CASE 2 ANTARCTIC COASTAL WATERS: THE BIO-OPTICAL PROPERTIES OF SURFACE MELTWATER

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In the Antarctic region, melting of sea ice and continental glaciers can create a surface lens of meltwater in coastal waters. When ice melts, particles concentrated within the ice are released into the water and can cause turbidity. Under these conditions, the optical properties of the water column are no longer related primarily to the phytoplankton and associated breakdown products (i.e., Case 1) and would be classified as Case 2. Using bio-optical data collected in conjunction with the Palmer Long Term Ecological Research Project, we compare the remote sensing reflectance spectra for meltwater conditions with the typical Case 1 spectra found in these waters. The Case 2 waters have significantly higher reflectance across all wavelengths than the Case 1 conditions, which is indicative of higher levels of backscattering. Measurements of backscattering conducted with the Hydroscat instrument further confirm that backscattering is high and uncorrelated to chlorophyll when the surface lens of meltwater is present. These results are discussed in the context of ocean color remote sensing of meltwater and the associated impact of meltwater on the biomass within the water column. Instrument records over the last half-century have shown a statistically significant warming trend in air temperature along the Antarctic Peninsula that is also evident by the destruction of the Larsen Ice Shelf and the retreat of continental glaciers. Thus, meltwater conditions may become more prevalent and have important implications for bio-optical properties of surface waters and, subsequently on the primary production in this climatically sensitive region.

INTRODUCTION

The optical properties of the waters west of the Antarctic Peninsula (WAP) are primarily influenced by the presence of phytoplankton and are therefore considered to be Case 1. Using data from over 1000 stations collected in conjunction with the Palmer Long-Term Ecological Research (LTER), previous research has characterized the unique relationship between reflectance and chlorophyll (Chl) in these Southern Ocean Case 1 waters (Dierssen and Smith, in press). However, in nearshore waters, the reflectance increases and becomes uncoupled to phytoplankton concentrations. High reflectance in the surface waters in nearshore regions of the WAP could be due to:

1) Runoff of meltwater from land surfaces (e.g., glacial melt, runoff from penguin colonies, etc.);
2) Melting of sea ice;
3) Resuspension of bottom sediments.

In the Antarctic, most of the sea ice is young first-year sea ice and is, therefore, not likely to release a lot of suspended particles into the water column. Furthermore, the Case 2 waters have significantly lower surface salinity than the Case 1 waters which suggests that turbidity is not merely due to resuspension of bottom sediments, but is a result of meltwater runoff. Therefore, in this region, the Case 2 waters are primarily caused by runoff of meltwater from glaciers and melting of snow pack from rock-covered land masses. Additional turbidity would be caused by runoff from islands hosting penguin colonies.

Here, we analyze the remote sensing reflectance from the Case 2 waters in the hopes that an optical signature can be found to identify meltwater conditions from remotely sensed ocean color observations. Satellite data provides enhanced ability to identify meltwater conditions of the large and often inaccessible coastal region of the Southern Ocean. Moreover, recent evidence suggests that due to potential warming trends in this region, meltwater conditions may become more prevalent throughout the Antarctic coastal region. Particularly, the WAP region has experienced a statistically significant warming trend during the past half century (King, 1994; Stark, 1994). Additionally, the glacier at Palmer Station has retreated substantially over the last few decades alone, (PAL/LTER unpublished observations) and is contributing significant amounts of meltwater to the ecosystem.

As part of the Palmer LTER project, we are uniquely equipped to address this issue. The interannual variability in this ecosystem, from the timing and magnitude of sea ice extent to the annual amount of primary production, is immense (see proceedings from Smith et al.). Clearly, observations from any single year can severely bias our understanding of the ecosystem. This contribution draws upon nearly a decade of bio-optical observations, both in the more productive nearshore waters of Palmer Station and in the less productive offshore waters of the larger WAP region.

