



On North Pacific circulation and associated marine debris concentration

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ABSTRACT

Marine debris in the oceanic realm is an ecological concern, and many forms of marine debris negatively affect marine life. Previous observations and modeling results suggest that marine debris occurs in greater concentrations within specific regions in the North Pacific Ocean, such as the Subtropical Convergence Zone and eastern and western “Garbage Patches”. Here we review the major circulation patterns and oceanographic convergence zones in the North Pacific, and discuss logical mechanisms for regional marine debris concentration, transport, and retention. We also present examples of meso- and large-scale spatial variability in the North Pacific, and discuss their relationship to marine debris concentration. These include mesoscale features such as eddy fields in the Subtropical Frontal Zone and the Kuroshio Extension Recirculation Gyre, and interannual to decadal climate events such as El Niño and the Pacific Decadal Oscillation/North Pacific Gyre Oscillation.

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1. Introduction

The Pacific Ocean is the largest of the world's oceans, and the North Pacific Ocean is the largest body of water in the northern hemisphere. The North Pacific spans several oceanographic regions formed by a basin-wide circulation system primarily driven by the wind. Complex ocean–atmosphere interactions in the North Pacific result in changes in the physical and biological properties of this ocean on seasonal to decadal time scales. The overall size of the North Pacific makes it difficult to directly observe in situ on synoptic or near-synoptic time scales, yet a large amount of oceanographic research has occurred, including a large-scale physical survey as part of the World Ocean Circulation Experiment (Woods, 1985). The results of these surveys, in addition to the recent influx of satellite-based observations, have provided a clearer picture of the physical and biological properties in the North Pacific, yet much is still unknown concerning these properties in this dynamic region.

The complex upper ocean circulation of the North Pacific primarily forms a rotating gyre system. The direction of the spin may aggregate passive items, such as floating marine debris, on the ocean surface. Marine debris, such as derelict fishing nets and plastic particles (Moore et al., 2001; Pichel et al., 2007), has long been recognized as an environmental issue in the global ocean (Anon., 1975; Carpenter and Smith, 1972) and has been shown to have negative effects on organisms in the North Pacific, for

example, sea turtles (Balazs, 1985), coral reefs (Donohue et al., 2001), seabirds (Auman et al., 1997; Fry et al., 1987; Young et al., 2009), and Hawaiian monk seals (Donohue and Foley, 2007; Henderson, 2001).

Although previous work has provided observations and proposed mechanisms for regional marine debris accumulation, a basin-wide overview of the North Pacific Ocean circulation in regard to marine debris transport and concentration is provided here. Focus is narrowed on the Subtropical Gyre and Transition Zone and their relationship with biological processes and marine debris concentration on large and intermediate (meso)scales. In addition to describing the spatial patterns, the major modes of temporal variability on annual and decadal scales are described. The objective is to provide a brief overview of the circulation of the North Pacific in the context of marine debris concentration and to speculate on potential climate-driven changes in these patterns.

2. Climatological characteristics of the North Pacific Ocean

2.1. Circulation of the North Pacific Ocean

Wind stress is the main driving force for upper ocean circulation (Pickard and Emery, 1990) and is responsible for the formation of the main horizontal circulation patterns. In the North Pacific, the prevailing winds form two large oceanic gyres, each bounded by major current systems (Fig. 1). At the southern boundary of the North Pacific Subtropical Gyre (STG) lies the westward flowing North Equatorial Current (NEC). At the western boundary of the Pacific, the NEC splits to join the North Equatorial Counter Current

