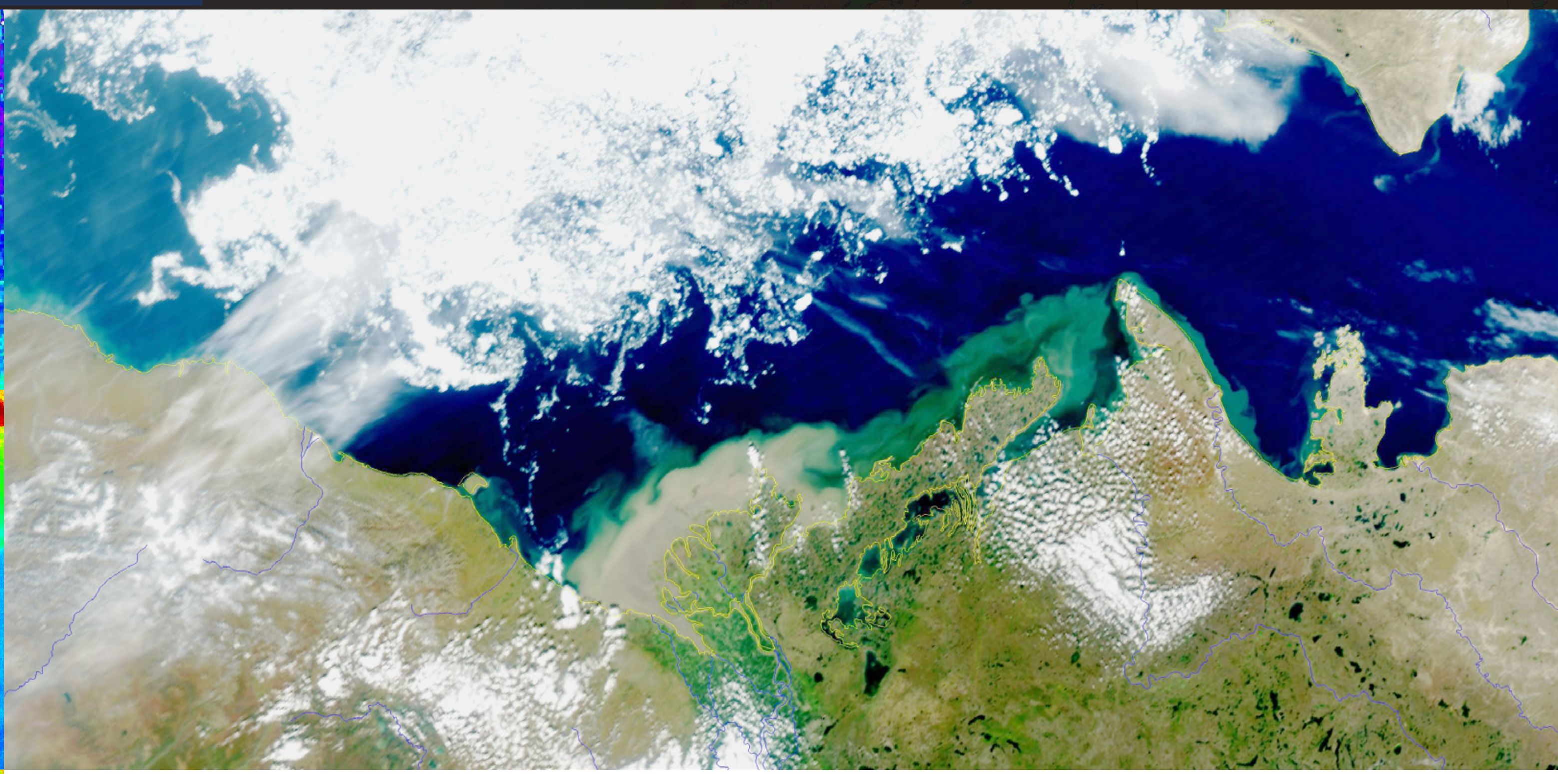
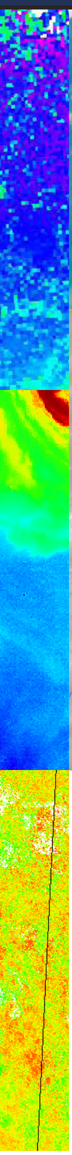
REPORT ON CANADIAN PRIORITIES

PHASE I REPORT 2014-2018





Net COLOR

NETWORK ON COASTAL, OCEANS AND LAKE OPTICS REMOTE SENSING

NETCOLOR: NETWORK ON COASTAL OCEANS AND LAKE OPTICS REMOTE SENSING, REPORT ON CANADIAN PRIORITIES.

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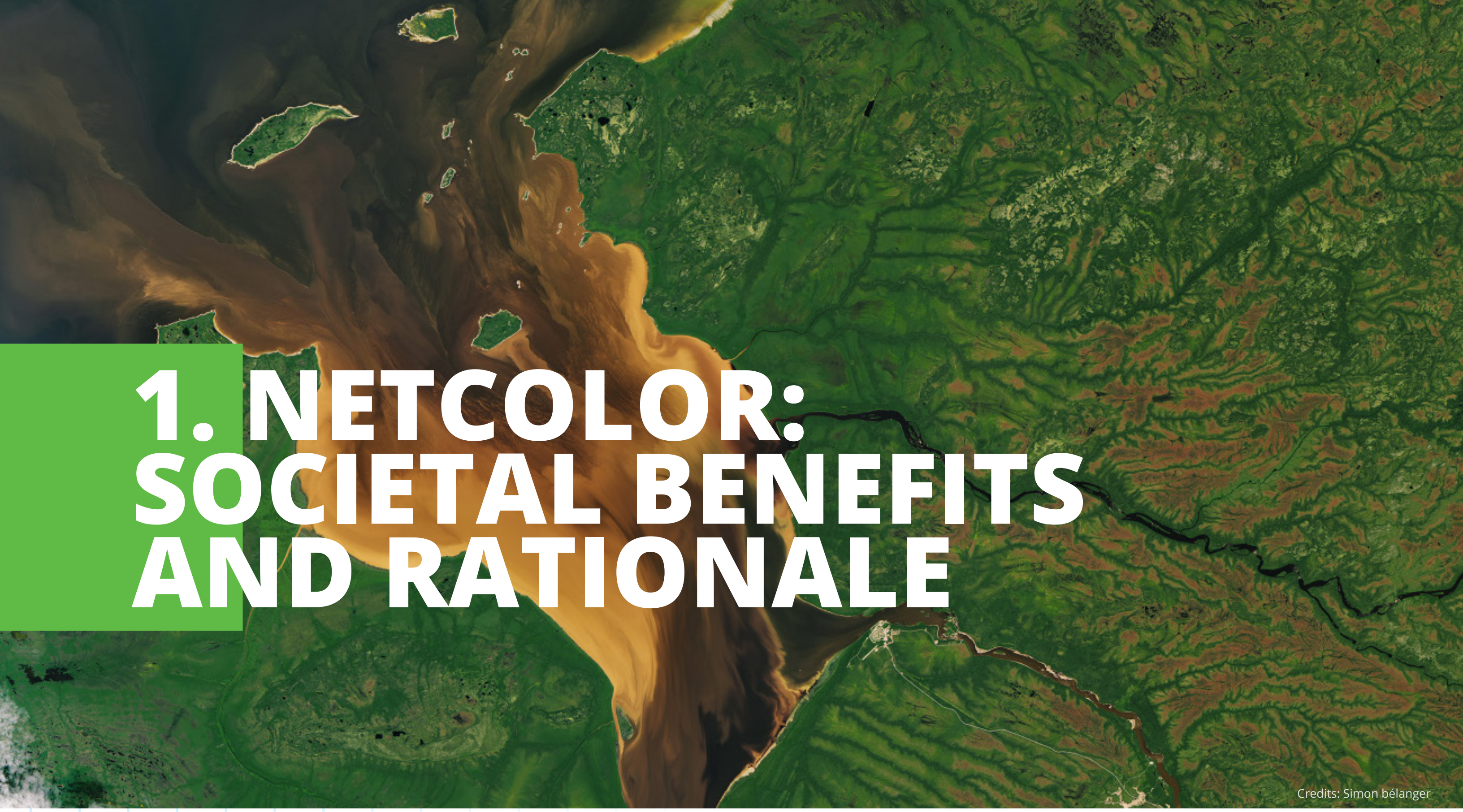


Credits: Simon bélanger

1. NETCOLOR: SOCIETAL BENEFITS AND RATIONALE

Spaceborne remote sensing of the "colour" of water in oceans and lakes (often referred to as ocean colour radiometry, or OCR) is a very powerful tool, providing recurrent measurements of global phytoplankton biomass at synoptic scales, as well as derived inherent optical properties of other key water constituents. Given the size of Canada's ocean environment, which includes the world's longest coastline bordering three major oceans (Pacific, Atlantic, and Arctic), as well as its vast freshwater resources, it is crucial to be able to monitor the water quality, biological activity and the bulk biogeochemical state in these aquatic systems.

There are many applications of the data acquired by aquatic colour spaceborne sensors, both in research and operational arenas, with many important societal and economic benefits that can further our understanding of the environment and the anthropic forcing, including: pollution, climate change, resource assessment (including commercial and recreational fisheries), and degradation of these resources, allowing for better environmental management, strategic planning, and sustainable exploitation of the ocean.

Phytoplankton are the "primary producers" in oceans and lakes, and form the basis of the aquatic food web. They act as a food source for animals over a large range of trophic levels, from microscopic zooplankton to small fish and invertebrates (including benthic organisms and shellfish), up to multi-ton whales. Another vitally important role of phytoplankton is that they consume carbon dioxide (CO_2) through the process of photosynthesis, and release oxygen into the atmosphere. The amount of CO_2 consumed by phytoplankton each year is on a scale equivalent to that of forests and land plants. They release half-of the oxygen present in the atmosphere. By taking up CO_2 and producing dimethyl sulfide (a gas involved in cloud formation and synthetized by some phytoplankton), phytoplankton play an important role in regulating our climate and weather patterns.

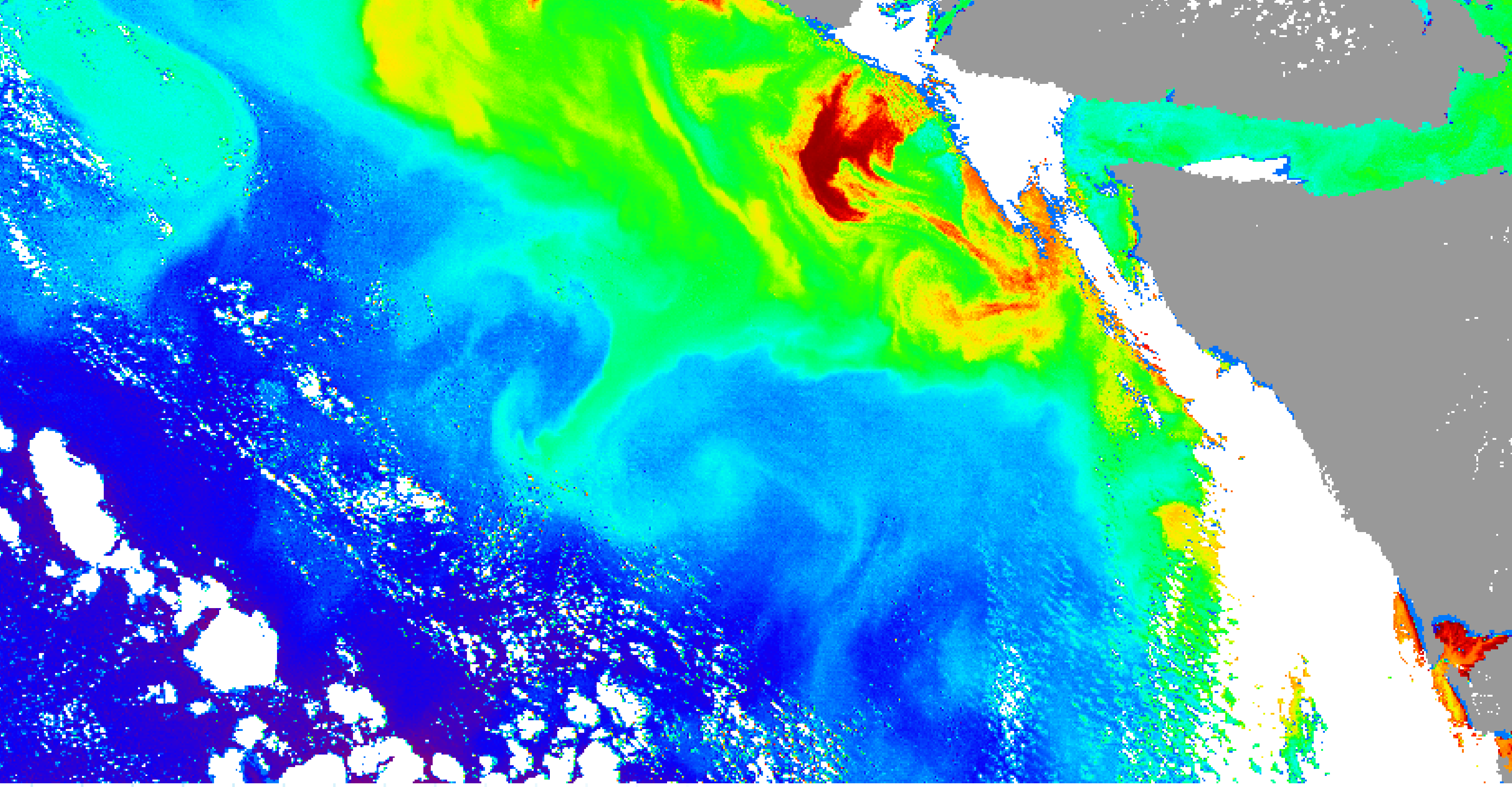
When phytoplankton die and sink, carbon contained in their skeletons is sequestered into the deep ocean. This process, often referred to as the "biological carbon pump", transfers approximately 5 - 15 GT of carbon each year from the surface ocean to deep sea waters. Since more than 30% of all our CO_2 emissions end up in the ocean, phytoplankton metabolism can therefore potentially reduce

human-induced CO_2 emissions in the atmosphere through carbon fixation. Continual monitoring of the concentration and composition of phytoplankton assemblages is essential in climate change studies.

