 1989, p. 271). However, it is thought that the petroglyph of the craft dates from AD 1680 - 1780, and the rock carvings on Maui are undated.

Petroglyphs found in Tonga have Hawaiian stylistic elements and are thought to date from AD 1400 to 1600 (Egan and Burley, 2009). A depiction of this rock art is seen in Figure 4.2. These elements have no precedent in the Tonga region, indicating that the petroglyph artists themselves had travelled to the island. The find of Hawaiian rock art in Tonga provides further evidence for the capability for Polynesian seafaring technology to support two-way voyaging between an extremity of the Polynesian triangle to West Polynesia.

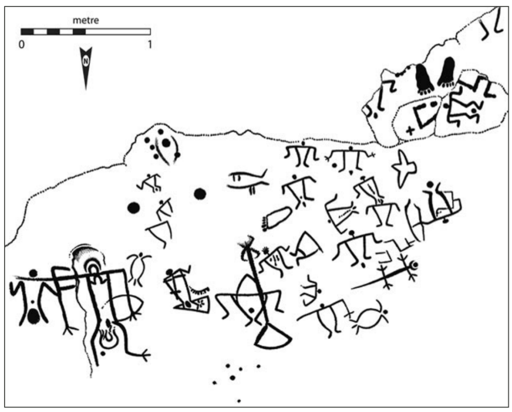


Figure 4.2: Rock art found in Tonga with stylistic similarity to petroglyphs that have been found in Hawaii dated to A.D. 1400 to 1600 (Egan and Burley, 2009).

These drawings by Polynesians present their perspective on their seafaring technology and provide an interesting contrast to the conclusions drawn by later researchers on the seafaring technology available to the Polynesians for their migratory efforts. Accounts by Europeans on seafaring technology used by Polynesians at the time of initial contact can be used to provide another source

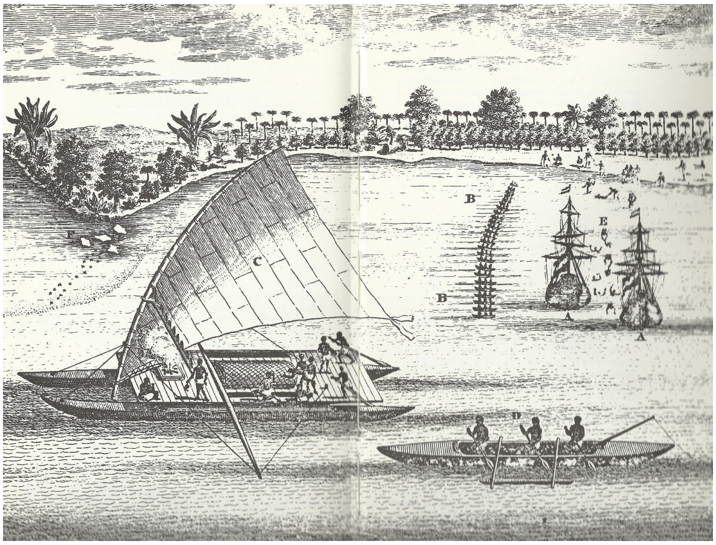


Figure 4.3: A *Tongiaki*, recorded by Schouten in 1616 A.D. (Originally recorded in Spieghel der AustralischeNavigatie, 1622).

of evidence. Some of these accounts have been reviewed in (McGrail, 2004), describing a range of different craft types. It is possible to classify Polynesian seafaring craft based on the number of hulls, sail type and method of upwind sailing.

A *Tongiaki* was seen by Schouten on his voyage to the South Pacific in 1616 A.D., Figure 4.3. This image shows a large crab claw sail which is supported by a centrally mounted mast and outrigger poles. An interesting feature is an open fire on deck, which could have provided warmth for survival and cooking. A similar canoe design to the "*Tongiaki*" was witnessed by a Spanish sailor, Prado, in 1606 (Mondragòn and Talavàn, 2008).

Spöring witnessed another canoe on arrival in New Zealand in 1769 AD, Figure 4.4. This canoe is likely to have only been able to sail downwind as there does not appear to be any mast to support the sail from the side. Joseph Banks, a sailor on Captain Cooks voyage recorded that he had never seen them sail except before the wind (Anderson, 2014).

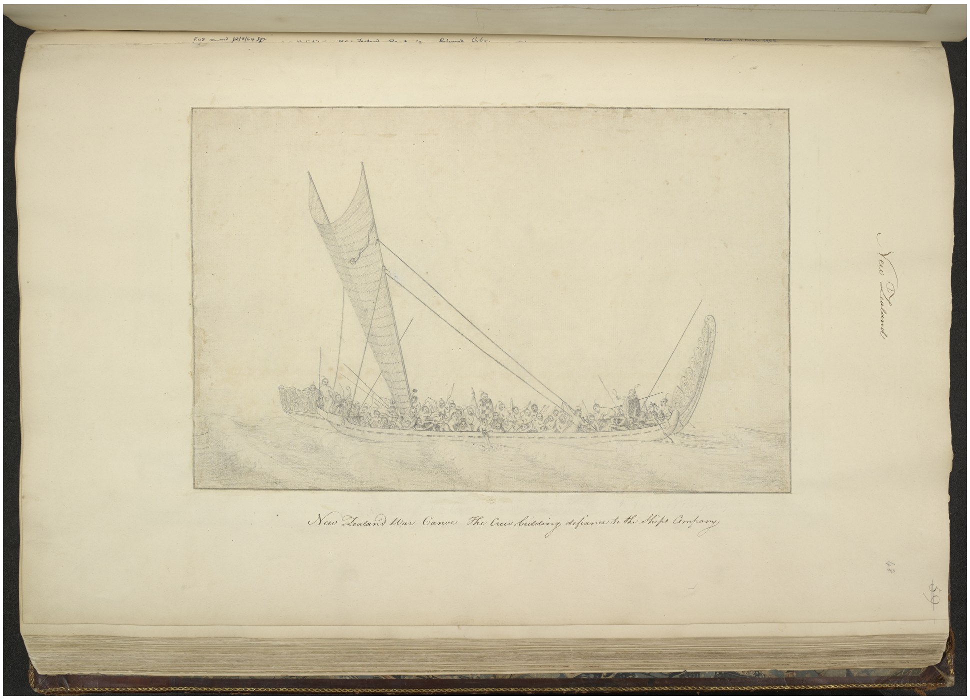


Figure 4.4: A New Zealand war canoe, recorded by Spöring in 1763 ©British Library Board (23920/48).

Figure 4.5 shows a sketch of the design of a *Tongiaki* which was recorded on Captain Cooks third voyage in 1777 (Haddon and Hornell, 1975). Each demihull is slender and appears to have a v-shaped midsection with bow and stern. They likely have different performance characteristics relative to modern catamaran hull forms which have been reviewed in Section 2.3.

One subject of debate is on the number and type of hulls that Polynesian voyaging craft possessed. Polynesian monohulls have been recorded as being used for conducting warfare but not for long-distance voyaging. For example, Fig. 12 (Bellwood, 1978) shows a war canoe with a large complement of warriors on board, but it is unlikely that it was used for anything other than amphibious warfare. Furthermore trees large enough for stable monohull craft were not found until

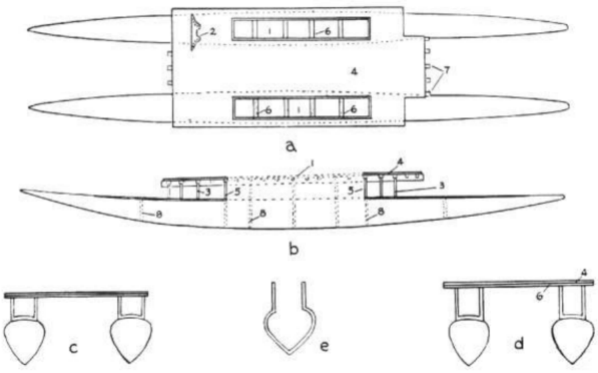


Figure 4.5: A sketch of a *Tongiaki* made on Captain Cooks 3rd voyage, reproduced by Haddon and Hornell (Haddon and Hornell, 1975).

New Zealand was reached (Beheim and Bell, 2011). Another recorded instance of a large monohull canoe was in the Tuamotu's (Haddon and Hornell, 1975, p. 76-78). However, this canoe was an adaptation of traditional boat building methods and materials to a European whale-boat design.

A strength of the double hulled voyaging canoe design is the improved roll stability (Abramovitch, 2005). The stability of double hulled canoes offer improved seakeeping abilities, larger deck area and the flexibility to use different types of sails (Irwin, 2008).

Hornell argues that the double outrigger canoe is less structurally sound than a double-hulled canoe, and would represent a significant increase in the risk of failure of design as a voyage progresses into more open water (Haddon and Hornell, 1975). Doran takes the view that rather than not being seaworthy enough, double outriggers are a later technology emanating from Indonesia and would not have reached Polynesia in the time period of interest, this investigation is reviewed in (Doran, 1981). Despite the somewhat opposing logic used by each author, the conclusion is the same: outrigger and double-hulled canoes are part of the same family of hull designs and are likely to have been the basis of voyaging craft design. The influence of the outrigger or double hull is one design feature which requires modelling in a parametric model of a Polynesian voyaging canoe design.

Polynesian voyaging craft utilised two different techniques of sailing to windward, these are the ‘tacking’ and ‘shunting’ methods. Figure 4.6 compares the tacking, shunting and wearing methods of sailing to windward. At the point of European contact craft which used either of these techniques were found to have evolved into very different designs.

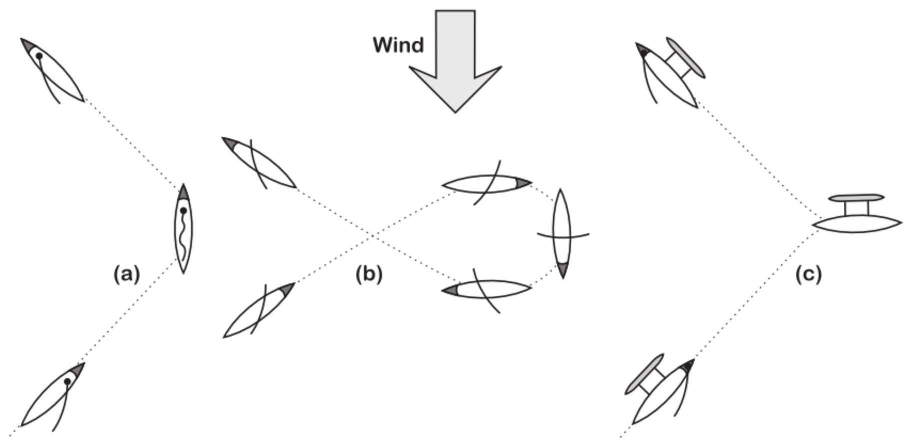


Figure 4.6: Different techniques to sail upwind (Cotterell, 1990, p. 254). (a) is known as ‘tacking’ and is where the bow of the craft travels through the direction of the wind. (b) is known as ‘wearing’ and is how a European square-rigged ship gybes through the wind. (c) is known as ‘shunting’ and is where the bow and stern of a Polynesian voyaging canoe change and the position of the sail is shifted across the craft.

The main hull of an outrigger craft design was recorded as having average dimensions of $11.5m \times 0.8m \times 1.1m$ (L $\times$ B $\times$ D), (McGrail, 2004). Cook recorded average lengths between $6.1 - 9.1$m and breadths of $0.51 - 0.56$m in Polynesia, 1773. If the craft tacked to windward, the position of the mast was fixed forward in the craft, and the hull generally had a definite bow and stern.

If the craft shunted to windward, then the hull was generally symmetrical fore and aft, with the outrigger always remaining to windward and usually to port of the main hull. Lee boards existed to allow the crew to move their weight in the opposite direction to the outrigger to trim the design. Outrigger designs were found in Eastern Melanesia, Micronesia and across Polynesia. The outrigger was held about $\frac{1}{3}$ of the length of the main hull away by booms. The outrigger itself could range from being a single log to having a hull shape similar to that of the main hull. The particular dimensions of outrigger designs varied hugely between regions (Haddon and Hornell, 1975).

Polynesian double hulled canoes can been classified into two types, a *Tongiaki* and an *n'Drua*,(Nuttall et al., 2014a). The *Tongiaki* is based around two equal sized hulls whereas the *n'Drua* uses a large hull and an outrigger. An example of an outrigger is the design investigated in Irwin and Flay (2015), shown in Figure 4.7.

The *Tongiaki* predates the *n'Drua* design and is recorded as being less able at sailing to windward (Nuttall et al., 2014a). The key design elements of the two double-hulled canoe types are two hulls and a triangular sail. The *Tongiaki* design had equal-sized hulls and could shunt or tack upwind, as shown in Figure 4.5. Cook recorded dimensions of $21m \times 3.7m \times 1.1m$ (L × B × D), whereas Paris recorded dimensions of $14.5m \times 2.01m \times 0.98m$ (L × B × D) (Haddon and Hornell, 1975, p. 19).

The critical difference between the *n'Drua* and *Tongiaki* designs are lie in the asymmetric hulls, sail design and method for sailing upwind. The *n'Drua* used asymmetric hulls in both size and shape. The hulls were recorded as having differences of up to 35% in length between hulls, with differences of 20% recorded in New Zealand and Fiji (Haddon and Hornell, 1975, p. 47). The *Tongiaki* has been identified as being the precursor to the *n'Drua* voyaging canoe. The *Tongiaki*

Figure 4.7: Model of an outrigger investigated in Irwin and Flay (2015). This is used as a proxy for the Outrigger or *n'Drua* design which succeeded the Tongiaki design. Note that the outrigger hull itself is missing from the model and would have been connected to the end of the wooden booms.

design was developed through fitting Micronesian sailing rigs on adapted Tongan hulls (Nuttall et al., 2014a). The asymmetry in hull length and shape means that the *n'Drua* must shunt upwind.

European explorers recorded a range of different sail types being used across Oceania. Figure 4.8 indicates the spread of sail types mapped to different proposed colonisation timelines. Each sail belonged to a specific type of standing rigging which could either tack or shunted. These sails were universally manufactured using pandanus matting. Sail types can be classified into those belonging to the Oceanic spritsail, Oceanic lateens and Oceanic lugsails (Di Piazza et al., 2014). It is possible to classify these sails based on their geographic location. Although the sails were recorded at a specific point in time an association can be drawn to the chronological order in which the islands were settled and the variation in sail performance. The use of a voyage modelling framework using

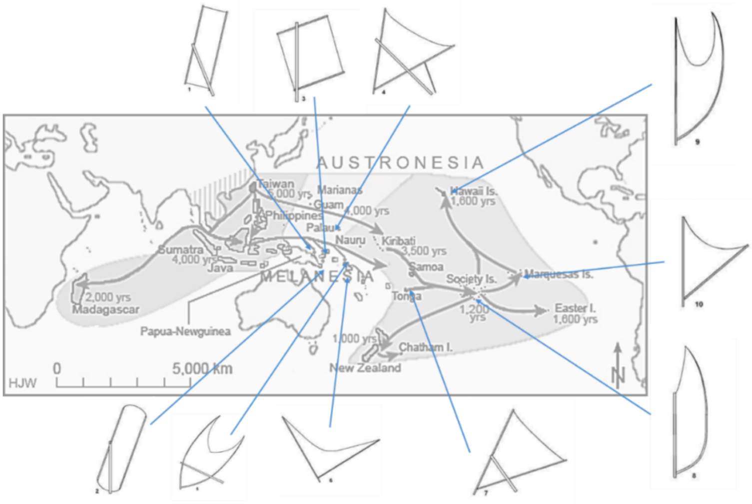


Figure 4.8: Diagram associating sail type with spatial and temporal context (Cannon et al., 2015). Sail classification uses the system devised by (Di Piazza et al., 2014). Sails 1 - 7 are shunting sails, with sails 6 - 10 used in tacking rigs. Sails 6 and 7 were tacked or shunted, and could have been the transition between tacking and shunting designs.

environmental conditions from each stage of the Polynesian colonisation could allow a comparison of the different success of each sail design given a base hull arrangement. This study could be one way to see if it is possible to validate the temporal context of the sails.

An experimental evaluation of an 18th century Maori rig found that it had good performance up to a beam reach (Anderson and Boon, 2011). This investigation argues that the performance of Maori rigs would have given Maori voyaging canoes sufficient performance to make voyages between islands in Central East Polynesia.

One study statistically investigated potential relationships between seafaring craft traits and location, amongst other factors (Beheim and Bell, 2011). This study found that it was possible to draw relationships between ecological and cultural aspects and canoe traits. One relationship is the identification of a loss of some canoe traits, such as double hulls, on arrival at islands with a large number of natural resources.

This section has identified that the Polynesian voyaging craft likely used two hulls and had a single sail for main propulsion. However, within this description, there are several critical technological variations. Either the two hulls were of similar size and shape in a configuration known as a 'double-hulled canoe', or the windward hull was much smaller in a configuration known as an 'outrigger' design. The method of making ground upwind was either through 'tacking' or 'shunting'. Each method has an associated set of design characteristics and sail choices. The final variation is the perspective taken on the Polynesian migration. This perspective could take the 'traditionalist' view, which argues for large voyaging craft which had dimensions significantly larger than those found at the time of European contact, based on ethnographic evidence. The 'historicist' viewpoint argues that this technology would have survived and taken the view that the evidence found at the time of European contact would be directly comparable to ancient voyaging canoe designs. Equally there could be an alternative position which merges aspects of either perspective or not at all. A parametric model of Polynesian seafaring technology performance which can relate the variation in performance to different aspects of Polynesian seafaring technology is required.

4.2.1 Contemporary Polynesian seafaring technology

Across Polynesia, there is a revival of traditional sailing craft and techniques. The first proponent of this revival was Ben Finney, who instigated the Polynesian Voyaging Society through the manufacture and operation of a range of reconstructed voyaging canoes.

The ability for the oar to be the main form of propulsion was investigated in a study which measured the speed achieved by two crews of trained rowers in a Polynesian double canoe (Horvath and Finney, 1969). The rowers were able to put out sprint speeds of up to 7 knots, although could only manage $3 - 4$ knots over longer periods of time. This study found that 16 hours of paddling over two days is an extreme effort, and would not likely have enabled long distance voyaging.

Figure 4.9 shows an example of a reconstructed voyaging canoe, the *Hōkūle'a*. The *Hōkūle'a* is a double-hulled voyaging canoe with two sails which combines multiple Polynesian design elements in a single craft (Finney, 1977). Hawaiians have taken ownership of the reinvention of Polynesian voyaging as it contributes towards ideas around their national identity and seafaring heritage (Finney, 1991). Another contemporary voyaging society is the Tonga Voyaging Society (Tonga Voyaging Society, 2020), illustrating that the revival in voyaging practice is pan-Pacific.

The design of the *Hōkūle'a* was meant to reproduce a voyaging canoe of the type in use between $600 - 1000$ years ago (Finney, 1977). The lack of the evidence meant the designers combined different design features which were common across Polynesia from reviewing Haddon and Hornell, a work which recorded Polynesian canoe designs in the early 20th-century (Haddon and Hornell, 1936). The canoe was manufactured using modern materials and manufacturing techniques.

Key design features of the *Hōkūle'a* include the selection of a sail plan using two Polynesian sprit sails and a semi-V shape hull. The spritsail is found throughout Polynesia, and could likely be a precursor to any variations in the sail which have been recorded. The hull shape was designed in a “semi-V” shape, common in Micronesia, but not in Polynesia. This hull shape is characteristic of Polynesian voyaging canoes such as the *Tongiaki* (Finney, 1977). Table 4.1 shows the key

Figure 4.9: The *Hōkūle'a* arriving in Honolulu, Hawaii from Tahiti in 1976 (Hokule'a, 2019).

parameters of the *Hōkūle'a*. The *Hōkūle'a* was able to maintain an angle of 75^o to the wind, with an average speed of 18.5 km/h in a sea breeze.

Table 4.1: Parameters describing the *Hōkūle'a* (Lewis, 1994).

Parameter	**Value**
LOA (m)	19.00
LWL (m)	16.46
BOA (m)	5.33
b/L	0.21
T (m)	0.76
Sail area (m^2)	50.0
Δ (tonnes)	11.34

Multiple reconstructed voyaging canoes have been built which attempt to place their design within the temporal context of the colonisation of Polynesia (Anderson, 2008a). These designs have used modern materials and design techniques to ensure the safety of the crew. However, some designs combine design elements aggregated from dissimilar sources, and usually have a significantly larger sail area than that found historically (Anderson, 2008a).

4.2.2 Polynesian seafaring techniques

Polynesian navigators developed complex navigation systems which were developed over thousands of years to guide them between islands. Polynesian sailors also possessed the means to sustain themselves while undertaking long ocean voyages. These means included the ability to store water and food, but also the seafaring culture necessary to maintain social cohesion over such vast distances.

Polynesian navigators had effective techniques and tools for ocean navigation at the time of initial European contact. A chart of Polynesia was created based on the Polynesian navigator Tupaia on Cooks voyage in 1769, which demonstrated comprehensive knowledge of islands in Polynesia, Figure 4.10. Polynesian navigators could communicate distance to European navigators based on the time taken for a canoe to sail between locations.

A contemporary record of Polynesian navigation techniques described a range of methods for accurate navigation without charts using a non-Cartesian perspective on the world (Lewis, 1994). Using back bearings on starting islands allowed a navigator to account for the influence of current. It was possible to sense the refraction of sea swell around islands to identify their relative location. At night, it is possible to observe phosphorescence flashing in the seas around islands up to $80 - 100$ miles away. The migration of birds could also be used to judge the location and distance from islands. The use of stick charts as instructional and mnemonic devices helps sailors navigate through the use of swell patterns (Lewis, 1994, p. 201).

Knowledge of astronomy taught through “star compasses” enabled Polynesian

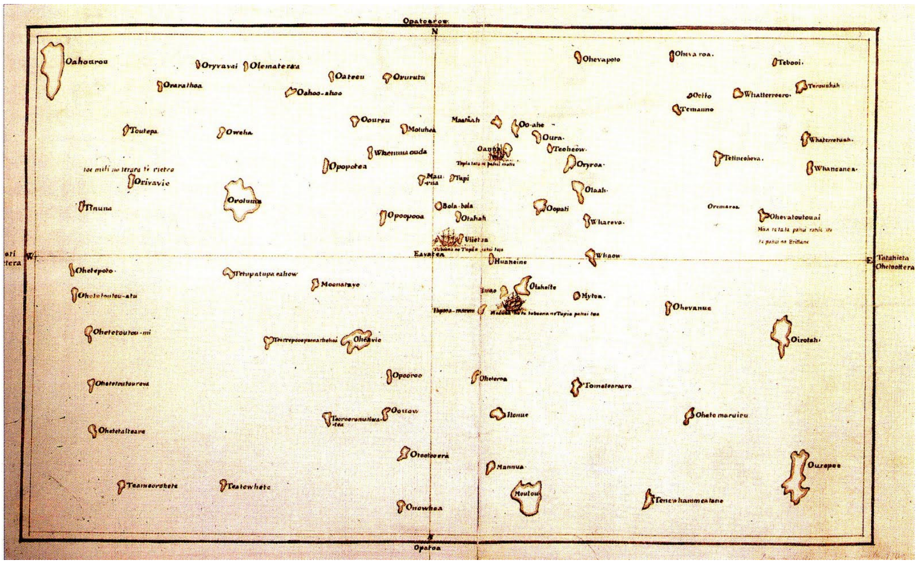


Figure 4.10: Tupaia's chart of Polynesia within 3200 km of Ra'iatea, Society Islands (Tupaia, 1769).

navigators to share knowledge and teach it the next generation (Chadwick and Paviour-Smith, 2016). Polynesian navigators had a fundamentally different understanding of space and time in comparison to European sailors. For example, Polynesian navigators might have seen the canoe as being in a fixed location relative to the rest of the world moving. Stick charts were used to record prevailing wind and wave directions. A review of Polynesian voyaging techniques is provided in Lewis (1994).

The depth of knowledge possessed by Polynesian navigators was highly valued by European seafarers who colonised islands within the Pacific in the 17th and 18th centuries. For example, Tupa'ia was an invaluable source of knowledge to Captains Wallis and Cook on their journeys throughout Polynesia (Salmond, 2008). While aspects of traditional Polynesian navigation have been lost, contemporary Polynesian navigators have been able to competently navigate without modern instruments over extremely long ocean voyages (Finney, 1988, 2007).

Voyage lengths were limited by the amount of food and water carried. Food such as dried breadfruit, pounded taro, coconuts, and a range of pastes were recorded as being in use across Polynesia (Lewis, 1994, p. 274). Canoe crew would have been able to catch fish and cook them on the cooking fires which existed on board, as seen in Figure 4.3. The limits of voyage length before running out of food have been suggested as being between 14 – 21 days (Banks and Cook respectively), although instances of survival after 42 days at sea have been recorded (Lewis, 1994, p. 275).

4.2.3 Modelling voyaging canoe performance

Quantifying the performance of Polynesian seafaring technology is essential in order to provide evidence which may support different theories of migration (Irwin and Flay, 2015; Lilley and ICOMOS, 2010). There has been a range of physical and computational investigations to estimate the performance of Polynesian seafaring technology. Two questions must be kept in mind in the following literature review: 1. to what extent does this model draw on specific types of evidence? 2. to what extent is this model able to capture the complexity of the real situation?

The sails are the most striking component of any sailing craft. Crucially, sails provide the aerodynamic driving force required for propulsion, Figure 2.4. Polynesian sail types are considerably different in design to Western types. Initial performance testing of “crab claw” sails which are the stereotypical Polynesian sail type identified that the optimum point of the performance was on a beam reach (Marchaj, 2003, p. 160). This research also identified that the design naturally de-powered at higher wind speeds through opening the top and spilling wind like a windsurf sail.

An investigation that performed wind tunnel tests on rigid sail models found that the windward performance of a sail improved as its origin moved Eastwards (Di Piazza et al., 2014), Figure 4.8. This investigation could imply that the windward performance of the sail improved as the colonisation progressed from West to East. The engineering investigation provides a good relative comparison between sail designs, but as the sail models were rigid, they would not have flexed realistically and thus would not provide useful data for performance modelling. Furthermore, the images that the sail models were based on are not temporally consistent with the time of the long pause (Haddon and Hornell, 1936). The performance data provided only covers the first 80 degrees of apparent wind, a wind direction found challenging by prehistoric (Nuttall et al., 2014b) and reconstructed canoes (Finney, 1977).

The influence of different sailcloth materials on the driving force found a significant decrease in drive force between the modern sailcloth and the traditional pandanus matting (Irwin and Flay, 2015). The sail design was based off a drawing of a Māori sailing canoe sailing downwind, and the performance was found to be comparable to other results in the literature (Di Piazza et al., 2014).

There have been three different experimental investigations into Polynesian sail performance (Cannon et al., 2015; Di Piazza, 2014; Irwin and Flay, 2015). These studies have manufactured sail model from images and then performed wind tunnel testing. These tests have then been used to compare sail types or as an input into the performance prediction of Polynesian voyaging canoes. There is uncertainty around the accuracy of identifying the size and shape of sails from 2D images, as well as how the sails are sized as part of the Polynesian design process. Due to the challenge of manufacturing sails out of traditional materials and the negative performance relative to modern sail materials, the real performance would likely be worse than that predicted in tests. The influence of mast height

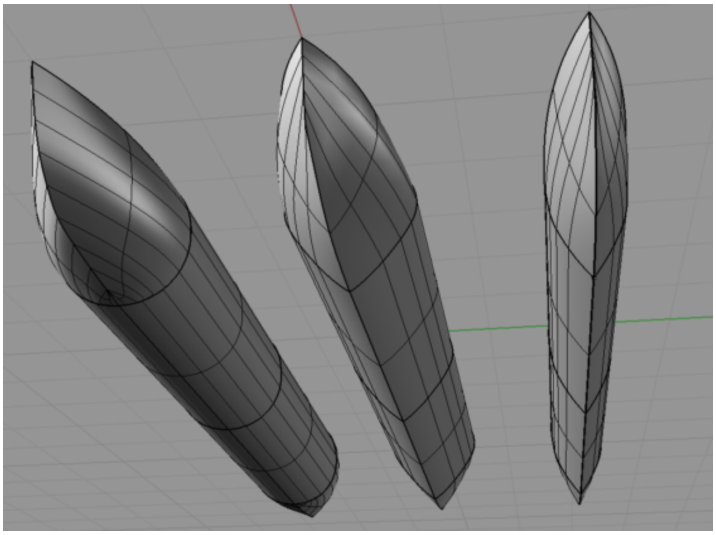


Figure 4.11: View of different canoe cross sections considered in the analysis in Boeck et al. (2012). From left to right, the canoe hulls were known as "U" shape, "semi-V" shape and "V" shape. The "V" shape hull provided better windward performance, but others have identified that the "semi-V" shape would have offered a compromise between storage area and speed for long voyages (Finney, 1977).

and location within the vessel has not been modelled. These factors are likely to influence performance considerably and are known to vary across different canoe designs.

A study was completed to investigate the amount of side force generated from a range of Polynesian hull forms, as seen in Figure 4.11, (Boeck et al., 2012). The “later” hull forms were able to generate more side force than earlier designs, indicating a better windward ability as seafaring technology developed. This study is a useful illustration of how changes in hull shape would have helped Polynesians complete voyages in more challenging weather conditions. The performance data was for an outrigger design which is smaller and has a different hull configuration to the *Tongiaki*, which is the vessel of specific interest in this research.

A design investigation into the performance of a *Tongiaki* design was undertaken at the University of Southampton (Cannon et al., 2015). This study investigated the performance of different areas of the design of the *Tongiaki*. The *Tongiaki* design itself was reconstructed based on archaeological evidence, such as Figure 4.5. Engineering estimates were made in order to fill in the gaps in the design. Fundamental limitations of the *Tongiaki* design are the challenges involved in tacking the rig and the reduction in strength of the rigging when it gets wet. A seakeeping analysis identified that there was a high probability of deck wetness and a structural analysis identified that the hulls would lose buoyancy if breached due to the placement of bulkheads. A study of the performance of the *Tongiaki* sail, as estimated, presented similar performance characteristics to those presented in Di Piazza et al. (2014). The *Tongiaki* was found to have relatively good windward performance. Further research estimated the resistance of a *Tongiaki* hull form experimentally for different draughts (Cannon, 2015)

Another study presented the predicted performance of an outrigger voyaging canoe design (Irwin and Flay, 2015). This study presented the results of two investigations, one into the performance of a Polynesian sail type using different sail cloths and the other into the hydrodynamics of different Polynesian hull shapes, based on previous research (Boeck et al., 2012). The performance of the sail was significantly reduced through the use of Pandanus matting, the material traditionally used for sail design in Polynesia. This performance reduction would likely scale up as the size of the sail increased, even if the Pandanus matting would have been able to take the strain, as found in other research (Cannon et al., 2015).

The central challenge in Polynesian archaeology is the lack of evidence on seafaring technology used at the beginning of the long pause. The production of any performance model of a Polynesian voyage canoe requires some form of assumption to be made. Key perspectives of how perspectives on the performance of Polynesian seafaring technology relate to the evidence have been described in Section 4.2. Improvements on research into the performance of Polynesian seafaring technology through the use of dynamic VPP, Section 2.2, require more information which cannot be obtained without making assumptions which are open to criticism.

A performance model of the Tongiaki which integrates existing data on hull and sail performance is necessary to perform relevant voyaging simulations. Although there is enough detail to estimate the performance using a static VPP, the use of a dynamic VPP would require more assumptions to be made and give a false sense of detail to the results. The influence of changes in aspects of Polynesian seafaring performance on the ability to complete voyages is investigated in Chapter 8.

4.3 The *Tongiaki*

The *Tongiaki* is identified as the earliest recorded canoe design which was being used for oceanic voyaging, and could possibly have been the design which enabled the colonisation of Polynesia. The *Tongiaki* is known to have made inter-island voyages from Tonga to Samōa and between Tonga and Fiji. The *Tongiaki* is a double-hulled voyaging canoe with a central rig supporting an oceanic lateen sail which could tack or shunt. The *Tongiaki* was the earliest design of ocean voyaging canoe which was recorded by European explorers and is believed to have preceded the development of technologically advanced n'Drua (or Kalia) canoe (Clunie and Anglia, 2015).

The *Tongiaki* was encountered by Europeans in 1616 (Koch, 1971) and later in the 1770's (Cook, 1777), at which point it disappears from the historical record (Clunie and Anglia, 2015). Previous research into the design of the *Tongiaki* has estimated the design parameters (Cannon et al., 2015), seen in Table 4.2. This research used the assumption that the dimensions were scaled as a function of the length of a man's arm span, 1.7m.

Table 4.2: Parameters describing *Tongiaki* hull form, (Cannon et al., 2015, p. 25).

Parameter	**Value**
L (m)	23
B (m)	6.5
T (m)	1
D (m)	1.3
b (m)	1.3
LWL (m)	17.83
L/b	17.69
S/L	0.23
Δ (kg)	14945.63
WSA (m2)	57.91
Demi hull C_B	0.248
Demi hull C_P	0.431

The dimensions of the hull were based on the sketch in Figure 4.5. This sketch describes a craft with a long slender hull form and a "v-shaped" cross-section. An estimation of the lightship weights and initial loading conditions returned an estimated draft of 1m (Cannon et al., 2015, p. 25).

The sail design is a triangular shape, where the sail is held between a lower boom and upper spar. The tack of the sail is fixed on one of the demi hulls. The upper spar is held at approximately 1/3 of its length aft by a hook at the top of a wooden mast. This design is based on observations by Cook and Schouten and is similar to the design derived by Di Piazza for experimental sail performance tests (Di Piazza et al., 2014).

The dimensions of the rigging was estimated based of drawings and the sail area was estimated based on the size required to generate a speed of between $10.7 - 11.7$ kts for a wind condition of 17.5 kts at 45^o. The sail performance used in this estimation was based on the performance of crab claw sail experimentally tested by Marchaj (2003).

The final estimate of the sail design has an area of 110m^2, a peak line of 20m, a leech of 11m and a foot length of 22.83m. These dimensions were used to create a model sail that was used for wind tunnel testing. The wind tunnel test results are reproduced in Figure 4.14 and are used to predict the performance of the *Tongiaki* in Section 4.5. A rendering of the design produced in this investigation is shown in Figure 4.12.

Figure 4.12: Rendering of the *Tongiaki* generated from archaeological and historical evidence (Cannon et al., 2015).

4.4 *Tongiaki* Hydrodynamics

A series of resistance tests were performed on a model of a *Tongiaki* demi hull which was manufactured based on the design reviewed in Section 4.3. The model series reviewed in Section 2.3 have different midsections and more asymmetric stern and bows, which is dissimilar to Polynesian canoe designs. It is difficult to justify the use of these model series without evaluating the hydrodynamics of a

Polynesian hull form.

The hydrodynamic resistance tests evaluated the resistance of a single *Tongiaki* demi-hull form at different draughts (Cannon, 2015). Table 4.3 describes the parameters of the *Tongiaki* hull for different draughts. Different draughts were examined to understand how the performance might change as the number of people or supplies varied. There was no investigation of different heel angles or side force.

Table 4.3: Range of parameters of the *Tongiaki* demihull for different draughts.

T (m)	**WSA (m^2)**	**Δ (Sea water, kg)**	**Δ (Freshwater, kg)**	**LWL (m)**
0.5	9.85	1325.88	1359.03	11.66
0.6	13.37	2101.04	2153.56	12.92
0.7	16.86	3100.66	3178.17	14.10
0.8	20.58	4335.90	4444.29	15.23
0.9	24.39	5777.20	5921.62	16.33
1	28.95	7473.17	7659.99	17.38

Comparing the experimental hydrodynamic resistance of the *Tongiaki* hull form with other model series and prediction programs will quantify how accurate existing methods are for modelling the performance of Polynesian hull hydrodynamics. The hydrodynamic resistance for the *Tongiaki* hull form was predicted using a program called “WaveSTL” and the WinDesign4 hydrodynamic model. The Wolfson Unit were not prepared to provide a reference for the hydrodynamic data used in the WinDesign4 hydrodynamic model due to the commercially sensitive data involved. These resistance curves are compared with experimental results in Figure 4.13.

