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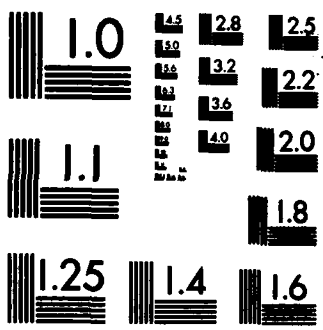

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AD-A146 334

NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

DEVELOPMENT OF A MICROCOMPUTER COUPLED ATMOSPHERIC
AND OCEANIC BOUNDARY LAYER PREDICTION MODEL

by

Gary Lee Tarbet

December, 1983

Thesis Advisor: Kenneth Davidson

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REPORT DOCUMENTATION PAGE

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1. REPORT NUMBER	2. GOVT ACCESSION NO. AD-A146 334	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Development of a Microcomputer Coupled Atmospheric and Oceanic Boundary Layer Prediction Model		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis December 1983
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Gary Lee Tarbet		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93943		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93943		12. REPORT DATE December, 1983
		13. NUMBER OF PAGES 52
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report)
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release, distribution unlimited

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Marine Atmospheric Boundary Layer, MABL, Oceanic Boundary Layer, OBL

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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Development of a Microcomputer Coupled Atmospheric and Oceanic Boundary Layer Prediction Model

by

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Lieutenant Commander, United States Navy
B.S., University of Utah, 1975

Submitted in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE IN METEOROLOGY AND OCEANOGRAPHY

from the

NAVAL POSTGRADUATE SCHOOL
December, 1983

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I. INTRODUCTION

Military leaders, engineers, and scientists have become aware of the environmental effects on electromagnetic (EM) and electrooptical (EO) signal propogation. Many of the current weapons guidance systems, command and control communications, and electronic countermeasures are critically dependent upon environmental parameters. One extreme case was recently brought to the attention of Pentagon officials when a new missile guidance system became totally ineffective in certain environmental conditions. The modern naval leader must not only be aware of the environment but must also know how to use the current environmental conditions to best advantage. The deployment of resources, decision of appropriate weapons systems, and overall tactics must include a consideration of EM/EO propagation. The overall effectiveness and the successful outcome of an operation could be tied to this very knowledge.

The atmospheric factors which effect EM/EO propogation are the temperature, humidity, vertical gradient of pressure, small scale inhomogeneities or turbulence, distribution of aerosols, and concentration of water vapor. The refraction of EM/EO signals is primarily affected by the first three factors. Turbulence affects the index of refraction through wave front distortions while the remaining factors cause extinction and dispersion. All of these effects are interlinked and they must be computed simultaneously. Another problem comes in measuring each of these factors. No known or planned system provides the accuracy required for direct measurement. Indirect methods will have to be employed by units in the operational arena for the foreseeable future.

An equally important problem is prediction of the mixed layer depth and sea surface temperature in the ocean. Research is underway to find the relationship between the synoptic scale weather patterns and the sea surface temperature. Naval operations generally take place in areas where the marine atmospheric boundary layer (MABL) has been extensively modified by contact with the ocean surface. The effects of heat flux from the ocean to the atmosphere warming the boundary layer, the subsequent increase in turbulence, the transfer of water vapor to the air, and the effects of salt and other aerosols being injected into the air by waves are all important to Naval operations. These fluxes of heat and water vapor can change the structure of the MABL to the extent that clouds or fog are formed. Clouds and fog will dramatically reduce the short wave solar radiation striking the ocean surface thereby reducing the surface heating due to radiation. The diurnal change in the sea surface temperature and mixed layer depth will be decreased.

In determining the effect upon acoustic propagation, both the depth and strength of the mixed layer gradient must be considered. Skip zones and ducting are examples of oceanic phenomena which must be considered in every naval operation. Unusually strong or weak diurnal affects can significantly alter these factors. To provide an optimum forecast of the OBL, the effective shortwave radiation, internal mixing forces, and atmospheric entrainment must be taken into consideration.

It is obvious that any attempt at modeling the MABL and OBL should be linked for optimum results. Microcomputer programs developed at the Naval Postgraduate School for the MABL (Davidson, et. al.) and for the OBL (Garwood) have been linked to provide the necessary feedback. While both of these models have been verified independently, the linking should improve forecast accuracy.

Determining situations where the linking has significant effects is the primary goal of this thesis. Sensitivity studies were also conducted in an attempt to determine which if any of the factors provide significant differences between the coupled and uncoupled models. Additionally, since the model is currently running on a Hewlett Packard 9836 microcomputer and the fleet units are and will be using Hewlett Packard 9845's for several more years, it is necessary to transfer the code to the latter unit. Since the internal architecture of the two systems is significantly different, changes in program structure will have to be verified for accuracy and consistency with the original model.

Having mixed layer forecasting capabilities onboard should enable the operational fleet units to use the environment to maximum advantage. Not only can forecasts be updated rapidly as on-site conditions vary, but those "what if" questions can be answered quickly and accurately.

II. DESCRIPTION OF BOUNDARY LAYER FEATURES

The MABL extends from the surface through the capping inversion which is typically .5-1.5 km above the surface. The MABL is cooler and more moist than the overlying air, and it is capped by an inversion 50-100 meters thick. Temperature increases and humidity decreases with height in this inversion. The air-sea interface is bordered by oceanic and atmospheric turbulent mixed layers which effectively insulate the quasi-geostrophic regions above the inversion and below the thermocline. The OBL or mixed layer in the ocean typically spans the upper 10-100M of the ocean. Mean velocity and density values tend to be vertically uniform in this region. At the bottom of the mixed layer a transition region exists called the thermocline. Turbulence in these well mixed regions is created by bouyancy, flux and velocity gradients that are a result of air-sea interactions. The vertical homogeneity of these two mixed layers can be attributed to the strong mixing by the turbulent motion.

Bouyancy driven energetic eddies fill the OBL and MABL. In the atmosphere the eddies entrain warm, dry air with high momentum from the free atmosphere into the boundary layer. If this entrainment causes the MABL to extend above the lifting condensation level, then clouds or fog will form. A typical profile of the MABL and OBL is shown in Figure 1. As

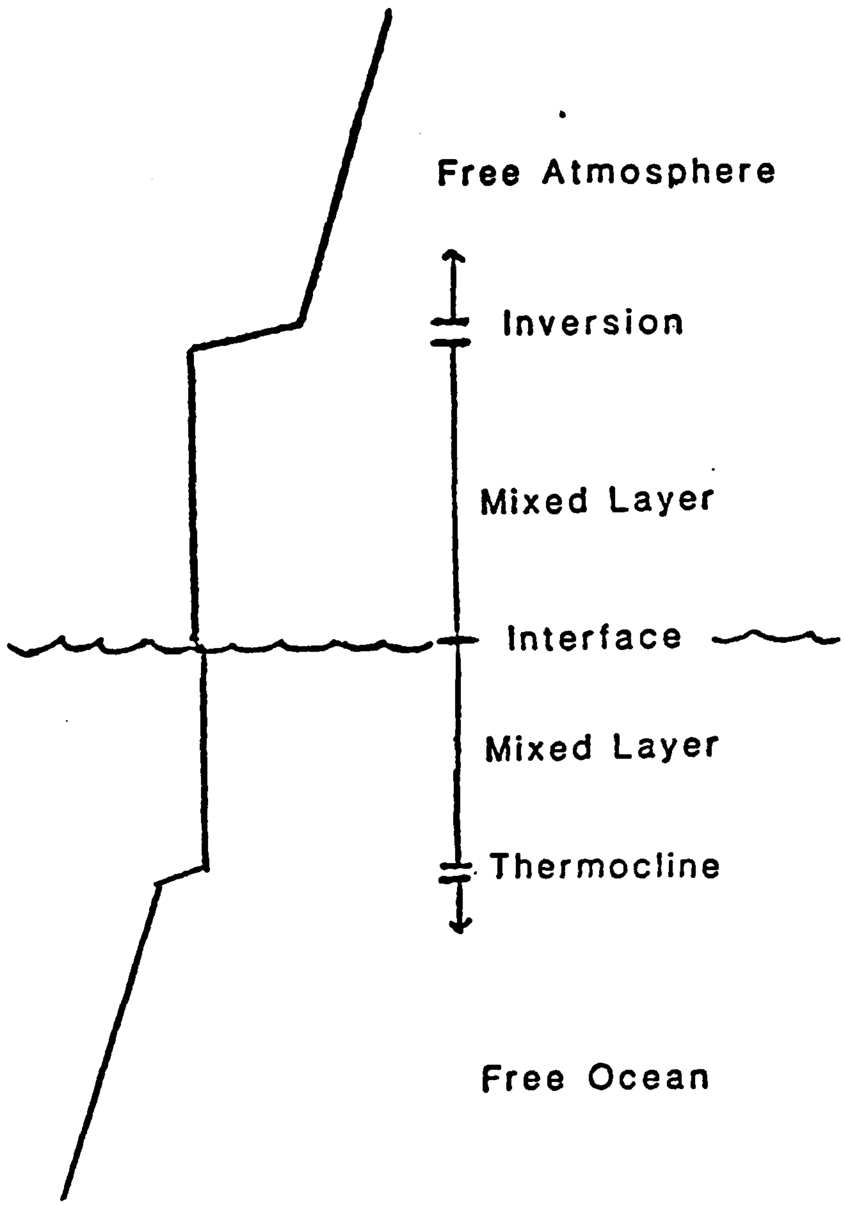

Figure 1. Simplified Atmospheric and Oceanic Boundary Layer Temperature Profiles

can be seen from Figure 2, the bouyancy driven fluctuations have an even more direct role in the mechanical energy budget for the OBL.

With the understanding of the importance of bouyantly driven entrainment effects, the necessity to couple the near surface prediction models is obvious. A cause and effect relationship is developed through the interactions of the ocean and atmospheric surfaces. Examples of this effect include:

1. Surface bouyancy flux induced entrainment not only increases the depth of the MABL, but it also changes its effect on the ocean mixed layer.

