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ON THE NUMERICAL PREDICTION OF OCEANIC THERMAL STRUCTURE

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U. S. NAVAL OCEANOGRAPHIC OFFICE
WASHINGTON, D. C. 20390

ABSTRACT

The general theoretical framework for oceanic thermal structure prediction is presented. A prediction scheme utilizing the general equation of heat conservation is proposed. The proposed scheme should provide more reliable predictions than are allowed by present empirical techniques and would fully utilize available, as well as projected, capabilities of meteorological and oceanographic automatic data-gathering and disseminating systems.

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INTRODUCTION

Prediction of oceanic thermal structure has become of increasing military importance since World War II. Major efforts of the Anti-submarine Warfare Environmental Prediction Services (ASWEPS) have been directed toward developing such a prediction capability. This paper reviews difficulties encountered in this problem and suggests an approach for obtaining a logical and unique prediction method. Though some of the ideas presented in this paper are not new, they are combined here for the first time in the form of a consistent approach.

Attempts have been made to develop subjective temperature prediction techniques (e.g., James, 1966). Also, first attempts at numerical prediction methods are being undertaken by the U. S. Naval Oceanographic Office (e.g., Gemmill and Nix, 1965) and the Fleet Numerical Weather Facility (e.g., Wolff, 1964). Unfortunately, results of past prediction schemes have not been sufficiently dependable. One reason for this is that the schemes do not take fully into account the variability of parameters affecting the thermal structure. Another reason, probably as important as the first, is that past efforts have not been adequately integrated into a proper physical model. This paper presents the general theoretical framework necessary for predicting oceanic thermal structure. Expected problems are discussed and possibilities for overcoming them are presented.

THEORY

The local rate of change of thermal energy (heat) at any particular point in the ocean is described by the following equation:

$$\frac{\partial H(\vec{x},t)}{\partial t} = - \vec{\nabla}_{\vec{x}} \cdot [\vec{V}(\vec{x},t)\ H(\vec{x},t)] + \vec{\nabla}_{\vec{x}} \cdot [A(\vec{x})\ \vec{\nabla}_{\vec{x}}\ H(\vec{x},t)] + G(\vec{x},t) \quad (1)$$

where H = the quantity of heat

$\vec{x}$ = three-dimensional position vector in rectangular coordinates

t = time

$\vec{V}$ = current velocity

A = turbulent exchange coefficient

G = representation of the sources and sinks of heat

The first term on the right of the equation, frequently referred to as the "advective" term, represents a transport of heat. Obviously a knowledge of $\vec{V}(\vec{x},t)$ is necessary for evaluating the term. $\vec{V}(\vec{x},t)$ may be obtained and used in a manner discussed below. The second term on the right of the equation describes the transfer of heat due to turbulent convective processes. The turbulent exchange coefficient, A, must be known in order to evaluate this term. Little is known of this variable despite the fact that a number of estimates of it have been made. Also, a sizeable body of literature is devoted to the discussion of the exchange coefficient (e.g., Defant, 1961). With this accumulated knowledge of A and possibly some additional measurements or research, a crude spatial estimate of A could be developed. Such an estimate probably would be sufficient during first attempts to solve equation (1), although in later work knowledge of the form and distribution of A would have to be refined.

The final term, $G(\vec{x},t)$, represents all other processes whereby heat may be lost or gained by a parcel of water, as discussed below.

Equation (1) is a general equation which completely describes the balance of heat in small or large regions of the ocean over short or long time intervals. The first attempts to solve equation (1) will be restricted to the upper layers of the ocean (say above 200m), because the values of $\vec{V}$ and A are best known in this region. It is important to remember, however, that the master equation describes an entire ocean. If $\vec{V}$ and A were known (or could be predicted) for the entire $\vec{x}$-space and if the influx of heat through the ocean bottom were known, then with a knowledge of G, the solution of equation (1) would describe the complete thermal structure of the ocean. The preceding discussion also applies to variations of $\vec{V}$, A, G, and H with time. The capability of predicting temperatures for all depths and over time spans of the order of days or even weeks will not be developed in the near future. However, numerical methods and a subsequent digital computer program which solve equation (1) can be constructed so as to be quite general. Any form of $\vec{V}$, A, or G could be substituted into such a general scheme, and solutions could be obtained. In other words, a general solution of the master equation would provide a framework for present, as well as any future, efforts to predict the oceanic thermal structure.

