AN ASSESSMENT OF PERMAFROST LONG-TERM MONITORING SITES WITH CIRCUMPOLAR SATELLITE DERIVED DATASETS

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1. ABSTRACT

The ESA DUE Permafrost service has been utilized to produce a pan-arctic database (25km, 2000-2014) comprising Mean Annual Surface Temperature, Annual and summer Amplitude of Surface Temperature, Mean Summer (July-August) Surface Temperature. Surface status (frozen/unfrozen) related products have been also derived from the ESA DUE Permafrost service. This includes the length of unfrozen period, first unfrozen day and first frozen day. In addition, SAR (ENVISAT ASAR GM) statistics as well as topographic parameters have been considered. The circumpolar datasets have been assessed for their redundancy in information content. 12 distinct units could be derived. This paper presents the result of this assessment and formulates recommendations for extensions of the in situ monitoring networks and categorizes the sites by satellite data requirements (specifically Sentinels) with respect to the landscape type and related processes.

2. INTRODUCTION

Requirements for space based monitoring of permafrost features had been already defined within the IGOS Cryosphere Theme Report at the start of the IPY in 2007 [10]. The WMO Polar Space Task Group [16] identified the need to review the requirements for permafrost monitoring and to update these requirements in 2013. Relevant surveys with focus on satellite data are already available from the ESA DUE Permafrost User requirements survey (2009), the United States National Research Council (2014) and the ESA – CliC – IPA – GTN –P workshop in February 2014. These reports have been reviewed, specific needs discussed within the community and a white paper submitted to the WMO PSTG [4]. Acquisition requirements for monitoring of especially terrain changes (incl. rock glaciers and coastal erosion) and lakes (extent, ice properties etc.) with respect to current satellite missions have been specified.

About 50 locations ('cold spots') where permafrost (Arctic and Antarctic) in situ monitoring has been taking place for many years or where field stations are currently established have been identified. These sites have been proposed to the WMO Polar Space Task Group as focus areas for future monitoring by high resolution satellite data. The specifications of these sites including meta-data on site instrumentation have been published as supplement to the white paper [3]. Many of these sites are equipped with bore holes (being part of GTN-P) and included in the CALM (Circumarctic active layer monitoring) program. Such sites are located where infrastructure is available. [5] identified areas where boreholes are required using statistical analyses (Voronoi tessellation) to identify spatial gaps based on the meta information of the dataset. It remains however unclear what the actual spatial representativeness is. Here we propose a satellite record based approach which utilizes the DUE Permafrost database and an additional circumpolar C-band SAR dataset which has been developed within the FP7 PAGE21 project. Landscape units are derived and discussed with respect to ground monitoring site networks.

3. INPUT DATA

Parameters which can be identified with satellite data and are relevant for soil processes and especially land-atmosphere exchange have been assessed for the retrieval of a circumpolar landscape units map.

3.1 C-Band SAR backscatter

A circumpolar representative and consistent wetland map is required for a range of applications spanning from upscaling of carbon fluxes and pools to climate modelling and wildlife habitat assessments. Currently available datasets lack sufficient accuracy and/or thematic detail in many regions of the Arctic. The development of the novel wetness level map has been described in [20]. Wetland classes are also included in land cover

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maps. However, the accuracy of landcover products for Arctic regions, specifically classes related to wetland types, and the product utility for various applications remains largely uncertain [11]. [15] compared coarse resolution land cover maps like GLOBCOVER, GLC-2000 and MODIS C4 and C5 for northern Eurasia and confirmed their low mean agreement in the northern taiga-tundra zone. Wetland classes, typical in tundra environments, are also only partially included in the widely used Global Lakes and Wetland database ([12],[2]). Circumpolar ENVISAT ASAR GM backscatter (1km resolution, 500m nominal resolution) data have been explored in subarctic and arctic environments with special emphasis on spatial wetness patterns. 25% of the land area north of the tree line has been identified as wetland based on ASAR GM December records while conventional maps (e.g. CCI GlobCover) state 1-7 %. Wetlands can be also associated with specific soil properties which have an influence on Thermal conductivity. The wetness level can be associated with different ranges of active layer thickness [21]. December ASAR GM backscatter data have been therefore used as input for the circumpolar landscape units to gain information about wetlands (Fig.5).

