STATISTICAL ANALYSIS THE EFFECT OF A COASTAL POWERPLANT COOLING SYSTEM ON UNDERWATER IRRADIANCE

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ABSTRACT

Estimating the effect of a powerplant cooling system on underwater irradiance was the goal of a six year study. Integrated hourly measurements were taken at two depths and seven locations over these years, which probably constitutes the largest existing database on underwater irradiance. Powerplant effects on average irradiance were estimated in three ways using ANOVA models with ARIMA errors. One way was a before-after/control-impact (BACI) comparison. The other ways were comparisons of synoptic measurements in plume and ambient waters, as defined by to physical plume models. The presented analyses demonstrate a powerplant induced change in irradiance nearby the outfall diffuser systems. This study indicates the importance of collecting baseline prior to an environmental impact.

INTRODUCTION

This paper describes methods for estimating the effect on underwater light of coastal powerplant cooling system that draws water from the sea and discharges it further offshore. Hourly integrated underwater irradiance measurements were taken at two depths and seven locations over a six year period straddling the start-up of the powerplant (Reitzel et al, 1987) to monitor powerplant effects on kelp forests (Dean, 1985). This large dataset was necessary to detect a significant powerplant effect because these irradiance measurements were highly variable with strong serial correlations . ANOVA models with ARIMA errors were used. There are very few databases on underwater irradiance (See Luning and During, 1979 and Luning, 1981) and, as far as we know, none of this extent.

THE PHYSICAL BACKGROUND

The powerplant in question Units 1 and 3 of the San Onofre nuclear Generating Station (SONGS), on the cost of southern California between Oceanside and San Clements. The combined cooling system of these two units draws in about 100 m/sec of seawater at intakes in water m deep, about 800 m from shore; this water is heated by 10 c while circulating through heat exchangers in the powerplant and is then discharged to the sea through a series of jets 2 m above the bottom, mounted on two diffuser lines end-to-end, extending a further 2000 m offshore from the intakes. These jets immediately entrain a flow on the order of ten times the discharge, diluting the discharge to meet standards for the allowable local rise in temperature (Fischer et al, 1979).

The jest are directed offshore with an upward tilt, while the prevailing currents are predominantly along-shore. The combined effect of the initial offshore momentum of the jest and the varying ambient current is to carry the whole flow of discharged and entrained water offshore and downcurrent. The direction and width of this plume varies with the speed of the current, from a narrow slightly diverging plume directed offshore in the absence of current, to a broad plume making only a small angle to the coastline in currents of 25 cm.sec or more. The initial dilution of the discharge also increases with current speed, from about 8 to 1 in very weak currents up to 20 to 1 or more in currents exceeding 25 cm/sec. The plume is often marked by a visible contrast of turbidity or color with the surrounding water.

The extinction coefficient, k, is a measure of the attenuation of underwater light level with depth. It is defined as the negative natural logarithm of the difference of irradiance at two different water depths divided by the distance between them. Since the extinction coefficient of costal waters generally decreases to seaward, one putative effect of the cooling system is to reduce the average underwater irradiance at times and places where ambient water is replaced, wholly or partly, by plume water that originated closer to the shore. Another putative effect, tending to offset, is a local increase of irradiance because the intakes and the entrainment by the jest act as a sink that draws water partly from offshore as well as from alongshore. Depending on the ratio of shorward advection in this make-up flow to natural dispersive transport, the presence of this sink may reduce extinction at times and places not under the plume, and also in the withdrawn and entrained waters, relative to what it would have been in the absence of the powerplant.

The high variability of natural irradiance in these waters extends over a very broad band of periods, from variations over hours and seasons due to insolation, waves, and weather, to large interannual variations due to changing of water masses, as in the El Nino event of 1982-84. Spatial variability over a horizontal scale of tens of kilometers along the shelf is less than temporal variability, but is still considerable, probably because of a patchy distribution of fine sediments that cause extinction when they are resuspended by waves. Powerplant effects on irradiance that come from redistribution of naturally suspended particles can also be highly variable, as is evident from the varying visible contrast between the plume and ambient water.

At San Onofre, the daily irradiance at the sea surface is generally about 50 E/m^2- day in midsummer and about 20 E/m^2 day in midwinter. The extinction in the local nearshore waters is highly variable, going from a minimum of about 0.1 m^{-1} to about 1 m^{-1} ; values between 0.25 and 0.4 m^{-1} are common. At a water depth of 14 m, where our study took place, bottom daily irradiance varies from 0.5 to 8.0 E/m^2 -day, with a typical average value of about 0.8 E/m^2 in the winter and 2.0 E/m^2 in the summer.

