Impacts of sea-ice thermodynamic stages on open water phytoplankton blooms in the Hudson Bay System

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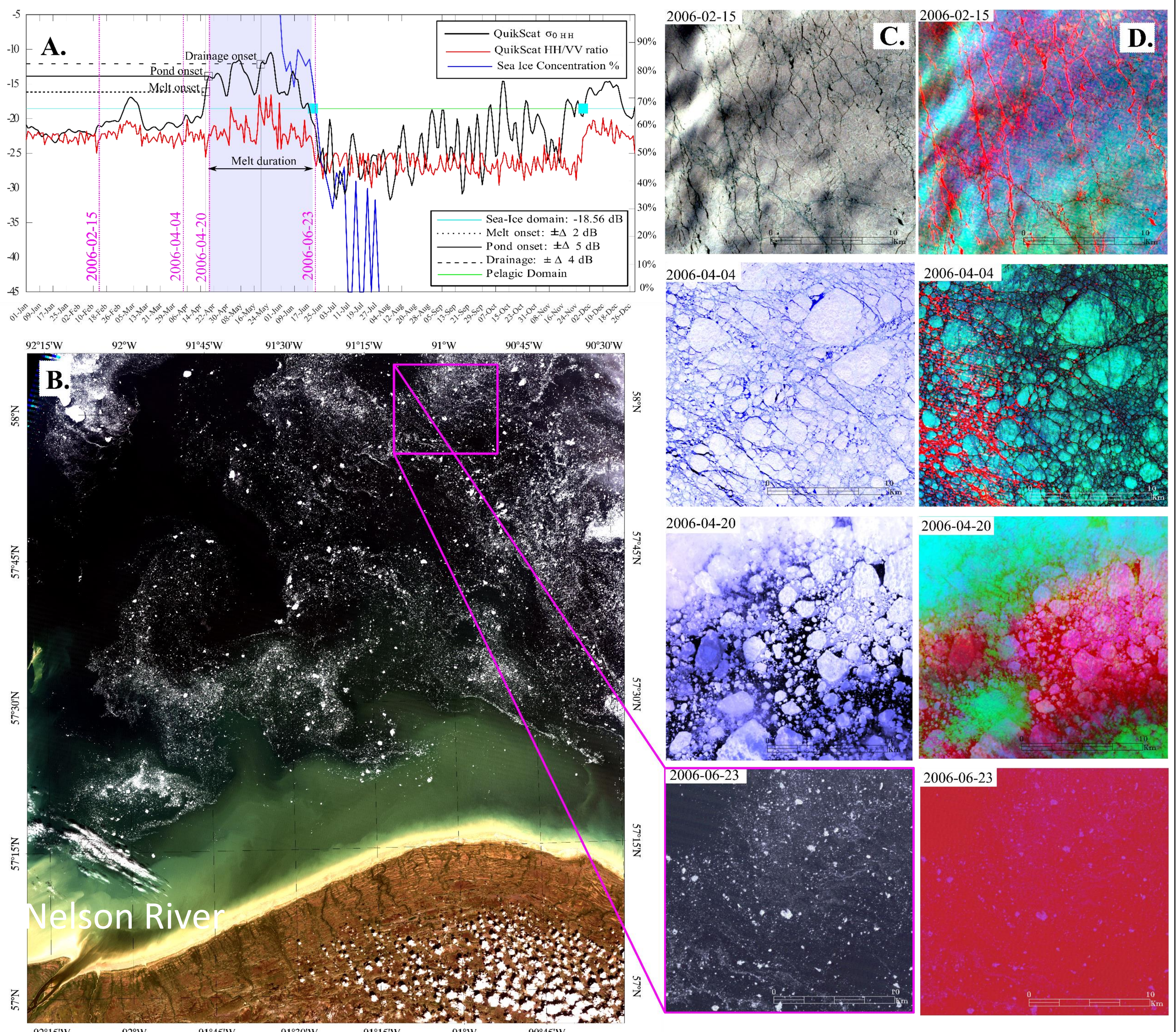
How the cryosphere dynamic affects phytoplankton spring-summer bloom?
To answer this question we proposed a novel methodology using multi satellite missions summarized by the following steps :

