THE EFFECTS OF TIDES
ON THE INCEPTION OF PHYTOPLANKTON BLOOMS
IN LAGOON-TYPE ESTUARIES

by

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ABSTRACT

A computer model has been constructed to examine the relationship between the tidal cycle and potential phytoplankton productivity in Arcata Bay. The results of the model indicate that the timing of the tidal cycle relative to solar noon can affect gross productivity by as much as 30 percent and that plankton blooms in the estuary may be possible at any time of year when clear skies coincide with mid-day high tides.
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INTRODUCTION

Phytoplankton blooms occur when the total energy captured through photosynthesis exceeds the energy needed to sustain the existing population. Sunlight is the primary factor which determines when this situation develops (Ryther 1956). Although a lack of nutrients or grazing by zooplankton or benthic filter feeders may limit the size or duration of a bloom, insufficient light generally prevents its inception.

The net productivity of a water column is related to the difference between the energy captured through photosynthesis and the energy used in respiration by the producers. In the ocean, since the viable population is limited to the mixed layer above the thermocline or pycnocline, the vast majority of phytoplankton photosynthesis and respiration takes place above this discontinuity. Gran and Braarud (1935) pointed out that phytoplankton biomass should decrease if the mixed layer of the water column is deep. Only those plankton above the compensation depth, where respiration equals photosynthesis, capture more energy than they need to live. Assuming the total mixed depth is great enough, losses below the compensation depth will outweigh gains above and the net
result will be a loss of biomass for the phytoplankton community as a whole.

Sverdrup (1953) extended this concept by predicting the inception of the spring phytoplankton bloom based on the thickness of the mixed layer and the compensation depth. As summer approaches and the days lengthen, the compensation depth increases, since phytoplankton are able to produce more while respiration remains relatively constant throughout the mixed layer. Meanwhile, the depth of the mixed layer decreases as the intensity of storms declines and the thermocline becomes shallower.

Sverdrup defines the concept of critical depth to be the depth above which the integrated productivity equals the integrated respiration. He argues that when the depth of the mixed layer is less than the critical depth, phytoplankton will bloom, since gains will be greater than losses for the population as a whole. Sverdrup tested this theory by measuring phytoplankton biomass, the depth of mixing, and compensation depth during the late winter and spring in the Norwegian Sea. Both his research and that of others has supported the idea that spring blooms occur when the critical depth exceeds the depth of mixing (Fogg 1991, Mitchell and Holm-Hansen 1991.)

Estuarine phytoplankton experience different conditions than their oceanic relatives. Instead of a mixing depth which changes with the season, the bottom of
the productive water column is often determined by the depth of the estuary, a value which changes with the state of the tide. Therefore, phytoplankton blooms in estuaries may not follow the same seasonal cycle as those in the ocean. In fact, Smayda (1983) has reported estuarine blooms in Narraganset Bay between November and February.

The possibility that estuarine phytoplankton blooms occur at different time of year from oceanic blooms may be especially high in shallow, tidally-dominated estuaries which contain large areas of mudflats. At a high tide, water is held over mudflats at a relatively shallow depth. If this situation occurs in the middle of the day, phytoplankton throughout the water column may be exposed to enough sunlight for productivity to be positive, even in the middle of winter. On the other hand, if low tides are occurring in the middle of the day, deep channels and relatively turbid estuarine waters may prevent adequate solar penetration at times when blooms are taking place in nearby ocean waters.

To test the hypothesis that the synchronicity of tidal cycles and solar noon may have a significant effect on the timing of phytoplankton blooms in shallow estuaries, I have created a computer model which predicts potential phytoplankton productivity. The model estimates the total daily photosynthesis of an estuarine water mass given different parameters for light and productivity. A
comparison of these values to predicted energy losses indicates that clear skies which coincide with mid-day high tides may yield conditions that will allow estuarine phytoplankton blooms to occur in any month of the year.
BACKGROUND

Study Site

The computer model developed here is based on measurements made in the northern branch of Humboldt Bay. This typical lagoon-type estuary is located on the north coast of California, which has a mild climate and mixed tides. The bay is divided into several distinctive water masses, each of which is highly productive and support a diverse ecology.

Lagoon-type estuaries

Barrier beaches enclosing shallow estuaries occupy 10-15 percent of the world's coastlines (Kennish 1990). Many of the lagoon-type estuaries formed by these beaches share several characteristics. They are often shallow, with extensive areas of mudflats which are exposed at low tide. Freshwater input tends to be limited, leading to a slow flushing, often taking 20 or more tidal cycles. The lack of depth and runoff allows tidal currents and wind to mix the entire water column, eliminating vertical stratification. Some examples of lagoon-type estuaries are Beaufort Sound in North Carolina, High Venice Lagoon in Italy, Chincoteague Bay in Maryland, Peconic Bay in New York, North Inlet in South Carolina, Barnegatt Bay in New Jersey, and Pamlico
Sound at Cape Hatteras, North Carolina (Boynton et al. 1982, Kennish 1990).

Humboldt Bay

Humboldt Bay (Figure 1), located at latitude 40°46'N and longitude 124° 14'W on the north coast of California, is another example of a lagoon-type estuary (Barnhart et al. 1992). At mean high tide, the bay covers about 90 km². At low tide, the water surface covers only 29 km² as nearly 70 percent of the area of the bay consists of exposed mudflats (Shapiro and Associates 1980). The drainage area for Humboldt Bay is only 805 km² and the total annual freshwater input to the bay is on the order of the ocean water exchanged on a single tidal cycle. As a result, the waters of the bay only display salt-wedge stratification for brief periods immediately following storms. For the most part, the water column is well-mixed vertically and tidal currents dominate the hydraulics of the bay (Costa 1982).

Arcata Bay

Humboldt Bay is divided into three major subbays: South Bay, Entrance Bay, and Arcata Bay. A long deep channel, the North Bay Channel, connects Arcata Bay to the ocean. This channel splits into two smaller channels, Samoa and Arcata, which lead to a network of drainage channels extending throughout the mudflats (Costa 1982). The sample
Figure 1. Map of Humboldt Bay showing South Bay, Entrance Bay, Arcata Bay, and the North Bay Channel (modified from Costa, 1982)
Estuary used in the model developed here was the northern arm of Humboldt Bay: Arcata Bay and the North Bay Channel.

At high tide, Arcata Bay covers 34.5 km² and has a volume of 8.51 \times 10^7 m³ (Shapiro and Associates 1980). At low tide, these numbers are reduced to 11.9 km² and 4.8 \times 10^7 m³. According to these figures, the average depth of the bay is 2.5 m at high tide and 4.0 m at low tide.

