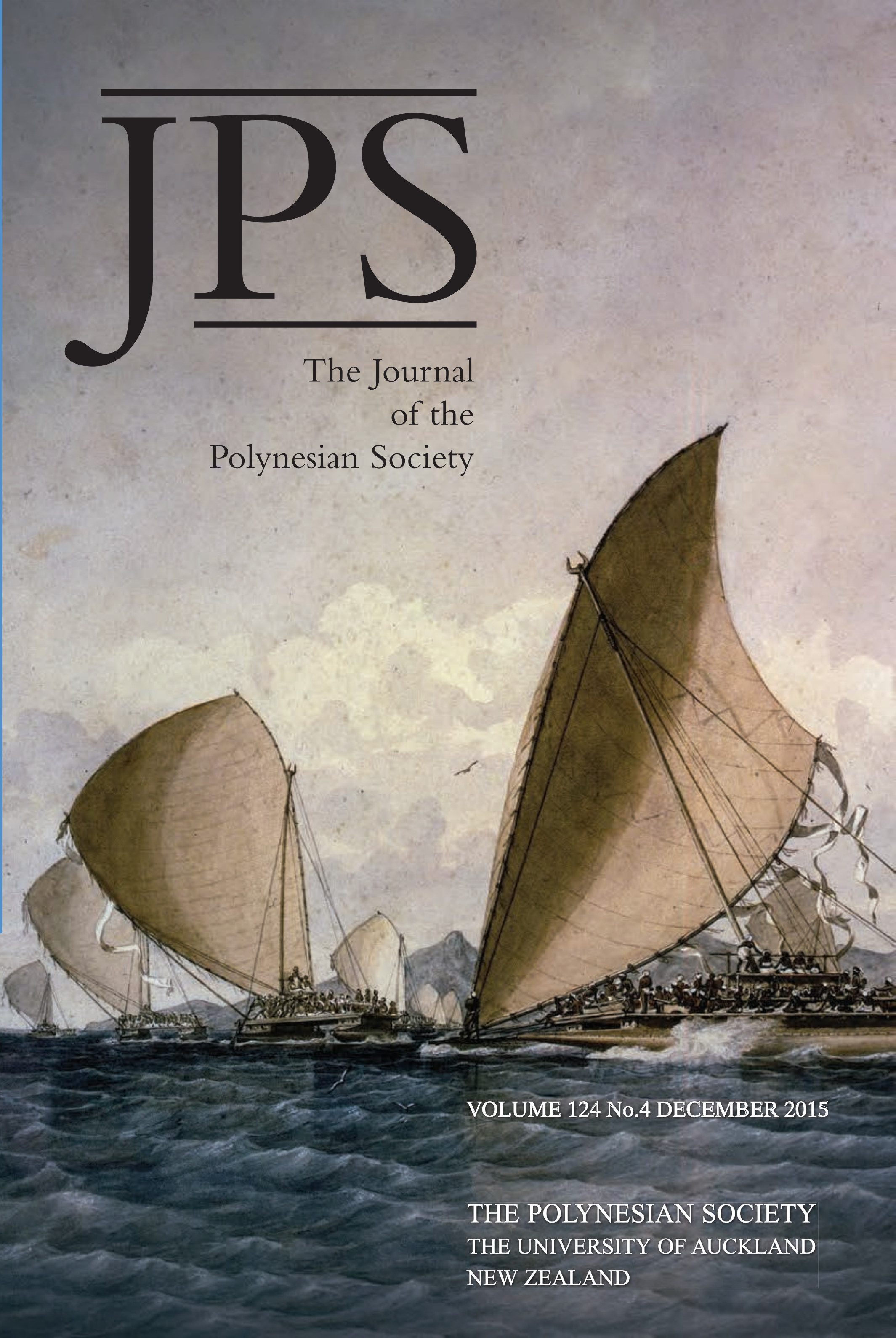

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# PACIFIC COLONISATION AND CANOE PERFORMANCE: EXPERIMENTS IN THE SCIENCE OF SAILING

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The voyaging canoe was the primary artefact of Oceanic colonisation, but scarcity of direct evidence has led to uncertainty and debate about canoe sailing performance. In this paper we employ methods of aerodynamic and hydrodynamic analysis of sailing routinely used in naval architecture and yacht design, but rarely applied to questions of prehistory—so far. We discuss the history of Pacific sails and compare the performance of three different kinds of canoe hull representing simple and more developed forms, and we consider the implications for colonisation and later inter-island contact in Remote Oceania.

Recent reviews of Lapita chronology suggest the initial settlement of Remote Oceania was not much before 1000 BC (Sheppard *et al*. 2015), and Tonga was reached not much more than a century later (Burley *et al*. 2012). After the long pause in West Polynesia the vast area of East Polynesia was settled between AD 900 and AD 1300 (Allen 2014, Dye 2015, Jacomb *et al*. 2014, Wilmshurst *et al*. 2011). Clearly canoes were able to transport founder populations to widely-scattered islands. In the case of New Zealand, modern Māori trace their origins to several named canoes, genetic evidence indicates the founding population was substantial (Penney *et al*. 2002), and ancient DNA shows diversity of ancestral Māori origins (Knapp *et al*. 2012).

Debates about Pacific voyaging are perennial. Fifty years ago Andrew Sharp (1957, 1963) was sceptical about the ability of traditional navigators to find their way at sea and, more especially, to find their way back over long distances with sailing directions for others to follow. To Sharp the obvious answer was island settlement by one-way voyages and accidental discoveries. Interestingly, navigational ability is no longer in contention after the ethnographic and experimental work of scholars and sailors (Finney 2006, Gladwin 1970, Lewis 1994); however, the capability of canoes is still in question (Anderson 2000, 2001, 2015, Anderson *et al*. 2014).

There has been on-going discussion about sailing conditions in the colonisation period and whether ocean routes were easier to traverse at times in the past than they are now. Bridgeman (1983) suggested that climatic change from the Little Climatic Optimum to the Little Ice Age could have

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influenced migrations, and Finney *et al.* (1989) suggested that colonising canoes could have used the anomalous westerly winds of El Niño to sail east. Anderson *et al*. (2006) pointed to the correspondence of ENSO events with eastward migrations attested archaeologically; however, their further suggestion that prehistoric canoes were restricted to downwind sailing is one we wish to investigate. Recent research on climate change by Goodwin *et al*. (2014) shows there were 20-year windows when reversals in prevailing winds coincided with the first settlement of Easter Island and New Zealand, which could have been settled by downwind sailing at those times. They also argue that all of the known colonisation routes of East Polynesia could have been negotiated by canoes lacking upwind capability. This can be regarded as a useful null hypothesis we consider below.

