Photosynthetically Active Radiation (PAR) Measurement

Subtitle

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Abstract

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List of Symbols

x	position
v	velocity
a	acceleration
t	time
F	force

Acronyms

ACC Antarctic Circumpolar Current. 3

MIZ Marginal Ice Zone. 4

PAR Photosynthetically Active Radiation. 6, 7

Glossary

frazil ice a collection of loose, randomly oriented ice crystals. 4

Chapter 1

Introduction

1.1 Background

1.2 Problem statement

The distribution of sea ice in the Southern Ocean's Marginal Ice Zone (MIZ) plays a crucial role in global climate patterns. Despite this, our understanding of this region suffers from lack of in situ data measurement, especially over the winter season. Sea ice acts as both a reflective boundary and physical insulator for the water below, affecting light transfer to the underlying water. This in turn impacts the energy available for phytoplankton growth. Recent studies have shown phytoplankton growth under sea ice in late winter, challenging previous assumptions that sea ice melting preceded or concurred with significant phytoplankton growth. Phytoplankton play an important role in the global system, contributing to the carbon uptake of the Southern Ocean, as well as acting as the base of the Antarctic region's food web. Thus, it become imperative to better understand the through-ice and under-ice radiative transfer, especially for this unique region.

Research grade Photosynthetic Active Radiation (PAR) sensors are traditionally very expensive, making them unsuitable for deployment in environments where they may not be recovered. The development of a robust and affordable PAR sensor using off-the-shelf components would greatly improve data measurement capabilities, and thus improve our understanding of this region. By providing an affordable and reliable measurement solution, this project aims to fill the knowledge gaps in Antarctic sea ice radiative transfer properties. This will in turn contribute to a deeper understanding of the role played by the MIZ in the global climate system.

1.3 Project objectives

The aim of this project is to design, test and validate a single sensor node. The sensor node should primarily be able to measure Photosynthetically Active Radiation (PAR) within and below sea ice. Additionally, the sensor node should include the optional addition of temperature, conductivity (salinity), or ultraviolet radiation sensors. The sensor node should be designed to be as low power as possible, and able to withstand extreme environmental conditions.

1.4 Scope, limitations and assumptions

1.4.1 Scope

While the overall goal of this project is the development of the optical sensor-chain for through-ice deployment, the scope of this research project is limited to the development, testing and validation of a single sensor node using off-the-shelf components.

The sensor node should be designed so it can be implemented in a sensor-chain. Accommodations will also be made in the node design for additional sensors, such as temperature and conductivity (salinity) sensors.

1.4.2 Limitations

The primary limitation of this project is the fixed 13-week period within which all the work must be completed. Additionally the availability of components within South Africa, and the associated shipping costs and delays add further limitations.

The extreme weather conditions in the Antarctic region limit design choices for the sensor node, as well as impacting the sensor reliability and accuracy.

Another limitation may be access to a research grade PAR sensor, which is vital to validating measurements and calibrating the sensor node.

1.4.3 Assumptions

This project assumes that the observed late winter phytoplankton growth is indicative of potential radiative transfer through sea ice, justifying the need for improved data measurement capabilities.

1.5 Plan of development

This remainder of this thesis is organised as follows:

- Chapter 2: Literature Review
- Chapter 3: Hardware Design
- Chapter 4: Software Design
- Chapter 5: Experiment Testing Rig Design and Setup
- Chapter 6: Experiment Procedure
- Chapter 7: Results
- Chapter 8: Discussion
- Chapter 9: Conclusion
- Chapter 10: Recommendation for Future Work

Chapter 2

Literature Review

2.1 The Importance of Antarctic Research

Antarctica and the Southern Ocean (the Antarctic) are intricately linked with the rest of the world through oceanic and atmospheric couplings, making them an essential component of the Earth system [Kennicutt et al., 2019]. Despite this inherent significance, the region has been historically neglected in terms of research, especially when compared to the Arctic region [Meredith and Brandon, 2017,Kennicutt et al., 2019].

Geographically, the two regions are significantly different. The Arctic region is an ocean surrounded by land, and is relatively sheltered [Kennicutt et al., 2019]. By comparison, the Antarctic region consists of a continental landmass surrounded by the Southern Ocean [Kennicutt et al., 2019,Meredith and Brandon, 2017]. These geographical differences have a significant impact on the climate and sea ice formation in each region. Thus, it is imperative that more research be conducted within the Antarctic region.

This section will further explain aspects of the Antarctic Region. First by explaining how the region impacts the rest of the world, then by further detailing the climate in the region. Finally, details regarding the sea ice structure and formation in the region will be expanded on.

