Study of the Distribution of Biological Thin Layers in Glacier Bay, Alaska

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Abstract

Glacier Bay, Alaska is a very productive coastal region supporting diverse marine, lotic and terrestrial food webs. Primary productivity and the seasonal formation of high algal biomass, lays the foundation for supporting all other life in the ocean and strongly structures the recruiting success of marine animals. Understanding the dynamic interactions between micro-organisms and their physical environment provides us with valuable information about processes and interactions that spatially structure the marine environment and thereby affect the feeding and recruiting success of higher trophic levels. Studies in the emerging field of phytoplankton thin layers, specifically for northern latitudes are very infrequent. This project encompasses spatial patterns of algal biomass in particular its aggregation or confinement, into “thin layers” within the water column that are thought to act as floating salad bars for higher order predators like zooplankton and planktivorous fish species. In March 19^{th}–22^{nd} 2008 the vertical distribution and frequency of phytoplankton thin layers throughout Glacier Bay was determined using a suite of in situ instruments and vertical tows totaling 31 stations. Thin layers were found closely associated with the pycnoclines. The depth at which the pycnocline and thin layer formation occurred was shallower at the mouth of Glacier Bay and got deeper as one travelled from the mouth of the Bay to the tip of the West arm. The overall chlorophyll concentration within the water column did not have a significant effect on the potential for thin layer formation, it is concluded that there must be an intricate balance between both physical and biological processes that contribute to the formation of thin layers.

Introduction

Discontinuities in salinity and temperature are frequent phenomena in natural waters (Harder, 1968). They occur regularly in marine environments where marked stratification exists. Temperature dominates the control on density stratification of ocean waters in most parts of the globe; however at higher latitudes salinity takes a more dominant role (Carmack, 2007). This is largely due to the relative temperature difference between surface and deep waters. At high latitudes this temperature gradient is much weaker than in temperate areas therefore; salinity plays a more dominant role in the density profiles of higher latitude waters. The stratification of Glacier Bay, Alaska is primarily controlled by salinity and its level of stratification is regulated by the magnitude of freshwater input from glacial melt and rivers. The magnitude of freshwater input varies significantly depending on the time of year, i.e. summer months, when the cloud cover is significantly less and the temperatures are warmer, the magnitude of freshwater input is much higher than that of the winter months. This annual variation in freshwater input shows a distinct signature in the level of stratification of the water column throughout Glacier Bay. The level of stratification of a particular body of water influences many physical properties of the water column, particularly the distribution of objects of differing density and sinking velocity such as suspended sediment, and more pertinent to this study sinking algae. The relative abundance of algae within the water column e.g. particularly in thin layers, has cascading effects on the dynamics of the marine food.

Density discontinuities, combined with other physical and biological forcings can cause the formation of "thin layers" within the water column that trap non-motile organisms, namely phytoplankton, but can also trap fine sediments and any other particulate matter in the upper water column. This focusing of phytoplankton and particulate matter can sometimes result in an incredible amount of biomass in a layer on the order of a few centimeters to a few meters thick. In a study of West Sound on Orcas Island in the San Juan Islands, a thin layer located in the upper water column had a thickness of 3.25m and contained 63.5% of the total biomass detected in the vertical water column (Holliday et al., 1998).

Experimental laboratory studies using an array of 2 L graduated cylinders, have shown with near zero uncertainty, the entrainment of planktonic organisms around density discontinuities in a wide variety of lighting conditions as well as various strengths in stratification in all experimental conditions tested (Harder, 1968). Such temporally and spatially coherent thin layers of phytoplankton can have important impacts on the biological structure and dynamics of marine systems (Dekshenieks et al., 2001). Most studies investigating thin layers have focused on the development of sampling devices and the documentation of physical and biological thin layers (Cowles et al., 1993, Desiderio et al., 1993, Dekshenieks et al., 2001), and hypothesize as to the ecological importance of thin layers (Clay et al. 2003). Thin layers of phytoplankton act as essential "salad bars" and as visual protection from predators and thereby provide zooplankton, fish and invertebrate larvae seeking thin layers with a competitive advantage (Menden-Deuer, 2008).

