Towards an observationally-constrained understanding of Northern high-latitude carbon cycle dynamics

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Overview

One of the largest uncertainties in projected greenhouse gas concentrations and temperature trends is the impact from terrestrial and marine carbon-climate feedbacks in the Northern high-latitudes (NHL).

Current operational space-based missions such as OCO-2 (and planned future missions such as the CO2M constellation) with their global observational coverage and coincident measurements of SIF and X_{CO2}, have the potential to inform differences in carbon cycle dynamics over large sub-continental scales. In this project, funded through NASA ROSES OCO Science Team AO, we have improved our knowledge of CO_2 retrievals over snow and ice surfaces and leveraged the space-based vantage point to quantify Arctic-Boreal carbon balance, diagnose its current state (net source or net sink or approximately carbon neutral) and spatiotemporal patterns.

OCO-2 coverage over the Northern high-latitudes

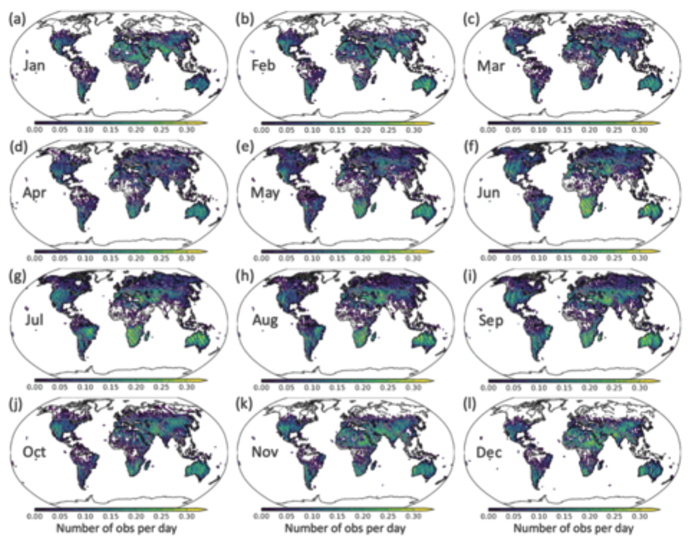


Fig. 1 (*LHS*): Spatial coverage of monthly land X_{CO2} retrievals averaged over four-years (2015 - 2018). See *Byrne et al.* [2022], Biogeosciences.

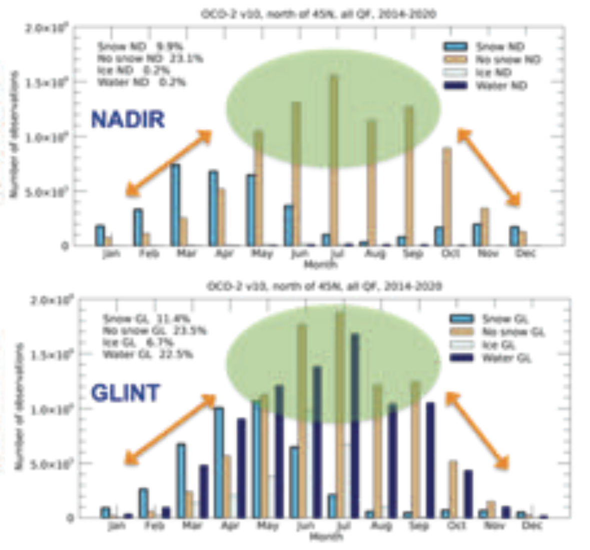


Fig. 2 (*RHS*): Histogram showing the distribution of observations in nadir and glint mode across months. Credit: H. Lindqvist (FMI).

