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Bio-optical Properties in the Southern Ocean in Support of Ocean Color Remote Sensing

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Introduction

The Southern Ocean due to its unique geography connects the various ocean basins and plays a critical role in the global ocean circulation, biogeochemical cycles and climate. This region is sensitive to climatic variations with changes in precipitation and ice melt influencing salinity, carbon uptake and the ecosystem that could influence the primary productivity, phytoplankton species and biomass, and dissolved organic matter content in the Southern Ocean (Arrigo et al. 2000; Sabine et al. 2004; Arrigo et al. 2008; Smith et al. 2012). The Southern Ocean contributes more than any other latitude band to the ocean storage of excess heat and carbon due to anthropogenic activities (Sabine et al. 2004; Levitus et al. 2005). The Antarctic Circumpolar Current (ACC), the planet's largest current that connects the ocean basins, and isolates the cold polar region from the warmer subtropics, plays an important role in regulating the Earth's climate. Future climate predictions indicate that the Southern Ocean air-sea heat balance and carbon system will account for most of the response of the ocean to climate change. The strengthening of the circumpolar westerly winds (IPCC, 2007) for example have been attributed to changes in temperature patterns caused by stratospheric ozone depletion and increases in greenhouse gases linked to anthropogenic influences (Fyfe et al. 2007; Marshall et al. 2004). The increase in winds in the region could result in the weakening of the Southern Ocean sink for anthropogenic CO_2 due to increases in upwelling and associated carbon from the deep ocean (Le Quere et al. 2007). Although there is much uncertainty about the extent of the changes on the ocean environment in the Southern Ocean, climate change effects have been reported or likely to impact among others, the ocean temperature, ocean acidification, melting ice, carbon uptake, and primary productivity.

Satellite ocean color remote sensing with its synoptic and frequent monitoring capability has improved our understanding of the oceanic biogeochemical processes. However, at high latitude polar regions such as the Southern Ocean, satellite estimates of phytoplankton chlorophyll and other bio-optical properties need further improvements as many of the standard ocean color algorithms were developed using field data obtained at lower latitudes (Dierssen and Smith 2000). A combination of field and improved satellite observations will thus provide a better understanding of the Southern Ocean biogeochemical processes. As part of this collaborative project with KOPRI, a joint study of the bio-optical properties of the Southern Ocean will be undertaken that will also help validate and assess satellite ocean color products of the proposed study area. Field bio-optical data (e.g., spectral absorption of dissolved and particulate matter) were or will be obtained during field campaigns to the Southern Ocean during the study period. The combination of field and satellite studies will provide a better understanding of both the particulate and dissolved organic matter distributions that should enhance carbon cycling studies in the New Zealand sector of the Southern Ocean.

Absorption properties of dissolved and particulate matter (phytoplankton and nonalgal particles such as detrital and suspended sediments) directly influence the water leaving radiance and thus the remote sensing reflectance. Spectral absorption properties of phytoplankton can reveal information on phytoplankton species while the colored dissolved organic matter (CDOM) optical properties of absorption and fluorescence provides useful information on CDOM source and water-mass mixing in the oceans (Stedmon et al. 2003; D'Sa and DiMarco 2009; Nelson et al. 2013). Fluorescence spectroscopy by means of excitation-emission matrices (EEMs) has also been widely used to characterize CDOM in various water masses over the globe (D'Sa et al. 2014 and references therein). The goal of this proposed collaborative research is to obtain a better understanding of the optical properties (e.g., absorption properties of the particulate and dissolved organic matter, scattering) and to assess satellite ocean color algorithms of the study area.

Key activities conducted during the study period

1. Analysis of bio-optical properties along the ARAON tract in the Southern Ocean from field measurements supported by satellite remote sensing data for the 2014 Austral summer

Bio-optical measurements (CDOM and particulate absorption, DOC and chlorophyll concentrations, CDOM fluorescence) obtained during the 2014 Araon cruise along the New Zealand sector of the Southern Ocean were furthered analyzed in conjunction with satellite data. Synthesis of the results comprising of field measurements and satellite data have been conducted and a manuscript is being written as part of this task and are briefly described.

