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Satellite Derived 30-Year Trends in Terrestrial Frozen & Non-Frozen Seasons, and Associated Impacts to Vegetation and Atmosphere CO2

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Introduction:

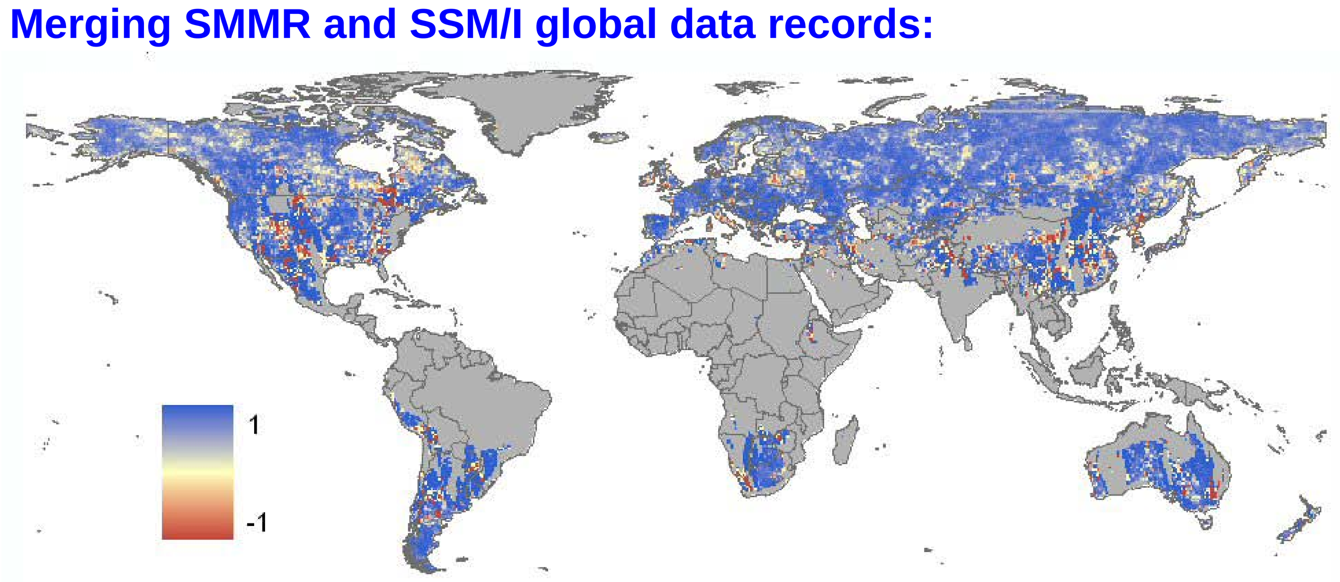
Approximately 66 million km^2 (52.5 %) of the global vegetated land area experiences seasonally frozen temperatures as a major constraint to ecosystem processes. The freeze-thaw (F/T) status of the landscape as derived from satellite microwave remote sensing is closely linked to surface energy budget and hydrological activity, vegetation phenology, terrestrial carbon budgets and land-atmosphere trace gas exchange. We utilized a seasonal threshold algorithm based temporal change classification of 37GHz frequency, V-polarized brightness temperatures (T_b) from the Nimbus-7 Scanning Multichannel Microwave Radiometer (SMMR) pathfinder and Special Sensor Microwave Imager (SSM/I) to classify daily F/T status for all global land areas where seasonal frozen temperatures are a major constraint to ecosystem processes. A temporally consistent, long-term (30 year) daily F/T record was created by pixel-wise correction of the SMMR T_b record based on empirical analyses of overlapping SMMR and SSM/I measurements acquired during 1987. The resulting combined F/T 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 frozen and non-frozen seasons. The F/T results were compared against other surrogate measures of biosphere activity including satellite AVHRR (GIMMS) based vegetation greenness (NDVI) and tower (FLUXNET) CO_2 fluxes.

