WAVE NAVIGATION IN THE MARSHALL ISLANDS

COMPARING INDIGENOUS AND WESTERN SCIENTIFIC KNOWLEDGE OF THE OCEAN

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ABSTRACT

Pacific seafarers developed indigenous navigational techniques to voyage between islands. In the Marshall Islands, navigators remotely sense land by detecting how islands disrupt swells. A recent project to revitalize Marshallese voyaging aimed to understand the science of wave navigation. Local wave concepts are described based on anthropological fieldwork with surviving navigators, including interviews and experience sailing with them. The wave transformation processes that give rise to these patterns are examined using navigators' demonstrations at sea, wave buoy measurements, satellite imagery, and wave model simulations. The scientific data account for one signal used by navigators to remotely detect land. Crossing wave trains extend tens of kilometers in the lees of islands, which can be simulated as refraction of the easterly trade wind swell. Navigators identified a superposition of incident swells with reflected waves 40 km upstream of islands. These reflected waves were too weak to be detected by the wave buoy, but they are conceptualized similarly within indigenous and scientific frameworks. Navigators described another pattern as a wayfaring link between distant atolls. This pattern does not clearly relate to a wave transformation process, suggesting that Marshallese navigators also use concepts of the ocean that do not easily translate into oceanographic terms.

INTRODUCTION

Pacific seafarers began to explore and settle the previously uninhabited islands of Remote Oceania (Eastern Melanesia, Micronesia, and Polynesia) about 3500–4000 years ago (Kirch, 2000). They developed navigational techniques to sail their deep-sea voyaging canoes over hundreds, and in some cases thousands, of kilometers of ocean without the aid of instruments or charts. Ethnographic investigations among surviving voyaging communities have sought to describe various indigenous solutions to the navigational tasks of orientation, steering a course, estimating position, and making landfall (Gladwin, 1970; Lewis, 1972; Thomas, 1987; Feinberg, 1988). They describe how navigators use elaborate mental representations of space, embodied knowledge of the ocean, and voyaging strategies to move through a seemingly undifferentiated environment.

One of the least understood navigation traditions comes from the Marshall Islands of Micronesia, where navigators developed a comprehensive system of wave piloting based on a common land-finding technique for detecting islands by how they disrupt ocean swells and currents (Davenport, 1960; Ascher, 1995; Finney, 1998). The Marshallese archipelago comprises 34 coral atolls and

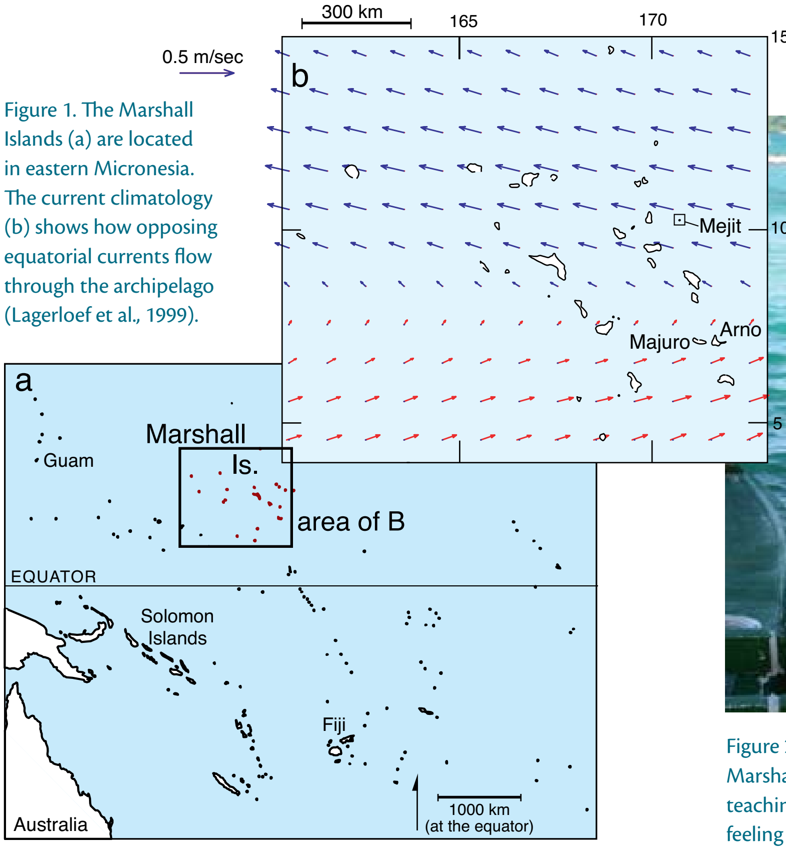

Figure 1. The Marshall Islands (a) are located in eastern Micronesia. The current climatology (b) shows how opposing equatorial currents flow through the archipelago (Lagerloef et al., 1999).

Figure 2. Captain Korent Joel, one of the last traditional navigators in the Marshall Islands, explains the wave concepts modeled within indigenous teaching devices and demonstrates how he detects the wave patterns by feeling how they alter the motion of an outrigger sailing canoe.

islands spread out in two parallel chains over 800 km along a southeast-northwest axis in the eastern part of Micronesia (Figure 1a). Strong, opposing equatorial currents (Lagerloef et al., 1999) make navigation difficult (Figure 1b). In addition, navigators may spend several days out of sight of land because the tops of coconut palms on these low-lying atolls can only be seen 20 km offshore. The indigenous response to these navigational challenges has been to remotely sense land based on disruptions of incident swells and currents.