Inland water systems are known to play a significant role in the global carbon budget as well. However, future changes to northern environments could alter these dynamics leading to either net carbon emission or sequestration. Canada's boreal forest biome is vast and contains a very high density of lakes, making this region challenging for long term monitoring. There is increasing evidence that boreal lakes are actively processing, emitting, and storing carbon. Yet, available estimates of carbon budget, pools and fluxes are missing for the vast majority of lakes across northern environments. Accordingly, long-term, system-wide approaches are required to accurately evaluate the importance of lakes for boreal carbon budgets in a changing environment. Satellite OCR appears to be the only tool capable of providing such a large-scale assessment. In fact, lake color is largely driven by the content of dissolved organic carbon, which can be assessed from space.

A major concern, from a Canadian perspective, is the water quality of inland and coastal waters, which are exposed to increasing external pressures resulting from climate change (e.g., increase in eutrophication and harmful algal bloom) and direct human activities e.g., agricultural, domestic and industrial pollutants, invasive species, tourism industry, intensive fishing and farming of aquatic organisms as well as increased greenhouse gases in the atmosphere. These pressures may act concurrently to reduce water quality and contribute to the deterioration of ecosystem health and its capacity to provide ecosystem services, such as supporting commercial fish stocks.

Assessments of "water quality" usually employed *in situ* techniques, which are time consuming, costly and have limited spatial coverage. Spaceborne remote sensing, on the other hand, is particularly useful for monitoring changes in water properties with frequent, synoptic coverage, and many operational aquatic-colour products can be used directly as water quality indicators. For example, spaceborne



sensor estimates of light attenuation can be related to water transparency, which is used to assess and classify lakes and coastal waters. In addition, operational colour products in combination with data from different platforms, can transform this information into operational water quality maps.

Eutrophication (the enrichment of water by nutrients leading to intense algal growth) is a widespread environmental threat to lakes, coastal waters and estuaries in Canada. Monitoring programs sample a set of parameters, including chlorophyll-a (an index of phytoplankton biomass), suspended particulate matter, turbidity, and phytoplankton composition, which are readily obtained from remotely-sensed data. These data, when coupled with *in situ* observations, provide eutrophication-indicator maps on a routine basis.

Eutrophic systems are often associated with harmful or nuisance algal blooms (HNABs) that can have deleterious impacts on ecosystems through massive production of biomass, resulting in anoxia (i.e., oxygen depleted waters) and mortality of marine and freshwater life. Some species of HNABs may cause fish kills and contaminate shellfish, even at low concentrations, through production of toxins, which can also seriously affect human health. Overall, HNABs can have a significant local economic impact, engendering losses in revenue from tourism, fish kills, and disruption of aquaculture industries and drinking water treatment facilities. Ocean-colour radiometry can play an important role in effective ecosystem management with regard to HNABs: routinely-acquired synoptic data relating to phytoplankton dynamics allow both a greater understanding of the variability of HNABs as ecologically-prominent phenomena, and a means of detecting and monitoring the extent and progression of these blooms in near-real time. Appropriate action can then be taken, such as issuing warnings to the aquaculture industry or communities relying on freshwater for drinking or leisure activities.

One of the advanced applications of spaceborne aquatic-colour data is the detection and quantification of suspended sediments and the observation of changes in bottom topography caused by sediment transport. This is particularly relevant in tidal estuaries and bays in Canada, which experience some of the highest tides in the world, and are often used for tidal power schemes. Active sediment transport can impact tidal energy production, can also alter the course of, or reduce the depth of, shipping channels and ports.

Credits: Caren Binding, ECCC

2. NETCOLOR PRIORITIES

The international optical aquatic science community has been a driving force for Earth observation (EO) over the last four decades. Among this large community, several Canadian scientists are forerunners, laying the path for the development of new instrumentation, innovative algorithms, and spaceborne applications for marine and freshwater issues. Between 1975 and 2015, eight Canadian members of this community produced 518 peer-reviewed articles, or more than 10 articles per year. These articles have been cited 22,700 times attesting to the important contribution of Canada to the current state of aquatic optical remote sensing[1].

Remote sensing of lakes and oceans has seen tremendous improvement since the launch of the first "ocean-colour" sensor by NASA in 1979 (Coastal Zone Color Scanner). While several ocean-colour multispectral sensors are currently in orbit (VIIRS, MODIS, OLCI and SGLI), the scope of spaceborne applications has broadened with the use of very-high spatial, broad-band sensors (e.g., Landsat, SPOT, Sentinel-2 MSI) and the future generation of hyperspectral sensors (e.g., PACE).

The Canadian aquatic colour community remains active and engaged and has arrived at a turning point with the responsibility of building on the legacy built over the last forty years. The need for a national strategy and long-term vision has unified our community under the leadership of NetCOLOR (Network of Coastal, Oceans, and Lakes Optics Remote sensing). The current document aims at addressing the future directions and objectives of the Canadian aquatic colour community to tackle issues related to the understanding, monitoring, and protection of our freshwater, estuarine, and marine environments, as well as bridging the gap with end-users to ensure that the most appropriate space- and air-borne products are available to help management make science-based decisions.

A wide range of products can be derived from visible spectral radiometry. Participants at a NetCOLOR meeting that took place in Québec City in March 2016 reviewed the state-of-the-art advancement in the field of aquatic colour at the international level and selected the 10 most pressing issues relevant to Canada's interests in monitoring and protecting its lake, coastal, and ocean environments. Note that the order of the 10 issues listed below does not reflect their priorities.

1 Statistics derived from Web of Science using the authors Platt T., Sathyendranath S., Lewis M., Cullen J., Bukata R., Gower J., Larouche P., Borstadt G.

Credits: landsat.visibleearth.nasa.gov/view.php?id=88843

2.1. ECOSYSTEM SHIFTS IN A CHANGING CLIMATE

Phytoplankton sustain aquatic life in oceans and lakes and changes to their abundance, rates of production, and species composition may have irreversible impacts on food webs, and ultimately on human economical activities. Shifts in the timing, duration, magnitude and composition of phytoplankton blooms can have significant impacts on aquatic ecosystem functioning. Such changes to marine spring phytoplankton bloom shape the higher trophic levels over the course of several years, since it has been shown to have an impact on larval fish recruitment of several commercially important fish species. Given that the properties of phytoplankton blooms vary significantly at the regional scale, only satellite ocean colour radiometry can resolve the spatial and temporal variability at the synoptic scales needed to characterise them accurately.

Several studies have demonstrated the link between the phytoplankton spring bloom and recruitment of fish and benthic organisms as well as breeding success of marine birds in several areas of Canada's three major oceans, including the Pacific (Malick et al., 2015, Borstadt et al., 2011) and the Atlantic (Platt et al., 2003, Trzcinski et al., 2013). Under warming climate conditions, the phytoplankton spring bloom tends to occur earlier in the Arctic (Kharu et al., 2010; Marchese et al., 2017), while a second bloom is developing in the fall (Ardyna et al., 2014). The impact of these changes on the food web is not yet fully understood. The response of phytoplankton to climate forcing, and notably water temperature, stratification, and chemistry (e.g., ocean acidification) has already been observed using spaceborne ocean-colour radiometry (Behrenfeld et al., 2006; McClain, 2009), for instance, coccolithophore blooms have progressed northwards with the increasing inflow of Atlantic waters into the Arctic and subarctic region (Neukerman et al. 2018). In lakes, pronounced changes in annual ice cover have been accompanied by important shifts in phytoplankton and bacterial community structure, with far reaching ecosystem effects and food web disruptions (Beall et al., 2015). Aquatic colour remote sensing is the only means of obtaining detailed information on phytoplankton distribution, community structure, and phenology (i.e. the seasonal variations) over Canadian oceans, lakes, and coastal areas, and is thus critical to monitoring and quantifying large scale changes in aquatic ecosystems.

Primary production sustains both pelagic and benthic marine ecosystems. Energy transfer between primary producers and consumers in aquatic ecosystems, in terms of carbon, depends on the size distribution of organisms (PSD), generally described by a power law. The steepness of the power law indicates the efficiency of energy transfer where a high slope of PSD indicates a low-transfer efficiency (Jonsson, 1986; Loisel et al., 2006). Recent advancements in ocean colour approaches allow phytoplankton size classes to be discriminated (IOCCG, 2014), which have led, for instance, to the derivation of size-class dependent primary production estimates (Uitz et al., 2012). Furthermore, the discrimination of major phytoplankton functional groups using spaceborne ocean colour radiometry has helped advance our understanding of the biogeochemistry and carbon cycles in marine ecosystems as well as climate change feedbacks. Studies in the Northwest Atlantic Ocean have also demonstrated that certain essential fatty acids are only produced by diatoms (which can be discriminated using ocean colour radiometry), making it possible to obtain information on standing stocks of essential fatty acids on synoptic scales (Budge et al. 2014). Spaceborne ocean colour thus represents a tremendous asset when studying spatial distribution and frequency of occurrence of phytoplankton functional types (PFTs) at the global scale, which in turn could be used as input to fisheries or other biological models. This type of application remains in the research domain but should find some operational application in the coming years.

2.2 CARBON CYCLE

Oceans sequester roughly 25 - 30% of CO_2 emitted into the atmosphere through the burning of fossil fuels and other anthropogenic activities (Le Quéré et al., 2016). The role of oceans is fundamental in the global carbon cycle, notably through the so-called biological pump. Aquatic colour remote sensing allows quantification of carbon standing stocks in the upper surface layer of the ocean, either in particulate or dissolved form, and the rates at which the biomass grows. Several spaceborne products such as column-integrated primary production, particulate and dissolved organic carbon (POC and DOC), and particulate inorganic carbon (PIC) are routinely generated for the global ocean. Merged spaceborne ocean-colour datasets from various sensors bring the global observational capacity to more than 20 years. Improvement in algorithm robustness and accuracy will help scientists to understand the processes involved in the global carbon cycle and notably the role of the continental margin in carbon export towards the ocean, in particular in the Arctic region where the thawing of permafrost increases not only the transport of POC and DOC toward the ocean, but also the rate of uptake of atmospheric CO_2. New technology with improved spatial resolution will allow us to assess coastal productivity, including marine macroalgae. Macroalgae are the dominant primary producers in the coastal zone and the quantification of their contribution to carbon sequestration remains in its infancy (Krause-Jensen and Duarte, 2016).

On the other hand, freshwater systems are globally significant sources of CO_2 to the atmosphere by processing the organic carbon produced on land (Cole et al., 2007). Tranvik et al., (2009) suggested that the global annual emissions of carbon dioxide from inland waters to the atmosphere are similar in magnitude to the carbon dioxide uptake by the oceans. Meanwhile, Monteith et al. (2007) documented recent widespread increases in DOC concentrations in lakes across North America and Europe attributed to changes in atmospheric deposition chemistry. Carbon stock in lakes and man-made reservoirs is currently unknown and could only be assessed from space. Aquatic colour radiometry can thus play a key role in the evaluation of carbon stocks in fresh water environments and eventually their emission to the atmosphere.

2.3 COASTAL EROSION AND SEDIMENT TRANSPORT

More than 40% of the world population lives in coastal areas (CIESIN, 2007). Sea level rise and storm activities increase coastal erosion with tremendous financial impact (Bernatchez et al., 2015, 2016). Higher precipitation in some regions increases the export of sediment from land to the coastal ocean, as recently observed for the Mackenzie River (Northwest Territories) (Doxaran et al., 2015). Spaceborne ocean colour sensors and notably high spatial resolution sensors (such as Landsat 8 OLI and Sentinel-2 MSI) provide a frequent revisit of coastal sites which can be used to monitor shoreline evolution with time (independently of the tidal cycle). In addition, robust algorithms to retrieve sediment concentration in turbid areas are now available, providing information on sediment transport and particulate organic carbon export when coupled with data on river discharge. Aquatic colour radiometry can contribute significantly to monitoring the global transport of sediments from land to the coastal ocean.

2.4 IMPACT OF SHORT DURATION EVENT (STORMS, OIL SPILLS)

Episodic events such as storms may enhance phytoplankton productivity through wind-induced nutrient injections into surface waters (Son et al., 2007, Chavez et al., 2011), or increased nutrient loading through storm runoff from the watershed, and at certain times of the year (e.g., fall season) this enhanced primary productivity may represent a key source of food for higher trophic levels (Sigler et al., 2014). The short duration and geographic location of such events make it difficult to sample *in situ*. Spaceborne aquatic colour radiometry is the only means of quantifying the impact of such


Credits: Julien Laliberté

short duration events. One of the limitations of spaceborne observation is that a single satellite pass might not be appropriate to monitor rapid changes in productivity. However, the use of multiple sun-synchronous or geostationary satellites can circumvent this pitfall. MODIS proved the ability of aquatic colour observations to monitor oil spills during the Deepwater Horizon incident (Grimaldi et al., 2011), and is routinely used by ECCC's ISTOP program to detect oil spills in Canada's coastal and inland waters. Spaceborne aquatic colour observations also have the capacity to provide specifics about the state of a marine ecosystem before a major event occurs, as well as information on its recovery.

