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A numerical investigation of the influence of land-sea breeze on the atmospheric effluents released at a coastal site

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सार — एक द्विआयामी संख्यात्मक परिसीमा स्तर निदर्श के उपयोग से एक तटीय वायुमंडलीय सीमा पर्त के मेसोस्केल लक्षणों, जैसे, स्थल-समुद्र परिचालन और ऊष्मीय आन्तरिक सीमा पर्त की संरचना की गई। क्षैतिज संवेग समीकरणों के लिए बूसिने सन्निकटन तथा ऊर्ध्वाधर संवेग समीकरण के लिए जलस्थैतिक सन्निकटन के प्रयोग द्वारा इस निदर्श से तटीय रेखा के दोनों तरफ 80 कि०मी० लम्बाई और 2 कि०मी० ऊंचाई के एक ग्रिड डोमेन पर उथले जल के समीकरणों का हल खोजा गया है। तट पर अवस्थित एक स्थान से नियमित रूप मे निकलने वाले/प्रदूषण फैलाने वाले पदार्थों पर स्थल पवन के प्रभाव का इसमें अध्ययन किया गया है। इसमें एक अपतटीय स्थान से स्थल पर टी० आई० बी० एल० में प्रदूषण फैलाने वाले धुएं का भी विवेचन किया गया है। इसमें निदर्श से संबंधित सीमाओं की भी चर्चा की गई है।

ABSTRACT. Mesoscale features of a coastal atmospheric boundary layer such as the land-sea circulation and the thermal internal boundary layer (TIBL) structure have been simulated using a two-dimensional numerical boundary layer model. Using Boussinesq approximation for horizontal momentum equations and hydrostatic approximation for vertical momentum equation, the model solves the 'shallow water' equations over a grid domain of 80 km length on either side of the coastline and 2 km height. The influence of the land-sea breezes on the dispersion of pollutants released from a continuous point source located at the coast has been studied. The fumigation of pollutants from an offshore source into TIBL over the land has also been illustrated. The limitations associated with the model are also discussed.

Key words — Atmospheric boundary layer, Sea breeze, Numerical simulation, Atmospheric dispersion, Air pollution, Thermal internal boundary layer (TIBL).

1. Introduction

The dispersion of air pollutants from industrial emissions and their impact on environment has been a cause for concern in the modern world. The problem is particularly important in coastal sites where the air flow and its stratification change significantly due to the change of surface temperature and terrain roughness between the land and water. The two important factors resulting from these changes are the large scale flow pattern, *i.e.*, land and sea breeze and the development of thermal internal boundary layer (TIBL). The importance to effluent dispersion of these two factors, as shown in Fig. 1, has been recognised for the last three decades; for example, Bierly and Hewson (1962) emphasised the influence of TIBL, whereas Lyons and Cole (1976) presented evidence showing that when an almost closed circulation of land and sea breeze was present, the particles advected by the previous day land breeze, were found brought back by the sea breeze. In addition they observed the fumigation of ozone or its precursor into the TIBL causing high concentration of ozone at the surface. Cass and Shair (1980) and many others have also confirmed their findings. A detailed review of coastal meteorological processes important to the modelling of pollution dispersion has been given by Ludwig (1983).

Although it is possible to estimate the ground level concentration under fumigation for a short range (10-20 km) by suitably modifying the Gaussian model (Turner 1979 Misra 1980, Venkatraman 1988), the problem is nevertheless fully three-dimensional and time varying. The first two-dimensional numerical sea breeze model was developed by Estoque (1961, 1962) and the first three-dimensional model by Mc Pherson (1970); both of them neglected the orography and moisture. The complexities of these two items were incorporated in his 3-D model by Pielke (1974). Numerous models have been developed thereafter, differing in the treatment of meteorological complexities and methods of numerical solution and a good review of some selected models can be found in Ulrike Pechinger (1983). Some of these models use first order closure scheme with simplified formulation for the eddy diffusivity (K). Recent trend in modelling is to solve turbulent kinetic energy (TKE) equation with higher order closure schemes in order to introduce more physical realism in turbulent diffusion. However, Asai and Mitsumoto (1978) support the constant K assumption and

