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Detection of landscape dynamics in the Arctic Lena Delta with temporally dense Landsat time-series stacks

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ABSTRACT

Arctic permafrost landscapes are among the most vulnerable and dynamic landscapes globally, but due to their extent and remoteness most of the landscape changes remain unnoticed. In order to detect disturbances in these areas we developed an automated processing chain for the calculation and analysis of robust trends of key land surface indicators based on the full record of available Landsat TM, ETM+, and OLI data. The methodology was applied to the ~29,000 km^2 Lena Delta in Northeast Siberia, where robust trend parameters (slope, confidence intervals of the slope, and intercept) were calculated for Tasseled Cap Greenness, Wetness and Brightness, NDVI, and NDWI, and NDMI based on 204 Landsat scenes for the observation period between 1999 and 2014. The resulting datasets revealed regional greening trends within the Lena Delta with several localized hot-spots of change, particularly in the vicinity of the main river channels. With a 30-m spatial resolution various permafrost-thaw related processes and disturbances, such as thermokarst lake expansion and drainage, fluvial erosion, and coastal changes were detected within the Lena Delta region, many of which have not been noticed or described before. Such hotspots of permafrost change exhibit significantly different trend parameters compared to non-disturbed areas. The processed dataset, which is made freely available through the data archive PANGAEA, will be a useful resource for further process specific analysis by researchers and land managers. With the high level of automation and the use of the freely available Landsat archive data, the workflow is scalable and transferrable to other regions, which should enable the comparison of land surface changes in different permafrost affected regions and help to understand and quantify permafrost landscape dynamics.

1. Introduction

The Arctic has been subject to a significant increase in air temperatures during the last decades, which are projected to further rise about 6 °C in terrestrial and around 10 °C in marine areas by the end of the 21st century (IPCC, 2013 — RCP 6.0). Such significant and, on geological time scales, sudden changes of climatic conditions have a potentially massive impact on thaw-vulnerable permafrost landscapes, which cover about 24 % of the northern hemisphere's land mass (Zhang, Barry, Knowles, Heginbottom, & Brown, 2008).

Increasing air and ground temperatures can lead to widespread thaw of permafrost soils and frozen deeper deposits, which are estimated to account for a carbon stock of more than 1.5 times that of the atmosphere (Hugelius et al., 2014; Strauss et al., 2013). Thaw and further warming of portions of this soil carbon pool would initiate and accelerate the decomposition of the largely inactive frozen soil carbon to carbon dioxide and methane, which in turn will contribute to further warming. The result is a positive feedback cycle with potentially global implications for climate and society (Grosse et al., 2011; Schuur et al., 2015). In particular, low-lying permafrost-dominated Arctic river deltas, located at the interface of terrestrial and marine realms, are highly vulnerable to landscape-scale changes driven by global warming. Important factors for these regions are permafrost thaw and terrain subsidence as well as changes in runoff patterns and sediment transport, seasonality and ice regimes, and relative sea level and coastline position (Burn & Kokelj, 2009; Ericson, Vörösmarty, Dingman, Ward, & Meybeck, 2006; Solomon, 2005; Terenzi, Jorgenson, & Ely, 2014; Walker, 1998).

Therefore, it is necessary to closely monitor the dynamics of Arctic river deltas to better estimate landscape scale climate change impacts and to quantify carbon fluxes. Due to the large size and remoteness of Arctic regions, many local and medium scale geomorphological, ecological, and hydrological processes remain unnoticed because field studies can only focus on limited and logistically accessible sites. Data on landscape-scale changes is sparse and heterogeneously distributed among few field study sites (e.g., Samoylov field station in the southern Lena Delta, Siberia) or natural resource exploration sites (e.g. Prudhoe Bay, Alaska). Various remote sensing data and techniques can provide excellent tools for detecting, monitoring, and scaling rapid disturbances as well as gradual changes in permafrost landscapes and overcome

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knowledge gaps. Field and high resolution remote sensing studies that have focused on local spatial extents include observations of permafrost thaw dynamics (Raynolds et al., 2014), surface hydrology (Karlsson, Lyon, & Destouni, 2014; Muster, Langer, Heim, Westermann, & Boike, 2012; Plug, Walls, & Scott, 2008) or coastal erosion (Günther, Overduin, Sandakov, Grosse, & Grigoriev, 2013; Lantuit et al., 2011).

