Section 3.1. Hydrology & Permafrost Working Group (HPWG)

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Overarching Objective:

The primary objective of the Hydrology and Permafrost Working Group (HPWG) is to understand the processes controlling changes in the distribution and properties of permafrost and hydrologic systems within the ABoVE domain, and the feedbacks and consequences of these changes on flora, fauna, carbon biogeochemistry and ecosystem services. Projects within the HPWG focus on identifying and characterizing recent spatial and temporal variability and shifts in active layer, thermokarst disturbances, deep permafrost and their influence on hydrologic pathways, landscape wetting and drying patterns, seasonal surface thaw and snow cover, and linkages between other critical ecosystem properties. Specifically, HPWG activities will identify and address key knowledge gaps for the ABoVE domain by targeting specific objective areas outlined below. Information gained through HPWG activities will be instrumental in identifying landscapes experiencing accelerated rates of change and characteristics, mechanisms and feedbacks that enhance ecosystem vulnerability to change under a warming climate. The HPWG will work with ABoVE managers and WG leaders to prioritize key observations and monitoring efforts, and to coordinate the collection of critical in situ permafrost and hydrology measurements among ABoVE project teams

Specific Objectives:

To quantify for the ABoVE domain the spatial and temporal patterns of recent change in, primary change drivers for, and physical process linkages between:

Obj. 1: *The timing and duration of annual surface non-frozen period;*
Obj. 2: *Active layer depth and thickness, permafrost temperature and thermokarst activity;*
Obj. 3: *Surface soil moisture, longer-term spatial and temporal patterns of land water inundation, lake area change;*
Obj. 4: *Snow cover characteristics (presence/absence, water equivalent, duration, timing of snow onset and melt);*
Obj. 5: *Associated influences of changing permafrost landscape and hydrologic characteristics on regional vegetation greening/browning, altered land-atmosphere carbon exchange, animal habitat and migration, transportation networks and ecosystem services to society within the ABoVE domain.*

Objective 1 Action Plan:

Kimball-04 will provide annual non-frozen period trend and anomaly maps for the ABoVE domain from 1980-2017 (Appendix: Table 1). These maps will identify the annual timing and duration of surface non-frozen period, locations of mid-winter thaw events, corresponding summary statistics and anomaly/trend plots highlighting major regions of change. Satellite data used to produce these maps will include 25-km resolution Daily Landscape Freeze/Thaw (FT) Status (V3) products derived from 36 GHz SSMR/SSMI/SSMIS and AMSRE/AMSR2 satellite sensors (Kim et al. 2014) and finer scale (~6-12-km resolution) FT products derived from AMSRE/AMSR2 (2003-present). Freeze-thaw retrievals for recent years from lower-frequency L-band measurements (SMOS; SMAP) will be utilized to better understand frequency dependence in the FT retrievals and to evaluate the potential for spatial downscaling using the limited period of SMAP 3-km resolution L-band radar measurements.

Objective 2 Action Plan:

The HPWG will characterize active layer depth (ALD) for the ABoVE domain using existing remote sensing products. Available annual ALD products include those described in Park et al. (2015) which incorporate 37 GHz daily surface FT retrievals from SSMR-SSMI/I, land cover maps, and MODIS (Terra and Aqua) Land Surface Temperature (MOD11CI and MYD11CI) inputs over the 2003-2009 period (Kimball-04). The static ALD product (Striegl-01) described in Pastick et al. (2015) is provided at a 30-m spatial resolution for the Alaska domain and uses input Landsat satellite imagery, climatic data, thematic maps, and field observations within an integrated decision and regression tree framework. The HPWG will explore opportunities to extend the Pastick et al. (2015) product to the entire ABoVE domain (currently, only Alaska is represented) and to extend the Park et al. (2015) product through 2016.

The HPWG will work with Schaefer-03 and Moghaddam-03 to further develop permafrost applications of data derived from spaceborne and airborne SAR for select regions within the ABoVE domain. Schaefer-03 used the Remotely Sensed Active Layer Thickness (ReSALT) algorithm (Liu et al. 2015A) to measure seasonal surface subsidence and to infer ALD and identify thermokarst features over select locations across the North Slope, Alaska (Barrow, Prudhoe Bay, Anaktuvuk, Happy Valley, Toolik Lake). Accompanying Ground Penetrating Radar (GPR) measurements are also available (Liu et al. 2015B). Satellite retrievals required to develop this product include C-band ERS-1/2 for 1991-2000 and L-band ALOS PALSAR for 2006-2010. Moghaddam-03 is investigating airborne AirMOSS and UAVSAR L- and P- band retrievals to characterize and detect seasonal changes in ALD properties, including profile soil moisture, water table depth and near-surface soil organic layer properties. The L- and P- band SAR retrievals complement other ABoVE projects by providing high resolution (approximately 15-m and 90-m) gridded data that can be used as observed targets for permafrost model simulations, inputs into terrestrial carbon models, and to validate satellite data derived soil moisture products and ALD maps. If feasible, extensive GPR active layer thickness (ALT) measurements collected at Barrow, Deadhorse and Toolik (Schaefer-03; Moghaddam-03) will validate AirMOSS and UAVSAR retrieval products (Moghaddam-03).

The HPWG will coordinate and consolidate the collection of ALD, organic layer thickness, and other key measurements identified by the WG as being essential environmental data variables. The WG will also identify other resources including borehole data, in addition to Circum-arctic Active Layer Monitoring (CALM) measurements, for distributed observations of ALD within the ABoVE domain to benchmark satellite and airborne products.