Glacier Bay, Alaska is a coastal region known for its high productivity throughout many trophic levels from primary production, to herring, to salmon, to whales (Etherington et al., 2007). Due to the highly productive nature of the region and apparent high fish recruiting success the potential implications of a thin layer study were far reaching. This investigation is the first study determining the frequency and distribution of thin layers in Glacier Bay. This study contributes to the emerging field of biological thin layers, in particular for northern latitudes where such studies are generally very infrequent. I have statistically analyzed the occurrence and frequency of thin layers distributed throughout Glacier Bay, proposing the potential benefits of thin layers for visual protection as well as their resource potential for higher trophic levels. I propose that thin layers are key links in energy transfer from primary production to higher trophic levels particularly early in the season where algal concentrations are generally low. I hypothesized that thin layers would form within or near the pycnocline throughout Glacier Bay as this is where the confinement of drifting matter by physical properties of the water column was most likely to occur.

Methods

Study Area

Glacier Bay is a large glacially carved fjord located in southeast Alaska (58°45' N, 136°20' W). Glacier Bay is a large "Y" shaped fjord averaging 233 meters in depth, is roughly 100 kilometers in length and 16 kilometers wide. Glacier Bay exchanges seawater with the Gulf of Alaska through a narrow, shallow silled mouth

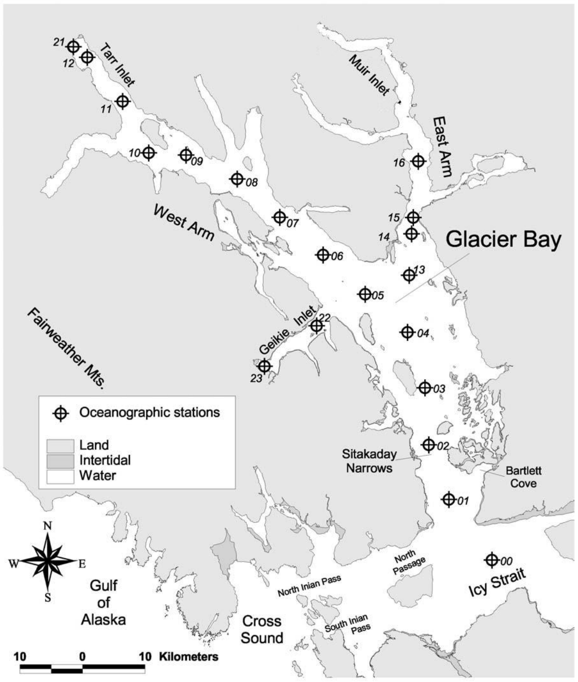

Figure 1: Map of stations where CTD profiles were taken. Map from (Hooge and Hooge, 2002) and modified for the purposes of this study. The latitude and longitude coordinates are identical to those of Hooge and Hooge.

open to Icy Strait. The Bay has three major sills that significantly impact water movement. Sills at the mouth and one at the base of each arm are responsible for much of the deep and surface water mixing.

Sampling Technique

In a four day study (March 19-22, 2008) aboard the R/V Thomas G. Thompson, fine scale profiles of biological and physical structure were measured in 31 profiles of the water column (Figure 1).

Using a Sea-Bird® CTD instrument, the temperature, salinity and depth were measured as well as chlorophyll using a CTD mounted in-situ fluorometer. All profiles were cast at an average resolution of one reading for every half a centimeter. The following analyses were used to locate biological thin layers.

Data Analysis

Criteria for Identifying Thin Layers: The first criterion for identifying thin layers in this study was that the chlorophyll signature, or spike on the fluorescence profiles, must be ≤ 2 m thick. This value was selected because it is finer than bottle and net sampling techniques can sample and is also within the thickness that previous studies have used to define thin layers (McManus et al., 2003, Birch et al., 2007, Ryan et al., 2008). The second criterion was that the spike in chlorophyll must be $\geq 30\%$ percent above the ambient level of chlorophyll in the water. This was calculated by taking the value at the tip of the fluorescence spike and dividing it by the value of the ambient level of chlorophyll at the same depth (Figure 2).

Results

Statistical Analysis

Correlations of variables were performed using:

The first relationship was to determine the overall average distribution of chlorophyll within Glacier Bay in what was defined as the "chlorophyll zone". The chlorophyll zone was defined as the depth integral in which chlorophyll concentration remained larger than zero and changes in chlorophyll concentration could be instrumentally measured. The average chlorophyll at each station was calculated by adding all depth values of chlorophyll within the chlorophyll zone divided by the total number recorded (Figure 3).