2.1.1 How the Antarctic Impacts the Global System

Changes in the Antarctic have extensive effects on the rest of the planet [Kennicutt et al., 2019]. The Antarctic Circumpolar Current (ACC) is the world's largest current system. It is responsible for the continuous transport of water eastwards around Antarctica [Meredith and Brandon, 2017]. The ACC is the main means of water exchange between oceans [Meredith and Brandon, 2017]. The Southern Ocean is also the main region in which deep waters are upwelled to the surface. This allows the deep water to be converted into both denser and lighter waters [Meredith and Brandon, 2017]. Upwelling is an important process, as it brings carbon and nutrient-rich waters up to the surface [Tamsitt et al., 2018].

The Southern Ocean accounts for 40% of the total anthropogenic heat and CO_2 uptake by the world's oceans [Deppeler and Davidson, 2017,Kennicutt et al., 2019]. This heat and carbon dioxide is then transported northward by the overturning circulation, leading to delayed warming near Antarctica and increasing the ocean inventory of anthropogenic heat and carbon dioxide further north. [Kennicutt et al., 2019].

2.1.2 The Antarctic Climate and Antarctic Sea Ice

Given the exposed nature of the Antarctic region, sea ice formation in the Southern Ocean is subject to extreme weather conditions. The region is subject to the world's most powerful prevailing (westerly) winds, the highest waves, as well as frequent storms [Maksym et al., 2012]. The Southern Ocean and its sea ice also experience the highest snowfall rates of any region on Earth [Simmonds, 2015].

Sea ice plays many vital roles in both the local Antarctic region as well as the global earth system [Parkinson, 2004]. Sea ice in the Antarctic is highly seasonally, varying from a maximum of 19 x $10^6 km^2$ to a minimum of 3 x $10^6 km^2$ [Simmonds, 2015]. The ice acts as a reflective barrier, reflecting most of the solar radiation incident on it (albedo). It also acts as an insulator, protecting the life below the ice from the cold polar atmosphere [Parkinson, 2004]. The sea ice also reduces wave motion and decreases evaporation rates of the ocean. [Parkinson, 2004].

The Marginal Ice Zone (MIZ) is the region where consolidated sea ice transitions to the open ocean. [Deppeler and Davidson, 2017]. The sea ice formed in this region is largely influenced by the extreme weather conditions in the Antarctic. The MIZ is composed of frazil ice which is formed when large amounts of heat are extracted in the turbulent conditions in the open ocean [Maksym et al., 2012, Arrigo and Thomas, 2004]. As these ice crystals accumulate and weather conditions become less turbulent, they begin to consolidate into pancake ice [Maksym et al., 2012].

Thus far, climate models have been unable to predict the sea ice extent (SIE) patterns in the Antarctic. While climate models have successfully (albeit conservatively) predicted the sea ice loss in the Arctic, the same models predict sea ice loss in the Antarctic. However, satellite observations have shown a small overall increase of the SIE in the Antarctic [Simmonds, 2015]. The inability of climate models to correctly predict the behaviour or Antarctic sea ice further highlights the neglect of the region in previous research efforts.

2.2 Phytoplankton

Phytoplankton form the base of the Southern Ocean food web [Deppeler and Davidson, 2017]. The term phytoplankton refers to all single-celled organisms that produce their own food via the process of photosynthesis [Pierella Karlusich et al., 2020]. Phytoplankton play various roles within the Southern Ocean ecosystem. Their primary role is as the base of the microbial food web. Phytoplankton that isn't grazed on by other micro-organisms sinks to the deep ocean, in a process known as biological pump [Deppeler and Davidson, 2017]. Carbon sequestered to the deep ocean via phytoplankton account for 10% of the total carbon uptake in the Southern Ocean [Deppeler and Davidson, 2017].

Phytoplankton account for only 1% of the Earth's photosynthetic biomass, however they are responsible for generating more than 45% of the global net primary production [Pierella Karlusich et al., 2020]. While the land and oceanic regions have similar total primary production, primary producers on land account for approximately 95% of Earth's biomass [Pierella Karlusich et al., 2020]. The contrast of biomass to primary production highlights the importance of fully understanding and modelling factors that effect phytoplankton growth.

2.2.1 Factors that Effect Phytoplankton

Phytoplankton's microscopic size means they are susceptible to changes in their environment, making them likely to be affected by climate change. Factors that effect the growth of phytoplankton include light-level, temperature, nutrients within the water, as well as wind strength. Other factors such as salinity, mixed layer depth and sea ice thickness can have a significant impact on the growth of phytoplankton in an area [Deppeler and Davidson, 2017].

2.2.2 Phytoplankton in the Southern Ocean

The Marginal Ice Zone (MIZ) accounts for most of the spring-summer phytoplankton blooms. In spring, during the ice melts, low salinity, iron-rich water is released. This results in the formation of a buoyant layer of freshwater, which traps phytoplankton in an environment ideal for growth [Deppeler and Davidson, 2017].

