Hydraulics Research
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WIND-INDUCED MIXING OF BUOYANT PLUMES

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ABSTRACT

In the absence of wind a buoyant plume of effluent discharged to the sea some distance from the shoreline is most frequently swept nearly parallel to the coast by the tidal currents. The main reason for a surface plume to approach the beach is if there is a wind blowing onshore. Although the wind has this adverse effect of allowing the effluent to reach the shore it tends at the same time to cause additional mixing so reducing the pollution risk. It is important in planning outfalls to know the extent of this extra mixing.

The processes causing plume dilution from outfall to shore are first reviewed in the absence of wind. The presence of a wind is found to cause extra mixing by two important physical processes. The first is the entrainment of ambient water into the plume caused by the turbulence in the plume induced by the wind. This process resembles that of thermocline deepening in lakes and oceans. Experiments, observations and theory are described for this related case. The entrainment rate depends on a Richardson number formed from the reduced gravity, surface friction velocity and surface layer depth. The second process is the shear layer dispersion caused by the wind-induced surface current. This process gives a horizontal dispersion coefficient larger than the turbulent diffusion and more effective at causing mixing.

In a simple bulk-flow model of an effluent plume these effects can be incorporated by introducing vertical entrainment of the ambient water and by augmenting the lateral turbulent diffusion with a shear dispersion term. In a 2D depth-integrated model only the shear dispersion is important and it can be modelled as an anisotropic diffusion coefficient. In a 3D model, on the other hand, all the physical effects are included. The only extra terms that might improve the representation would be the effects of surface and interfacial waves and extra turbulence at the surface where the wind shear induced turbulence is generated.

An example of a 3D model of a cooling water plume is given with realisations without wind and with a 5m/s and 10m/s wind. The results show that for a 5m/s wind the plume trajectory is changed, but little extra mixing occurs. With a 10m/s wind a great deal of mixing is found causing the surface isotherm areas to be much less than in the case without wind.

By making these additions to the basic plume models it should be possible to avoid making conservative approximations that tend to lead to over-cautious design of sea outfalls.

CONTENTS

FIGURES:

1 INTRODUCTION

The discharge of effluent to the sea usually leads to a buoyant surface plume. Such plumes may have severe environmental impacts and in the case of cooling water plumes it is also important to avoid recirculation. For this reason buoyant plumes are frequently modelled (eg Refs 1, 2, 5, 6 etc) in order to predict these effects before construction is begun.

In tidal waters a buoyant plume discharged offshore is usually carried to and fro with the tidal oscillation nearly parallel to the shore. In addition there is a weak tendency for the plume to move shoreward on the flood and seaward on the ebb. As the plume is on the surface a much more likely cause of the plume coming onshore, where the sensitive area is likely to be, is if there is an onshore wind. The surface water will acquire a velocity component of 1-3% of the wind speed in the direction of the wind vector. The return current is near the bed where it will not affect the plume until it gets very close to the shore.

However, although the onshore wind is believed to be very often the most adverse case it has other effects tending to reduce the magnitude of the pollution problem. The extra turbulence the wind generates causes vertical mixing, tending to deepen the plume and reduce the concentrations. In addition to this effect the wind generated current leads to a strong shearing layer, with different current speeds or directions at different depths, which tends to disperse the plume horizontally, again reducing the peak concentrations.

In order to quantify this case the plume dynamics in the absence of wind are examined first (Chapter 2). Numerical models used for buoyant plumes are also described. In Chapter 3 the vertical mixing and shear dispersion caused by a wind are examined in turn and suggestions for how they may be approximately modelled are given.

2 PLUME DYNAMICS WITHOUT WIND

An appreciation of the mechanisms that govern the mixing of a buoyant plume in the absence of wind is clearly necessary as a first step in examining the effect of the wind. These mechanisms will be described starting from the discharge point and proceeding through ever greater dilutions until the plume becomes completely mixed in with the ambient water at great distances from the outfall and long times after discharge. Figures 1, 2 and 3 show the main processes schematically.

2.1 Initial dilution

If the discharge structure is submerged then a combination of the jet momentum and the buoyancy of the effluent will cause the plume to rise to the surface. The turbulence of the rising plume causes ambient water to be entrained and dilution to occur (Fig 1). The amount of dilution depends strongly on the ambient current speed and for a sewage outfall may be tens or hundreds of times greater at times of maximum current than at slack water (Ref 1). This leads to characteristic poorly diluted patches of effluent being formed at slack water periods which are then transported by currents and wind (Ref 20). As these patches have large buoyancy and are therefore comparatively immune to mixing it is particularly important to predict their trajectories and estimate their concentration.

Power station discharges have high discharges and often very little initial dilution may occur especially as outfalls are frequently located in rather shallow water.

2.2 Buoyant spreading

After reaching the surface, even in a greatly diluted state, the density difference from ambient is usually large enough for buoyant spreading and radial spreading due to the injected mass to dominate strongly over the spreading due to turbulent diffusion as the plume is carried away by the tidal current. This is particularly the case for power station cooling water plumes with their often poor initial dilution (Ref 2). The physical processes of the interaction of plume and tidal currents at this stage are very complex (see Figs 1 and 2) and may include bifurcation of the plume downstream of the outfall (eg Sizewell, Ref 2) or the formation of an arrested plume upstream of the outfall (Ref 3).

The plume usually occupies a fairly shallow layer at this stage, for example at Eastney on the Solent (Ref 4) the sewage plume 500m from the outfall is about 2m deep. This is typical of many buoyant plumes, including cooling water plumes such as that at Sizewell (Ref 6).