The second relationship drawn was to plot the thin layers against density to determine whether or not thin layers formed at a specific isopycnal(s) throughout Glacier Bay (Figure 4).

The third relationship was to plot the thin layers as a function of distance from the pycnocline at each station as well as their distance from the chlorophyll-max to determine any correlation between the two (Figure 5).

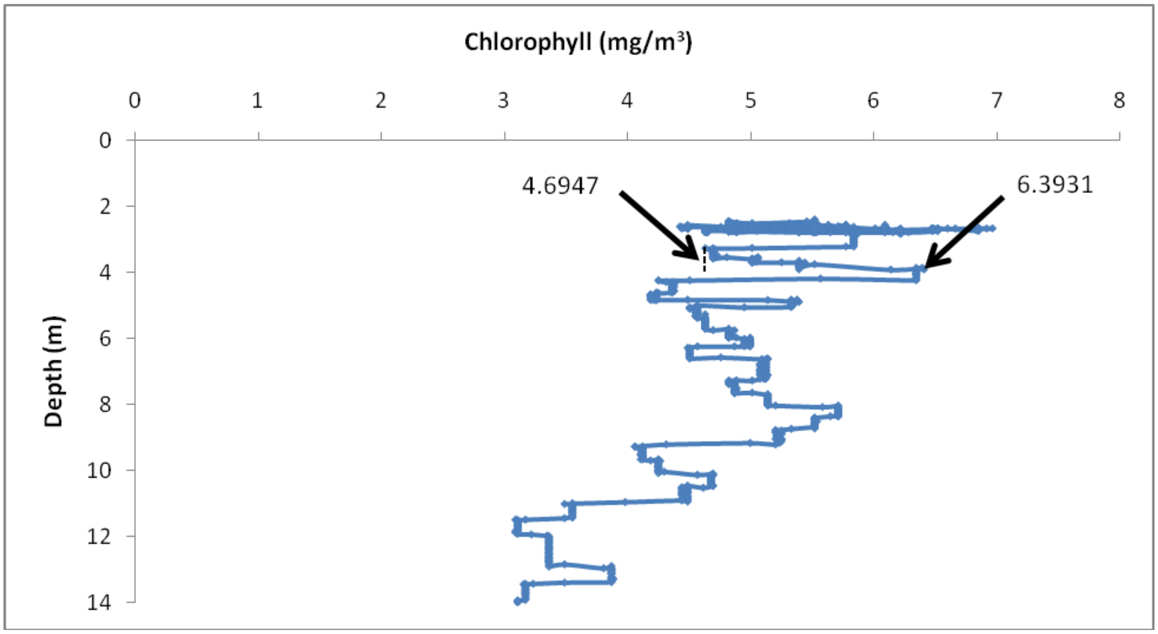

Figure 2: A fluorescence profile depicting the methods used to determine the existence of a thin layer. The value at the tip of the spike divided by the value of the ambient level of chlorophyll at that depth must be equal to or greater than 30%. Ex pictured: 6.3931 / 4.6947 = 37%.

