The North Pacific Gyre

New Mexico

Supercomputing Challenge

Final Report

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Team 36

Desert Academy

Team Members

Sean Colin-Ellerin

Sara Hartse

Mentors

John Paterson

Jocelyne Comstock

Contents

1. Executive Summary

Our project is focused on the phenomenon of garbage patches, particularly in the North Pacific Ocean, which form when municipal solid waste (referred to as MSW in general terms, *trash*, when applied to water agents and *garbage*, when applied to cities), particularly plastic, is transported into the center of oceanic gyres. The majority of the programming was done using Netlogo, with other work done in Matlab and Microsoft Excel. The simulation of ocean movement and MSW transport was completed using an agent based method; we succeeded in creating an advection diffusion simulation which takes place in an approximation of the North Pacific Basin geometry. The advection is driven by established ocean currents and the diffusion takes place as MSW is released into the ocean by specific cities on the Pacific Rim. These parameters resulted, as we had hoped, in the formation of highly concentrated areas of MSW in the center of the North Pacific Ocean. Various forms of data were collected from tests of the model, these include screenshots of the interface at certain timesteps and the contour mapping of MSW concentration data generated by agents over a time step of ten years. From this model, we were also able to gather information about the behavior of particles once they enter the North Pacific Gyre. We were also able to conclude that, based on model parameters such as current speed and location, population growth, diffusion rates and MSW production rates; the North Pacific Garbage Patch is a real and growing feature of the Pacific Ocean.

2. Introduction

2.1 Goal

The goal of this project is to create an ocean circulation model which can accurately simulate the characteristics of the North Pacific Gyre based on ocean surface currents and can model the formation of a garbage patch. Once the gyre is modeled, the formation of the garbage patch will be dependent on the size and source of the garbage inflow. We wish to be able to predict the growth of the garbage patch over the next decades, based on predicted population growth rates for several major cities on the Pacific Rim. The garbage inflow will also be based on the approximated MSW production rates per person of these cities and a general likelihood of MSW making it into the ocean. We hope that by studying the garbage patch in the North Pacific Gyre we will be able to model the growth of the patch and begin to understand the problem of ocean pollution as a whole.

2.2 Background

2.2.1 Oceanography

The Pacific is the largest and the oldest of earth's oceans; being the single ocean which surrounded the continent of Pangaea millions of years ago. The Pacific Ocean is now home to several garbage patches, which are located in the rotating expanses of ocean known as gyres. The largest and most well known garbage patch is located in the North Pacific gyre and is the subject of our project.

The most important subject in creating a model of the garbage patch is being able to accurately simulate the movement of the ocean. The planet's oceans are continuously moving and their motion can be attributed to several factors. Ocean tides are controlled by the gravitational pull of astronomical bodies like the sun and moon. Because the earth is a sphere, the effect of these gravitation pulls varies as the circumference changes between locations. At Earth's equator and assuming the ocean was limitless in depth and extension, the speed of tidal propagation or tidal celerity, could be up to 1600 km/h. However, the oceans are broken by continents and they have finite depths. The speed of water is very dependent on its depth, moving a much greater rate in deeper water. The average depth of global oceans is about 4 km, and taking into account the factors of landmass, longitude and depth, the tidal celerity at the equator is actually about 5.08 m/sec (12).

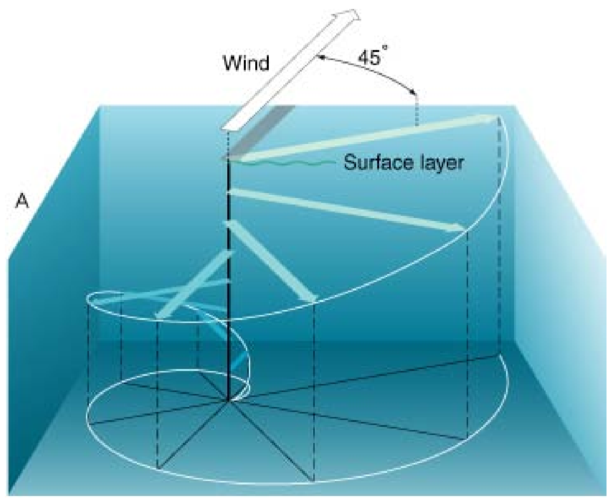

Fig. 1 The Coriolis Effect

Ocean circulation as a whole is caused by many different factors. In addition to astronomical tides mentioned above, it is determined by surface currents, which are affected by occurrences such as evaporation, precipitation, temperature, salinity, density and kinetic energy applied by wind. Another important force to be taken into account in computing ocean circulation is the Coriolis Effect, which results in what is known as the Ekman transport system. The Coriolis Effect exists because the earth is a sphere and its continuous rotation means that objects are deflected (to the right in the Northern

Hemisphere and to the left in the Southern Hemisphere) from their original paths (6). This applies to wind, the primary driver of surface currents. Wind blows across water and causes it to move as a result of the frictional drag on the surface. In ideal conditions, a wind blowing at an average rate for twelve hours produces a current about 2% of its velocity. If it were not for the Coriolis Effect, the wind would push the water in a single direction. Each successive layer of water would follow the path of the one above it, although at a slower rate. However, because of the Coriolis Effect, each layer of water is deflected slightly, the direction depending on which hemisphere it is in. In ideal conditions, wind driven currents would vary 45º in each successive layer (see Figure 1.) (12).

Surface currents are one of the most important ocean characteristics to account for in our gyre model. A gyre is a large, circular system of rotating ocean waters, determined by long term behavior of surface currents; they are essentially eddies (12,13). There are four primary oceanic gyres which are located in the North Pacific, the South Pacific, the North Atlantic and the South Atlantic oceans. The physical characteristics, like the surface currents of the gyres, vary, but they all share their becalmed central section of water that has historically been avoided by both humans and many animals. The slow moving waters make sailing in gyres very difficult and the desert-like ecosystem makes them poor habitats for many predators and large fish (3).

There are four main currents forming the North Pacific Gyre that dictate its size and location. The North Equatorial Current runs parallel to the equator, approximately in the area of the northeast trade winds at speeds of about 0.5 km/h. It then passes the Philippines and Taiwan, curving northwest. As it continues north it becomes part of the

Kuroshio Current, sometimes known as the Japan Current, which widens and slows as it passes Japan. The Kuroshio Current is the fastest current in the gyre; its average velocity is 3 to 4 km/h. It behaves in approximately the same way as the Gulf Stream in the

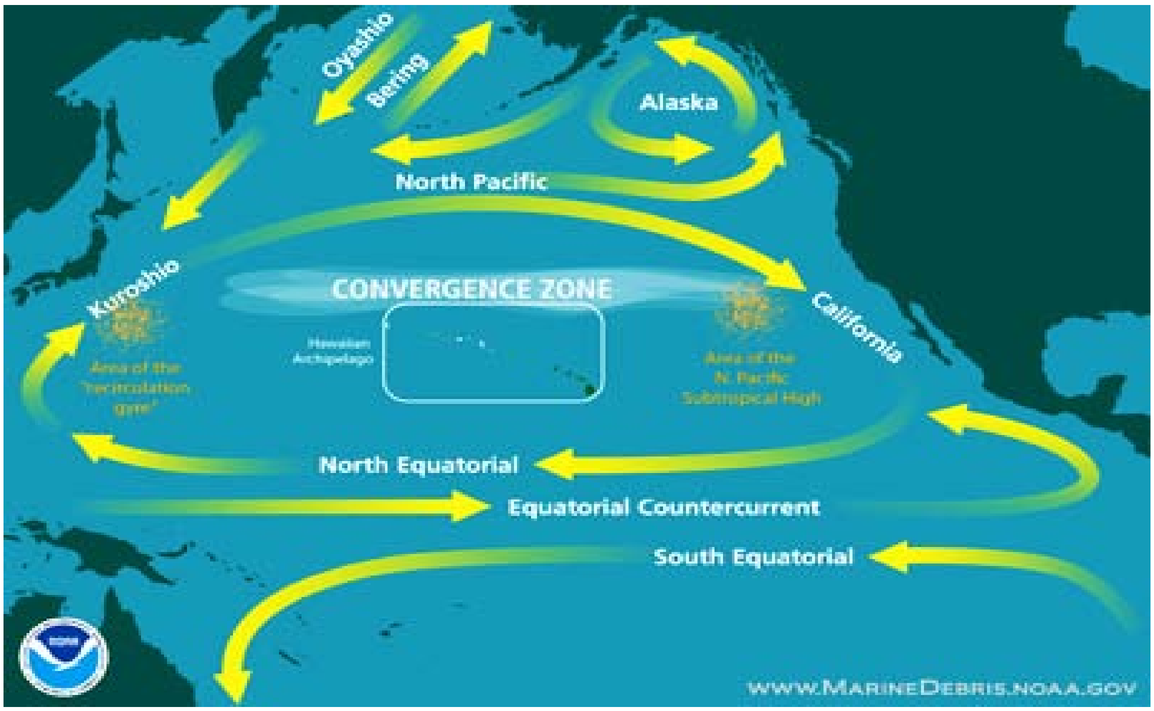

Fig. 2 Gyre with location of North Pacific Subtropical High indicated

Atlantic; transporting large amounts of warm, tropical water to higher latitudes. As it reaches increasingly arctic latitudes, the water in the Kuroshio Current cools, widens, slows and curves eastward, going between the Aleutians and Hawaiian Islands, where it has now become the North Pacific Current. As it approaches the North American continent, it then becomes the California Current. The California Current moves at a rate of around 1 km/h and is generally quite wide and slow and near the southern end of Baja California it curves to the west, rejoining the North Equatorial Current and completing the general clockwise rotation of the North Pacific Ocean (2).

The exact size and location of gyres are indeterminable due to the fact that they are constantly changing based on pressure and currents. Nevertheless, oceanographers can approximate the gyres' properties by their driving currents. The North Pacific gyre is estimated to cover about 17 million square kilometers. The general location of this gyre is in the Northern Pacific Ocean and the concentration of the garbage patch is roughly pinpointed halfway between the western coast of the mainland of the United States of America and Hawaii. The oceanic gyres all possess garbage patches of their own, but this particular garbage patch is the best documented and is believed to have the greatest amount of waste. Most of this waste is believed to gather in a high pressure, sub-tropical convergence zone, located in the central to eastern portion of the gyre (8).

2.2.2 Plastics

It is estimated that a large country such as the United States generates more than 400 million tons of trash each year. Some of this trash is recyclable, and some biodegrades, but most of it simply remains for hundreds of years with nowhere to go. The definition of biodegradability is a substance that can decompose without causing harm to its environment, which is why plastic is considered non-biodegradable (7). A significant portion of this non-biodegradable waste that is produced in the United States and on the Pacific Rim is transmitted to the Pacific Ocean currents to form a large mass called the Great Pacific Garbage Patch. This gyre of marine litter, referred to as municipal solid waste (MSW), is located in the North Eastern Pacific Ocean (10) (see Figure 2).