Another recent study by Bell *et al*. (2015) used epidemiological methods to compare four different colonisation theories in a single statistical framework. The results suggested that the two most likely strategies were for migrants to seek accessible islands, but not necessarily the nearest islands, and to travel mostly against prevailing winds on outward exploratory journeys to allow a safer return from failed searches (Irwin 1992). Distance was not a factor, suggesting early seafarers were already adept at long-distance travel.

More information about canoe performance is required to understand colonisation as a process and the nature of subsequent interisland voyaging. Several important questions depend upon the greater or lesser sailing capability of the canoes:

- To what extent was colonisation based on one-way or return voyaging? The former characterised more by voyages of exile and the accidental discovery of new islands, and the latter involving exploration followed by migration to known destinations?
- To what extent was colonisation a strategic process that minimised risk of loss of life at sea, or did one-way voyages into the unknown result in more collateral damage?
- To what extent was colonisation influenced by technological capacity, or by natural forces such as wind direction and climate change?
- To what extent were canoes capable of interisland voyaging after settlement?

Until now, our main sources of information about sailing canoes have included historical linguistics (Pawley and Pawley 1994), archaeological evidence of canoe remains (Irwin 2004, Johns *et al*. 2014, Sinoto 1979) and prehistoric interisland trade (McAlister *et al*. 2013). There is a rich historical literature from early European sailors, who sometimes spoke and sailed with Polynesians (Haddon and Hornell 1997, Salmond 2005). Ethnographic studies of surviving indigenous navigation and technology from around the Pacific provide useful information (Gladwin 1970, Lewis 1994), and there have been many experiments at sea in diverse boats including modern yachts, contemporary Pacific canoes, and quasi-replica canoes built of modern materials (Finney 2006). In addition, large numbers of virtual voyages have been made by computer (Avis *et al.* 2007, Irwin 2010). To these sources we add wind tunnel testing of model sails (Di Piazza *et al.* 2014, Jackson and Bailey 1999, Marchaj 1987, 1990), and computational fluid dynamics and towing tank tests of canoe hulls (Boeck *et al*. 2012, Flay 2013).

## UPWIND *VERSUS* DOWNWIND COLONISATION MODELS

We need to clarify a semantic issue which arises in canoe performance debates because *upwind* and *downwind* (sometimes referred to as *off-wind*) are terms used in different ways with different meanings. On one hand, they can indicate general directions in the ocean which relate to the prevailing wind direction. On the other hand, they can indicate the direction in which a canoe is heading in relation to the wind, in real time. Figure 1 concerns the second meaning and shows terminology for conventional points of sail. When a boat is heading between 0˚ and 90˚ it is in an *upwind* mode (going against the wind); but when it is heading from 90˚ to 180˚ it is going *downwind*. No boat can sail directly into the wind and no informed scholar suggests prehistoric Pacific voyaging canoes could sail within 75˚ from the wind, so that zone is shown as *no-go* in Figure 1. When a boat is sailing with the wind coming from the side it is in a *reaching* mode. In the diagram a *beam reach* is distinguished from a *broad reach*, which refers to wind coming from aft of the beam. Beyond approximately 150˚a boat is said to be *running* with the wind from behind. We have taken the cut-off between reaching and running at around 150˚ because that is where speed declines and, in a boat with two sails, the front sail would be blanketed by the rear one and no longer fill with wind.

Relating those directions to theories of sailing performance, Lewis (1994), Finney (2006) and Irwin (2006) all believe ancient Polynesian canoes could reach and run (sail between 75˚-180˚ from the wind). Goodwin *et al.*'s (2014) model identifies an off-wind sailing vector directly downwind plus a margin of ± 30˚ (150˚-180˚). Anderson has suggested that Māori, and perhaps Marquesan, canoes could have been hard-pressed to maintain a broad reach especially in gusty conditions (Anderson 2001: 33), but if they could manage a broad reach in suitable conditions, the sailing range would be approximately 120˚-180˚. Figure 1 shows the difference between so-called upwind or downwind models could be misleading. What has been referred to as an upwind model actually comprises only 15˚ upwind (75˚-90˚) plus 90˚of downwind sailing (90˚-180˚). The disputed area of the wind rose in

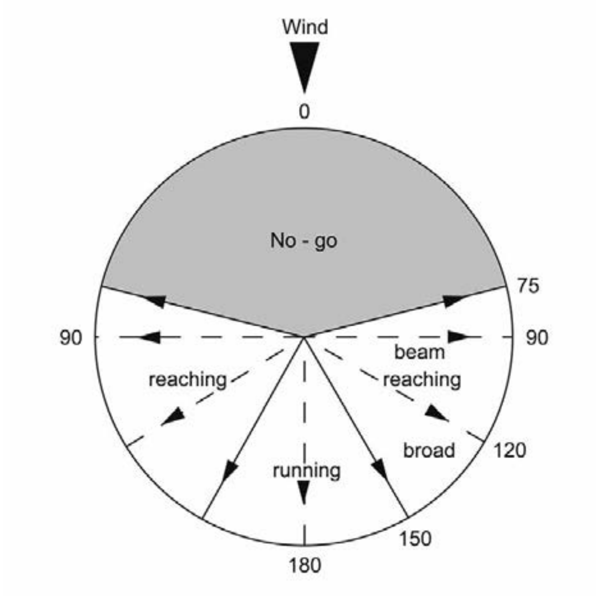


Figure 1. A wind rose shows conventional terminology for points of sail. No current theory proposes that canoes could voyage closer than 75˚ from the wind, but there is debate about whether canoes could sail between approximately 75˚- 120˚ from the wind.

Figure 1 is approximately 45˚ (75˚-120˚), and it would be more correct to define the debate as between predominantly reaching and running models.

The issue might seem trivial, but for the fact that the different points of view are associated with the difference between one-way and two-way voyaging and different models of colonisation follow. Theories about sailing capability of this order warrant scientific measurement and, as it happens, there is an established science of sailing.