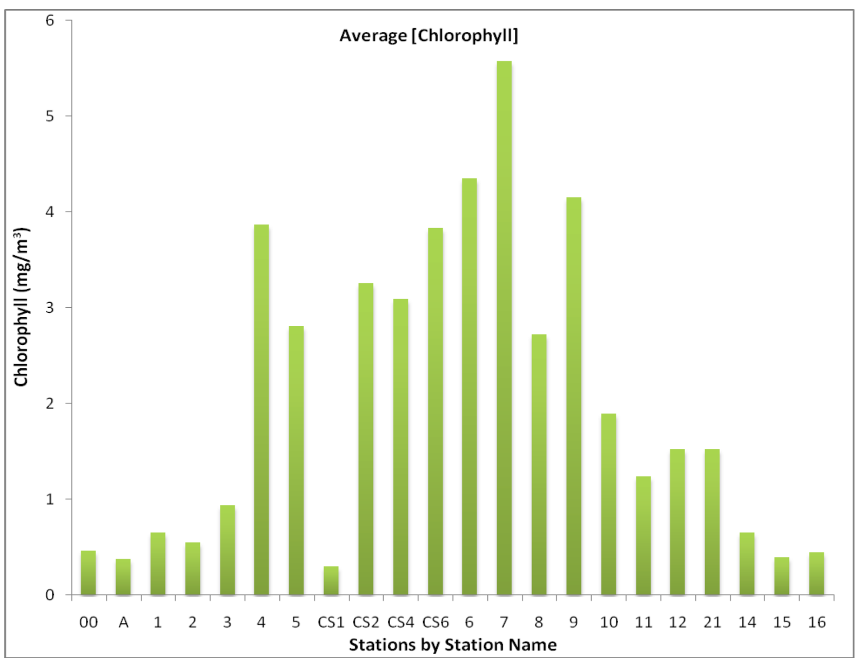

Figure 3: A graph of the average distribution of chlorophyll throughout Glacier Bay in the upper water column (chlorophyll zone). Chlorophyll zone was defined as the area above which chlorophyll fell to a value of near zero and did not vary from that value. This alleviated the bias of station depth, giving a more accurate distribution of chlorophyll throughout the Bay.

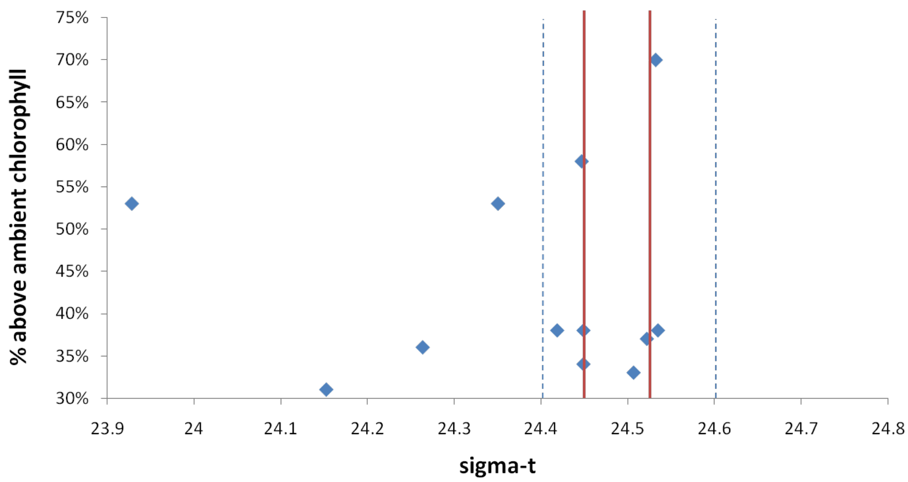

Figure 4: The 12 thin layers plotted against the density at which they formed. The the dotted lines depict the range in which $\frac{2}{3}$ of the thin layers fell and the y axis is the intensity or relative concentration of phytoplankton within the thin layer. Two isopycnals are align with 6 of the thin layers, depicted by the two solid lines.

Distinct phytoplankton layers were observed in fluorescence profiles on March 19-22. A 15 station transect from the mouth of Glacier Bay, north to the end of the West arm displays the structuring of fluorescence within the vertical water column as well as the average depth at which the evident thin layers formed (Figure 6). The average depth at which the layers formed was increasingly deeper going from the mouth of the Bay to the end of the West arm. The averaged chlorophyll values, within the chlorophyll zone, the maximum depth of which varied from 20 m to 100 m for each station, varied from 0.289 to 5.57 mg/m^3 and did not seem to be closely associated with the likelihood of layer formation. Out of the 31 profiles cast in Glacier Bay there was evidence of thin layers at 23% of them, or 7 stations, accounting for a total of 12 definitive thin layers.

All 12 thin layers were evenly distributed above and below the pycnocline, 6 lying above and 6 lying below. The zone within which 70% of the thin layers formed throughout the Bay was focused on an average density of 24.3799kg/m3 with a standard deviation of 0.18323kg/m3 (Figure 6). The average depth of thin layer formation and standard deviation from that depth, encompassing 70% of the evident thin layers in Glacier Bay, is shown as a function of distance from the pycnocline and chlorophyll-max (Figure 5). Seventy percent of the layers are contained within the boxes with the line depicting the average distance from both the pycnocline and chlorophyll-max and the error bars indicating the full range of the remaining 30% of the thin layers (Figure 5).