Exactly how Marshallese navigators find their way with reference to the waves has remained unclear. Researchers in the late nineteenth century and early twentieth century sailed with navigators to understand their concepts of the ocean, which center on either transformations of the dominant easterly trade wind swell (Laubenfels, 1950) or intersections of opposing or nearly opposing swells (e.g., east and west swells) (Winkler, 1898; Hambruch, 1912; Krämer and Nevermann, 1938; Davenport, 1960). However, a dramatic decline in long-distance voyaging throughout the Marshalls in the latter part of the twentieth century prevented more detailed ethnographic investigations of the traditional wave concepts. In addition, previous studies have not oceanographically validated the physical basis of the reported wave patterns or described the swell climatology in this region of the Pacific.

Fortunately, a few Marshallese survive today who learned traditional navigation and voyaging in their youths. One individual, a retired ship captain named Korent Joel (Figure 2), recently called for a concerted effort to revive Marshallese navigation and voyaging before he and others died without passing on their knowledge to the younger generation. For assistance he turned to *Waan Aelōñ in Majel* (Canoes of the Marshall Islands), an organization that had previously documented the construction

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techniques of traditional outrigger sailing canoes (Figure 3) and helped to revitalize the local sailing culture (Alessio and Kelen, 2004). To successfully transfer the navigational knowledge to the next generation, leaders of *Waan Aelōñ in Majel* recognized the importance of understanding the traditional wave concepts from a scientific perspective and creating innovative pedagogical tools, such as computer simulations of the waves. They requested the assistance of University of Hawai'i anthropologist Ben Finney, whose research in reconstructing and sailing Polynesian voyaging canoes (Finney, 1977, 1979) promoted the cultural renaissance of Pacific voyaging (Finney, 1994, 2003, 2007). In response to Captain Korent's request, we developed a collaborative and interdisciplinary project called *Kapeel in Meto* (Indigenous Knowledge of the Ocean) that aimed to synergistically research navigation and revitalize voyaging in the Marshall Islands (Genz and Finney, 2006). A combination of anthropological fieldwork, oceanographic modeling, and collaboration with local navigators and research counterparts has led to a detailed description of the cultural revival of Marshallese wave navigation (Genz, 2008).

In this paper, we describe the science of traditional Marshallese wave navigation. We examine indigenous knowledge of the ocean through the lens of anthropology and compare it to the oceanographic findings. Specific wave patterns used in Marshallese navigation are described based on interviews with surviving navigators and observations made during their traditionally navigated voyages. The wave transformation processes that give rise to these patterns are examined through navigators' demonstrations at sea, wave buoy measurements, satellite imagery, and wave model simulations. Through such comparisons, we articulate the similarities and differences between indigenous and Western scientific knowledge of the ocean.

Figure 3. A traditional Marshallese outrigger sailing canoe.

METHODS

Anthropological Materials and Methods

Ethnographic data-collection methods were used to understand and describe the indigenous concepts of the ocean. Anthropological fieldwork took place for 16 months between June 2005 and September 2006 on several atolls, including Majuro, Rongelap, Namu, Ujae, and Ailuk, where authors Genz and Kelen learned about traditional navigation from Captain Korent Joel and other navigation experts. The research was conducted in the Marshallese language. On land, Genz and Kelen learned by explicit instruction through demonstrations, diagrams, and models. We also conducted a variety of interviews and documented navigation stories, legends, chants, and songs. The ethnographic data were transcribed and translated for analysis. As the research progressed, we corroborated our understandings of the indigenous concepts with the navigators. At sea, we observed navigation in practice and gained practical experience in order to learn some of the embodied knowledge of navigation. For example, in one experiment, Captain Korent guided a yacht 220 km between two atolls using traditional navigation techniques.

Oceanographic Materials and Methods

The oceanographic data-collection methods aimed to understand the physical basis of the wave patterns used in traditional Marshallese navigation. To characterize the wave field, we constructed a swell climatology for the Marshall Islands that described the seasonal changes in the dominant swell. The European Centre for Medium-Range

Weather Forecasts (ECMWF) 40-Year Re-analysis Data (ERA-40) used in the study were obtained from the ECMWF Data Server (ECMWF, 2008).

We gained an overall visual understanding from the collection of satellite imagery. We obtained an Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) image of Mejit Island from the Marshall Islands Environmental Protection Agency.

We characterized swell conditions using in situ wave data collected at various locations by deploying a free-floating directional wave buoy. As it was not possible to reach Mejit by boat, we focused on the closely spaced atolls Majuro and Arno (see Figure 1b). Captain Korent treated these two atolls as a single navigational target because they are intervisible. The Datawell Directional Waverider G-4 wave buoy is designed to measure wave height, frequency, and direction through a GPS-based motion sensor. Directional wave spectra were obtained from 30-minute time series. This method allowed us to identify different swells based on different wave periods and directions. Captain Korent guided the wave buoy deployments. For each salient wave pattern that Captain Korent detected, we deployed the wave buoy at three locations: near shore (1 km), off shore (20 km), and farther off shore where he could not detect the wave pattern (40 km).

We used the Simulating Waves Nearshore (SWAN) model (Booij et al., 1999; Ris et al., 1999) to simulate wave transformations around island bathymetry. We focused on Mejit Island because the ASTER imagery was available for it, Mejit bathymetry is typical of many of the smaller circular atolls in the region, and there are no neighboring atolls or islands nearby to disrupt the regular flow of the dominant northeast trade wind swell. We used 180-m resolution bathymetry data for the Marshall Islands (Earth Reference Data and Models, 2008) to construct the SWAN bathymetry grid and set the incoming swell from the east with a typical wave period of 10 sec. The SWAN model grid was considerably larger than pictured in Figure 8 so as to minimize model boundary effects in the vicinity of the atoll. The spectral output from SWAN was decomposed into dominant swell trains by identifying multiple peaks in the wave directional spectrum at each grid point, and the swell trains were then used to construct the depicted wave orthogonals, lines that are perpendicular to the wave propagation direction and parallel to local wave crests. The regularity of the wave spectra allowed us to connect the wave orthogonals unambiguously across the model domain.