1a. Water mass properties using satellite and field data along the Southern Ocean transect

Surface water temperature, chlorophyll concentrations and CDOM absorption coefficients at 300 nm obtained along the Araon transect (Figures 1, 2, 3 –left) were examined and compared to satellite-derived sea surface temperature (SST-MODIS), phytoplankton chlorophyll (Chl-MODIS) and sea surface salinity (Salinity-Aquarius) (Figures 1, 2, 3 – right) for the same time period to better understand the linkages between physical and the bio-optical properties in the New Zealand sector of the Southern Ocean in the Austral summer of 2014. Surface water temperature and chlorophyll concentrations generally show patterns similar to that derived from MODIS (Figures 1, 2). Chlorophyll was high in the New Zealand and Antarctic continental shelves and along the Antarctic Polar Front (APF) and very low along the rest of the transect.

Variability of CDOM absorption (Figure 3-left) along the transect was better explained by using a combination of MODIS SST and Aquarius salinity (Figure 3-right). MODIS-derived SST revealed the various water masses in the study area (Figure 1-right), while MODIS-derived chlorophyll distribution in the study area (Figure 2-right) revealed elevated values along the Antarctic Polar Front (APF) and in the New Zealand and Antarctic shelf waters. A detailed analysis of the field and satellite data is being conducted as part of this study. The results and analysis will be compiled and submitted as a manuscript to a peer-reviewed journal.

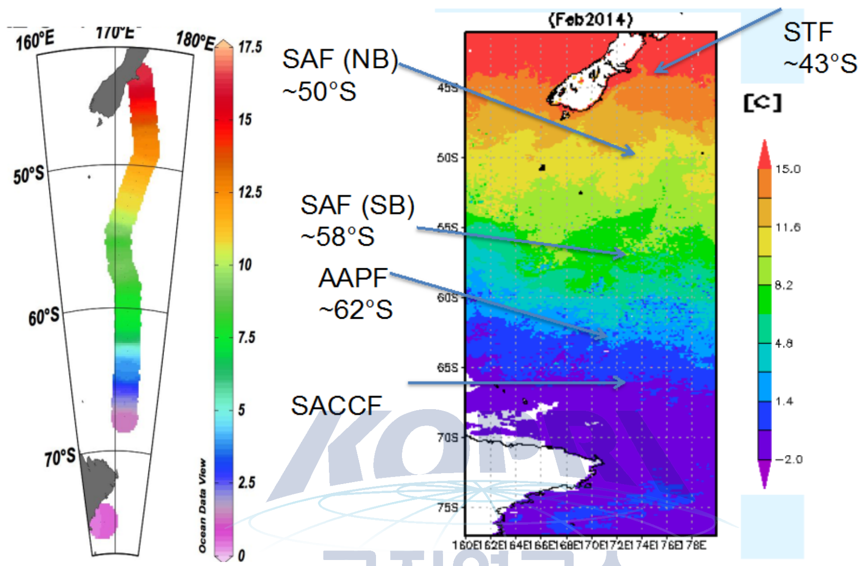

Figure 1. Sea surface temperature (ºC) from in situ measurements along the transect (left) and (right) MODIS-derived SST for the month of February 2014.

