ANL/OTEC-EV-3

A Far-Field Model of the Regional Influence of Effluent Plumes from Ocean Thermal Energy Conversion (OTEC) Plants

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by

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FOREWORD

This report presents the results of a research project, entitled *Regional Influence of OTEC Operation*, that was undertaken for the Ocean Minerals and Energy Division of the National Oceanic and Atmospheric Administration (NOAA) under Order No. NA-82-AAG-03675. It was initiated by NOAA in response to specific requirements of the Ocean Thermal Energy Conversion (OTEC) Act of 1980 (Public Law 96-320). The Act requires licensing of commercial OTEC plants to proceed in a manner compatible with protecting the marine environment and with other uses of the ocean. Regulations concerning licensing* and an environmental research plan‡ acknowledge that an important aspect of licensing activities is identifying the area or region of the ocean likely to be influenced by operation of one or more OTEC plants.

"Influence" can be defined in several ways -- in physical terms, such as modification of the local ocean temperature structure, or in more subtle ecosystem terms, such as the redistribution of nutrients in the water column or the effect on fisheries. To understand influence, a description is needed of the physical processes associated with discharge of large volumes of cold water into the upper ocean by OTEC plant operation. Both the fate of the cold water effluent in the upper ocean and the circulation induced by its discharge provide bases for understanding the influence of OTEC plant operation.

The approach taken in this study departs from those of previous mathematical modeling investigations of OTEC plant interactions with the ocean environment. In those models, effluent plumes and intake flows were superposed on fixed ambient ocean waters; that is, no way was provided to model changes in the ocean resulting from discharge.§ Such modeling provides a useful basis for screening procedures for license

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*National Oceanic and Atmospheric Administration, *Licensing of Ocean Thermal Energy Conversion Facilities and Plantships (as amended by 46 FR 61643 et seq., Dec. 18, 1981)*, 147 Fed. Reg. 39,388-39,420 (to be codified at 15 C.F.R. §§981) (1981).

‡National Oceanic and Atmospheric Administration, *Ocean Thermal Energy Conversion: Environmental Effects Assessment Program Plan, 1981-85*, Office of Ocean Minerals and Energy (1982).

§National Oceanic and Atmospheric Administration, *Final Environmental Impact Statement for Commercial Ocean Thermal Energy Conversion (OTEC) Licensing*, Office of Ocean Minerals and Energy (1981), and Paddock, R.A., and J.D. Ditmars, *Comparison of Limited Measurements of the OTEC-1 Plume with Analytical Model Predictions*, Argonne National Laboratory Report ANL/OTEC-EV-1 (1981).

applications as developed earlier for NOAA,* but it cannot address the effluent-ocean interactions that modify the ambient ocean. The present effort models the interaction of the discharge with the ocean, which permits determination of the modifications to the ambient ocean induced by the discharge. Changes in ambient circulation, temperature structure, and concentration of effluent and water column constituents are modeled.

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*Paddock, R.A., and J.D. Ditmars, *Initial Screening of License Applications for Ocean Thermal Energy Conversion (OTEC) Plants with Regard to Their Interaction with the Environment*, Argonne National Laboratory Report ANL/OTEC-EV-2 (Feb. 1983).

A FAR-FIELD MODEL OF THE REGIONAL INFLUENCE OF EFFLUENT PLUMES FROM OCEAN THERMAL ENERGY CONVERSION (OTEC) PLANTS

by

Dong-Ping Wang

ABSTRACT

Ocean thermal energy conversion (OTEC) plants discharge large volumes of cold water into the upper ocean. A three-dimensional, limited-area model was developed to investigate the regional influence of the far-field effluent plume created by the negatively buoyant discharge. The model was applied to discharges from a 40-MW_e OTEC plant into coastal waters characterized by various ambient ocean conditions. A typical ambient temperature structure and nutrient distribution, as well as the behavior of the effluent plume itself, were strongly modified by the discharge-induced circulation. Although temperature perturbations in the plume were small, upward entrainment of nutrients from below the thermocline was significant. The regional influence of discharges from an 80-MW_e OTEC plant, the interactions between the discharges from two adjacent 40-MW_e OTEC plants, and the effects of coastal boundary and bottom discharge were examined with respect to the regional influence of a 40-MW_e OTEC plant located in deep water off a coast (base case).

1 INTRODUCTION

1.1 ASSESSING ENVIRONMENTAL IMPACT

Ocean thermal energy conversion (OTEC) plants generate power by exploiting the temperature difference between the warm surface water and the cold deep water (750-1000 m) of subtropical and tropical oceans. The relatively small temperature difference (on the order of 20C°) available to run the heat engine requires that large quantities of warm and cold water pass through the facility. Warm and cold water flow rates of approximately 3-4 m^3/s each are required for each megawatt of net electrical energy generated by a closed-cycle OTEC plant.

After passing through the heat exchangers, the warm and cold water streams are discharged into the ocean, usually as a mixed effluent. For OTEC plants located offshore in deep water, the effluent discharge ports will probably be located in the upper 100 m of the ocean. The negative buoyancy of the mixed effluent carries it down and away from the warm-water intakes in the immediate vicinity of the facility (see Fig. 1). Nearshore OTEC plants could have their discharge structures near the bottom in relatively shallow water (see Fig. 2). However, concerns about recirculation of cool effluent to the warm-water intake and about nearshore environmental effects have resulted in designs that call for relatively long effluent pipelines from nearshore facilities to deeper waters offshore.

Many of the environmental concerns about OTEC facilities have centered on the large effluent flows and their effect on the ambient ocean. The mixed effluent adds to the ocean substances such as biocides (e.g., chlorine), which are used to control biofouling in the heat exchangers, and trace metals, which are the products of corrosion of heat exchanger components. Ambient distributions of temperature, nutrients, and other ocean constituents may be modified by the transfer of surface and deep waters to intermediate depths by the operation of an OTEC facility and by the circulation induced by the discharges. Finally, entrainment of planktonic organisms into the effluent plume (secondary entrainment) may affect primary production.

Predictions and interpretations related to the complex chemical and biological changes caused by OTEC plant operation must rely on accurate descriptions of the physical processes associated with the interactions between the effluent plume and the ocean. In other words, determining the regional influence of operating OTEC plants, whether defined in thermal, chemical, or biological terms, depends on the ability to predict the behavior of effluent plumes.

1.2 PREDICTING THE BEHAVIOR OF FAR-FIELD PLUMES

Typical operating temperatures for an OTEC plant are 5°C for the cold water and 25°C for the warm water. For a 40-MW_e OTEC plant, a mixed effluent of 15°C water would have a flow rate of about 280 m^3/s.

In the open ocean, areas of OTEC plant influence can be conveniently divided into the near field and the far field, based on the length scales of the physical processes important in each. In the near field, the effluent is characterized by a buoyant jet with high initial speed on the order of 1 m/s and with a dilution ratio on the order of 10. In the far field, the effluent is characterized by a buoyant plume, which drifts at about ambient ocean current speed and spreads laterally in response to gravity. (For certain analytical applications, the far field is subdivided into an intermediate field of active buoyancy spreading and a far field of passive dispersion.) The transition from a near-field jet to a far-field plume typically takes place at a distance of a few hundred meters from the plant and is accompanied by collapse of the jet at the equilibrium depth, or the level of neutral buoyancy of the diluted effluent.

Because the residence time for effluents in the near field is short, that is, on the order of 10 min, the far field is probably where the most influence is exerted with regard to regional environmental influence. Jirka et al. analyzed the spreading of a buoyant plume in a density-stratified environment by means of an integral model.[1] Their results indicate that for a 40-MW_e OTEC plant in typical ambient ocean conditions, the effluent plume is about 10 m thick and 5 km wide. Clearly, the horizontal extent of the far field is comparable with island shelf areas, which suggests appreciable influence, even for a

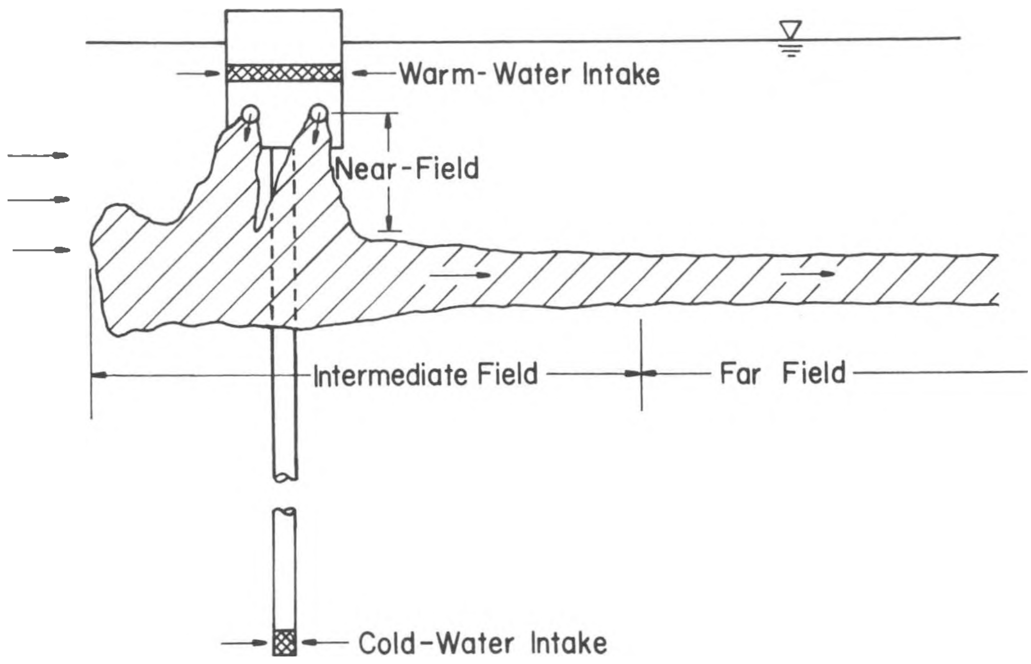

FIGURE 1 Schematic Diagram of an OTEC Plant Sited in Deep Water

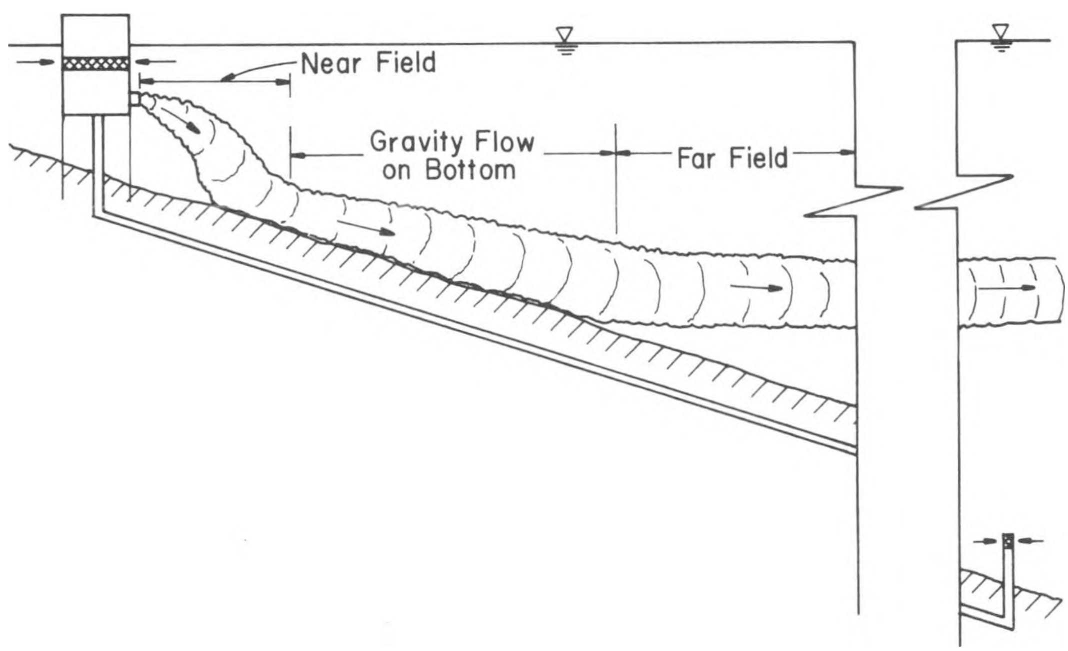

FIGURE 2 Schematic Diagram of an OTEC Plant Sited in Shallow Water

single OTEC plant of modest size in an island coastal environment. However, the integral model of Jirka et al. superposes the plume on a fixed ambient ocean; that is, it does not compute interactions between the plume and the ambient ocean. Hence, the model cannot address the important question of redistribution of water mass caused by circulation induced by the plume. Also, it is difficult to apply such an integral model to a coastal region where the effect of boundary geometry is important.

