MASTER

COASTAL SHELF TRANSPORT AND DIFFUSION

Annual Progress Report
1979

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November 1979

Prepared For

THE U.S. ENERGY RESEARCH AND DEVELOPMENT ADMINISTRATION
UNDER CONTRACT NO. DE-AC02-79EV10005

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Abstract

This contract supports work on physical properties of the coastal ocean relevant to energy related activities, in continuation of a project previously funded by DoE through a subcontract from Brookhaven National Laboratory. During the past contract year progress has been made in the analysis of observations within the coastal boundary layer (0-12 km from shore off Long Island), in the measurement of shear flow just below the air-sea interface and in the understanding of the dynamics of continental shelf circulation. A model of nearshore tidal currents has been constructed and related to observation, resulting in a quantification of frictional effects. A new method has been developed for observing the velocity distribution near a free surface. Long-term shelf circulation has been shown to be governed by two types of pressure field, a "trapped" field related to topography, and an "outer" field impressed on the shelf by large-scale oceanic gyres.

Introduction

The present report summarizes progress made during 1979 in research on Coastal Shelf Transport and Diffusion, a program begun in 1974 as a joint experimental/theoretical study between Brookhaven National Laboratory and the Woods Hole Oceanographic Institution. By September 1978 a joint field project off Long Island (the COBOLT or COastal BOUNDary Layer Transect experiment) had been completed. Under Contract EV 10005 work continued at Woods Hole on the evaluation and interpretation of the coastal boundary layer observations, on dynamical models of the continental shelf and slope, and of various aspects of exchange processes between the coastal zone and the outer shelf. The past year has seen the crystallization of ideas on shelf circulation into a conceptual framework which, at this point, is the major contribution under this contract. The underlying theory has been described in a series of recent papers (Csanady, 1978, 1979a,b) while its implications for energy-related activities are discussed in Appendix I to this report, in non-specialist language, for possible use by DOE staff.

The development of observational techniques for near-surface velocity profile determination, begun 1977-78, continued during the past contract year and also brought gratifying results. The product, the acoustically tracked Large Contact Surface (LACS) drogue, provides a tool not previously available for obtaining reasonably accurate, relatively high resolution velocity profiles within the first meter or two of the sea surface.

Appendix I also contains a brief discussion of the problem of the "flushing" velocity which arose recently in connection with debates on the seashore siting of thermal power plants. A preliminary analysis of the problem has shown that an average bulk Lagrangian velocity estimate must be used in

box diffusion models as a flushing velocity. Arriving at such Lagrangian velocity estimates is difficult and, at present, controversial. Further conceptual development is necessary before this question can be resolved, as well as experimental work.

Scientific Objectives

The scientific objectives of this project have been discussed before but will be reviewed here in light of recent progress. The fundamental objective is to explore and develop an understanding of the flow environment in the coastal ocean to the point where the environmental impact of energy related activities—power generation, production and transport of hydrocarbons, etc.—can be confidently assessed, as far as transport and diffusion of any contaminant is concerned. It is realized that several other Department of Energy supported projects have a similar overall objective. Our contribution to achieving this objective consists partly of the acquisition of descriptive knowledge in key areas where such knowledge is lacking, for example, in the coastal boundary layer, or in the surface shear layer just below the air-sea interface. In addition, we are carrying on efforts to develop a conceptual framework within which the observed facts may be understood, and to find a parameterization scheme with the aid of which transport and diffusion of contaminants may be quantitatively predicted.

More specifically, studies of an exploratory kind under this program continue to be directed at the flow structure of the coastal boundary layer along an open coast (the COBOLT experiment, 1977-1978), the velocity distribution in a surface mixed layer (SMILE experiment in 1975, the development of LACS drogues 1977-1978, their proposed exploitation, 1979-1980) and on the circulation of the inner continental shelf (pre-COBOLT and COBOLT experiments, 1975-1978, proposed LIST experiment, 1979). In all these cases the observations were designed to

fill large and important gaps in existing empirical knowledge. The LIST experiment is a second generation member of this class, the need for empirical information having arisen from previous progress under this project on the conceptualization of shelf circulation.

