LOCAL MODIFICATION OF COASTALCURRENTS BY THE OPERATION POWER PLANT COOLING SYSTEM

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ABSTRACT

Coastal current regime can locally modified by the operation of the seawater cooling systems of Nuclear power plants. A case history of San Onofre Nuclear Generating station (SONGS) is presented here. The offshore-directed discharge jets of the SONGS diffusers entrain large volumes of ambient water into a plume flowing offshore and downcurrent. The initial momentum flux of the discharge is equivalent in magnitude to that of typical coastal currents of 10 cm/sec from shore to 4 km offshore. Although a substantial percentage of the momentum is lost during the initial dilution a sufficient amount remains to measurably alter the flow field in the vicinity of the diffuseres. Changes in the local velocity field associated with the SONGS cooling system are evident in synoptic studies and in long-term current patterns shown by diagrams of principal current directions. The local kelp beads near the diffusers also retard and divert both ambient and SONGS-induced flows.

INTRODUCTION

Diffuser system that discharge wastewater or cooling water to the sea through multiple outflow jest attain high immediate dilution by the rapid entraitnment of surrounding waters in the expanding jet flows. The local circulation produced by the entrainment has a volume flow much larger than that of the discharge alone and may be great enough to modify the local current field appreciably. When a multijet discharge is large enough to significantly effect the ambient flow, it becomes difficult to predict the dilution and trajectory of the discharge with the accuracy that is desirable for designing diffuser systems or predicting environmental effects. Hydraulic modelling can be provide useful predictions, but field observations of system in operation are of obvious value in dealing with complications that are difficult to scale correctly.

here we report some filed observations of disturbances to the natural flow-field by a large thermal discharge thought diffusers with multiple jests. This discharge is from Units 2 and 3 of the San Onofre Nuclear Generating Station (SONGS), which together take in about 100 m^3 / sec of seawater for cooling, and discharge this water through 126 ports directed offshore, mounted on two diffusers extending from about 1 km to 2.5 km from the shore, in water depths from about 10 to 15 m. The discharged water is heated by 10.7° c as it cools the condenser in SONGS.

The initial velocity of the jest is 4 m/sec, so the total momentum flux is about 400 m^4/sec^2. This is comparable to the flux in a typical longshore current of 10 cm/sec extending from the beach to 4 km shore. In addition, the heat induced buoyancy of the discharged water increases the velocity of the rising column of water. This in turn, increases the mixing in the near field. It is to be expected, than, that the natural field of flow will be considerably distorted by the circulation induced by the combined intake and discharge and the entrained water. The most obvious modification of the flow is the plume of discharged and entrained water. The plumes goes offshore beyond the diffusers when the longshore current is weak, but is turned toward the downcurrent direction as the longshore currents get stronger. Ambient flow also altered by the addition of a make-up current consisting of the intake and entrained flows, to replace the water drawn in at the intakes, or entrained near the diffusers and carried away in the plume.

Beds of the gaint kelp Macrocystis pyrifera can exert enough drage to slow current appreciably within the beds (Jackson, 1983), and consequently to divert part of the flow around the beds. the kelp beds off San Onfore lie close enough to the diffusers to influence both the plume and the make-up flow, as well natural currents.

2. DESCRIPTION OF THE INTAKE THERMAL DISCHARGE SYSTEMS

The san onofre Nuclear Generating Station (SONGS) lies on the coast of southern California between Los Angles and San Diego, at the edge of a shelf roughly 6 to 10 km wide out to the 100 mm isobath. Figure (1) shows the locations of the SONGS intakes and outfalls relative to coastline and nearshore bathymetry, and to the areas of hard substrate that make local habitats for gaint kelp. The protrusion of San Mateo Point onto a locally narrowing shelf 5 km upcoast (northwest) from SONGS is the largest irregularity in the shoreline and bathymetry for 10 km to either side of SONGS. Throughout this paper "upcoast" signifies toward Los Angles and "downcoast" means toward San Diego. Upcoast (northwest) and downcoast (southeast) directions are indicated in Figure (1).

