2011

30-year Northern Hemisphere freeze/thaw seasonal trends and associated impacts to vegetation growing seasons and carbon exchange

Youngwook Kim

John S. Kimball
University of Montana - Missoula

K. Zhang

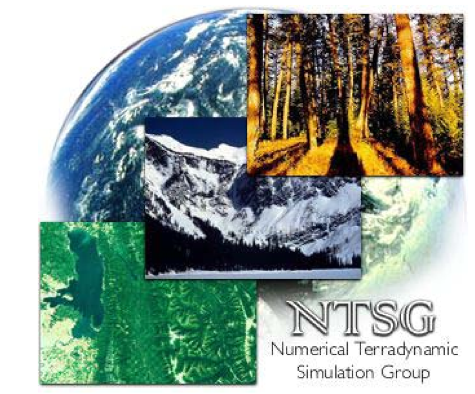
Kyle C. McDonald
City College of New York

Session: Global Change Impact & Vulnerability (220)

30-year Northern Hemisphere Freeze/Thaw seasonal trends and associated impacts to vegetation growing seasons and Carbon Exchange

Youngwook Kim[1,2,*], J. S. Kimball[1,2], K. Zhang[3], and K. C. McDonald[4,5]

[1]Flathead Lake Biological Station, The University of Montana 32125 Biostation Lane, Polson, MT, 59860-9659; *Corresponding author: youngwook.kim@ntsg.umt.edu
[2]Numerical Terradynamic Simulation Group, The University of Montana, Missoula, MT, 59812
[3]Department of Organismic and Evolutionary Biology, Harvard University, Cambridge, MA 02138
[4]Jet Propulsion Laboratory, California Institute of Technology, Pasadena, CA 91109-8099; [5]Department of Earth and Atmospheric Sciences, The City College of New York, New York, NY 10031



Abstract:

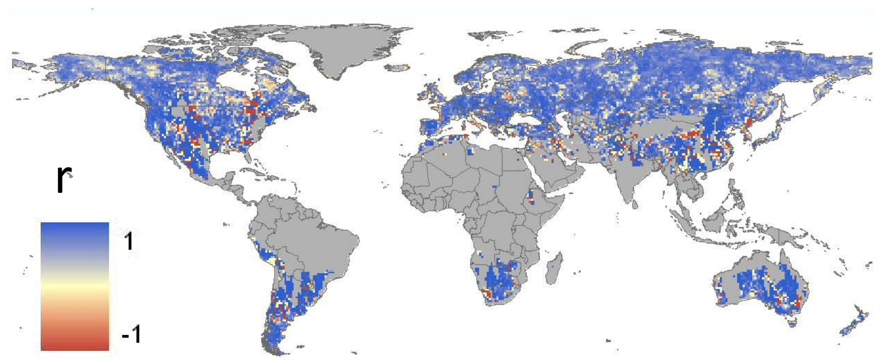
Landscape freeze-thaw (F/T) state is closely linked to vegetation phenology and land-atmosphere trace gas exchange where seasonal frozen temperatures are a major constraint to plant growth. We applied a temporal change classification of 37 GHz brightness temperature (T_b) series from the Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave Imager (SSM/I) to classify daily F/T status over global land areas where seasonal frozen temperatures influence ecosystem processes. A temporally consistent, long-term (>30 year) F/T record was created ensuring cross-sensor consistency through pixel-wise adjustment of the SMMR T_b record based on empirical analyses of overlapping SMMR and SSM/I measurements. The resulting F/T record showed mean annual spatial classification accuracies of 91 (±8.6) and 84 (±9.3) percent for PM and AM overpass retrievals relative to in situ air temperature measurements from the global weather station network. The F/T results were also compared against other measures of biosphere activity including satellite (MODIS) vegetation greenness (NDVI) and tower CO_2 flux measurements. A strong (P<0.001) increasing (0.189 days yr^{-1}) trend in Northern Hemisphere mean annual non-frozen period is largely driven by an earlier (-0.149 days yr^{-1}) spring thaw trend and coincides with a 0.033 °C yr^{-1} regional warming trend. The F/T defined non-frozen period largely bounds the season of active vegetation growth and net ecosystem CO_2 uptake for tower sites representing major ecoregion types. Earlier spring thawing and a longer non-frozen season generally benefit vegetation growth inferred from NDVI spring and summer growth anomalies where the non-frozen season is less than approximately 6 months, with greater benefits at higher (>45°N) latitudes and upper elevations. The F/T record also shows a positive (0.198 days yr^{-1}) trend in the number of transitional (AM frozen and PM non-frozen) frost days, which coincide with reduced photosynthetic activity inferred from tower and NDVI measurements. The relative benefits of earlier and longer non-frozen seasons for vegetation growth under global warming may be declining due to opposing increases in disturbance, drought and frost damage related impacts.

