Part I

Background

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Excerpt
More information

1

The Coastal Ocean

Man's interface with the ocean begins at the coast. Just the mention of estuaries, harbors, bays, lagoons, open coastline, and shelf seas conjures up a myriad of processes and scales with complex interactions. It is at the coast where human influences are most concentrated – waste disposal, construction, transportation, agriculture, aquaculture, recreation, mineral and biological exploitation. Equally, it is at the coast that the ocean most impacts humans, dictating patterns of everyday life and long-term viability. Oceanic motion mediates all these interactions, at several scales: surface waves, tide, storm surge, seasonal, decadal and beyond.

Our scope extends from land across the continental shelf to roughly the shelf break. The ocean dynamics change abruptly near the shelf break, as do many practical concerns including resource management, pollution, and navigation. This large, semienclosed region has come to be identified as the *coastal ocean*. Geographically the scope is approximately that of the Exclusive Economic Zone. The transport of matter within and through the coastal ocean is of paramount importance.

The understanding of water motion and its simulation in the coastal ocean is quite advanced. Many modeling methods are in use today that will give a faithful representation of currents and sea level. The resolution possible is surprisingly high and continually improving. Model output in the form of hindcasts and even forecasts is growing in availability as well. These trends are likely to continue. Simultaneously the geographic coverage of models is expanding under national and international guidance.

It is the current fields from these models that are our starting point. We seek to use them, not produce them. Together with their companion fields (temperature, salinity, nutrients, turbulence) they constitute a sophisticated base from which to examine many important issues.

The common starting point is to examine the tracks that simple particles follow. It is the connections among time, place, and a particle's past that make this such an important matter. Immediate applications include the tracking of floating objects or predicting the path of a stricken vessel or marine mammal. This "Lagrangian" description rises rapidly in complexity as one addresses marine chemistry and biota. Oceanic chemical interactions are complex enough in themselves; the uncontrolled outdoor environment enhances the difficulty in measuring and understanding them. A living organism will add its own behavioral motion and biochemical dynamics, both of which will develop as it matures and moves through the environment.

An excellent introduction to coastal ocean phenomena can be found in the text by Simpson and Sharples [419] and in the earlier text by Csanady [95]. Townsend [452] provides an excellent general introduction to marine science, with special emphasis on contemporary issues in biological oceanography. These texts are recommended as basic source material and a gateway to the wider oceanographic literature. For more advanced texts, the two Robinson/Brink volumes for processes [54] and regional studies [384] are entirely focused on the coastal ocean.

1.1 Typical Motions and Scales

Water movement on the continental shelf is heavily modulated by topography and coastline. Motions are steered by topography; water banks up against the coast; onshore flows can be diverted vertically. Typical horizontal motions in the coastal ocean can be crudely distinguished by four characteristics: velocity magnitude, time scale, length scale of variation, and size of displacement (Table 1.1). The "seasonal" category includes mean seasonal wind and mean baroclinicity reflecting seasonal water mass formation. These can extend across the shelf from land to the shelf break and account for significant and persistent along-shore displacement.

These motions can be strongly affected by local scale variations and the geographic setting. A small harbor in a straight coastline on a smooth continental shelf will experience very different scales of motion than those seen offshore, but still be driven principally by the larger scale shelf motions. River motions will tend to be dominant along the axis of the river, with transverse motions strongly influenced by curvature and longitudinal variations in width and topography. Coastline variations and structures can modify motions well up and downstream. With sufficient tide or surge, shallow areas can dry and dry areas can flood. There is no substitute for local resolution in all these cases, but it cannot come at the expense of geographic coverage. One needs both if the relevant motions are to be properly represented.

Below we elaborate on some physical processes, emphasizing the characteristics that will be important to transport and dispersion. There is an abundance of literature on such processes.

Tides

In the deep sea, the tides are forced primarily by gravitational interactions of the rotating and orbiting Earth, moon, and sun. The tidal motion on the shelf is driven

Table 1.1. *Scales of Motion*

	Velocity	Time scale	Length scale	Displacement
Tide	1 m/s	Daily, periodic	200 km	10 km
Wind	0.5 m/s (surface)	3-day events	100 km	100 km
Seasonal shelf setup	0.01 – 0.10 m/s	Monthly, steady	400 km	0.86–8.6 km/d

by co-oscillation with the astronomically driven deep ocean tides, with the direct gravitational forcing having a minimal effect. This shelf oscillation can be amplified and damped by the structure of the coastline and bathymetry. For example, the large tides in the Bay of Fundy are often attributed to a resonant oscillation (Defant [109]). Tidal resonance is a global phenomena seen in studies of the Bristol Channel [156], the Gulf of California [173], Ungava Bay and Hudson Strait [7], the Coral Sea [470], and even in relatively low-tide environments like the Gulf of Gabes, Tunisia in the Mediterranean Sea [399].