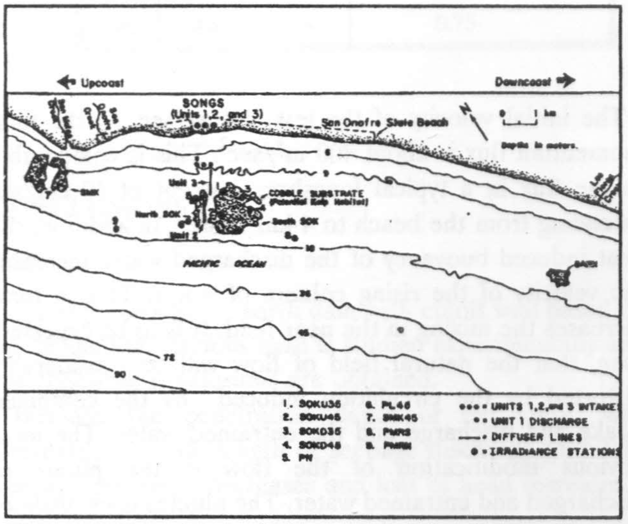

Figure 1. Locations of the SONGS intakes and outfalls relative to coastline and near shore bathmetry.

SONGS has three separate generating units, each of which has a once-through cooling system which pumps sea water through heat-exchangers to condense steam. Unit 1 circulates 22 m^3/sec from a point intake 900 m from the shore to a point discharge about 180 m directly inshore from the intake. Disturbance of the flow field by Unit 1 is highly localized, and this unit will not be further considered here.

SONGS'Units 2 and 3 each draws in 52 m^3/sec at intakes 970 m from shore deep (Fischer et al.1979). The intake is through vertical pipe whose orifice is at 3.5 m below water surface in water depth of 9.8m. Each unit discharges through a diffuser pipe 750 m long, perpendicular to the shore, with 63 ports spaced at 12 m intervals along the pipe. the diffuser of unit 3 is closest to shore, starting 1085 m from shore in 9.8 m depth end ending 1835 m from shore in 11.6 m depth> The diffuser of Unit 2 is 200 m upcoast from the Unit 3 diffuser and further offshore, starting at 1795 m from shore in 11.9 m depth and ending 2545 m from shore in 14.9 m depth.

The discharge ports are on risers which bring them to a height of 2.2 m above the bottom. The jets from the ports are directed offshore, with a tilt of 20° to one side, alternately upcoast and downcoast as shown in Figure 2. The port diameter is about .5 m and the initial velocity of the exiting jet is about 4 m/sec.

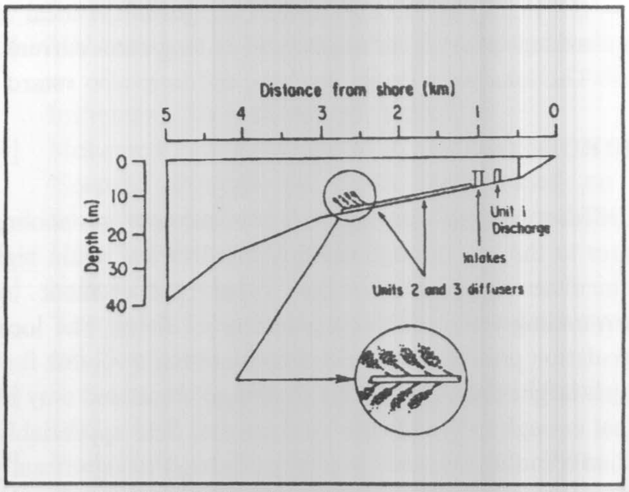

Figure 2. SONGS jet directions.

ENTRAINMENT OF AMBIENT WATER

Depending on the depth of water, the jets would start to impinge the sea surface at about 35 to 60 initial diameters from the ports in the absence of current; if each jet was isolated and unimpeded by boundaries it would entrain from about 9 to 16 times its original volume flow alonge this distance (see for example, Fischer et al., 1979, Figures (6-9). In actuality, the entrainment by each jet is restricted somewhat by the presence of the bottom, the surface, and the neighboring jets, so we should expect an average nearfield entrainment of 12 to be an upper limit when there is no current. Longshore currents will supply water from upstream, and will also bead the jets toward the horizontal downcurrent direction, keeping them away from the surface and from each other over a greater exial distance, so we may further expect that nearfield entrainment will increases with the strengt^Xxof the longhorn current.

This simple picture is fairly well-supported by thermal dilutions observed in a scaled-down hydraulic model of the SONGS cooling system (koh et al., 1974; see also Fischer et al., 1979) In modelled steady longshore currents equivalent to 5 cm/sec or less, maps od surface isotherms showed dilution a little under to 10 in a small region close to the inshore diffuser (Unit 3), and dilution between 10 and 13 to 1 in larger regions extending offshore along the axis of the model plume. In a model current equivalent to 13 cm/sec, the minimum dilution was greater than 13 to 1, and dilutions between 13 and 20 to 1 extended over the large central region of the plume. At a model-equivalent of 26 cm/sec, dilution over the whole plume was between 20 and 40 to 1.