The ecological importance of powerplant effects on irradiances comes from the presence of the San Onofre Kelp (SOK), a bed of the giant klep Macrocystis near the diffusers. Microscopic plants of this klep start life on the bottom, in depth of 10 to 16 m off San Onofre, and require a certain amount of irradiance to grow up into shallower depths where irradiance ceases to be a limiting factor. The existence of the San Onofre kelp is precarious, in the sense that successful recruitment of new plants occurs only about once in three years on the average, an interval comparable to the average lifetime of a plant. Even a moderate reduction of average irradiance on the bottom might increase this interval enough to have a serious, long-term effect on the kelp bed (Deysher and Dean, 1980).

METHODS

Paired-BACI Analysis

One method we have used is a variant of the general Before-After-Control-Impact design, called BACI for short (see Skalski and Mckenzie, 1982; Stewart-Oaten, 1986, and Stewart-Oaten, et al,1986). This design seeks to detect and estimate a change in mean irradiance that occurred only near the powerplant and only after it started operating, separate from natural differences of irradiance between places and time. This is done by setting up an Impact station near the powerplant and a Control station at a distance, and synaptically measuring the difference of irradiance $\Delta\ I_B$ (t) (Impact minus control) between these stations at many times in the Before period prior to startput of the powerplant. By dealing with synoptic differences, this paired-BACI design subtracts out natural temporal variations that are common to both stations, eliminating a large part of the natural variability. The time series of $\Delta\ I_B$ (t) may be examined to see if its mean $<\Delta I_B>$ can be taken as a stationary process mean. It is stationary, $<\Delta I_B>$ represents a constant natural difference due to location alone, which may be presumed to continue after the powerplant start-up.

A similar series of measurements at the same stations in the After period gives a set of differences ΔI_A (t), similarly free from temporal variations common to both stations, whose mean $<\Delta\ I_A>$ represents the difference between the locations in the presence of the operating powerplant. If $<\Delta I_B>$ were stationary, the difference of means $\Delta\Delta\ I = <\Delta\ I_A> - <\Delta I_B>$ represents a time by location interaction, a change of mean irradiance occurring only near the powerplant and only after it started operation. An important requirement to make this result valid is that the irradiance differences $\Delta\ I_B$ (t) respond additively to changes in natural conditions. If they do not, natural changes can masquerade as powerplant effects, as shown by the following example. Underwater irradiance varies exponentially with the extinction coefficient k. Natural changes in K will produce multiplicative rather than additive changes in Δ I. If average irradiance at the Impact station were twice that at control in the Before period, and if a uniform natural decrease in k doubled both values in the After period, the resulting $\Delta\Delta I$ would be non-zero without any effect of the powerplant. In this particular example, the difficulty could be avoided by dealing with ΔInI instead of Δ I as the primary variable. This would give the same Δ InI both Before and After, and $\Delta\Delta$ InI= O in the absence of any real powerplant effect.

In general, we are not sure in advance what variable may be additive; we have tried various transformations of the data, such as logarithms, powers, or roots. We tested the transformed datasets for nonadditivity, seeking a variable that was both additive and physically interpretable. The Tukey test for nonadditivity (Tukey, 1949) was applied to transformations of irradiance data, $(t)=f(I(t))$, from the Before period.

Let Δ $F_B(t)$ represent the difference of transformed irradiances (Impact minus Control) in the before period, Δ $F_A(t)$ represent the same difference in the After period, and $\Delta\Delta F(t)=\Delta F_A(t) - \Delta F_B$. A estimated non-zero time by location interaction $<\Delta\Delta F>$ may still be an artifact of limited sampling, due to the natural variability of $\Delta F(t)$. If the random fluctuations of $\Delta F(t)$ both Before and After were independent and normally distributed, the significance would be determined by a t-test on $<\Delta F>$. In this study, the fluctuations of $\Delta F(t)$ were a time series showing considerable autocorrelation, so that successive departures from the mean were not independent. This situation was reduced to indepent normal errors by the ARIMA methods of Box and Jenkins (1976).

The analysis was cast in the from of a linear multiple regression, modelling the time series of station differences

$$\Delta\Delta F(t) = A + B^*W(t) + e(t) \qquad (1)$$

with

$$e(t) = C_1e(t-1) + C_2e(t-2) + (t).$$

The indicator variable W(t) is a step function taking the value 0 for all times in the before period and 1 for all times in the After period. The Function e(t) models the departures of $\Delta\Delta F(t)$ from $A + B^*W(t)$ as second-order autoregressive errors plus independent normally distributed random errors (t). The coefficient B estimates the powerplant effect. The coefficients A, B, C1 C2 are estimated using methods of Box Jenkins (1976) that with the observed values in the place of F(t).