Discussion

The spatial pattern in phytoplankton composition identified in this study suggest that, the depth interval at which thin layers form in Glacier Bay gets increasingly deeper as one goes from the mouth of the Bay to the end of the West arm (Figure 6). The depth of the pycnocline followed this same pattern indicating a link between the depth of the pycnocline and the subsequent depth of thin layer formation. The identified thin layers contained as much as 70% higher concentrations of plankton than in

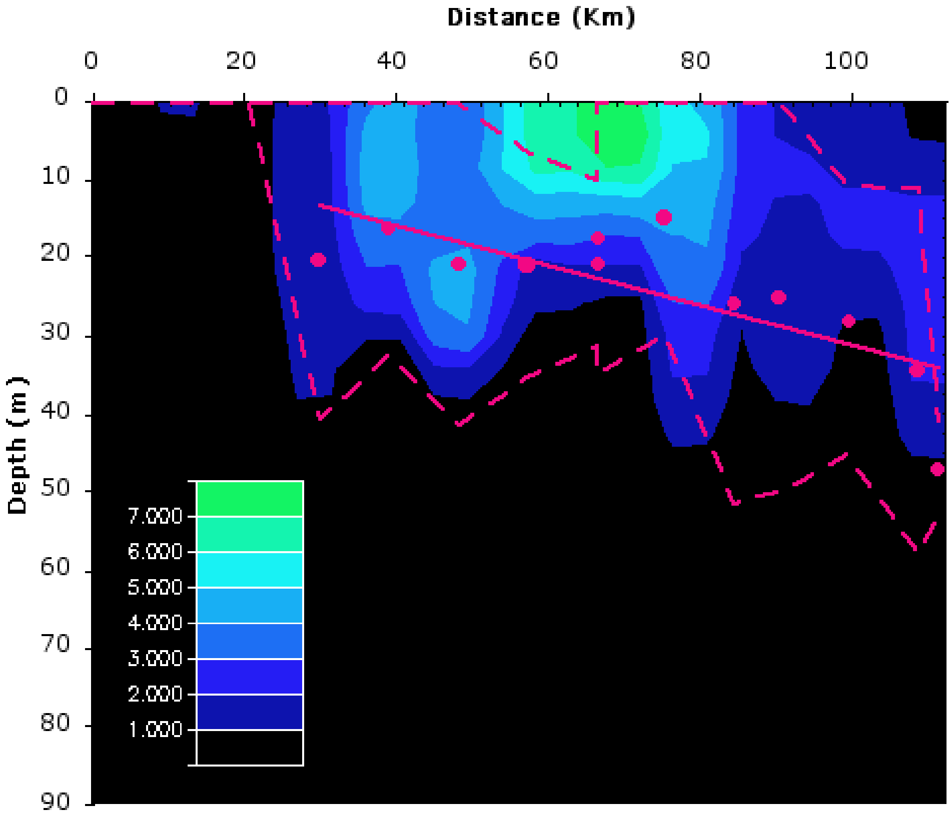

Figure 6: A 15 station transect from the mouth of Glacier Bay to the tip of the West Arm displaying the chlorophyll distribution. Distance is a measure of kilometers from the mouth of the Bay. The dotted lines depict the zone in which the thin layers formed. The line depicts the average depth of thin layer formation. The slope of the linear regression line is: $y = 0.2539x + 5.7326$ with an R^2 value of: $R^2 = 0.5716$.

surrounding waters indicating a distinct layering of the water column with respect to biomass concentration.

The thin layers in this study were indissolubly linked with the subsequent depth of the pycnoclines; or depth in the water column where the density gradient was the strongest (Figure 5). This has been documented in many other thin layer studies (Osborn, 1998, Dekshenieks et al., 2001, McManus et al., 2003, Menden-Deuer, 2008,) and supports my hypothesis that thin layers would be most likely to form within or near the pycnocline.

Thin layers are known to form in a number of circumstances from the balancing of physical environmental forcings like shear and turbulence to intricate biological predator-prey relationships (Osborn, 1998, MacIntyre et al., 1995, Ryan et al., 2008, Menden-Deuer, 2008). The diverse ways in which they form make prediction of their formation in any one location fairly difficult, but the nature of their variable formational circumstances also signifies their potential importance in a wide variety of coastal and open ocean regions.

