2014

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IN31A-3706

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Abstract:

A global satellite microwave Earth System Data Record of daily landscape freeze-thaw status (FT-ESDR) has been used to quantify frozen season constraints to productivity, phenology, evapotranspiration and the carbon cycle. Overlapping 37 GHz, vertically polarized brightness temperature (Tb) measurements from the Scanning Multichannel Microwave Radiometer (SMMR) and Special Sensor Microwave Imager (SSM/I) were integrated to produce a temporally consistent and continuous global daily FT data record from 1979 to 2013, and derived at 25-km pixel resolution. In this study, we develop and evaluate FT-ESDR enhancements, including expanded record length and spatial coverage, alternate algorithm calibrations, and a finer scale FT classification. A larger global domain is evaluated that encompasses all land areas affected by seasonally frozen temperatures, including urban, snow-ice dominant, barren, and permafrost landscapes. The FT retrieval is obtained using a seasonal threshold algorithm (STA) that classifies daily Tb changes in relation to frozen and non-frozen Tb reference states on a per-pixel basis. STA sensitivity to FT reference states is evaluated and alternative ancillary data are applied for defining Tb reference conditions, including surface temperatures from global reanalysis and MODIS land surface temperature (LST) seasonal climatology. The resulting FT record shows mean annual spatial classification accuracies of 93 and 87 percent for PM and AM overpass retrievals relative to in-situ temperature measurements. Despite the larger domain and longer record, the new FT-ESDR showed a 1-3 percent spatial classification accuracy improvement over previous FT-ESDR versions. Areas with enhanced accuracy include Central Asia, and North and Central Europe. Sub-grid land surface spatial heterogeneity effects on the aggregate FT retrievals are also assessed to refine FT-ESDR data quality metrics. The results of this study are being applied for continuing FT-ESDR production and utility enhancements, and to inform development of similar FT algorithms and products from the NASA SMAP mission.

Data and Methods:

Satellite microwave T_b observations:

- Nimbus-7 SMMR T_b series: 1979-1987, daily AM/PM, 37GHz, V-pol, http://nsidc.org/data/nsidc-0071.html;
- DMSP SSM/I T_b series: 1987-2013, daily AM/PM, 37GHz, V-pol, http://nsidc.org/data/nsidc-0032.html

Ancillary data used for FT-ESDR calibration and validation:

- NNR reanalysis: 1979-2012, 1.9°x1.875° resolution, daily 2m surface max/min air temperatures;
- MYD11C1 Land surface Temperature (LST) climatology: 2003-2011, mean daily day/night LST using good quality;
- ERA-Interim reanalysis: 1979-2013, 0.25°x0.25° resolution, daily 2m surface max/min air temperatures;
- NCDC: 1979-2013, daily summary of the day from WMO weather stations
- Global Lake and River Ice Phenology Database: 1981-1982, lake ice duration (days), http://nsidc.org/data/G01377
- Nenana Ice Classic: 1979-2003, Tanana River Ice Annual Breakup Dates, http://nsidc.org/data/nsidc-0064
- MEaSUREs Greenland Surface Melt Daily: 1979-2012, 25km x 25km, daily, http://nsidc.org/data/nsidc-0533
- Historical Arctic and Antarctic Surface Observation Data: 2001, daily surface average temperatures, http://nsidc.org/data/NSIDC-0190

Ancillary data for masking and quality assessment:

- MCD12C1: 2001-2012, CMG (5.6-km), 17-class IGBP (Friedl et al. 2010);
- GLOBE: Digital elevation map (GLOBE 1999);

FT algorithms: Seasonal Threshold Approach (STA)

$$\Delta(T_b) = \frac{T_b(t) - T_{fr}}{T_{th} - T_{fr}} \qquad FTstatus = \begin{cases} NF\ if\ \Delta T_b > Threshold \\ FR\ if \Delta T_b \le Threshold \end{cases}$$

T_{fr} = frozen reference state (mean T_b in January)

T_{th} = non – frozen reference state (mean T_b in July)