Plume-model Analysis

Another method which we call plume-model analysis, deals with the synoptic differences of irradiance between two stations near the powerplant, designated as north (N) and south (S). These stations lie symmetrically on opposite sides of the diffuser lines with the north station upcoast. The irradiance differences are averaged over hours when a specified model for the behavior of the plume classifies one station as being in the plume (P) and the other station as being out of the plume or ambient (A). The plume model is purely kinematic, with the classification of a time place as (P) or (A) depending on the recent history of the current and the location of the station relative to the diffusers. The current history may have a natural effect on irradiance, but the part of this effect that is common to both stations is removed by taking the differences. The difference of mean differences

$$\begin{aligned} <\Delta\Delta I> &= <I_{NP}-I_{SA}> - <I_{NP}-I_{SA}> \\ &= <I_{NP}-I_{SP}> - <I_{NP}-I_{SA}> = \ldots \end{aligned}$$

is twice the effect of the model plume minus any effect of the powerplant on water classified as (A), averaged over the two stations, plus the mean of any non-uniform current effect.

The regression model is given by equation (1) as before. The indicator variable W(t) takes the value O for any hour in which the north station is classified as (P) by the plume model and the south station is classified as (A); it takes the value I for any hour in which the south station is classified as (P) and the north station as (A). Hours for which the model classified neither or both of the station as (P) were dropped from the analysis. B/2 is the plume-minus-ambient difference of irradiance due to the powerplant, averaged over both stations, plus half of any natural nonuniform current effect.

The statistical requirements for validity are the same as in BACI analysis, but here there is no data-set free of powerplant influence that can be tested nonadditivity of natural changes. Analyses with I and InI gave generally consistent estimates of percent in irradiance, as described in Section 5; these changes were small enough to be approximately linear whether transformed or not.

RESULTS

BACT Analyses Of Irradiance Off San Onofre

Data are the hourly integrated irradiance recordings on the bottom and two meters above, at three impact stations within the San onofre kelp bed (SOKU 45, and SOKD 45, and SOKD 35). these stations are located 500 to 1300 m south of the diffuser lines, and at Control station in the San Mateo kelp bed (SMK 45) 5km north of the diffusers. The bottom depth is 13.7m at stations labelled 45, and 10.7m at stations labelled 35. The locations of these stations are shown in Figure (1). These stations were kept clear of kelp canopy at all times; another station in the kelp bed SOKU 35, was not used in BACT analyses because its irradiances were affected by changes in the density of kelp canopy from Before to After, making a large confounding effect. The Before period includes date from mid-1901 through April 30, 1983; the After period includes date from May 1, 1983 to the end of 1986.

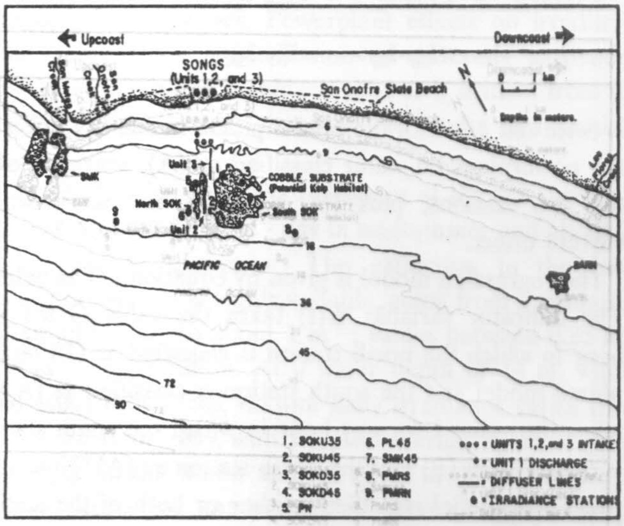

Figure 1. Study site and locations of stations.

At values of irradiance below.01 Einsteins/m^2-hour, such as are often observed in dawn or twilight hours, instrumental uncertainty may be a large part of the reading. In analyses of InI, dubious values on this order may have a large effect on the means and variances. For these reasons, we analyzed only the nine daylight hours between 7am and 4pm of each day, plus any other hours with an irradiance of .01 E/m^2 - hr or more, treating all other hours as missing values. The datasets of hourly station differences did not generally turn out to be amenable to Box-Jenkins methods, so we dealt instead with the daily means formed by adding hourly irradiances over the included hours, expressing the result in E/m^2 - day.

