CHAPTER FIFTY SIX

A THREE-DIMENSIONAL MODEL OF THE BEAUFORT SEA Shiao-Kung Liu^{*} and Jan J. Leendertse^{*}

Introduction

The Beaufort Sea borders the northern coasts of the United States and Canada. During the last decade, oil discovered at the Prudhoe Bay field contributes a substantial amount of the petroleum needs of the U.S. At present, it represents approximately 20 percent of the total domestic production. However, according to estimates made by the Department of the Interior, gas and oil lie under the Alaskan coastal waters (mainly in the Beaufort Sea) accounts for about 40 percent of the total domestic reserve.

To assist government agencies in their assessment of offshore oil exploration, the authors have been engaged, during the past nine years, in three-dimensional modeling work of the the Alaskan coastal area (Fig. 1). Results from the modeling work involving the Bering Sea and the Chukchi Sea have been reported at an earlier conference (Ref. 1).

This paper describes the formulation, coupling, and other essential aspects of the Beaufort Sea model (Fig. 2).

The Beaufort Sea, occupying a larger portion of the Alaskan coastal water, is dynamically interactive with other modeled areas. Most importantly, the exchange of water mass with the Chukchi Sea interconnects the Bering Sea through the Bering Strait (Fig. 3). Under certain weather conditions, ice in the Beaufort Sea can be transported toward the Bering Sea by an "ice breakout" process through the Bering Strait.

The purpose of the modeling work is to address coastal hydrodynamicrelated problems, in general, as well as the following specific objectives:

- o Tidal and density-induced baroclinic circulation patterns;
- o Water and ice movements induced by wind, including storm-surges;
- o The behavior of oil movements under various spill scenarios; and
- o Providing boundary conditions for the near-shore models of higher spatial resolutions (Fig. 3).

The Methodology and Modeling System

Formulated on an elliptical horizontal grid and variable vertical grid, the three-dimensional model solves the equations of motion for water and ice, continuity, state, the balance of heat, salt, pollutant, turbulent energy density, the dynamics and thermodynamics of ice. The model computes the generation, melting, and the movements of ice together with the nonlinear vertical shear coupling during cooling and heating processes. This is achieved by means of a turbulence-closure technique in which the potential and kinetic energetics are monitored and

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Fig. 1--Relative location between the Beaufort Sea model and other models covering the Alaskan coastal waters







Fig. 3--Due to the interactive aspects, the western portion of the Beaufort Sea Model (shaded) is overlapped with the Chukchi Sea Model. This technique not only minimizes the boundary's effects on the computed residual currents but also would allow oil spill trajectory computations to be continued into the neighboring models. Submodels improve the near-shore resolution.

transferred in a closed form.

The hydrodynamic model is coupled to a two-dimensional stochastic weather model and an oil trajectory model. The important components and the flow of information are illustrated in Fig. 4.

The inclusion of the weather model is essential because the model covers the area where one of the world's major low pressure systems in the Northern Hemisphere (i.e. the Aleutian Low) is situated.

In developing the model we first treat the weather system over the modeled area as a stochastic process whose evolution is represented by a series of transitions between certain "state" of the process. When the number of the states is finite, the process is of the Markov type. It can be described or simulated if the probabilities of transition are known via the matrix of transitional probability. Also needed are the steady state behavior of the process chain and the amount of occupation time the chain spreads in various states.

The required transitional probability matrices are generated using the daily synoptic weather data over the modeled area from 1945-1963. A ll x ll matrix is determined for each oceanic season. Within the sampled period, 98 percent of the daily surface pressure pattern over Alaska can be classified into eleven types. The most frequent pattern (with 23 percent occurrence) during summer is a low pressure system with several centers over Alaska. Surface winds at various locations are analyzed for each weather type.

During the simulation with the stochastic weather model, wind fields generated by the Markov model are being interrupted by a storm track model which is of the Poisson type. The initial location of the extratropical-low is generated from a two-dimensional density function derived from the long-term observed data (Fig. 5). Figure 5 also gives the comparison between the wind rose generated from the model and those observed at three major weather stations showing zonal climatological variabilities. Detailed analyses of the probability distributions for the wind speed, direction, homogeneity and storm interruption are discussed in Ref. 2. Surface winds during the passage of a storm are computed by the gradient wind equation and modified for speed and veering angle according to local marine boundary layer stability conditions.

Another component of the modeling system is an oil-spill trajectory model which synthesizes the hydrodynamic responses of the coastal system obtained by the three-dimensional model under various forcing to compute the movement of oil resulting from simulations of the stochastic weather model. The 3-D model also provides energy densities and dispersion parameters for various layers for the oil trajectory computation. These trajectory computations have extended to eight months in elapse time at half-hourly intervals.