2.5 EUTROPHICATION AND HARMFUL AND NUISANCE ALGAL BLOOMS

HABs occur frequently in lakes and coastal areas all over Canada. They cause extensive damage to aquaculture and tourist industries and ultimately can pose a risk to human health. Their economic impact is in the range of tens of millions of dollars. Several harmful algal groups and species have been identified in Canadian waters, such as cyanobacteria (e.g. *Microcystis spp*), both in fresh and marine waters, dinoflagellates (e.g, *Dinophysis* and *Alexandrium spp*), and diatoms (e.g., *Pseudo-nitzschia spp*.). Global warming of the surface ocean will provide environmental conditions that can increase the frequency and intensity of HABs (Paerl and Huisman, 2008). Spaceborne ocean colour is used to monitor the onset and progression of algal blooms in the Great Lakes (Stumpf et al, 2012) and other large Canadian lake systems (Lake Winnipeg and Lake of the Woods, Binding et al, 2011). Both broad-band, high spatial resolution (e.g., Landsat, Sentinel-2) and multispectral, medium spatial resolution sensors can provide information on the location and extent of HNABs, provided that they exhibit a unique optical signature. Another approach, when the HNAB optical signal is not detectable, is to rely on other proxies, such as the combined increase of chlorophyll concentration and sea surface temperature (SST), two properties than can be derived by spaceborne observation.

Monitoring and remediation of eutrophication of lakes and coastal areas is another issue that could benefit from aquatic colour remote sensing. Cyanobacteria are a source of concern for water quality in many lakes, notably affecting drinking

resources and decreasing the recreational value of water bodies. Current high spatial resolution and multispectral sensors could help define the baseline of trophic status in Canadian lakes where cyanobacteria are a potential or, in some instances, proven issue. It would also allow for the monitoring of intense blooms, their temporal patterns, and geographical distribution, as well as their long-term trends. Future hyperspectral sensors will provide even more capabilities to detect specific pigments and species (Ortiz et al., 2013; Wang et al., 2016).

2.6 VISIBILITY, FRONT, EDDIES AND INTERNAL WAVES DETECTION

Underwater visibility has many applications, from defence purposes to mapping bottom habitat in shallow coastal waters. It is an indicator of inland water quality, responds to the impacts of invasive species and affects the retrieval of bathymetry. Satellite Derived Bathymetry (SDB) is of great interest for defence departments, private enterprises and hydrographic offices as it offers a quick and cost efficient way to chart coastal waters. From the perspective of the Canadian Hydrographic Service (CHS), the goal is not to replace current hydrographic surveys, but to complement and support them, especially in remote areas with difficult access. Traditional surveys are highly accurate, but provide inefficient coverage of shallow waters for which the risk associated with the survey is also higher, two issues solved by SDB. With a first estimate of the bathymetry on hand, a hydrographic surveyor would be aware of potential dangers to navigation before going out on the water, therefore improving safety. Additionally, SDB can also be extracted for remote and hard to reach areas like the Arctic, which is an immense challenge to survey due to its size, remoteness and climate.

Fronts and eddies are ubiquitous features in the oceans that are often associated with enhanced biological activity (e.g. Doniol-Valcroze et al., 2007, Xu et al., 2017). Depending on the generation process, they are often linked to specific bathymetric features (shelves, capes, canyons, banks, shoals, etc.). Their spatial and temporal scales vary over several orders of magnitude, ranging from small river plume boundaries (a few meters and a lifetime of a few days) to western boundary currents such as the Gulf Stream (hundreds of kilometers and coherent in time for thousands of years). As they often act as hotspots against a lower biological

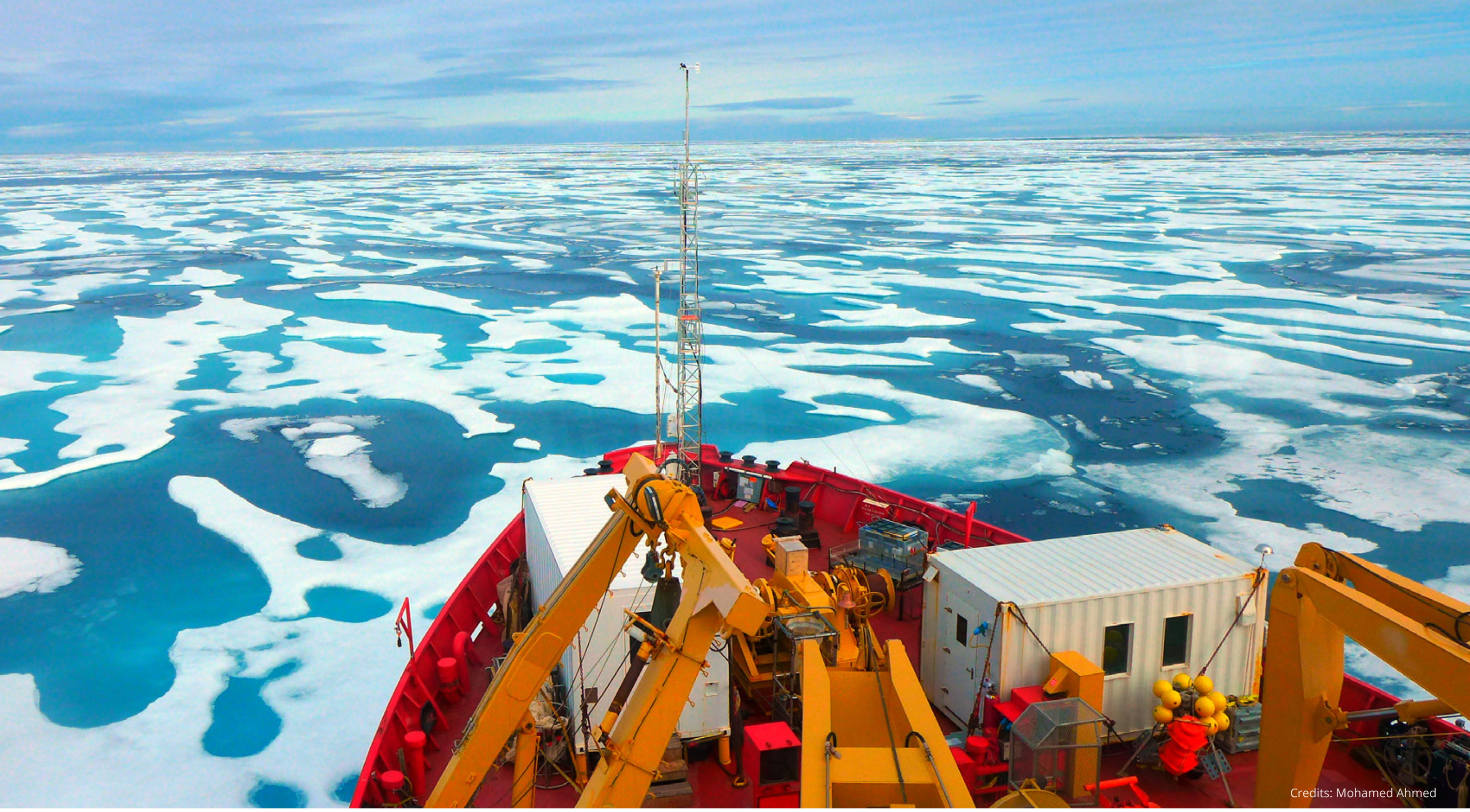

Credits: Lucas Barbedo de Freitas

production background, it is therefore important to understand how fronts are generated and how they influence biological production. Remote sensing has often been used to detect and characterize fronts and eddies based on their thermal or aquatic colour signatures (McGillicuddy et al., 2001; Miller et al., 2015). Although a climatology of fronts has recently been generated for Canadian coastal waters (Cyr and Larouche, 2015; Ben Mustapha et al., 2016), work remains to be done to evaluate their temporal variability and long-term evolution with implications on local productivity.

The specular reflection of the sky radiance and/or the direct sun beam at the air-sea interface, known as sunglint, can dominate the radiance received at the top-of-atmosphere (TOA) by a space-borne sensor. Sunglint depends on the sun and sensor viewing geometry and the wave facette geometry (Cox and Munk, 1954). Recently, sunglint patterns observed in low spatial resolution (1-km) images acquired by the Moderate Resolution Imaging Spectroradiometer (MODIS) have been used to detect internal waves at the global scale (Jackson, 2007). The near nadir viewing geometry of Landsat TM makes the acquisitions during summer prone to sunglint. Evidence of solitary and non-linear internal waves in coastal waters was also found using Band 5 (1.55 - 1.75 µm) of Landsat TM at 30-m spatial resolution (Artale et al., 1990; Borzelli et al., 1994). In this spectral range, for which the water body is completely black due to extremely high absorption by pure water (593.4 m-1; Kou et al., 1993), the TOA radiance is solely due to the sum of atmospheric scattering, sky glint and sunglint contributions. Recently, Normandeau et al. (2014) detected the presence of internal waves near Pointe-des-Monts in the Gulf of St Lawrence. Internal waves have been detected in many other locations within the St Lawrence Estuary using Landsat-8 imagery (Bélanger, unpublished results)

2.7 MARINE PROTECTED AREAS AND ECOLOGICALLY AND BIOLOGICALLY SIGNIFICANT AREAS INCLUDING WETLANDS AND VEGETATED COASTAL HABITATS

Canada has lagged for many years in the designation of marine protected areas. In 2016, under the Canada-US Joint Statement on Climate, Energy and Arctic Leadership, ambitious targets have been set by the federal government to increase the proportion of coastal and marine areas conserved from the current level of 5% to 10% by 2020. Spaceborne ocean colour has already proven valuable to identify zones of high primary production, which can support a large and biodiverse ecosystem, such as areas of recurrent upwelling (Silió-Calzada et al., 2008; Nieto and Mélin, 2017). High to medium spatial resolution (10 - 300m) multispectral sensors are well adapted to provide information on the



productivity of marine ecosystems in both coastal and pelagic regions. Multiple variable analyses (e.g., chlorophyll-a, SST) have been used to identify biomes or bio-geochemical provinces at global scales (Longhurst et al., 1995; Devred et al., 2007) and such approaches can be used to infer ecologically significant areas at regional and local scales (McIver et al., 2018). For coastal areas, the Landsat suite of satellites has been used to quantify kelp distribution along the western North American coasts (Cavanaugh et al., 2011) and to monitor their change with time. This type of approach could be used to delineate sensitive areas that have undergone high stress levels in recent years. These areas should be prioritized for protection.

2.8 CHARACTERIZATION AND MONITORING OF SEA AND LAKE ICE

The decrease in sea- and lake-ice extent, thickness, and the loss of multi-year ice, are changing marine and freshwater ecosystems. Surdu et al. (2016) presented evidence of recent changes in the ice regime of lakes in the Canadian High Arctic, with lakes experiencing earlier dates of summer ice minimum and water-clear-of-ice (WCI); and some lakes transitioning from a perennial/multiyear to a seasonal ice regime. Microwave and RADAR technology provide detailed information on ice concentration, structure, and thickness but become limited in spring when wet snow and melt ponds form at the ice surface, thus decreasing the usefulness of microwave radiation due to liquid water absorption. Ocean colour sensors, such as MODIS, have proven valuable for retrieving the distribution of melt ponds on bare ice at coarse spatial resolution (1 km). This is an important step to understand the onset of the spring bloom, when ice-algae and under ice phytoplankton present exponential growth. In some lakes, there is evidence that intense winter algal blooms are maintained beneath the ice and may have consequences for summer hypoxia and lake responses to climate change (Twiss et al., 2012). The use of spaceborne ocean colour sensors with an improved spatial resolution (i.e., Ocean and Land Color Imager, OLCI launched on Sentinel-3A in 2016 and Sentinel 3B in 2018) will provide information on the subsequent phases of ice retreat and the development of ice edge phytoplankton blooms. Such an approach, based on the radiative budget at the top of the water column, from ice-covered to open waters, will provide a unique insight into Arctic marine ecosystems as they evolve from the very low biological activity in the winter to high production within a matter of a few weeks in the spring and summer. Spaceborne ocean colour sensors are also used to complement other spaceborne information on sea-ice concentration. Although limited by cloud cover, their high spatial resolution combined with multiple passes per day (due to their near-polar orbits) are an asset for sea-ice observation. The Canadian Ice Service (CIS), for instance, includes aquatic colour observations in addition to RADAR observations in their database.

2.9 CHANGE IN ARCTIC PRODUCTIVITY

In addition to decreasing ice cover, warming of the Arctic Ocean will have a profound impact on phytoplankton community structure, phenology, and productivity. Models estimate a summer free-of-ice Arctic Ocean by 2050 (IPCC, 2014); numerous questions remain regarding the productivity in an open Arctic Ocean. Increasing stratification may promote oligotrophic conditions and dominance of small cells in some regions of the Arctic Ocean, (Li et al., 2009) in contrast to atmospheric-induced mixing of the water column, which may trigger local productivity (large cells). Recent increases in annual primary production in the Arctic Ocean have been mainly attributed to the increase of open waters (Arrigo et al., 2015), however, the long-term impact on the marine ecosystem remains unclear. Thawing of permafrost will increase carbon export (particulate and dissolved) to the continental shelf, which in turn will change the light regime in the water column, further impacting primary production. Aquatic colour observations have played a key role in detecting changes in the Arctic Ocean at the global scale, although some challenges remain to be addressed such as how to deal with atmospheric corrections or adjacency effects close to the ice edge. Numerous field campaigns have been carried out by Canadian researchers in the Arctic Ocean and we can expect some of these issues to be addressed in the near future. The recent (i.e., Sentinel-3 OLCI) and future (e.g., PACE) launches of spaceborne ocean colour sensors will provide new data that will help to better forecast future primary production in the Arctic Ocean.

2.10 STATUS AND TRENDS IN INLAND WATER BIOGEOCHEMISTRY AND ECOSYSTEM HEALTH

Canada's vast network of freshwater lakes covers almost 9% of the nation's surface area, with the Great Lakes alone, the largest freshwater system on earth, containing roughly 18% of the world's fresh surface water. These freshwater systems support multiple ecosystem services; important commercial fisheries, transport, popular leisure and recreational activities, while providing drinking water, and the generation of hydroelectric power. Inland waters are under increasing pressure from physical modifications of hydrologic regimes (urbanisation and hydroelectric development), watershed land-use change (intensification of farming and fertilizer use, loss of wetland habitats), release of hazardous pollutants and nutrients, introduction of invasive species and unprecedented change from modifications to our climate. Canadian lakes are key indicators of the impact of climate change; reduced periods of lake ice have significant impacts on lake ecosystems, warming temperatures affect the timing, severity and extent of HNABs and increased frequency of storm events affect runoff and nutrient loading to lakes. While detailed assessments and monitoring of lake ecosystem health are carried out often on a lake-by-lake basis, little is known on a cross-Canada scale, and this can only be addressed using Earth observation. Advancements in sensors and algorithm development make observations of Canada's millions of small lakes increasingly reliable, which is at the basis of the NSERC Canadian Lake Pulse network.

