The effects of suspended glacial sediments on light attenuation and primary productivity in Glacier Bay National Park, Alaska

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Abstract

A series of laboratory experiments measuring primary productivity using the ^{14}C method were conducted aboard the *Thomas G. Thompson* to examine how glacial flour affects primary productivity rates in Glacier Bay National Park, Alaska. The reasoning behind this project is that primary production is the base of the dynamic food web. Without it, high trophic level species fail to exist. Glacier Bay is known to exhibit phenomenally high primary productivity rates, but the study of the effects of glacial flour attenuating in coming solar radiation affecting primary productivity rates has not been studied. This project used a custom built, artificial light incubator, but the methods seemed to be at the detection limit exhibiting highly variable productivity rates ranging from 0.08 to 10.78 mg C (mg Chl *a*)$^{-1}$ h^{-1} with increasing light intensities. Glacial flour was also not present in high concentrations as first thought, but the attenuation of light by both algal biomass and glacial flour was still apparent. The use of *in situ* PAR sensor, transmissometer, and fluorometer were used to determine the low light intensities within the top 20m of the water column ranging from 0.74 to 29.11 µE m^{-2} sec^{-1}. The fluorometer and transmissometer were used in combination with each other to determine which regions in the bay were predominantly influenced by either algal biomass (through the use of *in situ* chlorophyll *a* concentration), glacial flour (through % transmissivity) or both. The highly variable primary productivity data in deciphering the biogeography of higher trophic level species proves a difficult task.

Introduction

Primary production by phytoplankton, the base of the food web in marine ecosystems, regulates energy availability to higher trophic level species (Forget 2007). Glacier Bay National Park, Alaska is known to exhibit phenomenally high primary productivity (Hooge 2002), but the study of the influences and effects of light attenuation and absorption (Yentsch 1962) by suspended glacial sediments as well as phytoplankton assemblages within the euphotic layer (Lorenzen 1972) on primary productivity has attained less attention.

As its name implies, Glacier Bay is a highly productive fjord-estuarine eco-system surrounded by fast retreating glaciers that produce high sedimentation loads that, with time, allow the formation of glacial flour (Hooge 2002). Glacial flour has the ability to strongly attenuate in coming solar radiation influencing

the rates of marine planktonic primary production (Lorenzen 1972). Under these constituents, regions within the bay that are heavily impacted by glacial retreat would exhibit more glacial flour therefore a reduction in primary productivity as well as a reduction higher trophic level species.

The cruise to Glacier Bay National Park, Alaska took place March 19 - 23, 2008 aboard the *Thomas G. Thompson*. For this project, the ^{14}C method was used to measure primary productivity as first proposed by Steeman-Nielsen (1952). The method used was altered as described by Strickland and Parsons (1972), and Lewis and Smith (1983) which consists of using small volume, short-incubation-time methods. These modified methods use a custom built incubator with chambers that exhibit artificial light with 25 different intensities. After short-time incubations, photosynthetic rates were calculated. This relationship is called a P vs. I curve. Primary productivity was measured along a transect from the mouth of Glacier Bay, northward through the West Arm to Tarr Inlet. Through this transect, it was assumed that with progression southward from Tarr Inlet, primary production will increase to the mouth as the waters are less influenced by glacial flour increasing primary productivity rates. The use of CTD (conductivity, temperature, and density) mounted fluorometer, transmissometer, and PAR (photosynthetically active radiation) sensor were used to gather data on the chlorophyll *a*, the transmissivity of the water and the PAR. Combining the information from the fluorometer, transmissometer, and PAR senor with the primary productivity measured at Glacier Bay provided some unusual conclusions to the state that Glacier Bay National Park was in during the 5 day cruise. This information and scientific research is important for Glacier Bay as it is a national park with little performed research. Gaining a grasp on understanding the biogeography, temporal, and spatial patterns of phytoplankton assemblages (Hooge 2002) and their primary production, can lead to a better understanding of the same for higher level trophic species as well as sustaining high species abundance (Pauly 1995) which is important in any ecosystem.

Methods

Water samples were taken from 4 depths; 0m, 10m, 20m, and the chlorophyll max at 8 USGS stations (Table 1; Fig. 1) during the 4 day cruise inside Glacier Bay National Park. CTD casts were conducted during daylight hours between 700 and 1500 local time to allow for the CTD mounted *in situ* PAR readings. Due to time constraints, water samples from Station 8 were taken during the evening, but PAR data from Station 07 was extrapolated to Station 08 and will always be referred to as Station 08.

Primary productivity was measured via the ^{14}C method as first proposed by Steemann and Nielson (1952) with modification by Strickland and Parsons (1968), and Lewis and Smith (1983) using small volume, short-incubation-time methods. At each station the CTD rosette was cast to collect water from each of the 4 depths. Each CTD cast was also recording *in situ* PAR using a Biosphereical Instruments Inc. PAR sensor, transmissivity using the WET Lab transmissometer and fluorescence using the WET Lab fluorometer. From each depth, one 1 L acid-washed polycarbonate bottle was filled on-board and taken inside the radiation van and kept cool in darkness until ready for processing and incubation. Each 1 L sample from USGS Stations 21, 12, 11, 08, 06, 05, 02, and 01 (Fig. 1) was divided into 6 – 15mL sub-samples (24 sub-samples per station) into 20mL acid-washed and seawater rinsed glass vials. Each 1 L sample from USGS Stations 21 and 5 were run in triplicate and divided into 18 – 15mL sub-samples (72 sub-samples per station) into 20mL acid washed and seawater rinsed glass vials. Each vial was inoculated with 40µL of 53.5mCi $mmol^{-1}$ sodium bicarbonate ($NaH^{14}CO_3$) (MP

Date	Station	Latitude	Longitude
March 22, 2008	01	58° 24'77.49" N	135° 59'57.34" W
March 22, 2008	02	58° 29'28.04" N	136° 03'04.92" W
March 21, 2008	05	58° 42'28.17" N	136° 13'85.98" W
March 22, 2008	06	58° 45'58.96" N	136° 20'96.25" W
March 21, 2008	08	58° 51'91.75" N	136° 35'51.37" W
March 19, 2008	11	58° 58'04.21" N	136° 54'51.67" W
March 20, 2008	12	59° 02'02.70" N	137° 00'96.47" W
March 19, 2008	21	59° 02'83.85" N	137° 03'35.07" W

Table 1: The dates and station locations of CTD casts and water samples taken at Glacier Bay National Park, AK.

Biomedicals, Inc.) and inverted several times to mix. All 20mL vial caps were previously labeled with station number, replicate, and depth. Once the inoculations were complete, each 20mL vial was sequentially put into a custom built incubation rig (Appendix A). The incubator chambers emitted 25 different light intensities (Table 2) over a range from 0 – 500 µE m^{-2} sec^{-1} using artificial light provided by high projection lamps with a 2 step temperature cooling system. Each of the 24 sub-samples was incubated for 1 hour. After the 1 hour incubation, each sub-sample was removed from the incubator and kept cool in a dark area until termination. Within 15 minutes each incubation was terminated by filtering the 15mL contents through 0.2µm Whatman GF/F filters. The vials were rinsed with 10% HCl and hand rolled to ensure acid contacts with all remaining liquid in the vial and then re-emptied into the filter rig with the corresponding filter. The filter chambers and filters were then rinsed with the 10% HCl to complete the termination and complete removal of ^{14}C. Each filter was then transferred to 7mL plastic vials and topped off with 5mL of biofluor scintillation cocktail. Each of the vials was allowed to rest for several days before counting with a Beckman Coulter LS6500 scintillation counter. After counting, CPM (counts per minute) and DPM (decays per minute) were recorded and the following equation as used in Miller (2002) for the calculation of photosynthesis: "The formula for ^{14}C-uptake production measurement is given by Strickland and Parsons (1972) using the following formula":

Photosynthesis (P; mg C m^{-3} h^{-1})

$$P = \frac{1.05W(R_s - R_b)}{RT}$$

Where: R = Counting rate to be expected for the entire addition of 14C

R_s = Counting rate for filtered sample

R_b = Counting rate for blank

W = Total weight of carbonate carbon in the water (mg C m^{-3})

T = Duration of incubation in hours

After the calculation of photosynthesis rates, the values were plotted with irradiance values from the incubator to create the P vs. I relationship. Each relationship was then fitted with a function to describe the relationship as a P vs. I curve (Platt 1980):

$$P = P_{max}\left(1 - e^{-\frac{\alpha}{P_{max}}}\right)e^{-\frac{\beta}{P_{max}}}$$

Where: P_{max} = Maximum rate of photosynthesis

α = Initial slope (dP/dI)

β = Intensity at the onset of photoinhibition.

