CALIBRATION AND VERIFICATION OF ENVIRONMENTAL MODELS

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INTRODUCTION

One of the weakest links in developing viable numerical models for environmental transport processes is the need for large comprehensive data bases for calibration and verification. The specific needs vary with the characteristics of the model under consideration. However, it has been found that the more complex the model is, the more difficult it is to obtain the adequate data base. In fact, often even before calibration and verification, the problem manifests itself in terms of specification of adequate boundary conditions for a well posed mathematical formulation. This paper deals with the unique problems of calibration and verification of mesoscale models applied to investigating power plant discharges.

Policastro (refs.1,2,3) in a series of reports has calibrated and verified a large number of thermal plume models with field data. He used a single data base to obtain comparative results from different models. Very few studies of this nature have been done primarily owing to the lack of comprehensive data bases. Lee et al (ref.4) summarized the importance of remote-sensing data in thermal pollution studies. Sengupta et al (ref.5) have demonstrated the important role of remote-sensing data in the development of numerical models. However, remote-sensing data usually provide only the surface conditions. For three-dimensional modelling it is imperative to have variations with depth. The role of in-situ measurements is therefore essential until remote-sensing techniques are developed for vertical profile measurement. Some studies of thermal plumes have been made using ground truth and remote-sensing data. Madding et al (ref.6) used a Texas Instrument RS-18A scanner mounted on a DC-3 together with in-situ measurements made by Argonne National Laboratory to study plumes from Point Beach Nuclear Power Plant located on the shoreline of Lake Michigan. Dinelli et al (ref.7) have discussed the use of thermal infrared scanner data in evaluating predictive models for thermal plumes. They studied the power plant sites at Vado Ligure and Porto Tolle in Italy. They discussed the use of IR data to develop plume models as well as verify them.

The thermal pollution group at the University of Miami is developing a package of three-dimensional models to predict and monitor thermal anomalies caused by power plant discharges. Remote-sensing IR data from satellites and airborne radiometers in conjunction with ground truth and in-situ measurements are used to calibrate and verify the models. The application sites are Biscayne Bay and Hutchinson Island in South Florida where a number of power plants are located. The details of the effort are presented in a series of reports by Lee et al (refs. 8 and 9). Hiser et al (ref.10) have presented the remote sensing effort. A brief description of the overall study is presented by Sengupta et al (ref. 11). Figure 1 shows the relationship between the data acquisition effort and modelling effort from the model development stage to verification and application stages.

THE MATHEMATICAL MODELS

The hydro- and thermodynamic behavior of a body of water in an ecosystem is affected by natural influences as characterized by the meteorological and hydrological characteristics of the domain as well as the anthromorphic disturbances generated by industry, agriculture and urban activity. The method of numerical modelling is to describe the system in terms of governing equations and boundary conditions that express the relevant physical laws and domain characteristics and then to simulate or solve the equations with numerical techniques, after approximations are made regarding variables as well as dimensions. We will consider three-dimensional "complete" models only, the data requirements being less stringent for simpler models.

The governing equations are the conservation of total mass, momentum and energy. The constitutive equation describing density as a function of temperature completes the set. The system consists of coupled, non-steady, non-linear, secondary, three-dimensional partial differential equations. The equations are presented by Sengupta et al(ref.5). Turbulence is modelled by eddy transport coefficients.

The rigid-lid assumption is made, thereby eliminating surface gravity waves and therefore the restrictive Courant-Levy Fredrichs' condition. This assumption has been used extensively in oceanic modelling by Bryan (ref.12) and others. Sengupta and Lick (ref.13) developed this idea for ecosystem modelling. However, where surface height fluctuations are dominant, a free-surface model has to be used. Therefore two sets of models, namely, rigid lid and free surface, have been developed by the University of Miami group to study thermal pollution.

