CO2 Exchange Forecasting of a Tundra Gradient in Greenland Between 1991 and 2100

Efrén López Blanco[1], Peter L. Langen[2], Mathew Williams[3], Jens Christensen[4], Fredrik Boberg[5], Kirsty Langley[6], and Torben Christensen[7]

[1]Greenland Institute of Natural Resources
[2]Aarhus University,Aarhus University
[3]University of Edinburgh
[4]Niels Bohr Institute, Copenhagen University
[5]Danish Meteorological Institute
[6]Asiaq, Greenland Survey
[7]Aarhus University

November 22, 2022

Posted on 22 Nov 2022 — CC-BY 4.0 — https://doi.org/10.1002/essoar.10510420.1 — This a preprint and has not been peer reviewed. Data may be preliminary.

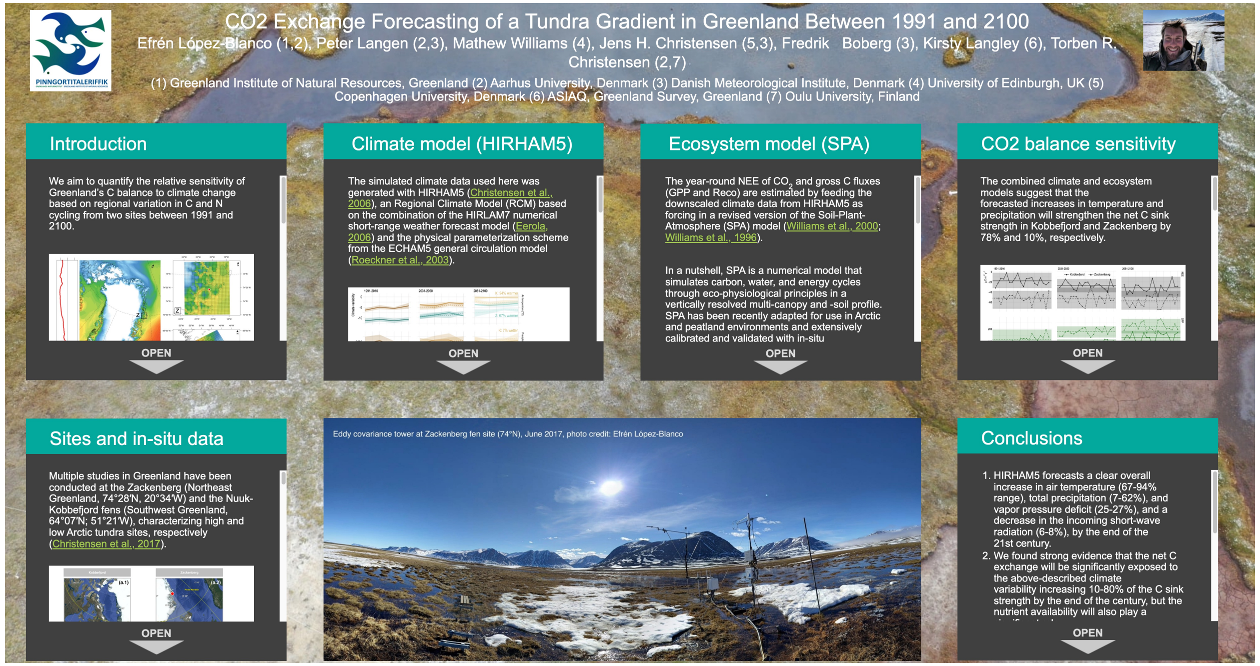
Abstract

The Arctic is one of the regions in our planet with strongest warming observed and it is also almost certain to continue to change in the near future. The continuous change in key indicators of Arctic climate change (e.g. increase of temperature, intensification of the hydrological cycle, and shortening of the spring snow cover) will have marked consequences on ecosystem carbon (C) sink-source functioning. Such consequences are, however, broadly uncertain. Comprehensively integrated ecosystem models with long-term in-situ data are essential to understand the Arctic C cycle sensitivity to climate change and explore robust future scenarios. Our aim is to quantify the relative sensitivity of Greenland's C balance to climate change based on regional variation in C and N cycling in a tundra gradient. The key roadblocks to this understanding have been limited time series of C fluxes, and limited regional data. Now with observations from multiple data streams measured by the Greenland Ecosystem Monitoring (GEM) program over the last two decades in conjunction with proven ecosystem and climate models we 1) analyse the underlying processes and links between present climate and terrestrial C and N cycling and 2) forecast the variation of plant phenology, productivity, and respiration forward in time. We use an established but novel C cycle model, the Soil-Plant-Atmosphere model, applied to two GEM wetlands relying on previous substantiated efforts on source-code model implementation, model calibration, and validation based on quality-controlled long-term