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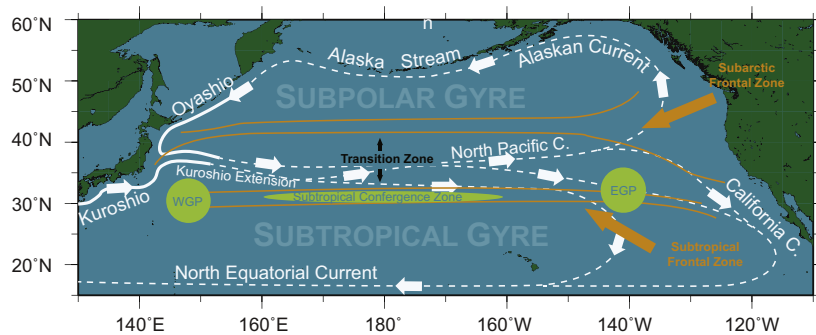


Fig. 1. Schematic representation of the major oceanic currents and zones in the North Pacific. Redrawn from Tomczak and Godfrey (1994) and Seki et al. (2005). The areas bounded by orange lines represent the frontal zones. The green shaded areas represent the major oceanic regions where accumulated marine debris have been reported. WGP – Western Garbage Patch, EGP – Eastern Garbage Patch.

in the south (NECC, not shown), with some flow going north to join the Kuroshio. This major current flows northeast past Japan where it meets the southward-flowing Oyashio at the Kuroshio-Oyashio front. The water from the Kuroshio then travels east to form the Kuroshio Extension (KE). As the Kuroshio passes 170°E, it forms the weaker eastward-flowing North Pacific Current (NPC). The NPC continues towards the North American continental shelf where it divides into northern and southern components. The southern component forms the southward-flowing California Current, connecting with the NEC and completing the subtropical gyre circulation. The northward-flowing component forms the poleward flowing Alaska Current (AC), which is also the northern boundary of the North Pacific Subpolar Gyre (SPG). The Alaska current continues west to flow into the Alaskan Stream, meeting the southward flowing Oyashio south of Kamchatka.

The net result of these major currents is to delineate three major oceanographic zones: a subtropical zone to the south, a subpolar zone to the north, and a transition zone between them. Recent studies have shown the importance of the subtropical and transition zones to the concentration and transport of marine debris (Donohue et al., 2001; Donohue and Foley, 2007; Moore et al., 2001; Pichel et al., 2007). These two zones will be the focus of the section below where their physical and biological characteristics are discussed in detail.

2.2. The North Pacific Subtropical Gyre

Similar to other oceans, the main circulation in the surface layer is the major anticyclonic (clockwise) North Pacific Subtropical Gyre (STG), which is also the main feature in the North Pacific Subtropical Zone (Fig. 1). The STG is the largest circulation feature on our planet and the earth's largest contiguous biome (Karl, 1999). The permanent STG is characterized by warm surface waters with low surface phytoplankton concentrations represented by low observed chlorophyll-*a* values ($<0.15 \text{ mg m}^{-3}$, Fig. 2e and f). This is in contrast to the colder, more productive waters of the subpolar region.

The prevailing clockwise rotation of the oceanic STG results in a pattern of regional convergence in this area, which acts to retain matter within the STG. This can also be observed in the atmosphere through climatological wind stress curl fields for February and August in this region (Fig. 2a). The curl of the wind stress field is a measure of the tendency of the horizontal stress vectors to induce rotation around the vertical (Tomczak and Godfrey, 1994). A majority of the oceanic STG is characterized by surface convergence with associated downwelling (negative curl, Fig. 2a and b), with the region of zero wind stress curl lying over the northern boundary of the STG (Pond and Pickard, 1983). The climatological

fields for February and August illustrate the seasonal changes in the wind stress and resultant curl fields. In February (boreal winter), the overall wind stress fields are much stronger than in August (boreal summer), with strong northwesterly winds converging with the west wind drift near 30°N, with the strongest negative curl (downwelling) west of 160°W (Fig. 2a). To the east, a large area associated with the central position of the North Pacific Subtropical High (NPSH) pressure cell can be seen near 130°W, 25°N, where the wind field results in an area of convergence. In August, the wind stress and curl fields are smaller in magnitude. There is a marked decrease in winds from the north and an increase in the westerly winds (Fig. 2b).