Data and Methods:

Primary datasets employed in the investigation:

(1) Nimbus-7 SMMR Pathfinder ascending & descending orbit, daily T_b series: 1979-1987, 37GHz, V-pol;
(2) DMSP SSM/I ascending/descending orbit, daily T_b series: 1987-2008, 37GHz, V-pol;
(3) MODIS Terra NDVI record: 2000-2008, 25 x 25 km global EASE-Grid;
(4) FLUXNET tower site daily C-flux data: Net ecosystem CO_2 exchange (NEE), Gross Primary Production (GPP)

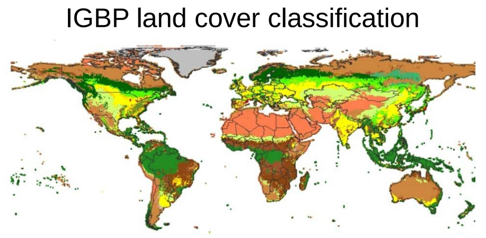
Merging SMMR and SSM/I global data records:



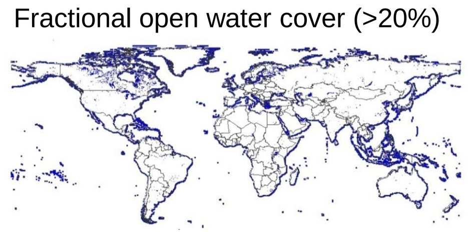
A correlation (r) map between coincident SMMR and SMM/I 37 GHz, PM overpass T_b series from DOY 192 to 232 (20 days) 1987 (**above**) shows predominantly favorable correspondence between SMMR and SSM/I T_b retrievals. Continuous missing days in 1987 for SMMR (Jan) and SSM/I (Dec) T_b values were gap filled using empirical relationships established between the respective T_b series and coincident global model reanalysis (NNR) based air temperatures on a grid cell-basis. The SMMR T_b series was adjusted to the SSM/I T_b series using the least-squares linear regression relationship between high quality (QC) SMMR and SSM/I T_b values during the 1987 overlap period (r^2~0.99 and RMSE=3.41-4.26K).

Ancillary data for masking and quality assessment:

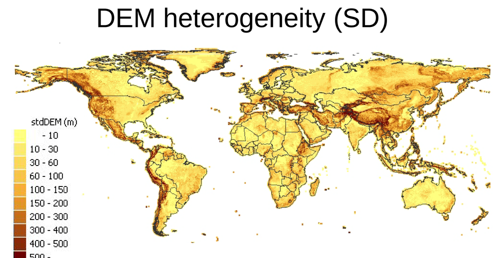
IGBP land cover classification



Fractional open water cover (>20%)



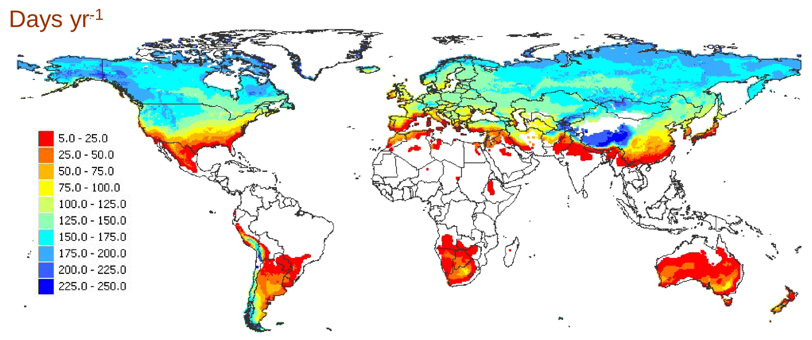
DEM heterogeneity (SD)



The F/T classification was conducted over a global domain at 25-km resolution. Global 1-km resolution land cover and elevation (DEM) maps (**above**) were used to mask cells with primary land cover as permanent snow & ice, urban/built-up and barren, or with >20% fractional open water cover. High quality T_b values used for developing the SMMR-SSM/I empirical adjustment algorithm were selected from cells having 0% open water cover, dominated (>95%) by a single land cover class, and with <10.0 m (SD) elevation variability.