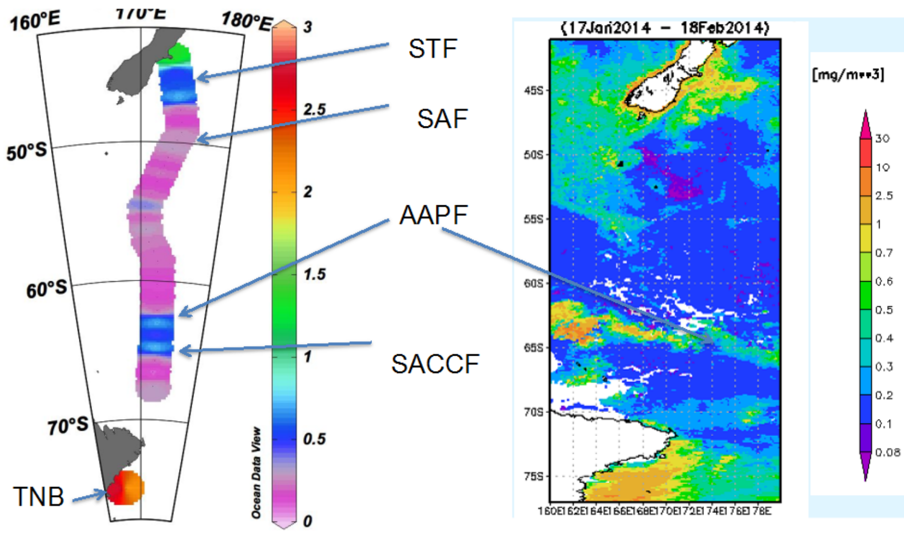

Figure 2. (Left) Chlorophyll concentrations (mg m^{-3}) and (right) MODIS-derived surface chlorophyll for the period 17 January-18 February 2014.

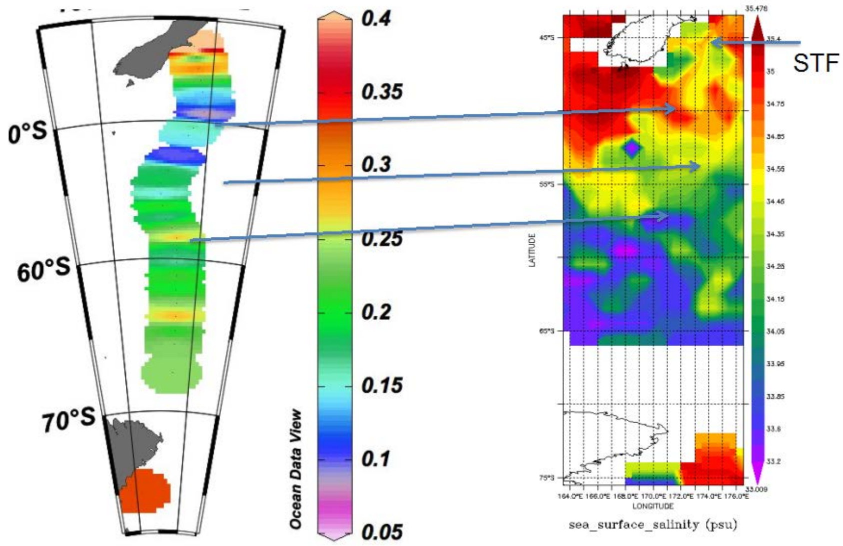

Figure 3. (Left) CDOM absorption coefficient at 300 nm (m^{-1}) measured along the ARAON tract in the Southern Ocean. (Right) surface salinity distribution from the Aquarius satellite.

1b. CDOM absorption properties along the New Zealand Southern Ocean transect:

Seawater samples acquired during the ARAON transect were filtered in the field and processed for CDOM absorption in the laboratory on a spectrophotometer. Absorbance data were processed to derive the absorption coefficients and the spectral slope between 275-295 nm wavelengths and are plotted along the latitudinal transect (Figure 4). The absorption coefficients at 300 nm generally show elevated values along the New Zealand and the Antarctic shelves. The spectral slope S show variability associated with the various water masses and will be examined in conjunction with hydrographic data.