- Landscape FT status classified from daily (AM & PM) orbit T_b retrievals from SMMR & SSM/I time series & STA (Kim et al., 2011, 2012, **above**). The STA uses a dynamic threshold defined annually on a grid cell-wise basis from empirical relations established between T_b retrievals & global reanalysis air temperatures (*ERA-Interim). STA based FT classifications derived as discrete frozen (0) or non-frozen (1) values from AM and PM overpass Tb data; The AM/PM FT classifications are composited at daily intervals to define Frozen (AM & PM), Non-Frozen (AM & PM), Transitional (AM frozen; PM thawed) and Inverse-Transitional (AM thawed; PM frozen) states;
- A modified single T_b reference state STA algorithm was applied for anomalous areas where the annual T_b frozen reference state exceeded the T_b non-frozen reference state (Kim et al. 2014a, b);

$$FTstatus = \begin{cases} NF\ if\ T_b > Frozen\ Tb\ reference \\ FR\ if\ T_b \le Frozen\ Tb\ reference \end{cases}$$

- FT classification over permanent snow/ice area (Tedesco et al. 2009);

$$FTstatus = \begin{cases} NF\ if\ T_b > Tc \\ FR\ if Tb \le Tc \end{cases} \quad where\ T_c = T_{fr} * 0.48 + 128$$

*ERA-Interim (1979-2013) reanalysis (0.25° x 0.25°);

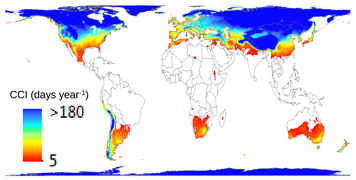
FT classification accuracy (%) :

$$T_{PM}(i,t) = \begin{cases} 1\ if\ FTPM(i,t) = S_{PM}(i,t) \\ 0\ if\ FTPM(i,t) \ne S_{PM}(i,t) \end{cases} \qquad Accuracy\ (\%) = \left(\sum_{i=1}^{N_i} \sum_{t=1}^{N_t(i)} T_{PM}(i,t) \div \sum_{i=1}^{N_i} N_t(i) \right)$$

$where\ i = cell\ and\ t = days$

Global FT-ESDR domain:

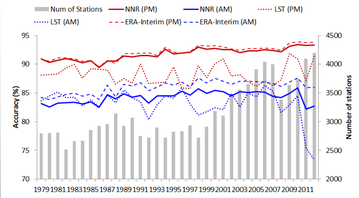
The FT-ESDR domain is defined using a global surface air temperature daily climatology (*ERA-Interim, 1979-2013) & [1]Cold Constraint Index [CCI, days yr^{-1}]. An expanded FT-ESDR domain was defined where CCI > 5 d yr^{-1}. The resulting domain represents ~60.5% (93.3 million km^2) of the global land area, compared to ~52.5% for prior FT-ESDR releases (Kim et al., 2013), & encompassing vegetation, urban, snow-ice dominant, barren & permafrost areas.



[1]Source: Jolly et al, *Global Change Biol* 2005.

*ERA-Interim (1979-2013) reanalysis (0.25° x 0.25°).

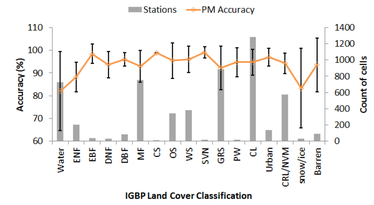
Sensitivity of FT accuracy to reference states:



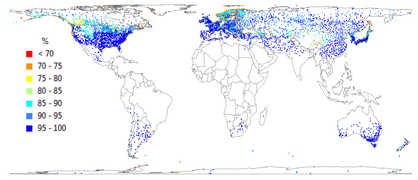
- FT data derived using reference states from 3 alternate sources: MYD11C1 day/night LST climatology, NNR & ERA-Interim surface mx/mn T_{air};
- Mean annual FT classification accuracies determined for PM (red) & AM (blue) retrievals vs. global weather station T_{air} records (NCDC) (**left**): NNR 91.8 (±1.0) & 84.3 (±1.0) %; MYD11C1 LST 88.3 (±1.7) & 83.1 (±2.6) %; ERA-Interim 92.1 (±1.1) & 86.0 (±1.1) %;
- FT-ESDR derived using ERA-Interim FT reference states shows best performance.