2.3 Mixing plume

While spreading out under buoyancy and being carried along by the current the plume is also mixing horizontally, mainly from the edges, decreasing the buoyancy until the lateral spreading rate due to turbulence exceeds that due to buoyancy (Fig 3). The plume may still be on the surface but it tends to assume a Gaussian lateral profile and spreads out as a result of ambient turbulence. In the absence of wind there is negligible shear between the plume and the ambient. The point at which this occurs may vary from one plume to another by a large amount, for example a sewage plume may be expected to lose much of its buoyancy very rapidly; Charlton (Ref 20) suggests this can happen within 50m.

As the plume is carried along by the ambient current an important process may occur which can be called "negative entrainment" (Ref 6). This results from the fact of the main source of turbulence generation in the absence of wind being at the bed. This causes the ambient water underneath the plume to be turbulent and the eddies can entrain water from the plume by engulfing small "packets" of it and incorporate it into the ambient below (Fig 3). Such plume water is mixed through the whole ambient water column contributing to the formation of the far-field.

2.4 Far-field

As a result of these diffusion processes the density difference between the plume and the ambient water decreases further until eddies can form that occupy all of the water column. The plume is then spread through the whole depth by these eddies and its buoyancy effects cease, in effect it becomes a tracer plume, this is the final state shown in Fig 3.

For different plume parameters the changeover to a well-mixed state can occur at different times after discharge. For a power station discharge it could well take a long time (perhaps several tides). On the other hand there is evidence that for a well diluted sewage plume it may occur fairly soon. At Eastney about 3 hours after discharge and 5km from the outfall the concentrations at ½m and 1½m below the surface were sensibly the same (Ref 4) implying a much greater depth for the plume, although not proving conclusively that it reaches the bed.

Over many tides the discharged water forms a background distribution which is very important for any pollutant with a long survival time (eg coliforms in fresh or tubid waters or heat). The strength of this background depends very strongly on whether there is a residual tidal flow to remove the pollutant from the area (Ref 2).

Corresponding to these different phases of plume development a variety of numerical modelling techniques may be appropriate. These have been reviewed by Odd (Ref 8), the most important will be described briefly here.

2.5 Diffusion models

The horizontal spreading of a surface plume as a result of turbulent diffusion can be readily modelled assuming Gaussian profiles of concentration across the plume. Such a model assumes negligible buoyant spreading but it may nevertheless be possible to assume that vertical diffusion is suppressed as a result of the density difference so as to give a constant depth layer. Of course if there is no density difference - a non-buoyant plume - then the vertical diffusion coefficient can be approximated

(Ref 9) and the plume spreads through the vertical readily until the bed is reached. Vertical diffusion coefficients in the absence of buoyancy (Ref 9) both observed and also obtained theoretically give values often of the order of $10^{-3}m^2/sec$ which is very small compared to horizontal dispersion coefficients which may be of the order of $0.1m^2/sec$. If the plume is buoyant this vertical diffusion coefficient may be reduced effectively to zero (Ref 10).

2.6 Depth-integrated transport models

When the plume has become mixed through the whole depth it is possible to use a standard depth-integrated transport model. Such a model is the Hydraulics Research TIDEWAY system program POLLFLOW-2D used for far-field studies of pollution. The necessary longitudinal and lateral dispersion coefficients can be calculated for a logarithmic velocity profile (Ref 9).

2.7 Three-dimensional models

Another kind of model which has become available in recent years is the 3D model. Such a model resembles a depth integrated model but it has several layers. A 3D numerical model can represent horizontal and vertical transport and turbulent diffusion and can also include buoyant spreading. As a result this kind of model is useful closer to the outfall than the previous two kinds of model.

In a 3D model the vertical turbulent diffusion has to be computed, often using a mixing-length theory (Ref 7), including the suppression of turbulence by vertical stratification. This type of model has been found particularly useful for large discharges from power stations which spread over a considerable area. Both unsteadiness and the plume's confinement near to the surface are realistically predicted in a 3D model.

Some further kinds of numerical model are described in Ref 8. Physical models may also be appropriate, the scaling laws require no vertical exageration so they are particularly valuable for modelling the region close to the outfall.

3 WIND EFFECTS

When a wind blows on a buoyant plume a surface current is induced. Turbulent kinetic energy is produced by the coupling of pressure fluctuations between wind and water and velocity shear in drift current and Langmuir cells. The current and turbulence penetrate downwards rapidly, and a mixed surface zone results. If the plume is confined to the surface, as a buoyant layer, then the mixed zone will reach the interface where turbulence will be strongly damped. At this stage two important effects come into play. The plume with its wind-induced turbulent eddies will start to entrain ambient water from below in the same way as thermocline deepening occurs in lakes or in the ocean. Any entrained ambient water will be mixed through the surface layer reducing the buoyancy at the same time. The other important result is the shear in the surface layer. This causes dispersion in the sense of Taylor (Ref 11). This dispersion may be larger than turbulent diffusion causing the centreline concentrations to decrease more rapidly than they would with no wind.

As the turbulence tends to decrease velocity gradients in the surface layer a strong shear layer will form at the interface. Because of the strong density gradient at the interface this strong shear does not act as a major source of turbulence.

If the plume is mixed through the depth the extra vertical mixing due to wind and wave induced turbulence is not important, the depth-mean current is only weakly affected by wind and the only important effect of the wind is in increasing the dispersion in the wind direction.

It follows from these complex interactions and also from the uncertainties in our knowledge of plumes even without wind effects (Chapter 2) that it is very hard to use observations to obtain an estimate of the extra mixing in the plume. In the case of a 3D model, on the other hand, many of the mixing processes, such as the effect of shear on the plume, are actually modelled whereas others, eg effect of waves, are known to be absent. Therefore it should be possible to compare results with observations with and without wind, when suitable observations are available.

