Theoretical, Numerical and Observational Studies of Coastal Ocean Electrodynamics

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LONG-TERM GOALS

We seek to understand and utilize environmental and deliberately produced electromagnetic (EM) signals in the coastal ocean. Our studies are undertaken to provide a means for communicating with and guiding autonomous underwater vehicle (AUV) and other autonomous sensor systems, such as moored instruments. We include various EM influences in our models such as environmental noise, seabed electrical conductivity, variable bottom depth and coastline, and deliberate EM signals. The ultimate goal is to understand these factors well enough to reliably estimate signal-to-noise ratios in planning coastal EM operations and to improve basic understanding of EM propagation and environmental noise in the coastal waters.

OBJECTIVES

The immediate objectives are to study the fundamental generation and propagation of EM fields in realistic shallow coastal environments having non-uniform, three-dimensional geometries and to examine various sources of environmental noise expected for such regions. The environmental EM noise includes fields generated by external sources in the ionosphere and magnetosphere, by the dynamo action of the ocean flow, and by artificial sources, such as from the 50/60 Hz power grids. It is appreciated that in coastal waters much of the natural environmental EM fields are not generated by local sources, and an accurate predictive model for a regional domain requires consideration of these large-scale sources. Hence, a proximate objective is to calculate and archive the global-domain ocean/earth response to standard sources (e.g., the ring current). These responses then provide (perhaps after scaling, e.g. to the current Dst index) the boundary conditions for predictive models of environmental EM fields in a particular coastal region.

An ancillary objective is as follows. A great deal of research is currently being conducted in the general area of ocean electrodynamics, but important results are spread among the disparate fields of the investigators. An objective of this study is to organize a survey report to provide a compact reference of these results that can be used to identify and evaluate potential ocean EM applications.

APPROACH

The first approach in this study has been to combine theory with numerical modeling. A primary element has been the development of a frequency-domain, finite difference/volume numerical model capable of calculating the generation and propagation of EM fields due to arbitrary sources in the presence of the strong land/air/sea conductivity contrasts and complicated 3D geometry of the realistic coastal ocean and land/sea/air environment.

Rather than use the standard Maxwell equations, a formulation in terms of electromagnetic gauge potentials is used, from which the electric and magnetic fields are calculated in post-processing. Gauge potentials have been successfully exploited in numerical models with applications ranging from scattering problems (in which the EM fields are wavelike, e.g., Biro and Preis, 1989) to low-frequency geophysical induction problems (in which the process is diffusive, e.g., Badea et al., 2001). Advantages of the gauge formulation for our applications are that the potentials are everywhere continuous and can be discretized on finite difference grids. The gauge formulation uses the gradients of conductivity (rather than resistivity) and allows arbitrary (including static) sources. Although it is a frequency-domain model it can be used to calculate the EM fields generated by arbitrary time-dependent ocean flow on the continental shelves as the associated EM fields are essentially in static adjustment.

We have called the model MOED (Model for Ocean Electrodynamics), as its primary intended use is in calculating the generation and propagation of low-frequency (< 1 kHz) EM fields in or near the ocean. But as displacement currents have been included at little extra cost (and for stability considerations), it is equally capable of tackling more general high-frequency cases.

MOED has been implemented with general orthogonal curvilinear coordinates such that it can accept ocean model (e.g., SCRUM/ROMS) data on native curvilinear or spherical coordinate grids. This allows MOED to both calculate the ocean generated EM fields as well as to use the particular model configuration in calculations involving atmospheric or artificial sources such that a consistent EM data set is added to the ocean model one. A manual describing MOED in detail and complete with validations and examples can be obtained at the website http://sirena.apl.washington.edu, and a package of the model distribution can be obtained by sending a request to R. Tyler <tyler@apl.washington.edu >.

Accuracy of the simulations with MOED is improved by using realistic spatial/temporal distributions of the electrical parameters, notably the electrical conductivity of the oceans and sediments. For this purpose we have calculated and archived the global and seasonal distribution of these parameters using seismic and historical ocean temperature/salinity data as will be discussed in the next section.

Finally, a very important element of our approach involves observations of EM fields in the coastal ocean. The observations serve several purposes: 1) To verify qualitative effects predicted from the theory and modeling; 2) To verify quantitative predictions of realistic model simulations; 3) To conduct electric field observations in combination with magnetic field observations taken by investigators at the Coastal Systems Station; 4) To test new technologies (e.g., the new carbon fiber electrodes developed by the Swedish Defense Research Establishment).

Theoretical and numerical work is primarily conducted by R. Tyler, S. Li, and T. Sanford (all at APL) while observational work is primarily conducted by T. Sanford, J. Dunlap, S. Li, and R. Tyler (all at APL), with contributions by T. Fristedt (Swedish Defense Research Establishment). Through a summer internship program by NASA, we have also received assistance by UW undergraduate C. Schneider-Mizell.

WORK COMPLETED

Work completed over the last year involves several aspects in theory, modeling, and observation. Theoretical work has been conducted primarily to assess the significance and behavior of the most important environmental sources, and these results are used to determine configurations for realistic simulations using MOED.

Primary effort has been to study the EM fields produced by deliberate sources in a coastal environment. Collaborating with Coastal Systems Station (CSS), we have successfully simulated the EM fields produced by both electric and magnetic dipoles. Also, different source configurations have also been investigated. To facilitate CSS using our simulation tools, we have been making improvement to MOED and writing a comprehensive document about this simulation tool. Our collaboration with CSS has answered many important questions and will provide essential guidance for the instrument and experiment designs.

