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Abstract

Data on the amount and type of small debris items deposited on the beaches of the Hawaiian Islands National Wildlife Refuge Tern Island station, French Frigate Shoals were collected over 16 years. We calculated deposition rates and investigated the relationship among deposition and year, season, El Niño and La Niña events from 1990 to 2006. In total 52,442 debris items were collected with plastic comprising 71% of all items collected. Annual debris deposition varied significantly (range 1116–5195 items) but was not influenced by season. Debris deposition was significantly greater during El Niño events as compared to La Niña events. Although often deduced to influence floating marine pollution, this study provides the first quantitative evidence of the influence of El Niño/La Niña cycles on marine debris deposition.

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1. Introduction

Marine debris from land-based and ocean sources continues to threaten wildlife and marine ecosystems around the world. The effects of this dangerous form of marine pollution are apparent throughout the islands of Hawaii, including the remote Northwestern Hawaiian Islands Marine National Monument (NWHI). The NWHI are home to endangered Hawaiian monk seals (Monachus schauinslandi), sea turtles, numerous species of seabirds, and an abundance of coral reefs (Miller and Crosby, 1998). Because of the NWHI’s unique and distinct bathymetry and relative geography, together with ocean currents aggregating derelict fishing gear and other forms of marine pollution (Kubota, 1994; Ingraham and Ebbesmeyer, 2001; Matsumura and Nasu, 1997; Henderson, 2001), marine debris continues to threaten coral reef ecosystems and associated wildlife of the NWHI (Donohue et al., 2001; Donohue, 2005; Donohue and Foley, 2007).

Ecosystem damage as a result of both large and small marine debris occurs at multiple trophic levels from coral reefs to marine mammals and other megafauna. In lower trophic levels, marine debris such as monofilament fishing line and derelict fishing gear, or ghost nets, damage coral reefs (Asoh et al., 2004). Active or derelict fishing gear,
The majority of research and large-scale removal efforts have historically focused on large debris items, such as derelict fishing gear, due to the severe and highly visible effects of this form of debris. However, smaller debris items such as bottle caps, lighters, and plastic pieces, are also hazardous to wildlife. Ingestion of these smaller debris items is a threat to many animals, particularly seabirds. Seabirds mistake plastics, Styrofoam, fibers, bags, bottle caps, and small toys for prey and ingest them (Harrison et al., 1983; Dickerman and Goelet, 1987). Ingestion of these debris items may cause intestinal blockage and injury, loss of nutrition, starvation and death (Redford et al., 1997; Derraik, 2002). Though the effects of smaller debris items are great, just one study to date has investigated the deposition of these smaller items in the NWHL at Midway Atoll National Wildlife Refuge and Hawaiian Islands National Wildlife Refuge Tern Island station, French Frigate Shoals, both known for their large populations of seabirds (McDermid and McMullen, 2004).

In past years, significant efforts have been conducted to remove derelict fishing gear and other large marine debris from the NWHL (see Donohue, 2003 for a detailed review of these efforts). In 1999, a multi-agency effort removed derelict fishing gear from Lisianski Island and Pearl and Hermes Atoll in the NWHL. Forty tons of fishing gear were removed and critical data were collected on the source and magnitude of this problem (Donohue et al., 2001). Efforts addressing the problem of marine debris in Hawaii have continued. In 2005, the US Department of Commerce, National Oceanic and Atmospheric Administration (NOAA) funded several marine debris projects including an aerial survey and debris removal project in the main Hawaiian Islands and an additional year of marine debris removal in the NWHL (NOAA, 2006).

While proximate mechanisms for the accumulation of marine debris on the NWHL remain under investigation, prior studies have suggested that circulation of the sea surface layer and effects of El Nino/Southern Oscillation (ENSO) events may play roles in the quantity and location of debris deposition in the Hawaiian archipelago (Harrison and Craig, 1993; Matsumura and Nasu, 1997; Ingraham and Ebbesmeyer, 2001). More recently, Donohue and Foley (2007) have documented increased Hawaiian monk seal entanglement during El Nino periods and attribute this to increased amounts of marine debris pushed further south by El Nino altered sea surface circulation.