2. Clouds in the MABL can be caused by a change in the ocean surface temperature which in turn affects the radiation budget.

The relatively complex models used to predict these features have been tested in both the coupled and uncoupled modes. While often little improvement is noted in the output in the coupled versus uncoupled modes, under certain circumstances the coupled mode is mandatory and produces significantly better forecasts. It is the goal of current research to determine exactly what factors have the strongest influence on coupling and under what circumstances coupled models must be utilized.

The purpose of this thesis is to show under what circumstances the coupled approach is most useful. The answers will hopefully be obtained through interpretive

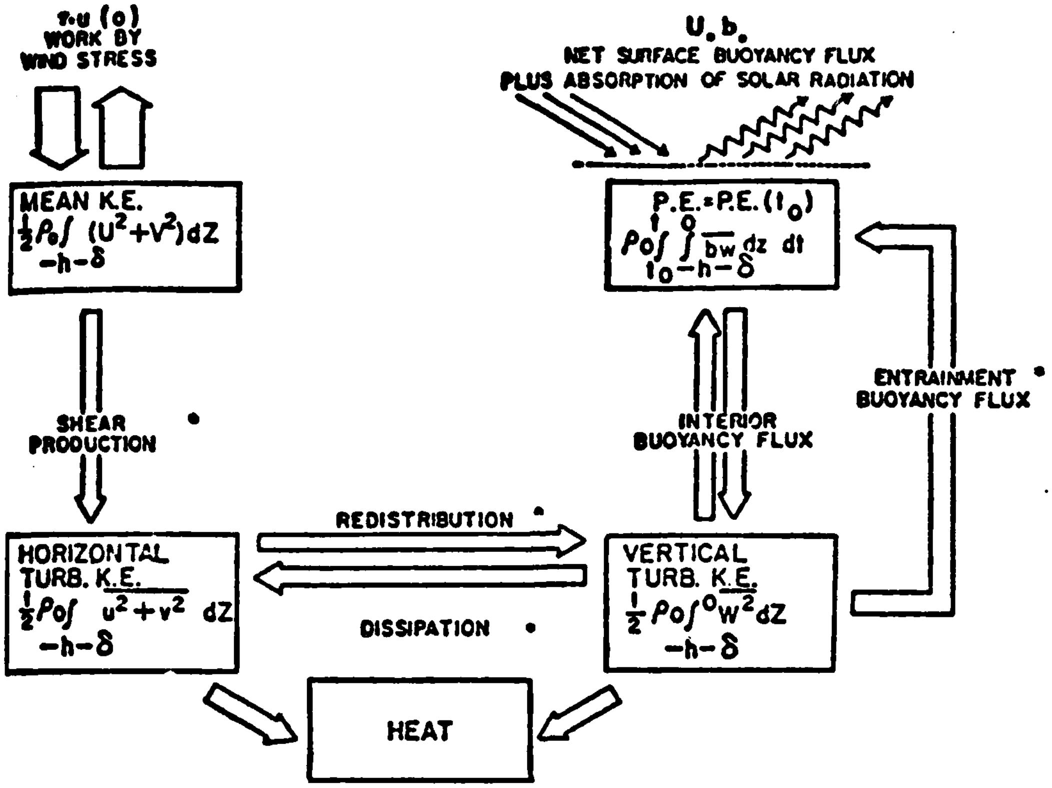

Figure 2. Mechanical Energy Budget for the Ocean Mixed Layer

efforts using the power of the computer. By varying the angle of radiation (latitude), amount of radiation (month), and start time for the program, each set of output will be compared and analyzed for consistency. A typical case will then be selected and further studies will be conducted. The effects of coupled versus uncoupled oceanic mixed layer depth variations and wind speed variations will be examined.

The magnitude and usefulness of this effort is illustrated in Figure 3. Outputs from the coupled model can

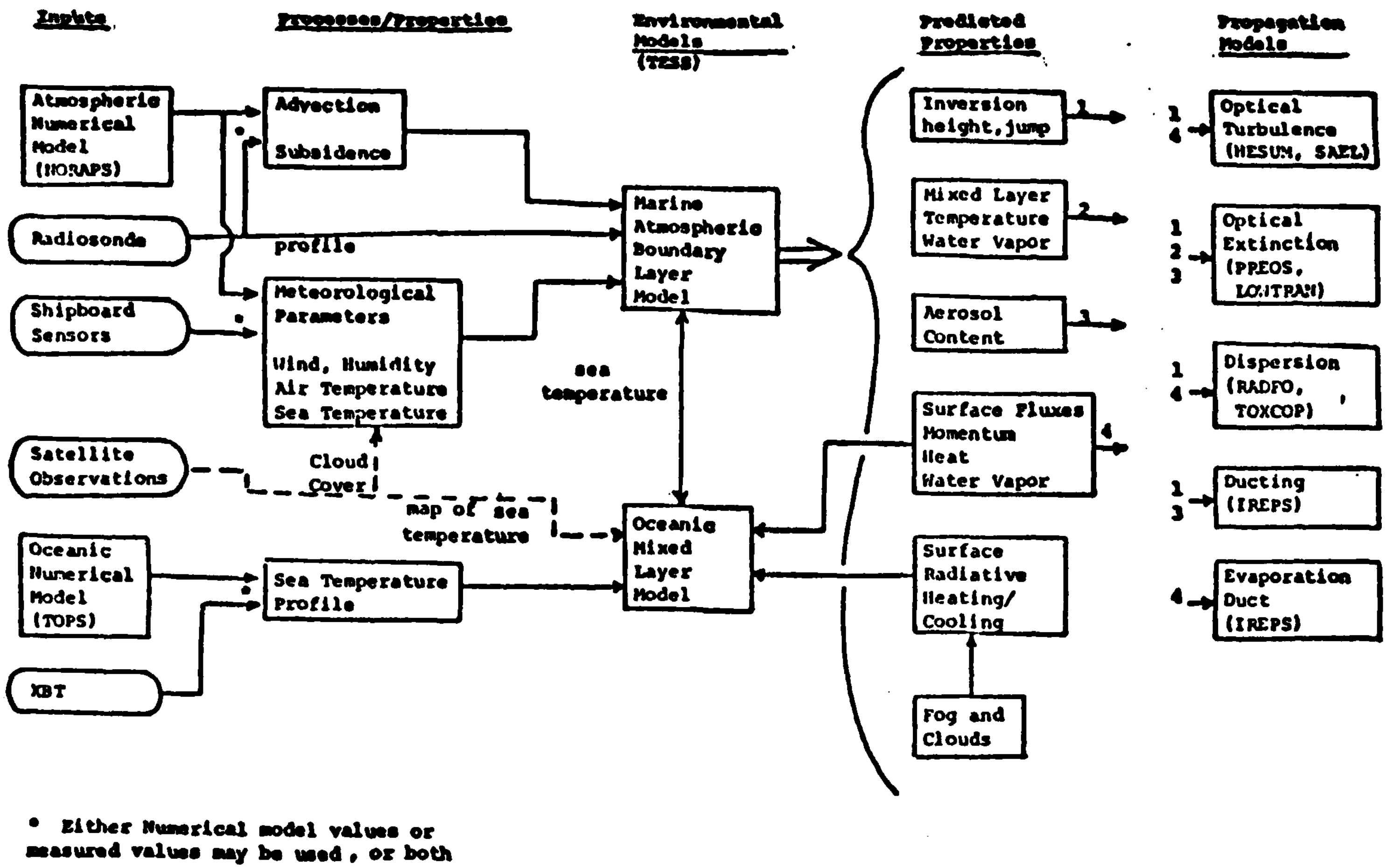

Figure 3. Simplified Flow Diagram of the Boundary Layer Model Showing Possible Configurations of Input Information, Interrelation Between Atmospheric and Oceanic Models, Model Outputs, and Tactical Models Which Use These Outputs

be used tactically in forecasts shown in the righthand column of Figure 3. The models to be used for the forecast include the Garwood Model and the Naval Postgraduate School Marine Atmospheric Boundary Layer Model. A detailed description of each model and the approach taken in coupling the outputs will be discussed. While this understanding is not necessary in the utilization of the output, it may provide useful information in obtaining maximum benefit from the program.

III. MODELS

A. MARINE ATMOSPHERIC BOUNDARY LAYER (MABL) MODEL

The NPS MABL model is a zero-order, two layer, integrated mixed layer model. The model assumes the atmosphere consists of two layers; a well mixed, turbulent boundary layer, and the relatively non-turbulent free atmosphere above. The model is based on radiative transfers described by Davidson, et. al. (1983) and entrainment energetics formulated by Stage and Businger (1981).

The two zones are separated by an inversion layer or transition zone. The zero-order model assumes this transition zone to be infinitely thin; therefore, a jump or discontinuity occurs at this point in the profiles of all conservative parameters.

The current model requires the following inputs:

1. An initial atmospheric sounding.
2. The geostrophic wind.
3. The surface temperature.

In an operational scenario the boundary layer winds can be estimated from standard meteorological charts. During this evaluation the actual hourly winds were input for initialization purposes. In the uncoupled version, sea surface temperature (SST) remains unchanged; however, when coupled, the SST does change with time and is predicted by the OBL model. The humidity and temperature in the well mixed MABL are predicted. Inputs of the surface wind and wind shear at the inversion are required by the MABL model. The large scale subsidence normally obtained from synoptic scale NWP products must also be prescribed for the model period.

The model is very sensitive to subsidence values; therefore, care should be taken in selecting this value for proper results. Three methods can be used to compute the subsidence (large scale vertical velocity) from single station observations. These three methods are the kinematic method, adiabatic method, and integration of the moisture budget equation (Q-method) which are all well described by Gleason (1982). Gleason's study showed the *Q-method* displayed the most merit as a single-station assessment of subsidence. Computation of the solar zenith angle, which is used to compute effective short wave flux, uses the latitude, julian day and start time which are initial input values.

As shown in Figure 4 the atmospheric model has a 30-minute time step. During each cycle, the program predicts the mixed layer temperature, humidity, and the jump of these values at the inversion. When clouds or fog are formed, the cloud top cooling and entrainment computations are important in the physical processes.