1.3 PURPOSE AND SCOPE

The purpose of this study is to investigate the regional influence of an OTEC plant in terms of the modifications to the physical ocean environment caused by the far-field effluent plume. A three-dimensional numerical model of the interaction between the OTEC effluent and the ocean at a regional scale was developed by modifying a three-dimensional ocean circulation model[2] to include the effects of discharges from an OTEC plant. While the model is in principle quite general, it was used here for the specific task of investigating regional influence for a set of important generic conditions. Although site-specific application of the model is possible, it was not the goal of the present work. Consequently, the report is not a user's manual. It focuses on the model predictions of plume behavior and the implications of such behavior for regional influence. The formulation of the model is described in Sec. 2.

The results of using the model to investigate regional influence are presented in the following manner: first, the behavior of the far-field plume is explained for a base case, and second, the results of studies of other generic conditions are related to those of the base case. The base case (described in Sec. 3) is that of a 40-MW_e OTEC plant sited in deep water off a coast. The mixed effluent is released into the upper ocean. The steady state distributions of velocity and temperature in the region were examined for both zero and typical ambient coastal currents. The plant effluent was modeled as containing dye to indicate the conservative fate of such effluent constituents as biocides or trace metals. Any modifications to the distribution of other constituents naturally distributed as a function of depth, such as nutrients, were predicted. The sensitivity of the model to parameterization of turbulent mixing and to plant intakes was studied.

The model was also applied under similar conditions to (1) an 80-MW_e OTEC plant located on the coastal margin; (2) two 40-MW_e OTEC facilities sited near each other, for the purpose of examining interference effects; (3) a 40-MW_e plant located farther offshore; and (4) the case of near-bottom discharge on a slope. The results of these applications and their implications for OTEC regional influence are summarized in Sec. 4.

2 MODEL FORMULATION

The model developed for this study is a limited-area model of the portion of the ocean that contains OTEC effluent. It differs from previous models of the far field in that it does not superpose the effluent on a fixed ambient ocean. Because superposition is avoided, the interactions between the plume and the ocean can be modeled -- the model simply does not distinguish between the plume and ambient ocean water.

The circulation model that was modified for this study[2] had been developed for simulating the naturally occurring circulation and temperature structure in a limited-area shelf region. The modified model simulates velocity and scalar fields at regional oceanographic scales but cannot treat the near-field behavior of the effluent in detail. Rather, the model requires external knowledge (i.e., near-field jet model results) to provide the basis for parameterization of the discharge close to the facility.

The model described below considers, for simplicity, discharges from a single facility. Multiple discharges (sources) can be modeled, however, and an application with two OTEC plants in relatively close proximity is treated in Sec. 4. As formulated here, the warm-water intake (sink) is not included in the model. The effects of near-surface intake on the upper ocean flow field are mainly confined to the region extremely close to the plant and are negligible in the far field relative to other motions, as demonstrated in Sec. 3. The cold-water intake also is not included because it is located well below the region of interest for the effluent plume, as indicated by the results presented in Sec. 3.

The far-field model developed for this study simulates the gravitational spreading of a buoyant discharge. Because gravitational spreading occurs in a horizontal plane, the vertical height of the effluent plume will be much smaller than the horizontal length, which means that the pressure will be essentially hydrostatic. The equations of motion for this case are:

$$\frac{\partial}{\partial t}u + \frac{\partial}{\partial x}(uu) + \frac{\partial}{\partial y}(vu) + \frac{\partial}{\partial z}(wu) - fv = -\frac{1}{\rho_o}\frac{\partial P}{\partial x} + \frac{\partial}{\partial z}(A_V \frac{\partial u}{\partial z}) + A_H \nabla_H^2 u \qquad (1)$$

$$\frac{\partial}{\partial t}v + \frac{\partial}{\partial x}(uv) + \frac{\partial}{\partial y}(vv) + \frac{\partial}{\partial z}(wv) + fu = -\frac{1}{\rho_o}\frac{\partial P}{\partial y} + \frac{\partial}{\partial z}(A_V \frac{\partial v}{\partial z}) + A_H \nabla_H^2 v \qquad (2)$$

$$0 = -\frac{\partial P}{\partial z} + g\rho \qquad (3)$$

$$\frac{\partial}{\partial t}T + \frac{\partial}{\partial x}(uT) + \frac{\partial}{\partial y}(vT) + \frac{\partial}{\partial z}(wT) = \frac{\partial}{\partial z}(k_V \frac{\partial T}{\partial z}) + k_H \nabla_H^2 T + Q_T \qquad (4)$$

$$\frac{\partial}{\partial x}u + \frac{\partial}{\partial y}v + \frac{\partial}{\partial z}w = Q_M \qquad (5)$$

$$\rho = \rho_o - \alpha T \qquad (6)$$

where:

x = cross shore coordinate,

y = alongshore coordinate,

z = vertical coordinate,

t = time,

u = cross shore velocity,

v = alongshore velocity,

w = vertical velocity,

f = Coriolis parameter,

P = pressure,

A_V = vertical eddy viscosity,

A_H = horizontal eddy viscosity,

g = gravity constant,

ρ = density,

ρ_o = reference density,

T = temperature,

k_V = vertical eddy diffusivity,

k_H = horizontal eddy diffusivity,

Q_T = heat source,

Q_M = mass source,

α = thermal expansion coefficient, and

$$\nabla_H^2(\;) = \frac{\partial^2(\;)}{\partial x^2} + \frac{\partial^2(\;)}{\partial y^2}.$$

A simplified equation of state is used in which the density depends on temperature only. (Although including a more complete equation of state is straightforward, Eq. 6 is adequate for most tropical ocean applications.)

In Eqs. 4 and 5, the heat and mass sources represent the near-field effects of the OTEC buoyant discharge. Because the near-field processes are not modeled explicitly, the source terms must be parameterized. Given conservation of mass and heat flux at the discharge location (x_o,y_o):

$$\Delta x \Delta y \int_{-H}^{0} Q_M(z)\, dz = Q_o \qquad (7)$$

$$\Delta x \Delta y \int_{-H}^{0} Q_T(z)\, dz = Q_o T_o \qquad (8)$$

where:

Δx = cross shore grid spacing,

Δy = alongshore grid spacing,

H = total water depth,

Q_o = discharge volume flux, and

T_o = discharge temperature.

In Eqs. 7 and 8, the model horizontal grid spacings are assumed to be larger than the near-field plume dimensions, so that the far-field solutions depend only on vertical distributions of the near-field plume. This assumption is consistent with the hydrostatic approximation in Eq. 3 that $\Delta z << \Delta x, \Delta y$. The vertical distributions of Q_M and Q_T generally are not equal; however, a simple z-dependence, f(z), is assumed for both Q_M and Q_T:

$$\begin{aligned} f(z) &= 1 \text{ if } -H_2 \leq z \leq -H_1 \\ &= 0 \text{ otherwise} \end{aligned} \qquad (9)$$

where H_1 and H_2 define the height of the near-field plume at the equilibrium depth, as indicated in Fig. 3. An integral jet model is used to guide the choice of H_1 and H_2.[3,4] The results of physical model studies of near-field plumes can be used as well. Because the details of the near-field plume are not parameterized in the far-field model, both single- and multiple-effluent outlets in close proximity can be handled so long as the vertical distribution, or thickness, of the resulting plume at the end of near-field mixing is known. Although separate warm-water and cold-water effluents can be simulated, only mixed effluents are treated in this report.

Equations 7-9 completely specify the mass and heat sources. In general, the horizontal momentum flux of the initial jet will also affect the far field. However, a momentum source is not included in Eqs. 1 and 2 because the dissipation of momentum flux cannot be adequately modeled in the far field. The buoyancy effect is expected to dominate gravitational spreading, and the neglect of a momentum source probably has little effect on the far-field solution.

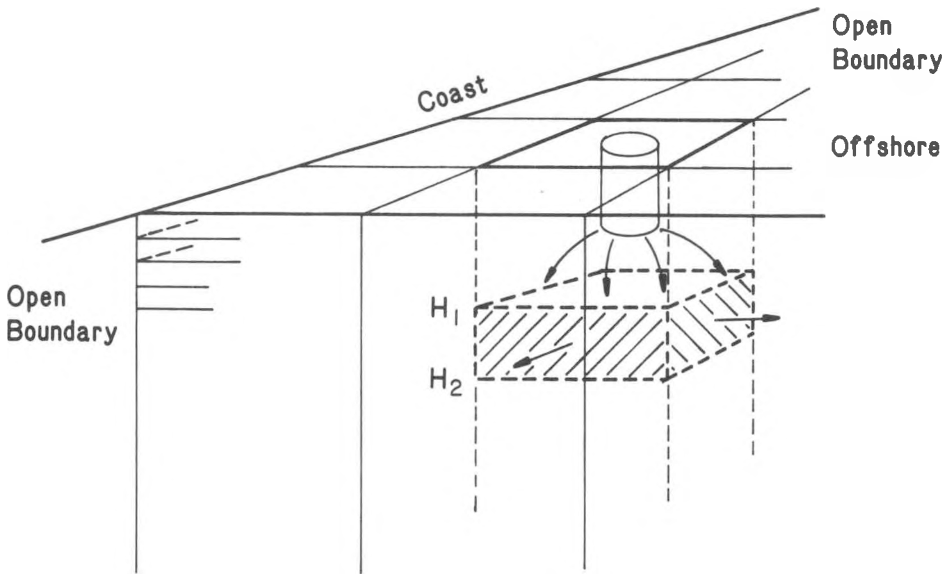

FIGURE 3 Region Modeled

An equation for a passive tracer in the discharge is also included:

$$\frac{\partial}{\partial t}D + \frac{\partial}{\partial x}(uD) + \frac{\partial}{\partial y}(vD) + \frac{\partial}{\partial z}(wD) = \frac{\partial}{\partial z}\left(k_V \frac{\partial D}{\partial z}\right) + k_H \nabla_H^2 D + Q_D \qquad (10)$$

where D is the tracer concentration and $Q_D = Q_M \cdot D_o$, with D_o being the discharge concentration. The tracer can represent biocides, metals, or other substances likely to be in the effluent but not likely to have significant concentrations in the ambient ocean. Thus, the tracer can define the effluent plume. The tracer can also represent a constituent that is present, though in different concentrations, in both the discharge and ocean (e.g., a particular nutrient).

The governing equations (Eqs. 1-10) are solved numerically using a finite-difference method.[2] The physical boundaries for the model include a straight coastline and a constant water depth, except for the sloping-bottom application. In the open ocean, a computational boundary is specified at a distance far from the OTEC plant (source). The initial conditions (ocean undisturbed by OTEC operation) include the distributions of ambient ocean temperature, current velocity, and tracer concentration. The boundary conditions are: no heat or mass flux at the coast, no surface or bottom heat flux, no surface wind stress, and a bottom drag force. At the open boundaries, radiation conditions are used to ensure minimum interference from the computational boundary on the interior solutions.[5] The computation is transient, beginning with the undisturbed ambient ocean state prior to introduction of the OTEC plant effluent and continuing until a "steady state" circulation field is established.

Differences exist between the general capabilities of the model and the relatively simple geometries and conditions assumed in this study. In principle, adding a more complex shoreline geometry, varying the water depth, and including a surface wind stress are rather easy to accomplish in a numerical model. However, the model need not be more complex for this study for the following reasons. The focus of the study was the behavior of the far-field plume. There was little point in confusing the effects of the buoyancy-driven effluent with those of other phenomena. Moreover, while the precursor to this circulation model predicts gross shelf circulation features correctly, it has not been exercised for all complexities. As in all modeling, site-specific and geometry-specific applications require careful calibration and testing against data. Finally, certain complexities are not warranted simply because they have little effect on the primary variables under investigation. For example, as shown in Sec. 3, variations in water depth do not affect the far-field plume because it remains in the upper ocean.