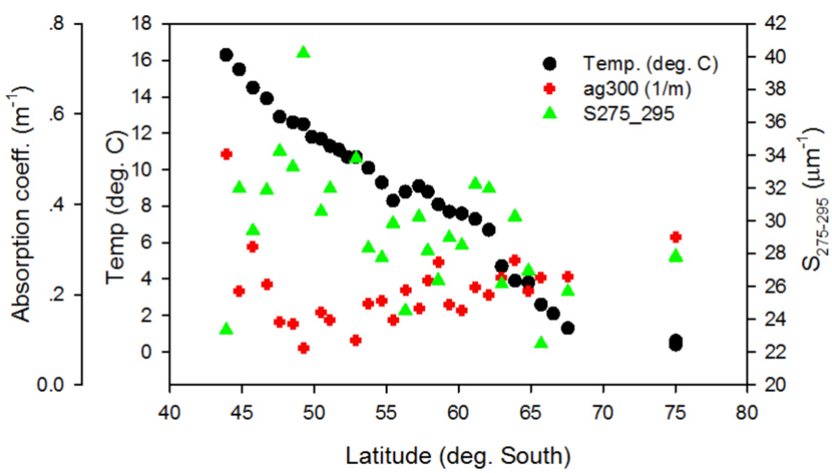

Figure 4. Surface absorption coefficients and spectral slope plotted along the ARAON tract in the Southern Ocean during 2014 austral summer.

1c. Particulate absorption properties along the Southern Ocean transect:

The absorption spectra of particulate matter (phytoplankton and nonalgal or detrital matter) of surface waters along the New Zealand sector of the Southern Ocean transect were generally low with phytoplankton absorption varying by an order of magnitude for the surface water samples along the transect. The particulate and CDOM absorption spectral characteristics at station 27 (Figure 5-left) indicates similar magnitude of CDOM and phytoplankton absorption at 443 nm. The absorption budget of phytoplankton, non-algal and CDOM at 443 nm (Figure 5-right) indicates the strong contribution by both phytoplankton and CDOM to the total absorption budget in the Southern Ocean. Variability in phytoplankton and non-algal absorption at 443 nm along the transect are shown in Figure 6.

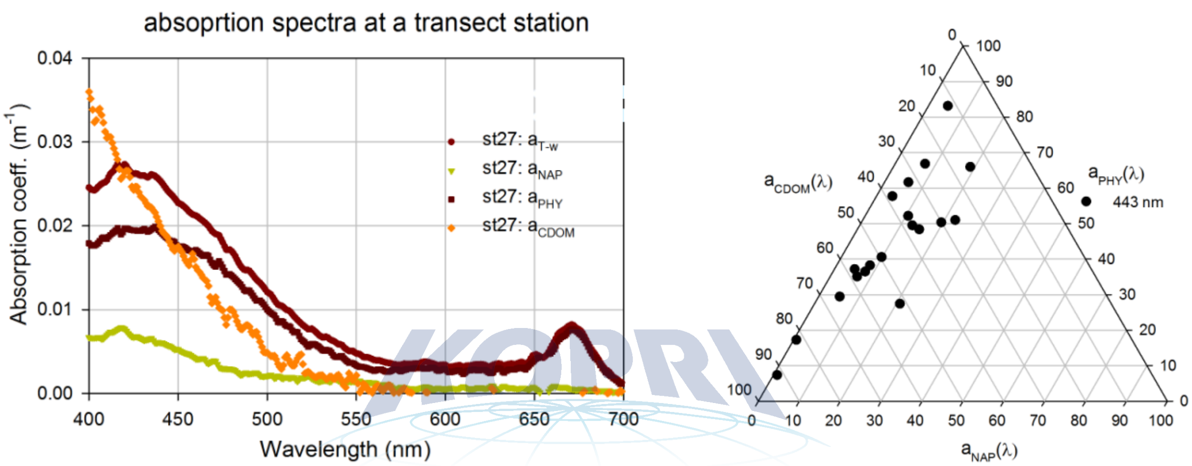

Figure 5. (Left) Absorption spectra of the various seawater constituents (CDOM, phytoplankton, non-algal particles) at station 27 along the transect. (Right) Absorption budget for the transect data through ternary plot of phytoplankton, non-algal and CDOM absorption at 443 nm.