3. NETCOLOR RECOMMENDATIONS AND ACTIONS

Credits: Julien Laliberté

For Canada to remain an international leader in the field of spaceborne observation of lakes and oceans using multi-spectral radiometric measurements, a number of mid- and long-term objectives have to be reached. The aim of the following section is to make recommendations to managers and funding institutions. Suggested actions are presented for the aquatic visible remote sensing community to achieve these goals.

3.1 ADDRESS ISSUES RELATED TO ATMOSPHERIC CORRECTION AND ADJACENCY EFFECTS

Aquatic remote sensing reflectance, the fundamental quantity to be derived from spaceborne aquatic colour sensors, is obtained once the effects of scattering in the atmosphere (~ 90-97% of the total top-of-atmosphere signal) have been accurately modeled and removed from the observed signal. Assumptions made in the open oceans to correct for the effect of the atmosphere do not hold in coastal and inland waters. There is a critical need to achieve high accuracy of atmospheric correction, including removal of the adjacency effect in coastal and inland waters, a problem that is acute in high latitude areas close to the ice edge. With the emergence of coastal, high spatial resolution imagers, and a strong interest in information for coastal and inland environments (e.g., investment by the Canadian government in the Oceans Protection Plan), NetCOLOR recommends that this issue become a priority when addressing spaceborne observation in coastal and inland waters.

Action: Support Canadian initiatives that link to international projects addressing atmospheric correction and adjacency effects.

3.2 DEVELOPMENT OF REGIONAL, COASTAL AND INLAND ALGORITHMS AND ASSESS ADDED VALUE OF HYPERSPECTRAL DATA

There is a consensus to focus on coastal and lake waters, notably for the development of algorithms that can account for the optical complexity of these environments. Whereas it is recognised that current generic algorithms do not perform well in Canadian inland and coastal waters, there are still no regional algorithms that have been demonstrated to perform well in domestic waters. Emergence of new hyperspectral capacities, such as PACE and possibly the Dual Imaging Spectrometer COCI Experiment (DICE) system, raises the need to thoroughly assess the improvement of such sensors over those that supply multispectral data. There is a need to define optimum spatial and spectral resolutions to address issues specific to highly dynamic inland and coastal environments.

Action: Create a working group on algorithm development and validation, including hyperspectral approaches for Canadian waters, including the Arctic Ocean. This working group would focus on the development of regional algorithms and conduct a systematic validation in Canadian waters. Support should be sought to carry out these activities.

3.3 SYNERGY WITH OTHER PLATFORMS AND TECHNOLOGIES AND CONTINUITY OF SPACEBORNE OCEAN COLOUR DATA

One of the main limitations of ocean colour sensors is that they cannot collect data under conditions of cloud cover, sea-ice, or during the night. To increase data coverage, we recommend developing synergies between spaceborne aquatic colour data and consolidating regional inter-calibrated and merged datasets from various sensors, such as the ESA-Climate Change Initiative (CCI) or the GlobColour approaches for the global scale, which utilise data archives from the MERIS, Aqua-MODIS, SeaWiFS, and VIIRS missions to ensure an uninterrupted time series of multi-sensor spaceborne global data products for climate research and modelling. In addition, synergy between various platforms should be attempted, not only for inland and coastal waters, but also in offshore waters. Canada will launch the RADARSAT Constellation Mission (RCM) in 2020 and is involved in the Surface Water Ocean Topography (SWOT) mission, which could create opportunities for synergies between missions. NetCOLOR also recommends developing synergies between in situ instruments (e.g., gliders, Bio-Argo floats, and moorings) for both validation and monitoring activities, since coupling these observational means would provide a three dimensional view of the ocean, adding a vertical dimension that is not possible with current spaceborne sensors.

Action: With CSA support, initiate projects on long term OCR data continuity and synergy between aquatic colour, RADAR, and altimetry technologies for sea-ice related research and mapping and monitoring of coastal habitats.

3.4 DATA MINING AND ARCHIVING

Large in situ bio-geo-optical datasets have been, and are currently, collected by Canadian scientists. NetCOLOR recommends urgent action to invest in data mining, quality control, and archiving of historic in situ datasets collected by Canadian PIs to support spaceborne data product validation, algorithm development, and other analyses. There is a need for a national repository that will be searchable and can provide relevant data to researchers in an advanced format, for example, using the format guidelines for the NASA SeaBASS or ESA MERMAID bio-optical data archive. SeaBASS data and files can be accessed and saved using a series of online search engines, e.g., the user can extract files for different variables to perform matchups.

Action: Under NetCOLOR's supervision, and together with financial support from various Canadian institutions, hire a technician or contract the private sector to develop a database that is accessible to Canadian members of the NetCOLOR community with the possibility to query. Open an international database in agreement with intellectual property policy.

3.5 CONSOLIDATING THE COMMUNITY, TRAINING OF THE NEXT GENERATION AND OUTREACH

Canadian researchers have made a strong contribution to international advances in the theory and application of bio-optics to spaceborne remote sensing for monitoring our marine and freshwater environments. For Canada to pursue its leading role at an international level there is a strong need to prepare the next generation of scientists in various fields of visible radiometry, from field operations to spaceborne data processing and the development of new algorithms. Simultaneously, we recommend a strong effort to maintain the cohesion


Credits: Lucas Barbedo de Freitas

of the community, through increased collaboration and regular meetings. In this respect, NetCOLOR can become a key player in achieving this objective. Applications of spaceborne aquatic colour radiometry have far reaching possibilities that trigger interest from a diverse community from fish stock assessment, to bathymetry information in coastal waters and water quality in coastal areas and inland lakes. We recommend fostering and strengthening exchange and collaboration between our community and end-users through targeted events, such as inviting end-users to NetCOLOR meetings and actively promoting the technology to managers and decision-makers, etc.

Action: Organise a training course under the NetCOLOR umbrella, as was previously done in 2006 (organised by IOCCG under CSA funding) targeting end-users and young researchers.

Canada has the human resources, technology, and know-how to address the challenges of Earth Observation and can help solve issues related to the marine and freshwater environments. By creating a network of experts in the field of aquatic bio-optics, our community aims to structure its activities, creating opportunities and collaborations, while directing outreach and applications towards end-users (including scientists from other disciplines, managers, and decision makers), and preparing the next generation of scientists. NetCOLOR also strives to increase visibility and achieve consensus when dealing with funding institutions and partners for the benefit of our entire community. The present document illustrates the results of such a collaboration where the views of individuals are confronted and debated to reach an overall agreement on issues such as the pressing questions that aquatic colour remote sensing can help tackle.

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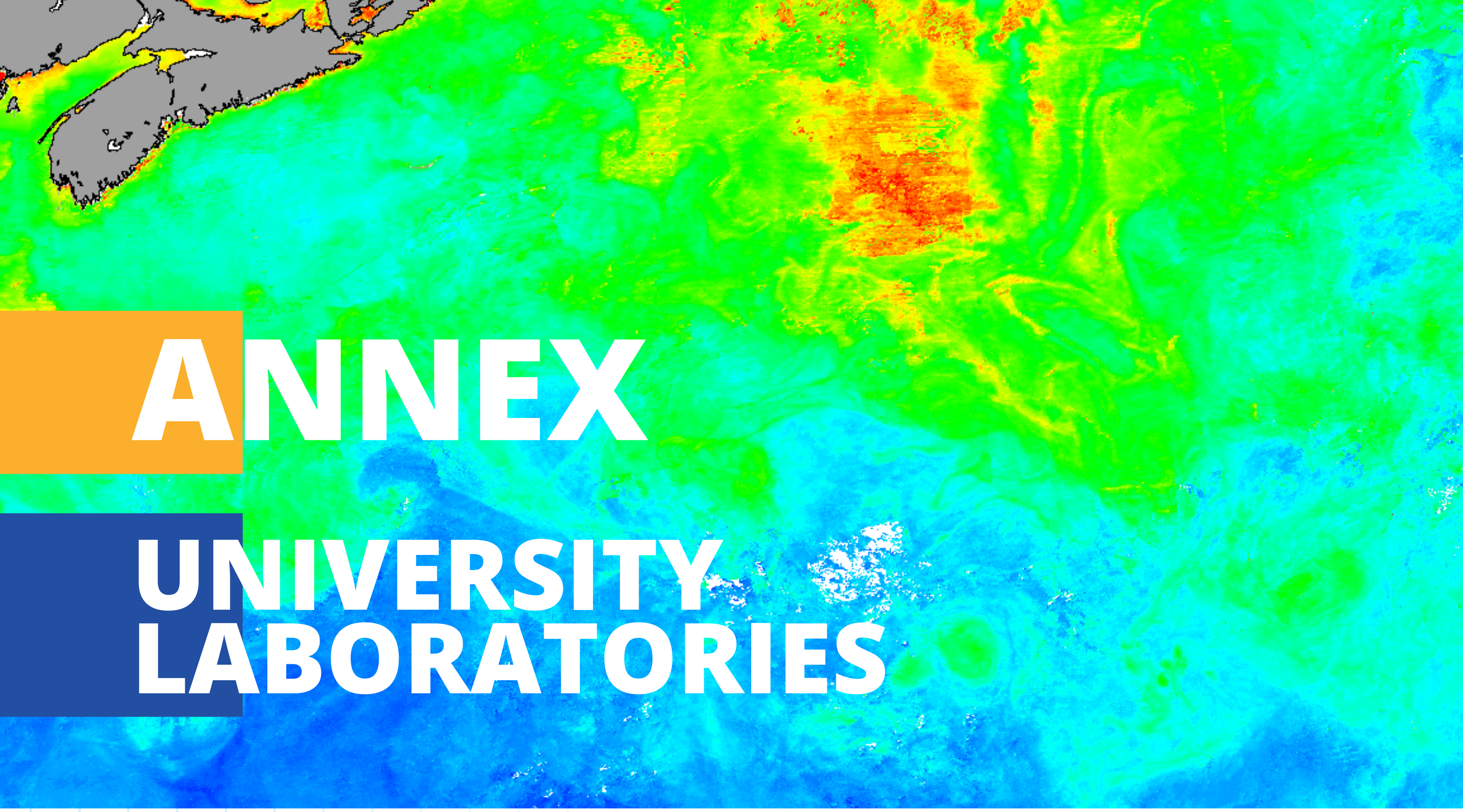
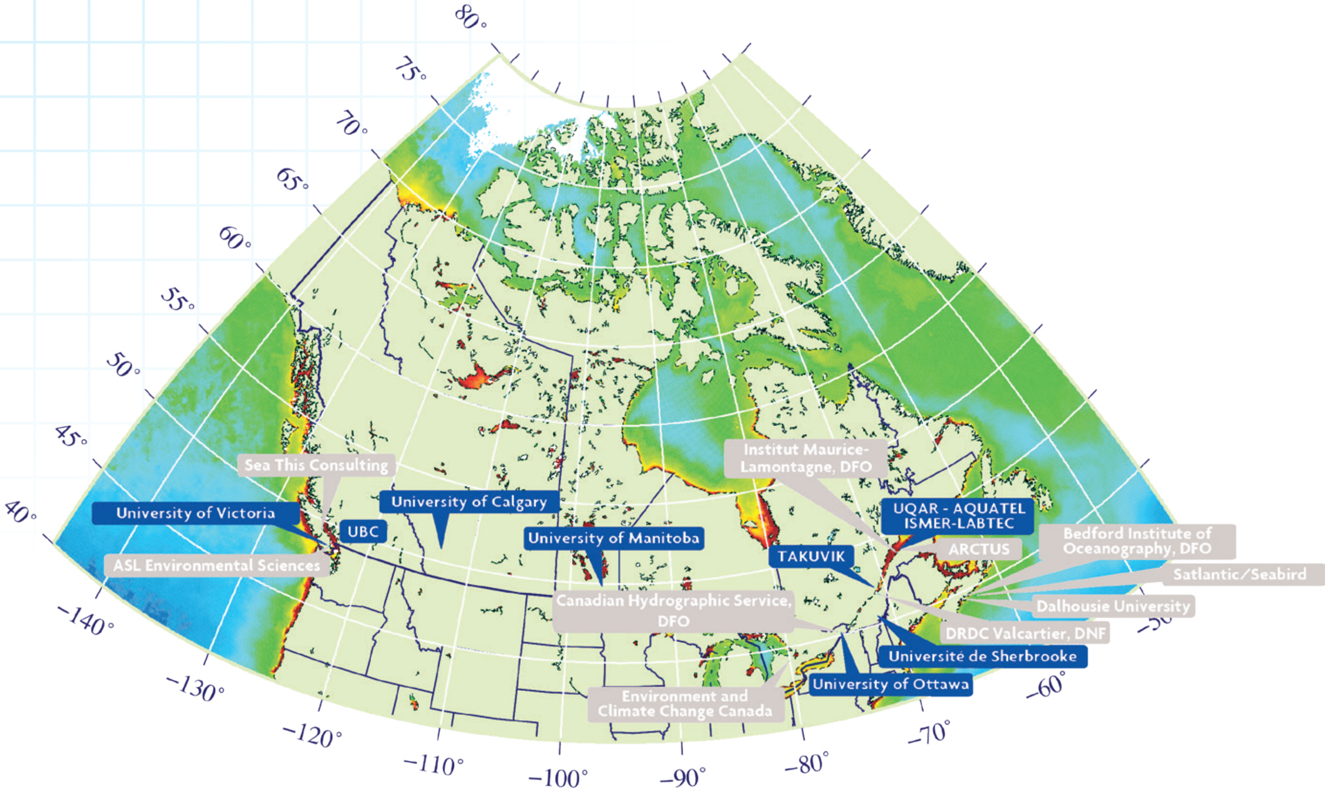


ANNEX

UNIVERSITY LABORATORIES



Data source MODIS OBGP - NASA

UNIVERSITÉ DE QUÉBEC À RIMOUSKI (UQAR)

Rimouski, QC

The Aquatel laboratory at the Université du Québec à Rimouski (UQAR) was created by Simon Bélanger in 2010 to train specialists in the development and use of remote sensing and optical technologies to assess the quality of water at the Earth's surface through spectral analysis. Aquatel is supported by research grants from DEC-Canada, CFI, NSERC and FRQNT, as well as the Canadian (CSA) and European (ESA) Space Agencies.