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) NOAA AVHRR GIMMS NDVI record: 1982-2006, 25 x 25 km global EASE-Grid;
(4) FLUXNET (LaThuile) tower site daily C-flux data: Net ecosystem CO_2 exchange (NEE), Gross Primary Production (GPP), Ecosystem Respiration (Reco)

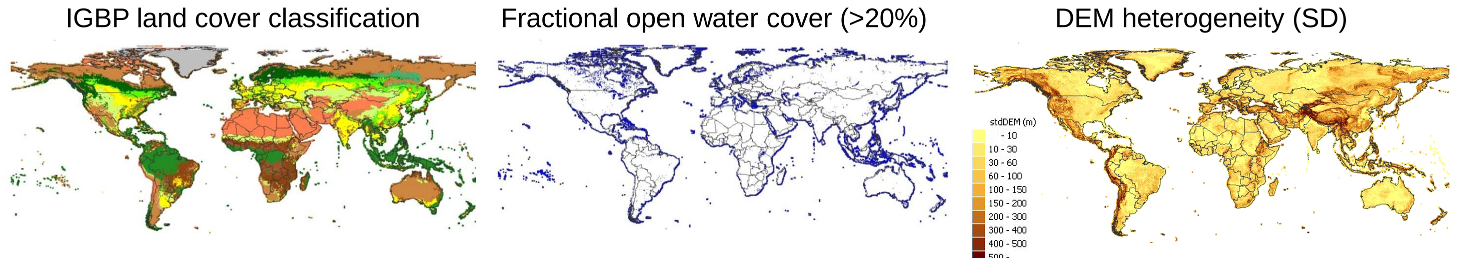
Merging SMMR and SSM/I global data records:



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 Tb 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 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 and SSM/I T_b values during the 1987 overlap period (r^2~0.99 and RMSE=3.41-4.26K).

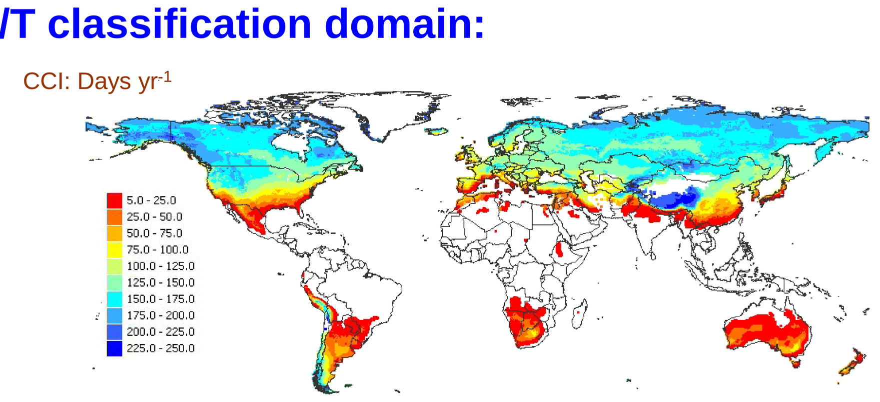
Ancillary data for masking and quality assessment:

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:



We defined a global F/T classification domain (**above**) using a global (*DAO) 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 km2) of the global land area and encompasses vegetated land areas where low temperatures are a major constraint to ecosystem processes.

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

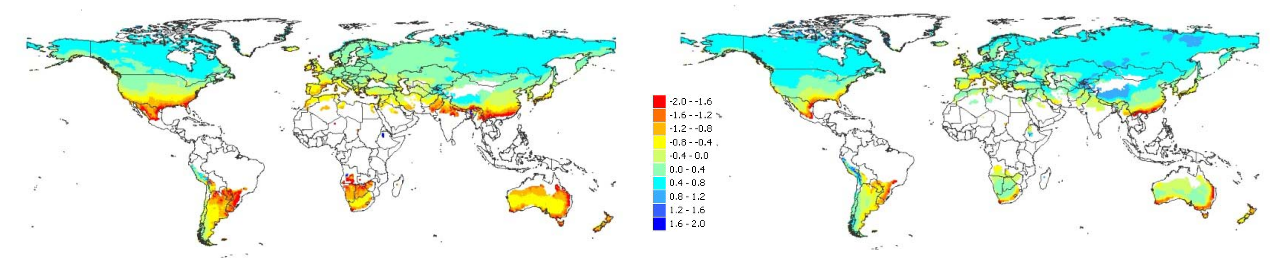
F/T Algorithms: Seasonal Threshold Approach (STA)