data. Additionally, our modelling framework is now forced with future projections from the regional climate model HIRHAM5 specifically designed to characterize the Greenland domain (typically left behind in global modelling analyses) following the IPCC greenhouse gas emission scenarios. We ask the ecological question: How sensitive is the C balance expected to be under warmer and wetter conditions forecasted for the 21st century? Although still preliminary, we found strong evidence that the net C exchange will be significantly exposed to higher temperatures and intensified precipitation levels increasing 10-80% the C sink strength by the end of the century, but lengthening of the growing season and nutrient availability will also play a significant role.

CO2 Exchange Forecasting of a Tundra Gradient in Greenland Between 1991 and 2100

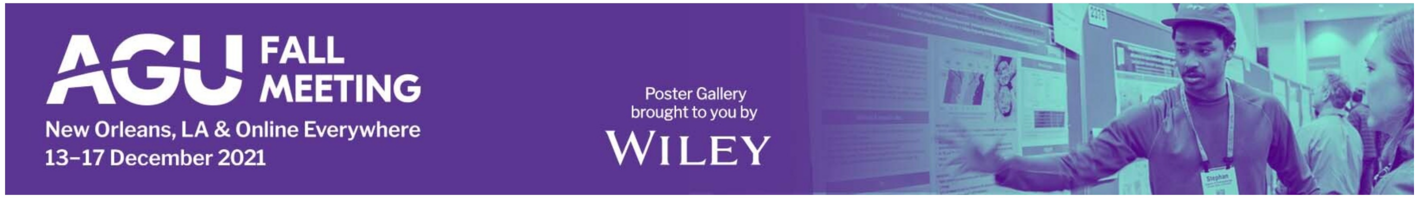
Efrén López-Blanco (1,2), Peter Langen (2,3), Mathew Williams (4), Jens H. Christensen (5,3), Fredrik Boberg (3), Kirsty Langley (6), Torben R. Christensen (2,7)

(1) Greenland Institute of Natural Resources, Greenland (2) Aarhus University, Denmark (3) Danish Meteorological Institute, Denmark (4) University of Edinburgh, UK (5) Copenhagen University, Denmark (6) ASIAQ, Greenland Survey, Greenland (7) Oulu University, Finland



Access to e-Poster: https://agu2021fallmeeting-agu.ipostersessions.com/Default.aspx?s=B9-0A-BA-AF-22-04-51-85-77-4E-B6-CF-30-18-A3-F2

PRESENTED AT:



B34D - The Resilience and Vulnerability of Arctic and Boreal Ecosystems to Climate Change V eLightning

Peter C Griffith[1], Michelle C Mack[2], Abhishek Chatterjee[3], Natalie Boelman[4] and Elisabeth K Larson[1], (1)NASA Goddard Space Flight Center, Greenbelt, MD, United States(2)Northern Arizona University, Center for Ecosystem Science and Society, Flagstaff, AZ, United States(3)Jet Propulsion Laboratory/Caltech, Carbon Cycle and Ecosystems, Pasadena, MD, United States(4)Lamont-Doherty Earth Observ., Palisades, NY, United States

Wednesday, 15 December 2021

17:30 - 18:45

Convention Center - eLightning Theater IV

Introduction

We aim to quantify the relative sensitivity of Greenland's C balance to climate change based on regional variation in C and N cycling from two sites between 1991 and 2100.