Some of the recent projects include:

- Impacts of climate changes on light-stimulated carbon fluxes in the Arctic Ocean: estimation of primary production and photooxidation using satellite remote sensing (NSERC).
- Development of algorithms to assess spectral irradiance reaching the sea surface at high latitude (NSERC-ArcticNET).
- Improvement of ocean color algorithms for Polar Regions (NSERC-ArcticNET-CSA-ESA).
- Changes in phytoplankton phenology and functional types (PFTs) in the eastern Canadian Arctic and Labrador Sea (ArcticNET-CSA-VITALS).
- Inherent optical properties and bulk biogeochemical properties of water constituents in the land-to-sea continuum (Riverscape project; FRQNT, NASA).
- Development of a network of optical buoys for the satellite validation of radiometric products and for the monitoring of the bio-optical state of the in the St. Lawrence Estuary and Gulf (NSERC, DFO).
- Impact of climate variability and river flow regulation on phytoplankton productivity in the Hudson Bay: a satellite-based assessment (BaySYS project; NSERC-industry with Hydro-Manitoba).
- Remote sensing of key indicators (or stressors) of the marine biodiversity and ecosystem functions and services in coastal embayment: case study of the Sept-Iles Bay (Québec, Canada) (Canadian Healthy Ocean Network project; NSERC-strategic).
- Remote sensing as direct observation of lakes water quality and organic carbon content: (Lake Pulse project; NSERC-strategic)

LABTEC: Martin Montes-Hugo's expertise in ocean color remote sensing of aquatic systems is mainly based on oceanographic LiDAR (light detection and range) systems. The research focus of LABTEC (Laboratoire de teledetection cotiere), his lab at UQAR/ISMER, is the study of suspended particulates in littoral waters based on passive and active remote sensing measurements. This effort involves in situ measurements, simulations based on radiative transfer models and processing of ocean color satellite images. In particular, his team develops inversion models for estimating microphysical attributes of organic and inorganic suspended particulates. This information is essential for understanding biogeochemical processes in estuarine and coastal waters and how these ecosystems respond to climate-mediated effects.

Recent LABTEC projects include:

- Optical remote Sensing models for estimating suspended Particulate matter in the st Lawrence Estuary (OSPLE) (2011-2016).
- Robotic Underwater Surveys in the Canadian Arctic (RUSCA) (2011-2017)

UNIVERSITÉ LAVAL

Québec, QC

Marcel Babin, director of the Takuvik Joint International Laboratory and laureate of the Canada Excellence Research Chair (CERC) in Remote Sensing of Canada New Arctic Frontier oversees all activities related to marine optics at Université Laval. Three research disciplines are being used to monitor the fate of the changing Arctic marine environment in the face of global warming and the subsequent recession of sea ice:

- The ecophysiology of Arctic phytoplankton species (e.g., chaetoceros, a diatom and micromonas, a green algae) are being studied under laboratory conditions. Their growth and bio-optical properties are examined under various temperature, light and nutrient conditions that simulate possible scenarios in a changing Arctic.
- A second group of researchers operates and develops bio-optical instrumentation and robotic platforms for use in the Arctic Ocean. Takuvik carries out annual sea-going fieldwork where a large panel of bio-optical parameters are measured, including IOP (Inherent Optical Properties), radiometric parameters like multispectral irradiances, used to derive AOP (Apparent Optical Properties), biogeochemical parameters (like nutrient and dissolved oxygen concentrations) and phytoplankton community structure. The instrumentation group also deploys Bio-Argo floats and gliders as part of Takuvik's efforts to understand the biogeochemical processes taking place in the Arctic Ocean. Furthermore, novel optical instruments are presently being developed that will permit critical new information about snow, sea ice and benthos to be collected.
- A third team carries out remote sensing satellite research activities related to ocean colour including algorithm development (i.e., primary production, chlorophyll-a concentration, suspended particulate matter, particulate inorganic carbon, etc.), the inclusion of new algorithms in processing chains, and the computation of time series of properties for all available ocean colour sensors. In addition, the remote sensing group hosts time series of SST, sea-ice concentration and thickness, and salinity.

These three research disciplines coalesce in GreenEdge, a large international program that Takuvik is currently leading, the aim of which is to study the fate of the ice-edge phytoplankton bloom in a changing Arctic. Observations from ice camps (2015 and 2016) and an oceanographic cruise (2016) are presently being analysed to determine the bio-optical properties of the ice-seawater system at all successive stages of the spring bloom ranging from snow covered sea ice to open water.

Similarly, Takuvik contributes to the international project Nunataryuk (2017-2022) by leading the workpackage 4 on the impact of thawing permafrost on the coastal waters, by integrating data from these three research disciplines.

UNIVERSITÉ DE SHERBROOKE

Sherbrooke, QC

The Canada Research Chair in Earth observation and phytoplankton ecophysiology, led by Yannick Huot at Université de Sherbrooke, works on different aspects of aquatic optics and remote sensing of ocean color, including: developing remote sensing algorithms mostly for sun-induced fluorescence studies; studying the inherent optical properties of phytoplankton cells including absorption, scattering, backscattering and volume scattering function; studying the impact of phytoplankton photophysiology on fluorescence emission; and examining the impact of small sources of variability on the remotely measured ocean color spectra.

The lab focuses on global studies of the ocean from remote sensing, field studies in different areas of the global oceans, and more recently has started to work on lakes. Members have access to a limited pool of optical instruments, which includes fast repetition rate fluorometers, a spectrophotometer, and a single angle backscattering meter. An instrument to measure the volume scattering function is currently being developed.

Yannick Huot collaborates widely and has been involved though collaborations on inversion methods to obtain information from the absorption coefficient, the volume scattering function and the absorption of pure water. He leads the NSERC Canadian Lake Pulse Network which will sample several hundred lakes across Canada for optics and many other variables with the aims of assessing lake health and developing remote sensing algorithms.

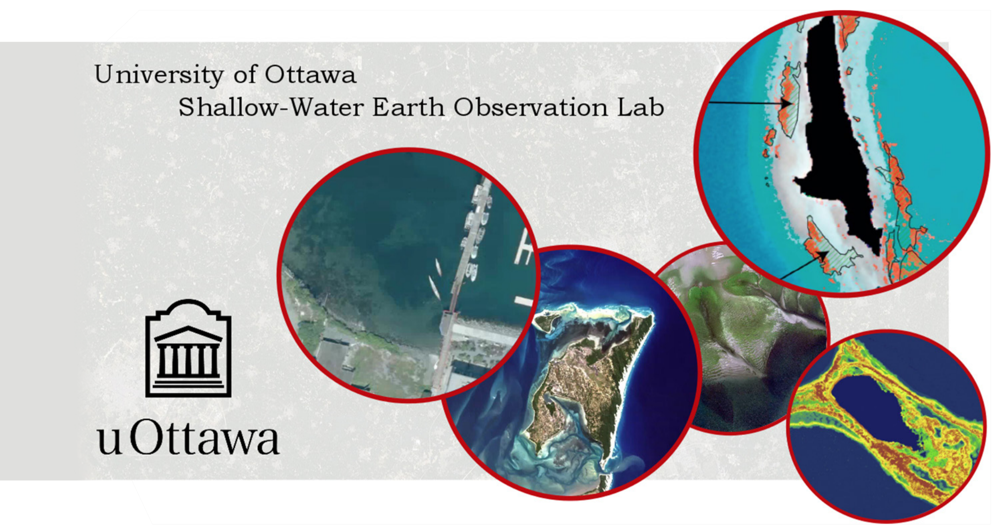
UNIVERSITY OF OTTAWA

Ottawa, ON

The present focus in the Anders Knudby lab is inversion of radiative transfer modeling for mapping of bathymetry using moderate- or high-resolution satellite data. The approach to such research has been developed over the last 20 years, but our work is novel because it focuses on:

- Testing of existing methods in less-than-ideal environments and with less-than-ideal data
- Development of per-pixel uncertainty assessment for the derived water depths
- Development of fast and operational algorithms
- Development of ensemble methods that use more than one data type or data from more than one overpass

The lab works in collaboration with the Canadian Hydrographic Service, and is developing a collaboration with Defense Research and Development Canada.



Anders Knuby hard at work

UNIVERSITY OF MANITOBA

Winnipeg, MB

The Centre for Earth Observation Science (CEOS) at the University of Manitoba conducts multidisciplinary research seeking to understand the complex interrelationships between elements of Earth systems, and how these systems will likely respond to climate change and human activities. The main focus of activity is on Arctic marine systems where in situ optical methods and remote sensing are used, in conjunction with other methods, to broadly study (i) processes and feedbacks that control solar radiation interactions in the Arctic coastal, marine and sea-ice environment, and (2) the composition, magnitude, timing, and fate of primary producers in ice-covered and open oceans; and to (3) characterize and trace water masses and their modification. Another focus is on the Manitoba Great Lakes where in situ sampling and remote sensing are used to determine how light and nutrient conditions affect algal community response over time. Information on recent and ongoing projects can be found at http://umanitoba.ca/ceos/ and http://www.asp-net.org.

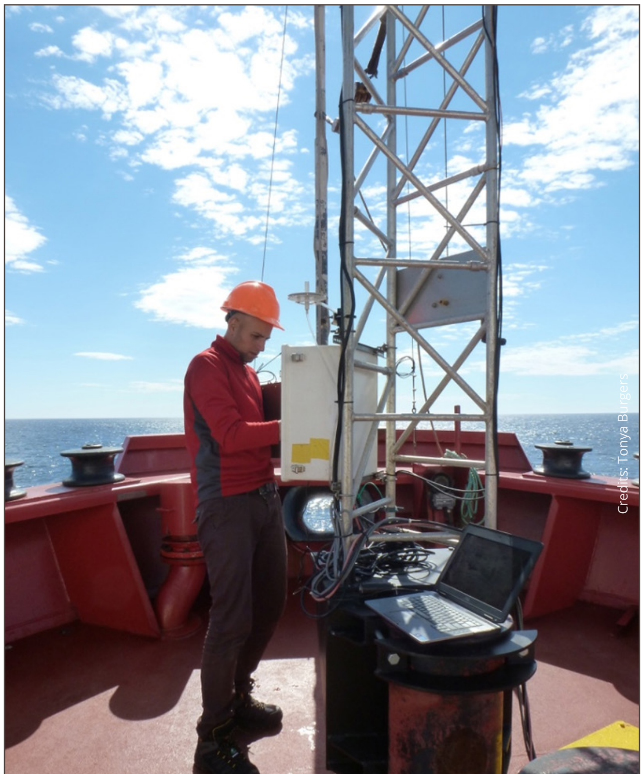
Available instrumentation includes:

- Perkin Elmer Lambda 650 spectrophotometer for particulate and dissolved absorption;
- FluidImaging FlowCam for measurements of microscopic particle sizes and taxonomic composition of algae;
- Horiba Aqualog for rapid spectral absorbance and fluorometry. Sequoia LISST-100x for in situ water column particle size estimations;
- A variety of spectral irradiance sensors for in situ measurements including: ASD FieldSpec and HandHeld, Satlantic HyperOCR SAS and HyperOCR Free-falling profiler, TriOS Ramses scalar and planar irradiance sensors;
- A SeaBotix remotely operated vehicle (ROV) for controlled measurements of spectral irradiance within the water column and beneath sea ice;
- Wetlabs ACS and AC9, Chl-a and CDOM fluorometers, C-Star transmissometers, numerous ECO tripletCTDs (Seabird/Idronaut) with PAR and/or turbidity sensors.

UNIVERSITY OF CALGARY

Calgary AB

The Else lab at the University of Calgary is currently using remote sensing to estimate air-sea CO_2 fluxes across Hudson Bay using a combination of ship observations and ocean colour remote sensing products. The objectives are to: (i) develop a remote sensing model to scale up the field measurements of surface seawater partial pressure CO_2 (pCO_{2sw}), (ii) identify the key biogeochemical factors that are responsible for the spatial variability of pCO_{2sw} in Hudson Bay and (iii) calculate the air-sea CO_2 fluxes across the Hudson Bay to determine whether it represents an overall source or sink for atmospheric CO_2. The *in-situ* field data includes pCO_{2sw} measurements, atmospheric measurements (e.g. wind speed and atmospheric CO_2 concentration), dissolved inorganic carbon, total alkalinity, sea surface temperature (SST) and sea surface salinity (SSS). The Visible Infrared Imaging Radiometer Suite (VIIRS) will be used to determine SST, Chlorophyll-a concentration (Chl-a), colored dissolved organic matter (CDOM), and Kd490, the diffuse attenuation coefficient. This project will use other satellite sensors such as the Advanced Scatterometer (ASCAT) to deliver wind speed and wind direction data, and RADARSAT-2 to obtain sea ice coverage. Results of this BaySys (NSERC funded) research will help to fill the current knowledge gap about air-sea CO_2 exchange in Hudson Bay and predict how the biogeochemical cycle in Hudson Bay might change in response to ongoing climate change.