Thin layers have recently been discussed as being important physical entities in marine environments offering highly concentrated resource patches for filter feeders and higher order predators as well as visual protection for zooplankton from planktivorous fish (Leising, 2001, Ignoffo et al., 2005, Menden-Deuer, 2006). This is quite possibly the case for Glacier Bay however thin layer studies investigating the potential for these

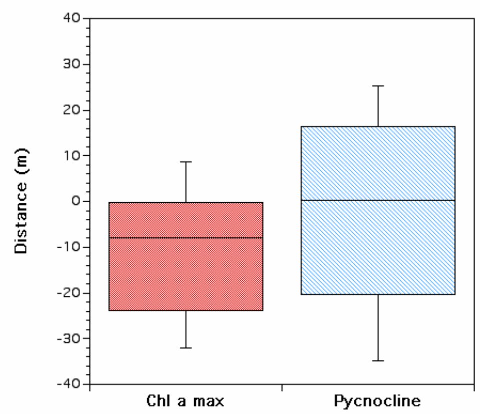

Figure 5: The thin layers plotted as a function of distance from the chlorophyll max and pycnocline. The box contains 70% of the thin layers with the intersecting line depicting the average distance from each respective variable. The capped lines depict the range of the remaining 30% of the thin layers explored in this study.

environmental benefits have yet to be carried out. The existence and persistence of planktonic thin layers generates extensive biological heterogeneity in the water column and may be important in maintaining species diversity and overall community structure (McManus et al., 2003). Thin layers were undoubtedly evident in Glacier Bay, brought to light in this study, and with further investigation it could be the case that these micro-layers play an important role in maintaining the species diversity seen throughout Glacier Bay today. In a case study by McManus et al., 2003, he proclaimed that thin layers, in effect, produce microenvironments of physical, chemical and biological parameters and that the persistence of these microenvironments on timescales as long, or longer than the generation times of many plankton species is likely to preserve and maintain species diversity by spatial partitioning of the pelagic environment.

The existence of phytoplankton thin layers, as mentioned before, has cascading effects into higher trophic levels primarily first order predators like zooplankton. Zooplankton benefit from dense patches of food (phytoplankton) because it reduces the amount of energy they must use to acquire the necessary resources they need to survive. The energy costs of finding food in the vast open ocean and even in small coastal regions, like Glacier Bay is very high considering the volume of water and subsequent patchiness nature of planktonic organisms. A copepod moving up or down in the water column has a much higher probability of encountering food-rich micro-patches if those patches are spread out into very thin layers effectively reducing their search strategy from three dimensions to one (Widder et al., 1999). This infers that thin layers are essential for the feeding and reproductive success of many first order predators by reducing the energy cost per unit food acquired and, in turn, passing that advantage up the trophic food chain to fish larvae and planktivorous fish which is likely no exception t o Glacier Bay.

Most studies indicating that the existence of thin layers of food (i.e. plankton) significantly increases the growth of zooplankters measured by various methods including egg and fecal production, to name a few, (Tiselius, 1992, Saiz et al., 1993) are essential to thin layer understanding but the results are difficult to 'scale up' to the field. This is due in part by the size of the vessels, restricting the movement of zooplankters over anything but the shortest time scales of observation (Leising, 2001). In situ studies, as difficult as they are to encompass or quantify all physical and biological parameters on an array of various temporal and spatial scales, are key to understanding what the 'real world' benefits of biological thin layers are. Key advancements in observational and sampling techniques may possibly hold the answer to the many questions surrounding thin layers and the potentially important and intricate role they play in Glacier Bay and the oceans worldwide.

Conclusions

- Thin layers are not closely associated with the overall chlorophyll within the water column, meaning that higher overall chlorophyll concentration within the water column do not necessarily increase the chances of thin layer formation.

- Thin layers are closely associated with the depth of the pycnocline in Glacier Bay.

- Thin layers form at deeper depths as one travels from the mouth of Glacier Bay to the tip of the West Arm in early spring.

- The depth of the pycnocline increases as one travels from the mouth of Glacier Bay to the tip of the West Arm in early spring.

- There must be an intricate balance between both physical and biological processes that contribute to the formation of thin layers.