Separate analyses carried out on these daily means for irradiance at the bottom and at a height of two meters above the bottom, with the three stations in the San Onofre kelp bed combined into one Impact station by averaging the daily mean irradiance from any of the three (usually all three) that were operating on a given day. The set of daily station differences at either height, then, was the set of combined-SOK stations minus SMK 45 for all days on which a daily mean was available from both.

Tukey's adaptivity test was carried out on the Before data incorporating autoregressive errors, like the model described above. The stationarity of irradiance differences was investigated by regressions over time to test for trends, and by inspection of successive three day means and standard deviations, plotted against time and against each other. All model fitting was done with the SAS procedure PROC AUTOREC with the Maximum Likelihood option, using the missing values.

BACI analyses using all the data did not show significant time by location interactions, but plume model analyses of data within the After period did show, broadly speaking, that irradiance was on the average significantly less on the downcurrent side of the diffusers than on the upcurrent side at the same time. We suspected that much of the variation within the After period might be due to an interaction of current with the diffusers, so we carried out a separate BACI analysis for the sets of Before and After days when the Impact stations were downcurrent (or upcurrent) from the diffusers, in order to remove this part of the variability.

Here we report five BACI analyses: one analysis using all days; two separate analyses using the subsets of days on which the hourly mean current was directed downcast (towards the southeast, see Figure (1) or upcost (towards the northwest) for nine out of nine daylight hours; and two separate analyses using the days on which the current ran downcast or upcoast for five or more out of nine daylight hours, so that every day dell into one analysis or the other. (The total number of data points in these last two analyses is less than that in the analysis for all days because the current direction was not recorded on every day.)

The results of the five BACT analyses are shown in Table 1. The first thing to look at in Table 1 is P_A, since a result from a nonadditive dataset can be seriously misleading. Adaptivity varies widely among datasets and variables, but it is clear that InI tends to be non-additive more often than I. This results is contrary to a physical expectation as discussed above. Whatever the reason, the tendency of I to be more often additive than InI is a characteristic of the BACI datasets, so the BACI estimates of powerplant effects B are better expressed as absolute rather than percent changes in irradiance.

Most of the result in Table 1 are of doubtful adaptivity or low significance or both. All the results are shown in the table because there is no set criterion for rejection, though we should certainly mistrust those with very low P_A.

The most reliable result have been marked with an (*) to the left.

The significant results for downcast current days at level 0 compel conclusion that average irradiance on the bottom at the SOK stations was reduced by approximately 0.5 E/m^2-day on downcast current days by the powerplant. The whole body of result makes it highly reasonable to conclude that the powerplant generally reduced irradiance at and near the bottom in SOK by about 0.4 E/m^2-day on downcast current days and increased irradiance by a comparable but somewhat smaller amount on upcost current days. This conclusion is consisted with the putative mechanisms by which the powerplant might decrease and increase irradiance, discussed in section 1.

Table (1) shows that there are more downcast current days than upcoast current days; about 60% of the time the coastal current is directed downcast. The net effect is a reduction of irradiance, ranging from about 0.25 E/m^2 -day it B for upcoast current days is actually zero, to about 0.1E/m^2-day if the upcoast current value of B is equal and opposite to the downcast to the downcast current value. This accords with the most nearly additive BACI estimate of the net effect, listed above under All Days, level 2, which gives a one standard error range of B from about 0.4 to + 0.1 E/m^2 -day.

Plume Model Analyses Of Irradiance Off San Onofre

The first plume model that was tried was simple. It classified a station as in the plume (P) in a given hour if the mean current in that hour ran from the diffusers toward the station, and as ambient (A) if the current ran the other way. This upstream-downstream model has obvious deficiencies, and we developed a more elaborate model to take account of the main characteristic of the actual plume, as well as they were known from field observations and hydraulic modelling of the system (Fischer, J.J., 1979). The essential operation of the model was to backtrack water at the station by means of the currents recorded over preceding hours, with allowance for the initial seaward momentum of the plume itself, and for dispersion from the boundaries of the plume. The backtracking computation was continued until the backtrack of the water from the station crossed the diffuser lines, or out to 25 hours. The number of hours, up to 25, from station to diffuser was called the plume age; for all the stations, almost all of the computed plume ages were either 10 hours or else undefined because the trace did not reach the diffuser within 25 hours. the model we chose classified a station and hour as (P) if the plume age was 10 hours or less, and otherwise classified this station and hour as (A).

