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Introduction:

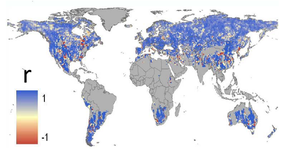
Approximately 66 million km^2 (52.5 %) of the global vegetated land area experiences seasonally frozen temperatures as a major constraint to ecosystem processes. The freeze-thaw (FT) status of the landscape as derived from satellite microwave remote sensing is closely linked to surface energy budget and hydrological activity, vegetation phenology, terrestrial carbon budgets and land-atmosphere trace gas exchange. 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 FT status over global land areas where seasonal frozen temperatures influence ecosystem processes. A temporally consistent, long-term (>30 year) FT 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 combined FT record was validated against *in situ* temperature measurements from the global weather station network and applied to quantify regional patterns and trends in timing and length of non-frozen seasons. The FT results were also compared against other measures of biosphere activity including satellite (MODIS) vegetation greenness (NDVI), tower CO_2 flux measurements and NOAA ESRL atmospheric CO_2 measurements (>45 ^{o}N).

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 daily C-flux data: Net ecosystem CO_2 exchange (NEE), Gross Primary Production (GPP)
(5) NOAA ESRL Globalview: Integration of atmospheric CO_2 concentration data[1] [1]Masarie & Tans *JGR* 1995

Merging SMMR and SSM/I global data records:

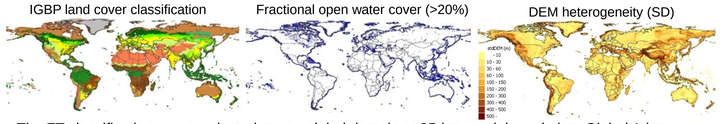


A correlation (r) map between coincident SMMR & SMM/I 37V GHz, PM overpass T_b series from DOY 192 to 232 (20 days) in 1987 (**left**) shows predominantly favorable correspondence between SMMR & SSM/I T_b retrievals. Continuous missing days in 1987 for SMMR (Jan) & SSM/I (Dec) T_b values were gap filled using empirical relationships established between the respective T_b series & coincident global model reanalysis (*NNR) based surface 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 & SSM/I T_b values during the 1987 overlap period (r^2~0.99 and RMSE=3.41-4.26K).

*NCEP/NCAR (NNR, 1979-2008) 6-hour reanalysis (1.875^{o} x 2^{o})

Ancillary data for masking and quality assessment:

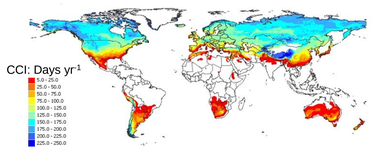
IGBP land cover classification | Fractional open water cover (>20%) | DEM heterogeneity (SD)



The FT classification was conducted over a global domain at 25-km spatial resolution. Global 1-km resolution land cover & elevation (DEM) maps (**above**) were used to mask permanent snow & ice, urban/built-up & barren areas, & cells 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, & with <10.0 m (SD) elevation variability.

We defined a global FT classification domain (**right**) using a global (*GMAO) model reanalysis daily surface air temperature climatology (2000-06) & [1]cold temperature constraint index [CCI, days yr^{-1}] that quantifies primary environmental constraints 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.

Global FT classification domain:



[1]Source: Jolly et al, *Global Change Biol* 2005.
*NASA GMAO (2000-2006) 6-hr reanalysis (1 x 1.25^{o}).

