CONSORTIUM RESEARCH PLAN, SEPTEMBER 11, 2017

1. Basic information

Consortium PI: Professor Jaana Bäck (JB), Department of Forest Sciences, Univ. of Helsinki (UH), Helsinki, Finland

Sub-project 1 PI: Research Professor Sergej Zilitinkevich (SZ), Finnish Meteorological Institute (FMI), Helsinki, Finland

Sub-project 2 PI: Professor Jaana Bäck, Department of Forest Sciences, UH, Helsinki, Finland

Russian partner: Professor Vladimir Melnikov (VM), Univ. of Tyumen (UT), Tyumen, Russia

Project title: **Mechanisms, pathways and patchiness of the Arctic ecosystem responses and adaptation to changing climate (ClimEco)**

2. Rationale

State of the art

Amplified warming of the Arctic and pronounced changes in Arctic ecosystems are well documented. The known functional responses (e.g., changes in species composition and productivity) of Arctic ecosystems to changes in climate could influence global climate through both direct impacts on the radiation and energy balance and the exchange of climate-relevant gases with the atmosphere (e.g., McGuire et al., 2009; Kramshøj et al., 2016). At the same time, mechanisms, pathways and patchiness of warming microclimates and feedbacks with changing ecosystems remain poorly understood. Our project responds to these challenging problems.

Arctic environment has undergone rapid changes induced by both general climatic trends and local land-use/cover changes (Serreze & Barry, 2011; Smedsrud et al., 2013; Vihma et al., 2014). More than 30 years of circumpolar remote sensing data (Park et al., 2016) revealed significant increase in biological production in tundra and forest-tundra ecotones, extension of the growing season, and northward advancement of shrub- and tree-lines. The observed 'greening' in tundra and forest-tundra biomes is however counterbalanced by a phenomenon called 'browning', i.e. loss of productivity in some evergreen and mixed forest types in the mid and south taiga region. The browning phenomenon is more pronounced on the patches of land disturbed by natural or anthropogenic impacts, wherein alternative ecosystem successions can gradually develop (Miles & Esau 2016; Kumpula et al., 2011; Moskalenko, 2012). Complex changes in ecosystem structure, species distribution and biodiversity will have important climatic, ecological and social consequences.

Arctic ecosystems are characteristically nutrient-poor with cold climates and short growing seasons (Hobbie et al., 2002) and the harsh climate often restricts the growth of less hardy plant species, reducing their diversity in a given ecosystem. In addition to temperature, edaphic factors such as soil moisture and nutrients mainly determine the vegetation type (Iturrate-Garcia et al., 2016). Higher Arctic air temperatures favour the growth of graminoids (grasses), deciduous shrubs and sparse larch stands, and specific patches of warm microclimate (Miles & Esau, 2016). Arctic ecosystems are extremely sensitive to anthropogenic impacts (in e.g., industrial deserts in Kola peninsula, areas with active oil/gas exploration, e.g. Tikkanen & Mikkola, 1990; Bäck et al., 1994; Nöjd & Kauppi, 1995; Kumpula et al., 2011); however, the climate-vegetation feedbacks in such 'disturbance' situations may strongly differ from the ones in natural ecosystems.

Vegetation strongly controls the water and energy exchange between soil and atmosphere, and changes in vegetation structure that increases sensible heating could feed back to enhance warming at local to regional scales. For example, because of lower thermal conductivity and absence of stomatal resistance, mosses reduce the energy exchange, enhance evapotranspiration and reduce temperatures, thus protecting the permafrost compared to shrub or graminoid-dominated vegetation. Reduction in evaporation shifts partitioning of the surface energy budget towards stronger sensible heat fluxes and higher surface temperatures. Thus, mosses are crucial for structure, functioning and composition of Arctic ecosystems as well as to the ecosystem-climate feedbacks (Gornall et al., 2011). Further, the extremely high temperature sensitivity of ecosystems in the changing Arctic (e.g., Kramshøj et al., 2016) indicates that the surface layer feedbacks may have significant consequences to regional and even global climate change.

Adaptation of Arctic ecosystems to warmer climate is not limited to gradual expansion of new, thermophilic ecosystems (grasses, shrubs and trees). As a consequence of the increasing industrial activities, alternative ecosystems can be formed due to plant successions on disturbed surface patches (e.g. Beringer et al., 2005) e.g. in areas of active oil/gas exploration (Moskalenko, 2012). Such ecosystems have lower albedo, better drainage, lower evaporation and larger snow accumulation, sustaining higher soil and air temperatures (Chapin et al., 2005) and longer growth season (Park et al., 2016), and they may also provide higher biological productivity even at times of negative productivity trends in other ecosystems (Miles & Esau, 2016).