The hydrodynamic resistance models are all reasonably similar for straight-line water resistance. However, the data does not exist to compare the resistance of the experimental *Tongiaki* test hull with the WinDesign4 at different yaw and heel angles, as might be encountered while sailing. The WinDesign4 hydrodynamic

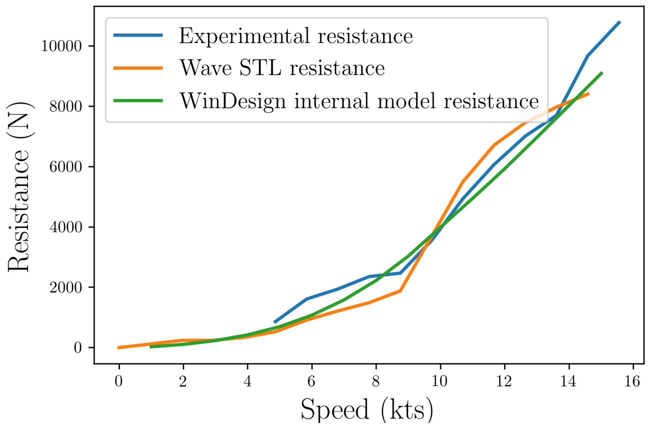


Figure 4.13: Comparison of different models of the total hydrodynamic resistance for the full-size *Tongiaki*.

model has a comparable trend and magnitude to the experimental data. However, the WinDesign4 model under predicts the resistance below 8 and above 10 knots of boat speed, which will result in the prediction of faster speeds than a real *Tongiaki* could achieve.

The resistance experiments had a full scale lower speed limit of $V_s = 4.86$ kts, corresponding to $Fn = 0.191$. This speed limit was set by the constraints of the towing tank and model size. The *Tongiaki* would likely have spent a significant amount of time sailing at or below this speed, meaning that accurate data for this speed region is essential.

The WinDesign4 prediction shows an increase in resistance around the $9 - 15$ kt region, likely to the wave interaction between the two hulls. In reality, it is unlikely that Polynesian canoes would have experienced significant resistance increase as a consequence of this effect as they would not have been travelling fast enough most of the time.

The WinDesign4 hydrodynamic model is identified as being suitable for estimating the resistance of the *Tongiaki* for this study. It has similar performance to the experimental model and the WaveSTL resistance prediction and has data on how the resistance changes at different heel and yaw angles. Despite the limitations of the WinDesign4 hydrodynamics model it possesses enough data to provide relevant predictions of the performance of a *Tongiaki* hull.

More experimental or computation investigations could be performed into the performance of the Tongiaki. These tests would require more information on the design of the Tongiaki which is only obtainable through making assumptions on the shape, size and the material used in the design. Instead, this thesis investigates the influence of overall uncertainty in performance model in Chapter 6 and then the uncertainty associated with different aspects of Polynesian seafaring technology in Chapter 8.

4.5 Influence of sail size

This section presents a study of how the size of the sail could influence the performance of a *Tongiaki*. Estimating the size of a sail from historical accounts is challenging due to the influence of different drawing styles or human error. Identifying the sensitivity of the performance of a *Tongiaki* to changes in sail size will allow the influence of different interpretations of the evidence. It will also indicate how realistic accounts of Polynesian seafaring technology are, as unrealistic accounts will return speeds which are too low or too high.

The aerodynamics of the sail type used must be combined with a hydrodynamic resistance model to estimate the performance of the *Tongiaki*. Research into the performance of a *Tongiaki* sail produced a set of aerodynamic performance coefficients, displayed in Figure 4.14.

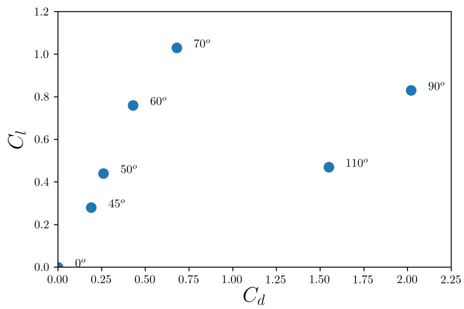


Figure 4.14: *Tongiaki* sail performance from experimental results (Cannon et al., 2015). Each point is labelled with the respective apparent wind angle.

The performance of a *Tongiaki* hull form with a range of sail sizes and wind conditions was simulated. The settings for the performance prediction experiments were:

- Sail sizes of $20, 50, 80, 110\text{m}^2$. The upper limit of 110m^2 was the estimate of the *Tongiaki* sail size used in previous research (Cannon et al., 2015).
- Wind angle varying from 80^o to 110^o. The *Hōkūle'a* was only able to sail constantly on a course of $70 - 75^o$ off the wind (Finney, 1977). It is highly unlikely that craft manufactured without modern materials and techniques would be able to sail steadily at lower wind angles.
- Wind speed varying from 4 to 35 kts. This range covers a range of wind speeds which may be encountered while at sea.

The 80m^2 sail size was the only sail size which produced solutions for each wind condition in the static VPP. The performance of a *Tongiaki* with an 80m^2 is shown in Figure 4.15. For true wind speeds up to 35 kts the boat speed increases as the apparent wind angle increases. However, the 35 kt true wind speed has a significant peak and dip at $120^o - 140^o$. This change can be linked to the significant increase in wind speed and the behaviour of the sail. The boat speed peaks around 100^o and experiences a dip around 140^o. This change could be linked to the change in sail performance seen at $\beta = 70^o$. The increase in speed could be due to the sail performance data being extrapolated outside its original region. Over all true wind directions the performance of the 110m^2 sail is 12.5% faster than the 80m^2 sail, and the 50 and 20m^2 sails are 13.2% and 40% slower respectively.

Note that the performance presented in Figure 4.15 presents opportunities for improvement if this study was a design exercise. However, the objective of this section is to recreate the performance of a Tongiaki using the available evidence rather than perform a design optimisation exercise on an idealised version of what the Tongiaki might be. Therefore, the performance of the Tongiaki with a sail area of 80m^2 is identified as being a suitable example of the performance of a voyaging craft used in deep history. There is a clear requirement to simulate the uncertainty associated with the performance model as a whole and also with the influence of different aspects such as the speed and the ability to sail into the wind.

Figure 4.16 shows the speed of these different performances non-dimensionalised for the speed of the 110m^2 sail craft. There is a decrease in performance of up to 50% as the sail size reduces to 30m^2. Although this is a significant decrease in speed, it appears that the *Tongiaki* could still have achieved some speed at low wind speeds. For downwind angles the sail size appears to matter less.

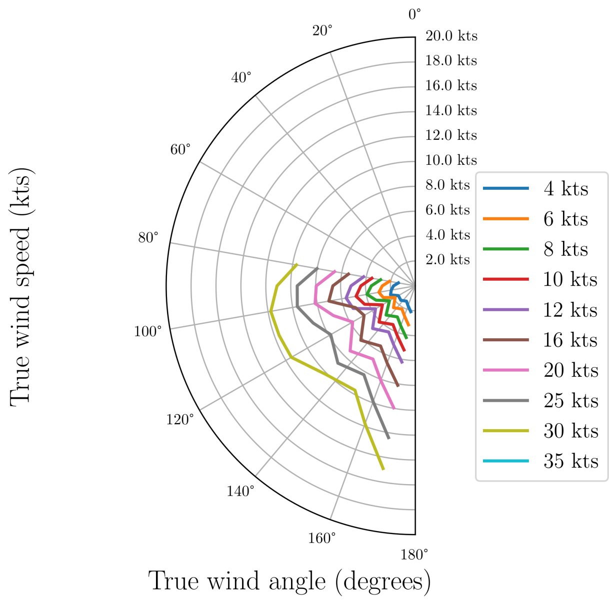


Figure 4.15: Performance of the *Tongiaki* hull with an 80m^2 sail.

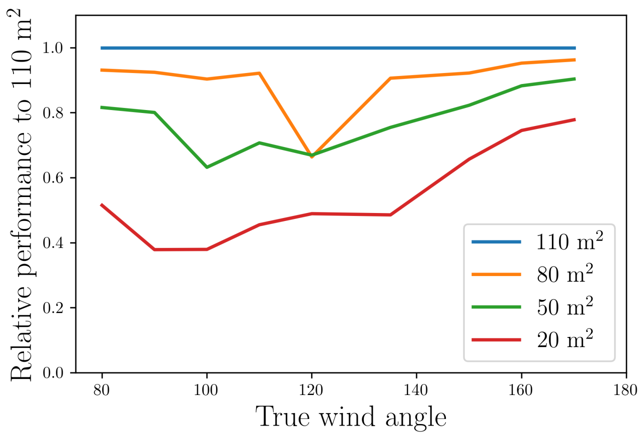


Figure 4.16: Reduction in performance as a function of sail size at a true wind speed of 12 knots. Some points have been interpolated from the nearest values for each performance.

4.6 Comparison to reconstructed canoes

This section compares the *Tongiaki* performance model with other Polynesian seafaring technology models in academic literature. Of interest is whether the VPP analysis produced results similar to those in the literature, and if not, how the trend of these results differ. By comparing the performance of different models, it will be possible to identify the strengths and weaknesses of different approaches to modelling Polynesian seafaring technology. The key parameters of each voyaging canoe compared are described in Table 4.4.

Table 4.4: Key parameters of different Polynesian voyaging canoes. The Nahelia is a reconstructed traditionalist voyaging canoe. The Tongiaki and Outrigger are versions of seafaring technology which might have been used before and after the long pause.

Parameter	Nahelia	Outrigger	Tongiaki
L	12.86	11.6	20.00
B	2.26	0.46	1.30
T	0.34	0.46	1.30
Displacement (m3)	2.24	2.25	15.00
Vert cent sail area (m)	7.00	6.50	10.00
Sail area (m2)	19.5	30.00	80.00
Reference	(Finney, 1977)	(Boeck et al., 2012)	Present investigation.

Two performance models of Polynesian seafaring technology are identified as being comparable, the Outrigger and the *Nahelia*. The performance of the Outrigger was predicted using hydrodynamics of different shaped hulls (Boeck et al., 2012) and the crab claw sail performance presented in Marchaj (2003). The sail area was 18.5m^2 and the canoe has an overall length of 14m. The performance of the Outrigger is shown in Figure 4.17 and is compared against other designs in Figure 4.18.

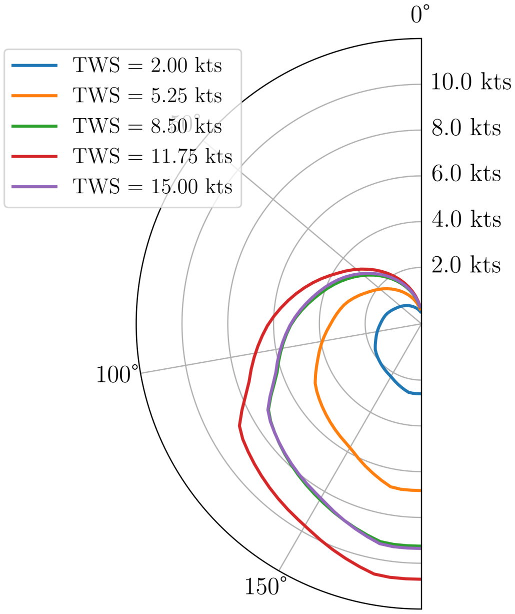


Figure 4.17: V_s as a function of true wind speed and direction for the predicted performance of the Outrigger canoe (Boeck et al., 2012). The Outrigger canoe is an example of how Polynesian seafaring technology developed after the long pause, and is used to contrast against the performance of the Tongiaki.

The *Nahelia* is a 12.9 m long single-masted Hawaiian sailing canoe, built to plans of a late 18th and early 19th-century voyaging canoe (Finney, 1977). Finney (1977) argued that the Nahelia represents the final evolution of Hawaiian seafaring technology. The sail area is approximately 19.5m^2.

Figure 4.18 shows the performance at 12 knots of true wind speed. It can be seen that for the majority of wind angles below 120^o, the *Tongiaki* performance is superior to that of the *Nahelia* and Outrigger designs. This performance increase is likely due to the larger sail size of the *Tongiaki*. The *Nahelia* and Outrigger have superior windward performance due to their hull size and sail type. The sail type is of the Outrigger design is a later Hawaiian or New Zealand design which was shown to have better performance at lower wind angles to the *Tongiaki* sail type (Di Piazza et al., 2014).

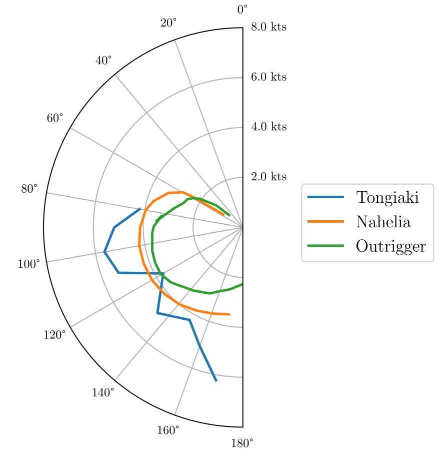


Figure 4.18: Performance of three different voyaging canoes at 12 knots of True Wind Speed.

4.7 Critical analysis of results and assumptions

The analysis presented in the previous sections has identified the likely performance of the earliest recorded example of Polynesian seafaring technology, the *Tongiaki*. This analysis has improved on existing knowledge as it is the first prediction of the performance of a craft of this type within the time period of the "long pause". This section will identify how the different assumptions used may have influenced these results.

The use of the WinDesign4 hydrodynamics model under predicts the resistance of a *Tongiaki* hull, as seen in Figure 4.13. This under prediction in resistance is increased by the difference in the material used in the construction of the modern test hulls and the rough wooden surface of a voyaging canoe.

The experimental performance data is only available for 5 data points with a limited range of apparent wind angles. For the higher wind angles, the sail performance data has had to be extrapolated within the VPP, which reduces confidence in the results. The non-linear performance of the sail type could also contribute to the spike and dip in the performance of the *Tongiaki*, seen between $100 - 140^o$ degrees.

The process of predicting the performance of an ancient voyaging canoe is not the classic design optimisation cycle seen in conventional naval architecture. This process involves making performance predictions of different aspects of Polynesian seafaring technology based on estimates of different design dimensions. The results presented in this Chapter are based on the best estimates of the dimensions of a *Tongiaki*. They allow the process of identifying the performance of prehistoric Polynesian seafaring technology to be started.

4.8 Summary

There is significant uncertainty associated with the prediction of the performance of prehistoric seafaring technology due to the considerable age of the problem and associated lack of records. However, it is possible to arrive at some performance estimates by deriving the design of the earliest recorded Polynesian voyaging canoe. This design, known as the *Tongiaki*, is believed to have been in service in Polynesian fleets before later developments after Polynesia was settled. A literature review identified that there is not enough evidence on the design of the *Tongiaki* to perform detailed engineering studies which give a false sense of accuracy. Instead, attention must be made to quantifying the impact of the uncertainty associated with the design based on a performance model constructed using existing data.

An investigation quantified how the sail type and sail size influenced the performance of a *Tongiaki*. As expected, the speed of a canoe reduced as the sail size reduced. The performance of the *Tongiaki* was predicted over a range of different sail sizes and shapes. A sail size of 80m^2 was selected as the representative *Tongiaki* performance model as this size allowed the VPP to solve for each wind condition, therefore physically made sense.

Performance predictions of the *Tongiaki* identify that it has better performance than reconstructed voyaging canoes on a beam reach. However, it is recorded that prehistoric voyaging canoes were unable to sail within 75^o of the wind, indicating inferior performance compared to later designs. Quantifying the significance of this performance difference is the focus of Chapter 7.

A study into the influence of sail design was limited due to the lack of sail data over the required range of wind angles. The sail data used was collected during wind tunnel tests of a *Tongiaki* type sail. The experimental nature of this sail performance data is believed to contribute towards the bump in the performance.

Chapter 5

Marine weather routing

5.1 Introduction

Polynesian seafaring technology can be placed within the context of colonisation voyaging using marine weather routing models. Seafaring is transient by nature, leaving little or no permanent trace that it has occurred. It is only possible to investigate archaeological seafaring through constructing models of the problem due to the lack of evidence, and associated uncertainty, on the use of seafaring technology. Physical and computational models are applied within Polynesian archaeology to investigate how seafaring technology, the climate and voyaging strategy may have influenced the challenge of completing voyages between islands.

The reconstructed voyaging canoe has been the most popular method of physically modelling the challenge of Polynesian seafaring. Reconstructed voyaging canoes have several significant disadvantages; the use of modern design techniques and materials and the high financial and time cost in deploying a canoe on trial. As a result, a significant amount of research has been conducted using computational models due to their flexibility for modelling a wide range of weather conditions and the ability to model multiple voyages, this research is described in Table 5.1.

Polynesian archaeology has a long history of using computational models to investigate Polynesian seafaring (Levison et al., 1973). Identifying how these models integrate voyaging canoe performance, weather data and utilise an algorithm to model the voyage itself will give insight into the limitations of research in this field.

Modern voyage modelling, also known as marine weather routing, is concerned with identifying the optimum route to take between two locations. It optimises the route based on variables such as time or fuel and requires information on the performance of the marine vehicle as well as weather information.

This chapter reviews the literature on Polynesian voyage modelling and modern marine weather routing methods. The focus is on analysing how this research has been able to model uncertainty in the performance models of seafaring technology, the weather and the limitations of the algorithm used to analyse the problem.

5.2 Polynesian voyage modelling

A range of studies into Polynesian voyage modelling have been undertaken, as seen in Table 5.1. It is possible to analyse each study based on the purpose of the investigation, the sources of environmental data, the type of movement being modelled and the performance model of the seafaring craft.

Table 5.1: Review of research into Polynesian voyage modelling.

Year	Reference	Investigation	Current data	Current resolution	Wind data	Wind resolution	Wave data	Wave resolution	Type of movement	Performance model
1973	Levison et al. (1973)	Voyaging strategy	n/a	n/a	(BMO, 1956)	5, Monthly averages	n/a	n/a	Drift	Downwind
1990	Irwin et al. (1990)	Voyaging strategy	n/a	n/a	(BMO, 1956)	5, biannual, summarised	n/a	n/a	Directed	Downwind
2007	Avis et al. (2007)	Lapita drift voyaging into Western Oceania	(Stammer, 2002)	1 at high latitudes, 1x0.3 in tropics, 1 day	(W. Ebisuzaki et al., 1996)	1.9x2.0, 1 day	n/a	n/a	Drift	Drift/ Downwind
2007	Di Piazza et al. (2007)	Intentional sailing between islands	n/a	n/a	LODYC	1x1, weekly	n/a	n/a	Intentional	Linear (Traditionalist)
2008	Montenegro et al. (2008)	Drift voyaging from East to West	(Stammer, 2002)	1 at high latitudes, 1x0.3 in tropics, 1 day	(W. Ebisuzaki et al., 1996)	1.9x2.0, 1 day	n/a	n/a	Drift	Drift/ Downwind
2008	Evans (2008)	Shortest path voyaging in the Polynesian triangle	n/a	n/a	SSM/I with ECMWF blended by NASA	2.5x2.0	n/a	n/a	Directed	Linear (Traditionalist)
2008	Avis et al. (2008)	Drift voyaging between islands in Polynesia	(Stammer, 2002)	1 at high latitudes, 1x0.3 in tropics, 1 day	(W. Ebisuzaki et al., 1996)	1.9x2.0, 1 day	n/a	n/a	Drift	Drift/ Downwind
2009	Fitzpatrick and Callaghan (2009)	Intentional sailing from Polynesia to South America	(U.S.N., 1995)	n/a	U.S.N. (1995)	n/a	n/a	n/a	Drift	Drift/ Downwind
2014	Montenegro et al. (2014)	Eastward voyaging between West and CE Polynesia	(U.S.N., 1995)	n/a	U.S.N. (1995)	n/a	n/a	n/a	Drift	Drift/ Downwind
2014	Di Piazza (2014)	Producing an isochrone map between West and CE Polynesia	n/a	n/a	BMO (1956)	1x1, weekly	n/a	n/a	Straight line	Linear (Traditionalist)
2016	Montenegro et al. (2016a)	Shortest path voyaging throughout Polynesia	(U.S.N., 1995)	n/a	U.S.N. (1995)	n/a	n/a	n/a	Drift	Sailing craft
2019	Current study	Influence of Polynesian seafaring technology	(Bonjean and Lagerloef, 2002)	0.5 (Latitude)	ECMWF (2019b)	0.5625, 1 hour	n/a	n/a	Shortest path	Sailing craft (Non-linear) and uncertain performance

The first computer simulation of Polynesian voyaging demonstrated the low statistical likelihood of undertaking colonisation voyages in random directions (Levison et al., 1973). The reliability of the voyaging craft was treated as a stochastic survival rate which predicted the absolute failure of a voyage after 182 days. Figure 5.1 shows the survival rate that was used in this study. The survivability data used was gathered from WW2 casualty rates and sporadic reports of contemporary Polynesian voyages so may not be directly relevant to the problem being modelled.

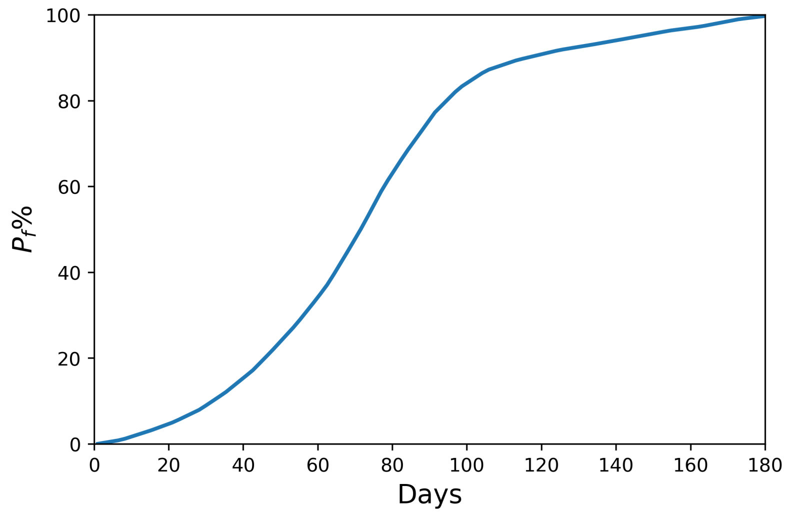


Figure 5.1: The cumulative probability of a voyage failing due to loss of entire crew as a function of time (Levison et al., 1973).

Explicitly investigating the voyaging strategy used by Polynesian seafarers was the focus of another investigation (Irwin et al., 1990). This work found that it was not possible to reach Central Eastern Polynesia from Samoa through using undirected voyaging without returning by navigating along the same latitude. The key conclusion was that the method of searching for new islands did not need to be more complicated than sailing a specific angle and returning along the initial latitude after a time period elapsed. If Polynesian navigators employed this method it would have helped organise their exploration voyages and improve the probability of survival.

A model of drift voyaging between islands within Western Oceania identified downwind and drift voyaging was likely to be successful in the summer monsoon season up to Fiji (Avis et al., 2007). However, successful voyaging Eastwards to Tonga, Samoa and Central East Polynesia required the utilisation of anomalous environmental conditions. Successful voyages often required El Niño conditions.

The use of reconstructed voyaging canoe performance facilitated the identification of successful voyage headings between different islands (Di Piazza et al., 2007). Larger arcs of successful headings act as a proxy for easier voyaging. The results indicated the existence of a significant navigational threshold between West and Central Eastern Polynesia, specifically between Rose and Palmerston islands - the longest gap between Samoa and the Southern Cook Islands.

The viable introduction of the sweet potato via drift voyaging from East to West has been simulated (Montenegro et al., 2008). These simulations assumed that the wind pushed South American balsa rafts downwind and the occupants were unable to steer. It demonstrated that for a maximum voyage length of 120 days, drift voyages were sufficient to enable sweet potatoes to spread throughout Polynesia.

Further drift modelling identified that it was not possible to voyage to Samōa or Tonga from the West under mean weather conditions (Avis et al., 2008). Specific combinations of weather conditions would have had to exist to enable voyages downwind.

A weather routing study for a reconstructed voyaging canoe simulated the shortest path to take between Mangareva, the Gambier Islands to Easter Island (Evans, 2008). The wind was modelled using real weather excerpts and a stochastic weather model. The performance model used was the Nahelia (Finney, 1977). This research showed a significant difference in the result of modelling of using real weather data and weather conditions generated from statistical sampling distributions, compared to previous research which used weather conditions of lower spatial and temporal resolution.

Simulations modelling intentional voyages between various Polynesian islands and South America attempted to investigate the existence of deep historic Polynesian chicken samples found in a site in Chile (Fitzpatrick and Callaghan, 2009). These identified that it was possible to reach South America from Samoa and Tonga in March and January/February respectively. The canoe performance model used was based on (Levison et al., 1973) and assumed a high paddling speed (Horvath and Finney, 1969) as well as the ability to sail at a beam reach.

Samoa was identified as being a more successful starting location than Tonga from an analysis conducted with traditionalist voyaging canoe performance and a statistical weather model (Montenegro et al., 2014). Other findings illustrate the ease of Eastwards voyaging at much higher or lower latitudes than Central East Polynesia. The windward ability of the voyaging canoe appeared to be an essential requirement for completing voyages.

The same model was applied to study the entirety of voyage modelling in Polynesia using weather conditions generated to represent those present at the time of the long pause (Goodwin et al., 2014b; Montenegro et al., 2016b). It identified that Samoa was the most successful start point for voyages to Central East Polynesia. However, the seafaring technology performance was simplistic and only modelled the performance in essential terms.

The production of an isochrone map based on the voyaging time for a reconstructed voyaging canoe gives insight into how Polynesian sailors might have thought about voyaging between islands (Di Piazza, 2014). This research showed that there was a significant increase in difficulty between voyaging in West Polynesia and then between Fiji, Tonga and Samoa towards the East.

The technical procedure of archaeological voyage modelling is described in Table 5.2. Previous research can be analysed based on several aspects: 1. performance model 2. routing algorithm 3. quality of environmental data 4. simulation fidelity. The fidelity of the simulation can be judged based on the quality of the environmental data used where the particulars of the optimum path algorithm haven't been presented.

The generation of performance models of Polynesian seafaring technology has been the focus of the previous Chapter 4. Given knowledge on the likely performance of prehistoric Polynesian voyaging canoe performance, it is possible to analyse research referenced in Table 5.1 critically. Some of the performance models used model a linear relationship between boat speed and wind speed, independent of wind direction (Levison et al., 1973; Montenegro et al., 2016a). Other modellers assume that the craft could only sail directly downwind (Avis et al., 2007, 2008). Results from Chapter 4 indicate that sailing directly downwind was unlikely. Research which has studied the performance of Polynesian sail aerodynamics has identified that downwind sailing is not the most efficient point of sail (Di Piazza et al., 2014).

Another aspect of performance is the reliability of a voyaging canoe. The influence of voyaging craft reliability has only been briefly addressed within a single study, even though it has been recorded that the reconstructed canoes have suffered swamping, multiple structural failures and crew fatalities (Finney, 1991). Reliability has only been addressed directly in a single study; through giving a canoe a 50% chance of surviving a Force 9 gale (Levison et al., 1973). Voyage modellers choose to model reliability through setting a time limit to drift voyages

Table 5.2: Required evidence for each stage of the voyage modelling process. Text in bold indicates areas which present opportunity for further investigation.

Stage	Input	Evidence
1. *Model initialisation*		
• Navigational strategy	Voyage direction	Historical accounts of navigators
• Craft performance	**Craft design**	Ethnographic designs and historic evidence
• Starting point	Geographic location	Theories of migration; Charts
2. *Route modelling process*		
• Environmental data	Wind speed, wave heights and current	Modern data justified by Archaeological research
• Craft performance	**Craft velocity**	Historical accounts; Velocity Prediction Programs run for historical designs
3. *Voyage ending criteria*		
• Craft design as failed	**Craft reliability**	Reliability analysis of design
• Crew have perished	**Crew endurance**	Capacity of design for supplies; Drift survival data; Historical accounts; humans factors research
• Destination reached	Geographic data	Charts

such as 60 or 200 days (Montenegro et al., 2016a).

The use of environmental information has ranged from probabilistic independent sampling from modern weather records (Di Piazza et al., 2007; Levison et al., 1973), and also modelling the evolution of different weather patterns (Montenegro et al., 2016a). It must be noted that voyage modelling relies on accurately modelling the evolution of weather patterns, as, without this, the physical loads acting on the sailing craft cannot be modelled accurately.

Polynesian navigators would have had to solve what is known in computer science as the "exploitation vs exploration" problem in order to make decisions regarding voyaging (March, 1991). Exploitation is the use of existing information to identify improved solutions and exploration is the process of gathering new information. Polynesian sailors would have had to explore the seascape in order to find new islands before committing resources for transporting colonisation populations to unsettled islands.

In the Polynesian literature, the "exploitation vs exploration" problem is analogous to the process of testing competing theories of migration. The influence of exploration strategy has been the focus of many voyaging studies. These studies illustrate that voyages could not have been undertaken at random but do not explain much more. It can be noted that in Polynesia the main bands of islands are aligned northwest-southwest and that islands would have been progressively discovered to the southeast irrespective of strategy (Anderson, 2014). Consequently, modelling voyaging strategy cannot show anything more than the voyages were not undertaken at random.

Historical voyage modelling to test different theories of the Polynesian migration relies upon accurate canoe performance data. However, much of existing research relies upon data which is either out of context to the time period or is oversimplified. This section has identified that canoe performance may be analysed in three areas; speed, endurance and reliability. Of these areas, only the speed of the canoe given its environment has been considered in any depth with that of the endurance of the crew being briefly considered (Levison et al., 1973). The ability to model reliability is also something that requires further investigation, having also been considered briefly in Levison et al. (1973). Although voyage modelling has investigated the potential for voyaging canoes to reach islands the ability to then settle these islands has not been modelled. Robust voyaging canoes are required to ensure settlement as opposed to exploration.

The modelling of Polynesian voyaging requires integrating data from many areas, and the most critical aspect is arguably identifying the performance of the voyaging sailing craft. The topic of sailing craft performance must also be considered from the perspective of achieving a successful colonisation rather than in successful voyaging between islands. A canoe may be able to transport a nominal founder population between islands. However, it is another question as to whether there will be enough of them to colonise an island successfully and whether they will be in a condition to do so after an arduous journey. Currently, this may be investigated through modelling the crew survival rate throughout a voyage, as the investigation of the human factors side is outside the scope of this thesis.

5.3 Marine craft routing

The objective of the general marine craft routing problem is to minimise some cost, whether that is energy efficiency, crew safety or time for a given route and craft design. Several classes of algorithm have been used in order to identify marine craft routes which minimise one or more variables; calculus of variations and dynamic programming, discrete optimisation methods and evolutionary algorithms (Walther et al., 2016). In order to identify the most suitable algorithm for application to sailing craft route modelling the emphasis of this review must focus on those algorithms which allow multiple criteria and physical constraints to be modelled robustly rather than those algorithms which allow a quick solution given a less accurate approximation of the physical model. This speed is relevant when considering the number of tacking decisions that are made by a sailing craft skipper.

Dynamic programming is a recursive method for describing optimisation problems, the solution of which produces a single optimal set of decisions which could be made. An iterative dynamic programming method was applied towards solving the minimum time problems for a trans-Atlantic route (Avgouleas, 2008). While it was found to overcome non-linear behaviour and allow for different constraints, its key drawback was the number of calculations required, i.e. the curse of dimensionality. Calculus of variation methods is useful for identifying a global minimum, although they are sensitive to the number of control variables (Walther et al., 2016).

An example of a discrete optimisation method is "isochrones". Isochrones are lines drawn over a specific area of a chart which show distances which may be traversed in equal times (Galton, 1881). They were introduced to marine craft routing in order to consider the impact of waves and current on the progress of a ship (James, 1959). A modified isochrone method allowed the solution of a discretised optimisation problem containing a single objective function with a given set of constraints for a sail-assisted vessel (Hagiwara and Spaans, 1987).

Evolutionary algorithms are a class of optimisation algorithm that has been successful in solving complex problems. It is possible to use a multi-objective genetic algorithm to identify Pareto optimum routes to optimise for sets of variables given constraints such as the sea state and wind (Hinnenthal, 2008). In this particular application, optimisation routines were found to take up to 14 hours to solve for a specific route. This application presents an example where the curse of dimensionality impacts the use of genetic algorithms due to the number of chromosomes used to model each decision. Another drawback of genetic algorithms is that it is conceptually difficult to model a sequential decision-making problem such as that found in sailing craft routing using a genetic algorithm. For this application it would require a real-valued chromosome for each decision point along the route, this may result in at least hundreds of chromosomes.

A Markov chain was used to solve the minimum time stochastic shortest path problem (Bertsekas and Tsitsiklis, 1991). The Markov chain was used to model the evolution of the stochastic variable within a dynamic programming solution to a minimum cost path problem. A Markov chain was first used to model the introduction of stochastic variables into the ship routing problem. This particular implementation was found to have exponential complexity (Azaron and Kianfar, 2003). The environmental model was integrated within the routing algorithm which reduced the feasible complexity of the environmental model.

Another example of the stochastic shortest path problem has been to the problem of routing hazardous materials around stochastic networks with a stochastic accident rate. The multi-objective solution procedure also optimised concerning the cost of transportation (Wijeratne et al., 1993). However, as with the previous paper, the critical drawback of this method is that there is only a single stochastic variable being modelled using a statistical distribution. In order to effectively solve the route, a significant number of simulations would be required to be solved. It can be argued that a statistical distribution is not complex enough to model a dynamic spatio-temporal process such as the evolution of a weather pattern. As a consequence, the ability to separate the weather model from the optimisation process would allow the accurate modelling of both aspects without prohibitively expensive computational costs.

Given the range of methods that have been applied, it can be noted that one of the more versatile algorithms for use is dynamic programming. It can model multiple constraints in a straightforwards manner due to its recursive nature.

Section 5.4 will illustrate the the dynamic programming (DP) has been well applied in the area of sailing craft route modelling.

5.4 Sailing craft route modelling

This section reviews the research that has been undertaken into sailing craft route optimisation problems and how different papers seek to model different aspects of the domain, such as the environment and craft performance. The section will then conclude through describing in distinct terms the areas of risk and reliability that have not been investigated.

The variables which comprise the state of the problem are the position of the craft, $\mathbf{x}, \mathbf{y}$ in terms of its latitude and longitude and the time, t relative to the beginning of the simulation. Section 6.1.3 will demonstrate how it is possible to add a fourth dimension in order to model the reliability of the sailing craft.

The decision variable is the vector determining the next leg of the voyage the sailing craft should take; this is described by the vector of the heading and the length of the next leg. The key exogenous stochastic variable is the vector wind field, defined on $\mathbb{R} \times [0, t]$. A further variable which will be shown to have been unaccounted for in the short course sailing craft routing literature are the sea conditions such as wave condition or current, variables which are considered in the wider marine routing literature.

Research into sailing craft routing problems has increased recently with the advent of improved scientific computing methods. These papers are summarised in Table 5.3, which identifies how each paper has contributed to different areas of the problem. It can be seen that there has been little attempt to model the influence of human factors with no attempt so far having modelled the influence of the risk of voyage failure on the successful completion of the voyage. Research has focused on either identifying the optimum route to take in order to minimise time or to minimise the probability of beating an opponent in a match race scenario. However, none have considered the influence of the structural reliability and crew safety or the influence of the stochastic spatio-temporal nature of the weather.