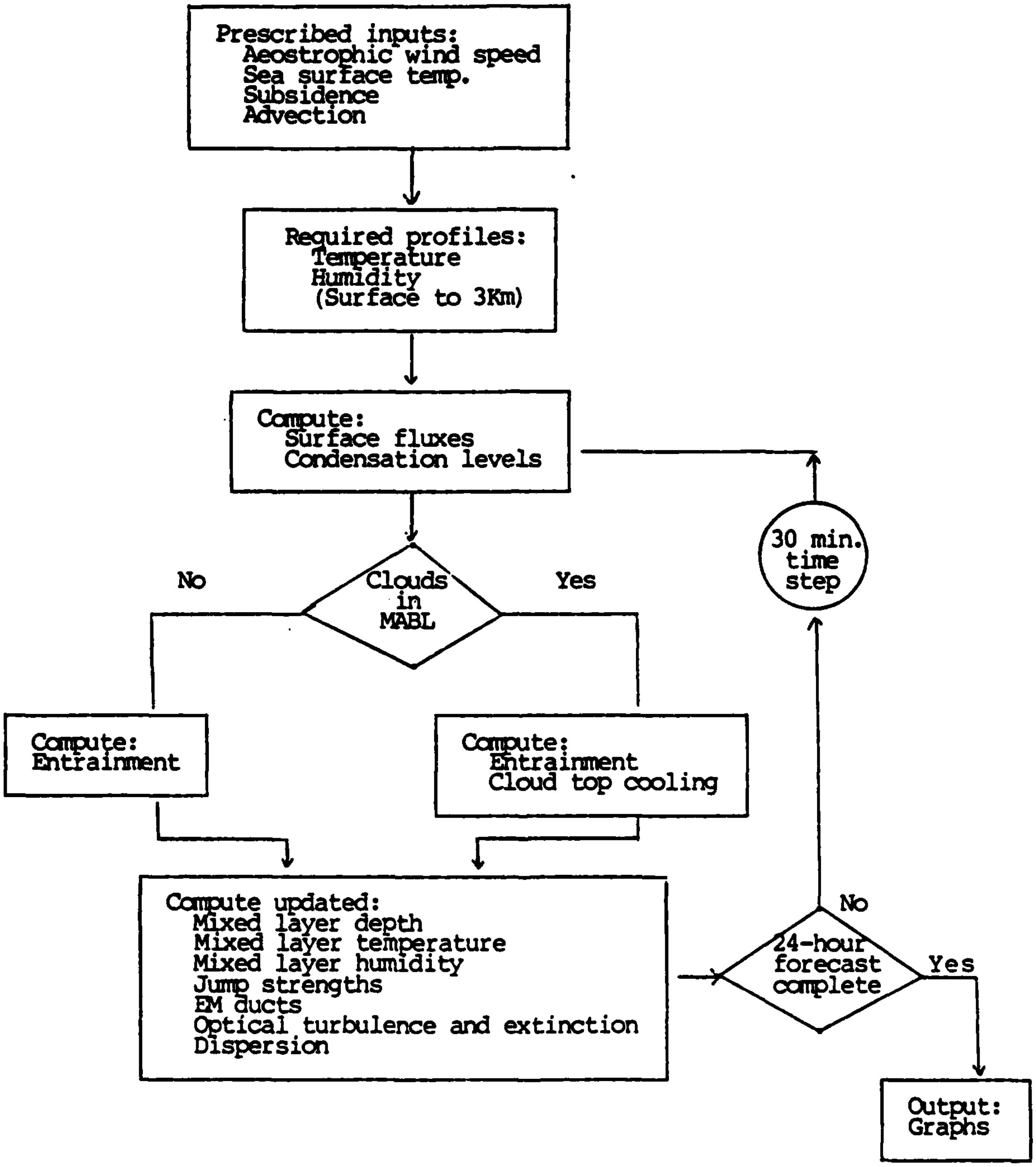

Figure 4. Input and Flow Chart for MABL Prediction Model

The conservative quantities and their jump at the inversion is predicted by using the standard integrated rate equations (Tennekes, et.al., 1981). The equations are:

$$h(Dx/Dt) = (\overline{w'x'})_0 - (\overline{w'x'})_h + \text{source} \tag{1}$$

$$h(D\Delta x/Dt) = h\Gamma x(\partial h/\partial t) - (\overline{w'x'})_0 + (\overline{w'x'})_h - \text{source} \tag{2}$$

Γ = Lapse Rate

$$\text{Source} = \begin{cases} -(F_{nh} - F_{n0})/\rho C_p & \text{for } x = \text{temperature} \\ 0 & \text{for } x = \text{humidity} \end{cases}$$

F_n = Net Radiative Heat Flux

The subscripts "h" and "0" refer to inversion height and surface values respectively.

To close this system of equations and to compute the variation in the inversion height (Stage, et.al., 1981) entrainment velocity parameterization is used. One additional assumption is used to close the system and that is that the dissipation rate of turbulent kinetic energy (TKE) is a fraction (1-A) of the production rate. The entrainment coefficient (A) is taken as .2 for the formulation.

The bulk aerodynamic formulas are used for surface fluxes of momentum, sensible heat, and latent heat.

$$u^* = C_d^{1/2} U_{10} \tag{3a}$$

$$T^* = C_\phi^{1/2}(\theta_0 - \theta) \tag{3b}$$

$$q^* = C_\phi^{1/2}(q_0 - q) \tag{3c}$$

These fluxes are given by:

$$\overline{u'w'} = u^{*2} \quad \text{(momentum)} \tag{4a}$$

$$\overline{T'w'} = u^*T^* \quad \text{(sensible heat)} \tag{4b}$$

$$\overline{q'w'} = u^*q^* \quad \text{(latent heat)} \tag{4c}$$

c_d and c_ϕ = ten meter stability dependent drag coefficient

ϕ = potential temperature

q = specific humidity

The subscript 0 denotes surface values.

In the MABL model, extensive work has been done on the radiation portion because of its significance to the OBL model and the sampling of the two models. The short wave radiative flux is computed through use of the delta-Edington Method. An excellent review of the delta-Edington Method including all parameters, atmospheric factors, and equations has been published by Fairall (1981). This portion of the model was added to account for the heating of the mixed layer by solar radiation.

In the boundary layer, short wave extinction is dominated by scattering vice absorption. This second short wave radiative component is usually referred to as diffuse solar radiation. Atmospheric particles such as cloud droplets and sea-salt aerosols are the primary scattering nuclei in the MABL. The current MABL model computes both direct and diffuse radiation components to determine a total short wave radiation flux value at the surface. In addition, the fraction of reflected short wave radiation, Ag, from the sea surface is prescribed as .1 in the MABL model.

The modeling of radiative flux transfer has been accomplished in numerous ways; however, even the simple models are extremely complex compared to other parameterizations used in the model. Even though long and short wave radiative fluxes are computed separately, there are numerous sources of error in these calculations. Some of these sources include:

1. Concentrations or lack of absorbing gases such as carbon dioxide, ozone, or water vapor in the atmosphere.
2. The uncertainty of quantity, size and distribution of background aerosols.
3. The size of various cloud droplets and their distribution.

Since this model primarily intended for use over ocean areas non-black stratus clouds were permitted by introducing cloud emissivity (ε_c) into the long wave radiative flux calculation. Cloud emissivity is a function of total cloud liquid content, w. Cloud liquid content profiles are approximately linear with height (Davidson, et.al., 1983) Cloud water content and emissivity are given by equations 5 and 6.

$$w = 0.5 \rho_a (h-Z_c) q_h \tag{5}$$

$$\varepsilon_c = 1 - \exp(-aw) \tag{6}$$

ρ_a = air density (1.25×10^{-3} gm cm^{-3})

h = height of the mixed layer (cloud top)

Z_c = lifting condensation level (cloud bottom)

a = 0.158 (Slingo, et.al., 1981)

q_h = liquid water content at cloud top

Using the Stefan Boltzman Law, the net long wave cloud top radiation flux, L_{nh}, can be calculated from the cloud top temperature, T_h. The cloud bottom temperature, T_c, and the sea surface temperature, T_s, are used to calculate the flux, L_{nc}, at the bottom of the cloud. These fluxes are given by:

$$L_{nh} = \varepsilon_c \sigma \,(T_h{}^4 - T_{sky}{}^4) \qquad (7)$$

$$L_{nc} = \varepsilon_c \sigma \,(T_s{}^4 - T_c{}^4) \qquad (8)$$

σ = Stefan's Constant (4.61×10^{-11}

ε_c = obtained from equation (4)

The net long wave radiation at the surface, F_{long}, becomes:

$$F_{long} = (\tilde{T}_s{}^4 - \varepsilon_c \tilde{T}^4 - (1 - \varepsilon_c) T_{sky}{}^4) \qquad (9)$$

$\tilde{T}$ = average cloud temperature

For the cloud free case, the net fluxes are calculated at $Z = h$ and $Z = 0$ by integrating the flux emissivity profile (Fleagle, et.al., 1978). The net long wave flux at the surface for the clear sky case is given by:

$$F_{long} = F_u - F_d \quad (10)$$

F_u = upward radiative flux

F_d = downward radiative flux

B. OCEANIC BOUNDARY LAYER (OBL) MODEL

A mixed layer model for the ocean using the continuity equation for an incompressible fluid, the first law of thermodynamics (heat equation), the conservation of salt equation, the Navier-Stokes equation of motion with the geostrophic component eliminated, an analytical equation of state, and a two-component vertically integrated turbulent kinetic energy budget was developed by Garwood (1977).

An understanding of the dynamics of the entrainment process is a key factor in predicting the variable changes in the mixed layer. The turbulence of the overlying mixed layer provides the energy needed to destabilize and erode the underlying stable water mass (Garwood, 1977). The turbulent kinetic energy equation is the basis for the entrainment. A closed system of equations is obtained by using the bulk buoyancy and momentum equations with the mean turbulent field modeling of the vertically integrated equations for the individual turbulent kinetic energy (TKE) components.