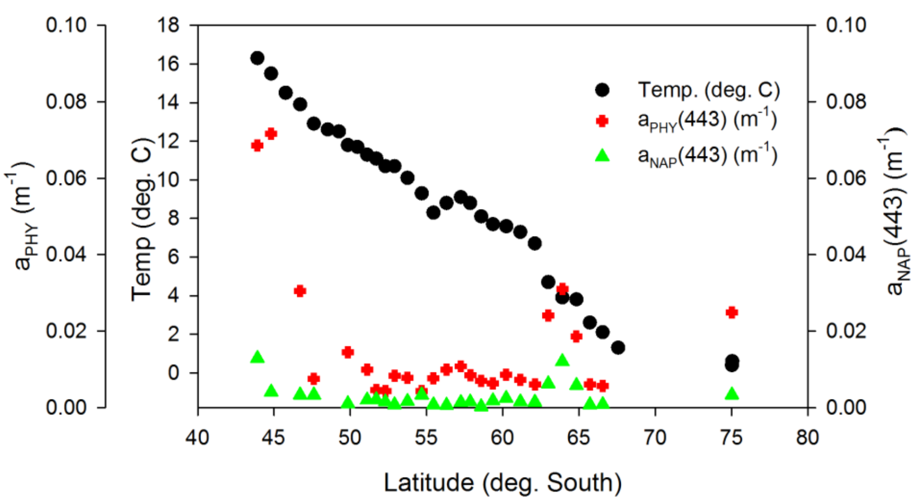

Figure 6. Phytoplankton (green), and nonalgal (red) absorption coefficient at 443 nm along the Southern Ocean transect.

1c. CDOM absorption and fluorescence properties along the New Zealand Southern Ocean transect:

Fluorescence of filtered seawater samples obtained during the 2014 Araon austral summer cruise through the Southern Ocean were obtained on a spectrofluorometer. The excitation-emission fluorescence matrices (EEMs) were acquired using successive excitation wavelengths to obtain emission spectra. The excitation-emission spectra were then used to generate plots of fluorescence as a function of excitation-emission wavelengths. These 3-dimensional EEM data were used in identifying classes of fluorophores in the seawater samples (Stedmon et al. 2003). An example of fluorophores present in three CDOM samples from the Southern Ocean is shown in Figure 7. Two significant fluorescent peaks corresponding to the marine humic substance peak M, and the proteinaceous (or tryptophan) peak T (Coble, 1996) were detected.

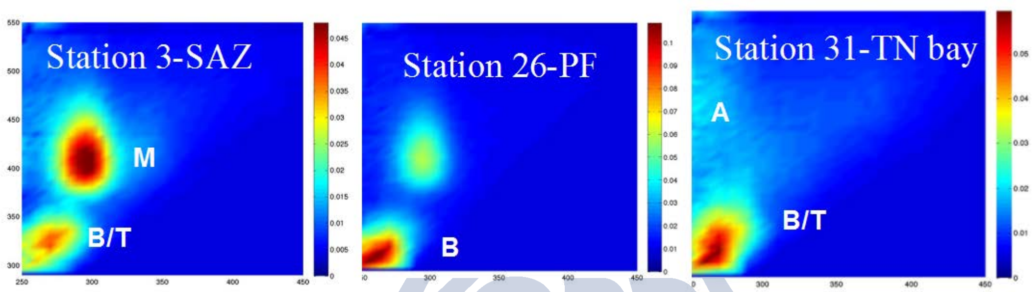

Figure 7. Excitation-emission matrix (EEMs) fluorescence of three seawater samples at stations 3, 26, and 31 measured along the Araon tract in the Southern Ocean.

These EEMs data were then processed using PARAFAC analysis that allowed for fluorescence characterization of CDOM waters in the New Zealand sector of the Southern Ocean. PARAFAC modeling was applied to the EEMs spectra of all the CDOM samples and the model identified four fluorescence components (Figure 8-left). The four fluorescent components comprised of two humic-like fluorescent components and two protein-like fluorescent components (D'Sa and Kim 2015) and their distribution is shown along the transect (Figure 8-right).