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References

Carmack, E.C.. 2007. The alpha/beta ocean distinction: A perspective on freshwater fluxes, convection, nutrients and productivity in high latitude seas. Deep Sea Research II. **54**: 2578-2598.

Clay, T.W., S.M. Bollens, A.B. Bochdansky, T.R. Ignoffo. 2003. The effects of thin layers on the vertical distribution of larval Pacific herring, *Clupea pallasi*. J. Exp. Mar. Biol. Ecol. **305**: 171-189.

Cowles, T.J., R. Desiderio, S. Neuer. 1993. In situ characterization of phytoplankton from vertical profiles of fluorescence emission spectra. Mar. Biol. **115**: 217-222.

Dekshenieks, M.M., P.L. Donaghay, J.M. Sullivan, J.B. Rines, T.R. Osborn, M.S. Twardowski. 2001. Temporal and spatial occurrence of thin phytoplankton layers in relation to physical processes. Mar. Ecol. Prog. Ser. **223**: 61-71.

Desiderio, R., T.J. Cowles, J. Moum, M. Myrick. 1993. Microstructure profiles of laser-induced chlorophyll fluorescence spectra: evaluation of backscatter and forward-scatter fiber-optic sensors. J. Atmos. Ocean. Technol. **10**: 209-224.

Etherington, L.L., P.N. Hooge, E.R. Hooge, D.R. Hill. 2007. Oceanography of Glacier Bay, Alaska: Implications for biological patterns in a glacial fjord estuary. Estuaries and Coasts. **30**: 927-944.

Harder, W.. 1968. Reactions of plankton organisms to water stratification. Limnology and Oceanography. **13**: 156-168.

Holliday, D.V., R.E. Pieper, C.F. Greenlaw, J.K. Dawson. 1998. Acoustical sensing of small-scale vertical structures in zooplankton assemblages. Oceanography. **11**: 18-23.

Hooge, P.N., and E.R. Hooge. 2002. Fjord oceanographic processes in Glacier Bay, Alaska. USGS: 1-148.

Ignoffo, T.R., S.M. Bollens, A.B. Bochdansky. 2005. The effects of thin layers on the vertical distribution of the rotifer *Brachionus plicatilis*. J. Exp. Mar. Biol. Ecol. **316**: 167-181.

Leising, A.W. 2001. Copepod foraging within patchy habitats and thin layers using a 2D individual-based model. Mar. Ecol. Prog. Ser. **216**: 167-179.

McManus M.A., A.L. Alldredge, A.H. Barnard, E. Boss and 21 others. 2003. Characteristics, distribution and persistence of thin layers over a 48 hour period. Mar. Ecol. Prog. Ser. **261**: 1–19.

MacIntyre, S., A.L. Alldredge, C.C. Gottschalk. 1995. Accumulation of marine snow at density dincontinuities in the water column. Limnology and Oceanography. **40**: 449-468.

Menden-Deuer S., D. Grünbaum. 2006. Individual foraging behaviors and population distributions of planktonic predators aggregating to phytoplankton thin layers. Limnology and Oceanography. **51**: 109–116.

Menden-Deuer S. 2008. Spatial and temporal characteristics of plankton-rich layers in a shallow, temperate fjord. Mar. Ecol. Prog. Ser. **355**: 21-30.

Osborn, T. 1998. Finestructure, microstructure, and thin layers. Oceanography. **11**: 36-43.

Ryan, J.P., M.A. McManus, J.D. Paduan, F.P. Chavez. 2008. Phytoplankton thin layers caused by shear in frontal zones of a coastal upwelling system. Mar. Ecol. Prog. Ser. **354**: 21-34.

Saiz E., P. Tiselius, P.R. Jonsson, P. Verity, G.A. Paffenhöfer. 1993. Experimental records of the effects of food patchiness and predation on egg production of *Acartia tonsa*. Limnology and Oceanography. **38**: 280–289.

Tiselius P.. 1992. Behavior of *Acartia tonsa* in patchy food environments. Limnology and Oceanography **37**: 1640–1651.

Widder, E.A., S.A. Johnsen, S.A. Bernstein, J.F. Case, D.J. Neilson. 1999. Thin layers of bioluminescent copepods found at density discontinuities in the water column. Marine Biology. **134**: 429-437.