The subject will be divided into two parts, firstly (Section 3.1) the vertical mixing will be investigated. The theory and experiments will be described as well as observations in lakes and the ocean. These are simpler than the case of a plume as the ambient is supposed to be at rest, or at least not turbulent, and the situation is supposed to be horizontal homogeneous. In section 3.2 the horizontal variations will be considered as the wind generates dispersion horizontally. This process occurs in the ocean also but as there are no horizontal gradients it has no consequences.

3.1 Vertical mixing

In this section the wind effect to be studied is the vertical mixing, so horizontal uniformity may be assumed. Bed generated turbulence is ignored as it is in most experimental and theoretical work - this should be a conservative assumption as the turbulence will reduce the peak concentrations.

The system therefore comprises a surface layer accelerated and made turbulent by wind stress over an ambient layer which is as yet unaffected by the wind. This is the case of the oceanic mixed layer and it is well known that thermocline erosion occurs. This is a one way process (ignoring any turbulence in the ambient) in which the ambient water is entrained into the plume which becomes more dilute as the interface deepens.

Over many years a great deal of work has been done on problems of this type theoretically, experimentally and observationally (see references in Ref 21). A brief discussion will be given to outline the physical processes involved in thermocline erosion. After this the implications will be considered for modelling the wind mixing of a plume both in the bulk plume model and in a 3D model. When the plume has been mixed through the depth in the far-field vertical mixing is no longer of interest so this domain will not be considered further.

The most relevant experiments are those in which a buoyant layer is set up in a tank over a denser layer and the surface is set in motion either by a screen or by enclosing the tank in a wind tunnel. Different tank geometries have been used including annular tanks which have no end walls. Such experiments are described in References 12-17. Early results (Refs 12, 13) showed that the rate of deepening (which is the same as the entrainment velocity w_e) depended on a Richardson number Ri based on density difference $\Delta\rho$, depth of surface layer h, surface friction velocity u_*, ambient density ρ_a and gravitational acceleration g. As an example various authors (Refs 13, 17) give formulae of the type:

$$\frac{w_e}{u_*} = \alpha \frac{u_*^2 \rho_a}{g \Delta\rho h} = \alpha \, Ri^{-1} \qquad (1)$$

where α is an empirical constant ($\alpha \sim 0.07$). This gives a rate of deepening of about 10mm/s for a 2m thick layer at 2°C above ambient with a 10m/sec wind.

This formula has been found to represent the thermocline deepening best when the effect of end walls has been felt so that the mean velocity in the surface layer is zero. An intermediate layer between the well-mixed surface layer and the ambient occurs in this case (Ref 16).

A more interesting case may be before the end walls have had an effect so that a strong shear is set up in the surface layer. In this situation a different (and larger) entrainment value is found:

$$\frac{w_e}{u_*} = \beta\, Ri^{-\frac{1}{2}} \text{ where } \beta \sim 0.6 \text{ (Refs 16,19).} \qquad (2)$$

This gives a rate of deepening of about 80mm/s in the case considered above. The reason for these two different regimes (Ref 18) is that end walls prevent mean shear between the upper layer and lower layer so one source of turbulence is absent in this case, the only source of turbulence is direct wind-mixing.

This is made clearer by the turbulent kinetic energy balance which has been written down for studying the upper layer in lakes. It has the form (Ref 21)

$$\tfrac{1}{2}\left(\frac{\Delta\rho}{\rho_a}\, gh\right) \frac{dh}{dt} = \frac{1}{2}\, C_k u_*^3 + \frac{1}{2}\, C_s u^2 \frac{dh}{dt} \qquad (3)$$

where C_k and C_s are constants and u is the upper layer velocity. The left hand side represents the energy required for mixing and the right hand terms represent energy inputs from wind stress and interfacial stress respectively. Other terms, unimportant in the present case, have been omitted from Equation 3. If there are end walls so that u = 0 then

$$\frac{dh}{dt} = C_k u_*^3 \;\Big/\; \left(\frac{\Delta\rho}{\rho_a}\, gh\right) = C_k u_*\, Ri^{-1} \qquad (4)$$

which has the same form as Equation 1.

Without end walls the balance is between the left hand side and the second term on the right ie

$$\frac{\Delta\rho}{\rho_a}\, gh = C_s u^2 \qquad (5)$$

As the surface layer velocity u increases like

$u_*^{\,2}\, t/h = u_*^{\,2}/\frac{dh}{dt}$, from the momentum balance,

it follows that $\frac{dh}{dt} = C_s^{\frac{1}{2}}\, Ri^{-\frac{1}{2}}$ (6)

which has the same form as Equation 2.

Observations in lakes and the ocean (Refs 21, 18) have been found to be in good agreement with predictions obtained from the equations in this section.

3.2 Shear effect

In a plume there will be strong shear in the direction of the wind which will also cause dispersion in that direction (Ref 19). This effect will have its greatest impact when the direction of the wind is one in which there are strong concentration gradients in the plume. In particular lateral shear, perpendicular to the plume centreline will be effective at reducing centreline concentrations.

In a bulk or diffusion model this effect should be included by direct enhancement of the lateral diffusion. In a depth-integrated model similarly the diffusion should be augmented in the wind direction (anisotropic diffusion). However, in a 3D model the Taylor dispersion process should be fully modelled, the interlayer shear causing both the differential advection to spread out the concentration field and the interlayer diffusion tending to mix it vertically. No correction to a 3D model should be necessary.

