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Frozen Season Impacts on Northern High Latitude Vegetation Growth Under Cold Temperature and Moisture Constraints

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Introduction:

The duration of the frozen season strongly influences vegetation dormancy and productivity at higher latitudes and upper elevations where frozen temperatures are a major constraint to plant growth. The landscape freeze-thaw (FT) signal from satellite microwave remote sensing is closely linked to frozen temperature constraints to vegetation phenology, productivity, land-atmosphere trace gas exchange and surface water mobility. We developed a consistent global record of daily landscape FT dynamics at moderate (~25-km) spatial resolution using a temporal change classification of overlapping 37 GHz frequency brightness temperatures (Tb) from AM and PM overpass retrievals of the Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave Imager (SSM/I) sensor records. A temporally consistent and continuous long-term (from 1979) FT record was created that distinguishes daily frozen, non-frozen and transitional (AM frozen and PM non-frozen) conditions. The FT record is used to quantify variability and regional trends in frozen seasons and transitional frost days over the northern high latitude (NHL) domain. The ecological significance of these changes is evaluated against atmospheric CO_2 seasonal cycles, satellite VI (NDVI, EVI) summer growth anomalies and estimated moisture and temperature constraints to productivity determined from global meteorological reanalysis. The FT metrics show a significant mean regional trend toward shorter (-2.4 days per decade; p<0.001) frozen seasons over the 30+ year record, driven largely by earlier spring thawing (-2.1 days per decade; p<0.001). A declining frozen season coincides with regional warming and is predominantly enhancing vegetation growth in cold temperature constrained regions, while these effects are reversed or reduced in more moisture constrained areas. Shorter frozen seasons increase the atmospheric CO_2 seasonal amplitude by enhancing ecosystem productivity and CO_2 emissions.

Data and Methods:

Primary datasets employed in the investigation:

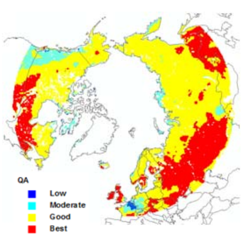
(1) FT-ESDR: Global Satellite Microwave Record of Daily Landscape Freeze/Thaw Status, Version 02 [1979 to 2010]. Digital media (http://freezethaw.ntsg.umt.edu; http://nsidc.org/data/nsidc-0477.html), 25 x 25 km global EASE-Grid;

(2) VIP ESDR vegetation indices (VIs): NDVI & EVI2, 1982 to 2010 (http://phenology.arizona.edu), 25 x 25 km global EASE-Grid;

(3) NOAA ESRL Globalview (http://www.esrl.noaa.gov/gmd/ccgg/globalview/): Integrated atmospheric CO_2 concentrations (≥50°N)*

*Masarie & Tans *JGR* 1995

FT-ESDR Quality Assessment (QA) for 1979-2010:

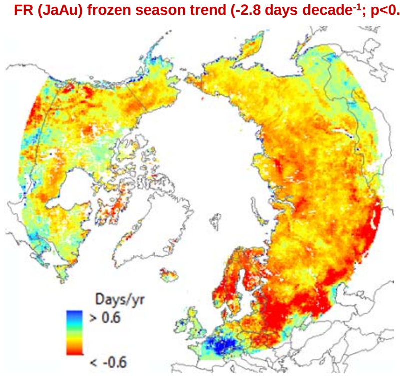


The FT-ESDR QA map (**left**) provides a discrete, qualitative indicator of FT product quality for each grid cell within the NHL domain. The QA map shows regions of relative high to low quality in relation to potential negative impacts from sensor data gaps, active precipitation, RFI, open water, terrain and land cover heterogeneity, and uncertainty associated with use of global reanalysis temperature data to define per grid-cell FT reference states for seasonal threshold algorithm (STA) based temporal change classifications. The QA based regressions accounted for ~44% of variability in FT classification accuracy inferred from the regional weather station network. The dimensionless (0 to 1) QA values were stratified into a smaller set of discrete categories ranging from low (estimated mean spatial classification accuracy < 70 %) to best (accuracy > 90%) quality. Mean proportions of the four QA categories encompass 30.6 % (best), 59.5 % (good), 9.2 % (moderate), and 0.7 % (low) of the NHL domain.