- OCO-2 retrievals provide good constraint on the growing season (May – September), but
- both the quality and the quantity of soundings drop off in the shoulder seasons (March – May, October – November)
- *note* need for sunlit conditions prevents measurements during polar nights, making retrievals during the peak of the cold season (December – February) impractical

Increased throughput of OCO-2 retrievals in the latest generation of retrievals (v11.1 / v11.2)

High-latitude retrievals pose a major technical hurdle due to challenges associated with both measurements and retrievals at high solar zenith angle, high airmass, complex albedo and surface conditions due to the presence of snow and ice. These issues result in time- and seasonal-dependent biases in our Northern high latitude retrievals.

We have characterized these biases in our current retrieval algorithms and explored choices related to the QAQC flags and threshold strategies for retrievals over snow & ice surfaces. Our latest dataset (v11.1/v11.2) now has more high-latitude retrievals than previous v10, due to a switch in the Digital Elevation Model (DEM) as well as updates to the ACOS Level 2 full physics algorithm. Jacobs et al. (2023) captures implementation of this new DEM in the ACOS algorithm and notes a subsequent ~100 TgC shift in inferred carbon uptake for the zones spanning 30 to 60°N and 60 to 90°N, which is on the order of 5-7% of the estimated pan-Arctic land sink.

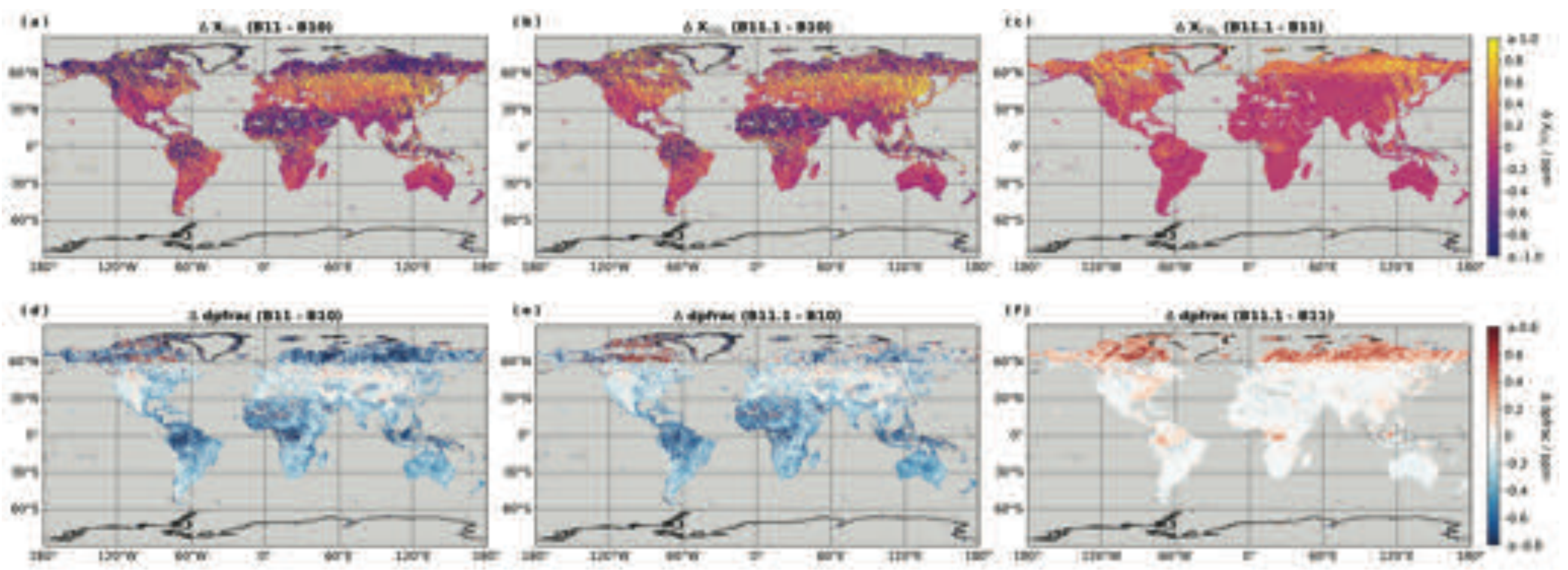


Fig. 3 (*LHS*): Change in X_{CO2} and dpfrac between various OCO-2 ACOS versions; (a) B11 - B10, (b) B11.1 - B10, (c) B11.1 - B10.