Global F/T classification domain:

CCI: Days yr^{-1}



We defined a global F/T classification domain (**above**) using a global (*GMAO) model reanalysis daily surface air temperature climatology (2000-06) and a [1]cold temperature constraint index [CCI, days yr^{-1}] that quantifies the primary environmental controls to vegetation net primary production. The resulting domain covers ~52.5% (66 million km^2) of the global land area and encompasses vegetated regions where low temperatures are a major constraint to ecosystem processes.

[1]Source: Jolly et al, *Global Change Biol* 2005.
*NASA GMAO (2000-06) 6-hr reanalysis (1 x 1.25°).

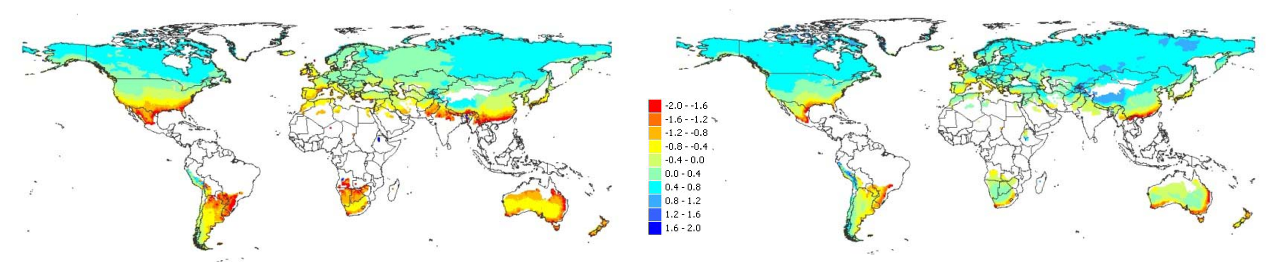
F/T Algorithms: Seasonal Threshold Approach (STA)

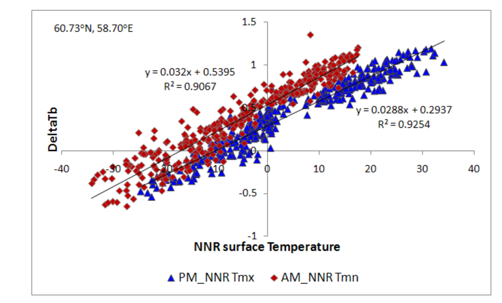
$$\Delta(\sigma \text{ or } T_b) = \frac{\sigma(t)-\sigma_{fr}}{\sigma_{th}-\sigma_{fr}}$$

σ_{fr} = frozen reference state (mean T_b or σ in Jan)
σ_{th} = non-frozen reference state (mean T_b or σ in Jul)

$\Delta(\sigma \text{ or } T_b) > T$ Thawed
$\Delta(\sigma \text{ or } T_b) \le T$ Frozen