The size of the dispersion term can be estimated from Reference 9. It is shown there that in a parallel flow the dispersion coefficient can be approximated by

$$K = \frac{h^2 \overline{u'^2}}{E} I \qquad (7)$$

where h is the depth of the layer, u' is a typical variation in the mean velocity, the overbar denotes the layer average, E is the layer average vertical turbulent diffusivity and I is a constant depending on the shapes of the velocity and diffusivity profiles. It is suggested in Reference 9 that I is always close to 0.1.

When the plume has become vertically well mixed and buoyancy effects have ceased the extra dispersion due to wind can be estimated from Equation 7. With a linear velocity profile 7 becomes

$$K = \frac{u^2 h^2}{120E} \qquad (8)$$

where u is the velocity range from top to bottom. If the vertical turbulent diffusion is supposed to be due to the tidal current then $E = 0.067hu_*$ where u_* is the bed friction velocity ($\sim u_a/20$) where u_a is the tidal current velocity. If u is supposed equal to $u_w/30$ where u_w is the wind velocity this gives

$$K = 0.003 \frac{u_w^2 h}{u_a} \qquad (9)$$

With a wind speed of 10m/s, a depth of 10m and a current of 1m/s this gives $K = 3m^2/s$.

For a surface layer it is difficult to provide an equivalent formula as the variation of current speed and vertical turbulent diffusivity across the layer are not well known. Using formula 9 can only give a first estimate, for example, if the plume thickness is 1m the dispersion coefficient becomes $0.3m^2/s$.

Such formulae only apply after the plume has become well mixed and there is a balance between differential advection and turbulent mixing.

It should be noted that using dye experiments where buoyancy is not included will give different values of the dispersion coefficient until the dye becomes well mixed through the depth. This is because in the absence of buoyancy there is no lower boundary to the plume's spreading and Equation 7 is therefore not valid. The plume will tend to spread rapidly because vertical diffusion continuously increases the range of velocities in the plume (see Ref 9).

3.3 Model example

As it seems that most of the effects of wind on a buoyant plume are correctly incorporated in a 3D model it was decided to use such a model to see how sensitive the results were to the wind speed. Tests were run for a $150m^3/s$ cooling water outfall in about 7m of water at a temperature excess above ambient of 11°C. The area concerned has a spring tide range of 4m and a current amplitude of 0.2m/s. The model was run with 4 layers of depth 1m at the surface and one more layer to represent the rest of the water column. The horizontal grid was 100m and the timestep was 3.8 sec. The model was run with no wind but also with offshore winds of 5m/s and 10m/s. Both the cooling water discharge and the wind began at high water so the processes associated with wind take a while to have an effect. The results for the three tests are shown in Figures 4-6. No surface cooling is included in these simulations.

Comparing Figures 4 and 5 shows that a 5m/s wind affects mainly the position of the plume but it seems that the extra mixing does not greatly affect the surface temperatures. Towards the end of the tide there is some indication of the isotherm areas being a little smaller than in the absence of wind. Figure 6, for a 10m/s wind, shows clearly the extra mixing that occurs. The surface layer temperatures are smaller than in the previous case as is shown by the reduced isotherm areas.

These model results indicate that for low wind speeds the plume trajectory may be altered with very little change to the mixing but how the mixing becomes very effective at higher windspeeds.

4 CONCLUSIONS

The dynamics of buoyant plumes without wind have been reviewed and types of numerical model to simulate them have been described.

The effect of the wind in making the surface layer turbulent and entraining the underlying ambient has been investigated. Experimental work has shown two important regimes depending on whether the surface layer is free to move (no end walls) or whether the presence of a coast means that there is no mean current in the surface layer. In the first case the entrainment rate is proportional to the inverse square root of the Richardson number. This is much larger than in the second case where there is no mean shear and the entrainment rate is inversely proportional to the Richardson number. As the Richardson number is of the order of hundreds the difference between these regimes is critical. Near to the outfall where the buoyancy is at its greatest the wind effect is unlikely to be important. Far from the outfall it is also unlikely to be important where the plume becomes well mixed through the water column.

The effect of the wind in causing lateral mixing by Taylor dispersion depends on the strength of the wind across the current.

In a simple plume model the wind effect has to be incorporated as an entrainment rate for vertical diffusion and a lateral dispersion coefficient. In a 2D depth-integrated model only the lateral dispersion coefficient is important and in a 3D model the effects are included in the model.

The 3D model has been run for a cooling water plume with and without a wind. The results show that the plume trajectory is initially more affected than the temperatures. As the wind strength increases, though, very strong mixing causes the rapid dissipation of the plume.

