Procedures for the measurement of primary production in Massachusetts Bay

Massachusetts Water Resources Authority

Environmental Quality Department
Report ENQUAD 99-07

Citation:

Taylor CD. 1999. Procedures for the measurement of primary production in Massachusetts Bay. Boston: Massachusetts Water Resources Authority. Report ENQUAD 99-07. 24 p.

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submitted to

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30 December 1998

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I. Approach to the Measurement of Primary Production in Massachusetts Bay.

The approach taken for computing primary production for the Massachusetts Water Resources Authority (MWRA) Harbor and Outfall Monitoring (HOM) Program in Massachusetts Bay combines measured depth dependent phytoplankton photosynthetic response properties with measurements of water column light attenuation and incident light time series data to provide estimates of this parameter vs. depth and over time. An advantage of using measured incident light time series is that effects of cloud-mediated fluctuations in light intensity over the course of the day and gradual seasonal changes in light are automatically incorporated into production calculations. Additionally, it is possible to experimentally manipulate the incident light field for the purpose of assessing phytoplankton response to an alternative light field. Cloudless day light fields may be implemented, for example, to assess potential or maximal production when actual production measurements were made on an overcast day.

Two types of primary production measurements were made. The first, more conventional approach has been to measure water column and phytoplankton photosynthetic properties aboard ship at select stations in Massachusetts Bay 6 or 17 times throughout the annual cycle. This information was incorporated with incident light time series measurements made on the roof of the MWRA lab building at the sewage treatment facility on Deer Island for calculation of primary production on each of the survey dates. These data, computed at 2 week to 2 month intervals, provided a measure of primary production over the course of the annual cycle and a means for estimating annual production. Because incident light is variable on a day to day basis there exists the potential for temporal aliasing if production is calculated using parameters measured solely on the days of the surveys. To begin addressing the effects of variable light field on production estimates, a second approach to the computation was implemented. For this approach light attenuation and photosynthetic properties were interpolated from cruise data to provide daily estimates of these parameters which in turn were used with continuous high resolution incident light time series to provide daily estimates of production. The details of how these computations are effected is the topic of this report.

II. Sampling Procedures and Laboratory Manipulations.

Light vs. depth profiles.
To obtain a numerical representation of the light field throughout the water column bin averaged CTD light profiles (0.5 m intervals) was fit (SAAM II, 1994) to an empirical sum of exponentials equation of the form:

$$I_Z = A_1 e^{-a_1 Z} + A_2 e^{-a_2 Z} \qquad \text{Equation 1}$$

which is an expansion of the standard irradiance vs. depth equation:

$$I_Z = I_0 e^{-kZ} \qquad \text{Equation 2}$$

where:

I_Z = light irradiance at depth Z.
I_0 = incident irradiance (Z=0).
k = extinction coefficient.
A_1, A_2 = factors relating to incident irradiance ($I_0 = A_1+A_2$).
a_1, a_2 = coefficients relating to the extinction coefficient.

Equation 1 was used in almost all instances as pigment absorption and light scattering was usually greater in the upper portion of the euphotic zone than at lower depths, which resulted in significant deviations from the standard exponential irradiance vs. depth (Equation 2). There was a gap in data between the shallowest light reading on the CTD and the sea surface. I_o must, therefore, be determined by extrapolation of the fitted data to Z=0 and that value used for percent attenuation determinations. The best fit profiles were used to compute percent light attenuation for each of the sampling depths (curvature in ln[% 4π light] vs. depth similar in appearance to that illustrated in **Figure 1**, panel 1). On occasion presence of a deep chlorophyll maximum resulted in greater attenuation at depth relative to surface waters. In these cases it was necessary to conduct a separate fit of Equation 1 on the data above and below the chlorophyll maximum. Light attenuation at the depth of sample procurement was calculated using the best fit equations.

Measurement of Incident Light Field.

High temporal resolution time series light measurements were made using a 2π scalar light sensor (Biospherical QSR-240) that was installed on the roof of the MWRA building at Deer Island. Data were collected every minute and the average incident light recorded at 15 min intervals. The 15 min interval incident light measurements collected over the photoperiod 0600 - 1800 hrs were used for primary production computations.

^{14}C Primary Production Field Procedures.

From each of the 5 productivity depths at each productivity station, samples were obtained by filtration through 300 μm Nitex screen (to remove zooplankton) from the Niskin bottles into opaque 1 gal polyethylene bottles. Under subdued green light, sub-samples were transferred by siphon into individual 75 ml acid cleaned polycarbonate bottles. Each bottle was flushed with approximately 250 ml of sample. A total of 16 bottles (14 light bottles, 2 dark bottles) were filled for each depth and incubated in a light and temperature controlled incubator. Light bottles from each depth are incubated at 14 light intensities (250 W tungsten-halogen lamps attenuated with Rosco neutral density filters) and incubated within ~2° C of the *in situ* temperature at each depth for 4-6 hr (actual time was recorded). Single bottles of sample collected from each depth was assayed for background (time-zero) activity.

The 75 ml samples were incubated with 5-10 μCi ^{14}C-bicarbonate and biological activity terminated by filtration of the entire contents of the bottles through 2.5 cm diameter Whatman GF/F glass fiber filters and immediate contact of the filters with 0.2 ml of a 20% aqueous solution of acetic acid contained in pre-prepared 20 ml glass scintillation vials (vials immediately recapped). For specific activity determination 0.1 ml aliquots of sample were placed in pre-prepared 20 ml scintillation vials containing 0.2 ml of benzethonium hydroxide (approximately 1.0 M solution in methanol; Sigma Chemical Company) to covalently sequester

the ^{14}C inorganic carbon (vials immediately recapped). Specific activity was determined from the measured activity and measurements of dissolved inorganic carbon (DIC).

Samples for DIC analysis were collected from the Niskin bottles into 300 ml BOD bottles, following collection procedures used for oxygen analyses. Within 6 hr. of BOD sample collection, duplicate 10 ml samples were injected into 20 ml crimp-sealed serum bottles containing 0.5 ml of a 2N aqueous solution of sulfuric acid for subsequent I.R. analysis (Beckman IR-315 infrared analyzer) of the gaseous phase (5 - 150 µl samples) at the W.H.O.I. laboratory.

^{14}C Primary Production Laboratory Procedures.

Sample processing. Upon arrival to the laboratory scintillation cocktail (10 ml Scintiverse II) were added to the scintillation vials containing the specific activity samples and analyzed liquid scintillation spectroscopy. Vials containing acidified filters were opened and placed in a ventilator in the hood for overnight to allow the filters to dry and excess ^{14}C carbon dioxide dissipate. The vials containing the filters were analyzed in 10 ml Scintiverse II by scintillation spectroscopy as described above.