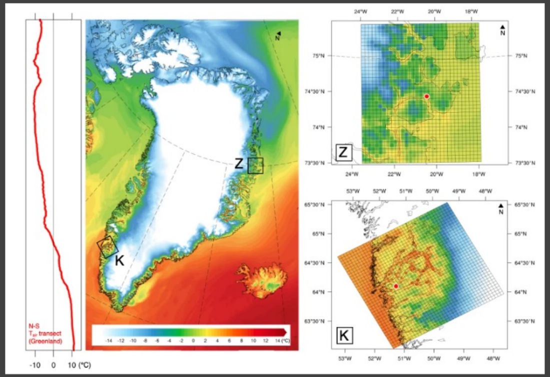


Figure 1. Example of downscaled air temperature from HIRHAM5 Regional Climate model featuring Greenland during August 1st, 2000 at a 5x5 km spatial resolution. [Z] and [K] maps zoom in on the Zackenberg and Nuuk-Kobbefjord surrounding areas of each research station (red dots).

The key roadblocks to this understanding have been limited time series of C fluxes and limited regional data. Now with observations from multiple data streams measured by the Greenland Ecosystem Monitoring (GEM; https://g-e-m.dk/) programme over the last two decades in conjunction with a proven ecosystem model (Soil-Plant-Atmosphere) and a downscaled regional climate model (HIRHAM5) we 1) analyse the underlying processes and links between present climate and terrestrial C and N cycling and 2) forecast the variation of plant phenology and C storage forward in time.

Zackenberg fen surroundings, September 2019 – drone image source: Johan Scheller

Sites and in-situ data

Multiple studies in Greenland have been conducted at the Zackenberg (Northeast Greenland, 74°28′N, 20°34′W) and the Nuuk-Kobbefjord fens (Southwest Greenland, 64°07′N; 51°21′W), characterizing high and low Arctic tundra sites, respectively (Christensen et al., 2017).

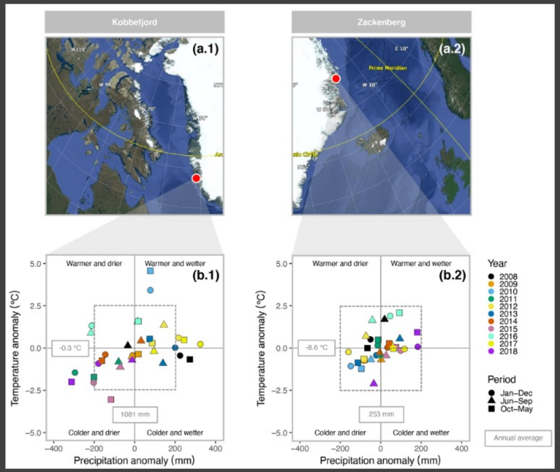


Figure 2. (a.1) and (a.2) Location of the Nuuk-Kobbefjord and Zackenberg sites, respectively (source: Google Earth Pro). (b.1) and (b.2) Annual temperature and precipitation anomalies within the analysed years (2008–2018) including annual (January to December), warm season (July to September) and cold season (October to May) averages.

Extensive terrestrial CO_2 exchange measurements have been conducted in both sites. The Zackenberg fen Net Ecosystem Exchange (NEE) of CO_2 presents a higher C sink strength (>170%) compared to Kobbefjord fen despite its higher latitude and markedly shorter growing season (López-Blanco et al. (2020).