## EARLY EAST POLYNESIAN AND NEW ZEALAND SAILS

We needed to reconstruct appropriate sails for testing in the wind tunnel and chose the Oceanic spritsail, which was widespread in East Polynesia when Europeans first arrived, and we make the case that it was the earliest form in marginal East Polynesia. The Oceanic spritsail is classified as a fore-and-aft sail which takes the wind from both sides, alternately, and is suited to reaching and running. Typically it had a V-shape with two spars, one stepped on the

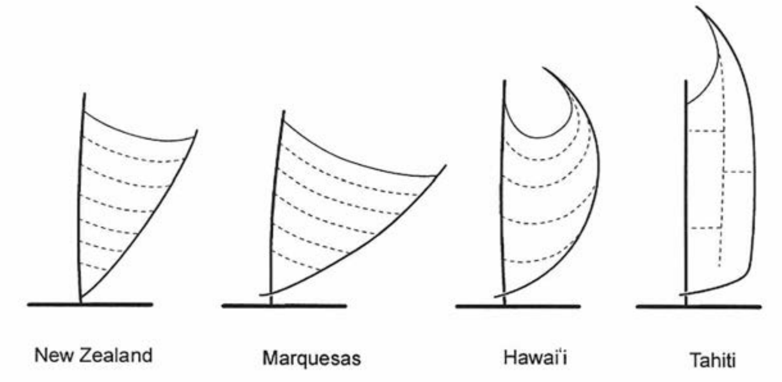


Figure 2. Schematic sketches of oceanic spritsails in New Zealand, the Marquesas, Hawai'i, and Tahiti in the 1770s (Haddon and Hornell 1997, Irwin 2008). The leading edges of the sail are to the left and trailing edges to the right. Details of standing and running rigging are not shown because the original artists' drawings may be unreliable.

canoe, like a mast, and a trailing spar attached to the bottom of the leading one, trimmed as the canoe sailed at different angles. Figure 2 shows various two-spar rigs recorded at the time of European contact in New Zealand, the Marquesas, Hawai'i and Tahiti (Haddon and Hornell 1997), although there is debate about the detail of the Māori sail (below). Often complete rigs—spars and sail—were put up and taken down together, as in New Zealand, but by historic times in Tahiti they were sometimes attached to standing masts.

The spritsail could have been the first sail type to reach East Polynesia because it was the only one known to reach the marginal islands of Hawai'i, the Marquesas and New Zealand, which were settled early and then isolated in later prehistory. Subsequent introductions or innovations in central East Polynesia did not reach the marginal islands. Thus, there was some common ancestry among sails in marginal East Polynesia, but later divergence in isolation on different islands. Basic elements shared by these widely distributed sails observed at the time of European contact can be used to inform us, in a general way, about possible ancestral sails.

There is substantial evidence of early historic sails in New Zealand. A Māori sail in the British Museum, possibly of pre-European age and thought to have been collected by James Cook, is shown in Figure 3. It is made of plaited flax and trimmed with feathers, and it measures 4.40 m high, 1.91

Figure 3. A Māori sail in the British Museum (Oc, NZ. 147), attributed to collection by a Cook expedition. There are loops down both sides of the sail for attachment of two spars, which would intersect below the sail. The leading edge of the sail is to the right and the pennant is attached to the trailing edge on the left, where it served as both a decoration and a "tell-tail". This sail could have been collected because it is particularly ornate.

m wide at the top and 0.34 m wide at the bottom. The spars are missing, but loops along both sides show they could have intersected below the bottom of the sail, which could have been rigged as an Oceanic spritsail. A pennant or "tail" of plaited flax 1.05 m long and 0.20 m wide, with feather trim, was attached to one side near the top. It may have been a decoration that also helped the sailors to trim the sail effectively.

A detailed plan of a Māori canoe with a spritsail was made by Pâris during Dumont d'Urville's expedition in 1827 (Dumont d'Urville 1833), but there were much earlier written descriptions and less formal drawings of sails from the Cook expeditions dating from 1769. Two early written descriptions are unambiguously of triangular Oceanic spritsails. The first refers to an encounter on 1 November 1769, near Whale Island in the Bay of Plenty, between the *Endeavour* and what Banks described as "… a large double canoe, or rather two canoes lashed together" (Beaglehole 1962: 368). The sail is described in the ship's journal attributed to Magra (Frost 1995: 82, from Magra [Matra] 1771), as:

> a sail of an odd construction,… made from a kind of matting, and of a triangular figure; the hypothenuse, or broadest part, being placed at the top of the mast, and *ending in a point at the bottom*. One of its angles was marled to the mast, and another to a spar with which they altered its position according to the direction of the wind, by changing it from side to side (our italics).

On Cook's second voyage, Forster described a sail seen in Queen Charlotte Sound in June 1773: "The sail consisted of a large triangular mat, and was fixed to a mast, and a boom *joining below in an acute angle*, which could both be struck with the greatest facility" (Best 1925: 254, [our italics]).

Figure 4 is a drawing by Spöring of the Whale Island canoe. It shows an upright triangular sail similar to, but larger than, the British Museum sail shown in Figure 3. It is filled with wind from behind and has two spars each supported by a running stay leading forward, and by a sheet leading aft. Magra had the opportunity to see the whole sail and his description is consistent with an Oceanic spritsail. However, Anderson has suggested that the two spars were attached separately to the canoe, unlike the fore-and-aft rig of an Oceanic spritsail, and that the first Māori sail seen by Europeans was misinterpreted by them and could have been some archaic quadrangular form that survived in New Zealand (Anderson *et al*. 2014: 29, 504, Anderson and Boon 2011). This proposition is conjectural because the bottom of the sail is partly concealed in Spöring's drawing and the attachment of the spars is not shown. We are not aware of such a sail recorded by early Europeans elsewhere in marginal East Polynesia and we doubt its existence in New Zealand. We think the early sails drawn and described would have set satisfactorily as

