

Stirring and Mixing of Marine Ecosystems

The ocean's plankton community sustains fish stocks and plays a key role in the Earth's carbon cycle. It also provides important feedbacks to the physical system of the upper ocean through light absorption and subsequent heating. Determining how the marine ecosystem will change in a changing climate is therefore imperative (see article by Hood, p. 12).

Observations of phytoplankton from space reveal a time-varying spatial structure on a vast range of scales (Figure 1). We can marvel at the richness of the structure, but it is not obvious how important the finer structure is. How does the spatial structure affect the functioning of the ecosystem as a whole? Does the heterogeneity of the system impact on the overall rates of production or the community structure, i.e. the species composition? Does the structure affect the way the biological system responds to changes to the environment? These are important questions.

Given the right conditions, which include sufficient light and nutrients, a massive growth of the marine algae occurs in a matter of a few days, referred to as the "spring bloom." The marine system is similar to a number of chemical and biological systems that exhibit excitable behavior in that a moderate size perturbation of the system can lead to explosive growth of one or more of the system's constituents. Much studied diverse examples include the Belousov-Zhabotinskii chemical reaction, slime mould, and the beating heart. The production of phytoplankton, as part of the marine ecosystem, is another example.

A major difference between the marine ecosystem and the other previously mentioned excitable systems is that it exists in a fluid environment. The fluid flow affects the ecosystem in a number of ways including the movement of nutrients into the euphotic zone and the vertical mixing of species and nutrients. **Kelvin Richards**, professor of oceanography and co-leader of the IPRC research team on Regional Ocean Influences, is focusing on an often-ignored aspect—lateral stirring and mixing. Large-scale (order 10–100 km) eddying motions stir the distribution of individual species down to a length-scale where mixing and reaction with other species and nutrients can take place. In the surface mixed layer of the ocean, where the mixing is caused by the three dimensional turbulence created by wind and buoyancy forcing, this mixing, or diffusive, length-scale will be typically a few tens of meters.

Snapshots from four different runs of a simple ecosystem model are shown in Figure 2. The combination of reaction, diffusion, and stirring produces effects that each activity cannot produce by itself. With reaction and diffusion alone, the system can support waves of reaction that travel at a speed related to the reaction rate and the diffusion coefficient. The importance of these waves is shown in Figure 2a. Emanating from a small patch where the system is excited (i.e. both phytoplankton and zooplankton have high values), reaction waves sweep through the whole community so that in a relatively short time the entire domain is excited, called a "global excitation." Stirring produces thin filaments (Figures 2b–d). The width of individual filaments, w_f , is controlled by the strain rate, diffusion coefficient, and reaction rate. The amplitude of the filaments can be enhanced if the reaction rate is fast enough (compare Figures 2c and d).

There are a number of timescales in the problem, but the timescale that determines whether or not the system becomes globally excited is the mix-down time, T_m , which is the time it takes for the stirring to reduce the length scale of a patch initially of size L_p down to the width of a filament, w_f . If T_m is too short compared to the reaction time, any inhomogeneities in the system will be mixed away before significant reaction takes place, and the system does not become excited. For longer mix-down times, the stirring and mixing produces global excitation. There is a twist in the tale. If the mix-down time is too long (if the diffusion coefficient is very small, for instance) reactions will have taken place before any significant mixing takes place. The result is again a weak response of the system.

The ecosystem and flow field used here have been chosen to be particularly simple in order to elucidate the more fundamental aspects of the problem. The results, however, will provide insight into the workings of more complex systems as they are considered.

These findings demonstrate the important role stirring and mixing has in the way a marine ecosystem behaves. Ignoring such effects may lead to erroneous results when "fitting" an ecosystem model to observations. At present these effects are not included in ecosystem models embedded in ocean general circulation models. The challenge and next step are to find ways of doing so.