To better define the mixing process, separate horizontal and vertical TKE equations are used. Energy for vertical mixing is provided by both buoyancy flux and shear production. The buoyancy equation is derived from the heat and salt equations coupled with the equation of state as shown in equation (11).

$$\bar{\rho} = \rho_0 \, [1 - \alpha(\tilde{\theta} - \theta_0) + \beta(\tilde{s} - s_0)] \quad (11)$$

Bouyancy is given by:

$$\tilde{b} = g \, (\rho_0 - \tilde{\rho})/\rho_0 \quad (12)$$

θ = temperature

s = salinity

ρ = density

g = gravity

α = expansion coefficient for heat

β = density coefficient for salt

Note: The tilde represents instantaneous values and the subscript 0 represents an arbitrary, but representative, constant value.

The effect of the salinity on the short-term density profile evaluation is generally found to be insignificant except at higher latitudes. Temperature is usually the dominating factor in the density profile. However, by using buoyancy instead of only temperature permits the model to be applied in situations where evaporation and precipitation contribute significantly to the surface bouyancy flux.

For extended forecasts, the Ekman wind-driven horizontal current profiles as well as the temperature and salinity profiles must be provided with initial values. The mixed layer depth, "h", as defined by the Garwood OBL model, is the shallowest depth at which the observed density value, σ_t, is .02 σ_t units greater than the observed surface density value. Additional ocean parameters which must be prescribed include the radiation extinction coefficient, the fraction of short wave radiation absorbed in the upper meter of the ocean, and the critical Richardson number which defines a stability adjustment at the bottom of the mixed layer. Surface boundary conditions required for the OBL model include air temperature (dry bulb), dew point temperature, wind speed and direction, the rate of evaporation (E) and precipitation (P), and the incident solar radiation.

Using the bulk aerodynamics formulas, the turbulent fluxes of sensible heat, Q_h, and latent heat, Q_e, can be computed as follows:

$$Q_e = C_d \ (.98 \ E_s - E_a) U_{10} \tag{13a}$$

$$Q_h = C_d \ (T_s - T_a) U_{10} \tag{13b}$$

The net back radiation is estimated from the empirical equation (Husby, 1978).

$$Q_b = 1.14 \times 10^{-7} (273.16 + T_s)^4 (.39 - .5 E_a^{1/2}) (1 - .6 C^2) \tag{13c}$$

E_s = saturated vapor pressure (.98 corrects for salt defects)

E_a = vapor pressure of air based on dew point temperature

T_a = air temperature

T_s = sea surface temperature

C = fractional cloud cover

The upward heat flux, Q_u, is then given by:

$$Q_u = Q_e + Q_h + Q_b \tag{14}$$

The solar radiation, Q_s, is given by:

$$Q_s = (1 - a \quad ^b) \ (1 - .66C^3) Q_0 \tag{15}$$

The constants "a" and "b" are adopted from Tabata (1964) and the cubic cloud cover correction from Laevestu (1960). Q_0 is the clear sky radiation given by Seckel and Beauday (1973):

$$Q_0 = A_0 + A_1 \cos\phi + B_1 \sin\phi + A_2 \cos 2\phi + B_2 \sin 2\phi \tag{16}$$

The coefficients A_0, A_1, etc. are calculated by harmonic representation of the values predicted in the Smithsonian Meteorological Tables with

$$\phi = (2\pi/365)(t-21) \tag{17}$$

where t is the julian day of the year (O'Loughlin, 1982).

A very small percentage of the incoming solar radiation penetrates the ocean mixed layer. Approximately 50 percent is absorbed in the first meter of the ocean in most parts of the open ocean. The portion absorbed varies from region to region and is highly dependent upon such things as suspended particulate matter and phytoplankton. More radiation will be absorbed in coastal regions than the open ocean because of the increased amount of suspended particulates. This portion of the absorbed radiation is considered to be part of the upward heat flux because very little of this heat is entrained into the deep ocean. Most of this energy is transferred upward out of the ocean and back into the atmosphere. The remainder of the short wave radiation does penetrate the mixed layer; however, an exponential attenuation does take place which is highly dependent upon water turbidity. With the fraction of solar radiation absorbed in the first meter, RF, the net heat at the surface is given by:

$$Q_{net} = Q_u + (RF)\ Q_s - Q_s \qquad (18)$$

From the equations discussed above, the momentum and surface fluxes of buoyancy (heat and salt) can be computed. The mixed layer temperature, salinity, bouyancy and velocity fluxes are given by:

$$(\overline{T'w'}) = Q_{net}/\ C_p \qquad (19a)$$

$$(\overline{S'w'}) = (P - E)\ S_0 \qquad (19b)$$

$$(\overline{b'w'}) = g[\alpha(\overline{T'w'}) - \beta(\overline{S'w'})] \qquad (19c)$$

$$(\overline{u'w'}) = U^{*2} \qquad (19d)$$

Subscript 0 refers to surface value. The friction velocity in air, U^*, is given by:

$$U^* = (t_s/\rho_a)^{1/2} \tag{20}$$

$$\text{where } t_s = \rho_a C_d U_{10}^2 \tag{21}$$

t_s = surface stress (dynes cm^{-2})

A positive surface buoyancy flux results when $Q_{net} < 0$ and $E > P$. During daytime periods, the solar heating at the surface dominates giving a negative buoyancy flux. At night the combination of long wave radiation and the upward turbulent fluxes of heat and moisture produce a positive buoyancy flux.

The ocean model, as shown in Figure 5, details the inputs discussed above. At each one-hour interval, new mixed layer depth, temperature, salinity, and wind-driven current profiles are predicted.

C. COUPLED BOUNDARY LAYER MODEL

The advantage of linking the two models described in the previous two sections is obvious when examining the inputs to each of the models. Allowing feedback of current input parameters to occur between the models at each time step can potentially produce significantly better forecasts. O'Loughlin (1982) accomplished the initial coupling on a Hewlett-Packard 9836 microcomputer taking care not to alter the physical process in each of the models and insuring all variable units were passed uniformly. The MABL model only requires the SST from the OBL model. The correct SST is extremely important to the MABL model and affects the entire output package as discussed in the next section.

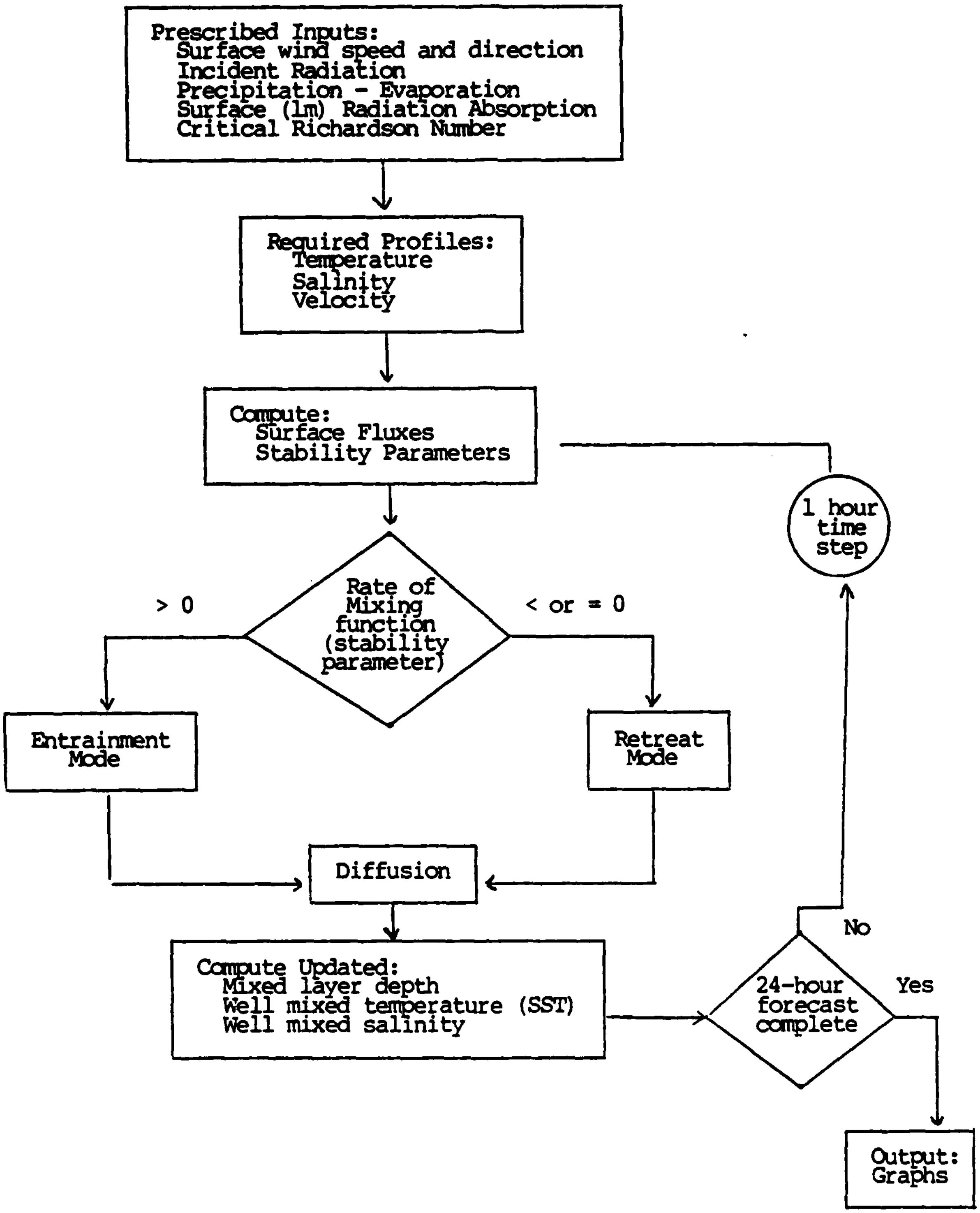

Figure 5. Input and Flow Chart for OBL Prediction Model

The initial coupling problems overcome by O'Loughlin [Ref. 13] included:

1. The atmospheric model uses a 30-minute timestep while the ocean model uses a 1-hour timestep. The coupled model calls the ocean model on every other timestep to overcome this problem.