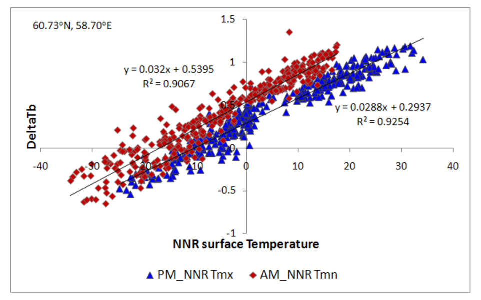
$$\Delta(\sigma \text{ or } T_b) = \frac{\sigma(t)-\sigma_{fr}}{\sigma_{th}-\sigma_{fr}}$$

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
$\Delta(\sigma \text{ or } T_b) \leq T$ Frozen

where T_b = brightnesstemperature and σ = backscatter



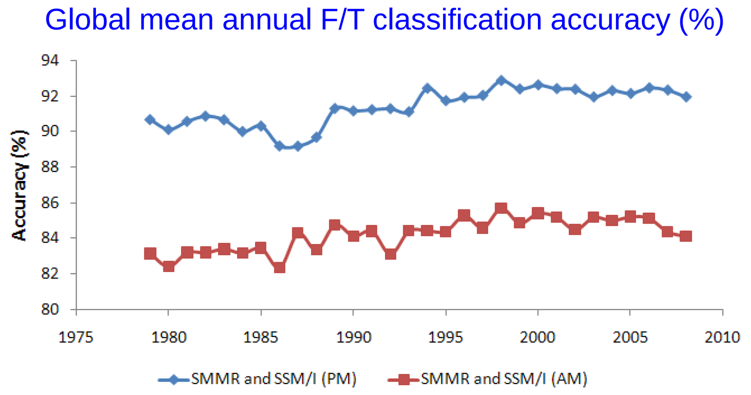


The landscape F/T status was classified from daily (AM & PM) orbit T_b retrievals from SMMR and SSM/I time series using a seasonal threshold algorithm ([2]STA, **top**). The STA uses a dynamic threshold defined annually on a grid cell-wise basis from empirical relations established between T_b retrievals 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.

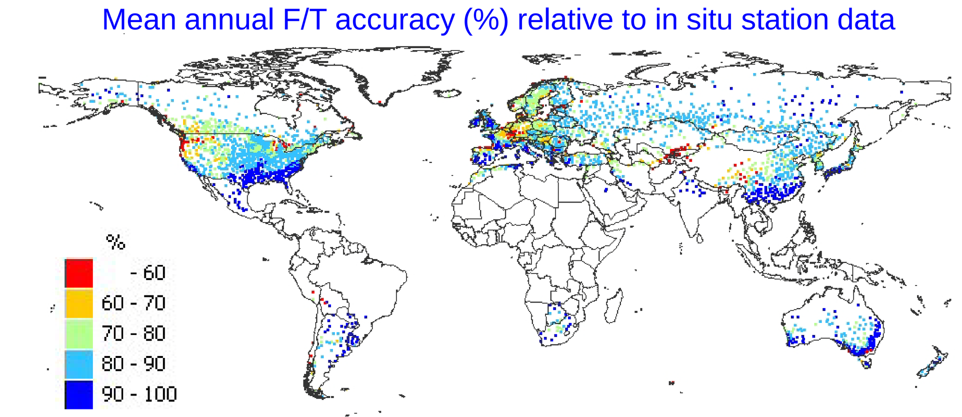
*NCEP/NCAR (NNR, 1988-2007) 6-hour reanalysis (1.875º x 2º);
[2]Kim et al. *IEEE TGARS* 2010.

F/T accuracy assessment using global weather stations:

Global mean annual F/T classification accuracy (%)



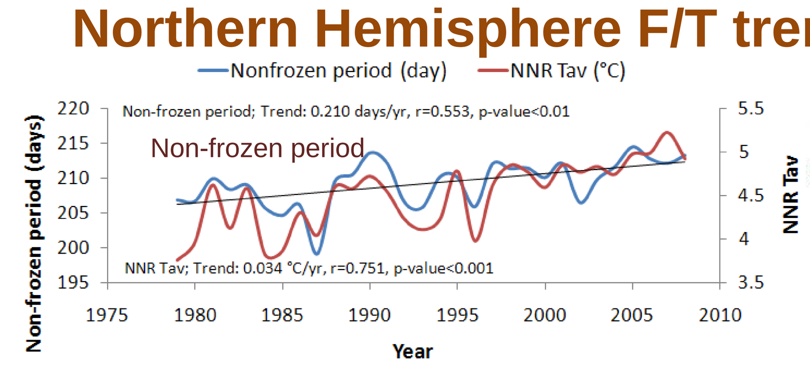
Mean annual F/T accuracy (%) relative to in situ station data



