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# Impact of thermal discharge from a tropical coastal power plant on phytoplankton

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**Abstract**

(1) The impact of thermal effluents from coastal power plant located on the east coast of India on phytoplankton was studied by field observations and laboratory experiments. (2) Monthly boat cruises (for 15 months) and laboratory experiments were carried out to study the effects of temperature and chlorine on phytoplankton. (3) Phytoplankton and chlorophyll *a* decreased during the transit of water from intake point to outfall, while at mixing point the chlorophyll values recovered significantly. (4) Laboratory experiments revealed that decrease in chlorophyll and productivity was largely due to chlorination than due to elevated temperature. (5) Combined temperature and chlorine treatment experiments on phytoplankton showed little synergistic effects. (6) It is concluded that the effect of thermal discharge from the power plant on phytoplankton in the receiving water body is quite localized and phytoplankton distribution and abundance in the coastal waters per se are not affected.


*Keywords:* Coastal power plants; Power plant; Thermal effluents; Phytoplankton; Chlorination

## 1. Introduction

Steam electric plants reject large amount of heat to cooling water during the process of steam condensation. Nuclear power plants require, on an average, about 3 $m^3$ cooling water per minute per megawatt of electricity (MWe) produced (Schubel and Marcy, 1978). Since once-through cooling system is the most economical way of condensing the exhaust steam from turbines, there is an increasing tendency for new nuclear and fossil fuel power plants to be located in coastal areas, so as to make use of the availability of the abundant seawater for condenser cooling (Winter and Conner, 1978). With an increase in the number of power plants along the coast to meet the growing demands of the society, there is a concomitant increase in the quantity of heated effluents being discharged into coastal marine environments. Planktonic organisms are drawn along with the cooling water into the plant cooling circuit, where they are subjected to various physical and chemical stress factors. Moreover, organisms in the receiving water body may also be entrained into the effluent plume, even if they do not pass through the plant cooling circuit. Apart from increased temperature, the discharges often contain chemical stress factors in the form of biocides (e.g., chlorine) used for biofouling control (Morgan and

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Carpenter, 1978). Thus, condenser effluents from coastal power plants have the potential to impart thermal and chemical stress and, therefore, may pose environmental problems to the receiving water body (Krishnakumar et al., 1991).

Temperature is one of the most important environmental variables, which affects the survival, growth and reproduction of aquatic organisms (Kinne, 1970; Langford, 1990). An increase in temperature of seawater results in an increase in the metabolic rate of the organisms and a reduction of its dissolved oxygen concentration. Residual chlorine also can affect the organisms by diffusing through their cell membrane, reacting with cytoplasm and thus inhibiting various metabolic activities (Strauss and Puckorius, 1984). Phytoplankton are a very important constituent of the coastal food chain and, therefore, qualitative and quantitative changes in the phytoplankton population in the receiving water body may have significant implications for the coastal ecosystem. As phytoplankton are drawn into the cooling circuit and then discharged back into the sea along with the effluents, it is possible that they suffer damages due to temperature and chlorine stress.

The present study was undertaken in the vicinity of the Madras Atomic Power Station (MAPS), which uses the coastal waters of the Bay of Bengal as a heat sink. It was hypothesized that the continuous discharge of condenser effluents may have an impact on the ecology of the coastal marine environment in the vicinity of the plant and a study was organized to understand the influence of the discharge on the phytoplankton population near the discharge zone. Boat cruises were carried out to measure phytoplankton standing crop in the coastal waters. We also carried out short-term laboratory experiments to evaluate the effects of thermal and chlorination shock on coastal phytoplankton. This paper gives an account of the results of the study, being carried out as part of a larger project on thermal ecology in the vicinity of the power plant discharge sites.

## 2. Materials and methods

### 2.1. Description of the study site

The study was carried out in the vicinity of MAPS, located at Kalpakkam (12°33″N and 80°11″E) on the east coast of India, about 65 km south of Chennai (Madras). It is an open sandy coast with negligible tidal currents. MAPS consists of two units of pressurized heavy water reactors (PHWR) with an installed capacity of 220 MWe each, down rated to 170 MWe each. The power station uses seawater as tertiary coolant at a maximum design flow rate of 35 $m^3 s^{-1}$. The seawater is drawn from an offshore well located about 400 m away