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FIGURES

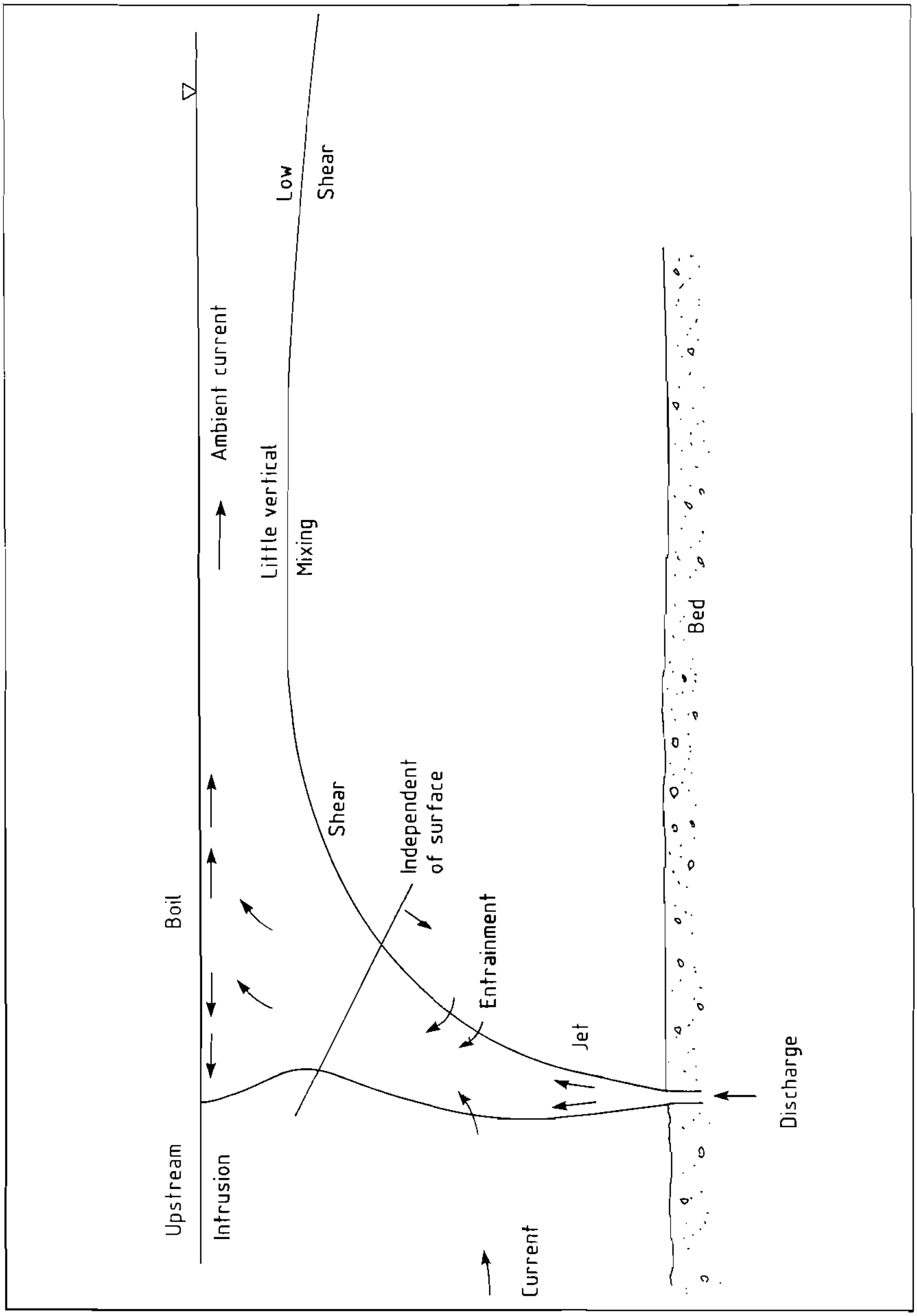

Fig 1 Plume schematic close to outfall - elvation