where T_b = brightness temperature and σ = backscatter



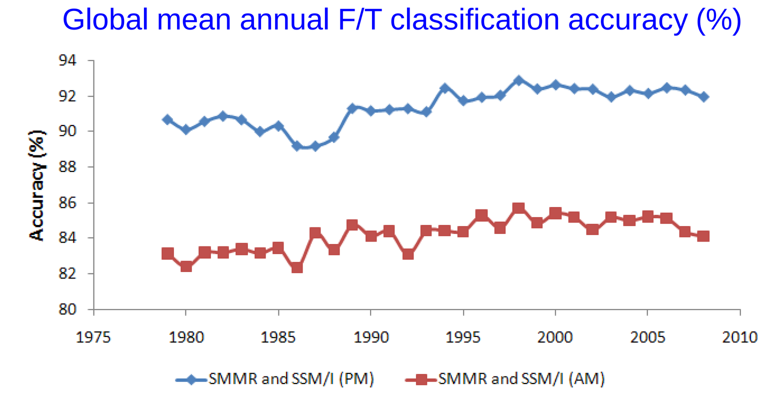


The landscape F/T status was classified from daily (AM & PM) orbit T_b retrievals from SMMR and SSM/I time series using a seasonal threshold algorithm ([2]STA, **top**). The STA uses a dynamic threshold defined annually on a grid cell-wise basis from empirical relations established between T_b retrievals and global model reanalysis (*NNR) based air temperatures (e.g. **above right**). The above maps show example T_b [K] threshold [T] maps derived using SSM/I P37V (PM overpass) and NNR T_{mx} (**left**) and SSM/I A37V (AM overpass) and NNR T_{mn} (**center**) in 2004. The STA based F/T classifications are produced as discrete frozen (0) or non-frozen (1) values from AM and PM overpass data; The AM/PM F/T classifications are composited to daily time series to define Frozen (AM & PM), Non-Frozen (AM & PM), Transitional (AM frozen; PM thawed) and Inverse-Transitional (AM thawed; PM frozen) conditions.

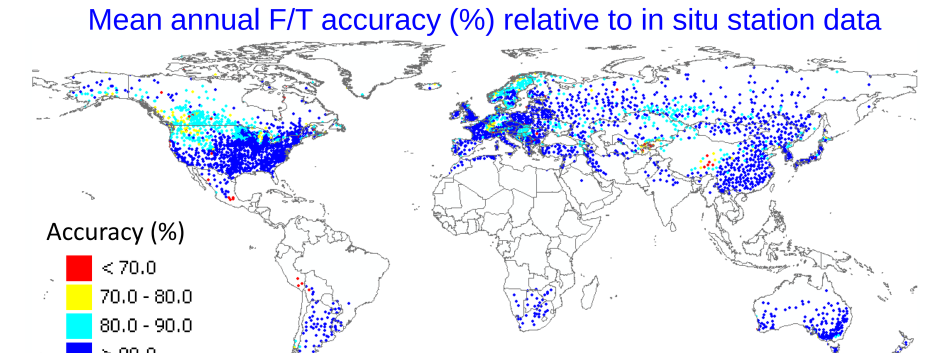
*NCEP/NCAR (NNR, 1979-2008) 6-hour reanalysis (1.875° x 2°);
[2]Kim et al. *IEEE TGARS* 2010.

F/T accuracy assessment using global weather stations:

Global mean annual F/T classification accuracy (%)