Table 1: Available circumpolar datasets

Parameter	Source	Spatial resolution	Time period	Comments
Topographic Wetness Index (TWI)	Marthews et al. 2015 [16]	0,004167 °	-	Post-processed within PAGE21 by TUW
Surface Soil Moisture Summer-Maximum (SSM SMAX)	Paulik et al. 2014 (ESA DUE Permafrost)[17]	25 km	2007 -2013	No values available in high latitude areas where surface can be frozen during July/August Post-processed within PAGE21 by TUW
Normalized Difference Vegetation INDEX	MODIS	1km	July 2010	Post-processed within PAGE21 by TUW
C-Band backscatter (SAR) (winter)	ENVISAT ASAR GM [27]	1km	2005-2012	Post-processed within PAGE21 by TUW
LST Maximum Summer (July/Aug) (MOD SMAX)	Duguay et al. (2014) (ESA DUE Permafrost))[6]	25km	2000 -2013	Post-processed within PAGE21 by TUW
Length of unfrozen period in days (UF)	Paulik et al. 2014 (ESA DUE Permafrost)[17]	25km	2007 -2013	Post-processed within PAGE21 by TUW
Slope > 3°	Santoro et al. 2012 (ESA DUE Permafrost)[21]	100m	-	Post-processed (mosaic and reclass) within PAGE21 by TUW
Combined mean annual surface temperature (LSCE MAST)	SSMI for snowfree period & reanalysis data during snow period [1]	25km	2000-2010	processed within PAGE21 by LSCE
MODIS mean annual surface temperature (MOD MAST)	Duguay et al. (2014) (ESA DUE Permafrost))[6]	25km	2000-2013	Post-processed within PAGE21 by TUW
Average first unfrozen day of year (ASCAT FUF)	Paulik et al. 2014 (ESA DUE Permafrost)[17]	25km	2007 -2013	Post-processed within PAGE21 by TUW
LST July/Aug amplitude (MOD SAmpl)	Duguay et al. (2014) (ESA DUE Permafrost)[6]	25km	2000-2013	Post-processed within PAGE21 by TUW

3.2 NDVI and terrain

Vegetation and terrain patterns are frequently used as proxy for active layer thickness. NDVI was therefore derived from MODIS data representing the month July in 2010. July is expected to represent the annual maximum. The year 2010 has been selected based on the NDVI time series records derived for PAGE21 sites as non-anomalous and is assessed as a further satellite dataset used for landscape unit retrieval. A global topographic Wetness index by [13] has been used in addition. The distinction between plains and slopes was done with the dataset of [17]. A binominal Map was created dividing the land surface in flat areas below a gradient of 3 degrees and sloped areas above this threshold (Fig. 5).

3.3 Surface Temperature and soil moisture

Of high relevance for permafrost presences and biogeochemical processes is temperature. The ESA DUE Permafrost service [7] has been utilized to produce a pan-arctic database with a resolution of 25km for the timespan 2000-2014 comprising Mean Annual Surface Temperature, Annual and summer Amplitude of Surface Temperature, Mean Summer (July-August) Surface Temperature. The latter is supplemented by records produced within PAGE21 based on passive microwave observations (SSMI) [1]. Such records have the advantage of not being biased towards cloud free conditions. However, SSMI is only applicable during the snow free period and needs to be combined with Re-Analyses data for Mean Annual value retrieval. In addition, records for frozen/unfrozen land surface are available from Metop ASCAT [17].

[18] and [8,9] showed that the clear sky bias in MODIS derived land surface temperature is in the order of 2-3 K in high latitudes. This bias is expected not to be included in SSMI-derived LST. Such data are however only available during the snow free period.

Gaps or underestimations of surface soil moisture can occur in high latitude areas where surface can be partially frozen within the footprints during July/August. Additionally, wind action over areas with high water fraction can lead to overestimation of surface soil moisture [22]. This leads to inconsistencies in the circumpolar dataset.

Table 2: Correlation matrix of selected potential input datasets (sources and abbreviations see Table 1. Selected layers for iso-clustering are marked in green.