Objective 3 Action Plan:

Kimball-04 will work with Carroll-01 to compare and validate AMSR fractional water products (5 & 25-km) and Landsat derived lake maps for the ABoVE domain. Kimball-04 will also provide downscaled (1-km) AMSR surface water inundation maps encompassing lake bodies, emergent vegetation and flooded surfaces for select regions within the ABoVE domain. Potential synergistic activities between Kimball-04 and NGEE-Arctic (Wullschleger-01) include comparisons of spatial/temporal patterns observed in satellite data records over the North Slope, Alaska (AMSR water inundation, surface FT, SSMI/MODIS ALD estimates) with finer scale (< 2 km) Terrestrial Ecosystem Model (TEM) thermokarst simulations. Carroll-01 will provide fine-scale (30-m) lake maps for the ABoVE domain using Landsat time series for three epochs

(1991, 2001, 2011) and supplemental MODIS imagery for the 2001 and 2011 epochs as needed to clarify the ice free period. Data provided will include nominal extent of water for the epoch during the ice-free season. Kimball-04 and Carroll-01 can work with Meyer-01 to compare AMSR and Landsat based surface water products with other fine-scale regional maps of lake change proposed by Meyer-01 (using L-band SAR and ALOS PALSAR, ALOS-2, SAOCOM, NISAR, etc.) and wetland/surface water change proposed by Cook-B-02 (Landsat, HyspIRI). Striegl-01 will coordinate with Carroll-01 to augment existing Landsat derived lake maps and enhance temporal analysis with focus on the Yukon Flats of Alaska. Augmentation includes detection of inundation of extracted lake/wetland features from Landsat data acquired between 1984 and present. Diachronic analysis will provide insight regarding long-term surface extent trends and place lakes/wetlands in homogeneous groups or clusters. Synchronous behavior will be identified, suggestive of surface and/or subsurface connectivity between lakes, wetlands, and river systems. Permafrost hydrology modeling will be used to explore lake area/permafrost dynamics and investigate processes supporting the evolution of inland water shallow subsurface connectivity in lake-rich lowlands.

Kimball-04 and Moghaddam-03 will combine efforts to validate SMAP, AirMOSS, and UAVSAR soil moisture products and provide recommendations for retrieval algorithm improvement. AirMOSS algorithms provide soil moisture estimates within the active layer, whereas UAVSAR and SMAP provide surface soil moisture estimates. Striegl-01 will provide estimates of soil moisture within the active layer and shallow permafrost using in situ Nuclear Magnetic Resonance (NMR) and electrical resistivity tomography (ERT) technology in central Alaska, and the associated protocols. Schaefer-03 and Moghaddam-03 will work to develop protocols for applying collocated GPR and in situ probe information to retrieve landscape soil moisture data. The HPWG recommends continued efforts to integrate in situ soil moisture observations with airborne and spaceborne retrievals to validate and improve remote sensing algorithms for the ABoVE domain. This will require coordination between ABoVE team members prior to and during field activities, the design and implementation of integrated in situ soil moisture monitoring systems and strategic field and airborne data collection at ABoVE core sites.

Objective 4 Action Plan:

Prugh-01 will produce time series maps for snow cover extent (SCE) and characteristics (depth, hardness, icing) over the Wrangell study area at a 100-m resolution (MERRA). In situ data and snow modeling simulations provided by Prugh-01 will be used to evaluate remote sensing snow cover products (e.g. NOAA IMS, MODIS Snow Cover). Loboda-03 will provide a 10-year, 1-km resolution dataset recording the earliest, mean, and latest dates of snow establishment and melt (Landsat, OLI, MODIS, ERS-1/2, Radarsat-1/2, ALOS PALSAR, ENVISAT). Kimball-04 will provide regional maps of the number of weekly snowpack melt days (1979-present) determined by merging coarse (25-km) resolution satellite FT and SCE products (Kim et al. 2015). Peter Kirchner (Kimball-04) will continue to work on a region-wide MODIS terrestrial snow metric product (Lindsay et al. 2015) with the Geographic Information Network of Alaska (GINA) to provide snow cover and snow onset and melt dates for Alaska and western Canada over the 2001-2013 period. A new blended multi-dataset snow water equivalent (SWE) product (Mudryk et al., 2015) will be utilized by Environment Canada (Kimball-04; Chris Derksen) to characterize variability and trends across the entire ABoVE domain. The

HPWG should also investigate the utility of 2-km resolution SnowDATA products produced by The Arctic Land Conservation Cooperative (LLC) and the University of Colorado for ABoVE investigators and possibilities to extend these datasets through 2016-2018.

Objective 5 Action Plan:

The HPWG will identify the primary drivers of regional change in surface hydrology for the ABoVE domain and linkages with vegetation productivity, vegetation "greening" and "browning" observed in satellite optical-IR records, and variability in land-atmosphere carbon fluxes. Drivers of change in surface hydrology and lake area extent may include seasonal, inter-annual variability and long term trends in evapotranspiration, precipitation (influenced by sea ice cover) and flooding (e.g. Chen et al., 2012), winter snow cover, permafrost ALD, and the timing and seasonal duration of non-frozen surface conditions. The HPWG will coordinate with Frost-01, Gamon-01, Woodcock-02, Goulden-02 and Cook-B-02 to identify the influence of changing regional permafrost and surface/sub-surface hydrology on trends observed in satellite vegetation indices (EVI; NDVI) in the Yukon-Kuskokwim Delta (YK Delta) region and elsewhere within the ABoVE domain. The HPWG will coordinate with Frost-01 to provide additional remote sensing records (e.g. SMAP) that can be used to design and implement a ground-based data collection effort focused on vegetation, soils, hydrology, and permafrost across environmental gradients in the YK Delta. The HPWG will coordinate with Loboda-03 to validate/compare permafrost ALD and soil moisture maps produced for tundra ecoregions characterized by different fire regimes including the Noatak River valley (Brooks Ridge), the Seward Peninsula, and foothills of the North Slope, Alaska with other available remote sensing products including SMAP Soil Moisture products (Reichle et al. 2015) and existing satellite data informed ALD maps (e.g. Park et al. 2015; Pastick et al. 2015). Phenocam measurements collected by Woodcock-02 can be used to verify start-of-season, length-of-season, etc. observed in remote sensing snow, FT, and surface water products.

The HPWG will establish joint modeling and remote sensing product validation activities with collaborators at NGEE-Arctic and UAF (Mark Lara; Wullschleger-01), NSIDC/INSTARR (Elchin Jafarov; Schaefer-03), the CALM network (Nikolay Shiklomanov), CHARS and Trail Valley Creek study areas with Canadian collaborators (McLennan-01, Chris Derksen, Phil Marsh), NASA GSFC (Carroll-01), JPL (Miller-C-02), USGS (Striegl-01), USC (Moghaddam-03), and the University of Montana (Kimball-04) to pinpoint recent changes and trends in ALD, surface water extent, and surface/subsurface water transport and the mechanisms and feedbacks driving these changes. This effort will incorporate a wide range of observations from satellite (e.g. AMSR; GRACE; Landsat; MODIS), airborne (e.g. CARVE; AirMOSS; UAVSAR) and reanalysis in conjunction with in situ measurements.