FT accuracy assessment:

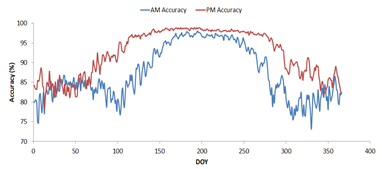
(d) Mean annual accuracy (%) by land cover class for 2012



(b) FT accuracy (%) relative to in situ station data for 2012

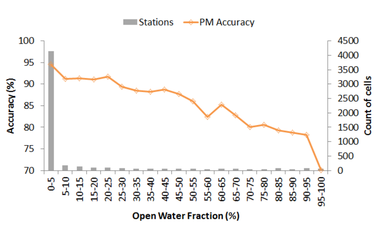


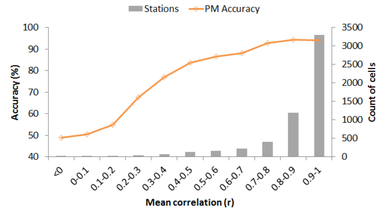
(c) Global mean daily accuracy for 2012

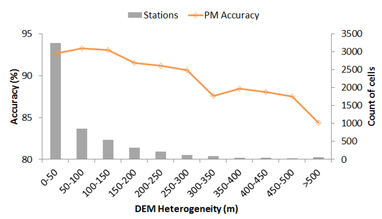


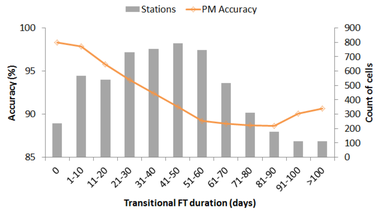
- Mean annual FT accuracies of 92.5 (±1.1) & 86.6 (±1.2) % for PM (red) & AM (blue) retrievals relative to independent weather station records (NCDC) for the 35-year FT record and global domain;
- Mean annual FT accuracy vs 4782 NCDC stations for 2012 (**b**);
- Mean daily FT accuracy generally lower during seasonal FT transitions in spring and fall (**c**);
- Mean annual FT accuracy (PM) for different land cover classes ranges from 82% (for snow/ice areas) to 99%; bar graph denotes number of T_{air} stations used for FT validation in each class, while vertical bars denote one spatial Std. Dev. range around the accuracy mean.

Factors affecting FT accuracy:



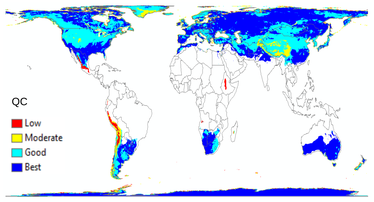






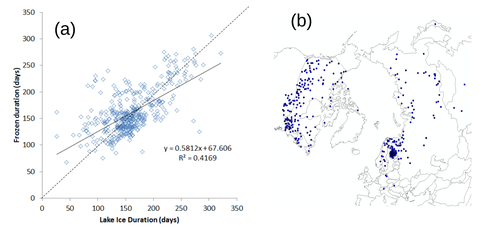
The FT-ESDR quality (QA) map (**right**) provides a discrete, pixel-wise indicator of FT product quality. The QA map shows regions of relative high to low quality in relation to potential negative impacts from open water fraction, terrain heterogeneity, transition FT duration, and correlation between ERA-Interim reanalysis temperature data and T_b retrievals to define per grid-cell FT reference states for the STA temporal change classifications (**above**). The QA based multiple regressions explain ~41% of variability in FT accuracy inferred from global T_{air} stations. The QA values were stratified into a smaller set of discrete categories ranging from low (estimated mean spatial accuracy < 70 %) to best (accuracy > 95%) quality. Mean proportions of the four QA categories encompass 54.7 % (best), 35.4 % (good), 7.6 % (moderate), and 2.3 % (low) of the FT-ESDR domain.