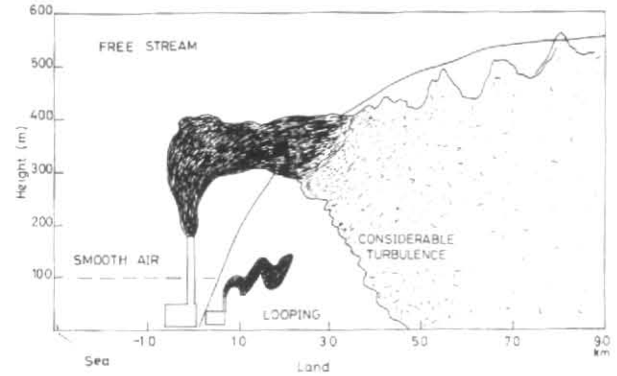


Fig. 1. Schematic representation of the fumigation of pollutants into TIBL (Lyons and Cole, 1976)

nowed that even by this, the substantial features of he flow field could be predicted. A review of higher order closure (TKE) models and the first order closure models and their comparative evaluation using one dimensional PBL model by Holt and Raman (1989) showed the same result.

In the present work, the dispersion of pollutants under the influence of land-sea breeze and TIBL will be studied numerically. An elevated point source of a smoke plume will be located in the model experiment and allowed to release in the wind circulation continuously. Fumigation of smoke plume into the TIBL over land will be simulated for an offshore oil source located in a marine boundary layer in order to study the cases of offshore oil well burning such as the Bombay High event. A two-dimensional numerical model is developed to provide the wind field and the TIBL structure prognostically. After reaching the steady state, the wind model is initialised for the release condition and the concentration of pollutants is obtained by solving the mass balance equation numerically along with the other primitive equations of momentum and heat in the model. Similar studies have been reported by Hiroyuki Ozoe *et al.* (1983) but the structure of the TIBL and the fumigation of pollutants into it has not been simulated by them. The present study makes feasible to use the model in an emergency regulatory frame work in the nuclear power plant located at the coastal site Kalpakkam, 80 km south of Madras city.

2. Methodology

2.1. *Outline of the land-sea breeze model*

Assuming that all the variables along the Y-axis are to be homogenous and applying Boussinesq approximation of incompressibility (which treats density as a function only of temperature and not pressure), the 'shallow water' equations of momentum, energy and continuity are written as follows :

$$\frac{\partial u}{\partial t} + u\,\frac{\partial u}{\partial x} + w\,\frac{\partial u}{\partial z} = fv - C_p\theta\,\frac{\partial \pi}{\partial x} + \frac{\partial}{\partial x}\left(K_h\,\frac{\partial u}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_z\,\frac{\partial u}{\partial z}\right) \qquad (1)$$

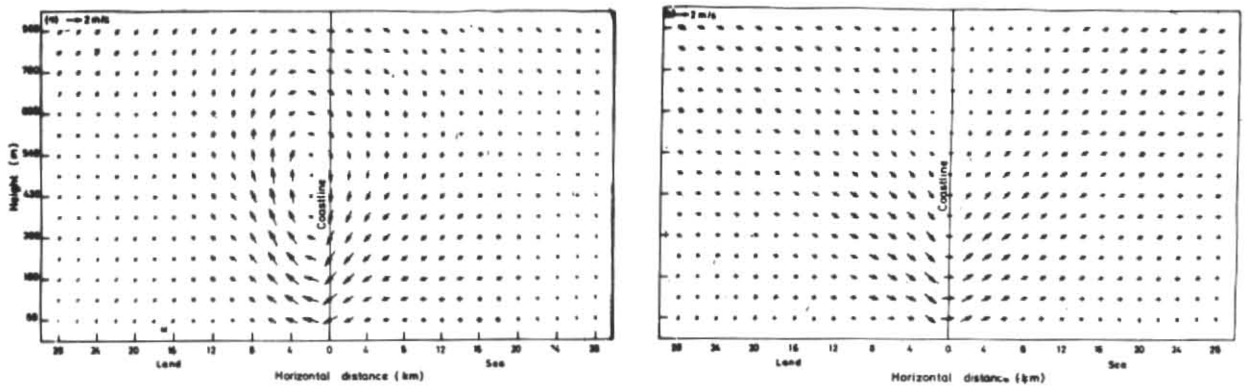
$$\frac{\partial v}{\partial t} + u\,\frac{\partial v}{\partial x} + w\,\frac{\partial v}{\partial z} = f(u-U_g) + \frac{\partial}{\partial x}\left(K_h\,\frac{\partial v}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_z\,\frac{\partial v}{\partial z}\right) \qquad (2)$$