Chlorophyll *a* concentrations were determined analytically at each station for each of

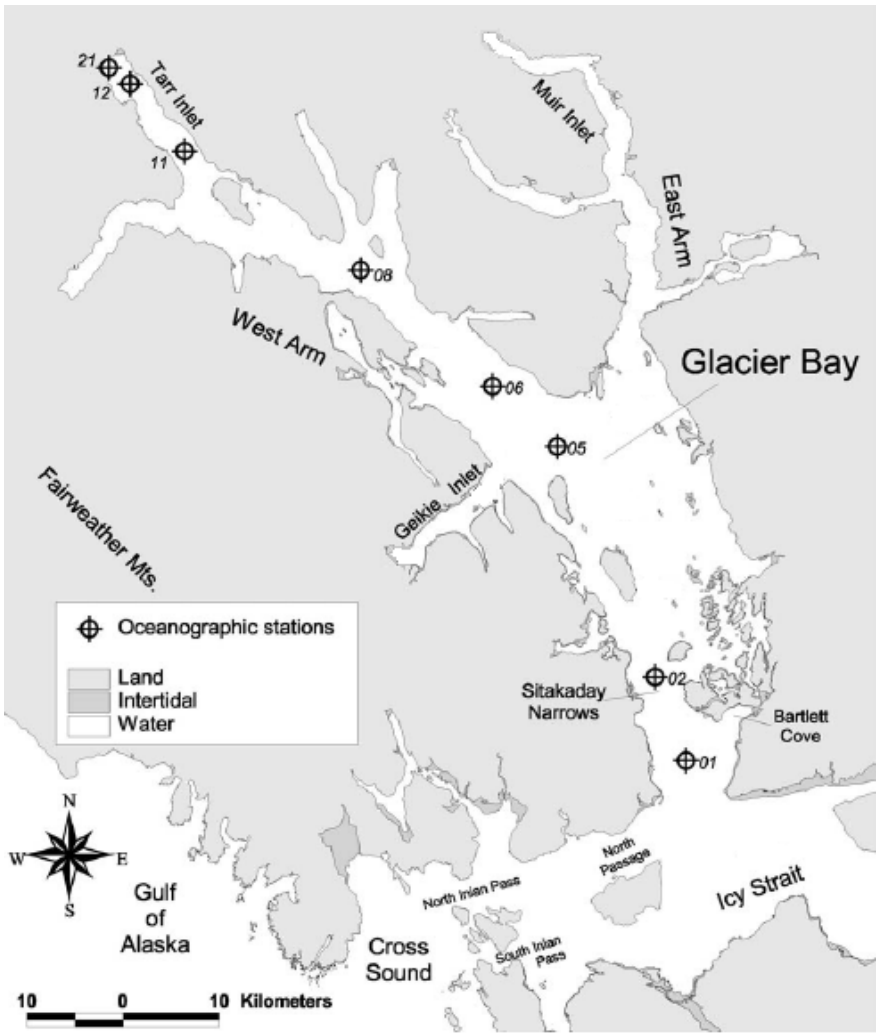


Figure 1: Map of station locations in Glacier Bay National Park, Alaska. Refer to Table 1 for latitudes and longitudes of each station.

the chlorophyll maxes using the chlorophyll *a* method (Newton 2002) using 0.2µm Whatman GF/F filters. The filters were analyzed by fluorometry after extraction in 10mL of 90% acetone. The following equations (Newton, 2002) were used to calculate chlorophyll *a* concentrations:

Chlorophyll *a* (mg m^{-3})

$$Chla = \frac{K_x(F_0 - F_a)\left(\frac{\frac{F_0}{Fa}}{\frac{F_0}{Fa} - 1}\right)}{V_w}$$

Where: $\frac{F_0}{Fa}$ = Ratio for a sample which contains only chlorophyll and no phaeopigments.

K_x = Calibration factor for the fluorometer.

V_w = Volume of water filtered, in liters.

The calculated chlorophyll *a* concentrations were used to normalize the values of primary production to formulate the ratio of photosynthetic rate (carbon uptake) per unit volume to chlorophyll concentration. This is termed the assimilation number.

Nutrient bottles for phosphate, nitrates, silicates, and ammonium were collected at specified depths for the entire cruise and returned to the University of Washington Marine Chemistry

Chamber #	Light Intensity ($\mu E\ m^{-2}\ sec^{-1}$)	Chamber #	Light Intensity ($\mu E\ m^{-2}\ sec^{-1}$)
1	5.1165	14	17.932
2	47.005	15	6.8638
3	29.1175	16	2.0488
4	0	17	11.03
5	0.4395	18	426.875
6	1.1207	19	22.3475
7	78.7225	20	3.4308
8	0	21	0.1446
9	7.2528	22	0
10	0.6344	23	41.7075
11	1.817	24	2.2803
12	27.39	25	4.186

Table 2: Light intensities in $\mu E\ m^{-2}\ sec^{-1}$ of each chamber in the incubator. The light intensities ranged from 0 to 426 $\mu E\ m^{-2}\ sec^{-1}$ with most of the intensities between 0 and 80 $\mu E\ m^{-2}\ sec^{-1}$.

Lab for processing. The procedures can be reviewed in Appendix B.

Results

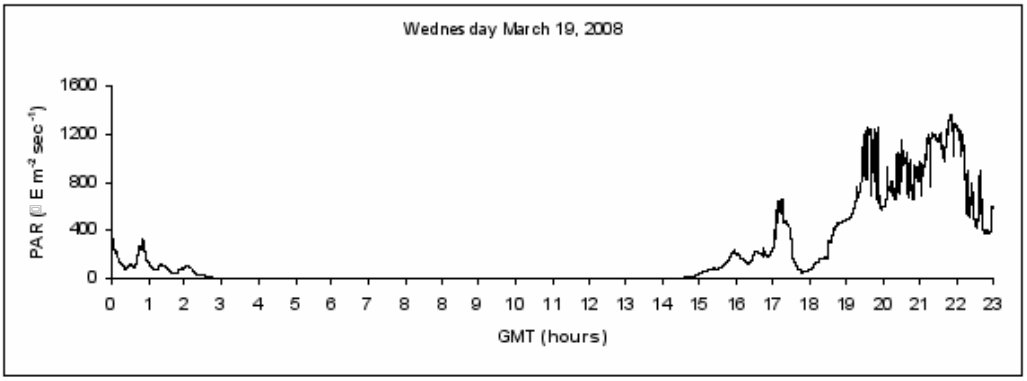
Photosynthetically active radiation

PAR measurements throughout Glacier Bay within the top 20 meters were low, ranging between 0.74 – 29.11 $\mu E\ m^{-2}\ sec^{-1}$ (Table 3).

Surface (0–5m) PAR measurements at the mouth of the bay northward to Tarr Inlet were exposed to light intensities between 0.89 $\mu E\ m^{-2}\ sec^{-1}$ at Station 08 and 29.11 $\mu E\ m^{-2}\ sec^{-1}$ at Station 11. Light intensities at each chlorophyll *a* maximum ranged between 0.74 $\mu E\ m^{-2}\ sec^{-1}$ at Stations 02 and 08 to 8.37 $\mu E\ m^{-2}\ sec^{-1}$ at Station 21. Atmospheric PAR measurements (Fig. 2a–d) recorded by the *R/V Thompson* shipboard system between day light hours (300-1500 local time) for the 4 days showed that Glacier Bay experienced light intensities ranging between 10 – 1372 $\mu E\ m^{-2}\ sec^{-1}$. Light intensities expressed some variability in surface waters from the mouth towards the beginning of the West Arm and then increased to Tarr Inlet, but generally increased northward to Tarr Inlet (Table 3). Figure 3 is a summary of vertical in situ PAR profiles for all USGS stations that illustrates chlorophyll *a* concentrations are not distributed proportional throughout the water column and decrease with increasing PAR showing the most dramatic decrease where PAR was approximately greater than $5\mu E\ m^{-2}\ sec^{-1}$.

Transmissivity and Chlorophyll

Light transmission values between 0m and ˜20m are taken into account as only this range of depths was used for primary production measurements (Table 3). The transmissivity values were stable through 20m at the mouth with increasing values northward to Tarr Inlet. At Stations 01 and 02, light transmission throughout the water column was stable through 20m at an average 89.47% and 86.17% respectively. At Station 05, light transmission was also stable through 20m at an average of 88.81%. Stations



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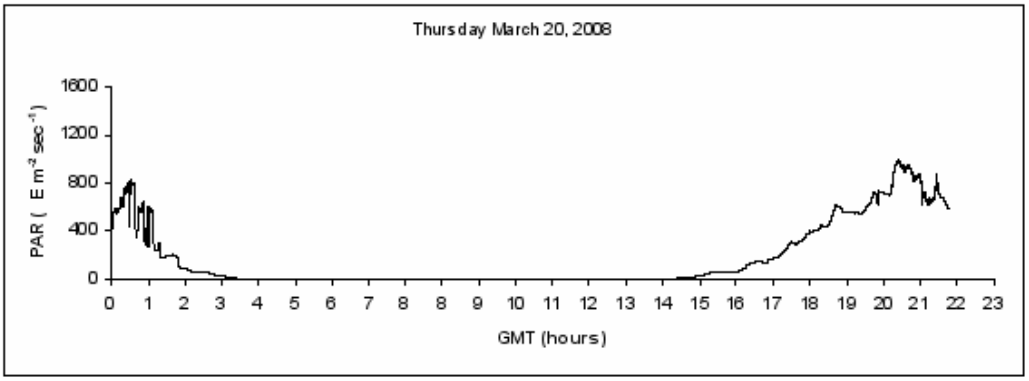

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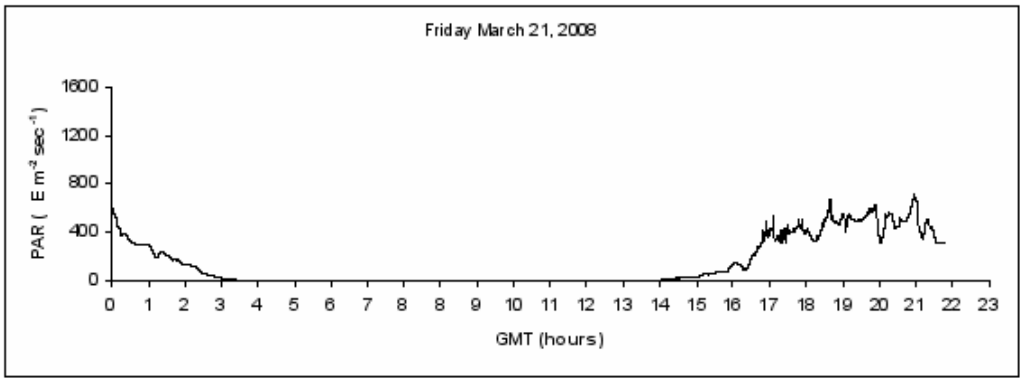

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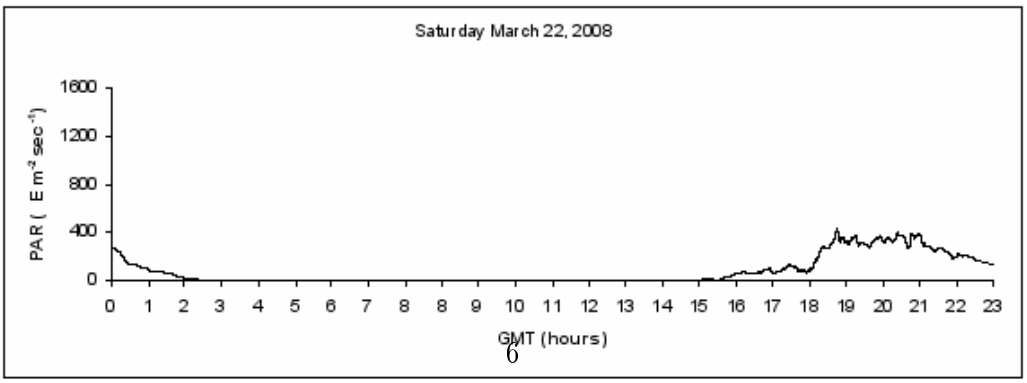


(d)

Figure 2: Light regime plots in GMT for the days inside Glacier Bay National Park.