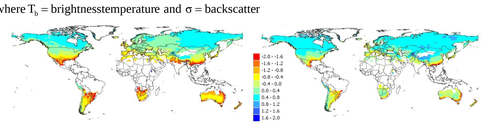
FT Algorithms: Seasonal Threshold Approach (STA)

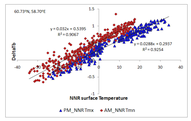
$$\Delta(T_b\, or\, \sigma) = \frac{\sigma(t) - \sigma_{fr}}{\sigma_{th} - \sigma_{fr}}$$

σ_{fr} = frozen reference state (mean T_b or σ in Jan) $\quad \Delta(T_b\, or\, \sigma) > T$ Thawed

σ_{th} = non − frozen reference state (mean T_b or σ in Jul) $\quad \Delta(T_b\, or\, \sigma) \le T$ Frozen

where T_b = brightnesstemperature and σ = backscatter



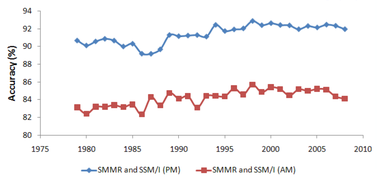


The landscape FT status was classified from daily (AM & PM) orbit T_b retrievals from SMMR & SSM/I time series using a seasonal threshold algorithm ([1]STA, **top**). The STA uses a dynamic threshold defined annually on a grid cell-wise basis from empirical relations established between T_b retrievals & 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 37V (PM overpass) & NNR T_{mx} (**left**) & SSM/I 37V (AM overpass) & NNR T_{mn} (**center**) data in 2004. The STA based FT classifications are produced as discrete frozen (0) or non-frozen (1) values from AM and PM overpass data; The AM/PM FT 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.

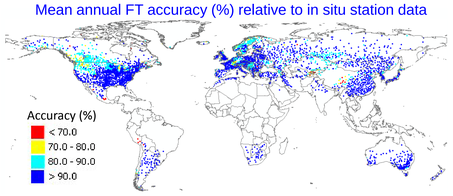
*NCEP/NCAR (NNR, 1979-2008) 6-hour reanalysis (1.875^{o} x 2^{o});
[1]Kim et al. *IEEE TGARS* 2011.

FT accuracy assessment using global weather stations:

Global mean annual FT classification accuracy (%)

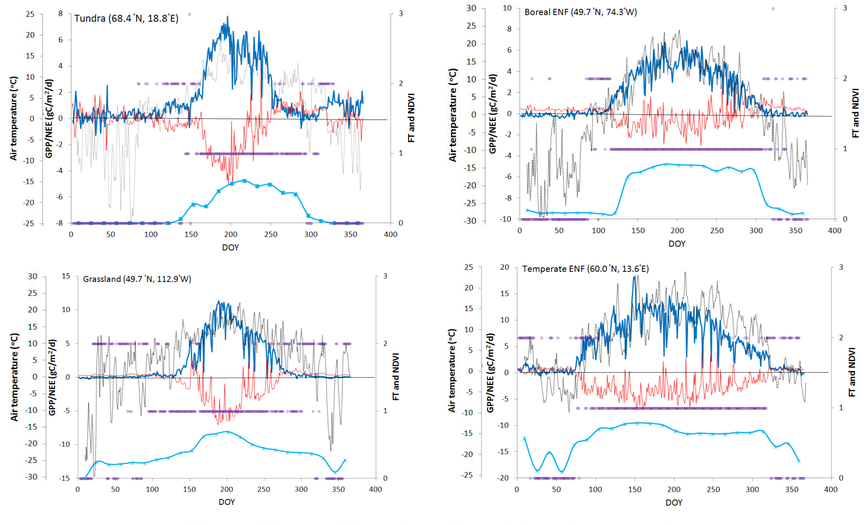


Mean annual FT accuracy (%) relative to in situ station data



FT classification accuracy is assessed using in situ daily air temperatures from global WMO weather stations. The stations are pre-screened for homogeneous land cover & terrain conditions within the overlying 25-km grid cell, resulting in ~3,701 validation sites selected in 2006 (**above right**). Mean annual FT classification accuracies of 91 (±1.0) & 84 (±0.9) % were determined for PM (blue) & AM (red) overpass retrievals relative to in situ station records for the 30-year FT record (**above left**); increasing FT accuracy trends are artifacts of global warming, while normalizing the trends relative to the mean global temperature trend shows no significant FT accuracy difference between SMMR & SSM/I portions of record.

