

Preface

The great Tohoku earthquake followed by the catastrophic tsunami inflicted heavy damage on the Fukushima Nuclear Power Plant in Japan. Large amount of radioactive water leaked directly into the ocean. The radioactive pollution was also caused by atmospheric deposition on the ocean surface. Fukushima-derived radionuclides, advected by oceanic currents and eddies, propagated over a broad area in the North Pacific. It was very important to know by which transport pathways they did that and which mesoscale eddies gained and retained radioactive water and for how long a time. Could the Fukushima-derived radionuclides cross the strong Kuroshio Extension current and propagate to the south?

In April 2010, the explosion at the Blue Horizon mobile drilling rig in the Gulf of Mexico caused the catastrophic offshore oil spill. It was not, of course, a problem to monitor the propagation of oil on the sea surface. The problem was a short-term prediction for a few days of the shape, deformation, and metamorphoses of the oil plume in an unsteady velocity field.

Is it possible to find more or less robust material (Lagrangian) structures in chaotic flows governing mixing and transport of tracers? Could some of them create transport barriers preventing diffusive-like propagation of a contaminant? If we could identify such structures in the ocean, we would predict for a short and medium time where a contaminant will move even without a precise solution of the Navier–Stokes equations. The standard approach is to run global or regional numerical models of circulation to simulate propagation of pollutants and try to forecast their trajectories. It has been, of course, made after each of those events. The outcomes provide the so-called spaghetti-like plots of individual trajectories that are hard to interpret. Moreover, majority of trajectories in a chaotic environment are very sensitive to small and inevitable variations in initial conditions. Those trajectories are practically unpredictable even for a comparatively short time [see Eq. (1.2)].

Hydrological fronts in the ocean, which are boundaries between waters with strong horizontal gradients of temperature, salinity, and density, have long been recognized by fishermen to attract squid, fish, mammals, and other marine organisms. These fronts are not stationary features, but they might change the form,

intensity, and location and could even disappear in the course of time. In order to know the origin and history of frontal water masses to estimate their productivity and fishery conditions, it is necessary to simulate advection of virtual particles in a given velocity field backward in time. It is also important to estimate how robust and strong the fronts could be and try to predict their location for a short and medium time.

We list a few but rather dramatic events and practically important issues which require not the Eulerian but Lagrangian approach to deal with it. In the Eulerian framework, the flow is described in terms of the velocity field, while in the Lagrangian one, it is characterized by trajectories of a large number of fluid tracers which are tagged and tracked individually [2]. While in the Eulerian framework we get frozen snapshots of data, Lagrangian diagnostics enable to quantify spatiotemporal variability of the velocity field. Lagrangian structures are difficult to extract from Eulerian data, as they do not show up in a Eulerian velocity field.

The development of the Lagrangian methods in oceanography in the last years was advanced due to several factors: (1) The impressive progress in satellite monitoring has provided us continuous, near-real-time and global data at high space resolution for many oceanic and atmospheric parameters and the global altimetric velocity field. (2) The recent advance in satellite technology has revolutionized measurements taken by buoys drifting in the ocean which provide real-time information about ocean circulation in a high-frequency manner. (3) The development of high-resolution numerical models of ocean circulation has opened up new opportunities in simulating mesoscale and submesoscale processes. The new branch of oceanography, Lagrangian oceanography, is developing rapidly [3, 14]. Our personal scientific interests have been inspired by the penetration of ideas and methods of dynamical systems and chaos theory in a geophysical context in recent decades [4–7, 9–13, 15].

The ocean is a highly turbulent medium and presents a variety of dynamical phenomena with different space and time scales ranging from millimeters to a few thousand of kilometers and from milliseconds to thousands of years. The ocean is subjected to a variety of small- and large-scale random perturbations. Some of them produce water movement that is supposed to be inherently unpredictable. The others generate well-ordered and long-lived coherent structures due to the Earth's rotation, density stratification, wind stress, and bottom topography. How to find some order in this chaos?

In this book, we focus on large-scale Lagrangian transport and mixing of water masses in the ocean. We mean by large scale the motions affected by planetary rotation when the effects of planetary rotation are large. The Rossby number, $Ro = U/Lf$, should be small for such a motion as compared to unity. Here, U is a characteristic velocity, and f is the Coriolis parameter. The horizontal scale of large-scale motion, L , can vary and exceeds a few kilometers in temperate and high latitudes where we work in this book.