$$\frac{\partial u}{\partial x} + \frac{\partial w}{\partial z} = 0 \qquad (3)$$

$$C_p\theta\,\frac{\partial \pi}{\partial z} = -g \qquad (4)$$

$$\frac{\partial \theta}{\partial t} + u\,\frac{\partial \theta}{\partial x} + w\,\frac{\partial \theta}{\partial z} = \frac{\partial}{\partial x}\left(K_h\,\frac{\partial \theta}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_z\,\frac{\partial \theta}{\partial z}\right) \qquad (5)$$

The first two equations are horizontal momentum equations in which the terms on left hand side refer to local and advective changes whereas the terms on right hand side of Eqn. (1) are the Coriolis, pressure gradient and horizontal and vertical diffusion respectively. The Coriolis force takes care of the rotation of earth and is represented by a parameter 'f' defined as $2\Omega sin\phi$, where Ω is the angular velocity of the earth (2π/24hr) and ϕ is the latitude of the site. Value corresponding to the proposed site (Kalpakkam, 12° 13'N and 80°E) of application of the model is given as the latitude. U_g in Eqn. (2) is the upper air geostrophic wind given as the stationary upper boundary condition. Eqn. (3) is the continuity equation for an incompressible (anelastic) fluid which is a valid assumption for the atmospheric boundary layer. Eqn. (4) is a hydrostatic approximation for the vertical momentum in which the static pressure gradient and gravity forces are in balance and derivation of the vertical velocity is ignored. Assuming that the air follows ideal gas law and moves



Figs. 2 (a & b). Simulated wind at (a) 2 PM on day 1 and (b) 2 AM on day 2

dry adiabatically, two scaling parameters for temperature and pressure are defined as follows :

the potential temperature

$$\theta = T \left({P_0} \big/ {P} \right)^{R/C_p} \tag{6}$$

and the exner function

$$\pi = \left({P_0} \big/ {P} \right)^{R/C_p} \tag{7}$$

where $P_0 = 1000$ hPa.

Instead of using the density and pressure as the variables in the equation, the use of θ and π does more justice to the compressibility of air. Eqns. (4) and (5) are the hydrostatic and temperature equations written using θ and π. The initial temperature profile is assumed for a stable atmosphere as follows :

$$\theta(Z) = \theta_{sea} + \gamma Z \tag{8}$$

where, $\gamma = 0.005°\text{K/m}$ and $\theta_{sea} = 283°\text{K}$. A sinusoidal temperature wave with a maximum amplitude of 10°K and a constant surface temperature over the sea water are specified as the initial conditions. It may be noted that it is the differential temperature between land and sea (*i.e.*, the amplitude) and not the temperature itself that drives the sea breeze circulation in the model. The boundary conditions are as follows :

at the lower boundary ($z=0$), $u=v=w=0$;

at the upper boundary ($z=h$), $u=u_g$, $v=v_g$, $w=0$; θ and π are constants; and

at the lateral boundaries

$$\frac{\partial u}{\partial x} \text{ and } \frac{\partial v}{\partial y} = 0 \tag{9}$$

Here, u_g and v_g are the components of the geostrophic wind and are assumed zero for the present simulation. The constants used for this system have their usual values. The value for K_h is 2000 m^2/s and K_z is 10 m^2/s.

2.2. *Numerical scheme*

A forward in time and centred in space (central differencing for horizontal diffusion terms and upstream indifferencing for advection terms) numerical integration scheme with one minute time step has been utilised. The model domain is resolved into 80 equal grid spacings of 2 km each in the horizontal and 50 grid spacings of 30 m each in the vertical. The domain is divided horizontally into two halves, each representing the land and sea terrain and the sinusoidal change of temperature with time over the land surface drives the dynamics of the system. The potential temperature equation is solved first and subsequently used to estimate the pressure diagnostically by integrating the hydrostatic equation downwards. The values of u and v are computed from the momentum equations. The vertical velocity is then calculated from the continuity equation by integrating upwards.