3.1.1 Overall schedule

This is still being determined at the time of this version of the working group document.

3.1.2 (Field Research)

Field measurements collected during ABoVE Phase I and Phase II activities are crucial for diagnosing model uncertainty, validating airborne and satellite products and reanalysis records, and improving understanding of mechanistic controls driving variability in ecosystem processes and response to climate change. Fundamental ecosystem indicators include soil hydraulic and thermal measurements, soil carbon content and organic layer, soil ice content, snow cover properties (presence/absence, duration, depth, density, SWE, albedo), frozen or non-frozen surface states, permafrost and active layer depth, surface deformation including ground subsidence and lateral erosion, surface inundation and drainage of water bodies, stream water discharge, sediment load, pH and electrical conductivity. Project members will collect a wide range of field measurements over the ABoVE domain during Phase I/Phase II activities (2015-2018) with focus on Ecosystem Dynamics science objectives outlined in the ABoVE Concise Experiment Plan (Kasischke et al., 2014) and identified HPWG objectives, the improvement of ecosystem models, interpretation and validation of airborne and spaceborne remote sensing products. Field research relevant to Hydrology and Permafrost focus areas is described here. A summary of expected field measurements and corresponding locations for field data collection are provided in the Appendix (Figure 1).

Soil Moisture and Thermal Properties

Soil thermal, moisture, and electrical conductivity sensor networks (Kimball-04) will be installed at two core eddy covariance (EC) tower locations within the ABoVE domain (e.g. Atqasuk and Ivotuk) and will provide a southward extension to the existing NGEE soil moisture/thermal grid in Barrow, Alaska (Go Iwahana; IARC). Daily soil and thermal information provided at these sites will complement ongoing data collection at other EC tower locations and will be instrumental for landscape scaling studies to assess carbon flux footprints and remote sensing retrieval sensitivity to changing surface/sub-surface conditions. Electrical conductivity measurements will provide indication of soil properties including texture, cation exchange capacity and dissolved ion content. Longer-term in situ soil moisture and temperature data records are available within the ABoVE domain. These include extended measurement records produced by the CALM network and the University of Alaska (UAF) Permafrost Lab, Alaska Long Term Ecological Research (LTER) sites, the Canadian High Arctic Research Station (CHARS), the Taiga Plains Research Network (TPRN), and Trail Valley Creek (Phil Marsh). The NOAA U.S. Surface Climate Observing Reference Network (USCRN) plans to provide a regional soil moisture and temperature sensor network for Alaska, with initial sensor installation and testing taking place at select locations in 2016. Soil moisture and temperature surveys will also occur during ABoVE Phase I/II activities at project field locations using portable sensors (e.g. Loboda-03, McLennan-01, Kimball-04, Bourgeau-Chavez-03, Natalie-01, Wullschleger-01, Wilson-01, Striegl-01). Landscape soil moisture profile data from collocated probe and GPR observations at Toolik Lake and Happy Valley (Schaefer-03) and along the Dalton Highway (Moghaddam-03) are also available. NMR soil moisture measurements collocated with ERT transects along the road network from the Canadian border to Toolik Lake are available (Minsley et al., 2016), and will be extended by Striegl-01

Permafrost Characteristics

The active layer is the portion of the soil overlying permafrost (substrates that remain frozen for two or more years) that thaws and freezes seasonally. Changes in ALD can strongly alter surface and subsurface hydrology, vegetation growth and productivity, soil biogeochemical processes and carbon budgets, and may have severe consequences for animal habitat, transportation networks, societal infrastructure and ecosystem services. Measurements of permafrost and ALD characteristics will be collected throughout the ABoVE domain (e.g. Wullschleger-01, Wilson-01, Kimball-04, Loboda-03, Schaefer-03, Moghaddam-03, Striegl-01) and will include tundra and boreal landscapes impacted by recent wildfire and their adjacent unburned areas (Loboda-03, Striegl-01). The HPWG encourages other project group members to collect permafrost active layer measurements whenever possible, using established protocols, to provide validation data for regional remote sensing products and modeling efforts. Corresponding measurements of water table depth, soil moisture, soil temperature and organic layer thickness, and site vegetation surveys should be collected to better identify driving mechanisms and processes regulating changes in the permafrost active layer. In addition, GPR transects collected at Barrow, Toolik Lake, Big Hole near Happy Valley, Prudhoe Bay, and along the Dalton Highway (Schaefer-03, Moghaddam-03, Wullschleger-01) can be used to characterize ALD and soil moisture properties. Deeper permafrost characteristics (up to ~10-15 m depth) will be investigated along electrical resistivity tomography (ERT) transects (Striegl-01). New ERT and NMR data will inform ALD and permafrost interpretations, and will augment recently acquired datasets along burned/unburned boundaries along the road system between the Canadian border and Toolik Lake (Minsley et al., 2016). At the regional scale, existing AEM datasets (Burns, 2006; Minsley et al., 2012) will be incorporated to understand deep (up to 100-m depth) geological and permafrost characteristics, their relationship to surface and groundwater systems, and to bridge field-scale and remote sensing interpretations of permafrost.

Annual active layer depth records for Alaska and western Canada are available through the Global Terrestrial Network for Permafrost (GTN-P) Thermal State of Permafrost (TSP) and CALM networks, CHARS and the TPRN. The CALM network and UAF Permafrost Lab provide active layer measurements from 1990-2015 at over 100 locations in Alaska and western Canada. Soil sensors installed at Alaska USCRN sites (at 10-cm intervals down to 100-cm) beginning in 2016 will provide daily long-term temperature observations that can be used to characterize seasonal development of the active layer and response to changing soil climate and atmospheric conditions. A compilation of ALD measurements Alaska, documented in Pastick et al. (2015) may also be available (Striegl-01). At least six ABoVE projects will use permafrost borehole temperature measurements (Natali-01, Mack-01, Wullschleger-01, Schaefer-03, Moghaddam-03, Striegl-01) for remote sensing and modeling calibration/validation. Borehole temperature measurements are readily available through the TSP network in coordination with the UAF Permafrost Lab, and the National Snow and Ice Data Center (NSIDC). A proposed ABoVE project (Nicolsky, 2016) in collaboration with the EarthScope Transportable Array network (Incorporated Research Institutions for Seismology) may greatly increase the spatial coverage of borehole temperature measurements across Alaska and western Canada.