2. The atmospheric model requires only wind speed and not direction. The ocean model requires wind direction to compute the horizontal ocean turbulent velocity flux, $U_w{*}^2$, for the momentum budget equation. A subroutine was added to compute the horizontal wind components from speed and direction input during the initialization.

A complete flow diagram of the steps in the coupled model's prediction computation is shown in Figure 6.

In 1982 and 1983 the Naval Oceanography Command purchased and distributed Hewlett-Packard 9845 microcomputers to all aviation support ships and selected detachments. These units were designated as interim TESS (Tactical Environmental Support System) units until the TESS system is deployed. The 9845 has proven itself as a structurally strong computer. Many application packages have been written for the unit and more are being distributed by The Naval Environmental Prediction Research Facility (NEPER)F all the time.

The original formulation of a coupled model was done on a Hewlett-Packard (HP) 9836 computer. Transferring this working code from the 9836 to the 9845 would, on the surface, appear to be a trivial matter. On the contrary, the 9836 is a 16 bit computer system based on the Motorola 68000 microprocessor capable of addressing one megabyte of memory.

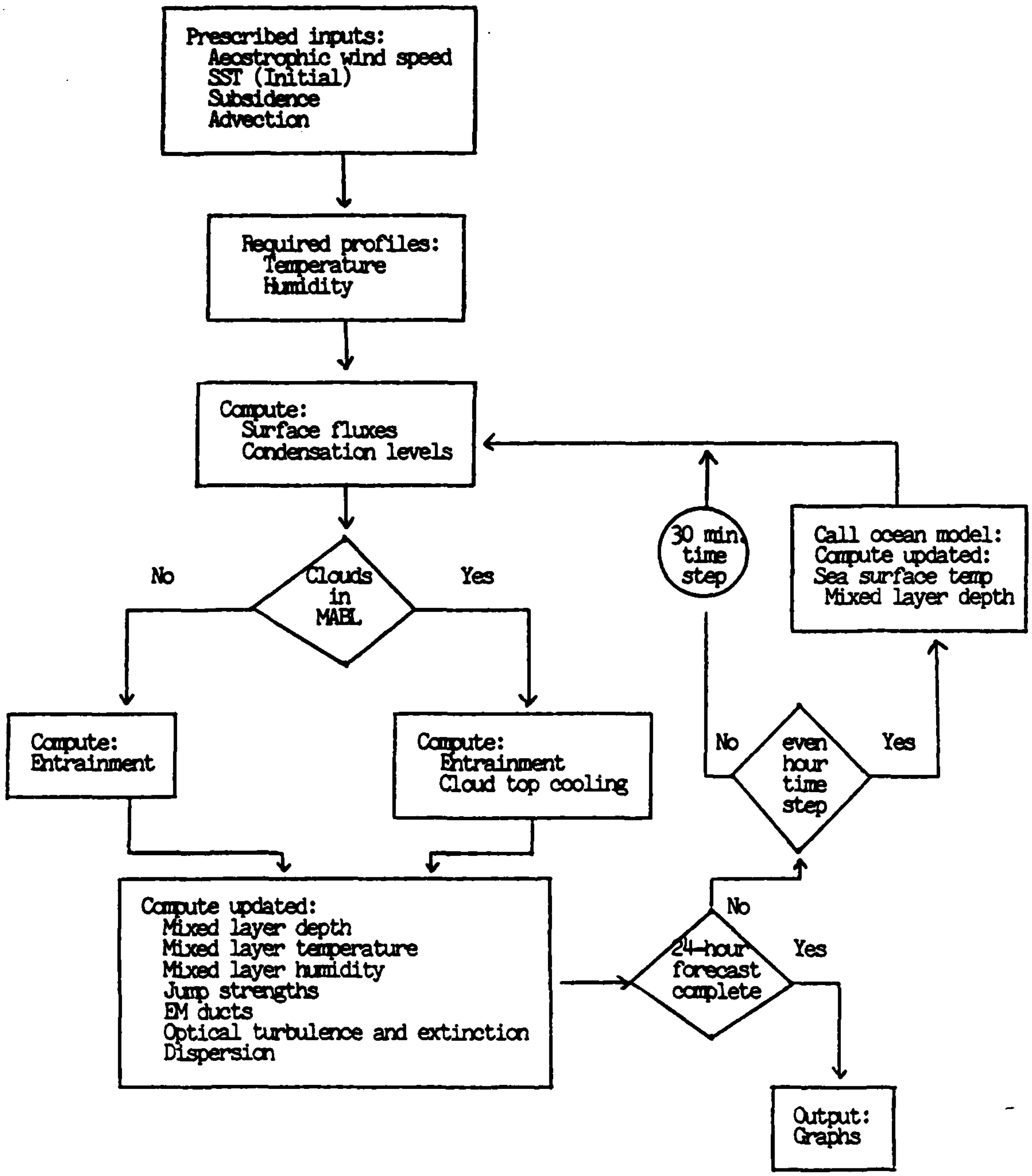

Figure 6. Input and Flow Chart for Coupled OBL and MABL Prediction Model

Having 16 bit accuracy and the large memory addressing capability allowed the relatively easy coupling of the initial model. The 9845 is advertised by HP to be a 16 bit computer with a proprietary processor to HP. The processor has the limited capabilities of an 8 bit processor in addressable memory (64K). This required extensive changes in the structure of the coupled model. In addition, while the company claims 16 bit accuracy with the 9845, the extensive changes in code require verification that model phys·cs and output have not been modified by the lack of precision or round off error within the computer system. Another factor in preparing the program was to reduce its overall size so as to use only one tape for the program and one tape for data to eliminate the confusing practice of continually swapping tapes during program execution. Transfer of information from or to tape units is slow and must be limited. Making the program as user friendly as possible is an additional consideration.

IV. DATA AND MODEL RESULTS

The data set used for this analysis of the model is a modified set from the Cooperative Experiment on West Coast Oceanography and Meteorology (CEWCOM-76) shown in Figure 7. The data set was modified to maximize the effects on the program output. Care has been taken to ensure the input is reasonable and representative of the area to be discussed. The primary goal of this application is to show the sensitivity of the program to variations in input. Additionally, these model results could easily form a scenario for a fleet application showing the utility of the program.

The problem to be posed for this analysis is "will clouds form within the next 24 hour period?" This problem could be quite significant if perhaps the forecaster was on a vessel with only the local observations. The availability of good facsimile and satellite products have greatly reduced the burden on present day forecasters. The other problem associated with forecasting for an afloat unit, especially any U.S. Navy ship, is that these forecast officers transfer positions. The forecaster does not have the opportunity to gain the expertise of an individual permanently assigned to one forecast office. Therefore, it is of paramount importance that adequate tools be made available to the

ATMOSPHERIC DATA SET

Date	21 June
Latitude	30° N
Surface Temperature	19° C
Temperature Jump at Inversion	3.5° C
Lifting Condensation Level	567m
Inversion Level	607m
Winds Average	~ 3.5 knots
Mixed Layer Specific Humidity	10.2 g/kg
Jump Strength	-2.4 g/kg

OCEAN DATA SET

Sea Surface Temperature	21.07° C
Mixed Layer Depth (initial)	2.0 m
Jump Strength	2.0° C

Figure 7. Data Set

forecaster. This program is just such a tool. Using onboard HP9845 assets, the fleet geophysics officer can input local observations and receive a 24-hour forecast for the OBL and MABL. In addition this program allows the forecaster to answer those nagging and sometimes critical "what if" questions such as:

1. What if the wind speed varies?

2. What if the mixed layer depth changes?

3. What if the subsidence rate varies?

To examine the coupled and uncoupled models and their interactions, the models were initialized using the following conditions. The overall synoptic situation is very stable. A large high pressure system is dominating the synoptic pattern in the region. Light winds averaging approximately 3 knots with the strong subsidence of the high pressure system has resulted in clear summer days. No change in the general synoptic pattern is forecast for the region by the numerical weather prediction (NWP) products produced from Fleet Numerical Oceanography Center (FNOC). The air temperature has remained around 19° C. The long periods of sunlight have caused a strong, shallow mixed layer to form on the surface of the ocean approximately 2.0 meters deep with a 2° C temperature jump at the boundary. Two soundings and hourly meteorological observations have been taken in the last 24 hours and are available for use. The date is June 21st and all data assumes a latitude of 30° N. Start time for each forecast is 1900.

A. UNCOUPLED MODEL RESULTS

The first output to be examined is that of an uncoupled (atmospheric model only) model. As seen in Figure 8, the mixed layer depth (MLD) is held fixed at the original value.