2.3. *Simulated wind and the TIBL structure*

The general features of the flow field over a coastal region could be simulated in our study. Fig. 2 (a) shows the wind field on $x-z$ plane at 14 hr (2 p.m.) when the sea breeze has penetrated around 20 km inland and as well as the counter flow aloft. Fig. 2 (b) shows the land breeze at 2 a.m. next day. The arrows indicate the resultant

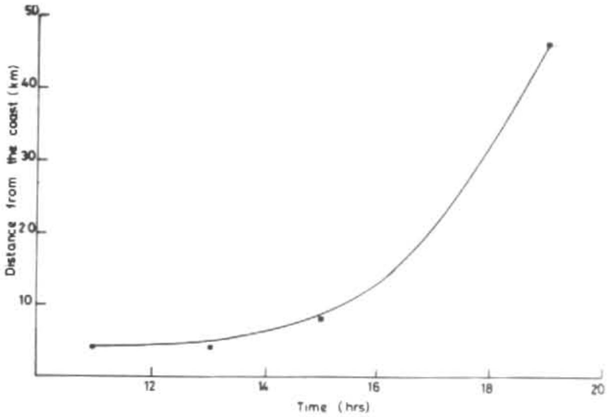


Fig. 3. Sea breeze front (W_{max}) movement

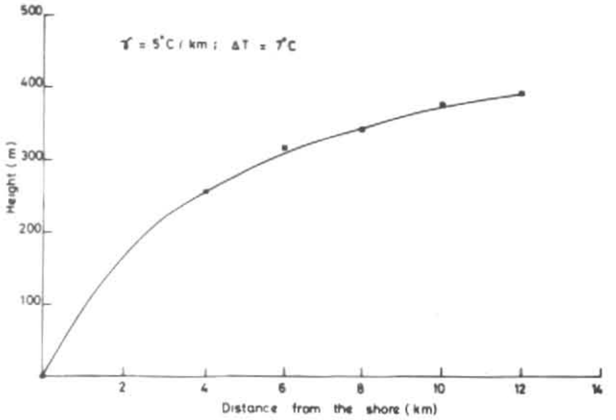


Fig. 4. Thermal internal boundary layer ($\gamma = 5°C/km$; $\Delta T = 7°C$)

wind vector of the longitudinal (u) and vertical (w) components of the wind. The vertical component is enhanced by a factor of 25 so that the circulation can be seen clearly. The wind spirals with height due to shear force and with time due to Coriolis force so that the lateral component (v) is in continuous change (not shown in the figures). Fig. 3 shows the position of the sea breeze front (defined as the position of the maximum vertical wind) inland with respect to time. The sea breeze accelerates once it moves landward after the time of maximum surface heating. Fig. 4 shows the height (Z_i) of the TIBL with distance inland. Observations of Z_i have yielded a dependence on the vertical temperature profile over water (γ), the temperature difference between land and sea surfaces ($\Delta\theta$) and the inland distance X of the following form as reported by Stunder and Sethuram (1985) and Venkatraman (1988);

$$Z_i = \frac{u_*}{U} \left\{ \frac{X|\Delta\theta|}{|\gamma|} \right\}^{0.5} \tag{10}$$

where u_* is the friction velocity characteristic of the wind shear close to the land surface. Similar dependence was observed in this model from the parametric studies and the power factor was found to be 0.57 which is in close agreement with the empirical formula.