**Tidal Cycle**

Humboldt Bay experiences mixed tides. The average difference in height between the higher-high and the lower-low is slightly less than 2 meters. The average difference in volume is 10⁷ meters³, representing a daily tidal prism of 44 percent (Barnhart et al. 1992).

**Water Compartments**

Even though the subbays of Humboldt bay are connected to each other and to the ocean, they have distinctly different characteristics and may be treated as separate water masses or "compartments" (Butler and Pequegnat 1979). Despite the large tidal prism, limited mixing occurs between the Arcata Bay water and the ocean water which enters the bay on an incoming tide. Butler and Pequegnat (1979) plotted the changing positions of various isotherms at different tidal stages which indicated a plunger-action by the flooding tide (Figure 2). Ocean water moves up the channels at the rate of about one mile per foot.
Figure 2. Simplified schematic of Arcata Bay water compartment at low, mid, and high tides. The left diagrams are top views while those on the right represent cross sections. As the ocean water (lighter shading) intrudes into the bay on an incoming tide, it acts like a plunger, forcing the bay water (darker shading) up the channels and out over the mudflats.
of tidal exchange, pushing bay water ahead of it. Eventually, bay water overflows the channels and spreads over the mudflats. Although some mixing definitely occurs along the ocean-bay water boundary, this mixing is not so great as to disturb the distinct chemical and biological character of each subbay (Pequegnat and Butler 1981). Research with zooplankton communities indicates that a relatively stable community structure exists in the Arcata Bay water compartment (Pequegnat and Haubenstock 1982).

The Ecology of the Bay

Harding et al. (1978) estimated the phytoplankton productivity of Humboldt Bay to be 1 g C/m$^2$/day, comparable to the most productive marine environments in the world (Boynton et al. 1982). This productivity supports a diverse ecology. As with other estuaries, the waters of Humboldt Bay act as a nursery area for numerous species of fish. Over 100 species of fish are found in and around Humboldt Bay (Gotshall et al. 1982). The bay is also the site of a commercial oyster fishery with over 56 million oysters (Anderson 1994) and acts as a primary stopover for birds migrating along the Pacific flyway (Springer 1982).

Climate

Fall and winter around Humboldt Bay are usually mild with the exception of a series of storms which drop about 85 cm of precipitation between October and May.
(Barnhart et al. 1992). The mean monthly air temperature varies from 47-56°F (Costa 1982). Dense morning fog is not unusual, especially in the late summer and early fall when the winds decrease in intensity.

**Light**

The amount of sunlight reaching a surface on the earth varies according to the time of day, the time of year, and current meteorological conditions. Because light is absorbed and reflected as it passes through water, the solar energy of light in water also depends on the depth of penetration and the turbidity of the water. By measuring light over time and at depth, it is possible to predict the effects of solar cycles, cloud cover, and attenuation of light in water.

**Measurement of Light**

Incident radiation is measured as irradiance or energy per unit area. Of particular importance to productivity studies are the wavelengths of light between 400-700 nm which are used by the photosynthesis (Tett 1990). This photosynthetically active radiation, PAR, can be measured by a quantum meter in Einsteins m² sec⁻¹.

**Incident Radiation**

Solar radiation goes through daily and yearly cycles as the earth turns and moves around the sun. Because of the tilt of the earth, the sun is higher overhead during
the summer than the winter. These cycles can be predicted accurately (Appendix C). However, the actual light which reaches the surface of the earth is affected greatly by meteorological conditions. Cloud or fog cover can reduce light by as much as 90 percent and causes greater daily fluctuation than the yearly changes (Zieman et al. 1991).

**Attenuation of light in the water column**

In a homogenous water column, light is attenuated exponentially with depth:

\[ I_z = I_0 e^{-kz} \]

where \( I_0 \) is the incident radiation at the surface, \( z \) is the depth, and \( k \) is an extinction coefficient (Kennish 1990). This decrease in light with depth is caused primarily by absorption and scattering of light by suspended particles and dissolved matter. Turbid water, such as is commonly found in shallow estuaries, does not allow much light to penetrate beyond the top few meters.

The extinction coefficient can be determined by measuring the light available at different depths with a quantum meter. Another common technique for determining turbidity is to lower a large white disk (a Secchi disk) into the water and measure the depth at which it disappears. An empirical relationship can be developed to convert from one form of measurement to the other (Appendix C).
The Photosynthesis:Irradiance Curve

Many researchers have measured photosynthesis as a function of irradiance. Yentsch (1980) refers to this P:I curve as "a cornerstone in studies of phytoplankton ecology". Although the curve has a characteristic shape, the exact form may depend on certain environmental factors such as temperature and nutrient concentrations. It may also vary with the time of day. Furthermore, there is some disagreement about the effects of high intensity light on natural populations. Despite these variables, several mathematical formulas have been suggested to represent this curve for use in a model.

Shape of the P:I curve

Early incubation experiments established that productivity increases at a linear rate, (alpha), with an increase in light up to a maximum rate (Ryther 1956). Researchers also discovered that if light continued to increase beyond this "saturation" level, (Pmax), a process called photoinhibition can causes the photosynthetic rate to decrease (Figure 3).

Response of P:I curve to environment

Several investigators have suggested that the shape of the P:I curve can be considered to be independent of environmental conditions and the species of the
Figure 3. The basic shape of a P:I curve showing an initial linear increase in photosynthesis with increasing light (slope = alpha), followed by a saturation level of Pmax, and then inhibition at high light intensities.
phytoplankton involved (Bannister 1974, Dunstan 1973, Ryther 1956, Ryther and Yentsch 1958). Other work has indicated that this may not be the case. Cote and Platt (1983) measured alpha and Pmax on a daily basis and found threefold variation in each parameter over time. These variations have been correlated with changes in temperature and community structure (Malone and Neale 1981), nutrient concentrations (Takahashi et al. 1973), and light history (Ziemann et al. 1991).

**Daily variations in P:I curve**

Other research has found changes in the P:I response over the course of a single day (Harris and Lott 1973, Malone 1971). It is possible that the morning maximum and an afternoon minimum described by many researchers (Marra et al. 1985) is due to these temporal changes in photosynthetic response. Different explanations have been offered to explain this phenomenon, including photorespiration (Harris and Lott 1973) and nutrient depletion (Vollenweider 1966).