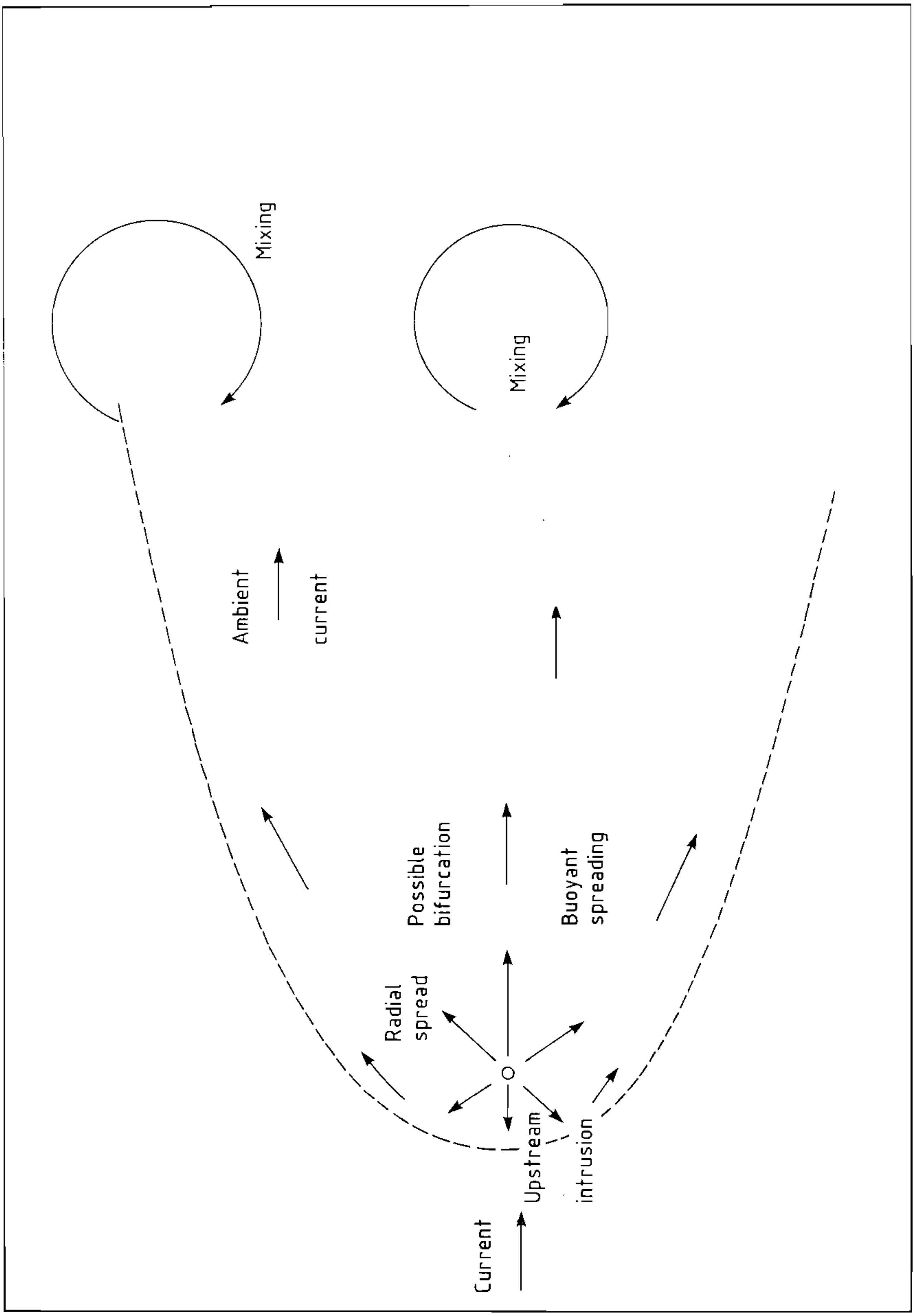

Fig 2 Plume schematic close to outfall-plan

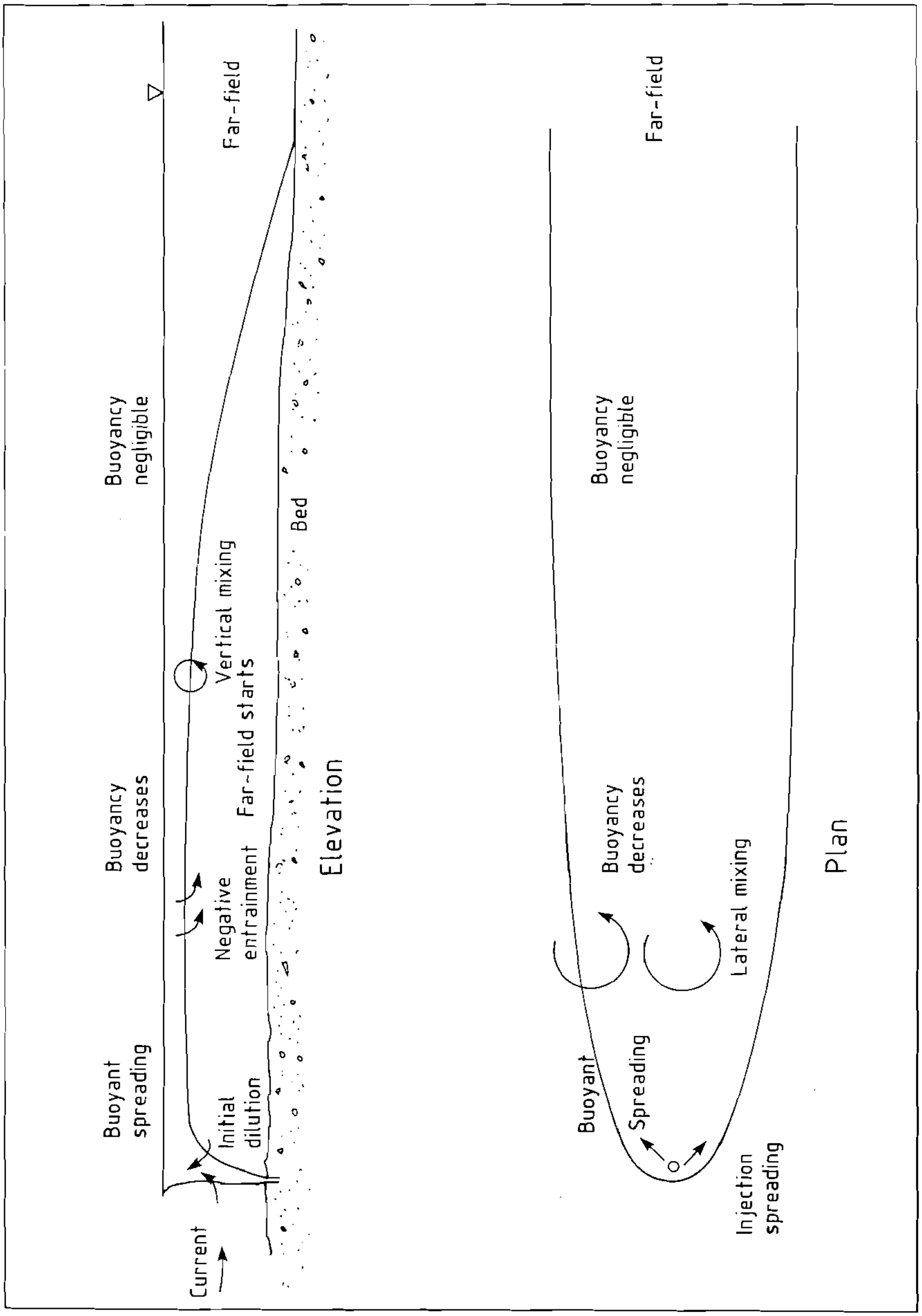

Fig 3 Plume schematic from near to far-field