Surface Water Characteristics

Freshwater data from lakes and streams (including water quality indicators) may be available from CHARS (McLennan-01) and NGEE (Wullschleger-01). Measurements collected through CHARS and NGEE (Barrow and the Seward Peninsula) include ions, water isotopes, nitrate isotopes, dissolved organic and inorganic carbon (DOC, DIC) and at some sites, methane. At least one ABoVE funded project (Striegl-01) will measure water/carbon residence times and DOC and DIC. Lake and stream temperature records can be obtained through The Alaska Online Aquatic Temperature Site (AKOATs). The Terrestrial Environment Observation Network (TEON) may have hydrology data for North Slope, Alaska. The U.S. Geological Survey (USGS) has point-location Alaskan real-time and historical streamflow data available through the National Water Information System (waterdata.usgs.gov/nwis). The Alaska Department of Natural Resources (ADNR) collects data on regional lakes, stream discharge, and water quality and the Alaska Lake Ice and Snow Observatory Network may provide records of lake/river ice onset and duration. Limited subsurface water level, surface water area and stream flow measurements will be collected and analyzed for sites in the Seward Peninsula (Wullschleger-01).

Snow Cover Properties

Snow cover regulates thermal interaction between the atmosphere and lithosphere. Radiative and heat-transfer depend on the thermal conductivity of the snow, which is greatly influenced by snow density and structure. Changes in snow cover duration and snow properties alter soil heat exchange and can reduce the seasonal freezing of underlying soils, enhancing active layer development and winter soil respiration. These changes can strongly impact other ecosystem dynamics including regional water budgets, vegetation community dynamics, and animal movement. Snow measurements collected during ABoVE Phase I/II activities will include snowpack characteristics (e.g. snow depth, SWE, density, hardness, grainsize/morphology) along 1-km transects at twenty sites in the Wrangell study area of Alaska (Prugh-01). Snow profiles collected at each transect will provide detailed snowpack stratigraphy. This information will be used to validate remote sensing snow products. Imagery obtained from remote cameras installed at these sites will provide data necessary to validate remote sensing based FT, start of growing season, and surface flooding. At least two other investigators (Natali-01; Wullschleger-01) will collect snow depth, snow cover, and SWE measurements in the ABoVE domain. Field observations of snow properties and distribution, ALD, vegetation (shrub and forest), and freshwater (full water balance) will be combined with high resolution distributed snow model experiments across targeted watersheds (i.e. Trail Valley Creek) by Canadian collaborators (Kimball-04: Phil Marsh; Chris Derksen). These efforts will provide process-level understanding of interactions between the terrestrial cryosphere, vegetation, and freshwater, and the validation of satellite and model-derived products. Long-term snow monitoring and survey records for Alaska (snow presence/absence, SWE) are available through the Natural Resources Conservation Service (NRCS) SNOTEL network and Alaska Snow, Water and Climate Services (AMBCS; http://ambcs.org/). Modeled 2-km resolution SnowDATA total annual water-equivalent snow precipitation, density, snow onset, duration, rain on snow events, and long-term trend products for Alaska and the Yukon (north of 62° latitude) from 1979-2012 are also available through The Arctic LLC and the University of Colorado (arcticlcc.org/projects/geophysical/snowdata).

Regional Water Budgets

Changes in seasonal and long-term water storage are expected to occur across the ABoVE domain under a warming climate. Thawing permafrost landscapes, melting of ground ice, and increases in atmospheric moisture demand can lead to the regional drainage of lakes and ponds, altering vegetation community composition and increasing sub-surface water transport and sediment load in streams and rivers (Rawlins et al., 2010). The timing of precipitation is also important as it influences snowpack composition, flood severity and surface erosion, vegetation productivity, and animal migration. Documented shifts in regional water budgets (e.g. Muskett & Romanovsky, 2011) and wetting/drying of surface soils may contribute to vegetation greening and browning within the ABoVE domain and other impacts to community ecosystem services. The integration of in situ data with remote sensing and modeling will better determine water budgets characteristics within the ABoVE domain, connectivity between changes in sea ice cover, surface meteorology, vegetation community characteristics, and shifts from surface water to groundwater storage and transport. In situ measurements of precipitation and evapotranspiration can be used to gauge terrestrial water availability and to validate satellite remote sensing products (Zhang et al., 2015).

A suite of in situ measurements are required to quantify local and regional water budgets. These include air temperature, precipitation, relative humidity, evapotranspiration, surface and groundwater measurements including lake volume and river discharge. These observations can be obtained for Alaska through NRCS SNOTEL and NOAA USCRN sites. Environment Canada can provide these data for the Yukon portion of the ABoVE domain. The NGEE-Arctic (Wullschleger-01) and tower EC sites (Table S3 in Kimball et al., 2015), including those participating in AmeriFlux and FluxNet, can also provide air and skin temperature, wind speed, heat flux, relative humidity and evapotranspiration data. The Alaska Climate Research Center (ACRC) provides data summaries for National Weather Service (NWS) stations across Alaska. The USGS provides some groundwater observations (e.g. depth to water table) for Alaska but these data are limited. The ADNR has additional groundwater, and community aquifer availability/use, and water quality information available through the Alaska Hydrologic Survey.

3.1.3 Airborne Remote Sensing

Detecting and quantifying changes in surface and groundwater storage and transport, frozen surface conditions including snow and ice cover, soil moisture and thermal properties, permafrost characteristics, thermokarst activity and land deformation are crucial to identify landscape vulnerability and regional impacts to ecosystem function and services. High spatial resolution airborne remote sensing systems provide key insight into land surface properties used as indicators of permafrost thaw, changes in snow cover duration and characteristics and associated changes in hydrology. Airborne retrievals also provide data needed to evaluate landscape scaling methods and data integration properties and to validate satellite remote sensing and ecosystem modeling products.