Proximate goals of analytical-theoretical studies under this contract include an understanding of coastal boundary layer dynamics, following the completion of the COBOLT experiment, and the estimation of the range of key empirical parameters likely to be needed in transport and diffusion models, such as bottom friction parameters, eddy transport coefficients (or other means of parameterizing interior turbulent transport), longshore pressure gradients. An important question is what Lagrangian mean ("flushing") velocity should be used in transport models and how this can be estimated from information routinely available.

Work Carried Out During the Past Contract Year

A brief summary of accomplishments under this contract during the past year is as follows. Paul W. May has completed his analysis of tidal currents in the Long Island coastal region, based on COBOLT 1977 and CMICE (Current Meter Intercomparison Experiment, 1976) data (May 1979). One important result is the effective "calibration" of the current meters used, possible on account of the deterministic nature and spatial near-constancy of tidal motions. A high fraction of the current meters deployed in May 1977 (13 out of 16) have been found to provide remarkably accurate data. Another important step taken by May was the development of a reflected Sverdrup wave model to represent tidal currents, a sophisticated rotational equivalent of the simple "co-oscillating tide" of one dimensional estuary and shelf models. The existence of a tidal current model of suitable accuracy will now enable us to interpret correctly non-tidal currents (observed by daily

boat surveys, for example). May has also determined from his tidal models key friction parameters (eddy viscosity and bottom resistance coefficient) and found them to be much as derived from earlier data, a practically important result further confirming the validity of a simple turbulence parameterization scheme proposed in some early contributions under this contract (Csanady, 1976; Scott and Csanady, 1976).

R. Chase has completed his work on longshore pressure gradients determined from coastal sea level observations (Chase, 1979) relating these to wind stress variability and other possible forcing. An important result was that at least along some portions of the coast longshore gradients are set up in response to weather systems, corroborating other dynamical studies of inner shelf response.

Mass exchange processes in the coastal boundary layer have been analyzed by Neal Pettigrew (graduate student). Models of the salt exchange over the range of the COBOLT observations have been constructed and related to observation. Pettigrew is also analyzing momentum balance within the coastal boundary layer. His thesis will contain a thorough analysis of the COBOLT observations focussing on nontidal currents, complementing the recently completed work of May on tides.

Following field trials of droguelets off Long Island during the summer of 1978 Bert Pade (Research Associate supported under this contract) continued the development of methods to observe near-surface currents with good accuracy and high vertical resolution (order 10 cm or better). It can be now stated that the Large Contact Surface (LACS) drogues constructed of matted packing material offer a unique tool in this respect. Analysis of the Long Island droguelet trials has already yielded important insight into the properties of the flow within the surface shear layer (of order 1 m thickness). The effective viscosity near the free surface and the effective hydrodynamic roughness of the surface have both been

found unexpectedly large. The properties of flow near the free surface on such a relatively small scale are important in various exchange processes and, more importantly, in the transport of oil slicks. The results of these investigations are described in a paper under preparation.

Perhaps the most gratifying aspect of work under this contract during the past year has been a "jelling" of the conceptual framework for the understanding of shelf circulation. The theoretical developments have been described in a series of three papers by the principal investigator (Csanady, 1978, 1979a,b). They have resulted in the recognition that non-tidal currents over the "inner" shelf are probably driven by pressure fields "trapped" within 30 km or so of the coast, the precise character of which is determined by the specific local geography of a given piece of coastline, as well as by forcing due to wind or to freshwater influx. In contrast, "outer" shelf currents (say, in water deeper than 50 m) are dominated by larger scale pressure fields originating in the massive deepwater gyres. A practically important aspect of this conceptual picture is that the inner shelf trapped fields cause semi-closed stream-line patterns, leading to an effective flushing of the inner shelf. Once coastal waters are flushed to the outer shelf, they are transported into the offshore deepwater gyre. Many details remain to be filled in in this conceptual framework, but it is already clear that the inner shelf trapped fields have considerable importance to mass exchange phenomena.