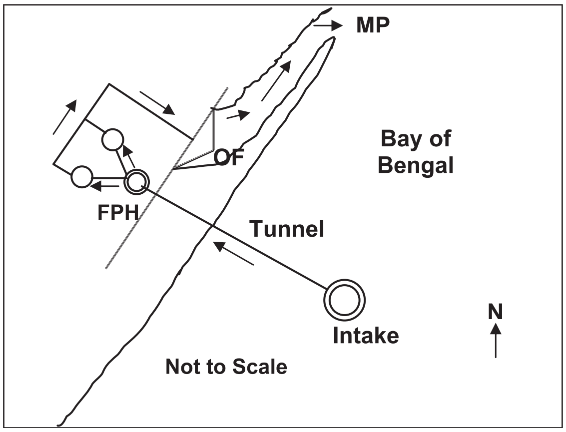


Fig. 1. Simplified schematic of the study site showing the power station intake, outfall and mixing point. (FPH—Forebay pump house, OF—Outfall, MP—Mixing point.)

from the shore through a 50 m deep sub-seabed tunnel. The intake point is accessible from land through an approach jetty. The main condenser of each unit is designed for a $\Delta T$ (temperature difference between inlet and outlet) of 10 °C. After passing through the steam condensers and other auxiliary heat exchangers, the seawater is discharged onshore through an outfall structure (situated on the northern side of the jetty). From the outfall point, the discharged seawater flows as a canal before it mixes with the sea (Fig. 1). The length of this naturally formed discharge canal varies (0.5–2.0 km) with season and is mainly controlled by longshore currents and littoral sediment transport.

### 2.2. Sampling strategy

Monthly boat cruises were undertaken in the sea during the period February 2001–March 2002, using a country fishing boat, in an area of about 2.5 $km^2$. Water samples were collected from 15 stations. The stations were fixed using global positioning system (GPS). A typical cruise plan is illustrated in Fig. 2. It was not possible to occupy the same positions during every cruise due to practical difficulties in manoeuvring and anchoring the small boat in turbulent nearshore waters. In addition to cruise samples, water and plankton samples were also collected from the intake point, outfall and the mixing point (point where the heated effluent mixed with the sea after passing through the discharge canal).

### 2.3. Water samples

Surface water samples were collected using a clean plastic bucket.

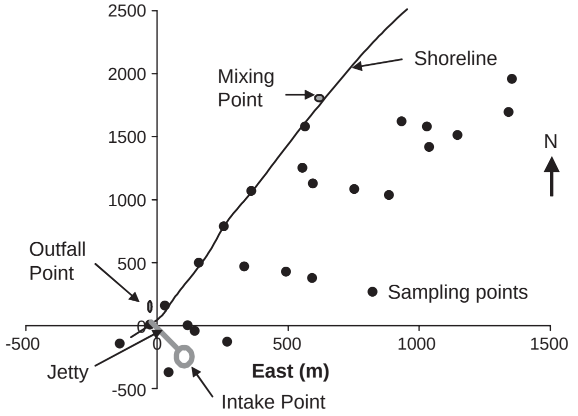


Fig. 2. Map showing the typical sampling stations (January 2002).

### 2.4. Temperature

Surface water temperature measurements were made using temperature probes (Saha probe—a temperature sensor developed in-house and kindly provided by Bidyut Saha of Indira Gandhi Centre for Atomic Research, Kalpakkam or a Datasonde model 4a Multiprobe (Hydrolab, USA), both with an accuracy of $\pm 0.05\,^{\circ}$C). The latter probe had additional sensors for pH, salinity, dissolved oxygen and turbidity, which were also operated.

### 2.5. Phytoplankton counts

An aliquot (100 mL) of seawater was allowed to settle in a measuring cylinder. The concentrated phytoplankton was preserved by addition of Lugol's iodine (1%). Phytoplankton were enumerated with the help of a haemocytometer (improved Neubauer) and the total number of organisms per mL of seawater was calculated.

### 2.6. Plant pigments

Chlorophyll *a* was estimated after filtering 500 ml of seawater onto a Whatman GF/C glass fibre filter paper. Pigment extraction was carried out in the dark using 90% acetone and its concentration was estimated spectrophotometrically as per Strickland and Parsons (1972).