A filed experiment with dye injected into the intake of Unit 3 (Elwany et al., 1989) gave calculated quasi-steady dilutions at 1 m below the surface increasing from 8 to 1 at 50 from the diffuser to 10 to 1 at 400 m from the diffuser, 18 to 1 at 650 m, and 24 to 1 at 1100m. On this occasion, Units 3 was operating at three-fourths of its normal pumping rate and the ambient longshore current outside the plume was about 7 cm/sec. The ambient temperature declined by about 1° over the upper 5 or so of the water column and was uniform midwater to bottom. This moderate stratification, as well as the presene of the San Onofre kelp bed, which were not modelled, are two likely explanations of hy the field dilutions were a little lower those expected from the model.

Overall, these dilutions indicate that in currents slower than about 5 cm/sec the original volume flow of 100 m^3 /sec is increased to approximate 1000 m^3 /sec by nearfield entrainment within two or three hundred meters of the diffusers, and is further increased to as much kilometer. In stonger currents the nearfield dilution is greater: a volume flow of 2000 m^3 /sec is attained closer to the diffuser, and subsequent entrainment is less.

If the original offshore momentum were conserved, we would expect to see offshore velocities approaching 40 cm/sec in a newly formed plume close to the diffuser (based on 10 to 1 initial dilution). Offshore plume velocities were not measured directly in the hydraulic model (koh et al., 1974), but may be inferred from the trajectories shown by streaks of dye in known ambient longshore velocities. These inferred velocities, and offshore velocities observed in the actual plume, never exceeded 20 cm/sec, and we may conclude that half or more of the initial offshore momentum in the jest is lost rather than exchanged with ambient water, In this situation, unlike that of an isolated jet in a large space, momentum need not be conserved, since both the upward momentum of the jets and buoyancy spreading can disturb the free surface and produce pressure gradient forces on the water in the jets and plume.

4. THE MAKE-UP FLOW

The plume of SONGS is often highly visible because of a contrast in turbidity and color. The other part of the total field of low induced by SONGS is the flow of water toward the intakes and diffuser jets that is required to make up the one or two thousand cubic meters per second flowing away in the plume. The intake and entrainment sinks of SONGS drive this make-up flow by drawing the sea surface in their vicinity, producing a downward slope of the surface toward SONGS that acceleration can be balanced by horizontal advection of momentum, and a steady state can be reached without transferring momentum to the bottom through turbulence and shear in the flow. It is an important characteristic of such convergent flows in unstratified water driven by surface slopes that are approximately uniform from top to bottom except very close to the sinks and in a frictional boundary layer at the bottom.

Disregarding bottom friction, we can approximate the make-up flow as a potential flow in the narrow wedge between the surface and the bottom of the sea (Lamb, 1945). The flow to a point sink of strength Q in A wedge with included angle, at a distance "a" from the shore, will be approximately the same as the flow ring-shaped sink of radius "a" and total strength 2π Q/B in infinite space, with the edge of the wedge (the shoreline) Lying normal to the plane of the ring and through its center. In cylindrical coordinates with the z-axis on the shoreline, the potential of this sink is:

$$\varphi = QK(m)/2\pi\beta ar/m),$$

in which K9m) is the complete elliptic integral of the first kind and

$$m = 4ar/ \{Z^2 + (r+a)^2\}$$

The derivatives of * with respect to r and z give the cross-shore and longshore components of velocity.

Figure (3) shows velocity of the potential flow toward the sinks SONGS< which are approximated by four equal point sinks at the locations shown in the Figure. The calculated values are for a bottom slope β of 15 m in 2.5 km, or .006 radius, and for a nominal total sink strength of 1000 m^3/sec for all four sinks together. With total sink of 200 m^3 /sec, say, the arrows would be twice as long but their direction would be unchanged. Close to the diffusers, the foursink approximation fails, but there the velocity can be directly estimated as about 2.5cm/sec by dividing the total sink strength by the vertical cross-section from top to bottom and from one end of the diffusers to the other.