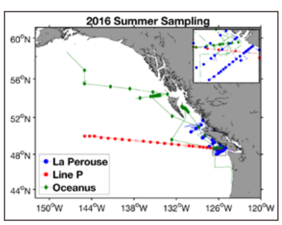
Mohamed Ahmed taking measurements aboard the *CCGS Amundsen* in 2016

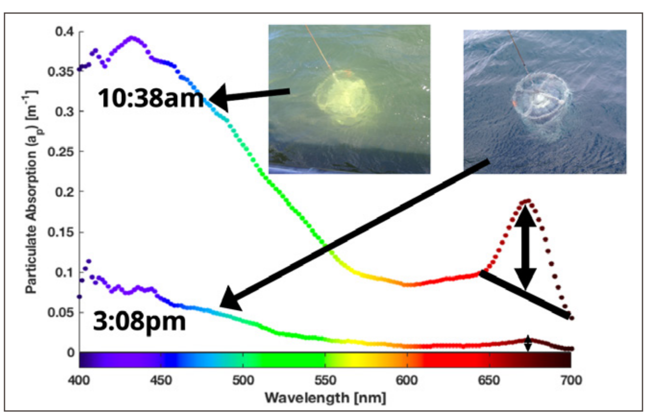
UNIVERSITY OF BRITISH COLUMBIA

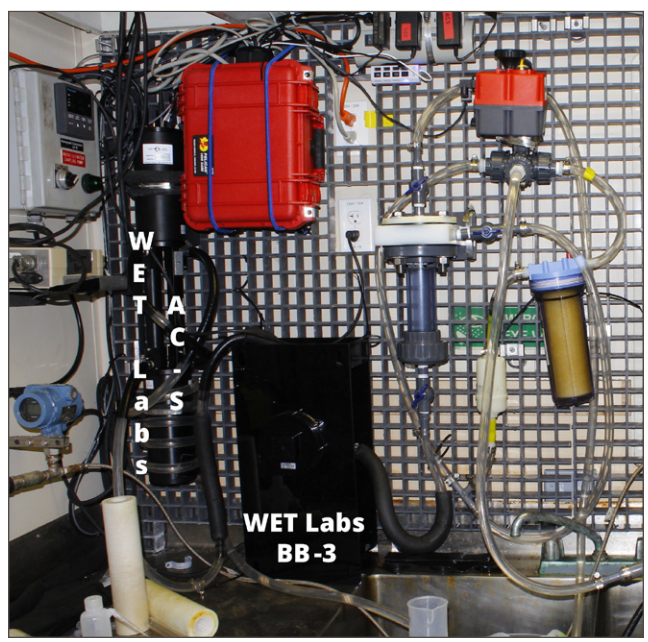
Vancouver, BC

THE UNIVERSITY OF BRITISH COLUMBIA

As of 2016, the optical properties of the SubArctic Pacific Ocean have been monitored by a group led by Dr. Philippe Tortell and Dr. William Burt at the University of British Columbia. In-situ datasets (absorption and back-scatter) are collected using flow-through instruments (Wetlabs AC-s and BB-3) plumbed into the seawater intake system of the *CCGS John P. Tully*, providing high-frequency (1-minute binned) measurements of hyperspectral absorption and attenuation, as well as particulate backscatter at three wavelengths. In 2016, the majority of measurements were taken during 3 summertime cruises, covering a spectrum of productivity regimes in the SubArctic Pacific, including iron-limited low productivity waters of the Gulf of Alaska, mesotrophic shelf waters along the central coast of British Columbia, and highly- eutrophic waters of the Vancouver Island upwelling regime. In 2017, sampling efforts will increase to include 5 major cruises from February to September, with the aim of covering a similar geographic area but with greater temporal resolution. Current applications for these data include derivation of indices for both phytoplankton biomass (e.g. Chl a, phytoplankton carbon) and phytoplankton size class. In-situ datasets are also compared with various remote sensing products, with the aim of developing improved satellite algorithms for the SubArctic Pacific region. Other future avenues of research include: 1) investigation into various phytoplankton physiological effects using optics and fluorometry measured in parallel, 2) determination of phytoplankton functional groups from space using neural networking techniques, 3) assessment of how temporal and spatial variability in phytoplankton productivity and community composition can help predict annual salmon, herring and tuna populations, 4) exploration into how phytoplankton and fisheries populations may change in future climate scenarios.







UNIVERSITY OF VICTORIA

Victoria, BC

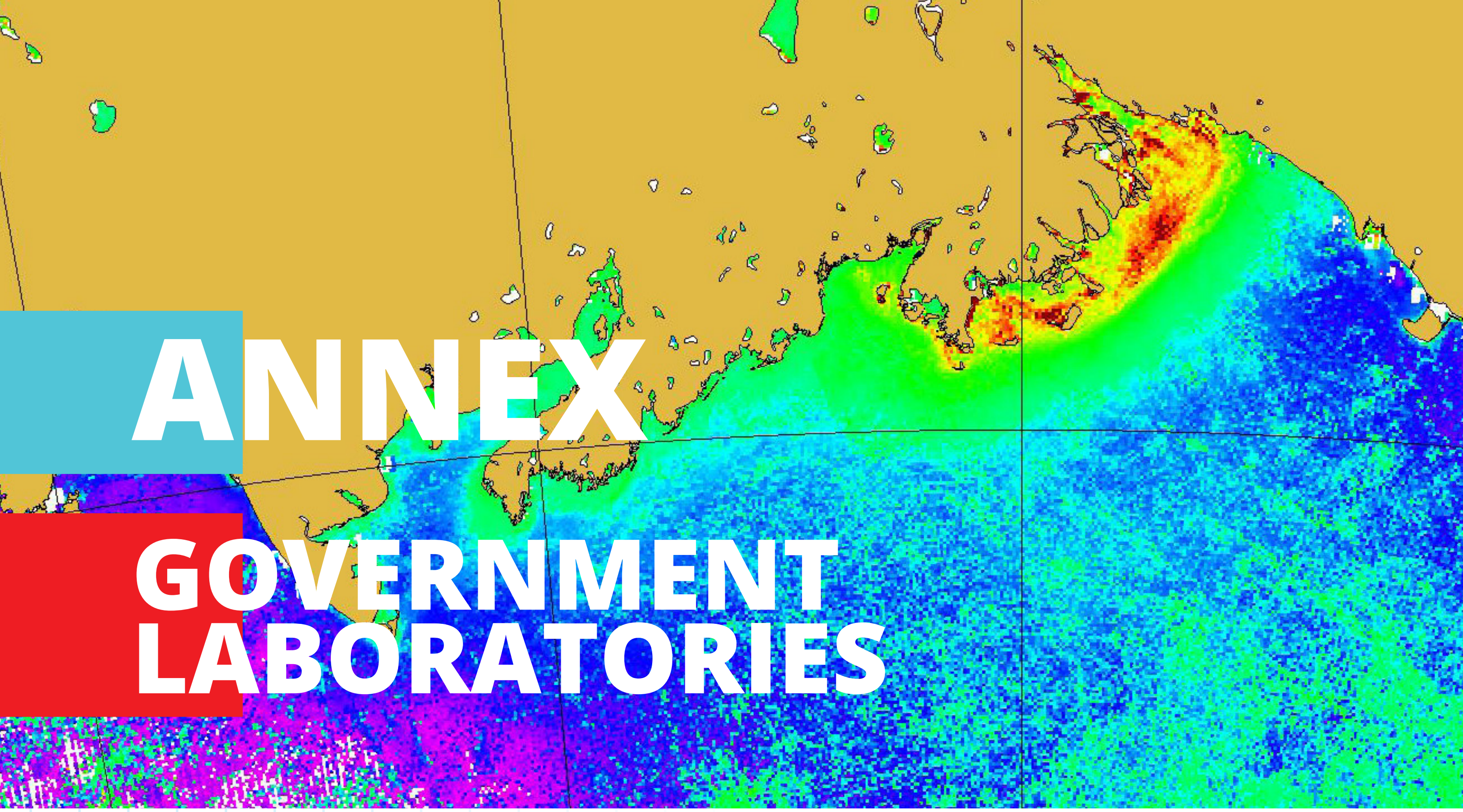
The Remote Sensing and Spectral lab is housed in the University of Victoria, BC Canada and lead by Dr. Maycira Costa. This is a state-of-the-art laboratory facility for investigating the interaction of light energy with organic and inorganic material in ocean and inland waters in the field and controlled lab environment. The lab is equipped with a high-precision liquid chromatograph for pigment analysis, particulate organic carbon analyzer, microscopes, centrifuges, oven, Satlantic hyperspectral radiometers for above and in-water measurements, Wetlabs fluorescence sensors for chlorophyll and CDOM, ac-s absorption, attenuation and backscattering hyperspectral sensors, CTDs, and a darkroom for simulating controlled environmental conditions. We also have two new Satlantic autonomous sun tracker above-water hyperspectral sensors planned for installation on two BC Ferries crossing the Salish Sea. This Ferry Ocean Colour Observation System, FOCOS, will be the first of its kind to go into full time operation in Canada. Through various partnerships (CFI, BC Ferries, MEOPAR, PSF, NSERC, ONC) this project presents a unique opportunity to combine resources and provide valuable and accurate ocean colour data that will be used to better understand the health of our coastal ecosystem.

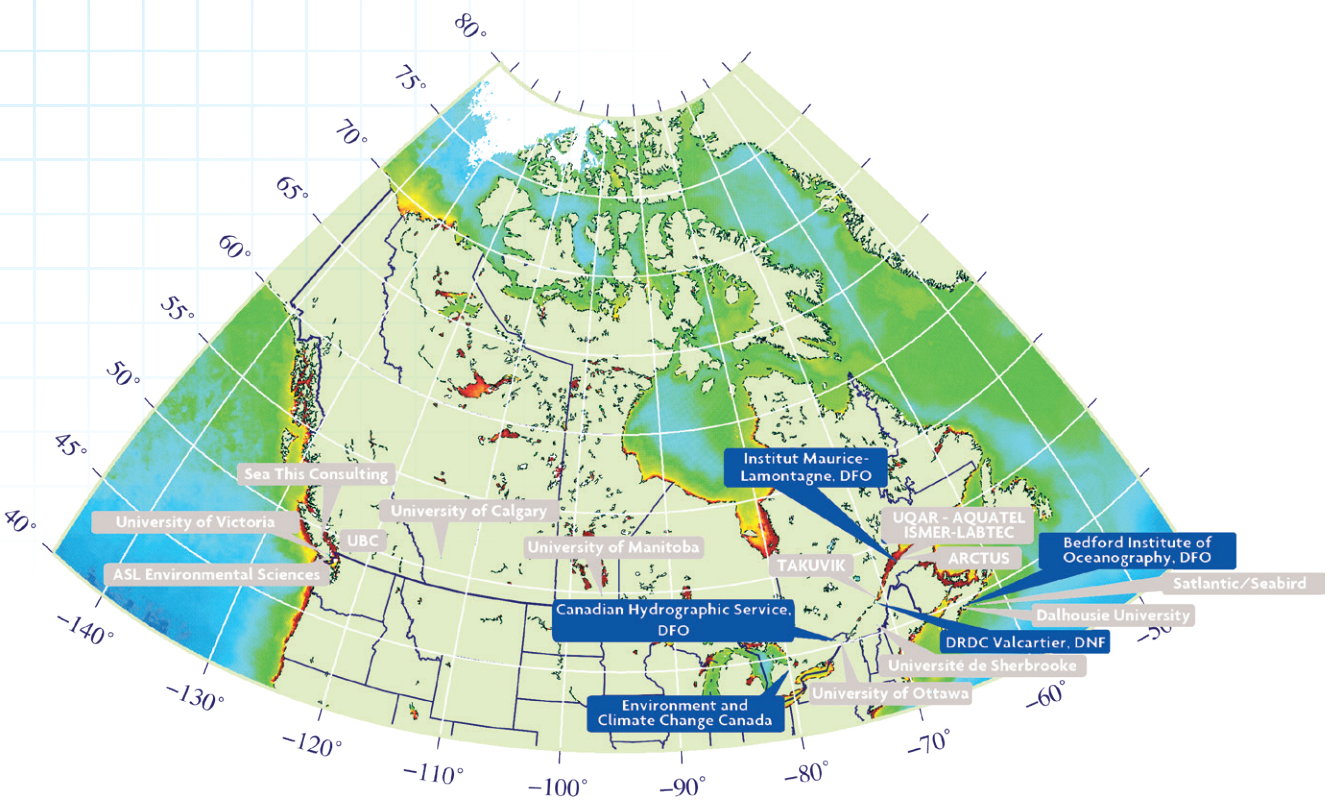
Their research focuses on using remote sensing technology (optical and microwave) for investigating (1) the spatial temporal dynamic of productivity and turbidity in west coast of Canada and its synergism with secondary production, and consequently salmon health status. (2) The spatial temporal dynamic of intertidal and subtidal fish habitat, specifically eelgrass and kelp. (3) Development of water optical proxies for tracking fish waste and harmful algae blooms in aquaculture farms. (4) Define constrains for light availability in coastal and riverine waters and possible effects caused by human use of the land and climate change. (4) Biogeochemistry, hydrology and biodiversity of tropical wetland ecosystems.

Stephen Phillips, Ziwei Wang and Maycira Costa abord a BC Ferry

ANNEX

GOVERNMENT LABORATORIES





Data source MODIS OBGP - NASA

BEDFORD INSTITUTE OF OCEANOGRAPHY, DEPARTMENT OF FISHERIES AND OCEANS

Dartmouth, NS

Pêches et Océans Canada   Fisheries and Oceans Canada

The Remote Sensing Group (RSG) at Bedford Institute of Oceanography (BIO/DFO) has been monitoring the North Atlantic using ocean colour products for more than 30 years. Optical sensors used include CZCS, POLDER, SeaWiFS, MODIS/Aqua, MERIS, OLCI and SGLI. The monitoring area is defined by the Atlantic Zone Monitoring Program but data acquisition is carried out over all Canadian waters. Routinely, RSG archives Level 2 and Level 3 ocean colour data from NASA and ESA for Canadian waters. The data are processed and maps are produced at various spacial and temporal resolution.