Initial ABoVE Phase I activities will utilize airborne AirMOSS and UAVSAR P- and L-band joint retrievals (Moghaddam-03) to characterize and detect seasonal changes in ALD, profile soil moisture, water table depth and near-surface soil organic layer properties as part of a NASA Interdisciplinary Research in Earth Sciences (IDS) project. Time-series acquisitions over seasonal cycles with dual frequency SAR (L/P-band) across select transects in Alaska covering existing permafrost borehole and EC tower sites can characterize patterns and seasonal changes in soil moisture profiles and ALD over regional gradients of permafrost degradation, surface moisture, and vegetation community type (Moghaddam-03). Ideally, three data acquisitions are needed during each observation year: early spring for fully frozen active layer, late summer for fully thawed active layer, and autumn for partially frozen active layer. Inter-seasonal time-series analysis and modeling of dual-frequency SAR will allow retrieval of soil subsurface structure (soil moisture, ALD, depth to water table, organic layer properties) down to the permafrost interface. Inter-annual time-series analysis will allow us to investigate longer-range trends of the ALD. Using the combination of L and P-band radars, the maximum observable ALD is estimated at 50 cm, which applies to much of the ABoVE domain. The IDS project (Moghaddam-03) has provided support for 6 flights (2 years, 3 flights each) of the P-band AirMOSS and 2 flights (Fall and Spring of year 2 only) of the L-band UAVSAR, ending in April 2016. These flights are used to validate the retrieval methodologies and to establish a baseline for ALD over the covered transect. Two more annual time series of L/P-band SARs should be acquired, over a potentially larger coverage area than supported by the IDS project, to investigate inter-annual trends and spatial landcover gradients. These data provide landscape scale observations corroborated against finer scale soil and ALD measurements, ground-based GPR sampling (Schaeffer-03) and regional ALD maps (Kimball-04; Striegl-01). The L- and P- band SAR retrievals complement other NASA EV-1 mission applications including CARVE (Miller-C-02) and provide high resolution (approximately 15-m and 90-m) gridded data used as observed targets for permafrost model simulations and necessary inputs into terrestrial carbon models (Moghaddam-03; Kimball-04). Existing aerial imagery (i.e. NAIP), airborne LiDAR (e.g. G-LiHT, Leica ALS60) and electromagnetic (AEM) surveys (Burns, 2006; Minsley et al., 2012) will be used in HPWG efforts (Striegl-01) within the Yukon Flats and along the Alaska Highway corridor to characterize key landscape physical properties influencing key hydrological and permafrost processes. Two existing Alaska AEM datasets will be released for broad use and existing datasets in Canada will be identified. New AEM surveys should be considered in Phase II to complement other planned airborne data collection (e.g. G-LiHT, AirMOSS) to provide a holistic characterization that spans both the near-surface and deeper subsurface environment. Aerial imagery along 30 randomized 5 km x 5 km sampling grids throughout Alaska along the statewide airphoto flight lines established by Jorgenson et al. (2007) will also be incorporated to quantify past permafrost extent, permafrost degradation rates, and landscape change (Striegl-01).

ABoVE Phase II activities should continue the research and development of integrated L- and P-band SAR airborne observing systems. Airborne L- and P-band SAR observations should target areas experiencing rapid change in surface hydrology including the Seward Peninsula, the Yukon Flats (Chen et al., 2014) and the Alaska Ivotuk-Atquasuk-Barrow coastal-to-upland tundra transect identified as having recent surface drying trends in contrast to other North Slope landscapes (Watts et al., 2014). Airborne L- and P-band SAR flight paths should also include well-instrumented Taiga Plains Research Network sites within the Canadian Northwest Territories that capture continuous permafrost-tundra to taiga gradients. In addition to continuing efforts to characterize soil moisture and ALD, polarimetric SAR modeling should explore using these retrievals to capture seasonal changes in depth to water table and soil organic layer thickness. The simultaneous use of these retrievals to detect/map surface water bodies and littoral zones should also be investigated. Airborne SAR observations obtained during ABoVE Phase II activities will provide high spatial resolution data to validate NASA SMAP L4 Soil

Moisture products and to characterize near-surface soil in permafrost and carbon biogeochemical modeling efforts and the evaluation/quantification of winter carbon respiration at core ABoVE EC flux tower and observation sites (Kimball-04; Natali-01).

ABoVE Phase I/II projects would benefit greatly from high resolution airborne thermal and hyperspectral airborne retrievals to track floristic composition of recovering post-burn and adjacent unburned landscapes (Loboda-03). Coinciding airborne L- and P- band SAR retrievals at these sites will greatly enhance scientific knowledge by providing high resolution near-surface mapping of soil moisture, ALT and organic layer thickness. Airborne L-band SAR is also requested over regional lakes during summer and winter periods to calibrate satellite retrievals (e.g. ALOS PALSAR; ALOS-2; SAOCOM; NISAR) used in lake area change mapping and detection of methane bubble emissions in frozen thermokarst lakes (Meyer-01). Winter L-band SAR retrievals can also be used to improve characterization of floating and grounded lake and river ice properties (e.g. Engram et al., 2013). Joint LiDAR (e.g. G-LiHT), hyperspectral (e.g. HyspIRI and AVIRIS+MASTER), L-band SAR, and CARVE CO_2 and CH_4 retrievals over core locations including NGEE (Barrow and Seward Peninsula) and flux tower sites will provide valuable high-resolution data used to link land-surface observations with subsurface properties. Airborne multiwavelength LiDAR can be used to explore remote sensing characterization of snow cover properties (Nolin, 2010) including snow depth and SWE (Prugh-01). Airborne LiDAR retrievals and Frequency Modulated Continuous Radar (FMCW) along snow transects could greatly assist in ground reference and validation of snow modelling (Prugh-01). These retrievals are also needed to validate satellite remote sensing snow cover (e.g. NOAA IMS; MODIS Snow Cover; ESA DUE GlobSnow-2). The Trail Valley Creek (TVC) watershed has been the site of experimental airborne campaigns in support of new satellite radar concepts for SWE retrievals. It is anticipated that Environment Canada will conduct airborne radar measurements over TVC during ABoVE Phase I/II in association with ongoing snow radar mission concept studies presently supported by the Canadian Space Agency and European Space Agency. Coordinated airborne retrievals can be used in conjunction with satellite remote sensing (e.g. SMAP L-band; Sentinel C-band; IceSat-2; GRACE) to provide a comprehensive, regional evaluation of changing surface/sub-surface hydrology and permafrost conditions including detection of pingos, ground surface subsidence, and other thermokarst features (e.g. Muskett, 2015)

3.1.4 Modeling Research

Priority modeling activities for ABoVE Phase I/II include developing high resolution datasets of key landscape indicators and parameters such as landscape soil moisture, ALD, snow cover extent, duration and properties, surface ice cover, and thermokarst features. Multi-spatial and temporal resolution mapping of surface water properties, including surface water bodies and inundated landscapes, are also needed to characterize contemporary ecosystem states and to detect trajectories of ecosystem change. Landscape modeling efforts integrating permafrost, soil thermal and hydrological components are needed to understand and quantify linkages between sub-surface properties, vegetation dynamics and soil carbon cycling (including shifts in respiration rates and CO_2:CH_4 emission ratios), meteorological forcing and landscape disturbances (e.g. fire; thermokarst).