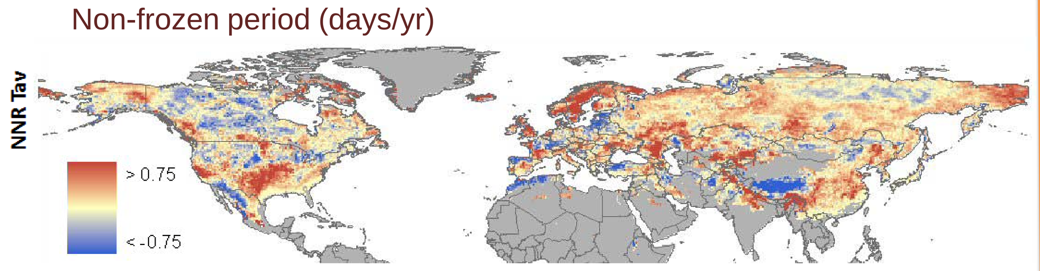
*NCDC daily summary of the day from WMO weather stations

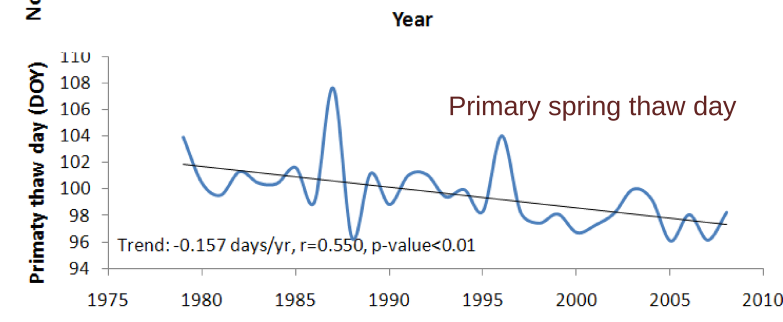
F/T classification accuracy is assessed from in situ daily air temperature data from global weather stations. The stations are first screened for homogeneous land cover and terrain conditions within the overlying 25-km grid cell, resulting in ~3,701 validation stations selected (**above right**). Mean 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**).

Northern Hemisphere F/T trends:

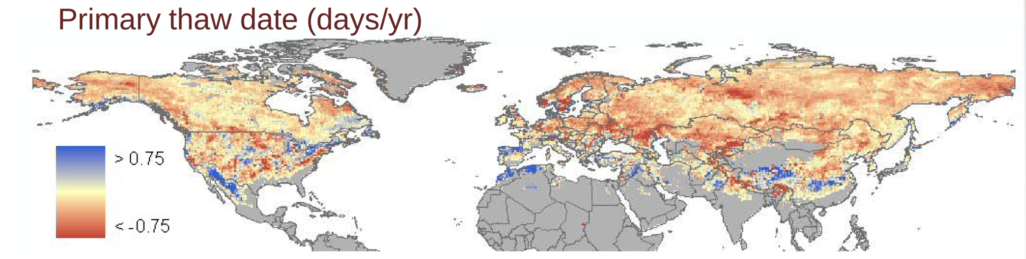


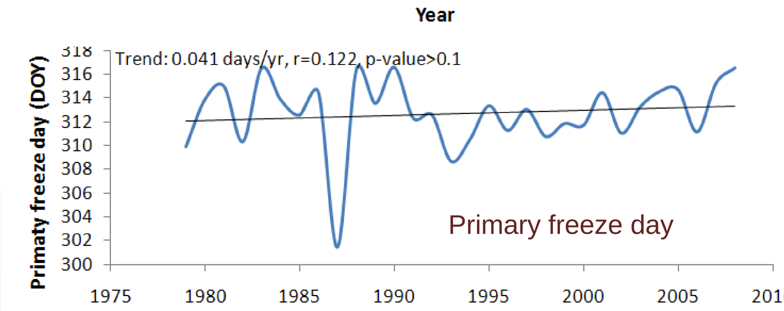
Non-frozen period (days/yr)