3 BASE CASE: REGIONAL INFLUENCE OF A 40-MW_e OTEC PLANT

3.1 BASIC CONFIGURATION OF THE MODEL

The far-field model was applied to predict changes in circulation and temperature induced by a mixed effluent from a 40-MW_e OTEC plant located in deep water off a coast. The model assumes a constant depth (H = 160 m), which is a small fraction of the ocean depth (>2000 m). However, since computations indicate that gravitational spreading is confined to the upper 100 m, this idealization of the geometry has no effect on the far-field solution. The model's grid spacings are 500 m by 500 m in the horizontal and 20 m in the vertical dimensions. The discharge was introduced at 2 km alongshore within the first grid spacing, that is, at less than 500 m from the coast (see Fig. 4).

The mixed effluent is characterized by discharge of 15°C water at a flow rate of 280 m^3/s. The ambient ocean temperature profile (see Fig. 5) exhibits a well-mixed upper layer at less than 40 m and a sharp thermocline at about 80 m. In typical OTEC designs, water is discharged to the upper ocean. Studies of near-field jet behavior for a range of OTEC plant sizes and designs indicate that the jet occupies most of the upper ocean above the thermocline.[4] Calculations for the 40-MW_e plant and the ambient ocean conditions assumed in this application indicate that values of H_1 = 20 m and H_2 = 80 m are appropriate for the vertical range of the mass and heat sources.

Other model parameters are: $A_V = 50\ cm^2/s$, $k_V = 10\ cm^2/s$, and $A_H = k_H = 10^5\ cm^2/s$. The rotation of the earth is neglected, as model simulations that include rotation at 20°N indicate a similar flow pattern. Two model simulations were carried out, one with no ambient current and the other with a uniform alongshore current of 20 cm/s. The model circulation and temperature field results typically reached a steady state in less than 10 hr.

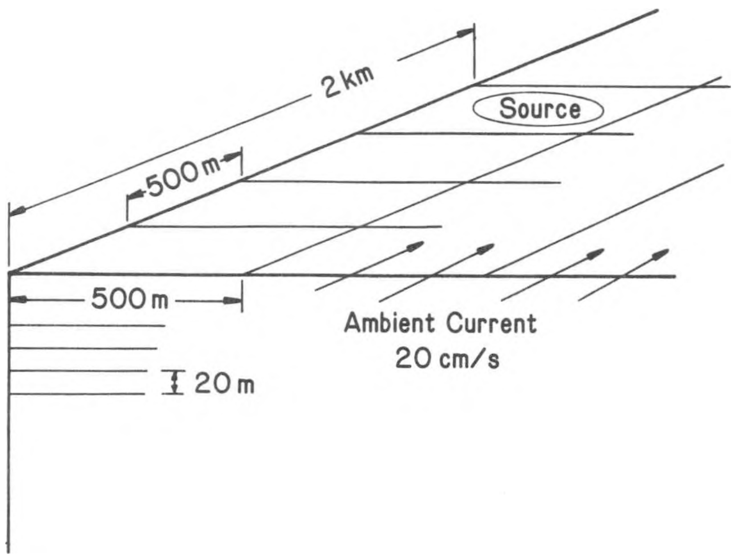

FIGURE 4 40-MW_e OTEC Plant Assumed for Base Case

3.2 EFFECTS OF A ZERO AMBIENT CURRENT

With zero ambient current, the flow pattern due to the buoyant effluent is symmetrical in the alongshore direction. Figure 6 shows the horizontal velocity distribution in the upper ocean at four levels; velocities below 80 m (thermocline) are very small. A strong two-layered flow is induced in the upper ocean, with a surface current moving towards the source (point of discharge) and a return flow at the top of the thermocline. The maximum velocity generated is about 7.5 cm/s.

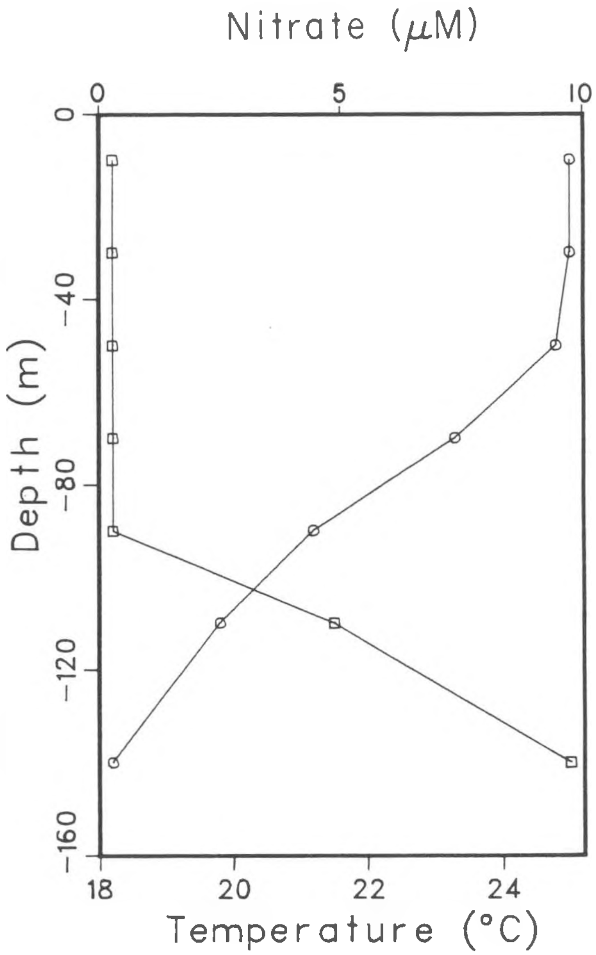

FIGURE 5 Vertical Profiles of Ambient Temperature (circles) and Nitrate (squares)

The temperature distribution in the upper ocean is shown in Fig. 7. The temperature is uniform (25°C) at the surface. In the subsurface, a thermal plume is formed, with a temperature perturbation from ambient values of about 0.2C°. Between depths of 20 m and 60 m, the plume is colder than the surrounding water; however, at the top of the thermocline, the plume is warmer. Although the plume contains cold mixed effluent, entrainment of warm surface water into the plume overcomes this initial temperature deficit by the time the plume reaches the top of the thermocline. The warm anomaly underneath the cold anomaly brings the total pressure perturbation in the upper ocean to zero. This result is consistent with gravitational spreading being confined to the upper ocean.

3.3 EFFECTS OF A 20-CM/S AMBIENT CURRENT

With an ambient alongshore current of 20 cm/s, the plume will be swept down current. Although changes in the ambient circulation field appear relatively small when viewed in terms of the total current, circulation has been impacted significantly by the buoyant discharge. The residual current induced by the OTEC discharge, that is, the difference between total current and ambient current, is shown in Fig. 8 at four levels. Compared to the zero-ambient-current case (see Fig. 6), the flow pattern shows a strong alongshore asymmetry. A sharp front containing strong vertical velocities is formed on the up-current side of the plume beyond which there is no residual current. On the other hand, the residual circulation stretches out on the down-current side. The maximum residual current is about 7 cm/s.

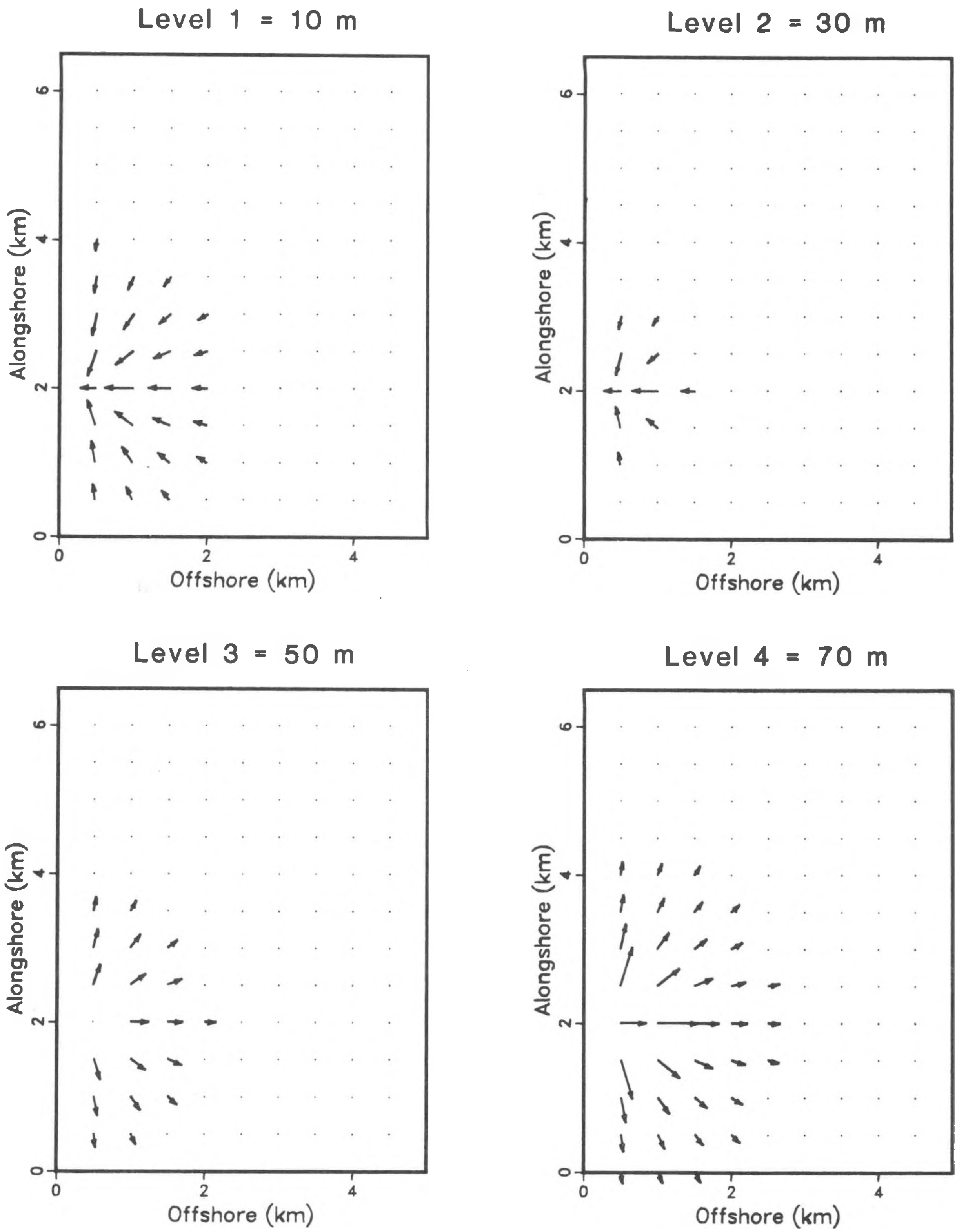

FIGURE 6 Horizontal Distribution of Velocity, with No Ambient Current (velocity scale = 7 cm/s between two grid points)