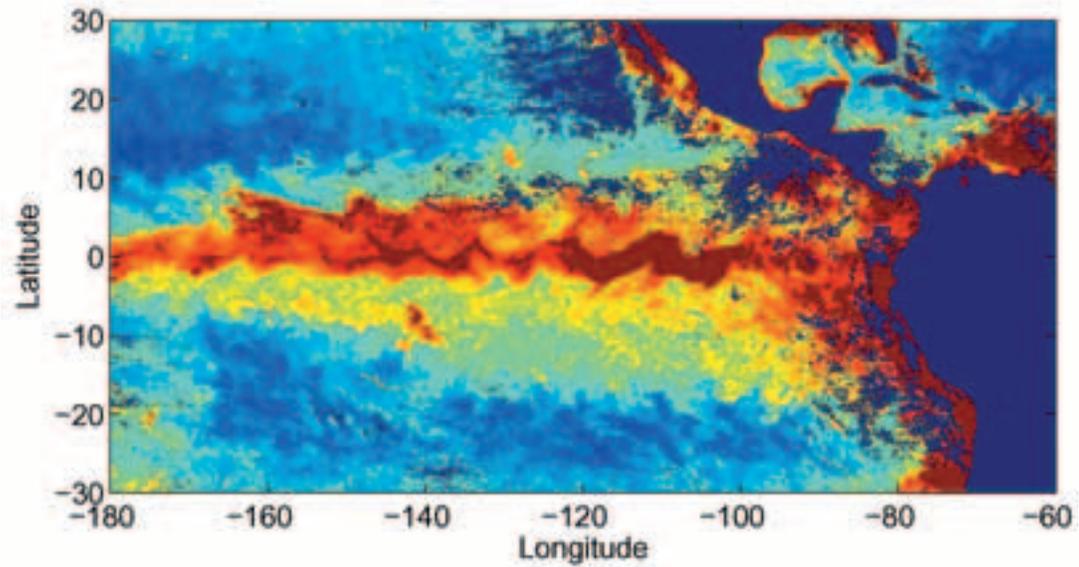


Figure 1. The distribution of chlorophyll in the eastern Pacific derived from a composite of data taken by SeaWiFS over the period 18–25 June 2003. Dark blue denotes cloud and land. The picture is dominated by the high production occurring in the Cold Tongue, caused by the upwelling of nutrient rich water. The imprint of Tropical Instability Waves is clearly visible, although there is structure down to the resolution of the instrument (4km).

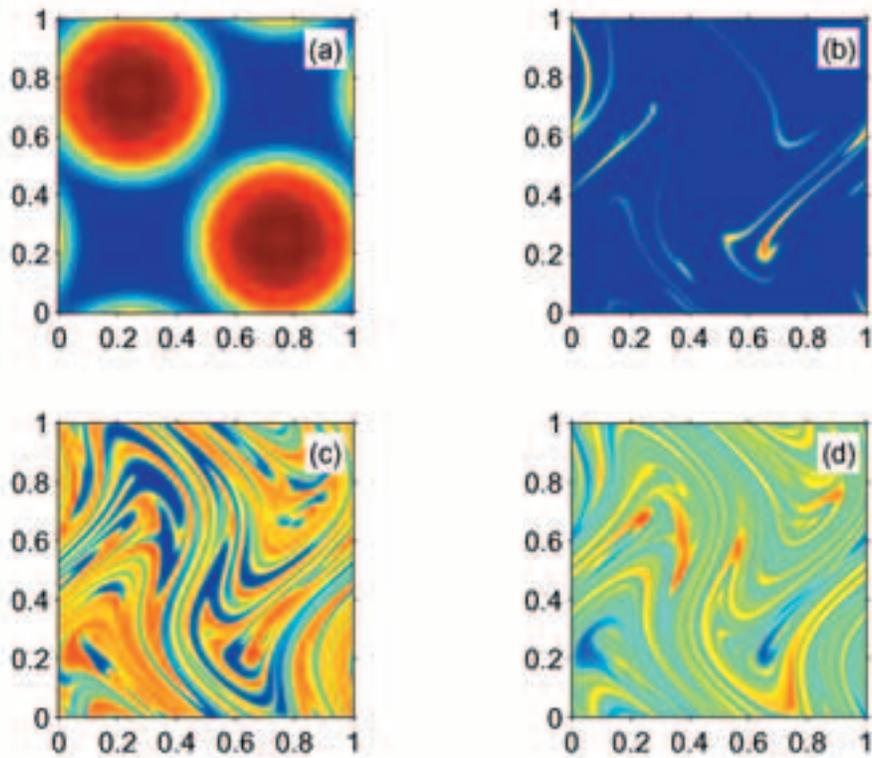


Figure 2. Snapshots of the horizontal distribution of the phytoplankton concentration for different configurations of a simple ecosystem model. The size of the domain is arbitrary, but can be considered to be 100m–1km for oceanic relevant parameters. (a) With no stirring the system is dominated by reaction waves that spread the regions of high concentration (red) across the domain. (b–c) Stirring produces thin filaments of high concentration. The evolution of the system is dependent on the fraction of the domain that is initially susceptible to excitation, A_i . With $A_i = 10\%$ (b) filaments are produced but the system does not become globally excited. Increasing $A_i = 25\%$ (c) produces a global excitation. (d) In contrast to a reactive tracer, the filamentary structure produced by stirring an inert tracer has a smaller amplitude.