The Level 3 products (derived geophysical variables that have been aggregated/projected onto a well-defined spatial grid over a well-defined time period), are mainly derived from the photosynthetic pigment chlorophyll a. However, other products generated include photosynthetically active radiation, diffuse attenuation coefficient, total suspended matter, coccolithophore concentration and sea surface temperature. Basic statistics for pre-defined areas of interest are compiled for each product. Climatology and anomaly maps are also routinely produced. These and custom products are available by request.

RSG generates Level 4 products (model output or results from analyses of lower level data or from variables derived from multiple measurements). For example: to characterize the phenology of spring and fall phytoplankton blooms. Other processes involve computation of primary production, identification of ecological provinces and the study of the impact of hurricanes on surface layers of the ocean. More recently, RSG has used ocean colour information to identify phytoplankton-rich areas to help in EBSA (Ecologically and Biologically Significant Area) definition, which has been useful in developing habitat suitability maps for whales. Our latest activities include the generation of water-clarity maps at 250m spatial resolution to aid in planning Lidar bathymetry missions by the Canadian Hydrographic Service.

Upcoming operational products include maps of diatom distribution, biogeochemical province boundaries, and products from sensors such as VIIRS (Visible Infrared Imaging Radiometer Suite) and OLCI (Ocean Land Colour Instrument).

INSTITUT MAURICE LAMONTAGNE, DEPARTMENT OF FISHERIES AND OCEANS

Mont Joli, QC

Pêches et Océans Canada   Fisheries and Oceans Canada

In the St. Lawrence Gulf and Estuary, IML conducted a series of 5 cruises (1997-2001) to measure a wide variety of optical and biochemical properties. This data set was recently archived in Seabass (doi: 10.5067/SeaBASS/OPTIQUE_ST_LAURENT/DATA001). Using this dataset and other remote sensing data, we are currently building a weekly climatology of phytoplankton biomass for the St. Lawrence ecosystem that will serve as a decision support system in the case of major oil spills. The project involves the development of a new algorithm to measure chlorophyll concentration using the EOF approach recently proposed by Susanne Craig. Work is still ongoing but preliminary results indicate an accuracy of the order of 30-35%, much better than by using operational algorithms (OC4, etc). Once available, the validated chlorophyll concentrations will be used to generate higher level products such as species dominance, primary production, and phenology of the plankton blooms for the St. Lawrence.

Vertical profiles of LISST-100X and biochemical data were gathered in the spring 2010. This data set will be used to study the particle size spectra spatial distribution in the St. Lawrence estuary. Results from that study are expected to be presented at Ocean Optics in 2016.

MLI is also involved in the study of the Gulf of San Jorge (Argentina) as part of a collaborative project between ISMER and Argentina. Optical (IOP and AOP) data were measured in the austral summer 2014 and are now being analyzed. The objective is to provide an optical characterization of the Gulf's waters, validate remote sensing algorithms and generate a climatology of phytoplankton biomass for this area that is subject to future oil exploration/exploitation, a situation similar to the Gulf of St. Lawrence. A particular attention will be given to areas known for the presence of quasi-permanent hydrographic fronts.

DRDC VALCARTIER, DEPARTMENT OF NATIONAL DEFENSE

Québec, QC

DEFENCE R&D DÉFENSE

Over the last 15 years Defence Research and Development Canada (DRDC) has been involved in studying airborne and space based Hyperspectral systems with emphasis on their application to land based surveillance problems. Less emphasis was originally given to maritime applications. However, the results available from Ocean Color satellites were routinely made available to the Canadian Navy and used in support of operations.

Recently, DND has shifted its oceanographic interest from blue (i.e. oceanic) to littoral waters. This renewed interest in coastal monitoring and surveillance technologies gave rise for instance to the concept of Rapid Environmental Assessment (REA) to support Canadian operations locally and abroad. In the maritime approaches to Canada and globally in CAF/DND's areas of interest, meteorological and oceanographic conditions have always influenced the performance of military sensors, weapons, vessels and personnel. There is a gap in deriving environmental products in the complex littoral waters and hyperspectral satellites with improved spatial and spectral resolution and processing algorithms are needed to more accurately derive the products required by CAF/DND for system performance assessment and optimization.

To support operations in the littoral zones and around the Coasts and inland waters of Canada and elsewhere in the world, Hyperspectral data at high spatial resolution is required to untangle the complex optical mix of signals from the water column, bottom, and surf zone into useful information. DRDC is currently working on quantifying the improvements available through the use of maritime Hyperspectral systems and on methods of integrating the hyperspectral data and analysis systems into the operational structure of the CAF/DND. Particular emphasis is currently given to deriving accurate current near-shore bathymetric information particularly in hard to reach areas such as the Arctic.

DRDC expects that in the near future Hyperspectral satellite missions will contribute significantly to CAF/DND's strategic surveillance and intelligence capabilities leading to improved: Maritime Domain Awareness; Arctic Intelligence; operational preparation of the operational environment; and tasking, collection, processing, exploitation and dissemination. The specific research outcomes DRDC is working towards are:

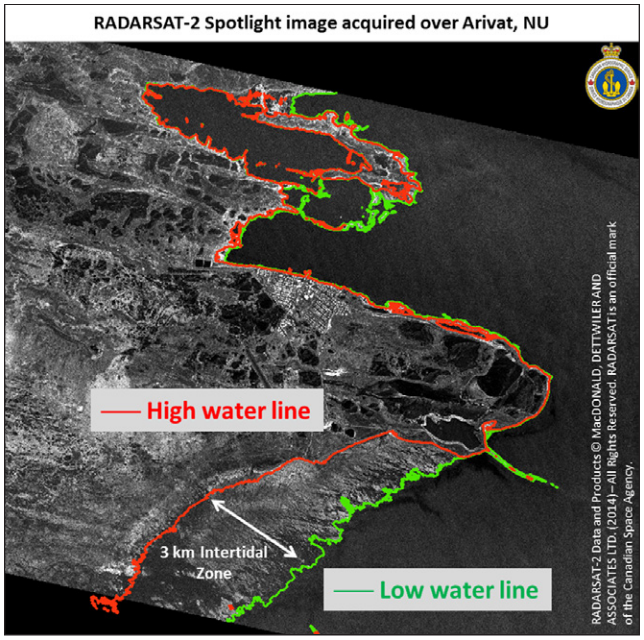
- Improved generation of static and dynamic environmental products in intertidal and near-shore zones to support CAF operations in littoral waters;
- Improved mine countermeasures route survey, near shore battlespace mapping, divers and submarine operations as well as search and rescue;
- Improved intelligence preparation of the operational environment in support of deployed forces;
- Improved tools and methodologies to handle high data rate sensor data and exploit the hyperspectral data for CAF applications.
- For the part of its research program involved in hyperspectral maritime application, DRDC is interested in leveraging and taking advantage of the joint ocean color expertise available in Canada through the NetCOLOR initiative which brings together all the significant players in the field in one common working group. This common expertise and information sharing platform has the potential to lead to an enhanced synergy in problem solving in their respective field of interest for all the participants.

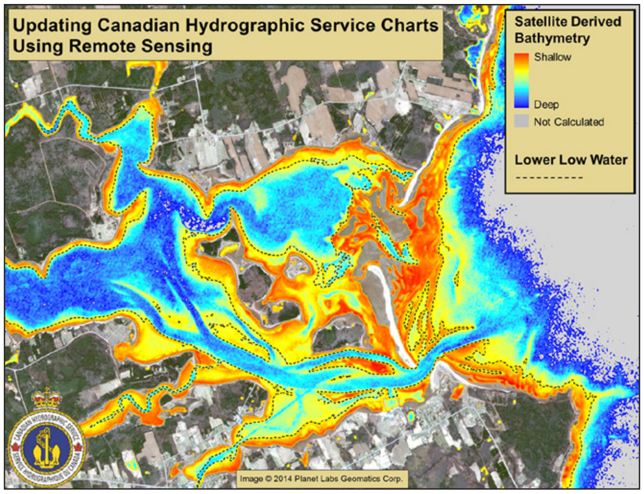
CANADIAN HYDROGRAPHIC SERVICE

Ottawa, ON

The Hydrographic Remote Sensing Center of Expertise (HRSCoE) within the Canadian Hydrographic Service (CHS) is responsible for researching and developing new methodologies that make use of remote sensing in order to extract hydrographic information. Currently, the HRSCoE R&D activities are done with the financial support of the Canadian Space Agency (CSA) in the form of a Government Related Initiative Project (GRIP) and a Radarsat Constellation Mission (RCM) Data Utilization & Application Plan (DUAP). Through these multiple projects along with CHS regular activities, the goal is to operationalize the use of remote sensing in three broad sectors of activities; (1) Satellite Derived Bathymetry (SDB), (2) coastline and intertidal zone extraction and (3) change detection.

While initial SDB methods were first developed some 40 years ago, most Hydrographic Offices (HO) have been slow to adopt SDB as a valid means of obtaining bathymetry. With the advent of more capable sensors along with the development of new algorithms, SDB is rapidly gaining in popularity both within CHS and internationally. With the HRSCoE leading the charge, developing robust methodologies and best practices, CHS is now at the forefront with other HO and members of academia in promoting the use of SDB internationally.





ENVIRONMENT AND CLIMATE CHANGE CANADA

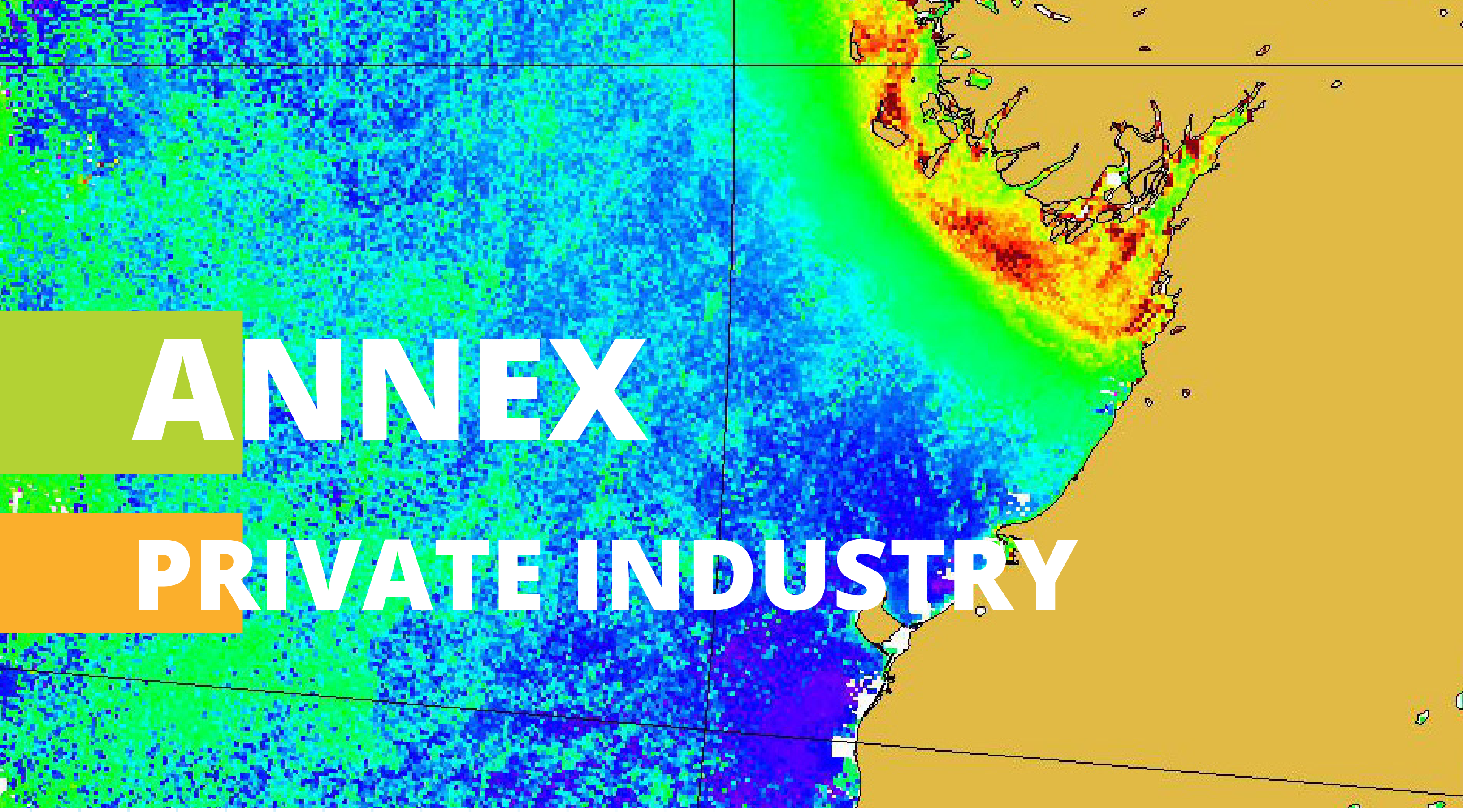
Canada Centre for Inland Waters, Burlington, ON