2.4. *Numerical scheme for the dispersion*

The procedure outlined by Hiroyuki Ozoe *et al.* (1983) is followed in our model. Concentration equation based on K-theory of diffusion is solved numerically to get the dispersion pattern. For a point source [it can be considered as a line source in the present 2D model since homogeneity is assumed in the lateral (y) direction] with constant emissivity located at (x_0, z_0) the concentration equation is as follows:

$$\frac{\partial C}{\partial t} + u\frac{\partial C}{\partial x} + w\frac{\partial C}{\partial z} = \frac{\partial}{\partial x}\left(K_h \frac{\partial C}{\partial x}\right) + \frac{\partial}{\partial z}\left(K_z \frac{\partial C}{\partial z}\right) + \delta\,(x-x_0,\ z-z_0) \tag{11}$$

where δ is the kronecker delta. The values of the eddy diffusivities K_h and K_z are assumed to be same as those used for other equations in the model and the equation is numerically integrated alongwith others in the system. The concentration (kg/m^3) is divided by the emission rate (kg/m^3/sec) to give the value of C (sec).

3. Results and discussion

The sea breeze model is run for a numerical period equivalent to 24 hr model simulation time to attain stability. After this, a continuous point source is set at a height of 120 m at the coastal line (resembling the stack release) and emission starts at 8 hr (model initial condition) in the morning. Fig. 5 illustrates the vertical pattern of the concentration contours predicted every 2 hr later. In order to understand the influence of the coastal air circulation alone, the effect of TIBL on the effluent dispersion is ignored in this case. The outermost contour corresponds to the value of 100 (sec) and the inner ones are incremented by 100 with respect to their immediate outer contour. Every unit on the abscissa corresponds to 4 km and in the ordinate (height), 60 m respectively. Unit 20 corresponds to the shoreline and the length of the land