This garbage patch is occupied by a collection of marine debris, primarily small pieces of floating plastic. It has the greatest number of pieces and greatest weight of plastic in any region of the North Pacific Ocean (8). In 1999, a register was conducted near the central pressure cell of the North Pacific sub-tropical high at eleven random locations. The record tallied 27,698 small pieces of plastic per km on the surface of the gyre. The collection of plastic sampled had an average mass of 5,114 g/km^2. This mass was calculated to be approximately 6 times that of the plankton in the water. The total average abundance above and below the surface was calculated to be 334,271 pieces/km^2 (11).

Plastics are basically petroleum-based mixes of monomers and polymers with extra chemicals to induce qualities like flexibility and inflammability. The primary problem is that these chemicalsare harmful to ingest; chemicals such as perfluorooctanoic acid (PFOA) are known to be carcinogenous, but nonetheless are used in microwavable food packaging. Polybrominated diphenyl ethers (PBDEs) and bisphenol A (BPA) are substances in plastics, which are used daily, despite the fact that they are known to be toxic to human reproductive systems. These chemicals are often hydrophobic, which means that they tend to repel water and float on the surface of the ocean; gathering around and being absorbed by plastic particles.

Scientists are worried that these highly toxic chemicals are changing the overall chemistry of earth's oceans (3).

Fig. 3 A microcosmic representation of the size and concentration of MSW in the gyre

The other issue with plastics is that they take centuries to break down. Charles Moore, who discovered the patch in 1997, notes “except for the small amount that’s been incinerated- and that’s a very small amount- every bit of plastic ever made still exists” (3). The molecular structure of plastic resists decomposition and even when it breaks down to a single molecule, it still cannot biodegrade (10). The tiny plastic fragments, known as nurdles are the reason that the patch had not been discovered before 1997 (see Figure 3). The patch is composed of these fragments of plastics which have permeated the entire water column and are invisible to the naked eye from aerial view. A recent survey estimates that nurdles make up about 10% of ocean debris (3).

2.2.3 Significance

The increasing concentration of plastics in Earth’s oceans is concerning to all of the planet’s inhabitants. Animals living in and around the ocean are in danger of being trapped by debris or of being poisoned by consuming them. It is broadly estimated that over a million sea birds, 100,000 marine mammals, and countless fish die each year in the North Pacific because of the plastic waste. The fish that mistakenly consume the plastic could be eaten and the toxic plastic would continue up the food chain, eventually reaching humans (3).

Solving the problem of Earth’s plastic oceans will be difficult and it is unlikely that total rehabilitation will be possible. The sheer quantity of debris and the minute size of the plastic particles make removing them from the ocean unfeasible. These plastics reach the ocean in various ways. Marine dumping is part of the problem and there are many nets abandoned at sea which still harm animals. The main source of the plastic is the mainland. Rainstorms wash MSW into rivers and rivers eventually lead to the ocean. Tighter waste disposal and recycling regulations are necessary, but this will not solve the long term problem. Human beings need to become less dependent on a material that will outlast them by thousands of years (5).

3. Model

3.1 Overview

Our initial plan was to construct a model based on the shallow water equations (SWE), particularly their non-conservative form. The SWE are a series of partial differential equations which are used to compute the propagation of motion within fluids, often in oceans, estuaries and rivers. The SWE make the assumption that the stretch of water being modeled is much wider than it is deep, hence ‘shallow water,’ eliminating the need to model vertical velocity (4,9). This assumption was logical for our ocean model because the Pacific Ocean, while deep, is shallow compared to the length of the ocean that we are modeling. However, the SWE are used to model wave behavior, particularly deviation in wave height based upon gravity, which is completely unrelated to our model, for example the water within a wave stays in the same place as a wave propagates through it. What we needed was a model that simulates ocean circulation and movement, in which water moves from location in ocean to another. We made the decision to simplify the fluid modeling aspect and switch to an agent-based method.

Our model is an agent-based Netlogo program which models the North Pacific Gyre and garbage patch based on approximate ocean circulation, MSW diffusion and advection, and population growth rates.

3.2 Ocean Circulation

The ocean circulation and fluid dynamics aspect of our model has been simplified from our original plan, but the model is successful in producing a gyre effect based on assigned current velocities. Further detail in the model cells or a mathematical quantification of fluid behavior would improve the realism of this ocean current model.

3.2.1 Geometry

To begin circulation, agents representing water are created within the North Pacific Ocean geometry. The geometry is a map of the Pacific Ocean that was simplified by Netlogo and divided into areas of water and land. The area of the mapped region is approximately 10,000 by 5,000 km. The Netlogo interface is composed of 300 x 152 patches, with each patch representing roughly 33 km. Immediately after an agent is created it is assigned to one of 32 ocean 'cells' which are dependent on location. Each cell is assigned a certain speed and heading. All water agents that are created or enter that cell are assigned those values. The headings and speeds are established as global

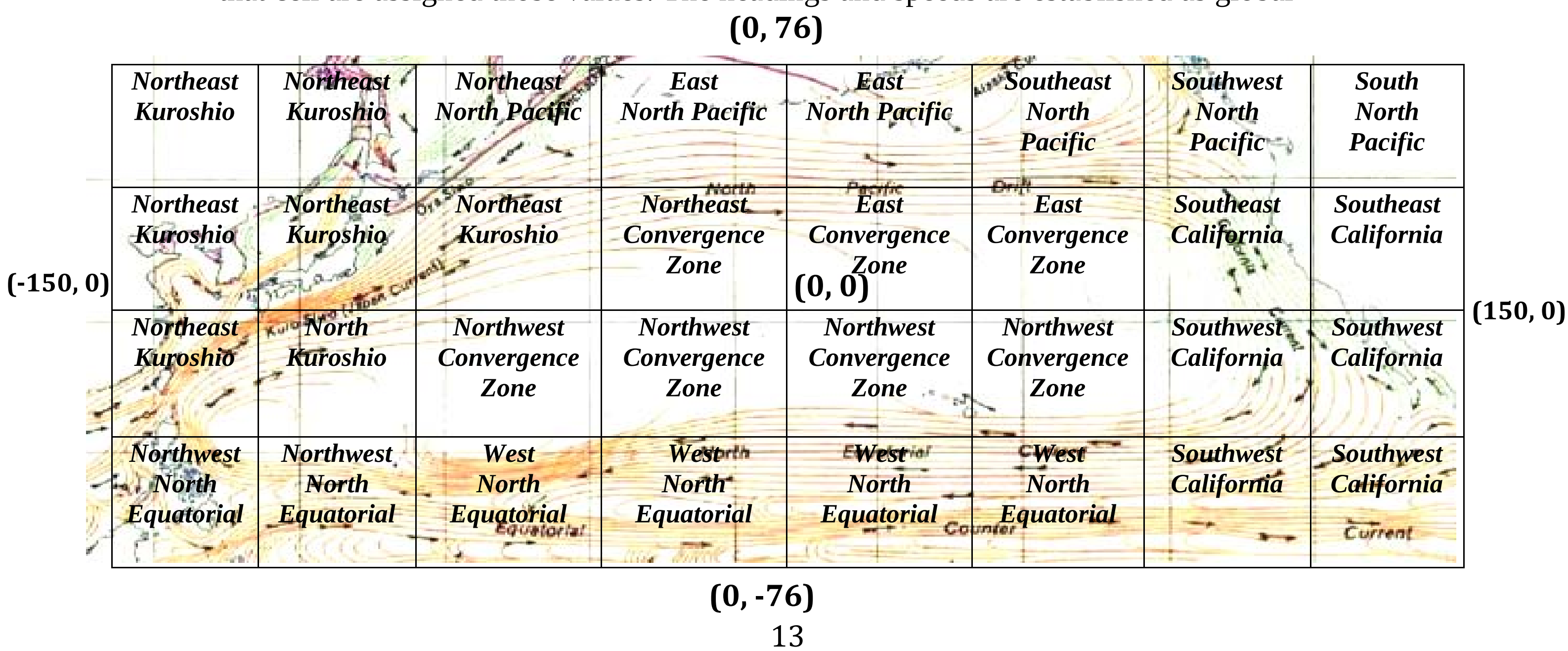

Fig. 4 A map of the North Pacific and its ocean cells with their respective headings and currents

variables; the headings have the names of compass directions that the currents in that part of the ocean tend to flow and the speeds are in accordance with prevalent currents for that part of the ocean (see Figure 4).

3.2.2 Circulation and Conservation

Every timestep, each water agent moves ahead the number of steps assigned to the current within its cell; each tick represents 1 hour, therefore by multiplying the current speed by 0.33 to account for scale, an agent moves at a rate of km/hour in its cell's assigned direction.

This produces a clockwise motion; however all of the water agents become trapped on the boundaries of the ocean cells. To fix this, an agent will die at a 50% probability if there are more than two agents already on its patch. To replenish the lost water and conserve mass, patches that have no water agents will generate one more. This effectively models the top layer of ocean water; the surface currents are set at observed speeds and directions from nature, which are already the result of wind speeds and the Coriolis Effect. The death and birth of ocean agents reflect certain effects such as evaporation and precipitation balance, as well as gravity, which causes water to disperse freely. While this function is probably not quantitatively accurate, it is an effective mechanism for preserving water conservation within the model.

3.3 Cities and Population

The inflow of MSW in our model is dependent on the population of various coastal cities on the Pacific Rim as well their growth rates and predicted growth rates.

The cities, or rather urban areas as counties are included, represented in the model are the Bay Area, Los Angeles, San Diego, Tokyo, Taipei, and Honolulu. Each city agent is generated to their approximated location and is assigned their recorded 2009 population. The population of a city will be related to estimated amount of MSW that enters the ocean from each city. This value is hard to obtain, but in this model it will be a function of the cities' populations and their waste disposal system ranking, or the chance that waste produced in the city will reach the ocean.

3.3.1 Mathematical Model and Data

Due to the fact the year of population projections varied, we calculated a growth rate base upon the population in the current year and the population projected. This rate then allowed us to calculate the projected population for each decade. By doing this, it enabled us to have the same reference points for time, therefore convertible to time steps in the model. Every time a year passes in the model, the population is increased based on yearly growth rate information for each city.

$$population = population_{initial} \times growth\ rate^{t}$$

Data was compiled about the of populations of major cities and their projected populations over several decades based upon those found in research and those calculated by growth rate projections (see Table 1).