Calculation of production from ^{14}C radioactivity measurements. Volume specific primary production was calculated from scintillation spectroscopy radioactivity measurements via spreadsheet (Appendix II) using equations similar to that of Strickland and Parsons (1972) as follows:

$$P(i) = \frac{1.05(DPM(i) - DPM(blk))}{V_s A_{sp} T} \qquad \text{Equation 3}$$

$$P(d) = \frac{1.05(DPM(d) - DPM(blk))}{V_s A_{sp} T} \qquad \text{Equation 4}$$

$$A_{sp} = \frac{DPM(sa) - DPM(back)}{V_{sa} DIC} \qquad \text{Equation 5}$$

where:

P(*i*) = primary production rate at light intensity *i*, (µgC $l^{-1}h^{-1}$ = mgC $m^{-3}h^{-1}$).
P(d) = dark production, (µgC $l^{-1}h^{-1}$ = mgC $m^{-3}h^{-1}$).
A_{sp} = specific activity (DPM/µgC).
DPM(*i*) = dpm in sample incubated at light intensity *i*.
DPM(blk) = dpm in zero time blank (sample filtered immediately after addition of tracer).
DPM(d) = dpm in dark incubated sample.
DPM(back) = background dpm in vial containing only scintillation cocktail.
V_s = volume of incubated sample (l).
T = incubation time (h).

V_{sa} = volume counted of specific activity sample (ml).
DIC = concentration of dissolved inorganic carbon (µg/ml).

III. Primary Production Calculations.

Survey Date Water Column Primary Production Calculations.
The procedure for calculation of water column primary production is diagrammatically illustrated in **Figure 1**. Three key pieces of information are required initially (row A): a) A profile of the attenuation of the 4π light field vs. depth, expressed in percent (panel 1). b) A time series measurement (15 min intervals over the photoperiod 06:00 to 18:00, standard time) of the scalar 2π (not cosine) incident light field expressed in $\mu Em^{-2}s^{-1}$. Incident light field time series on survey days (panel 2) were implemented for survey date production calculations and cloudless day light field time series (panel 3) were used to calculate "potential" or maximum production that could occur at that time of year. c) Determinations of hourly volumetric ^{14}C production (P(I) = P(*i*)-P(d) [Equations 3 and 4], $mgCm^{-3}h^{-1}$) on samples that were collected at 5 depths within the euphotic zone (Surface, Midsurface, Middle, Midbottom, Bottom) and incubated at a variety of light intensities (I, $\mu E\ m^{-2}s^{-1}$) in a shipboard photosynthetron (panel 4) to quantify their Photosynthesis vs. Irradiance (P-I) properties.

Shown in row B, *in situ* light intensity (panels 5 or 6) was determined at 15 min intervals throughout the photoperiod for each sampling depth from the percent light attenuation profiles (panel 1) and incident light time series measurements (panels 2 or 3). In Massachusetts Bay photoinhibition was not experienced at up to the maximum *in situ* light intensity, so the model by Webb et. al. (1974, Equation 6) was adequate to describe the P-I relationship. A non-linear fit (SAAM II, 1994) of the data from the ^{14}C P-I incubations (panel 4) to this equation was used to determine the photosynthesis parameters α^* and P_m^*:

$$P(I) = P_m^*\left(1 - e^{-\frac{\alpha^*}{P_m^*}\cdot I}\right) \qquad \text{Equation 6}$$

where:

$P(I)$ = production at incubation light intensity I.
P_m^* = light saturated production.
α* = initial slope of light dependent production.

The photosynthetic parameters P_{mz}^* and α_z^* determined for each sampling depth (Z) and *in situ* light field (I_{is}) were then used in Equation 7 (row C):

$$P(I_{is})_Z = P_{mz}^*\left(1 - e^{-\frac{\alpha_Z^*}{P_{mz}^*}\cdot I_{is}}\right) \qquad \text{Equation 7}$$

to calculate volumetric production at each sampling depth $P(I_{is})_Z$ for each 15 min time interval of the incident light time series (row C, panels 7 or 8). Production at the sea surface (Interface) was

calculated from incident light (panels 2 or 3) and the parameters P^*_{mz} and α^*_z derived from P-I incubations of samples from the uppermost sampling depth (Surface).

The *in situ* production time series (panels 7 or 8) were then numerically integrated (row D, panels 9 or 10) to obtain daily volumetric production ($mgCm^{-3}d^{-1}$) for each sampling depth (row E, panels 11 or 12, closed circles) as well as the sea surface (open circles). Daily areal production ($mgCm^{-2}d^{-1}$) was calculated by trapezoidal integration of depth dependent *in situ* production (row E, panels 11 or 12). Areal production was expressed over the course of the year (row F) and annual production (upper left of panel) estimated by trapezoidal integration.

Calculation of chlorophyll-specific parameters.
Chlorophyll-specific measures of the various parameters were determined by dividing by the average chlorophyll a concentration centered at the production sampling depths:

$$\alpha = \frac{\alpha^*}{[chla]} \qquad \text{Equation 8}$$

$$P_m = \frac{P^*_m}{[chla]} \qquad \text{Equation 9}$$

where:

α = chlorophyll-a-specific initial slope of light-dependent production $[(gC(gchla)^{-1}h^{-1}(\mu Em^{-2}s^{-1})^{-1}]$.

P_m = light saturated chlorophyll-specific production $[gC(gchla)^{-1}h^{-1}]$.

[chla] = chla concentration determined by averaging the intervals between sampling depths, centered upon each sampling depth.

High temporal resolution primary production measurements.

A potential source of uncertainty in the computation of annual production base upon a limited number of cruises (6 to 17 per year) is the effect of light field variability which can dramatically fluctuate from day to day. One can estimate an upper limit on annual production by the computation of "potential" production based solely upon cloudless day incident light fields throughout the year as discussed above. True annual production will for the most part lie somewhere below this upper limit because of cloud cover and fog. Potential for aliasing caused by sampling large amplitude, high frequency phenomena (Taylor and Howes, 1994) at low temporal resolution does not guarantee that production computed from light fields during cruise days are representative of production between cruises. The below described technique attempts to resolve this problem in part by incorporating at high temporal resolution the parameter of greatest variability into the calculation of primary production.

Parameters necessary for computation of high temporal resolution primary production is illustrated in **Figure 2** from station N04 in 1996. Panel A is the incident light field obtained from Deer Island and the parameters shown in panels B-E were gridded from 1996

photosynthesis station cruise data (17 times per year, closed circles). Depth-dependent light attenuation, expressed in percent (panel B), when coupled with the incident light time series (panel A) provided a quantitative measure of the *in situ* light field. High resolution photosynthesis rates were determined from the temporal and depth-dependent a) *in situ* light field, b) chl*a* concentration (panel C), and c) distributions of α and P_m (panels D and E) using a program written in Microsoft Quick BASIC 4.5 (see Appendix II).

Parameters computed were:

1. Daily production (mgC $m^{-3}d^{-1}$) vs. depth (1 m intervals) over the season (resolved to the day).
2. Areal production down to 30 or 40 m (mgC$m^{-2}hr^{-1}$) vs. hour of day (resolved to 15 min intervals) over the season (resolved to the day).
3. Daily areal production (mgC$m^{-2}d^{-1}$) over the season (resolved to the day). The program also computed areal production in upper 5 m and upper 10 m of the water column relative to areal P_m* ($P_m^* = P_m \cdot$ [chl*a*]) over the same depth intervals vs. hour of day (resolved to 15 min intervals). This computation yielded areal production expressed as percent saturation (e.g., [Areal $P_{0.5}$ */Areal P_m*] $\times$ 100) vs. hour of day over the above indicated depth intervals.