Such a prediction system would be automated and, hence, free of human error and subjectivity. In fact, with complete realization of the potential of this method, all input parameters would automatically be supplied to a large digital computer by weather satellites and oceanographic buoys. The only direct human effort required will be the operation of the computer and the utilization of the results.

SOURCES AND SINKS OF THERMAL ENERGY

The G-function of equation (1), representing the sources and sinks of thermal energy relative to that region of the sea considered by the model, is given by:

$$G(\vec{x},t) = I(\vec{x},t) - O(\vec{x},t) \tag{2}$$

where:

$I(\vec{x},t)$ = sources (input) of thermal energy

$O(\vec{x},t)$ = sinks (output) of thermal energy

The I-term for the surface may be taken as:

$$I(x,y,o,t) = Q_s\ (x,y,o,t) + Q_h'\ (x,y,o,t) + Q_e'\ (x,y,t) \tag{3}$$

Q_s = thermal energy introduced by absorption of radiation from sun and sky

Q_h' = sensible heat conducted from the atmosphere when $z = o$

Q_e' = latent heat released to the sea via condensation

The O-term for the surface may be taken as:

$$O(x,y,o,t) = Q_b\ (x,y,o,t) + Q_h''\ (x,y,o,t) + Q_e''\ (x,y,t) \tag{4}$$

where:

Q_b = thermal energy removed by effective back radiation from the sea surface when $z = o$

Q_h'' = sensible heat conducted to the atmosphere when $z = o$

Q_e'' = latent heat removed from the sea via evaporation

Realizing that all terms are variable in space and time, we have:

$$G_{sfc} = Q_s - Q_b + (Q_h' - Q_h'') + (Q_e' - Q_e'') \tag{5}$$

Many of the empirical representations of these surface Q terms are discussed by Gaul and Elder (1959) as well as elsewhere in the literature.

Obviously the heat budget terms important to the thermal structure of the surface layer are not the same as those of successively deeper layers. The proposed model, however, would incorporate such considerations. Examples of these considerations are differential absorption with depth of radiation from sun and sky, layer to layer radiation, layer to layer conduction, etc. Other factors which influence the total heat budget of the sea, such as the conversion of kinetic energy to heat, chemical and biological processes, radioactive disintegration within the sea, etc., are negligible and are not included in the theory.

The terms and environmental parameters required for their calculation relative to the surface layer are listed below:

$Q_s = Q_s$ (solar altitude, wind speed, cloud cover)

$Q_b = Q_b$ (sea surface temperature, air temperature, water vapor content of the atmosphere, atmospheric pressure, cloud cover)

$Q_e = Q_e$ (water vapor content of the atmosphere, sea surface temperature, air temperature, wind speed, atmospheric pressure, sea surface salinity)

$Q_h = Q_h$ (sea surface temperature, air temperature, wind speed)

In summary, the following quantities must be known (predictable) over the region for which the model is to be applied: solar altitude, wind speed, cloud cover, sea surface temperature, air temperature, atmospheric pressure, water vapor content of the atmosphere, and approximate sea surface salinity.

Where any of these quantities cannot be forecast, use will be made either of distributional summaries or of less restrictive forms of the terms of the G-function. The first of these two possibilities is discussed briefly in the following section. Clearly, the eventual perfection of such a prediction scheme will be contingent upon further knowledge of the required input quantities.

INITIAL, BOUNDARY, AND ENVIRONMENTAL CONDITIONS

Initial Conditions

The initial conditions for the problem can be supplied in some detail for we do have a reasonable idea of the gross features of the thermal structure of the ocean.