### 2.7. Laboratory experiments

Phytoplankton drawn into the cooling circuit of the power station are subjected to a temperature shock during their passage in the condensers, before they are released back into the sea. At MAPS, chlorination of the incoming water is done on a continuous basis. Chlorine is dosed at the intake point so as to provide a total residual concentration of about 0.3–0.4 mg $L^{-1}$. Considering that the entrained phytoplankton could be damaged by the thermal and chlorine stress, laboratory experiments were carried out to assess the effects of an acute temperature and chlorine shock on natural phytoplankton. Unfiltered phytoplankton samples collected from the intake point were subjected to 42 °C for 15 and 30 min (which was representative of the maximum temperature and contact time that the phytoplankton might experience inside the cooling circuit). Two litres of seawater taken from the intake point were transferred into a double-walled beaker maintained at a temperature of 42 °C. It took about 18–20 min for the seawater to reach 42 °C and this marked the start of the experiment. A subsample was collected immediately (0 min) and subsequent samples were collected after 15 and 30 min. Immediately after collection, the samples were filtered and analysed for chlorophyll *a*. In another experiment, seawater samples from the intake point (28 °C) containing phytoplankton were subjected to different concentrations of chlorine. Chlorine was added to the samples in the form of sodium hypochlorite stock solution so as to get a dose of 1, 2 and 3 mg $L^{-1}$. The total chlorine residual concentrations in the beakers were estimated at the end of the experiment by DPD method using the recommended tablets (DPD no.4) containing DPD (diethyl *p*-phenylenediamine) and a Lovibond comparator. The residual chlorine levels were in the range 0–0.02 mg $L^{-1}$, 0.14–0.20 mg $L^{-1}$ and 0.9–1.0 mg $L^{-1}$ for the applied doses of 1, 2 and 3 mg $L^{-1}$, respectively. In the third experiment, the combined effect of temperature (42 °C) and chlorine (dosage 1, 2 and 3 mg $L^{-1}$) on phytoplankton was studied. Here, the dosage of 1 mg $L^{-1}$ resulted in no detectable residual chlorine, while dosage of 2 mg $L^{-1}$ gave 0.04–0.06 mg $L^{-1}$ and dosage of 3 mg $L^{-1}$ gave 0.5–0.7 mg $L^{-1}$ residual at the end of the experiment. In another experiment, the effect of temperature and chlorine (2 mg $L^{-1}$ dosage) individually and in combination on phytoplankton primary productivity was studied. Primary productivity was estimated by the light and dark bottle incubation method described by Strickland and Parsons (1972). The seawater samples containing natural phytoplankton assemblage collected from the intake point were incubated in 300 mL BOD bottles at an irradiance of 40 $\mu E\, m^{-2}\, s^{-1}$ for 4 h. Estimation of dissolved oxygen (DO) was carried out titrimetrically by Winkler's method (Strickland and Parsons, 1972). Gross primary production was estimated by converting the value of evolved oxygen to carbon equivalent using a photosynthetic quotient of 1.2 (Strickland and Parsons, 1972).

### 2.8. Data analysis

#### 2.8.1. Shannon diversity index

Shannon species diversity index, which is based on the proportional abundance of a given species, was calculated using the formula

$$H' = -\Sigma p_i \ln p_i \quad (1)$$

where $p_i$ is the proportional abundance of the $i$th species.

#### 2.8.2. Similarity index (Sorenson measure)

Similarity index (SI) was calculated by analysing the similarity of pairs of sites in terms of species presence or absence, using the equation,

$$C_s = 2j/(a+b), \quad (2)$$

where $j$ is the number of species common to both sites, $a$ the number of species in site A and $b$ the number of species in site B.

Correlation between chlorophyll $a$ and phytoplankton cell counts was tested by Pearson correlation analysis. Analysis of variance (ANOVA) was used to determine the differences in the response of phytoplankton to thermal and chemical stress. Differences from control were considered significant at a $P$ level of $<0.05$ (95% confidence level).

## 3. Results

### 3.1. Effluent discharge and plume movement in the sea

The effluent discharged from the outfall flows towards the north, creating a natural canal along the shore, before it mixes with the sea. It was observed that the opening of the discharge canal into the sea (mixing point) shifts its position according to the prevailing longshore sediment transport pattern that results in the formation of a sand bar between the sea and canal (Fig. 1). The movement of sediment (littoral drift) along the coast is brought about by the longshore currents, which during most part of the year moves towards the north. As a result, the length of the discharge canal and the position of mixing point varied with season. During the study period, the position of the mixing point varied from 50 m (February 2001) to 2 km (January 2002) north of the outfall point. Using the 15 months cruise data, thermal plume movement in the sea was mapped on a monthly basis (data not shown here). The plume movement was observed to be primarily influenced by the longshore currents, which themselves were influenced by the southwest and northeast monsoons. The currents were predominantly towards the north from March to September and towards the south from October to January (Table 1). The two transition periods between the two monsoons, one during February and the other in September, when current reversal occurred, were characterized by slack currents. Consequently, during this period the plume movement was largely in the offshore direction.