Name	Layer	1	2	3	4	5	6	7	8	9	10	11	12
TWI	1	**1.00**	0.02	0.25	-0.15	0.04	0.25	-0.11	0.21	0.20	0.24	0.32	0.07
SSM	2	0.02	**1.00**	0.05	0.02	0.15	0.06	0.00	-0.08	-0.09	0.08	0.03	0.05
NDVI	3	0.25	0.05	**1.00**	-0.22	0.17	**0.72**	-0.06	**0.62**	**0.64**	0.45	**0.71**	0.04
SAR	4	-0.15	0.02	-0.22	**1.00**	-0.01	-0.12	0.11	-0.05	-0.03	-0.28	-0.27	-0.08
LST Max JA	5	0.04	0.15	0.17	-0.01	**1.00**	0.24	-0.01	0.07	0.07	0.21	0.12	0.00
UF Period	6	0.25	0.06	**0.72**	-0.12	0.24	**1.00**	-0.10	**0.68**	**0.69**	**0.56**	**0.78**	0.06
Slope	7	-0.11	0.00	-0.06	0.11	-0.01	-0.10	**1.00**	-0.06	0.07	0.07	0.00	-0.04
LSCE MAST	8	0.21	-0.08	**0.62**	-0.05	0.07	**0.68**	-0.06	**1.00**	**0.91**	0.22	**0.59**	0.06
MOD MAST	9	0.20	-0.09	**0.64**	-0.03	0.07	**0.69**	0.07	**0.91**	**1.00**	0.29	**0.64**	0.05
FUF	10	0.24	0.08	0.45	-0.28	0.21	**0.56**	0.07	0.22	0.29	**1.00**	**0.72**	0.08
FF	11	0.32	0.03	**0.71**	-0.27	0.12	**0.78**	0.00	**0.59**	**0.64**	**0.72**	**1.00**	0.11
LST Ampli. JA	12	0.07	0.05	0.04	-0.08	0.00	0.06	-0.04	0.06	0.05	0.08	0.11	**1.00**

4. RETRIEVAL OF LAND SCAPE UNITS

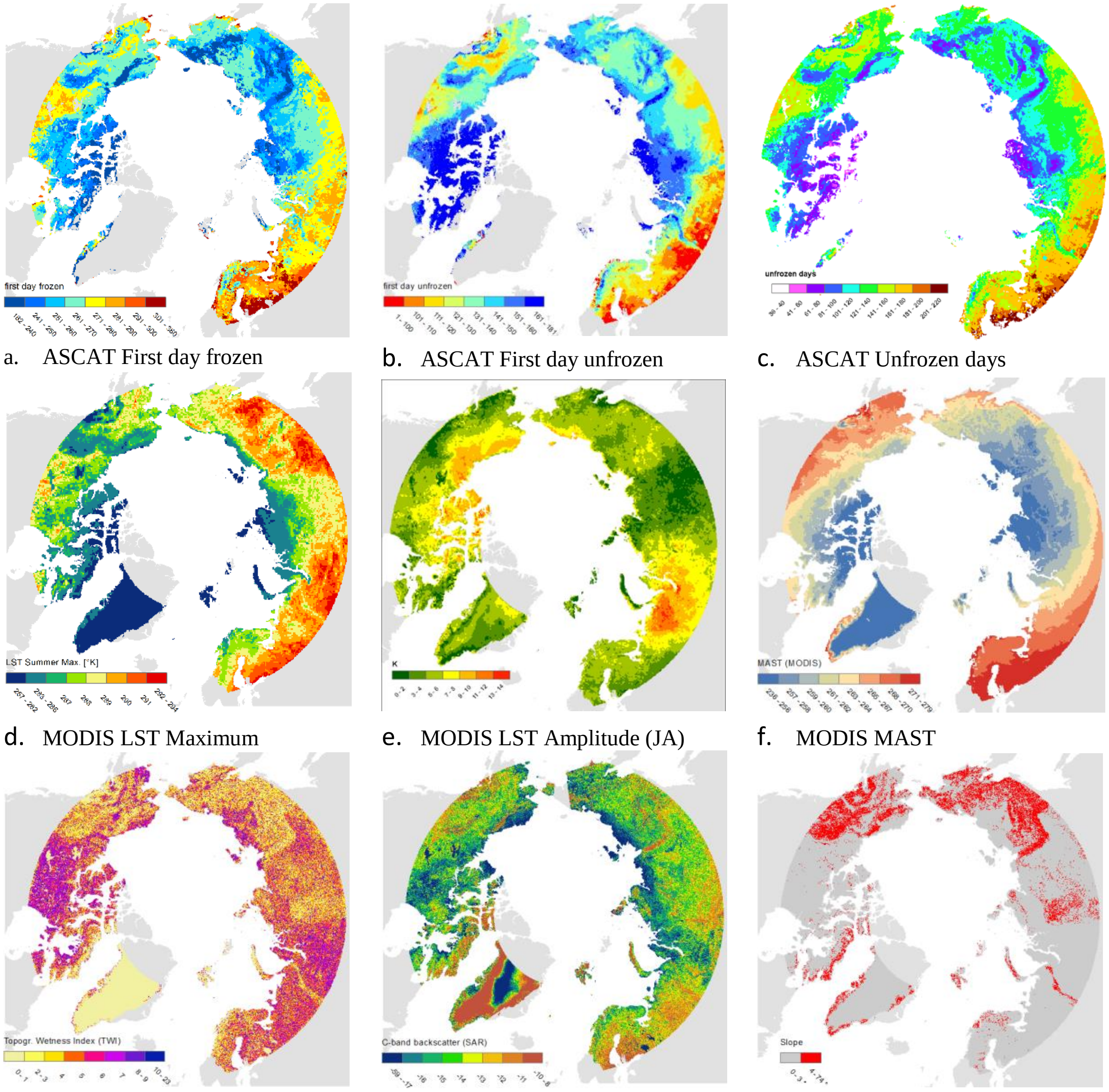
Tab. 1 details all datasets used for the Analysis. The output spatial resolution of the circumarctic landscape units is oriented at the coarser input with 25km. The final extent is confined by the slope map which does not include all land area north of 60°N.