Our primary objective in using SWAN was to examine wave refraction as incident swells from the east passed across the sloping topographies on the north and south sides of the atoll, resulting in the distinctive crossing wave pattern in the lee. We note that SWAN does have an algorithm for wave diffraction; however, the main crossing wave pattern of interest is not strongly affected by the diffraction code. Similar results are obtained with and without the wave diffraction computation.

> "MARSHALLESE NAVIGATORS USE WAVE PATTERNS FOR COURSE SETTING, ORIENTATION, ESTIMATING PROGRESS, AND REMOTELY SENSING LAND..."

INDIGENOUS NAVIGATION CONCEPTS AND MODELS

Surviving Marshallese navigators set a course, orient themselves, and track their progress according to the wave field, in contrast to the other Micronesians who rely primarily on the stars, and the Polynesians who focus on both winds and stars (Lewis, 1972). The Marshallese navigators set an initial course based on the known geographical configuration of the atolls and orient themselves in relation to the wave field. They conceptualize the wave field as swells arriving simultaneously from the four cardinal directions (east, west, north, and south). They know from practical experience, however, that not all four of these swells are present during normal wave conditions. The navigators detect swells by feeling the motion of the canoe. As the voyage progresses, they remotely sense the destination island by detecting particular wave patterns that indicate the direction and distance toward land. The navigators pilot, or guide, their canoes with reference to two different kinds of wave patterns—waves surrounding atolls and waves between atolls.

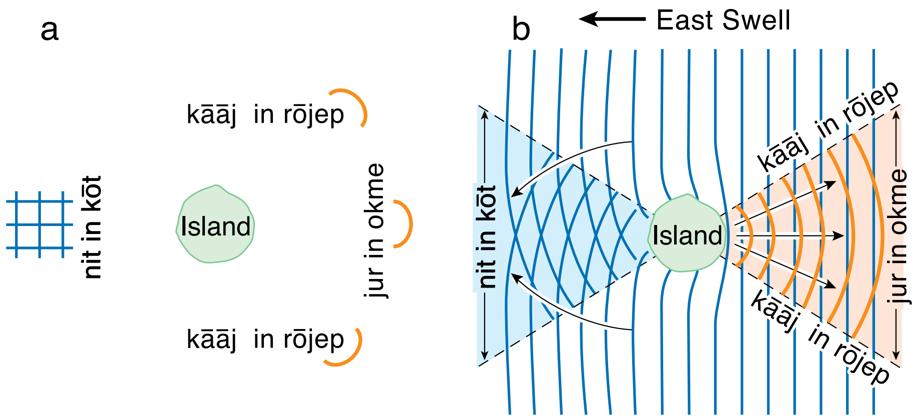


Figure 4. Traditional Marshallese navigators diagram (a) how distinctively shaped waves extend seaward from any island in specific quadrants and can be detected up to 40 km away. *Jur in okme* refers to a curved wave that resembles the shape of a pole traditionally used to harvest breadfruit, *kāāj in rōjep* refers to a similar wave that resembles the curved shape of a traditional fishing lure, and *nit in kōt* refers to a confused sea state by evoking the image of a cage used traditionally to capture birds. Traditional navigators conceptualize (b) these waves as transformations of the easterly trade wind swell, which reflects seaward as it hits an island to form *jur in okme*, a region delineated by waves called *kāāj in rōjep*, and then bifurcates to create *nit in kōt*, a zone of intersecting swells in the lee of the island.

Kōkļaļ (Navigation Signs)

One way that Marshallese navigators remotely sense land is by detecting wave transformations of the dominant easterly trade wind swell as it strikes and flows past atolls and small coral islands. The navigators identified at sea several wave patterns that signal the presence of land. These navigation signs, called *kōkļaļ*, extend seaward from any atoll or island in specific quadrants and can be detected up to 40 km away (Figure 4a). The relative strength of these radiating wave patterns indicates the distance toward land, while the specific wave signatures indicate the direction of land.

The meanings of the local terms are important in understanding how the Marshallese conceptualize the formation of the wave patterns. The imagery evoked by the terms relates to how the waves affect the movement of a canoe, which the navigators use as a swell gauging instrument. The term *jur in okme* refers to a pole or branch used traditionally to harvest fruit from a breadfruit tree. The end of this pole forks to create a V-shaped curve, which is used to twist the breadfruit from the tree. According to the navigators, this curve resembles the shape of the easterly wave pattern when reflected wave energy heaps up the incoming swell. The term *kāāj in rōjep* refers to a traditional fishing lure made of shell or bone used to catch flying fish. The curve of this hook similarly resembles that of *jur in okme* and indicates the shape of the reflected waves to the northeast and southeast of an island. Literally meaning a "pit for bird fighting," *nit in kōt* evokes the image of a small cage used traditionally to capture birds. The horizontal and vertical intersecting bars of the cage represent the crossing of waves from multiple directions.