The following data (depth resolved to 1 m intervals, season resolved to the day) were required for the above computations:

1. Deer Island incident light measurements at 15 min intervals from 0600 to 1800 hrs., standard time. Nighttime values were stripped from the file using a Microsoft Quick BASIC 4.5 program (Appendix II).
2. Percent subsurface light ($I_z/I_{z=0} \cdot 100$) vs. depth over the season, where I_z is the 4π light field at depth z recorded by the CTD, $I_{z=0}$ is the 4π light field just under the sea surface at depth zero.
3. Chlorophyll *a* concentration, [chl*a*], vs. depth over the season.
4. Chlorophyll-specific α vs. depth over the season.
5. Chlorophyll-specific P_m vs. depth over the season.
6. P_m^* and α^* computed as the products $\alpha \cdot$ [chl*a*] and $P_{max} \cdot$ [chl*a*] at each depth over the season.

ASCII grid files for items 2-5 were obtained by gridding respective cruise and computational data using Surfer for Windows (version 6, Golden Software Inc.). The Kriging gridding method was employed in all cases. An anisotropy of 0.1 was employed for gridding of the percent subsurface light data to minimize "tent pole" distortion of the data interpolated between cruises.

Photosynthesis was computed using nested loop routines by the BASIC program in a manner analogous to that described above. Briefly, the procedure was as follows:

For a given depth interval volumetric production was computed at each 15 min incident light interval using the algorithm:

$$P(I_{tZ}) = P^*_{mz}\left(1 - e^{-\frac{\alpha^*_Z}{P^*_{mz}} \cdot I_{tz}}\right)$$ Equation 10

Where:
$P(I_{tZ})$ = hourly volumetric production at the *in situ* light intensity at time t and depth Z.
$P^*_{mz} = P^*_m$ at depth Z.
$\alpha^*_z = \alpha^*$ at depth Z.
I_{tZ} = *in situ* light intensity at time t and depth Z (computed as the product of incident light at time t (I_t) and fractional light attenuation at depth Z.

Daily production at depth Z was computed by summation of $P(I_{tZ})/4$ as the program looped through each 15 min incident light intensity. The routine was repeated for each depth and each day of the season to permit graphical presentation as daily production vs. depth and time of year. Areal production was computed by summation of daily production values determined over the depth of the euphotic zone.

A similar nested loop routine was used to compute hourly areal production throughout the euphotic zone and % saturation (0-5 m; 0-10 m) vs. time of day and over the season.

Comparison of high resolution production with production determined on survey date.

Daily areal production using the high resolution light field for station N04 in 1996 is shown in **Figure 3** and compared with the same parameter determined on the days of the cruises using cruise day light fields and sunny day light fields for estimating cruise day and potential production, respectively. Potential for temporal aliasing of areal production is evident in this figure, as essentially every cruise throughout the fall bloom period (last 6 cruises) occurred by chance on a substantially cloudy day. The envelope over which fluctuating light influences the day to day magnitude of areal production spans a range of 2-5 fold. Hence, in 1996 the magnitude of fall production (period covered by high resolution estimates) in the outer nearfield was underestimated by 60% when day of cruise integral production was compared with production estimated by integration of the high resolution data (N04, 118 vs. 202 gCm^{-2} for day of cruise vs. high resolution production, respectively). Only when potential production estimates were included in the analysis would the investigator be alerted to the true magnitude of the fall bloom. In 1996 potential production suggested that the fall bloom had occurred in the mid-September to December time frame and provided an upper estimate on production (N04, 265 gCm^{-2}). It should be kept in mind that the potential for aliasing may not been completely removed in the high resolution data set. Tidal fluctuations in water column chlorophyll content can be up to two- or three-fold at certain times of the year and on a time scale comparable to fluctuations in the light field. This concern may be tempered to a degree, however, as chlorophyll field at the photosynthesis stations used for the high resolution computations are quite similar in pattern and magnitude to average nearfield water column chlorophyll distributions computed for the nearfield, which because of the time required for collection of the data will also tend to average possible high frequency tidally mediated fluctuations. Data from

program may also be presented in terms of depth dependent and areal production, and as percent saturation (Figure 4).

IV. Figures

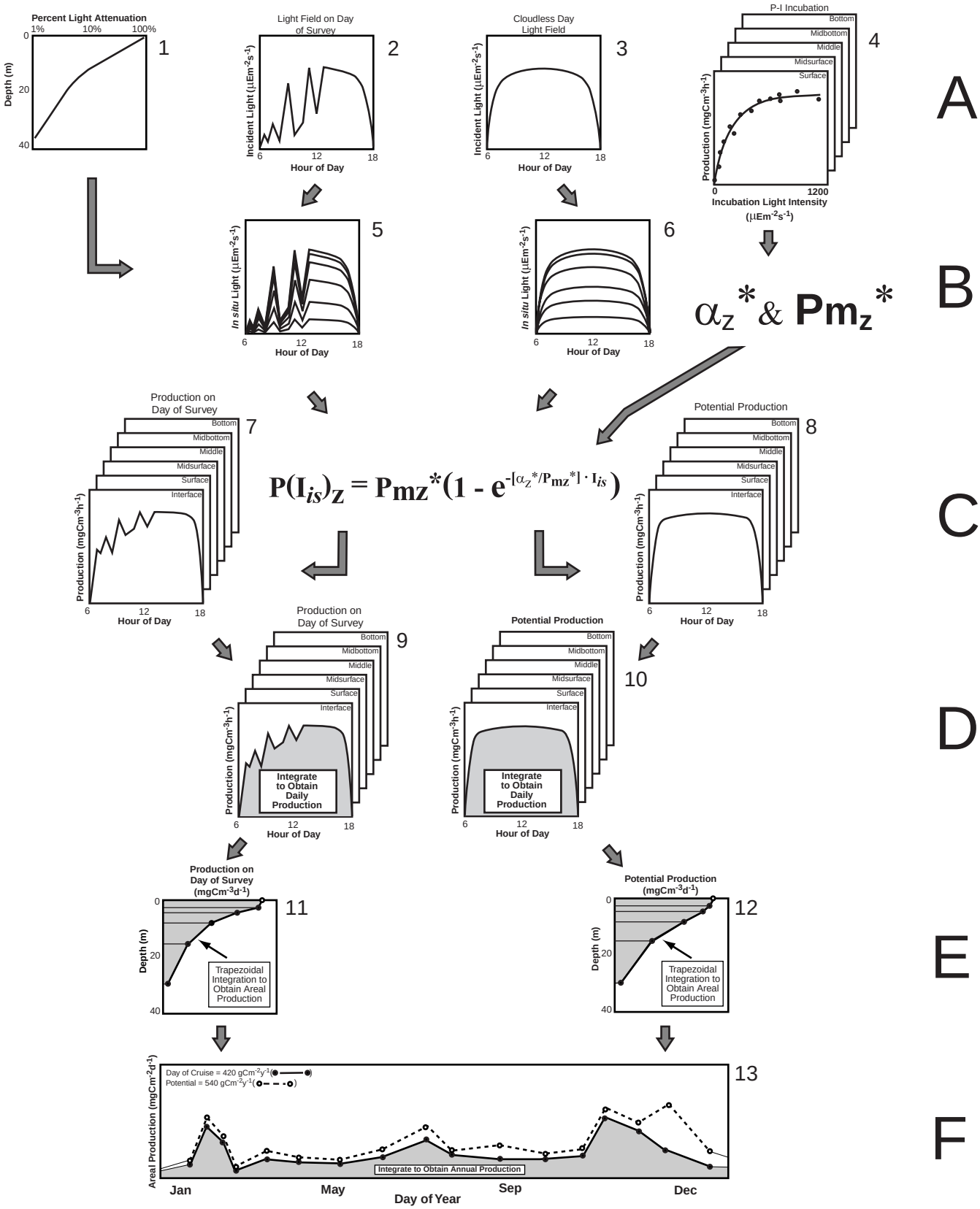

Figure 1. Sequence of primary production calculation.