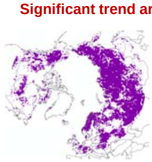
Results:

Regional Kendall's tau trend patterns (day yr^{-1}) and associated significant (p<0.1) trend areas (in purple) derived from the 32-year FT record (1979-2010) for frozen (FR) and transitional (TR) records from Jan to Aug (JaAu) :

FR (JaAu) frozen season trend (-2.8 days decade^{-1}; p<0.01)

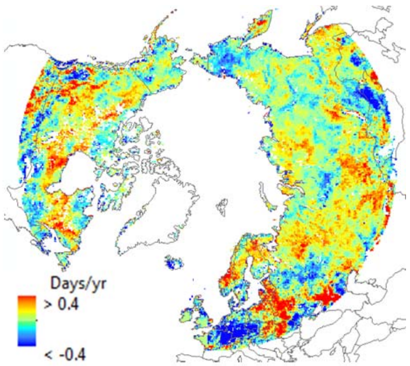


Significant trend areas

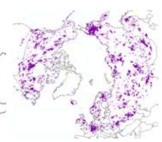


The satellite FT results show a strong, negative (decreasing FR season) NHL trend in mean annual frozen period (-2.8 days decade^{-1}; p<0.01). The annual frozen season (JaAu) is decreasing for 83.9% of the NHL domain. The relative proportions of cells with significant (p<0.1) frozen season trends is 52.1%.

TR (JaAu) frost days trend (0.09 days decade^{-1}):



Significant trend areas



The satellite FT results show a weak (p>0.1) positive NHL trend in mean annual number of transitional (AM frozen and PM thaw) frost days. The number of TR frost days is increasing for 44.8% of the NHL domain. The relative proportions of cells with significant (p<0.1) TR trends is 17.3%.

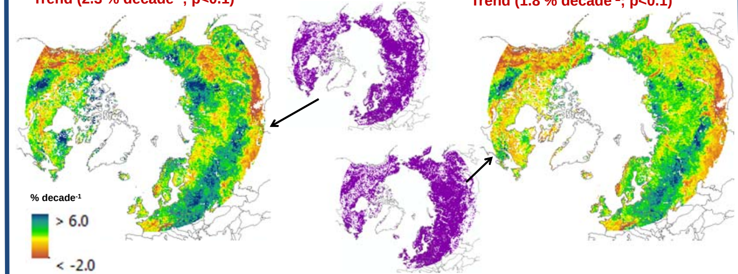
Regional Kendall's tau VI trends (% decade^{-1}) and associated significant (p<0.1) trend areas derived from the 29-year summer VI (Jun to Aug; JJA) records (1982-2010):

NDVI

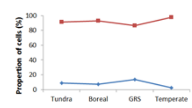
Trend (2.3 % decade^{-1}; p<0.1)

EVI2

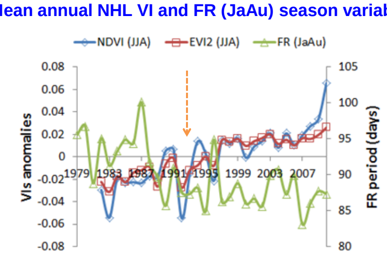
Trend (1.8 % decade^{-1}; p<0.1)



Mean summer (JJA) NDVI and EVI2 trends show strong, positive NHL decadal trends (p<0.1). Summer NDVI (EVI2) values are increasing for 87.3% (83.1%) of the NHL domain. The NHL FT metrics show generally stronger and predominantly positive VI impacts on spring rather than summer growth conditions; however, these relationships may be influenced by other artifacts independent of canopy growth changes, including snow effects on VI retrieval accuracy. Generally, positive NDVI trends are found in the four major biomes over the NHL domain (**right**).



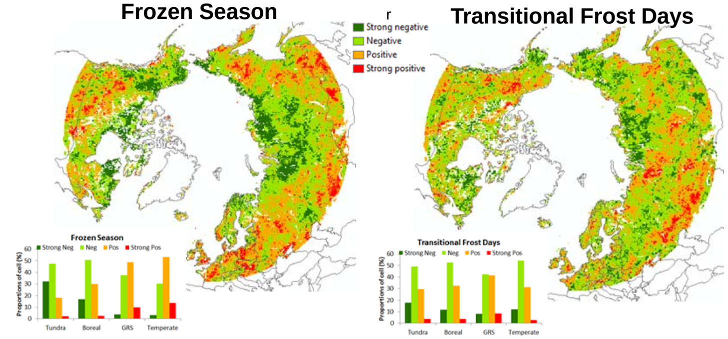
Mean annual NHL VI and FR (JaAu) season variability:



NHL mean annual summer VI (NDVI, EVI2) and FR season (JaAu) records (**left**). The VI anomalies are determined relative to their long-term means. Weak correspondence between the VIs and FR season variability reflects opposing FR season impacts on vegetation growth between energy and water constrained portions of the NHL domain. The Jun 1991 Mt. Pinatubo eruption is also denoted (vertical dashed arrow).