**Photoinhibition**

Several researchers have suggested that photoinhibition may be an artifact of experimental techniques (Harris and Lott 1973, Marra 1978a,b). Their argument is that incubation experiments which expose phytoplankton to constant light do not represent nature,
where turbulence in the water column causes organisms to be exposed to a changing light field. Since phytoplankton do not react immediately to higher light intensities, inhibition will not occur in a naturally-mixed water column. Some of their experiments with simulated vertical mixing have yielded greater productivity than fixed-bottle experiments. However, other experiments by Gallegos and Platt (1982) and Marra (1978b) did not find that vertical mixing increased productivity over that found in stationary bottles.

Mathematical representations of P:I curve

Many mathematical functions have been suggested to represent the P:I curve. Jassby and Platt (1976) compared many of these functions with data obtained at presaturation intensities and decided that the a hyperbolic tangent function based on alpha, the slope of the initial linear increase in productivity with increasing light, and Pmax, the saturation level of productivity.

Gallegos and Platt (1981), Vollenweider (1966), and Parker (1974) have suggested more complicated P:I functions which add parameters to describe photoinhibition. Unlike alpha and Pmax, these parameters do not represent any particular physical characteristic and are simply chosen so that the curve approximates data collected in incubation experiments.
Despite this variability in the parameters of the P:I curve and the disagreement over the existence of inhibition, Ryther and Yentsch (1957) were able to develop a function based on a P:I curve (with inhibition) which estimated phytoplankton production in the ocean based on chlorophyll, light, and extinction measurements. The results of this function agreed closely with *in situ* measurements. Although their results are not applicable to estuaries with a limited depth, they lend support to the validity of using a P:I curve based on mean parameters to estimate productivity.
THE MODEL

Whenever energy gained by a phytoplankton population through photosynthesis exceeds the energy used in respiration and other losses, a bloom is possible. To determine when this situation might develop, the model compares potential gross productivity each day of the year with energy losses. After laying out a general approach to this problem, I will describe the actual functioning of the computer programs involved and the assumptions that were made.

**General Approach**

In order to account for tidal effects, the model sums the productivity for each unit volume of water in the bay compartment at each moment of the day. Mathematically, this gross daily productivity can be represented as:

\[ \int \int \int \text{productivity} \, da \, df \, dt \]

where "a" is a unit area of the bay water compartment integrated over the entire area of the bay, "f" is a distance from the surface integrated over the entire depth of the water column, and "t" is time integrated over the 24-hour period.
Since area and depth are complex functions of the shape of the bay and the tidal cycle, no attempt has been made at an analytical solution. Instead, productivity has been estimated by converting the integrals into summations over discrete units of area, depth, and time. The gross productivity of a unit volume of the bay is calculated for one hour intervals given a particular depth and time of day. These productivities are summed over the entire volume of the bay compartment for each hour of the day. The result is then compared to energy losses which take place over the same period of time.

Gross productivity of a unit of water

The gross productivity of a particular unit of water is a function of the light reaching that body of water, the amount of phytoplankton it contains, and a number of environmental factors including nutrient concentrations and temperature. The light intensity reaching each unit is a function of the intensity of light at the surface, the turbidity of the water, and its distance from the surface. The intensity of light at the surface is a function of the time of day, the time of year, and the current meteorological conditions.

The model works its way backwards through these factors to arrive at the hourly productivity of a particular unit of water. It begins by calculating the amount of solar radiation for a particular day and time. Then it decreases
this amount based on cloud cover, turbidity, and distance from the surface. Finally, it uses a P:I function to estimate productivity given the available light and multiplies by the amount of chlorophyll.

Gross productivity of the bay

The gross productivity of the bay at a particular depth and a particular moment is the sum of the productivity of all the units at that depth. The area of the bay at a particular depth is a function of the tidal height at the moment in question. The total gross productivity of the bay at a particular moment is the sum of the productivity at each of its depths. And finally, the daily gross productivity of the bay is the sum of these sums for each moment during a 24-hour period.

After making assumptions about cloud cover, the model determines the amount of light available at the surface for a particular day and hour. It then assumes a degree of turbidity and calculates the amount of light which will reach each depth interval. Based on these light values, a P:I curve, and an estimate for chlorophyll concentration, it calculates productivities for water units at each possible depth and multiplies these values by the area of the bay at that depth for tidal stage which exists at the day and hour in question. The sum of all depths yields the total potential productivity of the bay for a given hour. Repeating this for each hour of the day gives
an estimate of the gross productivity of the bay for a particular day.

**Energy losses**

Phytoplankton populations lose energy or biomass through respiration, grazing, and flushing. These losses are a function of the quantity of phytoplankton, the quantity of grazers, temperature, precipitation, and the range of the tidal cycle. For the most part however, they do not depend on the time of day or the distance from the surface. Since the volume of water being considered does not vary and other factors do not change significantly during the course of most tidal cycles or days, the model uses a single figure to represent losses. In fact, zooplankton populations and their grazing activity will vary in response to phytoplankton blooms. However, this response always lags behind changes in the phytoplankton population and therefore may limit the duration of a bloom but should not affect its inception.

**Building the Model**

Two versions of the model were constructed. An Excel version calculates productivity for any given day in 1993. A Turbo Pascal version calculates the productivity for each day in 1993.

Two underlying spreadsheets provide data for Excel version of the model. The first contains the stage of the
tide for each day and hour. The second computes the volume of water at various depths in the bay for different tidal stages. The data from these spreadsheets were also output to text files which are read by the Turbo Pascal version of the model.

A number of supporting spreadsheets were also used in the development of the functions used in the model. Some were used to analyze the light and productivity data. Others were used to model light attenuation and P:I functions.

**Tidal heights**

The tidal spreadsheet, TIDES.XLS, contains information generated by a shareware Basic program, Tides V1.66, written by Edward P. Wallner. This program predicts tidal heights for a given time based on the amplitude and phase of 37 tidal constituents published in the NOS Tide Tables for the North Spit of Humboldt Bay. The output from this program was reformatted by a Turbo Pascal program so that it could be loaded into Excel and accessed by the model. Although the output of the program predicts tidal heights in tenths of a foot (Figure 4), these values are rounded to the nearest foot during the execution of the model.
Figure 4. Output of Tides program for the first four days in January, 1993, showing Humboldt Bay's mixed tidal cycle.
Dimensions of the bay

Several techniques were used to estimate the volume of the Arcata Bay water compartment at various depths. A Calcomp 9500 digitizer was used to measure the area of the bay at high and low tide from a 1979 NOAA chart of Humboldt Bay. This information was processed by the ARCINFO 3.4D program in the Graphical Information Systems lab at Humboldt State University. Soundings marked on the chart were counted to estimate the area and depth of those parts of the bay which are submerged when the tide is at mean lower-low water (MLLW).