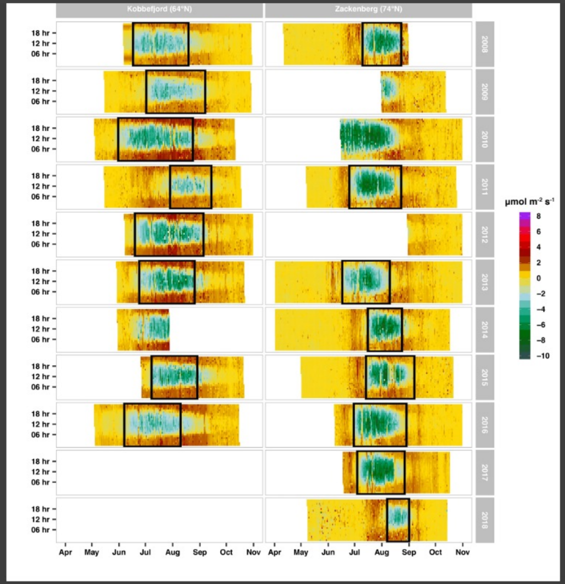


Figure 3. Time series of gap-filled NEE (2008–2018) based on the MDS algorithm from Reddyproc. Green represents C uptake while the orange-dark-red denotes C release. The black box delimits the period between the start and the end of the growing season.

In-situ carbon (C) and nitrogen (N) data show systematic larger C stocks, leaf mass per area, leaf N, leaf area index, and plant quality in Zackenberg compared to Kobbefjord. Additionally, the water chemistry data from the first 50cm also show higher levels of dissolved organic C and N, nitrates, ammonium, potassium, and electroconductivity in Zackenberg.

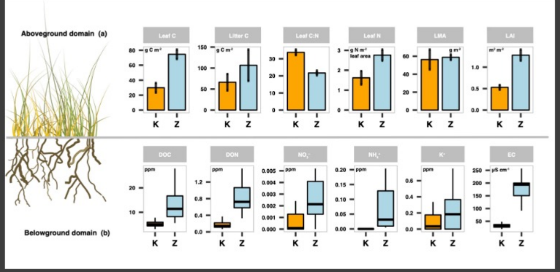


Figure 5. *In-situ* observations from aboveground biomass (a) and concentration levels of nutrients and minerals in soils (b) from Zackenberg fen (light blue) and Kobbefjord fen (orange). The bar plots characterize leaf and litter C stocks, leaf C:N ratio (i.e. plant quality), leaf N, leaf mass per area (LMA), and leaf area index (LAI) in the aboveground domain. The error bars contain the variability (standard deviation) out of the five fen plots. The box plots characterize soil water chemistry and catchment exports of dissolved organic carbon (DOC), dissolved organic nitrogen (DON), nitrate (NO_3^-), ammonium (NH_4^+), potassium (K^+), and electroconductivity (EC) between 2015 and 2017 at a maximum depth of 50 cm.

Climate model (HIRHAM5)

The simulated climate data used here was generated with HIRHAM5 (Christensen et al., 2006), an Regional Climate Model (RCM) based on the combination of the HIRLAM7 numerical short-range weather forecast model (Eerola, 2006) and the physical parameterization scheme from the ECHAM5 general circulation model (Roeckner et al., 2003).

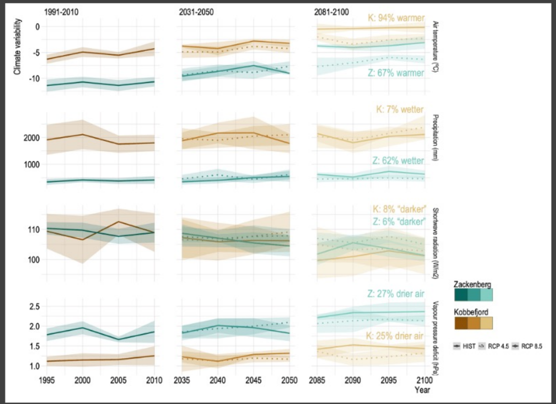


Figure 5. Recent past and future 5-year mean air temperature (°C), precipitation (mm), shortwave radiation (Wm^{-2}) and vapour pressure deficit (hPa) in Kobbefjord and Zackenberg estimated by HIRHAM5 Regional Climate model. The RCP 4.5 scenario future projections are displayed as dashed lines while the RCP 8.5 scenario is presented with solid lines.