The observed climatological patterns of satellite-derived surface currents correspond well for this period (Fig. 2c and d). Surface currents to the north of the STG during February move in a southeastward direction, with stronger currents west of 160°W (Fig. 2c). Weak surface currents and surface convergence are associated with the region under the climatological NPSH near 130°W, 25°N (Fig. 2a and c). The highest surface currents for this period are located in the KE area, and a weak but observable anticyclonic recirculation lies to the south of the KE near 25°N. In August, the climatological pattern changes with the KE shifting to an eastward and northward flow stemming from the NEC (Fig. 2d). The convergent “dead zone” of low surface currents also has an observable shift to the northwest, centered at 140°W, 35°N, similar to the wind stress curl field. While compressed temporally, it is evident from these climatological fields that large- and mesoscale convergent areas exist in the STG.

2.3. The North Pacific Transition Zone

The North Pacific Transition Zone lies directly between the North Pacific Subtropical and Subpolar (Subarctic) Gyres (Fig. 1). The boundaries of the transition zone are formed by two large frontal systems, the Subarctic Frontal Zone (SAFZ) to the north and the Subtropical Frontal Zone (STFZ) to the south (Roden, 1972). The STFZ is a physical front, which extends from about 28–34°N (Seki et al., 2002) and is characterized by a rapid change in temperature and/or salinity depending on the time of year. This large-scale front is made up of one or more individual fronts that at any given time are convoluted in shape, meander, and shed eddies (Roden, 1980). The Ekman transport resulting from the wind stress fields (Fig. 2a and b) forms surface layer convergence at the southern edge of the transition zone, which has been termed the Subtropical Convergence Zone (Pichel et al., 2007). A proxy indicator exists for this region of high surface water convergence at the southern edge of the transition zone. This indicator is the