Boundary Conditions

The specification of realistic boundary conditions will be essential to a reliable solution of equation (1). For instance, in the case of the North Atlantic introduction of warm and cool water by the Gulf Stream and Labrador Current, respectively, must be taken into account. Since the main features of these currents are fairly well known, proper lateral boundary conditions could be developed. These boundary conditions may be represented in the usual fixed sense or they could be couched in probabilistic notation to represent input fluctuation due to environmental factors.

Environmental Conditions

The determination of meteorological and oceanographic input information is more of a problem but may still be handled readily. The degree of cloud cover, as an example, must be known in order to calculate Q_s and Q_b. In mid-ocean, where ships infrequently travel, this would be a difficult quantity to know, even approximately, at a specific time. However, the Weather Bureau and other agencies have compiled atlases that give mean monthly expected values of cloudiness over the oceans. If mean values are used and assumed to belong to a Gaussian distribution (or any desired type of statistical distribution), then cloudiness could be included in the G-function in a meaningful way. The probability distribution for cloudiness would include a functional dependence on such parameters as atmospheric pressure and possibly air-sea temperature differences, both of which would be input information. A much more accurate and desirable estimate of the cloud cover distribution and its dependence on various environmental parameters could be achieved by re-analyzing accumulated raw data. This would also make it possible to look at temporal dependences in the probability function. With respect to making fully automated ocean-wide temperature predictions, it is of interest to note that work is now underway at the Weather Bureau which will make it possible to obtain detailed, on-site cloud information from the TIROS and ESSA satellites. TIROS information will be telemetered to a ground station and then to the large NWSC computer where cloud cover information will be calculated. This information could easily be saved for later inclusion into the general prediction scheme.

The probabilistic methods described above may be applied equally well to developing other necessary input information such as current velocity, air temperatures, etc. By describing these probability distributions in terms of a few basic input parameters, important quantities of equation (1) could be estimated more realistically.

COMMENTS ON METHOD OF SOLUTION

A second-order, nonlinear, partial differential equation has been proposed that, if solved, would describe the time history of the thermal structure in a variable-sized section of the ocean. Much of the necessary input information, and in fact possibly even the boundary conditions, would be available only in a probabilistic form. Obtaining a solution to this problem is, indeed, a formidable task. Problems of this type are found in many fields of physics, and certain techniques have been developed to deal with them. Foremost among these is the so-called Monte Carlo method. When the exact numerical solution to a problem appears impossible owing to either the nature of the problem itself or limitations of available computing machines, the Monte Carlo method may be employed. The method does not concern itself with every segment of the physical system but only with the character of the general ensemble of segments. The answers produced, therefore, are in the form of probability distributions of the unknown variable. Monte Carlo techniques are in general use today (e.g., Alder, et. al., 1963) and would seem well-suited to this particular problem.

While a statistical point of view is the most realistic way to think of temperature in the ocean, an explicit solution to equation (1) may be desired. In this case, comprehensive solutions of the proper finite difference equations would be required. Problems of convergence, stability, and accuracy now become more critical, and computer time required for a solution increases.

The exact size of the grid system chosen and the integral time step taken in the solution of equation (1) will be dictated by stability criteria. Nevertheless, it is clear that a very large amount of computer storage will be required if any meaningful-sized grid is to be considered.

One of the few classes of digital computers capable of handling these requirements is the C.D.C. 6600. With one of these machines now installed at the Weather Bureau, the realization of an automated, limited scale, thermal prediction capability need not be too far in the future.

CONCLUSIONS

A general equation has been proposed to describe the heat balance of a variable-sized section of the ocean over a variable time span. Brief comment has been made on some of the problems that will arise when attempts are made to solve this equation, and general methods have been proposed to overcome them. Much time and effort will be spent before thermal structure of the ocean can be reasonably predicted. In this paper we have provided the general direction in which this effort must proceed.

The problem as stated here is quite general, but additional study will lead to simplifying assumptions and approximations which will make the master equation tractable. These first simplifications will lead to restricted applications of the equation, but the results so obtained should be more reliable than present empirical techniques allow. Finally, the methods described herein will fully utilize presently available and projected capabilities of meteorological and oceanographic automatic data-gathering and disseminating systems.

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