A distinction can be drawn in the literature between research that focuses on short-term routes and long-term routes. This review introduces a formal distinction by stating that short term routes are completed in under three hours. The implications of this distinction lie in the accuracy of the algorithm used to solve the dynamic shortest path problem, the accuracy of the performance predictions required and the size of the state space being considered. The requirement to model exogenous uncertainty over a large state space requires the separation of the stochastic exogenous process from the shortest path.

Table 5.3: Summary of research completed into sailing craft route optimisation papers focusing on the different approaches taken to domain approximation. Most research doesn't consider the impact of the sea and of human factors. There is no consideration of the reliability of the sailing craft and of how it influences the performance of the sailing craft. There is no consideration of spatio-temporal weather other than through the use of deterministic forecasts.

Paper	Sea model	Algorithm	Human factors	Voyage risk	Objective variable	Weather model
Allsopp (1998)	Current	Dynamic Program (DP)	N	N	Time	Temporal
Philpott and Mason (2001)	Current	DP	N	N	Time	Temporal
Philpott et al. (2004)	N	DP	N	N	Time	Temporal
Laurent and Garcia (2004)	N	MDP (MCTS)	N	N	Time	Temporal
Scarponi et al. (2007)	N	MEUT	Y	N	Risk of losing	Simple
Kocsis and Szepesvári (2006)	N	MDP (MCTS)	N	N	Time	Simple
Stelzer and Pröll (2008)	N	DP	N	N	Time	Forecast
Ferguson and Elinas (2011)	N	MDP	N	N	Time	Landmass
Langbein and Stelzer (2011)	N	A*	N	N	Time	Forecast
Dalang et al. (2015)	N	DP	N	N	Time	Temporal
Tagliaferri et al. (2014)	N	DP	N	N	Risk of losing	Temporal
Spenkuch (2014)	N	Bayesian Belief Network (BBN)	Y	N	Risk of losing	Temporal
Belouaer et al. (2015)	N	MDP	N	N	Risk of losing	Temporal
Tagliaferri et al. (2015)	N	MDP	Y	N	Risk of losing	Temporal
Shen and Vladimirsky (2015)	N	HJB PDES	N	N	Time	Temporal
Ladany and Levi (2017)	N	DP	N	N	Time	Simple
Tagliaferri and Viola (2017)	N	DP	N	N	Risk of losing	Temporal
Ferretti and Festa (2018)	N	HJB PDES	N	N	Time	Temporal

The use of dynamic programming to solve long course sailing craft routing problems was introduced in Allsopp (1998); Philpott and Mason (2001), who were able to show how it was possible to model the uncertainty in the wind using a scenario tree. However, what was left unclear was the generation of the scenario tree given a set of scenarios and no consideration of the requirement to model the uncertainty in the weather process itself. The long course routing problem was also considered in terms of optimal control, although used a recursive dynamic programming procedure to solve for the minimum time route (Ferretti and Festa, 2018). The presence of tides and currents are modelled using lookup tables nested within the larger route optimisation problem (Allsopp, 1998).

The optimisation algorithm used in the majority of the sailing craft routing literature is the dynamic programming algorithm. There are several advantages to this algorithm, as Ferretti and Festa (2018) identifies:

1. There is a single optimal solution for a given craft and weather scenario, as a consequence of Bellman's principle of optimality (Bellman, 1957, Chap. III.3).
2. Costs associated with control changes, such as tacking or sail changes may be accounted for simply.
3. It is possible to deal with stochastic variables.
4. It is possible to cope with physical constraints in the domain, such as land and also the presence of tides and currents.

A sailing craft routing problem is an example of a Markov decision process with a large state space. A Markov decision process is a direct equivalent formulation of a stochastic optimisation problem. One optimisation algorithm introduced was the Monte Carlo Tree Search algorithm which models the problem as a decision tree where only the most promising decisions are recursively searched through (Kocsis and Szepesvári, 2006; Laurent and Garcia, 2004). The MCTS algorithm has since been exceptionally successfully and widely applied, for example, to the problem of playing chess (Silver et al., 2017).

The literature focuses on the problem of modelling short course sailing craft racing. This problem is distinct to long course racing as it takes place over a much smaller domain in terms of space and time and requires higher levels of accuracy. The increase in size has implications on the assumptions used to model the sailing craft performance and environment. A significant consideration is the optimisation algorithm used which has implications on the computational resources required and thus the size of the design space which can be investigated.

A race modelling program which uses a dynamic velocity prediction program which factored in wind effects from sailing craft in close proximity with a simple probabilistic wind model was introduced in Philpott et al. (2004). This model was improved through the introduction of a more advanced weather model allowing better strategic decision making during racing (Dalang et al., 2015). Another formulation of sailing craft routing problem as a Markov decision problem (MDP) also introduced a wind model that considered the influence of landmass (Ferguson and Elinas, 2011). This formulation was shown to produce logical results, although comparison with recorded wind would have allowed the accuracy of the method to be evaluated.

The use of the A* shortest path algorithm to solve for the minimum time routing for an autonomous sailing yacht was found to be useful in comparison to other existing commercial methods given a single weather scenario in the form of a General Regularly-distributed Information in Binary form file (Langbein and Stelzer, 2011). However, this implementation has a very low resolution, and the overall accuracy cannot be considered to be suitable for modelling purposes. A deterministic route planning algorithm has also been used in order to identify the minimum time route for an autonomous sailing craft (Cabrera-Gámez et al., 2013). However, it was limited in its ability to study the influence of deterministic wind conditions and no consideration of sea state.

Sailing craft have to tack or gybe in order to minimise the time taken to sail towards a specified position. The ability to model the decision when to tack and how that influences the minimum time taken to complete a voyage has received some attention. A study of how it is possible to model the human decision-making aspect in a yacht race model given a simple probabilistic wind model found that it was possible to model aspects of successful decision-making by racing sailors over a short course (Scarponi et al., 2007). Further work introduced the use of BBN and the ability to model different levels of expertise in the yacht race simulator (Spenkuch, 2014). However, this only examined the influence of decision making on beating an opponent around the racecourse and not the safe operation of a sailing craft.

It is possible to measure the time taken on the water for a specific sailing craft to tack or gybe. From practical experience, it reduces the Velocity Made Good (VMG) of the craft for a few minutes which is significant in the short course racing problem, although not in long course routing which takes place over days not hours. In general, long course models do not consider the time tacking, although this author has found that this results in an impracticable number of tacks or gybes modelled by the routing algorithm. Most short course sailing craft route modelling research has only considered the upwind racing scenario where the decision variable is to hold the course or to tack, and this limits the application of the method to purely upwind scenarios. It also limits their application to modelling Polynesian sailing craft which used different methods of sailing upwind compared to modern sailing craft. This is discussed further in Subsection 4.2.

A continuous model of sailing craft routing where the decision variable is a course vector has been shown to present robust results (Ladany and Levi, 2017).

However, while this model is accurate, it is computationally expensive for a simple short course routing scenario with deterministic wind conditions and therefore likely to be impracticable for the long course racing scenario.

Another method of modelling a sailing yacht race found that it was possible to model risk-seeking and risk-averse attitudes using a Markov chain that represented higher or lower probabilities of tacking given a particular wind condition (Tagliaferri and Viola, 2017; Tagliaferri et al., 2015). This research was able to show that it was more useful to attempt to beat an opponent rather than sail a minimum time course. A further method of modelling a yacht race found that exciting results could be generated through modelling it as a stochastic game (Belouaer et al., 2015). While these methods presented useful results for considering a single leg over a small spatio-temporal domain, it is difficult to apply these methods to a long-course problem due to the assumptions limiting the choice of the decision vector and the complexity of the wind model.

The influence of long term factors such as crew fatigue and structural reliability has not been considered due to the focus so far on short term routing, as can be seen in Table 5.3. This absence drives a requirement for including these factors in such a model. Another factor which has not received attention is the inclusion of wave resistance in short course routing; this is because most of the situations modelled are inshore and have assumed to have minimal influence from the waves. From the analysis of marine craft routing in Section 5.3 it is known that sea state has a significant influence on marine routing problems. Experimentally it is known that wave conditions have been shown to impact the speed achieved by a sailing craft (Gerritsma and Keuning, 1992) severely.

This section has reviewed the literature on sailing craft routing problems and has identified gaps in the literature concerning the integration of voyage risk modelling and the uncertainty in modelling the spatio-temporal weather process.

Risk in terms of losing a sailing yacht race has been modelled, although not in the context of a long course sailing yacht scenario. The discussion of what risk means and how it should be modelled is the focus of the next section.

5.5 Solution algorithms

The weather routing process predicts the optimum route for a sailing craft to take between two points. The method considers the performance model of the sailing craft, the optimisation algorithm and the environmental data used to identify the optimum path.

The first research into solving the sailing craft route optimisation problem used a recursive dynamic programming formulation which divided the domain into nodes over which the minimum time path was calculated Allsopp (1998). Different wind models Dalang et al. (2015); Philpott et al. (2004) or race strategy and opponent models Spenkuch (2014); Tagliaferri and Viola (2017) have been used to improve the accuracy of sailing routing models.

The influence of different methods of modelling the ability for a sailing craft to sail upwind has been explored Stelzer and Pröll (2008) along with modelling the time taken to complete course changes Ladany and Levi (2017). Sailing craft race modelling has typically minimised either the time taken to complete a course Ferretti and Festa (2018), risk of losing to an opponent Spenkuch (2014); Tagliaferri et al. (2014) or reliability (Dickson et al., 2018). However, the majority of sailing craft routing research only applies to a minimum time route sailed over a small spatial and temporal domain. Research has considered other factors such as risk (Decò and Frangopol, 2013), energy efficiency (Zaccone, 2017) and fuel and comfort (Zaccone et al., 2018).

The long course modelling problem can be characterised through its consideration of larger spatial and temporal domains over which the shortest path is solved. Typical drawbacks of short course routing methods involve their requirement for a predictable wind field and the requirement for the entire course to be modelled as being flat to the curvature of the earth. The haversine formula becomes accurate at distances longer than 1 nm (Allsopp, 1998); this indicates the crossover between short and long course routing methods.

The marine weather routing literature has developed a range of different shortest path algorithms. The different approaches were classified into the calculus of variations, grid-based approaches and evolutionary optimisation (Walther et al., 2016). A time-dependent approach based on the calculus of variations solved the shortest path problem through identifying the shortest path to take through considering a series of fronts reached within incremental time steps (Bijlsma, 1975). Forward dynamic programming approaches involve recursively solving the shortest path over a grid of locations generated along the great circle line between the start and finish locations (Allsopp, 1998). This approach can be two dimensional or three dimensional, considering how the variables such as time and fuel cost are optimised Hagiwara and Spaans (1987). A claimed improvement is to use a floating grid system which updates potential locations every time step (Lin et al., 2013). It was possible to optimise energy efficiency through varying the engine power and ship heading, using a 3D forward dynamic programming method, (Shao et al., 2012). These grids can be generated based on local wind conditions (Tagliaferri and Viola, 2017), although this approach would be challenging for larger spatio-temporal domains as found in long course routing.

Another route modelling approach has involved generating candidate routes using biased Rapidly exploring Random Trees which solve for the minimum energy path using the A* algorithm (Rao and Williams, 2009). A multi-objective genetic algorithm has been applied to solve for the optimum path considering multiple safety and fuel constraints (Hinnenthal, 2008). A real coded genetic algorithm allowed the consideration of ship rolling within the route optimisation process, thereby improving safety (Maki et al., 2011). The improvement came with the implementation of a fuzzy logic model to model the performance of a sail-driven vessel (Marie and Courteille, 2014).

A method of iteratively aggregating the minimum time path over multiple weather scenarios has been introduced (Allsopp, 1998). The approach of using ensemble weather scenarios is more accurate than single scenarios with application to marine weather routing (Skoglund et al., 2015). Multiple algorithms and objective functions have been implemented and applied to the marine weather routing problem. To the author's knowledge, there has been no study of how uncertainties within the solution algorithm and objective function influence the confidence that may be had in the final result.

5.6 Risk

Risk can be defined as *"(Exposure to) the possibility of loss, injury, or other adverse or unwelcome circumstance; a chance or situation involving such a possibility"* (Oxford English Dictionary, 2018). In the area of finance, it is possible to reduce all factors in a problem to purely financial terms and risk is a function of the probability that a certain amount of money will be irrevocably lost (Anderson et al., 2014). A vast array of mathematical techniques have been developed to study this problem, Shapiro et al. (2009) for example, and there is a continuing philosophical debate about the suitability of different mathematical models (Taleb, 2005, 2012). This section will clarify the term risk in its application to sailing craft routing problems considering reliability.

In the area of marine routing it has been shown that it is possible to apply risk in this manner to a case study where there was financial information on the marine vehicle being used, a high-speed transport catamaran, and the different failure modes it might undergo (Decò and Frangopol, 2013, 2015). This research showed that it was possible to consider the average risk experienced over a voyage as an objective variable, however it did not consider crew fatigue or the role that wind had to play in contributing towards this risk.

All sailing craft route modelling research has investigated the problem of improving the prediction of sailing yacht race decisions and finish times. The risk in this problem is framed as the probability that an opposing yacht will finish ahead of the modelled yacht. Different attitudes towards risk were modelled using Markov chains in the work of (Tagliaferri et al., 2014), who was able to show that for specific wind models a risk-seeking attitude was able to finish ahead of an opponent for the majority of the time. This competition between sailing craft was also modelled as a stochastic game between two players and was ultimately modelled using Markov chains to describe the wind and the choices available to the virtual skippers, i.e. to tack or not tack (Belouaer et al., 2015). Both applications consider risk in a limited form over an extremely constrained set of control choices and temporal-spatial limits. A new definition of risk in its application is required in order to capture the meaning defined in the sailing craft reliability route modelling problem.

One definition which may be suitable is *"risk is the probability that the craft or crew suffer irreparable failure at any point throughout their voyage"*. This definition allows the introduction of risk as a variable which may be optimised for at any point throughout the voyage. A second definition as *"the probability that a craft does not complete the voyage in the expected time"* allows the interpretation of results that are generated from a set of routing simulations. For example, the acceptable probability of failure may be varied as to reduce the risk of the sailing craft not completing its voyage in the mean time.

5.7 Numerical error

Uncertainty analysis is the process of quantifying how likely individual states of a system are given a lack of knowledge on how certain parts of the system operate. The choice of how to categorise and thus simulate uncertainty is significant in the scientific modelling process (Der Kiureghian and Ditlevsen, 2007). In the marine environment, it is possible to classify uncertainty as being aleatory uncertainty or epistemic uncertainty (Bitner-Gregersen et al., 2014). Aleatory uncertainty is the inherent randomness in a particular parameter; it is not possible to reduce this. Epistemic uncertainty is knowledge-based; it is possible to reduce this quantity by collecting more information on the process in question. Epistemic uncertainty can be broken down into data uncertainty, statistical uncertainty, model uncertainty and climate uncertainty. Data uncertainty is associated with the error associated with collecting data from experiment or model. Statistical uncertainty is a consequence of not obtaining enough data to model a given phenomenon. Climate uncertainty addresses the ability for the climate variables over a given spatial-temporal domain to be representative given the nature of the weather and climate change (Bitner-Gregersen and Hagen, 1990).

The error in a scientific model is the accuracy at which it estimates a real system. The critical source of error is the ability of the optimisation algorithm to identify the optimal path based on the discretisation of the environment. Typical discretisation error calculation methods require grids of significantly different sizes to be solved for a given set of initial conditions (Roache, 1997). Through examining the rate of convergence of solutions from different grids, it is possible to extrapolate the solution for an infinite discretisation.

5.8 Weather uncertainty

The weather has been described as a chaotic process (Lorenz, 1963). The chaotic nature of the weather limits the ability to utilise numerical models for predicting future weather conditions or for investigating what might have occurred in the past. A chaotic system can be thought of as one where the present state determines the future state, but the approximate present state does not determine the approximate future.

Uncertainty within the weather data used lies in the accuracy of specific values of climate variables, uncertainty within the weather model used and the error associated with interpolating the weather values to the grid used by the route optimisation algorithm. The weather conditions in this study are simulated though using reanalysis weather data (Copernicus Climate Change Service, 2018). The use of reanalysis weather data from the previous several decades relies on the assumption that this does not differ from the weather experienced at the time of the long pause. Reanalysis weather offers higher resolution data than that produced by proxies (Goodwin et al., 2014b). It is believed that the ENSO patterns seen today were established by 3000 B.P., indicating that the use of reanalysis weather data gives an indication of previous weather conditions (Liu et al., 2014).

Reanalysis weather data is generated using a climate model to solve for points where recorded weather data does not exist. The uncertainty associated with specific values qualitatively decreases as the dates simulated become more recent (Copernicus Climate Change Service, 2018). 10 ensemble weather scenarios are generated using slightly varied input parameters which aim to simulate the probabilistic behaviour of the weather in the regions which do not have recorded data. Ensemble weather scenarios mitigate uncertainty associated with simulating weather conditions through presenting equally probable realisations of what weather conditions might or may have been possible (Slingo and Palmer, 2011).

The error associated with interpolating the weather data to the grid used by the route optimisation algorithm contributes towards the numerical error, previously discussed in Section 5.7. Below the resolution of the weather data there is uncertainty associated with the accuracy of the weather model and the type of interpolation used. However, the uncertainty in the accuracy of the weather data is balanced against the improved route being sailed.

5.9 Summary

Computer simulations in Polynesian archaeology have had widespread application. They have been applied to understand the influence of climate, migration strategy with some limited application towards comparing different performance models. So far, no study has been able to model the influence of prehistoric seafaring technology on a physical scale, whether the performance model is meaningful. Furthermore, no simulations have been able to directly compare climate, environmental and performance models over key routes between West and Central East Polynesia. There has been no consideration of uncertainty in the application of the computer simulation, the performance model of the voyaging canoe. Uncertainty in environmental data has only been modelled using randomly sampled weather conditions, leading to unrealistic results.

The ability to model weather conditions has been a focus of modern marine weather routing simulations. The weather is modelled through the use of ensembles in forecasts or reanalysis data or through stochastic weather generators. The optimisation algorithm used in Polynesian voyage modelling is often opaque, but this is a source of keen development for modern marine weather routing. Although it is possible to get quick results using optimised algorithms, the only algorithm which can prove the correctness of its optimised solution is the Dynamic Programming algorithm. There has been little modelling of the risk of not completing voyages, and there exists no methodology for calculating the numerical error associated with the application of a marine weather routing algorithm.

This chapter has reviewed the literature on Polynesian voyage modelling and modern marine weather routing. Although these are two separate fields, they are ultimately focused on modelling the operation of marine vessels over specific routes. Neither literature provides insight into how it is possible to model the significance of numerical, performance and weather uncertainty relative to the optimised result. Implementing a marine weather routing methodology which can model the influence of performance, weather and numerical uncertainty is the focus of the next chapter.

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Chapter 6

Uncertainty in Marine Weather Routing

Several areas of uncertainty contribute towards uncertainty in the prediction of optimal route and voyaging time. The influence of these uncertainties must be quantified to provide credibility to the prediction of optimum voyaging time. Understanding the influence of uncertainty is relevant for modern marine applications, such as improving the operation of Autonomous Sailing Craft. Autonomous Sailing Craft must be able to operate for long periods of time without human intervention, an application requiring a high level of reliability and understanding of sources of uncertainty. This chapter presents an investigation into how different sources of uncertainty within the marine weather routing process influence the uncertainty in the voyaging time and path.

Figure 6.1 shows the method developed in this chapter. The initial conditions, such as the route and environmental conditions, are specified. A suitable routing algorithm is identified and implemented. The numerical error is then estimated, and the influence of performance uncertainty is modelled. This chapter concludes

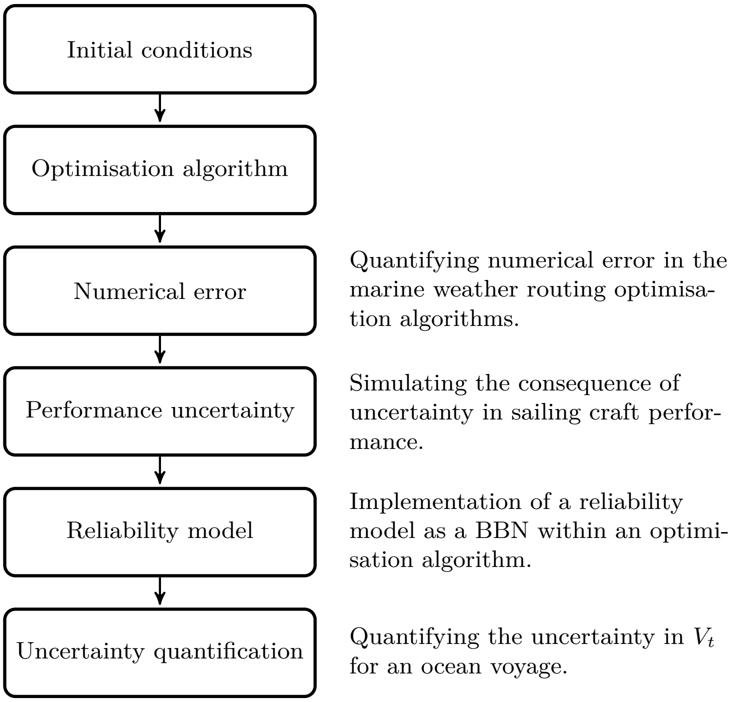

Figure 6.1: Method used to quantify uncertainty in marine weather routing. Comments specify the novel developments of this method.

with an analysis of the impact of performance uncertainty and numerical error on the interpretation of the final set of voyaging time results.

6.1 Methodology

This Dynamic Programming algorithm applied to the marine weather routing problem, described in (Allsopp, 1998), was implemented in the SailRoute.jl package written with the Julia programming language (Bezanson et al., 2017). A fundamental difference with previous research in stochastic weather routing is that each weather scenario is treated separately as opposed to integrating the results at each stage of the optimisation algorithm. This analysis provides a realistic indication of what the optimal routes would be, rather than just averaging the best decision at each node.

6.1.1 Numerical error

The discretisation of the environment is the primary source of numerical uncertainty in the solution algorithm. The critical parameter determining the fidelity of the simulation is the distance between nodes, d_n. In order to consider the influence of the discretisation of the domain on sailing craft routing results, the lower limit of d_n must be identified, which will allow two coarser grid sizes to be chosen.

Other factors which influence the selection of d_n include the discretisation of the sailing domain and the spatial and temporal resolution of the weather data used. For example, if the time taken to travel between two locations is longer than the temporal resolution of the weather data set, then changes in weather conditions are not modelled.

The weather data is linearly interpolated to the discretisation of the nodes in the environment. If the distance between nodes is much larger than the original spatial discretisation of the weather data, then the change in the weather conditions will not be adequately modelled. The voyaging time is used to look up the closest weather data time step.

The accuracy of the performance model is limited to specific scales. Consequently, it may not make physical sense to apply such a model below a certain length of time or distance. Despite this, a quantification of the numerical solution algorithm required in order to identify whether the minimum time solution is stable. One index used to quantify numerical uncertainty in CFD is the grid convergence index (GCI) (Ghia et al., 2008; Roache, 1997) which has only recently been applied to the sailing craft routing problem (Dickson et al., 2018).

The method of numerically quantifying error using the Grid Convergence Index (GCI) is described in Ghia et al. (2008). It involves solving the algorithm over multiple discretisations of the environment which exponentially increase in detail. The grid height, d_n, is the measurement unit of grid size and is calculated using Equation 6.1. ΔA_i is the size of the ith cell, and N is the total number of the cells used for computation. The solution trend from the three distinct grid sizes is extrapolated towards $d_n \to 0$, where the extrapolated solution is used to estimate the associated discretisation error.

$$d_n = \Big[\frac{1}{N}\sum_{i=1}^{N}(\Delta A_i)\Big] \tag{6.1}$$

6.1.2 Performance uncertainty

The cost function for this craft interpolates the performance from the polar performance diagram, seen in Figure 4.17. An example of how the performance is varied for a specific wind condition is shown in Figure 6.2, where the performances were manipulated by a percentage of the original boat speed. Note that modelling uncertainty stochastically outside the performance model results in the optimisation process selecting the best random draws from the stochastic function which skews the V_t to be faster than what was intended. This approach has been taken in other research, for example Barde et al. (2018), and will be examined further in Section 6.2.

6.1.3 Reliability

It is possible to consider reliability within the velocity prediction program or the cost function of the routing algorithm. Marine craft reliability has been

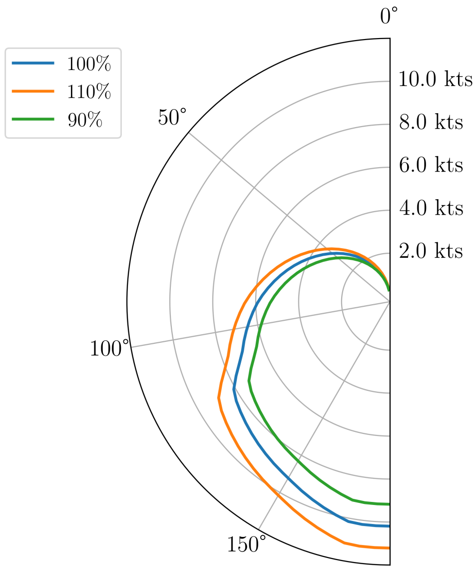

Figure 6.2: V_s varied 10% about the original performance for a wind speed of 10 kts. See Figure 4.17 for the full set of polars.

simulated within the performance model and as a function of the entire route. The performance model is the location within the optimisation problem that simulates the physics of the sailing craft.

Bayesian Belief Networks (BBNs) has been used to model a complex network of empirical data and expert opinion which calculated the probability of Autonomous Underwater Vehicle failure given a specific voyage scenario (Brito and Griffiths, 2016). Various reliability engineering and design problems are capably modelled using BBNs (Friis-Hansen, 2000). Given the lack of data on sailing craft design, the flexibility to incorporate different failure mechanisms and sources of information mean that BBNs offer the most suitable framework to model the reliability of an Autonomous Sailing Craft. The output of a BBN is a probability of some event occurring given a range of input factors which can be structural or environmental.

The performance of the Autonomous Sailing Craft can be specified in terms of its speed and failure mechanisms. The failure mechanisms may be estimated from structural analysis or empirical data on past failures. If no information exists, then it is possible to specify a different combination of environmental parameters which are likely to cause failure. Using these parameters, it will be possible to avoid environmental conditions which are likely to cause failure.

Figure 6.3 illustrates an example of a BBN which relates environmental parameters describing the wind and the waves to the calculation of the probability of voyage failure. The top rank of nodes takes the values of the environmental parameters as inputs. The middle rank accept the inputs and calculate the probability of craft failure if neither parameter causes a failure, a single parameter causes failure, or both will cause failure. It is possible to model three different failure levels in this manner, although due to the flexibility of the BBN it is possible to integrate different physical models into the calculation of failure probability.

Bayesian belief networks use Bayes rule, Equation 6.2, in order to relate the probability of a specific event occurring given that other events have already occurred. $P(A|B)$ is the probability of event A occurring given that event B is true, $P(B|A)$ is the likelihood of B occurring given that A is true and $P(A), P(B)$ are the likelihoods of A and B occurring independently of each other.

$$P(A|B) = \frac{P(B|A)P(A)}{P(B)} \tag{6.2}$$

The failure model used in this section relates two failure conditions based on the wave height and apparent direction to the probability of voyage failure. The joint probability distribution can be defined as being $P(F, WD, WH) = P(F|WD, WH)P(WD)P(WH)$. The names of the model have been abbreviated as F = voyage failure (true/false), WD = apparent wave direction failure (true/false) and WH = wave height (true/false). Note that it is possible to use continuous distributions to model events rather than binary criteria.

If the criteria for the apparent wave direction failure are met, then it is possible to calculate the likelihood of voyage failure using Equation 6.3. The weather conditions at a specific point determine whether the failure criteria are triggered. Table 6.1 defines the conditional probability table, which enables the calculation of the probability of failure as a consequence of a single or either wave failure criteria being met. Note that it is possible to use continuous probability distributions within a BBN which would allow more realistic modelling of reliability.

$$P(F=T|WD=T) = \frac{P(F=T,WD=T)}{P(F=T)} = \frac{\sum_{WH \in T,F} P(F=T,WH,WD=T)}{\sum_{WD,WH \in T,F} P(WD,WH,F=T)} \tag{6.3}$$

Table 6.1: Conditional probability table relating failure criteria combination to the probability of failure.

WH Criteria	WD Criteria	Pass	Fail
T	F	0.1	0.9
F	T	0.1	0.9
F	F	1.0	0.0
T	T	0.0	1.0

Algorithm 1 shows how the failure model is incorporated within the cost function of the optimisation algorithm.

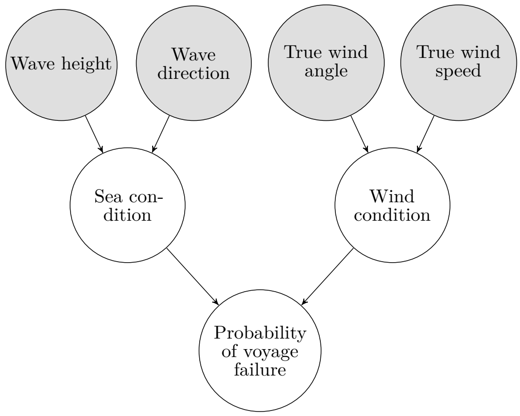

Figure 6.3: A Bayesian Belief Network to model the relationship between environmental conditions and the probability of voyage failure.

Algorithm 1 Cost function

function $c_{seg}(\mathbf{x}_i, \mathbf{x}_j, t, ap_f, \text{Weather scenario})$
  WH_i, WD_i, TWA_i, $\mathrm{TWS}_i \leftarrow$ Weather scenario ▷ Weather conditions
  $p_f \leftarrow$ BBN Failure(WH_i, WD_i, TWA_i, TWS_i, t)
  if $p_f < ap_f$ **then**
    $V_(t, seg) = Distance_{c_{seg}}/V_s(\mathrm{WH}_i, \mathrm{WD}_i, \mathrm{TWA}_i, \mathrm{TWS}_i)$
  else
    $V_{t,seg} = \inf$
  end if
end function

6.1.4 Weather data

For the studies in this thesis, the weather conditions are modelled using reanalysis weather data. Reanalysis weather data are past weather conditions that are estimated from a combination of a weather model and sampled data. Factors considered include the requirements of the problem being modelled, the limitations of computer storage and the length of simulation time. Section 5.8 has confirmed that reanalysis weather data from recent years is suitable for the purpose of modelling the conditions experienced in deep history.

The data set used for the modelling in this research is the ERA5 reanalysis data set (Copernicus Climate Change Service, 2018). This data set has a spatial distribution of 0.5625^o and a temporal distribution of 1 hour. To simulate the influence of probabilistic elements of the model the input factors are varied to produce different realisations, or ensembles, of what the weather conditions might be. 10 ensemble scenarios are used to simulate the uncertainty within the ERA5 model. Each ensemble scenario is simulated using slightly different settings within the weather model. 10 scenarios have been found to provide robust analysis and are provided within the data set.

6.1.5 Method summary

Algorithm 2 describes the uncertainty simulation routine for a specific route at a specific time. It shows how the minimum time, $V_{t,d_n,unc}$, for a specific combination of start time t, height d_n, and performance uncertainty level unc is simulated for a given route. A range of grid heights, h_n, are selected based on studying how the estimates from the routing algorithm converge as the height is reduced. The lower limit of d_n is selected based on the minimum distance at which the cost function retains accuracy.

Algorithm 2 Route modelling uncertainty simulation routine for a specific start time t and route.

procedure ROUTING UNCERTAINTY SIMULATION
    for d_n in $[h_1, h_2, h_3]$ **do**
        Generate discretized environment
        Spatially interpolate wind, wave and current data for each node
        for $P_{unc} in [50\%, ..., 150\%] \times P_{prediction}$ **do**
            for i in Ensemble weather scenarios **do**
                $V_{t,d_n,unc,i} \leftarrow$ Minimum time path(t, d_n, P_{unc}, i)
            end for
        end for
    end for
end procedure

6.2 Application in a simple environment

The marine weather routing process is a complex system with multiple interdependent processes. Identifying how different aspects of uncertainty contributes to uncertainty in the optimal route will assist in identifying whether this is an aspect which should be modelled, and if so, to what extent. The results in this section present investigations into the modelling of different sources of uncertainty in an environment which only considers the influence in the wind.

The contribution of weather uncertainty, modelling performance uncertainty, and numerical error to the uncertainty in optimal voyaging time were simulated. The "simple environment" only models the influence of the wind on the speed of the sailing craft. The domain is based on euclidean geometry rather than an approximation of the earth's surface. An example of the optimal routes produced by this method can be seen in Figure 6.4. The wind model used in this study is described in more detail in Appendix A.

The influence of sailing condition and grid discretisation on the optimal voyaging time was investigated; the results are shown in Figure 6.5. The V_t decreases as

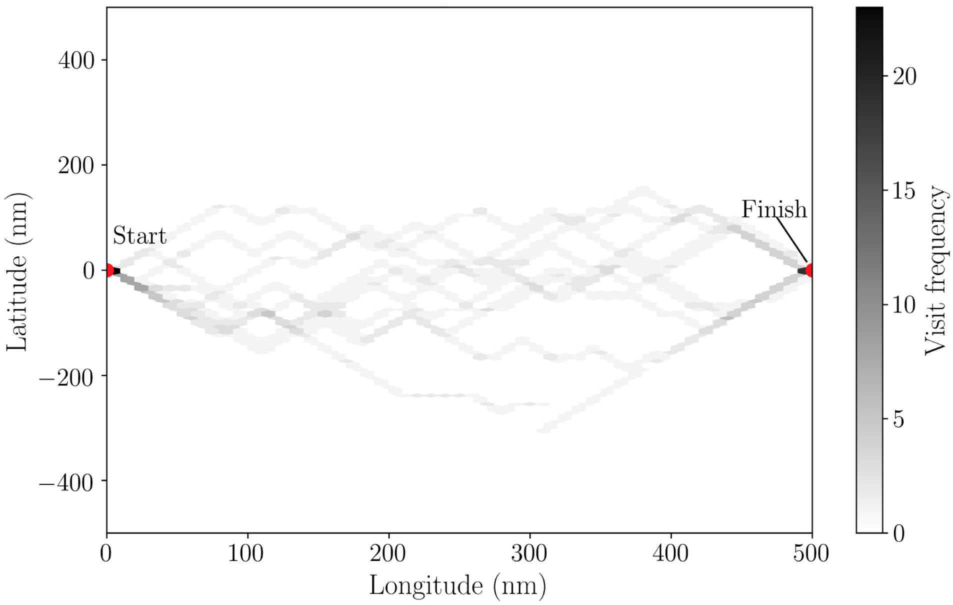

Figure 6.4: Heat map showing the frequency for each point in the domain was visited for the optimal routes of a sailing craft sailing from left to right.

the grid size decreases. This result indicates that the reduction of grid size allows the sailing craft to sail at improved angles to the wind condition, thus reducing voyaging time.

The increase in grid fidelity reduces the distance that a sailing craft sailing upwind or downwind would have to sail. It would have little influence on one which was sailing beam on to the wind. Furthermore, if the weather condition varied realistically, then non-linear behaviour would be seen. Estimating the error associated with the discretisation of the environment is necessary.