It is not possible to use the chart to estimate the areas of the bay at various depths between low and high tide. A series of photos taken as part of the Humboldt Bay Project were measured with a planimeter and the results were published in an appendix to that report (Costa 1984). Although these data only covered the two extremes of the tidal cycle, linear regressions were used to estimate the rate of change in area near high and low tide. Personal observation, in conjunction with the Tides program mentioned above led me to estimate the height of the mudflats at approximately 2.5 feet above MLLW. Plugging in this figure and assuming a rapid and steady increase in area as the tide covers the flats led to the spreadsheet AREAS.XLS.
Unlike most other studies, I have treated the Arcata Bay water compartment as a constant volume of water which changes shape with changes in the tidal stages. Since most other studies treat the bay as a fixed area with a changing volume of water, my figure of $53.4 \times 10^6 \text{ m}^3$ comes closest to matching other published figures for low tide volume of Arcata Bay. As discussed earlier, ocean water on a flood tide moves up the main channel like a plunger, pushing the bay water in front of it and out over the mudflats. Since the model is concerned with the productivity in the Bay compartment only, the spreadsheet subtracts the area of the Bay which is covered by ocean water at high tide and includes this area as the ocean water recedes.

The output of AREAS.XLS shows the average depth of the bay decreasing rapidly from over four meters to just 1.5 meters as the tide covers the mudflats and then slowly increasing back to two meters as the tide continues to rise (Figure 5). Meanwhile, the surface area of the bay initially increases and then slowly decreases after the mudflats are fully covered and the ocean water extends further up the channels.

Representation of the topography of Humboldt Bay above lower-low tide involved a number of simplifications and assumptions. A series of flyover photographs taken hourly might give enough data to more accurately represent
Figure 5. Changes in the average depth and surface area of the Arcata Bay water compartment as a function of tidal height.
the areas of the various depth slices used. While this type of information might make application of the model to Humboldt Bay more precise, it should not affect the conclusions about lagoon-type estuaries in general.

**Incident Radiation**

Solar radiation data for the light spreadsheets was collected with a Li-Cor datalogger and a quantum meter at the Telonicher Marine Lab in Trinidad, CA (15 miles north of Arcata Bay). A complete description of this data and the functions derived from it can be found in Appendix A.

Light data was not collected over a long enough period of time to allow reasonable predictions of changing cloud cover during the year. Therefore, a default value representing "average" cloud cover was used for the entire year. With more data, a better approach might have been to use a different value for each month.

**The P:I Curve**

The model uses the hyperbolic tangent function suggested by Jassby and Platt (1976) to estimate the photosynthesis produced by a particular amount of solar radiation. This function is based on the saturation level, Pmax, and the slope of the curve at lower light intensities, alpha. For the purposes of an estuarine model, it is probably unwise to neglect inhibition. Even if deep-mixing in the ocean suppresses the effects of high light, the
shallowness of estuaries may well expose organisms to inhibitory intensities for longer periods of time. Therefore, I have added Vollenweider's photoinhibition term. The result is a function of the form:

\[
P = P_{\text{max}} \frac{\tanh \left( a \frac{I}{P_{\text{max}}} \right)}{\sqrt{1 + (\text{inhibit} \times I)^N}}
\]

Appendix B contains a description of the origin of this curve and the data used to calibrate it.

**Units**

The area has been measured in km². Depth has been represented in feet to match the soundings on the chart. Time has been measured in hours. Productivity has been measured in terms of the weight of oxygen produced and phytoplankton biomass has been represented by the weight of chlorophyll a present.

**Default parameters**

Unless otherwise mentioned, the following parameters have been used during modelling runs:

1) chlorophyll a concentration = 6 mg/meter³
2) secchi depth = 1 meter
3) respiration = 1 mg O²/mg chlorophyll a/hr
4) the volume of the bay = 53.4 X 10³ meter³
5) $\alpha = 0.06 \text{ mg O}_2 \text{ m}^2 \text{ sec/mg chlorophyll } a/\text{hr/\mu E}$
6) $P_{\text{max}} = 7 \text{ mg O}_2/\text{mg chlorophyll } a/\text{hr}$
7) inhibition = 0.005
8) $N$ (inhibition exponent) = 2

Assumptions
The model makes a number of simplifying assumptions. The most important are the following:

1) Homogeneity of water within a compartment. Bay water is assumed to be thoroughly mixed, both horizontally and vertically. This implies a constant turbidity, temperature, and phytoplankton distribution throughout the bay compartment and throughout time. While this is not exactly true at all times, especially horizontally, it is hoped that changes which might affect productivity at one end of the bay will be offset by changes in the other direction at the opposite end of the bay.

2) Constant P:I curve. Variations in $P_{\text{max}}$ and $\alpha$ over time have not been explained clearly in terms of other environmental variables and cannot be accurately predicted (Cote and Platt 1983). Similarly, although it can be measured in static incubation experiments, the effects of photoinhibition in nature are also largely unknown. Because of these unknowns, the model considered the P:I curve to have a constant shape over both time and space. However, data gathered in Humboldt
Bay for this project and others indicates that Pmax and alpha are not constant and that photoinhibition is taking place.

3) **Adequate nutrients.** During much of the year, productivity in the bay may be limited by a lack of nutrients, rather than light availability (Pequegnat and Butler 1981). The model, however, assumes that nutrients are always in adequate supply. I have done this because of my focus in the timing of bloom inceptions. During periods of negative net productivity, nutrients have an opportunity to accumulate. Nutrient depletion should not be significant until after the phytoplankton population's initial bloom.

4) **Constant phytoplankton population.** The concentration of phytoplankton/chlorophyll is assumed to be a constant throughout the year. While this is clearly not the case in nature, the principle changes take place after blooms commence and have been ignored.

5) **Constant losses.** The model assumes that energy losses are constant. Clearly, flushing, respiration, and grazing do vary over time or space in nature. However, flushing is a somewhat random event which will also cause a balancing loss of productivity. Respiration, which will clearly increase with an increased
population, would also be balanced by increasing photosynthesis. And grazing by benthic macro fauna will remain fairly constant (Tenore and Dunstan 1973), while zooplankton grazing will increase only after a bloom has commenced (Kennish 1990, Riley 1967, Smayda 1983).