Table 1. Results of BACI Analyses.

Variable	Height[a]	$Days_B$[b]	$Days_A$[c]	$\hat{B}$[d]	s_B[e]	P[f]	PA[g]
All Days							
* I	0	377	1101	+.15	.17	.37	.06
* I	2	249	861	−.13	.25	.61	.62
ln(I)	0	327	1066	−.18	.16	.25	.001
ln(I)	2	238	855	−.14	.12	.27	.15
Downcoast Current Days, 9 hours out of 9							
* I	0	83	369	−.60	.23	.01	.98
* I	2	85	295	−.39	.32	.22	.50
ln(I)	0	83	369	−.42	.23	.07	.04
ln(I)	2	85	295	−.01	.16	.93	.0001
Upcoast Current Days, 9 hours out of 9							
* I	0	27	220	+.51	.32	.11	.97
I	2	16	170	+.41	.49	.40	.0001
ln(I)	0	27	220	+.38	.28	.17	.96
ln(I)	2	16	170	−.29	.26	.28	.0001
Downcoast Current Days, 5 or more hours out of 9							
* I	0	119	590	−.46	.21	.03	.86
* I	2	111	484	−.43	.29	.14	.20
ln(I)	0	119	590	−.31	.20	.13	.34
ln(I)	2	111	484	−.06	.14	.69	.0001
Upcoast Current Days, 5 or more hours out of 9							
* I	0	59	465	+.02	.26	.93	.31
* I	2	30	367	+.41	.42	.33	.82
ln(I)	0	59	465	−.14	.22	.53	.56
ln(I)	2	30	367	−.05	.23	.82	.01

I is in units of Einsteins/m^2-Day.
* The most reliable results.
[a] Height from the bottom in meters.
[b] Number of Before-period days used in calculations.
[c] Number of After-period days used in calculations.
[d] Estimate of power plant effect.
[e] Standard error of estimated power plant effect.
[f] P-level for BACI tests.
[g] P-level for additivity tests.

The actual algorithm for plume age used the record of longshore current to find whether the longshore coordinates of water discharged at the beginning and end of the preceding hour bracketed the longshore coordinates of the station. If they did not, the repeated for the next preceding hour. If they did, say for the n^{th} preceding hour, cross-shelf coordinates of water discharged that hour from the inner and outer ends of the diffuser line were computed from the cross-shelf current history, with two additional kinds of cross-shelf motion: an added seaward velocity of .05m/sec at both ends representing the initial momentum of the plume; and for the n^{th} preceding hours, a displacement of 10.8 $n^{3/2}$ meters, seaward from the outer end and shoreward from the inner end, representing the mean-square dispersion distance according to the relation of Okubo (okubo, 1974). If the cross-shelf coordinates of the water from the two ends did not bracket that of the station, the whole computation was repeated for the next preceding hour; if they did, a plume age of n hours was assigned to the station and time. The current record used for these computations was computations was a composite of several stations some distance to either side of the diffusers, to represent ambient current alone and avoid counting plume-induced velocities twice.

The data for plume-model analyses are recording of hourly integrated irradiance, in E/m^2-hours, at 0 and 2m above the bottom, at four stations south of the diffusers in SOK and another station called PMRS about 2.5 km south of the diffusers, plus a set stations north of the diffusers to be paired with the south stations. the names of the paired stations are listed in the tables of results, and the locations of all are shown in Figure (1). The datasets of north-south station differences comprise all hours between 7am and 4m in the years 1985 and 1986 in which both stations of a given pair were operating, plus any other hours in which both station had hourly irradiances of .01 E/m-hour or more, units 2 and 3 of SONGS were in normal operation though not wholly uniform of continuous operation, throughout this period.

The statistical tests and procedures on the data-sets were the same as for the BACI analyses (Section 3.1), with one exception: Tukey adaptivity tests were not done because there were no subsets of the data uninfluenced by the powerplant. Instead, we analyzed all the data both with Δ I and with Δ InI as primary variables (dropping any zero irradiances from analyses of ΔInI), and estimated percent change in irradiance, relative to the ambient mean, as B/2<I>) from the analysis with 1, Δ and as exp (B/2)-1 from the analysis with ΔInI. if the two computations substantially agreed, we concluded that the changes were small enough to remain approximately linear under transformation, so that errors from nonadditivity would be minor.