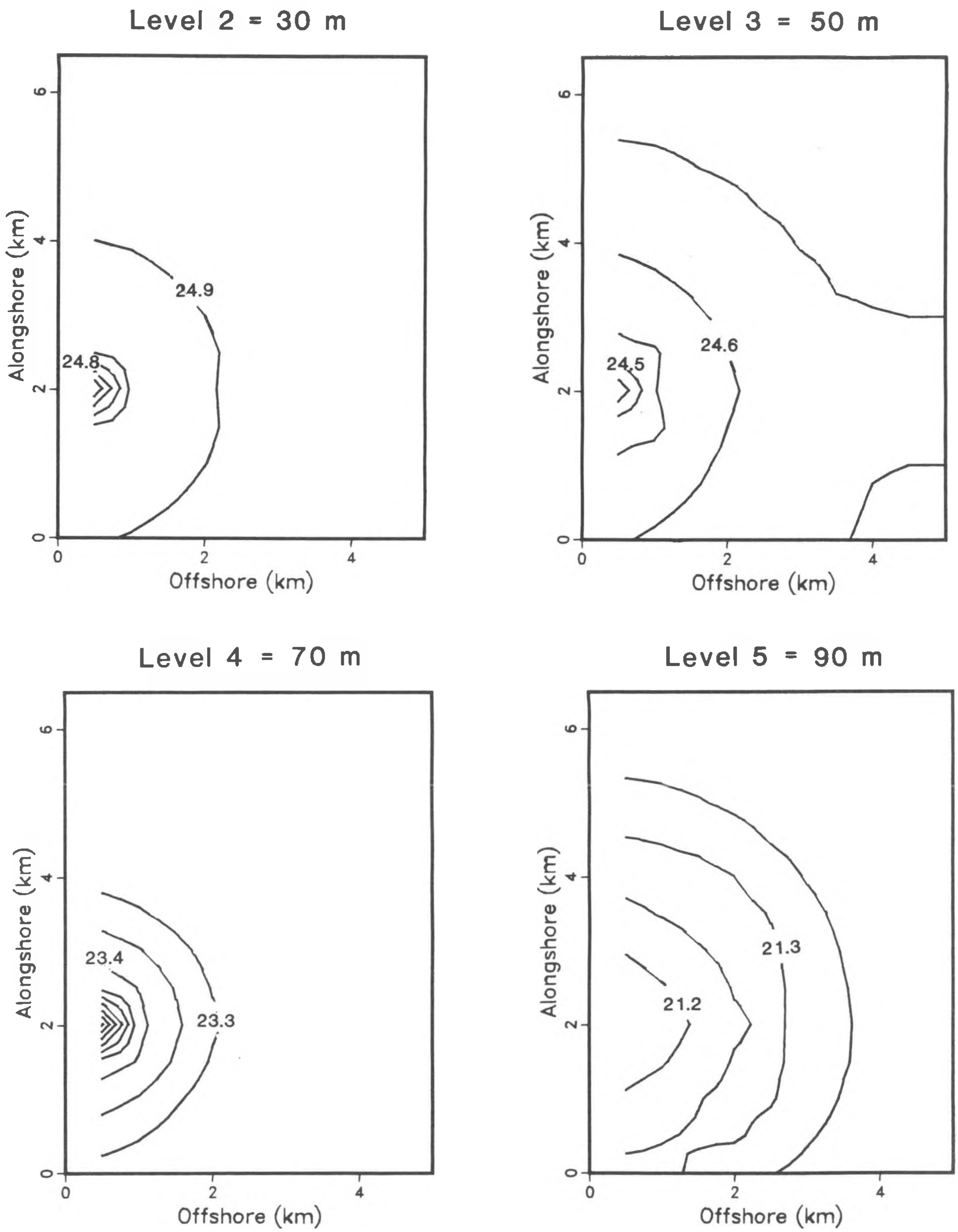

FIGURE 7 Horizontal Distribution of Temperature, with No Ambient Current (contour interval = 0.05°C)

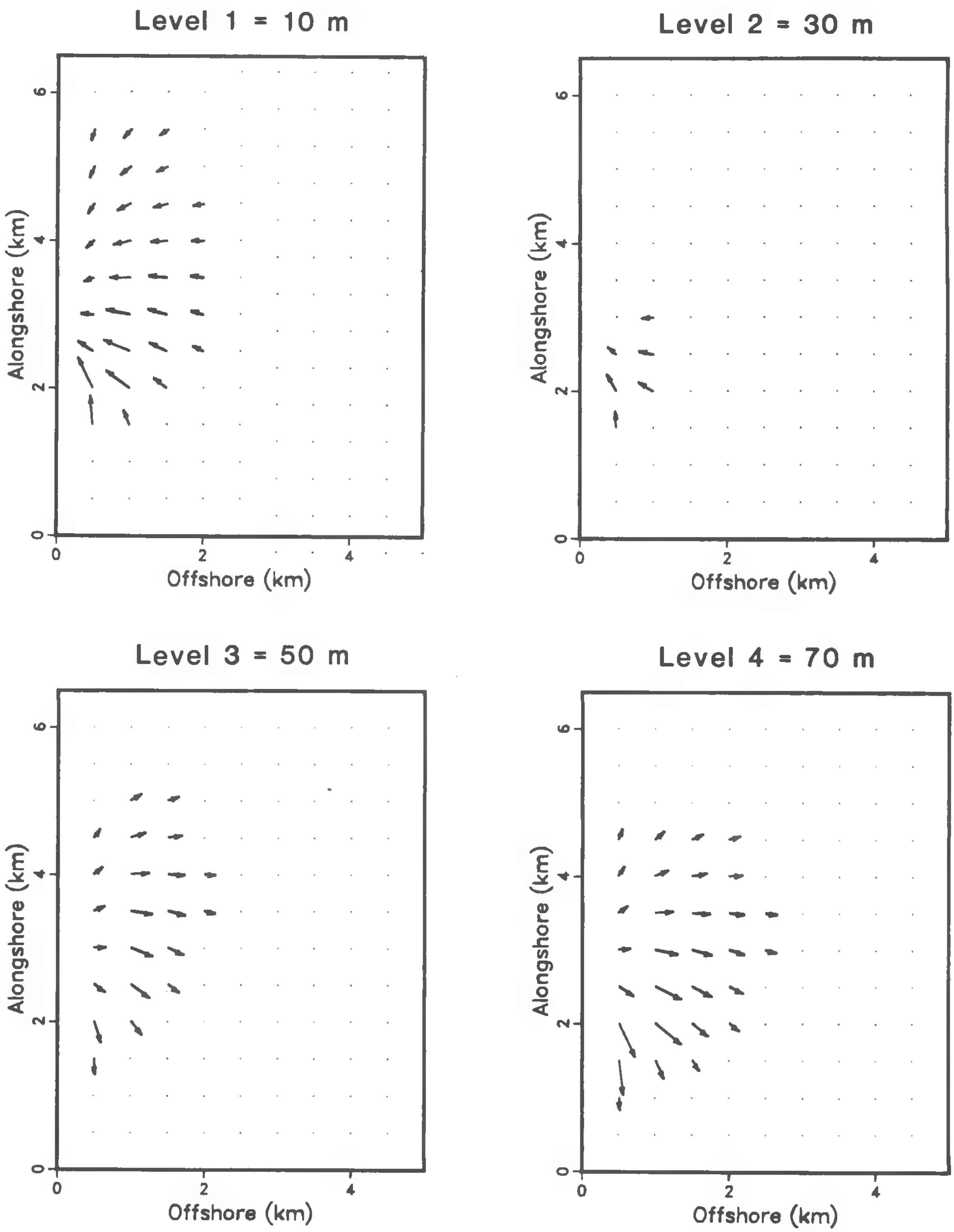

FIGURE 8 Horizontal Distribution of Residual Velocity (total velocity minus ambient velocity), with an Ambient Current of 20 cm/s Alongshore (velocity scale = 7 cm/s between two grid points)

The temperature distribution in Fig. 9 indicates a complex thermal plume. A temperature front, which coincides with the velocity front, is formed on the up-current side. On the down-current side, thermal plumes appear to be swept downstream and offshore at levels 3 and 4 (between 40 m and 80 m); in contrast, the plume is along the coast at level 2. The amplitude of temperature perturbations from ambient values is about 0.2C°, which is comparable to that in the no-ambient-current case.

The vertical circulation shown in Fig. 10 is for an alongshore section at 1 km off the coast and 500 m offshore of the plant location. Generally, the water sinks within the plume and upwells along the plume boundary. Secondary upwelling also occurs below the plume. The strong upwelling on the up-current side indicates that most of the sinking water is returned within a narrow frontal zone facing the ambient current.

3.4 EXTENT AND DILUTION OF THE EFFLUENT PLUME

Temperature alone is not a good indicator of the extent of the effluent plume, since temperature varies with depth in the ambient ocean. If dye is added to the discharge as a tracer, and the dye concentration is initialized at zero in the ambient ocean, a view is provided of the fate of conservative effluent constituents. Investigating conservative constituents of a plume provides a basis for examining the effects of additions to the ocean of biocides and trace metals present in the OTEC plant effluent.

The distribution of dye at four levels in the upper ocean is shown in Fig. 11 for a 40-MW_e OTEC plant and a 20 cm/s ambient current. The discharge concentration of dye is 10, and the background concentration is zero. Because the near-field plume is discharged between 20 m and 80 m, and the vertical motion is downward near the surface, the dye concentration is zero in the upper 20 m. The dye concentration increases rapidly with depth between 20 m and 80 m, and is zero below 80 m. This vertical distribution indicates that the near-field plume collapses and spreads out on the top of the thermocline. The maximum dye concentration is about 5% of the initial concentration, which is equivalent to a dilution factor of about 20.

While the horizontal dye distribution is generally similar to that of the temperature distribution, some distinct differences are evident. For example, the temperature plume is larger and more diffuse than the dye plume. Also, no appreciable vertical variation occurs in the amplitude of temperature perturbations as compared with the sharp increase in dye concentration with depth in the upper ocean. These differences highlight the effects of plume-induced circulation on the redistribution of constituents in the water mass. The temperature distribution reflects not only the dilution of the discharge effluent but also the vertical displacement of the ambient temperature field caused by the induced circulation. Because the initial ambient dye concentration was zero, the dye distribution reflects only the dilution of the discharge effluent.

3.5 REDISTRIBUTION OF NUTRIENTS

Effluent constituents such as biocides and trace metals are added to the ocean, whereas existing ocean constituents are redistributed by the effluent plume and the

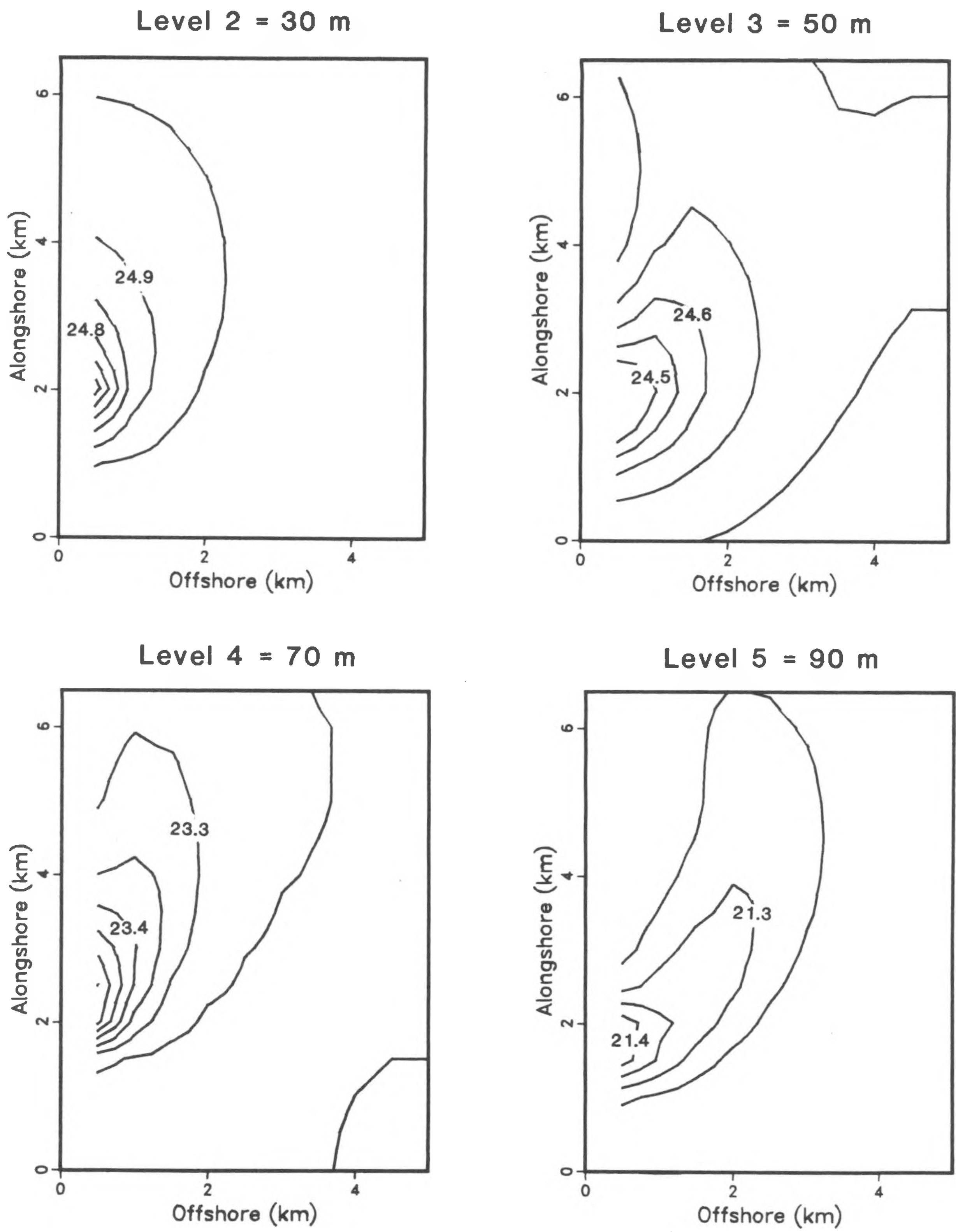

FIGURE 9 Horizontal Distribution of Temperature (°C), with an Ambient Current of 20 cm/s Alongshore (contour interval = 0.05°C)