FT quality assessment for 2012:

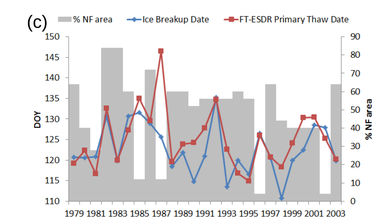


FT metrics comparison against independent Cryosphere data:

Global Lake and River Ice Phenology:

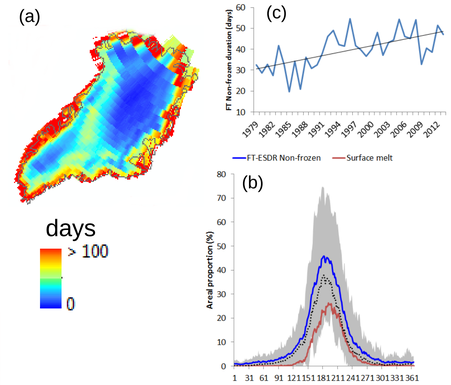


Tanana River AK Annual Ice Breakup:

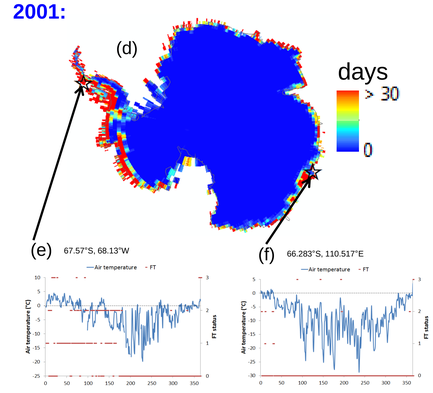


- Correspondence (r=0.65; p<0.01) between lake ice duration and FT-ESDR frozen season duration (1981-1982) for 412 lakes indicates direct frozen season impact on river ice phenology (**a**); Lake locations are displayed in (**b**).
- Correlation (r=0.67; p<0.01) between annual Ice breakup date for Tanana River (64.56°N, 149.09°W), Alaska and average FT-ESDR primary thaw date for the surrounding Tanana River basin from 1979-2003 indicates direct spring thaw impact on river ice breakup timing (**c**). Percent NF areas were determined within the surrounding Tanana River basin at annual primary thaw date.

Greenland surface melt season :



Antarctic Surface Observation Data for 2001:



- FT-ESDR shows a mean annual non-frozen (NF) season (1979-2013) of 40.8±32.3 [Spatial-SD] days over Greenland, with longer NF season but lower FT quality (QA) along coastal regions from open water contamination (**a**). NF season and MEaSUREs Greenland Surface Melt records show a similar seasonal climatology, with NF conditions preceding surface melt (**b**); shading denotes two standard deviation range around the NF season mean. The dotted black line represents daily areal proportion (%) of FT-ESDR NF season over lower open water contaminated cells (open water fraction < 5%). The Greenland NF season shows a strong increasing trend (5.3 days decade^{-1}; p<0.01) from 1979-2013 (**c**);
- FT-ESDR shows a mean annual NF season (1979-2013) of 41.7±51.8 days over Antarctica, with longer NF season over west Antarctic Peninsula and coastal areas (**d**). FT accuracy assessment vs mean daily T_{air} measurements from selected Antarctic surface stations for 2001 (**e, f**); the FT-ESDR results represent discrete (0=Frozen; 1=Non-Frozen; 2=Transitional; 3=Inverse Transitional) classifications of predominant frozen or non-frozen conditions within the ~25-km scale satellite footprint. The FT-ESDR results generally coincide with FT conditions at the selected sites.

Conclusions:

- New FT-ESDR produced with expanded global domain, longer record and 1-3% improved spatial classification accuracy over previous FT-ESDR versions;
- Favorable FT classification accuracy over non-vegetated areas (mean annual spatial accuracy from 82-97%);
- Lower FT accuracy with larger fractional open water cover, greater DEM heterogeneity, and during seasonal FT transitions;
- General FT-ESDR consistency with other cryosphere data: FT sensitivity to lake and river ice seasonality; similar FT NF season and snowmelt cycles over Greenland; realistic FT patterns over Antarctica;
- These results are being used for continuing NASA MEaSUREs FT-ESDR production and enhancements, and to inform development of similar FT algorithms and products from the NASA SMAP mission;
- FT-ESDR available online through the NASA NSIDC DAAC: **http://nsidc.org/data/nsidc-0477.html**;

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Acknowledgements

This work was conducted at the University of Montana under contract to NASA, & supported under the NASA Making Earth Science Data Records for Use in Research Environments (MEaSUREs) program (NNH12ZDA001N-MEaSUREs).