In a first step all datasets have been assessed for redundancy in information content. Correlations are presented in Tab. 2. Several layers have been excluded due to high correlation with other layers. (e.g. NDVI and the length of the unfrozen period). All remaining datasets (Fig. 1) have been included in an isocluster analyses.

5. RESULTS AND ASSESSMENT OF UNITS

Twelve distinct landscape units could be derived for the land area north of 60° latitude (Fig. 2). The landscape units reveal similarities between North Slope Alaska and the region from the Yamal Peninsula to the Yenisei estuary. Northern Canada is characterized by the same landscape units like western Siberia. North-eastern Canada shows similarities to the Laptev coast region. PAGE21 sites represent 9 of the 12 units (taking into account location in transition zones between units). The three remaining units (in total 20% of the area) are characterized by high slope gradients.

Well represented within the ground networks are units 10 and 12. These correspond to tundra sites. This agrees with findings by [5] who showed that more than one third of all sites represent lowland tundra vegetation. These areas represent only 12% of the analyzed region. Least represented are mountainous regions (units 3, 4 and 8) which account for 20% of the land area north of 60°. This includes also none-permafrost areas. The majority of mountain areas in high latitudes are however expected to be characterized by permafrost.



a. ASCAT First day frozen
b. ASCAT First day unfrozen
c. ASCAT Unfrozen days
d. MODIS LST Maximum
e. MODIS LST Amplitude (JA)
f. MODIS MAST
g. Topographical Wetness Index
h. ASAR GM Backscatter
i. Slope > 3°

Figure 1: Selected layers for iso-clustering (for details see table 1)

Long term monitoring sites are lacking in lowland areas with low mean annual temperatures and high annual amplitude. This applies to a large part of eastern Siberia. The Mackenzie River valley and Alaskan North slope are well instrumented but represent only very few of the landscape units. Especially units five, six and eight also correspond to areas within and outside of permafrost. Large parts of Scandinavia are included in these classes. A higher number of clusters might be required in order to separate these areas. The coarse spatial resolution is also expected to contribute to the low separability

6. CONCLUSIONS

Circumpolar satellite records provide information on similarities and differences in surface properties over large parts of permafrost terrain. Landscape units allow the assessment of representativeness of monitoring sites and can point out data gaps not only regarding distances between the sites but also with respect to landscape characteristics. Gaps exist for especially mountain areas und regions with high annual and summer temperature amplitudes (almost 30%). Well instrumented regions such as the Alaskan North Slope, the proximity of the Mackenzie River in Canada and the Vorkuta area in Russia represent only 20% of high latitude landscapes.