i. To detect the sea-ice thermodynamic stages in Hudson Bay System using active microwave scatterometer (QuikSCAT) following Howell et al. [2006];
ii. To evaluate the QuikSCAT-derived sea-ice thermodynamic stages using high resolution (30 meters) multispectral imagery of Landsat;
iii. To combine passive and active microwaves information to establish the chronology of the sea-ice stages : melt, pond and drainage onsets and ice-free season;
iv. To assess the impacts of sea-ice stages variability on phytoplankton blooms at the Marginal Sea-Ice Zone (MIZ) using satellite-derived chlorophyll-*a* concentration (*Chl*) (GSM - Globcolour Project).

Validation of sea-ice stages detected by QuikSCAT using Landsat ETM+7 at 91ºW 58ºN in 2006 offshore the Nelson River.



(A) QuikSCAT timeseries of σ_0 (black line), co-polarization ratio HH/VV (red line) applied to detect sea-ice stages using *Howell et al.* [2005, 2006, 2009] method based on dynamic thresholds and sea-ice concentration (SIC) [Comiso, 2000] (blue line). (B) Landsat ETM+7 true-color composite (RGB: bands 3, 2, and 1) in Jun 23, 2006 shows ice floes interaction with coastal dynamic in the Nelson river plume, colored dissolved organic carbon results in dark-waters. (C) True-color (RGB: bands 3, 2, and 1) and (D) thermal (RGB: bands 6, 5, and 4) composites equalized to highlight sea-ice patterns. QuikSCAT reaches good performance to detect sea-ice stages in HBS. During the consolidated sea-ice stage, leads and long fractures are widespread (Feb 15) which produces corner-reflection and high variability in QuikSCAT timeseries. Also, these features release latent heat stoked in the upper ocean layer to atmosphere as highlighted by Landsat thermal band 6 (10.40-12.50 nm). The transition toward melt and pond onset is marked by an increase of sea-ice fractures or leads and decrease of ice floe size (April 4). The melting process is intensified by ice floes dispersion. Around April 20, the pond onset was detected by QuikSCAT, while Landsat shows significant changes in the sea-ice floe size ranging from 1 to 5 km. Finally, even after open water onset detected by the QuikSCAT algorithm (~June 20) sea-ice floes remains as seen be Landsat corresponding to a sea ice concentration of ~50% according to passive microwaves (blue line, right axis).

Sea-Ice thermodynamic stages using Landsat imagery in whole Hudson Bay System:

- A total of 12 positions were validated in distinct oceanographic domains of Hudson Bays System between 2006 and 2008;
- Hight frequency of fractures and leads during the consolidate winter stage and divergence and convergence of ice floes in advanced melting stages are significant sources of errors of Howell et al. [2005, 2006 2007] methodology;
- Pond onset [Howell et al. 2005, 2006 2007] marks a significantly increase of lead frequency and triggers the most notable process of changing in the sea-ice thermodynamic;
- Pond coverage can be less expressive than lead frequency in control the light incoming beneath the sea-ice pack;
- Concerning the sea-ice impact on light attenuation, the time duration between pond onset and SIC of 10% is more suitable to assess the sea-ice stage impact on phytoplankton dynamic in the marginal sea-ice zone in Hudson Bay System.