An initial investigation identified that modelling performance uncertainty within the optimisation algorithm produced skewed results. This investigation modelled the V_t as a function of distance for a Tongiaki voyaging craft where the uncertainty associated with weather and performance was varied. A deterministic change in performance varied the speed of the sailing craft by a deterministic fraction

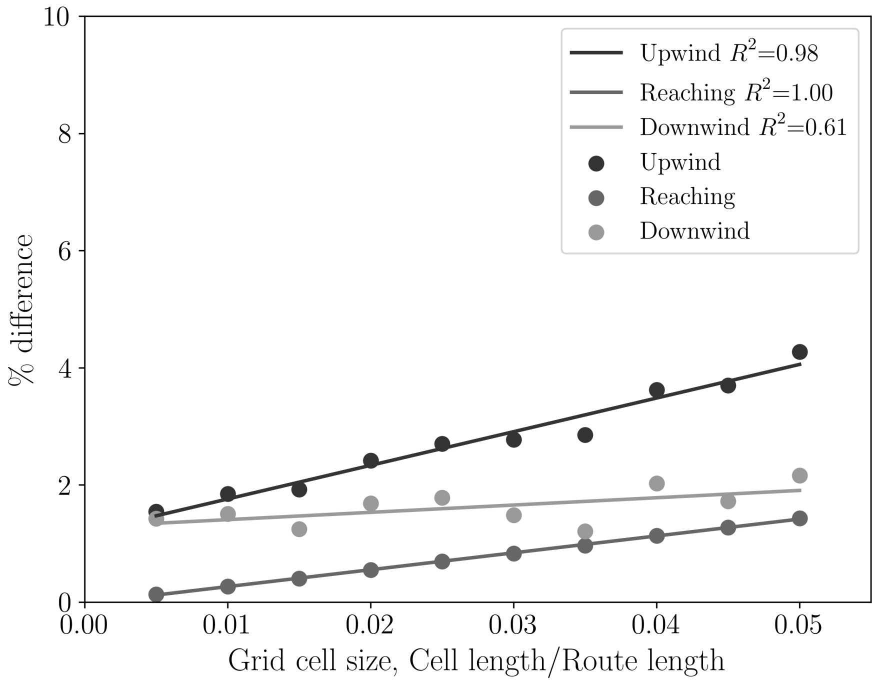

Figure 6.5: Influence of sailing condition and grid size on optimal routing time.

at each call of the performance model. A stochastic change in the performance model varied the speed by a stochastic fraction which changed at each call of the performance model.

Figure 6.6 shows the results for a deterministic variation in performance. The results of a stochastic performance model introduced within the optimisation algorithm are shown in Figure 6.7. The stochastic performance model produces faster V_t results as the optimisation algorithm selects the best "draws" from the random performance model. This demonstrates that uncertainty must be simulated in the inputs to the marine weather routing model rather than within the solution process itself.

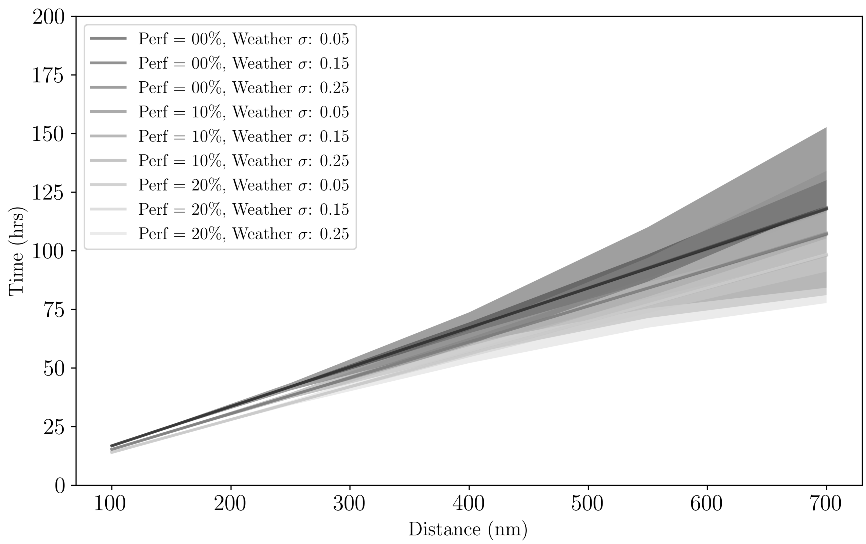

Figure 6.6: Deterministic performance model uncertainty.

Figures 6.6 and 6.7 illustrate that modelling performance within the optimisation algorithm produces incorrect results. The modelling of performance uncertainty must be done before the optimisation algorithm is solved. These results call into question the utility of other implementations of marine weather routing

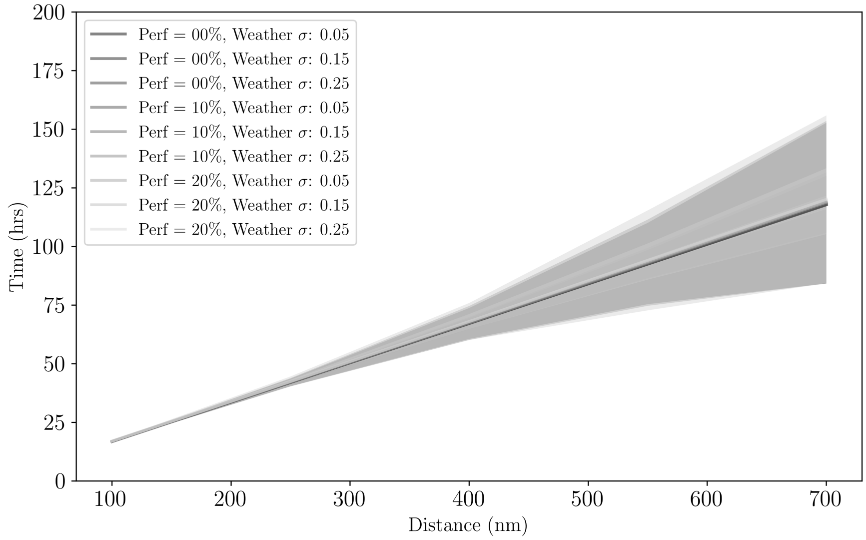

Figure 6.7: Normal random performance model uncertainty.

algorithms, (Tristan-Ka, 2018) for example.

6.3 Autonomous routing application

Autonomous Sailing Craft are being used over increasingly longer ranges. Modelling how their optimal route might change given likely failure conditions will assist the mission planning of any voyages. This section illustrates that application of aspects of the methodology described in Section 6.1 can be applied to modern as well as archaeological problems.

The route simulated is the East-West MicroTransat route (Microtransat, 2018) using the performance of an ASV, the Maribot Vane. The Maribot Vane has an experimentally validated performance model (Dhomè, 2017), although it does not precisely meet the class rules of the MicroTransat challenge. The wind condition across the domain has been set at 15 knots from the North. The fixed wind condition isolates the source of any variation in voyaging time to the variation in grid size.

The Grid Convergence Index (GCI) can be used to calculate the numerical error as a function of the discretisation of the domain (Ghia et al., 2008; Roache, 1997). The GCI index calculates the difference between the estimated result and the extrapolated result calculated as a function of the trend of the previous grid sizes. This index is often used in Computational Fluid Dynamics to calculate a 95% confidence region. As it has not previously been used to interpret weather routing optimisation results, this index can only be used to guide the interpretation of whether the grid size used is fine enough for the purpose.

The grid size may be selected as soon as the voyaging time results have started to converge asymptotically as there will be little improvement in accuracy at the expense of high computational cost. The grid size must be small enough to enable accurate modelling of the problem. If the grid size is too large then it may not be able to capture the complexity of the routing problem being solved. Equally, if the cell size is too small it will result in high computational costs which may not bring associated improvements in accuracy.

The predicted voyaging times for a range of grid sizes are shown in in Figure 6.8. It can be seen that as the discretization of the environment increases, i.e. grid size decreases, the error associated with the prediction of voyaging time at zero grid size reduces from $d_n = 36.34$ km and below. The GCI index quantifies the uncertainty associated with using results at larger discretisations for predicting how the value changes at higher resolutions in the environment. If the index for a result is reducing it indicates that the system being modelled, a routing simulation in this case, has entered a steady state and simulations at lower fidelity are not required.

For this case, the wind was modelled as being 15 knots from the North across the whole domain. The start location was 45^o N and 12^o W and the finish location was 17.5^o N and 60.0 W. Relative to the scale of the simulation the error associated with a grid height of 36327.16 is 0.298%, corresponding to ±2.1 hours. Throughout a route lasting roughly 703 hours, an error of ±2.1 hours is acceptable.

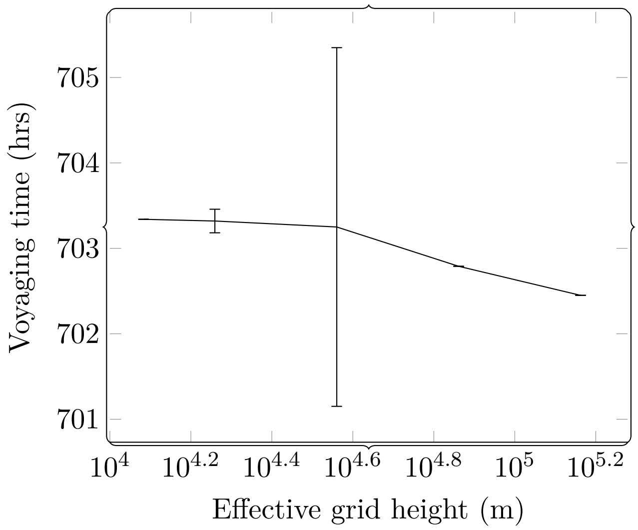

Figure 6.8: Grid discretization size study. The error bars are showing the 95% confidence intervals calculated using GCI.

6.3.1 Influence of failure model on routing time

This section demonstrates the application of the novel reliability routing method using a control weather scenario. The weather scenario was modified to include patches of weather designed to activate the failure model. The control weather scenario encompasses the entire routing domain and has weather parameters which are independent of time. The simulations were run using a grid spacing of 36 km as this was found to give results with reasonable accuracy in Section 6.3. A grid spacing of 36 km corresponds to 160 nodes along each edge with 25600 nodes to be visited in total.

A challenge regarding the modelling of Autonomous Sailing Craft failure is the lack of available data on their failure and potential failure modes; this is likely a consequence of the impracticality of their recovery in the event of voyage failure. A failure model is constructed using a BBN where the probability of failure is a consequence of a different combination of environmental parameters being exceeded.

The failure model implemented has three discrete levels of failure. The initial level represents no failure criteria being exceeded, the second level represents a single failure criterion being exceeded, and the final level represents routing despite any combination of failure criteria being exceeded. This model uses the structure of the BBN illustrated in Figure 6.3.

Two wave statistics are assumed to be significant with regards to causing the failure of an Autonomous Sailing Craft, the wave direction and the wave height. For this control weather scenario, the triggering failure criteria are when the wave height exceeds 4m, and the apparent wave direction is under 60^o. These parameters are selected in order to illustrate the ability of the BBN to avoid failure conditions rather than from any real performance data. Ship design uses the mean wave height of an area as part of the design process to estimate the motions that the ship will have to survive. Sailing directly into waves is known to be challenging. Therefore it is useful to demonstrate an ability within the routing algorithm to avoid this occurring.

Two rectangular patches have been introduced into the domain with specific environmental conditions designed to trigger one and then both failure criteria. Area 2 is the larger patch with the co-ordinates $\pm 5^o$ about the central point at 40^o W 33^o N and has the wave height parameter set to 4m and is designed to provoke the single failure criteria. Area 1 has the wave direction set to 240 degrees, approximately the reciprocal bearing of the East-West Trans-Atlantic course and is a rectangular area with the points $\pm 3^o$ about the central point at 40^o W 33^o N. The combination of Areas 1 and 2 will provoke the second (double) criteria failure model. The hypothesis is that without a failure model, the shortest path will cross both areas, a double failure model will skirt Area 1, and the single failure model will skirt Area 2.

Three different simulations were run with different failure criteria. Figure 6.9 shows the shortest path where the failure model allows for two failure criteria to be met; the shortest path travels directly through both areas. The single failure criteria route avoids area 1 but travels through area 2, as shown in Figure 6.10. The double failure criteria route, shown in Figure 6.11, shows that the failure model can avoid both areas. The route takes 29 days and 7 hours ignoring any failure criteria, with the time taken increasing by 49 hours to avoid two failure criteria and by another 49 hours in order to avoid any failure criteria.

The results illustrated in Figures 6.9 to 6.11 illustrate the ability for the routing algorithm to avoid areas where the failure model calculates an unacceptable probability. Each routing result differs by an amount significantly over 2.1 hours, the estimated accuracy of the original routing algorithm, indicating that the variation in the result is due to the failure model.

6.3.2 Discussion

Autonomous sailing craft competing for the MicroTransat competition have suffered some form of critical failure before they have been able to finish. To model this problem, this section has introduced a novel methodology by introducing a failure model within the sailing craft routing algorithm. In order to demonstrate

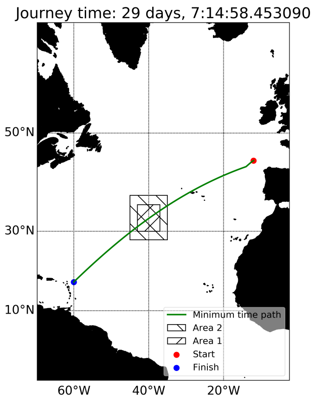

Figure 6.9: Shortest path with no failure model.

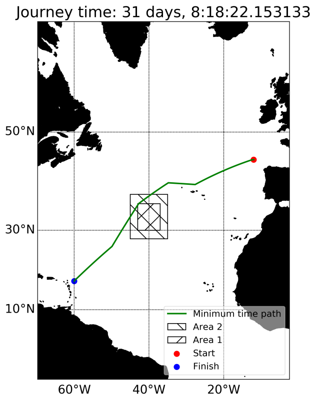

Figure 6.10: Shortest path avoiding two failures.

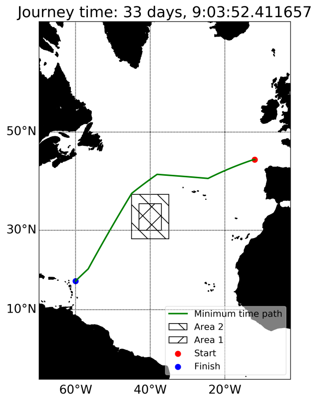

Figure 6.11: Shortest path avoiding one failure.

the impact of the routing model, the accuracy of the routing algorithm needed to be quantified.

Routing algorithms are generally based on a discretisation of a continuous domain that results in an error. This error is reduced as the accuracy of the discretisation process is increased but increases the computational cost of running the simulation. The error was calculated using the grid convergence index, a parameter borrowed from the discipline of Computational Fluid Dynamics and measures the difference between the simulated result and the actual result inferred based of a trend of previous results. The grid convergence index was calculated for a series of routing simulations which were solved for a range of different grid sizes. A balance between computational run time and accuracy was achieved through using a sufficient grid height of 36 km to discretise the domain. This grid height has an error of ± 2.1 hours over a voyage lasting 703.25 hours.

A failure model has been implemented that can model two levels of failure, thereby demonstrating the flexibility of the Bayesian Belief network with regards to modelling different combinations of failure causes. The levels of failure modelled are a function of the mean wave height and direction. This model has modelled the difficulty for autonomous sailing craft to maintain a course when either sailing in heavy seas or sailing into the wave direction.

6.4 Archaeological application

The uncertainty route modelling analysis procedure is applied to quantifying the performance of Polynesian voyaging canoes, an application with previously irreducible levels of uncertainty. Modelling the voyaging time for ethnographic voyaging craft to complete specific routes will assist in understanding how it was possible for Polynesia to be colonised, one of Pacific archaeology's most significant unanswered questions (Irwin and Flay, 2015). Of interest is the influence of the ENSO, a critical weather phenomenon in the Pacific, on voyaging time (Montenegro et al., 2016a). This section applies the methodology developed in this chapter to a subset of the simulations which are undertaken to study the colonisation of Polynesia.

One route of interest is between Tongatapu, Tonga and Upolu, Samoa. Through simulating the influence of performance uncertainty on the voyaging time for a colonisation voyage, it will be possible to quantify the influence of seafaring technology on the ability to make colonisation voyages safely. At the heart of this problem is the solution of a marine weather routing algorithm with a prior requirement to simulate uncertainty.

The minimum time path between Tongatapu and Upolu was estimated for a range of different grid sizes, performances and start times. Twenty-one different performances were generated, which linearly varied the performance model of the

Outrigger from −50% to +50% of the original performance. Voyages were started every 24 hours using weather data for the first Quarter of 2004, running from the 1st January to the 31st March 2004. This time period is a weak El Niño event. Seafaring between West and CEP may have occurred in deep history therefore these results can be applied to the modelling undertaken in Chapters 7 and 8.

The performance of an Outrigger canoe was used to model how a later pre-European contact voyaging canoe might behave. The performance model was predicted based off CFD simulations for the hull configuration and aerodynamic experiments for the sail. The full details for the performance prediction may be found in (Boeck et al., 2012). It should be noted that it is possible to substitute in any performance model within this framework, allowing an application to all marine vehicles.

The cost function for this craft interpolates the performance from the polar performance diagram, seen in Figure 4.17. An example of how the performance is varied for a specific wind condition is shown in Figure 6.2. The wind and wave data were sourced from the ERA5 weather model (Copernicus Climate Change Service, 2018). The current data used was sourced from (Bonjean and Lagerloef, 2002).

6.4.1 Numerical uncertainty

Illustration of simulation convergence

The numerical error in the routing algorithm is a function of the discretisation of the domain, parameterised by the grid width, d_n. Figure 6.12 illustrates simulated routes between Tongatapu and Upolu where d_n was reduced in stages of 10 nm between 90.0 nm to 30.0 nm. 1911 V_t simulations were performed for each d_n setting. 1911 simulations of 1 voyage started every 24 hours for 21 performance models which linearly vary ±50% from the original performance model. 30 nm was the smallest d_n which could be solved on a single CPU on Iridis 5, the supercomputer used for these simulations.

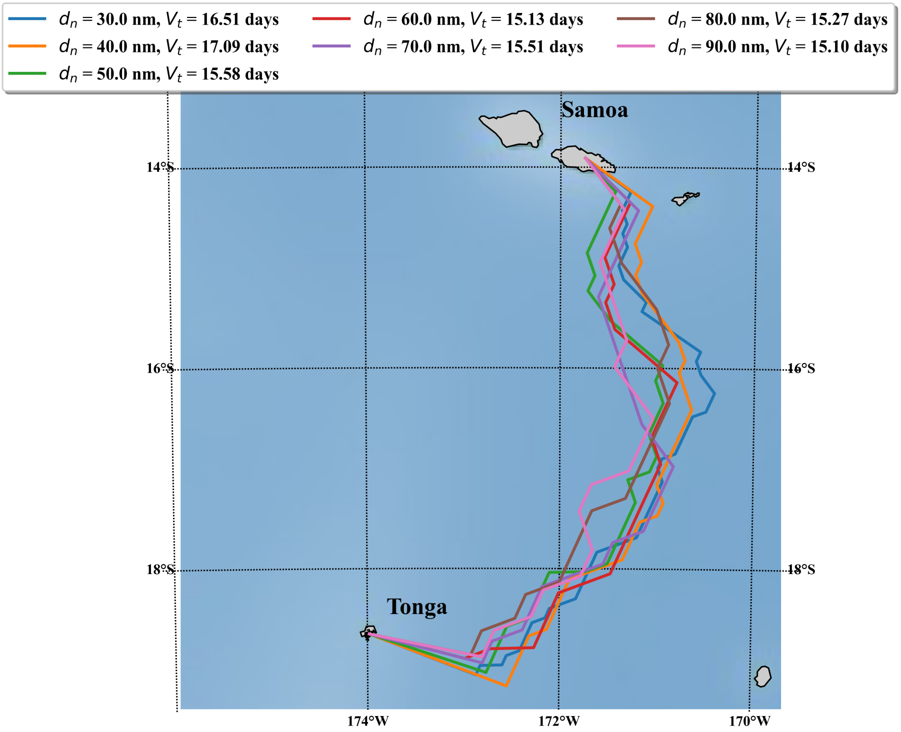

Figure 6.12: Routes between Tongatapu, Tonga and Upolu, Samoa starting at 00:00 GMT on the 2nd March 2004 solved over several different grid widths.

A plot of V_t as a function of d_n is shown in Figure 6.13. As d_n reduces the voyaging time increases. As the fidelity of the simulation increases there appears to be a slight increase in V_t at $d_n = 80$nm before the V_t enters a more linear relationship with d_n from 70nm onwards. The lines of best fit illustrate how the rate of convergence influence the extrapolation of V_t to $d_n = 0$. It can be seen that the extrapolated value of V_t reduces as the fidelity increases. When the order of convergence is below 1, as it is in this case, then the computational cost of increasing the fidelity of the simulation out weighs the benefit of more accurate solutions.

The original weather data was downloaded at a fidelity of $0.5^o \times 0.5^o$. It is then interpolated to the grid of $d_n \times d_n$ for the routing analysis. It would be expected that the relationship between d_n and V_t is going to be linear below $d_n \approx 37.25$nm as the weather data is interpolated linearly below this resolution. Any behaviour that is seen is more likely to be a function of the interpolation method as opposed to the behaviour of the weather.

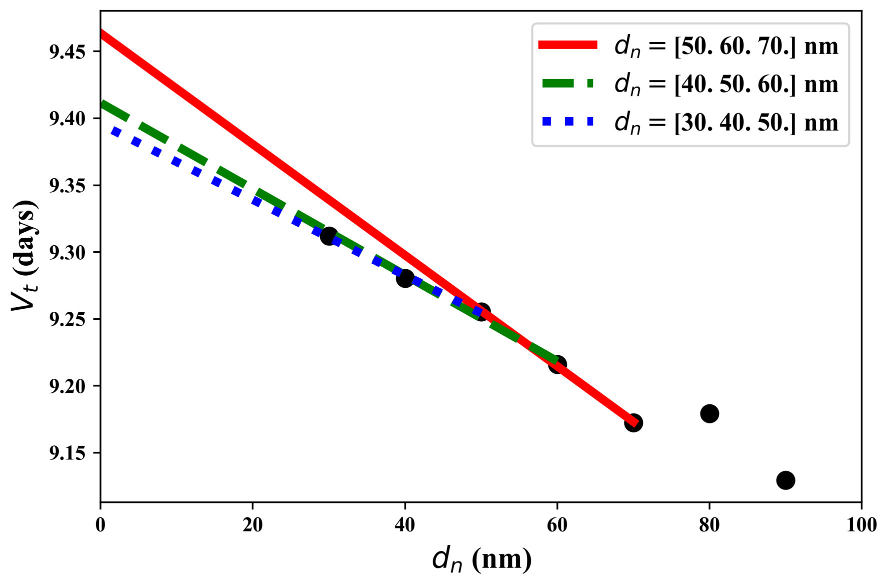

Figure 6.13: The mean voyaging time, V_t, for each set of results for d_n varying from 90 to 30 nm in increments of 10 nm. The lines of best fit illustrate how each consecutive group of 3 points extrapolate V_t at $d_n = 0.0$ nm.

The resolution of the weather data could contribute towards inaccuracy at lower values of d_n. The resolution of the weather data is at 37.25 nm, and the results may also suggest that as d_n decreases significantly below the resolution of the weather data the solutions may become dependent on the interpolation techniques used to retrieve the weather data.

There is a substantial computational cost associated with finer simulations which prohibits the number of simulations required to explore uncertainty in voyaging time. These results show that the GCI calculation method for estimating numerical error must be applied in a manner considering the physical implication of the parameters but also the computational run time of the simulations.

The selection of d_n is a compromise between simulation accuracy and computational run time. Simulation accuracy is determined by the smallest and the largest scales that the cost function can be applied to. The Haversine formula is used to calculate the distance between two points on the Earths surface. The Haversine formula is inaccurate below distances of 1nm (Allsopp, 1998), which provides a limit to the resolution that can be achieved with the routing algorithm. Although it is possible to distribute individual simulations across a computing cluster there the accuracy of a single simulation itself is limited. In this case, 30nm was the smallest scale which could be simulated within the memory limits of a single core on the Iridis 5 super-computing cluster.

The largest scale of useful simulation is determined by the fidelity of the spatio-temporal environmental data. A setting of $d_n = 30$nm is finer than the spatial distribution of data but would probably have individual legs of the route lasting longer than 1 hr, the temporal fidelity of the data. Reducing d_n would improve the accuracy but would reduce the number of simulations which could be used to investigate the voyaging problem.

The smallest scale is determined by the Haversine formula, which has significant levels of error for distances below 1 nm. The largest scale is determined by the rate at which spatio-temporal environmental data becomes available. Parallel computing provides significantly more resources than available previously allowing an increase in the number of different initial conditions that are required to be simulated.

Figure 6.13 illustrates that as d_n is reduced the simulation enters a linear relationship between V_t and d_n. d_n also influences the rate at which new weather data is retrieved and processed. If the journey time for a particular arc between two nodes lasts longer than the time between weather conditions being updated, then the solution is being solved over incomplete information. The weather could be interpolated although that adds another error source which requires quantification. The desire for accuracy must be balanced against computational limitations. There is a cubic relation between the computational run time and fidelity of the simulation. From this set of simulations, it may be proposed that the $d_n = 30$ nm provides a suitable height for future simulations.

Numerical error of voyaging simulations

The numerical error from the application of the routing algorithm must be calculated to quantify the limits of the solution process. Each set of initial conditions require a new estimate of numerical error. The average numerical error across a range of simulations will give insight, and confidence, into how well the routing algorithm can solve across a range of initial conditions.

The order of convergence, GCI value, and extrapolated voyaging time were calculated for different grid sizes of $30, 40$ and 50 nm. The order of convergence measures the rate at which the difference between the magnitude of each result changes as a function of the change of the grid width. For this data set the mean values of GCI and extrapolated V_t are 0.09% and 9.49 days. A mean GCI of 0.09% indicates a very low error associated with the converged results. The order of convergence ranged from 0.0049 to 27.73, with an average value of 3.57. 75.56% of the simulations had an order of convergence greater than 1, an indication of stable behaviour.

The lack of convergence is due to the solution of a minimum time path algorithm, a sequential decision-making problem, over a chaotic environment. For those remaining results, it is possible to investigate the lack of convergence through running simulations at reduced grid widths. For now, the use of the numerical error reduction procedure helps to identify which combinations of initial conditions result in complex behaviour requiring more analysis.

The relationship between V_t and GCI is shown in Figure 6.14 for OOC greater than 1. From the fitting of the line to the data, it can be seen that there is no relationship between V_t and GCI. This is because the same number of calculations are being performed over each grid size. Large values of GCI indicates sets of initial conditions where more analysis is required in order to arrive at credible predictions. The average GCI value is 0.09%. For the slowest performance, the mean voyaging time is 33.23 days with a numerical error of $\pm$9.75 hrs. For the fastest performance, the mean voyaging time is 2.83 days $\pm$0.83 hrs. The numerical error was dimensionalised by multiplying the mean V_t by the GCI value.

Quantifying the numerical error is a necessary stage for the application of any numerical method. The magnitude of the numerical error is significant if the weather conditions are fully known, such as in design situations or historical investigations. However, forecast data currently has a Reciever operating characteristic (ROC) score of approximately 0.7 for predictions at the 120 hr time period (ECMWF, 2019a). The ROC score is a fraction which describes the accuracy of a prediction. Higher ROC values are associated with more accurate predictions. The accuracy of the forecast decreases rapidly after 120 hrs. The reduction in the accuracy of the weather data suggests that the numerical error is much smaller than the forecast uncertainty.

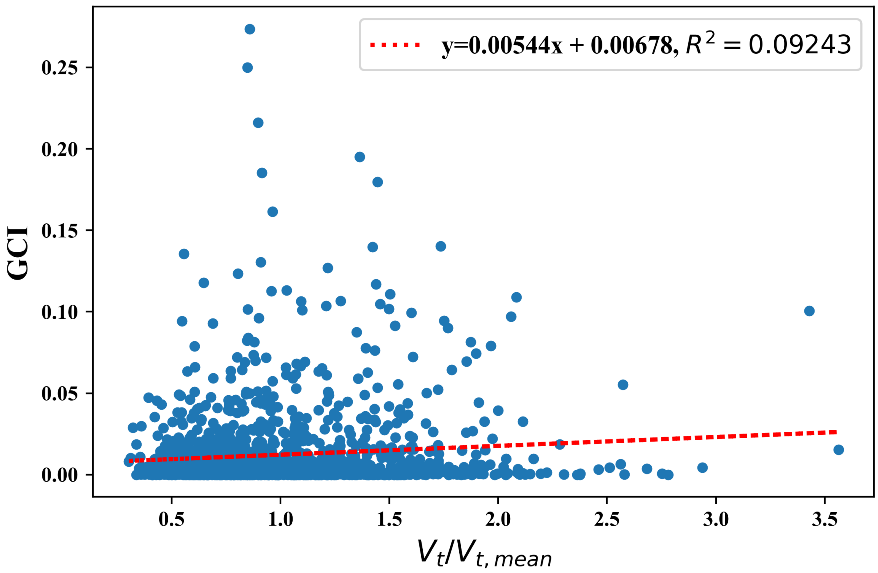

Figure 6.14: Relationship between GCI index and voyaging time.

6.4.2 Performance uncertainty

Archaeological voyage modelling is an example of a typical marine craft design problem, albeit one with high levels of uncertainty. Voyages between Tongatapu, Tonga and Upolu, Samoa were started every 24 hours from the 1st January 2004 to the 31st March 2004. The performance model was varied in 21 intervals between 50% and 150% of the original performance. Section 4.5 shows that variations in sail size can cause relative changes in performance of up to 40%, therefore simulating ±50% will be able to capture the variation in performance caused by changes in Polynesian canoe design. Simulations were solved over a grid size of $d_n = 30$ nm.

Figure 6.15 shows large variations in voyaging time for any given performance and over all changes in performance model. For the unaltered performance, the V_t lies between $4.22 - 14.54$ days. The variation in V_t is solely due to variation in environmental conditions. This result illustrates that even if there was a high level of confidence associated with the accuracy of the performance model, the weather conditions contribute significantly to the variation of voyaging time.

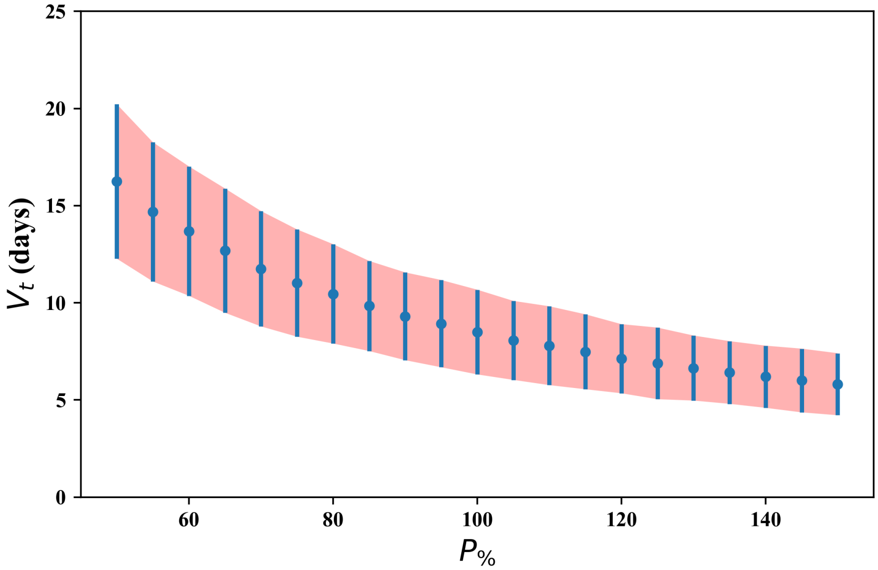

Figure 6.15: Voyaging time as a function of the different variations of performance. The standard deviation is illustrated using error bars.

A considerable variation in voyaging time is shown in the results. The minimum voyaging time is 2.83 days, with a maximum of 33.23 days. Increasing uncertainty in the accuracy of the performance model contributes to the variation in voyaging time. To reduce this uncertainty, the accuracy of the performance model must be quantified before performing a routing study, so it is possible to bound the uncertainty associated with the minimum voyaging time.

Of interest is how the voyaging time varies as a function of performance model change. Understanding the influence of how varying performance changes the voyaging time indicates the degree of confidence that should be held in a given voyaging result, given the confidence in the performance model.

Figure 6.16 shows the relationship between performance variation and the voyaging time non-dimensionalised concerning the original performance voyaging time for each start date. This figure illustrates how variations in performance from the original model significantly alter the expected voyaging time. It can be seen that as the model varies from the initial performance, the standard deviation of the voyaging time increases. As time is a reciprocal of speed, it can be seen that the magnitude of the reduction of voyaging time in response to performance *improvement* is slightly smaller than the magnitude of the increase of voyaging time in response to performance *reduction*.

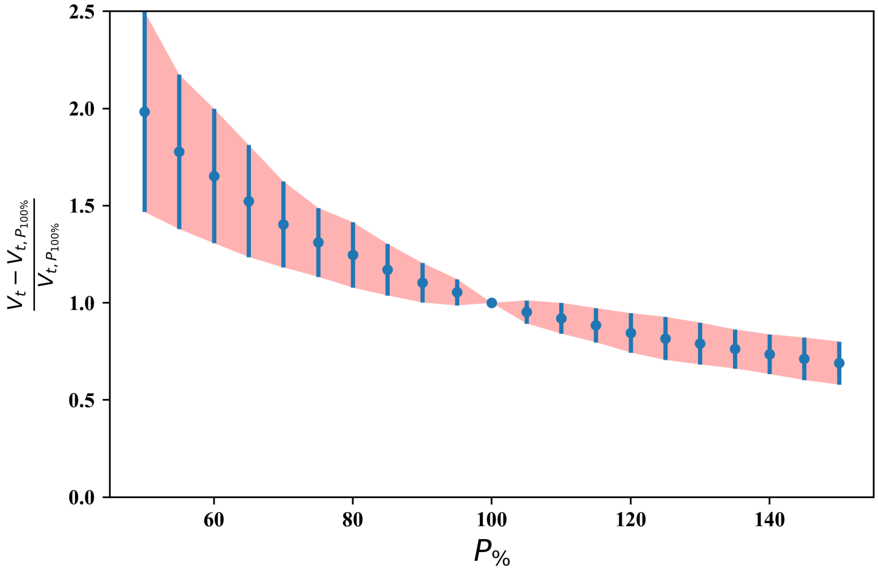

Figure 6.16: Relationship between the voyaging time and change in performance. The standard deviation is plotted as the error bars.

There is also a difference between the change in the standard deviation of V_t for equivalent magnitude variations about the original performance. As the performance decreases, we see more significant reductions in speed and much more substantial increases in standard deviation as the performance increases the magnitude between successive improvements decrease along with a reduction in standard deviation. Reductions in performance have more significant negative impacts on voyaging time than equivalent improvements. This non-linear response is due to the slower craft spending more time at sea and consequently being exposed to more variation in the weather.

Figure 6.17 shows how the standard deviation of the voyaging time varies as a function of the performance variation. The average numerical error is overlaid to provide an indication of how significant it may be when using the results of this study. Figure 6.17 indicates that the contribution of performance uncertainty is much larger than the numerical error of the algorithm. A variation in performance of $\pm 2.5\%$ causes a standard deviation of $2.19 - 2.55\%$, equivalent to $4.46 - 5.21$ hrs for the mean voyaging time of 266.40 hrs. As the variation from the original performance increases to $\pm 5\%$ we see that the standard deviation increases rapidly to $5.95 - 6.78\% V_t$, or, $12.14 - 13.82$ hours.

These results illustrate the influence of performance uncertainty on V_t. It is likely that the uncertainty associated with forecast data is still the dominant source of uncertainty, as has been specified earlier in this section. However, the influence of performance model uncertainty must still be quantified in order to provide context to the voyaging time predictions.

The weather conditions are updated every hour. The magnitude of the numerical error and influence of low levels of performance uncertainty indicate that it is possible for multiple changes in the weather to not be modelled. It is difficult to quantify the impact of this error on the ability for the weather routing model to approximate the real situation. Studying the variation in V_t as a function of discretisation is the only way of investigating how increasing simulation fidelity impacts voyaging time.