Table 1. Coastal City Populations

City	1980	1990	2000	2009	2020	2030	Increase/yr
Bay Area (17)			6,900,000	7,395,000	8,000,000	8,550,000	1%

San Diego County (17)	1,861,840	2,512,365	2,825,395	3,001,072	3,301,179	3,631,297	0.97%
Los Angeles County (17)	7,477,239	8,878,157	9,544,112	9,862,049	10,848,253	11,933,079	0.93%
Honolulu County (17)	762,565	838,534	875,054	905,034	986,487	1,075,270	0.095%
Tokyo (16)	11,620,000	11,860,000	12,060,000	12,989,000	14,287,900	15,716,690	0.96%
Taipei (15)				23,165,000	23, 437,000		0.05%

3.4 Waste Propagation

The garbage, or MSW represented in this model is not a separate agent, it is an agent variable which is referred to as *garbage* when applied to city agents and *trash* when it belongs to water. Each city is assigned an initial *garbage* value and when water agents come within a one kilometer radius of it, the water increases its *trash* value and the city decreases its *garbage*.

3.4.1 Mathematical Model and Data

The amount of *garbage* produced by each city every 24 hours is dictated by the following equation:

$$garbage = population \times \frac{MSW}{day} \times \%MSW\ to\ ocean \times \%MSW\ plastic$$

Once water agents possess *trash*, the *trash* begins to diffuse. This is calculated by summing the *trash* value of all water agents within a 1-kilometer radius and dividing it evenly between all agents within the radius. In order to preserve the mass of *trash* belonging to ocean agents, while still killing and recreating them to conserve mass, the code tells agents that are about to die to set they current patch color to their *trash* value. The next agent who moves into that patch gains that value of *trash*. The MSW is visualized by pink shading, the agents without *trash* are blue, the lowest concentrations of *trash* are black and the highest concentrations are pink and white (see Figure 5.1). The table below is a list of the values used for variables in the MSW equation.

Table 2. Values for the MSW equation

MSW per capita (19)	2.204 kg
Percent of MSW that reaches ocean (19)	10 %
Percent of MSW that is plastic or floats on surface (17)	30 %

Table 3 displays the calculated relationship between the growing populations of cities on the Pacific Rim cities to the total about of MSW present in the model.

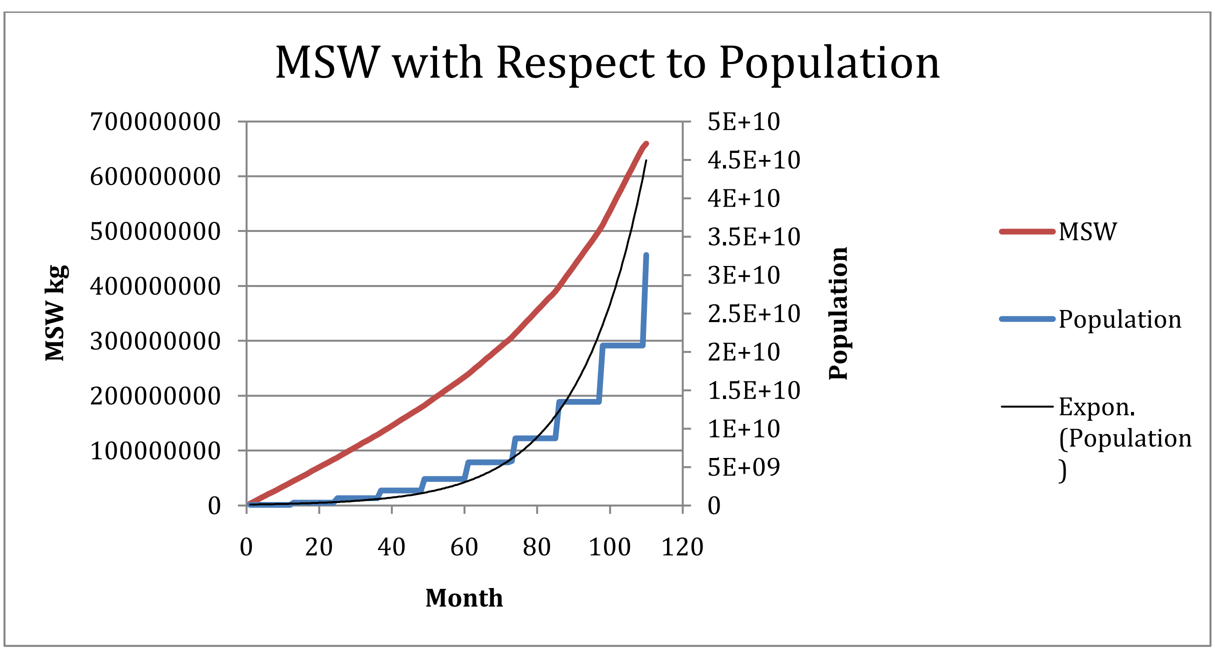

Table 3.

4. Data and Results

4.1 Two Forms of Visualization

The data for the concentration and location of trash is presented below in two different forms of visualization. The first is a collection of screenshots taken after 1 month, 6 months, 1 year, 3 years, 6 years, 8 years, 9 years, and 10 years. The reason for the unequal variation in time between screenshots is that a large difference occurs within the first year, after which changes become more gradual.

The second form of visualization is a contour map created in Matlab. There is a map for each of the ten years the model was run, rather than the time increments used for the first visualization because concentration levels are more important in the topography maps, which illustrate general locations with a better representation of relative concentrations, and no substantial variance in the degree of changes occur within the months of the first year relative to the first visualization. Thus, the constant increase of one year seems applicable. The data was collected by a Netlogo procedure which has every agent report its x coordinate, its y coordinate and it *trash* value. After exporting this data to excel and converting it into a useable *x*, *y*, *z* format, we were able to visualize it in Matlab.

We wrote a short piece of code to create this visualization, with two representations for concentration. One is the height and the other is a color spectrum ranging from blue to red, with blue representing low concentration and red high concentration.

```
tri = delaunay(x,y);
plot(x,y,'.')
h = trisurf(tri, x, y, trash);
axis vis3d;
axis off;
l = light('Position',[-50 -15 29]);
set(gca,'CameraPosition',[208 -50 7687]);
lighting phong;
shading interp;
colorbar EastOutside;
axis([-150 150 -75 75 0 10000 0 100])
```

The code processes the imported *x*, *y*, *z* data, divides them into useable triplets, plots the *x* and *y* coordinates and then surfaces the *trash* with respect to *x* and *y*. The remaining code sets up the display.

The first form of visualization is considered more qualitative because one can see better the distribution, while still gaining an understanding of the approximate concentration at different locations. The second form is a more quantitative representation of the data, showing the great difference between the concentration of *garbage* in cities and the concentration of *trash* at a point in the ocean due to diffusion.

4.2 Screenshots of the Model

At eight different time periods, as discussed above, during the running of the model, we took a screenshot of the model's interface. This allows one to see a visual representation of the change in concentration and location of *trash* over time. The lighter that a point is on the interface, the greater the concentration of trash is at that point. The blue are the water agents and the green is land mass.