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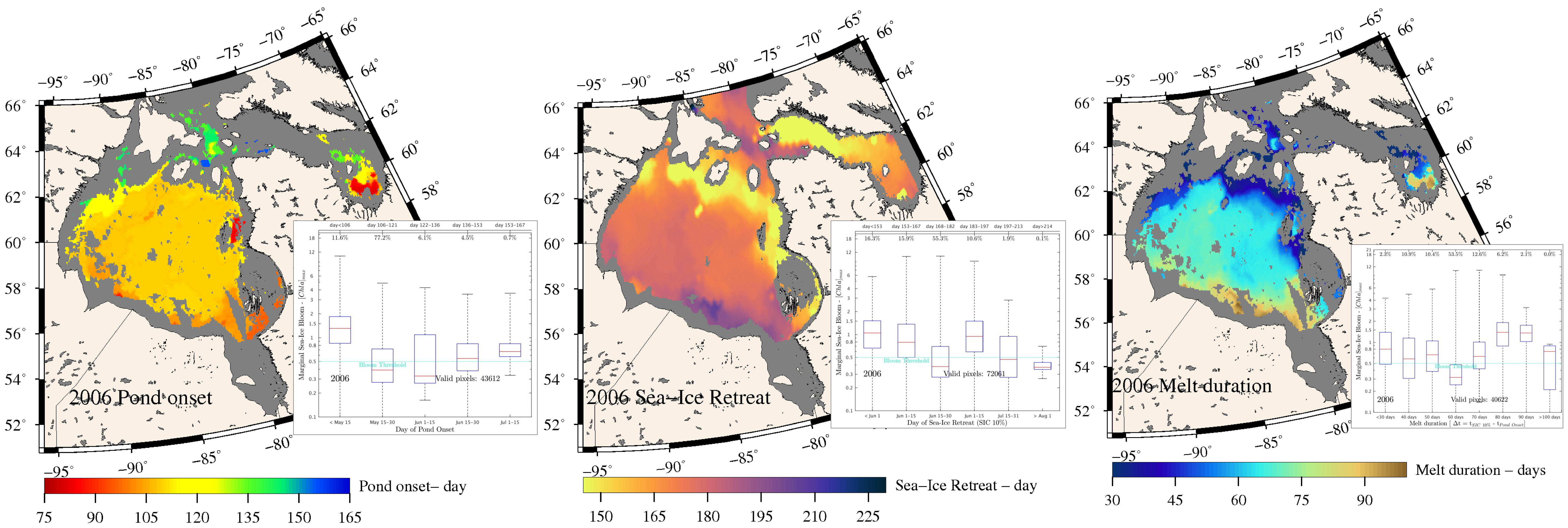