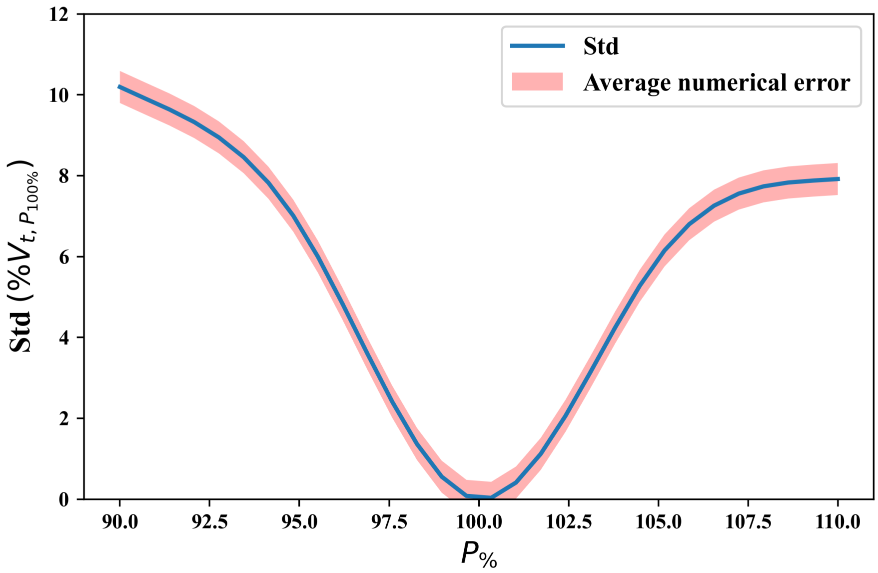

Figure 6.17: Relationship between performance variation and the standard deviation of $V_{t,P_{100\%}}$.

6.4.3 Discussion

The key results of this study can be summarised as follows:

1. uncertainty in performance and the numerical error reduce the accuracy of marine weather routing, the dominant source of uncertainty is likely to lie with meteorological uncertainty for applications relying on forecast data.
2. The numerical error must be calculated for each set of initial conditions. For this problem, 75.57% of all simulations converged with an average of $0.09\%V_t$ across the entire data set. For the slowest performance, the mean voyaging time is 33.23 days with a numerical error of ±9.75 hrs. For the fastest performance, the mean voyaging time is 2.83 days ±0.83 hrs.
3. As slower craft spend more time at sea they are exposed to more variance in the weather conditions, likely contributing towards the non-linear response of voyaging time to performance variation. This result means that

the uncertainty in the performance model must be quantified to provide credibility to voyaging simulations.

4. The influence of uncertainty in the performance model rapidly becomes more influential than the numerical error. The relationship between uncertainty and the standard deviation of voyaging time increases sharply with variations of 2.5% in performance being associated with standard deviations of $\pm 4.46-5.21\%$ about the mean voyaging time.
5. The weather data used updates every 3 hours. The combination of numerical error and uncertainty in performance model may mean that the approximation of the minimum time path is being calculated based off incomplete sets of weather data or solved using more weather data than would be encountered in practice.

This method of quantifying the numerical error of the solution algorithm and performance uncertainty could be applied to other cases involving marine vessels such as cargo ships. This would allow an understanding of the maximum level of accuracy that could be achieved within commercial route modelling. Another investigation could be into the uncertainty levels associated with the recorded reanalysis weather data used and how this might influence the result.

Through applying an uncertainty analysis method to the marine weather routing problem, it has been shown that the influence of performance uncertainty is much more significant than any uncertainty associated with the optimisation algorithm used. To provide more accurate routing the uncertainty associated with the performance model used must be reduced.

6.5 Summary

A methodology for quantifying uncertainty in marine weather routing has been introduced and applied to problems in modern and archaeological naval architecture. These techniques individually represent novel contributions within the marine weather routing modelling community as well as substantive improvements over state of the art in Polynesian voyage modelling.

The utility of studying the influence of weather and performance uncertainty was applied within a simple environment that only considered the action of the wind. It was shown that uncertainty must be modelled within the performance model, rather than the cost function, in order to produce accurate results.

A reliability model was implemented and applied to a autonomous sailing craft routing problem. This illustrated the utility of modelling reliability with a BBN which was able to influence the cost function in order to travel away from a specific area. This application demonstrated the relevance of the uncertainty route modelling process for modern and prehistoric sailing craft.

Finally, the numerical error, performance uncertainty and weather uncertainty were quantified within a setting that considered wind, wave and current conditions. This study showed that in order to provide credible results it is essential to quantify the uncertainty associated with the performance model in order to give sufficient context to routing results. The weather was shown to be the dominant source of uncertainty, followed by the performance model and the numerical error.

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Chapter 7

Polynesian voyage modelling

7.1 Introduction

It is not known to what extent the performance of Polynesian seafaring technology influenced the ease of voyaging between West and Central East Polynesia (CEP). Quantifying the influence of seafaring technology allows the influence of other factors such as climate or human agency to be understood, of critical importance to the wider Pacific archaeological community. Modelling the time taken for different Polynesian voyaging canoes to complete colonisation voyages under different weather conditions will give insight into the challenge of voyaging. The analysis in this chapter improves on previous research through using more realistic Polynesian voyaging canoe models as well as weather data sets and optimisation algorithms of improved accuracy.

The study presented in this chapter compares the performance of the *Tongiaki*, developed in Chapter 4, against that of an Outrigger design (Boeck et al., 2012), over a series of routes and weather conditions. The first route investigated is between Tonga and Samoa and was achievable at the beginning of the long pause.

The second route is between Samoa and Aitiutaki, in the Southern Cook Islands. This route was completed at the end of the long pause and enabled the settlement of CEP with OEP following soon after. The evidence identifying these two routes has been reviewed in Section 3.2. The weather conditions are selected to mimic the range of conditions which may have occurred over the long pause.

The specific questions this study is investigating are:

1. How do the different voyaging canoes compare?
2. What is the influence of climate on voyaging time?
3. What is the influence of seasonality?
4. What is the difficulty of completing voyages either side of the 'long pause'?

7.2 Colonisation voyages

The voyage modelling problem is bounded through identifying the voyages which occurred before and immediately after the end of the long pause and the colonisation of East Polynesia. Samoa was the last archipelago in West Polynesia to be colonised at the beginning of the long pause and was likely colonised from Tonga (Cochrane, 2018). It has been posited that the settlement of the Sāmoan archipelago is essentially contemporaneous with Tonga (Clark et al., 2016).

Previous research investigating the entirety of Polynesian drift voyaging has identified that successful colonisation of East Polynesia was only possible by sailing from Samoa to the Southern Cook Islands (Montenegro et al., 2016a). The Southern Cooks are approximately 756 nm East from Samoa, with the Society Islands being another 490 nm to the West. Archaeological evidence for chicken has been found in Tonga, the southern cook islands and the Society islands (Anderson, 2009b), indicating that settlers had canoes which were large enough to move livestock between islands.

The locations of Tonga, Samoa and the Southern Cook Islands are illustrated in Figure 7.2. The distance between Tonga and Samoa is approximately 400 nm and the distance between Samoa and Aitiutaki in the Southern Cook Islands is approximately 2000 nm.

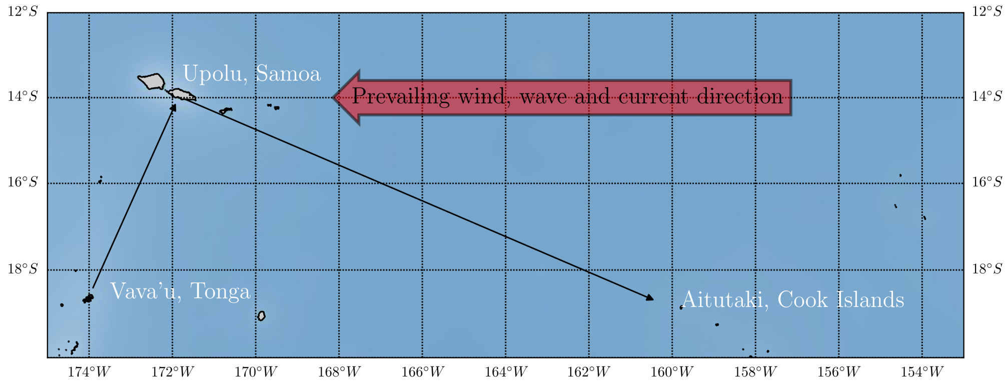


Figure 7.1: The locations of Tonga, Samoa and the Southern Cook Islands.

The final voyage to be simulated is from Tonga to Tahiti. It is a long voyage and it is unlikely that a navigator would have chosen to complete it without breaking up the journey. Nevertheless, it is being simulated as it might illustrate how different sailing craft would behave over longer distances and what islands they might encounter along the optimal route.

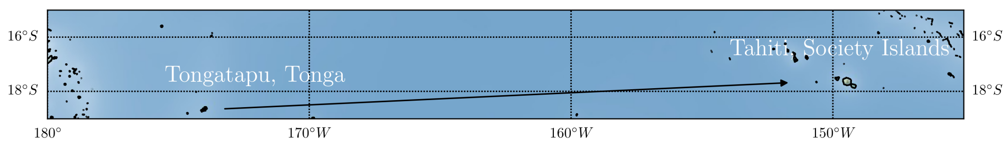


Figure 7.2: The locations of Tonga and Tahiti, in French Polynesia.

7.3 Climate data

The key variables in marine weather routing studies are the wind condition and the current. A review of the key factors which may have influenced the “long pause” has identified that the interannual variation in weather conditions due to the ENSO phenomenon could have been key to enabling settlement efforts. The weather data used must be able to cover the range of ENSO conditions seen throughout the ‘long pause’. The extremes of the ENSO phenomenon could have been influential as these would have represented the most significant deviations from the prevailing weather conditions which would normally have hindered any eastwards sailing.

Figure 7.3 shows the El Nino 3.4 index plotted as a function of time. The El Nino 3.4 index can be used to identify the extremes of the ENSO phenomenon which are known as El Niño and La Niña. The excepts of weather data used in the modelling in this Chapter are shaded in yellow. These dates fall within the range of weather data accessible from the ERA5 model and cover 4 La Niña and El Niño phases. 8 years of weather data is used, which is split into quarters for the routing simulations.

The ERA5 model was chosen as the source of wind and wave data used for this study (Copernicus Climate Change Service, 2018). The ERA5 model provides a higher temporal and spatial resolution of weather data and simulates uncertainty through producing 10 ensemble scenarios. The temporal resolution is hourly and the spatial resolution is 64km (34.6 nm).

The current data used is the mean annual current (Bonjean and Lagerloef, 2002). The mean current conditions are shown in Figure 7.4. It can be seen that the current travels East to West, directly against voyaging towards CEP. It can be seen that the magnitude of the current decreases or the direction reverses as the

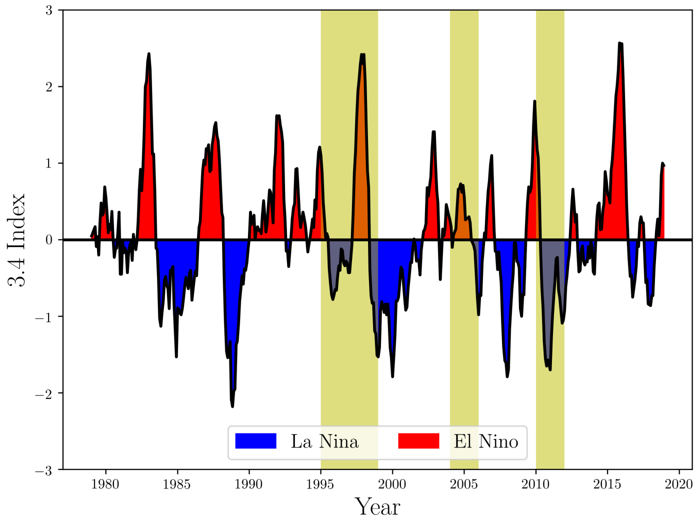


Figure 7.3: El Nino 3.4 index with the shaded areas denoting the weather data used in the simulations.

distance from the equator increases. This could favour voyaging away from the equator, although the length of the voyage would determine whether there is benefit to this strategy.

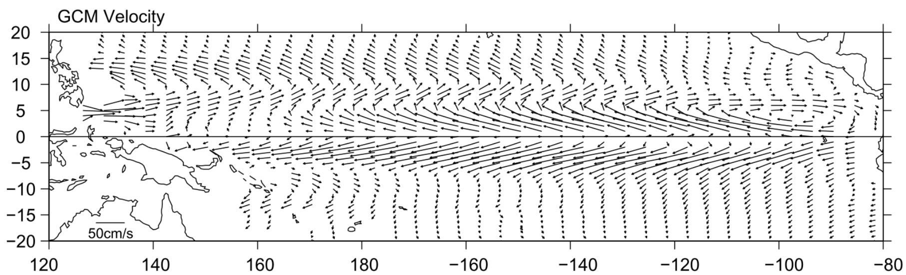


Figure 7.4: The mean current conditions for the Pacific generated from the global circulation model (Bonjean and Lagerloef, 2002).

7.4 Simulation summary

The simulations in this chapter aim to estimate the performance of early Polynesian seafaring craft over a range of routes in different environmental conditions. Two performance models of voyaging canoes used around the time of the 'long pause' have been described in Chapter 4, the *Tongiaki* and the Outrigger. Three routes have been identified as being of interest which were completed pre and post settlement of CEP.

The weather data used simulates several sources of weather and model uncertainty. The key sources of weather variation are in the interannual variability of the ENSO phenomenon and the season. These weather variations are modelled through using several recent years of weather data which vary in ENSO index. The contribution of uncertainty in the weather reanalysis model is simulated through 10 ensemble scenarios.

Three routes are being investigated. Two describe the most likely voyages which would have been completed either side of the 'long pause' in the colonisation sequence. Simulating these voyages will shed insight into the relative difficulty in seafaring either side of the 'long pause'. The third voyage, from Tonga to Tahiti, is likely to be the longest voyage that any sailor could envisage and is the toughest voyage which might have been sailed. The different sets of variables being simulated are now summarised;

1. **Performance model.** The Outrigger and *Tongiaki* designs.
2. **Interannual variation.** A range of years have been selected based on the requirement to simulate high, low and intermediate ENSO conditions. These years include 1995, 1996, 1997, 1998, 2004, 2005, 2010 and 2011.
3. **Season.** Simulations occur over the course of each year of data.
4. **Weather model uncertainty.** 10 ensemble scenarios are used within

each simulation.

5. **Route.** Three routes;
   (a) Samoa to Tonga.
   (b) Samoa to Aitiutaki, Southern Cook Islands.
   (c) Tonga to Tahiti.

The *Iridis 5* supercomputer was used to run the number of simulations necessary to model the various combinations of settings. Several thousand simulations are required to test the range of parameters needed to examine the influence of the different sources of uncertainty, this would not have been possible without access to high performance computing resources. The package SailRoute.jl contains the logic used in the simulations in this Chapter and Chapter 8. The repository containing the settings and scripts used to apply this logic to the simulation of Polynesian seafaring is in route_analysis.jl.

7.5 Results

7.5.1 Heatmaps

The optimum routes from the simulations can be used to infer general patterns of how it was possible to complete voyages in the past. Heatmaps are used to investigate how changes in seafaring technology influence the choice in route. The routing simulations have been aggregated as a function of seafaring technology and time of year. Heatmaps showing the popularity of travelling through different locations between Tonga and Samoa are shown in Figure 7.5 for the Tongiaki and Figure 7.6 for the Outrigger. Each quarterly heatmap shows the most popular locations visited over each voyage by aggregating the results for each quarter over the years of weather data used. The colour bar indicates the percentage of voyages which travelled through the area and the red line plots an actual voyage deemed representative of those sailed.

The heatmaps showing the popularity of different locations for the voyages between Samoa and the Southern Cook Islands are shown in Figures 7.7 and 7.8 for the Tongiaki and Outrigger respectively. Finally, the aggregated results between Tonga and Tahiti are shown in 7.9 and 7.9. The heatmaps for each year of simulation are included in the Appendix, Section B.2. The years are plotted in chronological order, and the middle four are the El Niño years for the Figures in Section B.2.

Figure 7.5 shows the routes travelled by the Tongiaki between Tonga and Samoa. For Q1 and Q4 for 95-98 and 05-06 there appears to be a popular route which heads NE before tacking and sailing directly to Samoa. However, Q1-Q4 for 10-11, a strong La Niña phase, there is no particular pattern. For Q2 and Q3 for all years the NE region is more popular, with smaller number of routes travelling to the West.

The routes travelled by the Outrigger between Tonga and Samoa are shown in Figure 7.6. Routes to the West side of the domain are popular, as in Figure 7.5 and there are similar trends in popular voyages. The V_t for the Outrigger is about 3 days faster than the Tongiaki, and has a reduced standard deviation. The reduction in standard deviation is a consequence of the reduced time at sea, hence reduced exposure to chaotic weather patterns.

Figures 7.7 and 7.8 show the routes travelled by the Tongiaki and Outrigger between Samoa and Aituitaki. Several strategies appear, the primary one being to sail North to the extreme of the domain, to then sail South East and then tack back to Aituitaki. This pattern is strongly present in Q2 and Q3 for each year. Another strategy involves sailing directly between the two islands, as seen in Q4,

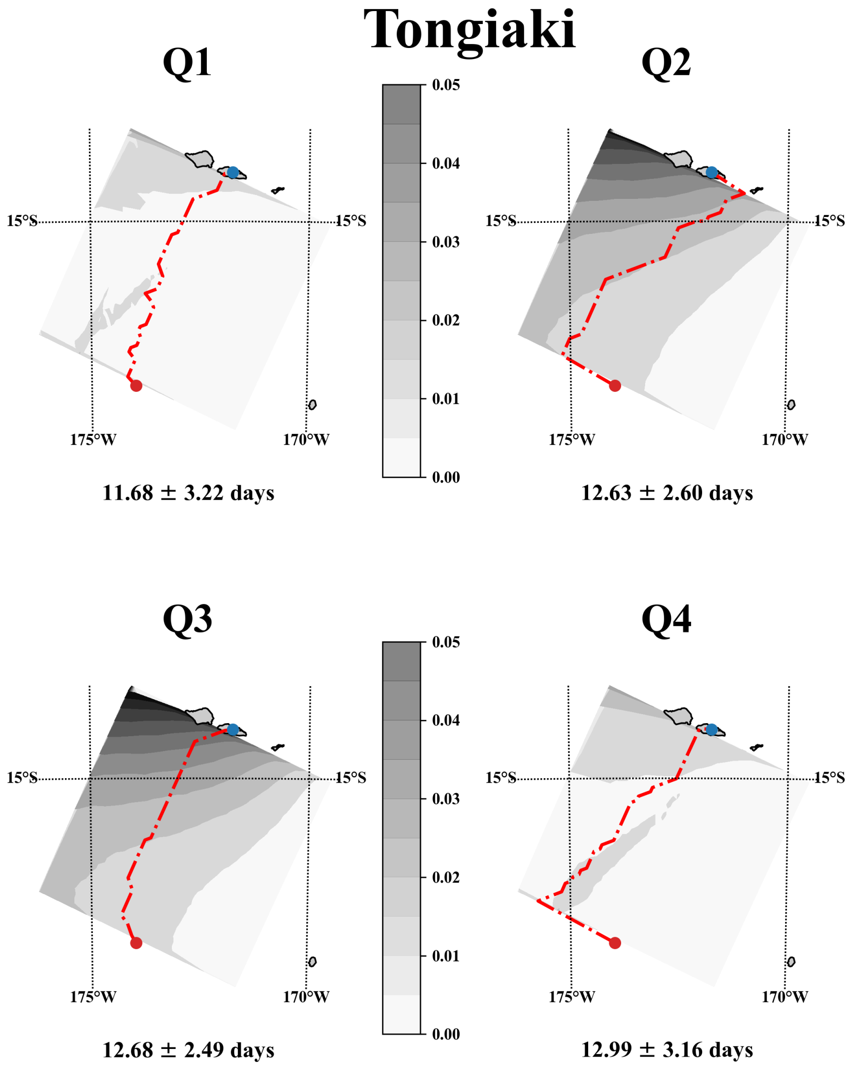


Figure 7.5: Density plot for Tongiaki voyages between Va'vau, Tonga (red) to Upolu, Samoa (blue). Each heatmap presents the results for each quarter, aggregated over all the weather data used. The density represents the fraction of voyages passing through each location along the course of a voyage.

Figure 7.7. Figure 7.8 shows that the Outrigger has similar voyaging strategies to Tongiaki.

The results for the Tonga to Tahiti voyage are shown in Figures 7.9 and 7.10. Both

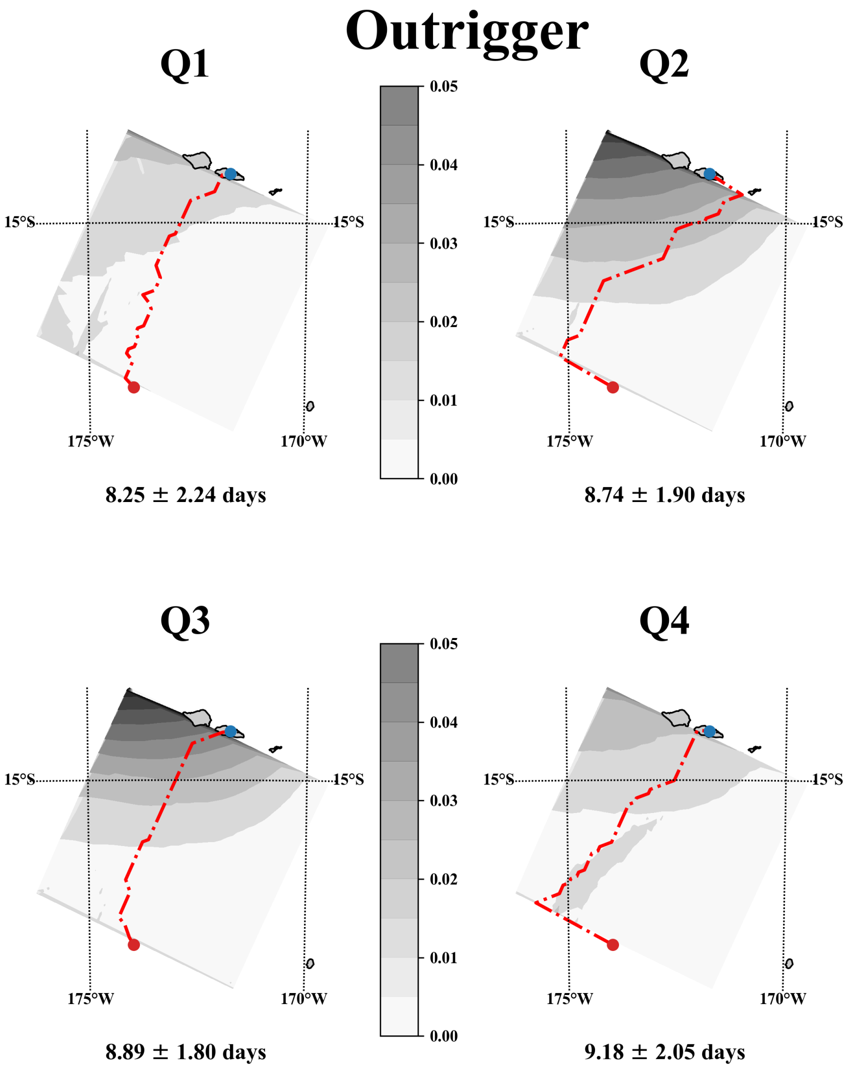


Figure 7.6: Density plot for Outrigger voyages between Va'vau, Tonga (red) to Upolu, Samoa (blue).

craft take a significantly longer amount of time to complete these voyage than the other two which have been modelled. Both craft appear to favour voyages which head South East before tacking and sailing due North to Tahiti. This route avoids the prevailing wind and wave conditions and hits reduced currents South of 10^o S.

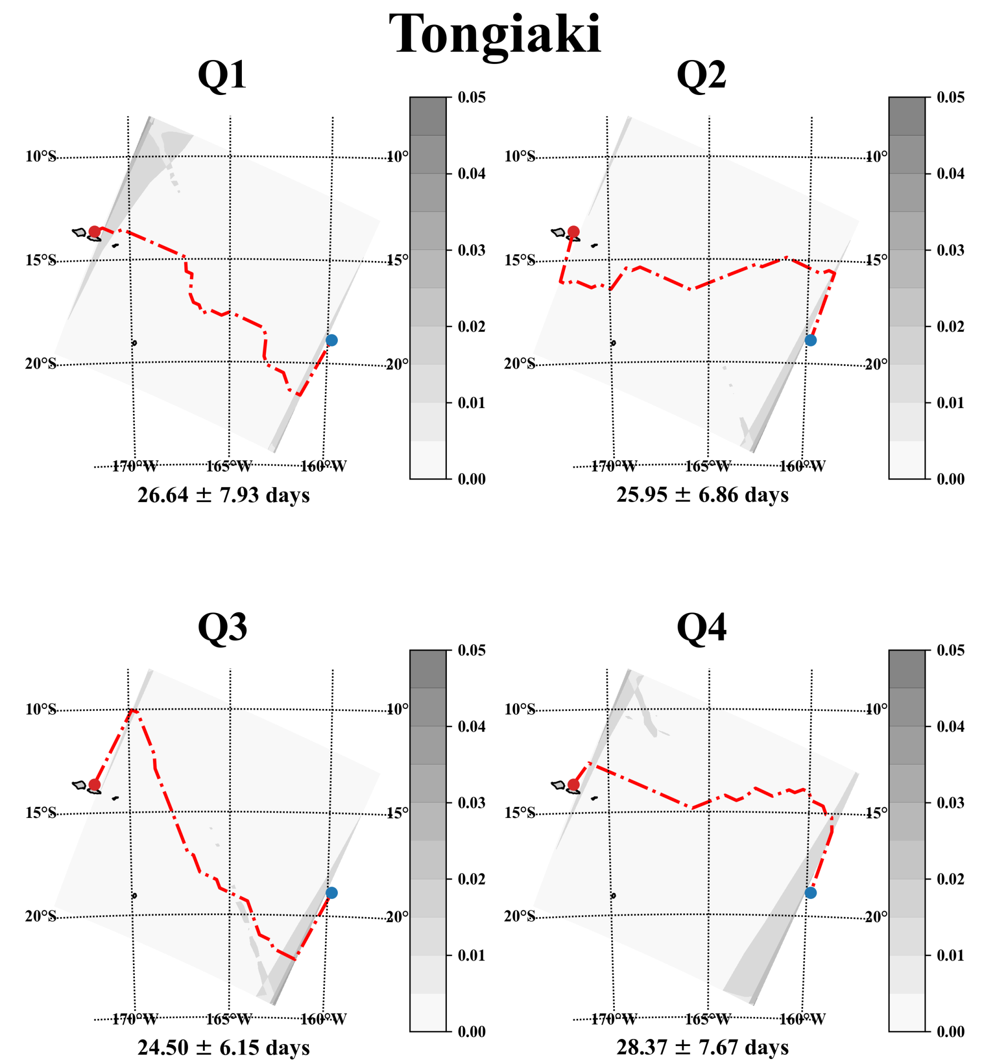


Figure 7.7: Density plot for Tongiaki voyages between Samoa (red) to Aituitaki, Southern Cook Islands (blue). The scale indicates the fraction of voyages that pass through the specific location.

Some weather scenarios have very mixed strategies. Q1, Figure 7.9 illustrates voyages which tend to sail along the latitude between Tonga and Tahiti. Voyages tend to sail South before returning North. This minimises exposure to adverse wave and current conditions.

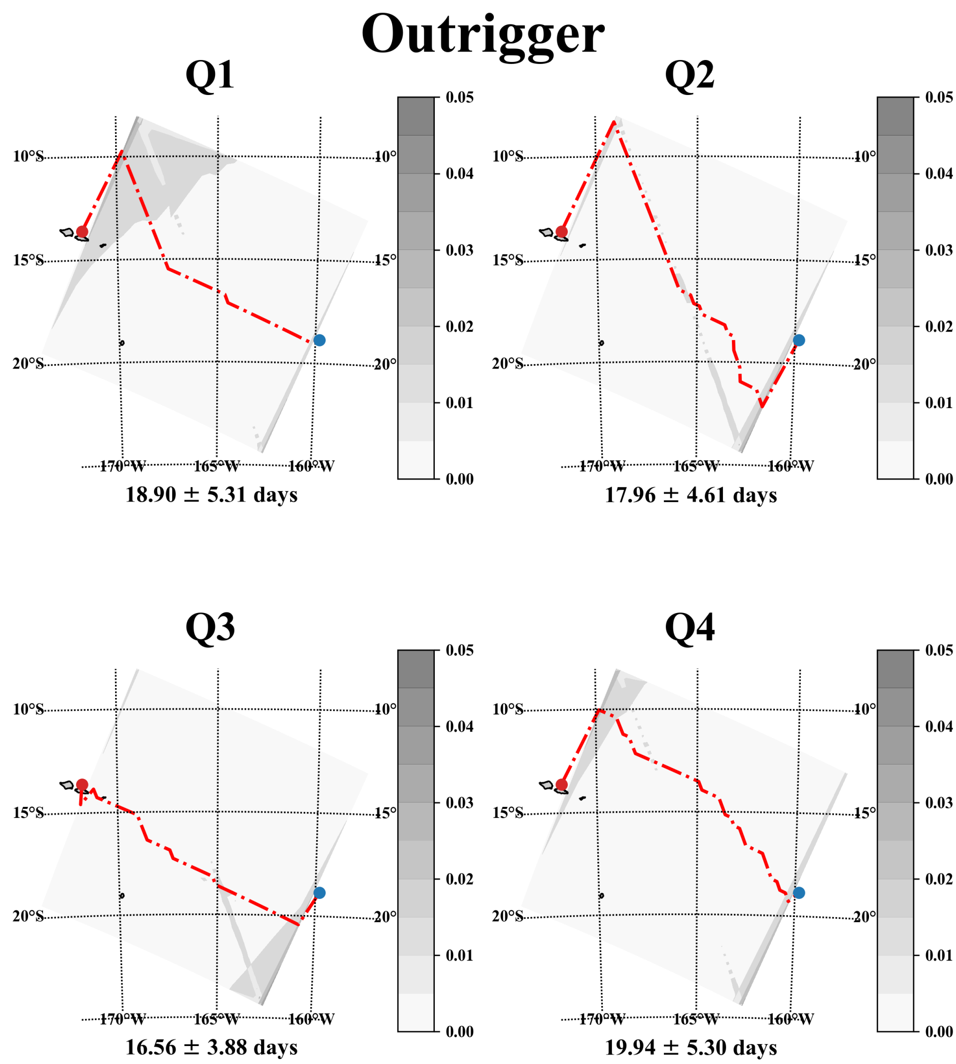


Figure 7.8: Density plot for Outrigger voyages between Samoa (red) to Aituitaki, Southern Cook Islands (blue).

The most popular strategy is to sail South West before tacking towards the destination island. This allows the sailing craft to avoid the prevailing wind and wave conditions and pick up the slower Easterly currents which are present further South. Some

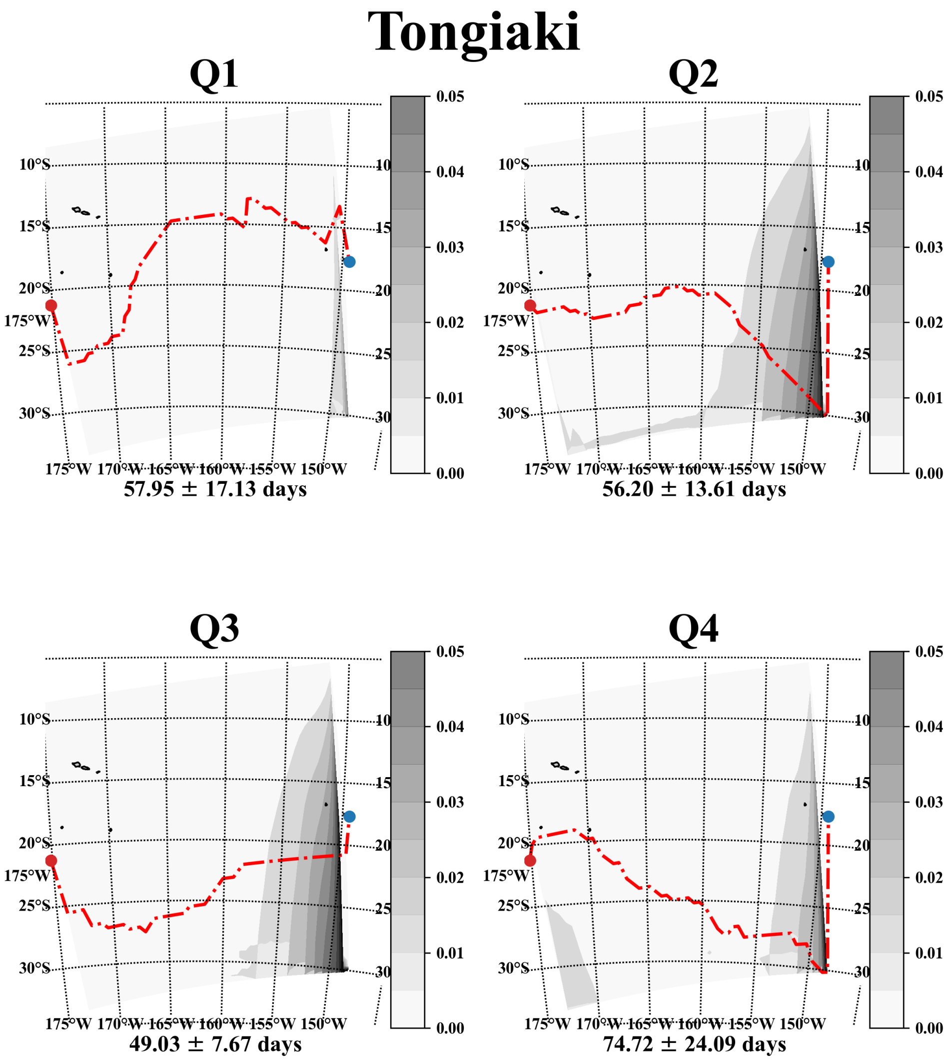


Figure 7.9: Density plot for Tongiaki voyages between Tonga (red) to Tahiti (blue).

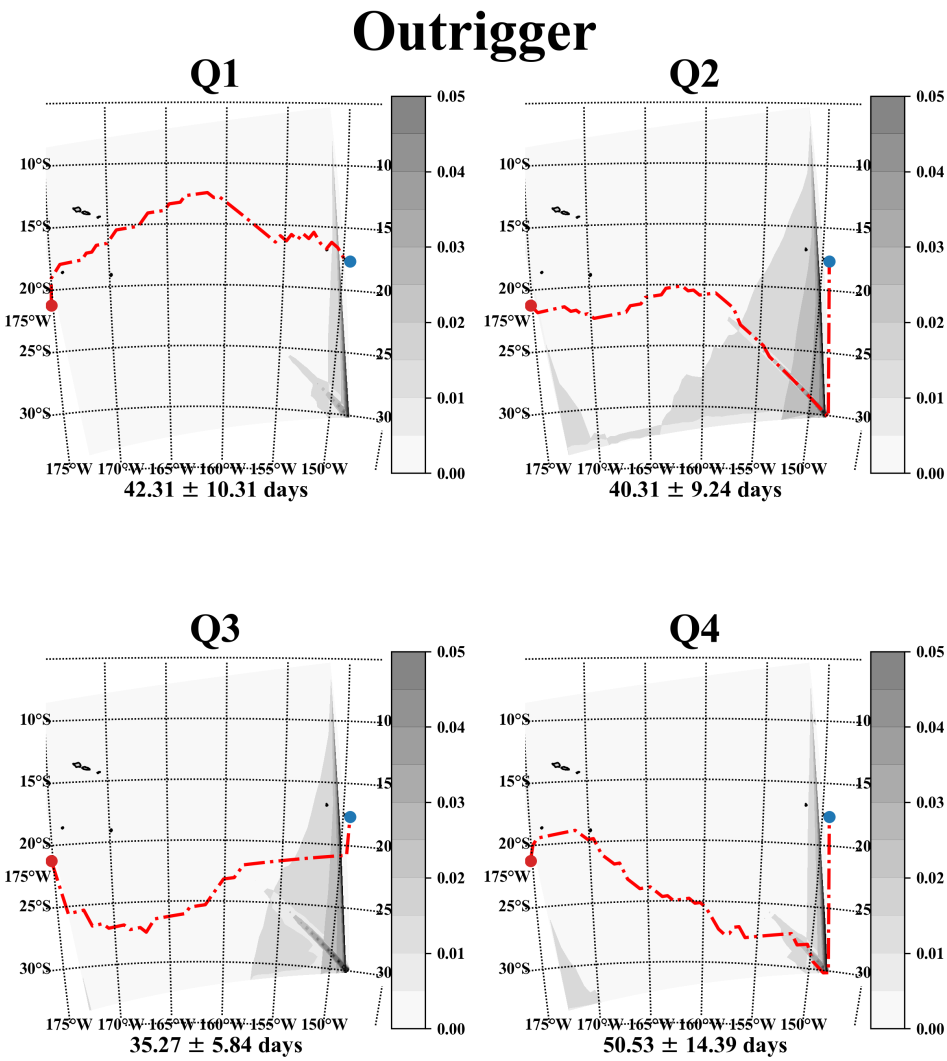


Figure 7.10: Density plot for Outrigger voyages between Tonga (red) to Tahiti (blue).