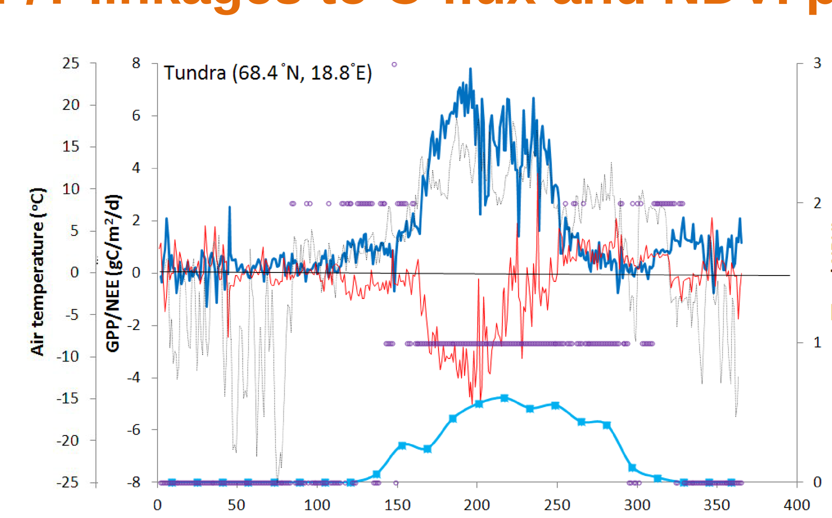


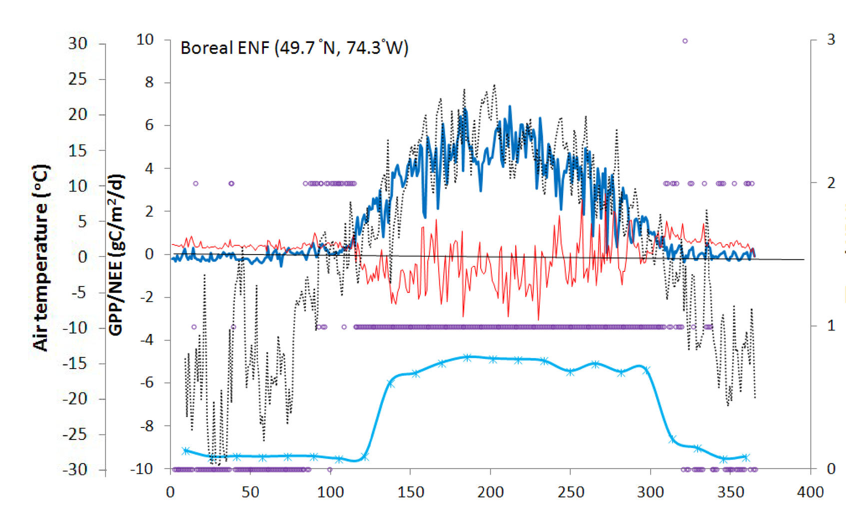
Mean annual F/T accuracy (%) relative to in situ station data

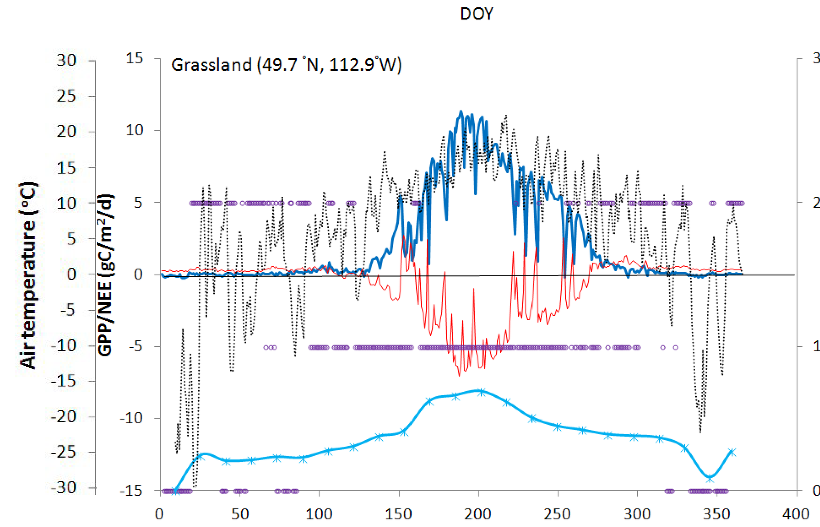


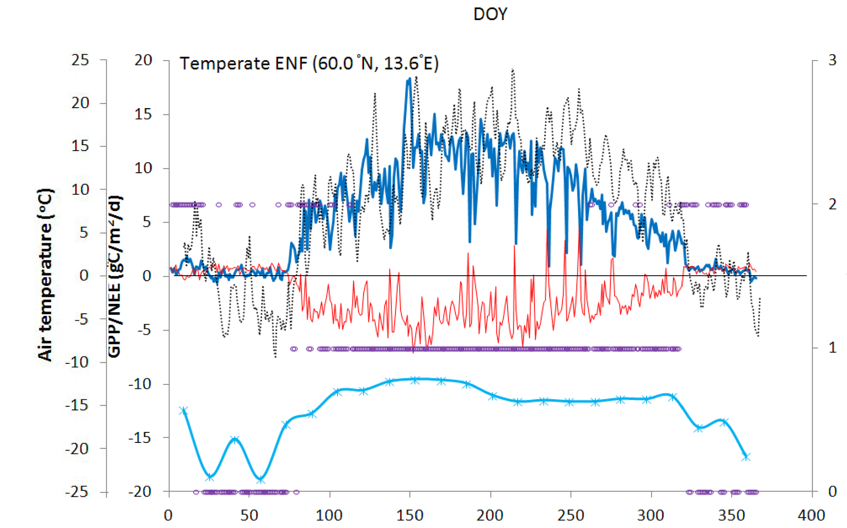
F/T classification accuracy is assessed from in situ daily air temperature data from global weather stations. The stations are first screened for homogeneous land cover and terrain conditions within the overlying 25-km grid cell, resulting in ~3,701 validation stations selected in 2006 (**above right**). Mean annual F/T classification accuracies of 91 (±1.0) and 84 (±0.9) percent were determined for PM (blue) and AM (red) overpass retrievals relative to in situ weather station records for the 30-year F/T record (**above left**).