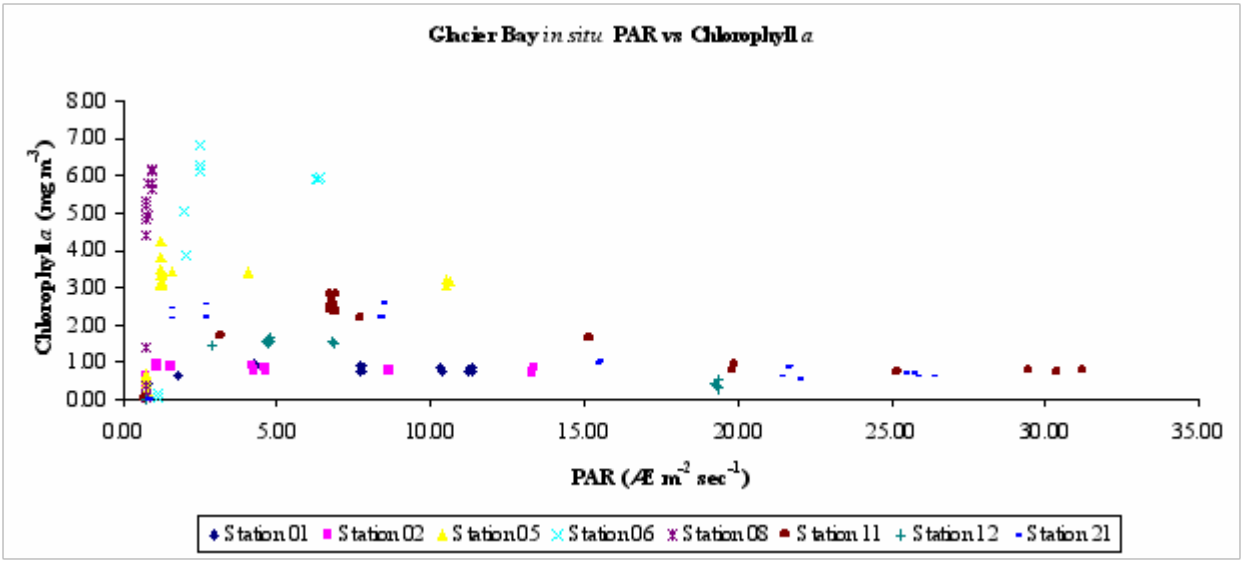


Figure 3: In situ PAR vs. chlorophyll a concentration in Glacier Bay, AK

06, 08, 11, 12, and 21 however had increasing values with depth in the water column to the chlorophyll max and decreasing there after (Table 3). The transmissivity values account for absorption and attenuation of light by both phytoplankton assemblages and CDOM (colored dissolved organic matter) due to glacial flour and other forms of particulate organic matter. To differentiate between phytoplankton assemblages and CDOM (Holdaway 1998), the CTD mounted fluorometer measured in situ fluorescence as a proxy for chlorophyll *a* biomass.

The highest chlorophyll *a* concentrations observed were at the beginning of the West Arm at Stations 05, 06, and 08, following Stations 11, 12, and 21 with Stations 01 and 02 with the lowest concentrations (Table 3; Fig. 4). Figure 5 exhibits the relative concentrations with depth of chlorophyll *a* relative to PAR through the entire length of Glacier Bay.

Station 01 and 02 are fairly homogeneous in relation to chlorophyll *a* concentration through 20m with average values of 0.81 to 0.55mg m^{-3} respectively. Station 05 chlorophyll *a* concentrations slightly increased with depth to 20m, averaging 3.26 mg m^{-3} with a chlorophyll *a* max at 4.25mg m^{-3}. Station 06 chlorophyll *a* concentration increases to 8m with a chlorophyll max value of 6.81mg m^{-3} and sharply drops to 0.09mg m^{-3} at 20m. Station 08 had similar values dropping from 6.20 to 1.42 mg m^{-3}. Stations 11, 12 and 21 all expressed similar trends with low chlorophyll *a* values (0.76, 0.54, 0.57 mg m^{-3}) respectively at the surface and increasing to 1.72, 1.45, 2.24 mg m^{-3} at 20m.

The ratio of chlorophyll concentration to % transmissivity (Fig. 6) was used as a qualitative measure to differentiate which stations were influenced primarily by chlorophyll *a* as a proxy for algal biomass, glacial flour and CDOM or both.

Stations 01 and 02 were defined to be neither primarily influenced by chlorophyll or glacial flour. Station 11, 12, and 21 were defined to be partially influenced by both chlorophyll *a* and glacial flour, but more influenced by glacial flour. Station 05, 06, and 08 were again partially influenced by both chlorophyll and glacial flour, but proportionally more influenced by chlorophyll *a* algal biomass pigment absorption.

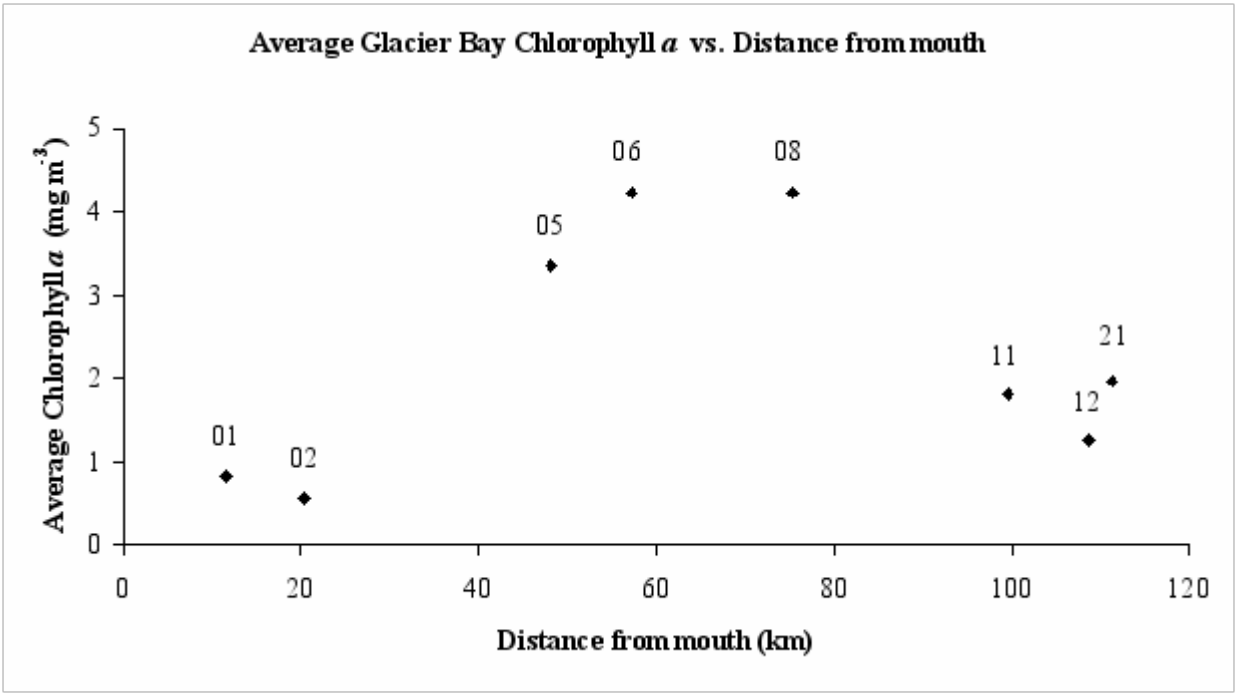


Figure 4: Average Glacier Bay chlorophyll a concentration vs. distance from mouth. Highest values were recorded at Stations 05, 06, and 08.

Nutrients

All nutrient concentrations decreased moderately with an increase in PAR (Fig. 7a–c).

NO_3, NO_2, and NH_4 were combined to get the total inorganic nitrogen which ranged from 26.39 to 19.94µM with a decrease in concentration with an increase in PAR (Fig. 7a). Phosphate (PO_4) also showed a decrease in concentration with an increase in PAR (Fig. 7b) ranging from 2.11 to 1.75µM. $Si(OH)_4$ also exhibited a decrease in concentration with an increase in PAR (Fig. 7c). Figures 8a–c exhibit that as chlorophyll *a* concentrations increase nutrient levels decrease.

Primary Productivity

Chlorophyll *a* specific primary productivity (PP) values throughout Glacier Bay were unexpectedly variable with no statistical trend (Fig. 9) with combined production values for each station ranging from 0.00045 to 10.74 mg C (mg Chl *a*)$^{-1}$ h^{-1}. Although not trend was visible, through back envelope calculations using estimates based on the relationship between primary production, chlorophyll *a* biomass, and light, primary productivity measured in Glacier Bay were within the values that should have been calculated. Each station exhibited variable P vs. I curves and values. No general trends of increasing PP with increasing PAR were visible (Fig. 10). Also note that the equation for fitting the line to the plot was neglected due to inconsistent data.

Figure 11 shows PP measurements in relation to each chamber intensity (Table 2) for all of Glacier Bay indicating no general trend of increasing primary production with increases in light intensity. Note that light intensities in the 400 µE m^{-2} sec^{-1} were excluded because most of the data points fall within the first 50 µE m^{-2} sec^{-1}.