References

- Chase, R.R.P. (1979) The coastal longshore pressure gradient: Temporal variations and driving mechanisms. J. Geophys. Res. 84, 4898-4904
- Csanady, G.T. (1976) Mean circulation in shallow seas. J. Geophys. Res. 81, 5389-5399
- Csanady, G.T. (1978) The arrested topographic wave. J. Phys. Oceanogr. 8, 47-62
- Csanady, G.T. (1979a) The pressure field along the western margin of the North Atlantic. J. Geophys. Res. 84, 4905-4915
- Csanady, G.T. (1979b) Longshore pressure gradients caused by offshore wind. J. Geophys. Res. (in the press)
- May, P.W. (1979) Analysis and interpretation of tidal currents in the coastal boundary layer. Ph.D thesis, MIT/WHOI, 197 pp.
- Scott, J.T. and G.T. Csanady. (1976) Nearshore currents off Long Island. J. Geophys. Res. 81, 5401-5409

Appendix I

Recent Progress under this contract in light of energy-related goals

An important stumbling block in the licensing of coastal power plants is the claim sometimes advanced that the waste heat or radionuclides released into the coastal ocean will lead to a significant long-term buildup of temperature or concentration in the neighborhood of the plant, with undesirable biological consequences. Some of the delay in the construction of the Seabrook, N.H. station was apparently caused by a failure to demonstrate the insignificance of any long-term buildup of heat. The current debate on the Charlestown, R.I. power plant is complicated by numerical model predictions that under certain circumstances such a buildup may reach 13°F in excess of present sea-surface temperatures. The latter conclusion is reached mainly because the receiving waters of Block Island sound are, in the model, supposed stagnant. In fact, however, these waters are quite active, subject to tidal, wind driven and long term mean motions. The results of recent work on the Coastal-Shelf Transport and Diffusion project help dissipate fears in regard to long term heat or concentration buildup. Three aspects of these results are described below and related to the problem of waste heat or material disposal.

(1) Trapped Pressure Fields

One of the early ideas in coastal oceanography was that a "mound" of water that was generated off a straight open coast could not persist for very long because surface level disturbances propagate very rapidly upcoast and downcoast, if not out

to sea. High tides, for example, are mounds of water that come and go, propagating with speeds approaching 100 kilometers an hour. A few years ago, it was universally thought that when winds—for example in a hurricane—pile up the water locally against a coast, the disturbance propagates away rapidly.

Recent work under the Coastal-Shelf Transport and Diffusion project has shown that this was a misconception, and that a coastal mound or hollow of water, if accompanied by an appropriate distribution of currents, can be quite persistent. Key factors contributing to the persistence of mounds or hollows on the surface of the coastal ocean are, in addition to the wind, the rotation of the earth, and the changing depth of shelf and slope regions with distance from shore.

For simple coastal zone models, it is possible to calculate the distribution of highs and lows that may persist indefinitely with a given distribution of surface wind. The calculated sea level distribution for a straight sloping beach under variable longshore wind is illustrated in Figure 1. The illustration shows a series of mounds and hollows elongated in a direction at some angle to the coast. The elevation or depression of the surface becomes negligible at some distance from the coast, or, in common theoretical terminology, the pressure field is coastally "trapped". This distribution of surface levels arises as the combined effect of earth rotation, bottom slope, and friction: delete any one of these, and the trapped field disappears. On the other hand, changing the magnitude of the bottom slope, or of friction, merely changes the width of the trapped field. One may therefore be fairly sure that in the more complex natural geometry of the coastal waters similar trapped fields also arise.

Model calculations also yield a streamline picture of the flow field that accompanies the pressure field (Figure 2). Very close to shore the flow is everywhere downwind: it is upcoast where the wind blows upcoast, downcoast where the wind blows downcoast. Far from shore, on the other hand, the flow is perpendicular to the wind, the familiar Ekman drift. The width

of the coastally trapped pressure field (beyond which the elevation disturbance becomes small) is typically 30 kilometers. Wind effects, with their localized mounds and hollows tied to the orientation of the coastline, are therefore strongly felt over the "inner" shelf, roughly in water less than 40 m deep.

Coastally trapped pressure fields also arise in response to other factors. The offshore wind component is somewhat less effective in this regard (surprisingly, perhaps), but nevertheless practically quite important. The influx of fresh water, especially from such giant sources as the St. Lawrence estuary, generates local mounds, somewhat downcoast of the discharge. The St. Lawrence mound apparently extends over the entire shelf off Nova Scotia and even portions of the Gulf of Maine. All of these effects are essentially confined to the vicinity of an open coastline, or to pronounced embayments such as Long Island Sound and the Gulf of Maine.