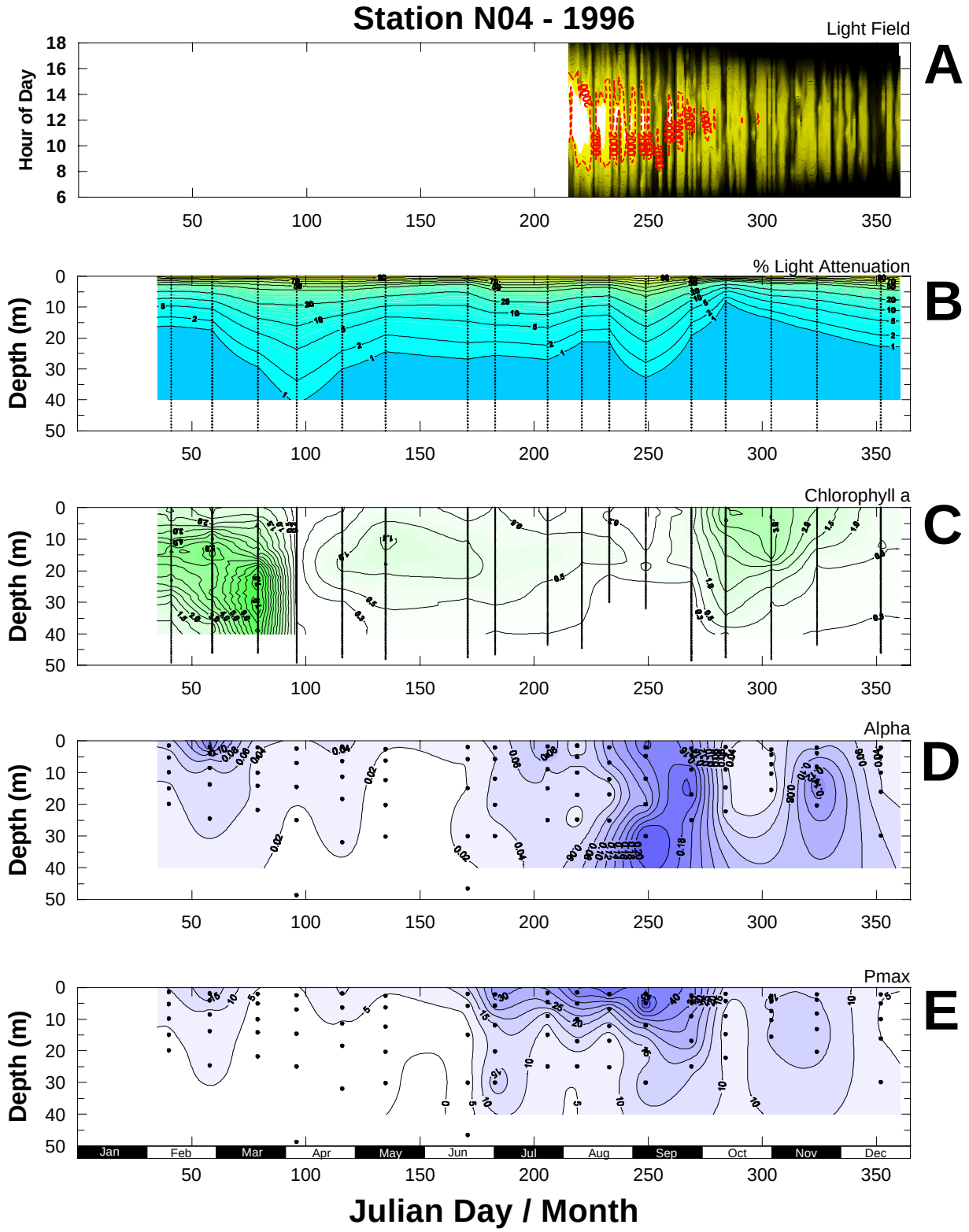

Figure 2. Parameters used for computation of high temporal resolution primary production. Panel A, Deer Island incident light measurements at 15 min intervals from 0600 to 1800 hrs, standard time. Panel B, percent subsurface light (Iz/Iz=0 / 100) vs. depth over the season, where Iz is the 4pi light field at depth z recorded by the CTD, Iz=0 is the 4pi light field just under the sea surface at depth zero. Panel C, Chlorophyll a concentration, [chla], vs. depth over the season. Panel D, chlorophyll-specific alpha vs. depth over the season. Panel D, chlorophyll-specific Pmax vs. depth over the season.