The navigators conceptualize *jur in okme*, *kāāj in rōjep*, and *nit in kōt* as transformations of the easterly trade wind swell (Figure 4b). Superposition of the incoming trade wind swell and reflected wave energy produces distinctive wave patterns to the east of an atoll. The farthest extent of this reflected wave energy is called *jur in okme* directly east of an atoll and *kāāj in rōjep* to the northeast and southwest of an atoll. The navigators describe how the curved wave patterns *jur in okme* and *kāāj in rōjep* induce a vessel into a surfing motion toward the direction of land. We experienced this wave motion while Captain Korent searched for land during a series of wave buoy deployments to the southeast of Arno atoll. Captain Korent was guiding us to the northwest in the general direction of land by steering relative to a dominant easterly swell when he detected the southeastern *kāāj in rōjep* about 40 km offshore. The entire crew felt and saw how this particular wave lifted the stern of the vessel and pitched the bow forward such that the vessel accelerated slightly in a surfing motion down the wave. Captain Korent adjusted his course based on how the *kāāj in rōjep* directed the vessel. We felt the wave pattern several more times until we sighted the tops of coconut palm trees about 20 km away from land.

The easterly trade wind swell wraps around an atoll and crosses in the direct lee, creating a confused sea state called *nit in kōt*. The navigators envision how the easterly trade wind swell bifurcates around the atoll, such that the southern component flows northward and the northern component flows southward. They also conceptualize how the west swell reflects seaward. This lee wave crossing pattern alerts the navigator of an atoll located upwind. The navigators describe the multiple ways *nit in kōt* affects the motion of a canoe. We experienced and saw these movements to the west of Majuro atoll during a series of wave buoy deployments. The dominant easterly trade wind swell diminished in energy as we moved into the protected wave shadow west of the atoll. About 10 km offshore, diminished swells from the north-northeast and south-southeast rocked the vessel from side to side with equal intensity. Captain Korent also indicated that he could feel a subtle pitching motion in response to the west swell and its reflected wave, but the rest of the crew could not detect this movement.

The descriptions and use of the various *kōkļaļ* apply for normal sea conditions, in which the dominant easterly trade wind swell is present. In adverse sea conditions, the navigators modify the directions of the *kōkļaļ* within their original conceptual framework. For example, during a traditionally navigated voyage between two atolls, a storm replaced the easterly trade winds with a strong westerly wind. A wind-driven west swell dominated the ocean and masked other swells and most of the more subtle *kōkļaļ*. The destination island lay 200 km directly west of the home island. Under normal conditions, Captain Korent should have been able to detect the leeward *nit in kōt* of the home island as we departed and then searched for the windward *jur in okme* of the destination island as we approached it. Instead, he mentally reversed the directions of the *kōkļaļ* in relation to the islands, envisioning how the west-wind-driven swell would create a zone of confused and diminished seas in the lee of the destination island. Indeed, about 30 km away from land, he detected this *nit in kōt* eastward of the island.

Dilep (Wave Path Between Islands)

The Marshallese navigators use *kōkļaļ* that result from transformations of the easterly trade wind swell to locate land, but they describe a different type of wave pattern called *dilep* that forms between pairs of atolls or islands. *Dilep* means "backbone" and refers to waves that form a straight line between islands. The navigators describe how they set an initial course toward the destination island and monitor the direction and strength of swells. As they sail out of sight of their home island, they begin to search for the *dilep* of the destination island. For example, upon leaving Majuro atoll to the north (see Figure 1b), an observant navigator could discern the wave signatures of several northern atolls and then feel his way toward land by staying on one particular wave "path." The navigators' highest art is to maintain the canoe on the *dilep*. In the event that they stray from this line of waves or can no longer detect it, they use the screen of *kōkļaļ* that surrounds each island to remotely sense the destination island.

The navigators describe how to use the *dilep* as a wayfaring signal, but we cannot presently explain its formation. They conceptualize the *dilep* as the crossing of opposing or nearly opposing swells (Figure 5). For example, the crossing of east and west swells creates nodes of intersection called *booj* ("knots") that extend between northern and southern islands, and the crossing of north and south swells creates similar *booj* that extend between eastern and western islands. From our scientific perspective, we cannot explain why this succession of distinctive waves forms on the direct sailing course between islands rather than on either side of it. We also cannot explain why *dilep* toward multiple islands can be present simultaneously

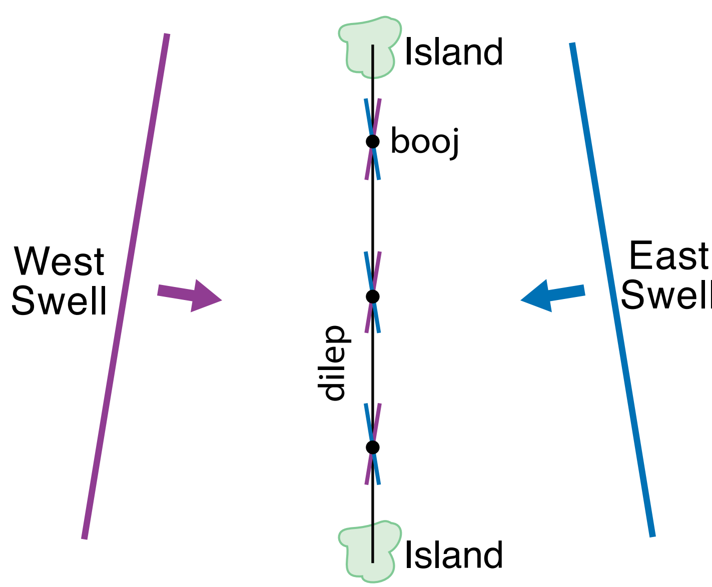


Figure 5. Traditional Marshallese navigators describe a wave pattern called *dilep* that forms between pairs of islands. They conceptualize *dilep* as the crossing of opposing or nearly opposing swells (e.g., east and west swells), which creates nodes of intersection (*booj*) between islands.

when the wave field is not characterized by multiple, opposing swells.