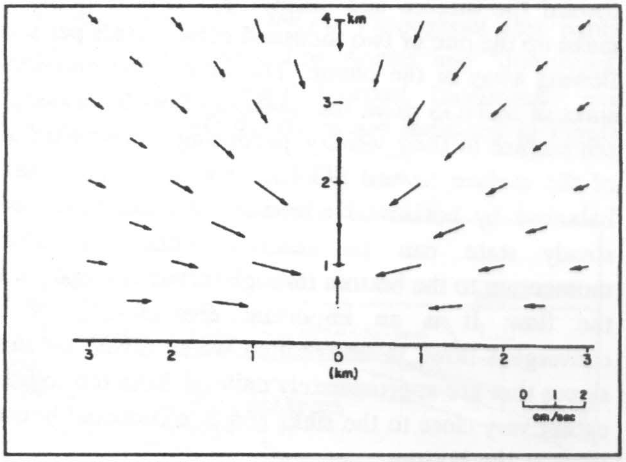

Figure 3. Velocity vectors of the potential flow toward the sinks of SONGS.

These velocity vectors are for the make-up flow by itself, as it would appear in the absence of longshore current outside the region occupied by the plume. The total field of flow would be approximately shown by superposing the velocities of the ambient current and the plume and make-up flows appropriate to that current, adding vectorially at every point.

At ranges of about 3 km or more, the make-up flow is approximated by a velocity $V = Q/2\ R_2$ directed radially inward the point on the shoreline nearest the diffusers, R being the distance from that point and the slope of the bottom. this approximation gives a quick estimate of the make-up velocity at distance: for $Q = 100\ m^3$/sec and bottom slope = .006, we expect V to be about 1 cm/sec at 3 km from the shoreline point, and about 0.3 cm/sec at 5 km.

5. SYNOPTIC FLOW PATTERNS NEAR SONGS

To introduce the discussion of observed flow-fields, we begin by describing some short-term patterns observed over periods of several hours.

Sets of successive hourly current vectors recorded at fixed stations are shown in Figure (4), (5) and (6) Measurements were carried out at 3 m below the water surface. In Figure (4) the prevailing current seen at the distant stations 14 and 20 is downcoast and somewhat inshore, with a speed of about 20 cm/sec. At the up-current stations 18 01 near the diffusers, the current is distinctly turned inshore by the make-up flow, probably with some shielding effect from the Sok-north kelp at station 0.1. At stations 19 and 20, the current is turned strongly offshore by the offshore momentum in the plume, while stations 11 and 17 show the obstruction and diversion of the plume by the south kelp.

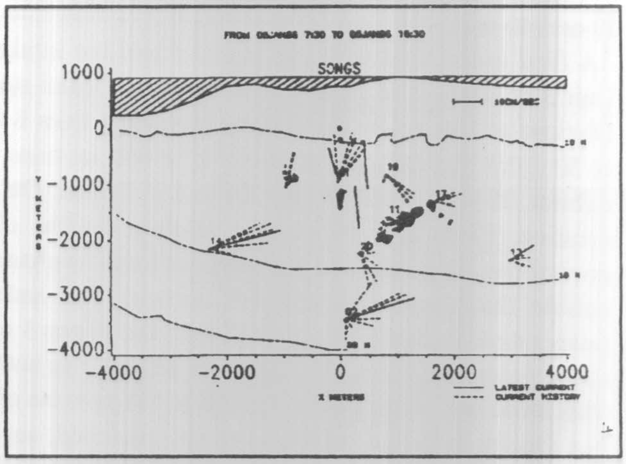

Figure 4. The prevailing current seen at the distance stations 14nd 02.

Figure (5) shows patterns in a very strong prevailing current directed upcoast and a little offshore at about 30 cm/sec. In this instance, the plume is not visible by its velocity, but the make-up flow appears cleary in the inshore component that it seen only at stations 19 and 11. Recall that the hydraulic model (koh et al., 1974). showed near-field dilution approaching 40 to 1 in model current equivalent to 26 cm/sec. so the total make-up flow have approached 4000 m3 /sec at this time.

Figure (6) shows velocity vectors during weak prevailing current, when the convergent make-up flow and the plum going directly offshore can be seen by themselves. The velocities at stations 17 and 18 are in opposite directions, both being toward the diffusers. At station 20, there is an offshore component of about 15 cm/sec in four out of the five hours when longshore velocity was very small.

