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A Mobile Instrumented Sensor Platform for Long-Term Terrestrial Ecosystem Analysis: An Example Application in an Arctic Tundra Ecosystem

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ABSTRACT. To address impacts of climate change on natural ecosystems, researchers need efficient and integrated ground- based sensor systems capable of detecting plant to ecosystem alterations to productivity, species composition, phenology, and structure and function over seasonal, inter-annual, and decadal time scales. Here, we introduce the Mobile Instrumented Sensor Platform (MISP), a versatile robotic sensor system that is suspended above or within the canopy and is designed to be adaptable for both short and long-term observations, and suitable for multiple ecosystems. The system is novel in that it is mobile, rather than static, the suite of sensors can be customized, and installation and operation requires minor surface disturbance relative to comparable systems already in use. MISP was developed as a contribution to the Arctic Observation Network's International Tundra Experiment (AON-ITEX), where at five locations between the low and high Arctic we record observations of different tundra plant communities over a 50 m transect. Observations include air temperature, surface temperature, incoming and outgoing long- and short-wave radiation, albedo, Normalized Difference Vegetation Index (NDVI), three-dimensional video, two and three-dimensional photography, and hyperspectral reflectance. Data analysis has proven the system's suitability for detecting subtle ecosystem changes across small-scale soil moisture and other gradients due to the mobile nature of the sampling. Long-term studies will benefit from this approach because sampling is repeatable with high spatial and temporal resolution and the system can be adapted to incorporate future technologies.

Keywords: Arctic tundra vegetation, vegetation change, land cover change, remote sensing, Alaska

1. Introduction

Ecological responses to recent changes in climate are becoming increasingly noticeable (Walther et al., 2002; Hinzman et al., 2005; Cleland et al., 2007; Post et al., 2009; AMAP, 2011; Callaghan et al., 2011) and the provision of ecosystem goods and services are being impacted (Powledge, 2006). Accordingly, the research community is faced with the difficult task of quantifying the climate change responses for a gamut of land-atmosphere and other system interactions and feedbacks to enhance our understanding of and capacity to predict future Earth System states (McGuire et al., 2006). A shift in terrestrial plant communities and ecosystem structure and function has the potential to affect the global climate system (McGuire et al., 2006) by altering land-atmosphere exchange and sink-source dynamics of carbon dioxide (CO_2) and or methane (CH_4). Shifts in species distributions and plant communities also have the capacity to dramatically alter surface energy balance (Chapin et al. 2005). Thus, improved understanding and model parameterization of the factors and processes controlling these dynamics is imperative for advancing our knowledge of the future arctic and Earth System (Hart and Martinez, 2006; Huete and Saleska, 2010).

Determining which technologies will provide the most robust, efficient, and accurate means of detecting plant to landscape phenological dynamics and change at adequate spatial scales to account for small-scale heterogeneity is a fundamental challenge (Asner et al., 1998). Advances in engineering and computing over the past few decades have catalyzed vast improvements in sensor design, processing power, and remote data transmission that enable improved capacities for rapid and efficient data collection, transmission, and analysis for large sampling areas or numerous sampling locations. Zerger et al. (2010) describe how cutting-edge technology provides the means to improving our real-time understanding of environmental phenomenon in biology, geology, hydrology, and climatology to name just a few disciplines that have benefitted from this realm of technological innovation. A va-

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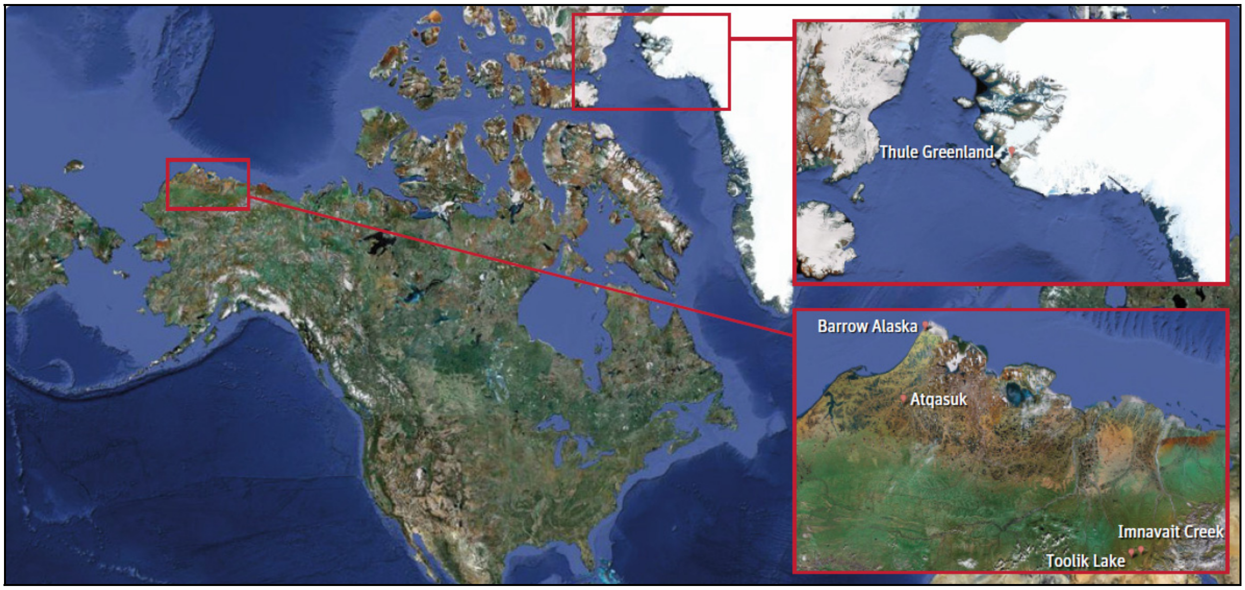