F/T linkages to C-flux and NDVI patterns at FLUXNET sites:





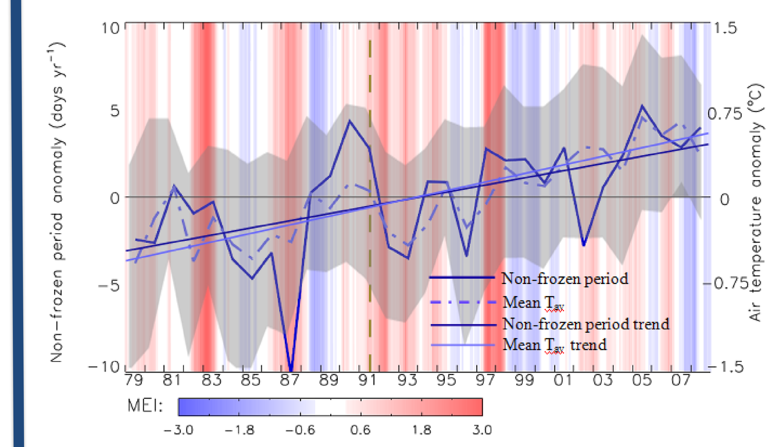




The daily F/T results were evaluated in relation to satellite (MODIS) 16-day composited NDVI records and in situ daily tower eddy covariance CO_2 measurement based GPP & NEE records at selected [1]FLUXNET sites within the Northern Hemisphere domain (>45°N) for 2005. Results are presented (**above**) for selected tundra, boreal & temperate Evergreen needleleaf forest (ENF), and grassland (GRS) sites. The F/T results represent discrete (0=Frozen; 1=Non-Frozen; 2=Transitional) classifications of predominant frozen or non-frozen conditions within the ~25-km scale satellite footprint. The satellite derived F/T results generally bound the growing season at the tower sites, indicated by seasonal increases in GPP & net CO_2 (NEE) uptake by vegetation and canopy (NDVI) growth.

[1]Tower site data provided courtesy of FLUXNET PIs: Christian Bernhofer (DE_Tha), Torbjorn Johansson (SE_Abi) , Hank A. Margolis (CA_Qfo) and Lawrence B. Flanagan (CA_Let)

Mean annual Northern Hemisphere non-frozen period trends:

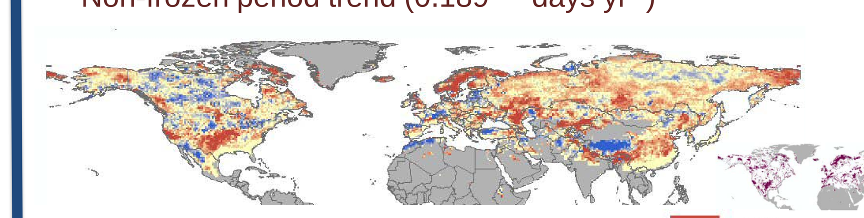


Trends in mean annual non-frozen period and reanalysis derived mean annual surface air temperature (T_{av}) for the Northern Hemisphere domain are shown (**Left**). Grey shading denotes the maximum and minimum range around the ensemble T_{av} mean (NNR[1], NCEP2[2], MERRA[3]). The observed annual non-frozen period is lengthening (p<0.001) by 0.189 day yr^{-1} over the period of record (1979-2008) and coincides with 0.033 °C yr^{-1} T_{av} warming (p<0.001). The multivariate ENSO index (MEI) is shown as vertical red and blue shading denoting respective positive (El Niño) and negative (La Niña) MEI values. The Jun 1991 Mt. Pinatubo eruption is also denoted (vertical dashed line).