6) **Constant volume.** The volume of the bay compartment is a constant. Although the area and depth change with the tidal cycle, the model only considers the water which exists in the bay at all times and ignores ocean water which intrudes at high tide. It also ignores the effects of extremely low tides or periods of high runoff when bay compartment water may be lost to the ocean. This assumption allows us to draw conclusions about the potential productivity of the bay compartment without considering what happens in the ocean water which moves into the bay on an incoming tide.
DISCUSSION

Basic Output of Model

The output of the model are curves which represent daily potential productivity for a particular set of parameters. These curves are plotted along with a line which represents respiration and other losses (Figure 6).

The Inception of Blooms

Net productivity is the difference between energy gains due to photosynthesis and energy lost to respiration, grazing, and flushing. When a line representing photosynthesis is below the line representing losses, net productivity is negative and the population will shrink. When photosynthesis first exceeds respiration, a bloom may commence. It will continue until photosynthesis drops below respiration or the population growth is stopped by grazing or nutrient depletion.

When the model is run for four different values for cloud cover and all other parameters at their default values, the curves for maximum and average light both cross the respiration line at least once during every month between February and November. Thus, assuming normal cloud cover or less, the model indicates the possibility of a bloom exists in Arcata Bay almost year-round.
Figure 6. Potential phytoplankton productivity in Arcata Bay as predicted by the model using four different values for cloud cover and default values for all other parameters. The four curves, from top to bottom, represent clouds blocking 0%, 33%, 66%, and 90% of the maximum solar radiation. The flat line represents energy losses of 7690 kg oxygen/day.
Effects of tides

The productivity curves output by the model all show distinct fortnightly fluctuations which demonstrate the strong effect that the synchronicity of the tidal and the solar cycles have on phytoplankton productivity in shallow-water estuaries. When plotted on an hourly basis over 8-day periods, this interaction is clear (Figure 7). Various dips and peaks in the productivity curve can be traced to the relative phases of the solar and tidal cycle.

Since the higher-high tide is about 50 minutes later each day, the two cycles move in and out of phase about every two weeks. The result is gross productivity which varies by as much as 50 percent in a week during the winter and 30 percent during the summer.

Effects of solar cycle

The overall trend of daily potential productivity figures produced by the model follows a clear seasonal cycle, peaking in the summer and reaching a low in the winter. The size of the solar/tidal fluctuations is greater in the winter than in the summer because less inhibition is taking place. Between May and October, the productivity curve remains above the respiration line. During the rest of the year, net productivity is only positive when high tides are occurring near solar noon and light is not reduced significantly by cloud cover. This result fits the conclusions of Boynton et al. (1982) and Smayda (1983) who
Figure 7. Potential phytoplankton productivity in Arcata Bay (line) with maximum solar radiation (dark pattern) and tidal height (lighter pattern) for three 8-day periods during 1993. All model parameters were set at their default values.
found phytoplankton productivity in shallow-water estuaries to be extremely variable during the year, but generally highest between May and October.

Effects of cloud cover

There is almost no difference in the productivity experienced at maximum light conditions and that of "average" light, when 35 percent of incident radiation is blocked by cloud cover. In fact, the yearly output under average conditions was $2.86 \times 10^6 \text{ kg } O_2$, slightly higher than the $2.81 \times 10^6 \text{ kg } O_2$ yielded by maximum light conditions. Evidently, the increased photosynthesis at depth is more than balanced by increased inhibition at the surface.

Even when two thirds of the incident radiation was blocked by clouds during the summer, productivity continued at nearly the same rate as that experienced when no cloud cover was present. This denser cloud cover had a greater effect during the winter, lowering the productivity curves by up to 20 percent and preventing net productivity from ever being positive. Again, reduced surface inhibition during the summer makes up for losses at depth. Because inhibition is less pronounced during the winter, reduced photosynthesis at depth becomes more significant.

When only 10 percent of the incident radiation reached the bay, the productivity curve remained well below the respiration line, even in the middle of summer.
appears that heavy overcast can prevent blooms at any time of the year.

**Sensitivity of the model to parameters**

The model was run several times while varying the values used for the extinction coefficient or the P:I parameters to evaluate the effects of these parameters (Figures 8 through 16). The values for the parameters were chosen to match ranges found in the literature or measured in Humboldt Bay (Appendix B and C).

**The extinction coefficient**

Based on the variation in 15 secchi disk measurements made between January and August of 1979 (Butler and Pequegnat 1979), 0.4 meters (one standard deviation) was added and subtracted from the mean value of one meter. The model was then run for each of these values while defaulting all other parameters to study the effects of changing the extinction coefficient (Figure 8).

Decreasing the extinction coefficient from the average used in most of the model runs caused a 9 percent increase in summer photosynthesis and a 19 percent increase in the winter. More turbid water had a greater effect, causing a drop of 17 percent in summer productivity and 25 percent in winter. This change was significant relative to the timing of phytoplankton blooms. Increasing the extinction coefficient by just one standard deviation
Figure 8. Predicted potential phytoplankton productivity in Arcata Bay with three different levels of turbidity: secchi disk disappearance depths of 0.6, 1.0 and 1.4 meters. The higher lines correspond to greater disappearance depths. All other model parameters were set at their default values. The flat line represents energy losses of 7690 kg oxygen/day.
dropped potential photosynthesis line below the respiration line for nearly the entire year.

Thus, activities which increase the turbidity of the bay may delay the inception of phytoplankton blooms. Storms which temporarily increase runoff and the amount of suspended material in the bay may prevent a bloom even when followed by a sunny period. Turbidity can also increase as a result of phytoplankton blooms themselves, lowering net productivity and possibly causing the end of a bloom.

Activities such as logging or dredging which may increase the extinction coefficient for a longer period of time may even prevent blooms from occurring altogether and could affect the viability of the bay in general.

The photosynthesis:irradiance parameters

As indicated earlier, the relationship of photosynthesis to irradiation is central to the model. Selection of values for Pmax, alpha, and inhibition, the parameters which define the shape of this function, have a significant effect on the output of the model. Values used in the model were derived from a variety of sources, including values measured in Humboldt Bay. To evaluate the sensitivity of the model to these parameters, all other values where held steady while Pmax, alpha, and the photoinhibition parameters were changed.
Photosynthetic saturation. According to data collected by Ryther and Yentsch (1958), a mean value of 3.7 g C/g chl a/hour can be used for Pmax, the photosynthetic saturation rate. Cote and Platt (1983) reported a mean of 4.93 g C/g chl a/hour from their work in Bedford Basin. Malone and Neale (1981) found values around 10 g C/g chl a/hour in Hudson estuary water between 10 and 16°C. However, they also reported 22 g C/g chl a/hour from nanoplankton incubated at temperatures up to 26°C. Harding et al. (1978) measured values in Humboldt Bay that varied from 2.5-21 g C/g chl a. For most of this project, an intermediate value of 4.8 g C/g chl a/hour (6 g O₂/g chl a/hour) was used.