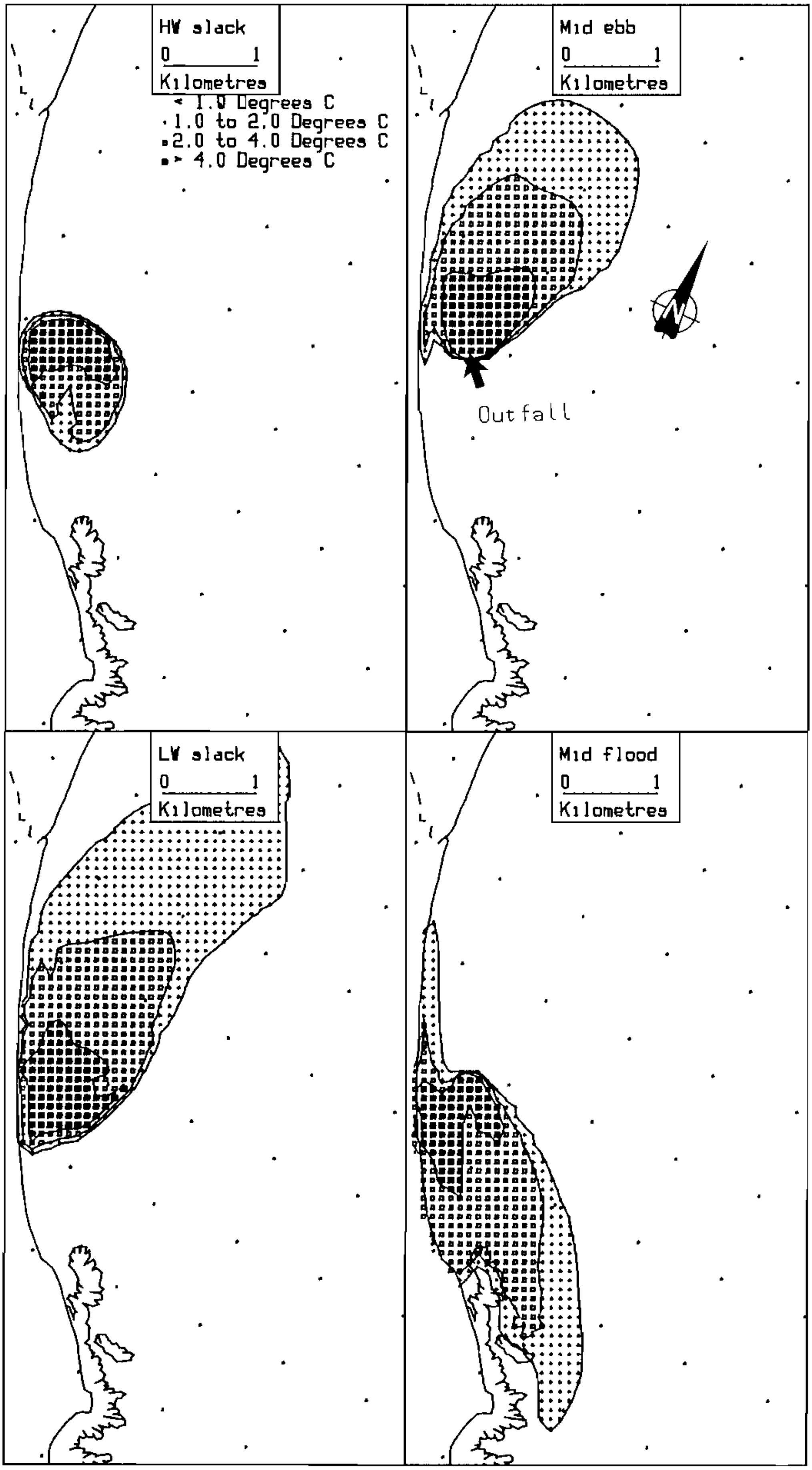

Fig 4 Contours of surface excess temperature no wind

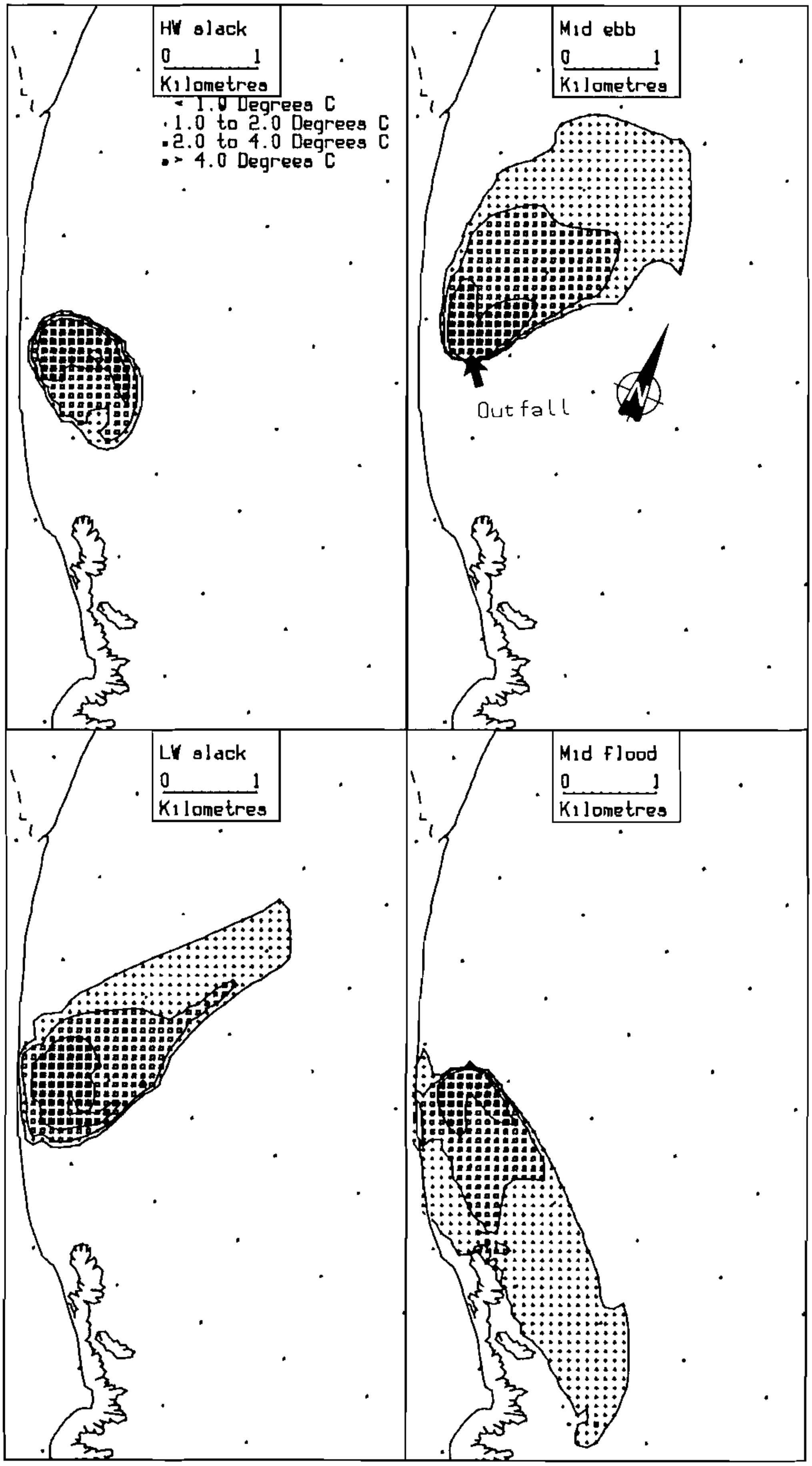