Sensitivity of Arctic ecosystems to climate change has been investigated in Arctic Warming Experiment (Elmendorf et al., 2012) and case studies (Leibman et al., 2015), including those in North Siberia (Pavlov & Moskalenko, 2002). These revealed pronounced changes: notably, patches of more reflective but drier soil (sand and sandy loams) creating "warm islands" due to strongly reduced heat-consumption by evapotranspiration. This exemplifies the impact of ecosystem structure to the energy budget and leads to the interesting research question regarding the feedbacks between vegetation and the boundary layer phenomena.

Climate-biosphere feedbacks involve phenomena of very different nature and origin. Albedo and evapotranspiration control the near-surface budgets of energy and matter (the surface fluxes) and, in turn, are essentially controlled by ecosystems - through partitioning of the surface energy budget between sensible and latent heat fluxes (Brunsell et al., 2011). Besides, microclimate is controlled by physical processes in atmospheric Planetary Boundary Layer (PBL): turbulence, radiation, evaporation, etc. PBL is affected by local ecosystems and traps local impacts within PBL due to strongly reduced turbulent exchange at the PBL upper boundary. By this means a mosaic of microclimates, associated ecosystems and ecosystem responses is maintained (Muster et al., 2015; Davy & Esau, 2016; Miles & Esau, 2016; Davy et al., 2017).

The feedbacks between ecosystems and PBL are still insufficiently understood (Eugster et al., 2000; Pavlov & Moskalenko, 2002; Blok et al., 2010; Barichivich et al., 2014; Ford & Frauenfeld, 2016; Nauta et al., 2015). Their quantification is essential for understanding and modelling of interactions between ecosystems and climates (Jeong et al., 2011; Loranty et al., 2014). Adjustment of PBL to large-scale features of climate depends on both global warming and surface fluxes. Here, key is the height of PBL determining it sensitivity to external impacts. PBL height crucially depends on properties of the underlying terrain (see Fig. 1), e.g. height and structure of canopy, leaf area index (LAI), albedo, thermophysical properties of soil, etc. As mentioned above, capping inversions at the PBL upper boundary essentially restrict the energy and matter exchanges between PBL and free atmosphere and to a large extent block local impacts from Earth's surface within PBL. This is why microclimates over heterogeneous terrain are often so variable. The PBL height quantifies the largest possible length-scale of PBL's own motions integrating finer-scale impacts from the surface and determining microclimate's vertical and horizontal dimensions (Zilitinkevich et al., 2015).

Many of the above phenomena, especially those with interactions between physical and biological processes, are insufficiently understood, and require improved understanding of interconnected changes in Arctic climate and ecosystems, cross-disciplinary approach and integration of concepts of microclimate and ecosystem into a unified local-environment system. To do this, collection and analysis of observational data, experimentation with changing conditions, and field investigations of interactions between microclimates and ecosystems in representative sites is required.

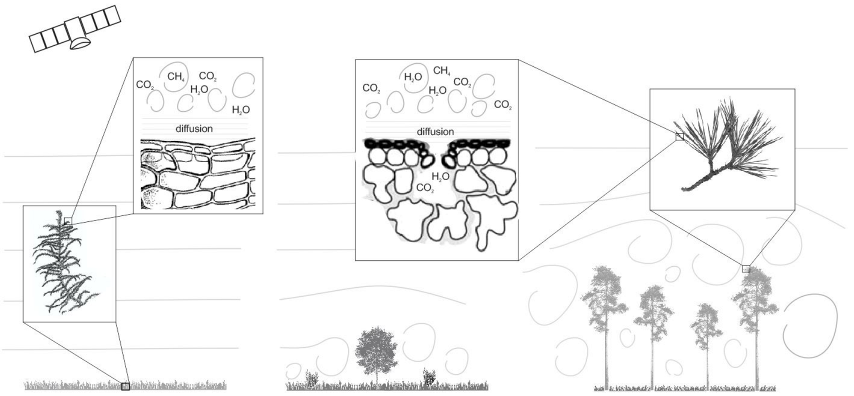

Figure 1. Schematic illustration on the PBL turbulence and scales included in ClimEco, including the different surface properties in the Arctic ecosystems: left: tundra; middle: shrubland or semi-open wetland; right; woodland. Local disturbances and temperature increase can change the ecosystem-PBL interactions. INSERTS: left: moss leaf surface; middle: pine needle surface; right: pine shoot with short shoots formed by groups of needles.