A review and analysis of marine debris deposition rates were calculated from data collected between 1990 through 2006 at the Hawaiian Islands National Wildlife Refuge, Tern Island station, French Frigate Shoals, Northwestern Hawaiian Islands Marine National Monument. Specific objectives of the study were to describe the amount and type of marine debris deposited on Tern Island, and test whether deposition is correlated with year, climatological seasons, and El Nino/Southern Oscillation (ENSO) including both El Nino and La Nina periods. For a subset of years, 1990–2000, we test if local sea surface temperature is a suitable indicator of relative marine debris deposition and ENSO events.

2. Materials and method

Marine debris data were collected from 15 March 1990 to 16 March 2006 on Tern Island, French Frigate Shoals, Northwestern Hawaiian Islands (23° 52' N, 166° 17' W) (Fig. 1). Due to the remoteness of Tern Island and the presence of only a few scientists and volunteers on the island, who remove all waste associated with their activities, it was assumed that marine debris on Tern Island was from exogenous sources. Every two weeks, three US Fish and Wildlife Service (USFWS) personnel collected marine debris and associated deposition data on three beaches: Crab and Shell Beaches along the north side of the island and South Beach. A fourth beach, East Beach, is an ephemeral beach and was surveyed opportunistically. All marine debris on the study beaches up to the landward berm was collected before 0800 Hawaii Standard Time on all survey days in order to minimize disturbance to the critically endangered Hawaiian monk seal. Any visible debris items pushed above the berm by wind or wave action were also collected and documented.

Collected debris items were counted and identified to one of 50 individual categories such as light sticks, metal lids and Styrofoam floats. Debris items were also compiled into seven materials categories: plastic, Styrofoam, rope, glass, metal, rubber, and wood. For biweekly totals, all debris items from all beaches surveyed were pooled. Derelict fishing nets were documented, but are not included in this analysis and will be addressed in future publications.

Climatological seasons were defined as follows for analysis: winter = December 21 through March 19; spring = March 20 through June 20; summer = June 21 through September 20; and, autumn = September 21 through December 20 (US Naval Observatory, 2003). Because the temporal scale and pattern of deposition were unknown but unlikely to be meaningfully represented by a calendar year, for seasonal analyses the total number of items collected during each season for all years were pooled.

Because the duration of El Nino/Southern Oscillation events did not correspond to calendar years, blocks of El Nino and La Nina periods were identified for analysis. Months occurring neither during an El Nino or La Nina...
were also identified and characterized as “non-event” months. The less conservative bi-variate El Niño/Southern Oscillation time series developed by Smith and Sardeshmukh (2000) was employed to increase the potential of detecting a statistically significant signal. This time series is based upon the combination of the atmospheric Southern Oscillation Index and oceanic Niño 3.4 sea surface temperature. El Niño months were defined as: June 1991–June 1992, March 1993–July 1993, September 1994–February 1995, May 1997–April 1998, June 2002–February 2003, and August 2004–October 2004; La Niña months were defined as: July 1998–February 1999; December 1999–February 2000, and October 2000–February 2001; non-event months were defined as all other months. Complete data for the El Niño, La Niña, and non-event months were available through February 2005.

Reynolds sea surface temperature (SST) data were provided by the National Oceanographic and Atmospheric Administration’s Cooperative Institute for Research in Environmental Sciences, Climate Diagnostics Center in Boulder, Colorado. These SST data were provided as monthly climatology means (°C) spanning the years 1990–2000 for the area 165.5° W–166.5° W and 23.5° N–24.5° N, encompassing French Frigate Shoals, NWHI. Because debris deposition data were collected in biweekly periods which sometimes spanned two months (e.g. 5/28/90–6/11/90) approximate monthly debris deposition were calculated so that such values could be examined relative to monthly SST measures. In detail, monthly debris totals were calculated by dividing each biweekly total by the total number of days during that period, resulting in an estimated number of debris items deposited per day. That value was then multiplied by the number of days in each month encompassed during that particular biweekly period. Daily deposition estimates for each month were summed, which resulted in an approximate monthly debris deposition total. The use of sea surface temperature anomalies were evaluated as an additional potential debris deposition index, but are not included in the analysis as the decadal time span for the data (1990–2000) did not achieve the 25–30 years typically used in calculating rigorous SST anomalies.