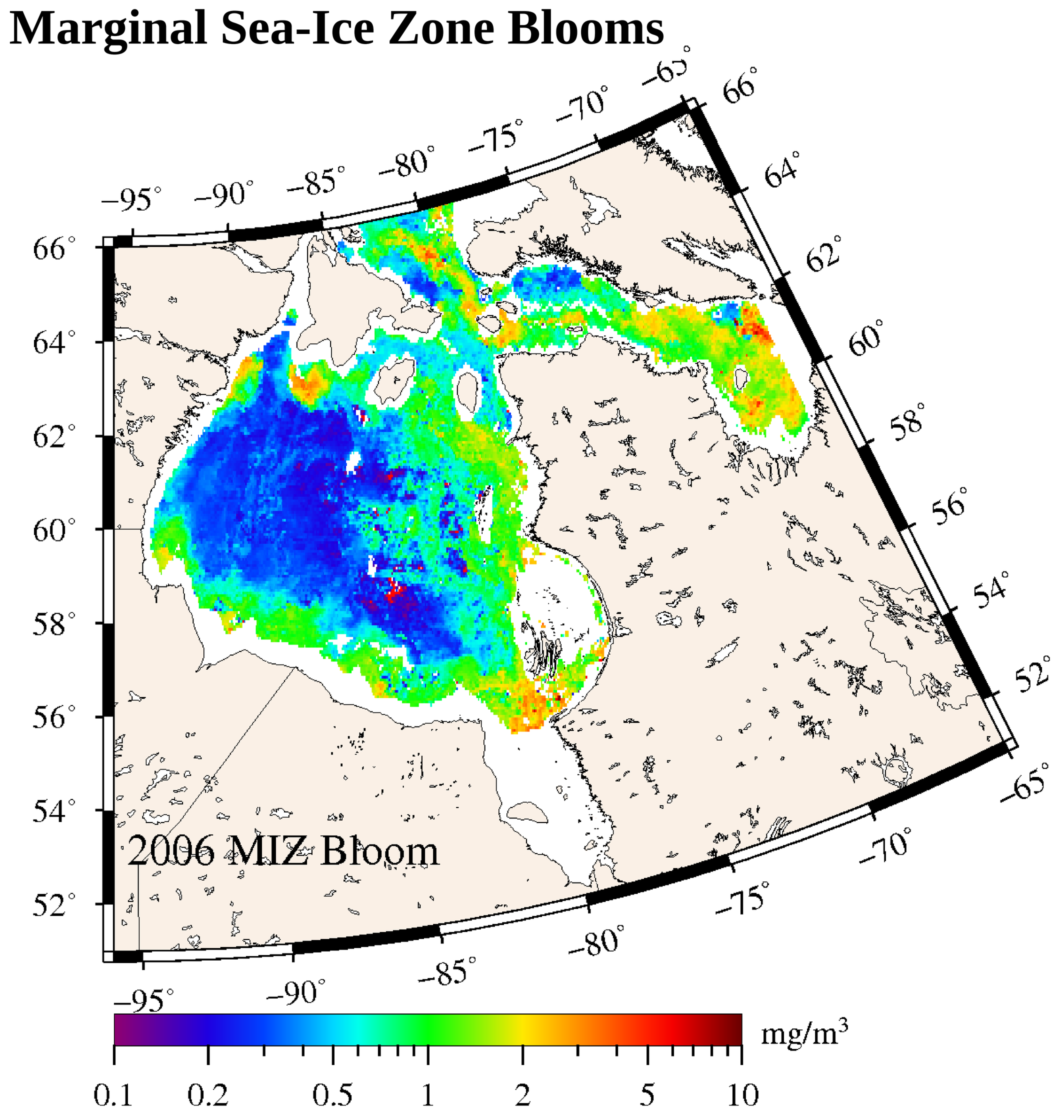
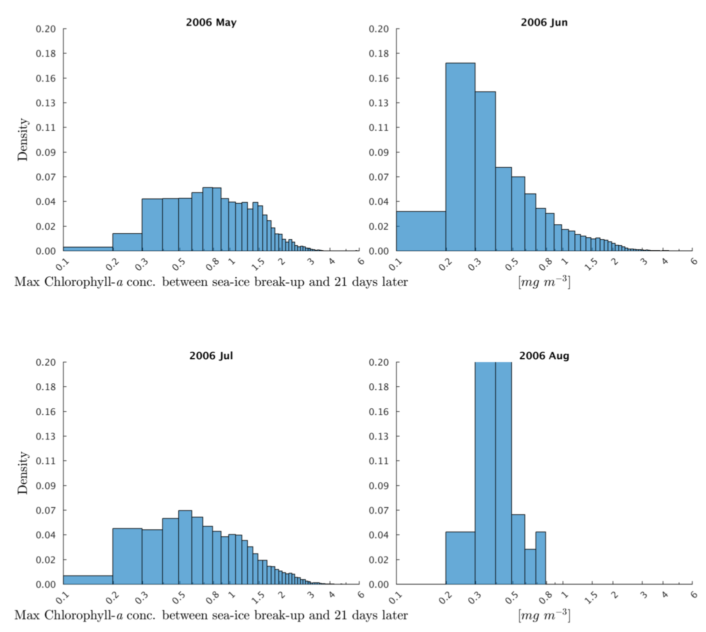