Combined primary productivity data for all incubations were put into a box plot (Fig. 12) to

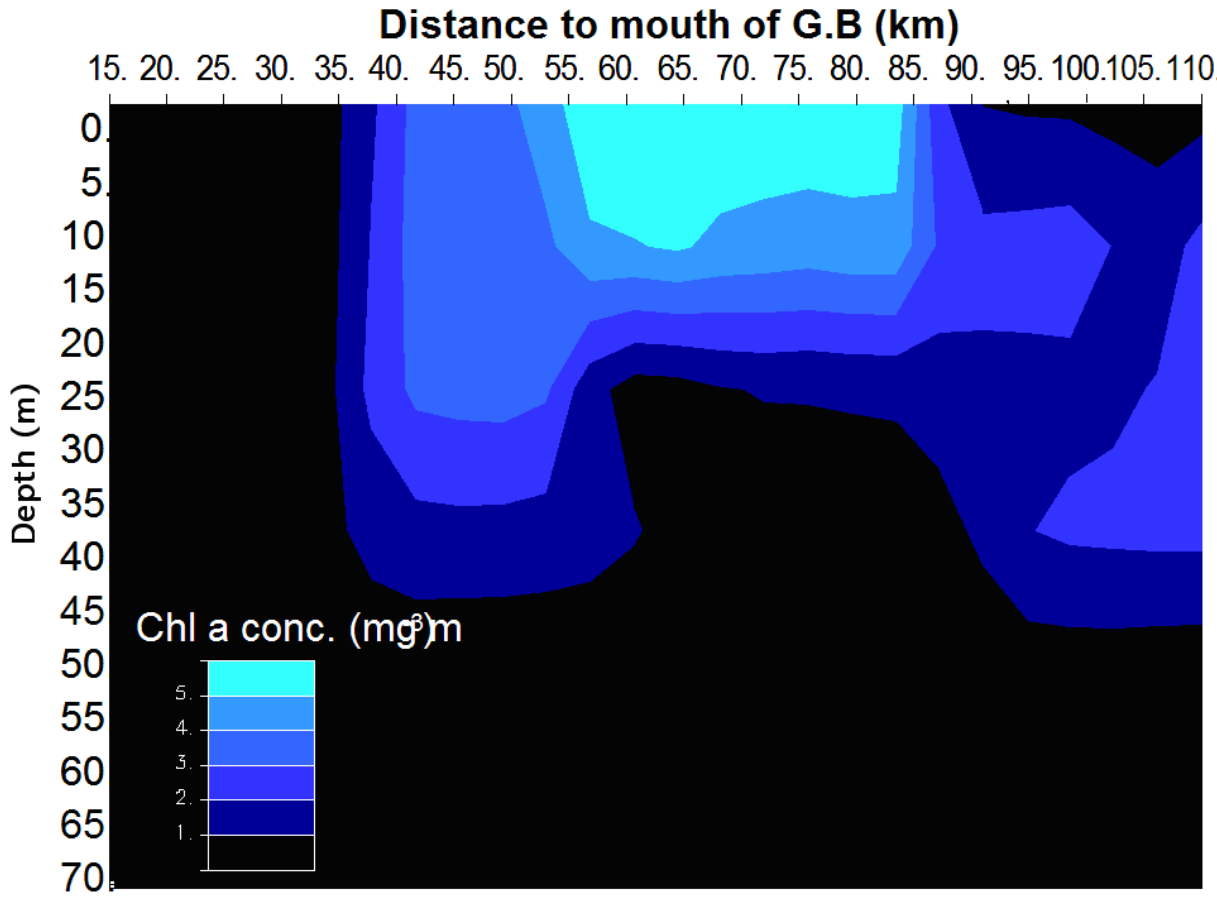


Figure 5: Isopleths contour map of relative chlorophyll a distribution with distance from the mouth.

determine which light levels from the incubator had the highest primary productivity values.

Statistically looking at figure 12, one might suggest that the data shows no trends with increasing light intensities and that there are quite a few outliers that make the data seem inconclusive with increases in light intensity. The max values are variable with increasing light intensity. Interestingly, at 0.00 µE m^{-2} sec^{-1} there is a significantly high max which would indicate high primary productivity at that station with no light. Values at 426.88 µE m^{-2} sec^{-1} are relatively similar to light intensities between 4.19 and 78.7 µE m^{-2} sec^{-1}.

Discussion

The purpose of this study was to evaluate the impacts of suspended glacial sediments (glacial flour) and CDOM on primary productivity within Glacier Bay. Additionally, another goal was to identify the predominant factor(s) responsible for allowing Glacier Bay to comprise levels of productivity high enough to sustain higher trophic level species with the hypothesis that regions within the bay that are heavily impacted by glacial retreat would exhibit more glacial flour therefore a reduction in primary productivity as well as a reduction higher trophic level species. Unfortunately, the primary production data was highly variable and presumably inconclusive showing no general trend in relation to variable light intensities

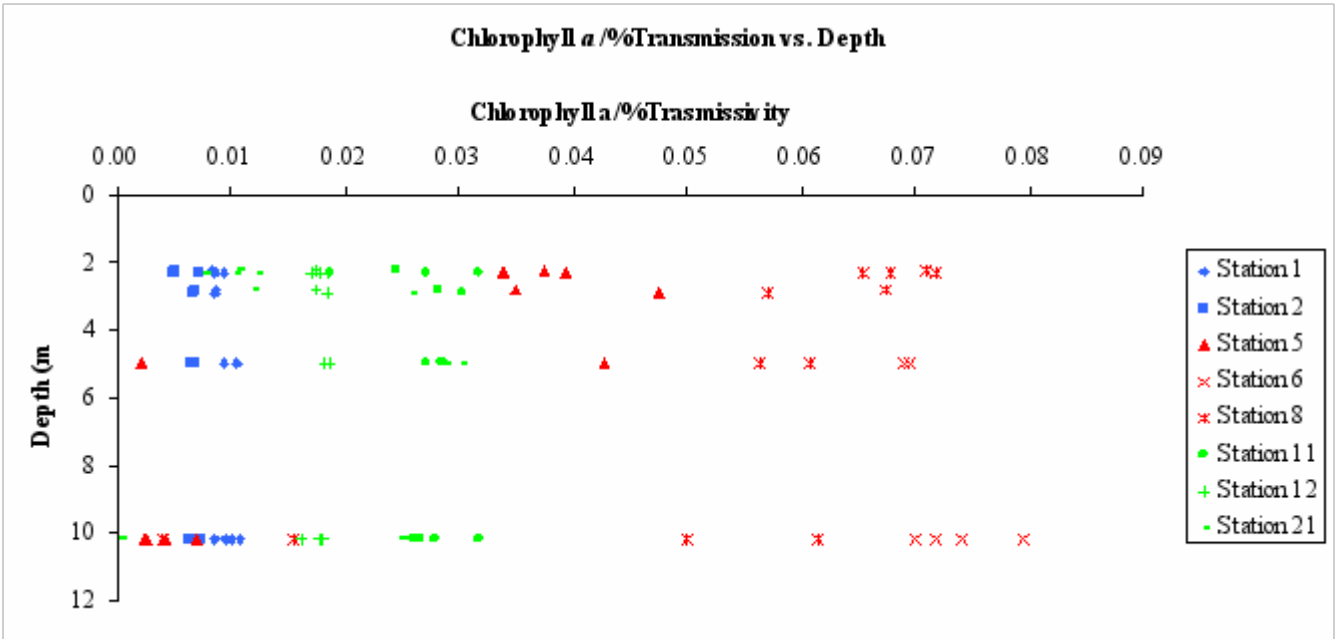
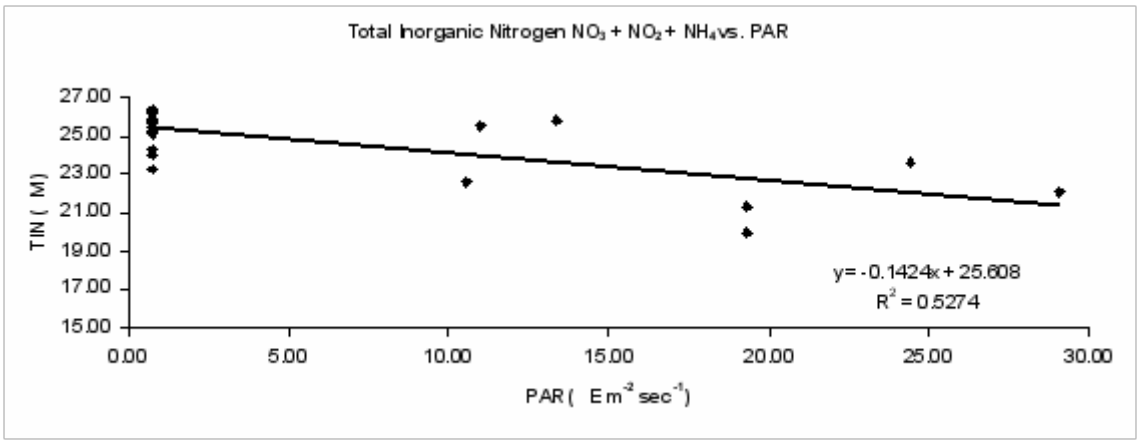


Figure 6: The ratio of chlorophyll a to % transmissivity vs. depth. This plot is used to define the relative influence of light attenuation by chlorophyll *a* biomass, glacial flour and CDOM or both.

(Fig. 10a–l). Due to this variation in primary productivity values makes it impossible to determine the most productive regions within the bay. Also, glacial flour was not as predominant as previously thought especially in regions of the bay heavily impacted by glacial retreat in Tarr Inlet. The cruise date was too late in the winter and too early in the spring to have significant glacial melting or the spring bloom. Although the empirically calculated primary productivity values may have been highly variable, through back envelope calculations based on the relationship between primary productivity, chlorophyll *a* concentration, and light intensity, the variable measured primary productivity values were within the range expected to be seen within the bay. The order of magnitude in the numbers of cells per sample was reasonable for the calculation. The method used seemed to be at the detection limit on the primary productivity occurring in Glacier Bay at the time of the cruise. Overall, very low chlorophyll *a* concentrations and *in situ* PAR in the late winter/early spring imposes methodological and procedural that resulted in perceived high variability of primary productivity measurements.