In the presence of sloping topography, tidal motions can be rectified to produce a mean subtidal circulation (Huthnance [204]). For example, through an examination of Stokes drift, Loder [257] noted that there were significant differences between the Eulerian and Lagrangian mean currents around Georges Bank. These motions have major ecological importance; the processes can be expected to be operative over steep topography in tidally energetic waters.

Simpson and Hunter [418] called attention to the importance of vertical mixing fronts initiated by bottom stress during tidal flow. They found that at a particular value of the ratio h/u^3 (h is the mean water depth, and u is the depth-averaged current of the spring tide) the water would be vertically mixed. The frontal boundary between tidally mixed areas and the surrounding stratified waters tend to be associated with enhanced biological activity. "Bottom trapped" fronts have been identified in a great many coastal ocean locations.

Wetting and Drying

In many nearshore applications, explicit treatment of the moving boundary between land and water is a necessity. Accurately representing this process is a challenge for both modeling and observation. Drying schemes can be implemented in models at various levels of complexity [31, 70, 155, 179]. Greenberg [181] has demonstrated that in tidally energetic areas with extensive tidal flats, there can be significant dynamic influences hundreds of kilometers away. Bilgili Mclaughlin et al. [307] found that even on shorter length scales, the tidal prism can have significant contributions from wetting/drying areas, with important distortions in deeper currents.

Westerink et al. [480] found that properly simulating inundation in southern Louisiana required extreme resolution to reproduce the overtopping of small structures. This has been a critical concern and requires land use and other data not typically part of oceanography. A remarkable feature of this model is the coupling of these finely resolved local flooding dynamics to broad basin–scale coverage necessary to replicate hurricane processes.

Wind Response

The surface wind stress can strongly influence the circulation of coastal seas. Wright and others [487] computed the large-scale response to regional wind using a simple linearized two-dimensional (2-D) barotropic model of the Gulf of Maine and adjacent continental shelf. They showed that to get a reasonable representation it was necessary to account properly for upstream shelf influences (in the sense of trapped topographic waves) outside the model domain through appropriate specification of the open boundary (see also Hayashi et al. [191]). An improvement on this study was done in Greenberg et al. [177] in a three-dimensional (3-D) model where the domain boundaries were expanded outward along the shelf and into the deep sea. This demonstrated the importance of surface and bottom Ekman layers leading to vertical structure in the currents, giving rise to wind-driven upwelling and downwelling, distinct surface currents, and circulation patterns in deep channels and along steep topography.

Buoyancy-Driven Flow

Density gradients influence many ocean flows and processes. They are critical to many biological processes, as illustrated in Boicourt et al. [43]. The arrested topographic wave of Csanady [93] describes the basic motion of coastal freshwater trapped along the coast under the influence of friction and the Earth's rotation. The motion is very much dependent on topography [409]. Wright [486] showed how on a flat shelf the transport would migrate to the shelf break and Chapman and Lentz [77] demonstrated that the bottom boundary layer, even when thin, is a major component of the dynamics. The buoyancy flows can be driven along the coast by coastal trapped freshwater as described in Chapman and Lentz [77] and Lentz and Fewings [247] and by dense bottom water as seen in Shaw and Csanady [409] and Brooks and Townsend [57]. Wind and waves will change the circulation patterns associated with coastal river input [247], but the meteorological influence is very much dependent on the scale of the river outflow [246].

Buoyancy-driven circulation is ubiquitous in the coastal ocean, but as seen earlier, the motion is often heavily modified by other forcings. Although simple in concept, an accurate physical description of the compounded processes involved can be very complex.