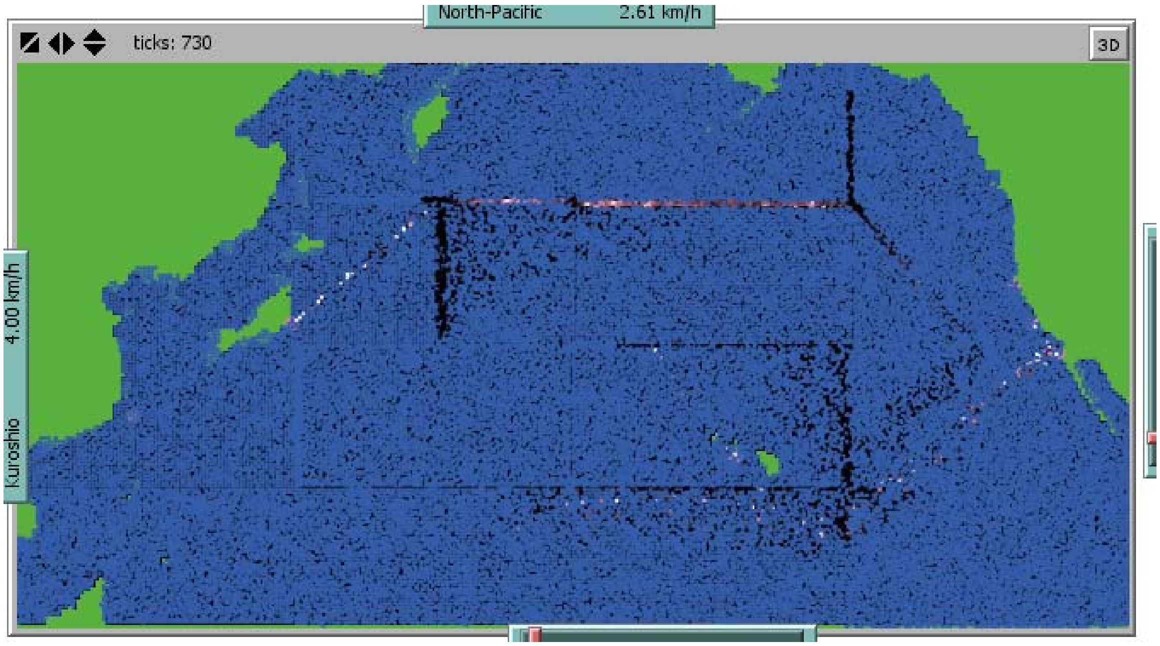

Fig. 5.1 Screenshot of model after 1 month

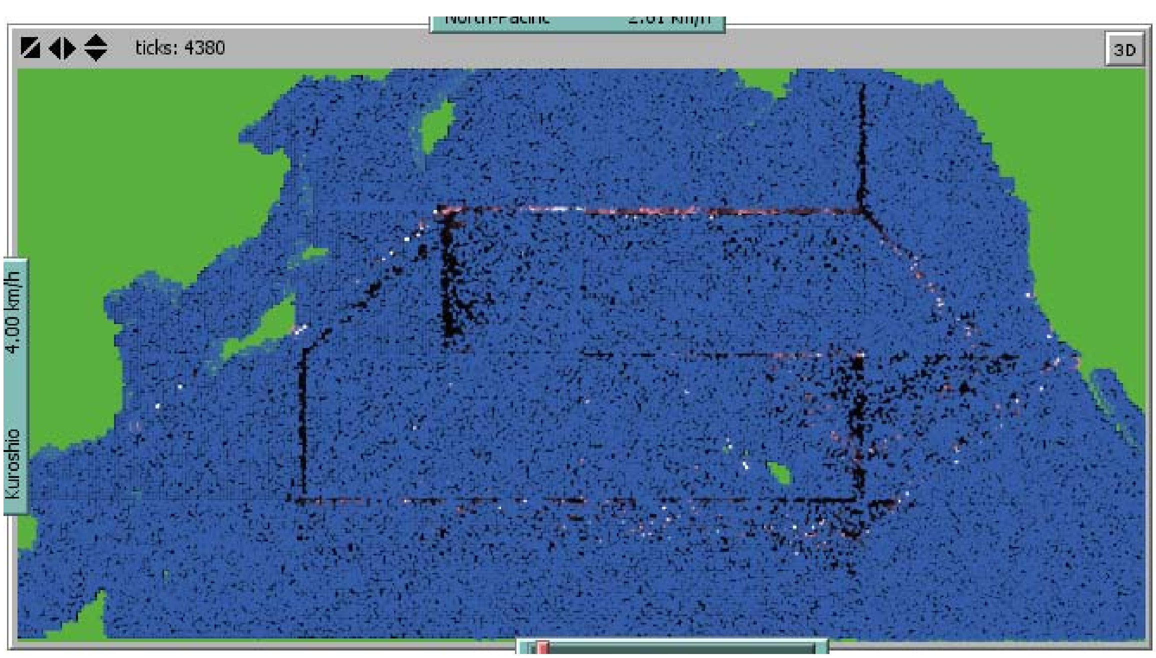

Fig. 5.2 Screenshot of model after 6 months

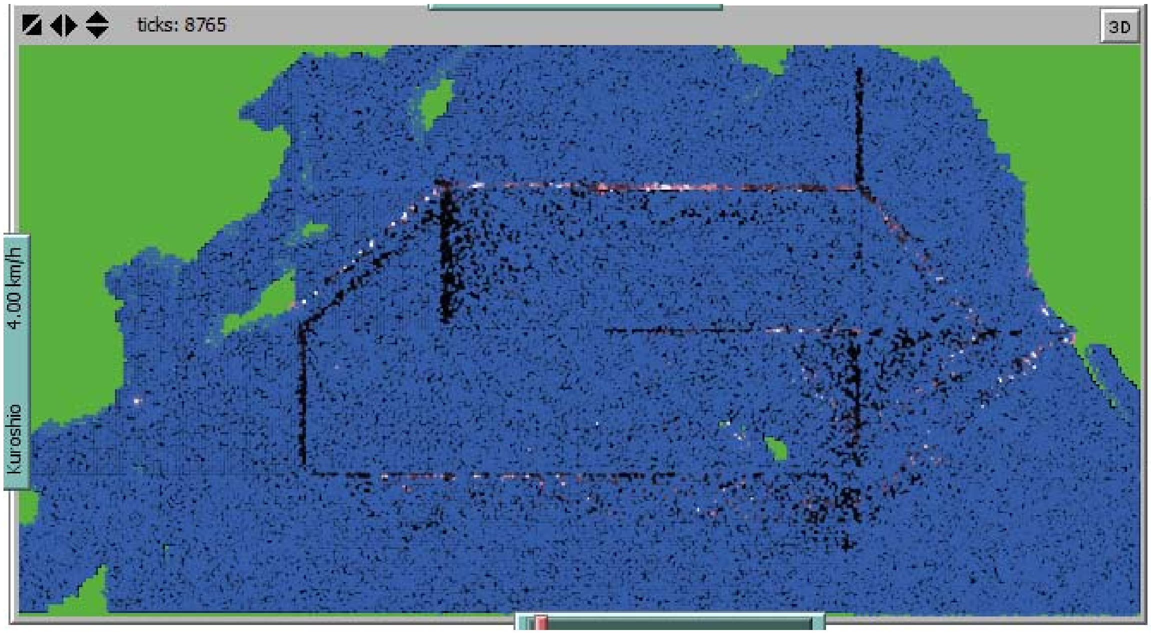

Fig. 5.3 Screenshot of model after 1 year

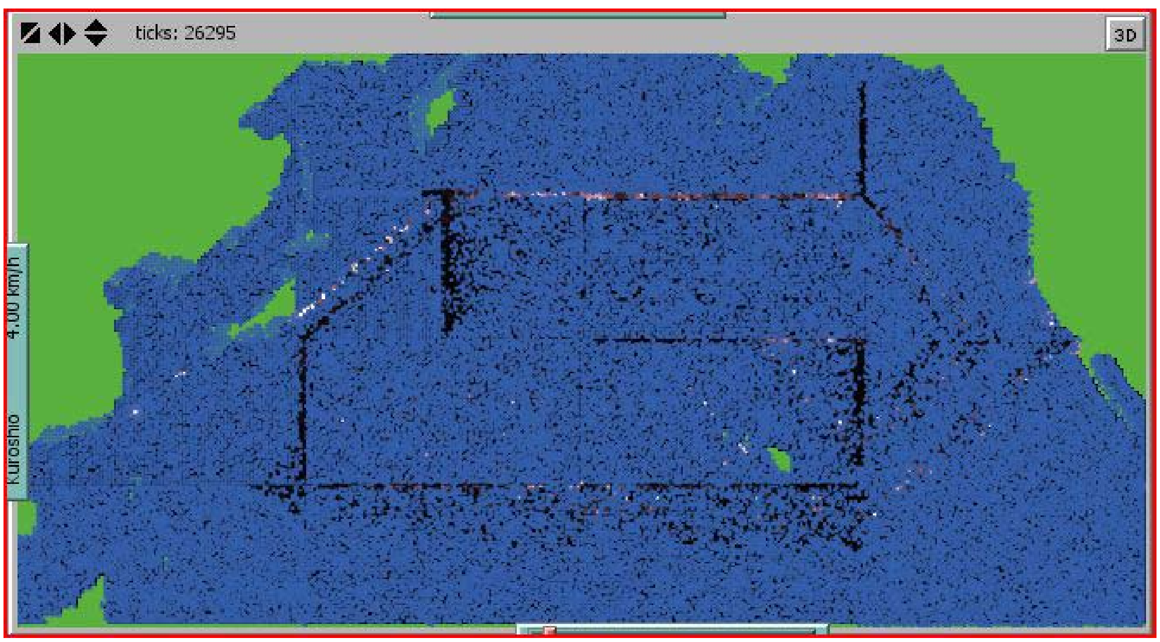

Fig. 5.4 Screenshot of model after 3 years

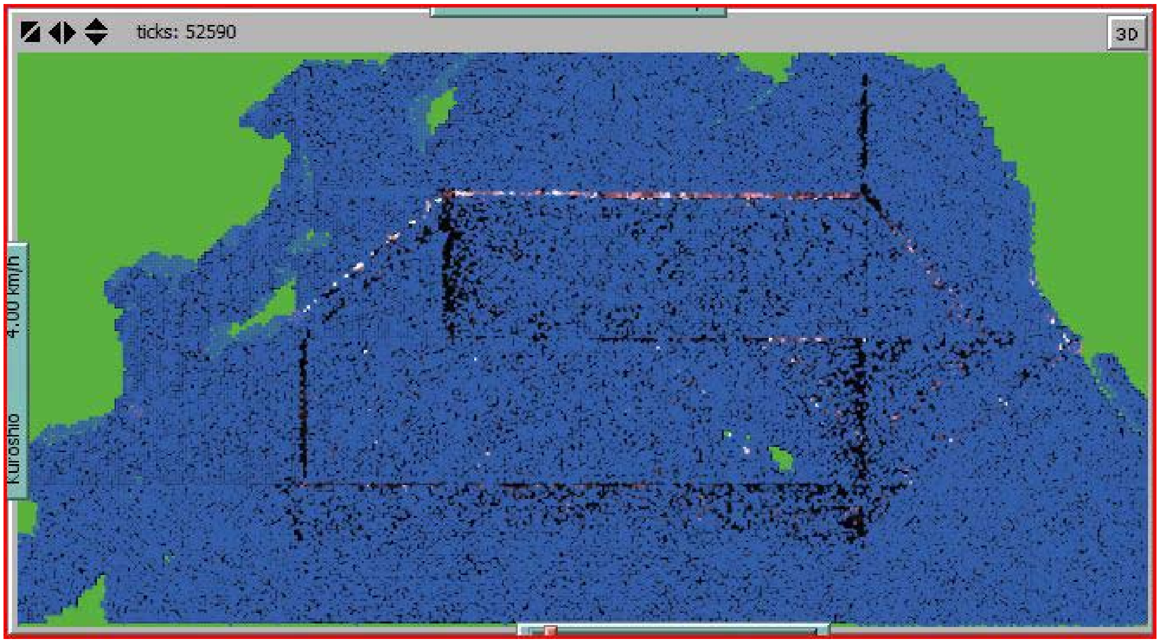

Fig 5.5 Screenshot of model 6 years

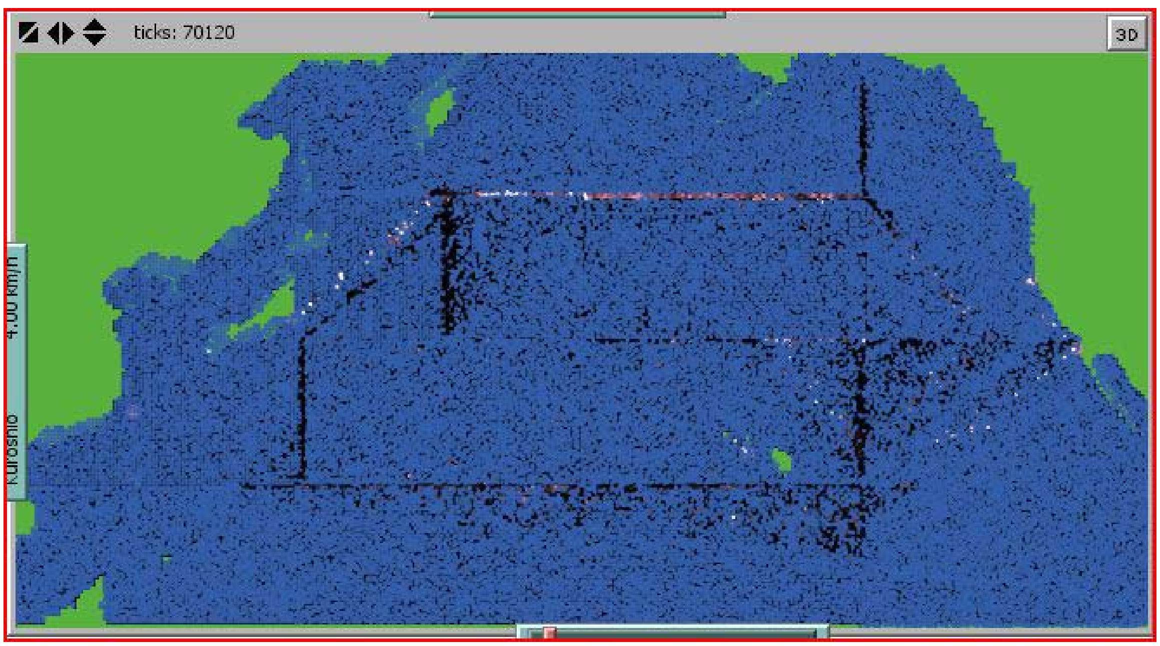

Fig. 5.6 Screenshot of model after 8 years

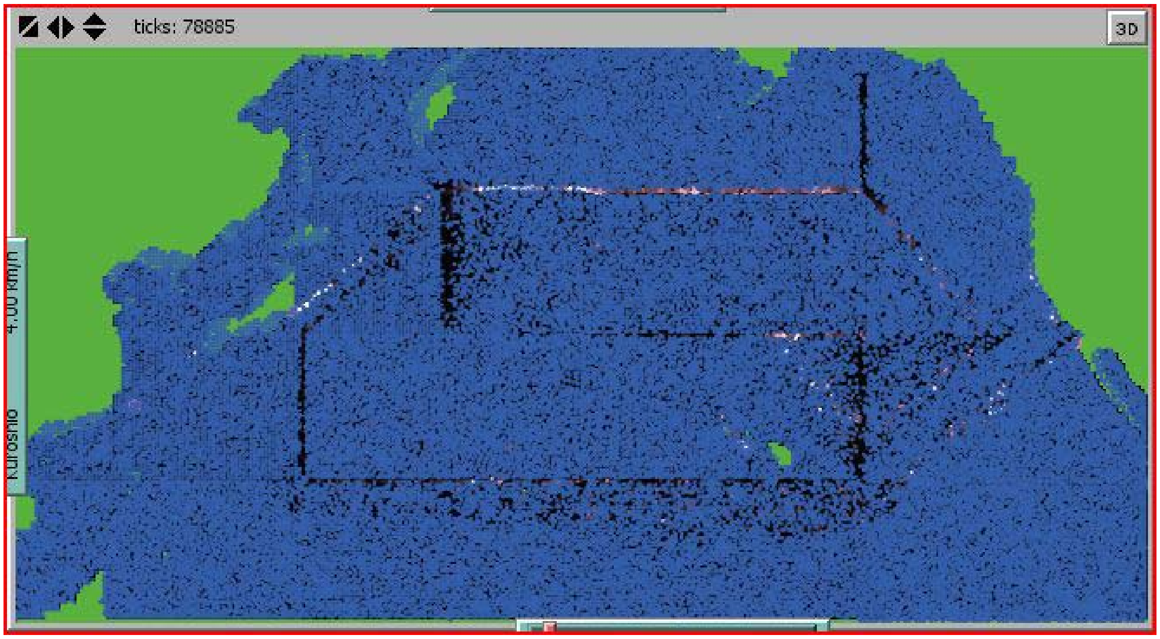

Fig. 5.7 Screenshot of model after 9 years

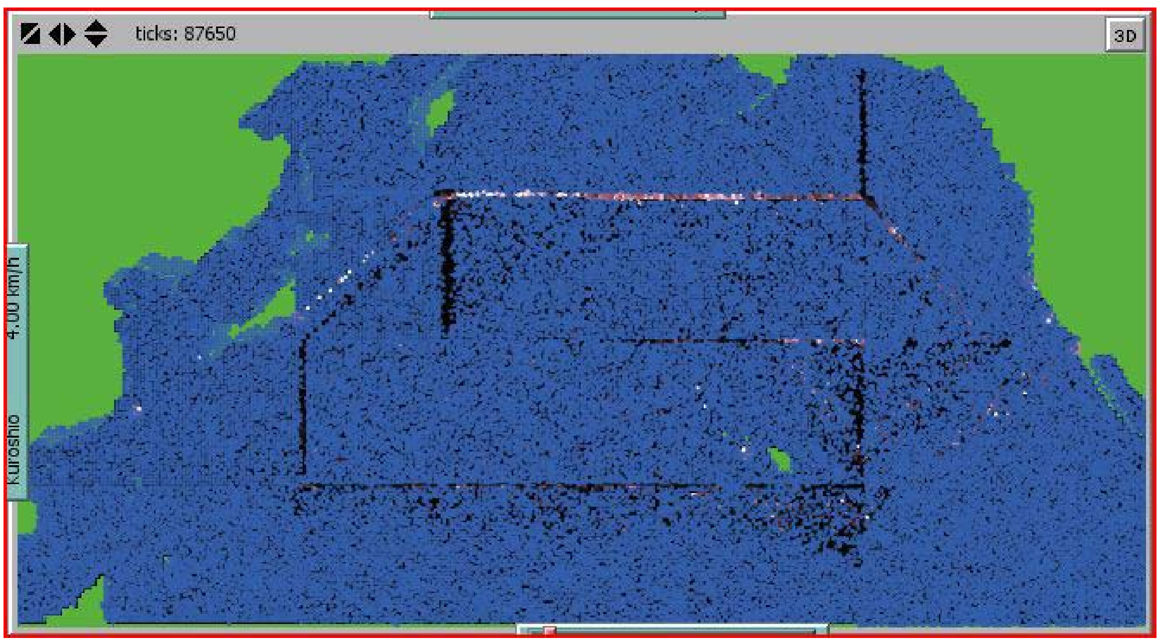

Fig. 5.8 Screenshot of model after 10 years