Broad-scale processes in the Arctic or even globally, such as hydrological, vegetation or climate dynamics, are generally monitored with remote sensing data at a high temporal-, but a limited spatial resolution of 250m or coarser (Stow et al., 2004; Beck & Goetz, 2011; Fensholt & Proud, 2012; Goetz et al., 2011; Urban et al., 2014). While these approaches capture hemispheric-scale patterns, a large proportion of relevant landscape changes occurs at rather small spatial scales with high temporal dynamics, such as thermokarst lake changes or thaw slump development and escapes observations. The magnitude and abundance of these processes thus remains unnoticed in most places.

With increasing computation capacities and novel processing techniques in conjunction with the free availability of the entire Landsat archive, it becomes viable to exploit this valuable and consistent data source to assess multi-scaled land surface dynamics in the high latitude permafrost regions. Recently, the focus of monitoring high resolution land cover changes or disturbances shifted from the analysis of single, widely spaced observations towards a high-frequency multi-temporal analysis using the entire Landsat archive, with over 40 years of continuous acquisitions. Examples include mostly forestry applications, for example disturbance and recovery monitoring (Fraser, Olthof, Carrière, Deschamps, & Pouliot, 2012; Hansen et al., 2013; Kennedy, Cohen, & Schroeder, 2007; Olthof & Fraser, 2014; Pflugmacher, Cohen, & Kennedy, 2012), monitoring of glacial flow velocities (Rosenau, Scheinert, & Dietrich, 2015), or observations of snow cover persistence in Alaska (Macander, Swingley, Joly, & Raynolds, 2015). These studies are predominantly based on the analysis of temporal trajectories of multi-spectral indices (MSI) or the original spectral bands. In terrestrial permafrost areas, robust linear trend analysis of Landsat Tasseled Cap (TC) index time-series has been proposed (Fraser et al., 2012) and applied in different studies of land changes in Northwestern Canada, such as post-fire forest recovery (Fraser et al., 2014), the evolution of thaw slumps (Brooker, Fraser, Olthof, Kokelj, & Lacelle, 2014) and land cover change classification (Olthof & Fraser, 2014). Other studies on disturbances and changes in permafrost regions, based on multi-temporal Landsat data are available, such as thermokarst lake evolution or permafrost degradation (Beck, Ludwig, Bernier, Lévesque, & Boike, 2015; Karlsson et al., 2014; Plug et al., 2008). However, these studies do not fully exploit the temporal capabilities of the full Landsat archive.

In this study we present the multi-temporal analysis of Landsat-based land surface properties for the entire Lena river delta, an approximately 29,000 km^2 large permafrost-dominated region in Northern Siberia, for the 1999 to 2014 period. We provide robust calculations of linear trends of different well-established MSI (Landsat Tasseled Cap, NDVI [Vegetation], NDWI [Water], NDMI [Moisture]) and use these to assess the recent dynamics in this deltaic lowland landscape. We further identify and highlight diverse permafrost related processes and disturbances associated with the calculated spectral trends on different temporal and spatial scales.

2. Study area and data

2.1. Study Area

The Lena Delta is located in northeastern Siberia's continuous permafrost zone between 72° and 74°N and 123° to 130°E (Fig. 1). With an approximate size of 29,000 km² it is the largest Arctic river delta and one of the largest deltas globally (Walker, 1998; Schneider, Grosse, & Wagner, 2009). It is surrounded by the Laptev Sea with the adjacent New Siberian Islands to the north and the Chekanovsky and Kharaulakh mountain ranges to the south.