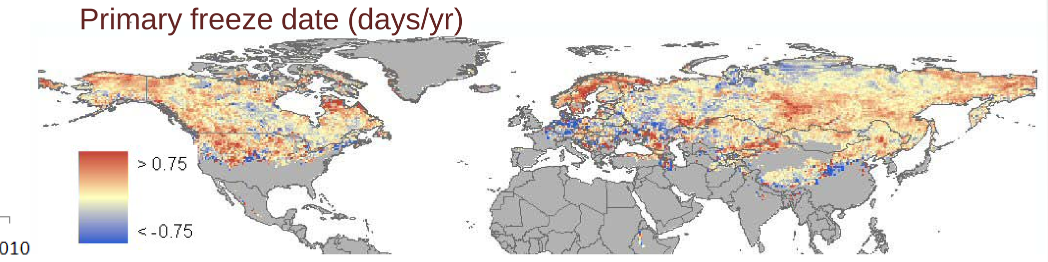


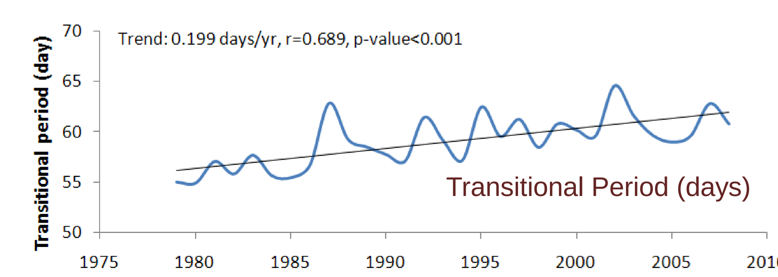
Primary thaw date (days/yr)



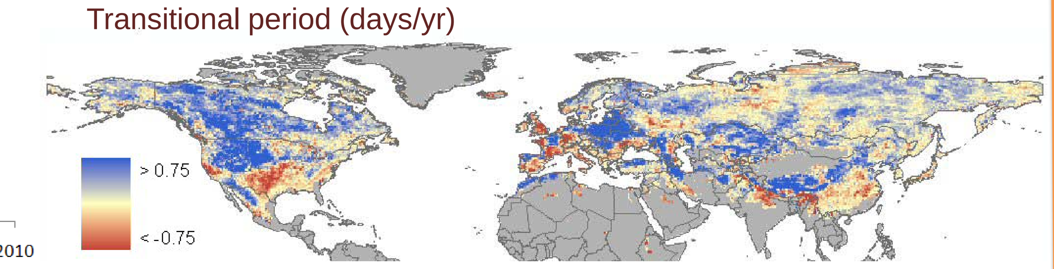


Primary freeze date (days/yr)





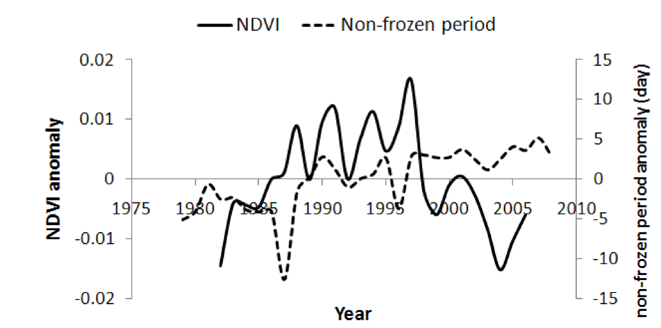
Transitional period (days/yr)