There are several factors that may have contributed to the variability of the primary productivity measured at Glacier Bay for instance, nutrient availability, the affects of glacial flour and the attenuation of light, and the affects of high algal biomass and the attenuation of light, (both of which can affect the availability and intensity of light). There are also other concerns about the methodological aspect and procedural problems that may have contributed to the variability of the primary production values determined in this study such as the small volume, short incubation time method (Lewis 1983), the use of glass instead of polycarbonate incubation vials with the implication that trace mental contamination (Miller 2004) could have had an affect on the production values, and possible filtration process problems (Gieskes 1979) such that ^{14}C in smaller molecules is lost due to cell breakage. Another possibility for the variable PP values is that something strange may have been going on in Glacier Bay that the methods



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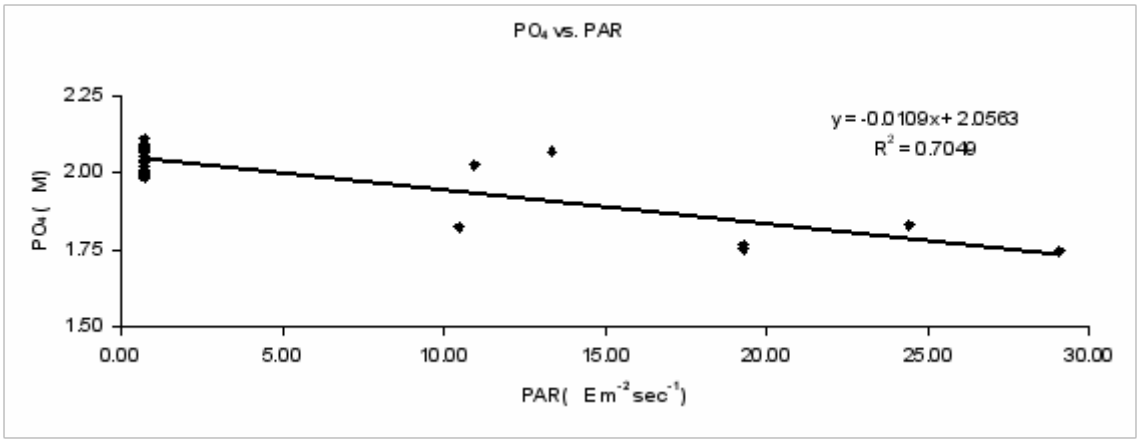

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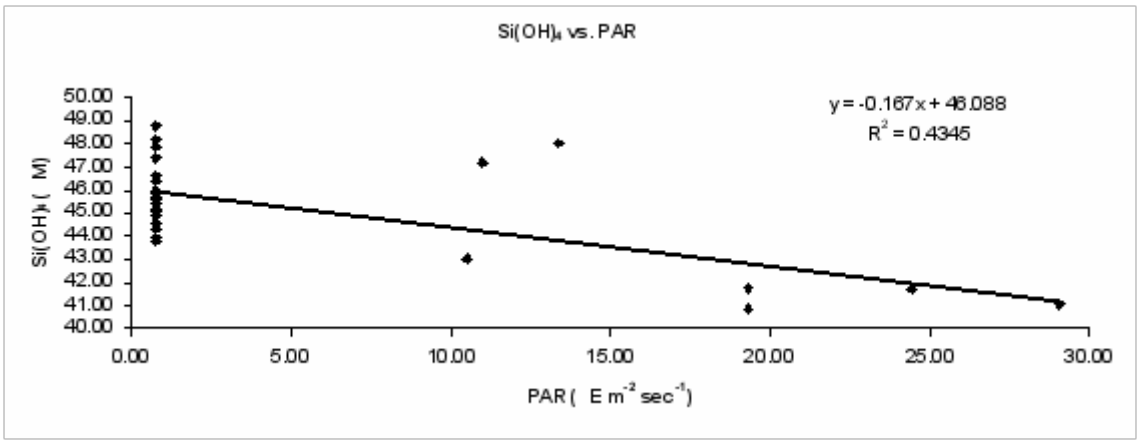

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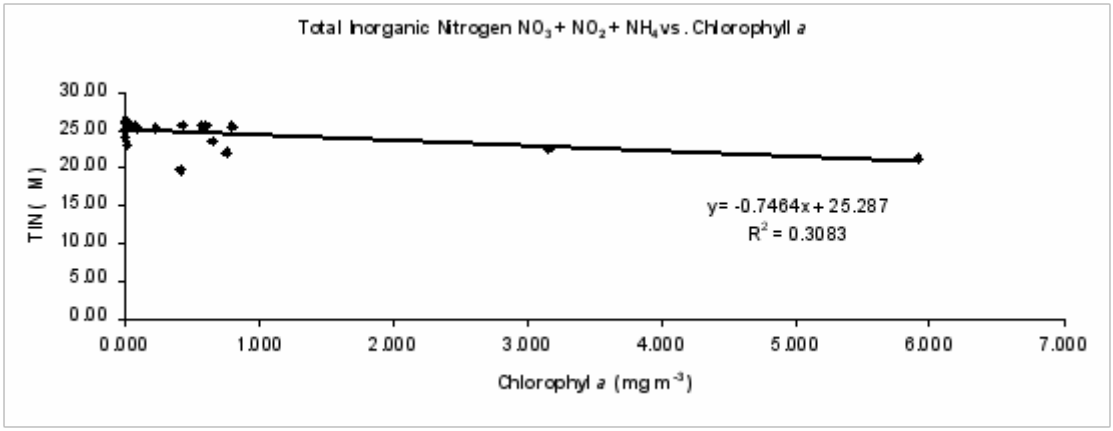
Figure 7: Decreasing concentrations of nutrients with increasing PAR.



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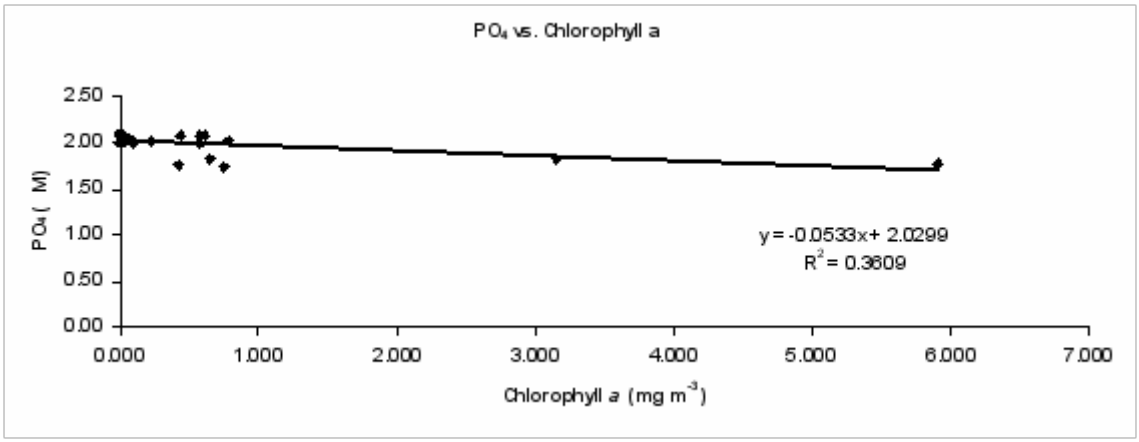

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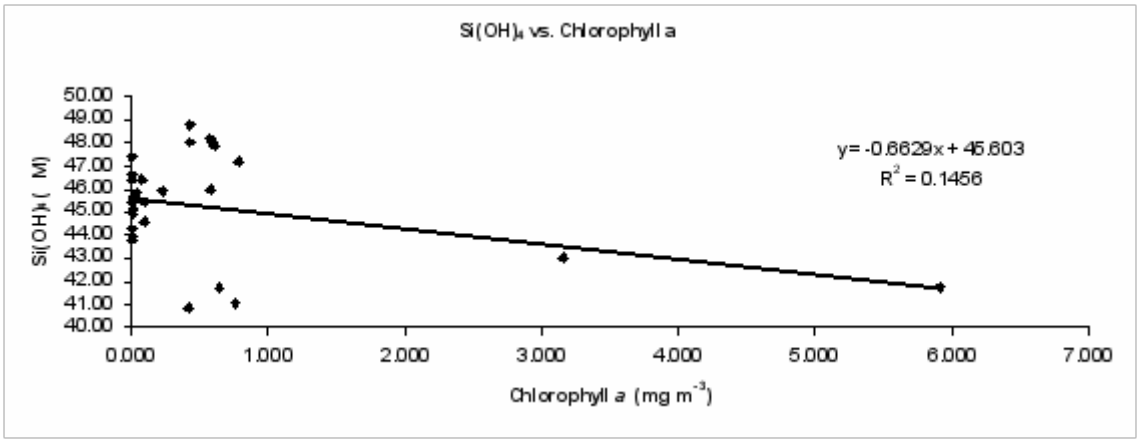

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Figure 8: Decreasing concentration of nutrients with increasing chlorophyll a concentration.