The results of the plume-model analyses are shown in Table (2). Every analysis of I should a highly significant negative B/2 representing an average reduction of irradiance on the order of 0.05 E/m2-hour in the model plume relative to ambient water at the same time, with an average fractional reduction of 24%. Every analysis of InI showed a highly classified the SOK stations as in the plume (P) for percentages of all hours ranging 17% to 28%, but classified PMRS as (P) in only 3% of all hours.

The percent changes from Table (2) are plotted in Figure (2) against the mean distance from the diffuser line to the stations in a pair. It will be seen from this plot that the nominal powerplant effects are somewhat large for the station pairs inclosing SOKD stations, at mean distances of about 100m from the diffusers, than they are for the pairs including SOKU stations, at mean distances of about 500m. The effect for the pair PMRS-PMRS, each about 2500m from the diffuse, is about the same as the effect at 100m.

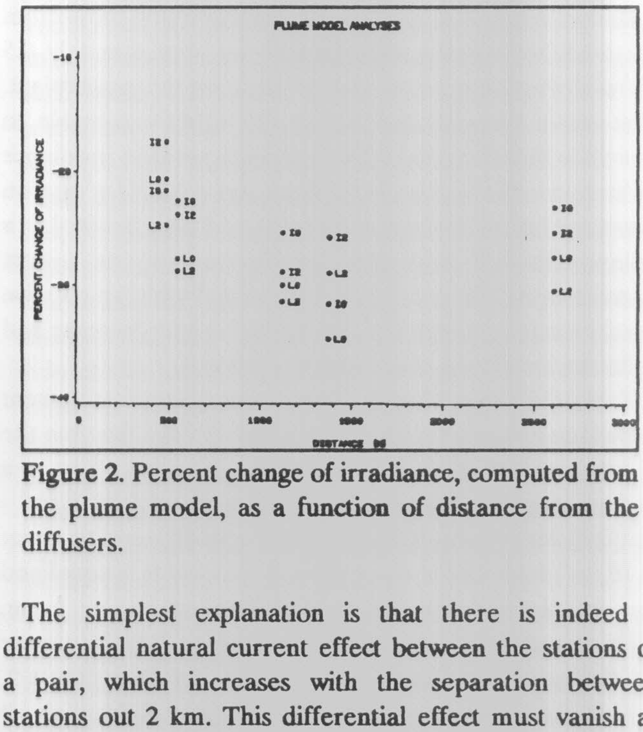

Figure 2. Percent change of irradiance, computed from the plume model, as a function of distance from the diffusers.

The simplest explanation is that there is indeed a differential natural current effect between the stations of a pair, which increases with the separation between stations out 2 km. This differential effect must vanish as the separation goes to zero, so it can be eliminated by extrapolating the results toward the diffusers. A rough linear extrapolation from 1100 to zero on Figure (2) would give a mean fractional reduction in the model plume relative to ambient water of something like 15% close to the diffusers, due to the [powerplant alone. This need not be the true explanation; the actual plume and make-up flow are obstructed and diverted in a complicated way by the kelp beds themselves, and this may be the cause of the increase of plume-minus ambient difference with distance.

Table 2. Results of plume-model analyses 1985-86.

Station Pair[a]	Height[b]	%South[c]	%North[c]	δI[d]	$\%(\delta I/\langle I_A \rangle)$[e]	$\delta \ln(I)$[f]	$e^{\delta \ln(I)}-1$[g]
SOKU45 (PL45)	0	22	37	-.028	-21.6	-.231	-20.6
600m	2	17	39	-.042	-17.4	-.282	-24.6
SOKU35 (PN)	0	27	23	-.037	-22.5	-.323	-27.6
500m	2	28	27	-.072	-23.7	-.338	-28.7
SOKD45 (PL45)	0	22	29	-.054	-31.7	-.428	-34.8
1100m	2	21	30	-.073	-25.7	-.341	-28.9
SOKD35 (PN)	0	23	24	-.054	-25.3	-.356	-30.0
900m	2	26	23	-.108	-28.8	-.378*	-31.5
PMRS (PMRN)	0	03	05	-.037	-23.1	-.321	-27.5
2600m	2	03	06	-.051	-25.3	-.364	-30.5

[a] The top station in the first column is the south station, below that in parentheses is the north station, and under that is the distance of the south station from the diffusers.
[b] Height from the bottom in meters.
[c] Percent of time the plume is over the north or south stations.
[d] The estimated powerplant effect from the analysis of I.
[e] Percent of δI relative to mean irradiance at the ambient station.
[f] Estimated powerplant effect from the analysis of ln(I).
[g] Percent change of irradiance from δln(I).
[*] The significance levels of all I and ln(I) analyses are less than p=.0002, except for *, which is .004.