See N. Jacobs et al. (2023) for more details and analysis related to the changes in v11.1, especially the DEM and subsequent impact on X_{CO2}, bias correction and flux estimates. v11.2 will automatically include this new DEM.

Development and implementation of a neural network-based filtering approach further increases throughput in late winter and spring months (Figure 4) - this new filter not only dramatically expands OCO-2 observational coverage in the spring shoulder season but also increases the overall mean precision (relative to high-latitude TCCON sites) for the entire season. We are letting through more data, but more “good-quality” data and removing outliers.

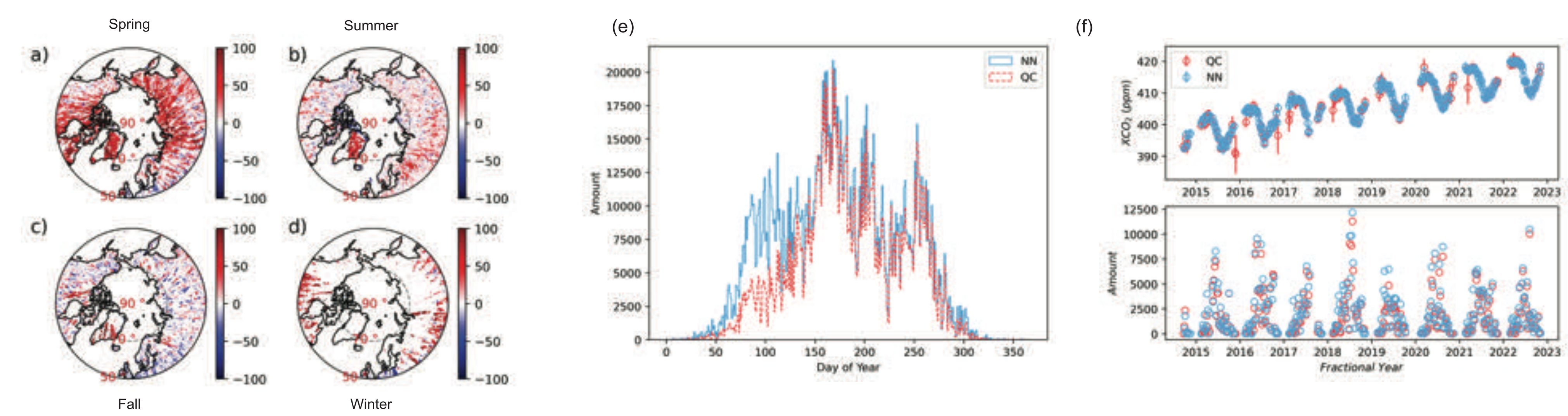
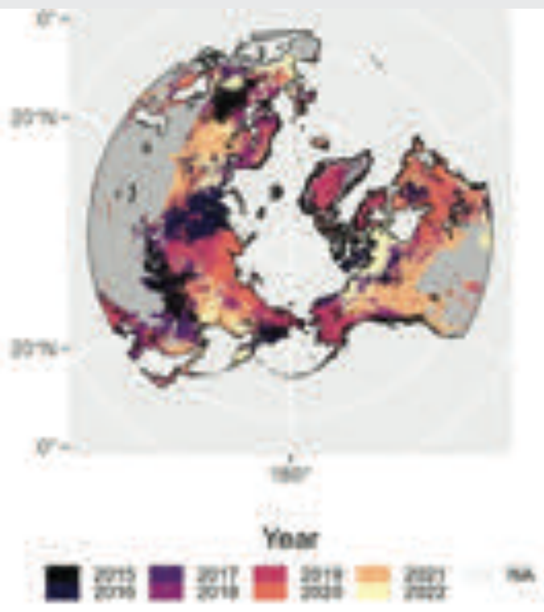