4.3 Contour Maps

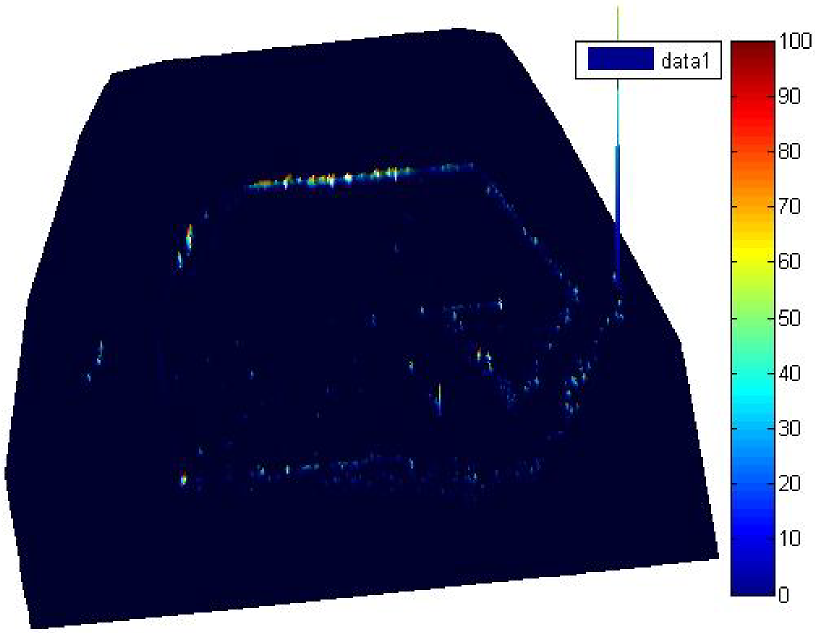

Fig. 6.1 Map after 1 year

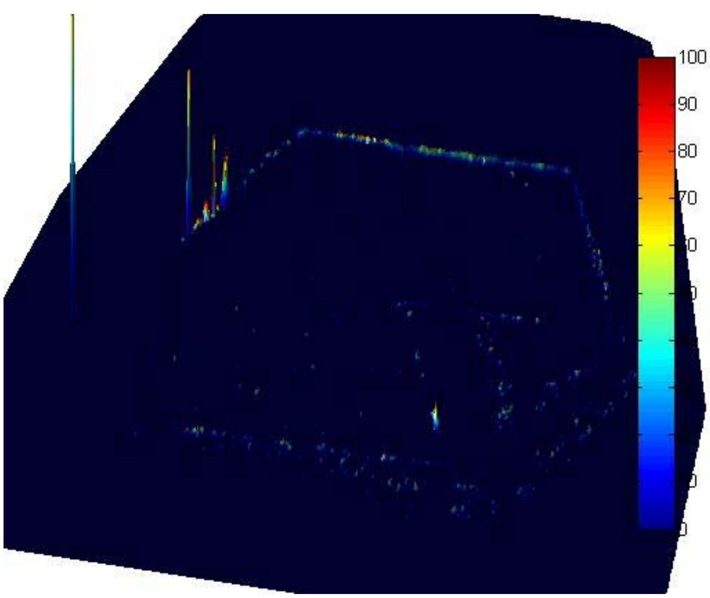

Fig 6.2 Map after 2 years

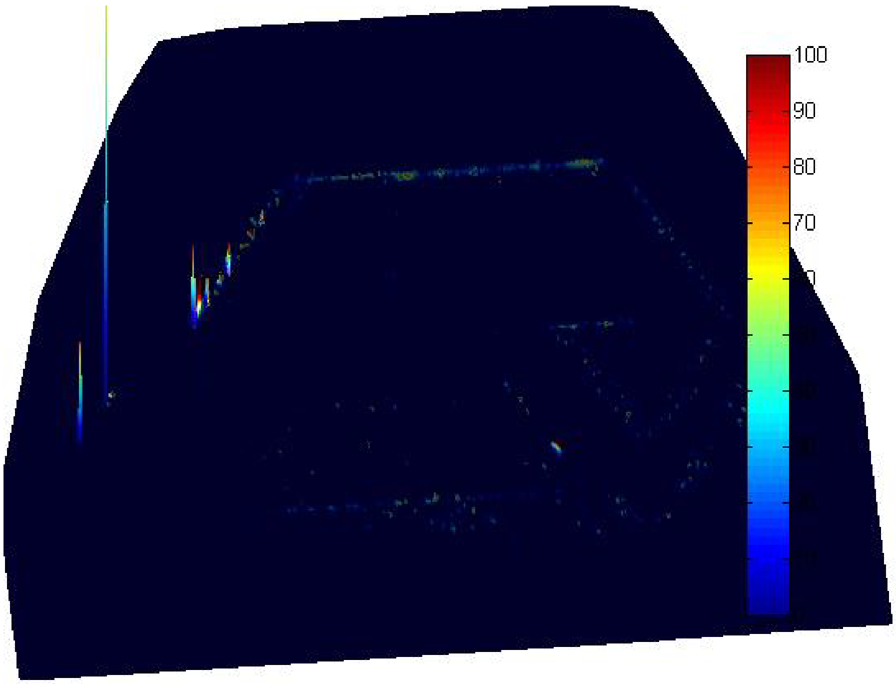

Fig. 6.3 Map after 3 years

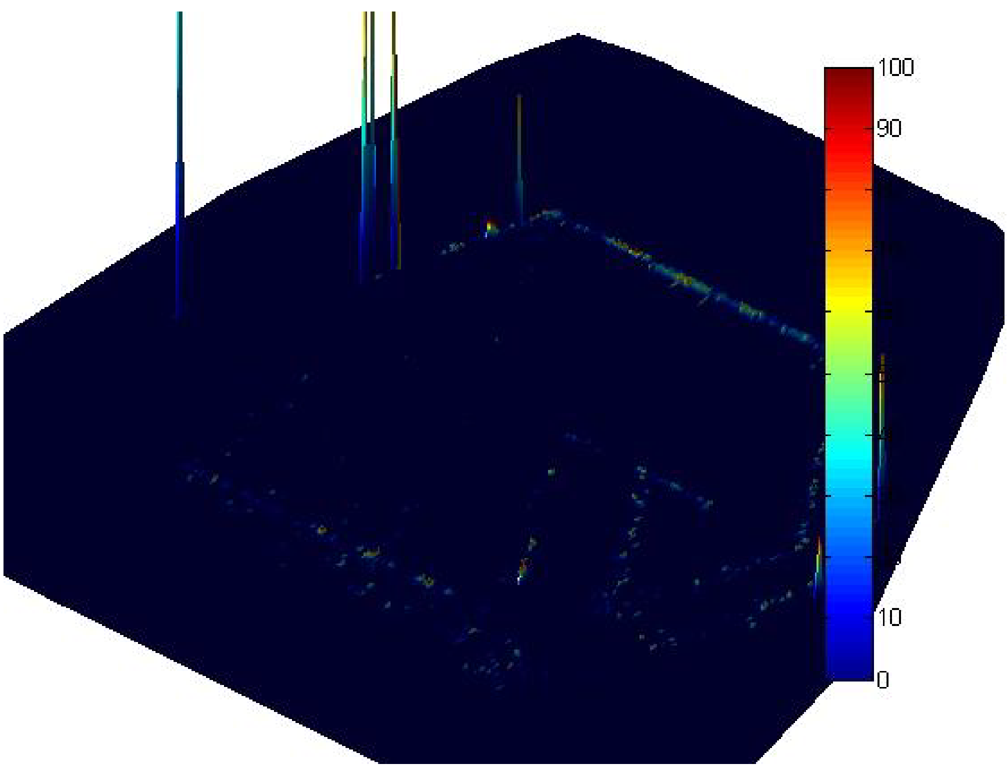

Fig. 6.4 Map after 4 years

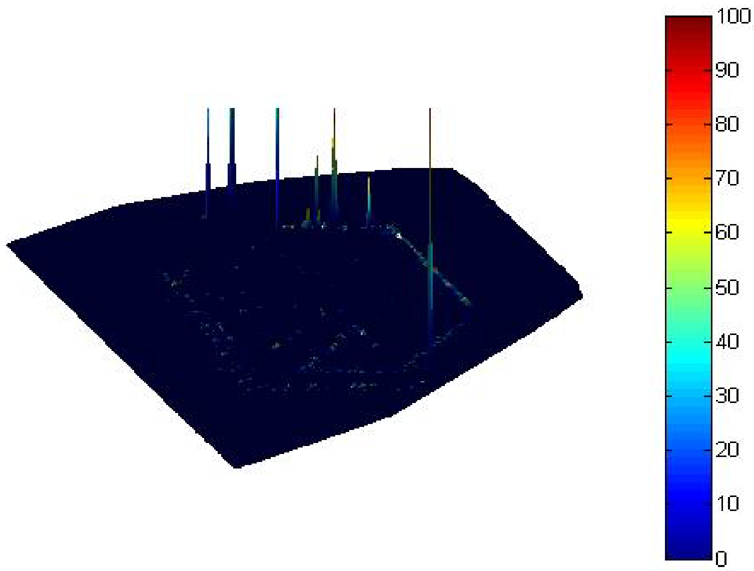

Fig. 6.5 Map after 5 years

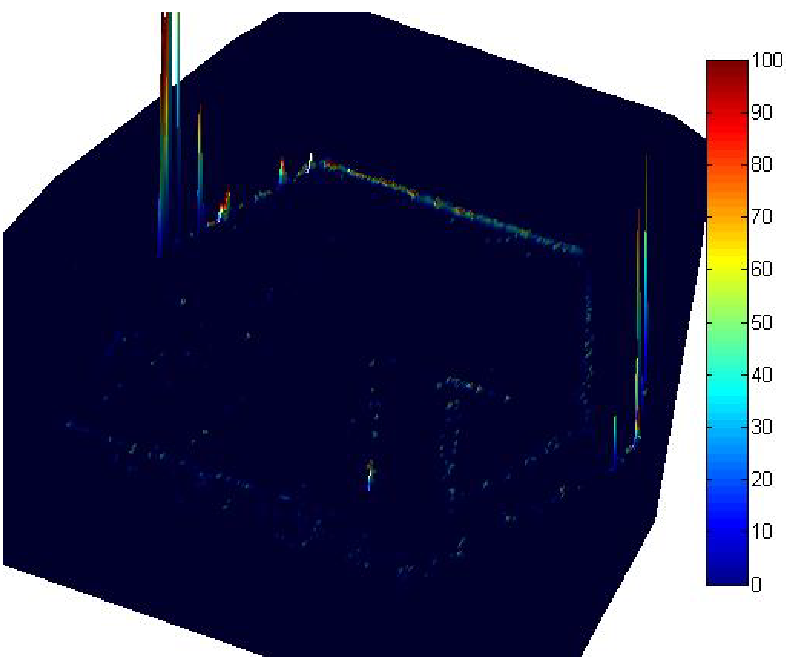

Fig 6.6 Map after 6 years

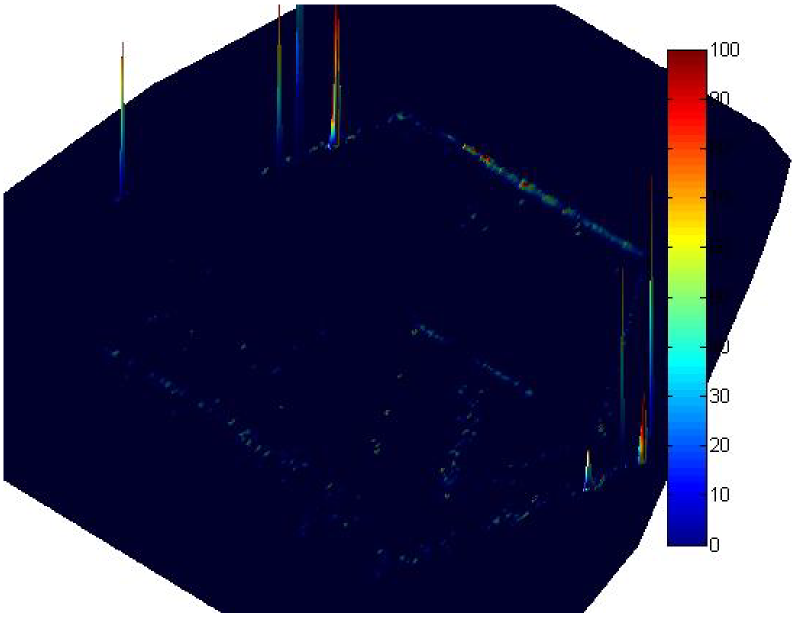

Fig 6.7 Map after 7 years

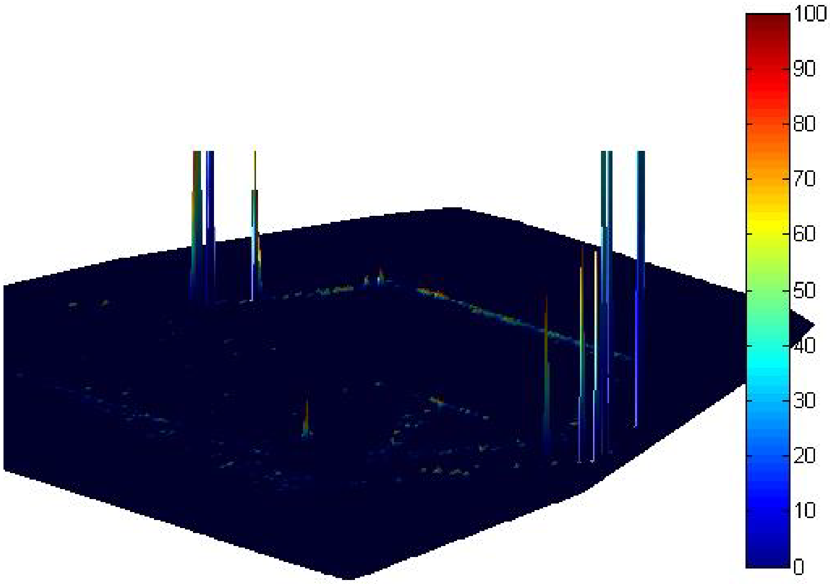

Fig. 6.8 Map after 8 years

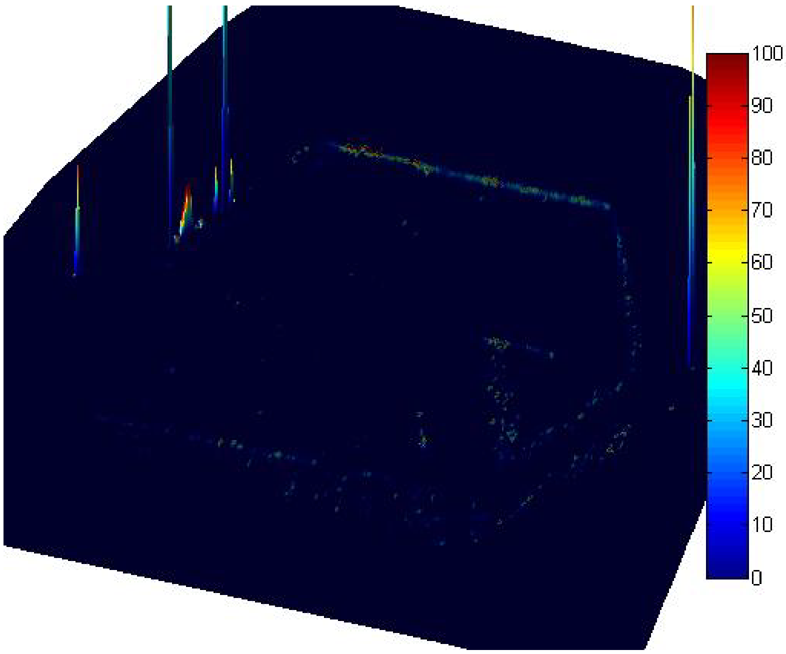

Fig. 6.9 Map after 9 years

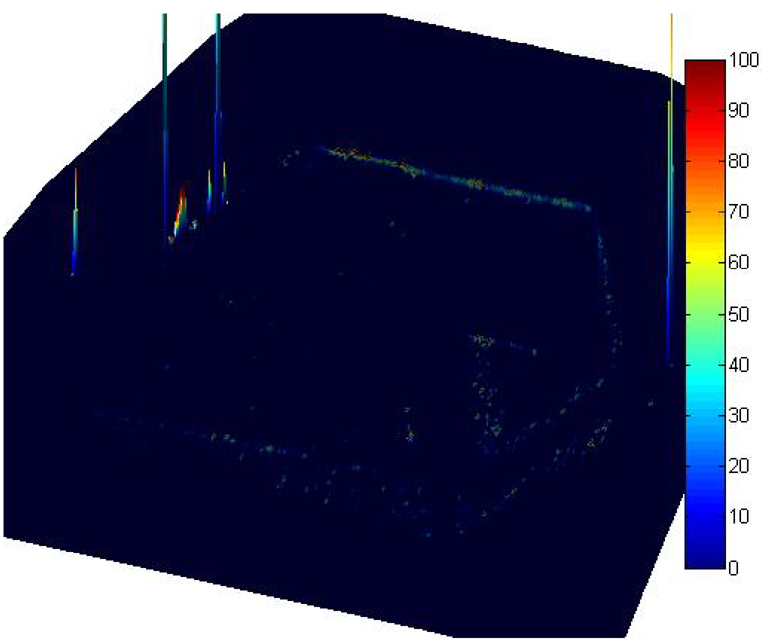

Fig. 6.10 Map after 10 years

5. Analysis

5.1 Screenshots

The main insight that can be gained from observing the screenshots is the locations of the MSW and the change thereof over time. In Figure 5.1, one can see MSW entering the Pacific Ocean and diffusing from the coast of the United States and the Asian coastal cities. The MSW from Asia, after only 1 month, a large concentration had already entered the North Pacific Current, with more arriving via the Kuroshio Current. The MSW from the U.S coastal cities had moved toward Hawaii, due to the southward moving California Current, most of which remains there, with small amounts moving westward with the North Equatorial Current.