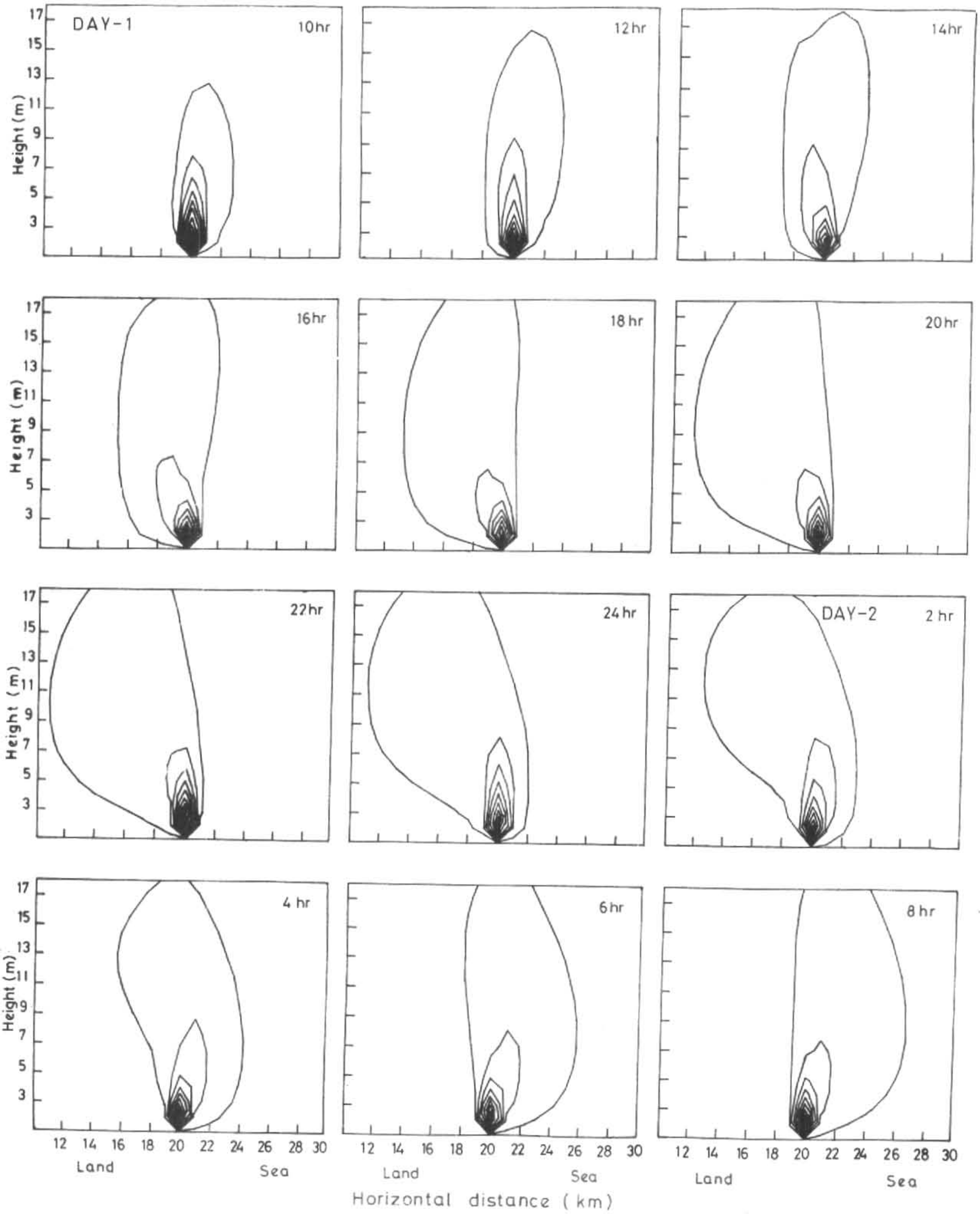


Fig. 5. Vertical pattern of the concentration contours of a continuous point source located at the coast. Release time : 8 hrs on day 1.

Scale : 1 unit on X-axis = 4 km 1 unit on Y-axis = 60 m Unit 20 corresponds to the shoreline location

Contours : Outermost = 100 (sec), inner ones incremented by 100 (sec) with respect to the immediate outer contour