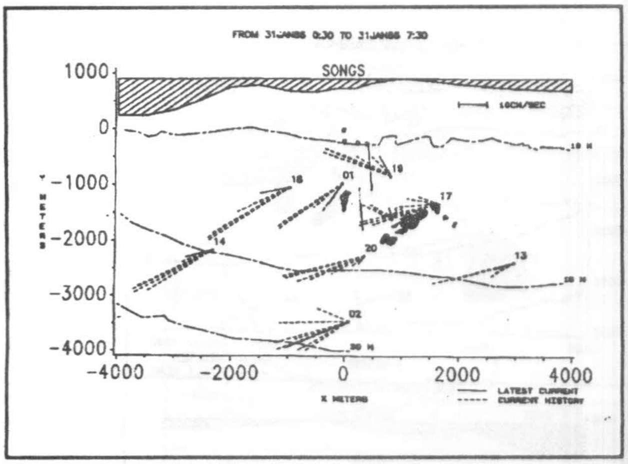

Figure 5. Patterns in a very strong prevailing current directed up coast and a little offshore at about 30 cm/sec.

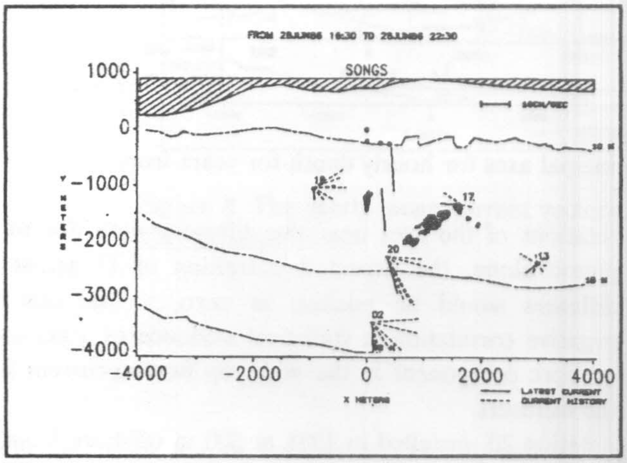

Figure 6. Velocity vectors during weak prevailing current.

6.LONG-TERM FLOW PATTERNS

The flow patterns discussed in the previous section are typical SONGS area. To show that they represent persistent patterns related to SONGS, we considered how they are revealed in long-term statistics of current vectors, using records taken both before and after Unit 2 ad 3 went into operation in May, 1983.

The joint distribution of hourly longshore current V and crosshore current U potted on X and Y exes is likely to have a more or less elliptical shape, whose axes may not be closed to the X and Y axes by which the current components were defined. A useful way to define the prevailing direction of current variation is to displace the origin of the plot to the means of V and U, and then to rotate the exes so as to maximize the variance on one of the rotated axes. This same rotation will minimize the variance on the other axi, which is orthogonal to the first axis. these are called principal exes. Calculations for these principal axes are given in Cooley Lohnes (1971). The axis of maximum variance, then, defines a prevailing direction in a least-squares sense; if the variances on the two axes are more or less equal, this direction is correspondingly illdefiend. The direction of the mean current vector is a different measure of prevailing direction, which may or may not be close to the prevailing direction of current variation.

The yearly mean current vectors and principal axes for hourly mean currents recorded at 3 m depth, for each year from 1977 through 1986 are shown in Figure (7) through (9). In these Figures, each station is located by a dot; the mean current vector is an arrow proceeding from this, and the of the principal axes of variation is set at the head of this arrow. The length of each principal semi-axis is the standard deviation of current in that direction. Also on these plots are the approximate locations of the San Onofre kelp beds depicting where medium to high density kelp (greater than 4 plants per 100 m^2)were found each year (Reitzel et al., 1987 b).

In this set of figures there are some evident year-to-year variations in pre-operational years and at stations distant from SONGS; some of these may be due to seasonal bias in the shorter records, and some may simply show that a year of record is not enough to establish stationary statistics of the current. In discussing persistent effects of SONGS on the observed flow-field we should not make too much of any single station in a single year, but rather look for patterns that are consistent among stations and years.