To resolve the topography of Greenland adequately, the spatial resolution of HIRHAM5 RCM grid was downscaled to 0.05°x 0.05° corresponding to ~5.5 x 5.5 km grid cell sizes. Due to limits in computational resources and expensive computing power, the datasets available from Boberg et al. (2018) only include five 21-year time slices instead of a full transient coverage of the 21st century. This study covers a historical time slide (1991-2010), and four future slices forecasting the middle (2031-2050) and the end (2081-2100) of the century.

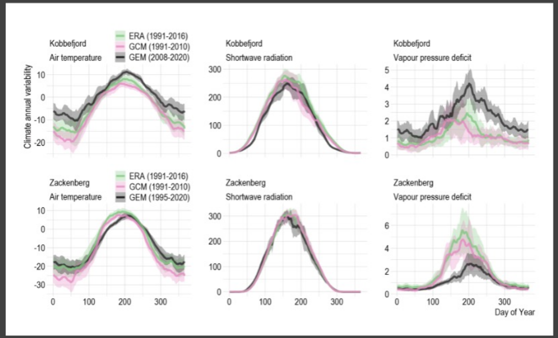


Figure 6. Daily-aggregated seasonal variability of temperature, radiation, and humidity from *in-situ* GEM observations and HIRHAM5 ERA and GCM driven outputs at the Kobbefjord and Zackenberg sites.

Ecosystem model (SPA)

The year-round NEE of CO_2 and gross C fluxes (GPP and Reco) are estimated by feeding the downscaled climate data from HIRHAM5 as forcing in a revised version of the Soil-Plant-Atmosphere (SPA) model (Williams et al., 2000; Williams et al., 1996).

In a nutshell, SPA is a numerical model that simulates carbon, water, and energy cycles through eco-physiological principles in a vertically resolved multi-canopy and -soil profile. SPA has been recently adapted for use in Arctic and peatland environments and extensively calibrated and validated with in-situ meteorological, C flux, and CN stock data both from Kobbefjord (López-Blanco et al., 2018) and Zackenberg (López-Blanco et al., 2020) across the 2008-2018 period.

A more dedicated overview of SPA's overall structure and parameterization can be found in (López-Blanco et al., 2018).

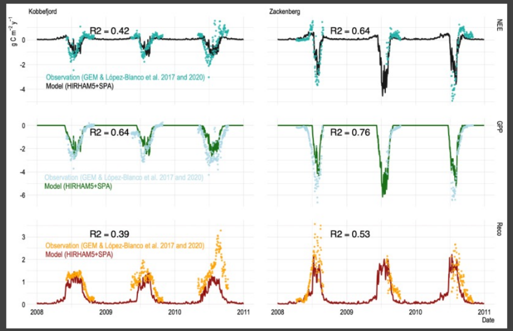


Figure 7. Time series of observed and simulated C fluxes (NEE, GPP, and R_{eco}) using the SPA model in Kobbefjord and Zackenberg sites for the 2008-2010 period forced with HIRHAM5 climate estimates. The model uses the parameterization for Kobbefjord data (López-Blanco et al., 2018) and Zackenberg data (López-Blanco et al., 2020) including modifications of the initial C stocks, leaf N, leaf mass per area (all based on *in-situ* field data). Goodness-of-fit (R^2) are displayed for the available validation period 2008-2010.

CO_2 balance sensitivity

The combined climate and ecosystem models suggest that the forecasted increases in temperature and precipitation will strengthen the net C sink strength in Kobbefjord and Zackenberg by 78% and 10%, respectively.

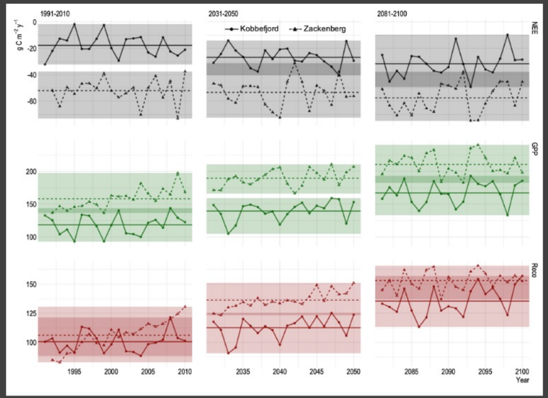


Figure 8. Recent past and future annual mean net ecosystem exchange (NEE), gross primary production (GPP), and ecosystem respiration (R_{eco}) forecasted in Kobbefjord and Zackenberg by the SPA model driven with HIRHAM5 forcing RCP 4.5 scenario.