Vichi and Hague found that 90% of observed phytoplankton growth occurred before the ice retreat. Vichi and Hague theorised that the phytoplankton have either adapted to grow in extreme low-light conditions, or light is more readily available in the under-ice environment [Hague and Vichi, 2021].

Given the importance of phytoplankton to the global climate, as well as their sensitivity to environmental changes, it is essential to collect data on the factors that impact their growth. It is especially important to gather data during the winter months, where most data is lacking [Hague and Vichi, 2021].

Figure 2.1 shows the interactions of phytoplankton with the larger food web, as well as environmental factors mentioned in subsection 2.1.2.

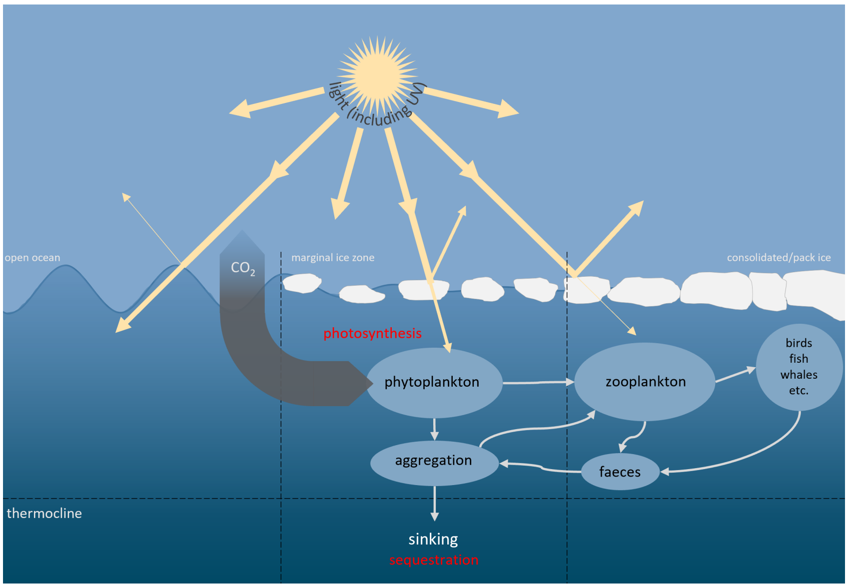


Figure 2.1: Diagram showing connections between phytoplankton and larger food web and the processes driving carbon transfer, modified from [Deppeler and Davidson, 2017]

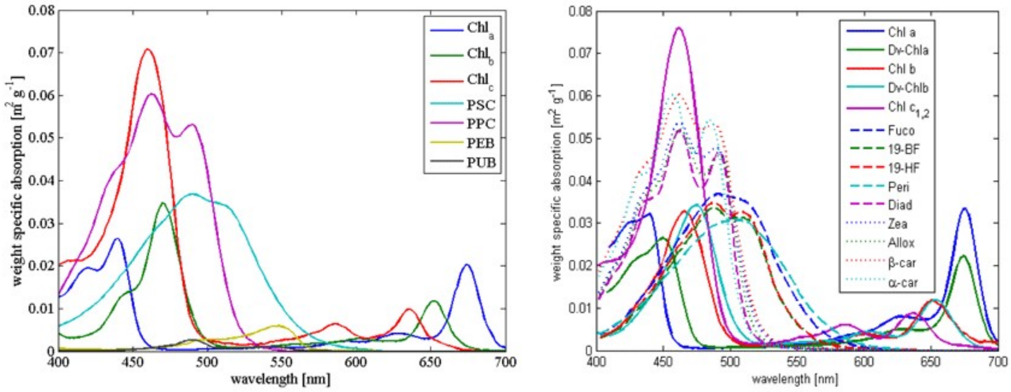
2.3 Photosynthetically Active Radiation (PAR)

Photosynthetically Active Radiation (PAR) is the part of light that allow photosynthetic organisms to photosynthesise. The wavelengths range of PAR is from $400nm$ to $700nm$ [Ross and Sulev, 2000].

2.3.1 Phytoplankton PAR Absorption Properties

There exist thousands of different species of phytoplankton, with over 350 species having been identified in the Southern Ocean [Deppeler and Davidson, 2017, Scott and Merchant, , Cetinic, 2021]. These species can be grouped based on their specific characteristics, with the most common classes being diatoms, coccolithophorids and dinoflagellates [Cetinic, 2021, Pierella Karlusich et al., 2020]. The different classes and species of phytoplankton can be distinguished by their size, shape, ideal temperature for growth as well as light absorption characteristics [Pierella Karlusich et al., 2020, Scott and Merchant, , Cetinic, 2021].