7.5.2 Influence of Interannual variability

This section investigates how the climate influences the voyaging time, V_t, of the two performance models over different routes. The V_t for a series of simulations are plotted as a function of the ENSO 3.4 index, the proxy used to describe the strength of ENSO. Routing simulations were started every 24 hours over each excerpt of climate data, presented previously in Figure 7.3. The discretization of the environment is 30 nm.

Figure 7.11 shows the voyaging time for the Vavau to Upolu. The times for Samoa to Aituitaki are shown in Figure 7.12 and the results for the Tonga to Tahiti voyage are shown in Figure 7.13. It can be seen that the Outrigger is faster than the Tongiaki for all voyages over all ENSO indices.

V_t and ENSO index are uncorrelated for the voyage between Vavau and Upolu, as seen in Figure 7.11. The majority of the voyaging time results fall within or under the estimated endurance of a voyaging craft. ENSO index and voyaging time appear to be uncorrelated. The Outrigger completes the journey in about 8 days, with the Tongiaki having a mean voyaging time of 12 days. It appears that the Tongiaki has a higher dispersion of voyaging times than the Outrigger. These results show that the voyage between Tonga and Samoa was safe to complete and was not influenced by ENSO index or by either design.

Figure 7.12 shows that voyaging between Samoa and Aitiutaki represented a significant increase in difficulty. Higher ENSO indexes correlate with lower V_t values, as expected as El Niño phases offer improved sailing conditions to the East. It appears that the majority of the Outrigger results fall in or under the endurance of a voyaging canoe. The Tongiaki is only fast enough to endure the voyage between Samoa and Aituitaki at higher ENSO indexes.

Neither voyaging craft completes the voyage between Tonga and Tahiti within

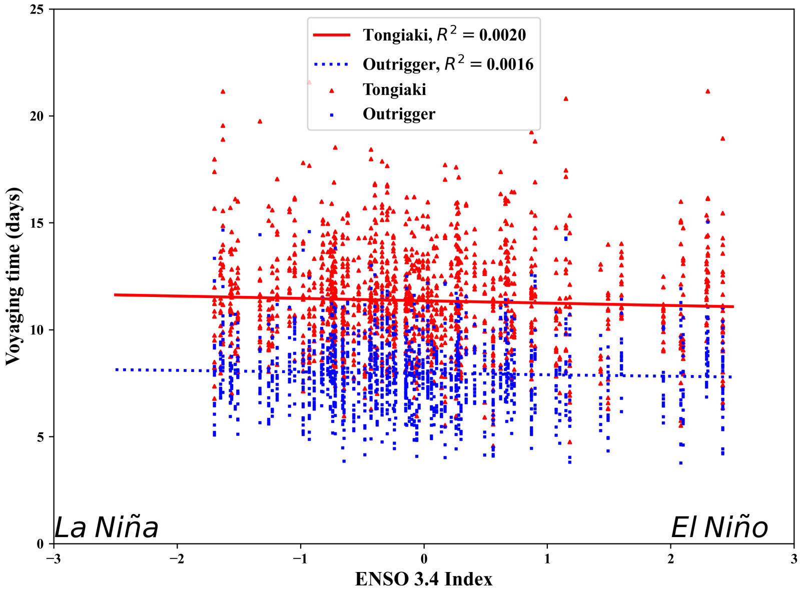


Figure 7.11: Voyaging time as a function of ENSO index for the Vavau to Upolu route. There appears to be little relationship between ENSO index and voyaging time and the majority of voyages are completed under 14 days.

the maximum endurance of Polynesian voyaging craft, Figure 7.13. There are multiple archipelagos which would be passed on a voyage between these two islands which would have allowed restocking of supplies and the opportunity to wait for more favourable weather. The Outrigger is faster than the Tongiaki, as in line with the other two voyages.

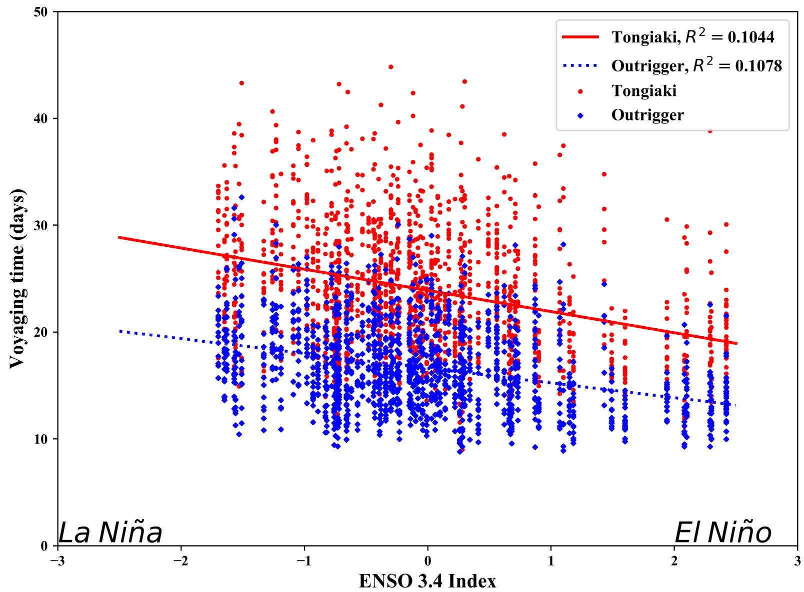


Figure 7.12: Plotting the voyaging time as a function of ENSO index for the Samoa to Aitiutaki route .

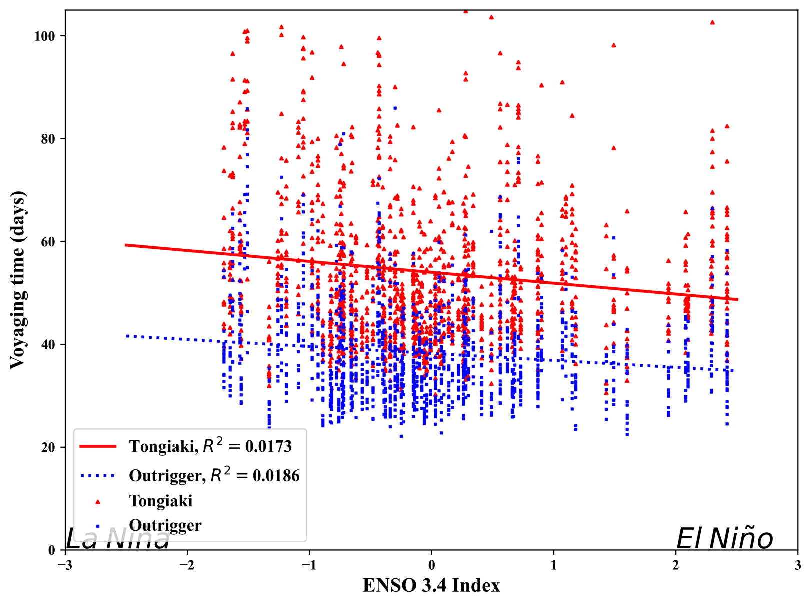


Figure 7.13: Plotting the voyaging time as a function of ENSO index for the Tonga to Tahiti route.

7.5.3 Influence of seasonality

This section investigates the relationship between seasonality and V_t. The mean voyaging time for each month is calculated over each year of data and plotted in Figures 7.14, 7.15 and 7.16. The mean ENSO index value of the weather data used is included to identify the existence of a bias towards the El Niño or La Niña climate. The weekly voyaging times can be seen in Appendix B, Section B.1.

Figure 7.14 shows that the Tongiaki is consistently slower than the Outrigger across the year. The slight reduction in ENSO index appears to be matched by a slight increase in voyaging time. The V_t for both craft does not vary much as a function of season.

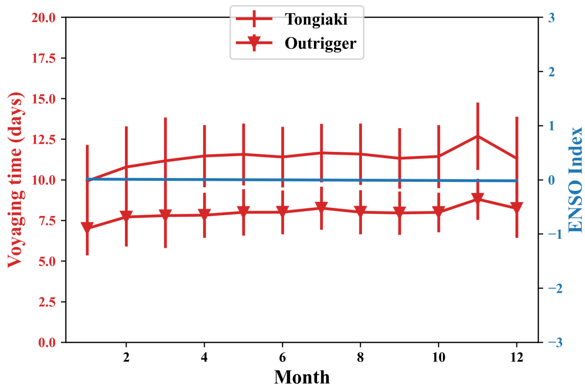


Figure 7.14: Mean monthly voyaging times over the Va'vau to Upolu route.

Season seems to have a larger influence on V_t for the Samoa to Aitiutaki route, Figure 7.15. The faster times are in the Austral Winter with V_t peaking in October and November.

Voyaging times between Tonga and Tahiti experience a huge increase in Q4 and at the end of Q1, as seen in Figure 7.16. The Tongiaki appears to experience a significant increase in V_t relative to the times of the Outrigger.

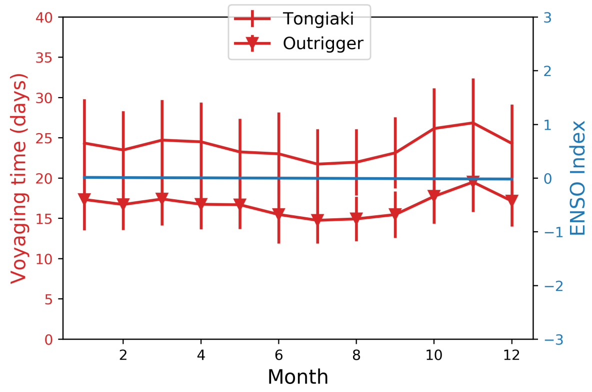


Figure 7.15: Mean monthly voyaging times over the Samoa to Aitiutaki route.

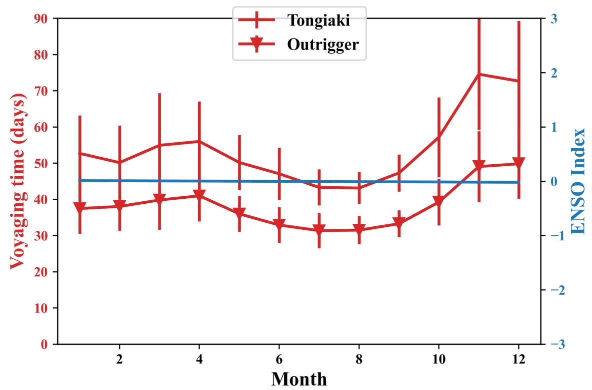


Figure 7.16: Mean monthly voyaging times over the Tonga to Tahiti route.

7.6 Discussion

The V_t results produced in this model are longer than those produced by reconstructed voyaging canoes. For example, *Hōkūle'a* completed the voyage between Samoa and Aituitaki in 10 days (Egan and Burley, 2009). The results presented are for simulations undertaken in all weather conditions. It is likely that navigators would have only undertaken voyaging in the best weather conditions, for example, if the breeze was blowing from the West.

The trend in voyaging time for both performance models appears identical, although the *Tongiaki* is much slower than the Outrigger design for identical start time, route and weather scenario. Therefore, the difference in voyaging time is due to performance model. The *Tongiaki* appears to have faster speed on a beam reach, Figure 4.18. It appears that the Outriggers improved windward performance results in faster voyaging times. Investigating the influence of windward performance on the general performance of a voyaging craft is the focus of Chapter 8.

The Tonga to Samoa voyage takes between $7 - 13$ days to complete for both craft, Figure 7.11. The voyaging time increases to $17 - 25$ days between Samoa and Aitiutaki and $38 - 72$ days for Tonga to Tahiti. These times illustrate that the increases in distance and regional changes in weather contribute to increases in the difficulty of voyaging further East, regardless of performance model. For each of these voyages there appears to be a spectrum of voyaging times indicating that the performance of a voyaging canoe is a significant influence.

The Samoa to Aituitaki voyage is thought to have enabled the colonisation of Central East Polynesia. Quantifying the difficulty of this voyage will shed insight into the barriers which stopped Polynesian sailors colonizing Central East Polynesia, as the majority of Central East Polynesia can be reached using the same craft which could sail between Samoa and Aituitaki. The Outrigger completes this voyage safely for all ENSO conditions. The Tongiaki can only complete this voyage under weather conditions associated with high ENSO indexes, supporting earlier hypotheses on the strategic use of ENSO conditions (Irwin, 2008). These results show that the Tongiaki could only complete the key colonisation voyage between West and Central East Polynesia in El Niño conditions.

The seasonal variation of voyaging time can be seen in Figures 7.14 - 7.16. The Outrigger is roughly 50% faster than the *Tongiaki*. There is increased variation in voyaging time in the Southern Hemisphere winter, with faster voyaging during the summer. The variation in the weather on a day to day basis contributed significantly towards the variation in voyaging time.

The marine weather routing algorithm estimates the optimum voyaging time given perfect knowledge of the weather conditions. This is an unrealistic situation and can only be used to compare the performance of the sailing craft being modelled. It is possible to infer that any voyages which occurred in reality would have been much longer as the navigator would not have known of the weather conditions. Accurate weather forecasts using modern weather prediction models have high levels of uncertainty associated beyond 10 day forecasts (Buizza, 2000). These results differ from previous research through using real weather data in simulations over a finer spatial and temporal scale.

7.7 Summary

This Chapter has presented novel results comparing the performance of Polynesian seafaring craft over a range of routes and environmental variables which provide insight into the challenge of colonisation voyaging in Polynesian deep history. It is now possible to understand exactly how performance, climate and seasonal weather variations contribute towards the time taken to complete modelled voyages between West and East Polynesia.

The Outrigger completes voyages in shorter times than the Tongiaki across all routes and weather conditions. This can be linked to the inability for the Tongiaki to sail close to the wind. The influence of windward ability and speed on voyaging time will be studied in Chapter 8.

The voyage between Samoa and Aituitaki could be sailed safely by the Outrigger under the majority of environmental conditions, but could only be completed by the Tongiaki under El Niño conditions. Therefore, ENSO directly enabled the completion of this key voyage. ENSO has relatively smaller influence in the completion of the Tonga - Samoa and Tonga to Tahiti voyage.

The performance models used in this study over predict the performance of the craft. This study highlights the difference in performance between two different Polynesian voyaging canoe designs for different routes and weather conditions. The results generated within this model can be compared, but it is likely that any voyages which were conducted in real life would have taken much longer.

Chapter 8

Influence of Uncertain Seafaring Technology

Quantifying how the seafaring technology and environmental factors contribute towards the voyaging time taken to complete principal voyages will help understand whether these factors would have presented obstacles to colonisation. The relationship between specific voyaging canoes, environmental conditions, voyaging route and V_t was modelled in Chapter 7. This analysis did not investigate how uncertainty in key canoe performance parameters would have influenced the time taken to complete colonisation voyages. The investigation presented in this chapter describes the impact of the systematic variation of performance characteristics on the voyaging time to complete specific voyages.

The seafaring technology used at the time of the settlement of West Polynesia and the later settlement of Central East Polynesia is not known. The existing evidence was reviewed in Chapter 3 and is fragmentary at its best. This thesis has modelled principal colonisation voyages using different voyaging canoe models and identified the significance of the change of performance model, route and climate condition. There has been a keen debate between competing positions on the ability of Polynesian seafaring technology. Previous research has not investigated the significance of this uncertainty in the performance of Polynesian seafaring technology on the ability to complete colonisation voyages.

This chapter presents an investigation which quantifies the influence of uncertainty in the performance of Polynesian seafaring technology on voyaging time. A parametric performance model is defined that produces performance polars describing the performance of a hypothetical voyaging canoe. The parameters of this model are varied to model the performance of the historicist and traditionalist positions on Polynesian seafaring technology. A series of simulations are performed and analysed to quantify how this performance model influences the voyaging time over principal voyages.

8.1 Modelling the influence of uncertain technology

The performance of seafaring technology was integral to the success of the colonisation of Polynesia. The purpose of this section is to investigate how significant the performance of seafaring technology is for completing voyages, given the range of environmental conditions and routes to complete.

The metric for measuring the difficulty of completing intentional colonisation voyages is the minimum time taken to complete a specific voyage. The mean and standard deviation of the voyaging time is calculated for each performance model for a specific combination of simulation settings. The optimised voyaging time for a specific set of input parameters represents a voyage where the navigator has been able to anticipate the variation in the weather correctly. Consequently, it is safe to assume that any voyaging, in reality, would have taken longer.

Table 8.1: Excerpts of weather data used to simulate the high and low ENSO conditions, the ENSO 3.4 index values are in brackets. Each two quarters were chosen as the two excerpts of data which had the most extreme ENSO 3.4 Index values in the weather data used in Chapter 7.

ENSO Condition	Year	Quarter
High (2.42)	1997	4
	1998	1
Low (-1.70)	2010	4
	2011	1

8.1.1 Climate

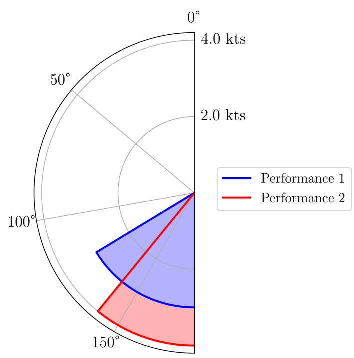
The weather data used focuses on the quarters surrounding the specific high and low ENSO values of the weather data used in the previous investigation, Subsection 7.3. The highest value was 2.42 in December 1997, and the lowest value was -1.71 for January 2011. Table 8.1 summarises the weather data used. ERA 5 reanalysis data was used for the wind data (Copernicus Climate Change Service, 2018).

8.1.2 Parametric performance model

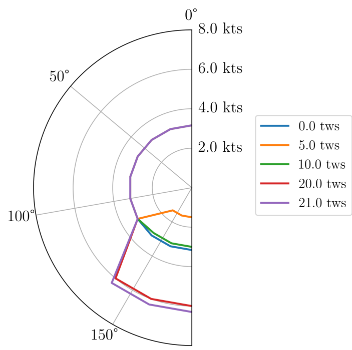
This section introduces a parametric performance model which is based on the Tongiaki. The performance model is parametrically varied to describe historicist and traditionalist views on early Polynesian seafaring technology. It is possible to use this parametric variation to isolate how changes in technology actually influence the ability to complete colonisation voyages. Equation 8.1 describes how the performance of voyaging canoes is a function of the V_s/TWS, β_{Min} and paddling speed. If the apparent wind angle of the wind acting on the canoe is such that it cannot sail, then it is assumed to paddle at a given speed. The BSP/TWS ratio describes the efficiency of the sail set and hull at converting true wind speed into boat speed. This value has previously been used to describe the performance of Polynesian seafaring craft (Finney, 1977). The minimum sail-able wind angle, β_{Min}, is the minimum angle at which the craft is deemed to be sailing and not travelling at the paddling speed.

$$V_s(\text{TWS, TWA}) = \begin{Bmatrix} TWS \times \frac{V_S}{V_T}, & \text{for Min TWA} \leq \text{TWA} \leq 180.0 \\ \text{Paddling speed,} & \text{for } 0 \leq \text{TWA} \leq \text{Min TWA} \end{Bmatrix} \tag{8.1}$$

Figure 8.1a shows how Equation 8.1 can be used to generate two different performance polars. The polars for a specific performance are shown in Figure 8.1b. It can be seen how changes in speed and windward sailing capability actually influence the performance of a voyaging canoe.



(a) Boat speeds for two different performance models for a single wind speed.



(b) Boat performance for a minimum wind angle of 120.0 degrees and a V_s/V_t coefficient of 0.3. Below an TWA of 120^o a paddling speed of 3 kts is assumed.

Figure 8.1: Generating Polynesian voyaging craft polars using the performance model described in Equation 8.1. These figures illustrate how different performance models can be generated and illustrated what a full description of a canoe performance model looks like.

Figure 8.2 illustrates how the two different positions on the performance of

Polynesian seafaring technology are related to speed and windward ability. The traditionalist perspective is associated with selecting evidence which advocates higher speed designs which sail closer to the wind. As the speed and windward ability of the sailing craft decreases, the performance becomes closer to the position proposed by the historicist position.

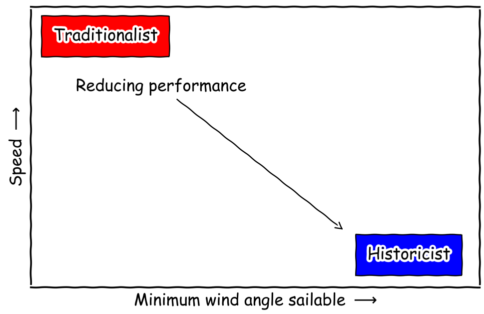


Figure 8.2: Relating performance characteristics to perspectives on Polynesian seafaring performance.

The speed and the windward ability are parameterised in the following manner;

- The speed ratio,V_s/V_t, is varied from 0.2 to 0.5. This range covers a range of potential performances below the performance of the Tongiaki and Outrigger performance models.
- The minimum sail-able wind angle, β_{min}, ranges from 75 to 160 degrees. 75^o was the minimum angle that a reconstructed voyaging canoe was able to sail at, and was taken as the minimum value that a prehistoric voyaging canoe could reach (Finney, 1977).
- The paddling speed of the voyaging canoe was set to be 2.0 kts. This is much lower than the value measured in previous research (Horvath and Finney, 1969), but is likely more representative of an achievable speed over long periods of time.

8.2 Results

The time taken to complete the voyage between Samoa and Aitiutaki was simulated for a range of performance models. The performance models aim to simulate the range of performance characteristics which Polynesian voyaging canoes may have possessed. The performance model was parameterised as in Section 8.1.2. Three performance models were generated for each combination of parameters. One model increases the speed by 10% across all conditions, the second has the speed reduced by 10% and the third has the speed unaltered.

The weather data used covers four quarters and aims to simulate the difference between an El Niño and La Niña climate. Voyages were started every 24 hours with a discretisation of 30nm. A total of 6552 voyages were simulated per quarter.

8.2.1 El Niño

Figure 8.3 and 8.4 show the mean and standard deviation of V_t for the 1997 Q4 and 1998 Q1. It can be seen that the V_t increases as the ability of the performance model decreases, as hypothesised in Figure 8.2. The fastest performance for Q4, 1997 is 32 ± 15.13 days, and the slowest is 75.27 ± 11.3 days. There is a major increase in voyaging time between the two ends of the spectrum. These voyaging times are extremely long relative to the endurance of Polynesian voyaging craft.

The Tongiaki has an average performance ratio of 0.35 over wind speeds from 4 to 30 kts at a TWA of 80^o. The results for $[75, 0.3]$ and $[75, 0.4]$ are averaged to estimate the performance of the $[75, 0.35]$ case. For Q4, 1997, a performance model of $[75, 0.35]$ corresponds to a voyaging time of $V_t = 33.69$ days with a standard deviation of 15.17 days ($V_t = 33.69 \pm 15.17$ days). The simulations from Chapter 7 for this quarter return voyaging times of between $55 - 85$ days for

Q4, 1997. The difference between models is because the uncertain performance model allows paddling, whereas the Tongiaki must complete longer legs to avoid adverse weather. The standard deviation of the voyages appears to peak around the $[100, 0.5]$ performance model, indicating that the changes in minimum sailable wind angle for lower speeds are influential.

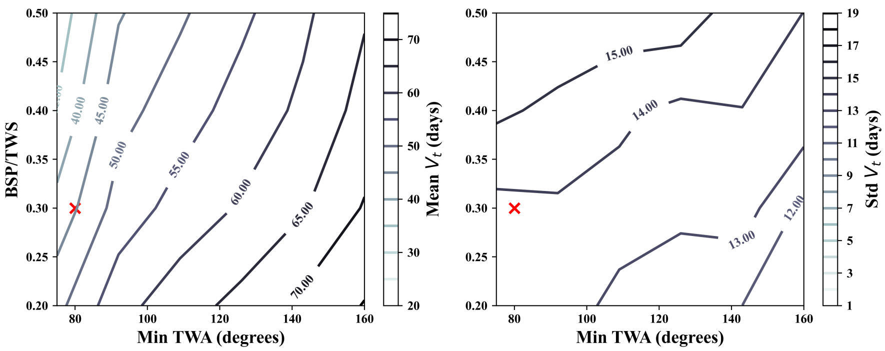


Figure 8.3: The mean (left Figure) and standard deviation (right Figure) of V_t for 1997 Q4 for the uncertain performance model. The performance model of the Tongiaki is marked with a red cross.

For Q1 1998, the fastest performance is 22.9 ± 12.0 days and the slowest returns a V_t of 73.45 ± 11.2 days. These times are slightly faster than the previous quarter. The $[75, 0.35]$ model returns a time of $V_t = 24.3 \pm 11.78$ days, which is faster than the weekly voyaging times for the Tongiaki for $42 - 65$ days. This difference is again likely due to the introduction of the paddling model, as this is the only change in performance model.

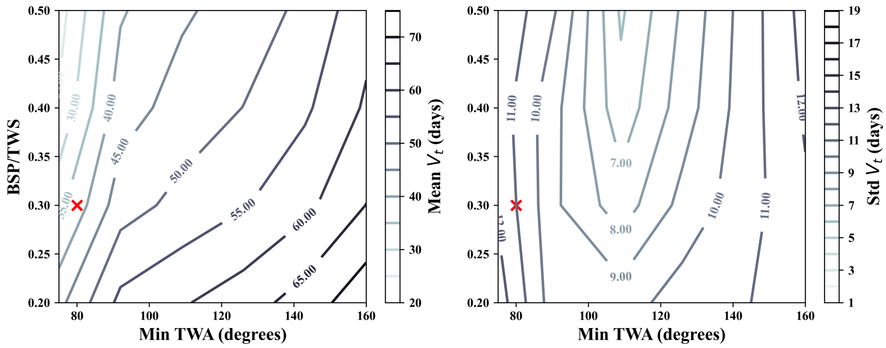


Figure 8.4: The mean (left Figure) and standard deviation (right Figure) of V_t for 1998 Q1 for the uncertain performance model. The performance model of the Tongiaki is marked with a red cross.

8.2.2 La Niña

The variation in V_t for 2010 Q4, shown in Figure 8.5, is similar to the El Niño simulations. The fastest time was $V_t = 51.2 \pm 15.2$ days, increasing to 77.7 ± 7.8 days. The $[75, 0.35]$ performance model took 52.82 ± 14.78 days which is similar to the Tongiaki mean weekly voyaging times of between $45 - 85$ days. The reduction in voyaging time relative to the El Nino is likely due to the less favourable wind conditions seen in the La Niña ENSO condition. This means that all the canoes will be travelling slowly, even if the wind angle allows them to sail.

The fastest and slowest performances for Q1, 2011 are 50.56 ± 12.8 days and 77.7 ± 9.44 days, Figure 8.6. The $[75, 0.35]$ performance model returned a time of 52.02 ± 13.15 days. The Tongiaki completed voyages lasting between $45 - 75$ days which is similar to the $[75, 0.35]$ performance model.

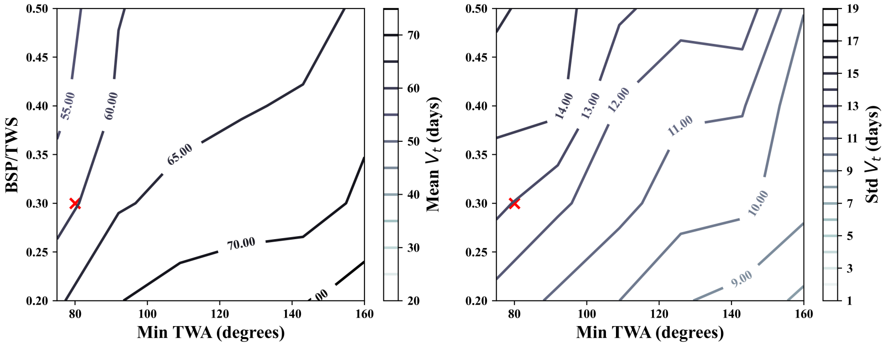


Figure 8.5: The mean (left Figure) and standard deviation (right Figure) of V_t for 2010 Q4 for the uncertain performance model. The performance model of the Tongiaki is marked with a red cross.

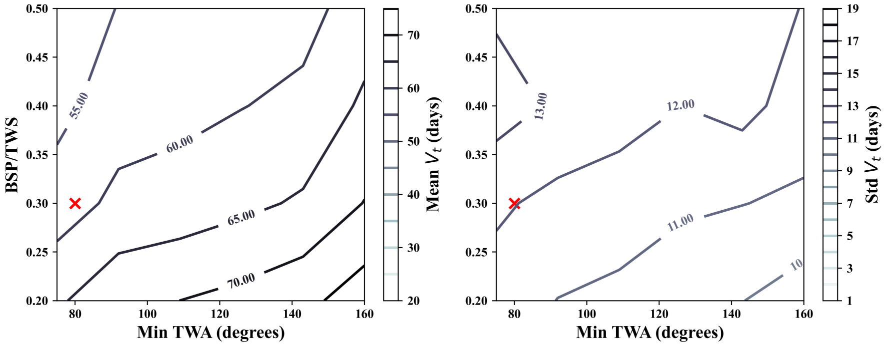


Figure 8.6: The mean (left Figure) and standard deviation (right Figure) of V_t for 2011 Q1 for the uncertain performance model. The performance model of the Tongiaki is marked with a red cross.

8.2.3 Trends in performance

Slices of the data sets have been taken to identify whether non-linear behaviour exists in V_t as a function of speed and minimum wind angle variation. If non-linear behaviour exists, it may offer insight into potential step changes in performance which could have led to improved voyaging performance. The aim of the following figures are to isolate the influence of performance, minimum wind angle and the combination of the two. Section 8.2 focused on identifying plausible ranges of parameters which could describe the performance of the Polynesian voyaging canoes, the voyaging times presented here serve to compare parameters rather than to present sensible potential designs.

Figure 8.7 shows the relationship between the mean V_t and wind angle for a fixed performance level. There is an increase in V_t across all quarters as the minimum wind angle sailable increases. The magnitude of this increase in V_t reduces as wind angle increases. This trend indicates that until seafaring technology allowed voyaging canoes to sail below approximately 92.0^o, the minimum wind angle of sailing craft would not have significantly influenced the results. At this point, it would have been possible for a sailing craft to complete upwind voyages. The parametric canoe performance models presented in this Figure take longer to complete the the Samoa to Aituitaki voyage longer than the designs examined in Chapter 7, it should be noted that at $BSP/TWS = 0.2$ they are 57.4% of the speed of the Tongiaki.

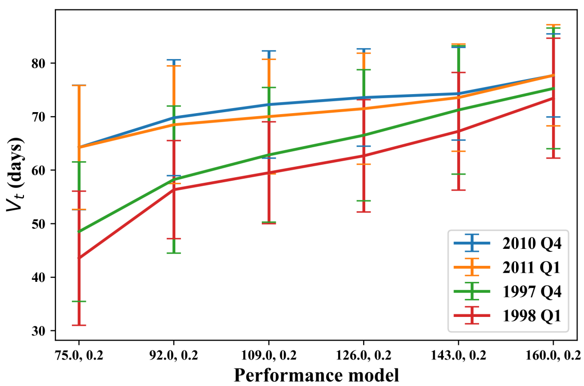


Figure 8.7: Variation of V_t for a fixed performance level for all quarters simulated, the standard deviation is plotted as the error bar. The nomenclature $[75, 0.2]$ describes a performance model with a V_s/V_t of 0.2 and a minimum true wind angle of 75.0^o.

Figure 8.8 shows that increases in voyaging canoe speed reduces V_t. The time reduction is larger for the El Niño weather periods than the La Niña weather periods. As the performance of a voyaging canoe improves, so too does V_t. The relationship between speed and V_t appears to be linear, as expected. It appears that the maximum speed of a voyaging canoe is not as influential as the minimum wind angle it may sail at as the changes between performances are not as substantial.

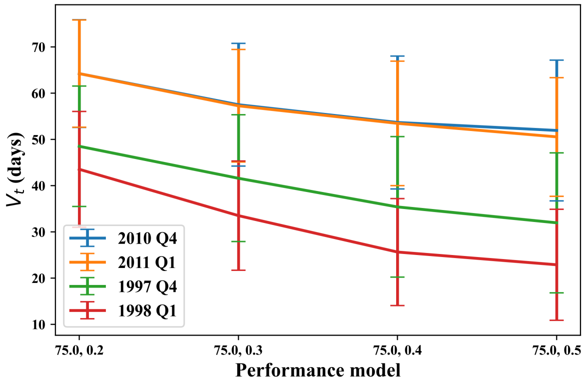


Figure 8.8: Variation of V_t for a fixed minimum wind angle.

Figure 8.9 takes a slice through the diagonal of each data set. This slice is used to compare the influence of increasing speed against that of improving windward ability. If the influence of speed was equal to the influence of windward ability for this range of parameters then the plot should be level. The El Nino quarters (1997, Q4 and 1998, Q1) have shorter mean voyaging times than the La Nina quarters by approximately $10 - 15$ days, suggesting a correlation between season and voyaging time.

In Figure 8.9 the El Nino seasons the performance models between $[92, 0.3]$ and $[120.0, 0.5]$ appear to have a level trend but see a reduction in voyaging time for the $[75, 0.2]$ model. The trend indicates that windward ability is more influential than speed. The step change in performance between $[75, 0.2]$ and $[92, 0.3]$ suggests that the ability to sail upwind, rather than on a beam reach, reduces the time taken to complete the voyage. There is no clear trend for 2010, Q4 and the trend for 2011, Q1 indicates that the speed dominates the influence of windward ability.

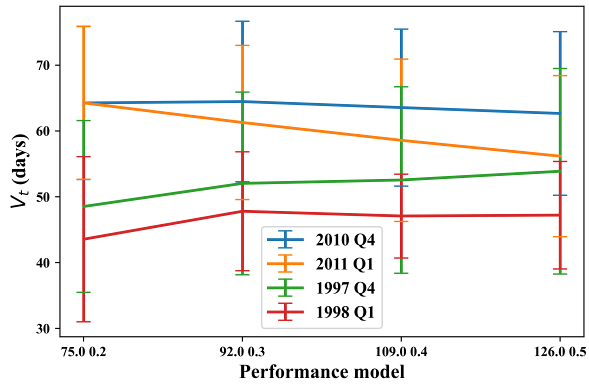


Figure 8.9: Variation of V_t for increasing speed and increased minimum wind angle.

It can be seen across Figures 8.7, 8.8 and 8.9 that Q1 for both low and high weather excerpts are lower than Q4. The high index weather excerpts have lower V_ts than the low index weather conditions. This change may indicate that the latter part of the Austral summer is better than the first half and that there could be a relationship between climate condition and voyaging time.