In Figure 5.2, there were some significant changes from Figure 5.1 that are worth noting. Firstly, a substantial amount of the MSW that was concentrated in the eastern side of the North Pacific Current moved into the northern section of the California Current. Meanwhile, this MSW that moved out of the North Pacific Current was replenished by more entering from the Kuroshio Current. Even more importantly, a large amount of the MSW in the northern section of the California Current entered the eastern center region of the gyre, where the MSW is known to be located. In addition to this, the MSW that was accumulating near Hawaii has increased, as more entered from the US coastal cities.

Only small changes occurred between Figure 5.2 and Figure 5.3, which supports the argument above that significant changes in location occurred within the first few months, then become more moderate. Nonetheless, there are some notable differences. The first is the greater amount and greater concentration of trash in the west portion of the North Equatorial Current. The second difference is the occurrence of the entirety of the North Pacific Current containing MSW rather than simply covering the majority of the current.

Figure 5.4 is an anomaly in the data. The MSW in the North Pacific Current appears roughly the same, while the concentration or amount in the California Current and the central eastern region of the gyre had decreased. In addition to this the amount and concentration in the western portion of the North Equatorial Current is also less. Admittedly, there is the two-year difference between the snapshots, however this cannot explain widespread decrease in two currents as well as the garbage patch itself.

The screenshot for 6 years, Figure 5.5, returns to the pattern seen previously. Although the North Equatorial Current continues to be scarce in MSW, the amount and concentration in the North Pacific Current has certainly increased and the concentration in the garbage patch has increased from Figure 5.3, as well as the concentration in the California Current.

The model changes very little between 6 years and 8 years. The only explicit new occurrence that can be observed in Figure 5.6 is a greater concentration of MSW in the North Pacific Current. However, after 9 years, there were some substantial changes that became visible. The MSW remained concentrated in the North Pacific Current, and more importantly, there is the definite formation of a garbage patch in the eastern central region of the gyre, whose concentration and area appears to be greater. In addition to this, it should be noted, the MSW in the North Equatorial Current after one year has, for the most part, ceased to be visible.

The final screenshot of the model, after 10 years, appears to have a more concentrated garbage patch, with less area covered and the northwest region of Hawaii appears to have increased substantially in MSW. Further, the far eastern section of the North Pacific Current has increased greatly in concentration.

5.2 Contour Maps

The skyscrapers in the contour maps represent extremely large concentrations are the coastal cities. The best map to illustrate this is Figure 6.8, with the camera positioned at southeast of the geometry and facing northwest. In this map, the skyscrapers on the right are the U.S coastal cities and the skyscrapers on the left are the Asian coastal cities.

The contour maps comprehensively demonstrate the nature of diffusion and the way in which it manifests itself in our model. One can see the lack of any noticeable height in any part of the currents, or within the gyre. This shows how great the concentrations of MSW are when it is first disposed of by a city and how widely dispersed it is by diffusion and advection, with some of it concentrating in the currents. This diffusion results in the concentration in the currents being extremely low in comparison to the concentrations in a city. Although, Figure 4.3.8 is the best example of this, the pattern continues without with no significant deviation in this great disparity.

6. Conclusions

There are many conclusions that can be drawn from the analysis above. However, first it should be noted that the model was only run for ten years because each tick in the model equaled an hour in the model. Regardless of this short time period, there is a definite formation of a garbage patch in the eastern central region of the gyre, the approximate location in the real-world. From the pattern of growth throughout the years our model was run, it can certainly be posited that the concentration and area of trash in this region would continue to increase innumerably for many more years.

There were some significant patterns that were discussed in the Analysis above, which we hypothesize are due to current speeds and directions. The recurrence of high concentrations and widespread MSW in the North Pacific Current was certainly the most prominent pattern. This is a result of the large concentrations of MSW that enter the North Pacific Ocean from the Asian coastal cities and soon enter into the Kuroshio Current, the fastest current of the gyre. The North Pacific Current is slower than the Kuroshio Current yet faster than the California. This causes MSW to move into the North Pacific Current faster than it can exit into the California Current and therefore a greater concentration occurs in this current than any other current.

The near disappearance of MSW in the North Equatorial Current after 1 year only seems to have one explanation. The North Equatorial Current is the slowest of all the currents and therefore, once MSW enters the current, little of it exits the current before diffusing into the surrounding areas of the current. In contrast to the North Pacific Current, where its faster speeds cause the trash to move in one direction, rather than diffusing into the surrounding areas.

Throughout the model there are many areas in which we can expand and improve our investigation. Our model makes many simplifications, some of which are unavoidable, but many are in places which could be developed and expanded. One of the largest areas of simplification within our model is our depiction of physical oceanography. At the moment the currents are assigned boundary conditions which are broadly correct, but not precise. This could be improved by assigning more detailed ocean cells or by importing velocity or wind speed data from existing ocean models. An increasingly complex ocean model would also take into account various other smaller ocean currents which, in nature, also collect some of the MSW. The population factors in the model could also be expanded to include more cities or even just populations of people living on the Pacific Rim.

The model also makes the assumption that all populations produce MSW at an equal rate and that an equal amount makes it to the ocean; further MSW data including varying consumption rates and environmental protection laws and efforts of various communities could improve the realism of the simulation. The mathematical diffusion of MSW is also simplified and particles spread at an equal rate, therefore further data about the rate and behavior of oceanic debris movement would improve the realism of the particle motion.

Undoubtedly the most important result of the model was, that by using realistic parameters such as current speeds, population growth and MSW production, we were able to simulate the formation of a gyre and a garbage patch. We feel much can be learned from the formation and general location, and thereafter growth of a garbage patch, both from the point of view of oceanography and environmentalism. A model like this could be used to track the progress of spill chemicals throughout the ocean or as a tool in avoiding fish caught in particularly toxic parts of the ocean. We feel that our greatest original contribution to this problem is the development of an advection diffusion model which can produce data about the location, formation and growth of garbage patch in the North Pacific Gyre.

Appendix A

Works Cited

1. Bischof, Barbie, et al. "The North Equatorial Current." 2004. Ocean Surface Currents. February 2011 <http://oceancurrents.rsmas.miami.edu/atlantic/north-equatorial.html>.

2. Bowditch, Nathaniel. American Practical Navigator . Washington DC: United States Hydrographic Office, 1920.

3. Casey, Susan. "Plastic Ocean." Bowermaster, John. Oceans. Washington, DC.: Island Press, 2010. 71-82.

4. Dawson, Clint and Christopher M Mirabito. "The Shallow Water Equations." University of Texas, Austin , 29 September 2008.

5. Evans, Terry. "Pacific Garbage Patch Mitigation Stratigies and Solutions." n.d.

6. Hutchinson, Stephen and Lawrence E. Hawkins. Oceans: A Visual Guide. Sydney, Australia: Weldon Owen Inc., 2005.

7. Marine Debris Biodegradation Timeline. 5 January 2011 <http://cmore.soest.hawaii.edu/cruises/super/biodegradation.htm>.

8. Marine Debris Program . 8 December 2010 <http://marinedebris.noaa.gov/info/patch.html#1>.

9. Moler, Cleve. "Shallow Water Equations." 8 August 2009. Mathworks. 20 October 2010 <http://www.mathworks.com/moler/exm/chapters/water.pdf>.

10. Moore, Charles. Alguita. 25 November 2010 <http://www.alguita.com/index.html>.

11. Moore, Charles, et al. "A Comparison of Plastic and Plankton in the North Pacific Central Gyre." Marine Pollution Bulletin (2001).

12. NASA. Ocean Motion . 2 January 2011 <http://www.oceanmotion.org>.

13. Raffert, John P. Gyre. 8 December 2010 <http://www.britannica.com/EBchecked/topic/250463/gyre>.

14. Randall, David A. The Shallow Water Equations. Fort Collins : Department of Atmospheric Science, Colorado State University , 2006.

15. The Statistical Yearbook of the Republic of China. Population Projections. 2010. March 2011 <http://eng.stat.gov.tw/public/data/dgbas03/bs2/yearbook_eng/y020.pdf>.

16. Tokyo Metropolitan Government. "Population of Tokyo." 2006. Overview of Tokyo. March 2011 <http://www.metro.tokyo.jp/ENGLISH/PROFILE/overview03.htm>.

17. UNEP. "Municipal solid waste composition: for 7 OECD countries and 7 Asian cities." 2004. Environmental Knowledge for Change. March 2011 <http://maps.grida.no/go/graphic/municipal_solid_waste_composition_for_7_oecd_countries_and_7_asian_cities>.

18. United States Census. Googel Public Data. 2009. March 2011 <http://www.google.com/publicdata/home>.

19. United States Evironmental Protection Agency . 2011. Science and Technology: Land, Waste and Cleanup . March 2011 <http://www.epa.gov/gateway/science/land.html>.