Statistical analysis was performed using SigmaStat 2.03 (Access Softek, Inc.) and α was set at $P \leq 0.05$. Mean

![Map of the Hawaiian Archipelago including the main Hawaiian Islands and Northwestern Hawaiian Islands with an inset view of Tern Island, French Frigate Shoals, Northwestern Hawaiian Islands Marine National Monument.](image_url)
values are provided with the standard error of the mean unless otherwise noted.

3. Results

Large numbers of marine debris items were documented in each year of this 16 year study, with over 3000 items collected annually in nearly one-half of all years surveyed. From 1990 to 2006, a total of 52,442 marine debris items were deposited on Tern Island beaches with annual deposition ranging from 1116 to 5195 items in 2001 and 2004, respectively (Fig. 2). The high variability between deposition amounts each year is evidenced by significantly different mean values among years ($P = 0.006$); annual mean deposition for all years pooled was $3085 \pm 293$ items.

Plastic comprised 71% of marine debris deposited on Tern Island, significantly greater ($P < 0.05$) than glass which was the second most abundant debris type at 17%, followed by Styrofoam, rope, metal, rubber, and wood comprising less than 13% as a pooled group (Fig. 3). A total of 11,851 items (22.6%) collected in this study originated from the maritime industry. The composition of those items included plastic, glass, rope and Styrofoam items.

Mean seasonal debris deposition did not differ significantly after accounting for effects of year (two way ANOVA, $P = 0.18$). Each summer a mean of $148 \pm 14$ debris items were deposited, followed by spring ($133 \pm 9$ items), winter ($126 \pm 13$ items) and autumn ($113 \pm 11$ items) (Fig. 4).

Biweekly debris deposition totals during El Niño events ($149.13 \pm 13.9$ items) were greater than those for La Niña periods ($67.73 \pm 9.42$ items) or non-event periods ($129.55 \pm 6.9$ items). Deposition amounts during both El Niño and non-event periods were significantly greater than...
La Niña periods ($P < 0.05$) (Fig. 5). These results are exemplified by the biweekly deposition means of the most common type of debris, plastic. A biweekly mean of 103 plastic debris items were deposited during El Niño events, 46 plastic debris items during La Niña events, and 92 plastic debris items during non-events.

![Graph showing marine debris deposition by season](image1)

**Fig. 4.** Mean number of marine debris items (±standard error of the mean) deposited for each season on all beaches surveyed at Tern Island, French Frigate Shoals, Northwestern Hawaiian Islands Marine National Monument from 1990 to 2006. Debris deposition means for autumn were significantly less than those for spring and summer ($P < 0.05$).

![Graph showing marine debris deposition by event type](image2)

**Fig. 5.** Mean number of items (±standard error of the mean) deposited on all beaches surveyed on Tern Island, French Frigate Shoals, Northwestern Hawaiian Islands Marine National Monument during El Niño ($n = 92$), La Niña ($n = 33$), and non-events ($n = 258$) from 1990 to 2006. Debris deposition means for La Niña events were significantly less than those for El Niño and non-events ($P < 0.05$).
It has been well documented that marine debris tends to accumulate in an area north of the Hawaiian Archipelago due to ocean and atmosphere interactions (Dotson et al., 1977; Mio and Takehama, 1988; Wakata and Sugimori, 1990; Kubota, 1994). Oceanic currents (Ekman and Stokes drift and geostrophic currents) together with atmospheric winds provide the mechanism for movement and accumulation of marine debris north of Hawaii (Kubota, 1994). Accumulation in Hawaii, especially in the NWHI, is contingent to the location of the North Pacific subtropical high and associated Subtropical Convergence Zone (STCZ) (Donohue et al., 2001; Pichel et al., 2003; Donohue and Foley, 2007). In 2005, a study conducted by Airborne Technologies, Inc. and the US Department of Commerce, National Oceanic and Atmospheric Administration’s Fisheries Service documented marine debris in the STCZ utilizing satellite imagery, confirming the STCZ contains high densities of marine debris (NOAA PSD/ETL, 2005).