Map 1. Mobile Instrumented Sensor Platform (MISP) locations in the arctic - Thule, Greenland (76°32' N, 68°42' W); Barrow, Alaska (71°18' N, 156°40' W), Atqasuk, Alaska (70°27'N, 157°24'W), Toolik Lake, Alaska (68°38' N, 149°36' W) and Imnavait Creek, Alaska (68°37' N, 149°18' W) (Source: Kipp & Zonen, 2013).

riety of technological approaches and sensor systems have been developed for answering ecological questions, but all include vastly different sensor systems, instrument platforms, and data transmission methods that are often only suited to answering very specific questions or are not suited for cross-ecosystem deployment (Kaiser et al., 2004; Rahimi et al., 2004 Gamon et al., 2006; Jordan et al., 2007; Rundel et al., 2009; Goswami et al., 2011). While these sensor systems have contributed to scientific advancement, an increasing challenge for the ecological research community has been the design of standardized sensor systems that can be deployed and maintained effectively across multiple ecosystem types, thereby enhancing capacity for cross-ecosystem comparative analysis.

Impacts of, and responses to climate variability and climate change differs between ecosystems (Walther et al., 2002; Walker et al., 2006; Elmendorf et al., 2012a). For the past 30 years, the Arctic ecological community has largely relied on satellite-derived measurements of the Normalized Difference Vegetation Index (NDVI; Kriegler et al., 1969) to derive landscape-level trends in arctic ecosystem productivity (Myneni et al., 1997; Epstein et al., 2012; Raynolds et al., 2012). Since 1997, the community has come to recognize that Arctic tundra landscapes are mostly greening (Jia et al., 2003; Verbyla, 2008; Bhatt et al., 2010, Forbes et al., 2010), suggesting species distributions have altered and/or that plant cover and productivity have increased over time (Xu et al., 2013).

To enhance inter-comparison between study locations, ecologists are increasingly seeking standardized cyberinfrastructure including information technology and sensors to collect sustained high frequency observations of ecosystem properties. Designing sensor systems to detect seasonal to long-term changes in plant to landscape phenology and community composition and the accompanying shifts in eco-system carbon, nutrient, and water cycles requires an interdisciplinary approach that merges spectral imaging, pattern analysis, plant and soil biology. In this study we report on a newly designed mobile robotic sensor system that can repeatedly, objectively, and non-intrusively observe high resolution near-surface phenomenon to provide data that are critical for understanding long-term connections between plot- (Hollister et al., 2005; May and Hollister, 2012; Elmendorf et al., 2012b) and landscape to regional-scale properties and processes (Kerr and Ostrovsky, 2003; Stow et al., 2004) to better quantify changes to Arctic land surfaces.

We developed the Mobile Instrumented Sensor Platform (MISP) to quantify seasonality of critical ecosystem properties (i.e. incoming and outgoing long- and short-wave radiation (including albedo), air and surface temperature, three-dimensional imagery of the ecosystem surface, and hyperspectral reflectance of radiation) using commercially available sensors and data processors to define trajectories of change, tipping points, the direction of land-atmosphere interactions and feedbacks. Specific to this study, we employ what we believe to be a unique suite of sensors on a light-weight mobile robotic sampling platform mirrored at five locations spanning the high to low Arctic as a contribution to the Arctic Observation Network (AON) and the International Tundra Experiment (ITEX) (Map 1).