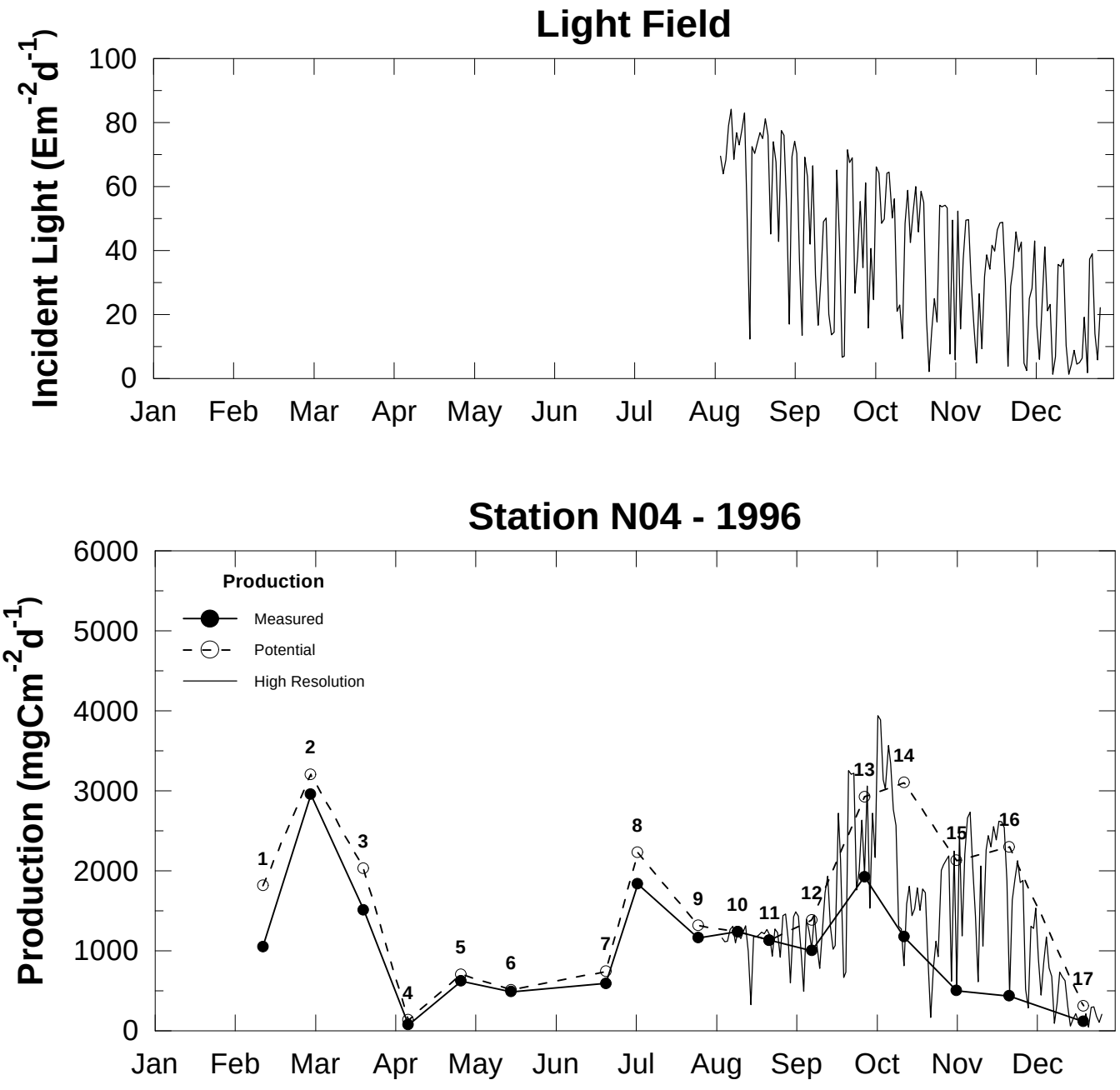

Figure 3. High temporal resolution areal production at Stations N04 and N10 during the fall of 1996. Upper panel, integrated incident light obtained by summation (BASIC program) of the 15 min sensor readings (mEm-2s-1) multiplied by 900 sec (sample)-1 and by 10-6 E mE-1 to yield total incident light exposure over the 24 hr diel cycle (Em-2d-1). Panel 2, areal production for Station N04. Closed circles-solid line, areal production (mgCm-2d-1) determined on the survey day indicated by the number using the incident light field that occurred on that day. Open circles-dashed line, potential areal production determined on the survey day using a cloudless day incident light field that would occur at the time of year of the survey. Thin solid line, high resolution areal production computed using the Deer Island incident light time series and gridded photosynthesis parameters as described in text.

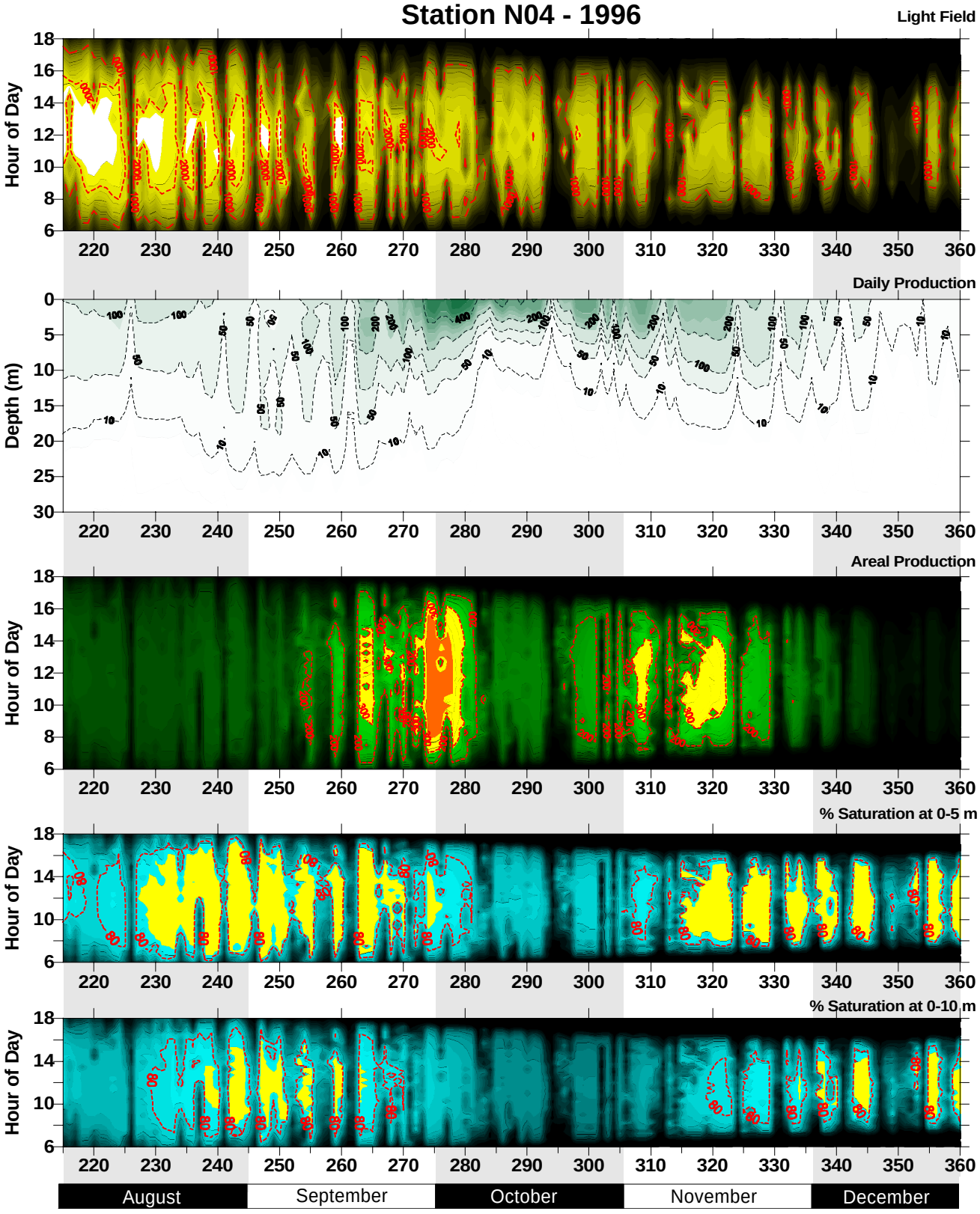

Figure 4. High temporal resolution production at station NO4 as determined by BASIC program. Panel 1, fall light field expressed in uEm-2s-1. Panel 2, daily production (mgC m-3d-1) vs. depth (1 m intervals) over the season (resolved to the day). Panel 3, areal production down to 40 m (mgCm-2hr-1; note production goes to zero before 40m) vs. hour of day (resolved to 15 min intervals) over the season (resolved to the day). Panels 4 and 5, areal photosynthesis percent saturation from 0-5 m and 0-10 m depth vs. hour of day (resolved to 15 min intervals) over the season (resolved to the day), respectively.