Photosynthesis will grow around 41% in Kobbefjord and 33% in Zackenberg, while respiration will also increase (34% and 44%, respectively). Therefore, by 2100 Kobbefjord will see enhanced plant uptake more significantly while Zackenberg will experience the opposite, stronger respiration releases. However, the overall photosynthetic inputs in both sites will keep dominating the respiratory outputs, similar to what is observed in the field today.

The results suggest that Kobbefjord will partially bridge the gap on C sink strength magnitude with Zackenberg towards the end of the 21st century. Climate will significantly contribute to the forecasted increase of C sink strength in the Kobbefjord, but nitrogen availability appears to remain as the key contributor to the terrestrial C cycling in Zackenberg, as argued by López-Blanco et al. (2020).

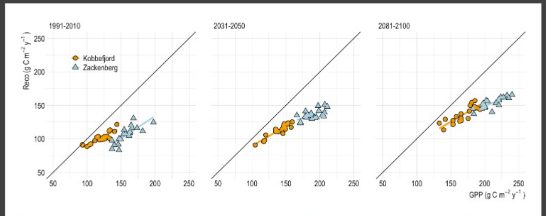


Figure 9. Interannual variability between GPP and Reco relationships in Zackenberg (light blue) and Kobbefjord (orange) between 1991 and 2100.

Conclusions

1. HIRHAM5 forecasts a clear overall increase in air temperature (67-94% range), total precipitation (7-62%), and vapor pressure deficit (25-27%), and a decrease in the incoming short-wave radiation (6-8%), by the end of the 21st century.
2. We found strong evidence that the net C exchange will be significantly exposed to the above-described climate variability increasing 10-80% of the C sink strength by the end of the century, but the nutrient availability will also play a significant role.
3. These types of forecasting exercises are essential as we should find and explore the common ground between the very local scale field observations and the “coarse” resolution climate simulations focusing on Greenland, typically left behind in global modelling analyses due to its complexity and lack of data.
4. Multiple challenges and uncertainties remain. This work will establish robust baselines for model calibration and validation for future upscaling exercises at different spatial scales focusing on Greenland.


Eddy covariance tower at Zackenberg fen site (74°N), June 2017, photo credit: Efrén López-Blanco