2. Arctic Study Site Details

The MISP systems were established at participating AON-ITEX sites spanning a gradient from the high to low Arctic located near (1) Thule, Greenland (76°33' N, 68°33' W; 170 m a.s.l.); (2) Barrow, Alaska (71°18' N, 156°40' W; 7 m a.s.l.); (3) Atqasuk, Alaska (70°29' N, 157°25' W; 21 m a.s.l.); (4); Imnavait Creek, Alaska (68°37' N, 149°18' W; 927 m a.s.l.) and (5) Toolik Lake, Alaska (68°37' N, 149°36' W; 736 m

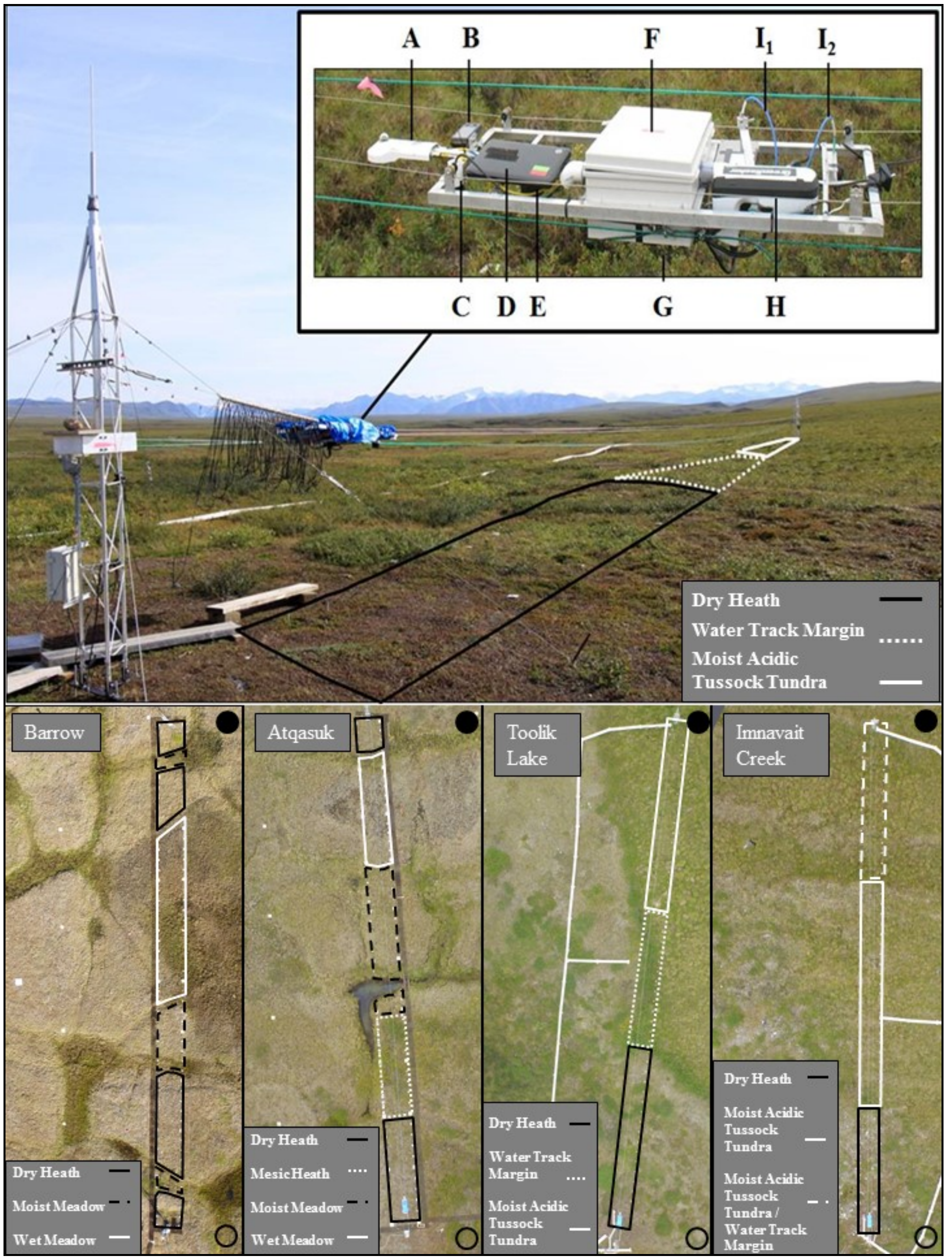

Figure 1. The MISP at Toolik Lake (above): Kipp & Zonen CNR4 Net Radiometer (A), Fuji 3-D Camera (B), Apogee Instruments SI-111 infrared temperature sensor (C), Hewlett Packard Mini PC shown outside of enclosure for illustration purposes (D), Campbell Scientific SR50a sonic distance sensor (E), enclosure with Campbell Scientific CR3000 data logger (F), thermocouple wire (G), Trimble GreenSeeker RT100 (H), and Ocean Optics Jaz Combo-2 Spectrometer (inside enclosure) with fiber optics - one viewing a white reference panel (I_1) one viewing the surface(I_2). Note the power cord supported by one of the support cables to the left of the system. Aerial photographs collected via Kite Aerial Photography of the four 50m Alaskan transects with vegetation types outlined (below). High-resolution aerial imagery for the Thule, Greenland site is currently unavailable.