In the pre-operational year 1977-8, both the mean current vectors and the major axes of variation generally lie on direction close to the local·isbaths. In the early operational years 1983-4, this overall pattern continues, but we see the beginning of a positive rotation (toward onshore from downcoast) of the principal axes at station 01 which persisted in the following years. One local anomaly worth noting is the very high mean velocity of about 13 cm/sec at station 09 over the latter half of 1983. This is certainly absent from the generl current field over that period (compare station 08, 1.4 km upcoast) and probaly results from the position of 09 just at the offshore edge of the San Onofre kelp bed. If the kelp bed was obstructing and diverting both the ambint currenys and the

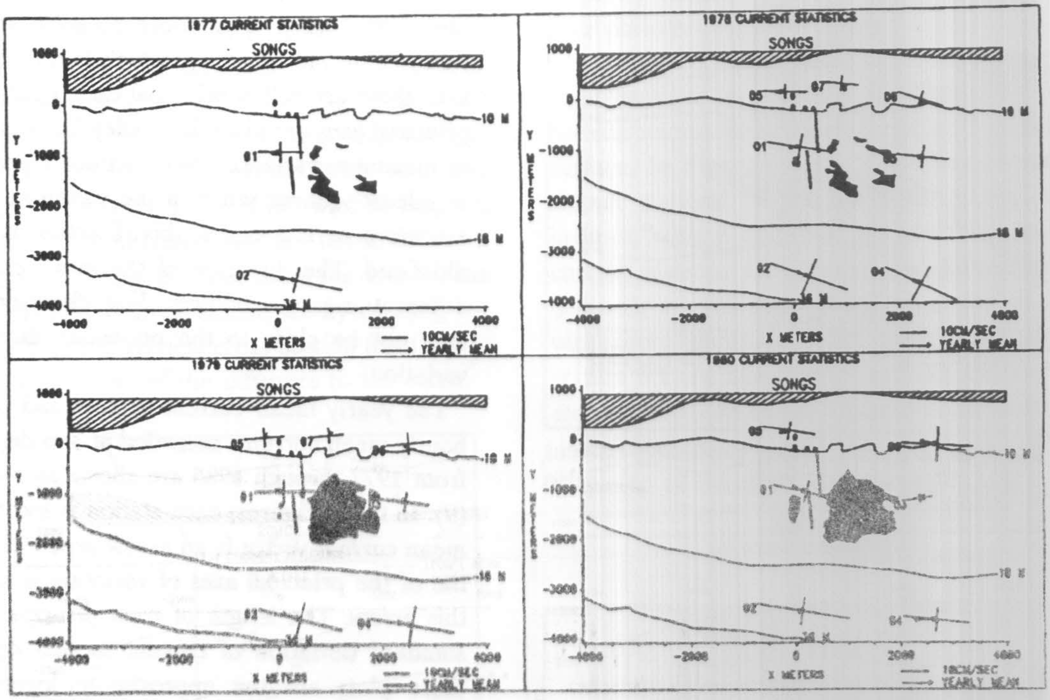

Figure 7. The yearly mean current vectors and principal axes for hourly depth-for years from 1977 through 1986.

plume of Units 2 at this time, a concentration of flow along its offshore edge would be expected.

In 1985 and 1986 a dense array of stations was in place, and spatial patterns can be seen more fully. Considering the stations nearest SONGS first, there is a highly consistent pattrn of positive rotation at the upcoast stations 18 and 01, with negative rotation st station 19 on the other side of the diffusers (compare with the patterns shown by the arrays of 1978-80). The temporal relations that go with this spatial pattern are shown in table 1, which gives the correlation matrices for V and U among the three stations 18, 01, nd 19 for all hourly currents recorded in 1985-86. For longshore velocity V, the correlations are all positive and large, and the correlation between the pair 18 and 01 is the same as that between the pair 01 and 91, which has about the same longshore separation. For cross-shelf velocity U, the correlation between 18 and 01 is again positive and large, but 01 and 19 show a moderate through significant negative correlation (r = -.24, P = .0001) where r is the correlation coefficient and P is the significance level for testing if r = 0.These proncipal direction and correlation matrices together establish a definite association of onshore velocity upcurrent from the diffusers in the same hour. If the rotations of the axes near the diffusers were due to the plume alone, the expected correltion of U across the diffusers would be positive or zero, so the observed negative correlation is statistical evidence of a persistent onshpre component in the make-up flow upcurrent from the diffusers.

station 20, installed in 1985 at 500 m offshore from the end of the diffusers-lines, has an offshore component for the mean current vectors for 1985 and larger than at any neighboring station. This is most reasonably attributed to the offrshore velocity in the plume at times of slack longshore current when the plume swings past this point. Station 11, near the inshore and upcoast edge of the San Onfre kelp bed as it was in 1985-6, has a small mean velocity downoast and offshpore, with a nearly circular distribution of the variation both in 1985 and 1986. This is in accord with its location being in a region where the plume may impinge on the kelp and be partly diverted to one side or the other depending on its angle of approach. Station 17, at the inshore-downcoast end of the kelp, shown a consistent positive rolation of the major axis that accords with partia diversion of the current and plume alonge the inshore side of the kelp, as has been shown in a number of synoptic studies.