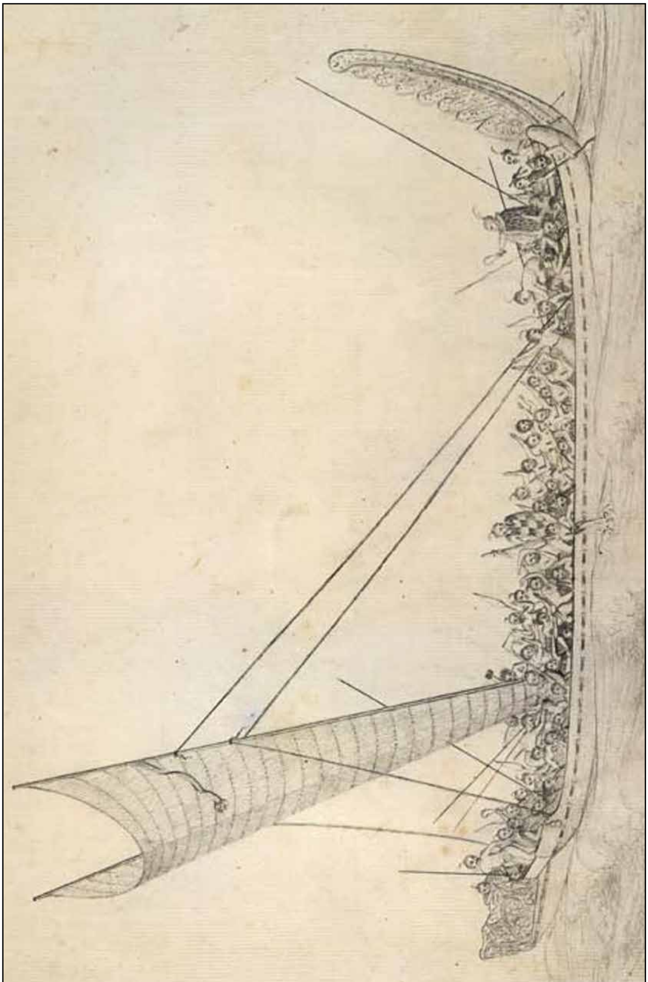

Figure 4. Spöring's drawing of a double canoe seen at Whale Island in November 1769 (Add. MS 23920 f.48, British Library). The two hulls are forms often seen as single canoes; the longer hull (at rear) is a *waka taua* 'war canoe', and the shorter undecorated hull (foreground) is a type described as a fishing or travelling canoe by Haddon and Hornell (1997). Early Māori sails were triangular in shape with apex down and had two spars.

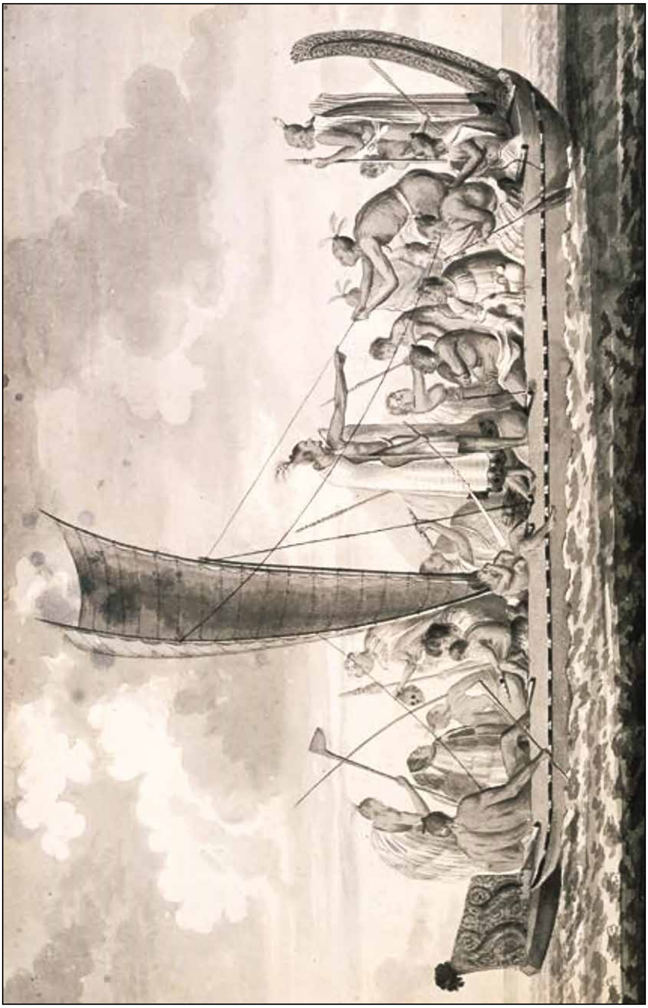

Figure 5. A New Zealand Māori canoe drawn by Sidney Parkinson in 1770 during Cook's first voyage (Add. MS 23920 f. 49, British Library)

spritsails, but not with two spars lashed separately to the hull. While it might work as a makeshift arrangement for running downwind, it would set badly on a reach, and sometimes need a means—such as a third spar—to hold the other two spars apart.

Early historical sketches can be ambiguous because they show sails and spars in different configurations according to the direction of the boat in relation to the wind, which makes it possible to misinterpret different *points* of sail as different *types* of sail, which could explain this issue. Also, unlike photographs, they may not accurately record every detail, particularly of ropes and rigging, and the drawings may have been finished after the event. The point is illustrated by a drawing of a Māori canoe made by Parkinson in 1770, also on Cook's first voyage to New Zealand, shown in Figure 5. This may not have been made of an actual canoe, but drawn from Parkinson's general observations. It shows an upright triangular spritsail, similar to other contemporary Māori sails, but it depicts a mast that Parkinson more likely saw in Tahiti than in New Zealand.

## PACIFIC CANOES AND THE SCIENCE OF SAILING

Sailing boats conform to the laws of physics and there is a well-established science of sailing (Garrett 1996). There are known forces at work as shown in Figure 6. Prediction of sailing performance requires analysis of both sails and hulls and here we describe three stages of the first phase of testing at the University of Auckland.

1. The aerodynamic performance of three selected model sails was tested in a wind tunnel.
2. The hydrodynamic performance of three different model hull forms, taken to represent diversity of Pacific canoes, was tested in a towing tank, and independently by computational fluid dynamics (CFD).
3. By combining this information we were able to compare the speed of three different kinds of canoe in varying conditions of wind speed and direction of travel by using a velocity prediction program (VPP).