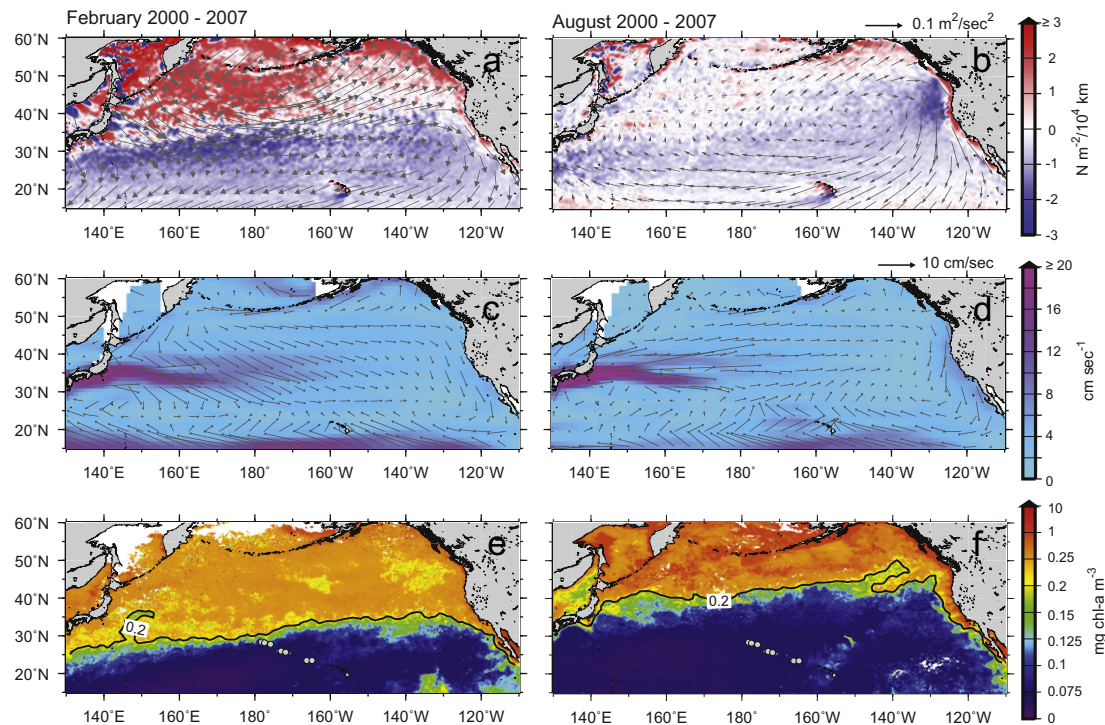


Fig. 2. Climatological averages of QuikSCAT Ocean Wind stress (grey arrows) and curl (color) (a and b), OSCAR surface currents (grey arrows) and surface current magnitude (color) (c and d), and SeaWiFS ocean color (e and f) for February (left column) and August (right column) 2000–2007. The wind stress curl is a measure of the strength and sense of rotation in the wind. The OSCAR surface currents represent the combination of the Ekman and Geostrophic components. The black line in panels (e) and (f) represents the Transition Zone Chlorophyll Front which is used as an indicator of surface convergence.

Transition Zone Chlorophyll Front (TZCF) and indicates the zone of surface convergence where cool, vertically mixed, high chlorophyll surface water on the north side sinks beneath warm, stratified, low chlorophyll water on the south side (Polovina et al., 2001). The TZCF is defined as the $0.2 \text{ mg chlorophyll-}a \text{ m}^{-3}$ isopleth and can be observed with satellite-measured ocean color data. The seasonal migration of this biological indicator of surface convergence can be observed in Fig. 2e and f. Wind stress forcing in February pushes surface waters to the south and the TZCF is observed near its southernmost point across the basin. A decrease in wind stress to the north and an increase in insolation through the summer months occur in August. Therefore, TZCF will be observed close to its highest latitudinal position during August (Fig. 2e and f).

3. North Pacific convergence zones and reported marine debris concentration

As described above, the large-scale circulation pattern of the North Pacific results in several large areas of surface convergence. These regions then become either natural accumulation or retention areas (or zones) on various spatial scales. The difference between these two regions can be described following Franks (2006): an accumulation zone is characterized by convergent particle paths (i.e., organisms or passive particles are continuously advected toward a region and become concentrated), while a retention zone is characterized by closed particle paths (i.e., organisms or passive particles cycle continuously about a closed orbit). The distinction between retention and accumulation zones is important—there is no physically induced change in the amount of biomass in a retention zone. Described below are three observed accumulation (i.e. concentration) zones for marine debris based on published results and in situ observations and their relation to oceanographic features.

3.1. The North Pacific Subtropical Convergence Zone

As stated earlier, a convergent zone exists at the southern edge of the North Pacific Transition Zone associated with the southern boundary of the westerlies. The seasonal generation and intensification of this southern front (i.e., frontogenesis) depends on the initial temperature and salinity (i.e., thermohaline) gradients and the flow field configuration in the surface waters (Roden, 1981). For example, during the winter in the STFZ, increased winds force the Ekman transport of cool, saline waters to the south where warm, fresher waters stay geographically static. This Ekman transport forms surface convergence in this region with the more dense waters from the north sinking on the north side of the convergent frontal zone during the winter (Niiler and Reynolds, 1984). While this is most prevalent during the winter associated with the increased winds and storm tracks, numerical analysis has shown that the surface Ekman convergence in the STFZ can be frontogenetic throughout the year (Dinniman and Rienecker, 1999). This would result in a permanent, yet latitudinally shifting convergent region in the North Pacific (i.e., the STCZ).