In practice, the *dilep* is perhaps the most difficult of the wave patterns to detect. At sea during several voyages and wave buoy deployments, Captain Korent identified the *dilep*, but we could not discern the motion of this wave pattern from the wave field. During the traditionally navigated voyage described previously, Captain Korent could not detect the *dilep*, as the strong storm-driven westerly swells masked the presence of other swells. Without these guiding waves, he could not easily monitor his progress, but he remotely detected land by feeling the *nit in kōt* of the destination island. Captain Korent's successful landfall without the aid of the *dilep* illustrates how navigators' practical experience at sea differs from their idealized concepts of wave transformations.

Wapepe (Indigenous Wave Model)

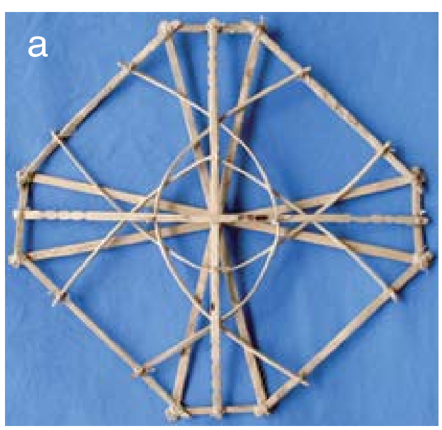
The navigators modeled the wave field and swell transformations for us by weaving the mid-ribs of coconut palms (*Cocos nucifera*) or thin sections of the aerial roots of pandanus (*Pandanus tectorius*) into a latticework of lines and curves. They constructed three varieties of models. One of these, the *wapepe* (Figure 6a), is strikingly similar to those documented in the late nineteenth and early twentieth centuries (Schück, 1902). Scholars initially interpreted these models as "stick charts," believing they showed the positions of islands, sailing courses, and sea conditions (Gulick, 1862; Meinicke, 1863). Later studies, however, showed that they were not nautical charts or instruments, but rather teaching devices that depicted the direction of predominant swells, the bending of swells and their intersections, and the resulting sea conditions (Winkler, 1898).

The *wapepe* models the interplay of oceanographic phenomena and land masses by uniformly depicting four swells from perpendicular directions, symmetrically placing islands and reducing them to points, and reducing the wave patterns to lines or points of intersection (Ascher, 1995). The *wapepe* can be interpreted in three ways (Figure 6b). First, it models the wave field. The intersecting lines at the center of the latticework represent an island, and the four overlapping curves indicate the directions from which swells flow (east, west, north, and south). Second, the *wapepe* models the wave transformations (*kōkļaļ*) of the easterly trade wind swell. With the center of the latticework representing an island, the intersections of the four curves indicate the positions of the windward *jur in okme* and *kāāj in rōjep* and the leeward *nit in kōt*.

Third, the *wapepe* models the *dilep*, or sailing courses between pairs of atolls. In this perspective, the entire latticework represents the ocean. The center point of each short edge of the latticework (right, left, up, and down) represents an island in the eastern, western, northern, and southern parts of the ocean. The central straight vertical line indicates the *dilep* between northern and southern islands, and the central straight horizontal line refers to the *dilep* between eastern and western islands.

WAVE OBSERVATIONS AND MODEL SIMULATIONS

Remote and in situ wave measurements and wave models validate several indigenous wave concepts and provide new data on the regional wave climate and island-induced wave transformations. A regional swell climatology for the archipelago, constructed from a global wave model data set (ECMWF, 2008;



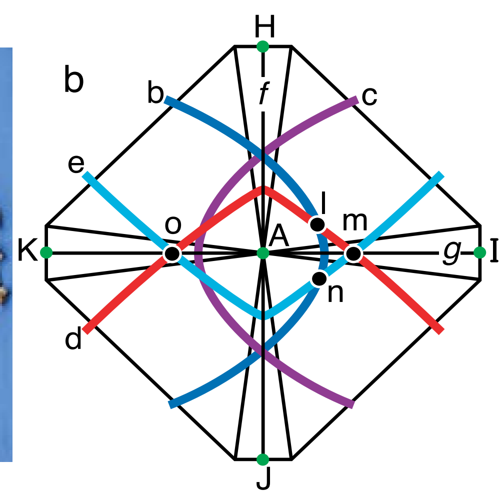


Figure 6. Traditional Marshallese navigators constructed a wave model called *wapepe* (a) by lashing pandanus roots into a latticework. A diagram of the *wapepe* (b) shows how swells approach an island (point A) from the east, west, north, and south (curves b, c, d, and e, respectively). Wave transformations of the easterly swell form *jur in okme* (point m), *kāāj in rōjep* (points l and n), and *nit in kōt* (point o). The crossing of swells from the east and west form a *dilep* (line f) between a northern island (point H) and a southern island (point J), and the crossing of swells from the north and south form a *dilep* (line g) between an eastern island (point I) and a western island (point K).