Comprehensive Subtidal Circulation

The increasing complexity of circulation models is demonstrated by the incremental improvements in studies of the subtidal circulation in the Gulf of Maine. The two-dimensional structured approach of Greenberg [182] and Wright et al. [487] mentioned previously, showed the importance of tidal, wind, and boundary forcing. Lynch et al. [278] included baroclinic computations using an unstructured mesh and a linear harmonic model. Lynch and Naimie advanced this by expanding the domain and increasing the resolution over the outer banks of the Gulf of Maine [278, 286]. These two studies provided the physical fields for a major Lagrangian investigation into the fate of cod and haddock early life stages [478]. Further advances were made by Greenberg et al. [177] looking at detailed wind-driven solutions. Naimie et al. [326] included the major nonlinearities by iterating on the linear harmonic solutions. The work progressed to fully nonlinear prognostic modeling with the development of a comprehensive model by Lynch et al. [282]. Naimie [327], taking advantage of the flexibility of a triangular unstructured mesh, showed that locally adding high resolution around Georges Bank without changing the topography gave more accurate solutions.

Mixing, Residence Time, and Exchange Rates

The study of mixing, residence time and exchange rates relates to many practical problems. Historically box models and tidal prisms have been used to approximate the dynamic. Needless to say this can be a highly aggregated form of analysis, leaving many questions unaddressable. A good introduction can be found in Zimmerman's papers [504, 505, 506] and in Fisher et al. [153].

Bilgili et al. [31] assert "... residence and exchange are inherently Lagrangian concepts and are best treated as such." There are many complexities involved in making Lagrangian computations, part of the motivation for this book. Thompson et al. [447] demonstrate how in tidal computations, the work of particle tracking can be reduced by using a Markov chain approach linking specific subregions. Bilgili et al. [31] use the technique in a complex estuary system. Differences in retention due to the choice of particle release time (high or low water) were significant. This echoes results found by Ridderinkhof et al. [381], where exchange was very much dependent on the starting tidal phase. All of these findings rely on tidal-time particle tracking.

Zimmerman and Ridderinkhof used tidal-time particle tracking and found "Lagrangian chaos" in periodically forced tidal simulations. This "chaotic stirring" occurred in areas of very irregular topography and coastline [380, 507], despite the expectation of ordinary, periodic behavior. The variation from regular to chaotic can depend on the relative scales of the topography and tidal excursion [379]. Particle tracks can be interpreted as manifolds delineating fixed points that are either elliptic (centers of eddies) or hyperbolic (saddlepoints where streamlines converge and separate) [379, 256]. Saddlepoint analysis provides another method of describing the chaotic versus regular state of the regime.

Proehl et al. [366] demonstrated the importance of wind forcing over complex tidal–time flows. Significant horizontal dispersion was found in modeled and observed systems, effectively created through 3-D tidal time advection of particles and their 1-D vertical diffusion. No horizontal eddy diffusivity was used, the operative mechanism was shear dispersion; and it was very much event specific. The accurate modeling of the near-surface response to wind stress is of crucial importance.

With respect to coastal ocean motion, we can perhaps generalize Zimmerman's [507] parting words: "Thinking about the latter regime [Lagrangian chaos] particularly has prompted this paper's title [The Tidal Whirlpool ...], which stands as much for the complex dynamical reality of a tidal area, as it is a metaphor for the state of mind one enters in trying to get a grip on it." (p.152)

Summary: Motion, Processes, Scale

There are still challenges in the modeling of many coastal ocean processes. There will always be a need for site-specific knowledge and understanding; and there will always be processes unresolved. Particle tracking can help expose shortcomings in circulation models; it will certainly benefit from the constant progress being made in modeling methodology and application.

1.2 Particle Simulation

We simulate many individual oceanic particles. Each particle will have its own dynamics, subject to numerous, variable influences. All outcomes will be retained at the individual particle level. At any time, these outcomes can be summarized or aggregated without loss of any information. Rather than simulate the average particle, we simulate many particles and average the results when appropriate.

1.2.1 Motion

In terms of motion, we have to account for particle advection, dispersion, and behavior; all jointly determine the individual trajectory $\mathbf{X}_i(t)$. There will be a deterministic component – the advective fluid velocity $\mathbf{v}$ – that depends on a particle's location in space and time. In addition, the motion will have an individualized random displacement $\mathcal{R}$, representing unresolved or unknown motion – this will be parameterized with an eddy diffusion coefficient A. Both $\mathbf{v}$ and A are assumed available as gridded fields from a computational coastal ocean model. There may be other parameters influencing the random $\mathcal{R}$, including an individual particle's condition or memory. If the particle is finite in size or mass, then an additional law of motion is required, dealing with particle drag and inertia. Finally, there is the influence of the boundary layers encountered – air–sea, land–sea, benthic etc. – these may or may not be resolved in a coastal ocean model; but their effects need to be recognized.