METHODS

The field data presented in this paper was collected in collaboration with the Palmer Long Term Ecological Research (PAL/LTER) project (Smith *et al.*, 1995). The sampling regime involves an approximately weekly time series for primarily two nearshore stations around Palmer Station (64.77S, 64.06W) and a January cruise that covers stations over a larger grid area (20-200 km offshore, 400 km alongshore). Chlorophyll *a* concentrations (chl) were estimated using standard fluorometric techniques and subtracting the phaeopigment concentration determined by sample acidification (Smith *et al.*, 1981). Vertical profiles of downwelling spectral irradiance and upwelling radiances were measured using a Bio Spherical Instruments Profiling Reflectance Radiometer (PRR) operated in a free-fall configuration. Remote sensing reflectance just above the sea surface, $R_{rs}(0^+,\lambda)$ is estimated as the ratio of upwelling radiance to downwelling irradiance. Data processing and extrapolations across the sea surface are described in (Dierssen and Smith, in press). Backscattering was measured using a HOBILabs Hydroscat-6 Spectral Backscattering Sensor.

IDENTIFICATION OF CASE 2 WATERS

The reflectance spectra for over 1000 Case 1 stations sampled as part of the PAL/LTER program from 1991 to 1999 is shown as a dotted line in Fig. 1. $R_{rs}(0^+,555)$

remains low as chl increases and is significantly different when compared to data collected from other regions of the world's oceans (Dierssen and Smith, in press). However, Case 2 waters, shown in blue on Fig. 1, have much higher R_{rs} across all wavelengths. Here, we define the Case 2 waters as those stations where $R_{rs}(0^{+},555)$ was greater than two standard deviations from the mean measured for all stations or 0.0039 str^{-1} or a water-leaving radiance, $L_{wn}(555)$, of around 0.778. Greater than 90% of the Case 2 stations were sampled as part of the PAL/LTER weekly time series collected nearshore at Palmer Station.