a.s.l.) (Map 1; Figure 1). The locations of the MISP systems were established to span a range of representative plant communities across distinctive soil moisture gradients (ex. Dry Heath to Wet Meadow). Table 1 depicts the dominant species comprising the different vegetation types of each transect. Data collected from the MISP systems, plant cover assessments, and kite aerial photography (KAP) of the MISP locations are freely available via the Advanced Cooperative Arctic Data and Information Service (ACADIS - http://www. aoncadis.org). For details regarding all projects contributing to the ACADIS data repository, including AON-ITEX, visit http: //www.aoncadis.org/projects.

Table 1. Description of the Vegetation Types at each Arctic MISP Location

Moisture	Thule	Barrow	Atqasuk	Imnavait Creek	Toolik Lake
Dry	Dry Heath / Barren	Dry Heath / Mesic Heath	Dry Heath / Mesic Heath	Dry Heath	Dry Heath
	Dryas integrifolia, bare soil	*Salix rotundifolia, Carex aquatilis-stans, Luzula arctica*	*Vaccinium vitis-idaea, Ledum palustre, Cladonia spp.*	*Arctous alpina, Vaccinium vitis-idaea, Betula nana*	*Arctous alpina, Vaccinium vitis-idaea, Betula nana*
Intermediate	Prostrate Dwarf-Shrub/Herb Tundra	Moist Meadow	Moist Meadow	Moist Acidic Tussock Tundra	Water Track Margin
	Dryas integrifolia, Salix arctica	*Salix rotundifolia, Carex aquatilis-stans, Eriophorum spp.*	*Salix pulchra, Vaccinium vitis-idaea, Ledum palustre*	*Eriophorum vaginatum, Spagnum sp.*	*Betula nana, Salix pulchra, Ledum palustre*
Moist or Wet	Hemiprostrate Dwarf-Shrub Tundra	Wet Meadow	Wet Meadow	Moist Acidic Tussock Tundra / Water Track Margin	Moist Acidic Tussock Tundra
	Cassiope tetragona, Salix arctica	*Carex aquatilis-stans, Dupontia fisherii, Eriophorum spp., pleurocarpous mosses*	*Carex aquatilis, Eriophorum russeolum*	*Eriophorum vaginatum, Betula nana, Spagnum sp.*	*Eriophorum vaginatum, Carex bigelowii, Spagnum sp.*

[*] Dominant species within each vegetation type at each location are also included.

[**] Sources of the vegetation classifications are as follows: Thule, Greenland (Walker et al., 2005); Barrow (Webber, 1978); Atqasuk (Webber, 1978); Imnavait Creek (Walker and Walker, 1996);Toolik Lake (Walker and Walker, 1996; Walker and Barry, 1991).

3. Materials and Sensor System

The four sites in Alaska are equipped with two meteorological towers approximately 50 m apart and connected with suspended stainless steel cables that support the robotic sensor system between 1.1 ~ 0.8 m over the canopy at each site. In Greenland, steel pipes anchored in cement footings are used instead of the meteorological towers. To minimize disturbance, we have not installed support for the cables between the towers. Figure 1 and Table 2 describe the MISP transects, instruments, and the intended use of each instrument. The infrared thermometers, net radiometers, NDVI sensors, and sonic distance sensors are all factory calibrated while the spectrometers and 3-D video recordings are calibrated on-site for each individual daily scan. The MISP consists of an aluminum frame suspended from the cables on pulleys with double shielded stainless steel bearings and quick button releases for easy saddling and unsaddling (Figure 2A-2B). A looped nylon-coated steel cable (Figure 2C) runs over a gearhead motor at Tower 1 and a pulley at Tower 2 (Figure 2D-2E), which is fastened to the MISP to enable mobilization of the platform at a rate of roughly 3 cm s^{-1}. The motors are controlled by a Campbell Scientific CR200 data logger (Camp- bell Scientific: Logan, Utah, USA). To monitor the distance the mobile platforms travel along the cables, which is essential for co-locating repeat measurements, a rare-earth magnet is mounted onto the drive pulley that trips a magnet switch with each pulley rotation (Figure 2F-2G). To geolocate measurements made by sensors on the mobile platform, data from the MISP are time-synched with the number of pulley rotations from the drive tower. The weight of the sensor platform is approximately 7 kg.

Our systems are currently undergoing developmental review and we are interested in moving toward full automation in the near future. We currently require personnel on-site to (1) supply power to the system via opening circuit breakers, (2) calibrate the spectrometers before each daily scan, (3) operate 3-D video recording devices, (4) start (and stop) the motors at the beginning (end) of each daily scan, (5) infrastructural adjustments including leveling support cables and securing guy wires on towers, (6) record weather conditions at the time of a scan, and (7) make note of senor performance and infrastructural integrity each day as part of the developmental review.