Pond onset, sea-ice retreat (SIC 10%), and melt duration (days between pond onset and sea-ice retreat) maps. Boxplots of each sea-ice parameters and *Chl* in the marginal sea-ice zone show how melting stages can influence the magnitude of phytoplanktonic blooms in Hudson Bay System, these relations present substantial inter-annual variability (not showed here). There is a predisposition for marginal sea-ice blooms in areas of early pond onset, and oligotrophy for late pond onset. The earliest pond onset occurs in low Photosynthetically Active Radiation *PAR*(+0) conditions, generally below 10 µE m^{-2} day^{-1} in March. In contrast, oligotrophic waters (<0.5 mg m^{-3}) are widespread in the pelagic system in case of late pond onset during the summer solstice in June, when *PAR*(+0) can be higher than 40 µE m^{-2} day^{-1} [Frouin and Pinker, 1995; Laliberté et al., 2016].

Marginal Sea-Ice Zone Blooms

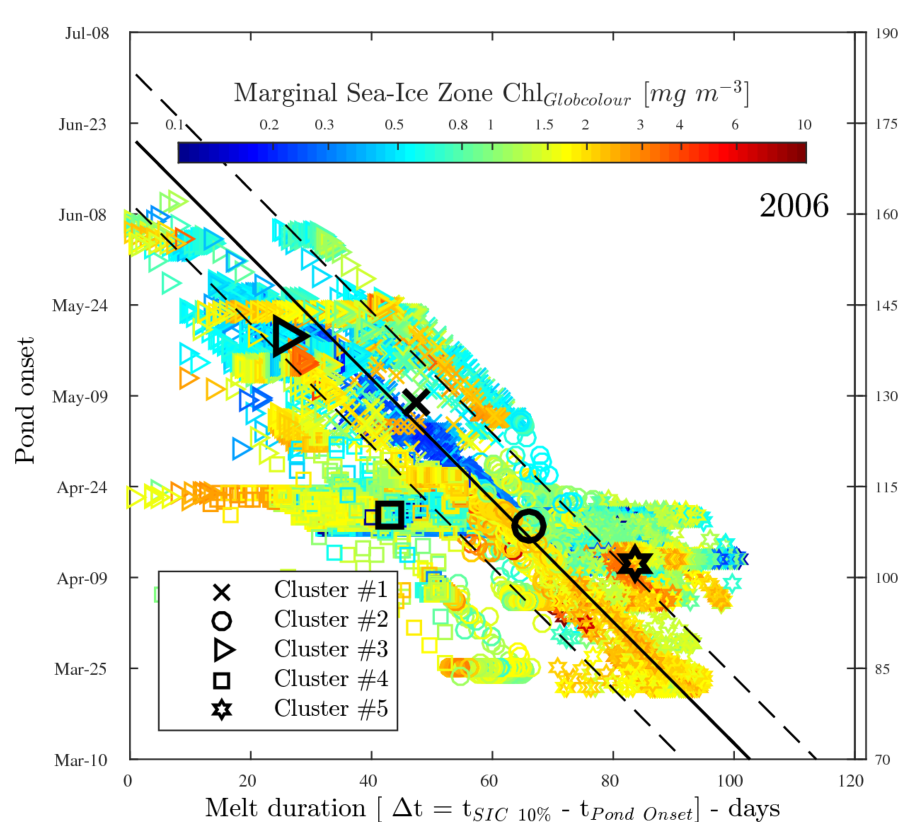


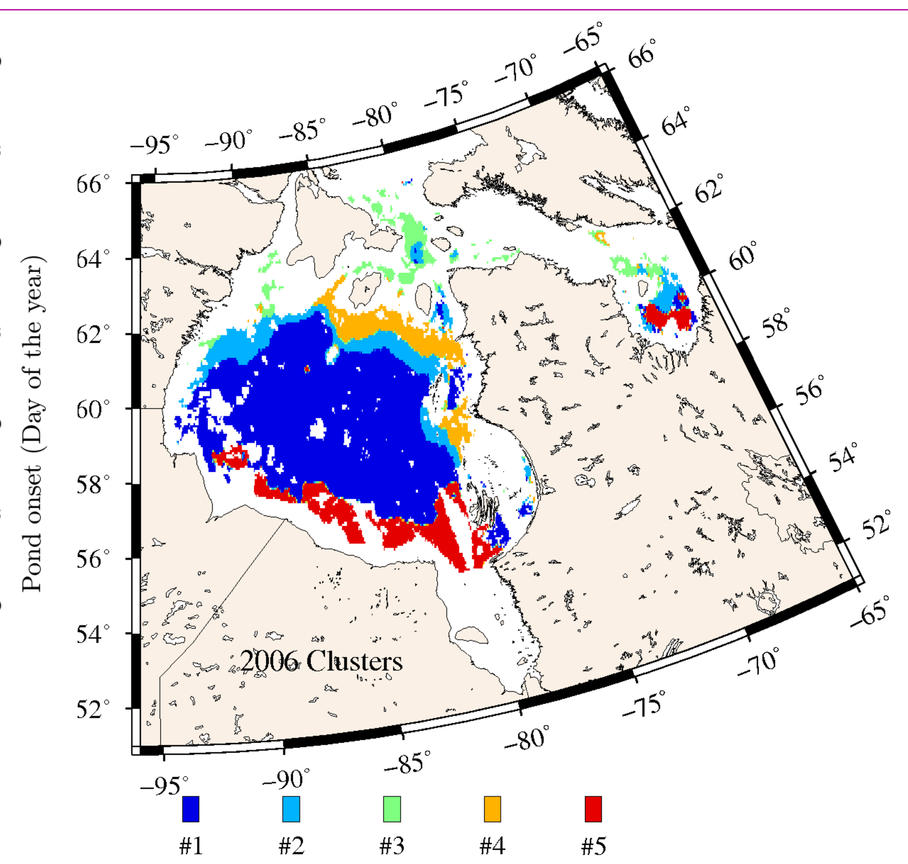


A fixed *Chl*-based threshold of 0.5 mg m^{-3} during the follow 21 days after the sea-ice retreat (SIC 10%) is selected to detect marginal sea-ice blooms [Perrette et al., 2011]. Depths shallow than *50 m* are exclude from analysis to avoid sediments, turbid waters and river plumes.

Photosynthetic Active Radiation controls on balance between under-ice and pelagic phytoplankton dynamic

Pond increases considerably the light transmission throughout the ice-pack [Frey et al., 2011; Arrigo et al., 2014]. It is assumed that pond onset determines the beginning of under-ice production season. Thus, pond fraction and time of onset can effectively control the balance between under-ice and pelagic production throughout the MIZ. This balance also depends on timing in relation to seasonal cycle of *PAR*(+0) and nutrients availability. In case of late melting season, the sea-ice transition to open-waters will occur simultaneous to the seasonal peak of *PAR*(+0). Hudson Bay sea-ice is generally thinner than in higher Arctic region (1.3-1.7m; Wang et al., 1994) allowing potentially more light to penetrate in spring time which may trigger massive under ice blooms even during a short time period and consequently, a scenario of nutrient depletion might be left to the subsequent pelagic system. Then, MIZ goes toward an oligotrophic set up, which is assumed by low phytoplankton abundancy in upper layers and a sub-surface *Chl* maximum stabilized out of ocean color remote sensor range [Ferland et al., 2011; Ardyna et al., 2013].