During winter months the STCZ, as evidenced by the Transition Zone Chlorophyll Front (TZCF), along with the North Pacific subtropical high, shifts southward over the area 30–35° N latitude (Polovina et al., 2001; Pichel et al., 2003). This southward shift is exaggerated during El Niño events (Donohue and Foley, 2007). It has therefore been thought that an increased amount of marine debris would accumulate and be deposited on NWHI beaches, which lie at approximately 23–28° N latitude, during the winter with relatively more debris deposited during El Niño periods (Ingraham and Ebbesmeyer, 2001; Pichel et al., 2003).

However, we found no effect of seasonality on marine debris deposition at French Frigate Shoals despite the large sample sizes. Current patterns and eddies in and around French Frigate Shoals may have affected deposition amounts and patterns, confounding the measurement of any overall effect of the southward shift of the STCZ during winter months. Debris might also be trapped in nearshore surface currents and eddies and latently deposited during summer months, though gross ocean basin scale accumulation may have occurred during the previous winter. Studies of the macro- and micro-circulation patterns of the NWHI would likely contribute to the understanding of causal mechanisms of debris deposition on monument beaches and provide managers with information on best practices for long-term marine debris mitigation such as the optimal timing of removal efforts.

This study is the first to document quantitative support for the hypothesis that the deposition of small marine debris items in the NWHI is greater during El Niño events. In addition, reduced debris deposition during La Niña events suggests that physical conditions during these events result in a reprieve from what appears to be a continuous and significant deposition pattern during other times. Ocean circulation in the tropical Pacific behaves “unusually” when an intense El Niño event occurs, as in the 1982/1983 El Niño event (Harrison and Craig, 1993). Previous studies have suggested a positive effect of El Niño on debris deposition,
i.e. an increased deposition of debris during El Niño years. For example, the 1991/1992 El Niño event was postulated as a mechanism for the increase in debris deposition on Yukutat, Alaska beaches (Cannon et al., 1985; Reed and Schumacher, 1985). Studies also suggested that the 1991/1992 El Niño influenced surface currents and winds, and caused a strong northward flow which resulted in the increase in debris deposition in this particular area as compared to other areas in the Gulf of Alaska (Cannon et al., 1985; Reed and Schumacher, 1985). Both debris sightings and animals entangled in marine debris have been reported as more frequent during El Niño years throughout the Hawaiian Archipelago (Pichel et al., 2003; Donohue and Foley, 2007). This is thought to be caused by the southward shift of the STCZ, as occurred in the strong El Niño event of 1997/1998. During the subsequent 1999 strong La Niña event, a reduced latitudinal range of the STCZ was noted (Polovina et al., 2001). Due to the southerly extent of the STCZ during El Niño events and the reduced range during La Niña events, it has been hypothesized that marine debris deposition is higher during El Niño events, and lower during La Niña events (Pichel et al., 2003). The results from this study are the first to quantitatively evaluate the influence of El Niño/Southern Oscillation and La Niña events on marine debris deposition.

4.1. Sea surface temperature

Prior studies have suggested that the circulation of the sea surface layer during El Niño events, and the accordant increased SSTs, play a role in the quantity and location of debris deposited in the Hawaiian Archipelago (Harrison and Craig, 1993; Matsumura and Nasu, 1997; Ingraham and Ebbesmeyer, 2001). Of the 11 years of data available on SST in this study, no relationship was found between monthly SST and monthly debris deposition totals. As SST increased, deposition amounts remained variable suggesting that El Niño/Southern Oscillation event-defining variables, other than SST, are potentially masking or swamping any signals of debris deposition accounted for by SST. These variables might include: sea-level pressure, zonal and meridional components of the surface wind, surface air temperature, and total cloudiness fraction of the sky, some of which may prove useful as indices of marine debris deposition when investigated further.

In closing, a review of plastic disposal and littering laws and regulations both in the US and abroad would illuminate the circumstances under which large amounts of plastic continues to consistently enter the Pacific Ocean and the NWHI. Clearly, outreach and infrastructure to support the responsible use and disposal of plastic items by consumers/users is also needed. We propose that the worldwide plastics industry as well as the manufacturers, distributors and vendors of plastic items all have obligations to ensure their products are used and disposed of in a way that does not degrade the environment.

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