Power is supplied as 12-volt DC and 115-volt AC by two 12-volt batteries (2.5 kW·h total) charged by photo-voltaic panels with a maximum solar generation capacity of 260 W (yielding roughly 1.5 kW·h·day^{-1}), which surpasses the demand of our system but allows for multiple daily observations in the event of sustained overcast skies or charge malfunction and the addition of more sensors. AC/DC converters onboard the MISP systems are used to convert the AC current to 5 and 12-volt DC needed by system components. Light AC power cord from the distribution panel is attached to 25 mm long pieces of 25 mm diameter polyvinyl chloride (PVC) tubing, which slide over one of the support cables, to provide power to the MISP as it traverses the 50 m transect without interfering with sensor footprints or contacting underlying vegetation (Figure 1). This cable curtain approach could be replaced with an onboard 12-volt battery and a DC/DC converter, although this might add weight to the system and require routine battery recharge or docking with a base charge station. Currently, the net radiometer (Kipp & Zonen: Delft, Netherlands), infrared thermometer (Apogee Instruments Inc.: Logan, Utah, USA), sonic vertical distance sensor (Campbell Scientific: Logan, Utah, USA), and GreenSeeker NDVI sensor (Trimble Navigation Ltd.: Sunnyvale, California, USA)

Table 2. Instrumentation Hosted on Our Current Systems and the Ecological Variables Derived from these

Figure 1	Instrument
A	Kipp & Zonen CNR4 Net Radiometer (Kipp & Zonen: Delft, Netherlands)
B	Fuji Finepix Real 3-D Digital Camera (Fuji Film Corp.: Tokyo, Japan)
C	Apogee SI-111 Infrared Thermometer (Apogee Instruments Inc.: Logan, Utah, USA)
D	Hewlett-Packard Mini PC 1104 (Hewlett-Packard Co.: Palo Alto, CA, USA)
E	Campbell Scientific SR50a Sonic Distance Sensor (Campbell Scientific: Logan, Utah, USA)
F	Campbell Scientific CR3000 Data logger (Campbell Scientific: Logan, Utah, USA)
G	Thermocouple wire
H	Trimble GreenSeeker RT100 (Trimble Navigation Ltd.: Sunnyvale, California, USA)
I_1, I_2	Ocean Optics Jaz Combo-2 Spectrometer (Ocean Optics Inc.: Dunedin, Florida, USA)
	Intended use
A	Net radiation, albedo
B	Vegetation greenness, vegetative growth, and vegetative composition
C	Leaf temperature, stomatal opening, moss water content
D	Operation of Jaz Spectrometer
E	Plant height growth and leaf area development
F	Data repository
G	Air temperature
H	Normalized Difference Vegetation Index (NDVI)
I_1, I_2	Vegetation greenness, Normalized Difference Vegetation Index (NDVI), Photochemical Reflectance Index (PRI), Enhanced Vegetation Index (EVI), Water Band Index (WBI), and many others

*Each instrument is identified by a letter corresponding to those used in Figure 1.

are controlled by a Campbell Scientific CR3000 data logger (Campbell Scientific: Logan, Utah, USA). The spectrometer (Ocean Optics Inc.: Dunedin, Florida, USA) is controlled by a mini-PC (Hewlett-Packard Co.: Palo Alto, CA, USA). We collect data at all sites during the snow-free season between late May late August every day around midday (within 2 hours of solar noon) except for periods with excessive rain, snow, or wind.

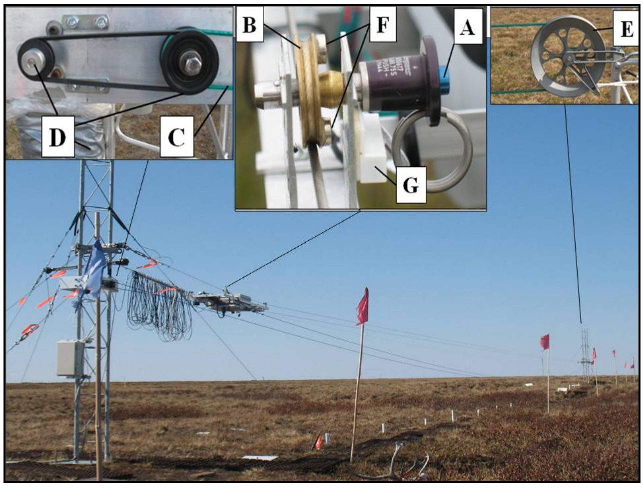

Figure 2. The MISP at the site near Atqasuk, Alaska showing the location of: push-button quick-release pins (A) and pulleys that support the mobile platform on stainless steel cables (B); nylon-coated steel drive cable (C); gearhead motor (D); pulley that supports the nylon-coated drive cable (E); Rare-earth magnets mounted a pulley wheel (F); and the magnetic switch (G).