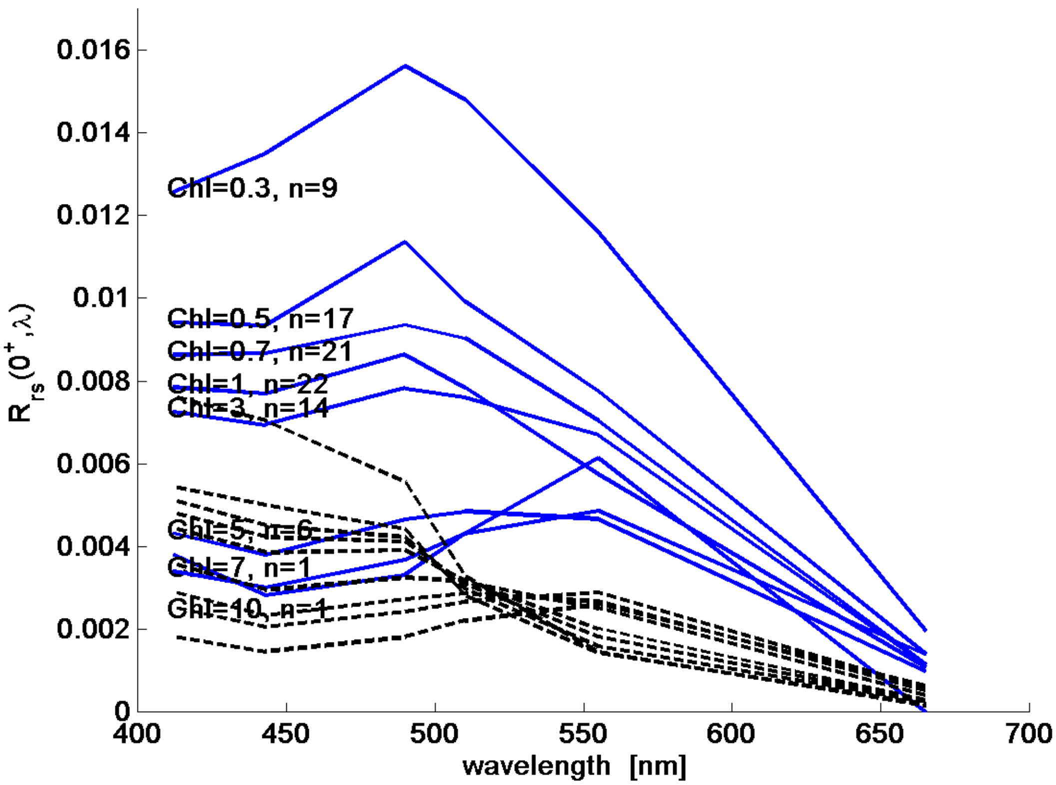

Fig. 1. The blue lines are remote sensing reflectance (R_{rs}) measured for the Case 2 waters. Each line represents the mean R_{rs} averaged over stations with different concentrations of chl +/- 20%. The dotted black lines are for the same chl categories, but measured for over 1000 Case 1 stations.

The L_{wn}555 criteria for screening Case 2 waters can be used to identify other waters along the Antarctic coast that are potentially influenced by glacial melt using SeaWiFS data (Fig. 2). Highly reflective waters (Fig. 2, shown in red) can be found in the Ross Ice Shelf polynya and scattered along the continent. However, this criteria also triggers a band of highly reflective pelagic waters following the Antarctic Circumpolar Current and Polar Front regions of the Southern Ocean. Whether these waters are subject to errors in SeaWiFS processing or have high reflectance due to in-water properties is still under debate. Because of the distance from land, the high reflectance in these pelagic waters is not likely due to glacial melt and is not considered further in this analysis.

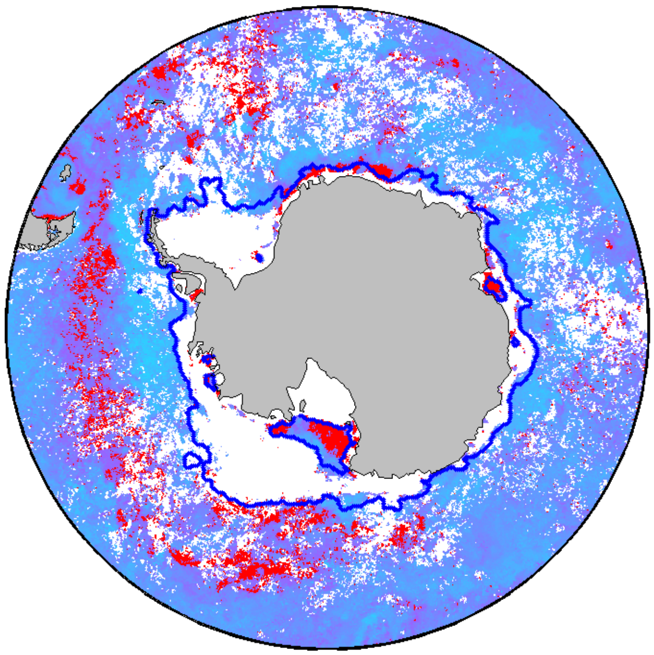

Fig. 2. Standard mapped monthly images of $L_{wn}(555)$ derived from SeaWiFS (Version 3) for January 1999. Pixels in red have high reflectance ($L_{wn}(555)>0.778$) and exceed the criteria developed here. The sea ice edge, shown in dark blue, is considered to be the 15% ice concentration contour derived from the SSM/I passive microwave satellite data for this month.

OPTICAL PROPERTIES OF CASE 2 WATERS

In the January 1999 cruise, we measured backscattering for two Case 2 stations that were influenced by meltwater. Compared to the Case 1 waters, these stations had high levels of backscattering that are uncorrelated to chl concentrations (Fig. 3). Particulate backscattering (b_{bp}) at 488 nm, for example, was three times higher for the meltwater stations than for stations with correspondingly low chl.