Beyond these aspects of motion is behavior – something that develops as an individual develops, for example, buoyancy, swimming speed, preferred location, etc. This is a Lagrangian property of an individual particle; it is a prime example of coupling of Lagrangian biology with physical motion. It is critically important to include this behavioral portion of motion in the vertical; the scales of motion and resolution in most intended applications make the horizontal motion not subject to behavioral modification. Of course, if an individual changes its depth, it can dramatically alter its environment including the basic fluid motion and several of the environmental variables important to it.

The computational task is simple and well explored: integrate $\dot{\mathbf{X}}_i = \mathbf{V}_i(\mathbf{X})$ with particle velocity $\mathbf{V}_i$ dependent on the current particle location, history, and environment, plus some randomness.[1]

An individual is presumed to have embedded memory – memory of where it has been, how it reacted to the environment then/there, and how it has accumulated development. There are dynamical relations for random walk memory as well as biotic rates of change; these have to be embedded in a "particle." We thus imagine a particle's state to include location; sufficient to collect all environmental variables; plus a group of "onboard" relations and rates, sufficient to process the environment, generate vital rates and process random influences; plus a memory of its past and whatever it inherited from either initial conditions, launch or birth. A special possibility for biotic particles is to retain lineage through generations.

The *passive* particle is the fluid mechanical baseline; an inert particle follows the 3D fluid motion, including upwelling, surface and boundary activity, etc. At the other extreme, there is the *fixed depth* particle – this is familiar in analysis, and compatible with simple forms of drifting instruments (surface or drogued at fixed depth). This is not a passive situation, however – implied by perfect depth regulation is potentially vigorous vertical motion to maintain position. Examples include drogued drifters and larvae with assumed diel or seasonal migratory behavior.

Floating objects involve special considerations of motion associated with atmospheric or surface-wave forcing occurring in the surface boundary layer. Typical models do not have adequate resolution here, so some form of vertical subgrid closure is needed. These considerations pertain to search-and-rescue operations, as well as to the motion of floating plankton and other material.

[1] Throughout we use $\mathbf{v}$ for the gridded fluid velocity, $\mathbf{V}$ for the particle velocity.

1.2.2 Rates

In terms of biotic processes, an individual must carry with it a complete description of the relevant state and its rate of change, sufficient to integrate its particular dynamics. For each individual, there is a collection of ordinary differential equations (ODEs) with individual parameters, forced by deterministic and stochastic influences, coming from within (the individual) and without (the environment).

There is an important history of modeling many biotic and chemical processes in this way – and in identifying state variables and their rates of change. A fundamental form is

$$\frac{1}{B}\frac{dB}{dt} = r(B, E\,|\,\alpha) \tag{1.1}$$

r is the process rate, B the biological state, E the environment, and α the parameters.

If there is a useful reference state with rate r_o, for example, low abundance or an equilibrium, then this may be expressed as

$$\frac{1}{B}\frac{dB}{dt} = r_o \cdot L_o(B, E\,|\,\alpha) \tag{1.2}$$

where $L_o = r/r_o$ is a rate limiter, unity when in the reference state. For example, the popular Michaelis–Menten form has $L_o = \frac{B_h}{B_h+B}$, with parameter B_h, the "half saturation constant." $L = 1$ at low B, the reference state, and decreases monotonically through 0.5 at half-saturation to zero at large B. The reaction is saturated at high B; r is slowed to nothing. In Appendix D we summarize this and some other well-used rate expressions. We anticipate putting this level of realism to work onboard every particle.

These rates describe continuous changes, for example, growth, weight gain, etc. Some transformations however, are fundamentally *binary*. Examples include instrument failure or stranding; death; reproduction; morphological transition. In these situations every individual is binary, say with probability P it will die during the coming timestep; the aggregation of outcomes (number of positive versus negative outcomes) will obey the binomial distribution, there being many combinations of individuals for a given aggregate outcome.

For N identical particles, the total number of transitions will have mean NP, such that on average, $\frac{\Delta N}{N} = P$. This is intuitive. The outcome will be variable, however, with standard deviation $\sigma = \sqrt{NP(1-P)}$. A single realization will have

$$\frac{\Delta N}{N} = P + \epsilon \tag{1.3}$$

with the random number ϵ having zero mean and standard deviation scaling with $\frac{1}{\sqrt{N}}$. At high N we approach the limit of vanishing variability even though each individual