4. Examples of Initial Observations

We integrate daily scans of one- and three-second observations to represent roughly 45 cm segments along each 50 m transect sampled. Each segment is roughly 1-2 m in width depending on the height of the sensor platform and each sensor's field-of-view. Thus, we provide observations of Arctic vegetation communities with fine spatial and temporal resolution that is well suited to scaling plot-level vegetative community, function, and structure observations to higher spatial scales. Landscape-scale characterization of different variables (ex. albedo, surface temperature, etc.) for dominant land cover types (ex. Dry Heath, Wet Meadow, etc.) is possible through the integration of manual plot-level examinations (e.g. estimates of species cover and abundance) with concurrent semi-automated observations from the mobile platform. Integrating automated and manually sampled data in this fashion is important for parameterizing regionally-based models that utilize satellite and/or aerial imagery (Weller et al., 1995; Boelman, 2004; Stow et al., 2004; Vorosmarty et al., 2010).

A novel finding from our initial data analysis is an inverted relationship between deviations from daily mean (Δ) surface temperature and albedo in Dry Heath, Water Track Margins, and Moist Acidic Tussock Tundra at Toolik Lake in 2010 (i.e. decrease in albedo associated with lower temperatures and vice versa) (Ahrends et al., 2012; Figure 3) compared to expected large-scale trends for the same variables (Wang and Key, 2003; Bender et al., 2006; IPCC, 2013; Urban et al., 2013). For instance, the most recent report from the Intergovernmental Panel on Climate Change (IPCC) quantifies the radiation loss related to global mean albedo at 100

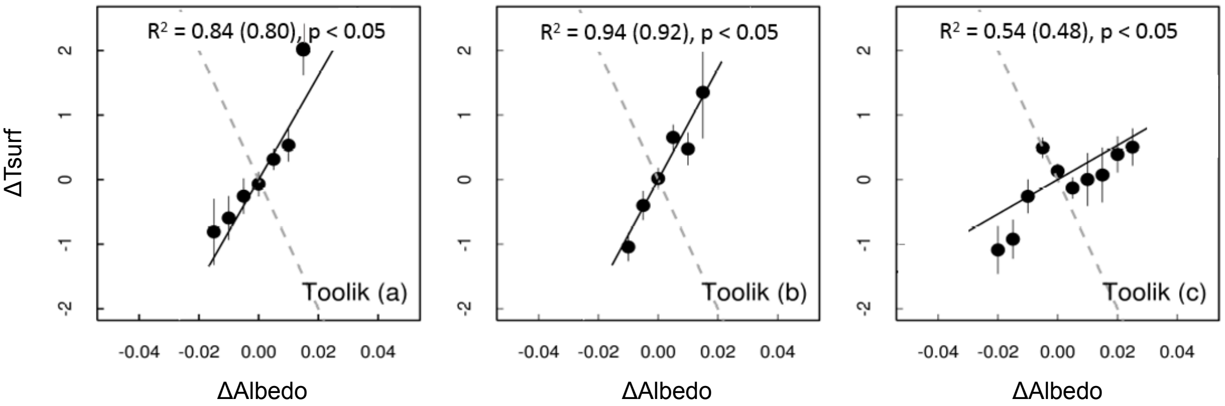

Figure 3. Linear regression fit between binned averages of relative surface temperatures based on Apogee IR radiometer measurements (ΔTsurf) and grouped relative albedo (ΔAlbedo) values in Dry Heath (a), Water Track Margin (b), and Moist Acidic Tussock Tundra (c) at Toolik Lake, Alaska in 2010 (Ahrends et al., 2012). Points represent positive or negative deviations relative to the daily mean values (mean-centered data) for each vegetation type over the 2010 season from June-August. The dashed gray line indicates the decrease of surface temperatures of 1 K due to an increase of albedo values of 1% that is expected in large-scale studies (IPCC 2013; Bender et al., 2006; Urban et al., 2013; Wang and Key, 2003).