### *Aerodynamic testing*

Early wind tunnel experiments by Marchaj compared six different sailing rigs from around the world and revealed the high performance of the "crab claw rig" of the Pacific (Marchaj 1987, 1990). In 1992 a model based on a detailed sketch of a Marianas "flying *proa*" made in 1742 during Anson's circumnavigation was tested in a wind tunnel at the Yacht Research Unit at the University of Auckland and reported by Jackson and Bailey in the proceedings of the *Vaka Moana Symposium 1996*, sponsored by UNESCO, the University

Vessel making way due east in a wind from the north

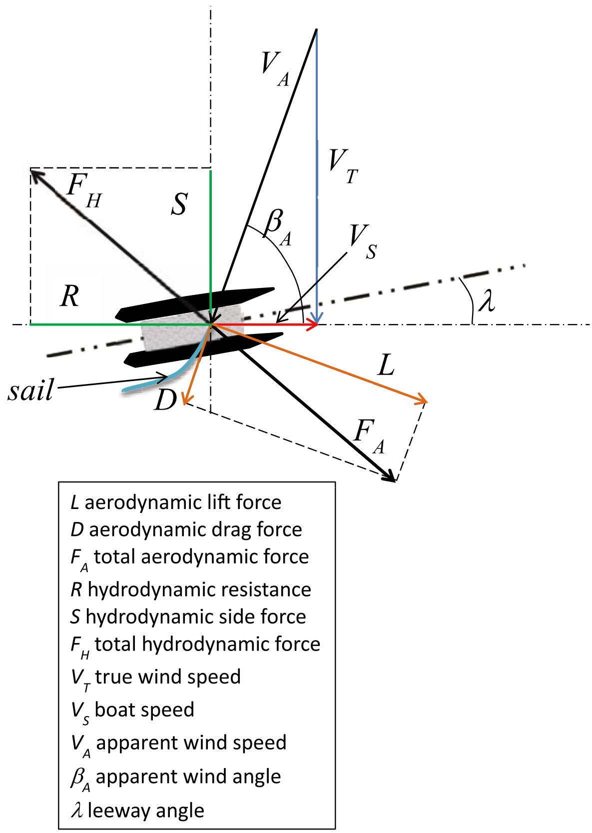


Figure 6. A diagram showing the various aerodynamic and hydrodynamic forces on a Pacific sailing canoe. The apparent wind angle is the angle between the vessel's heading and the wind direction experienced by the vessel. Stages of performance analysis involved (1) testing selected model sails in a wind tunnel (2) testing model hulls in a towing tank and by computational fluid dynamics (CFD), and (3) calculating the speed of different canoes in varying conditions of wind speed and direction of travel using a velocity prediction program (VPP).

of Auckland and the New Zealand National Maritime Museum (Bader and McCurdy 1999). In 2003 Jacobs wrote an Anthropology Master's thesis on mathematical modelling of Oceanic canoe performance using Jackson and Bailey's results, beginning a collaboration of archaeologists in the School of Social Sciences and engineers from the Yacht Research Unit, which has focussed on canoes of the pre-European era.

In 2008 a 1/5th scale model of a 14 m canoe was designed from ethnohistoric sources by Irwin and Flay and built by R. May (2008) for wind tunnel testing (Fig. 7). It could be set up as a double canoe, a canoe with double outriggers, or with a single outrigger set either to windward or leeward. The sail followed the triangular form of the Māori sail, with similar proportions to the Cook sail shown in Figure 3, but adding some curvature to the trailing

Figure 7. A model canoe in the Twisted Flow Wind Tunnel at the University of Auckland in 2008. In this experiment a 2.8m hull was set up as a single outrigger canoe with a triangular *pandanus* sail 1.74m high, 0.71m wide at the top, and with a curvature 120mm deep added as an arc to the trailing edge. The model was rotated on a balance which measured forces and moments at 10˚ intervals and "tell-tails" attached to the sail allowed the trim to be controlled remotely by miniature electric winches. Data were recorded by computer and cameras.

edge, as seen elsewhere in East Polynesia. The sail area was modest and represented the equivalent of 18.5 m$^2$ on a 14 m canoe, set with the top of the sail 10 m above sea level. One focus of the experiment was on sail material and two sails were made to the same design, one of modern dacron sailcloth and another from a finely-woven pandanus (*Pandanus tectorius*) mat. The sails were set up on bamboo spars. We also made a smaller pandanus sail, to investigate the influence of sail size.

The model was mounted on a balance embedded in a turntable in the Twisted Flow Wind Tunnel at the University of Auckland. The model was tested at angles to the wind between 30˚ and 180˚, at 10˚ intervals. The sail trim was adjusted by small electric winches on the model using tell-tails on the sail to get the trim resulting in the largest driving force. The data were recorded by computer and cameras recorded the shape of the sail. Here we describe results with the leading spar set at a rake of around 10˚ and with a single windward outrigger. Figure 8 shows the driving force coefficient (*Cdf*) as a function of the apparent wind angle (*AWA*) for the three sails. The dacron sail performed slightly better than the pandanus sail up to a wind angle of around 110˚ but thereafter was much the same. We also recorded

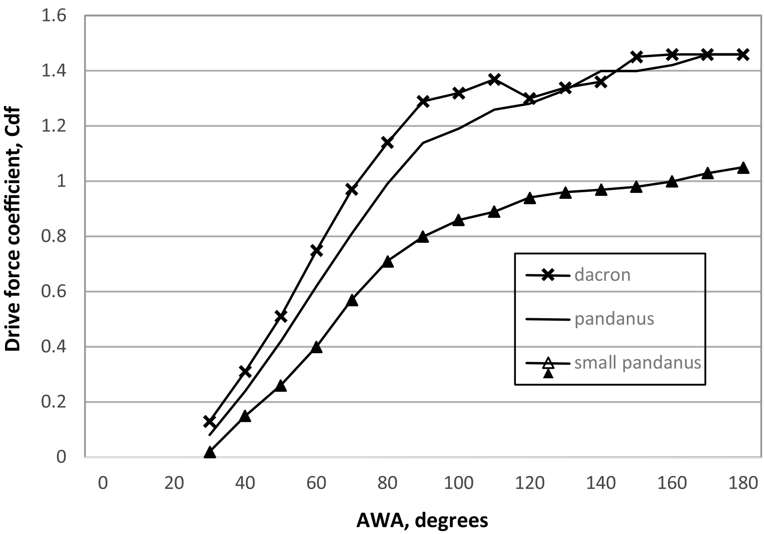


Figure 8. The driving force coefficient (*Cdf*) plotted against the apparent wind angle (AWA) for three sails—dacron, pandanus and small pandanus.

the side force coefficient (*Csf*) and the rolling moment coefficient (*Crm*), as functions of the *AWA*.

We can tentatively compare these results with wind tunnel tests of ten traditional rigs by Di Piazza and colleagues (2014), based mainly on scaled drawings by early Europeans and chosen to represent the diversity of sails across the Pacific. Their study found Oceanic lugsails of the western Pacific (Ninigo, Massim and Arawe), together with the Oceanic lateen of Santa Cruz, to be most efficient, especially at low heading angles. There was variability among the remaining Oceanic lateens and Oceanic spritsails (Di Piazza *et al*. 2014: 20). In addition, the "Marianas *proa*" of Jackson and Bailey (1999) was found to be consistent with their Oceanic lateens. Although different methods and materials were used, our dacron and pandanus sails appear to be of a similar order to some of their lateens and spritsails. Subsequently, further experiments have been conducted at the Yacht Research Unit with the pandanus sail set at different angles of rake.