The details of the rigid-lid model have been presented by Sengupta and Lick (ref.13) and Lee et al (ref. 9). The governing equations are continuity, two horizontal momentum equations, the hydrostatic equation, the energy equation and the equation of state. A predictive equation for surface or lid pressure (no longer atmospheric) derived from the vertically integrated momentum equations completes the system of equations. The boundary conditions are no-slip and no-normal velocity at solid surfaces. At the air-water interface wind stress and heat transfer coefficients are specified. The solid surfaces are considered adiabatic. Influx conditions for velocity and temperature are specified at open boundaries. Explicit schemes are used to integrate the momentum and energy equations. Iterative schemes are used to calculate the surface pressure from the predictive equation for pressure. Forward time, central space schemes are used for the diffusion terms which use the Du Fort-Frankel scheme. Single-sided schemes are used at the boundaries. A vertical normalization with respect to local depth is used to map a variable depth domain to constant depth.

The free-surface model uses essentially the same set of equations as the rigid lid except that height is now a variable. Therefore an equation for surface height is obtained from the vertically integrated continuity equation. The pressure at the surface is atmospheric. The boundary conditions at the air-water interface are obtained from wind stress and surface heat transfer coefficient. At solid walls slip conditions are used except for the bottom. All solid walls are assumed adiabatic. An open boundary, temperature and either height or velocities are specified. Explicit schemes with central diffuse in time and space are used.

Both the rigid-lid and free-surface models are applied to far-field and near-field situations. The near field is that region affected by thermal discharges. The far field affects the near field and not vice versa. Specifically, in Biscayne Bay the whole bay is considered far field whereas the near field is those regions where significant thermal anomalies are caused by discharges. Thus we have four sub-models (1) free-surface far field, (2) free-surface near field, (3) rigid-lid far field, and (4) rigid-lid near field.

DATA REQUIREMENTS

Table I shows the data requirements for the models for initialization, specification of boundary conditions, calibration and verification. It is necessary to specify values of all dependent variables throughout the three-dimensional domain as initial conditions. Remote sensing can at present provide surface temperatures throughout the domain but vertical profiles have to be obtained by in-situ measurements, which are usually sparce and non-synoptic. Therefore compromises in specification of initial conditions have to be made. One of the common assumptions is to start with isothermal domain and zero velocity field. Where data is available, interpolation schemes are used to approximate conditions in the domain using available measurements. Boundary conditions on closed boundaries are easier to specify since they can be derived from strict requirements of no-slip and no-normal velocity. Adiabatic conditions are commonly used. Boundary conditions on open boundaries are considerably more difficult to prescribe. For the free-surface model, values or gradients of any three velocity components and surface heights are required. Surface height variations may be obtained for tide gauge stations. For the rigid-lid model at open boundaries all velocities and temperatures have to be specified. For open boundaries which separate near field from far field the boundary conditions are specified from far-field calculations in conjunction with remote sensing and interpolated in-situ measurements. The surface conditions for both models consist of surface wind stresses and heat transfer coefficients. For calibration and verification the requirements are similar to those for specification of initial conditions. At discharge locations the values of all dependent variables have to be specified at all times, except for surface height which can be calculated subsequently from the velocity field. The eddy transport coefficients have to be specified; they are not isotropic. These are obtained either from empirical relations or by trial and error during the calibration process.

DATA GATHERING PROCEDURE

The thermal IR data used for the study is received at Wallops Island, Virginia, from the NOAA-2 and NOAA-3 satellites and is processed at the National Environmental Satellite Services (NESS) facility in Suitland, Maryland. Data for the Florida area are available on southbound passes at approximately 0945 EDT (1345 Z) and on northbound passes at 2100 EDT (0100 Z)(ref.14).

The NASA-6 system is a Daedalus scanner which uses the 8-14 micron window for water surface temperature measurement. It's field of view is 2-5 milliradians and it scans through 77° 20' degrees of arc normal to flight path. It has an 10°C useable dynamic range and for this study is calibrated to measure temperatures from 24°C to 34°C. The analog readout is recorded on magnetic tape aboard the aircraft. Data is later transferred to 70 mm film at Kennedy Space Center. A calibration of the film gray scale density in terms of temperature is provided.