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Appendix B

Netlogo Code

```
;These are the variables used in the model, they belong to either water,
cities, patches or are universal

breed [city cities]
breed [water]
city-own [population pop-growth garbage name garbage-per-person percent-to-
ocean percent-floats water-nearby starting-garbage percent-on-coast]
globals [ total-population north east south west NE StE SW NW month year BA-
Garbage LA-Garbage SD-Garbage H-Garbage T-Garbage TP-Garbage total-garbage]
patches-own [water? land?]
water-own [speed trash trash-nearby]

;The setup procedure initializes the geometry of the North Pacific Basin by
importing an image and portioning it into 'land' and water'
;next the procedure establishes certain global variables, establishes agent
breeds and initializes the city garbage values

to setup
  ca
  import-pcolors "map.png"
  ask patches
   [if pcolor = black [set pcolor green set land? true]
    if pcolor != green [set pcolor black set water? true sprout-water 1 [set
heading 180 set color blue]]]
  set north 0
  set east  90
  set south  180
  set west  270
```

```
  set NE  45
  set StE  135
  set SW 225
  set NW  315
  setup-cities
  set-default-shape water "water"
  Set-default-shape city "city"
  set year 0
  ask city
  [set garbage-per-person 2.204 set percent-to-ocean .1 set percent-floats .3
    set starting-garbage ( ( population * garbage-per-person * percent-to-ocean
* percent-floats ) / 24 ) ]
end

;This procedure setups up the various cities by positioning them on the map and
assigning values to their variables

to setup-cities
  ask patches
   [;Bay Area
    if pxcor = 119 and pycor = 16 [sprout-city 1 [set name 1 set size 4 set
color pink set population 7395000 set pop-growth 1.01
        set garbage starting-garbage set total-population total-population +
population ] ]
    ;Los Angeles
    if pxcor = 124 and pycor = 6 [sprout-city 1 [set name 2 set size 4 set
color pink set population 9862049 set pop-growth 1.0093
        set garbage starting-garbage set total-population total-population +
population ] ]
     ;San Diego
    if pxcor = 131 and pycor = -2 [sprout-city 1 [set name 3 set size 4 set
color pink set population 3001072 set pop-growth 1.0097
        set garbage starting-garbage set total-population total-population +
population ] ]
    ;Honolulu
    if pxcor = 44 and pycor = -30 [sprout-city 1 [set name 4 set size 4 set
color pink set population 905034 set pop-growth 1.00095
        set garbage starting-garbage set total-population total-population +
population ] ]
    ;Tokyo
    if pxcor = -76 and pycor = 6 [sprout-city 1 [set name 5 set size 4 set
color pink set population 12989000 set pop-growth 1.0096
        set garbage starting-garbage set total-population total-population +
population] ]
    ;Taipei
    if pxcor = -119 and pycor = -19 [sprout-city 1 [set name 6 set size 4 set
color pink set population 23165000 set pop-growth 1.0005
        set garbage starting-garbage set total-population total-population +
population] ]
    ]
end

;This procedure divides the geometry into 32 different 'Ocean Cells' and
assigns the agents within each cell a certain speed and heading

to setup-cells
 ask water
    [ifelse patch-ahead pcolor != green
    ;first row above origin
    [if xcor < 0 and xcor > -37.5 and ycor > 0 and ycor < 39 and pcolor !=
green
    [ set heading NE  set speed Convergence-Zone * 1 * .33]
    if xcor < -37.5 and xcor > -75 and ycor > 0 and ycor < 39 and pcolor !=
green
    [  set heading NE  set speed Kuroshio * 1 * .33]
    if xcor > 0 and xcor < 37.5 and ycor > 0 and ycor < 39 and pcolor != green
    [ set heading east set speed Convergence-Zone * 1 * .33]
     if xcor > 37.5 and xcor < 75 and ycor > 0 and ycor < 39 and pcolor !=
green
    [ set heading east set speed Convergence-Zone * 1 * .33]
    if xcor < -75 and xcor > -112.5 and ycor > 0 and ycor < 39 and pcolor !=
green
```

```
    [ set heading NE  set speed Kuroshio * 1 * .33]
    if xcor < -112.5 and ycor > 0 and ycor < 39 and pcolor != green
    [ set heading NE  set speed Kuroshio * 1 * .33]
    if xcor > 75 and xcor < 112.5 and ycor > 0 and ycor < 39 and pcolor !=
green
    [ set heading StE set speed California * 1 * .33]
    if xcor > 112.5 and ycor > 0 and ycor < 39 and pcolor != green
    [ set heading StE set speed California * 1 * .33]

    ;firsth row beneath origin
    if xcor < -75 and xcor > -112.5 and ycor < 0 and ycor > -39 and pcolor !=
green
    [ set heading NE  set speed Kuroshio * 1 * .33]
    if xcor < -112.5  and ycor < 0 and ycor > -39 and pcolor != green
    [ set heading NE  set speed Kuroshio * 1 * .33]
     if xcor > -37.5 and xcor < 0 and ycor < 0 and ycor > -39 and pcolor !=
green
    [ set heading  NW set speed Convergence-Zone * 1 * .33]
     if xcor > -75 and xcor < -37.5 and ycor < 0 and ycor > -39 and pcolor !=
green
    [ set heading  NW set speed Convergence-Zone * 1 * .33]
     if xcor > 0 and xcor < 37.5 and ycor < 0 and ycor > -39 and pcolor !=
green
    [ set heading  NW set speed Convergence-Zone * 1 * .33]
    if xcor > 37.5 and xcor < 75 and ycor < 0 and ycor > -39 and pcolor !=
green
    [ set heading  NW set speed Convergence-Zone * 1 * .33]
    if xcor > 75 and xcor < 112.5 and ycor < 0 and ycor > -39 and pcolor !=
green
    [ set heading SW set speed California * 1 * .33]
    if xcor > 112.5  and ycor < 0 and ycor > -39 and pcolor != green
    [ set heading SW set speed California * 1 * .33]

    ;second row above origin
    if xcor < 0 and xcor > -37.5 and ycor > 39 and pcolor != green
    [ set heading  east set speed North-Pacific * 1 * .33]
    if xcor < -37.5 and xcor > -75 and ycor > 39 and pcolor != green
    [ set heading  east set speed North-Pacific * 1 * .33]
    if xcor > 0 and xcor < 37.5 and ycor > 39 and pcolor != green
    [set heading StE set speed North-Pacific * 1 * .33 ]
    if xcor > 37.5 and xcor < 75 and ycor > 39 and pcolor != green
    [set heading StE set speed North-Pacific * 1 * .33 ]
    if xcor < -75  and xcor > -112.5 and ycor > 39 and pcolor != green
    [set heading NE set speed Kuroshio * 1 * .33]
    if xcor < -112.5  and ycor > 39 and pcolor != green
    [set heading NE set speed Kuroshio * 1 * .33]
    if xcor > 75 and xcor < 112.5 and ycor > 39 and pcolor != green
    [set heading SW set speed North-Pacific * 1 * .33]
    if xcor > 112.5 and ycor > 39 and pcolor != green
    [set heading SW set speed North-Pacific * 1 * .33]

    ;second row beneath origin
    if xcor > -37.5  and xcor < 0 and ycor <  -39 and pcolor != green
    [ set heading  west set speed North-Equatorial * 1 * .33]
    if xcor > -75  and xcor < -37.5 and ycor <  -39 and pcolor != green
    [ set heading  west set speed North-Equatorial * 1 * .33]
    if xcor < -75 and xcor > -112.5 and ycor < -39 and pcolor != green
    [ set heading   NW set speed North-Equatorial * 1 * .33]
    if xcor < -112.5  and ycor < -39 and pcolor != green
    [ set heading   NW set speed North-Equatorial * 1 * .33]
    if xcor > 0 and xcor < 37.5 and ycor < -39 and pcolor != green
    [ set heading  west set speed North-Equatorial * 1 * .33]
    if xcor > 37.5 and xcor < 75 and ycor < -39 and pcolor != green
    [ set heading  west set speed North-Equatorial * 1 * .33]
    if xcor > 75 and xcor < 112.5  and ycor < -39 and pcolor != green
    [set heading  SW set speed California * 1 * .33 ]
    if xcor > 112.5  and ycor < -39 and pcolor != green
    [set heading  SW set speed California * 1 * .33 ] ]
    [set heading (heading - 180) forward 1] ]
end

;This procedure manages city growth, which takes places after one year
```

```
to grow-cities
 ask city
    [ if month != 0 and remainder month 12 = 0
      [set population population * pop-growth
        set total-population total-population + (population * pop-growth) ] ]
end

;This procedure produces water movement and conservation by having the water
die if there are too many agents already on a patch or that
;patch is green and having water be born if a patch has no water

to move-water
  ask water
    [set heading heading + random 10
      if pcolor = green [set pcolor trash die]
    forward  speed
    if count turtles-here >= 2  and random 10 = 5  [set pcolor trash die]
    if random 1000 = 5 [set size 5 ]
    if pcolor != black and pcolor != green [set trash trash + pcolor if water?
= true [set pcolor black]
    if land? = true [set pcolor green] ] ]
  ask patches
    [if count water-here = 0 and pcolor != green [sprout-water 1 [set color
blue ] ] ]
end

;This procedure converts city garbage values into global variable which can be
accessed by water agents

to distribute-trash
  ask city
   [ set garbage garbage + ( (population * garbage-per-person * percent-to-
ocean * percent-floats) / 24 )
     if name = 1 [set BA-Garbage garbage]
     if name = 2 [set LA-Garbage garbage]
     if name = 3 [set SD-Garbage garbage]
     if name = 4 [set H-Garbage garbage]
     if name = 5 [set T-Garbage garbage]
     if name = 6 [set TP-Garbage garbage]
     set total-garbage total-garbage + garbage]
end

;This procedure manages the transfer of garbage from certain cities to their
surrounding water agents and the diffusion of trash
;between water agents
to advect-trash
 ask water
  [if city-trash = true and xcor = 119 and ycor = 16  [set trash (BA-Garbage /
count water in-radius 1) ]
  if city-trash = true and xcor = 124 and ycor = 6  [set trash (LA-Garbage /
count water in-radius 1) ]
  if city-trash = true and xcor = 131 and ycor = -2  [set trash (SD-Garbage /
count water in-radius 1) ]
  if city-trash = true and xcor = 44 and ycor = -30  [set trash (H-Garbage /
count water in-radius 1) ]
  if city-trash = true and xcor = -76 and ycor = 6  [set trash (T-Garbage /
count water in-radius 1) ]
  if city-trash = true and xcor = -119 and ycor = -19  [set trash (TP-Garbage /
count water in-radius 1)]
    if trash > 0 [set color scale-color pink trash 0 100]
 set trash-nearby ( sum [trash] of water in-radius (1 / 2 ) )
 set trash (trash-nearby / count water in-radius (1 / 2 ) ) ]
  ask city
  [set water-nearby count water in-radius (1)
    if water-nearby > 0 [set garbage 0]]
ask patches [if land? = true [set pcolor green]]
end

;The 'go' procedure initiates all the other procedures and converts the
timestep of ticks (hours) into months and years
```

```
to go
 tick
  setup-cells
  move-water
  distribute-trash
  advect-trash
  update-plot
  if remainder ticks 730 = 0 [ set month (month + 1)]
  if month != 0 and remainder ticks 8765 = 0 [set year (year + 1) set month 0]
  grow-cities
  if remainder ticks 8765 = 0 [stop display-concentration]
end

;This procedure generates concentration data

to display-concentration
  ask water
 [ output-print xcor
  output-print ycor
  ifelse trash > .0000000001 [output-print trash] [output-print 0]]
end

 ;This controls the plot

 to update-plot
   set-current-plot "population and MSW"
   set-current-plot-pen "population"
   plot total-population
   set-current-plot-pen "MSW"
   plot total-garbage
 end
```