V. References

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1994. Taylor, C.D. and B.H. Howes. Effect of sampling frequency on measurements of primary production and oxygen status in nearshore coastal ecosystems. Mar. Ecol. Progr. Ser. 108, 193-203.

Webb, W.L., M. Newton and D. Starr. 1974. Carbon dioxide exchange of Alnus ubra: A mathematical model. Oecologia. 17, 281-291.

VII. Appendix I - MS Quick Basic 4.5 Programs

A. Program for calculating high resolution production.

```
REM MWRA.BAS
REM 3/3/98; 14:00

REM PROGRAM TO COMPUTE DAILY VOLUMETRIC & AREAL PHOTOSYNTHESIS & % SAT'N GIVEN
'   CHLA, ALPHA, PMAX, LIGHT ATTNUATION, DAILY LIGHT TIME SERIES.

REM Variable Definitions:
'MAXYD = Maximum stretch of days of season computation is conducted (max 365).
'YD = Day in year (incremented in 1 day intervals).
'MAXHRDAY = Maximum number of SPAR readings taken over day (48).
'HRDAY = Decimal hour of day (6.00 - 18.00, incremented at 0.25 hr intervals).
'MAXDEPTH = Maximum depth of computation (max. 50 m).
'DEPTH = Incremental depth (at 1 m intervals).
'DEPTH2 = Incremental depth used for locating YD for "XXXXXTOT.DAT."
'CHLA(DEPTH) = Chlorophyll a concentration (ug/l).
'CALPHA(DEPTH) = Chlorophyll-specific alpha.
'ALPHA(DEPTH) = alpha (calpha*chla(YD,depth)).
'CPMAX(DEPTH) = Chlorophyll-specific pmax.
'PMAX(DEPTH) = pmax (cpmax*chla(YD,depth)0.
'SPAR(HRDAY) = Surface 4-pi scalar light intensity.
'PLITE(DEPTH) = Fractional subsurface light at specified YD and depth (.005-1).
'ISLITE(HRDAY) = In situ light intensity [SPAR(HRDAY)*PLITE(DEPTH)].
'INTLITE = Integrated SPAR over photoperiod.
'VOLPROD = Volumetric production at depth and time of day.
'DAYPROD = Daily volumetric production at YD and DEPTH.
'AREALPROD = Areal production for the day.
'AREALPMAX = Depth integrated maximum production using gridded values of Pmax
'TOTPROD = Areal production for the day computed in photic zone prod & %sat'n routine.
'UPPERDEPTH = Depth to terminate %saturation computations

REM ********* FORMAT FOR INPUT AND OUTPUT DATA FILES **********
'INPUT FILES:
'XXXXXINP.DAT = YD, DEPTH, CHLA, CALPHA, CPMAX, PLITE
'96TIMLIT.DAT = YD, HRDAY, SPAR

'OUTPUT FILES:
'XXXXXVOL.DAT = YD, DEPTH, DAYPROD
'XXXXXARE.DAT = YD, AREALPROD
'XXXXXDAY.DAT = YD, HRDAY, PHOTIC ZONE AREAL PROD'N, PHOTIC ZONE %SAT'N
'XXXXXSAT.DAT = YD, HRDAY, AREAL PROD'N TO DEFINED DEPTH, %SAT'N TO DEFINED DEPTH
'XXXXXLIT.DAT = YD, INTLITE
'XXXXXTOT.DAT = YD, AREALPROD (Computed during calc of XXXXXDAY.DAT and should
'             equal values in XXXXXARE.DAT.

REM ********* DEFINE VARIABLES *************

SCREEN 9: CLS
INPUT "Enter beginning Julian day of year - "; YEAR1
INPUT "Enter ending Julian day of year - "; YEAR2
INPUT "Enter maximum depth (m) - "; MD
```

```
INPUT "Enter maximum depth for computing %Saturation - "; UD

MAXDEPTH = MD + 1: MAXHRDAY = 49: MAXYD = (YEAR2 - YEAR1) + 1: UPPERDEPTH = UD
PATH$ = "C:\QB45\DATA\": INEXT$ = "INP.DAT": TIMLIT$ = "96SPAR.DAT": IN$ = "ITEST"
OEXT1$ = "VOL.DAT": OEXT2$ = "ARE.DAT": OEXT3$ = "DAY.DAT": OEXT4$ = "SAT.DAT"
OEXT5$ = "LIT.DAT": PHOTORECORD = MAXDEPTH * MAXYD: LITERECORD = MAXHRDAY *
MAXYD
OEXT6$ = "TOT.DAT"
DIMPHOTORECORD = MAXDEPTH * MAXYD + MAXDEPTH: DIMLITERECORD = MAXHRDAY *
MAXYD + MAXHRDAY

REM ********* DIM Statements ***********

DIM CHLA(DIMPHOTORECORD), CALPHA(DIMPHOTORECORD), ALPHA(DIMPHOTORECORD),
CPMAX(DIMPHOTORECORD)
DIM PMAX(DIMPHOTORECORD), PLITE(DIMPHOTORECORD), SPAR(DIMLITERECORD),
ISLITE(DIMLITERECORD)
DIM YD(DIMPHOTORECORD), DEPTH(DIMPHOTORECORD), YDD(DIMLITERECORD),
HRDAY(DIMLITERECORD)

REM ********* INPUT FILENAMES ************

REM GOTO START  'Insert REM to inactivate the skip filename input section
LINE INPUT "ENTER FILENAME FOR DATA INPUT 'XXXXX'  "; IN$
INFILE$ = PATH$ + IN$ + INEXT$: OUTPVOL$ = PATH$ + IN$ + OEXT1$: OUTPDAY$ = PATH$ + IN$ +
OEXT3$
INLITE$ = PATH$ + TIMLIT$: OUTPAREAL$ = PATH$ + IN$ + OEXT2$: CLS
OUTPSAT$ = PATH$ + IN$ + OEXT4$: OUTPLIT$ = PATH$ + IN$ + OEXT5$
OUTPTOT$ = PATH$ + IN$ + OEXT6$
REM ****READ PHOTOPARAMETERS AND LIGHT TIME SERIES DATA FROM DAT FILES****

START:

'Input photosynthesis parameters from file

OPEN INFILE$ FOR INPUT AS #1
FOR N = 1 TO PHOTORECORD
  INPUT #1, YD(N), DEPTH(N), CHLA(N), CALPHA(N), CPMAX(N), PLITE(N)
  ALPHA(N) = CALPHA(N) * CHLA(N): PMAX(N) = CPMAX(N) * CHLA(N)
NEXT N
CLOSE #1


'Input light

OPEN INLITE$ FOR INPUT AS #2
FOR N = 1 TO LITERECORD
  INPUT #2, YDD(N), HRDAY(N), SPAR(N)
NEXT N
CLOSE #2

OPEN OUTPVOL$ FOR OUTPUT AS #3
OPEN OUTPAREAL$ FOR OUTPUT AS #4
OPEN OUTPDAY$ FOR OUTPUT AS #5
OPEN OUTPSAT$ FOR OUTPUT AS #6
```

```
OPEN OUTPLIT$ FOR OUTPUT AS #7
OPEN OUTPTOT$ FOR OUTPUT AS #8
REM ********************BEGIN COMPUTATIONS************************

PRINT "COMPUTE DAILY VOLUMETRIC & AREAL PRODUCTION"
'Compute daily volumetric and areal production
LLIT = 1: DDEP = 1
FOR DAY = 1 TO MAXYD
  FOR DEPTH = DDEP TO DDEP + MAXDEPTH - 1
    FOR LIT = LLIT TO LLIT + MAXHRDAY - 1
      'Compute in situ light
      ISLITE = SPAR(LIT) * (PLITE(DEPTH) / 100)
      'Compute volumetric production at depth at time of day
      VOLPROD = PMAX(DEPTH) * (1 - EXP(-ALPHA(DEPTH) * ISLITE / PMAX(DEPTH)))
      DAYPROD = DAYPROD + VOLPROD / 4
    NEXT LIT
    'Save daily volumetric production at depth DEP
    WRITE #3, YD(DEPTH), DEPTH(DEPTH), DAYPROD, PLITE(DEPTH)
    'Compute areal production for the day
    AREALPROD = AREALPROD + DAYPROD: DAYPROD = 0
  NEXT DEPTH
    'Save daily areal production at given YD
    WRITE #4, YD(DEPTH - 1), AREALPROD: AREALPROD = 0
    LLIT = LLIT + MAXHRDAY
    DDEP = DDEP + MAXDEPTH
NEXT DAY
CLOSE #3, #4


'Compute photic zone areal production at 15 min intervals during day
'and compute daily areal production to compare with areal computation above.
PRINT "COMPUTE PHOTIC ZONE PRODUCTION & %SAT'N OVER COURSE OF DAY"
LLIT = 1: DDEP = 1: DEPTH2 = 1: AREALPMAX = .001: AREALPROD = 0: TOTPROD = 0
FOR DAY = 1 TO MAXYD
  FOR LIT = LLIT TO LLIT + MAXHRDAY - 1
    FOR DEPTH = DDEP TO DDEP + MAXDEPTH - 1
      ISLITE = SPAR(LIT) * (PLITE(DEPTH) / 100)
      IF ISLITE < SPAR(LIT) * .005 THEN GOTO SKIP1
      VOLPROD = PMAX(DEPTH) * (1 - EXP(-ALPHA(DEPTH) * ISLITE / PMAX(DEPTH)))
      AREALPROD = AREALPROD + VOLPROD: AREALPMAX = AREALPMAX + PMAX(DEPTH)
SKIP1:
    NEXT DEPTH
WRITE #5, YDD(LIT), HRDAY(LIT), AREALPROD, (AREALPROD / AREALPMAX) * 100
  TOTPROD = TOTPROD + AREALPROD / 4
  AREALPROD = 0: AREALPMAX = .001
  NEXT LIT
  LLIT = LLIT + MAXHRDAY: DDEP = DDEP + MAXDEPTH
  WRITE #8, YD(DEPTH2), TOTPROD: TOTPROD = 0: DEPTH2 = DEPTH2 + MAXDEPTH
NEXT DAY
CLOSE #5, #8


'Compute production and light saturation for specified upper depth interval
PRINT "COMPUTE PRODUCTION & LIGHT SATURATION TO CHOSEN DEPTH OVER COURSE OF DAY"
LLIT = 1: DDEP = 1: AREALPMAX = .001: AREALPROD = 0: COUNTDEPTH = 0
```

```
FOR DAY = 1 TO MAXYD
  FOR LIT = LLIT TO LLIT + MAXHRDAY - 1
    FOR DEPTH = DDEP TO DDEP + MAXDEPTH - 1
      IF COUNTDEPTH > UPPERDEPTH THEN GOTO SKIP2
      ISLITE = SPAR(LIT) * (PLITE(DEPTH) / 100)
      IF ISLITE < SPAR(LIT) * .005 THEN GOTO SKIP2
      VOLPROD = PMAX(DEPTH) * (1 - EXP(-ALPHA(DEPTH) * ISLITE / PMAX(DEPTH)))
      AREALPROD = AREALPROD + VOLPROD: AREALPMAX = AREALPMAX + PMAX(DEPTH)
SKIP2:
    COUNTDEPTH = COUNTDEPTH + 1
    NEXT DEPTH
    WRITE #6, YDD(LIT), HRDAY(LIT), AREALPROD, (AREALPROD / AREALPMAX) * 100
  AREALPROD = 0: AREALPMAX = .001: COUNTDEPTH = 0
  NEXT LIT
  LLIT = LLIT + MAXHRDAY: DDEP = DDEP + MAXDEPTH
NEXT DAY
CLOSE #6

PRINT "COMPUTE DAILY INTEGRATED LIGHT"

FOR DAY = 1 TO MAXYD
  FOR LIT = LLIT TO LLIT + MAXHRDAY - 1
    INTLITE = INTLITE + (SPAR(LIT) * 900) / 1000000
  NEXT LIT
  WRITE #7, YDD(LIT - 1), INTLITE: INTLITE = 0
NEXT DAY
CLOSE #7

END
```