The delta is characterized by numerous river channels and more than 1500 islands of various sizes (Are & Reimnitz, 2000; Grigoryev, 1993). Morphologically, the delta can be divided into three distinct terraces (Grigoryev, 1993; Schwamborn, Rachold, & Grigoriev, 2002). The first terrace, further divided into the recent and the Holocene floodplains, is the youngest and currently active part of the delta and covers most of the east-northeastern areas as well as the southern and southwestern-most parts. Its surface predominantly consists of wetlands with ice wedge-polygonal tundra and thermokarst lakes (Morgenstern, Grosse, & Schirrmeister, 2008). The second terrace, also referred to as the *Arga Complex*, is located in the northwestern part and contains mostly sandy, comparably dry soils with low ground-ice content. Large, mostly oriented lakes and depressions are abundant in this area (Morgenstern et al., 2008). The third and oldest terrace appears in isolated patches in the southern delta region, and consists of remnants of a Late Pleistocene accumulation plain (Schirrmeister et al., 2003; Schirrmeister, Grosse, Schnelle et al., 2011). It is characterized by very ice-rich, organic-rich, fine grained sediments (*Yedoma*), which form a polygonal tundra landscape with deep thermokarst lakes and basins as well as thermo-erosional gullies (Morgenstern et al., 2008; Morgenstern, Grosse, Günther, Fedorova and Schirrmeister, 2011).

The geological and hydrological surface conditions are well reflected in the vegetation types. Within the 1st and the 3rd terraces, wet or moist Tundra is the dominating land-cover. However, drier tundra conditions are not uncommon. On the 2nd terrace and particularly in the northwestern delta region, seasonally drier conditions prevail with dry tundra being the most typical land-cover interspersed with wet or moist tundra, (see Fig. 2) (Schneider et al., 2009).

Near-surface permafrost soils of the Lena Delta contain a large organic carbon pool that is potentially vulnerable to mobilization upon thaw (Zubrzycki, Kutzbach, Grosse, Desyatkin, & Pfeiffer, 2013). Deeper sediments, in particular in the 3rd terrace, also contain a large organic carbon pool and may be thaw vulnerable due to their high ground ice content (Schirrmeister, Grosse, Wetterich et al., 2011).

The study area's climate is typical for the High Arctic with a mean annual temperature of -12.5 °C, measured at Samoylov station in the southern Lena Delta (Boike et al., 2013; observation period: 1998-2011). The seasonal temperature differences are pronounced with mean temperatures of 10.1 °C in July and −33.1 °C in February. Precipitation amounts are low with an average of about 200 mm, predominantly falling as rain during the short summer period. In the study area, the permafrost is continuous with depths of around 500-600m, though there is potential for permafrost-penetrating taliks underneath the major delta channels. The active layer depths range from 30 to 90 cm (Boike et al., 2013; Grigoryev, 1993). Vegetation cover in the Lena Delta is dominated by sedge, grass, moss and dwarf shrub wetlands (Schneider et al., 2009).

The Lena Delta is affected by pronounced seasonal runoff dynamics partially driven by a very large watershed integrating contributions from several climate zones. A significant spring flood during snowmelt and ice breakup results in water levels increased by several meters and temporary flooding of low-lying areas, followed by a strong drop of water levels in channels and a gradual decline of discharge through the summer season (Fedorova et al., 2015; Yang et al., 2002)

2.2. Data

The entire Landsat (LS) image archive of Thematic Mapper (TM), Enhanced Thematic Mapper + (ETM +) and Observing Land Imager (OLI) sensors was searched and filtered over all Worldwide-Reference System-2 (WRS-2) tiles intersecting the Lena Delta. In total 14 WRS-2 tiles were selected for this study (Table 1). The data were acquired in radiometrically and geometrically terrain-corrected state (processing level L1T) from the United States Geological Service (USGS) via the *GLOVIS* and *EarthExplorer* platforms. The imagery has a spatial resolution