THE ASSOCIATION OF TUNAS WITH FLOATING OBJECTS AND DOLPHINS IN THE EASTERN PACIFIC OCEAN

V. Simulated trajectories of floating objects entering the eastern Pacific Ocean

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ABSTRACT

A Lagrangian simulation model is used to predict and analyze the trajectories of floating objects entering the eastern Pacific Ocean through five selected locations near the mouths of major rivers of the region.

For each location, basic characteristics, seasonality (especially in relation to precipitation patterns), and annual variability (with emphasis on the impact of El Niño events) are presented and discussed.

The main conclusions are that: (1) through either cyclic current patterns or oscillating north-south movements, most objects are retained relatively close to their source for considerable periods; (2) practically all the transport offshore occurs along 10°N, which receives objects from the north and south; (3) El Niño events alter the patterns substantially, increasing the velocity of the offshore movements of the objects, but always along 10°N.

It is suggested that the association of tunas with floating objects is a retention mechanism, keeping the tunas in the rich coastal areas, and eventually carrying them west through the most productive areas of the eastern Pacific Ocean.

There are many other potential uses for the drift trajectories, among them studies of biogeochemical cycles involving the floating objects, distribution of marine debris, distribution of juveniles of marine organisms such as sea turtles, and regional and transoceanic dispersal.
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INTRODUCTION

In Paper I of this series, tropical rivers that empty into the ocean after crossing forests, jungles, and mangrove swamps were identified as the primary sources of natural floating objects to the eastern Pacific Ocean (EPO). During the rainy season, floods and augmented river flow increase the transport of tree trunks and parts and other floating objects to the ocean. It is of ecological interest to know what happens with all this material after entering the ocean.

What kind of material enters the oceans, and in what quantities? How long do these floating objects last in the surface layers? Are they spread by diffusion or do they concentrate in some areas? How long do they remain in the coastal zone? What proportion becomes stranded on beaches? Are there areas of the ocean floor that receive large amounts of these objects? How does the decomposition process work in these areas? Do nutrients and organic matter re-enter the surface layer and, if so, how long does this take? We are interested in the population dynamics of floating objects: their "recruitment" seasons and areas, their movements, their "mortality rates," and their role as focal points for faunal communities and as dispersal agents for species. We are also interested in their role in biogeochemical cycles. The answers to many of these questions will probably be of significance to the ecology of tunas, and may help us understand why they associate with floating objects.

One of the main questions from the point of view of the association of tunas with floating objects is where do the objects go after they enter the ocean? To answer this question two limited experiments were carried out off Colombia and Ecuador, in which natural logs were tagged with numbered plastic squares (Anonymous, 1988; 1989). Cayré and Marsac (1990) made a similar study in the western Indian Ocean. In all cases the number of recoveries was low or the results were limited by the number of objects studied. A different approach is described here, based in the use of a simulation model of the surface circulation in the area. The main underlying processes that affect the dynamic behavior of the oceans have been modelled by several authors: Busalacchi and O’Brien (1980, 1981) and Busalacchi et al. (1983) described the seasonal and interannual variability of the equatorial Pacific, using a wind-forced, reduced-gravity, linear transport model. Luther and O’Brien (1985) described the use of a non-linear reduced-gravity model to simulate the wind-driven circulation in the Indian Ocean. Parés-Sierra and O’Brien (1989) used a similar model to describe the variability of the California Current system. Seckel (1972) used a simple wind-driven circulation model to study the contribution of the currents to the migration of skipjack that enter the North Equatorial Current (NEC) in the eastern Pacific and to support the hypothesis that skipjack may travel from the eastern Pacific to Hawaii by swimming randomly and drifting with the current. Power (1986), using an advection-diffusion model, demonstrated that variations in the location and time of spawning of the northern anchovy and changes in the magnitude of Ekman transport have significant effects on the larval distribution of the species.

The main objectives of this study are to model the movement of floating objects entering the EPO from the rivers of South and Central America, and to relate these movements to the proposed migrations of yellowfin tuna. The study is focused on natural objects, mostly trees and parts of trees, the most abundant type of floating object found (Paper III).

The main questions we want to explore are:

1. For a general introduction to this series of papers, see Paper I, Environmental background and fishing areas

Simulated trajectories of floating objects
- Direction, velocity, and other characteristics of the trajectories.
- Influence of the origin of the object on its final destination.
- Seasonal and annual variation in the trajectories of objects with a common origin.
- Effects of El Niño events (Table 1) as a special case of annual variability.