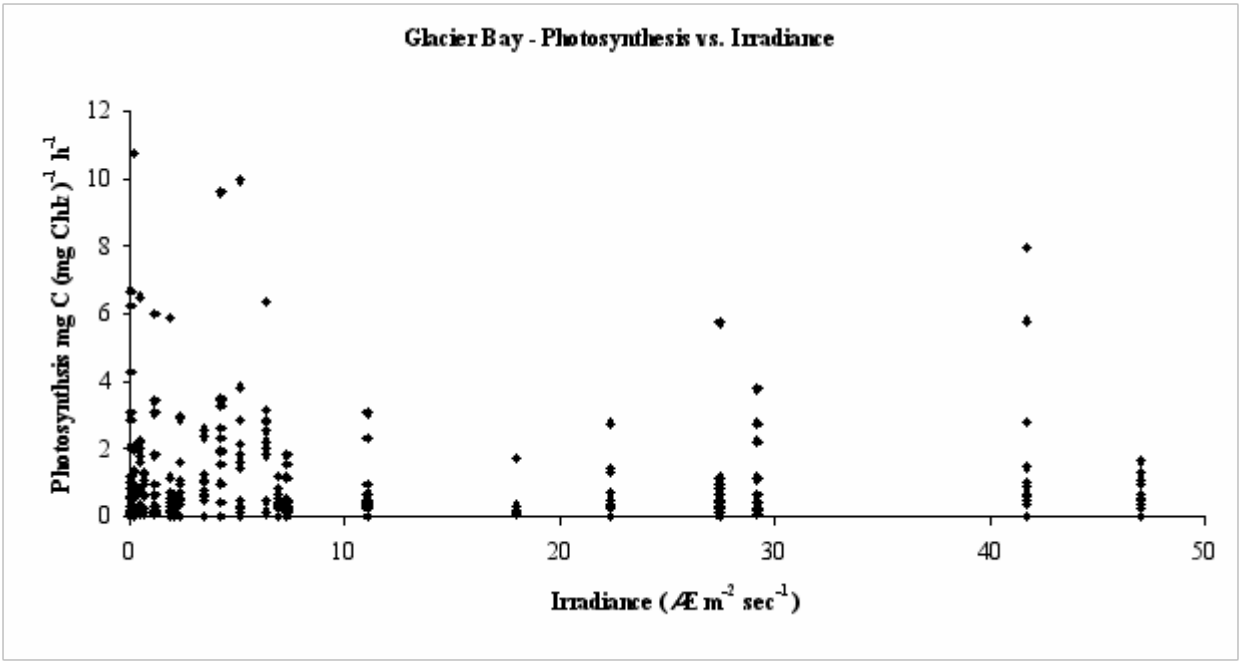

Figure 9: Primary productivity vs. irradiance (P vs. I)

used were at the detection limit. Of course there are several habitat determinants and procedural problems that may come into play, but only the described above will be investigated in this manuscript.

Nutrients in relation to PAR and chlorophyll *a* concentration

Nutrients samples were taken at each station at a variety of depths and were later measured in the Marine Chemistry Lab. Figures 7a–c exhibit a decrease in nutrient concentration with an increase in light. Figures 8a–c also illustrate a decrease in nutrients with increases in chlorophyll *a* concentration. The nutrients however are not limiting for phytoplankton growth.

Effects of attenuation on light intensity

The penetration of light into the ocean is of fundamental importance since primary production can only occur when light intensity is above a minimum level (Lorenzen 1972). The weather during the 4 days inside the park exhibited some variability with snow some days and sunshine on others (Fig. 2). The effects of weather (clouds and snow) were inferred upon the light regime of the upper 20m using the atmospheric PAR data recorded by the *R/V Thompson* which can account for some of the variability of the PAR values taken each day. Atmospheric PAR measurements were continually measured and recorded every 5 seconds and ranged from 1 – 1400 µE m^{-2} sec^{-1} (Fig. 2a–d). Interestingly, in situ PAR measurements recorded a range only between 0.74 and 30 µE m^{-2} sec^{-1} within the top 20 meters of the water column (Table 1). This significant decrease of about 98% in light intensity illustrates the relatively high attenuation and absorption of light compared to other coastal environments (Lorenzen 1972). The intensity of light within the top 20 meters is controlled by the absorption and scattering within the water column, but identifying the factor(s) at each station that contributed most to the attenuation and absorption of light required further investigation.

From the list of factors that could have had

affected the low irradiance through the water column, algal self shading can be significant (Jensen 1998). During the cruise, many aboard *Thompson* assumed there was a large phaeocystis bloom at the surface waters that was probably a large factor in the absorption and shading of light into the water column at certain staions. The noticed phaeocystis abundance was so high that plankton nets and filters were frequently clogged by phaeocystis colonies. This large bloom is a perfect sign of high production, but the primary production values measured do not exemplify that. Glacier Bay did however exhibit similar chlorophyll *a* concentrations in relation to Etherington (2007) Fig. 13.

Phaeocystis can interfere with short term ^{14}C incubations. According to Lancelot and Mathot (1987) and Tang (2003) when Phaeocystis *pouchetii* bloom, they form "hollow, spherical, mucilaginous colonies that vary from micrometers to millimeters in size" and "the filtration procedure universally used for isolation of phytoplankton cells disrupts the colonies and solubilizes the mucus into seawater". The implication of this observation could be the possible cause for extremely variable scintillation counts. The short incubation period of 1 hour may not have been sufficient to allow inorganic ^{14}C to assimilate through the mucus. Likewise, partial adsorption of the ^{14}C radio tracer into the mucus matrix and insufficient removal during the filtration process could have resulted inaccurate measurements and high variability.

Light transmissivity data was measured and recorded at each station to determine the percentages of light that were transmissible through the water column. The problem with this is that it takes into account that light is being attenuated and absorbed by both phytoplankton assemblages and glacial flour comprised of CDOM and other particulate organic matter. To differentiate between phytoplankton and glacial flour the CTD mounted fluorometer recorded fluorescence as a proxy for chlorophyll *a* biomass. Figure 6 exhibits how each of the stations could be grouped into groups of relative light attenuation. Station 01 and 02 were neither predominantly influenced by chlorophyll *a* biomass or glacial flour as the CTD profiles of these two stations were relatively homogenous with depth. Stations 11, 12, and 21 fall in the middle of the plot suggesting that light attenuation at these stations was influenced by both chlorophyll *a* pigment absorption and glacial flour, but predominantly influenced by glacial flour as these stations were relatively close to Margerie and the heavily sedimented Grand Pacific Glacier. Stations 05, 06, and 08 are predominantly influenced by chlorophyll *a* pigment absorption and less by glacial flour. Stations 05 and 06 were several kilometers from the nearest glacier, but Station 08 was within relative proximity to Rendu Inlet and Queen Inlet consisting of Rendu and Carroll glaciers, but data (Fig. 6) suggests light attenuation was primary due to chlorophyll *a* pigment absorption rather than glacial flour.

Effects of light intensity on primary productivity

Changes in vertical light intensity through the water column are significant (Lorenzen 1972) and its affects on photosynthesis are minimized by glacial flour and substances of biological and non-biological origin. In relation to the values of primary productivity measured in Glacier Bay, the hypothesis was an increase in light would produce increased rates of photosynthesis and therefore higher values of carbon assimilation. According to the incubation data, this was not the case. The PP values were highly variable and seemed almost "random" showing no general trend with increases in PP with increasing light intensity (Appendix C). One variable that may have contributed to variable data is the incubator light intensity range. The incubator was set up with chambers of different intensities (Table 2) that ranged from 0.000 to 426.8750 $\mu E\ m^{-2}\ sec^{-1}$. A problem that could have contributed to such variable primary produc-

tion data is the unequal range and low light intensities on the incubator. For instance, there were 4 light intensities that ranged from 0.000 to 0.6344 µE m^{-2} sec^{-1}, 10 intensities that ranged from 1.1207 to 11.0300 µE m^{-2} sec^{-1}, 4 intensities that ranged from 17.9320 to 29.1175 µE m^{-2} sec^{-1}, 3 intensities that ranged from 41.7075 to 78.7225 µE m^{-2} sec^{-1} and 1 light intensity at 426.8750µE m^{-2} sec^{-1}. There should have been a better series of light intensities without having intensities that were so low (0.6344 µE m^{-2} sec^{-1}) and of similar intensity. A better set up may have included light intensities (in µE m^{-2} sec^{-1}) for instance as displayed in Table 4:

Having a series of light intensities within the described range in Table 4 as well as a longer (3-4 hour) incubation time may have turned up with more useful data.

Problems with methods and procedures

The general method for measuring primary production is the carbon-14 method first proposed by Steeman-Nielsen (1952). A bottle of seawater is incubated at the depth from which it was collected in the saw after the addition of radioactive sodium bicarbonate. After a specified time interval, depending on the type of primary production (gross vs. net), the bottles are retrieved, the plants are filtered off, and the amount of ^{14}C incorporated in them is measured by scintillation counting. Since the 1970s several problems have been recognized with the ^{14}C method (Lean 1979; Strickland 1972) some of which have been listed below:

1. The measure of primary productivity (mgC m^{-3} day^{-1}) is not exact or absolute. Effects of confinement and the like cannot be determined. The numbers are indices of production, not measures. (Miller 2004)

2. Bacterial uptake is significant and may differ between dark and light bottles(Miller 2004)

Chamber	Project Setup	New Setup
1	0.00	0.00
2	0.00	0.00
3	0.00	10.00
4	0.14	20.00
5	0.44	40.00
6	0.63	60.00
7	1.12	70.00
8	1.82	80.00
9	2.05	100.00
10	2.28	120.00
11	3.43	140.00
12	4.19	160.00
13	5.12	170.00
14	6.26	180.00
15	6.86	200.00
16	7.25	250.00
17	11.03	300.00
18	17.93	350.00
19	22.35	400.00
20	27.39	450.00
21	29.12	500.00
22	41.71	550.00
23	47.01	600.00
24	78.72	650.00
25	426.88	700.00

Table 4: Light intensities used in for the incubation and the suggested light intensities to be used for future reference.

3. Isotope effects are not quantified and should differ with species mixture of the phytoplankton. The fudge factor of 1.05 is uncertain. (Miller 2004)

4. Total carbonate is not usually very precisely estimated in practice, which adds to the uncertainty of the final measure. (Miller 2004)

The procedures outlined by Steeman-Nielsen were similar to this study, but due to Univer-

sity of Washington regulations, the procedure was done in a controlled radiation van on the *R/V Thompson* in a custom built incubator (Appendix A). The altered method is based off a small volume, short incubation time method proposed by Lewis (1983) where 1mL vials are used for 1 hour incubation. Also, the use of 7mL glass vials were used instead of 7mL polycarbonate vials as suggested to this study to negate the possible contamination of trace metals.

There have also been such procedural problems relating to volume size (Gieskes 1979) showed that larger bottles have higher values, implying that lower surface/volume ratios improve conditions which could be due to few cell-on-wall impacts or to less source glass supplying trace metals. For this experiment, previously used glass vials were used for the incubations. Each vial was subsequently acid rinsed 3 times and seawater rinsed 3 times before the addition of incubation seawater and inoculation. There have also been many problems with the filtration process itself where carbon in smaller molecules is apparently lost due to cell breakage (Gieskes 1979).

