OCEAN MIXING

The stratified ocean mixes episodically in small patches where energy is dissipated and density smoothed over scales of centimeters. The net effect of these countless events affects the shape of the ocean's thermocline, how heat is transported from the sea surface to the interior, and how dense bottom water is lifted into the global overturning circulation. This book explores the primary factors affecting mixing, beginning with the thermodynamics of seawater, how they vary in the ocean, and how they depend on the physical properties of seawater. Turbulence and double diffusion are then discussed, which determines how mixing evolves and the different impacts it has on velocity, temperature, and salinity. It reviews insights from both laboratory studies and numerical modeling, emphasizing the assumptions and limitations of these methods. This is an excellent reference for researchers and graduate students working to advance our understanding of mixing, including oceanographers, atmospheric scientists, and limnologists.

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With love to Carol,
God's gift to me as wife, companion, lover, and encourager for 57 years.

Contents

Color plates can be found between pages 180 and 181

Preface

This book began over thirty years ago as a joint endeavor with Chris Garrett, but was repeatedly put off as the need for ever more detailed funding proposals increased. Taken from the name of a course I taught for many years at the University of Washington, the title reflects the focus on thermodynamic mixing, the final stage of the cascade of energy and scalar variance from the size of ocean basins to centimeters. In presenting results of decades of research as well as the most important outstanding issues, the book concentrates on the stratified ocean, the flywheel of Earth's climate.

The understanding of mixing described here stems from work begun in the late 1960s that has reached a first-order understanding by comparison with prior ignorance. This confidence comes from comparing aspects of mixing that we can measure with thickening rates of tracer clouds. We must be mindful, however, that the microstructure part of the edifice is based on a string of ad hoc approaches bridging gaps in our observational capability. Going forward, filling in these gaps should be a high priority. Both the gaps and possible future directions are presented, in part using short 'perspective' sections with my personal views.

Beginning with an overview of mixing, Chapter 1 proceeds to the role of mixing in the meridional overturning circulation and concludes with ocean-wide budgets of energy and scalar variances. Chapter 2 treats the physical properties of seawater affecting mixing and the application of thermodynamics to those properties. The resulting heat and salt conservation equations lead to equilibrium and well-mixed reference states for mixing, and later are used to infer turbulent diffusivities from measured dissipation rates.

Focusing on how microstructure is measured and interpreted, Chapter 3 is not intended as a stand-alone treatment of turbulence. The aim, rather, is to examine turbulent cascades of energy and scalar variance to ultimate dissipation and diffusion, with an eye to how well they can be estimated with one-dimensional measurements. Differential diffusion and horizontal cascades are also examined as topics of increasing interest. Concentration on dissipation-scale processes concludes with double diffusion in Chapter 4. After reviewing its theoretical basis and the conditions for its occurrence, the discussion shifts to diapycnal fluxes, staircases, and thermohaline intrusions.

With the spatial scales that must be measured having been established, Chapter 5 examines sensors and vehicles. Most direct mixing measurements have come from airfoils and thermistors; other probes show promise, but none are regularly producing useful data. Owing to the enormous span of dissipation rates in the ocean, all sensors have limited spatial resolution, sensitivity, or noise level when outside the range of weak-to-moderate turbulence produced by internal waves close to background levels. Owing to the importance of finescale (1–100 m) structures in generating and modulating mixing, these probes are also examined, particularly as they affect the vertical scales over which density overturns can be resolved. Because these probes are carried on many types of vehicles, the discussion examines how the capabilities and limitations of the platforms shape what we can observe.

Chapters 6 and 7 focus on internal waves and their interactions that drive mixing. Beginning with the basic equations, the discussion includes signatures of internal waves most often observed, as well as the degenerate solution termed the ‘vortical mode’. An appendix, prepared with R.-C. Lien, develops expressions needed to apply the Garrett-Munk internal wave spectrum to observations. After reviewing production and propagation of internal wave energy, the emphasis is on energy transfer from large to small scales, the expressions used to quantify it, and how they compare with observations. The saturated range of length scales separating linear internal waves from turbulence is also considered.

The final chapter, 8, examines how the different aspects of mixing come together in the pycnocline of the open ocean. After considering the structure of the pycnocline, the nature of its finestructure is examined as the basis for the first global maps of mixing. After discussing patterns in these maps, mixing patches are characterized, including identification of which ones are produced by salt fingers. The chapter concludes with overviews of mixing in three important regions where mixing differs greatly from the open-ocean pycnocline: the Southern Ocean, the Arctic, and ocean ridges.

Because the subject is evolving rapidly and has much to do before embalming accumulated knowledge for display, I include background of how the topics came to their present state, hoping that this approach may aid readers to better see paths to explore. In addition to colleagues, graduate students, and postdocs who have educated me along the way, I am deeply indebted to Ren-Chieh Lien, Howard Stone, Rob Pinkel, Eric Kunze, Tom Sanford, and Matthew Alford for critiquing the chapters. They, however, could do only so much, and remaining problems are mine.

Since the book was completed, my close friend and colleague Tom Sanford died unexpectedly. His work is cited in many places throughout the text, but here I wish to acknowledge the important role he played in my research and the value of the encouragement he provided during the decades of our collaboration. His integrity, scientific acumen, and good sense helped me greatly, and I know that many others also benefited from knowing Tom.