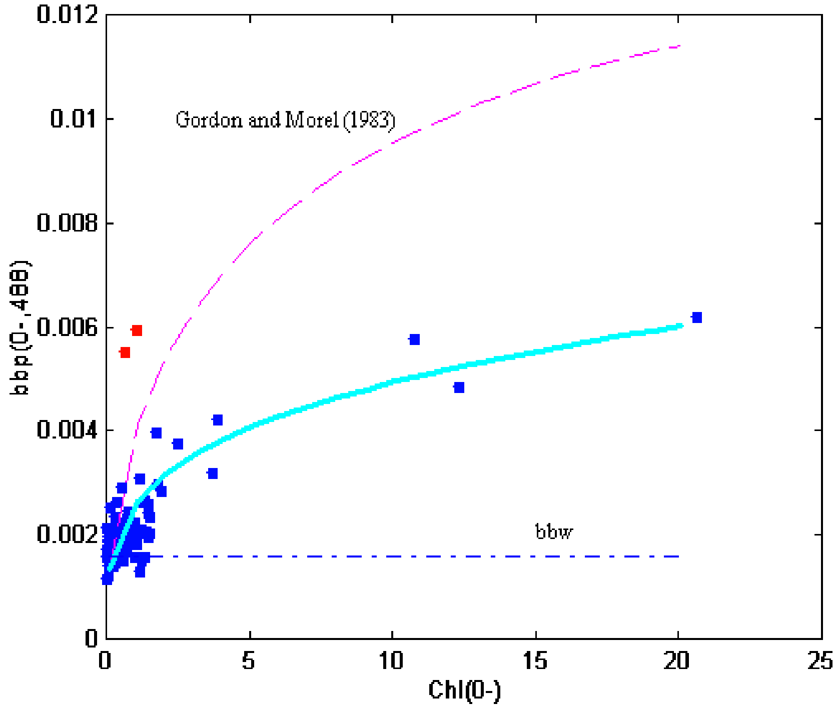

Fig.3. Surface chl versus particulate backscattering (b_{bp}(488)) measured for stations collected along the PAL/LTER grid in January 1999. Red stations are the Case 2 waters with meltwater conditions. The cyan line is the best fit to the Case 1 data and the dotted magenta line is the relationship developed by Gordon and Morel (1983). The backscattering due to water is shown in the blue dot-dashed line.

MODELING CHL FOR CASE 2 WATERS

For the meltwater Case 2 waters, using ratios of R_{rs} to model chlorophyll is highly inaccurate (Fig. 4). For Case 1 waters, the maximum band ratio approach of SeaWiFS OC4V4 algorithm (i.e., using the maximum of R_{rs}(441,490,510) divided by R_{rs}(555)) explains around 85% of the variability and the magnitude can be easily adjusted to match the OC4V4 slope (Dierssen and Smith, in press). In contrast, the Case 2 waters (green squares) all have the approximately the same R_{rs} ratio regardless of chl concentration. The stations with higher chl (>1 mg m^{-3}) will be more accurately modeled than the stations with low chl.