*Hydrodynamic testing*

Pacific canoe hulls are long and narrow, and have no keels. Stability is provided by outriggers attached by booms. They provide a *righting* moment that offsets a *rolling* or *overturning* moment, and linguistics dates outriggers of some form to Lapita times (Pawley and Pawley 1994). When lifted from the water their weight rotates them back to the surface, and when pushed down into the water their buoyancy restores them to the surface. They have been described as the world's oldest feedback mechanism and in this sense the double canoe is a member of the outrigger family, and it is immaterial which developed first (Abramovitch 2005). Roll stability is fundamental because it allows sailing with the wind coming from the side as well as from behind.

The earliest canoes probably had round hulls from trees; however, time and experience of manoeuvring across the wind would have influenced canoe design. In order to reach or sail upwind a sail must develop sufficient driving force in the desired heading, and the aerodynamic side force which comes with the driving force has to be balanced by hydrodynamic lift. In the absence of keels, hydrodynamic side force had to be generated by the hulls. By ethnographic times there was a diversity of underwater hull profiles and we envisage an evolution of sectional form from U-shape to V-shape as the latter are better able to generate side force.

The relationship of sailing performance and sectional shape of narrow hulls has been investigated in the Yacht Research Unit with computational fluid dynamics (CFD) (Boeck *et al*. 2012), and towing tank tests by Flay at Newcastle University (Flay 2013). Model shapes were investigated in the

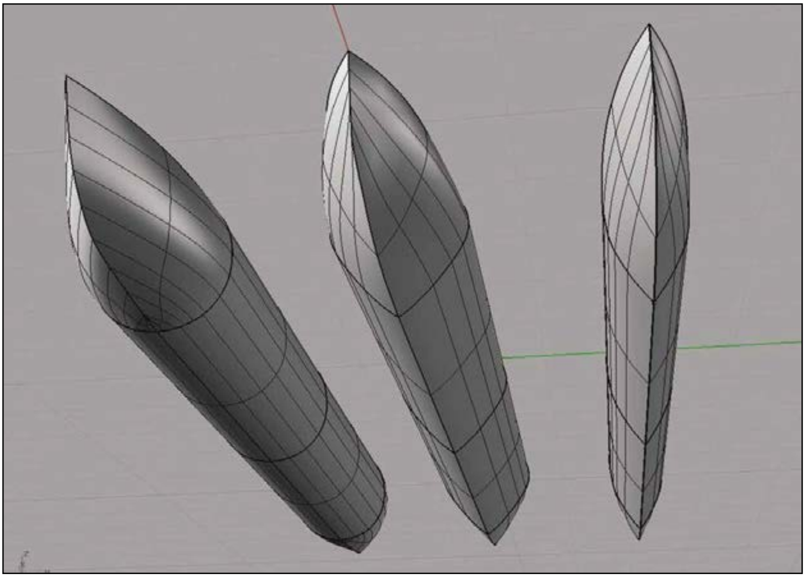

Figure 9. Underwater profiles for three symmetrical canoe forms, U, V1 and V2 representing the diverse canoe hulls found in the Pacific at European contact (adapted from Boeck *et al*. (2012).

towing tank at a scale of 1:10 representing canoes 12 m long and 1.2 m wide. Figure 9 shows three models, a U-shaped design, a moderately V-shaped design V1, and a highly V-shaped design V2. Predictions of lift and drag were made at leeway angles of 0˚, 5˚, 10˚ and 15˚. Analysis shows a windward side force is generated by vortex systems which develop on the stem and follow the line of the keel. The fluid at the windward hull surface is accelerated and induces a low pressure area which results in a net hydrodynamic side force. Good agreement was found between the CFD and towing tank test results, and the hypothesis that narrower V-shaped hulls would generate more side force when at leeway than a rounded hull was confirmed (Flay 2013).

The influence of the pressure distribution loses its impact towards the back of the hull producing a *yawing* moment which has to be balanced. Yawing (changing the heading from side to side of the direction of motion) can be controlled by steering paddles, and according to historical linguistics, these existed in Lapita times (Pawley and Pawley 1994).

*Velocity Prediction Programs (VPP)*

VPPs are a conventional mode of performance analysis in yacht design based on finding the equilibrium of forces and moments acting on a vessel, and predicting the lift and drag on sails and hull in any conditions of wind speed, heading and heel. Figure 10 is an example of preliminary VPP results modelled in the Yacht Research Unit (Boeck *et al*. 2012), a polar diagram showing boat speeds for canoes with U, V1 and V2 hulls, plotted radially against the true wind direction, including leeway, in a true wind speed of 6 metres per second (m/s), equivalent to 11.7 knots, which is a light to moderate breeze.

This example supports a general comparison of the advantages of different V-shaped hulls over U-shaped ones in terms of direction into the wind. Figure 10 shows that a U-shaped canoe of this configuration would reach its maximum speed of around 4.7 knots on a broad reach. At 90˚ to the wind it would be sailing at a speed of around 1.5 m/s, or 2.9 knots, and at 75˚ the speed reduces to 1.9 knots. A V1 canoe in the same wind conditions would be sailing at 2.8 m/s or 5.4 knots at 90˚ and still at 2.4 m/s or 4.6 knots at 75˚. The V1 canoe is almost as fast on a beam reach as on a broad reach and the V2 is better again. Speed quickly reduces for all three hull shapes when running directly downwind. Tacking downwind is generally preferable to

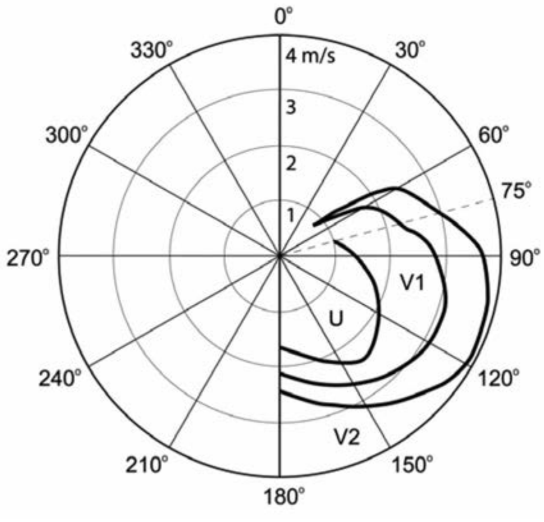


Figure 10. Polar plots of boat speed as a function of true wind direction (0-180°) for a true wind speed of 6 m/s (11.7 knots), for hull profiles U, V1 and V2.

running because of the larger driving force generated while broad reaching (Marchaj 1987:61), and also because sailing with waves coming from behind is uncomfortable and unstable, and there is a risk of a dangerous gybe (wind catching the sail from the wrong side).