Upstream-Downstream Analyses

The plume-model analyses excluded about half of all hours with recordings at pairs including SOK stations, and 90% of all hours with recordings at PMRS-PMRS. Except for a very few occasions when the model classified both stations in a pair as (P), the excluded hours were times when the model classified both station as (A). To investigate powerplant effects in this large fraction of the time when the plume model was inapplicable, we analyzed excluded hours with the original upstream-downstream model. This model classifies a station as downcurrent from the diffusers in a given hour if the direction of the current is such that water flows over the diffusers and then toward the station, denoted as (P). An upcurrent station in a given hour, denoted as (A), occurs when the current is such that the waters pas over the station before the diffusers. Applied to a pair of stations on opposite sides of the diffusers. This model will always call one station (P) when the other is (A) & The results of these upstream-downstream analyses are shown in Table (3). The percent of hours called are the percent of hours analyzed by this method, rather than all recorded hours.

Every analysis of I resulted in a negative B/2 with magnitude on the order of .025 E/m2 - hour, for reduction averaging 11% Every analysis of lnI gave negative B/2, with an average reduction of 8%. The upstream-downstream model classified the south station in a pair as (P) for a percentage of all analyzed hours ranging from 46% to 69%.

The percent changes given by upstream-downstream analyses are plotted against mean distance from the diffusers in Figure (3). The upstream% downstream results also showed tendency for the nominal powerplant effect to increase with distance out to 100m or so from the diffuser.

Table 3. Results of upstream-downstream analyses 1985-1986.

Station Pair[a]	Height[b]	%South[c]	%North[c]	δI[d]	$\%(\delta I/\langle I_A \rangle)$[e]	$\delta \ln(I)$[f]	$e^{\delta \ln(I)}-1$[g]
SOKU45 (PL45)	0	59	41	-.014	-10.9	-.042*	-4.1
600m	2	57	43	-.017	-7.5	-.034**	-3.3
SOKU35 (PN)	0	46	54	-.016	-10.5	-.129	-12.1
500m	2	51	49	-.021	-8.8	-.056	-5.4
SOKD45 (PL45)	0	68	32	-.020	-13.9	-.097	-9.2
1100m	2	69	31	-.033	-13.2	-.080	-7.7
SOKD35 (PN)	0	55	45	-.025	-13.5	-.104	-9.9
900m	2	60	40	-.032	-10.6	-.077	-7.5
PMRS (PMRN)	0	58	42	-.015	-11.4	-.091	-8.7
2600m	2	62	38	-.026	-13.5	-.105	-9.9

[a] The top station in the first column is the south station, below that in parentheses is the north station, and under that is the distance of the south station from the diffusers.
[b] Height from the bottom in meters.
[c] Percent of time the plume is over the north or south stations.
[d] The estimated powerplant effect from the analysis of I.
[e] Percent of δI relative to mean irradiance at the ambient station.
[f] Estimated powerplant effect from the analysis of ln(I).
[g] Percent change of irradiance from δln(I).
[*] The significance levels of all I and ln(I) analyses are p = .04 or less, except for * , which is .12 , and ** , which is .10.

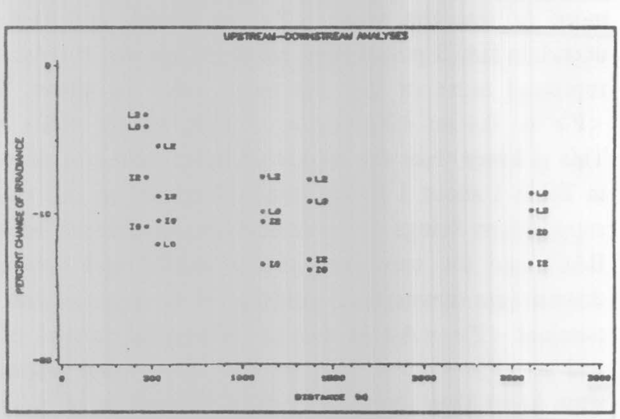

Figure 3. Percent change of irradiance, computed from the upstream-downstream model, as a function of distance from the diffusers.

Of these results to zero separation would give the powerplant effect chose to the diffusers as a reduction in the neighborhood of 5% applying to the hours when both stations were classified as (A) by the plume model.