Permafrost and hydrology research occurring during ABoVE Phase I activities will utilize a wide range of models. These models include radiative transfer algorithms used in satellite and airborne remote sensing (e.g. AMSR Land Surface Parameter and AirMOSS retrievals; InSAR Frozen Ground Algorithm; ReSALT algorithm), geophysical models describing snow properties and snowpack evolution (e.g. SnowModel), coupled permafrost and hydrology (e.g. SUTRA 4.0), and a suite of biophysical models including those used by NGEE-Arctic to explore land surface processes and interrelationships at scales ranging from plot level (e.g. PFLOTRAN, ATS) to ecosystem (e.g. ED; TEM) and climate scales (e.g. ACME/ALM), and integrated remote sensing informed models diagnosing impacts of changing soil moisture and permafrost properties on landscape fire (e.g. CanFIRE) and terrestrial carbon cycling (e.g. TCF-PWBM; Yi et al. 2015).

The HPWG will identify ways to improve satellite and airborne remote sensing observations of land surface features thorough integrated research incorporating in situ measurements and evaluation against outcomes observed in biophysical model simulations. Identified target areas include research into the integrated use of L- and P- band SAR for characterizing ALD seasonal changes and permafrost conditions, soil profile soil moisture, and soil organic layer characteristics. Enhancements to the AirMOSS retrieval algorithms will add additional soil layers and introduce an organic layer to the current two-layer model structure to better model partially frozen soil conditions and seasonal changes in ALD (Moghaddam-03). The ability to distinguish between fully frozen and residual water states is needed to inform winter carbon respiration modeling and the characterization of soil thermal/hydrologic properties. Additional modifications in the radar forward model will accommodate different soil structures to better represent seasonal soil states (e.g. maximum thaw, partial thaw, fully frozen) and vegetation roots. The HPWG will also identify and evaluate various statistical modeling approaches for remote sensing land surface classification and mapping used by ABoVE Phase I project members. These include Random Forest, decision trees, support vector machines and other machine learning techniques for mapping permafrost ALD, soil moisture, peatland/wetland types (e.g. Loboda-03; Bourgeau-Chavez-03).

3.1.5 Integration and Synthesis Research within ABoVE WGs

The HPWG will coordinate with: 1) the Modeling Framework & Comparisons WG to make recommendations for model validation and algorithm improvements; 2) the Wildlife & Ecosystems WG to identify impacts of changing regional snow cover properties, winter thaw events and surface flooding on wildlife distribution and movement; 3) the Fire Disturbance WG to identify effects of regional surface wetting/drying, changes in snow cover, non-frozen season, and landscape water budgets on fire disturbances; 4) the Carbon Dynamics WG to assess landscape wetting/drying, changes in snow cover, annual non-frozen season and ALD impacts on vegetation productivity, carbon flux magnitudes (GPP, Reco, NEE, CH_4) and ecosystem shifts from carbon sink to carbon source; 5) the Core Variables & Standards and Geospatial Products & Standards WGs to ensure appropriate data collection protocols, data reporting, formats and metadata. Data products produced by the HPWG will be distributed to ABoVE science team members to identify model/algorithm limitations and gaps in process understanding, which can be used to guide further field data collection efforts and model refinement activities.

3.1.6 Integration and Synthesis Research with Non-ABoVE Investigators

The HPWG has identified the following investigators as potential ABoVE affiliated team members:

Antonio Mannino (NASA GSFC): Mannino is the lead principle scoping study investigator for NASA Arctic-Colors **(**Arctic-Coastal Land Ocean inteRactions). This NASA-funded field campaign is designed to quantify the response of the Arctic coastal environment, including riverine deltas and estuaries to global change and anthropogenic disturbances.

Philip Martin (USFWS; Goetz-03). Martin is Science Coordinator for the Arctic Landscape Conservation Cooperative (ALCC). Recent ALCC FY15 research efforts include the development of snow datasets for Alaska and the Yukon, ecological mapping and water quality database management for the North Slope region, LiDAR data processing and management, human system data initiatives, and meteorology, surface water, soils/permafrost and vegetation monitoring initiated in the Kuparuk River watershed in 2015 in partnership with the Natural Resources Conservation Service, US Fish and Wildlife Service (USFWS) and the UAF Geophysical Institute. These activities are summarized here: http://www.iarpccollaborations.org/members/updates/3666?utm_medium=email&utm_source=transactional&utm_campaign=Bi-weekly

Nikolay Shiklomanov (GWU) and Vladimir Romanovsky (UAF): Shiklomanov leads the National Science Foundation (NSF) funded CALM network which provides long-term ALD, soil temperature and soil measurements across the ABoVE domain and pan-Arctic region. Romanovky directs the UAF Permafrost Laboratory and has led efforts to establish a permafrost observatory network in Alaska. The CALM network and UAF Permafrost Laboratory are active members of the Global Terrestrial Network for Permafrost (GTN-P). Romanovsky has provided borehole permafrost profiles for Moghaddam-03 and will be instrumental in ABoVE U.S. Array sensor deployment to obtain soil organic layer, active layer and permafrost borehole temperature in Alaska and western Canada.

Howard Diamond (NOAA): Diamond is program manager at the NOAA National Center for Environmental Information and provides oversight for the soil moisture and temperature sensor network that will be integrated into existing Alaska USCRN sites. This project is scheduled to begin in summer 2016 at select locations. The HPWG should coordinate with the USCRN to identify high priority locations for initial soil thermal/moisture sensor testing and data collection that will benefit ABoVE activities and model/remote sensing product validation efforts.