The model was run using minimum, maximum, and average values of Pmax measured by Harding (Figures 9 and 10), assuming an average value for alpha and no inhibition. Although the solar/tidal fluctuations are still obvious, the huge variation in Harding's values affect the output of the model greatly. For the two larger values, productivity always exceeds respiration. For the smallest value, the reverse is true for all except the middle of the summer.

Assimilation ratio. To test the effect of varying the assimilation ratio alpha, minimum, mean, and maximum values were selected from Platt and Jassby (1976). All three curves were generated with Pmax equal to 6 g O₂/g chl a/hour and no inhibition (Figures 11 and 12). Increasing
Figure 9. P:I curves for $P_{max} = 26, 13$ and $3 \text{ mg O}_2/\text{mg chl a/hr}$ with no inhibition and $\alpha = 0.06 \text{ mg O}_2/\text{m}^2/\text{sec/mg chl a/hr}/\mu\text{E}$. All other model parameters were set at their default values.

Figure 10. Predicted potential phytoplankton productivity in Arcata Bay given the P:I curves in Figure 9 and holding all other parameters at their default values. The flat line represents energy losses of 7690 kg oxygen/day.
Figure 11. P:I curves for the minimum, maximum, and mean alpha reported by Jasby and Platt (1976): 0.012, 0.06, and 0.154 mg O₂ m² sec/mg chl a/hr/μE. Each curve is based on the hyperbolic tangent formula developed by Marra et al. (1985) with Pmax set to 6 g O₂/g chl a/hour and no inhibition. All other model parameters were set at their default values.

Figure 12. Potential productivity based on the three P:I curves in Figure 11. The upper curves result from higher values for alpha. The flat line represents energy losses of 7690 kg oxygen/day.
alpha raised the potential productivity curves, but did not seem to affect the fortnightly fluctuations.

**Photoinhibition.** The effects of photoinhibition were also explored by testing three sets of inhibition coefficients (Figures 13 and 14). All three P:I curves were designed to reach the same maximum level of photosynthesis, but drop off at different rates as irradiance increased. Maximum inhibition caused a 10 percent decrease in productivity in winter and a 24 percent decrease in summer when compared to the medium inhibition. No inhibition led to a 13 percent increase in the summer when compared to medium inhibition, but had no effect in the winter. If inhibition may be ignored or is less powerful than indicated by static incubation studies, then blooms may be possible even earlier during the year.

**Incubation results.** Three efforts were made to match the P:I curve to data from the incubation study (Appendix B). The model was run with each of the resulting curves (Figures 15 and 16). The two curves which assuming a lower Pmax did not yield production equal to respiration even during the summer. Clearly, these values are not indicative of year-round values, or phytoplankton would not exist in Arcata Bay. The third curve, which assumed a higher value for Pmax with greater inhibition produced more
Figure 13. P:I curves for three levels of inhibition. Each curve is based on the hyperbolic tangent formula developed by Jasby and Platt (1976), modified by Vollenweider's (1966) inhibition term. All curves set alpha to $0.06 \text{ mg O}_2 \text{ m}^2 \text{ sec/mg chl a/hr/\mu E}$. The top curve represents no inhibition and $P_{\text{max}}$ of $4.9 \text{ mg O}_2 /\text{mg chl a/hr}$. The middle curve adds inhibition = $0.001$ and $N = 2$. The bottom curve increases $P_{\text{max}}$ to $7.0$, but also increases the inhibition to $0.005$ with $N = 2$.

Figure 14. Potential productivity based on the three P:I curves in Figure 13. The flat line represents energy losses of $7690 \text{ kg oxygen/day.}$
Figure 15. Three curves use different Pmax, alpha, and inhibition parameters for the P:I curve to try to estimate the data collected in the incubation experiment (Appendix B). Each curve is based on the hyperbolic tangent formula developed by Jasby and Platt (1976), modified by Vollenweider's (1966) inhibition term. The triangles represent data from ocean water collected in the bay at high tide, while the triangles were data from two different stations in the bay compartment.

Figure 16. Potential productivity based on the three P:I curves in Figure 15. The top curve is the result of using a higher Pmax and greater inhibition, the middle curve used no inhibition, and the bottom used a lower Pmax and inhibition. The flat line represents energy losses of 7690 kg oxygen/day.
reasonable results. These values were used as the "standard values" used for the majority of the model runs.
CONCLUSIONS

The output of the model clearly shows that the timing of a high tide relative to solar noon has a significant effect on the potential phytoplankton productivity in the bay. All output of the model demonstrates strong fortnightly fluctuations as the tidal cycle and solar cycle move in and out of phase.

These fluctuations may explain the variations in the timing of estuarine phytoplankton blooms noted by Smayda (1983). Using a reasonable set of parameters, the model indicates that blooms may occur during almost any month of the year when clear skies coincide with mid-day high tides. However, sensitivity to changes in the P:I curve parameters compromise the effectiveness of the model at accurately predicting the actual timing of a phytoplankton bloom.
REFERENCES CITED


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APPENDIX A. SOLAR RADIATION AT HUMBOLDT BAY.

Introduction

As the earth revolves around the sun, both the length of day light and light intensity go through yearly cycles. In the summer, the days are longer and the sun is brighter than in the winter. In order for the model to provide an estimate of light intensity at any hour of any day, data has been collected, analyzed, and simulated with trigonometric functions.

Methods

Light data used to calibrate the model was collected with a Li-Cor quantum meter located on a water tank behind the Telonicher Marine Laboratory in Trinidad, California. Data was recorded at 15 minute intervals on a data logger on 46 days during the 1st half of 1983. This data was transferred to a microcomputer and analyzed using Microsoft Excel.

Results and Discussion

Maximum daily values varied from 855-1920 µE sec\(^{-1}\) m\(^{-2}\) in January and June respectively. Cloud cover caused the data to vary considerably from day to day as well (Figure A-1). The maximum intensity reached on cloudy June days was less than that found on clear January days (1061-1316...
Figure A-1. Record of incident solar radiation measured at Trinidad, California on five sample days during 1993.
μE sec⁻¹ m⁻²). Many days demonstrated low values in the morning, followed by nearly maximum values in the afternoon, presumably caused by coastal morning fog burning off or being blown away during the day.