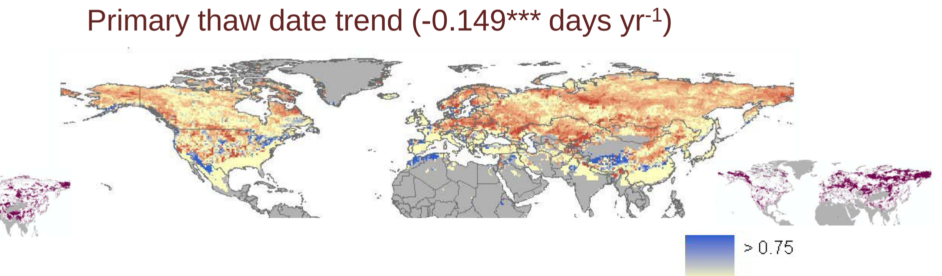
[1]NCEP/NCAR (NNR, 1979-2008) 6-hour reanalysis (1.875° x 2°);
[2]NCEP/DOE (NCEP2, 1979-2008) 6-hour reanalysis (1.875° x 2°);
[3]MERRA GEOS-5 (MERRA, 1979-2008) 6-hour reanalysis (1/2° x 1/3°)

Northern Hemisphere F/T trends:

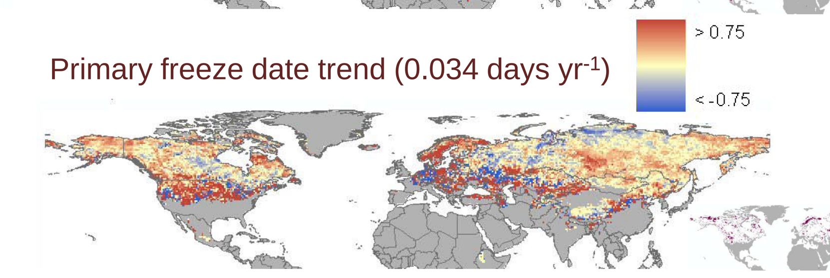
Non-frozen period trend (0.189*** days yr^{-1})



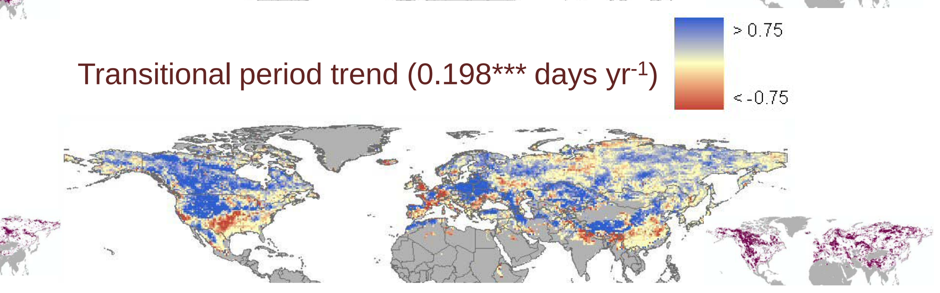
Primary thaw date trend (-0.149*** days yr^{-1})



Primary freeze date trend (0.034 days yr^{-1})



Transitional period trend (0.198*** days yr^{-1})