The major functions for in-situ measurements are to provide (1) ground truth for evaluation of remotely sensed measurements, (2) boundary conditions and verification of the mathematical model, particularly vertical profiles, and (3) assistance in the development of new techniques for remote sensing.

The most significant measurements are those of current magnitude and direction, horizontal and vertical temperature profiles, surface temperatures using infrared detectors and salinity. Current is measured by an impeller type instrument, the Endeco 110. It has been modified to measure low flows. Direct contact temperatures are measured using thermistors accurate to within 0.2°C. Salinity is measured using an induction type meter.

CALIBRATION AND VERIFICATION

The calibration and verification procedure for the rigid-lid model far-field application will be discussed here. The application site was Biscayne Bay in South Florida. This is a shallow bay open on the northeast side to the Atlantic Ocean. At the north end a causeway effectively isolates the bay; at the south end a series of banks enclose the bay. Figure 2 shows a map of Biscayne Bay. At the middle is the Featherbed Banks which is a shallow region. There are a number of creeks in the south bay open to the ocean.

The procedure for obtaining an adequate data base was to use thermal scanner flights on a north-south route. Figure 2 shows the flight lines. The coverage is not exactly synoptic since the time lapse between the eastern most flight and the western most flight is around 3 hours. The IR data was corrected using ground truth data from boats. The resulting data was then interpolated to draw surface isotherms for the whole bay. The boat measurements also provided vertical profiles.

Many different meteorological conditions were modelled. The details are presented by Lee et al (ref. 9). The conclusions indicated that tidal flows dominate wind driven effects. The tide flows primarily into and out of the south bay. The creeks only play a localized role. The velocities are small over the Featherbed Banks. They are high in the deeper regions adjacent to these banks. The temperature distribution is predominantly determined by bottom topography. Vertical diffusion is the dominant heat transfer mechanism.

After values for eddy viscosities and heat transfer coefficients were calibrated, the model was ready for verification. The vertical eddy diffusion coefficient was 5 cm^2/sec. The surface heat transfer coefficient was 176 W/m^2-^oC (750 BTU/day-^oF-ft^2). The tide was taken as incoming at 10 cm/sec and the wind was from the southeast at 4.8 m/sec (10 MPH). On April 15, 1975 a field experiment was made. NASA-6 IR data was used to draw surface isotherms. The model was run for 6 hours with an isothermal initial temperature of 24.5^{o}C at 8 A.M. Figure 3 shows a comparison between the surface isotherms from model prediction and IR data. The model not only accurately predicts the qualitative nature of the temperature field, but the actual difference is within 1^{o}C throughout the bay. This is remarkable considering that the IR data is not truly synoptic. The comparison of vertical temperature profiles obtained from in-situ measurements and model agreed to within 1^{o}C (ref. 11).

CONCLUDING REMARKS

It is imperative that model development be integrated with adequate data acquisition effort. Remote sensing is the only way to obtain required data bases, for most complex models. Satellite data is not directly useable at present for mesoscale studies. However, airborne radiometer data is invaluable. It has been demonstrated that even with incomplete data bases a three-dimensional model has been calibrated and verified to give results within 1^{o}C accuracy for Biscayne Bay in South Florida.

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TABLE I

DATA REQUIREMENTS

	Initial Conditions	Boundary Conditions (Open)	Boundary Conditions (Closed)	Surface Conditions	Calibration and Verification
Free-Surface Model	All velocity components Surface pressure Surface heights Temperature	Specify conditions on any three of the velocity components and surface height. Surface pressure, temperature density		Wind stress Heat transfer coefficient Atmospheric pressure	Three-dimensional fields for velocities and temperature, Surface heights at some selected locations.
Rigid-Lid Model	All velocity components Surface pressure Temperature, Density	Specify conditions on velocities, temperature density		Wind stress Heat transfer coefficient No vertical velocities	Three-dimensional fields for velocities and temperature