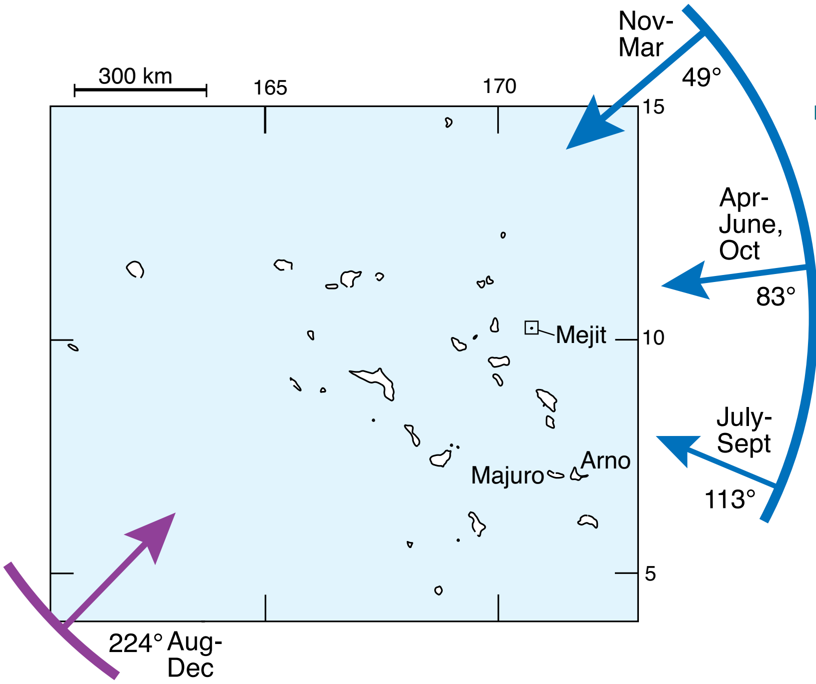


Figure 7. A regional swell climatology model, constructed from a global wave model data set (European Centre for Medium-Range Weather Forecasts [ECMWF], 2008), shows that the swell direction varies seasonally with the trade winds, arriving from the northeast in boreal winter and the southeast in boreal summer. A southwest swell sporadically complements the east trade wind swell, but does not contribute substantially to the overall wave field.

Figure 7), shows that the dominant swell direction varies seasonally with the trade winds, arriving from the northeast in boreal winter and the southeast in boreal summer. Southwest swells occur from August through December, but these intermittent events are limited in duration and would seem to be unreliable for navigational purposes. Extratropical storms in the North Pacific can lead to unexpected waves, such as an event in December 2008 that caused flooding in the Marshall Islands. However, these storms are too strong and irregular for navigation.

To visualize how the dominant easterly trade wind swell transforms as it encounters the atolls, we first analyzed satellite imagery. An ASTER image shows how an east swell bifurcates northward and southward around Mejit Island, resulting in a zone of intersecting wave trains in the island lee (Figure 8a). Navigators identified the regions of intersecting swells in the image as *nit in kōt*.

The SWAN wave model shows how an east swell with a 10-sec period transforms at, and past, the Mejit Island bathymetry (Figure 8b). The bending of crests is due primarily to wave refraction over the sloping sides of the island. Model tests with and without wave diffraction show little difference in the simulated lee wave field, except in a small zone in the immediate shadow of the island. The model indicates that the crossing lee wave pattern extends tens of kilometers downstream, consistent with the ASTER image and with descriptions provided by the navigators. Although the lee-wave crossing pattern is well documented in the oceanographic literature (Bascom, 1964; Massel, 1996), we have not found descriptions of the pattern so far from the island source. The present version of SWAN does not simulate wave reflection from the atoll shoreline and the ASTER image does not seem to indicate the presence of reflected wave crests to the east of Mejit.

We do not have ASTER images or in situ observations to document wave transformations around islands larger than Mejit. We suspect that disturbances of the trade wind wave field may stretch for tens of kilometers in the lee of the larger islands. These longer wakes may be due to the blocking of the dominant swell by the island, which allows directionally spread wave components to create a crossing wave pattern in the island shadow zone (Chawla and Tolman, 2008).

To further validate the lee-wave pattern and to search for reflected wave energy, we gathered directional wave data at navigation signs (*kōkļaļ*) surrounding the closely spaced Majuro and Arno atolls through a series of wave buoy deployments under the guidance of navigator Captain Korent (Figure 9). The data are consistent with a bending of 10-sec period easterly swells into north and south components as they encounter the atolls; however, multiple incident swell trains from multiple directions during the experiment made it difficult to validate the lee-wave crossing pattern conclusively. As described previously, a specific motion of the vessel was detected west of Majuro that the navigator identified as *nit in kōt*. At this location, diminished swells arriving from the north-northeast and south-southeast rocked the vessel from side to side with equal force.