B. Program to remove night time and negative numbers from incident light time series data sets from Deer Island light sensor.

```
REM PROGRAM TO REMOVE NIGHTTIME LIGHT DATA FROM LIGHT TIME SERIES
CLS : SCREEN 9
'SSS = SUBDIRECTORY; F23, N10, N16, or N04
'XXXXXXXX = FILENAME

PATHOUT$ = "D:\SURFER\BOSHARB\CALC\1996\": EXTOUT$ = ".CSV"
PATHIN$ = "D:\SURFER\BOSHARB\LIGHT\1996\": EXTIN$ = ".DAT"
PRINT "INPUT PATH = "; PATHIN$
LINE INPUT "ENTER INPUT FILENAME 'SSSXXXXX' ", FILEIN$
PRINT : PRINT "OUTPUT PATH = "; PATHOUT$
LINE INPUT "ENTER OUTPUT FILENAME '\SSS\XXXXXXXX' ", FILEOUT$
PATHFILEIN$ = PATHIN$ + FILEIN$ + EXTIN$: PATHFILEOUT$ = PATHOUT$ + FILEOUT$ + EXTOUT$

OPEN PATHFILEIN$ FOR INPUT AS #1
OPEN PATHFILEOUT$ FOR APPEND AS #2

DO UNTIL EOF(1)
  INPUT #1, YD, HOURDAY, LIGHT
```

```
  IF HOURDAY < 6 OR HOURDAY > 18 THEN GOTO SKIP1
  IF LIGHT < 0 THEN LIGHT = 0
  WRITE #2, YD, HOURDAY, LIGHT
SKIP1:
LOOP
CLOSE #1, #2
```