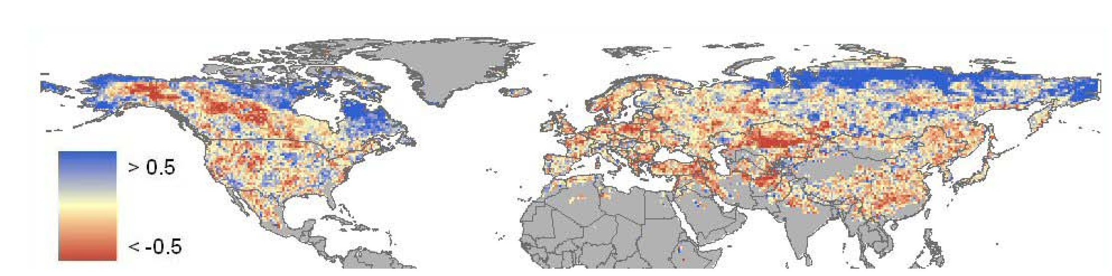
Mean annual trends of the merged (SMMR/SSM/I) F/T parameter series (**left**) and corresponding Northern Hemisphere F/T trend patterns (**right**). Primary thaw day is defined as the first day of 12 out of 15 consecutive non-frozen days between Jan and Jun; Primary freeze day is the first day of 12 out 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.

Summer NDVI and Non-frozen period:

Mean annual summer NDVI and non-frozen period anomalies:

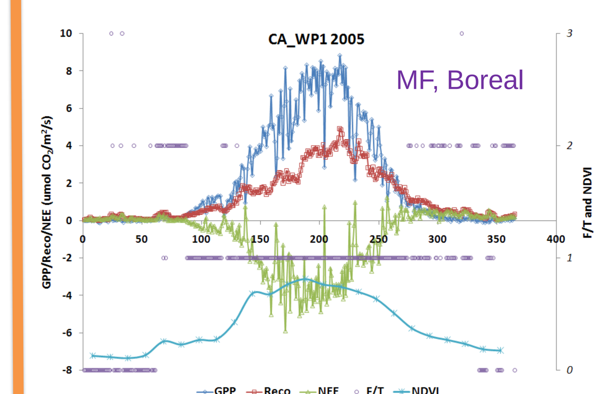


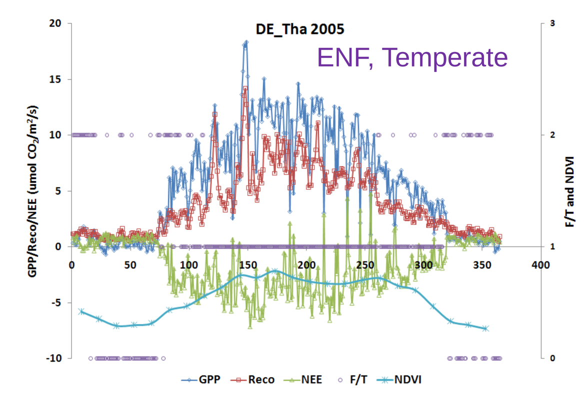
Pixel-wise correlation (r) between summer NDVI and non-frozen period

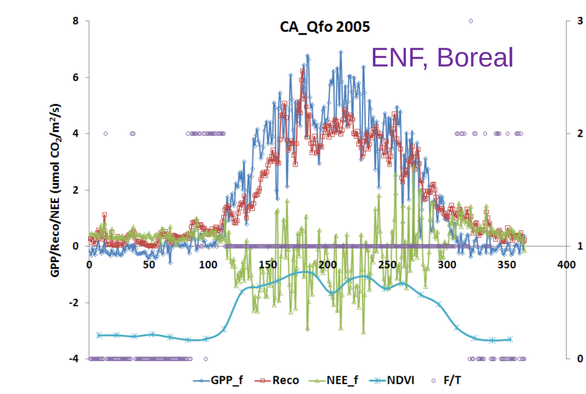


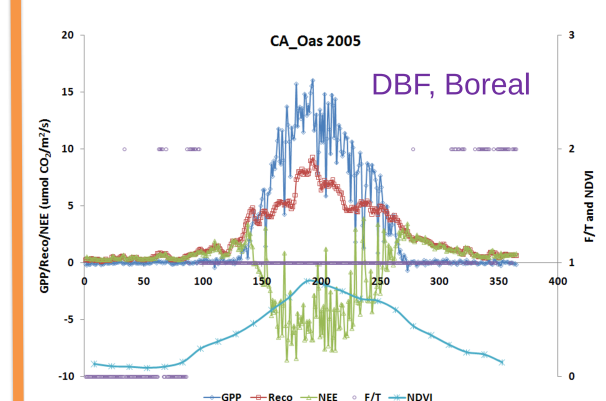
Mean annual variation in summer (JJA) NDVI and non-frozen period (Jan-Aug) anomalies (**left**) and the spatial pattern of correlation (r) between these parameters (**right**) for two decades. Non-frozen period is derived from Jan-Aug, prior to the summer NDVI values. Summer NDVI was used to assess annual variations in vegetation productivity and associated linkages to the F/T parameters. The non-frozen season effectively bounds the potential growing season for vegetation. In energy limited Arctic tundra areas, years with relatively longer non-frozen seasons promote generally higher vegetation productivity (NDVI), whereas shorter non-frozen seasons promote the opposite response. In other areas a lengthening non-frozen season coincides with recent (post 1990's) declining summer NDVI trends linked to increasing drought impacts to vegetation productivity; drought frequency and severity may be exacerbated under projected warmer & longer non-frozen seasons.