The mechanisms that work to form this front also work to aggregate buoyant organic and inorganic matter. The horizontal convergence associated with an active frontal zone works to constrain both active and passive material with increased retention at the surface. Particles must be able to overcome the vertical component of the flow field to stay at the surface. Passive matter (e.g., marine debris, inactive plankton) must be sufficiently buoyant, while active movement by organisms would be enough to overcome the weak vertical flow. This results in the STCZ being important for both active and passive matter including marine debris and biological organisms, especially during the winter and early spring. This has been observed and reported for both organic and inorganic matter (Donohue et al., 2001; Donohue and Foley, 2007; Pichel et al., 2007; Polovina et al., 2001; Seki et al., 2002). Pichel

et al. (2007) reported high densities of surface marine debris within the STCZ during early spring. Additionally, detailed descriptions of marine debris deposition and removal have been reported in the higher latitude of the Northwestern Hawaiian Islands (NWHI) (Boland and Donohue, 2003; Dameron et al., 2007; Donohue et al., 2001; Donohue and Foley, 2007; Henderson, 2001; Kubota, 1994; Morishige et al., 2007). This region is influenced by the variable wintertime latitudinal position of the STCZ, with a reported infusion in biological matter (Baker et al., 2007) and marine debris (Donohue and Foley, 2007; Morishige et al., 2007) to the NWHI during periods when the STCZ nears the island chain. The physical and biological fronts associated with the STCZ (the STF and TZCF, respectively) have been shown to be an important zone for primary producers (Polovina et al., 2001). These associated fronts are also an important forage and migration pathway for many species, including albacore tuna (Polovina et al., 2001), swordfish (Seki et al., 2002), and loggerhead turtles (Howell et al., 2010, 2008; Polovina et al., 2004).

On the large-scale, the transition zone and associated frontal zones (e.g., STFZ) are semi-permanent features of the climatological circulation. On the mesoscale however, a dominant characteristic of this region is the numerous eddies that are highly variable in space and time (Roden, 1991). Fig. 3a and b shows this variability in eddies for May 1997 and April 2008. This region is dominated by mesoscale eddy activity in both years, yet there is an increase in anticyclonic eddy activity to the north in 2008. Eddy activity in this region is important as eddies may aggregate or repel matter depending on the spin direction. In conjunction with the large-scale seasonal movement of the STCZ, eddies may transport matter within mesoscale patches as they propagate westward. Concentration of organisms within isolated eddies and eddy fields associated with fronts has been observed in many oceanic regions (Olson et al., 1994). The inclusion of the mesoscale is imperative in predicting where marine debris may occur in the oceanic realm.

Once debris is found within the STCZ, the fate of the material is uncertain. Passive biological material is more ephemeral compared to resilient marine debris that may last decades, depending on the

chemical composition and rate of degradation. As described above, marine debris may be “beached” on areas such as the NWHI or may be trapped in the prevailing clockwise current structure of the North Pacific STG.

Although it is unknown how long marine debris remains in circulation within the North Pacific, numerical simulations of floating matter or “pseudo” marine debris have provided some insight (Kubota, 1994; Ryan, 2008; Wakata and Sugimori, 2000). Model results from Wakata and Sugimori (2000) using surface currents calculated from ship drift data, estimated that simulated debris circulates around the North Pacific Ocean on a three year time period. Kubota et al. (2005) simulated debris driven by satellite-derived surface currents and found that retention of particles northeast of Hawaii occurred within one to five years from release.

3.2. The “Eastern Garbage Patch”

A climatological atmospheric high pressure zone marked by positive wind stress curl, leads to anticyclonic surface currents with a minimum in the oceanic region between Hawaii and California (Fig. 2a–d). This “dead zone” of currents is closely associated with the position in the atmosphere of the seasonally and interannually variable NPSH. As visible in Fig. 2a–d, the prevailing wind and current structure is anticyclonic, resulting in a convergence to the center of the clockwise rotation. This region has been anecdotally called “The great Pacific garbage patch,” based on reported observations of debris in this area and is the “Eastern Garbage Patch” or “Great Pacific Garbage Patch” referred to in the media. A 2001 study of 11 random sites close to the position of the NPSH on August 23 and 26, 1999 reported a large calculated mean abundance (334,271 pieces/km²) and weight (5114 g/km²) of plastic pieces in the North Pacific Ocean (Moore et al., 2001). Results from a recent model study showed a greater concentration of modeled drifters in this region, with an increase in drifter density as much as 15 times their original density before beginning to dissipate (Maximenko, 2009). The overall size of this region is difficult to ascertain, yet