C. Program for calculating daily integrated incident light.

```
REM ******INTLIGHT.BAS***05/15/97***10:00

REM ********* FORMAT FOR INPUT AND OUTPUT DATA FILES **********
'INPUT FILES:
'96TIMLIT.DAT = YD, HRDAY, SPAR

'OUTPUT FILES:
'XXXXXLIT.DAT = YD, INTSPAR

REM ********* DEFINE VARIABLES ************

SCREEN 9: CLS
INPUT "Enter beginning Julian day of year - "; YEAR1
INPUT "Enter ending Julian day of year - "; YEAR2

MAXDEPTH = MD + 1: MAXHRDAY = 49: MAXYD = (YEAR2 - YEAR1) + 1
PATH$ = "C:\QB45\DATA\": INEXT$ = "INP.DAT": TIMLIT$ = "96SPAR.DAT"
OEXT1$ = "96INTLIT.DAT": LITERECORD = MAXHRDAY * MAXYD

REM ********* DIM Statements ************

DIM SPAR(LITERECORD), YDD(LITERECORD), HRDAY(LITERECORD)

REM ********* INPUT FILENAMES ************

INLITE$ = PATH$ + TIMLIT$: OUTINTLITE$ = PATH$ + OEXT1$

REM ****READ LIGHT TIME SERIES DATA FROM DAT FILES****

START:

'Input light

OPEN INLITE$ FOR INPUT AS #2
FOR N = 1 TO LITERECORD
  INPUT #2, YDD(N), HRDAY(N), SPAR(N)
NEXT N
CLOSE #2

OPEN OUTINTLITE$ FOR OUTPUT AS #3

REM ********************BEGIN COMPUTATIONS**************************
```

```
LLIT = 1: INTLIGHT = 0
FOR DAY = 1 TO MAXYD
  FOR LIT = LLIT TO LLIT + MAXHRDAY - 1
    INTLIGHT = INTLIGHT + (SPAR(LIT) * 900) / 1000000
  NEXT LIT

  WRITE #3, YDD(LLIT), INTLIGHT
  LLIT = LLIT + MAXHRDAY: INTLIGHT = 0
NEXT DAY
CLOSE #3
```

VIII. Appendix II - Instructions for using spreadsheets.

There are two primary Quattro Pro for Windows 5.0 spreadsheets used for computation of volumetric production and areal production on a given cruise. The first is notebook **CRSYYNN.WB1** (YY = year; NN = cruise number) which calculates production rates at the different incubation light intensities and provides the data for conducting the nonlinear curve fits of P-I data to determine non-chlorophyll specific α^* and Pm*. The second is notebook **pYYNN.WB1** which is used to compute volumetric and areal production. The notebooks evolved separately over time and therefore could be streamlined and perhaps functionally combined. The descriptions below will get you going on worksheets. I have included blank worksheets which tell more of where to manually place data entries.

Notebook CRSYYNN.WB1

This notebook is composed of 5 sheets: ***Prodn, Prodnvslight, Report, Graph1, Graph2.*** Data may be entered in any order and cells will be computed as data are entered. Description of the functioning of each sheet is as follows:

Prodn. This is the primary sheet for entry of raw data. The sheet will handle computations for two stations at each of the 5 sampling depths. Station and cruise information is entered as strings in top left region of sheet. Data entries are a) activity of Specific Activity sample counts (DPM, 0.1 ml sample taken from each incubation bottle), b) concentration of DIC in mM (entry made in top cell of each table only, automatically copied to remaining cells), c) activity in blank filter (DPM, isotope introduced into sample and filtered within seconds), d) activity of filtered incubated samples (DPM) and e) hours of incubation. Specific activity, production over incubation and hourly production (µmolC/l/incub, µgC/l/incub, µgC/l/hr) are computed. There are 16 samples analyzed for each sampling depth, 14 at various light intensities (cubicals 1-14) and two dark bottles (cubicals 15 and 16).

Prodnvslight. The left block of 5 tables is for entry of measured light intensity readings made in each cubical. Hourly production is automatically copied from sheet ***Prodn***. The light readings are made with a flat plate cosine sensor that snugly fits into cubicals. Readings are made at bottom of cubical. Right hand block of 5 tables performs the following computations. a) a cosine to 4π conversion (calibration factor determined using 4π sensor located in center of incubation bottles under conditions of the incubations) for comparison with cosine sensor readings made at bottom of cubicles without bottles, b) correction of hourly production for average dark bottle activity (avg of cubicals 15 & 16), and c) Q_{10} correction of data for temperature differences between *in situ* and incubation temperatures. The data in the right-hand block of tables are exported for nonlinear curve fits of P-I to obtain non-chlorophyll specific α^* and Pm*.

Report. This sheet is formatted for easy entry of data into database. Volumetric daily production, areal production, α^*, Pm* are imported from notebook **pYYNN.WB1** are imported.

The term Beta is 0 virtually 100% of the time. Photoinhibition essentially does not occur in these waters.

Graph1, Graph2. These sheets are plots of raw production data from ***Prodn*** to QA the P-I curves. They are used only for preliminary inspection of data.

Notebook pYYNN.WB1

This notebook is composed of 6 sheets: ***Prod, LiteProf, LiteTime, ChlorProf, LiteLim, PProd***. Data can be entered in pretty much any order. Cells will be computed as data are entered. Description of the functioning of each sheet is as follows:

Prod. This sheet computes the following: a) *in situ* PAR at 6 depths (5 sampling depths plus the air-sea interface) for each 15 min interval over the 12 hr photoperiod (left table, PAR), b) volumetric hourly production at each depth and each 15 min time interval over the day (right table, P(i)), c) volumetric production at each depth integrated over the photoperiod (daily volumetric production, gray shaded cells in upper small table), d) depth integrated production (small table upper right, red numbers). Upper left table includes a) sampling depth (entered here), b) % subsurface light (carried over from sheet ***LiteProf***), c) non-chlorophyll specific α^* and Pm* (entered here, these terms for surface sample also used for interface), average chlorophyll at sampling depths. Daily production computed by summation of values in the 6 columns P(i) and divided by 4. Formulas in the Areal production cell (red numbers) perform trapezoidal integration of daily production given depth interval and daily production. Production in the interface region between zero depth and surface sample is significant and must be included in areal production computation (compare two red numbers) and is the number used for the database.

LiteProf. Light attenuation curves determined from 4π CTD profiles at photostations that are fit to an exponential series indicated in upper table. Coefficients A1, A2, A3, A4 and a1, a2, a3, a4 determined by a nonlinear fit using separate software (SAAM II). Factors are entered into Parameter table. Almost always the light profile can be described by using only two sets of coefficients A1, A2 and a1, a2. It is *rarely* sufficient to fit the profile with a single exponential equation. When there is a chlorophyll maximum, sections of the profile must be fit separately and factors copied into the appropriate section of the data column. Computed profiles are graphed for inspection and % light attenuation computed for each sampling depth (depths are automatically copied from sheet ***Prod***) in upper right table. The % attenuation values are automatically copied to sheet ***Prod***.

LiteTime. Incident light from 2π (not cosine) sensor at Deer Island on day of cruise copied to Surface Light column. Copy sunny day light field for this time of year into the Theo Surface Light column. These incident light values are multiplied by % light attenuation values (divided by 100) at each sampling depth in sheet ***Prod*** to compute *in situ* light as described above.

PProd. This sheet is identical to Prod except that the Theo Surface Light field (column C, sheet ***LiteTime***) is substituted. This yields Potential Production.

LiteLim. This sheet is used to determine production at each depth and time of day in terms of % saturation.

ChlorProf. This sheet is not really used for any of the computations described above.

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