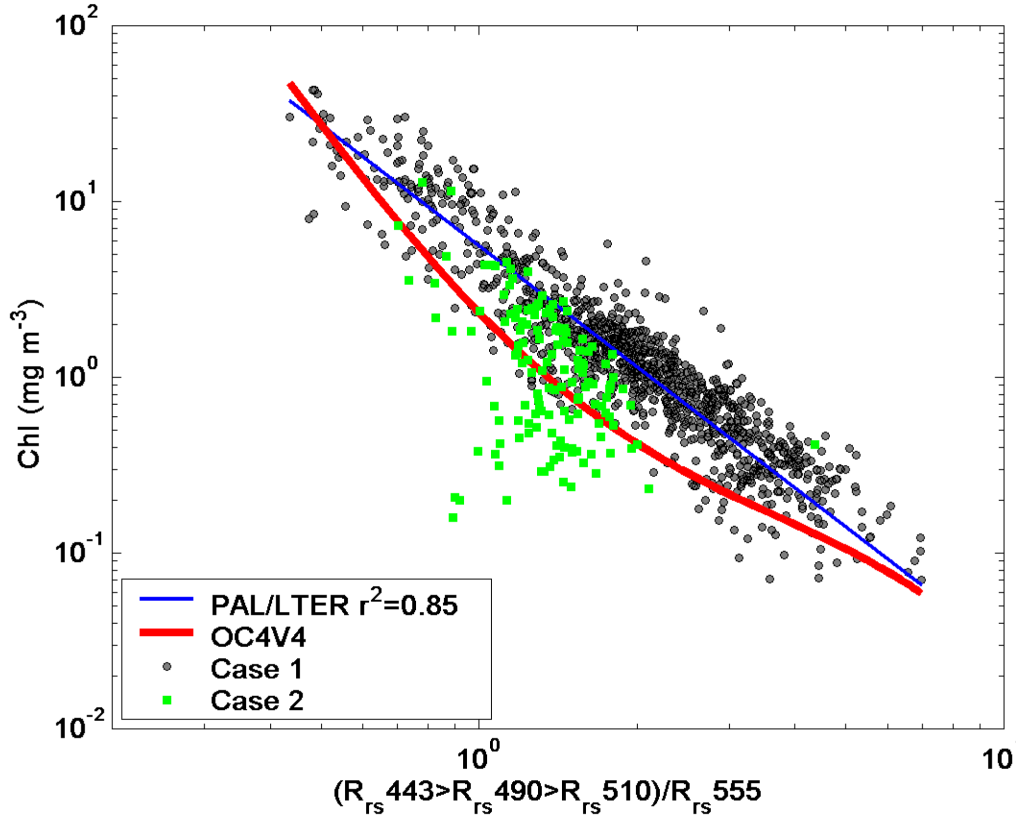

Fig. 4. The maximum band ratio of SeaWiFS OC4V4 algorithm versus Chl for all of the PAL/LTER Case 1 waters (black dots) and the Case 2 meltwater stations (green squares). The OC4V4 relationship is shown in red and the best fit for these data is the blue line (log(Chl)=-2.29log(x) + 0.746).

Because of the low correlation between the R_{rs} spectral shape and chl, techniques for modeling chl using spectral ratios or curvature are ineffective for these Case 2 waters. However, a relationship exists between the amount of reflectance and the chl concentration (see Fig. 1). Similar to Case 1 waters, each chl category has a unique mean spectra and reflectance in the blue decreases as chl increases. A simple logarithmic correlation between Chl and R_{rs}(443), for example, explains 37% of the variability in the chl, such that:

$$\log(Chl) = 1.72\log(R_{rs}(443)) - 3.57$$

SUMMARY

Here, we have shown how meltwater increases the remote sensing reflectance in the water column and changes the relationship between chl and Rrs from that found in Case 1 waters. A criteria for identifying Case 2 meltwater was developed using the enhanced reflectance seen in Lwn(555). When applied to SeaWiFS-derived Lwn(555), other nearshore stations along the Antarctic continent were similarly identified as Case 2 waters. The backscattering was found to be three times higher for stations with meltwater than for typical Case 1 waters. Spectral ratioing techniques, such as that used by SeaWiFS OC4V4 algorithm, perform poorly at retrieving Chl from these Case 2 waters. The effects of meltwater on water column biomass and primary production are still being investigated. While no direct correlation exists between surface salinity and chl-a, the general patterns of phytoplankton biomass over the course of a season do not appear to be influenced significantly by the presence of highly reflective meltwater.

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