Pond onset, melt duration and MIZ Bloom

Scatterplot of pond onset, melt duration and MIZ *Chl* (color scale) [*Perrette et al.*, 2011] in 2006. These parameters are clustered by *K*-means and represented by symbols which are colored according *Chl* values, cluster centroids (black symbols) are selected by ascending order of Chl_{median} (#1 < #2 < #2 < #4 < #5). The spatial distribution of each cluster is showed on map to point specific patterns of sea-ice stages influence on pelagic bloom in Hudson Bay System. High phytoplankton abundance is more frequent for early pond onset (cluster #5). Melt duration and pond onset have a well-marked inverse linear relation, long (short) melt duration is triggered by an early (late) pond onset.

General discussion

Phytoplankton phenology in polar region can be largely influenced by sea-ice thermodynamic stages at the end of the winter and in spring. Melt, pond and drainage onsets, for example, are good indicators of the light transmission through the ice, which is a key component controlling the phytoplankton bloom initiation. The timing of physical processes are center to understand the phytoplankton phenology. Events those preceding a phytoplankton bloom, if well characterized can supply important information for quantify, understand and predict impacts on phytoplankton dynamic.

Highlights and conclusion

- Our novel multi-satellite approach is promisor to evaluate how sea-ice time shifts can impact the balance between under-ice and pelagic phytoplankton dynamic;
- Melting process in areas of thin sea-ice like Hudson Bay System is ruled fracturing process. Thus, light incoming beneath sea-ice pack can trigger bloom even before pond occurrence, forced by widespread sea-ice fractures and leads;
- Sea ice melting duration and pond onset have a well-marked inverse linear relation;
- The synchronicity between seasonal *PAR*(0+) and sea-ice stages are critical to the balance between under-ice and pelagic phytoplankton abundancy. Long melting duration under low *PAR*(0+) cannot be efficient to deplete nutrients in the upper ocean layer, while short melt duration during the peak of *PAR*(0+) can result in massive under ice bloom and consequently an oligotrophic set-up in pelagic system after sea-ice retreat;