The yearly cycles of sunlight are caused by the tilt in the earth's axis relative to the rotation of the earth around the sun. At the winter solstice, the sun is at its southernmost position, over the Tropic of Capricorn. In the northern hemisphere, days are shorter and the light is less intense since the sun is further away. Conversely, days are longer and the noontime sun more intense closer to the summer solstice since the sun is over the Tropic of Cancer and closer to us. To represent these characteristics in the model, I combined three trigonometric functions.

The first function is a cosine curve which estimates the average day length, varying from a maximum on June 22nd to a minimum on Dec 22. Assuming solar noon to be about 12:15 PDT, sunrise and sunset are calculated from the predicted length of day. Although this is a simplification of the actual motion of the sun, the resulting predictions are quite adequate for the purposes of the model (Figure A-2).

A second cosine function estimates the amount of light that would be available at a clear solar noon on a particular day based on the data given above. Its output varies from a minimum on Dec 22nd to a maximum on June 22.
Figure A-2 Sunrise and sunset times predicted by the model plotted along with sunrise and sunset times published in 1993 Dot's Fishing Guide. During most of the year, the lines for predicted and published are nearly indistinguishable.
The value for Dec 22nd was selected so that the curve would pass through the maximum measured on Jan 2nd. Both of the first two Excel functions took the form:

$$(\cos((\text{days})/\text{year}*2*\pi+\pi)/2+0.5)\times \text{range}+\text{low}$$

where days is the number of days after Dec 22nd, year is the number of days in the year, range is the difference between the value on June 22nd and low, the value on Dec 22nd.

The final function is the top half of a sine curve, representing the light intensity at a particular time on any given day. It varies from 0 to the maximum intensity and back to zero as the sun goes from sunrise to sunset. The maximum, sunrise, and sunset are as given by the first two functions. Its formula in Excel is:

$$\text{MAX}((\sin((\text{time}-\text{sunrise})/(\text{sunset}-\text{sunrise})\times \pi)\times \text{maxI}, 0)$$

The results of these functions were compared to measurements from two clear days, Jan 2nd and June 22nd. This initial model overestimated the amount of light available at the ends of the day. A one hour correction factor was introduced to both the time of sunrise and sunset. The result was a function which closely approximates actual measurements (Figure A-3).

The total radiation on each day was then compared to the total predicted by the model. Clouds and fog were able to block 90 percent of the incident radiation. The average daily radiation measured was about 64 percent of the predicted maximum value (Figure A-4).
Figure A-3. Maximum light intensities predicted by the model plotted with measured values on two clear days in 1993. The predicted light intensities are similar to the measured values, except for a lag in the morning caused by a shadow from the coastal mountains at the measuring location.
Figure A-4. Minimum (hollow diamond), maximum (hollow box), and mean daily irradiance (filled diamond) predicted by the model plotted with measured values (solid box) for three different periods of 1993. The discontinuities are due to the breaks between the three different periods that data were being collected.
Conclusions

The data collected show solar radiation to be extremely variable on the coast of Humboldt county. For the purposes of this model, I have chosen three light curves. The first represents the maximum amount of sun which would be available on a clear day. The second function represents the amount of light available on a day with an average amount of overcast. The final function gives the minimum amount of light expected under the most opaque meteorological conditions. While none of the curves accurately represents any given day, actual conditions should lie between the maximum and minimum curves and are best approximated by the average curve.
APPENDIX B - AN INCUBATION STUDY

Introduction

A field study was undertaken to help calibrate the productivity model with data from Humboldt Bay. Water samples were collected at three different locations in Humboldt Bay and incubated under different light intensities. Oxygen concentrations were measured before and after incubation, and in "dark" bottles to determine respiration rates and photosynthesis as function of solar radiation. These data were used to estimate photosynthetic saturation, respiration, and photoinhibition in the model.

Methods

Three water samples were collected between 1000 and 1040 on June 18, 1993 in large carboys. An effort was made to shield these containers from sunlight after they had been filled. At each station, we noted the time, location, surface water temperature, secchi disk depth, and light attenuation with a quantum meter. The "Samoa" station was located in the Samoa channel just north of the Samoa bridge. The "Channel" station in the North Bay Channel at day marker 2 opposite the LP smoke stack. The third location, the "Ocean" station, was near buoy 11 at the gas docks close to the entrance to the Bay.
The water samples were taken to the HSU Marine Laboratory in Trinidad, about 25 miles north of Humboldt Bay. Working in a darkened room, water was placed into 72 60-ml clear glass incubation bottles. Three bottles from each location were placed in each of 4 sections of an incubation rack. The chambers were covered respectively by zero, one, two, and three neutral-density screens, which allowed 100, 60, 36, and 21 percent of the incident radiation to reach the bottles. "Dark" bottles, covered with aluminum foil, were placed in the same rack to determine respiration and some "initial" bottles were fixed immediately as a reference to determine changes in oxygen content.

The apparatus was then placed in direct sunlight. Water from the marine lab salt-water system was allowed to run over the bottles, maintaining a constant temperature of 18° C throughout the incubation period. The bottles were incubated for three hours centered around solar noon. All bottles were then fixed and oxygen was measured using a modified version of the Winkler titration method (Ryther 1956?).

While the bottles incubated, 1-liter water samples were filtered through millepore membrane filters and glass fiber filters. The following week, pigments were extracted with acetone and chlorophyll measurements were made by measuring light absorption at selected wavelengths in a
spectrophotometer. Calculations were completed using formulas from Parsons, Maita, and Lalli (1984).

**Results**

The Samoa and Channel water samples represented water from the bay compartment while the Ocean sample contained primarily ocean water which entered the bay on the flooding tide. The Ocean water was noticeably colder than the other two sites, 11.2° C vs 14.4° and 16.7°. The ocean water was also clearer than the bay samples, (secchi depth of 2.4 meters versus 1.5 and 1.2) and contained a higher concentration of chlorophyll (7 mg chl a / m³ versus 5). These figures are consistent with other data reported for Humboldt Bay (Harding et al. 1978, Pequegnat and Butler 1982, Barnhart et al. 1992) and also with those reported for other lagoon-type estuaries (Boynton, et al, 1982).