MATERIALS AND METHODS

A 1.5 reduced-gravity, non-linear model (Figure 1a), based on the equations described by Parés-Sierra and O’Brien (1989), was used to obtain the underlying ocean currents of the Equatorial Pacific Ocean. This equatorial model differs from that described by Busalacchi and O’Brien (1980, 1981) only in the resolution of the borders and the introduction of non-linear terms. The model was adapted by redefining in more detail the western coast of the American continent, and solved on a grid of 663 by 182 0.25-degree squares, covering the equatorial Pacific from 20°S to 25°N. The model was forced using realistic values of wind speed and direction for the area from the Comprehensive Ocean-Atmosphere Data Set (COADS). The model equations were integrated from 1971 to 1987, obtaining monthly matrices of current vectors and thickness of the upper layer. These matrices were input for a Lagrangian simulation model to compute the trajectories of the drifting objects. The drift direction and speed of an object was calculated as the vector resulting from the linear interpolation of the current components on the four corners of the square in which the object is located (Figure 1b). The possible effects of the object’s shape and depth and of direct wind-induced drag on the object were ignored. For each of five selected areas, one-year-long simulations of the trajectory of five objects were run for each month in the 1976-1986 period. The starting point of each object was a random point in a circle of radius 0.25 degrees drawn around the center of each selected area. The model was run on the CRAY-YMP supercomputer in the San Diego Supercomputer Center. For the interpretation of the current patterns, the maps of circulation vectors from Wyrtki (1965) were used (Figure 2).

RESULTS AND DISCUSSION

Location of Sources (Origins)

The origins were defined based on the location of the mouths of the main rivers of the area (Figure 3). A total of 15 entry points were selected, and from those we chose the following five for a more detailed discussion. Precipitation values are approximate.

Area 1: Centered at 16°N, 104°W. The most important river in southern Mexico, the Balsas River, is located in this area. Rainy season occurs between May and October, with peaks in June-July (>300 mm/month); dry season takes place from November to April, with the lowest precipitation levels in February-March (25 mm/month) (Figure 4).

Area 2: Centered at 13°N, 93°W, off the Guatemalan coast, and probably influenced by the Suchiate (Mexico), Coyolate (Guatemala), and Lempa (El Salvador) rivers. Abundant rain (1200 - 3200 mm/yr). Rainy season occurs from May to October, with the peak in June (390 mm/month). The dry season takes place from November to May, with the lowest rainfall in January (<10 mm/month) (Figure 4).

Area 3: Centered at 7°N, 86°W, off Costa Rica; receives water from the Tempisque, Pirris, and General rivers. High precipitation (>3200 mm/yr). Rainy season occurs from May to November, with peaks in

Simulated trajectories of floating objects
September and October (300 mm/month). Dry season takes place from December to April, with the lowest precipitation level in January (25 mm/month) (Figure 4).

Area 4: Centered at 4°N, 79°W, off Colombia; receives water from many Colombian rivers, including the Bando, San Juan, San Juan Micay, and Patía. Highest precipitation in the entire continent (Figure 4); extended rainy season occurs from May to November, with peaks in September and October (900 mm/month), and the lowest levels in February-March (650-700 mm/month).

Area 5: Centered at 3°S, 83°W, off the Gulf of Guayaquil. Includes the Guayas River, the main river of the west coast of South America. The rainy season occurs from January to April, with peaks in February-March (300 mm/month). Dry season takes place from May to December, with low levels of precipitation (<10 mm/month) (Figure 4).