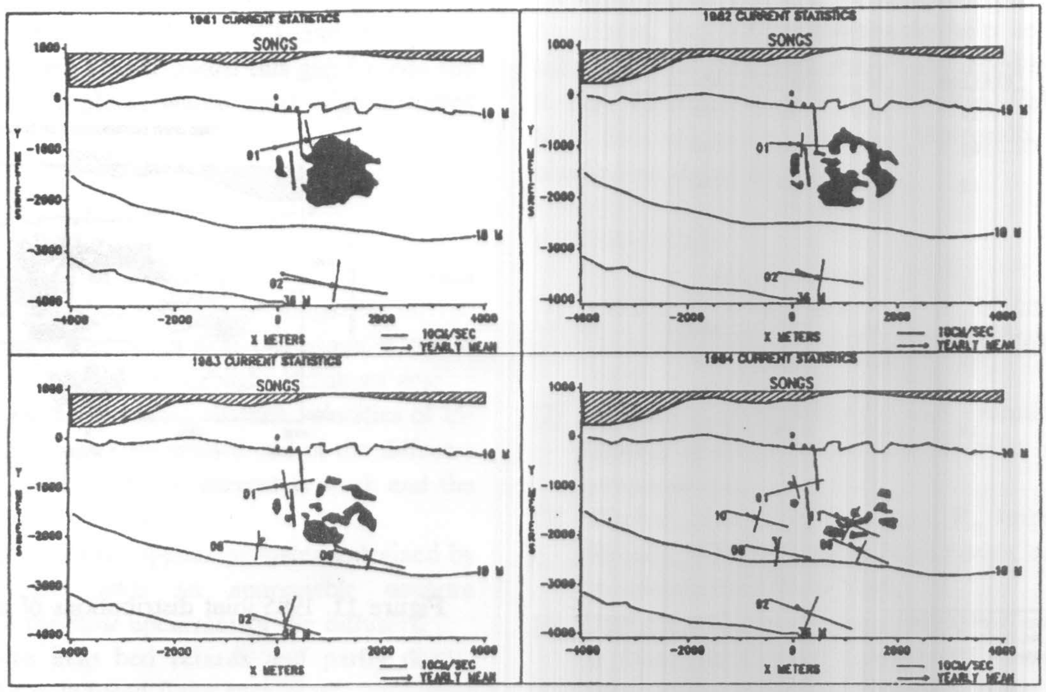

Figure 8. The yearly mean current vectors and principal axes for hourly depth-for years from 1977 through 1986.

On the outer arc of stations 16, 14, 20, and 15, the principal directions show complicated behavior. Through 1984, nearly all major axes lay more or less along isobaths, with small negative rotations, if any. In 1985 and 1986, the new station 14 and 13 showed consistent positive rotations that were not shared by station 16 and 15, at distance to either side, or by 02 in between. If this is entirely a natural pattern, it is remarkable for the back-and-forth swings of the major axes along the arc, and also for its apparently sudden appearance in 1985.

We cannot say with confidence whether or not SONGS has anything to do with the positive rotations at 14 and 13. Probably the make-up velocity has fallen off to 1 or 2 cm/sec at these stations and cannot have much of an effect on their principal directions, but the plume might reach 14 with an offshore velocity of 5 cm/sec or more and contribute to a positive rotation of the axes. An unimpeded plume would produce a negative rotation at 13, but we have already seen that the intervening kelp can remove most of the offshore momentum from a plume going downcoast.

We can say something about the behavior of the major axes of 02 and 20, which lay along the isobaths in 1985, but rotated to lie parallel with the axes of 14 and 13 in 1986. To do this, we examined the actual joint distributions of V and U for those years, shown in Figure (10) & (11).

At most stations, these distributions are fairly simple and similar in the two years. The main directions are generally the same for high and low speeds, so the rotations of major axes discussed represent all conditions and are not dominated by particular events. An exception to the simplicity o shape is seen st Station 20, where the distributions have a distinct offshore lobe beaus the plume of SONGS reaches the station only at times of weak longshore current.

Table 1. Correlation matrices of longhorn and cross-shore currents[a]

Longshore (V)

Station	18	01	19
18	1.00	.80	.72
01	.80	1.00	.80
19	.72	.80	1.00

Cross-shore (U)

Station	18	01	19
18	1.00	.76	-.06
01	.76	1.00	-.24
19	-.06	-.24	1.00

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[a] correlation coefficients are computed from the hourly currents measured at 3m below the water surface in the period between 1985-86.