FT linkages to C-flux and NDVI patterns at FLUXNET sites:

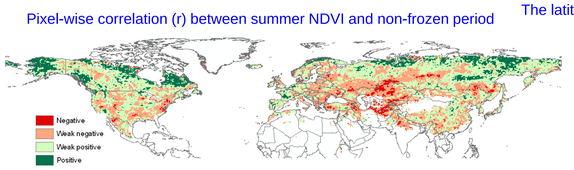


The daily FT results were evaluated in relation to satellite (MODIS) 16-day composited NDVI records and in situ daily tower eddy covariance CO_2 measurement based GPP & NEE records at selected [1]FLUXNET sites within the Northern Hemisphere domain (≥45°N) for 2005. Results are presented (**above**) for selected tundra, boreal & temperate Evergreen needleleaf forest (ENF), & grassland (GRS) sites. The FT 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 FT results generally bound the growing season at the tower sites, indicated by seasonal increases in GPP & net CO_2 (NEE) uptake (negative C flux) by vegetation & canopy (NDVI) growth.

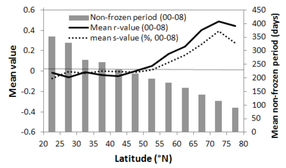
[1]Tower site data provided courtesy of FLUXNET PIs: Christian Bernhofer (DE_Tha), Torbjorn Johansson (SE_Abi) , Hank A. Margolis (CA_Qfo) and Lawrence B. Flanagan (CA_Let)

NDVI productivity and Non-frozen period:

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



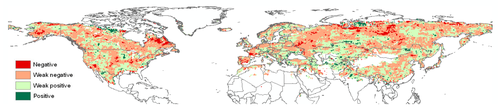
The latitudinal variation in mean r and slope (s) values



Latitudinal gradients in mean annual non-frozen period & mean correlations (*r*) and slope (*s*) between summer (JJA) NDVI & non-frozen season (Jan-Aug) anomalies is presented (**right**); the Northern Hemisphere NDVI & non-frozen season correlation (r) map for the 2000-2008 period is also shown (**left**). Longer non-frozen seasons promote generally greater NDVI summer growth anomalies at higher latitudes where the non-frozen season is shorter than approximately 6 months. The relative FT impact on NDVI growth is reduced at lower latitudes where seasonal frozen temperature constraints to vegetation growth are reduced. In other areas a lengthening non-frozen season coincides with declining summer NDVI growth linked to increasing drought impacts. The corresponding latitudinal variations of *r* and *s* show predominantly positive mean values above approximately 50^{o}N & increasing trend patterns up to approximately 70^{o}N.

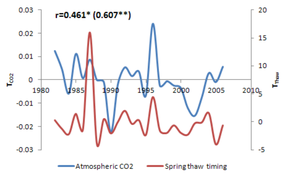
NDVI productivity and Transitional period :

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



The Northern Hemisphere NDVI & FT transitional season correlation (r) map for the 2000-2008 period is shown (**left**). The FT transitional season anomalies show widespread negative correlations with summer NDVI growth anomalies over 56.3% of the Northern Hemisphere domain, indicating predominantly negative impacts of these events on vegetation growth.