Fig. 4 (*a-d*): Percent increase in throughput of “good-quality” soundings by using the neural network filter relative to the standard QC filter employed in v11.1/v11.2. Results are shown for one representative year, 2018. (*e*) Histogram of throughput over Siberian taiga shows clear increase in soundings during late winter and spring months. (*f*) Time-series of X_{CO2} and throughput shows a “cleaner” looking weekly mean X_{CO2} with less outliers, thus potentially improving flux inversions and scientific analysis.

OCO-2 data enables understanding the response of NHL carbon cycle to extreme climate events, like heatwaves

Information derived from OCO-2 X_{CO2} and SIF retrievals have been integrated with MODIS remote sensing (land surface and vegetation products) to test specific hypotheses about the drivers and impacts of environmental change on the Arctic-Boreal carbon cycle. For the time period of OCO operations, major heatwaves are evident over Siberia in 2020 and north-west North America in 2021 (Figure 5). The 2020 Siberian heatwave was notorious - it extended from at least January all the way through summer. Higher spring and early summer temperatures increased vegetation productivity, as suggested by the OCO-2 MIP NBE anomalies (Figure 6).



As summer progressed, the unrelenting high temperatures had cascading impacts as soils dried, vegetation productivity declined (Figures 7-8) and wildfires continued to occur across the region (*Madani, Berner, Chatterjee et al.*, in prep.).

OCO-2’s space-based vantage point and X_{CO2}, SIF measurements have been critical for understanding the impact of these heatwaves on the magnitude and interannual variability of the pan-Arctic carbon cycle and quantifying the impact of early spring onset on the seasonal cycle, primary productivity and ecosystem respiration dynamics over this domain.

Fig. 5 (*LHS*): Annual maximum land surface temperature anomalies for the period of OCO-2 operations across northern high latitudes derived using 8- day MODIS Aqua data at 1 km² resolution (MYD11A2 Version 6). For each grid-cell the annual LSTmax anomaly is relative mean annual LSTmax from 2002 to 2020. Notable are the summer heatwaves across parts of Siberia, Alaska, and Canada in 2020.

Fig. 6 (*LHS*): Monthly (June-July-Aug) NEE anomalies from the v10 OCO-2 MIP. The impact of the heatwaves in central Russia during **2020** is evident in the NBE anomalies, with increased uptake during June 2020 but release during July-August 2020.