Chlorophylls, found in all phytoplankton cells, give rise to two dominant peaks in their absorption spectra. The primary peak occurs at the blue part of the spectrum ($440nm$) and the secondary being at red part of the spectrum ($675nm$). The absorption spectrum of phytoplankton, $a_{phyto}(\lambda)$, varies in both magnitude and shape due to the diverse cellular pigment composition and pigment packaging across different phytoplankton species [Cetinic, 2021]. The absorption spectra found from in vivo measurements from [Bidigare et al., 1990] and [Bricaud et al., 2004] can be found in Figure 2.2



(a) (b)

Figure 2.2: Mass-normalized absorption of phytoplankton pigment based on studies by (a) [Bidigare et al., 1990] and (b) [Bricaud et al., 2004]

2.4 PAR Measurement

Measurement of PAR can be achieved using various methods. Each method has its respective accuracy as well as cost. The main methods for PAR measurement can be divided into three groups, as per [Ross and Sulev, 2000]:

1. Measurements using spectroradiometers and estimation of PAR by integrating spectral irradiance over the PAR wavelengths.

2. Measurements by pyranometers covered with hemispherical glass filters or by pyrheliometers covered with identical flat filters.

3. Measurements using silicon photodiodes or quantum sensors (silicon photodiode covered with a visible bandpass filter and coloured glass filter) [Ross and Sulev, 2000].

The focus of this paper is surrounding the use of silicon photodiodes to measure PAR. Thus, the rest of this section will explore previous applications of silicon photodiodes to measure PAR, and outline and compare their various successes and failures.

2.4.1 Research Grade PAR Sensors

2.4.2 Measuring PAR using photodiodes

Appendix A

Additional information

Bibliography

[Arrigo and Thomas, 2004] Arrigo, K. R. and Thomas, D. N. (2004). Large scale importance of sea ice biology in the southern ocean. *Antarctic Science*, 16(4):471–486.

[Bidigare et al., 1990] Bidigare, R. R., Ondrusek, M. E., Morrow, J. H., and Kiefer, D. A. (1990). In-vivo absorption properties of algal pigments. In *Ocean Optics X*, volume 1302, pages 290–302. SPIE.

[Bricaud et al., 2004] Bricaud, A., Claustre, H., Ras, J., and Oubelkheir, K. (2004). Natural variability of phytoplanktonic absorption in oceanic waters: Influence of the size structure of algal populations. *Journal of Geophysical Research: Oceans*, 109(C11).

[Cetinic, 2021] Cetinic, I. (2021). Phytoplankton.

[Deppeler and Davidson, 2017] Deppeler, S. L. and Davidson, A. T. (2017). Southern ocean phytoplankton in a changing climate. *Frontiers in Marine Science*, 4.

[Hague and Vichi, 2021] Hague, M. and Vichi, M. (2021). Southern ocean biogeochemical argo detect under-ice phytoplankton growth before sea ice retreat. *Biogeosciences*, 18(1):25–38.

[Kennicutt et al., 2019] Kennicutt, M. C., Bromwich, D., Liggett, D., Njåstad, B., Peck, L., Rintoul, S. R., Ritz, C., Siegert, M. J., Aitken, A., Brooks, C. M., et al. (2019). Sustained antarctic research: a 21st century imperative. *One Earth*, 1(1):95–113.

[Maksym et al., 2012] Maksym, T., Stammerjohn, S. E., Ackley, S., and Massom, R. (2012). Antarctic sea ice— a polar opposite? *Oceanography*, 25(3):140–151.

[Meredith and Brandon, 2017] Meredith, M. P. and Brandon, M. A. (2017). *Oceanography and sea ice in the Southern Ocean*, chapter 8, pages 216–238. John Wiley Sons, Ltd.

[Parkinson, 2004] Parkinson, C. L. (2004). Southern ocean sea ice and its wider linkages: insights revealed from models and observations. *Antarctic Science*, 16(4):387–400.

[Pierella Karlusich et al., 2020] Pierella Karlusich, J. J., Ibarbalz, F. M., and Bowler, C. (2020). Phytoplankton in the tara ocean. *Annual Review of Marine Science*, 12(1):233–265. PMID: 31899671.

[Ross and Sulev, 2000] Ross, J. and Sulev, M. (2000). Sources of errors in measurements of par. *Agricultural and Forest Meteorology*, 100(2):103–125.

[Scott and Merchant,] Scott, F. J. and Merchant, H. J. Antarctic marine protists.

[Simmonds, 2015] Simmonds, I. (2015). Comparing and contrasting the behaviour of arctic and antarctic sea ice over the 35 year period 1979-2013. *Annals of Glaciology*, 56(69):18–28.

[Tamsitt et al., 2018] Tamsitt, V., Abernathey, R. P., Mazloff, M. R., Wang, J., and Talley, L. D. (2018). Transformation of deep water masses along lagrangian upwelling pathways in the southern ocean. *Journal of Geophysical Research: Oceans*, 123(3):1994–2017.