$W \cdot m^{-2}$ (IPCC, 2013 - AR5, Chapter 2). If this value decreases by 1%, then an increase in global mean radiative temperature of + 1 K can be expected with a range 0.6 to 2.5 K based on the range of climate sensitivities of the models (IPCC, 2013 - AR5, Chapter 9). To account for observation date-specific offsets for albedo and surface temperature observations, the relative difference (Δ) of each value is calculated by subtracting the corresponding mean observation value obtained during each specific date and each vegetation type. Our 2010 seasonal datasets constitute roughly 100 ~ 200 data points depending on the length of the vegetation type. Resulting values represent positive or negative deviations relative to the daily mean values (mean-centered data) for each vegetation type over the 2010 season from June-August. We calculated Pearson correlation coefficients between the mean centered data values separately for each vegetation type (p values < 0.05 were considered significant). For linear regression analysis, single values of the different vegetation types were grouped in intervals depending on their frequency. The points appearing in Figure 3 represent aggregated values from the albedo data which were used for bin averaging the surface temperature data. When the frequency of the resulting albedo bins is greater than five they are used for a linear regression analysis with the grouped surface temperature data. Due to the fact that our finding is contrary to published expectations, we are currently evaluating whether our small-scale analysis can appropriately be compared to large-scale trends. This study highlights how a better understanding of how local-scale, short term phenolmenon could potentially influence modelling of regional-scale, long-term climate impacts in the arctic.

NDVI is an especially important parameter as part of the MISP measurement packages because of the gaining popularity of NDVI measurements in field-based ecological studies (e.g. Walker et al., 2003; Fensholt and Proud, 2012; Raynolds et al., 2012; Walker et al., 2012; Gamon et al., 2013). As a result of such studies extrapolation of ecologically important metrics from optical properties is increasingly possible. For example, NDVI has been found to correlate strongly with biomass (Reidel et al., 2005a; Reidel et al., 2005b), shrub cover, and to ecosystem CO_2 exchange (Anderson-Smith et al., 2010; Boelman et al., 2003; Jia et al., 2004). Application of our findings to the observed 11% increase in NDVI of moist acidic tussock tundra in the Kuparuk River watershed of Alaska between 1982 and 2003 suggests an 88% increase in peak season deciduous shrub cover, a 43% increase in mid-day midsummer gross primary production (GPP) and a 66% increase in mid-day mid-summer net ecosystem exchange (NEE) (Anderson-Smith et al., 2014). These findings, while having only been recently well defined for moist acidic tussock tundra, exemplify the scaling capacity of *in situ* canopy reflectance measurements to ecosystem biogeochemical cycles that could have local to global consequences. This scaling capacity is especially powerful considering that Moist Acidic Tussock Tundra is > 40% of the Alaskan Arctic and 20% of the circum-Arctic tundra surfaces (Walker et al., 2005). To demonstrate how data collected from the MISP system can be visualized to show spatiotemporal trends, we display observations of NDVI along transects at all five sites for the 2012 sampling period (Figure 4). A linear interpolation for each segment in each month between June and August was used to generate estimations of NDVI for days without data collection as a result of logistical constraints, rain, snow, or excessive wind.

Limitations to our system include weight carrying capacity, cable sag (0.01 ~ 0.3 m) due to the weight of the system, and an inability to withstand excessive wind greater than ~12 ms^{-1}, rain during data collection, or snow during data collection. Each sensor's field-of-view is affected by the height of the MISP and, therefore, will require attention when attempting to scale MISP data down to plot-level and up to landscape-level analyses to ensure accurate representation of vegetation from each MISP observation. MISP has proven to be robust and well suited for monitoring the response of tun-