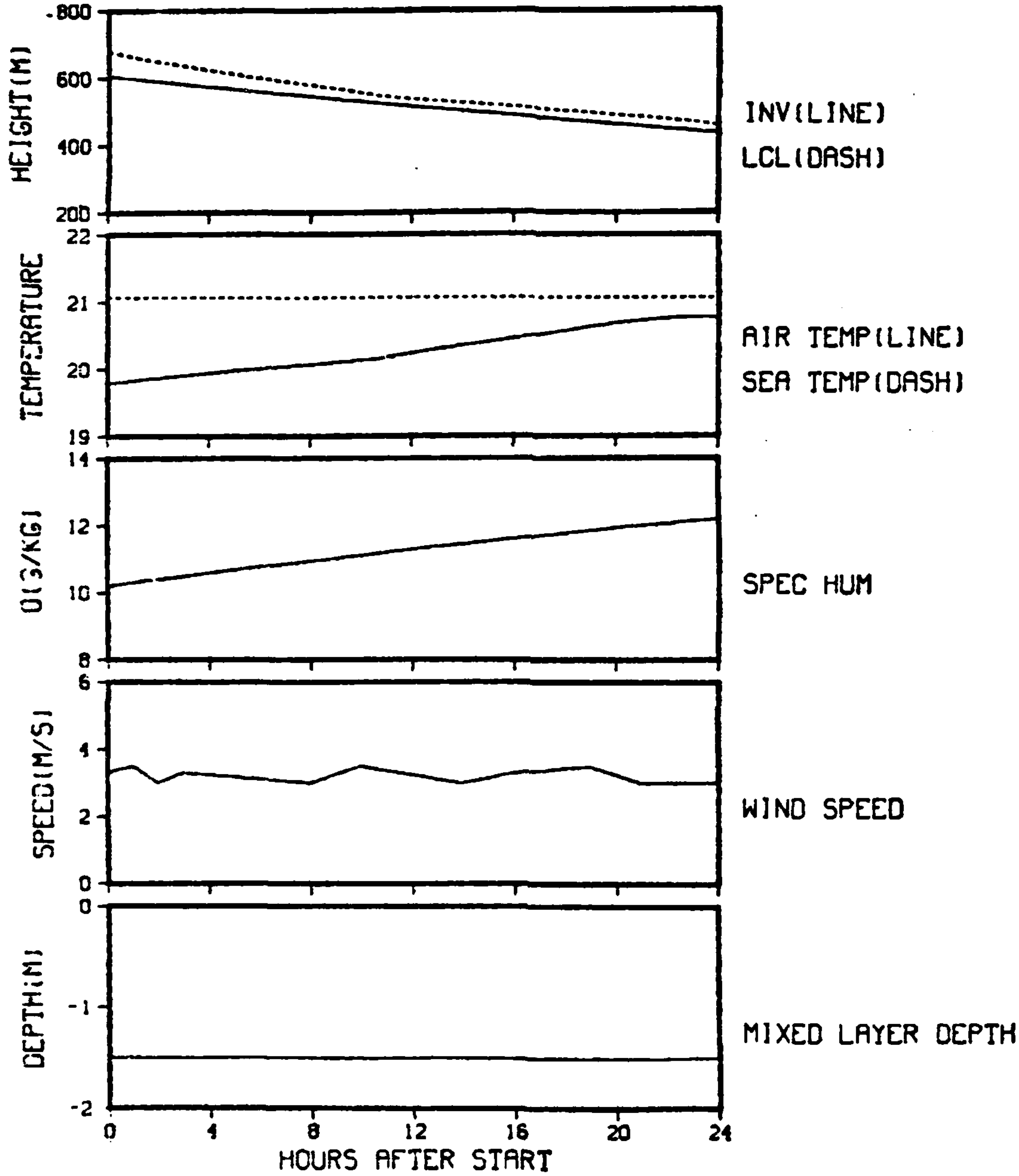

Figure 8. Uncoupled Air Sea Boundary Layer Model 24-Hour Forecast Using Fixed SST and MLD Values

Winds for this run were forecast to remain light and variable and generally out of the north. The specific humidity shows an almost linear rise throughout the forecast period as heat and moisture is transferred from the ocean surface into the MABL. Evidence of this heating can also be found in the plot for the MABL temperature. The plot shows an almost linear increase toward the sea surface temperature (SST) during the first 20 hours. Looking closely, a slight steepening of the gradient does occur with the rising of the sun, and the gradient decreases sharply late in the period as the solar altitude decreases and the strong temperature difference has been removed. The difference in height of the lifting condensation level (LCL) and the inversion decreases early in the period and then becomes parallel. Looking at this forecast, no clouds will form, however, the LCL and inversion height are very close together and asking a couple of the "what if" questions listed above would seem appropriate.

B. COUPLED MODEL RESULTS

In Figures 9 and 10 the differences in the coupled model output can be examined. As discussed earlier, many cause and effect relationships exist between the ocean and atmosphere. The changes in SST and mixed layer depth are input at each time step into the atmospheric model. Changes in air temperature and winds are fed back to the ocean model. It would

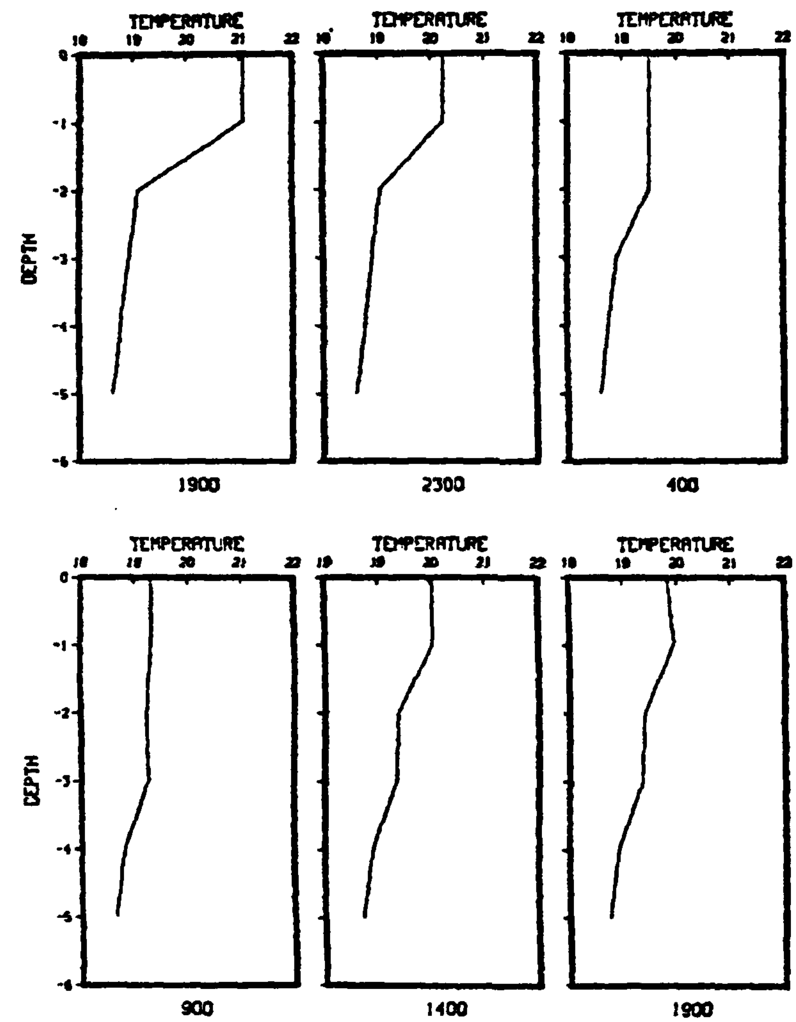

Figure 9. OBL 24-Hour Forecast for Original Input Conditions

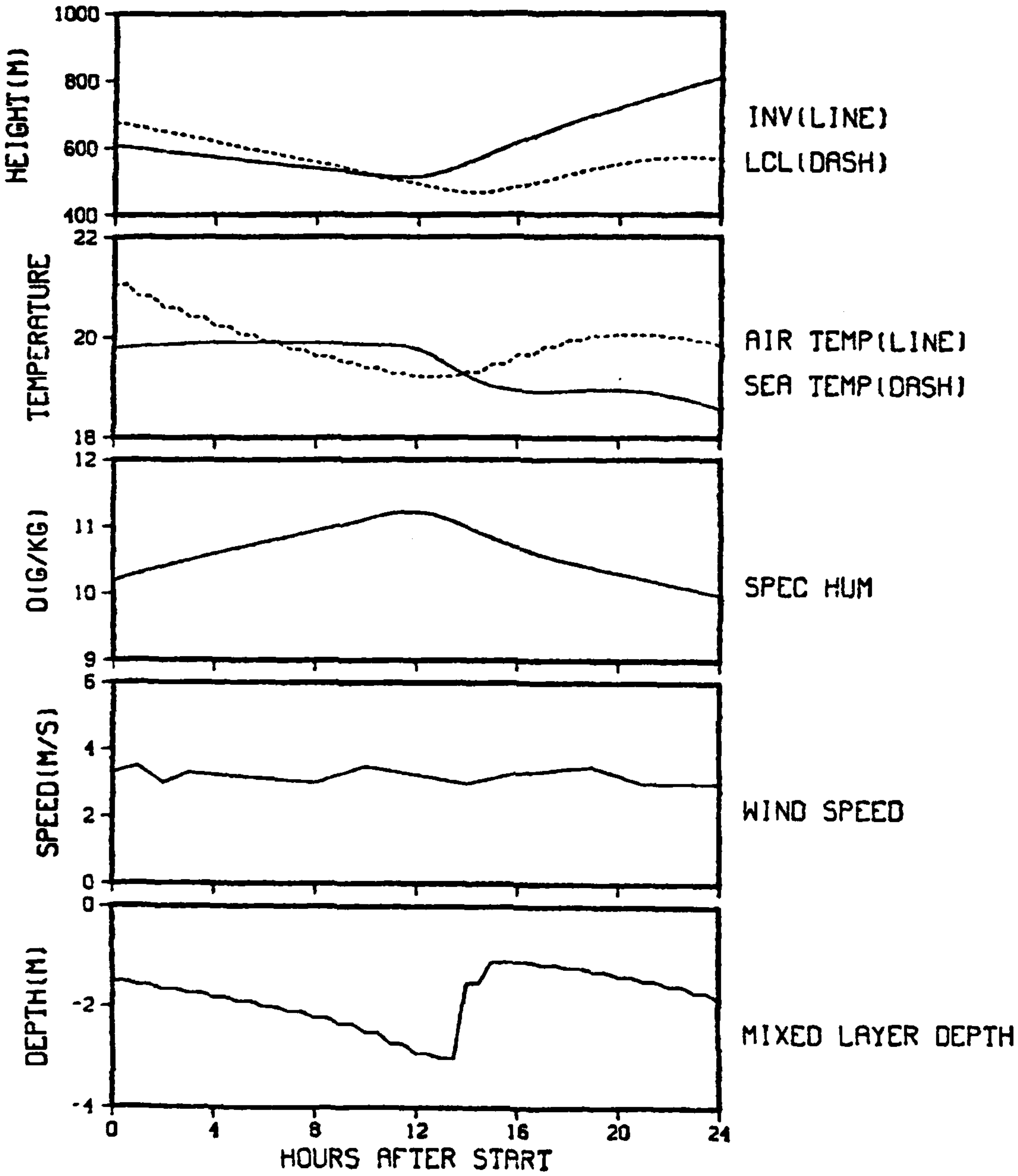

Figure 10. Coupled Air Sea Boundary Layer 24-Hour Forecast for Initial Input Conditions

seem logical that the coupled model should produce a better forecast since many of these factors are taken into account.