### 3.2. Temperature data

Among the 15 sampling stations occupied during each cruise, a station about 500 m south of the MAPS jetty end was not influenced (in terms of temperature) by the discharge from the power plant. This station, which represented ambient sea conditions, was designated as

Table 1
Details of power plant status and temperature data (February 2001 to March 2002)

| Period | Power MW (e) | | Intake (°C) | OF (°C) | MP (°C) | OF—intake $\Delta T$ (°C) | MP—intake $\Delta T$ (°C) | Dir |
|---|---|---|---|---|---|---|---|---|
| | Unit 1 | Unit 2 | | | | | | |
| Feb 2001 | 170 | 170 | 27.3 | 36.3 | 33.0 | 9.0 | 5.7 | T |
| Apr | 170 | SD | 29.6 | 36.9 | 33.0 | 7.3 | 3.4 | N |
| May | 170 | 170 | 28.1 | 37.6 | 33.6 | 9.5 | 5.5 | N |
| Jun | 170 | 170 | 27.1 | 36.2 | 32.5 | 9.1 | 5.4 | N |
| Jul | 170 | 170 | 28.0 | 36.5 | 33.7 | 8.5 | 5.7 | N |
| Aug | SD | 165 | 28.2 | 37.5 | 32.7 | 9.3 | 4.5 | N |
| Sep | 165 | 170 | 28.3 | 36.8 | 33.2 | 8.5 | 4.9 | T |
| Oct | SD | SD | 29.3 | 33.0 | 31.0 | 3.7 | 1.7 | S |
| Nov | 170 | 160 | 28.5 | 36.7 | 33.8 | 8.2 | 5.3 | S |
| Dec | 170 | 165 | 26.7 | 35.2 | 32.5 | 8.5 | 5.8 | S |
| Jan 2002 | 170 | 165 | 26.7 | 34.2 | 32.3 | 7.5 | 5.6 | S |
| Feb | 170 | SD | 27.7 | 35.0 | 33.6 | 7.3 | 5.9 | T |
| Mar | 170 | SD | 29.5 | 37.3 | 35.0 | 7.8 | 5.5 | N |

$\Delta T$—Temperature difference, MP—Mixing point, SD—Shutdown, T—Transition period (slack current), N—Northerly, S—Southerly, Dir—Longshore current direction, OF—Outfall.

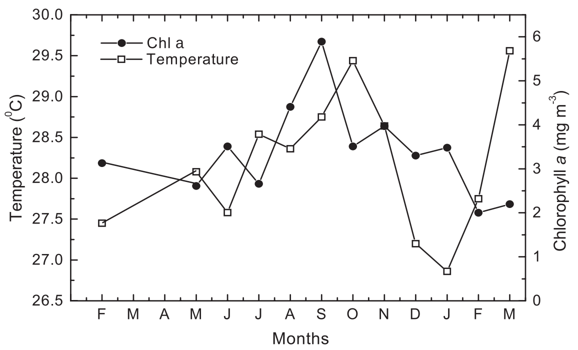


Fig. 3. Seasonal variation of surface water temperature and chlorophyll *a* at control station in the coastal waters of Kalpakkam (February 2001–March 2002).

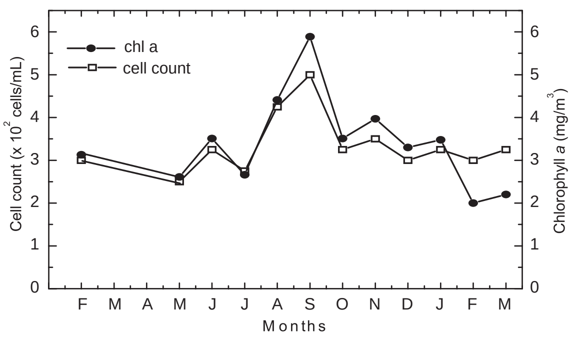


Fig. 5. Seasonal variation of phytoplankton cell counts and chlorophyll *a* at control station in the coastal waters of Kalpakkam (February 2001–March 2002).

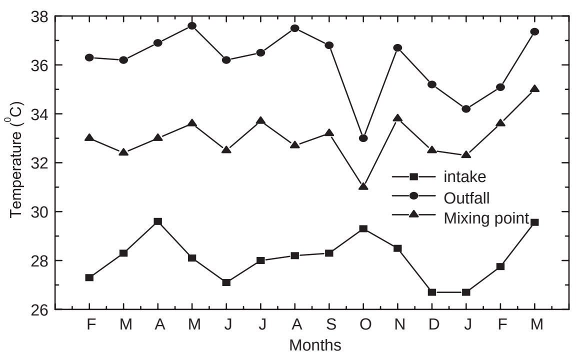


Fig. 4. Variation of temperature at intake, outfall and the mixing point during February 2001–March 2002.