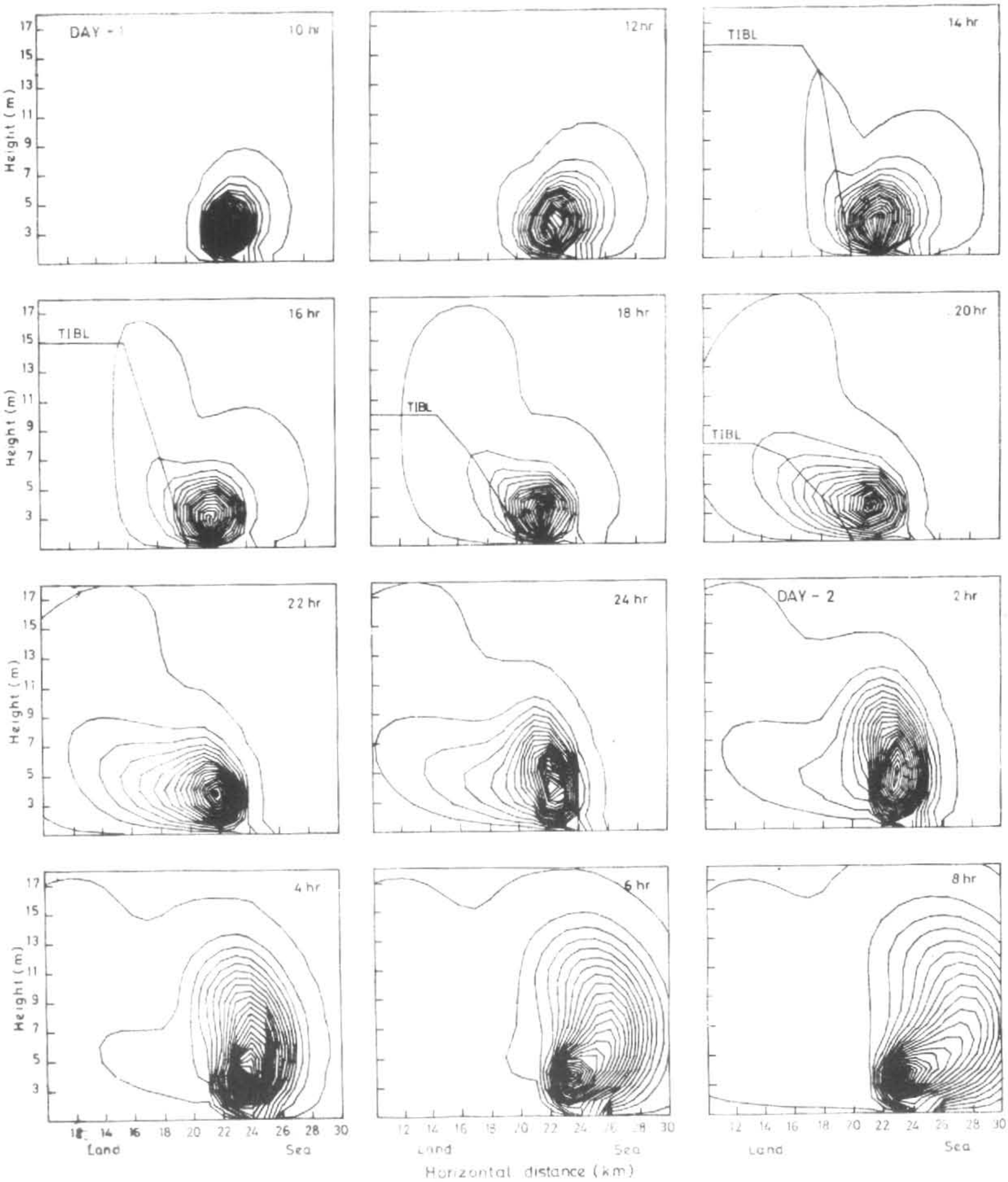


Fig. 6. Same as Fig. 5 but with enhanced turbulence eddy diffusivity within the TIBL over land (*i.e.* fumigation)

and sea should be calculated from the number of units on either side of it. Since the release is continuous, there is a growth of concentration in the flow field. The effect of the sea breeze and the counter current aloft can be seen clearly, particularly in the outer most contour. The vertical component of the wind velocity increases with inland distance; as a result, the plume is bent.

In order to study the fumigation into TIBL clearly, the continuous point source is set at a height of 180 m and a distance of 10 km offshore. Strictly speaking an area source should be considered in order to simulate the smoke from offshore oil well burning. However to avoid the boundary effects in the model and for simplicity, the source is assumed to be an elevated point source. A higher value of vertical eddy diffusivity ($K_z = 10\ m^2s^{-1}$) below TIBL representing unstable condition of the atmosphere and a lower value of the same ($K_z = 1\ m^2s^{-1}$) above TIBL has been assumed for the concentration equation alone, leaving the corresponding values of other equations undisturbed. Fig. 6 shows the concentration pattern obtained in this condition. The intense diffusion over land can easily be noticed. This result is due to the sudden fumigation of pollutants when they meet the TIBL over land. The parabolic nature of the TIBL can be noticed if the picture close to the coast is magnified. It becomes linear beyond a distance of 12 km approximately.

The fact that the effluent diffuses horizontally to a large distance upwind makes no meaning as the vertical diffusion is expected to be more than the horizontal. The concentration contours on the other hand show a large horizontal diffusion in addition to transportation during the initial period of release. This 'artificial' diffusion problem is known to be associated with any Eularian model such as Box model. One way of eliminating this problem is to assign to sufficient number of grids an initial distribution of pollutants calculated using Gaussian model and then solve the concentration equation. The best way is to treat the pollutant particles in a Lagrangian way and count the number of particles in a grid cell to know the concentration. Models like MATHEW-ADPIC and SPEEDI solve the dispersion problem using this technique (Maramichi and Hirohiko 1989). At the same time, wind field in these diagnostic models is supplied by interpolation techniques which can not simulate the sea breeze frontal movements and the TIBL. Hence coupling the prognostic sea breeze model with a suitable Lagrangian scheme will provide the desired result at a coastal site.

4. Conclusion

The sea breeze model simulates the general features of the flow field over a coastal site in conformity with similar models by others reported in the introduction. The influence of the flow on the air pollutants has been illustrated qualitatively in this study. The structure of the TIBL is obtained prognostically and the fumigation of pollutants into it is clearly shown. It is realised that this model possesses the drawbacks like, artificial numerical diffusion, unrealistic assumption of constant eddy diffusivities with height and time, omission of the atmosphere surface layer characteristics, etc. The numerical diffusion can be overcome by treating the pollutants in a Lagrangian way and a more physically realistic modelling of eddy diffusion is possible by improving the closure scheme to higher orders and coupling the boundary layer model with a suitable surface layer model. The present model is the basic one in which all these improvements will be incorpoated.

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