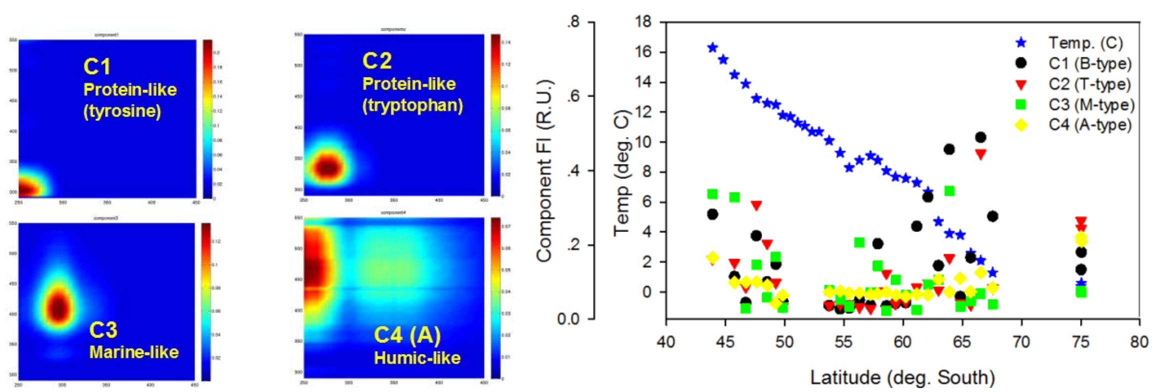

Figure 8. PARAFAC model identified four components (left). The four fluorescent components plotted along the ARAON 2014 tract in the Southern Ocean (right).

2. Processing of field samples for bio-optical properties during the Austral summer of 2015 along the New Zealand sector of the Southern Ocean and in the Ross Sea

During the 2015 austral summer, seawater samples were collected along the Araon transect as well as CTD stations in the Ross Sea (Figure 9-left). The filtered seawater samples (dissolved and particulate matter) were then processed in the laboratory. Measurements of CDOM spectral absorption (not shown), particulate (total, phytoplankton and non-algal) absorption coefficients were then obtained following measurements on a spectrophotometer. Figure 9 (right) shows the total particulate absorption spectra of all samples collected during the 2015 Araon cruise.

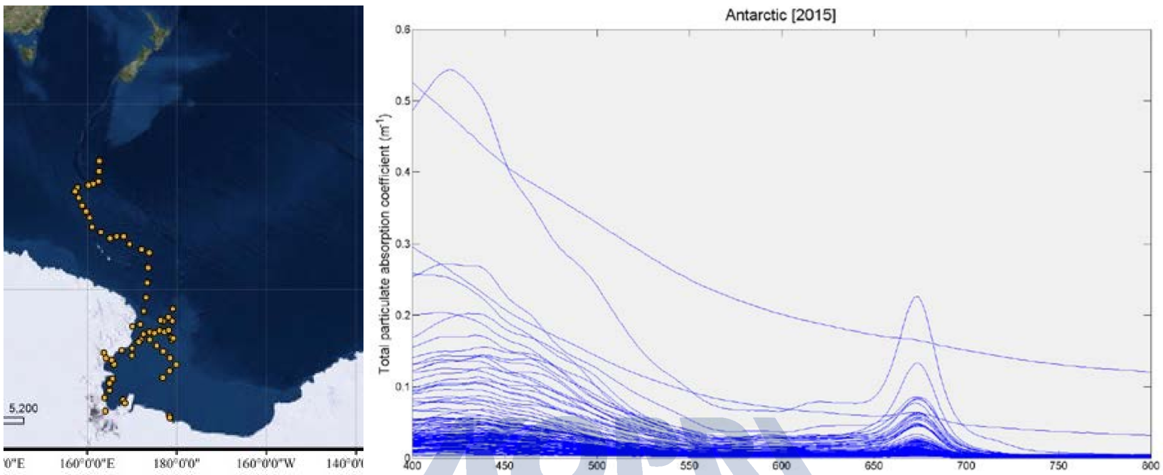

Figure 9. (Left) Sampling stations during the 2015 Araon cruise to the Southern Ocean. (Right) Total particulate absorption coefficients of all the seawater samples obtained along the ARAON transect at at stations in the Ross Sea.

Using the QFT technique and following methanol extraction, absorption spectra of non-algal particles were obtained. Phytoplankton absorption spectra were then derived as the difference between total and non-algal particles (Figure 10). Typical particulate spectral absorption coefficients (total, phytoplankton, and non-algal) are shown for two stations (34 and 71) at different depths located in the Ross Sea.