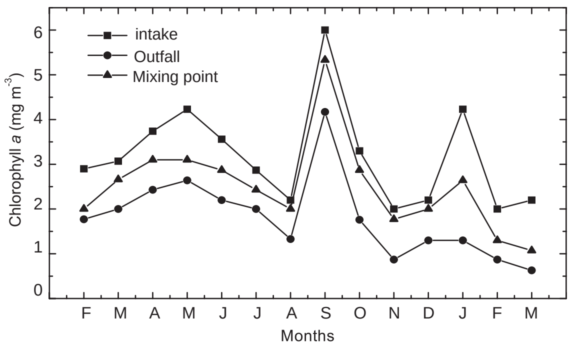


Fig. 6. Variation of chlorophyll *a* at the intake, outfall and the mixing point during February 2001–March 2002.

the control station, for the purpose of determining seasonal variation of temperature and phytoplankton in the coastal waters. Annual seasonal variation of temperature in the control station is given in Fig. 3. It shows a bimodal pattern with two peaks, one in March and another in October. The highest temperature (29.6 °C) was recorded in March and the lowest (26.9 °C) in January. Table 1 gives details of the power plant operation and $\Delta T$ (temperature difference with respect to the intake water) during the period February 2001–March 2002. The outfall water showed a $\Delta T$ of 7.3–9.3 °C, when the two units were operational (Fig. 4). A smaller $\Delta T$ of 3.4–5.9 °C (with respect to the intake point temperature) was recorded at the mixing point.

### 3.3. Phytoplankton data

Analysis of the 15 months data on salinity, pH, dissolved oxygen and nutrients (nitrate, nitrite, ammonia, phosphate and silicate) showed that the thermal discharge from the power plant did not affect the distribution of these parameters in the coastal waters (data being published separately). Seasonal variations of chlorophyll and phytoplankton cell counts at the control station are shown in Fig. 5. Chlorophyll *a* concentration showed a maximum of 5.89 mg m$^{-3}$ in September. Cell counts revealed that phytoplankton comprised (numerically) 94% diatoms, 3% green algae and 3% dinoflagellates. Chlorophyll *a* and phytoplankton cell counts showed a positive correlation ($r^2 = 0.85$) in the cruise samples collected from the sea. Good correlation ($r^2 = 0.78$) between the two was also observed for the samples collected from the other three stations: intake, outfall and mixing point. Chlorophyll *a* and phytoplankton cell counts were invariably reduced (by about 35–70%) at the outfall point as compared to the intake point (Fig. 6). However, at the mixing point, chlorophyll *a* and phytoplankton counts were only 15–50% lower as compared to the intake point (Fig. 6). During most of the months, cruise stations close to the mixing point did not show any difference in chlorophyll *a* concentration or phytoplankton cell count, as compared to the other stations in the sea. However, on a few occasions (April 2001, September 2001 and January 2002), stations close to the mixing point showed a decrease in chlorophyll *a* concentration and phytoplankton counts.

Shannon diversity indices of phytoplankton collected from the intake, outfall and the mixing point were $2.72 \pm 0.14$, $2.67 \pm 0.22$ and $2.75 \pm 0.15$, respectively. ANOVA revealed that the difference in diversity was significant ($P = 0.03$). Microscopic observations showed some differences in species composition between intake, outfall and mixing point (data not shown). To quantify the differences in the algal species composition, SIs were calculated. The similarity of phytoplankton between the intake and the outfall was $63\% \pm 0.08\%$. The SIs between the outfall and mixing point and between the intake point and mixing point were $64\% \pm 0.09\%$ and $73\% \pm 0.13\%$, respectively.

### 3.4. Short-term exposure experiments

Short-term laboratory experiments showed that exposure of phytoplankton to 42 °C for contact times of 15 and 30 min did not result in any significant change in chlorophyll *a* as compared to the control ($P = 0.10$). However, addition of $1\,mg\,L^{-1}$ chlorine caused 45–48% reduction ($P = 0.0006$) in chlorophyll, while a chlorine dose of $2\,mg\,L^{-1}$ caused 66–69% reduction ($P = 0.002$) and $3\,mg\,L^{-1}$ dose caused 79–82% reduction ($P = 0.0002$) (Fig. 7). Combined treatments of temperature (42 °C) and chlorine (1, 2 and $3\,mg\,L^{-1}$) caused less decrease in phytoplankton pigments as compared to chlorine alone (Fig. 8). Temperature (42 °C) with $1\,mg\,L^{-1}$ chlorine caused 44–49% reduction ($P < 0.0001$) in chlorophyll, while $2\,mg\,L^{-1}$ chlorine caused a reduction of 51–56% ($P = 0.0001$) and $3\,mg\,L^{-1}$ chlorine caused a reduction of 74% ($P = 0.0003$). Contact time did not seem to influence the results; the change in chlorophyll concentration after 15 and 30 min were comparable. Laboratory experiments on phytoplankton