The wave buoy data do not indicate reflected energy in the regions east of

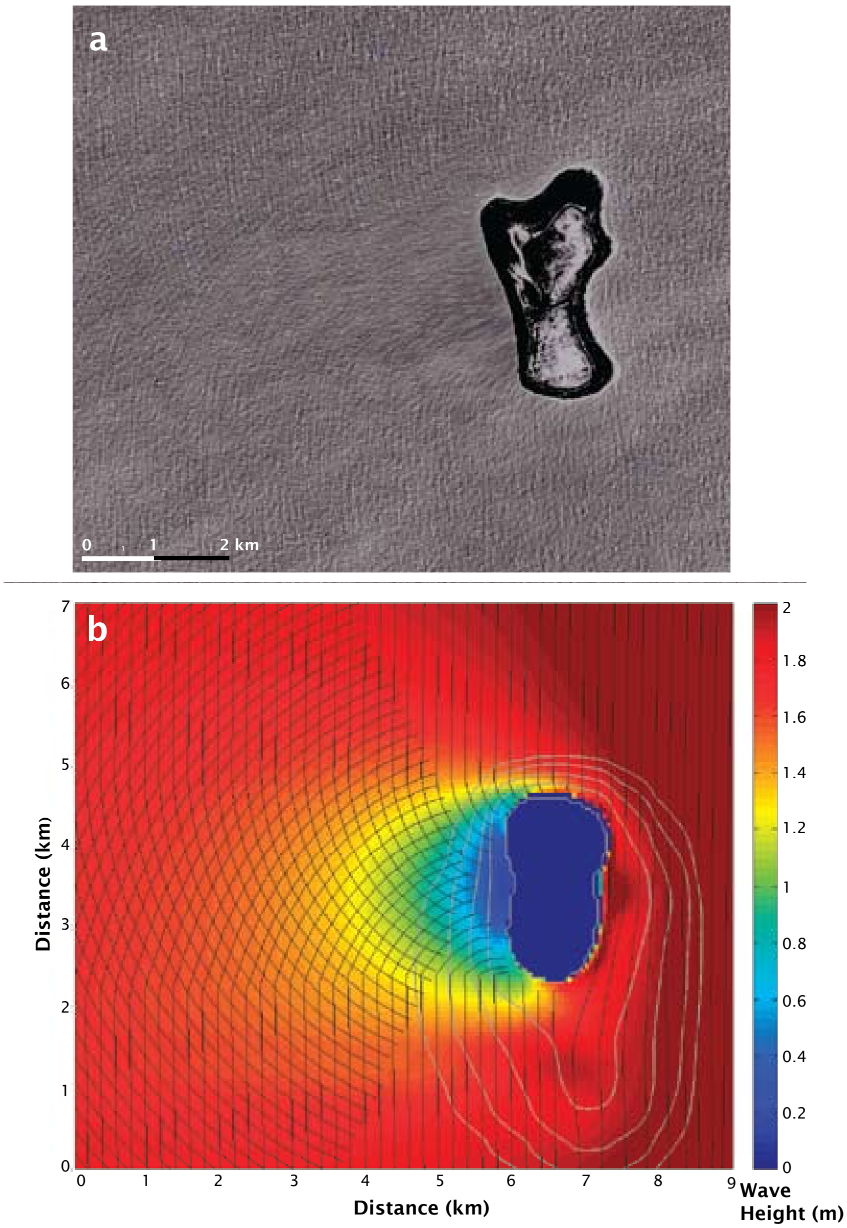


Figure 8. Wave transformations at Mejit Island. An Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) image (a) shows how an east swell bifurcates northward and southward around the island, resulting in a zone of intersecting wave trains in the lee. *Courtesy of the Marshall Islands Environmental Protection Agency*. A Simulating Waves Nearshore (SWAN) model simulation (b) of a unimodal, 10-sec period easterly swell shows similar results in terms of significant wave height (color). Crests are shown in black and 50-m contours in gray. The overall energy is reduced in the direct lee of the island, and the bending of crests is due primarily to wave refraction over the sloping sides of the atoll. This crossing lee wave pattern extends tens of kilometers downstream of the island.

Arno designated by the navigator as *jur in okme* and *kāāj in rōjep*. Apparently, much of the incoming swell is dissipated on the atoll reefs, resulting in weak wave reflection. However, we felt how a vessel intermittently pitched forward in response to swells with increased wave heights 40 km offshore of the south-eastern side of Arno. As described previously, Captain Korent guided us toward land by following this *kāāj in rōjep*. It is likely that an expert may be able to detect an extremely weak or intermittent reflected wave signal that is below the sensitivity threshold of the buoy.

To understand the physical basis of the *dilep*, we gathered directional wave data along the *dilep* extending from Majuro to Aur, an atoll 100 km directly north of Majuro. Several times during this northern voyage, Captain Korent described a rocking motion from intersections of east and west swells. He followed a succession of these *booj* along the *dilep* toward land, but the wave buoy data from these locations indicated only an east swell. However, our field study was limited to a short series of wave buoy deployments for such an extensive wave pattern.

DISCUSSION

The application of the global wave climatology model to the Marshall Islands shows that this region of Oceania is characterized by a dominant easterly trade wind swell for the entire year. The model supports navigators' emphasis on detecting transformations of the trade wind swell, but contrasts with the local conceptualization that swells flow consistently from the four cardinal directions. This apparent incompatibility between local and scientific knowledge systems may reflect differences in terminology and temporal perspectives. First, the Marshallese navigators name each of the four main swells, but a four-point orientation framework can only be used to indicate direction very generally. For example, a swell coming from the northeast could equally be called an east swell or a north swell. Second, the terminology may focus on the immediate sea conditions rather than tracing the wave transformations through time. For example, an east swell that is refracted by an island to flow to the north is referred to as a north swell in the Marshallese language rather than a refracted east swell. This combination of local terminology and a temporal perspective in the immediate present helps explain why the local conceptualization of the wave field differs from the wave climatology model.

The oceanographic data support the physical basis of the navigation sign *nit in kōt* as a lee-wave crossing pattern, and this oceanographic perspective conforms strongly with the indigenous explanation. However, additional measurements are needed to understand the physical basis of the other wave patterns (*jur in okme*, *kāāj in rōjep*, and *dilep*). *Jur in okme* and *kāāj in rōjep* are conceptualized similarly within indigenous and scientific frameworks as reflections of the trade wind swell. The steep island slopes are favorable for wave reflections; however, reflected wave energy was not detected, perhaps due to the limited duration of the buoy tests and the inability to sample a wide range of wave conditions.