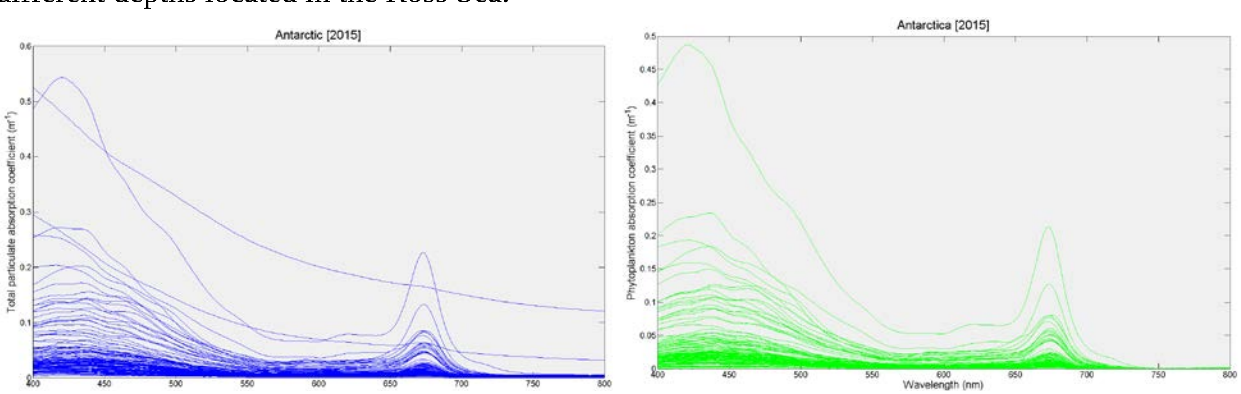

Figure 10. (Left) Phytoplankton and (right) non-algal spectral absorption coefficients from all the seawater samples obtained during the 2015 Araon cruise to the Southern Ocean.

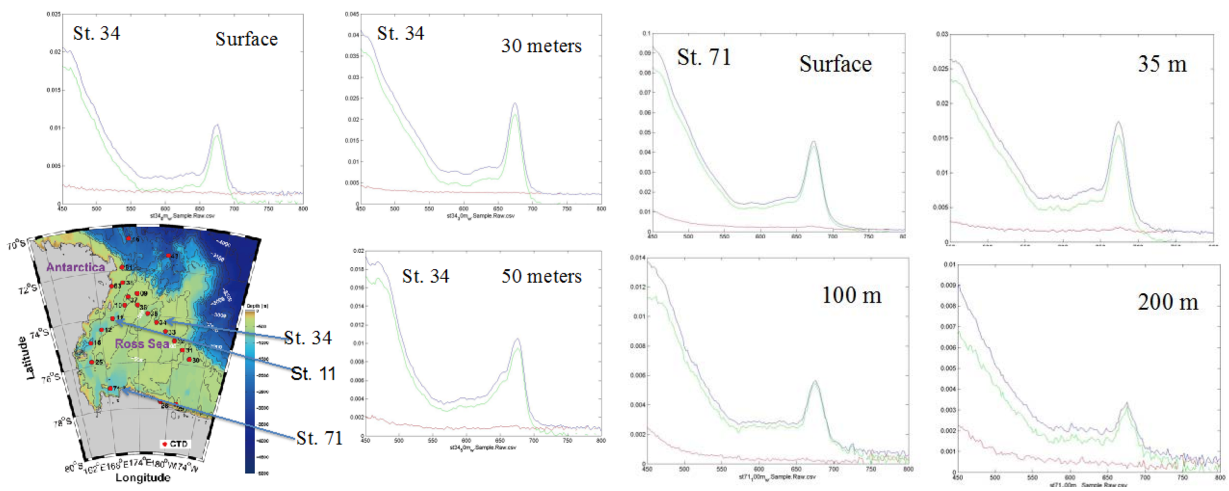

Figure 11. Particulate spectral absorption coefficients (total, phytoplankton, and non-algal) at station 34 (depths – surface, 30 m, and 50 m) and at station 71 (surface, 35 m, 100 m, and 200 m) located in the Ross Sea.