Seasonal and Annual Variation: Area Studies

Area 1: Seasonal and annual variability is quite pronounced in this area. The current system is the result of the interaction between the Costa Rica Coastal Current (CRCC), moving northwest along the coast of Central America, and the Counter Current of Southern Mexico (CSM), flowing southeast toward the Gulf of Tehuantepec. There is an annual cycle in the intensity and location of both currents. During May to July, both are present, and the CRCC is close to the continent. During August and September, the CRCC is the dominant current. From October to April, the CSM comes closer to the continent, displacing the CRCC to the southwest. This process peaks in February-March, when the CRCC is completely replaced as the dominant force by the CSM flowing southeast. This is clearly seen in Wyrtki's (1965) charts of monthly surface circulation (Figure 2). Objects entering the ocean in the rainy season (June-July) start drifting to the southeast, eventually turning toward the continent or to the west when they reach the Gulf of Tehuantepec. Objects entering the ocean between August and October start drifting to the northwest, under the influence of the CRCC, reaching the Cape Corrientes area of Mexico. Objects reaching Cape Corrientes during May-July continue north and then turn south near the mouth of the Gulf of California to return to Cape Corrientes (Figure 7, January). Objects arriving at Cape Corrientes between December and April approach the coast and begin a return movement to the southeast (Figure 7, August and September).

For floating objects in this area, the simulations show that there is a high probability that they will eventually reach the northern end of the Gulf of Tehuantepec, where they are carried to the west by the North Equatorial Current (NEC). The current system carrying the objects from the Gulf of Tehuantepec to the west varies among seasons and years, especially when there is an El Niño event. In some seasons, the objects reach farther south, to the edge of the Costa Rica Dome, before turning west (Figure 5a), or turn west just off the Gulf of Tehuantepec (Figure 5b).

The most obvious El Niño effect in this area is a faster than normal westward movement. The objects that entered the Pacific in 1983 in this area followed the same trajectories regardless of the season: an initial drift to the southeast, a turn to the northwest, and then due west to the NEC (Figure 6). Similar trajectories can be seen in the weak El Niño event of 1976 (Figure 7).

Area 2: Trajectories in this area are similar, and seasonal changes are not very pronounced. Figure 2 shows the three main currents that influence this area: (1) the CRCC, flowing toward the northwest along the coast; (2) the CSM, influencing the October-April period, and flowing toward the southeast; and (3) the anticyclonic gyre of Central America, especially noticeable during February-March.
Many trajectories resulted in stranding of the objects, frequently in the northern end of the Gulf of Tehuantepec (Figure 8). Even if the model is not accurate in predicting movement close to the coast (because of local topography and tides, and other factors more detailed than the model's resolution), the trajectories are similar to surface-current vectors on the charts (Figure 2). Throughout the year, the Gulf of Tehuantepec is dominated by a coastal current, branching off from the northwest-flowing CRCC and deviating toward the southwest as a consequence of the topography in the north of the Gulf (Blackburn, 1962). This deviation and the influence of local currents may be the reason for the number of objects stranding in this area.

Floating objects entering the ocean during the rainy season drift west along 10°N. This movement becomes more obvious as the season progresses (Figures 9 and 10), and is particularly noticeable for objects entering the ocean in September. From June to October, both the CRCC and CSM turn west just off the Gulf of Tehuantepec (Figure 2), and the trajectories go to the NEC.

As in Area 1, the effect of El Niño events is to accelerate the westward drift after an initial move to the southeast (Figure 11). The pattern for 1977 is peculiar, with objects entering the ocean in August-December drifting southwest and eventually turning toward the east at 5°N in the Equatorial Counter Current (ECC) and returning to the coastal areas (Figure 12).

Area 3: This area is influenced by two current systems (Figure 2): (1) from May to January, the prevailing currents come from the ECC; and (2) during February to April, when the ECC withdraws to the west, the area is dominated by a cyclonic eddy around the Costa Rica Dome.

The trajectories of objects entering in this area show strong seasonal and annual variations (Figures 13 and 14). There are two distinct patterns during the rainy season: (1) objects entering the ocean between June and August drifted near their entry points, followed the coastline or moved southwest, in several cases finishing their year in the Gulf of Panama (Figure 14, June and July); (2) objects entering during September-November drift to the northwest to 10°N and, in some cases, turn west into the ECC. The CRCC is probably responsible for the first stage of this transport (Figure 13).

The effect of El Niño events in this area is interesting. During the early part of the 1982-1983 event (Figure 15), the drift to the northwest and then west along 10°N became faster, but after February 1983 the trajectories change drastically, going to the southeast, entering the area where the ECC is normally found, and finally turning east, finishing at the mouth of the Gulf of Panama (Figure 16).

Area 4: This area shows very limited seasonal and annual variability. The Colombian coast has abundant precipitation during the whole year (Figure 4), and is probably an important source of floating objects. However, most of them remain within the Panama Bight-Gulf of Panama area, even after a full year adrift.