DISCUSSION

BACI analyses have demonstrated a powerplant induced change in irradiance at Impact stations, relative to an estimate of what it would have been without the powerplant. Plume-model analyses have demonstrated a powerplant induced difference of irradiance between plume water and ambient water, as defined by a specified plume model, and upstream-downstream analyses have done the same with a different plume model. There is no way to make a strict comparison among these results, and even the roughest comparison requires a chain of suppositions.

First we must suppose that the plume model and upstream-downstream criteria are more or less equivalent. each is applied to about half the total of hours analyzed, so we can then average their results to say that the average plume-minus-ambient difference over all hours, which we may call <P-A> or <P>-<A>, is about -0.04 E/m2- hours, or very approximately -0.4 E/m2-day accumulated over the daylight hours. This round number comes from the averages at the three SOK stations used in the BACI analyses, with no extrapolation to zero separation.

To compare this with the BACI results, we have to suppose next that the mean BACI powerplant effect of about -0.4E/m2-day on downcast current days represents more or less the same <P> as above, and that the uncertain BACI powerplant effect on upcoast current days represent more or less the same <A> as above. With <P> =- 0.4 an <P>-<A> = 0&4, we get <A> = 0. This is lower than the highly additive estimates of <A> in Table 1 about 1 to 1.6 standard errors, so this chin of suppositions brings us to reasonable agreement between BACI and the combined plume model and upstream-downstream-downstream analyses. If we suppose that half nominal <P>-<A> is due to differential current effect, and set<P>-<A>= -0.2, we get <A>=-0.2 instead of zero, lower than the additive BACI estimates of <A> by about 1.5 to 2.2 standard errors barely at the edge of agreement.

there is no reason to believe that the quantities <P> and <A> estimate exactly the same thing in the three different kinds of analyses, but it is reassuring to find by this comparison that they are not grossly different.

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REFERENCES

[1] Box, G.E. and Jenkins, G.M. (1976), "Time Series Analysis Forecasting and Controls" *Oakland C*: Holden-Day.

[2] Dean, T.A. (1985), The Temporal and Spatial Distribution gf Underwater Quantum Irradiation in a Southern California kelp Forest, "Estuarine Coastal and Shelf Science, 21, 835-844.

[3] Deysher, L.E & and Dean, T.A. (1986), In situ recruitment of Sporophytes of the giant kelp Macrocustas pyrifera(l.) C.A. Agardh: effects of physical factors," *J. Exp. Mar. Boil Ecol.*, 103, pp. 41-63.

[4] Fisher, H., List, E., koh, R.S. Imberger, J. and Brooks, N., (1979), "Mixing in Angland and Coastal Waters," *New York: Academic Press*, Ch. 10.5.3, 430-441.

[5] Luning, K. (1981;, In "The Biology of Seaweeds, *:Ed. C. S. Lobban and M.J. Wynne. University of California Press* Berkeley, pp. 327-354.

[6] Luning, K. and Dring, M. J. (1979), "Continuous Underwater Light Measurement near Helgoland (North Sea) and its significance for characteristic light Limits in the subittoral Region," *Helgoander Wissenchaftliche Meeresuntersuchungen*, 32, 403-424.

[7] Okubo, A., (1974), "Some Speculations of Oceanic Diffusion Diagrams," *Rapp. P.-V. Cons. Int. Explor. Mer*, 167, 77-85.

[8] Reitzel J., Elwany, M.H.S., Erdman, M.R. and Zabloudid, K., (1987), "SONGS Physical and Chemical Genography Program: Summaries of data," Marife Review Committee, Data Report No. D87-163, Department of Biological Sciences, university of california, Santa Barbara, CA.

[9] Savir, N.E. and White, K.J., (1978) "Testing for Autocorrelation ith Missing Observations", *Econmetraca*, 46, 59-66.

[10] Skalski, G.R. and Mckenrie, D.H., (1982), "A Design for Aguatic Monitoring Programs," Journal of Environmental Management, 14, 237-251.

[11] Stewart-Oaten, A., (1986) S "The Before-Afer/Control-Impact Pairs Design for Environmental Impact Assessment," Marine Review Committee, Technical Report, June 20, 1986, Department of Biological Sciences, University of California, Santa Barbara, CA.

[12] Stewart-Oaten, A, Murdock, W.W. and Parker, K & R., (1986), "Environment Impact Assessment,"*PSE Replication Inb Time*", Ecology, 67, 929-940.

[13] Tukely, J.W., (1949), "One degree of freedom for nonadditivity", *Biometrics*, 5, 232-242.