A typical EEMs fluorescence spectra at station 11 (surface, 20 m, and 45 m) and located off the Terra Nova Bay is shown in Figure 12. At all depths, we observe a strong contribution by the protein-like fluorophore to the CDOM pool. The EEMs will be processed using PARAFAC model and a detailed analysis in conjunction with hydrographic data will be done as part of the proposed work.

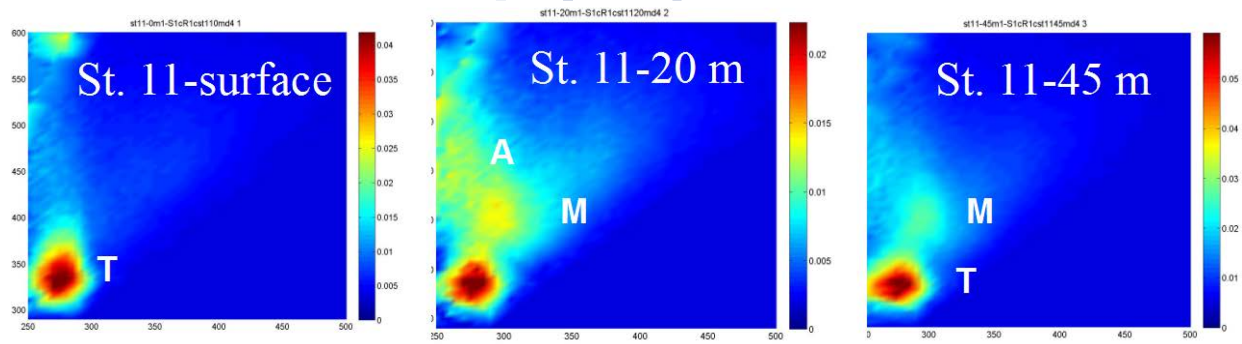

Figure 12. (Left) EEMs fluorescence spectra of seawater samples from station 11 (depths – surface, 20 m, and 45 m) located off the Terra Nova Bay.

3. Preliminary analysis of 2015 field (New Zealand sector and Ross Sea) bio-optical properties

A preliminary analysis of the CDOM and particulate absorption properties has been undertaken in conjunction with physical properties (temperature and salinity). Also, analyses of fluorescence properties and water mass relationships have been conducted.

Summary results

Surface optical properties along the ARAON transect in the New Zealand sector of the Southern Ocean during 2014 cruise showed variability associated with different water masses. Both CDOM absorption and particulate matter absorption (indicative of CDOM, phytoplankton and non-algal matter concentrations) were generally higher off New Zealand coast and in the Terra Nova Bay, Ross Sea. However, along most of the transect that spanned the different water masses, CDOM and particulate absorption were very low, often close to the instrument detection limit. Satellite remote sensing data provided additional insights into the water masses present along the New Zealand Southern Ocean transect. Sea surface salinity from the new Aquarius satellite sensor provided important information on the frontal pattern (e.g., Subtropical Front (STF) which influenced the CDOM distribution and further added to the understanding of the in situ bio-optical data. PARAFAC modeling of the fluorescence excitation-emission matrix (EEM) data revealed the presence of four fluorescence components in the CDOM pool of the Southern Ocean. CDOM optical data has been further examined for linkages between the optical properties (CDOM, phytoplankton, nonalgal particles) and the different water masses (as indicated by satellite salinity data) along the New Zealand sector of the Southern Ocean. Results of this study were presented at the ASLO Aquatic Sciences Meeting and the 21st Polar Symposium in 2015. Work on a manuscript for submission to a peer-review journal has been initiated. During the 2015 project year, a large number of seawater samples were obtained during the Araon cruise to the Southern Ocean. Samples were obtained both along the New Zealand Southern Ocean transect and at CTD stations in the Ross Sea. These samples were processed in the laboratory for CDOM and particulate absorption coefficients. Further, DOC concentrations and EEMs fluorescence of the seawater samples were also obtained as part of this project. These data will be examined in conjunction with hydrographic data.

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