Conclusion

In late winter/early spring, algal biomass was still relatively low resulting in primary productivity values that were highly variable and inconsistent with other studies (Furuya 1998; Perterson 1980; Ryther1965) The ability to infer how suspended glacier sediments have any implications on primary production rates proves difficult. These kinds of data make it hard to decipher how primary productivity plays a key role in Glacier Bay comprising higher trophic level species within its pristine waters before the onset of phytoplankton spring blooms. Of course the bay does contain an abundance of high trophic species (Hooge 2002), but the ability to infer the implications of mixed primary productivity data on the biogeography of these species is almost impossible and must be looked at from an improvised perspective. Although, the productivity values may be inconsistent and possibly at the detection limit of the method used, something different, perhaps related to changes in global climate may be happening within the Glacier Bay waters.

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Appendix A – Incubation rig

Photosynthetic measurements as a function of light intensity (P vs. I) yield important information on the productivity patterns of phytoplankton. The small compact incubator is designed to allow rapid measurement of P vs. I curves at sea, based on ^{14}C-carbon assimilation. The incubator provides accurate, flexible regulation of temperature and selection of 25 different light intensities over a range from 0-1600µE m^{-2} sec^{-1}. Set-up time for one measurement is 10 min. the phytoplankton sample is incubated with high specific activity ^{14}C-carbon in a 1 to 7mL total volume in a liquid scintillation vial. Unincorporated ^{14}C-carbon is removed at the termination of the incubation by acidification; precision of

^{14}C-bicarbonate removal is very high. The simultaneous use of several incubators makes it possible to determine a profile of P vs. I curves with depth.

Appendix B – Nutrient analysis

Phosphate

Organic-Phosphate was analyzed using a modification of the Bernhardt and Wilhelms (1967) method. Ammonium molybdate was added to a water sample to produce phosphomolybdic acid, which was then reduced to phosphomolybdous acid (a blue compound) following the addition of dihydrazine (or hydrazine) sulfate. The sample was passed through a 50 mm flowcell and absorbance was measured at 820 nm.

Silicate

Silicate was analyzed using the basic method of Armstrong et al. (1967). Ammonium molybdate was added to a water sample to produce silicomolybdic acid which was then reduced to silicomolybdous acid (a blue compound) following the addition of stannous chloride. The sample was passed through a 15 mm flowcell and absorbance was measured at 820 nm.

Nitrate/Nitrite

A modification of the Armstrong et al. (1967) procedure was used for the analysis of nitrate and nitrite. For NO_3 + NO_2 analysis, a water sample was passed through a Cd column where the NO_3 is reduced to NO_2. This nitrite was then diazotized with sulfanilamide and coupled with N-(1-naphthyl)-ethylenediamine to form an azo dye. The sample is then passed through a 15 mm flowcell and absorbance is measured at 540 nm. A 50 mm flowcell is required for the nitrite. The procedure is the same for the NO_2 analysis less the Cd column. Nitrate concentration equals the (NO_3 + NO_2) concentration minus the NO_2 concentration.

Ammonium

A modification of the Slawyk and MacIsaac (1972) procedure was used for the analysis of ammonium. A water sample was treated with phenol and alkaline hypochlorite in the presence of NH_3 to form idophenol blue (Berthelot reaction). Sodium nitroferricyanide was used as a catalyst in the reaction. Precipitation of Ca and Mg hydroxides was eliminated by the addition of sodium citrate complexing reagent. The sample stream as passed through a 55 degree C heating bath, then through a 50 mm flowcell and absorbance was measured at 640 nm.

Appendix C – Sample scintillation count data from Station 06

	Depth (m)	PAR (µE m^{-2} sec^{-1})	Chl*a* (mg m^{-3})	Transmissivity (%)
Station 01	Surface	11.28	0.778	89.56
	Chl_{max}	4.26	0.898	89.46
	10	4.26	0.898	89.46
	20	1.82	0.645	89.16
Station 02	Surface	13.35	0.440	86.18
	Chl_{max}	0.74	0.600	86.05
	10	4.19	0.600	86.13
	20	1.51	0.590	86.21
Station 05	Surface	10.53	3.150	88.17
	Chl_{max}	1.23	3.400	89.12
	10	4.03	3.400	88.08
	20	1.59	3.450	88.75
Station 06	Surface	6.34	5.910	85.07
	Chl_{max}	2.49	6.417	85.38
	10	2.01	4.455	87.29
	20	1.12	0.115	93.77
Station 08	Surface	0.89	5.940	86.02
	Chl_{max}	0.74	5.137	86.29
	10	0.74	4.400	88.16
	20	0.74	1.420	91.58
Station 11	Surface	29.11	0.755	86.98
	Chl_{max}	6.87	2.540	88.85
	10	7.74	2.170	88.50
	20	3.18	1.720	90.36
Station 12	Surface	19.32	0.418	82.34
	Chl_{max}	4.71	1.589	88.55
	10	6.82	1.570	88.00
	20	2.87	1.450	89.54
Station 21	Surface	24.44	0.645	82.30
	Chl_{max}	8.37	2.420	86.35
	10	8.37	2.420	86.35
	20	2.61	2.395	88.63

Table 3: The averages of PAR, fluorometer (proxy for chlorophyll *a*) and transmissivity data for each station and each of the 4 depths.

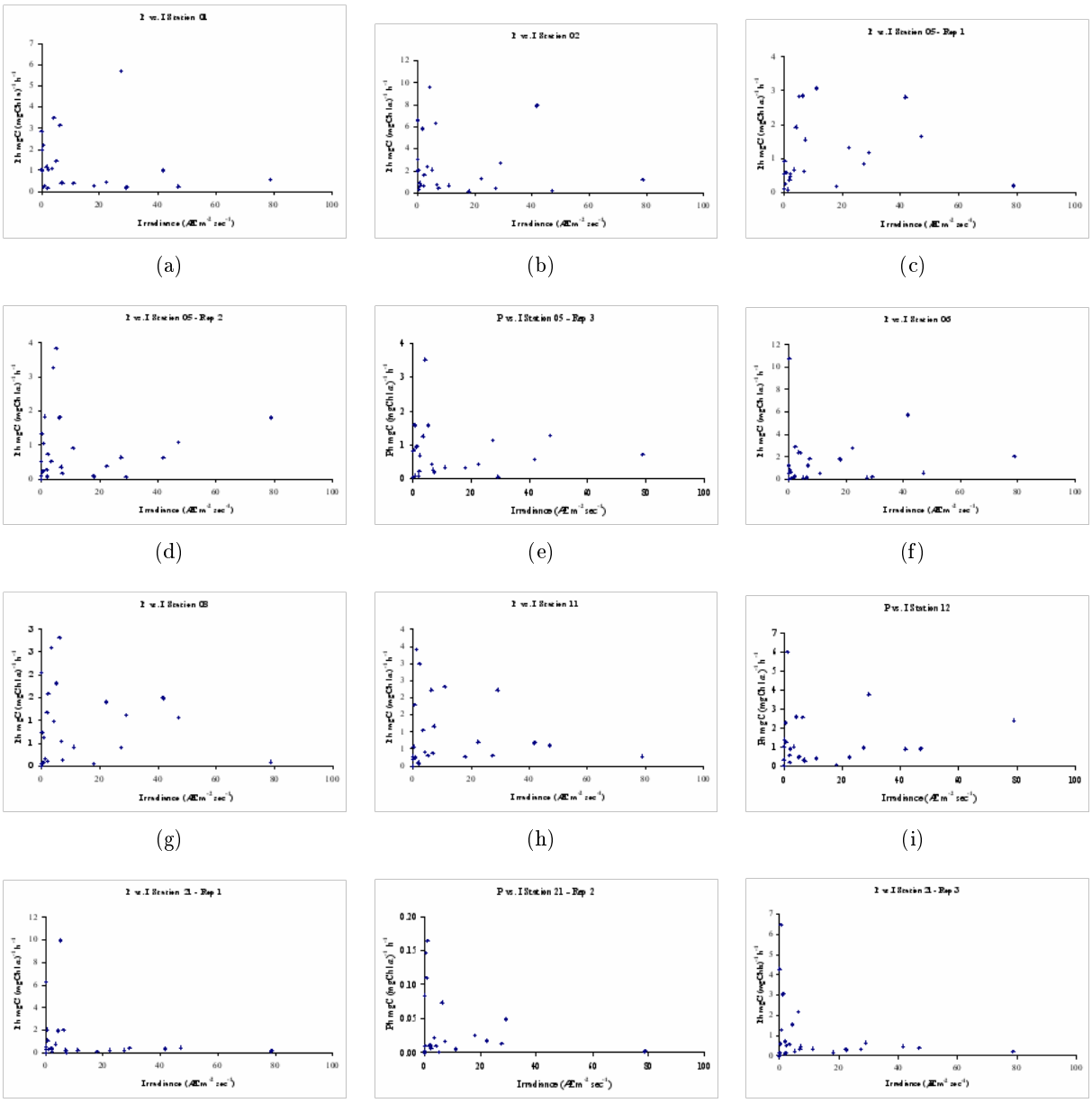

Figure 10: P vs. I curves for each station in Glacier Bay. Stations 05 and 21 were run in triplicate.