The VPP results also show that increasing or decreasing the wind speed, increases or decreases the boat speed accordingly. However, the relative differences in boat speed by angle into the wind for U, V1 and V2 canoes are maintained at different wind speeds, and we can compare the performance of the three different canoes. Altering the experimental methodology would affect these results; however, our analysis was generally conservative. Historic Micronesian V2 canoes were clocked at speeds of 15-20 knots (Finney 2006), but in this study our interest is more in the simpler canoes of an earlier period in prehistory.

## DISCUSSION

### *The Relative Age of Sail Forms in Remote Oceania*

We selected Oceanic spritsails for testing in the wind tunnel because sails of this general form were widespread in marginal East Polynesia at the end of prehistory and, on that basis, could have been the earliest to reach central East Polynesia. However, the rig used on Lapita canoes 2000 years earlier is an open question. There are different theories about the relative age in Oceania of the three-spar lateen and the two-spar spritsail, and the wider distribution of the lateen has been taken to suggest it was the earlier form (Kirch 2000). Di Piazza *et al*. (2014:23) also consider on linguistic grounds that the spritsail could have been a later innovation somewhere in West Polynesia during the long pause before the settlement of East Polynesia.

On technological grounds, an alternative case can be made that the spritsail was the earlier form. A two-spar rig, with no standing mast, is more basic than a three-spar rig with a mast. Also, spritsails in East Polynesia were associated with canoes which changed direction by tacking, and single outrigger canoes had poor balance with the outrigger on the leeward tack. Elsewhere in Remote Oceania, single outrigger canoes which changed direction by shunting,[1] always kept the outrigger to windward and they were usually associated with lateen rigs. We see merit in Doran's (1981) theory that the third spar, or mast, of the Oceanic lateen functioned as a crane to move the rig from end to end during shunting.

Wind tunnel testing may confirm that the Oceanic lateen was generally more efficient than the spritsail. The three-spar rig also allows more control of the rake of the sail, and we have found that when sailing on a tight reach it is advantageous to increase the rake, which reduces the overturning moment while maintaining the driving force (Flay *et al*. n.d.). If shunting canoes with lateen sails can be regarded as a more developed form than tacking canoes with spritsails, then they could have been an innovation or introduction that occurred after the Lapita period, somewhere in western Remote Oceania, which spread eventually and by stages into Fiji and West Polynesia late in prehistory (Haddon and Hornell 1997).

Irrespective of which of the two was earlier, a further case can be made that the Oceanic spritsail and Oceanic lateen were more similar to each other technologically and hence more closely connected historically, than either is to the lateen sail of the Indian Ocean. Both Oceanic lateen and spritsail have spars on both sides of the long axis of the sail (see Figure 2). In contrast, the Indian Ocean lateen lacks a spar on the lower side of the long axis of the sail; it is loose-footed, and its sailing characteristics have been found to be very different (Marchaj 1990).

*Lapita voyaging*

Archaeological outcomes inform us of the effectiveness of Lapita voyaging and linguistic reconstructions of a vocabulary of boats speak of elements of sailing present at the time (Pawley and Pawley 1994). Terms for sails and spars invoke driving force, and hulls invoke drag. The existence of some form of outrigger invokes an overturning moment *versus* a righting moment and sailing by reaching as well as running. Steering paddles invoke a yawing moment and the alignments of the side forces of sail and hull. One cannot be sure precisely what artefact forms are referred to in Austronesian proto-languages, but there is linguistic continuity.

Assuming Lapita canoes had U-shaped dug-out hulls and simple spritsails, our preliminary VPP results suggest they could beam reach, but were better adapted to broad reaching. We make no predictions here about boat speed, but suggest this level of technology was enough to sustain the Lapita expansion of the western Pacific. It would allow return journeys in seasonally alternating wind systems.

The current dating of Lapita sites allows an interval after settlement in Near Oceania by 1300 B.C., before expansion into Remote Oceania around 1000 B.C. (Sheppard *et al*. 2015). Some technological development of sailing canoes could have occurred in this interval, and there were probably advances in way-finding. Sailors who knew the night sky, and that its appearance changed when travelling north and south, but not when travelling east or west (when it is time that changes), could have eventually extended their range 200 nautical miles from the Solomons to Santa Cruz. They could sail across the latitude and return with seasonal winds under the same sky. Sailing north or south became safe when it was realised that one could return to a familiar sky. Such understanding was like an invention and it was evidently widely shared. From around 1000 B.C. many canoes crossed a navigational threshold into Remote Oceania to both Western Micronesia and West Polynesia, within a very brief period of archaeological time.

*Early East Polynesian voyaging*

In East Polynesia the direct evidence of canoe hulls and appendages has recently improved. The remarkable find of a large section of a canoe hull with a sea turtle carved at its waterline, at Anaweka in New Zealand, dates around AD 1350–1400 (Johns *et al*. 2014), close to the settlement of marginal East Polynesia (Jacomb *et al*. 2014, Wilmshurst *et al*. 2011). This canoe had a sophisticated composite hull which approached a V1 profile (Flay *et al*. n.d.).

It has been suggested that the double canoe was an innovation during the long pause in West Polynesia, but we can now add hydrodynamic advances in hull form. Our preliminary VPP analysis suggests that return voyaging was feasible for early canoes of East Polynesia, of a type represented by the Anaweka *waka*, notwithstanding changes in prevailing winds during periods of climate change, and we suggest this level of technology was enough to sustain the rapid migration attested by archaeology. This is essentially a reaching model rather than a running model as our VPP results show the speed of all three canoe forms tested fell off when running directly downwind. The independent evidence of computer simulation supports a theory of return voyaging by demonstrating that one-way voyaging would result in an unsustainable loss of lives at sea in discovering isolated islands such as Easter Island and Hawai‘i (Irwin 1992).