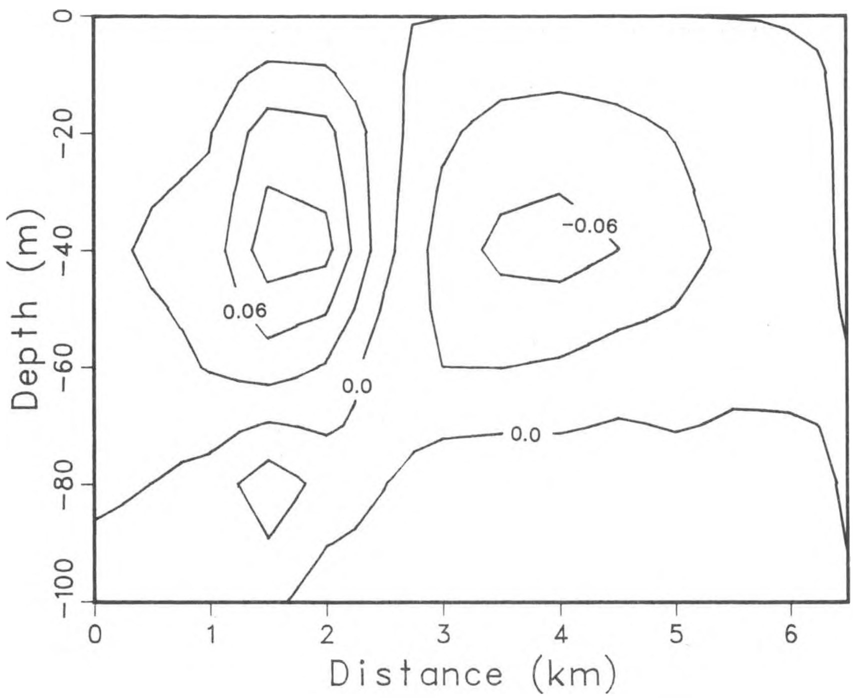

FIGURE 10 Vertical Velocity Distribution (cm/s) on an Alongshore Plane at a Distance 1 km Offshore (positive velocity indicates upwelling)

circulation induced by it. For example, nutrient concentrations in the upper ocean are low while those in the deep ocean are high. A mixed effluent in the upper ocean contains higher nutrient concentrations than the receiving water. Moreover, the natural gradient of nutrient concentration with depth, combined with the circulation induced by the far-field plume, provides an additional mechanism for redistribution of nutrients in the vicinity of the OTEC plant. Although nutrients and particulate matter are not conserved quantities, a first-order approximation of the redistribution of such constituents as a result of OTEC plant operation can be found by using the conservative tracer aspect of the model.

As an example, the conservative redistribution of nitrate was investigated using the 40-MW_e OTEC plant base case. The nitrate concentration in tropical waters is typically zero above the thermocline, but increases to more than 30 μM in the deep ocean.[6] In this example, the nitrate concentration is assumed to be 15 μM in the mixed effluent, and the ambient nitrate concentration is assumed to be zero from the surface to a depth of 100 m, 5 μM at 110 m, and 10 μM at 160 m (see Fig. 5). Figure 12 shows the nitrate distribution predicted by the model at depths of 70 m and 90 m. Because the ambient nitrate concentration is zero in the upper ocean, the nitrate distribution above the thermocline (<80 m) is almost identical to the corresponding dye distribution. In the thermocline, secondary upwelling below the plume brings up nitrate from greater depths (see Fig. 10). Consequently, a significant increase in nitrate concentration occurs at a depth of 90 m; in contrast, the dye concentration is zero in the thermocline. The total upward nitrate flux caused by circulation induced by the plume is about equal to the

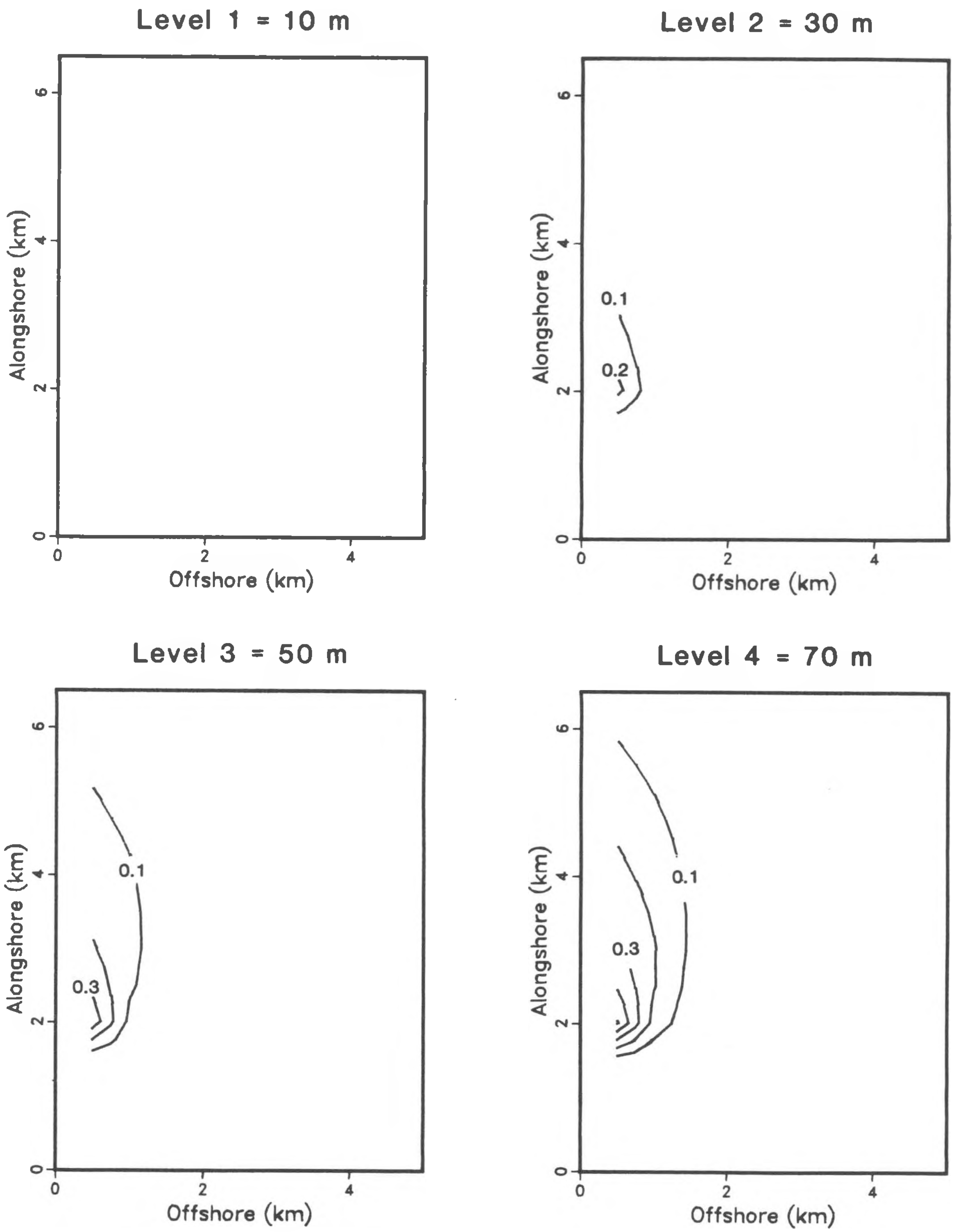

FIGURE 11 Horizontal Distribution of Dye, with an Ambient Current of 20 cm/s Alongshore (initial concentration = 10; contour interval = 0.1)

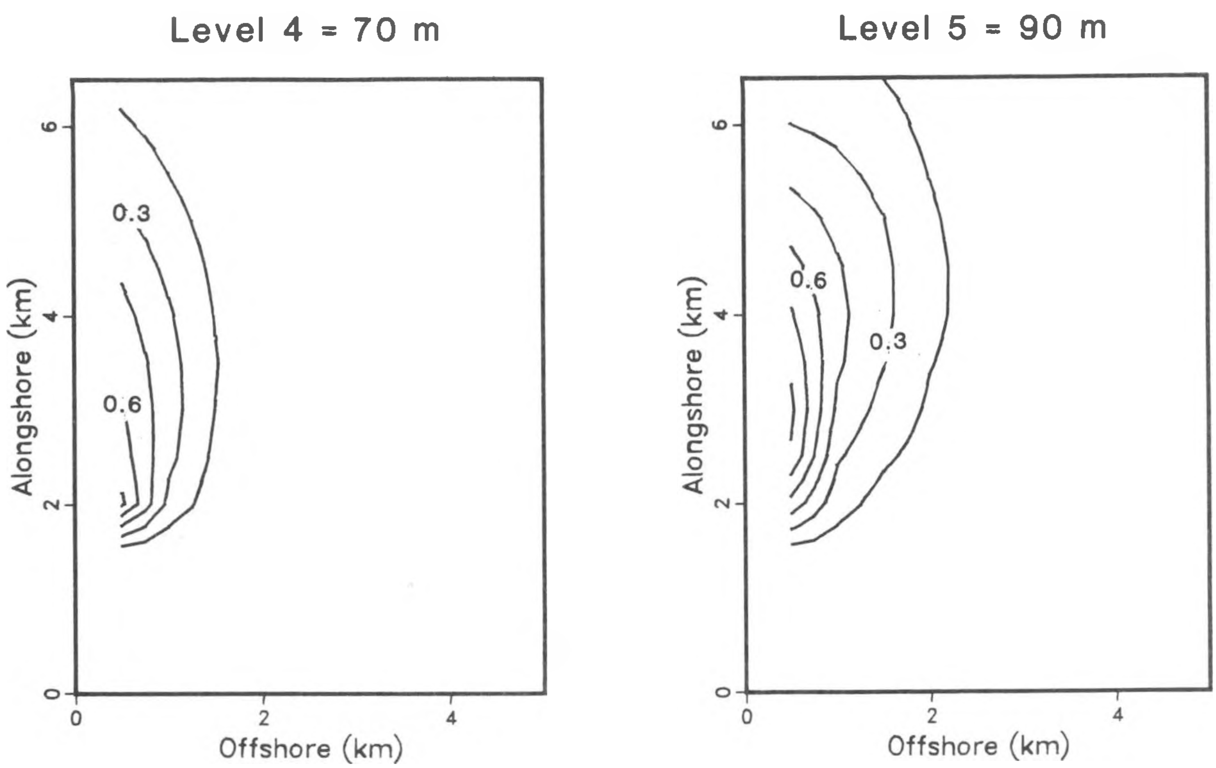

FIGURE 12 Horizontal Distribution of Nitrate (μM), with an Ambient Current of 20 cm/s Alongshore

nitrate flux from the mixed effluent. In other words, entrainment from below the thermocline increases the total nitrate input into the upper ocean by about 100%.

A similar computation can be made for phosphate, which may exist in higher concentrations than nitrate in the thermocline region. The mixed-effluent concentration of phosphate is assumed to be 1 μM, and the ambient concentration is assumed to be zero above the thermocline and 0.5 μM just below the thermocline.[6] The computation shows that the phosphate flux resulting from plume entrainment is 1.5 times larger than that resulting from the mixed effluent.

3.6 SENSITIVITY ANALYSES

The model does not include sinks to simulate the intake effects of an operating OTEC plant. The cold-water intake cannot influence the far-field plume because the plume is confined to depths well above it. However, the effect of neglecting the warm-water intake was investigated because it is located in the upper ocean. For a 40-MW_e OTEC plant, the warm-water intake has a flow rate of 140 m^3/s. If it is assumed that the intake flow can be represented in the model as a mass sink in the surface layer (H_1 = 0 and H_2 = 20 m in Eq. 9), the resulting induced circulation in the zero-ambient-current case indicates a radial flow confined to the upper mixed layer (water depth <40 m). The maximum current is about 0.3 cm/s, compared with a maximum current of 7.5 cm/s in the discharge plume. This result is relatively conservative, as the intake flow was assumed to be distributed over 20 m in the vertical dimension. Selective withdrawal analysis suggests that it might extend over the entire mixed layer at regional scales, thereby reducing the induced current. Thus, the effect of the warm-water intake is local and small and can reasonably be neglected in the regional influence model.