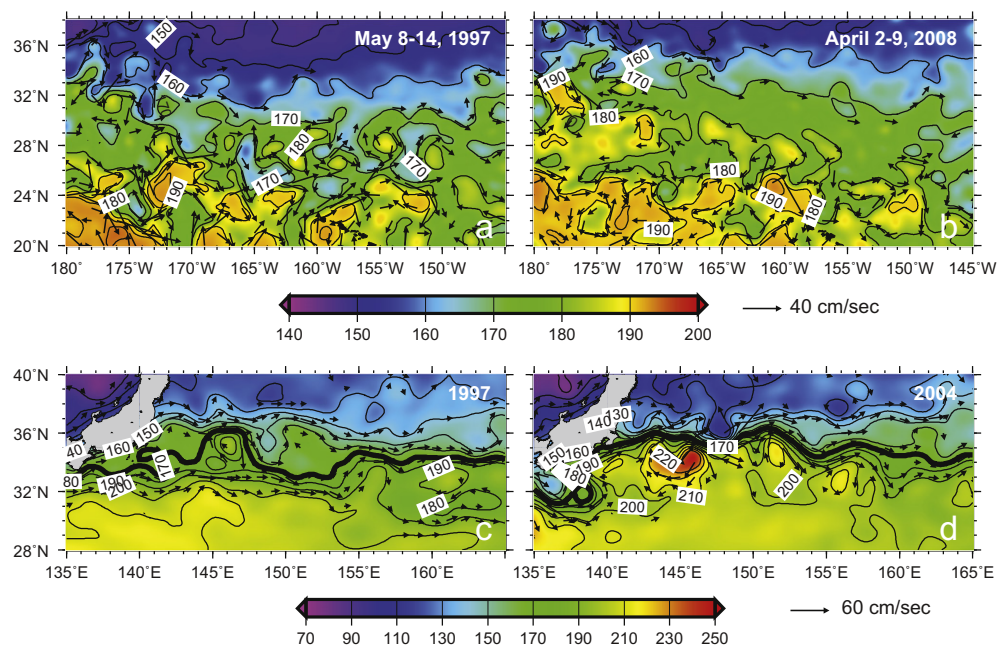


Fig. 3. Weekly AVISO sea surface height for (a) May 8–14, 1997 (after Seki et al., 2002) and (b) April 2–9, 2008. Yearly averaged AVISO sea surface height following Qiu and Chen (2005) for the Kuroshio Extension area during (c) 1997 and (d) 2004. The black vectors represent the magnitude and direction of the geostrophic currents. The black solid lines represent the contours of sea surface height, with the 170 cm contour representing the axis of the Kuroshio Extension highlighted in panels (c) and (d). Notice the difference in color scales and vector legends for each region.

is expected to correspond to the convergent region within the center of the anticyclonic portion of this “gyre within a gyre.”

3.3. The “Western Garbage Patch”

Recent attention has been given to the area southeast of the Kuroshio Extension (KE) near Japan. For example, a recent study of Laysan Albatross concluded that the foraging area of adult albatross originating from Kure Atoll overlapped with the reported range of the western garbage patch (Young et al., 2009). This resulted in a transfer of marine plastics from this area by adult albatross to their chicks.