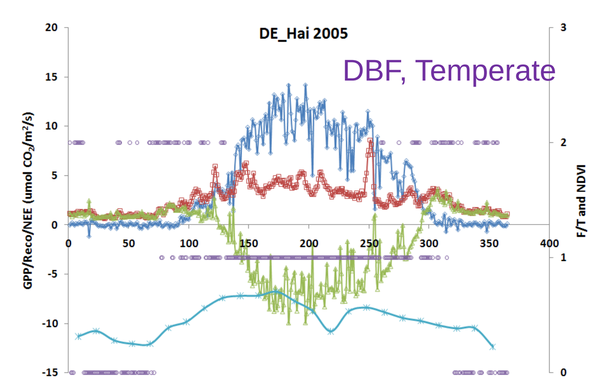
F/T linkages to C-flux and NDVI patterns at FLUXNET sites:

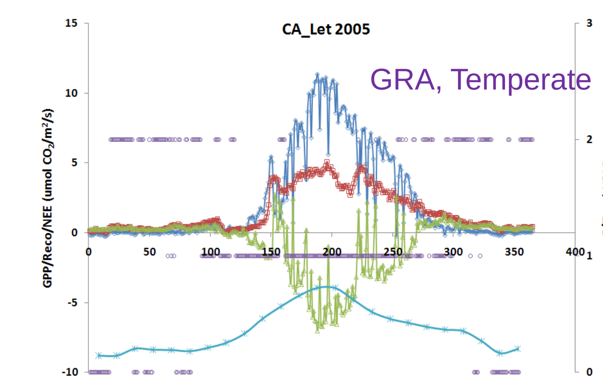












The daily F/T results were evaluated in relation to satellite (GIMMS) 16-day composited NDVI records and in situ daily tower eddy covariance CO_2 measurement based GPP & Reco records at selected [1]FLUXNET sites within the Northern Hemisphere domain (>45°N) for 2005. Results are presented (**above**) for selected boreal & temperate Evergreen needleleaf forest (ENF), Deciduous broadleaf forest (DBF), mixed ENF/DBF forest (MF) & 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 & Reco, & CO2 (NEE) uptake by vegetation and canopy (NDVI) growth.

[1]Tower site data provided courtesy of FLUXNET PIs: L. B. Flanagan (CA_WP1, CA_Let); C. Bernhofer (DE_THA); H. A. Margolis (CA_QFO); A. T. Black (CA_Oas); A. Knohl (DE_Hai)

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<0.01) long-term trends in non-frozen period (0.210 days/yr) & largely driven by earlier onset of spring thaw (-0.157 days/yr) and a general delay in the arrival of the frozen season in Fall (0.041 days/yr).;
- The F/T trends coincide with a mean 0.034 °C/yr surface air temperature warming trend for the domain as derived from global model reanalysis;
- The F/T results generally bound the vegetation growing season as defined by satellite (GIMMS) based NDVI temporal anomalies and in situ tower eddy covariance measures of active CO_2 uptake and vegetation productivity;
- The F/T results correspond significantly with summer NDVI trends. However, correspondence between non-frozen period and summer NDVI is weaker after the 1990's relative to earlier decades due to recent increases in the extent and severity of drought and associated water balance limitations to productivity;
- The FT_ESDR is available online at (**http://freezethaw.ntsg.umt.edu/**) and at the NSIDC DAAC (**http://nsidc.org/data/nsidc-0477.html**).

Acknowledgements

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