The transport of waste heat or materials released into the coastal zone is likely to be importantly affected by cellular flow structures associated with trapped pressure fields, of the type illustrated in Fig. 2. Such horizontal flow cells act as very large eddies and effectively mix the inner shelf waters with those of the outer shelf. Effluent released at a given point along the coastline only affects a limited downstream portion of the coast before being carried out by an offshore leg of a trapped circulation cell.

(2) Outer Shelf Circulation

Circulation over the outer portion of the continental shelf is uniform over long distances alongshore. Along the east coast of North America, for example, the shelf waters move generally northeastward from Miami to Cape Hatteras, and southwestward from the Grand Banks of Newfoundland to Cape Hatteras. The proximate cause of the southwestward drift north of Cape Hatteras is a sloping down of the sea surface southwestward. Geodetic

levelling carried out in North America in the 1930s, which at that time was thought to be quite precise, showed such a sea level slope. Later work led scientists to question the accuracy of geodetic levelling and to reject the result relating to coastal sea level slope. However, more recent studies on shelf circulation, including work under the Coastal-Shelf Transport and Diffusion project, reestablished conclusively the reality of sea-level slope.

One argument is that the water moving toward the southwest must be running downhill against the opposing eastward force of bottom friction and wind-force because there is no other plausible force that could drive it. There are, however, other more subtle clues to the presence of a longshore sea level slope. If such a slope is indeed present, and if it is not trapped within a narrow coastal band as in the models illustrated before, but is more or less the same at increasing distances from shore, then its influence should be stronger as the water gets deeper, because the force of gravity there acts on a larger water mass. The larger total gravity force should drive the deep water faster. Current meter studies have shown precisely such behavior. Furthermore, in deeper water—100 meters or so—the middle of the water column is outside the direct influence of wind force or bottom friction and the flow should be in geostrophic balance. This means that where the sea surface slopes southwestward, an onshore component of the flow should be superimposed on the southwestward drift. This again is found to be present not only over the shelf, but also well beyond the shelf-break. The result shows not only that a southwestward slope is present, but also that it extends, more or less undiminished, a long distance from shore, quite unlike the trapped fields discussed previously.

A sea level slope over large regions of the continental shelf and slope is a much larger scale phenomenon than the trapped fields discussed previously. It is plausible to suppose that pressure fields of such scale relate to deepwater oceanic gyres (basin-wide circulation of large bodies of water).

A mathematical model was constructed of shelf circulation, on similar principles to the trapped field, but with the longshore slope impressed at the seaward edge of the shelf. This model reproduced the observed features of shelf circulation with remarkable accuracy. In a manner of speaking, the deepwater gyre drives the larger scale shelf circulation, or a little more accurately, shelf circulation is a boundary-layer component of a deepwater gyre.

Off the east coast, north of Cape Hatteras, the deepwater gyre driving shelf-slope circulation is a long and narrow elliptical flow structure squeezed between the Gulf Stream and the mainland (Fig. 3). The southwestward leg of this gyre over the shelf and slope transports a large quantity of water, in the neighborhood of ten million cubic meters per second. A small fraction—2 to 3 percent—of this passes over the continental shelf proper, depending on precisely where one places the shelf boundary. This large scale counterclockwise gyre is not some local effect, but is produced by the action of the atmosphere on the ocean, exerted over many thousands of square kilometers.

What can one learn from these newly gained insights into the mechanics of outer shelf circulation from the point of view of such practical matters as power plant siting? One general result is the awesome scale of the counterclockwise deepwater gyre north of the Gulf Stream, which is actually small by oceanic standards. Its total longshore transport ($10^7 \text{m}^3 \text{sec}^{-1}$) is equal to the discharge of 500 Mississippi rivers, all flowing within some 200 kilometers of the shore. The waste heat of a thousand large power plants (1,000 megawatts each) would only heat this stream up by 0.3 degrees Fahrenheit. Considering also that circulation cells associated with trapped pressure fields effectively connect the inner shelf to this massive offshore current, one can be comfortably sure that long-term heat or concentration problems along open pieces of a coastline are not going to be significant.