The role of the Kuroshio in transporting debris was hypothesized (Day et al., 1990) and later verified through observation (Yamashita and Tanimura, 2007). The area to the east of the KE is characterized by two quasi-stationary meanders and a tight recirculation gyre to the south (Jayne et al., 2009; Qiu and Chen, 2005). Wijffels et al. (1998) first hypothesized that this closed recirculation gyre is bounded by the bathymetric features of the Izu Ridge (141°E) and the Shatsky Rise (153°W) (Fig. 1). While a semipermanent feature, the overall strength of the recirculation gyre is related to the dominance of cyclonic (weakening) or anticyclonic (strengthening) eddies within this region caused by fluctuations in the wind stress field (Qiu and Chen, 2005). An example of two states of the KE Recirculation Gyre can be seen in Figs. 3c and d. The annual average sea surface height field for 1997 shows a weak KE flow and its location farther south with increased meandering and a weaker KE Recirculation Gyre (Fig. 3c). In contrast, the KE flow is stronger in 2004, with an increase in sea surface height and a stronger recirculation gyre (Fig. 3d). The variability in the strength of the recirculation gyre would most likely have an impact on the concentration and retention of marine debris, with a greater accumulation and retention effect expected during periods of stronger flow. This retention and recirculation of marine debris within this region appears to result in a western garbage patch south of Japan (Fig. 1).

4. Spatial and temporal variability in the North Pacific

The climatological circulation pattern results in several semi-permanent marine debris concentration sites, yet there is considerable spatial and temporal variability on large- and mesoscales. Mesoscale variability is important for local effects within specific regions, while large-scale climate variability plays an important role across all regions of the North Pacific. Here we discuss the leading modes of climate variability in the North Pacific, and describe their implications to patterns of marine debris accumulation and retention.

4.1. The El Niño Southern Oscillation (ENSO)

The major mode of interannual variability in the North Pacific Ocean is the El Niño Southern Oscillation (ENSO), which consists of three phases, a climatologically “normal” or ENSO-neutral phase, an El Niño phase, and a La Niña phase. The climatological wind and current patterns in Fig. 2a–d represent the average conditions for the North Pacific. During an El Niño event, the Aleutian Low pressure system intensifies and moves farther southward (Bjerknes, 1969) and is associated with a weaker Subtropical High. This increases the strength of the westerlies during the winter months while also displacing the wind field to the south, resulting in a southward movement of the Subtropical Convergence Zone (STCZ) and associated storm tracks in this period. This is indicated by the southward displacement of the TZCF in the El Niño period of February 1998 when the convergence zone reached the northern

edge of the NWHI (Fig. 4). This southern displacement of the front during El Niño events has been associated with an increase in marine debris concentration and Hawaiian monk seal entanglement in the NWHI (Donohue and Foley, 2007; Morishige et al., 2007).

During the La Niña phase, there is a pronounced weakening and strengthening of the Aleutian Low and Subtropical High pressure systems, respectively (Schwing et al., 2002). This results in a northward shift of the westerlies and the underlying storm tracks that results in a northward shift of the STCZ. Again, this is indicated by the northward constraint of the TZCF during February 1999, a La Niña period (Fig. 4). Marine debris deposition in the NWHI during La Niña periods is less pronounced (Morishige et al., 2007), yet the accumulation of debris from the north may still entrain debris within the northern zonal currents of the STG.

4.2. Decadal variability in the North Pacific

The North Pacific Ocean exhibits modes of decadal variability similar in spatial scope to interannual variability patterns. An analysis of climate data records for the 1900s identified a robust, recurring pattern of ocean–atmosphere climate variability centered over the midlatitude North Pacific basin (Mantua et al., 1997). These results showed that the Pacific Ocean appears to remain in either a “warm” El Niño-like or “cool” La Niña-like phase for decades with irregularly varying phase oscillations occurring historically. This climate pattern was termed the Pacific Decadal Oscillation (PDO) and was initially tied to changes in physical oceanic properties (e.g., surface temperature) and salmon landings within the North Pacific (Mantua et al., 1997). Phase shifts in the PDO are expected to have similar effects as ENSO on larger time scales. For example, during the “warm” PDO phase temperatures increase off the US coast as during El Niño, and the intensification of the Aleutian Low strengthens winds and winter mixing in the central North Pacific. This results in cooler surface temperatures and a southward displacement of the STCZ during winter in these periods.