Section 7.5.2 has suggested that there was little evidence for a linear relationship between climate index and V_t. The figures reviewed in this section have shown that there is a slight difference in voyaging time between different climate conditions and season. The focus of the next section is the identification of the magnitude of these differences, and on whether these differences are significant.

8.3 Quantifying the influence of environmental variables

Section 8.2.3 identified the existence of a qualitative difference in V_t as a function of climate data. Identifying whether the climate or the season has a more considerable influence on voyaging time has an impact on understanding how prehistoric voyagers may have endured different weather conditions. It could be possible that the response of the island ecosystem drove the decision to voyage. For example, if it was possible to sail equally well despite changes in climate then an unexpected drought could have caused people to migrate Eastwards.

The problem of identifying whether climate or season has a greater influence on V_t can be reduced to the problem of comparing two sets of data. Multiple statistical methods exist which can compare two sets of data. Previous work in Polynesian voyage modelling has used the frequentist t-test to compare two sets of voyaging results. Evans (2008) was able to show that the two sets of voyaging time data were definitively different. However, this methodology was not able to provide statistically justified answers as to the difference in magnitude. Bayesian estimation can provide information on the difference in mean of the two sets of data, the difference in standard deviation and the effect size (Kruschke, 2013).

Challenges with the application of frequentist null hypothesis significance testing include the challenge of relating choices and interpretations of the null hypothesis h_0 or significance level P to the actual problem (Johnson, 1999). Further issues relate to the lack of information a single hypothesis gives the investigator (Goodman, 1999). Bayesian estimation is better able to statistically compare two data sets in order to identify meaningful information about how they differ.

8.3.1 Method

This analysis applies the methodology of Bayesian estimation for comparing two sets of data (Kruschke, 2013). This is because Bayesian estimation allows the probabilistic quantification of the difference between data sets. This is more accurate and faster than running multiple frequentist hypothesis tests to calculate the same quantity.

The data used is the same as for Section 8.2. This methodology involves specifying what prior information exists on the data being compared and then updating this prior information with the experimental data in order to return a posterior distribution which describes the current knowledge on the behaviour of the data.

Both sets data are assumed to behave like a Student-t distribution, Equation 8.2. The mean prior, μ for both data sets is assumed to be Normally distributed with a mean of the total data set and a standard deviation of twice the standard deviation of the data set. The prior standard deviation of each data set is assumed to lie between 48 and 240 hrs. These priors apply very diffuse information and do not favour either data set a priori.

$$f(x|\mu,\lambda,\nu) = \frac{\Gamma(\frac{\nu+1}{2})}{\Gamma(\frac{\nu}{2})}\left(\frac{\lambda}{\pi\nu}\right)^{\frac{1}{2}}\left[1+\frac{\lambda(x-\mu)^2}{\nu}\right]^{-\frac{\nu+1}{2}} \tag{8.2}$$

A uniform probability distribution of between 1 and 10 days is assumed for the group standard deviations. Different values for ν were varied from 3 to $n-1$ where n is the number of samples and were found to have little influence on the final results. $n-1$ was used as the final value for ν. The Highest Posterior Density (HPD) is analogous to a credible interval, and indicates the most probable range of values which an unobserved parameter could fall within.

8.3.2 Results

Table 8.2 shows the statistics comparing the results of the two-quarters of weather data, Q4 and Q1. There is a difference of 7.33 days (95% HPD interval of 6.98 – 7.68) between the two quarters.

Table 8.2: Statistics comparing Q4 and Q1 data sets. Positive numbers mean that Q4 results are higher than Q1.

	Mean	**Standard Deviation**	**Error**	$\mathrm{HPD}_{2.5}$	$\mathrm{HPD}_{97.5}$	n_{eff}	$\hat{R}$
Mean difference	7.33	0.18	0.0	6.98	7.68	11302.03	1.0
Std difference	0.0	0.0	0.0	-0.01	0.01	10075.14	1.0
Effect size	0.73	0.02	0.0	0.7	0.77	11305.18	1.0

The analysis comparing El Niño and La Niña voyaging times is recorded in Table 8.3. El Niño has a mean V_t which is 11.73 days (95% HPD interval of 11.39 – 12.06) shorter than La Niña. The effect size is -1.17 (95% HPD interval of 1.14 – 1.14).

The difference between El Niño and La Niña is more substantial than that for seasonality alone. These results indicate that ENSO is a significant influence on completing voyages between Samoa and Aituitaki.

Table 8.3: Statistics comparing El Niño and La Niña data sets. Negative numbers indicate El Niño has faster V_t than La Niña.

	Mean	**Standard Deviation**	**Error**	$\text{HPD}_{2.5}$	$\text{HPD}_{97.5}$	n_{eff}	$\hat{R}$
Mean difference	-11.73	0.17	0.0	-12.06	-11.39	11955.67	1.0
Std difference	0.0	0.01	0.0	-0.01	0.02	10862.01	1.0
Effect size	-1.17	0.02	0.0	-1.21	-1.14	11966.53	1.0

8.4 Discussion

The performance model introduced in Section 8.1.2 produces similar results to the Tongiaki results, as described in Section 8.2. The Tongiaki performance model cannot paddle if the weather conditions are unfavourable. The inability to paddle explains why the Tongiaki returns slightly higher V_t results than for a $[0.35, 75^o]$ model, averaged results between the $[75, 0.3]$ and $[75, 0.4]$ models respectively.

An investigation into the influence of sail size on the speed attainable by a Tongiaki found that for a sail size of 80m^2 it was possible to vary the performance by $12.5 - 13.2\%$ through increasing or decreasing the sail area by 30m^2 (Section 4.5). This investigation illustrates how changes of around 10% in the performance of a canoe could be achieved, and justifies the use of varying the original performance model by $\pm 10\%$. The modelling presented in Section 8.2 showed that a wide range of voyaging times were possible even for a single performance model. This analysis demonstrates that variations within a single design are possible through directly manipulating design parameters and do contribute towards changes in the predicted voyaging time, which is corroborated with the analysis described in

Section 6.4.2.

The results in Section 8.2.3 show that windward ability has a more significant influence on V_t than the speed of the performance model. The ability to sail into the wind reduces the distance that the voyaging canoe would have to sail, especially given the prevailing wind and wave conditions in East Polynesia. The improved windward ability gives a navigator more options when identifying suitable routes and weather conditions to sail in.

The windward performance of Polynesian sail designs improved from West to East (Di Piazza, 2014). The Polynesian hull design changed from a 'U' to 'V' shape from West to East . The change in Polynesian hull design from West to East also resulted in better windward performance. The simulation results contribute towards an understanding of how exactly improvements in windward performance contribute towards improved voyaging times. These results indicate that it is highly likely that changes in seafaring technology would have contributed towards the ability to make the crossing between Samoa and Aituitaki.

The analysis in Section 8.3 has shown that ENSO has a more significant impact on V_t than seasonality. Seasonality still influences V_t. These results are the first results where the influence of ENSO on voyaging have been demonstrated using the performance of Polynesian voyaging canoes. These results agree with those of earlier research which identified that ENSO influences Eastwards voyaging (Montenegro et al., 2014).

The V_t results are likely high as the model simulates for all weather conditions, not just the ones most suited to Eastwards voyaging. Navigators would have been able to avoid or wait for bad weather conditions to pass, this would lower the mean voyaging time but would also result in periods of the year where voyaging would not have been conducted.

8.5 Summary

This chapter has investigated the influence of uncertain performance characteristics and different environmental conditions on time taken to complete a voyage between Samoa and Aituitaki. The dominant performance characteristic is the ability to sail into the wind. This characteristic mirrors the improvements in windward sailing ability seen in Polynesian sail and hull design. The archaeological and modelling evidence suggests that an improvement in windward sailing capability enabled Polynesians to sail to Central East Polynesia.

The second analysis in this chapter compared the V_t for different ENSO and seasons. It was seen that the El Niño V_t results were significantly lower than the contribution from seasonality. These results add to previous work by illustrating the influence of ENSO using Polynesian canoe performance models within a higher fidelity model.

The influence of windward ability on the voyaging time indicates that it was a significant factor which would have determined the success of any exploration or colonisation effort. It is highly likely that the windward ability of the Tongiaki would have hampered it being sailed outside of strong El Niño conditions. Developments in hull and sail technology which improved windward ability would also significantly improve the chances of completing voyages in Polynesia. The improved windward performance of the Outrigger would have naturally deselected the Tongiaki as the craft of choice, as was recorded by later European explorers.

Chapter 9

Conclusions

This thesis has investigated how modelling engineering and archaeological uncertainty contributes towards the understanding of Polynesian voyaging throughout the “long pause”. The thesis has generated insight into several critical areas through developing a novel methodology to model key voyages within Polynesia under varied weather conditions using different voyaging canoe models. The contributions of this thesis to Polynesian marine archaeology are listed in Table 9.1.

The *Tongiaki* is the earliest recorded example of Polynesian seafaring technology. This thesis has presented a performance model which combines previous experimental work on the performance of *Tongiaki* sail and hull design. The performance prediction of the *Tongiaki* was limited to 75^o AWA in line with the stable performance achieved by reconstructed voyaging canoes. The performance of the *Tongiaki* over predicts the performance due to the inability of the performance model to estimate sources of friction accurately. Changes in performance of between 12.5% and 40% were achieved by modifying the sail area by 30% to 60%m^2. The measured change in performance of the Tongiaki as a response to design parameter variation illustrates how the linear variation in performance model captures a range of design modifications which alter the performance of a Polynesian voyaging canoe.

This thesis has presented new results comparing the voyaging times of two Polynesian voyaging canoes over different routes and environmental conditions. The Outrigger is the name given to the performance model of a later Polynesian voyaging canoe (Irwin and Flay, 2015). The Outrigger outperformed the *Tongiaki* over all routes and in all weather conditions. The archaeologically recorded change from *Tongiaki* to n'Drua design is a consequence of improved performance, as is reflected in voyaging simulations. It is likely that only a fast and weatherly design, such as the Outrigger, could have enabled reliable voyaging throughout Polynesia. However, the simulations still show that the Tongiaki might have been able to complete voyages if the crew were able to have an endurance of $3-4$ weeks rather than the $2-3$ suggested by contemporary European sailors (Cook, 1777).

A theme in Polynesian archaeology is on how archaeological evidence on Polynesian seafaring technology is used to infer the performance of Polynesian canoes in prehistoric times. The "Historicist" and "Traditionalist" perspectives have opposing views on whether the Polynesian voyaging canoes used at the time of the long pause were slower or faster than is advocated for. This thesis has illustrated how it is possible to use different parameters to describe these different perspectives. Although given the lack of evidence it is quite possible that both of these perspectives do not capture the designs used in reality.

The challenge of completing voyages from West to Central East Polynesia increases significantly across any performance that has been modelled in this thesis. The last colonisation journey made in West Polynesia was between Tonga and Samoa. The journey from Samoa to Aituitaki enabled the colonisation of Central

East Polynesia. Simulations quantify that the Samoa to Aituitaki voyages are significantly longer, thus harder than those taken between Tonga and Samoa.

A parametric performance model was implemented to understand how different aspects of Polynesian canoe performance influence voyaging time. Simulations were undertaken to quantify the influence of windward capability and speed on voyaging time. This analysis showed that the ability to sail into the wind was more influential than improving speed performance alone. These simulations link the archaeologically known improvements in Polynesian seafaring technology to the reality that these improvements would have significantly improved the success of colonisation voyaging.

None of these new insights into the Polynesian archaeology would have been possible without the development of an engineering methodology which could quantify the influence of uncertainty in the marine weather routing process. This method integrated the quantification of numerical error, performance model uncertainty and weather uncertainty on voyaging time predictions. The methodology for investigating how the reliability of a sailing craft design could influence voyaging route was applied to modelling Autonomous Sailing Craft routing. The validation of the reliability in routing method enables future research investigate the influence of Polynesian sailing canoe reliability on the time taken to complete colonisation voyages safely.

This methodology was applied to the Tonga to Samoa voyage to quantify the contribution of uncertainty in weather, performance model and numerical error to the prediction of voyaging time. The numerical error was found to be an average of 0.09%, which is roughly 10 hours over a 33 day voyage. This error would be significant for modelling racing craft but unlikely to be considered for other purposes. Regardless, quantifying the numerical error is essential for giving secure context to the V_t predictions.

The influence of weather dominates uncertainty in marine weather routing. However, even small variations in performance model uncertainty contribute to significant changes in voyaging time. This result has broader implications for marine weather route modelling for any purpose. Understanding how performance uncertainty contributes towards variation in V_t is a necessary step in any marine routing application. The ability to leverage high-performance computing resources using a modern programming language has been essential to the ability to perform thousands of simulations.

This thesis has presented new insight into how seafaring technology and environmental conditions influenced the length of the "long pause" between the colonisation of West and Central East Polynesia. It has shown that the performance of the earliest recorded example of Polynesian seafaring technology could have made the crossing to Central East Polynesia, although only in El Niño conditions. The probability of making successful colonisation voyages was increased through developments in improving windward sailing capability. A novel marine weather routing methodology underpins these results for modelling a range of different areas of uncertainty.

Table 9.1: Contributions of this thesis to Polynesian archaeology.

Area	**Existing knowledge**	**Contribution**
Tongiaki performance	No performance predictions for the *Tongiaki* (Section 4.2.3).	Performance model for the *Tongiaki* produced based on relevant models of the sail and hull forces (Section 4.5).
Comparative performance of Polynesian seafaring technology performance models	No knowledge into the relative performance of Polynesian voyaging canoes from the era of the long pause.	The Outrigger voyaging canoe is significantly faster than the *Tongiaki* over all routes and conditions (Section 7.5).
Variation in seafaring technology	Archaeological evidence for the improved windward performance of Polynesian seafaring technology as the originating location of the technology moves from West to East (Section 4.2.3).	Improvements in windward capability are more useful than improvements in speed for completing the key voyage between Samoa and Aituitaki (Figure 8.9).
Influence of weather variability	ENSO has been identified as an influencing factor.	• The influence of ENSO on voyaging between West and CEP has been quantified. ENSO significantly influences the ability to complete voyages between West and Central East Polynesia (Section 8.3). • The *Tongiaki* can only complete voyages to Aituitaki in El Nino conditions (Figure 7.12)
Voyaging routes, pre- and post-long pause	• Navigational boundary identified East of Samoa (Di Piazza, 2014) • Shortest path modelling using simple performance models (Table 5.1).	• Voyaging between West and Central East Polynesia is significantly harder than within West Polynesia using sailing craft performance models (Figure 7.14 compared with Figure 7.15). • Voyaging within West Polynesia is not influenced by ENSO (Figure 7.14).

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Chapter 10

Future work

This thesis has shown how environmental and technological factors would have influenced the challenge of sailing between West and East Polynesia, thus ending the period of the long pause. However, questions remain surrounding the role of human factors, specific elements of seafaring technology and the role of specific weather patterns.

Human factors drive the full understanding of the challenge of colonising Central East Polynesia. Contextualising changes in seafaring technology, considering other factors is the next logical step in the study of Polynesian archaeology.

The ability to model sailing craft reliability within the routing algorithm has proven useful for identifying safer routes for autonomous sailing craft. Future research would involve developing the routing model to include the modelling of Polynesian sailing craft reliability. The materials used in the rigging of Polynesian voyaging canoes are known to reduce performance significantly in wet conditions. Identifying the exact performance reduction as a consequence of wet conditions would add new insight into the challenges faced by Polynesian sailors.

Introducing a time-dependent current model would improve the accuracy of the simulations. It would likely reduce the voyaging times in the El Niño phase and increase the voyaging times for La Niña. Generating the current data would require running specific simulations of an ocean circulation model. Alternative source of reanalysis weather data could be investigated. The influence of wave conditions on the performance of a voyaging canoe hull must be investigated, as this data would provide more evidence on how Polynesians might have fared at sea.

Investigating the added wave resistance experienced by a Polynesian seafaring canoe through experiment would allow the influence of waves to be considered within the routing model. Currently, it is only possible to infer the influence of the waves from the wind as the mechanism generating them is linked. It will be possible to improve the realism of the analysis by improving the performance model of the Tongiaki through including its response to added wave resistance.

A large amount of data generated presents new opportunities for data analysis for understanding and modelling sailing craft routing. One such opportunity lies in the use of clustering techniques for statistically identifying popular routes and weather conditions. This method would present an alternative way for analysing optimum routes rather than merely providing a single average optimum solution.

The opportunity to investigate multiple engineering problems have been generated from implementing an open-source software package for performing marine weather routing simulations. It is possible to use this package with high-performance computing resources to simulate thousands of different combinations of settings. This can be used to model commercial routing problems to a higher level of detail for a negligible time cost.

Part I

Appendix

Appendix A

Supporting equations

A.0.1 Temporal wind model

A wind model is required to introduce known quantities of stochasticity into the routing model. The key requirement of the weather model is that is able to generate realistic weather data which has a known quantity of stochasticity. The method presented here is a modified version of the stochastic wind model used in (Dalang et al., 2015; Philpott et al., 2004). This method is modified to consider the wind as a function of a North-South component V and an East-West component U, where $U, V \in \mathbb{R}$. It is assumed that the craft sails to the wind it is experiencing at the current moment and that the wind condition is independent of location.

The simplest possible model assumes that each of the vector components consists of a trend and fluctuations around this trend, this gives Equation A.1. The processes $X = (X_t, t \in \mathbb{R}_+)$ and $Y = (Y_t, t \in \mathbb{R}_+)$ are defined by the stochastic differential equations in Equations A.1 and A.2.

$$U_t = X_t + \mu_u t \qquad V_{tws} = Y_t + \mu_v t \tag{A.1}$$

$$dX_t = -s_x X_t + \sigma_x dB_t^1 \qquad dY_t = -s_y Y_t + \sigma_y dB_t^2 \tag{A.2}$$

There are several assumptions that must be made in order to apply this model;

- The processes U and V are independent. This is not the case in reality (Hering et al., 2015), but is satisfactory for the purpose of generating stochastic weather conditions.
- Each noise process (B_t^i) has independent increments.
- The noise processes are Gaussian. There is not enough data to argue against this assumption (Philpott et al., 2004).
- The parameters $s_u = s_v = 0$, so U_t and V_{tws} are Brownian motions with drifts.

Subsequently there are four parameters that are available to fit to wind data if required; $\mu_x, \mu_y, \sigma_x, \sigma_y$. To generate samples from the stochastic differential equations presented the Euler-Maruyama method is one popular method that provides an approximate solution. An example stochastic differential equation is shown in Equation , with initial condition $X_0 = x_0$, where W_t is the Wiener process, also known as Brownian motion, and the time interval to be solved over is $[0, T]$. a and b are functions of X_t.

$$dX_t = a(X_t)dt + b(X_t)dWt \tag{A.3}$$

The Euler-Maruyama approximation to the true solution X is the Markov chain Y. Initially the time interval is partitioned into N equal sub intervals of width $\Delta t > 0$ as shown in Equation A.4.

$$0 = \tau_0 < \tau_1 < ... < \tau_N \text{ and } \Delta t = T/N \tag{A.4}$$

Then $Y_0 = x_0$ and Y_n is recursively defined for $1 \leq n \leq N$ using Equation A.5 where $\Delta W_n = W_{\tau_{n+1}} = W_{\tau_n}$. The random variables ΔW_n are independent and normally distributed random variables with expected value 0 and variance Δt.

$$Y_{n+1} = Y_n + a(Y_n)\Delta t + b(Y_n)\Delta W_n \tag{A.5}$$

Example wind plots can be seen in Figures A.1 and A.2. These are examples of a single wind scenario generated using Brownian motion. The wind being simulated is coming from the North and has no drift component. The initial values of U and V, the x and y components of the wind vector, were 0.0 and 10.0 and then $\sigma_x, \sigma_y = 0.1$.

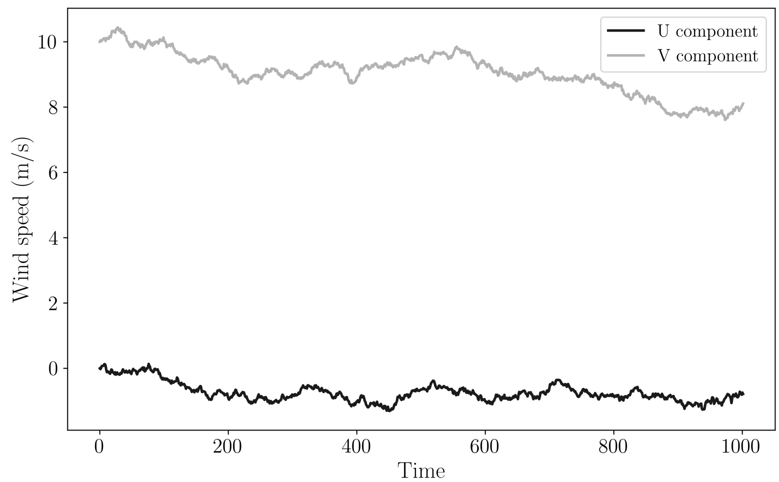

Figure A.1: Trace of synthetic wind generated using Brownian motion.

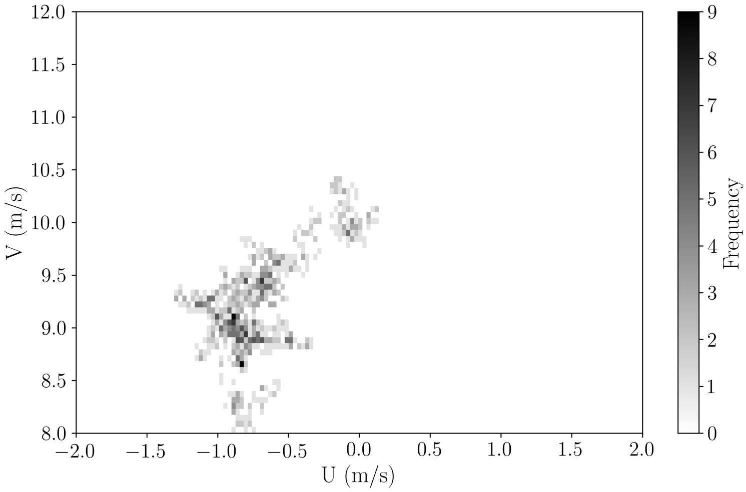

Figure A.2: Example synthetic wind histogram plot.

Appendix B

Route modelling results

B.1 Weekly voyaging times

Figures B.1 - B.6 show the weekly voyaging times for the three routes which are simulated in the results in Chapter 7.

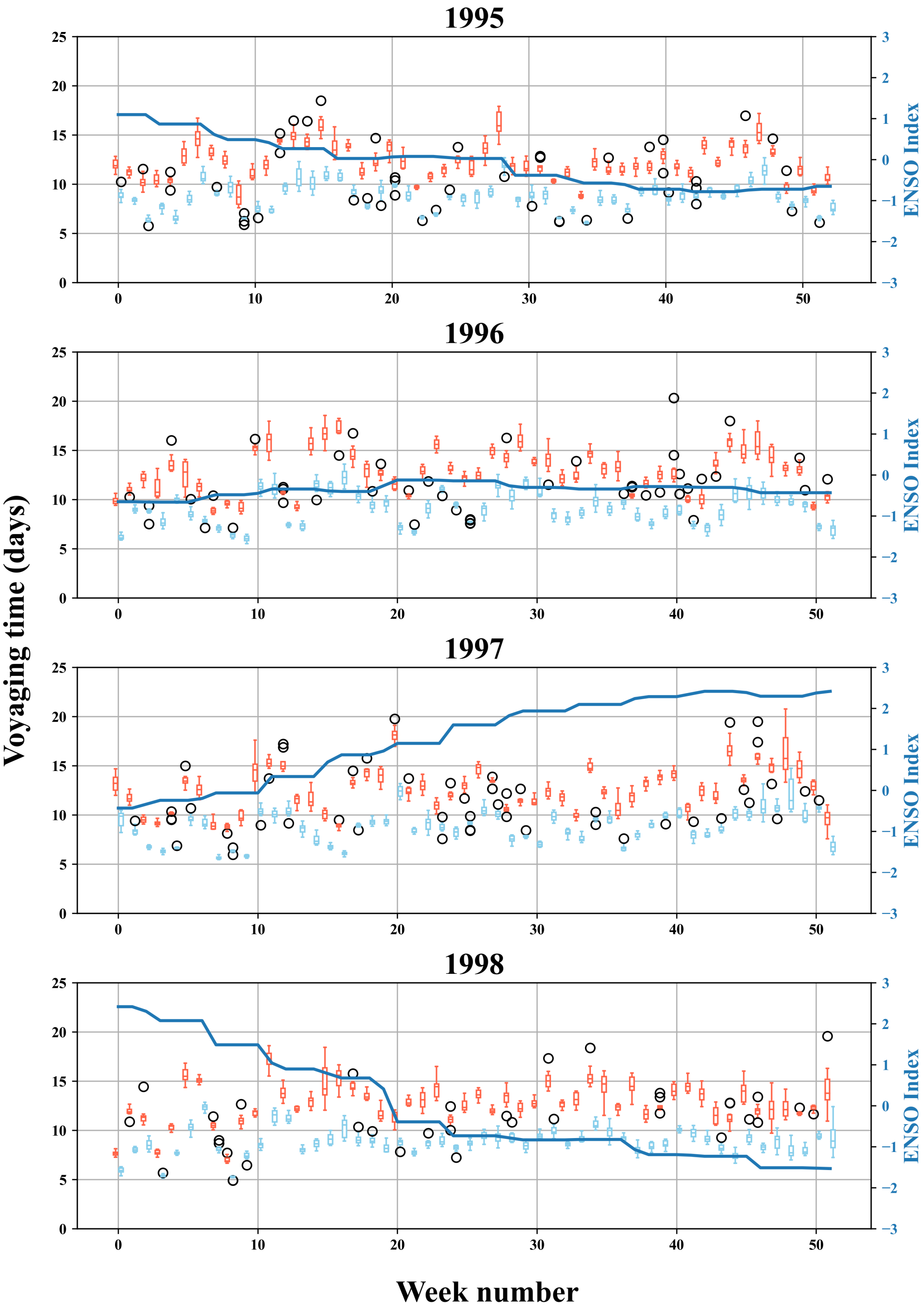

Figure B.1: Mean weekly voyaging times over the Vavau to Upolu route for 1995-1998.

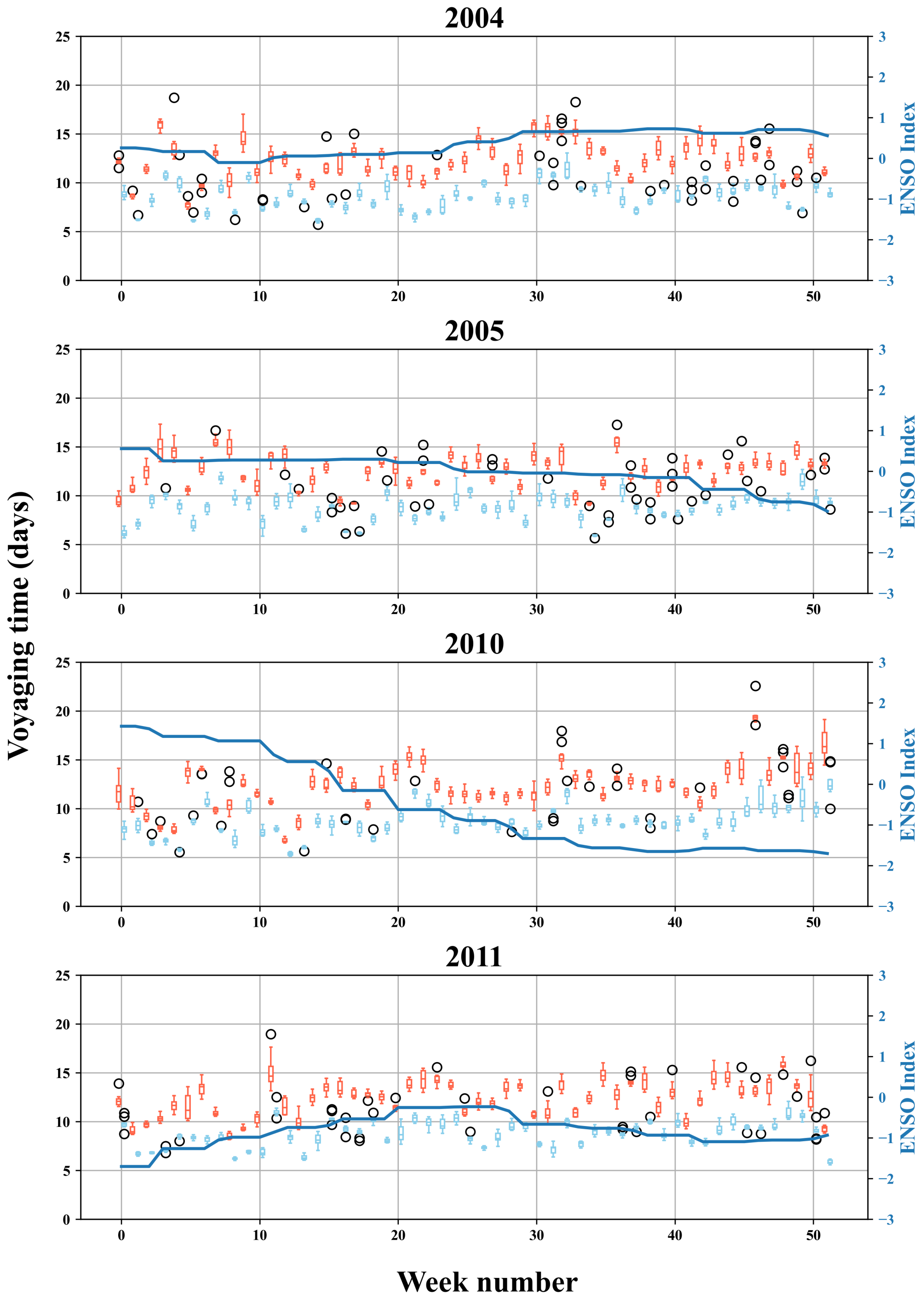

Figure B.2: Mean weekly voyaging times over the Vavau to Upolu route for 2004-2005 and 2010-2011.

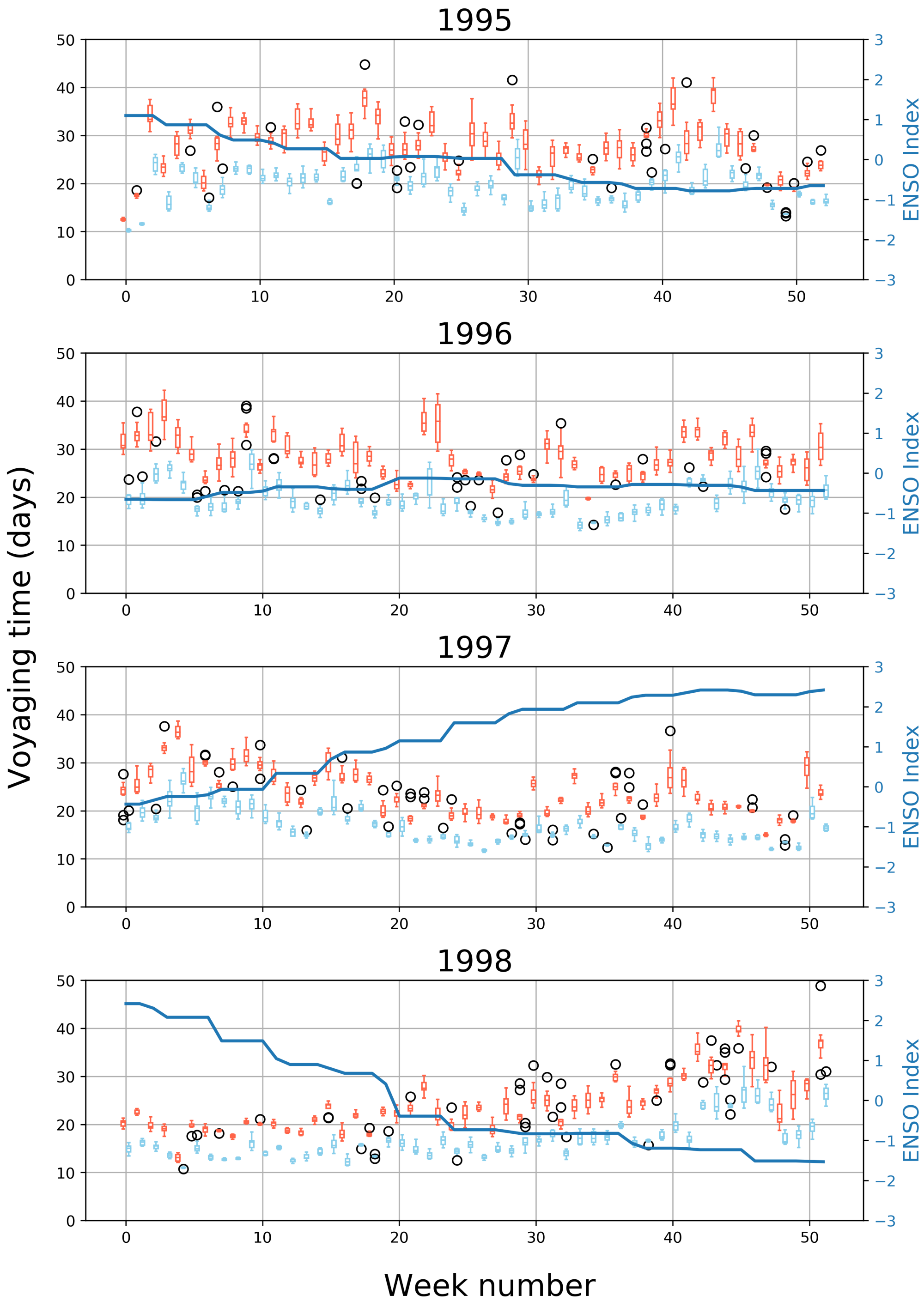

Figure B.3: Mean weekly voyaging times over the Samoa to Aituitaki route for 1995-1998.

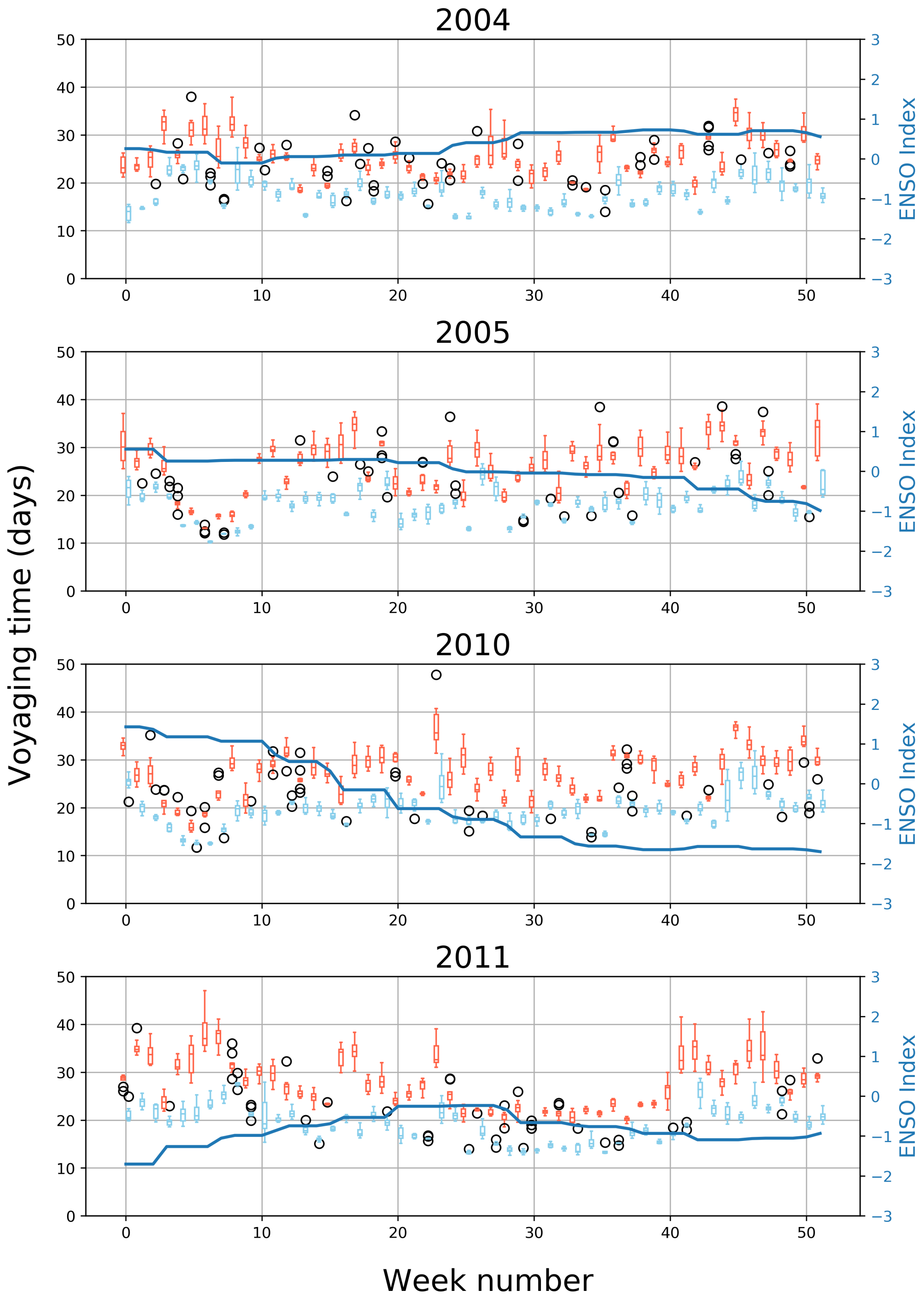

Figure B.4: Mean weekly voyaging times over the Samoa to Aituitaki route for 2004-2005 and 2010-2011.