3.1.7 Key Data Gaps in ABoVE Phase I Projects (Hydrology and Permafrost):

The HPWG has identified a lack of emphasis on tracking regional stream/river flow and lateral surface/sub-surface water movement in ABoVE Phase I projects. The regional monitoring of water transport and sediment load is required to effectively quantify water and material (C, N, sediment) export to coastal regions and to identify hydrological changes and potential shifts in water quality, including increased base flow resulting from permafrost warming. The HPWG should identify ways to integrate new data collection with in situ observation networks, geophysical surveys, hydrology and permafrost modeling, and satellite and airborne remote sensing retrievals to better identify changes in lateral water transport and discharge within the ABoVE domain. The HPWG has also identified a lack of ABoVE Phase I project focus on ecosystem dynamics with very little emphasis on permafrost dynamics and hydrology. The HPWG recommends that ABoVE Phase II activities include at least one funded project that explicitly targets the use of air/spaceborne remote sensing data and geophysical modeling to improve the monitoring of ALD, permafrost presence/absence and changes in surface and sub-surface hydrology for the ABoVE domain.

The HPWG will identify new data integration and modeling platforms that incorporate satellite and airborne optical-IR/thermal and microwave (passive & active) retrievals to provide higher spatial resolution (≤ 100 m) lake and river ice detection and monitoring (e.g. ice presence/absence, ice thickness, surface deformation and thermokarst mapping. Satellite-based maps and monitoring platforms to detect changing freeze/thaw patterns on lakes and ponds and rivers are needed for the ABoVE domain. For example, a recent study (Surdu et al. 2014) using ERS-1/2 SAR determined that the annual duration of ice coverage near Barrow decreased by 24 days between 1950 and 2011. Other areas of exploratory research include using surface NMR to measure the thickness of unfrozen sediments beneath lakes. Research into lateral movement of water in low relief areas will be greatly aided by a fine resolution (10-m) DEM. Above Phase I project members and the HPWG will work collectively to identify opportunities for regional data compilations or meta-analyses that would link to larger community activities including the Permafrost Carbon Network (PCN).

The HPWG will develop collaborations with the University of Alaska Fairbanks (UAF) Arctic Lake Ice Systems Science (ALISS) team to identify existing snow/lake ice measurement networks in Alaska, lake ice data product development efforts and applied analyses (e.g. Arp et al., 2015). The HPWG will identify/coordinate joint efforts and target areas that can be achieved through collaboration with NASA Arctic-Colors (Arctic-Coastal Land Ocean inteRactions). This NASA-funded field campaign is designed to quantify the response of Arctic coastal environments, including riverine deltas and estuaries to global change and anthropogenic disturbances (Mannino et al., 2015). The HPWG may consider engaging with PalEON community members who are reconstructing lake and wetland conditions in Alaska to identify regions that have experienced substantial surface wetting/drying in the past. Paleoecology and knowledge gained from local tribal members can provide important insight into past climate conditions and vegetation characteristics, natural variability in boreal and tundra-fire regimes and shifts in system characteristics as a response changing surface hydrology and a warming climate.

3.1.8 Stakeholder Engagement and Public Outreach

The HPWG will coordinate joint efforts to engage stakeholders and public outreach activities across the ABoVE domain. Engaging with local community members and resource managers will provide a mechanism to refine research target areas, identify data/information gaps and communicate research findings in a timely manner. Project members will hold community visits and knowledge exchange meetings to identify the concerns, perceptions and expectations of local residents and to facilitate the collection and exchange of local knowledge and observations relevant to changing hydrology, snow and ice cover and conditions, and land disturbances resulting from permafrost thaw, water erosion, and changing land cover. Information collected during the ABoVE field campaign will be distributed in a manner that readily benefits local communities and resource managers whenever possible. The HPWG will work with the Stakeholder Engagement & Public Outreach Working Group (SEPOWG; Libby Larson) to ascertain additional "hazard" or "indicator" maps that can be readily produced as part of HPWG member projects. For example, Meyer-01 will produce ice hole hazard maps for local communities as part of anticipated project mapping efforts. Other indicator maps could include the locations of increasing rain-on-snow events, mid-winter thaw events, changes in onset/offset of frozen ground conditions, and shifts in the duration and magnitude of surface flooding.

Organizations identified by the HPWG that can be used by project members for coordinated outreach and knowledge distribution include but are not limited to:

- *The Exchange for Local Observations and Knowledge of the Arctic* (ELOKA) provides data management and user support services as part of the National Snow and Ice Data Center (NSIDC) to facilitate the collection, preservation, exchange, and use of local observations and knowledge of the Arctic (http://eloka-arctic.org/projects**)**. Project focus areas within ELOKA include the Circumpolar Biodiversity Monitoring Program (CBMP), the Seasonal Ice Zone Observing Network (SIZONet), The Snowchange Project, Strategic Needs of Water on the Yukon (SNOWY), and the Yup'ik Environmental Knowledge Project/Atlas which is documenting Indigenous knowledge in the Bering Sea Coastal Region of Alaska.

- *The Arctic Landscape Conservation Cooperative* (ALCC; http://arcticlcc.org/) provides applied science and tools to land managers and policy makers, with focus on eco-regions including the Brooks Range, the Arctic Foothills and the Arctic Coastal Plain. Target projects include the Terrestrial Environment Observation Network (TEON) which supports infrastructure for northern Alaska by collecting, distributing and synthesizing long-term observational data to detect and forecast effects of changing climate, hydrology, and permafrost on wildlife, habitat and infrastructure.

- *The Imiq Hydroclimate Database and Data Portal* provides a repository for hydrology, climate and soils related data in Alaska and nearby regions.

- *The Interagency Arctic Research Policy Committee* (IARPC) was formally created by Executive Order 12501 with activities coordinated by NSF and the U.S. Office of Science and Technology Policy. IAPRC Collaborations provides a platform for scientists from Federal, State, academic, and non-governmental organizations to share knowledge and resources to accelerate the progress of Arctic research.