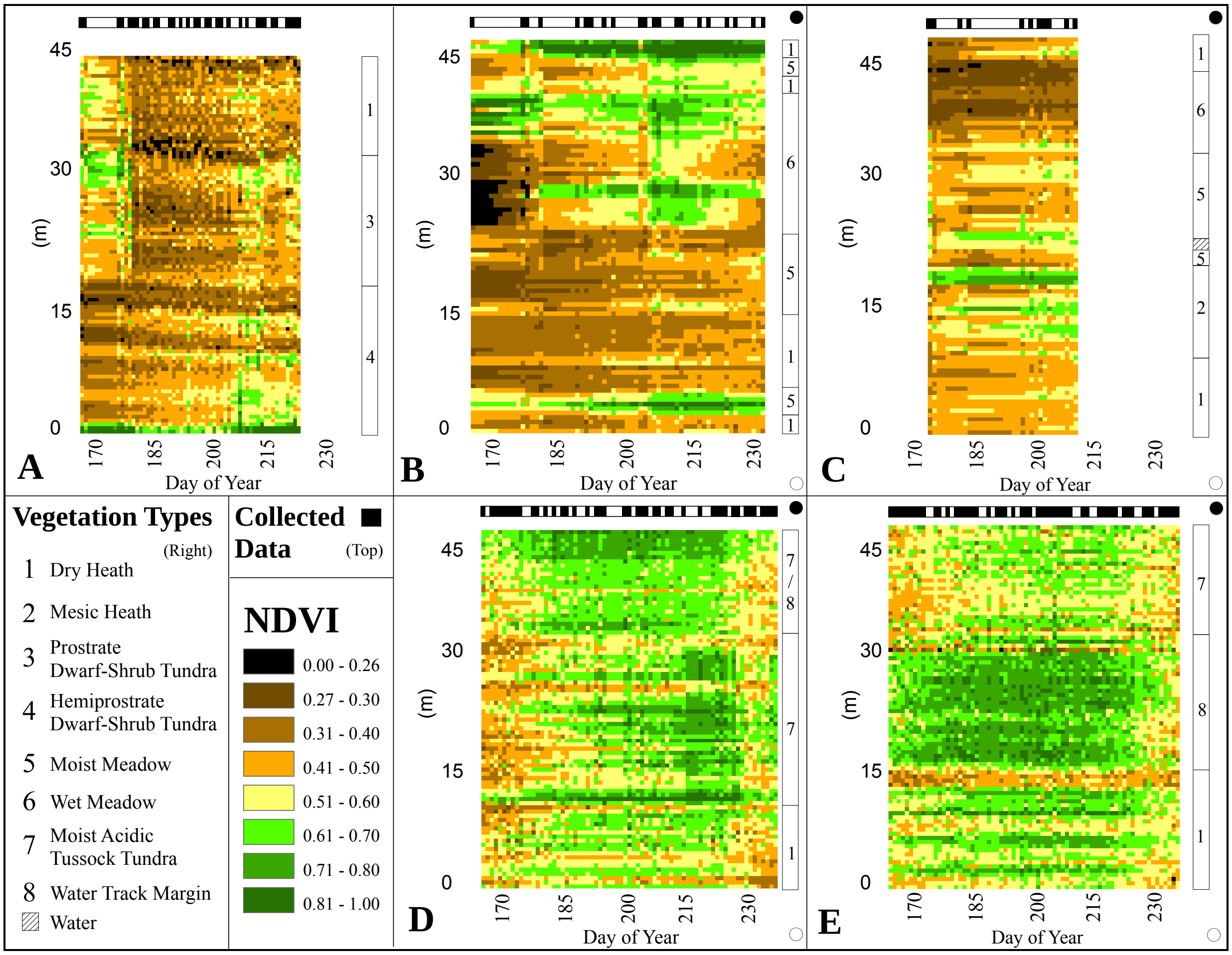

Figure 4. Observations of Normalized Difference Vegetation Index (NDVI) acquired by the Trimble GreenSeeker NDVI sensor at Thule, Greenland (A), Barrow, Alaska (B), Atqasuk, Alaska (C), Imnavait Creek, Alaska (D), and Toolik Lake, Alaska (E) collected during the 2012 field season (June-August). Missing data due to inclement weather or logistical constraints were determined using interpolations from linear regressions of data collected for each segment and each month (June-August). Vegetation types for each transect are displayed to the right of each panel. For clarification of transect orientation relative to Figure 1, the open and solid circles that appear to the right of each transect align with those to the right of each panel. Sources of the vegetation classifications are as follows: Thule, Greenland (Walker et al., 2005); Barrow (Webber, 1978); Atqasuk (Webber, 1978); Imnavait Creek (Walker and Walker, 1996);Toolik Lake (Walker and Walker, 1996; Walker and Barry, 1991).

dra plants, plant communities, and landscapes to seasonal, inter-annual and decadal time scale climate variability and change (Ahrends et al., 2012). Yet, our system is flexible and expandable allowing researchers to select sensors to meet the unanticipated new needs of future data collection in any ecosystem.

5. Summary

The MISP system has been shown to collect meaningful observations that reveal relationships that would otherwise have been difficult to collect with commercial off-the-shelf equipment or other sampling platforms we are aware of. Continuing to collect observational data should prove invaluable to future scientific inquiry that includes connections to arctic landscapes as well as other ecosystems across the globe. Future technological advances will likely improve the system, which is specifically designed to be adaptable and easily modified to be accepting of additional sensors relevant for ecological, meteorological and other studies. For ground-based measurements of plant and ecosystem phenology and productivity tundra ecologists have typically relied on individual plant and plot-level measurements (Oberbauer et al., 2013; Huemmrich et al., 1999; Arft et al., 1999). Approaches at both spatial scales have merit and provide unique insight as to the nature of the changing Arctic; however integrating measurements across spatial scales is important (Vorosmarty et al., 2010; Boelman, 2004; Williams et al., 2008; Stow et al., 2004), especially in areas like the Arctic where consistent cloudiness make use of high frequency satellite data difficult.

Accurate observation of changes to Arctic vegetation macrostructure and function requires sensor systems with the ability to detect biophysical interactions at a range of spatiotemporal scales (Asner et al., 1998). We have, nonetheless, found the existing system to have the potential to be highly effective for the examination of seasonal and inter-annual variability in ecosystem structure and function and establishing a new mechanism for being able to parameterize models and scale between plot-level and satellite-derived observations at the landscape level. Moreover, our data aligns with the data sharing policies of AON and is freely available from ACADIS.

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