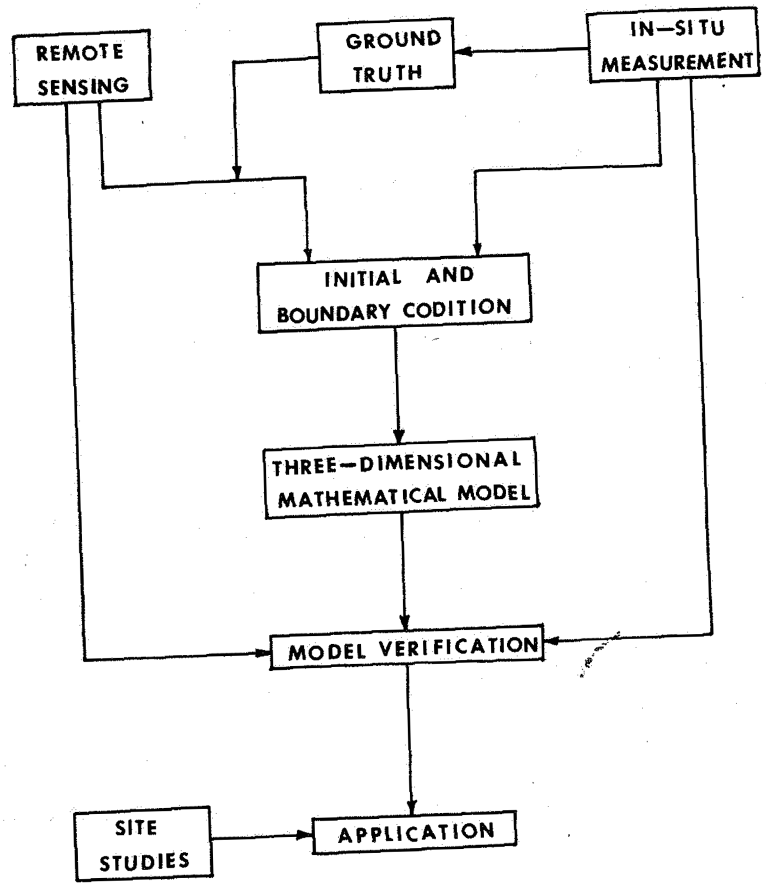

Figure 1.- Relations between various phases of the study.