The lack of data to support the navigators' conceptualization and use of *dilep* suggests that it does not translate easily into oceanographic terms. This indigenous concept requires the presence of a persistent sea state with four swells flowing from the cardinal directions. However, the swell climatology shows that opposing easterly and sporadic southwesterly swell characterize the wave field only during a few months of the year. It is possible that navigators can detect other swells that are too weak to be measured and modeled. Even if swells arrive from opposite directions, however, their refracted crests would intersect only a few hundred meters offshore. Within sight of land, these wave transformations would not be navigationally useful. Waves may transform as they pass through the spatially varying current field (see Figure 1b); however, we were not able to link this process to *dilep* between all possible island pairs.

Alternately, *dilep* might be a conceptual device rather than an oceanographic phenomenon. Navigators throughout Remote Oceania steer their voyaging canoes during the day by calibrating the angle of dominant swells to the fading stars at dawn (Lewis, 1972). Observations during traditionally navigated voyages suggest that Marshallese navigators set their initial course toward

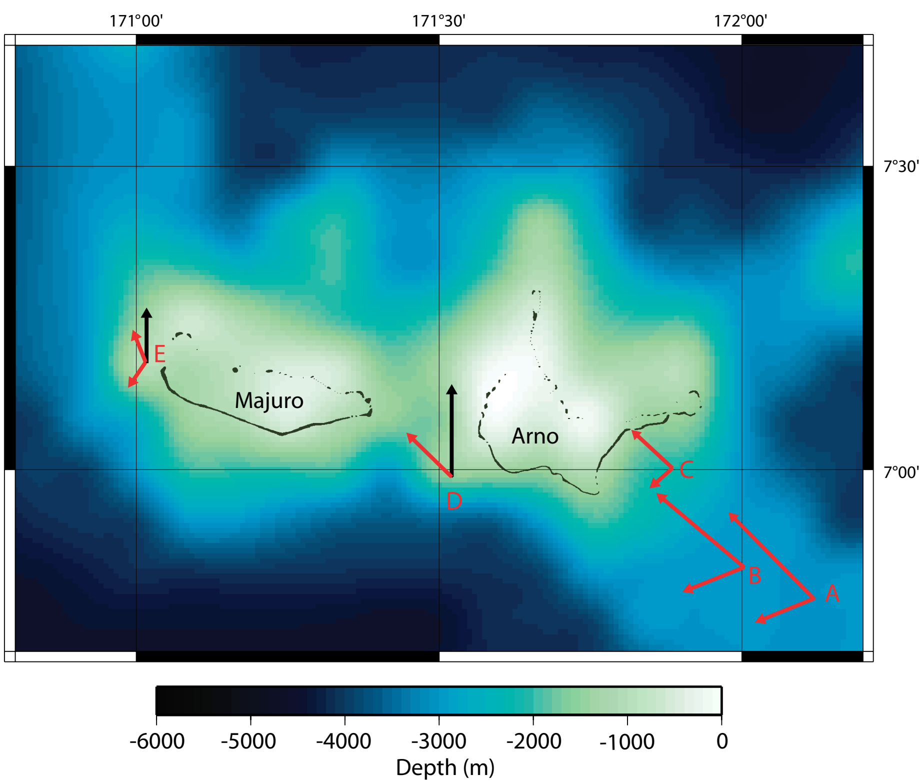


Figure 9. Wave displacement data near Majuro and Arno atolls. Arrows at five locations show individual swell components scaled to wave height. The wave field to the east of Arno is characterized by a primary southeast swell and a smaller east-northeast swell (A–C). The data do not indicate reflected energy, which the navigator identified as *kāāj in rōjep* (B). These swells bifurcate into north and south components as they encounter the bathymetry (color), such that the wave field to the west of Majuro is characterized by diminished south-southeast and north-northeast swells (E). The navigator identified this crossing lee wave pattern as *nit in kōt*. Black arrows indicate a south swell that does not contribute to the formation of *nit in kōt*.

the approximate geographic direction of the destination island and then calibrate it to the angle of the swells. If they can detect subtle swells from several directions, they may be able to steer by following the same angle of intersection. However, the navigators maintain that following the *dilep* is distinct from steering by the relative angle of the swells.

> "FURTHER INVESTIGATIONS MAY REVEAL WHETHER... DIFFERENCES BETWEEN LOCAL AND WESTERN SCIENTIFIC KNOWLEDGE REFLECT DIFFERENCES IN TERMINOLOGY OR DISCREPANCIES BETWEEN INSTRUMENT SENSITIVITY AND HUMAN PERCEPTIONS."

CONCLUSION

Marshallese navigators use wave patterns for course setting, orientation, estimating progress, and remotely sensing land, which supports the notion that Marshallese navigation is a system of wave piloting (Davenport, 1960; Ascher, 1995; Finney, 1998). Our oceanographic perspective conforms strongly with one indigenous concept—a lee-wave crossing pattern that results from refraction of the easterly trade wind swell (*nit in kōt*). Such converging explanations highlight similarities between indigenous and Western scientific knowledge (Agrawal, 1995).

The other indigenous concepts of the ocean are presently more difficult to translate into oceanographic terms. First, the scientific data do not account for the reflected windward wave patterns (*jur in okme* and *kāāj in rōjep*). Second, the modeled wave field shows one dominant swell while navigators' conceptualize four swells. Third, the scientific data do not account for the indigenous concept of wave patterns between islands (*dilep*). Further investigations may reveal whether such differences between local and Western scientific knowledge reflect differences in terminology or discrepancies between instrument sensitivity and human perceptions. It is also possible, however, that the Marshallese have alternative ways of conceptualizing the ocean that do not easily fit within a scientific framework.

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