The trajectories show several basic patterns: (1) some objects become stranded after short movements north or south (Figure 17a); (2) some drift north to the Gulf of Panama (Figure 17b); (3) some drift in a circular pattern or erratically near the origin (Figure 17c); and (4) some move southwest as far as the equator, and then return to the area of origin (Figures 18a and 18b). The most frequently observed patterns are (1) and (4). The displacement to the south may be caused by the effect of the ECC on the area, but the
lack of seasonal variability in this pattern is hard to explain, given the strong seasonality shown by the ECC itself.

The annual variability is practically non-existent. The only visible El Niño effect is a more pronounced displacement to the south (Figure 18a).

The exceptionally low drift velocities, combined with the trajectories described above, make this area a major retention zone for floating objects, and perhaps for the tunas associated with them. It is likely that, at least for part of the year, the retention is caused by the presence of the ECC “blocking” westward movement from the Panama Bight (Williams, 1972) and by the coastal topography. Because of the abundance of floating objects entering the ocean in this area, and the high retention rate, this area probably has the highest density of floating objects in the EPO.

Area 5: Seasonal and annual variability are quite small in this area. Objects entering the ocean here generally have a net drift toward the southeast, zigzagging along the coast due to the effects of the Peru Current. Some seasonal variation is noticeable in the differences in penetration of the objects to the south. The year 1981 is a good example of this (Figure 19): objects entering the ocean during the rainy season (January-March) drift along the coast to the southeast, and after a year are found close to 8°S. Objects entering the ocean soon after those months reach much farther south (11°S). During the rest of the year, the trajectories stop short around 6°S, or head east toward the shore.

Another seasonal effect is the variability observed in the initial phases of the drift. In most cases, before heading south, the objects drift toward the northwest, probably due to changes in the intensity and location of the Peru Current. Objects entering the ocean in December to July show an initial movement to the northwest, or some deviations in that direction. Those deviations may take the object as far west as 90°W and, during the strong El Niño event of 1982-1983, to the 94°W meridian.

Of the annual variations, the effects of El Niño are the most conspicuous (Figure 20). The differences in the trajectories seem to indicate that during El Niño years the velocity of the drift is higher, the objects reach much farther south, and the initial northwest deviation is more pronounced.

Summary of Results: Drift of Floating Objects in the EPO

Summarizing our results, we can describe in general terms the main features of the circulation of objects entering the eastern Pacific Ocean. There are four basic characteristics, shown schematically in Figure 21.

(1) Most of the drift trajectories remain within the coastal zones, except in El Niño years, and in many cases remain close to the origin.

(2) The only area between 0° and 20°N where objects leave the coastal zone and move offshore is located at 10°N, between 90°W and 100°W. Objects can reach this area from both north or south, but in all cases they are driven westward to the NEC along the highly-productive equatorial front.

(3) The coastal water masses off Colombia and Panama are areas of low drift velocity and cyclic circulation patterns that result in long retention periods for objects entering the area. Of all the areas studied, this is probably the most isolated from neighboring areas.
(4) There is little evidence of transport of floating objects between the areas north and south of the equator.

Figure 21 shows, in addition to the basic patterns described above, the four main "circulation circuits" and their influence areas.

CONCLUSIONS

Perhaps the most significant conclusion is the prolonged retention time in the coastal zone that results from many of the trajectories. Either because of oscillating north- and south-drifting periods, or because of circular current patterns, most drifting objects appear to be very close to their sources even after a full year at sea. As most trees are likely to become waterlogged and sink in less than a year, it appears that much of this material will sink close to its source. This suggests that the continental contribution could have a patchy spatial distribution, with some areas receiving large amounts of material and others very little.

Tunas, by associating with floating objects, would also remain within the productive coastal zone.

Another salient feature is the westward movement of many objects offshore along 10°N. This parallel marks the east-west axis of the purse-seine fishery and is biologically one of the richest offshore areas of the EPO. This is probably another reason for the adaptiveness of the association of tunas with floating objects; tunas that drift offshore with floating objects end up in a rich frontal zone rather than in the less productive central gyres to the north and south. Objects from the north and south eventually converge on this parallel.