In addition to data synthesis, the oil trajectory model computes the surface and subsurface oil concentrations while the oil/weather processes take place.

Modeling Results

Our first step in the model development has been the determination of tidal and baroclinic residual circulation. The latter is caused by



Fig. 4--Essential components of the two-dimensional stochastic weather simulation model; also showing their inter-relationship between the three-dimensional hydrodynamic model and the oil-spill trajectory model. Transitional probabilities of the weather states are derived from 19-year synoptic weather data.



Fig. 5--Top graph shows the probability density function (pdfx10000) of the occurrence of extra-tropical cyclones within the modeled area. Lower graphs show the comparison between the wind roses generated by the long term simulation of the stochastic weather model and the observed wind roses at three ground stations for the month of July.

the density field and is interactive with the former. Originating from the Arctic Ocean, the tides in the Beaufort Sea generally move in a clockwise direction. The computed co-tidal chart for the semi-diurnal component is illustrated in Fig. 6. Also presented are the comparisons between the computed and the observed values at several locations. The agreement is generally quite good except near Herschel Island where the measured value is two centimeters higher. The difference may be attributable to the location of the gauge which, for practical reasons, was deployed behind the barrier island.

The computed tidal current ellipses, including baroclinic components for the surface layer is presented in Fig. 7. Figure 8, also for the surface layer, is the residual circulation pattern. The plotting scale for the current vector is two kilometers for each model grid-spacing.

The combined effects of residual circulation and the weather's effects can be illustrated by a map showing the trajectories of hypothetically spilled oil as they are released at various locations in the Beaufort Sea (Fig. 9), all under idential sequence of weather state. The daily movement of oil (depicted by a dot) reflects the local circulation as well as the evolution of weather states. The series of wind vectors plotted on top of the graph represent the l2-hour mean wind at Point Barrow. From Fig. 9, the shore's effect on the movement of oil is quite obvious.

In order to evaluate the risk (probability) associated with the oil development, a sequence of oil-spill scenarios have been selected at important locations representing platforms, pipelines, and transportation routes.

Figure 10 shows the comparison between trajectories of five satellite-tracked buoys deployed by the U.S. Coast Guard for a period of three months, and 30-day trajectories launched from five locations computed by the oil-spill trajectory model. They generally agree both in speed and in direction of movement.

Also needed for the evaluation of ecological impact, the concentrations of the spilled oil are computed. This computation includes the evaporation, dissolution, and spreading across the vertical layers.

Figure 11 shows the daily envelope of one-part-per-billion concentration contour of a hypothetical 30-day continuous spill of 500 barrels of crude oil per day under a summer condition. Loops in the plume's centerline indicating the occurrence of three low pressure centers move across the Bering Sea area. Under identical weather sequence, oil released from other areas, experiences an entirely different drift pattern.

The effects of shoreline and zonal climate difference on the movements of oil can be illustrated in Fig. 12. The peninsula in the figure exerts substantial influence on both near-shore residual currents as well as on the local wind pattern.

Conclusions and Discussions

Soon after the beginning of our modeling effort, it became clear that hydrodynamic computations per se cannot sufficiently address important policy issues. Other types of models such as for oil, ice, and weather related processes were needed. Weather models are of particular

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Fig. 7--Computed tidal and baroclinic current ellipses in the surface layer using a plotting scale of 15 cm/sec equal to a grid space









Fig. 9--Thirty day oil spill trajectories launched from hypothetical spill locations. Near shore trajectories within the ice-free area tend to move downwind whereas the oil in the offshore area tend to have various turning angles depending on the local ice concentration.





Fig. 11--Daily envelope of one-part-per-billion concentration contour of a hypothetical 30-day continuous spill of 500 barrels of crude oil per day under a summer condition



Fig. 12--The effects of shoreline and zonal climatic difference on the movements of oil

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importance as the weather is often the major driving force for the generation of currents, movement of ice, and the dispersal of oil.

The stochastic-type of weather model is more suitable for the coastal area than the steady-state type of model in which winds are randomly generated based on a given wind rose. The latter method can be used under open ocean conditions where the drift duration is long and the nonlinear dynamic effects induced by the coasts are less significant. In coastal areas, the sequential occurrences of weather types tend to govern the final landfall location, particularly where coastal features and orographic influences have to be taken into consideration.

Finally, numerical models are particularly useful in remote areas where observed data are scarce and difficult to obtain, such as the one reported here. A preliminary model, formulated according to fundamental parameters and existing data, would serve as a starting point. Results from the initial analysis would then indicate the data needs. It can also assist in designing an effective field sampling program.

With new data, the investigators can thence improve the model formulation and proceed in an efficient manner.

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