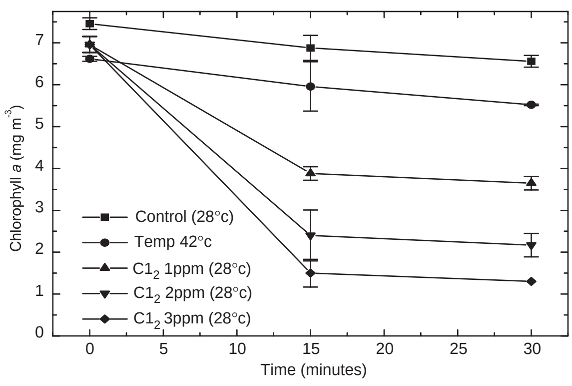


Fig. 7. Effect of temperature and chlorine on chlorophyll content of phytoplankton (error bars represent ±1 SD).

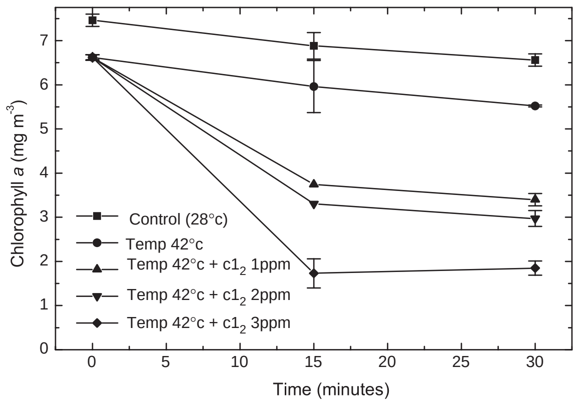


Fig. 8. Combined effect of temperature and chlorine on chlorophyll content of phytoplankton (error bars represent ±1 SD).

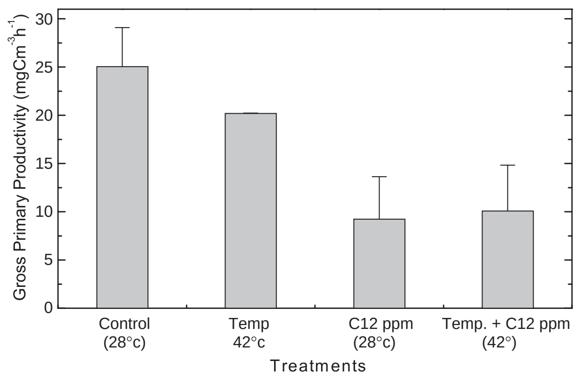


Fig. 9. Effect of temperature and chlorine ($2\,mg\,L^{-1}$ dosage) individually and in combination on phytoplankton productivity (error bars represent ±1 SD).

primary productivity showed that exposure to 42 °C for 15 min caused 19% reduction in productivity as compared to the control (Fig. 9). Chlorine dose of $2\,mg\,L^{-1}$ caused 63% reduction in productivity. Combined treatment of temperature (42 °C) and chlorine ($2\,mg\,L^{-1}$ dose) caused 59% reduction in productivity as compared to the control. These reductions were statistically very significant ($P = 0.001$).

## 4. Discussion

Impact of thermal stress on marine and estuarine organisms is quite extensively studied in temperate waters (Videau et al., 1979; Erickson and Hawkins, 1980; Margreay et al., 1981; Hall et al., 1982; Sellner and Kachur, 1987; Langford, 1990; Karås, 1992; Mallin et al., 1994). However, not much work has been carried out in tropical waters, despite the fact that organisms in the tropical waters live at ambient temperatures that are close to their lethal limits. In the Kalpakkam coastal waters, which receive thermal effluents from the MAPS, there have been a few studies. Ahamed et al. (1992) and Suresh et al. (1993) have studied the effects of cooling water effluents on the planktonic and benthic fauna. In the present study, the effects of power plant effluents on phytoplankton in the receiving water body were examined. The reversal of the coastal currents twice a year, together with the spatial shifting of the mixing point, provided a unique opportunity to study the thermal effect under different thermal plume movement conditions on the same coast.

Measurement of temperature at different points along the cooling water circuit (Table 1) showed that entrained organisms (those organisms drawn into the circuit along with the incoming water) experienced a relatively higher temperature than those at the mixing point (which might have been entrained into the plume). Wave-induced turbulent mixing within the breaker zone ensured a rapid fall in temperature at the mixing point, as can be seen from Table 1. Subsequently, the discharged water formed a plume that moved north, south or in the offshore direction, depending on the direction and magnitude of the prevailing longshore current.