Turbulent mixing and dissipation in the ocean are poorly understood; hence, realistic parameterization of these processes is not likely. The effects of turbulence parameterization on the flow field in this model were examined for two other turbulence schemes for vertical mixing of momentum and mass:

$$A_v = 10 \text{ cm}^2/\text{s} \tag{11a}$$

$$k_v = 10 \text{ cm}^2/\text{s} \tag{11b}$$

$$A_v = 0.1 + 50(1 + 10\,R_i)^{-1/2} \text{ cm}^2/\text{s} \tag{12a}$$

$$k_v = 0.1 + 50(1 + 3.3\,R_i)^{-3/2} \text{ cm}^2/\text{s} \tag{12b}$$

where R_i is the local Richardson number, that is:

$$R_i = -\frac{g}{\rho_o}\frac{\partial \rho}{\partial z}\left[\left(\frac{\partial u}{\partial z}\right)^2 + \left(\frac{\partial v}{\partial z}\right)^2\right]^{-1/2} \tag{13}$$

For a mixed effluent from a 40-MW_e OTEC plant in a zero ambient current, the resulting velocity profiles computed using the two turbulence schemes are virtually identical as shown in Fig. 13. The profiles also agree with the results from the base case computations where A_v = 50 cm^2/s and k_v = 10 cm^2/s. In other words, on a regional scale, vertical mixing and dissipation have little effect on plume structure. Horizontal velocity is governed by the balance between the pressure gradient and the momentum advection; the temperature and dye distributions are determined by entrainment and horizontal advection. However, mixing and dissipation may be important at larger scales down current from the buoyancy-driven portion of the plume.

3.7 IMPLICATIONS OF THE BASE CASE

The applications of the model to a 40-MW_e OTEC plant with a mixed discharge indicate that the effluent plume is confined mainly to the top of the thermocline exhibiting a typical temperature profile. In the case of an ambient alongshore current of 20 cm/s, the effluent plume is about 20 m deep, 2 km wide, and 4 km long, and is diluted from the initial discharge value by factors of 20-100. Because the plume is driven primarily by the buoyancy flux of the discharge, the regional influence of the plume does not depend on details of the mode of discharge, such as whether there is an individual discharge port or multiple ports, or whether there is mixed discharge or separate cold-water discharge.

The results given above agree qualitatively with the results of integral analyses of OTEC effluent plumes.[4] However, significant additional information is provided in the model applications that cannot be gleaned from integral models. The temperature structure of the ambient ocean and the ongoing dilution of the effluent are such that the plume blends into the ambient temperature structure without much of a temperature signature. In fact, the plume is best denoted by the dye concentrations. The most important feature of the model results, and part of the reason why the thermal plume blends into the ambient temperature field, is the circulation induced by the OTEC plant discharge, a feature that cannot be produced by an integral, or superposition, model.

The residual current patterns show clearly the entrainment flows and the strong fronts with vertical velocities associated with them. The effects of induced circulation are demonstrated in the temperature and dye contours, but the results of this influence are particularly vivid in the study of nutrient redistribution. Redistribution of other constituents, including plankton, by downwelling of surface waters and upwelling from the thermocline region may be important processes to be considered in assessing environmental effects.

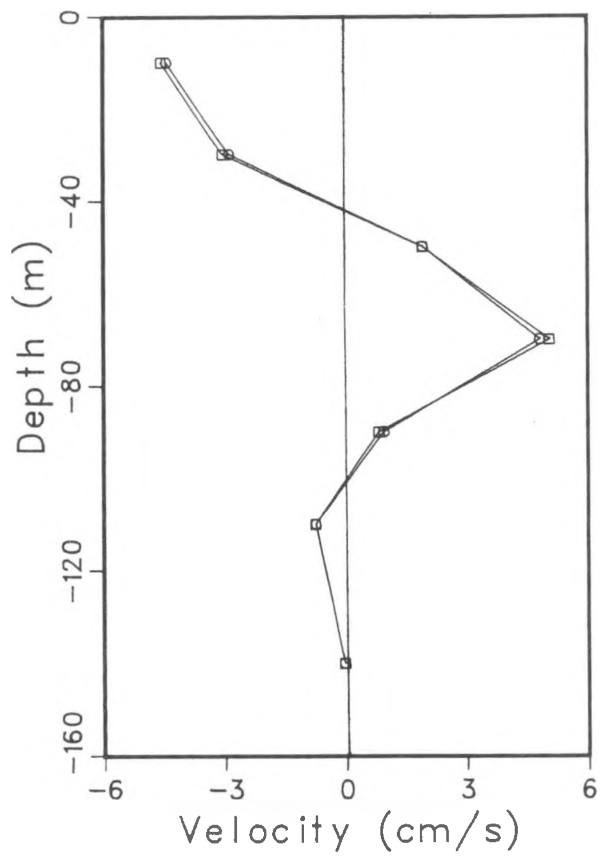

FIGURE 13 Vertical Profiles of Cross Shore Velocity at a Distance 1 km Offshore from the Discharge Port (circles = constant viscosity; squares = variable viscosity)

4 APPLYING THE MODEL TO OTHER OTEC CONFIGURATIONS

The 40-MW_e OTEC plant examined in Sec. 3 provides a base case against which to measure the regional influence of other OTEC configurations. The base case also establishes the particular features of the far-field effluent plume and induced circulation that have regional influence. The regional influence of larger OTEC plants; the interferences between two adjacent 40-MW_e OTEC plants; and the effects of ambient current, coastal boundaries, and bottom impingement are examined in Sec. 4. The model formulation and the ambient ocean stratification are identical to those for the study of the regional influence of a 40-MW_e OTEC plant in Sec. 3. An ambient current of 20 cm/s along the coast is assumed, unless otherwise noted.

4.1 REGIONAL INFLUENCE OF LARGER OTEC PLANTS

This application of the model assumes an 80-MW_e OTEC plant in an ambient current of 20 cm/s alongshore. The mixed effluent is characterized by 15°C water discharged at an assumed flow rate of 560 m^3/s, that is, twice the flow rate of a 40-MW_e OTEC plant. The residual circulation (see Fig. 14) is similar to that from a 40-MW_e OTEC plant discharge in an ambient current (see Fig. 8). For example, a velocity front forms on the up-current side, and a plume forms on the down-current side. The maximum residual current is about 13 cm/s, compared with a maximum current of 7 cm/s in the base case. Typically, residual currents are increased by about 50-80%.

Because the residual current does not increase proportionally with the discharge flow rate, the dilution factor of the effluent changes with the plant size. The maximum effluent concentration, which occurs at the top of the thermocline, is 9.4% of the initial concentration for the 80-MW_e OTEC plant discharge (see Fig. 14). This dilution factor of about 11 is considerably smaller than the dilution factor of 20 in the 40-MW_e OTEC plant discharge. Also, comparison of the vertical profiles of dye concentration for discharges from the 40- and 80-MW_e OTEC plants indicates that the dye concentration increases more rapidly toward the top of the thermocline for the 80-MW_e OTEC plant discharge.

When the discharge flow rate is increased to 1120 m^3/s, which corresponds to a 160-MW_e OTEC plant mixed effluent, the maximum residual current is about 17 cm/s, and the maximum effluent concentration is 12.8% of the initial concentration. While a larger plant does cause a higher effluent concentration, the rate of increase of effluent concentration is not proportional to the rate of increase of plant size. For example, the effluent concentration is almost doubled between a 40- and an 80-MW_e OTEC plant, whereas the effluent concentration is increased by only 36% between an 80- and a 160-MW_e OTEC plant. Also, because the residual current decreases rapidly away from the source, the offshore extent of the effluent plume is about the same for an 80- and a 160-MW_e OTEC plant.

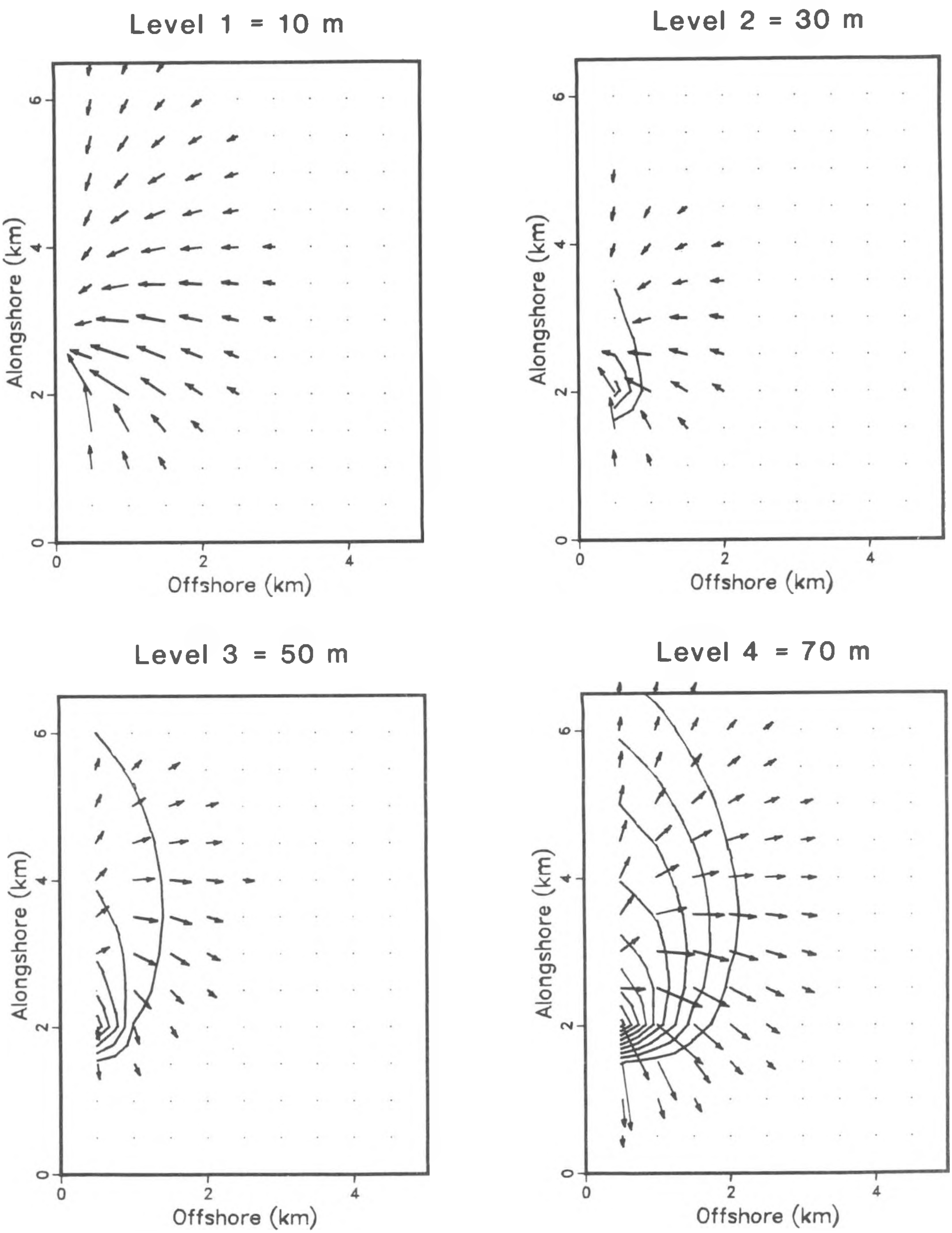

FIGURE 14 Horizontal Distribution of Velocity and Dye, 80-MW_e Plant, with an Ambient Current of 20 cm/s Alongshore (velocity scale = 7 cm/s between two grid points; initial dye concentration = 10; outermost contour = 0.1; contour interval = 0.1)

4.2 INTERFERENCE BETWEEN TWO ADJACENT 40-MW_e OTEC PLANTS

Two 40-MW_e OTEC plants located about 500 m offshore are assumed to be separated by 2 km along the coast. Each facility is a base-case plant; that is, each plant has a mixed effluent of 15°C water discharged at a flow rate of 280 m^3/s. The residual current and dye distributions of the adjacent plants (see Fig. 15) have a plume structure comparable to that of a single 80-MW_e OTEC plant discharge (see Fig. 14). This result suggests that the area influenced by effluent discharged from 40-MW_e OTEC plants with separations on this order or less is not sensitive to the distribution of the plants.

Noticeable differences occur in residual circulation and effluent distribution between the two OTEC plant sites. The circulation at the up-current OTEC plant site is identical to the circulation induced by a single 40-MW_e OTEC plant. On the other hand, the circulation at the down-current OTEC plant site has stronger offshore flow but weaker alongshore flow than at the up-current site. The maximum effluent concentration is higher by about 25% at the down-current site. The modification of residual circulation and effluent distribution at the down-current OTEC plant site is the consequence of the down-current plant being located in the "wake" of the up-current OTEC plant discharge, which has a length scale of about 4 km (see Fig. 11).