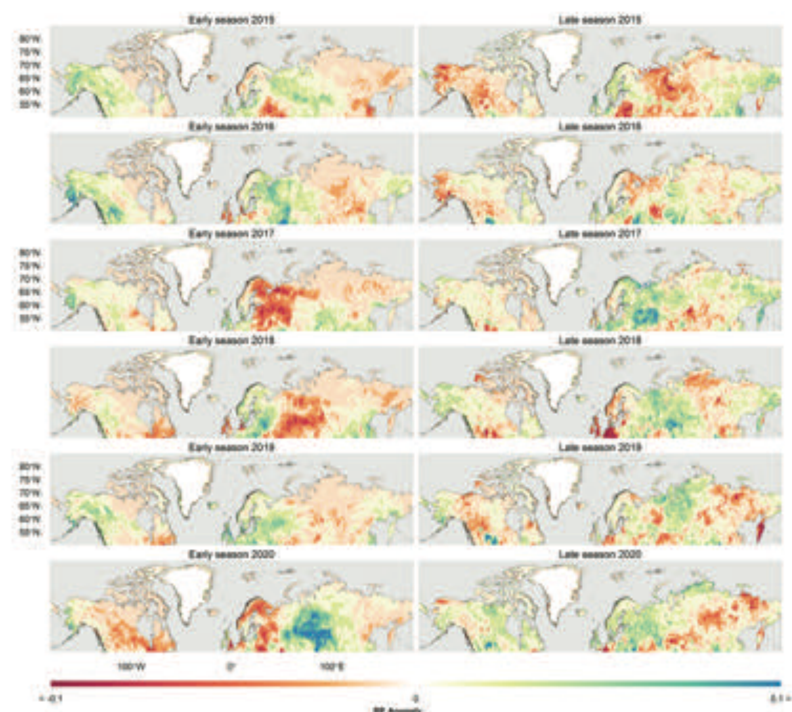


Fig. 7 (*RHS*): shown are the anomaly in the SIF data for the early season (Apr-May) versus late season (Aug-Sep). Anomalies are calculated relative to monthly climatology from CSIF for 2000-2020. Of particular interest is the late season anomaly in SIF for 2020, corresponding to the Siberian heatwave extreme event.

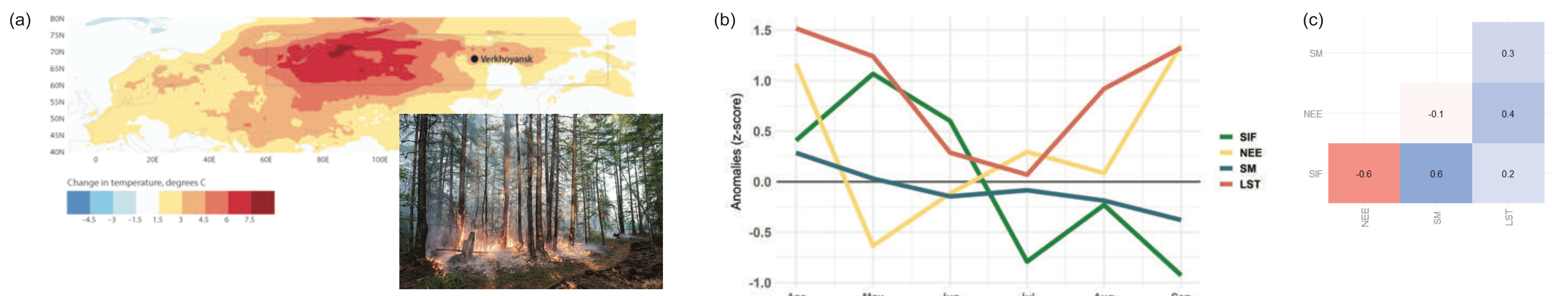


Fig. 8 (*a*): January – June 2020 average temperatures compared to normal (1981-2010) over Siberia (Ciavarella, A, et al. 2021) while the inset shows a forest fire in central Sakha Republic, Russia. Credit: ITAR-TASS News Agency / Alamy Stock Photo. (*b-c*) Anomalies in CSIF, MERRA-2 soil moisture, land surface temperature and OCO-2 MIP NEE for the year 2020 in eastern Siberian Taiga. Decrease in SIF follows expected decrease in primary productivity, while the increase in NEE captures increasing ecosystem respiration even as GPP drops. Cross-correlation between the environmental drivers and NEE and SIF response is captured in Panel (c).

Summary and next steps

OCO-2, from its space-based vantage point, is providing a comprehensive and detailed understanding of carbon cycle dynamics over the Northern high-latitudes, capturing changes unfolding over that critical domain and its interaction with the global carbon cycle.

While our current retrievals from OCO-2 are a significant improvement over previous versions, we continue to push the boundaries by refining our filtering and bias correction approaches and modifying the core retrieval algorithm to better capture characteristics of snow & ice-covered surfaces. For example, a critical piece of work that will be concluded this year is the testing and implementation of a BRDF model describing snow surface reflection, polarization and spectral dependence at different wavelengths within the ACOS algorithm. We anticipate this development to also benefit CO2M, GOSAT-GW and future GHG missions that aim to monitor GHGs over snow/ice surfaces.

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