The seasonal distribution of chlorophyll *a* and phytoplankton cell counts at Kalpakkam showed a maximum during September, which coincided with the current transition period. Earlier, Saravanane et al. (2000) also reported relatively high values of nutrients in the near-shore waters during the transition periods. Diatoms dominated the phytoplankton and there was no indication of any dominance by cyanobacteria or other harmful algal species, as a result of the thermal discharge. Chlorophyll *a* and phytoplankton cell counts showed a reduction from the intake point to the outfall, indicating loss during the transit. At the mixing point, chlorophyll *a* and phytoplankton cell counts were intermediate between those at the intake and the outfall points. This can be attributed to mixing of the ambient seawater with the discharged water, which tended to restore the phytoplankton to ambient levels. In spite of the consistent reduction in chlorophyll during the passage of cooling water from the intake to the outfall, stations close to mixing point did not show any significant change in chlorophyll *a* concentrations and phytoplankton cell counts, as compared to the other stations in the sea, during majority of the months. This revealed that at the mixing point, mixing of the effluents with the ambient seawater was rapid and very extensive. SIs also revealed greater similarity between the intake and mixing point than between intake and outfall. The results, therefore, indicate that the effect of thermal discharges on phytoplankton is marginal and confined to a relatively small area, while the coastal waters per se are not adversely affected.

Phytoplankton passing through the power plant cooling water system experience combined mechanical, chemical and thermal stresses, which vary in duration and magnitude, depending on the flow rate, thermal exposure regimes and chlorination procedures. Earlier workers have discounted mechanical stress as a possible cause of significant mortality in entrained organisms (Bienfang and Johnson, 1980; Karås, 1992). At MAPS, chlorination for biofouling control is carried out on a continuous basis. Chlorine is dosed to get a combined residual of about 0.3–0.5 mg $L^{-1}$. Results showed that chlorination, in combination with elevated temperature in the cooling system, resulted in a reduction in the chlorophyll concentration and phytoplankton abundance at the outfall point (Fig 5). In a similar study, Choi et al. (2002) also reported a reduction in chlorophyll at discharge outlet of the Hadong Power Station in Korea. In order to understand the effects of the two major stress factors, we carried out short-term experiments in which the stress factors were tested individually and simultaneously. Results of the experiments suggested that acute (15–30 min) exposure to 42 °C did not cause significant damage to phytoplankton and that inhibitory effects were mainly due to chlorination. Interestingly, Choi et al. (2002) observed that heterotrophic nanoflagellates subjected to 40 °C for 2 h suffered no damage, while chlorination caused a significant damage. In an earlier study, Mallin et al. (1994) also observed that direct thermal effect of cooling water discharge on phytoplankton communities was either localized or non-significant, depending upon site-specific circumstances.

Phytoplankton are known to be sensitive to chlorine (Morgan and Carpenter, 1978). There are several reports in the literature about the effects of residual chlorine in discharged waters on phytoplankton and productivity (Brook and Baker, 1972). Morgan and Stross (1969) reported the absence of measurable primary production in a tributary of Chesapeake Bay that was attributable to chlorination. In freshwater systems also, significant reduction in productivity has been observed following chlorination (Brook and Baker, 1972; Brooks and Liptak, 1979). Fox and Moyer (1975) reported a reduction of 57% in productivity at a plant on Florida's West Coast, where the chlorine residuals varied from 0.1 to 1.0 mg $L^{-1}$. At the same time, temperature increase ($\Delta T$ of 4.4–5.5 °C) resulted in a reduction of only 13%. Eppley et al. (1976) also reported depression of photosynthesis to the extent of up to 80%, when chlorine was dosed at a rate of 1.0 mg $L^{-1}$. Carpenter et al. (1972) reported depression of photosynthetic productivity by an average of 79% in a New England power plant, when chlorination was done at a dosage of 0.1 mg $L^{-1}$, though it resulted in no detectable residual at the discharge point. They argued that since effective antifouling required chlorination at a dosage of 0.2–0.5 $mg\,L^{-1}$, there could be no safe biocidal dosage of chlorine that was not detrimental to entrained phytoplankton. Schubel and Marcy (1978), Brooks and Liptak (1979) and Videau et al. (1979) reported destruction of chlorophyll as a result of chlorination. In the case of MAPS, the measured total residual chlorine concentration at the discharge point usually ranged between 0.1 and 0.2 $mg\,L^{-1}$. Chlorophyll *a* concentration at the discharge point during field studies showed 35–70% reduction as compared to that at the intake point. Similar reduction (66–69%) at a residual chlorine concentration of 0.12–0.20 $mg\,L^{-1}$ was also observed in our laboratory experiments. The percentage chlorophyll reduction also correlated with loss in primary productivity, thus confirming that addition of chlorine caused degradation of chlorophyll making it non-functional.