We have significantly extended the applications of MOED, here we describe three of the most important examples.

Telluric currents: A primary source for telluric currents (electric currents passing through the earth and ocean) is the excitation of the ring current that is described by the time-varying Dst index. We have used MOED to calculate the global distribution of the telluric response due to a normalized ring current. These results are archived to be used in specifying boundary conditions for regional-domain simulations. The situation is analogous to that of regional modeling of tidal flow. Just as a regional tidal model requires results from a large-scale model for specification of flow and elevation at the boundaries (indeed, flow in these regional models is forced by the boundary specifications), telluric currents in a regional domain can be modeled by using the large-scale telluric results (scaled to the current Dst) to specify the electric currents fluxes at the boundaries.

EM fields due to tidal flow: Using the flow results from the tidal model of Egbert and Erofeeva (2002), we have calculated the EM fields generated by the interaction of the tidal flow with the earth's main magnetic field. These tidally generated EM-field results include the electric currents in the ocean and land as well as the magnetic fields reaching satellite altitudes.

Propagation of atmospheric 'Schumann resonant' EM fields into the coastal ocean: At any moment there are about 2000 thunderstorms taking place worldwide which fill the cavity between the conducting ground and ionosphere with atmospheric EM radiation. A persistent feature is the resonant modes with a base frequency of about 8 Hz. It is known from theory and observations (including our own) that these fields refract and enter the ocean. In the open ocean, simple theory can be used to describe the propagation of these fields down from the ocean surface. In coastal regions, however, the situation is more complex as these fields can also enter the ocean from below by following a path through the beach and under the coastal waters. We have been using MOED to study this effect including polarization effects due to the coastal orientation with respect to the thunderstorm sources.

Another primary task of the last year has been the creation of a database describing the global spatial/temporal distribution of electrical conductivity in the oceans and sediments. As ocean conductivity depends primarily on salinity and temperature, we have been able to calculate and archive a four-dimensional data set of ocean conductivity. Specifically, from salinity/temperature climatologies we have calculated the 1x1 degree global spatial distribution of ocean conductivity together with its seasonal variation. We have also calculated global 1x1 degree sediment conductances following the method of Everett et al. (2001) that uses seismic estimates of sediment thicknesses.

RESULTS

The most exciting result of the last year concerns a MOED prediction that has recently been shown from observations to be both correct and remarkably accurate. Our theoretical work suggested that the magnetic fields generated by ocean tides should be observable by the German CHAMP satellite. We then used a configuration of MOED to predict these effects (results were presented at the last assembly of the European Geophysical Society and an example movie of these results can be obtained at the website http://sirena.apl.washington.edu). Recently, in collaboration with CHAMP investigators (S. Maus and H. Luehr) we have extracted magnetic signals from the satellite records which match those predicted by MOED, confirming MOED's prediction and showing for the first time that ocean flow generates magnetic fields which can be detected by satellite observatories (Tyler et al., 2002). There are also several implicit results associated with the success of MOED's tidal prediction. Primarily, this success supports our assumed neglect of various confounding effects and gives us greater confidence in our ability to predict environmental EM fields in the ocean.

Other applications of MOED, such as the calculation of realistic telluric currents, have provided results that appear to be correct and naturally extend from previous results. We are currently working to validate these model predictions with observations (both existing observations and ones we will measure) and will describe these results in detail subsequently.

As described, we created a four-dimensional array describing global ocean conductivity and its seasonal variations (Schneider-Mizell and Tyler, 2002). The results, while not surprising, are needed to improve the accuracy of the model predictions. Essentially, ocean electrical conductivity variations are seen to track temperature over most of the ocean except for the Arctic where salinity changes due to large river runoff have a primary effect. Surface conductivity varies geographically from about 1 S/m to 6 S/m while the variations in depth-averaged conductivity are typically less (3 to 4.5 S/m in deep water). While there are strong seasonal changes in surface conductivity, the seasonal changes in depth-averaged conductivity is small and is typically less than the geographic variability.

IMPACT/APPLICATIONS

There is a need for non-acoustical means of navigating and controlling AUVs, communicating with autonomous instruments, and detecting submerged and buried objects in shallow water. In principle, the extremely low-frequency EM signals (<1 kHz) we are investigating can be used for these purposes. In practice, however, not enough is known to predict reliable signal-to-noise ratios for particular applications. This is both because the propagation paths in the coastal environment are themselves non-trivial and because the background environmental fields are not well understood. MOED can be immediately used to calculate the EM signals due to an arbitrary artificial source in a specified realistic configuration. Our current effort is primarily focused on using MOED to further our understanding of the environmental fields.

TRANSITIONS

We are actively transferring both our simulation results and our simulation tools to Coastal Systems Station (CSS). At the same time, MOED is also being used by the Swedish Defense Research Establishment, the University of Paris and other academic institutions. The observational side of our program also includes hardware development (electrometers) to be used in experiments lead by CSS.

RELATED PROJECTS

The theoretical and numerical tasks are partially supported under a related NASA project (NAG5-10570). Although the NASA project is primarily interested in ocean generated EM fields outside rather than inside the ocean, the two projects are obviously related as they share theoretical and numerical results.

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