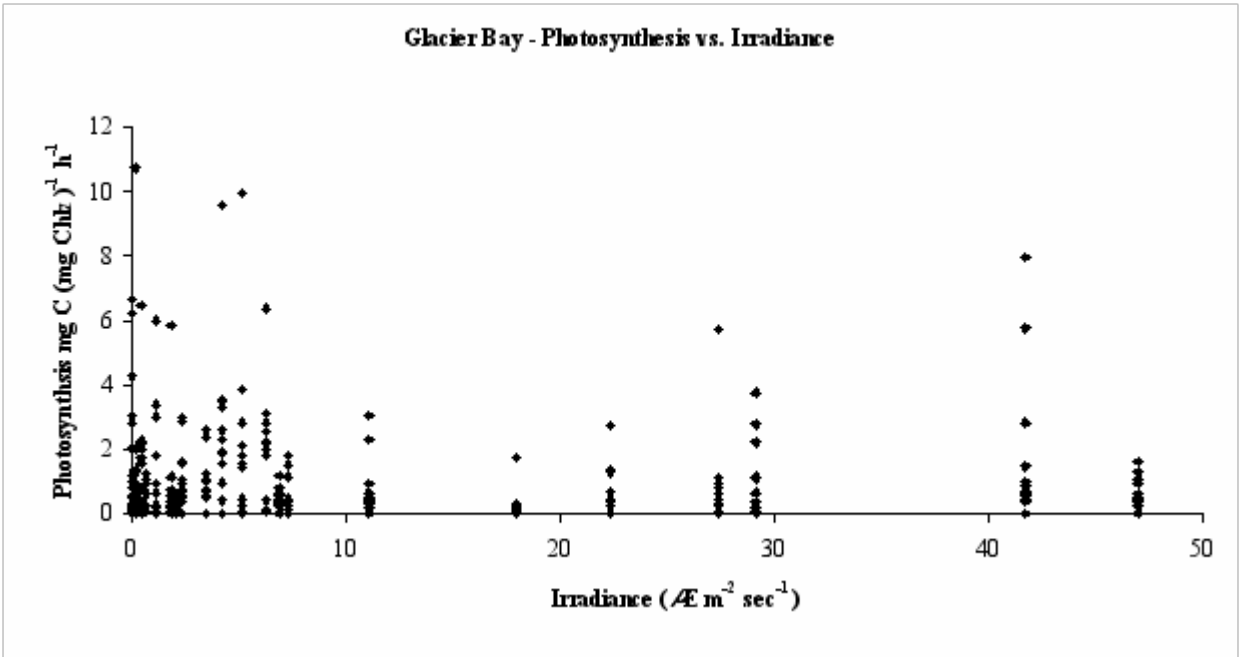

Figure 11: Combined primary productivity values vs. irradiance that show no general trends with increasing irradiance.

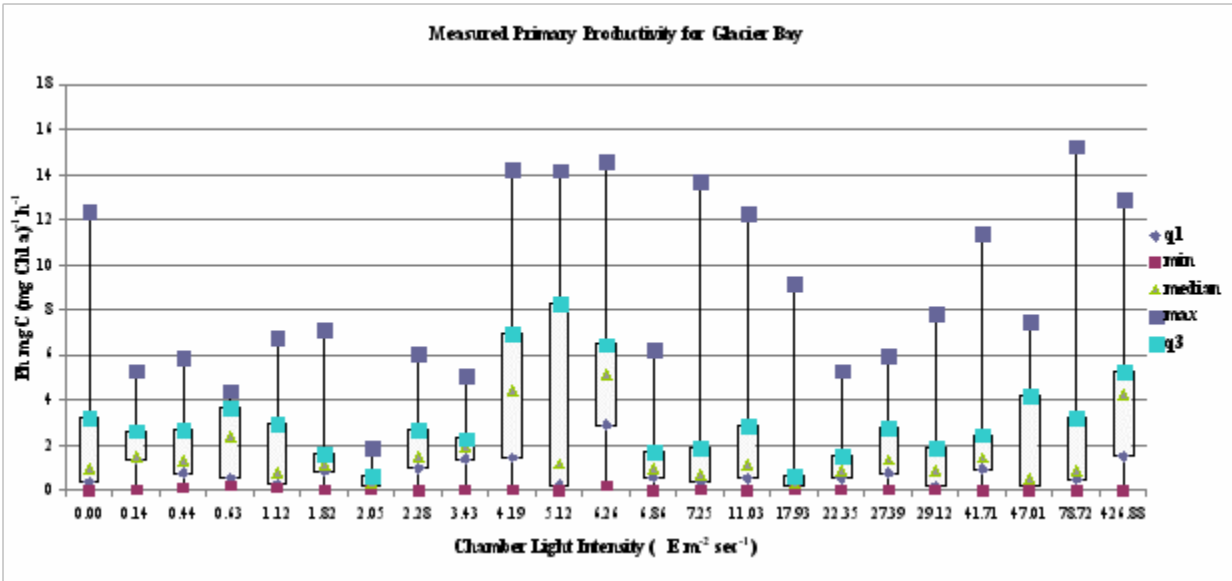

Figure 12: Box and whisker plot of all measured primary productivity in Glacier Bay. Maximum growth calculated was between 4.19 and 6.26 µE m^{-2} sec^{-1}.

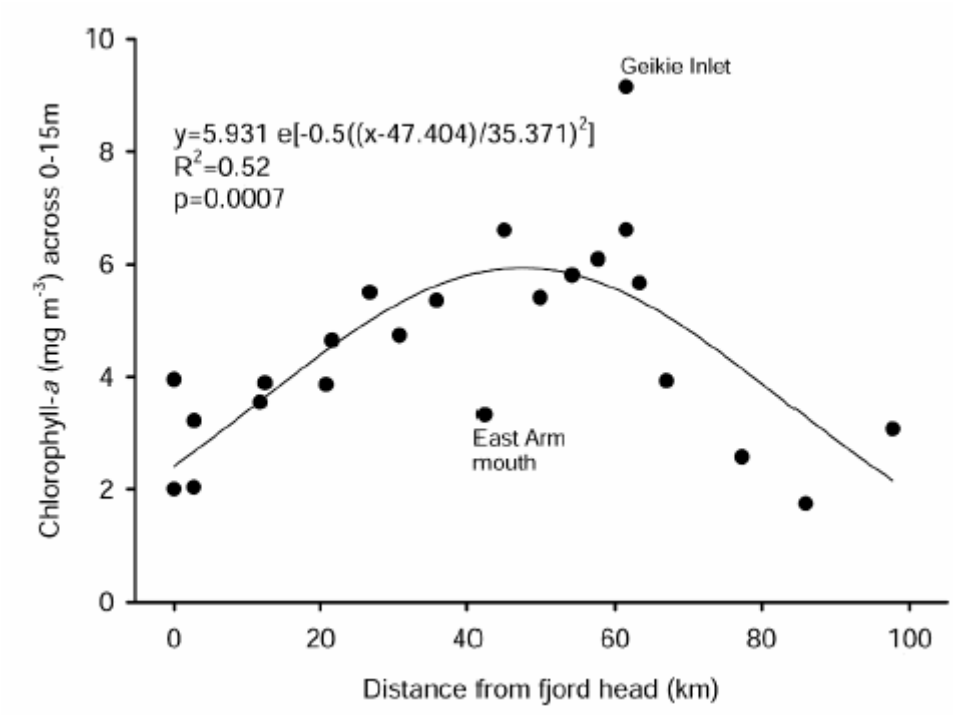

Figure 13: In relation to Fig. 4, Glacier Bay exhibited the same chlorophyll a distribution in relation to distance from the mouth. (Etherington 2007)

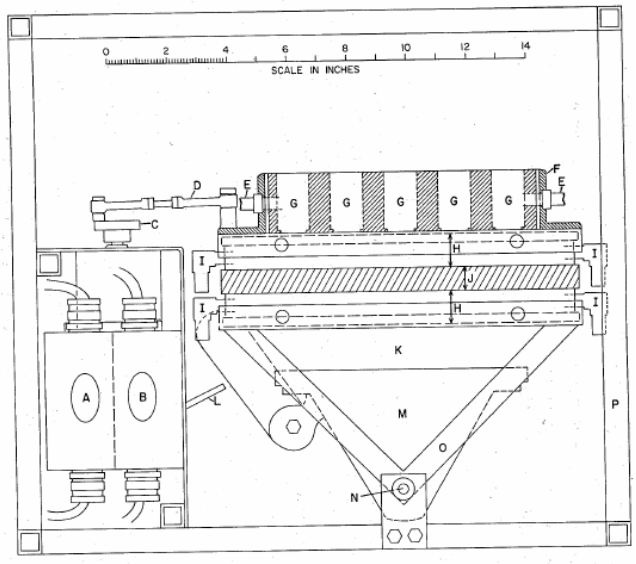

Figure 14: Components are as labeled: A rocker motor; B fan motor; C eccentric; D pitman ; E refrigerator water bath connectors ; F aluminum black with slots ; G for sample vials ; H chambers for cooling seawater ; I connectors for H ; J heat mirror ; K air space ; L air baffle for fan ; M lamp with filament ; N fulcrum ; O pivot support ; P support frames

Chamber #	Light Intensity (µE m^{-2} sec^{-1})	Station/Depth/Rep	C14 CPM	C14 DPM	CPM/DPM
1	5.1165	Station 6/0m	170.60	180.90	94.31%
2	47.0050	Station 6/0m	994.00	1047.66	94.88%
3	29.1175	Station 6/0m	376.40	401.64	93.72%
4	0.0000	Station 6/0m	2242.89	2376.27	94.39%
5	0.4395	Station 6/0m	1497.20	1575.40	95.04%
6	1.1207	Station 6/0m	121.20	127.65	94.95%
7	78.7225	Station 6/Chl_{max}	4080.40	4289.62	95.12%
8	0.0000	Station 6/Chl_{max}	1117.80	1170.68	95.48%
9	7.2528	Station 6/Chl_{max}	3660.36	3841.42	95.29%
10	0.6344	Station 6/Chl_{max}	1203.60	1258.05	95.67%
11	1.8170	Station 6/Chl_{max}	363.40	379.84	95.67%
12	27.3900	Station 6/Chl_{max}	230.60	242.82	94.97%
13	6.2638	Station 6/10m	224.40	236.11	95.04%
14	17.9320	Station 6/10m	2456.59	2602.12	94.41%
15	6.8638	Station 6/10m	1690.20	1768.65	95.56%
16	2.0488	Station 6/10m	364.40	386.29	94.33%
17	11.0300	Station 6/10m	710.20	743.11	95.57%
18	426.8750	Station 6/10m	517.40	546.65	94.65%
19	22.3475	Station 6/20m	121.60	127.41	95.44%
20	3.4308	Station 6/20m	107.00	112.12	95.43%
21	0.1446	Station 6/20m	408.20	428.34	95.30%
22	0.0000	Unused	Unused	Unused	Unused
23	41.7075	Station 6/20m	229.40	240.28	95.47%
24	2.2803	Station 6/20m	125.20	131.81	94.99%
25	4.1860	Station 6/20m	105.80	110.77	95.51%

Table 5: Sample scintillation count data from Station 06