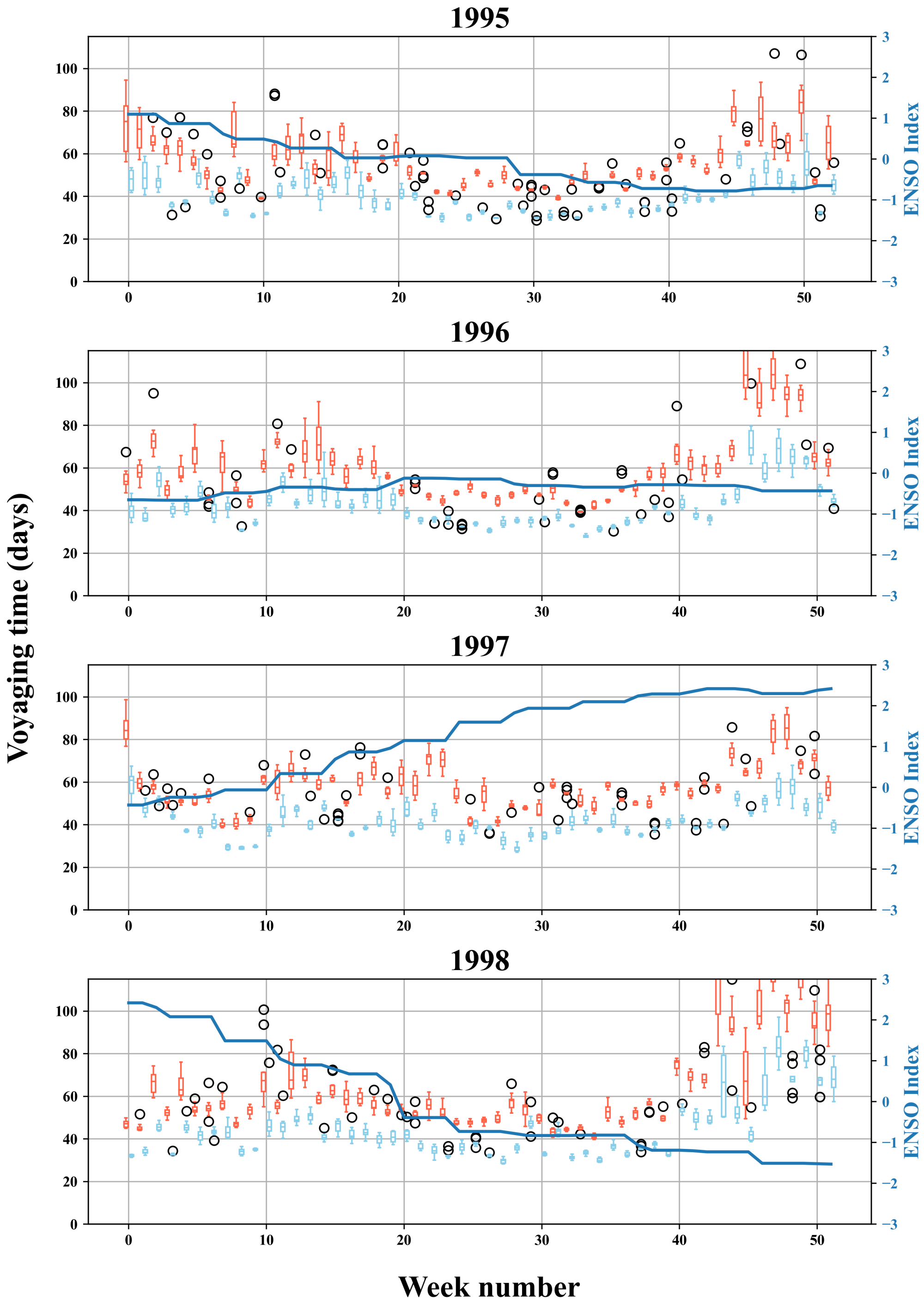

Figure B.5: Mean weekly voyaging times over the Tonga to Tahiti route for 1995-1998.

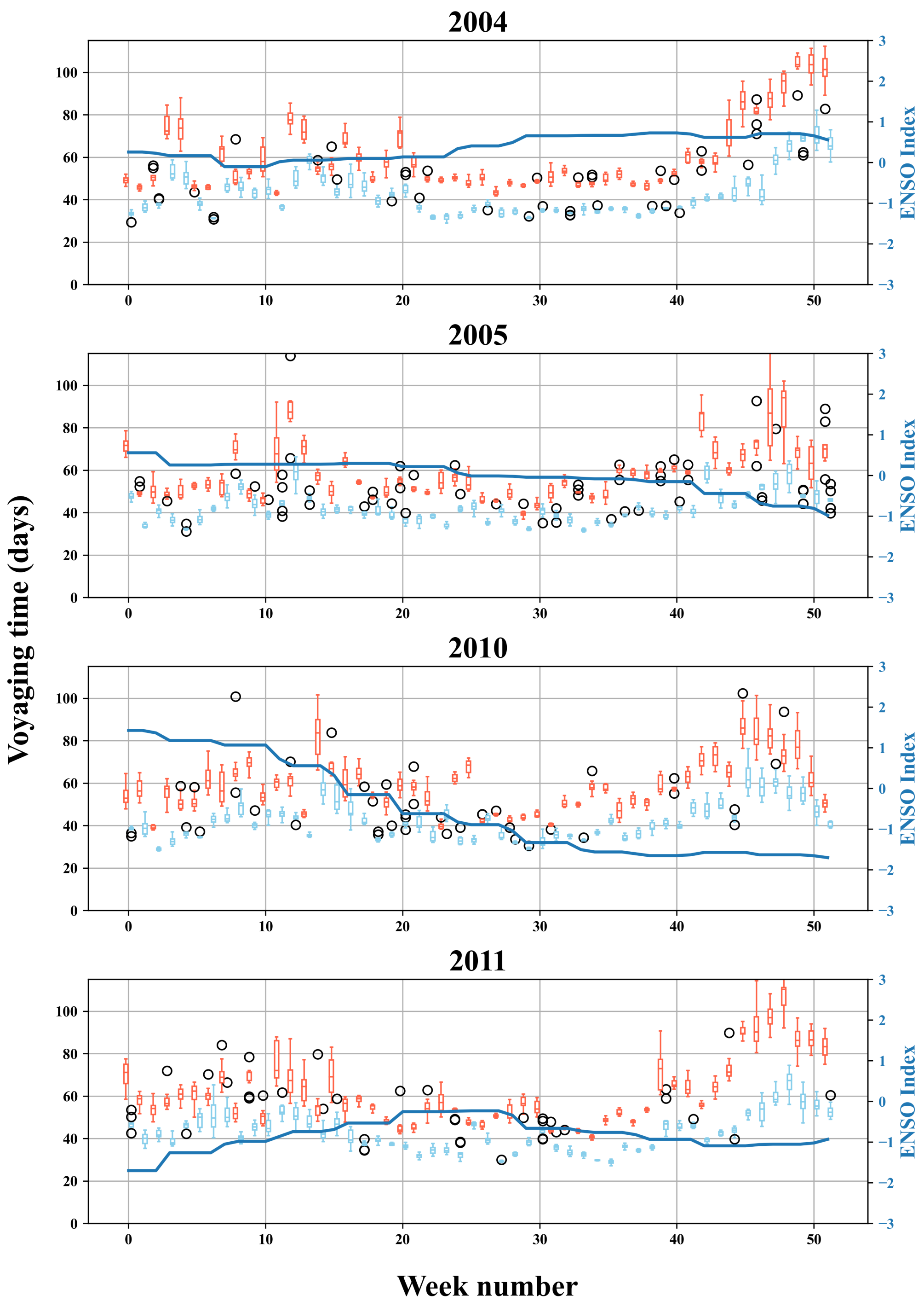

Figure B.6: Mean weekly voyaging times over the Tonga to Tahiti route for 2004-2005 and 2010-2011.

B.2 Quarterly Heatmaps

Figures B.7 - B.12 show the quarterly voyaging heatmaps for each year of weather data. The colour bar shows the frequency for each location being visited.

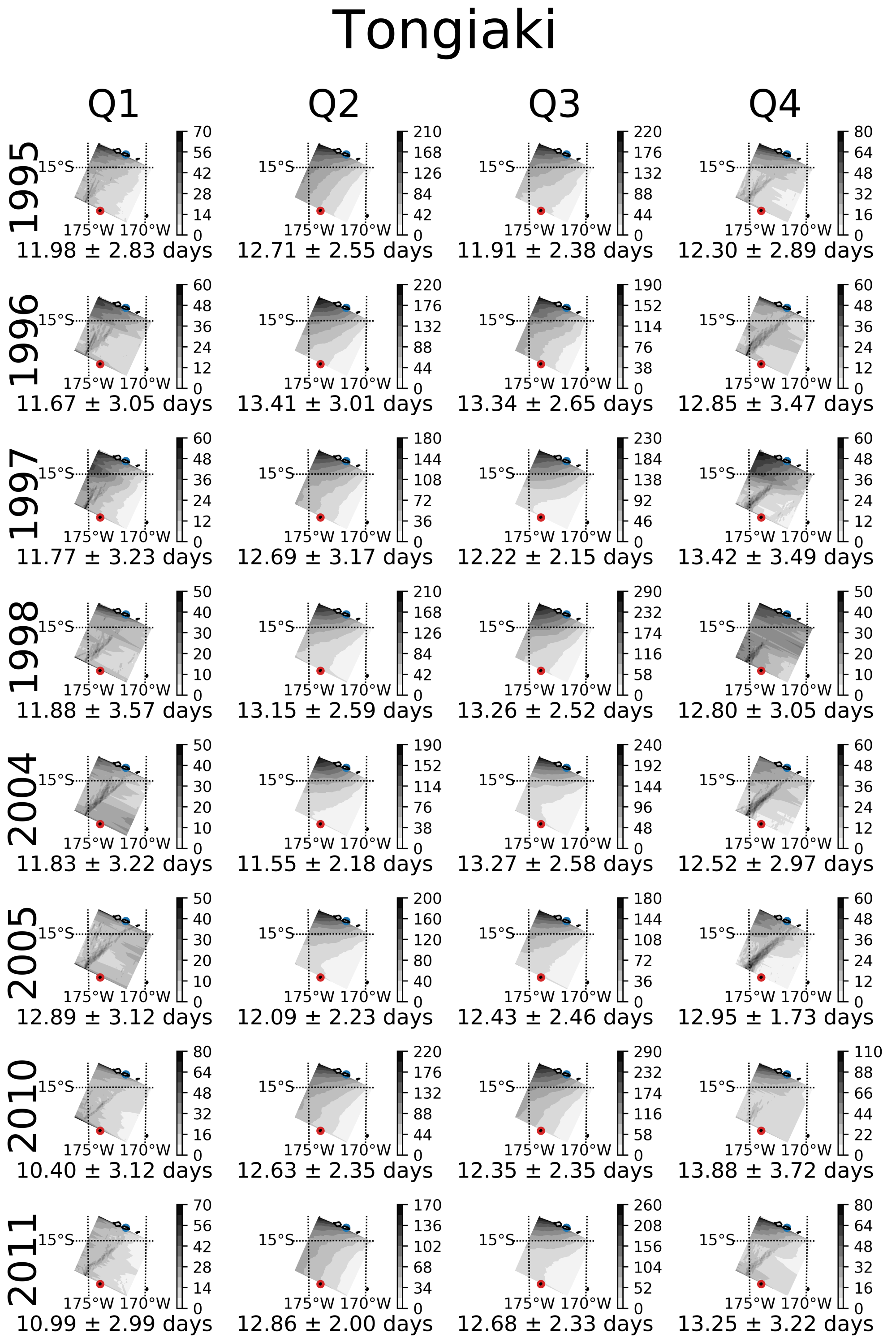

Figure B.7: Quarterly voyaging heatmaps between Vavau and Upolu for the *Tongiaki*.

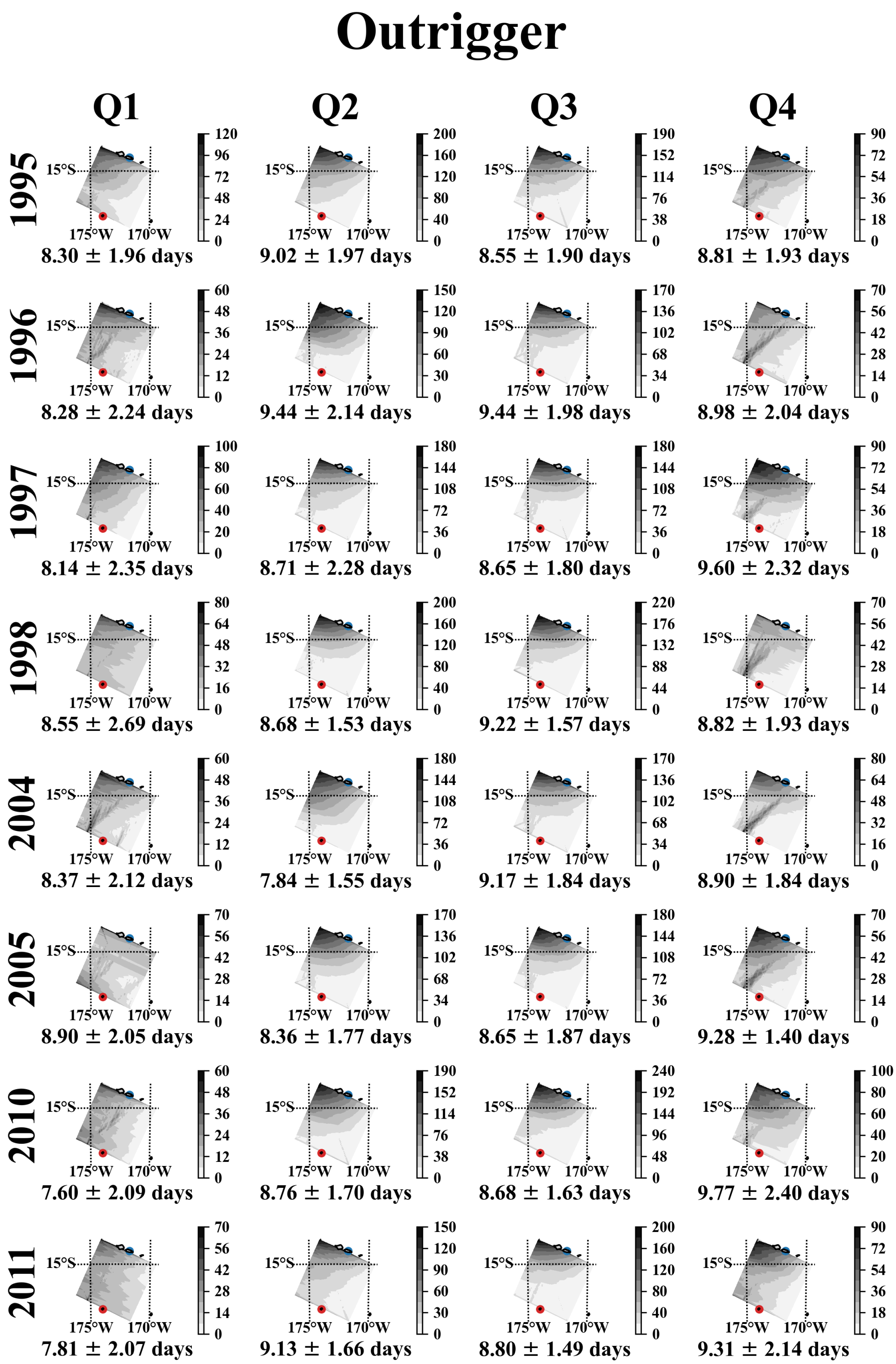

Figure B.8: Quarterly voyaging heatmaps between Vavau and Upolu for the Outrigger.

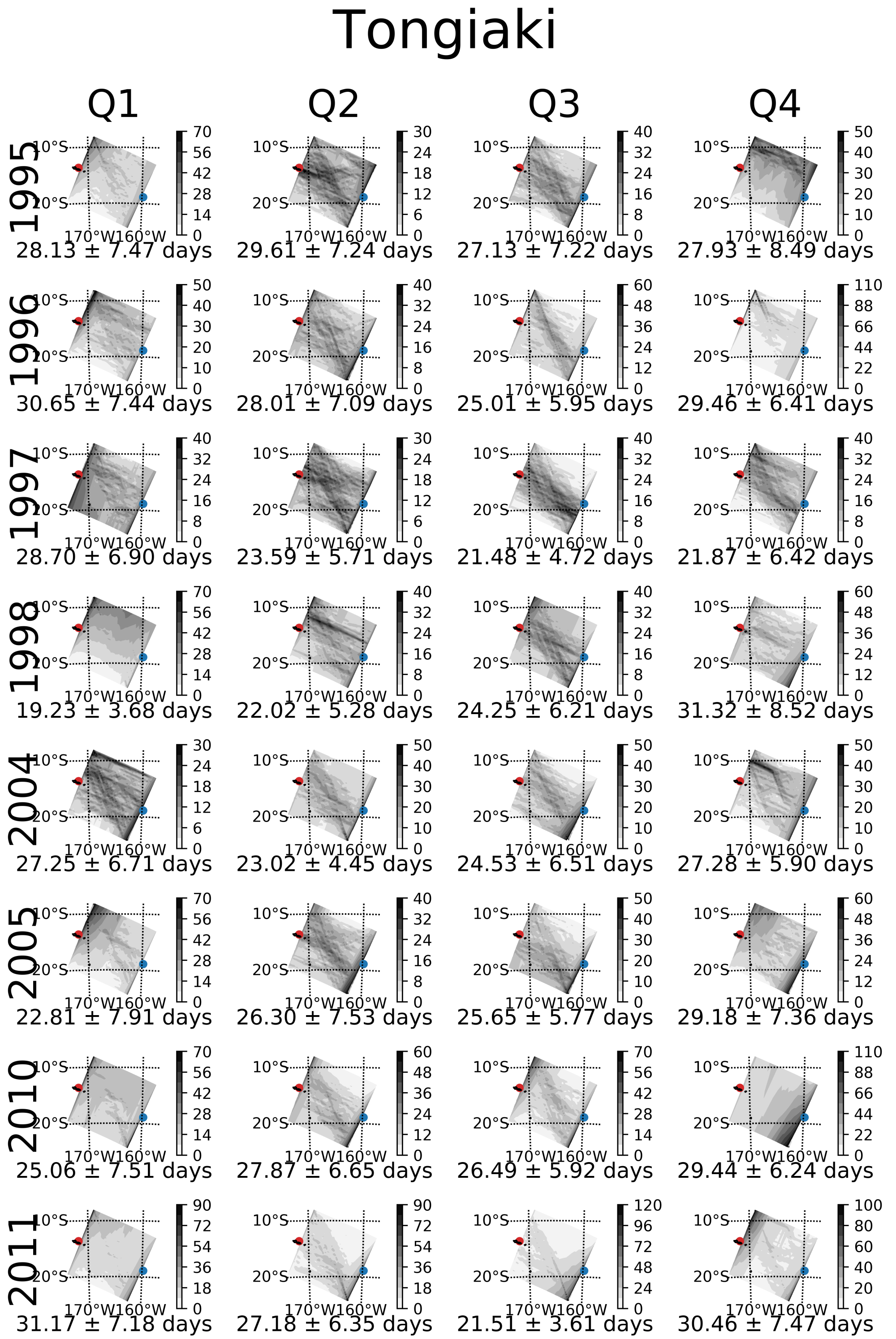

Figure B.9: Quarterly voyaging heatmaps between Samoa and Aitutaki for the *Tongiaki*.

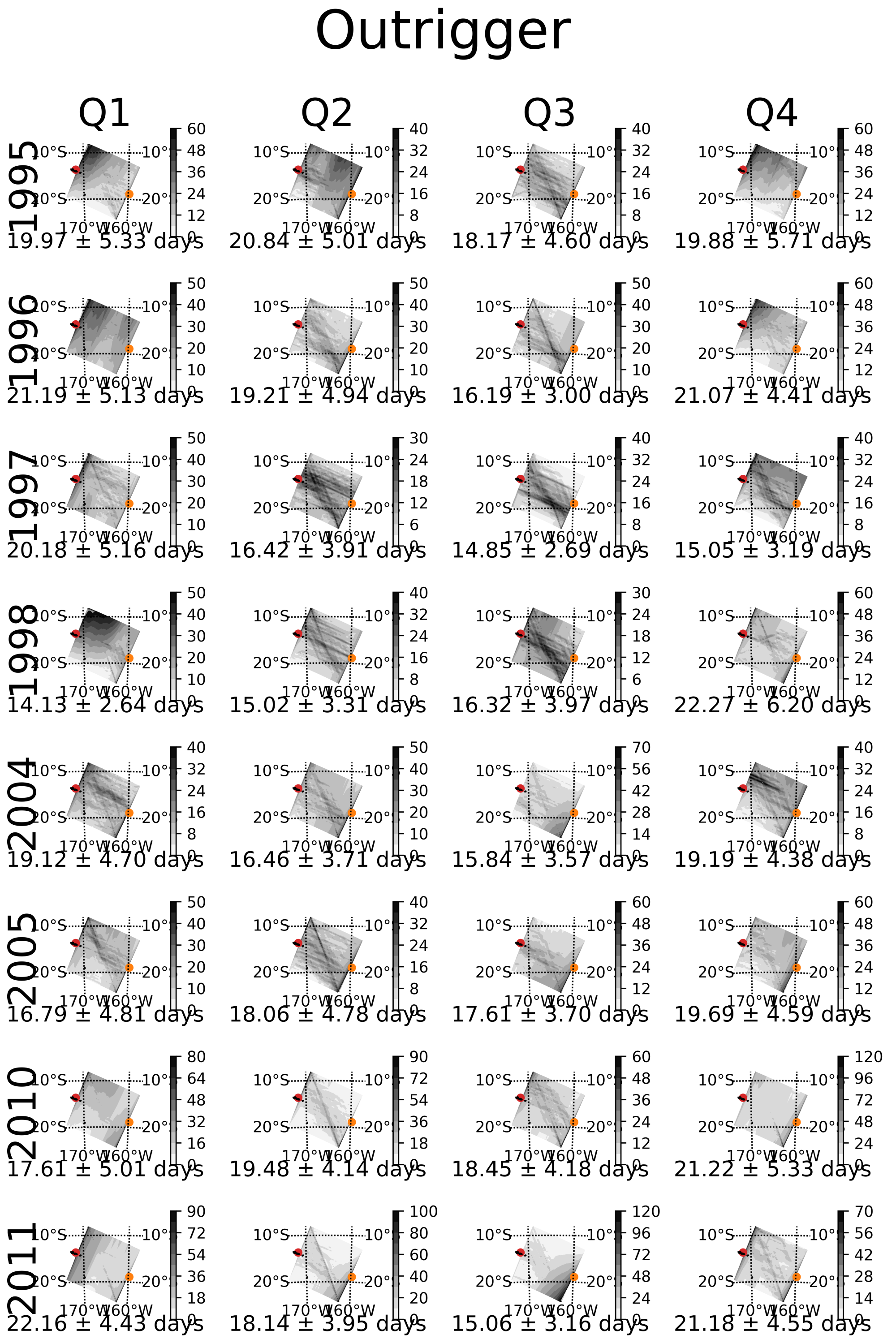

Figure B.10: Quarterly voyaging heatmaps between Samoa and Aitutaki for the Outrigger.

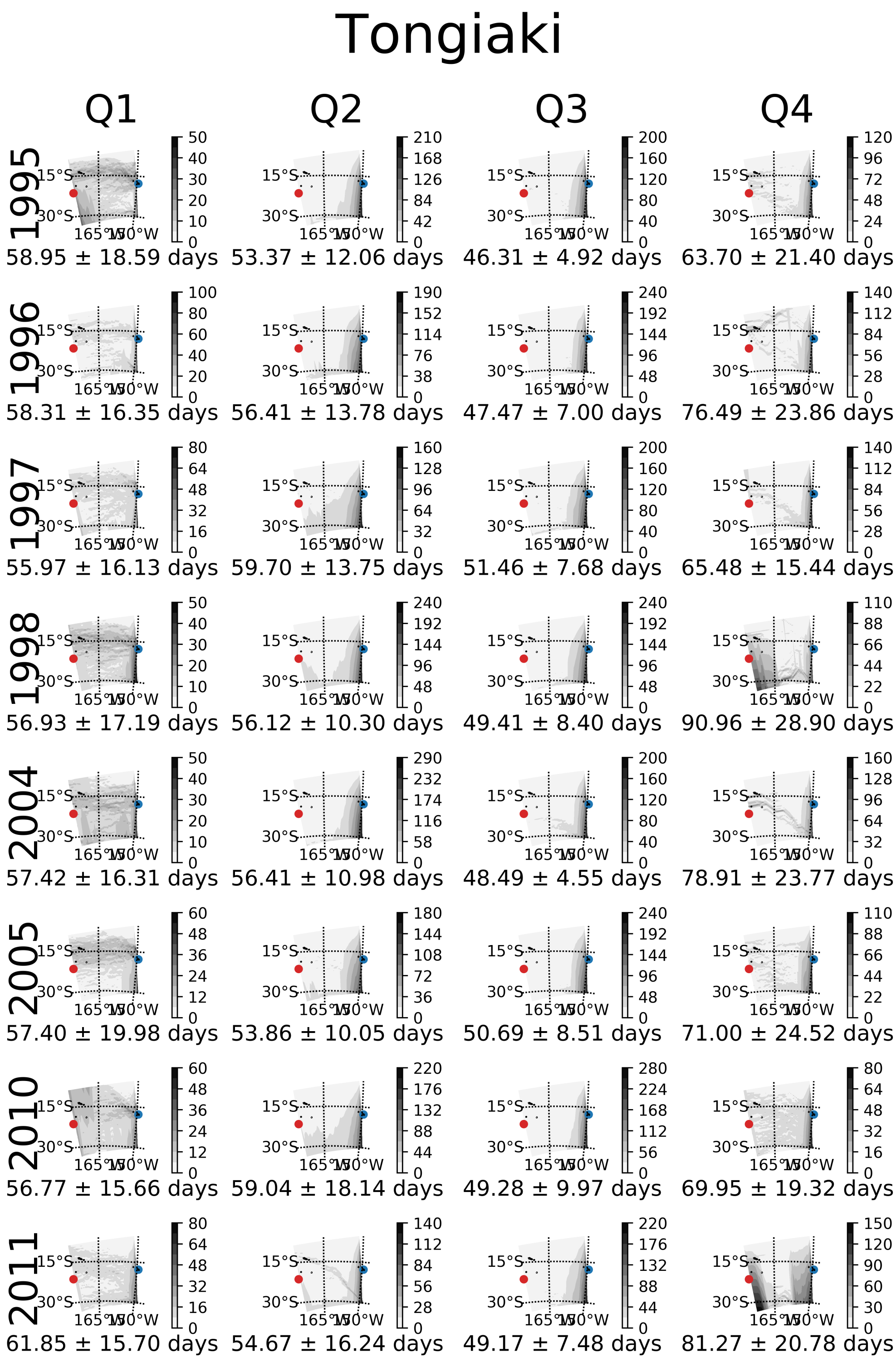

Figure B.11: Quarterly voyaging heatmaps between Tonga and Tahiti for the *Tongiaki*.

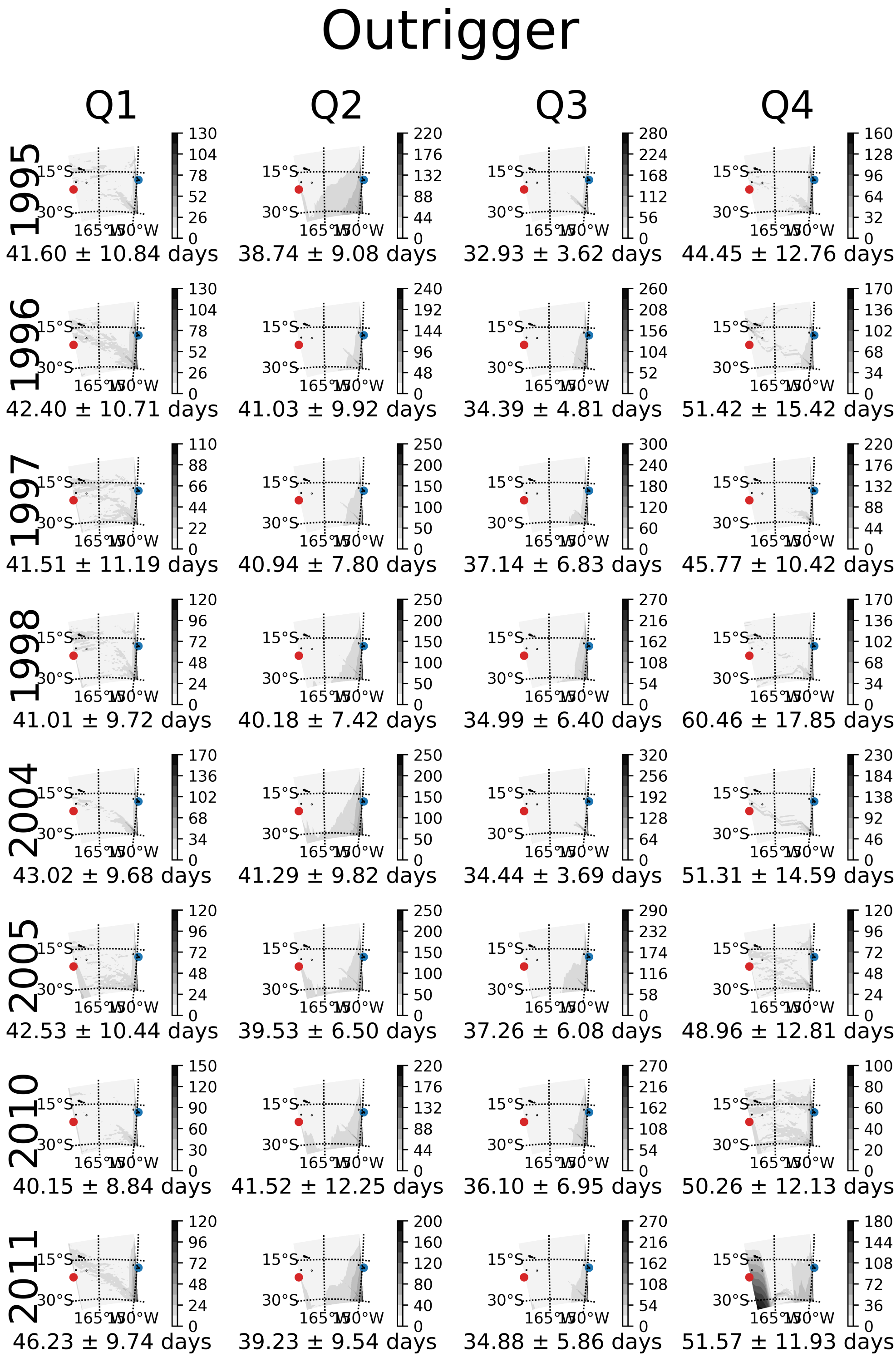

Figure B.12: Quarterly voyaging heatmaps between Tonga and Tahiti for the Outrigger.

Glossary

Autonomous Sailing Craft An unmanned sailing craft which is able to operate independently of human instruction after it begins its voyage.. 107, 111, 120, 123, 183

close hauled When the sailing craft is sailing at a true wind angle of between $35 - 50°$. The craft can also be said to be sailing "upwind".. 17

curse of dimensionality A plethora of problems experienced when considering analysing and organising data in high number of dimensions. As the state space of a problem increases the number of calculations required to solve it increase significantly.. 89

downwind A state where the sailing craft is sailing at a true wind angle greater than 90°.. 17

dynamic programming The process of breaking a complicated problem into smaller sub-problems which can be solved recursively. The final solution meets Bellman's principle of optimality *"An optimal policy has the property that whatever the initial state and initial decision are, the remaining decisions must constitute an optimal policy with regard to the state resulting from the first decision"* (Bellman, 1957, Chap. III.3).. 89, 94

El Niño A phase of the ENSO oscillation where ocean temperature and rainfall increases in the tropical Pacific. The prevailing wind conditions reduce in strength or reverse from Easterlies to Westerlies (L'Heureux, 2014).. 33, 144

General Regularly-distributed Information in Binary form GRIB files are collections of numerical data which usually describe some form of meteorological data. . 95

La Niña A phase of the ENSO oscillation marked by a cooling in sea temperatures around the eastern and central Pacific. The prevailing Easterly winds are strengthened (L'Heureux, 2014).. 33, 144

Markov decision process A problem where a decision maker chooses action a_t at time t based on observing state s_t. The decision maker then receives a reward r_t. The state evolves probabilistically based on the current state and action taken by the decision maker. The key assumption is that the next state depends only on the current state and action and not on any prior state or action. This is known as the *Markov* assumption.. 94

reaching A state where the sailing craft is at a true wind angle of around 90°.. 17

velocity prediction program A physical model of the sailing craft which is able to predict the optimum speed for a sailing craft given a set of environmental conditions. The model will also return the value of control variables such as craft heel, sail trim and crew position.. 18, 19, 20, 21, 23

Acronyms

BBN Bayesian Belief Network. iii, 93, 96, 108, 111, 112, 139

CEP Central East Polynesia. ix, 1, 8, 9, 36, 126, 141, 144, 145, 181

ENSO El Niño Southern Oscillation. ix, 3, 33, 34, 103, 126, 143, 144

GCI Grid Convergence Index. x, 121, 122

LDEN Long Distance Exchange Network. 40

MCA Medieval Climate Anomaly. 33, 36, 37

MDP Markov decision problem. 95

OEP Outer East Polynesia. ix, 1, 141

RMP Race Modelling Program. v, 23, 22, 23

ROC Reciever operating characteristic. 132

TWA True Wind Angle. 17, 18

TWD True Wind Direction. 18

TWS True Wind Speed. 18

VMG Velocity Made Good. 96

VPP Velocity Prediction Program. ix, 7, 18, 19, 20, 21, 23, 64, 65, 71, 73, 76, 77

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