The combined treatment of temperature and chlorine also caused a significant decrease in phytoplankton pigments. But the percentage decrease was less as compared to that when chlorine alone was used. This was most likely due to a smaller residual chlorine concentration, caused by an increase in the temperature. Davis and Coughlan (1983) reported that as temperature increased, chlorine demand and decomposition increased. Therefore, it is possible that an increase in temperature resulted in faster disappearance of chlorine and hence reduced the exposure of the phytoplankton to chlorine stress. In the present study also, chlorine residuals were found to be lower in experimental vessels which were subjected to 42 °C than those left at room temperature, though both were given identical chlorine doses. Addition of chlorine to seawater causes the formation of hypochlorous acid (HOCl), which dissociates to form hypochlorite ion ($OCl^-$). This dissociation is influenced by pH and temperature; increase in pH and temperature increases the dissociation. The biocidal efficiency of hypochlorite ion is less than that of undissociated hypochlorous acid. This may be the reason why combined treatment of temperature and chlorine resulted, contradictory to our expectation, in reduced damage to phytoplankton. Choi et al. (2002) also could not observe any synergistic effect of temperature and chlorine on heterotrophic nanoflagellates at a power station site in Korea. From their study, they concluded that effects of chlorine would be more dominant than that of high temperature to coastal bacteria and nanoflagellates. The present results, however, are different from those of Roberts (1977), who observed synergistic effect of chlorine and temperature increase on photosynthesis in natural phytoplankton.

The results of the present study clearly showed that power plant-induced effect on phytoplankton is relatively quite localized. Coastal waters close to the plant discharge showed no reduction in phytoplankton standing stock, attributable to the power plant discharge. Though there was a reduction in phytoplankton during the transit of water through the cooling circuit, it was not recognizable beyond the mixing point, due to rapid and effective mixing of the discharge with the ambient seawater. Thermal discharge criteria for power plants are formulated by regulatory bodies on the assumption that temperature is the most dominant stress factor. This has been true in the case of power plants located in temperate latitudes also, where subsequent scientific findings showed that grave ecological consequences originally predicted for several aquatic populations have not been borne out (Dey et al., 2000; Mayhew et al., 2000; Melton and Serviss, 2000). In a coastal power plant using once-through cooling water system, entrained organisms are subjected to damage due to thermal and chemical stresses. From the present study, it is clear that chemical stress assumes equal or even more importance than temperature. This observation is also supported by laboratory and field studies by others (Choi et al., 2002). While the overall damage to the environment appears to be marginal, it is important to point out that the undue significance attached to $\Delta T$ (difference in temperature between intake and outfall) in the regulatory regime might actually be counterproductive. For example, attempt to bring down the $\Delta T$ of new plants from the existing limits, done with the intention to further reduce thermal damage, may actually result in more environmental damage. Given the fact that for a power plant the total quantum of waste heat to be rejected to the cooling water remains constant, a reduction in $\Delta T$ will result in abstraction of a larger volume of water for heat load rejection. The entire cooling water has to be chlorinated to control biofouling, which may result in increased mortality rate, owing to the fact that chemical stress effects dominate over thermal effects. Moreover, in tropical waters the annual range of seawater temperature is quite narrow (see Fig. 3) when compared to that in temperate waters. It is arguable whether a limit on $\Delta T$, which is specified with the intention of maintaining the natural cycle of variation in ambient water temperature, is valid under narrow annual temperature regime that exists in tropical waters. Under such circumstances, it may be prudent to stipulate a maximum allowable temperature inside the cooling circuit, instead of a specified $\Delta T$, as is presently practiced. Admittedly, this requires further research before it can be adopted as an alternative. The major advantage would be that utilities will be able to make maximum use of the cooling capacity of the abstracted water, thereby reducing cooling water abstraction rate and consequently, the mortality rate due to chlorination. This assumes greater importance, as previous studies have indicated subtle sublethal effects of chlorination, such as inhibitory effects on bacterial production and heterotrophic grazing rates, attributable to relatively long-lived chlorination by-products in the sea (Choi et al., 2002). In order to understand such indirect ecosystem level impact of thermal effluents, there is a need to carry out long-term studies using mesocosm facilities. Presently, such work is underway in our laboratory.

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