As the distance separating the two plants becomes smaller, the effect of interference on the down-current plant is stronger. For example, when the distance is reduced to 1 km, the maximum effluent concentration at the down-current plant site is about 7.6% of the initial concentration, an increase of 50% over that of a single plant. On the other hand, because the residual current is smaller than the ambient current, the effluent concentration at the up-current plant site is not affected by the discharge from the down-current plant, even when the two plants are separated by only 1 km.

4.3 EFFECTS OF AMBIENT OCEAN CONDITIONS

Dispersion of the OTEC plant effluent is not sensitive to the small ambient temperature variations (<1°C) typically found in tropical oceans. For the effects of ambient coastal currents, the case of a 40-MW_e OTEC plant in a 20-cm/s ambient current can be compared with that of a 40-MW_e OTEC plant in a zero ambient current (see Secs. 3.2 and 3.3). Apart from the obvious difference in the plume structure, the maximum residual currents are about the same for the two cases. The maximum effluent concentrations are also about the same. Thus, for ambient currents of 20 cm/s or less, no significant interaction occurs between the plume from a 40-MW_e OTEC plant and the ambient current. The plume is simply advected by the ambient current.

For an ambient current of 40 cm/s, the plume from a 40-MW_e OTEC plant is confined to the coast, and the maximum effluent concentration is about 2% of the initial concentration (see Fig. 16). The residual circulation is much weaker than in the case of a 20-cm/s ambient current. In other words, the effluent plume is rapidly diluted in a strong ambient current. On the other hand, the strong ambient current causes the velocity "plume," that is, the region affected by the recirculation, to extend much farther down current than in the base case.

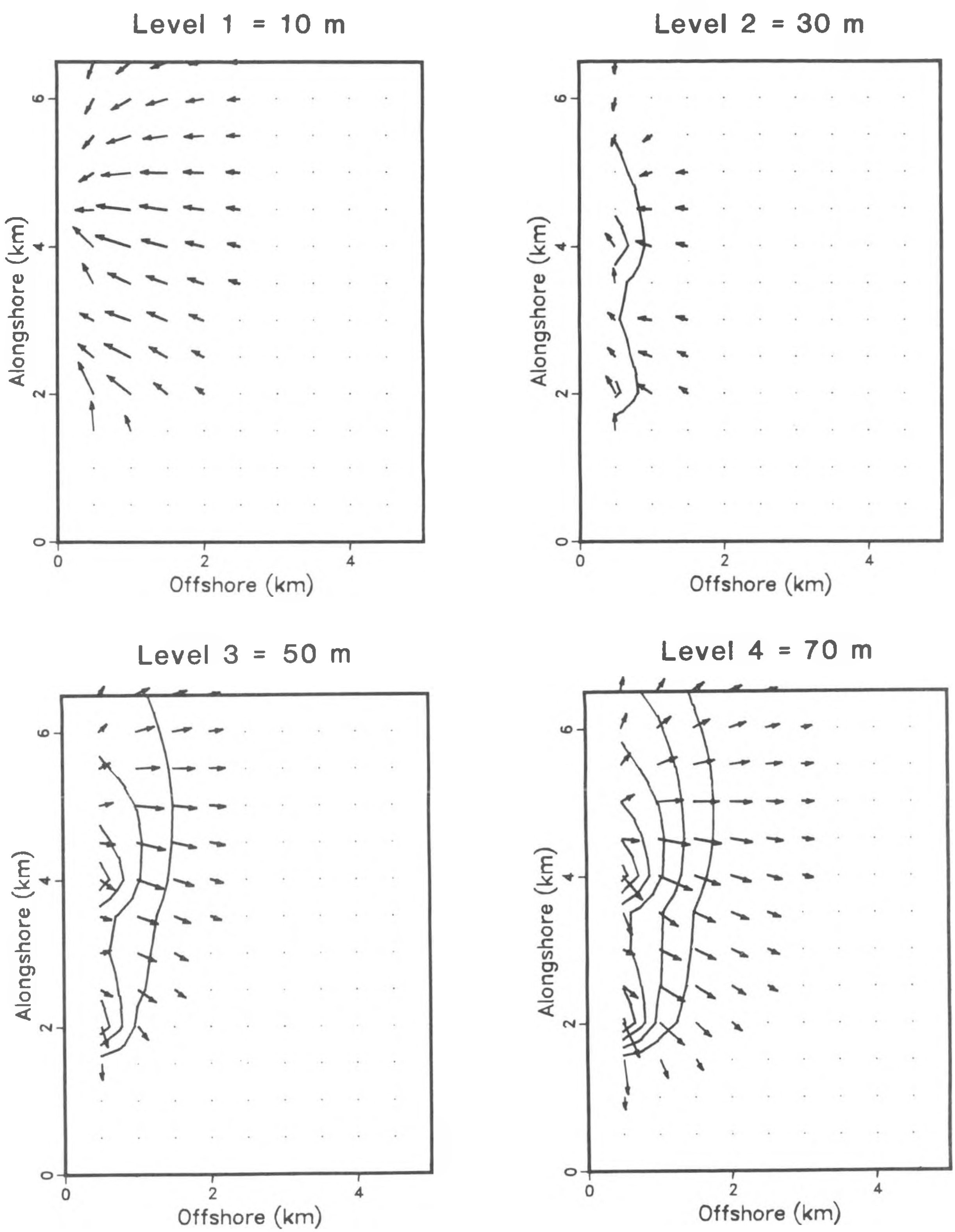

FIGURE 15 Horizontal Distribution of Velocity and Dye, Two Adjacent 40-MW_e Plants, with an Ambient Current of 20 cm/s Alongshore (velocity scale = 7 cm/s between two grid points; initial dye concentration = 10; outermost contour = 0.1; contour interval = 0.1)

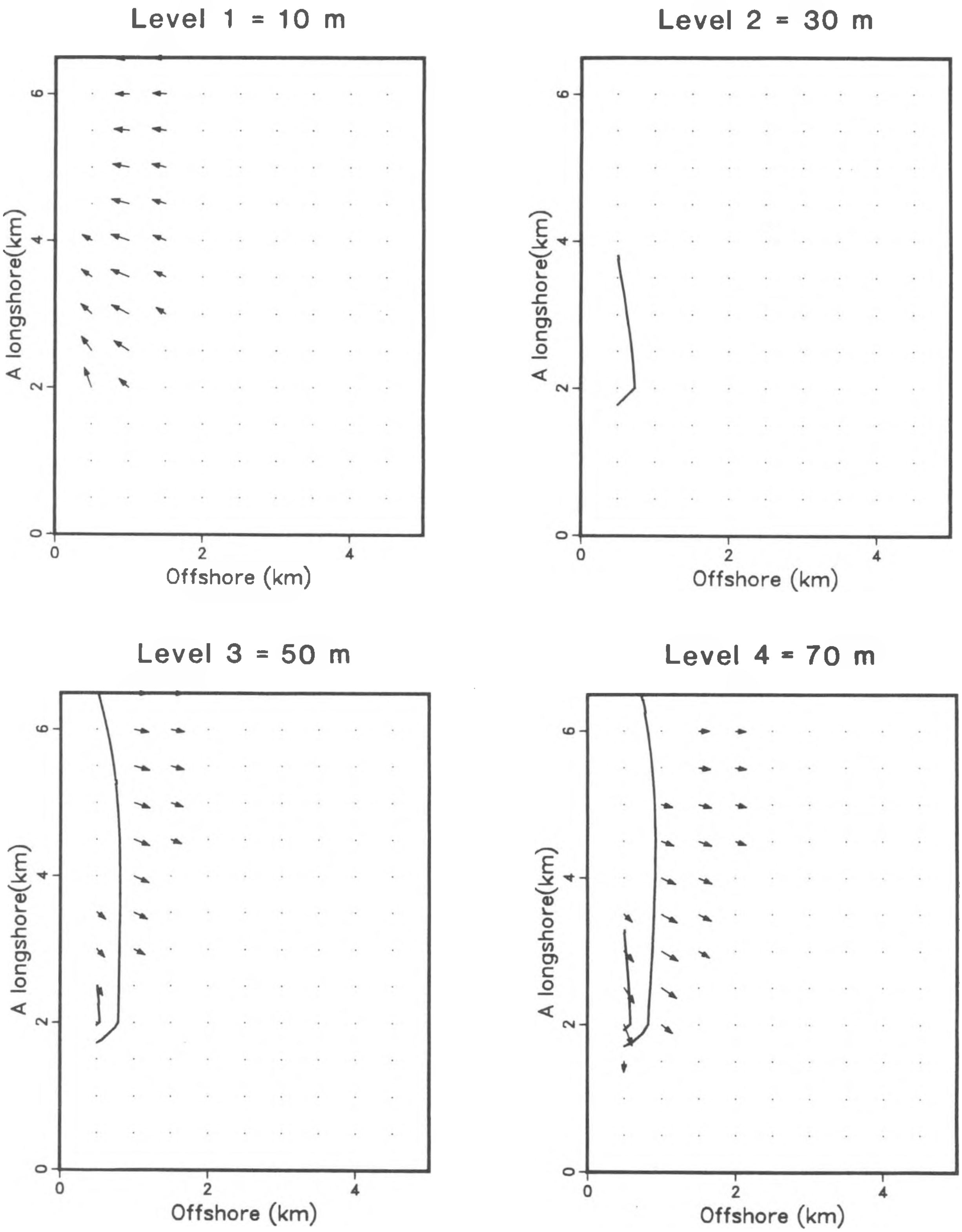

FIGURE 16 Horizontal Distribution of Velocity and Dye, 40-MW_e Plant, with an Ambient Current of 40 cm/s Alongshore (velocity scale = 7 cm/s between two grid points; initial dye concentration = 10; outermost contour = 0.1; contour interval = 0.1)

4.4 EFFECTS OF A COASTAL BOUNDARY

To consider the effects of a coastal boundary, the mixed effluent from a 40-MW_e OTEC plant is assumed to be discharged at 2 km from the coast, rather than at less than 500 m in the base case. The effluent is characterized by 15°C water at a flow rate of 280 m^3/s, with all other conditions the same as in the 40-MW_e base case. The resulting plume is about 1.5 km wide at the top of the thermocline (see Fig. 17), which is narrower than the plume from the plant closer to the coast. The residual current and the maximum effluent concentration values for the open-water discharge case are also smaller than those for the plant nearer the coast.

When the effluent is discharged at 2 km from the coast, the effluent plume is symmetrical about the discharge port. As the effluent is discharged closer to the coast, the effluent concentrations become higher offshore than inshore of the discharge port. However, the differences are small, indicating that the coastal boundary has no significant effect on plume distribution.

4.5 EFFECTS OF BOTTOM IMPINGEMENT

Studying the effects of bottom impingement requires a significant departure from the base case and the other configurations already examined. The effluent is discharged just above the ocean floor, which slopes offshore very steeply. (Water depth is more than 100 m at a distance of 500 m from the coast.) If discharge occurs along a steep bottom slope, the near-field dilution is much smaller than that caused by discharge nearer the surface. Near-field plume calculations show that, for the bottom discharge of a 40-MW_e OTEC plant, the near-field plume leaves the slope at the depth of the thermocline, with the height of the plume being about 20 m at the separation point.[4] Hence, H_1 = 60 m and H_2 = 80 m were picked as the bounds on the vertical range of the mass and heat sources.

In the far field, the residual circulation is weaker and the dilution is smaller in the case of bottom discharge (see Fig. 18) than in near-surface discharge. The maximum residual current is about 4.6 cm/s, and the maximum effluent concentration is about 9.1% of the initial concentration. Also, because of the small amount of dilution, the plume penetrates deeper into the thermocline. In all the other cases studied, it slid only into the upper thermocline. The effluent concentration at the 90-m level is about 25% of the effluent concentration at the 70-m level, whereas the effluent concentration is zero at the 90-m level for the near-surface discharge of the base case.