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Appendix A: protocols

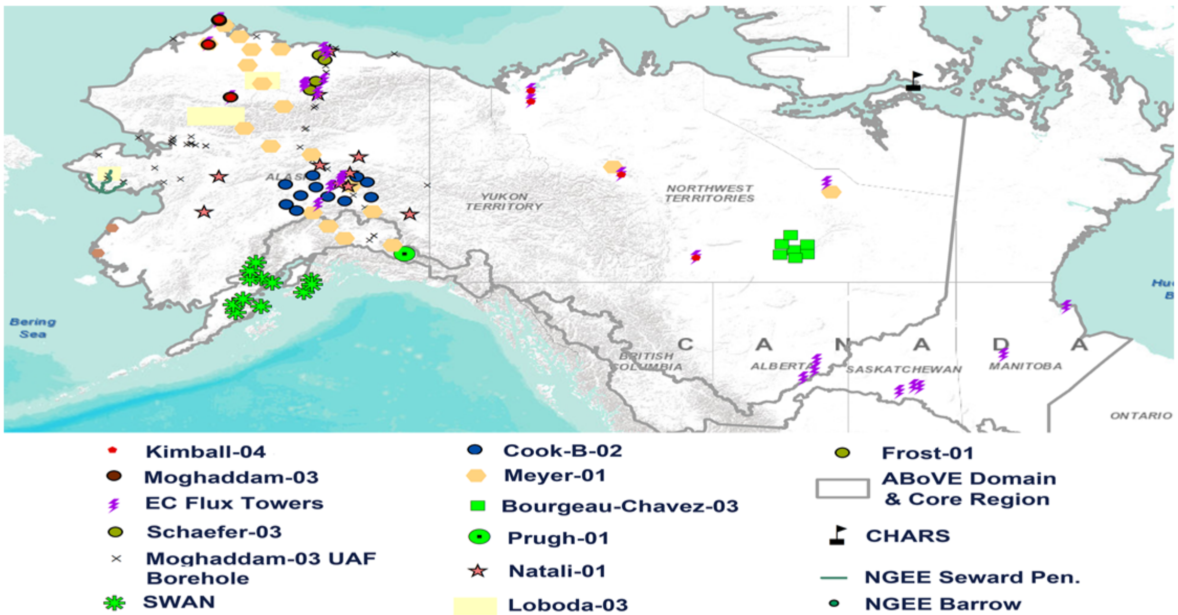
Permafrost active layer monitoring protocols adopted by the Circum-polar Active Layer Monitoring (CALM) network, including sampling design, mechanical probing, frost tubes and soil temperature measurements: http://www.gwu.edu/~calm/research/measurements.html; http://permafrost.gi.alaska.edu/sites/default/files/TSP_manual.pdf

Volumetric soil moisture protocols used by the CALM network, including stationary and spatial measurements using gravimetric methods and soil moisture probes: http://www.gwu.edu/~calm/research/measurements.html

Stream temperature protocols provided in the Alaska Natural Heritage Program (UAA) *Stream Temperature Data Collection Standards and Protocols for Alaska* handbook: http://aknhp.uaa.alaska.edu/aquatic-ecology/akoats/

Additional protocols will be developed for:

- Field and lab characterization of soil moisture (volumetric and gravimetric), soil texture, and soil porosity; calibration of soil moisture sensors (portable, etc.)
- Snow properties
- GPR data collection
- Hydrologic data collection
- Validation of satellite and airborne remote sensing products using in situ measurements.



Field Measurements

Active Layer	Relative Humidity	Lake Area Thickness	Organic Layer Thickness
Air Temp	Stream Flow	Precip.	NO_3^- Isotopes
Soil Temp	Stream/Lake Temp	Snow Depth	H2O Isotopes
Soil Matric Potential	pH/Salinity	SWE	GPR
Pore Water EC	DOC/DIC	Surface Albedo	NMR
Water Table Depth	Aquatic CH_4	Solar Radiation	ERT

Figure 1. Map of ABoVE project locations for field data collection during Phase I activities and a corresponding list of key in situ variables to be measured at these sites.

Table 1. Summary of expected Hydrology & Permafrost data products delivered by pre-ABoVE and Phase 1 Investigators.

Project	Description	Spatial Extent	Temporal Coverage	Spatial Res.	Sensors Used
Surface Freeze/Thaw, PF and Active Layer Characteristics					
Kimball-04	FT Trend and Anomaly Maps	ABoVE Domain	1980-2017	6; 12; 25-km	AMSR; SSMR/I; SSMIS; SMOS; SMAP
Kimball-04	Annual ALD Maps	ABoVE Domain	2003-2009	25-km	SSMR/I; MODIS LST
Striegl-01	Static ALD; sub-surface PF Maps	Alaska; Regional	2011	30-m	Landsat; **NIAP; G-LiHT; Leica ALS60**
Schaefer-03	Surface Subsidence; ALT Maps	Sub-region, North Slope	1991-2010	30; 100-m	ERS-1/2; ALOS PALSAR
Moghaddam-03	ALD; WTD; SM; OLT Maps	Alaska Transects		15; 90-m	**AirMOSS; UAVSAR**
Frost-01	Thermokarst Maps	YK Delta Region			AVHRR; SSM/I; MODIS; Landsat; NGA; **Lidar?**
Loboda-03	ALD; Soil Temp Maps	Regional			Landsat
Wullschleger-01	Ground Ice; ALT; Soil Thermal Maps	Barrow; Seward Pen.			Landsat, etc.
Natali-01	Multi-scale FT Maps	Regional			TBD
Surface Water Distribution & Soil Moisture					
Carroll-01	Lake Extent & Change Maps	Alaska & Canada	1991; 2001; 2011	30-m	Landsat; MODIS
Kimball-04	Surface Inundation Maps	ABoVE Domain	2003-2017	25; 5; 1-km	AMSR
Kimball-04/Moghaddam-03	Soil Moisture Validation Maps	Regional	2015	9-km; 15, 90-m	SMAP; **AirMOSS; UAVSAR**
Meyer-01	Lake Change Maps; Ice Hazard Maps	Regional			ALOS PALSAR; ALOS-2; SAOCOM; **NISAR**
Cook-B-02	Wetland/Surface Water Change Maps	Regional			Landsat; **HyspIRI**
Loboda-03	Drainage & Soil Moisture Maps	Regional			Landsat; InSAR
Bourgeau-Chavez-01	SM Maps (pre & post burn); ALD	Great Slave Lake Region	2015-2018		PALSAR; Radarsat-2; ERS; Sentinel; SMOS; SMAP; Landsat; DigitalGlobe
Snow Cover Characteristics					
Prugh-01	SCE; Depth; Hardness Maps	Wrangell St. Elias Region	(Kennecott)	100-m	TBD
Loboda-03	SCE; Onset; Duration Maps	Regional		1-km	Landsat; MODIS; ERS-1/2; Radarsat-1/2; ALOS PALSAR; ENVISAT
Kimball-04	Weekly Snowpack Melt Maps	Regional	1979-2016	25-km	AMSR; SSMR/I; SSMIS
Kimball-04	SCE; Onset; Melt Maps	ABoVE Domain	2001-2013	500-m	MODIS
Kimball-04	SWE	ABoVE Domain	1981-2010		