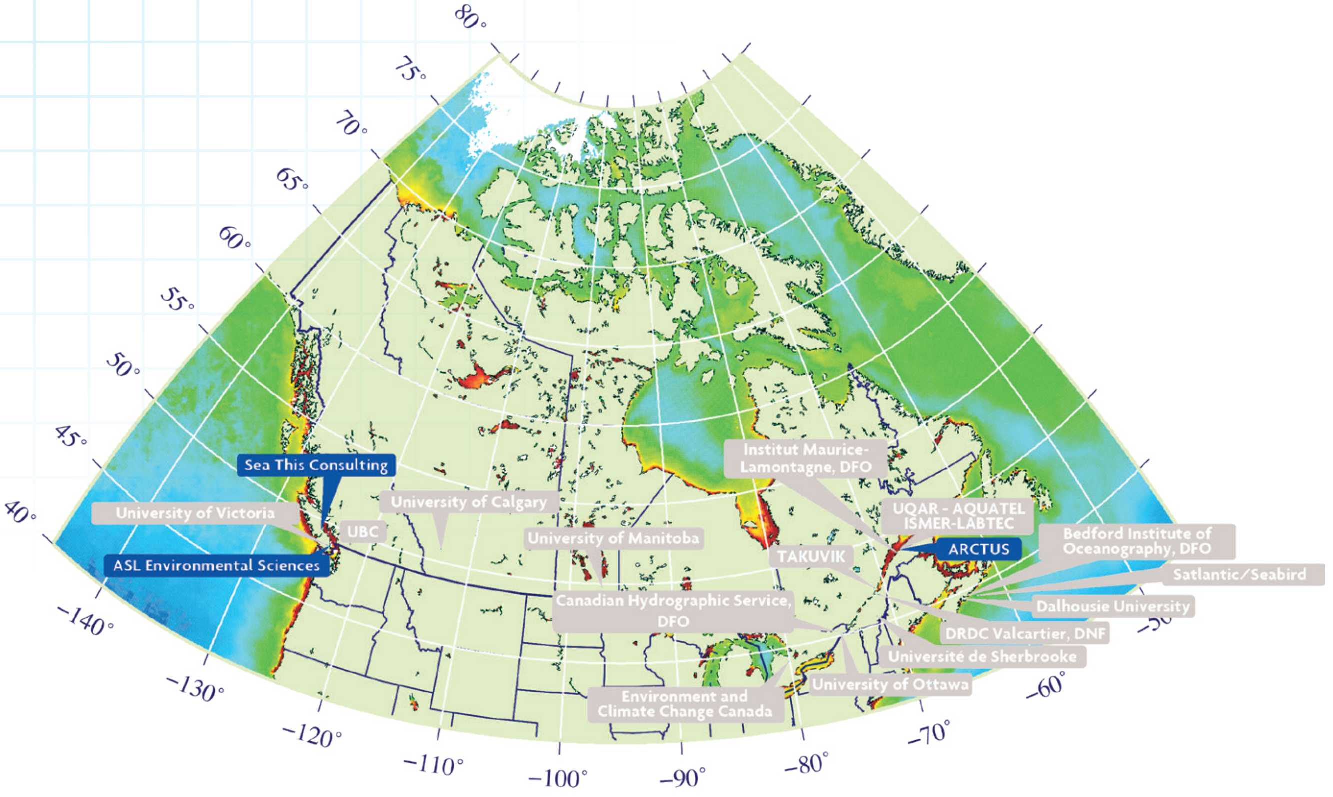
Environment and Climate Change Canada / Environnement et Changement climatique Canada

ECCC conducts monitoring and research that leads to the protection of inland water quality to ensure that all Canadians may have access to clean, safe and healthy water. Within the Water Science and Technology Directorate, the Aquatic Optics and Remote Sensing Group carries out research into inland water optics, the development and validation of algorithms for water quality retrievals from aquatic colour sensors, and implementation of remote sensing approaches for lake management applications and near real time satellite water quality monitoring. Satellite observations have been used to document variability in lake water quality in response to in-lake and watershed processes, the impact of invasive species, and climate change, including the detection and forecasting of algal blooms. Of note presently are priority programs in the Great Lakes, Lake Winnipeg and Lake of the Woods, which aim to better understand the role of nutrients in lake water quality and widespread potentially harmful algal bloom occurrences. These programs have led to the development and implementation of satellite remote sensing tools for detecting the onset of algal blooms, and reporting on their extent, duration and severity.

ANNEX

PRIVATE INDUSTRY





Data source MODIS OBGP - NASA

ARCTUS

Rimouski QC

ARCTUS is a private R&D company based in Rimouski, QC. Since 2009, it has been providing research support, development and applications for remote sensing, Earth Observation (EO) and Geographical Information System (GIS) technologies to governmental agencies, scientific communities and the general public. The company is specialized optical remote sensing of aquatic environments, from lakes to oceans. ARCTUS works in close collaboration with academic (UQAR/ ISMER, ULaval) and government (IML/DFO/CSA) institutions and is developing activities with other regional partners such as the Technopole Maritime du Québec (TMQ).

ARCTUS was created to fulfill the increasing need of the use of remote sensing technologies in such applications in aquatic environments. The company is particularly active in the observation of polar regions where environmental changes are ongoing at higher rates than everywhere else on the planet. Use of space-based technologies is critical when dealing with such extremely remote and harsh ecosystems.

ARCTUS has been involved in various projects as consultant or as higher-level data providers. Here are a few examples:

- **Sentinel-3 Mission Performance Centre (S-3 MPC):** ESA and EUMETSAT set up the S-3 MPC to ensure the highest quality of products ensue from the mission. ARCTUS will be the Expert Support Laboratory (ESL) responsible for the Algorithm Maintenance and Evolution of the Marine L2 products. That includes the OLCI radiometric products validation using moored buoys operated by DFO. ARCTUS created an automated processing chain for the array of buoys in the St-Lawrence estuary. Three sites were in operation in 2016 (IML4–Rimouski, IML6-Shediac, IML10-Anticosti/Newfoundland) and several new sites will be instrumented in the coming years. ARCTUS will contribute to the technological improvement of the buoy for the satellite validation purposes.
- **Canadian Coastal and Inland Waters (Watersat) Microsatellite Mission:** ARCTUS was subcontracted by MDA to match its expertise in water color applications using space sensing instruments including atmospheric correction, sensor characterization and calibration and derived product validation with MDA expertise in satellite remote sensing technologies and ABB in hyperspectral sensor and payload development. The principal role of ARCTUS in the project was to provide support and research expertise to MDA and ABB's technical teams to
  - understand ocean color user requirements for imaging sensor requirements;
  - assist with definition and verification of requirements for imagers or optical components for atmospheric correction algorithms needed for ocean color applications;
  - assist with definition and verification of imaging sensor requirements for stray light and polarization;

  - provide input and insights into appropriate calibration and validation approaches that may be suited to the mission concept and payload instruments;
  - aid interpretation of user requirements and data needs for standard and pre-operational ocean color applications, and
  - provide a user perspective on use of hyperspectral imaging by the ocean color community.
- **WWF Racer project:** The World Wildlife Foundation (WWF) launched the Rapid Assessment of features and areas for Circumarctic Ecosystem Resilience in the 21st Century (RACER) project to identify the regions of the global Arctic that are being most severely impacted by environmental change. ARCTUS supplied expert guidance and data validation services as well as providing a reliable estimate of biologic activity using a genuine satellite-based primary production model that is driven by various satellite images from different sources.
- **Remote sensing of *Vibrio non cholerae* in coastal waters: a review:** ARCTUS expertise was requested to perform a literature review for the Public Health Agency of Canada on the state-of-the-art in terms of remote sensing of *Vibrio non cholerae* in coastal waters. The review included as well the description of the actual monitoring and predicting systems in used in other countries (also for of *Vibrio cholerae*).

ASL ENVIRONMENTAL SCIENCES

Victoria, BC

Remote sensing expertise at ASL Environmental Sciences Inc. (ASL) is largely based on the intact team from Borstad Associates Ltd. with whom they merged in 2009. Both companies' experience in remote sensing technology (optical and acoustic) and applications began in the late 1970s. ASL has worked across the globe in optical, hyperspectral, thermal, RADAR, and high resolution remote sensing across a broad range of applications. The remote sensing group has undertaken more than 350 projects in more than 35 countries with work ranging from training, instrument development, and data acquisition to advanced data analysis. In 2017, ASL's remote sensing group includes eight senior remote sensing scientists and analysts (3 PhDs, 2 MSc, 3 BSc) with 15-40 years' experience.

ASL has been performing water quality assessment since early 1980s using a series of airborne and spaceborne data sources. The senior remote sensing scientist, Dr. Gary Borstad, was involved in the early development of water colour sensors, including the Fluorescence Line Imager (FLI) and the Compact Airborne Spectrographic Imager (CASI). Over the years, they have flown their CASI for many water quality projects, including surveys of the entire coastline of England, rivers in central Florida, ice leads in the Canadian Arctic, and ponds and reservoirs on mine sites. They have also used CASI to monitor chemical and thermal discharge plumes, and to map oil spills. More recently, with improvements to satellite sensors, they have undertaken many satellite-based studies of water quality, including the development and testing of new or customized algorithms. These include studies of chlorophyll, temperature and turbidity along the BC coast, in the Great Lakes and Chilko Lake, BC, in the Gulf of Mexico, and near Kitimat, BC. Currently, they are using satellite-derived turbidity products in support of engineering studies for LNG port developments in coastal BC.

Their long experience with water quality mapping has enabled them to serve in an advisory role on user needs and applications of remote sensing in freshwater and marine environments to groups such as the Canadian Space Agency (CSA) and Fisheries and Oceans Canada (DFO). They use spaceborne-derived chlorophyll and sea surface temperature in studies of seabirds. They have been using historical thermal and water colour satellite time series to map the timing of oceanographic events in the North Pacific for the last 25 years. This ground-breaking work has shown links between the timing of phytoplankton blooms and the success of seabirds, herring, and salmon. A primary paper written by one of our scientists with government research collaborators resulted in a national award in applied oceanography to the ASL scientist involved. ASL has used airborne remote sensing to assist with stock assessments of capelin, herring, and sardines for DFO. The group has also developed and successfully applied remote sensing methods to map bathymetry in tropical lagoons, northern lakes, and temperate coastal areas.

ASL's recent projects include:

- **DICE (Dual Imaging Spectrometer COCI experiment):** ASL is an active member of the User & Science Team of the CSA Coastal and Ocean Colour Imager (COCI), a hyperspectral imaging system designed to acquire data over coastal areas. COCI is based on WATERSAT, the Canadian

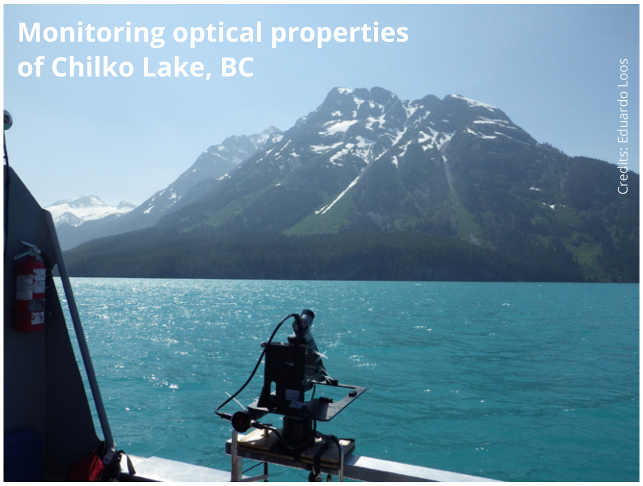
Coastal and Inland Waters sensor for which ASL provided expert advice.

- **Water Quality of Chilko Lake (British Columbia, Canada): Optical Properties and Impact on Sockeye Salmon (LakeView)**: improvement and development of regional lacustrine optical models based on satellite data and radiative transfer modelling to better understand the relationship between environmental conditions and salmonid production and mortality.
- **Semi-Automated Classification of Oil slicks at sea using RADAR and Optical imagery (SACORO)**: development of automated procedures for use with RADARSAT-2 and Earth Observation (EO) imagery to improve detection of oil slicks and thickness characterization at sea.


Credits: Eduardo Loos

Eduardo Loos at Roberts Bank, BC

- **Spaceborne Ocean Intelligence Network (SOIN**: extraction of chlorophyll concentration and ocean fronts between 1997-2010 from RADARSAT-2 and MODIS along the coast of British Columbia.
- **Turbidity**: generation of maps of relative turbidity, a natural tracer of surface water movement, for coastal BC inlets from red bands as input to modelling of ocean currents.


Credits: Eduardo Loos

Monitoring optical properties of Chilko Lake, BC

SEA THIS CONSULTING

Nanaimo, BC

Sea This is a small research and environmental consulting company located on Vancouver Island. Owned and directed by Stephanie King, Sea This has been involved in a range of ocean colour research projects over the past 10 years. With Jim Gower (Emeritus) at DFO's Institute of Ocean Sciences, Stephanie worked on the detection of intense plankton blooms with the maximum chlorophyll index (MCI) from the European Space Agency's (ESA) MERIS sensor. A complete processing of the global MCI dataset with ESA's Grid Processing on Demand (GPOD) initiative resulted in discoveries of new patterns and phenomena never before seen from space. One discovery was the ability of MCI to detect and track pelagic S*argassum*. Communities in the Gulf of Mexico and Caribbean have been particularly interested in these results because of major changes in the temporal and spatial distribution of S*argassum* in recent years. The MCI global composites were also used to track 'superblooms' in Antarctic Ice. From 2002 to 2012, we observed a considerable increase in the spatial coverage and intensity of these blooms. Other work with the Gower's lab included monitoring intense plankton blooms on the west coast of Canada and in Monterey Bay, California, and monitoring global distribution of *Trichodesmium.* With the launch of OLCI in early 2016 we plan to continue monitoring these types of high concentration phytoplankton events.

Currently, Sea This is working on improving MODIS algorithms for monitoring phytoplankton blooms in coastal waters of western Canada. We have shown that the Fluorescence Line Height (FLH) algorithm, based on the peak radiance at 685 nm, performs better than the standard satellite chlorophyll products in British Columbia's coastal waters. Using MODIS FLH and in situ measurements, we are able to describe patterns of phytoplankton bloom phenology and mechanisms for bloom initiation in the Salish Sea. One application for the work includes understanding the timing of spring bloom in the Strait of Georgia which is thought to impact early marine survival of juvenile Salmon.

Other recent ocean colour remote sensing projects include using satellite chlorophyll and sea surface temperature products to develop critical habitat maps for basking sharks in the Northeast Pacific. We also developed improved ocean color composites and climatologies for input into high resolution biogeochemical circulation models.

Sea This Consulting is active in the PORSEC (Pan Ocean Remote Sensing Conference) Association. Since 2008, we have assisted in training and education in countries looking to develop their remote sensing programs. Training courses for students and young scientists have been organized in China, Taiwan, India and Indonesia.