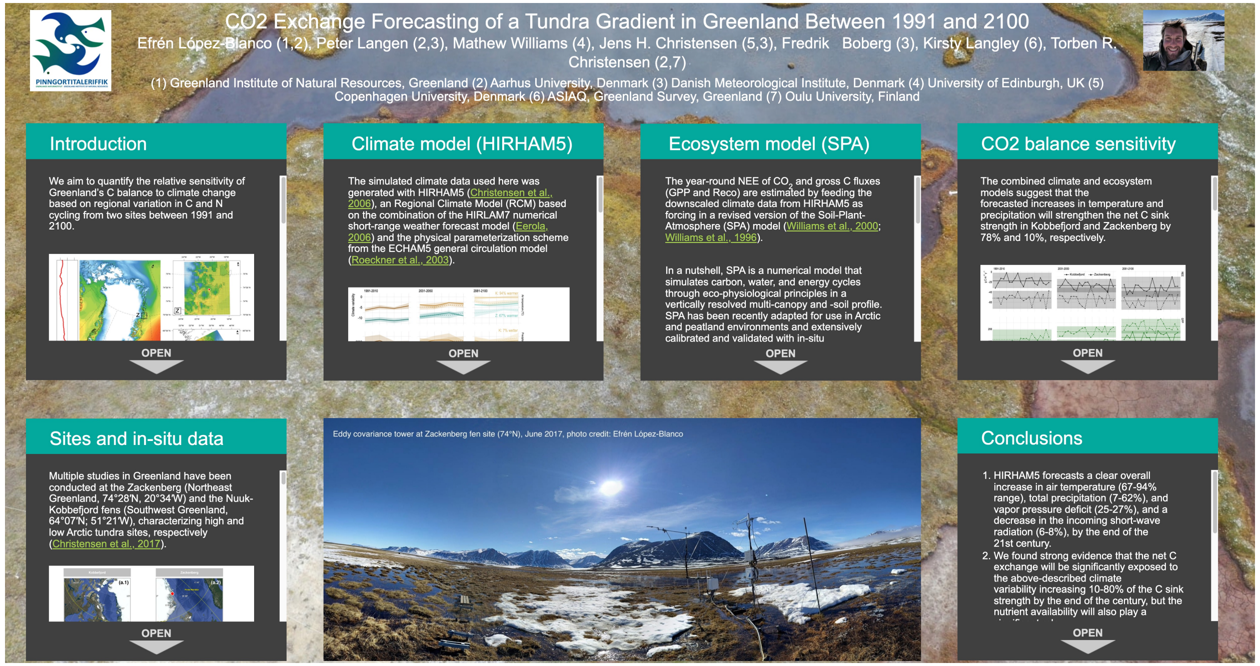

Kobbefjord hut (64°N), June 2015, photo credit: Efrén López-Blanco


Kobbefjord valley (64°N), June 2015, photo credit: Efrén López-Blanco

CO2 Exchange Forecasting of a Tundra Gradient in Greenland Between 1991 and 2100

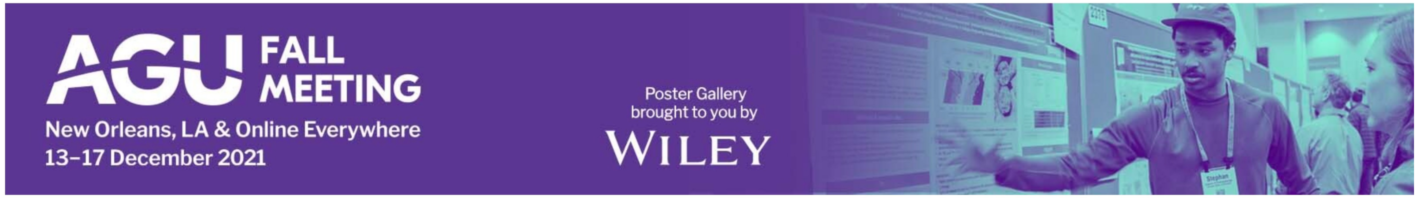
Efrén López-Blanco (1,2), Peter Langen (2,3), Mathew Williams (4), Jens H. Christensen (5,3), Fredrik Boberg (3), Kirsty Langley (6), Torben R. Christensen (2,7)

(1) Greenland Institute of Natural Resources, Greenland (2) Aarhus University, Denmark (3) Danish Meteorological Institute, Denmark (4) University of Edinburgh, UK (5) Copenhagen University, Denmark (6) ASIAQ, Greenland Survey, Greenland (7) Oulu University, Finland



Access to e-Poster: https://agu2021fallmeeting-agu.ipostersessions.com/Default.aspx?s=B9-0A-BA-AF-22-04-51-85-77-4E-B6-CF-30-18-A3-F2

PRESENTED AT:



B34D - The Resilience and Vulnerability of Arctic and Boreal Ecosystems to Climate Change V eLightning

Peter C Griffith[1], Michelle C Mack[2], Abhishek Chatterjee[3], Natalie Boelman[4] and Elisabeth K Larson[1], (1)NASA Goddard Space Flight Center, Greenbelt, MD, United States(2)Northern Arizona University, Center for Ecosystem Science and Society, Flagstaff, AZ, United States(3)Jet Propulsion Laboratory/Caltech, Carbon Cycle and Ecosystems, Pasadena, MD, United States(4)Lamont-Doherty Earth Observ., Palisades, NY, United States

Wednesday, 15 December 2021

17:30 - 18:45

Convention Center - eLightning Theater IV