The strong gradient near the surface is evident in Figure 9. Note that a small decrease in temperature at the surface has a marked effect on the depth of the mixed layer. Throughout the early period heat is being transferred into the atmosphere with no replenishment. This trend is reversed later in the day when short wave radiation absorbed by the sea surface is converted into heat, re-establishing the shallow mixed layer. Changes in the mixed layer are also traced in the lower plot of Figure 10. The wind speed has been prescribed and is the same as for the previous case. The specific humidity curve is markedly different. While the early results show the same increase approximately 14 hours into the forecast, a strong decrease is noted in the specific humidity. This change is associated with the formation of clouds in the MABL and reduction of the moisture flux as the atmosphere becomes warmer than the SST. The temperature profiles are also markedly different. Allowing the SST to vary at each time step allows the atmosphere and sea surface temperatures to come together very rapidly. The sea surface continues to cool until short wave radiation inputs reverse the trend. Early in the period the LCL and inversion heights are similar to the uncoupled case; however, the feedback process does allow the two levels to intersect, predicting the formation of a thin cloud deck. In time this cools the atmosphere by cloud top radiation, allowing the stratus deck to thicken as the inversion and LCL heights diverge. This case is obviously quite different from the uncoupled case, and it would result in a markedly different forecast.

C. COUPLED MODEL VARYING MIXED LAYER DEPTH RESULTS

As noted earlier, this model is useful in that it not only provides a 24-hour local forecast but conditions can be varied and examined for their effect on the output. A couple of "what if" circumstances will be examined for the current problem. First, "what if during local maneuvers of the task force an ocean front is crossed and the mixed layer is suddenly 10 meters deep rather than the current 2 meters?" Will this affect the model output? Examining Figure 11, the new MLD is evident with the same strong temperature gradient as in the previous case. Changes in surface temperature no longer have the strong effect on MLD previously noted. This is correct as the heat capacity of a 10 meter mixed layer is much greater than that of a 2 meter mixed layer. The near surface heating which took place in the previous case late in the period is also repeated in this case. A time variance of the surface MLD is shown graphically in the lower panel of Figure 12. The same wind speed profile as used in the two previous cases is evident. Of interest is the large variance in the specific humidity profile.

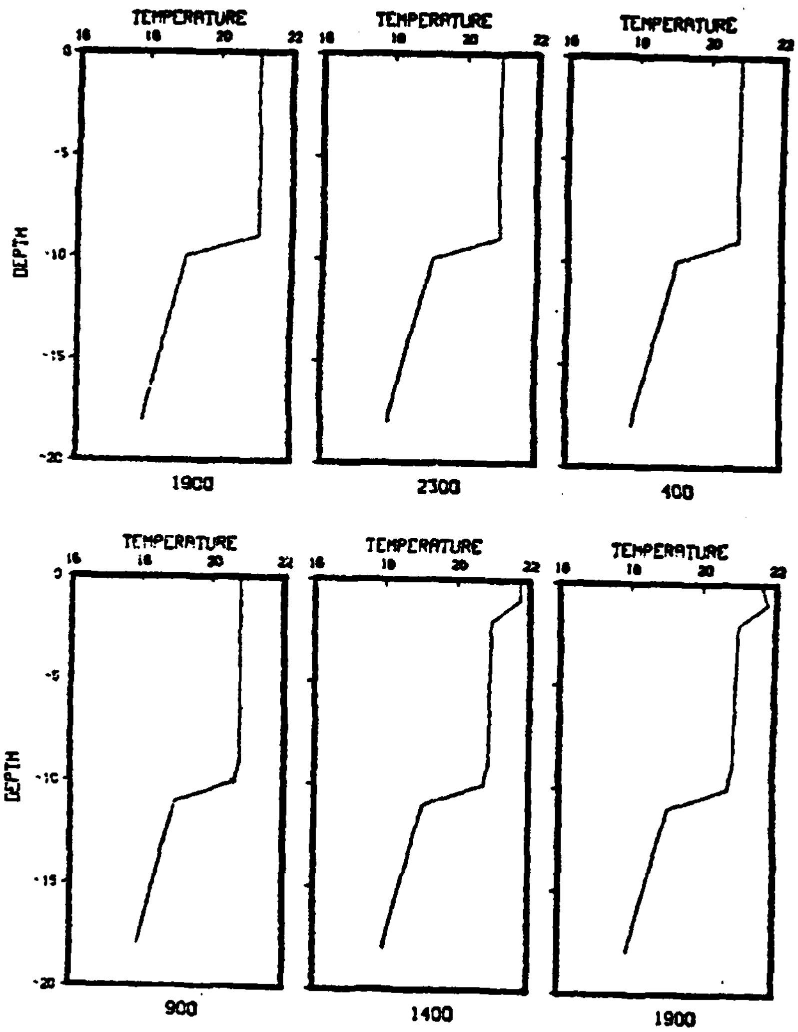

Figure 11. OBL Forecast With Initial MLD Set at 10 Meters. All Other Input Values are Held Constant

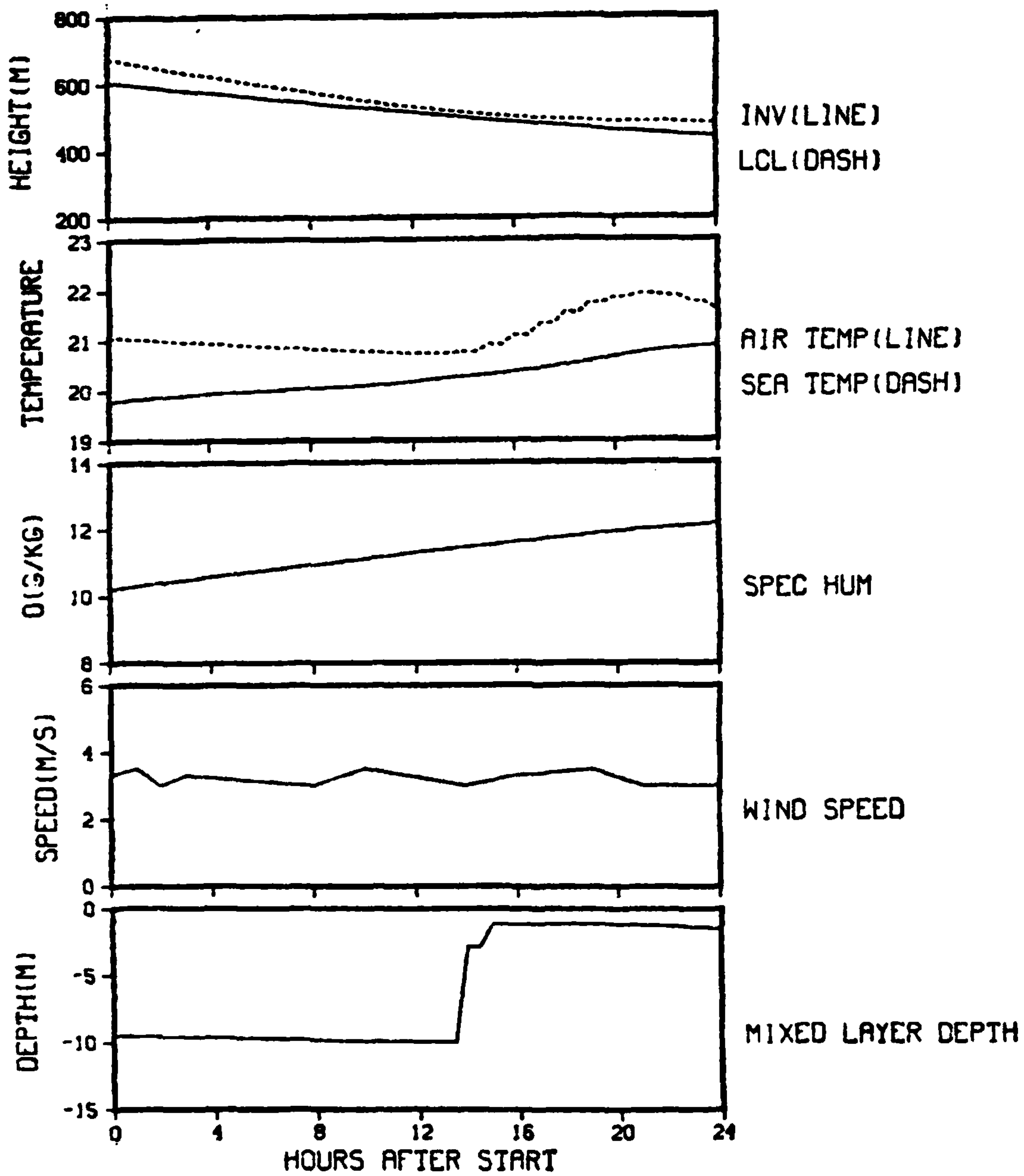

Figure 12. Coupled Air Sea Boundary Layer 24-Hour Forecast Varying Initial Sea Surface MLD to 10 Meters Vice Initial Input of 2 Meters

This case looks identical to the uncoupled case with no humidity decrease as in the previous case. The air temperature profile also matches the uncoupled case while the SST has the same trends as in the coupled case. The amplitude of variance is much less in this case, and the SST and air temperature are never equal. As discussed before, heat and moisture are being transferred into the atmosphere. However, prior to the two temperatures becoming equal, the effects of solar radiation upon the SST cause the two temperatures to diverge again. The LCL and inversion plots also have the same general characteristics of the uncoupled model. The only difference is the slight divergence of the two heights late in the period which results in no clouds being formed during the period.