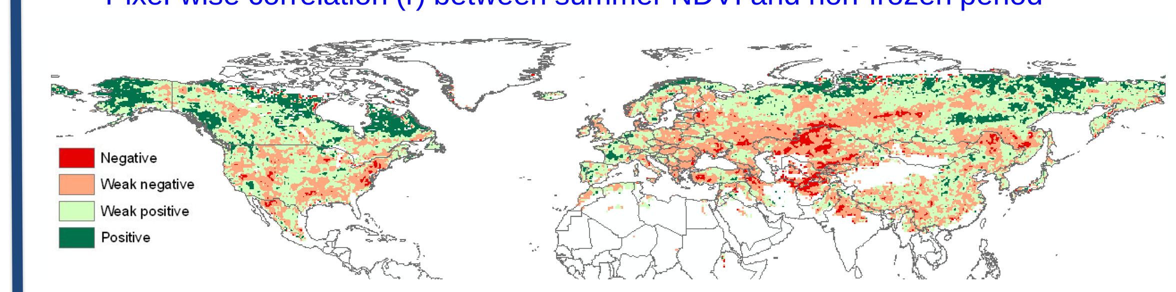


Regional Kendall's tau[1] trend patterns (days yr^{-1}) and associated significant (p<0.1) trend areas (in purple on adjacent inset maps) for the 30-year F/T record (1979-2008). Primary thaw day is defined as the first day of 12 out of 15 consecutive non-frozen days between Jan and Jun; Primary freeze day is the first day of 12 out of 15 consecutive frozen days between Sep and Dec. Areas in white and grey were masked from the analysis. The results show strong Northern Hemisphere trends toward a longer non-frozen period, driven by advancing spring thaw trends and associated delay in fall freeze-up, and consistent with global warming. The number of transitional F/T days is generally increasing with warming, but decreasing at lower latitudes and elevations.

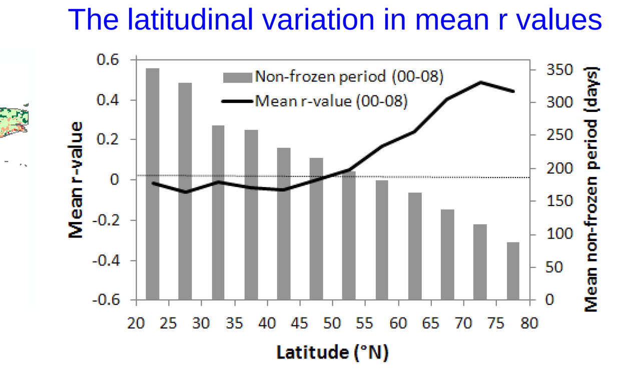
[1]Hirsch et al, *Water Resources Res* 1984.
*p<0.1; **p<0.01; ***p<0.001

Summer NDVI and Non-frozen period:

Pixel-wise correlation (r) between summer NDVI and non-frozen period



The latitudinal variation in mean r values



The latitudinal variation in mean correlation (r) between summer (JJA) NDVI and non-frozen period (Jan-Aug) anomalies (**right**) and the spatial pattern of correlation (r) between these parameters (**left**) for 2000-2008. The satellite detected non-frozen season effectively bounds the potential growing season for vegetation. Relatively longer non-frozen seasons promote generally higher NDVI summer growth anomalies at higher latitudes and elevations where the non-frozen season is shorter than approximately 6 months, whereas shorter non-frozen seasons promote the opposite response. In other areas a lengthening non-frozen season coincides with recent declining summer NDVI growth linked to increasing drought impacts to vegetation productivity; drought frequency and severity may be exacerbated under projected warmer & longer non-frozen seasons.

Conclusions:

- The merged (SMMR-SSM/I) 30-yr F/T record shows mean annual classification accuracies of 91 (±1.0) and 84 (± 0.9) percent for PM and AM overpass retrievals relative to in situ weather station records;
- The F/T record shows significant (P<0.001) long-term trends in non-frozen period (0.189 days yr^{-1}), largely driven by earlier onset of spring thaw (-0.149 days yr^{-1}) & general delay in the arrival of the Fall frozen season (0.034 days yr^{-1}).;
- The F/T trend coincides with a mean 0.033 °C yr^{-1} surface air temperature warming trend determined from global model reanalysis;
- The F/T based non-frozen season generally bounds the vegetation growing season defined by MODIS NDVI & tower eddy covariance measures of vegetation productivity & active CO_2 uptake;
- Earlier & longer non-frozen seasons are promoting widespread NDVI summer growth at higher latitudes; these relations may be weakening due to relaxing cold temperature constraints & increasing water limitations to productivity;
- The F/T record is available online at NTSG (**http://freezethaw.ntsg.umt.edu/**) and the NSIDC DAAC (**http://nsidc.org/data/nsidc-0477.html**).

Acknowledgements

Portions of this work were conducted at the University of Montana and Jet Propulsion Laboratory, California Institute of Technology 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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- Kim, Y., Kimball, J. S., Zhang, K., & McDonald, M. C. 2011. Satellite Detection of Increasing Northern Hemisphere Non-Frozen Seasons from 1979 to 2008 and Associated Impacts to Vegetation Growth and Carbon Exchange. *RSE* (In Revision).