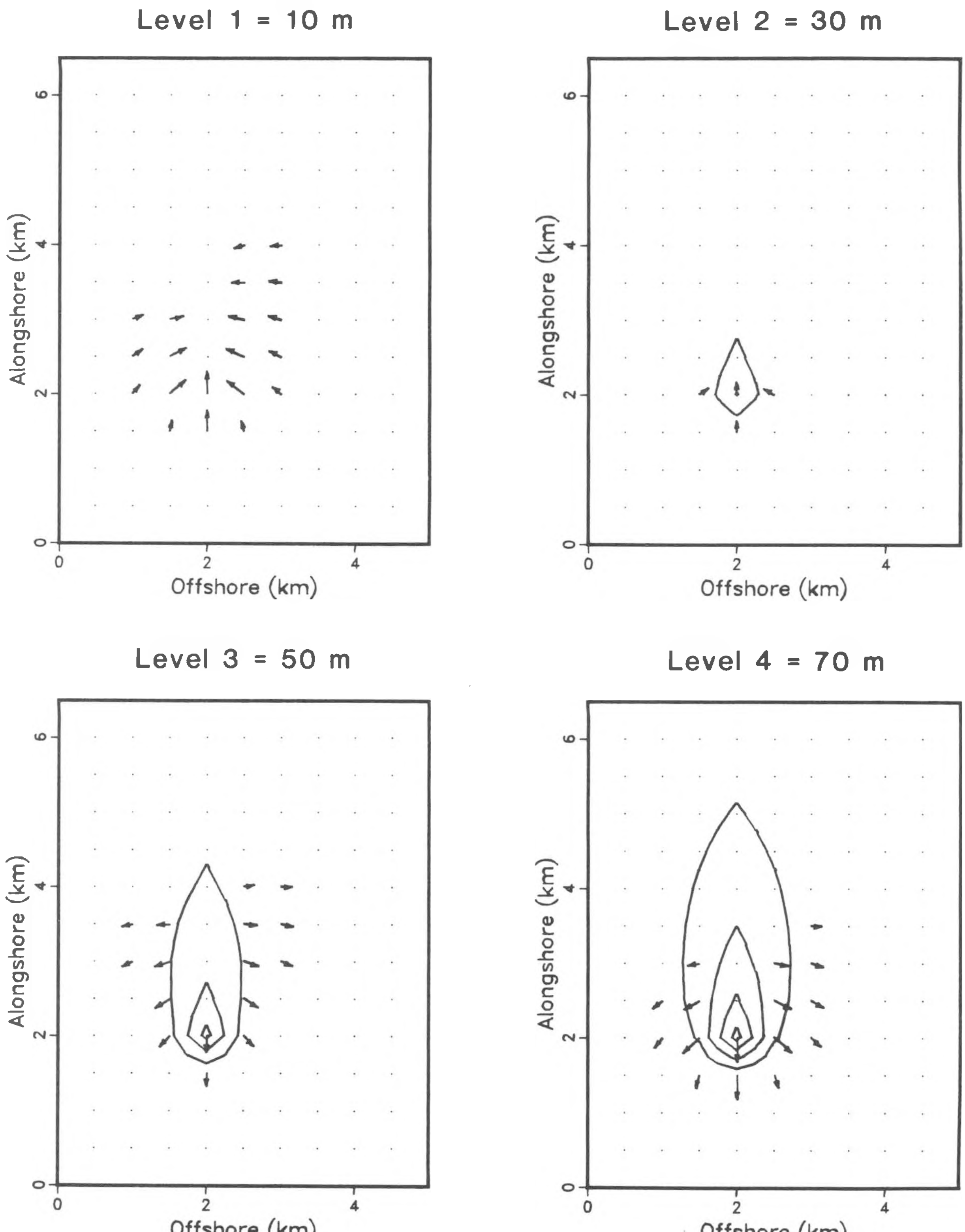

FIGURE 17 **Horizontal Distribution of Velocity and Dye, Off-shore Discharges with an Ambient Current of 20 cm/s Alongshore (velocity scale = 7 cm/s between two grid points; initial dye concentration = 10; outermost contour = 0.1; contour interval = 0.1)**

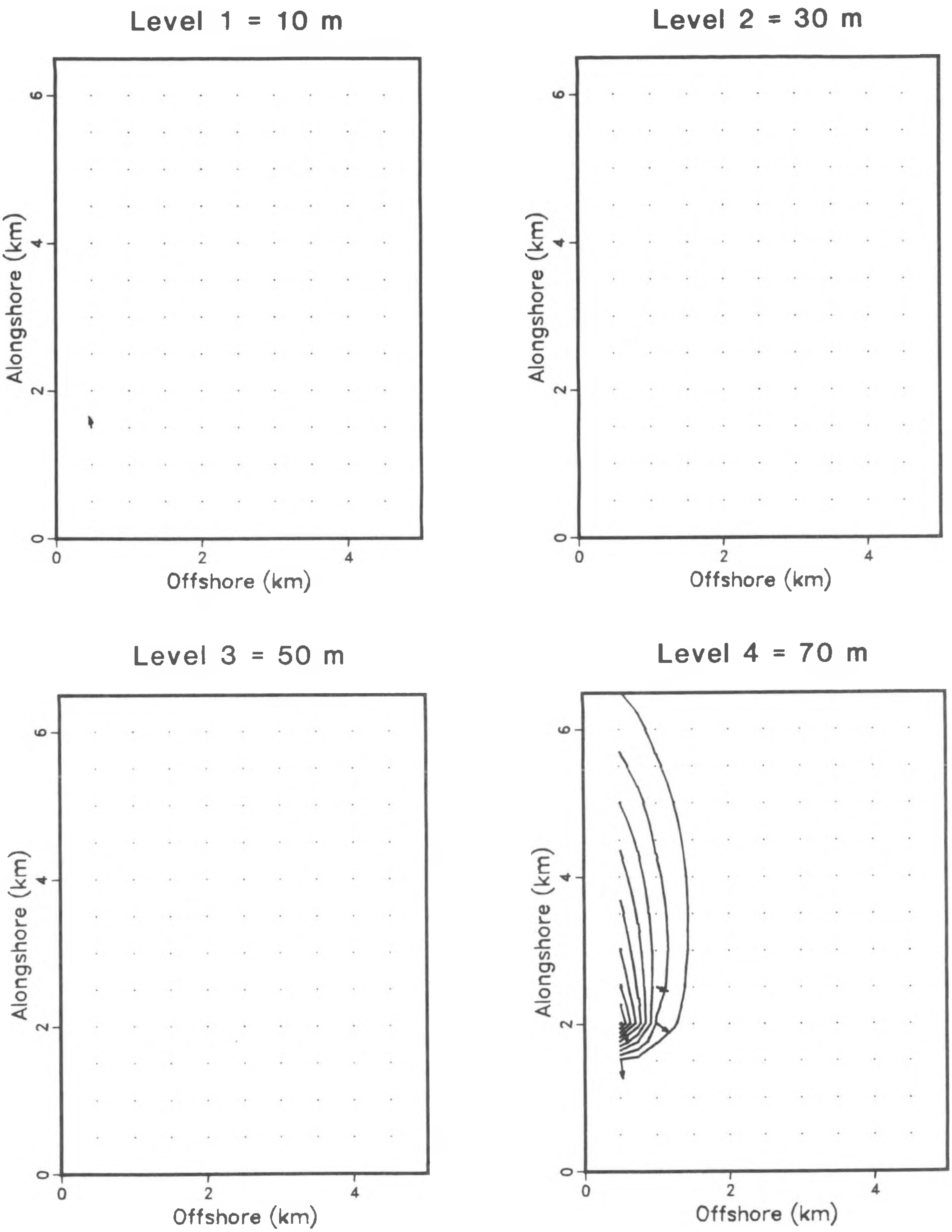

FIGURE 18 Horizontal Distribution of Velocity and Dye, Near-Bottom Discharges, with an Ambient Current of 20 cm/s Alongshore (velocity scale = 7 cm/s between two grid points; initial dye concentration = 10; outermost contour = 0.1; contour interval = 0.1)

5 CONCLUSIONS

A model of the far-field plume was used to investigate the region of the ocean likely to be influenced by operation of OTEC plants in several different configurations. Regional influence refers to displacements of water and subsequent alterations in the distributions of water constituents. For a 40-MW_e OTEC plant located in deep water on a coastal margin, the mixed effluent plume is confined mostly to the top of the thermocline. With an ambient alongshore current of 20 cm/s, the effluent plume is about 20 m deep, 2 km wide, and 4 km long; it is diluted by ambient ocean water by a factor of 20-100. Because the plume is mainly driven by the buoyancy flux of the effluent, regional influence does not depend on the details of the mode of discharge (i.e., separate cold discharge or mixed discharge).

Temperature perturbations are caused by dilution of the effluent and by redistribution of the ambient temperature field. For discharges from a 40-MW_e OTEC plant, temperature perturbations are less than 0.2 C° and are distributed almost uniformly between the bottom of the surface mixed layer and the top of the thermocline. The circulation induced by interaction of the buoyant discharge and the ocean not only influences plume dilution and temperature structure but also the redistribution of ocean constituents. For example, computing a nitrate profile subjected only to the physical (conservative) aspects of OTEC plant operation indicated that the nitrate flux into the upper ocean is derived both from the mixed effluent and from the discharge-induced deep upwelling, or entrainment. The two processes appear to contribute about equally to the nitrate flux into the upper ocean.

Examining the effects of discharges from two adjacent OTEC plants showed that regional influence can be computed as a superposition of two individual plumes, given reasonable separation between the plants. When two 40-MW_e OTEC plants are separated by 2 km alongshore, the effluent concentration near the up-current plant is about the same as the effluent concentration for a single 40-MW_e OTEC plant, whereas the effluent concentration near the down-current plant is increased by about 25%. When two plants are separated by 1 km, significant interaction occurs, with the effluent concentration near the down-current plant being increased by about 50% from that of a single 40-MW_e OTEC plant.

In the presence of an ambient current, the plume will be stretched in the down-current direction. The effluent concentration, however, is not affected unless the ambient current is very strong, in which case the effluent is rapidly diluted. Also, the regional influence is not sensitive to the effects of a coastal boundary. On the other hand, the concentration of the effluent plume is greatly increased for discharges into shallow water or along the bottom because the near-field dilution is much smaller. For a 40-MW_e OTEC plant with bottom discharge, the maximum effluent concentration will be about 10% of the initial concentration, which is about twice the typical maximum concentration of effluents discharged nearer the surface. The plume also penetrates deeper into the thermocline than in the case of near-surface discharge.

Applying the model to several OTEC configurations demonstrated the importance of the discharge-induced circulation and the interactions between the effluent plume and the ambient ocean. The region of influence of an OTEC plant is clearly greater than the simple geometric extent of the plume as determined by integral jet models with fixed ambient ocean conditions.

Because the purpose was to investigate regional influence in a generic sense, the applications of the model were restricted to a simple coastal geometry and constant ocean currents. In cases where the coastal geometry is more complex, the effluents that are advected down current may accumulate in a convergence zone. The effluent plume may also be swept away by storm currents and impinging eddies. To determine the regional influence of OTEC plant operations in such site-specific cases, the plume model will have to be coupled to descriptions of coastal circulation provided by observations or other models. The plume model may also be coupled to a biological model that predicts nutrient uptake and its effects on marine biota to assess potential environmental changes in either a generic or site-specific mode.

REFERENCES

1. Jirka, G.H., J.M. Jones, and F.E. Sargent, *Theoretical and Experimental Study of the Intermediate Field Dynamics of Ocean Thermal Energy Conversion Plants*, Environmental Engineering Department, Cornell University, Ithaca, N.Y. (1980).

2. Wang, D-P., *Development of a Three-Dimensional Limited-Area (Island) Shelf Circulation Model*, J. Physical Oceanography, *12*:605-617 (1982).

3. Koh, R.C.Y., and L.-N. Fan, *Mathematical Models for the Prediction of Temperature Distributions Resulting from the Discharge of Heated Water into Large Bodies of Water*, U.S. Environmental Protection Agency Report 16130 DWO (1970).

4. Paddock, R.A., and J.D. Ditmars, *Initial Screening of License Applications for Ocean Thermal Energy Conversion (OTEC) Plants with Regard to Their Interaction with the Environment*, Argonne National Laboratory Report ANL/OTEC-EV-2 (Feb. 1983).

5. Orlanski, I., *A Simple Boundary Condition for Unbounded Hyperbolic Flows*, J. Computational Physics, *21*:251-269 (1976).

6. Noda, E.K., P.K. Bienfang, and D.A. Ziemann, *OTEC Environmental Benchmark Survey off Keahole Point, Hawaii*, Department of Ocean Engineering, University of Hawaii, Honolulu (1980).

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