Archaeological dating of East Polynesian colonisation has improved in the last decade but there are issues still to be resolved (Allen 2014). The theory that the islands of marginal East Polynesia were settled more or less simultaneously, within the limits of radiocarbon dating (Wilmshurst *et al*. 2011), has been taken "… to refute the proposition that there was a systematic strategy of exploratory sailing with respect to prevailing winds" (Anderson 2015: 3). However, the argument is actually that the strategy related to *seasonal variations* in prevailing winds (Irwin 1992). Moreover, different approaches to chronological analysis can suggest time-lags between the settlement of different islands, as recently proposed between Hawai‘i and New Zealand by Dye (2015). Such intervals would accommodate exploration by return voyaging, which our estimates of canoe performance suggest was feasible.

*Voyaging after Colonisation*

The diversity of canoes in Oceania at the time of European contact speaks of multiple strands of history possibly too complex to unravel. Over time, a range of hull profiles developed, generalised here as U, V1 and V2. There was also a development of construction methods from simple dugouts to complex planked canoes with internal frames, but there was an ecological dimension to their historic distribution as planking often occurred on islands without large trees. Over time, sailing capability evidently developed, or declined, in different island groups. The early Anaweka *waka* shows that a more sophisticated sailing technology arrived in New Zealand than survived there. New Zealand offered very big trees and large and elaborate single canoes such as *waka taua* 'war canoes' developed; however, those without the stability of outrigger or double hull could only sail downwind (Irwin 2006). In both Hawai'i and the Marquesas voyaging continued in late prehistory within but not beyond the archipelagos, and historic canoes with spritsails had dug-out hulls described as U-shaped (Haddon and Hornell 1997). On Easter Island voyaging canoes were lost altogether and it is telling that many coastal *moai* statues faced introspectively inland, rather than out to sea.

In the historic period, V-shaped hull profiles persisted in some of the voyaging spheres of Oceania, consistent with the need for sailing performance adequate to sustain inter-island communication. For example, in central East Polynesia, the *pahi*, said to be a Tuamotuan canoe type in the Society Islands, had a V-shaped hull (Haddon and Hornell 1997). Further west, the voyaging sphere of Tonga, Samoa and Fiji was expanding at contact and both U-shaped and V-shaped sailing canoes were represented. The U-shaped canoes could well have managed inter-island passages with predictable seasonal wind shifts. The V-shaped canoes perhaps could have done rather better. In 1616 a *tongiaki*-style canoe was encountered at sea by Schouten and Le Maire, possibly on its way between Tonga and Samoa (van Spilbergen 1906), and others were seen at Niuatoputapu and Tafahi. A later description by Cook (Haddon and Hornell 1997) indicates the *tongiaki* had a V-shaped hull, although with a lateen rig that was cumbersome to tack; but some passages would not have required much tacking. In the Polynesian Outliers V-shaped canoes were recorded in Anuta and Tikopia. A traditional Tikopian canoe, *Rakeitonga,* gifted to Auckland War Memorial Museum in 1916, has a V1 form and is reported to have made return voyages to Anuta and Vanuatu. In wider Micronesia, the sustainability of long-term atoll occupation depended critically on continuing interisland communication and canoe design became most sophisticated there, with V2 hulls of asymmetric form which produced extra hydrodynamic lift. When first encountered by Europeans these were the fastest sailing craft in the world.

* * *

There is a longstanding interest in voyaging in Pacific prehistory. Recent developments include new information on climate change and sailing conditions (Goodwin *et al*. 2014), new statistical models that match the dynamic nature of colonisation (Bell *et al*. 2015), accumulating evidence of interisland contact and trade (McAlister *et al*. 2013), and new archaeological discoveries of canoe remains (Johns *et al*. 2014). Theories about canoe capability invoke the science of sailing and we describe initial research on aerodynamic and hydrodynamic aspects of performance.

Evidence for climate change is particularly significant (Goodwin *et al*. 2014), but the conditions for sailing during prehistory and canoe sailing performance are independent variables and more information is needed about both. It is worth noting that while climate can change by the decade, weather can change by the day, and canoes react to changes in wind and waves in real time. Prevailing winds are not always constant and more clarity about seasonal variability of weather during times of change in prevailing winds would be welcome.

Between approximately 1300 BC and 1000 BC, sailing experience in Near Oceania led to innovations in ocean navigation, which opened routes into Remote Oceania. Our conclusions for sailing in the Lapita period are tentative without evidence of canoes or sails, however, our hypothesis is that voyaging canoes could beam reach and were well adapted to broad reaching. By negotiating seasonal weather strategically, return voyages between islands were possible, especially over shorter distances.

Our estimation of the performance of early East Polynesian canoe hulls is supported by archaeological evidence of the Anaweka *waka* (Johns *et al*. 2014), and our reconstruction of an early sail is informed by distributional evidence and ethnohistory. Preliminary VPP results suggest that during periods of adverse winds and climate change the ability of canoes to sail across the wind could accommodate return voyaging. As in the Lapita period, the performance of canoes running directly downwind was poor, and does not favour a downwind colonisation model.

With regard to the nature of colonisation our estimates of canoe technology suggest that a period of exploration and a strategic order of island settlement were feasible for East Polynesia. This would accord with accumulating archaeological evidence for planned migration, as in the case of New Zealand.

There is a further implication which concerns America—the successful settlement of East Polynesia put a suitable technology into place and brought America within range.

The study of Pacific sailing canoe performance is at an early stage and can be refined. This paper reports the first phase of testing at the University of Auckland and discusses the implications. A second phase of testing which more precisely relates to recent discoveries of early Maori canoes is in hand (Flay *et al*. n.d.).

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NOTE

1. A canoe changes direction by tacking by turning its bow through the no-go zone so the direction of the wind changes from one side to the other. In shunting the front of the sail is transferred to the other end of the boat, the canoe exchanges one end for the other, and the wind continues to come from the same side.

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## ABSTRACT

We report on a collaboration between archaeology and the Yacht Research Unit at the University of Auckland to investigate the sailing characteristics of Pacific canoes, both ancient and modern. Archaeology provides a chronology for the colonisation of Pacific Islands, but one mystery that remains is how well the canoes could sail. We describe the first phase of testing reconstructed model hulls and sails. By combining aerodynamic and hydrodynamic information it was possible to compare the performance of three different kinds of canoe representing simple and more developed forms. We offer tentative suggestions about the sailing performance of canoes of the Lapita period and also conclude that canoes involved in the colonisation of East Polynesia were able to make return voyages between islands on passages that encountered adverse winds as well as fair ones.

*Keywords:* Pacific voyaging, colonisation, canoe performance, naval architecture, wind tunnel

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