Fig 5 Contours of surface excess temperature
5 m/s offshore wind

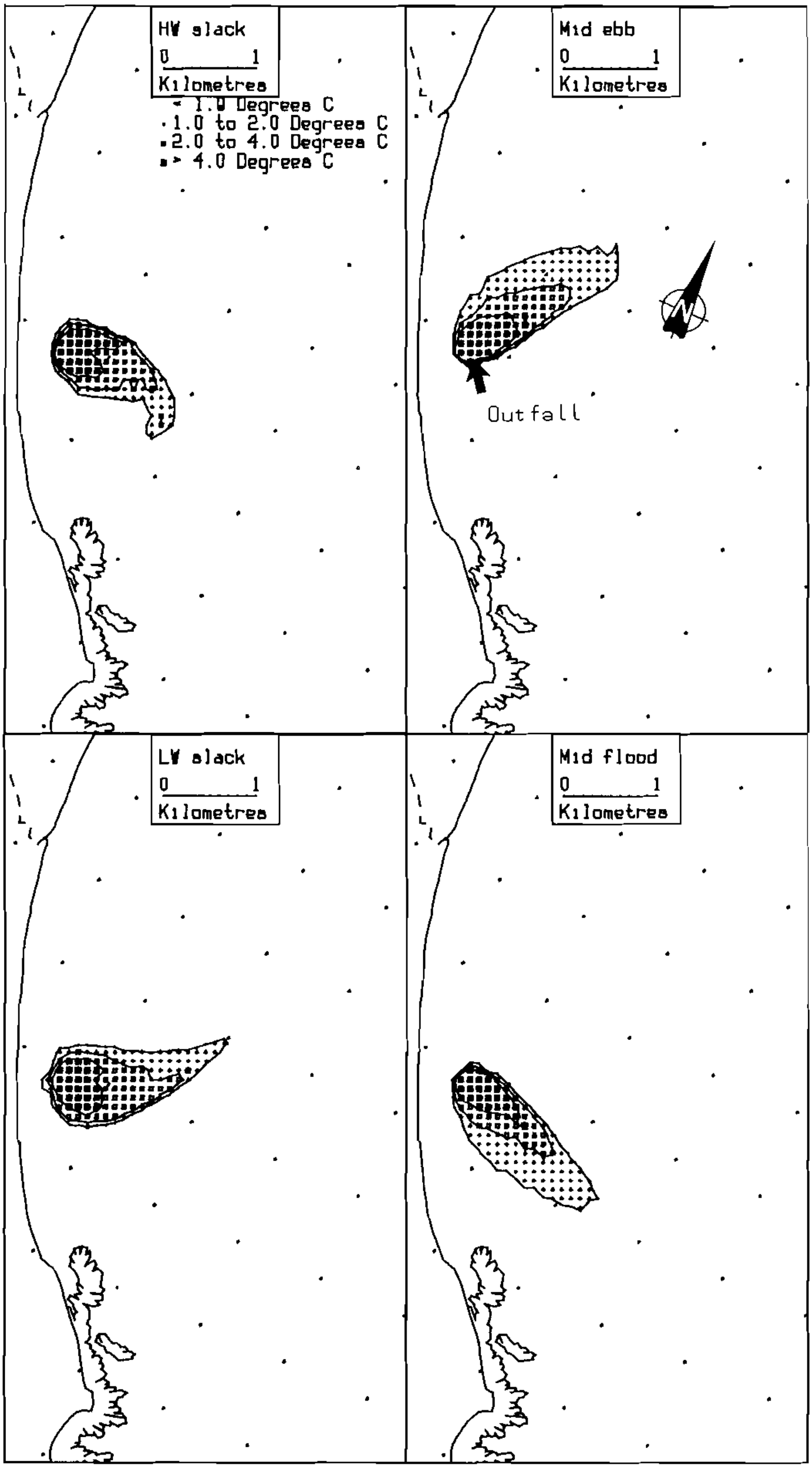

Fig 6 Contours of surface excess temperature 10m/s offshore wind