D. COUPLED MODEL VARYING WIND SPEED RESULTS

The second "what if" case to be examined is one in which the wind speed is varied. What if the winds increased from the current conditions to 10 knots late in the period? As shown in Figure 13, the extra mixing reduces the SST rapidly and drives the MLD down much more rapidly than in the previous cases. The early temperature reduction is much stronger than in previous cases. There is no near surface heating late in the period which occurred in both of the coupled cases examined previously. The rapid decrease in MLD is again

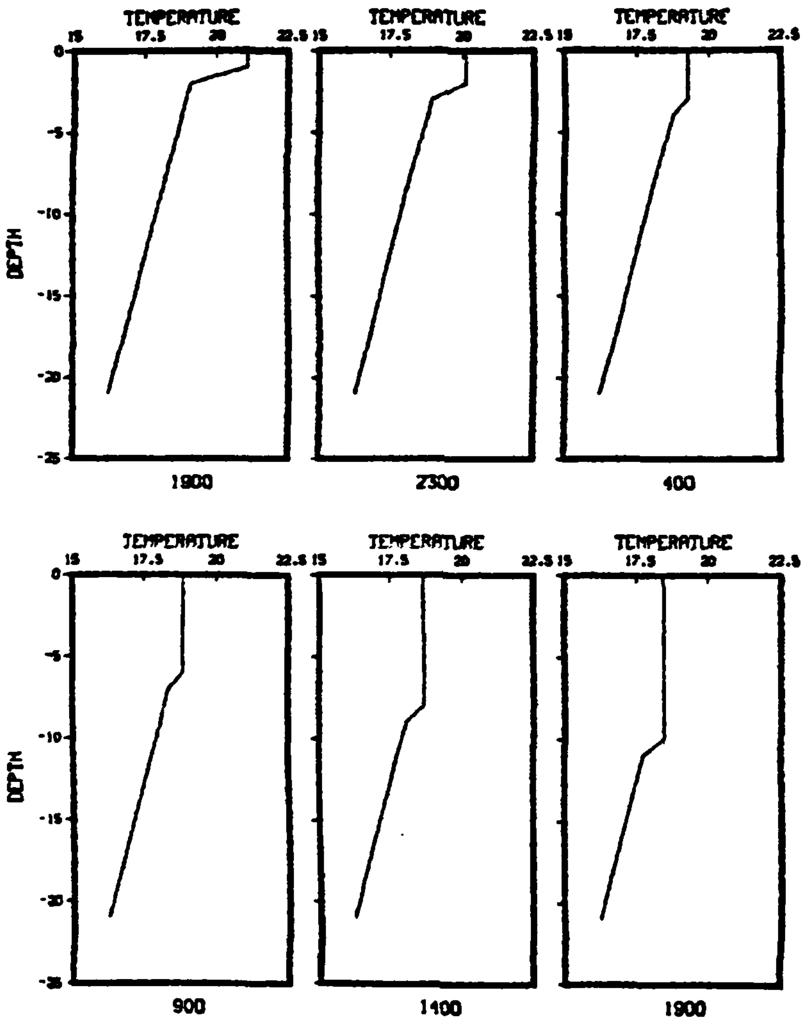

Figure 13. OBL 24-Hour Forecast With Wind Speed Increasing from 4 to 10 Knots in the Forecast Period

shown graphically in the lower panel of Figure 14. The slow increase in wind speed is depicted in the next panel.

The specific humidity has the same general trends shown in Figure 10; however, the gradients are much steeper early in the period and fall off rapidly when clouds begin to form. The increased wind speed allows the heat and moisture to be transferred into the atmosphere much faster than in the previous cases. This increased mixing is also apparent in the rapid convergence of the sea surface and air temperatures. Also, the SST shows a continual decrease throughout the period as heat is transferred out of the water creating convective turbulence in the upper ocean. However, the early formation of clouds effectively reduces the incoming short wave radiation which would heat the sea surface.

Cloud top cooling affects the MABL temperature between 6 and 10 hours into the forecast period. However, this effect is negated by the trapping of heat in the boundary layer between the stratus deck and the sea surface. This effect is apparent during the latter half of the model run. The inversion height moves above the LCL almost immediately after the first increase in wind speed. As the wind increases, the depth of the stratus layer also increases. While the initial cloud top cooling does lower the LCL slightly, the surface heating quickly overcomes this effect. This causes the LCL to rise late in the period and affects cloud base height.

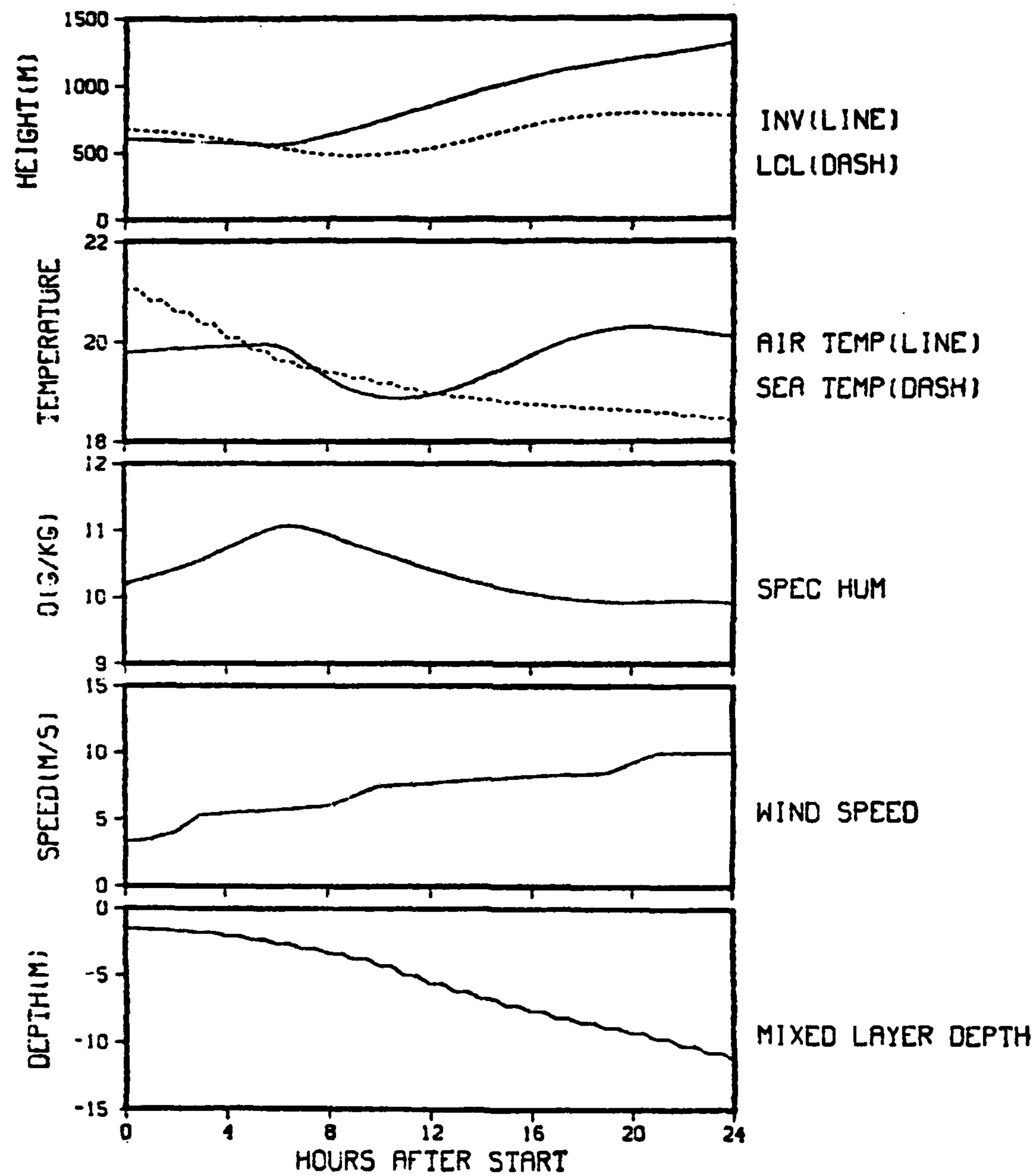

Figure 14. Coupled Air Sea Boundary Layer 24-Hour Forecast Varying Wind Speed from 4 to 10 Knots in the Forecast Period

V. RESULTS AND CONCLUSIONS

While no verification data exist to indicate which of the above forecasts was most correct, the primary goal of showing the utilization of the model has been demonstrated. As with any computer generated product, the forecast generated is a direct reflection of the quality of the initialization data. The finest computer model will generate poor output given poor input. The requirement for more man-machine cooperation with this model is such that, with the use of a little common sense and some meteorological theory, the program should prove useful to the naval geophysicist. Operating in data space regions and often adverse communications areas the ability to use local conditions as inputs to a locally generated forecast should improve forecaster performance.

In the numerous runs which have been completed the performance of the model has proven to be at least a good predictor of trends. While often little difference exists between the coupled and uncoupled model outputs it is those cases which are critical to naval operations that the difference is appreciable. Regions of fog and stratus formation is one of these circumstances. The formation of fog can be critical to the ability of naval aircraft being able to accomplish their mission.

EM/EO propogation is strongly affected by changes in the temperature and/or humidity profiles. The ability for a task force screen to properly guard a carrier or for a task force to remain hidden from enemy radar lies in its ability to properly use the environment. Changes in the MLD and the subsequent focusing or ducting of sound can be used to find enemy targets as well as to hide convoy noise from these same forces.

Improvements in model input techniques and coupling of output from this model to IREPS would provide an improved package. Making inputs as straight forward and non-subjective as possible will aid the fleet operator in obtaining a useful product for presentation purposes. Having an onboard capability to produce short range single station forecasts should help the environmentalists in better serving fleet operations. Through proper use of the Air-Sea Boundary Layer Model and other environmental data, the trust in forecasts presented should improve, and the readiness of other fleet units will improve by the efforts of the entire geophysics community.

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