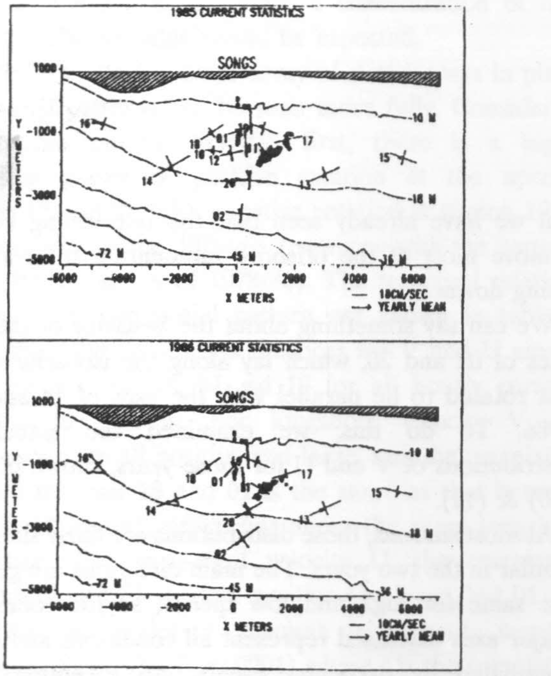

Figure 10. The yearly mean current vectors and principal axes for depth-for years from 1977 through 1986.

between 1985 and 1986. Most of the differences come from the addition in 1986 of many points representing high speeds in the onshore-downcast quadrant, superposed on the 1985 distribution. A complete inspection of the hourly vectors over 1985-6 showed clearly that these points come from several episodes of very strong overall downcoast currents in 1986, during the current vectors at 20 and 20 swung to extreme inshore directions. At these extremes, the current at 02 and 20 was directed toward the gap between the Unit 2 diffuser and the south kelp.

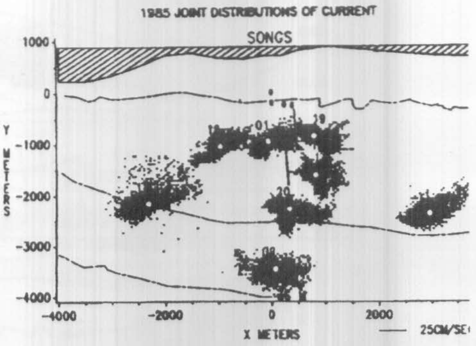

Figure 11. 1985 joint distributions of current.

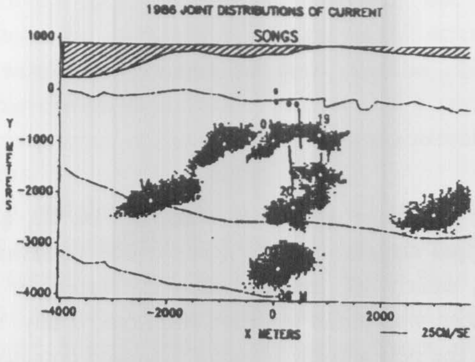

Figure 12. 1986 joint distributions of current.

These would be times of maximal near-field entrainment (40 to 1 or more, according to the hydraulic model), and probably of maximal diversion of flow by kelp (supposing that drag within the kelp goes up as V^2), and we may be seeing a convergence of flow toward this gap to feed the high entrainment in a plume whose outer edge is walled off by the kelp.

7. CONCLUSION

The diffuser system of SONG produced in the local current field that are observable in the long-term atterns of principal current directions at different points, a well as synaptically. The most clearly-established changes are:

1) The ischarge plume produces offshore velocities of 15-20 cm/sec just beyond the seward end of the diffusers at times when the longshore current is weak and the plume goes directly offshore.
2) The make-up flow hat supplies he water entrained by the diffuser jets adds an appreciable onchore component to the flow upcurrent of the diffusers.

The San Onofre kelp bed retards and partly diverts natural and SONGS-induced flows such that:

1) In moderate downcoast currents, the discharge plume can hown points of near-stagnation where it impinges on the kelp bed, and between the separate plume of Units 2 and 3. These stagnation points represent possibl areas of deposition for suspended particles.
2) In strong downcoast currents, the plume may be diverted inshore of the kelp bed, and a make-up flow toward plume may be concentrated as a shoreward flow into the gap between the diffusers and the kelp.

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