There are many other possible uses of the simulation models, some of which are part of our future plans, among them:

- Study and experiment with a dispersion parameter in the Lagrangian model, to produce stochasticity in the trajectories.
- Generate probability contours for the dispersal of logs from each source over a given time.
- Introduce parameters related to the longevity of the various types of floating objects.
- Based on the previous two results, predict areas of possible accumulation of wood on the sea floor.
- Perform experiments with satellite-tagged logs.
- Simulate long-term dispersal with multiyear trajectories.
- Refine the model to include effects of coastal topography, tidal currents, and other features that are not incorporated in the present version.
- Simulate migratory movements of tunas using drift patterns for nocturnal movements and foraging patterns for daytime movements.
REFERENCES

Williams, F. 1972. Consideration of three proposed models of the migration of young skipjack tuna (Katsuwonus pelamis) into the eastern Pacific Ocean. Fish. Bull. 70: 741-762.
FIGURES

Figure 1  The circulation model: (a) Parés-Sierra and O'Brien non-linear, reduced-gravity model equations and symbols; (b) linear interpolation of the current components at the four corners of the 0.25-degree square in which the object is located.

Figure 2  Eastern Pacific Ocean circulation charts (from Wyrski, 1965).

Figure 3  Location of the five areas used as entry points for the simulations.

Figure 4  Mean annual precipitation (mm) in the continent and mean monthly precipitation (mm) at selected stations. Shaded areas indicate zones of high precipitation. Based on Hoffmann (1975), Anonymous (1976) and Steinhauser (1979).

Figure 5  Variation of the westward turning point of objects entering Area 1: (a) year 1979, entry month April; westward turn is made at the edge of the Costa Rica Dome; (b) year 1986, entry month March; westward turn is made off the Gulf of Tehuantepec.

Figure 6  Simulated trajectory of objects entering Area 1, year 1983.

Figure 7  Simulated trajectory of objects entering Area 1, year 1976.

Figure 8  Examples of objects that entered Area 2 with trajectories stranding in the Gulf of Tehuantepec.

Figure 9  Simulated trajectory of objects entering Area 2, year 1980.

Figure 10  Simulated trajectory of objects entering Area 2, year 1986.

Figure 11  Simulated trajectory of objects entering Area 2, year 1983.

Figure 12  Simulated trajectory of objects entering Area 2, year 1977.

Figure 13  Simulated trajectory of objects entering Area 3, year 1980.

Figure 14  Simulated trajectory of objects entering Area 3, year 1981.

Figure 15  Simulated trajectory of objects entering Area 3, year 1982.

Figure 16  Simulated trajectory of objects entering Area 3, year 1983.

Figure 17  Three basic drift patterns for objects entering Area 4: (a) year 1978, entry month February; stranding after short erratic drifting; (b) year 1978, entry month March; drift toward the Gulf of Panama; (c) year 1985, entry month March; drift around the entry point.

Figure 18  Examples of southwest drift of objects entering Area 4: (a) year 1983, entry month January; (b) year 1984, entry month is March.

Figure 19  Simulated trajectory of objects entering Area 5, year 1981.

Figure 20  Simulated trajectory of objects entering Area 5, years 1982 and 1983.

Figure 21  Scheme of possible drifting trajectories and circuits of objects in the eastern Pacific Ocean.

Table 1. Recent El Niño events in the EPO.

<table>
<thead>
<tr>
<th></th>
<th>Started</th>
<th>Ended</th>
<th>Peak warming</th>
<th>Comments</th>
</tr>
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<tbody>
<tr>
<td>1972-73</td>
<td>Jan 72</td>
<td>Mar 73</td>
<td>Jul-Aug 72</td>
<td>Strong over nearshore EPO</td>
</tr>
<tr>
<td>1976</td>
<td>Feb 76</td>
<td>Feb 77</td>
<td>Aug 76</td>
<td>Primarily equatorial</td>
</tr>
<tr>
<td>1982-83</td>
<td>Jul 82</td>
<td>Nov 83</td>
<td>Nov 82-Feb 83</td>
<td>Very strong over entire EPO</td>
</tr>
<tr>
<td>1986-87</td>
<td>Dec 86</td>
<td>Dec 87</td>
<td>Apr-May 87</td>
<td>Weak over tropics</td>
</tr>
</tbody>
</table>
FIGURE 1. The circulation model. (a) Pares-Sierra and O'Brien non-linear, reduced gravity model equations and symbols. (b) Linear interpolation of the current components on the four corners of the grid in which the object is located.
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