The PDO captures a relatively high percentage of the large-scale climate variability in the North Pacific and has been tied to fluctuations in many marine ecosystems (Mantua and Hare, 2002). Recent work, however, shows that an additional large-scale climate pattern exists, which explains biological variability that is poorly correlated with the PDO. This additional pattern of climate change was defined as the North Pacific Gyre Oscillation (NPGO) and its variability was significantly correlated with fluctuations of salinity, nutrients, and chlorophyll in the eastern North Pacific (Di Lorenzo et al., 2008). Statistical decomposition of sea surface temperature and height fields shows that the PDO and NPGO represent the first two major independent “modes” of variability in the system (~25% and 10%, respectively, of SST variability; Di Lorenzo et al., 2008). As expected, these two patterns show different responses in the North Pacific, and thus have different expected impacts on the concentration of marine debris. The PDO time series is related to the winter placement of the STCZ, which is expected to affect the deposition of

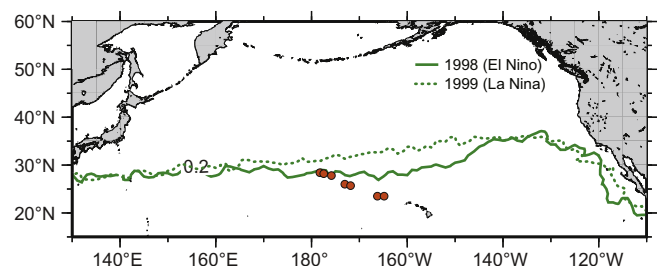


Fig. 4. The position of the 0.2 mg chlorophyll-*a* m⁻³ contour line measured by the SeaWiFS sensor for the February 1998 (El Niño) and 1999 (La Niña) periods. The circles represent the major features of the Northwestern Hawaiian Islands chain.

marine debris on the NPHW. The NPHW time series shows a relation to flow strength of the NPHW and the circulation speed of the STG (Di Lorenzo et al., 2008). A positive NPHW would be associated with increased downwelling conditions in the STG and may increase the concentration and retention of less-ephemeral passive matter (e.g., buoyant marine debris) in areas of anticyclonic spin within the STG (i.e., the “Eastern Garbage Patch”).

It has been shown that atmospheric changes in the eastern North Pacific may impact the western North Pacific circulation. In a study of the KE, Qiu (2003) concluded that PDO-driven surface wind fluctuations in the eastern North Pacific forced lagged changes in the strength and path of the KE. During a positive phase of the PDO, the KE jet would strengthen, corresponding to the strengthening of the KE recirculation gyre (Qiu and Chen, 2005). The opposite effect occurs during the negative PDO phase. A strengthening of the KE recirculation gyre could lead to enhanced marine debris accumulation and retention in the region described as the “Western Garbage Patch”.

The actual effects of these large-scale climate patterns on debris distribution are not known. Based on model studies and observations (Donohue and Foley, 2007; Kubota, 1994; Moore et al., 2001; Pichel et al., 2007), however, it seems plausible that these large-scale fluctuations would affect the mechanisms for marine debris concentration and retention in these areas.

5. Conclusions and future expectations

The North Pacific Ocean shows a complex circulation pattern that varies on multiple spatial and temporal scales. Climatological patterns exist that describe mechanisms for marine debris accumulation and retention in several areas, yet variability on a number of time scales have major effects on the system. Additional work to fully understand the connections between climate variability, circulation, and debris is essential. The importance of this is highlighted by recent observed changes in the physical and biological components of the North Pacific ecosystem (Polovina et al., 2008). Changes in climate may affect circulation patterns and marine debris movement, accumulation, and retention in space and time. Model analyses indicate that the climate system of the North Pacific will warm in the 21st century, and in coming decades the anthropogenic effect on warming will eclipse natural variability (Overland and Wang, 2007). The effects of these changes on North Pacific circulation and resultant marine debris accumulation and retention are unknown. Only through synthesis of climate, ocean, and model research can we expect to predict changes within this complex system.

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