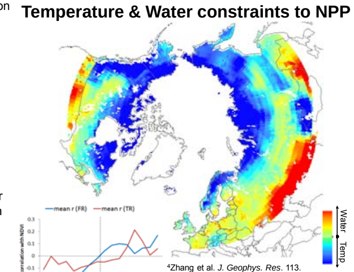
Pixel-wise correlations (r) between frozen and transitional seasons (JaAu), and NDVI summer growth anomalies :

Frozen Season **Transitional Frost Days**



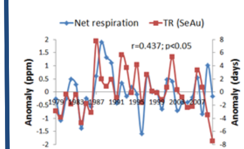
The spatial correlation pattern between summer NDVI & FR/TR season (JaAu) anomalies (**above**) shows generally negative correspondence in predominantly cold constrained NHL regions, and reduced or reversed correspondence in more water limited areas (**right**); the relative climate constraints to productivity (NPP) are derived using temperature and moisture constraint [4]factors determined from global reanalysis data. Four r-value categories are classified by their significance level above, including strong negative (p≤0.1), negative (p>0.1), positive (p>0.1) and strong positive (p≤0.1) levels. Regional increases in TR (JaAu) frost days negatively impact NDVI summer growth for ~61% of the NHL domain; decreases in the number of FR (JaAu) days promotes greater summer NDVI growth for ~57 % of the domain. Spatial extent of NDVI relationships of FR/TR (Jan to Aug) anomalies are shown as the proportion (%) of regional biomes the bar graphs (**above**). The EVI2 result (not shown) is largely consistent with NDVI. The mean NDVI and FR season correlations (line graph, **right**) indicate a greater increase in NHL vegetation productivity with decreasing frozen season trends under stronger temperature constraints; however, positive trends in TR frost days appear to negatively impact canopy growth in both temperature and moisture constraint areas.

Temperature & Water constraints to NPP



[4]Zhang et al. *J. Geophys. Res.* 113.

Frozen season influence on NHL atmospheric CO_2 seasonal cycle:



The satellite microwave derived TR (T_{TR}; day yr^{-1}) season (Sep to Aug; SeAu) anomalies coincide with net ecosystem respiration (T_{CO2} ; ppm yr^{-1}) defined as the difference between annual max and min Atm. CO_2 concentrations from northern NOAA ESRL Globalview monitoring sites (**left**). Positive correspondence between T_{TR} and T_{CO2} (r=0.437, p<0.05) indicate adverse impacts of frost events on net ecosystem productivity, though soil frost events may benefit productivity in some ecoregions; negative correspondence between frozen season anomalies (T_{FR}; day yr^{-1}) and T_{CO2} (r=-0.402, p<0.05; not shown) indicate that shorter FR seasons increase the CO_2 max-min concentration anomaly by either increasing ecosystem respiration (increasing CO_2 max) or enhancing ecosystem productivity (decreasing CO_2 min), or both within the NHL domain.

Conclusions:

- The 32-yr (1979-2010) FT-ESDR record shows mean annual classification accuracies of 91 (±1.1) and 84 (± 0.9) percent for PM & AM overpass retrievals relative to in situ weather station records;
- The FT record shows that the FR season is significantly decreasing for 50.2% of the NHL domain and 1979-2010 period;
- The NDVI and EVI2 trends indicate that NHL vegetation is predominantly greening & coincident with a declining FR season;
- A declining FR season is generally promoting vegetation growth in NHL cold temperature constrained areas, while these effects are weaker or reversed in more water constrained areas; potential benefits of a shorter FR season are offset by apparent negative productivity effects of an increasing trend in TR frost days in some areas.
- Annual variability in FT processes has a significant impact of atmospheric CO_2 seasonality; years with more (fewer) TR frost days or shorter (longer) FR season coincide with larger (smaller) seasonal amplitude in atmospheric CO_2 concentrations.

Acknowledgements

This work was conducted at the University of Montana under contract to NASA. This work was supported under the NASA Making Earth Science Data Records for Use in Research Environments (MEaSUREs) program (NNH06ZDA001N-MEaSUREs).

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