7. ACKNOWLEDGEMENTS

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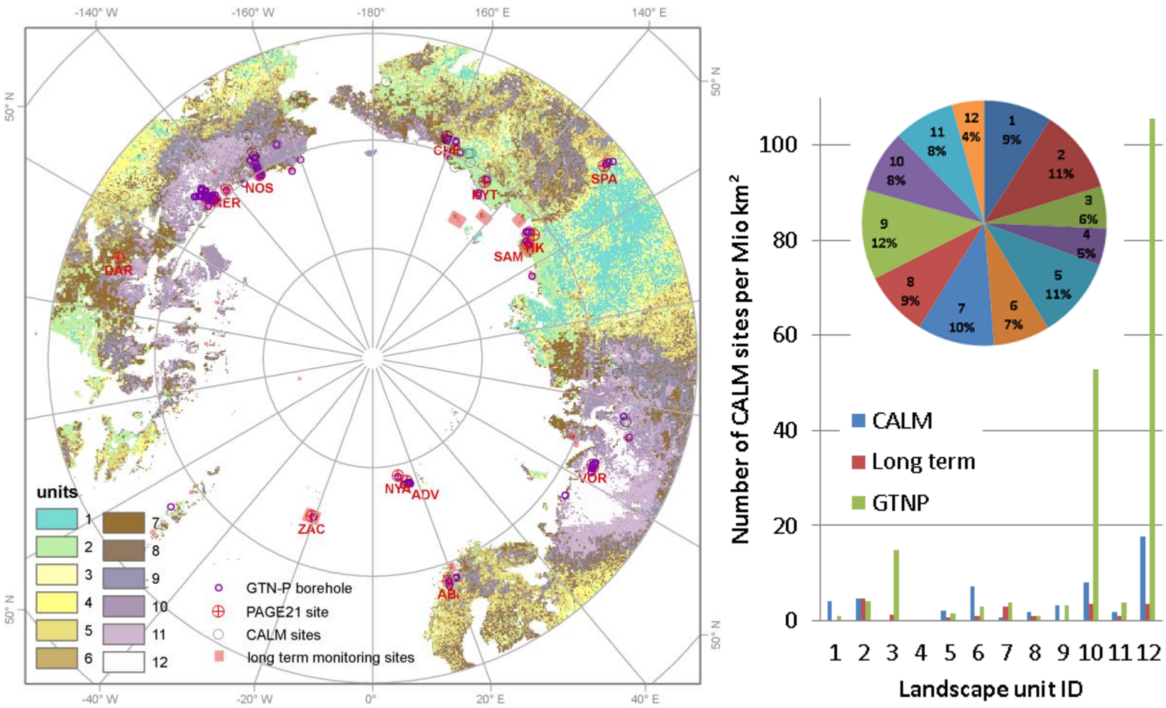

Figure 2: Left: Circumpolar landscape units (primary and secondary sites of the PAGE21 project are indicated with red crosses, for labels see Tab. 3); right: Number of active layer monitoring sites per km² for each landscape unit

Table 3: Unit characteristics and PAGE21 sites (multiple listings in case of transition zone location)

Units	Site	Topography Average gradient+STD	Specific properties	Average days of unfrozen P.
Unit 1	SPA,TIK	1° / Stdv = 1°	low MAST, high JJA Amplitude	128
Unit 2	SPA, KYT, CHE, SAM,TIK	1° / Stdv = 2°	low MAST , low JJA Amplitude, Late first unfrozen day	114
Unit 3		3° / Stdv = 5°	medium first unfrozen day, low max LST	125
Unit 4		3° / Stdv = 4°	Medium STD of first unfrozen day and max LST, high average max JJA LST, low max LST summer amplitude	133
Unit 5	ABI	2° / Stdv = 4°	high MAST , high average max LST	138
Unit 6	ABI	2° / Stdv = 3°	High STD max LST and low STD for frozen/unfrozen day	130
Unit 7	DAR, ADV, NYA	1° / Stdv = 3°	Low MAST with low STD, medium LST summer amplitude	116
Unit 8		4° / Stdv = 6°	High MAST an high STD for unfrozen day	134
Unit 9	DAR	3° / Stdv = 5°	High max LST with medium STD	128
Unit 10	NOS, ADV	1° / Stdv = 1°	Low MAST with low STD, high summer LST amplitude, high STD for first unfrozen day	122
Unit 11	HER	1° / Stdv = 3°	high max LST amplitude with low max LST STD	135
Unit 12	VOR	1° / Stdv = 2°	Medium max LST with low STD	136

SPA = Spasskaya Pad, TIK = Tiksi, KYT = Kytalyk, CHE = Cherskii, SAM = Samoylov, TIK = , ABI = Abisko, DAR = Daring lake, NOS = Norh Slope, VOR = Vorkuta, HER = Herschel Island, ADV=Adventdalen, NYA=Ny Alesund

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