(3) The Flushing Velocity Problem

In calculating the long-term buildup of temperature or concentration in the neighborhood of a coastal discharge of waste heat or waste material, an important parameter is the so-called "flushing" velocity, U . By this is meant the velocity of the mean flow, averaged over at least one full tidal cycle, affecting the initial mixing zone which surrounds the discharge. It may be shown by a simple "box model" calculation, or by a more sophisticated classical diffusion model, that, in the absence of other limiting factors, the long-term rise of temperature or concentration in the neighborhood of the discharge is proportional to U^{-1} .

The estimation of the flushing velocity from observational data available on coastal currents has become a matter of controversy. It is sometimes asserted that a good estimate of the flushing velocity may be obtained from the long-term average of fixed-point (Eulerian) current velocity at the discharge. Because such Eulerian average currents are sometimes quite low, arising from vigorous flow episodes in opposite directions which nearly cancel each other out, fairly high background temperature of concentration buildup estimates may be arrived at, in conflict with experience at many existing coastal heat or waste outfalls.

In many coastal locations, tidal oscillations contribute most of the kinetic energy of observable motions. Because tidal displacements are oscillatory, it would seem at first sight that they are of minor importance in the dispersal problem. The most important reason why this is not so is that a fixed outfall does not participate in the tidal excursions. As the coastal waters move bodily past an outfall in the course of their tidal oscillations, the water discharged is distributed over a considerable water mass, much as if the waters stood still and the outfall moved over an elliptical path, several km long and about one km wide, in the opposite direction to tidal motion.

Over the long term, the "mean" velocity of interest is thus the bulk translation velocity of a fairly large coastal water mass,

over which the effluent has been distributed over a tidal cycle. For periods of the order of weather cycles (typically 4 days) we have found that coastal waters move bodily upcoast or downcoast, presumably reaching a typical daily displacement of some 5 - 15 km (for periods of unidirectional flow current meter observations presumably provide a realistic estimation of particle displacements). However, our coastal current observations have also shown that, when the non-tidal current reverses direction, a substantial bulk displacement occurs of the water mass which previously occupied the coastal zone. The (Lagrangian) bulk velocity calculated for periods longer than that of unidirectional shore-parallel flow then becomes very different from the Eulerian mean calculated at a fixed point near the discharge. Over two periods, one each of opposing flow, the Eulerian mean velocity may nearly vanish. Yet the coastal zone has been effectively flushed during both halves of the two-period cycle, with a velocity about equal to the Eulerian mean velocity magnitude in each of the two separate longshore flow periods.

One concludes that a long-term average Eulerian velocity at a fixed point is not a realistic estimate of the effective flushing velocity. On the other hand, a rectified version of the same velocity, or average Eulerian non-tidal velocity magnitude is: this is typically much greater than the Eulerian average taking sign into account. In particular, a mean Lagrangian velocity cannot realistically be supposed to vanish in almost any open coastal location.

The estimation of Lagrangian bulk velocity for a larger coastal water mass is a problem not so far addressed in either the theoretical or experimental literature of coastal oceanography. Preliminary theoretical work under this contract has suggested that estimates are possible from a pattern of current meter data, such as is available from the COBOLT studies off Long Island. One of the major goals of the project within the next year or two will be to develop an appropriate theoretical framework for the estimation of flushing velocity and to subject a theory to experimental verification.

Legends for Illustrations

- Figure 1 Contours of constant sea level elevation calculated for model sloping shelf. A full "wave" of the long-shore wind is shown from $k_y = -\pi$ to $+\pi$. At $k_y = 0$, the wind blows with maximum strength to the left, at $k_y = \pm\pi$ to the right. The y axis is the coastline. Significant elevations are confined to a narrow nearshore band of order 30 km width. The long-shore wavelength $2\pi/k$ is in practice fixed by the geography of a coastline.
- Figure 2 Streamline picture of steady flow associated with elevation pattern of Figure 1.
- Figure 3 Counterclockwise deepwater gyre between the Gulf Stream and the North American continent.