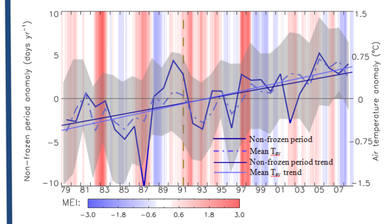
Atmospheric CO_2 spring drawdown and spring thaw timing:



The satellite microwave sensor derived spring thaw anomaly (T_{thaw} , d yr^{-1}) coincides with the initiation of the growing season & net seasonal uptake of atmospheric CO_2 by vegetation productivity. Annual anomalies of regional (>45^{o}N) mean T_{thaw}, timing correspond with the mean spring drawdown of atmospheric CO_2 from northern NOAA ESRL Globalview monitoring sites (T_{CO2}) (**left**). Temporal correspondence between T_{thaw} and T_{CO2} is predominantly positive (r=0.461*; r=0.607** without 1987 anomaly), indicating that relatively earlier (later) onset of the non-frozen season coincides with earlier (later) growing season onset & associated spring drawdown of atmospheric CO_2.

*p<0.1; **p<0.01; ***p<0.001

Mean annual Northern Hemisphere non-frozen period trends:

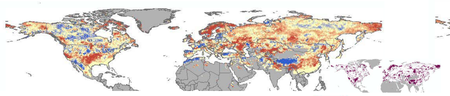


Trends in mean annual FT non-frozen period & reanalysis derived mean annual surface air temperature (T_{av}) for the Northern Hemisphere domain are shown (**left**). Grey shading denotes the maximum & minimum range around the ensemble T_{av} mean (NNR[1], NCEP2[2], MERRA[3]). The FT observed annual non-frozen period is lengthening (p<0.001) by 0.189 day yr^{-1} over the period of record (1979-2008) & coincides with a 0.033 °C yr^{-1} T_{av} warming trend (p<0.001). The multivariate ENSO index (MEI) is shown as vertical red & 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).

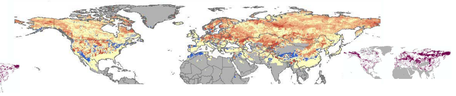
[1]NCEP/NCAR (NNR, 1979-2008) 6-hour reanalysis (1.875^{o} x 2^{o});
[2]NCEP/DOE (NCEP2, 1979-2008) 6-hour reanalysis (1.875^{o} x 2^{o});
[3]MERRA GEOS-5 (MERRA, 1979-2008) 6-hour reanalysis (1/2^{o} x 1/3^{o})

Northern Hemisphere FT trends:

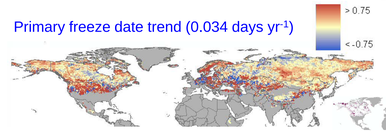
Non-frozen period trend (0.189*** days yr^{-1})



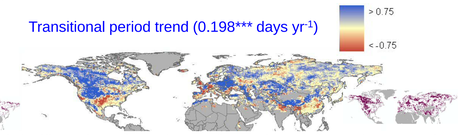
Primary thaw date trend (-0.149*** days yr^{-1})



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 FT record (1979-2008). Primary thaw day is defined as the first day of 12 out of 15 consecutive non-frozen days between Jan & Jun; Primary freeze day is the first day of 12 out of 15 consecutive frozen days between Sep & Dec. Areas in white & grey were masked from the analysis. The results show strong regional trends toward a longer non-frozen period, driven by advancing spring thaw trends & associated delay in fall freeze-up, & consistent with global warming. The number of transitional frost days is generally increasing with warming, but decreasing at lower latitudes.

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

Conclusions:

- The merged satellite microwave (SMMR-SSM/I) 30-yr (1979-2008) FT record shows mean annual classification accuracies of 91 (±1.0) and 84 (± 0.9) percent for PM & AM overpass retrievals relative to in situ weather station records;
- The FT 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 anomalies and enhancing atmosphere carbon sequestration at higher latitudes; the relative growth benefits of earlier/longer non-frozen seasons may be weakening due to relaxing cold temperature constraints, increasing frost damage related impacts & increasing water limitations to productivity;
- The Northern Hemisphere FT trend coincides with a regional mean 0.033 °C yr^{-1} surface air temperature warming trend;
- The FT 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 FT record is available online at the NSIDC DAAC (**http://nsidc.org/data/nsidc-0477.html**).

Acknowledgements

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