The starting point in the Lagrangian approach is a velocity field which is supposed to be derived analytically or given as an output of a numerical model of

circulation or estimated from satellite altimetry or radar measurements. If advected particles rapidly adjust their own velocity to that of a background flow and do not affect the flow properties, they are called passive and satisfy simple advection equations (1.3). Solutions of those equations can be chaotic in the sense of exponential sensitivity to small variations in initial conditions and/or control parameters as in Eq.(1.1), even if the Eulerian velocity field is supposed to be absolutely deterministic. It means that even a simple time-periodic deterministic velocity field may cause practically unpredictable particle trajectories, the phenomenon known as chaotic advection [1, 8].

In the first two chapters, we introduce and analyze in detail some simple deterministic models of chaotic oceanic flows. We do not assume that the reader is familiar with dynamical systems theory and theory of chaos. The most important mathematical notions, used in the text, are **bolded** and explained in the Glossary in the end of the book.

The other chapters are devoted to modeling large-scale mixing and transport in the Northwestern Pacific Ocean and in some adjacent marginal seas. In this book, we are interested, mainly, in mesoscale processes on the scale of ten kms and more which are simulated by integrating trajectories of artificial tracers advected by altimetry-derived AVISO velocity fields or by velocity fields generated in high-resolution numerical models of circulation. In Chap. 3, we review briefly the present state of operational and satellite oceanography. The fourth chapter is a methodological one, where we describe the Lagrangian tools used to simulate and analyze mixing and transport. They include a number of Lagrangian indicators and specific Lagrangian maps which we compute to plot and visualize a large amount of information. We present a method for computing finite-time Lyapunov exponents and a brief description of the so-called Lagrangian coherent structures.

In the rest of the book, we focus on specific features and phenomena. The fifth chapter is devoted to Lagrangian statistical analysis of near-surface transport of subtropical waters in the Japan Sea based on altimeter data. In the sixth chapter, we apply Lagrangian tools to study mesoscale eddies, rotating coherent features which exist almost everywhere in the ocean. It is shown here how to analyze by Lagrangian methods the formation, structure, evolution, and splitting of large mesoscale eddies over the Kuril–Kamchatka trench in the Northwestern Pacific Ocean based on altimetric velocity field and hydrological in situ observations of those eddies. To study the vertical structure of eddies in the ocean, we need not the altimetric but a numerical velocity field generated in an eddy-resolved multilayered circulation model. We use a regional model to analyze from a Lagrangian perspective the vertical structure of simulated deep-sea anticyclonic eddies in the Japan Sea constrained by the bottom topography.

The last part of the book deals with applications of elaborated methods and tools to some practical problems. In the seventh chapter, we apply the developed Lagrangian approach to simulate propagation of Fukushima-derived radionuclides advected by altimetric velocity field in the Northwestern Pacific Ocean. The results of the simulation are compared with in situ measurements of levels of ^{134}Cs and ^{137}Cs concentrations just after the accident and 15 months later. Different

Lagrangian diagnostics are used to reconstruct the history and origin of synthetic tracers imitating measured seawater samples collected inside the mesoscale eddies with the risk to be contaminated.

In the eighth chapter, we introduce the notion of a Lagrangian front which is defined as a boundary between waters with strongly different values of a Lagrangian indicator. The Lagrangian fronts can be identified in a given velocity field by computing Lagrangian maps. We study the connection of Lagrangian fronts with fishing grounds and catch locations for Pacific saury and neon flying squid in a region in the Northwestern Pacific Ocean with one of the richest fisheries in the world. This diagnostic is shown to be a new indicator for potential fishing grounds. In this chapter, we also review recent studies on the foraging behavior of top marine predators as great frigatebirds, elephant seals, and Mediterranean fin whales and their relationship with specific Lagrangian coherent structures.

The book is intended for graduate and postgraduate students and research scientists and for those oceanographers, physicists, and applied mathematicians who are interested in applications of ideas and methods of dynamical systems theory to geophysical fluid dynamics. It is our great pleasure to thank our co-workers who participated in obtaining some of the results presented in this book: Andrey Andreev, Pavel Fayman, Vladimir Goryachev, Konstantine Koshel, Vyacheslav Lobanov, Denis Makarov, Vladimir Ponomarev, and Eugene Samko.

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