The day of the study was extremely clear. Average light intensity during the incubation was 1850 μE/c²/sec. As a result, productivity of samples from all three locations demonstrated photoinhibition, with productivity greater in bottles under screens than in those exposed to direct sunlight (Figure B-1). This agrees with data reported by Harris (1980), who found inhibition usually occurs above 300 μE/m²/sec. At the lowest light intensity (369 μE/m²/sec) all three samples produced about 2.4 g O₂/g chl a/hr. Converting this to grams of C by multiplying by 1.25 (Ryther 1956) gives a value of 3 g C/ g chl a /hr, a
Figure B-1. Estimates of gross productivity measured at different light intensities for three water samples collection in Arcata Bay. The upper line represents ocean water sampled in the North Bay Channel at high tide, while the other two lines were samples collected in the bay compartment water.
figure which is close to the average values for photosynthetic saturation reported by Ryther and Yentsch (1957).

Respiration values were very similar in the three water samples, ranging from 0.8 to 1.1 g O₂ / g chl a/hour. These figures are consistent with those reported by Harris (1980).

Discussion

The intent of this study was to calibrate the P:I function in the productivity model. Since all samples showed a decrease in photosynthesis when exposed to increasing light intensity, it is clear that photoinhibition is taking place at all except perhaps the lowest irradiance used in the study. It is, therefore, not possible to deduce the shape of the curve at light intensities which are not strong enough for maximum photosynthesis from these data. Therefore alpha, the assimilation ratio, cannot be determined. For the purposes of this model, alpha will be estimated from the literature.

Although all three samples showed reduced productivity at full light intensity, results were mixed as light was reduced. The Ocean samples showed productivity rates that were almost equal at all lowered irradiances while productivity in the Channel samples increased almost linearly as light was reduced. Productivity in the Samoa samples increased as light was reduced, but not
consistently. Since all samples showed approximately the same productivity at minimum light, it is possible that this value represents Pmax, the photosynthetic saturation. However, it is also possible that inhibition was still taking place in all treatments and that the maximum photosynthetic rate is actually greater than anything measured in this study.

I have constructed a P:I curve based on the research of Marra (1985) and Jassby and Platt (1976). Their analysis found that a hyperbolic tangent function provided the best approximation of photosynthesis up to the levels of inhibiting light. To account for photoinhibition, I have added a correction term to the function from Vollenweider (1966). The result is a curve which reaches a maximum level of 2.4 g O2 / g chl a/ hour light intensities of about 100 μE/m²/sec (per Harris, 1980) and begins dropping at 300. By trial and error, I was able to find parameters which caused the function to pass through values close to those we measured at high intensities (Figure 15).

Temperature, turbidity, and chlorophyll data all support the assumption that the Ocean station sampled ocean water while the other two stations were more representative of bay water. However, productivity and respiration data from all three stations were quite similar. The fact that data from the Channel station all fall between that of the Ocean and Samoa stations in each of these categories
demonstrates that some mixing was taking place between the bay water compartment and the ocean.

At full light intensity, the gross productivity dropped so low that it was close to respiration values. Unless vertical mixing shields phytoplankton from prolonged exposure, very little net productivity takes place at the surface of the bay in the middle of a sunny, summer day.

The maximum value for gross photosynthesis measured in this experiment was quite low relative to values reported in the literature (Jassby and Platt 1976). It is possible that nutrient limitation prevented maximum photosynthetic rates. For the purposes of the model, the main value of this experiment was to reinforce the need to include inhibition as a component of the P:I function.
APPENDIX C - LIGHT ATTENUATION

Introduction

Turbidity and light extinction data were collected at three different locations in Humboldt Bay during the summer of 1993. This data was used to calibrate light attenuation in the model.

Methods

These data were collected at the same time water was collected for the incubation study, (time and place in Appendix B Methods). At each site, a secchi disk was lowered until it disappeared. This depth was measured. Measurements with a quantum meter were taken at the surface and at various depths, including the secchi depth.

Results and Discussion

Measurements of the light available at the depth the secchi disk disappeared averaged 21 percent of the surface radiation. This led to a value for the extinction coefficient (m$^{-1}$) equal to 1.7 / secchi-depth.

Turbidity and the concurrent light attenuation increased with distance from the mouth of the bay (Figure C-1). Secchi depths varied from 2.5 meters to 1.3 meters, with corresponding extinction coefficients of 0.68 to 1.24 m$^{-1}$.
Figure C-1. Plot of the percentage of surface light versus depth in Humboldt Bay on June 18, 1993. The upper curve represents a secchi depth of 2.5 meters ($k = 0.68$/meter) measured in ocean water intruding into the bay at high tide. The lower lines are bay compartment samples with secchi depths of 1.3 and 1.5 meters ($k = 1.01$/meter and 1.24/meter).
A comparison of light intensity measured just under the surface with simultaneous measurements in air revealed that between 1-12 percent of the incident radiation was reflected. These measurements agree with Sverdrup (1953), who reported that three to six percent of incident light was reflected when the sun is greater than 30 percent above the horizon. An average loss of six percent has been used for calculations in the model.
APPENDIX D - COMPUTER FILES

Most of the work on the project has been done on 80386 and 80486-class microcomputers using Excel 4.0 and Turbo Pascal 6.0. The model was originally built using spreadsheets. When it became obvious that calculation speed would be a problem, the functions were rewritten in Pascal. Output from the Pascal programs were reimported into Excel for final presentation.

The following files are located on a floppy disk, available at the Telonicher Marine Laboratory on request:

- AREAS.XLS - Excel spreadsheet with Humboldt Bay topography
- AREAS.TXT - output from AREAS.XLS used by MODEL.PAS
- DEFAULT.TID - data file for TIDES
- FIELD.XLW - Excel workbook with data from 6/93 field study
- HUMBLTBY.TID - Humboldt Bay parameters for TIDES
- LIGHT.XLW - Excel 4.0 workbook with light data and model
- LIGHT.TXT - output from LIGHT.XLW used by MODEL.PAS
- MODEL.XLW - Excel one-day version of model.
- MODEL.PAS - Turbo Pascal 6.0 source code for the model.
- MODEL.EXE - executable version of MODEL.PAS
- TIDE1993.DAT - output from TIDES used by MODEL.PAS
- TIDES.XLS - Excel 4.0 spreadsheet with output of TIDES
- TIDES.EXE - Tides 1.6 shareware program
- TIDES.DOC - documentation for the TIDES program
- YEAR.XLW - Excel 4.0 workbook with output from MODEL.PAS