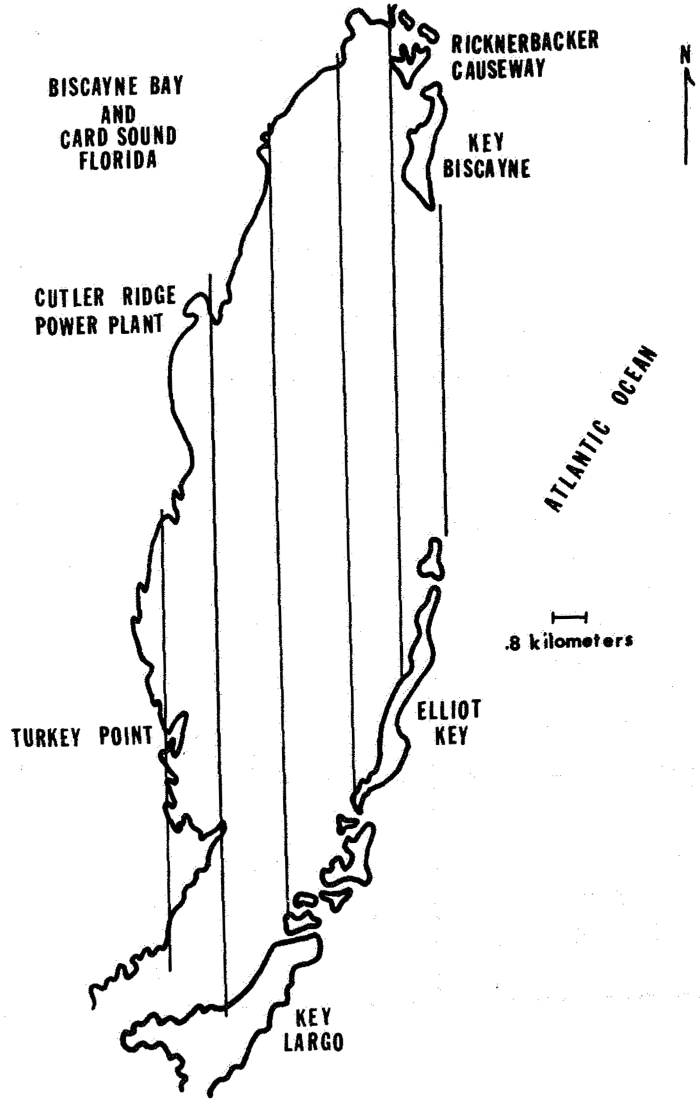

Figure 2.- Biscayne Bay, showing NASA-6 flight lines.

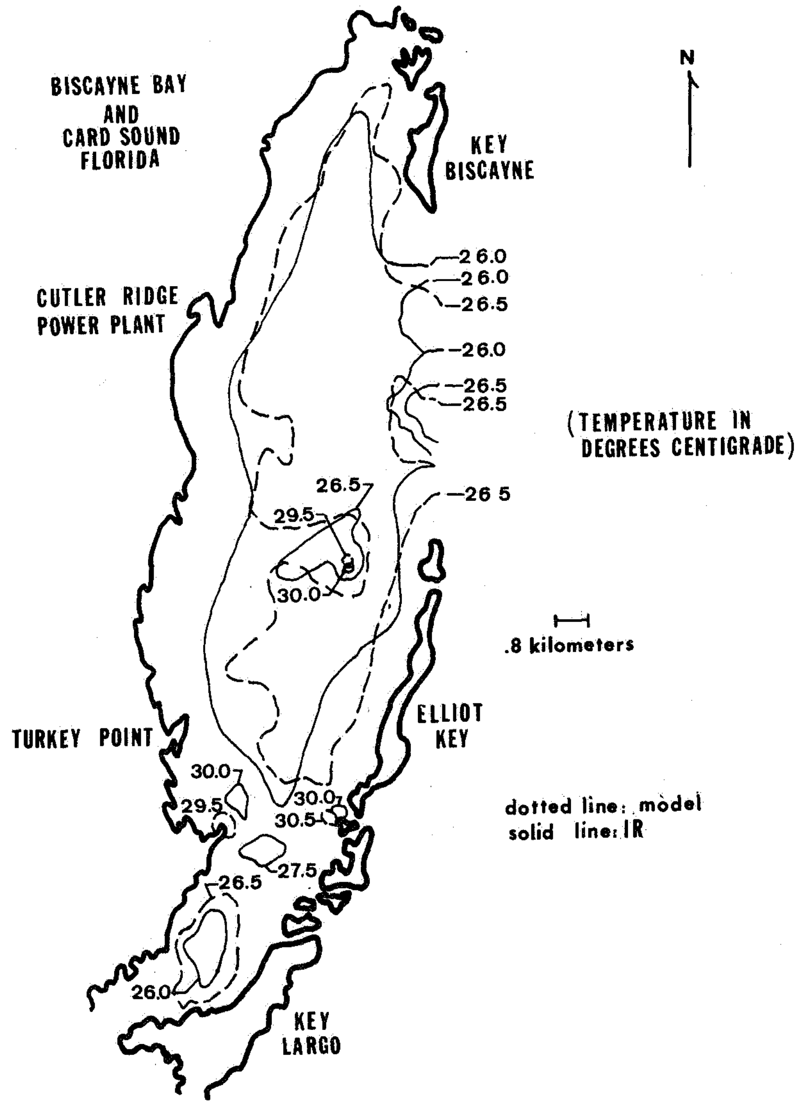

Figure 3.- Comparison of IR data with predicted results (4/15/75).