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Spatial Heterogeneity and Its Relation to Processes in the Upper Ocean

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Abstract

In the ocean, the spatial distribution of biogeochemical tracers is affected by their physical transport in the fluid medium. Many tracer distributions such as sea surface chlorophyll and temperature are highly correlated at length scales of 1–100 km on account of a commonality in the transport processes that affect them. We characterize and differentiate between the spatial heterogeneity of the tracers by using a variance-based measure for “patchiness.” When we analyze the satellite-derived fields of surface chlorophyll and temperature, we find that chlorophyll is more patchy than temperature (i.e., a greater proportion of its variance occurs at small scales). We explain such differences in heterogeneity by taking the approach that the observed spatial heterogeneity of a tracer results from a balance between processes that generate variance and those that shift the variance from one length scale to another. The longevity of the tracer determines the extent to which the variance can be shifted to another scale. In the surface ocean, variance introduced at large scales due to geographic variations can be driven to smaller scales by the horizontal stirring and stretching of fluid filaments. On the other hand, small-scale vertical motion associated with fronts introduces small-scale variance that spreads to larger scales if the tracer anomalies are long lasting. For the latter case, we derive a quantitative relationship between a tracer’s patchiness and the timescales of processes that modify its concentration in the upper ocean. This relationship links the observed spatial heterogeneity in the system to the processes that contribute to its generation. It lends hope to our being able to use quantitative measures of spatial heterogeneity, like the patchiness parameter defined here, to gain information about processes or, *vice versa*, to predict how the spatial heterogeneity might be modified as a result of a change in processes.

Introduction

A key factor that influences spatial heterogeneity in the ocean and distinguishes it from heterogeneity in landscapes is that substances or properties in the ocean are transported within the fluid medium, which is in motion. Hence, the variability in the distribution of properties is largely linked to the dynamics of the fluid, which is complex, as it varies in both space and time. Spatial heterogeneity in the ocean is constantly evolving in time, in contrast to terrestrial systems, where the variability of the underlying medium (e.g., the geology or soil conditions) is more or less static on the timescales of relevance in the ocean. The fluid dynamical processes act over a wide range of time and length scales. In addition, there are a number of processes like warming or cooling at the surface, evaporation and precipitation, biological production of phytoplankton, and air-sea gas exchange that alter the properties of the ocean. Some processes generate variability and others annihilate it; our objective is to understand the net effect of these factors on the distribution of properties.

Transport in the ocean occurs through the process of advection, which carries properties along with the flow, and diffusion, due to which substances or energy can spread through the fluid. Diffusion is generally associated with small scales; it is important to individual plankton and bacteria and they may rely, for example, on the spatial variation in the concentration of a nutrient for its transport. A net diffusive flux occurs without the input of energy when the concentration gradient of a substance is spatially varying. The molecular diffusivity κ , of most substances is small and thus diffusive transport (quantified as $\kappa \nabla^2 c$, where c is the tracer concentration and ∇ the gradient operator) is relevant only at small length scales [the diffusive length scale $L_{\text{diff}} \sim (\kappa T)^{1/2} \approx 1 \text{ mm}$, for $\kappa = 10^{-5} \text{ ms}^{-2}$ and a time interval $T = 10 \text{ s}$]. At longer times T , and at length scales greater than a centimeter or so in the upper ocean where typical velocities U are in the range of 0.01 to 1 ms^{-1} , advective transport by the fluid by far dominates diffusion. A net advective flux of tracer, $\mathbf{u} \cdot \nabla c$ occurs when there is a concentration gradient in the tracer ∇c , in the direction of the fluid velocity \mathbf{u} . The length scale associated with advection, $L_{\text{advec}} \sim UT$, increases linearly with time T , as compared to the $1/2$ power in the case of diffusion. Hence, with increasing time, advection affects larger length scales than diffusion. A process of considerable relevance in the ocean, and somewhat different from pure advection and diffusion, is mixing. It transfers energy and property gradients from larger to smaller scales and results in the homogenization of properties over the region on which it operates on relatively short timescales. Mixing, which is often induced by shear and convective instability, contributes much more to the flux of energy and tracers than molecular diffusivity, which is relatively negligible for length scales of more than a few centimeters. The effective flux of energy or tracer generated by random turbulent motions is often parameterized as a diffusion-like process by using an enhanced “eddy” diffusivity κ_{eddy} .