Links of the project to previous research by PIs and their teams

PBL, microclimate, and atmosphere – Earth surface interaction: The physical background for the part of proposed research addressing triple climate-PBL-ecosystem interactions includes the following theoretical developments and parameterizations: EFB turbulence closure theory and tools for modelling various types of PBL (Zilitinkevich et al., 2007a, 2009, 2013); refined concept for calculation of surface fluxes (Zilitinkevich, 2013; Zilitinkevich et al., 2006; Zilitinkevich & Esau 2007); new PBL height equations (Zilitinkevich, 2012; Zilitinkevich & Esau, 2002, 2003; Zilitinkevich et al., 2007b, 2012); new surface drag and heat/mass transfer laws (Zilitinkevich et al., 2001; Zilitinkevich & Esau, 2005; Zilitinkevich et al., 2008; Troitskaya et al., 2016, 17). These results have been obtained in recent projects coordinated by PI-1: EU Marie Curie Chair *PBL theory, modelling and role in Earth System* (UH, 2004-07); ERC *Atmospheric PBLs: physics, modelling and role in Earth system* (FMI, 2009-13); Russian Mega-grant *Air-sea/land interaction* (U. Nizhny Novgorod - UoNN, 2011-2015); ERC PoC *Integrated monitoring and forecasting system for local weather and microclimate* (FMI, 2014-15); Academy of Finland (AoF) (bilateral RU-FI call) *Atmosphere-hydrosphere interaction in Baltic Basin and Arctic Seas* (FMI, 2014-17); Russian Science Foundation: Grant *Physical Nature and Modelling of Atmospheric Boundary Layer over Heterogeneous Terrain* (UoNN, 2015-17).

Ecosystem structure, functions and composition: Ecosystem structure and functions are centrally depending on climatic conditions, and forecasted to be particularly sensitive to climate change in the Arctic areas. In this respect, the previous studies by the **UH team** include studies on reactive trace gases (e.g. Bäck et al., 2012, Aalto et al., 2014, 2015; Aaltonen et al. 2012), O_3 deposition (Altimir et al., 2006; Rannik et al., 2012), GHG fluxes with chamber and EC methods (Kulmala et al., 2015; Hari et al., 2017a,b), responses to disturbances (Bäck 1994; Bäck et al., 1994; Kukkola et al., 1997), and dynamics of Arctic ecosystems and populations (Hunter et al., 2014; Matkala et al., 2017). Significant funding for this purpose has recently been obtained from *AoF Center of Excllence* (2002-19, JB as team leader), *FP7 I3 EXPEER* (2010-15, JB as National PI) and *Maj and Tor Nessling Foundation SOKLI-project* (2015-17). The Finnish infrastructures belong to *INAR Ecosystems RI* funding from AoF (JB coord) and the ICOS ERIC, AnaEE and eLTER ESFRIs.

The GHG research group in **FMI** (leader T. Laurila) has studied ecosystem-atmosphere exchange of GHGs with micrometeorological, chamber and atmospheric concentration-inversion modelling methods, including 12 flux sites located north of the Arctic Circle. This research was conducted and ongoing within the following EU and AoF projects: *EU-FP7: Changing Permafrost in the Arctic and its Global Effects in the 21st Century* (2011-15); *EU-Life+: Climate change indicators and vulnerability of boreal zone applying innovative observation and modeling techniques* (2013-17); *AoF: Greenhouse gas, aerosol and albedo variations in the changing Arctic* (2013-17), *Carbon Balance under Changing Processes of Arctic and Subarctic Cryosphere* (2015-18), *Carbon dynamics across Arctic landscape gradients: past, present and future* (2016-20) and *Role of upland forest soils in regional methane balance: from catchment to global scales* (2017-21).

The Univ. of Tyumen (UT): work in polar regions (led by V. Melnikov): *Circumpolar Active Layer Monitoring Network-CALM, International Polar Year 2007-08, Land-Cover and Land-Use Change (LCLUC) project, Interdisciplinary integration projects of the SB RAS*. The proposed studies will continue research carried out by UT during the last decades. Studies of changes in landscapes and permafrost due to climatic changes were carried out at the Nadym site (Ponomareva et al., 2015), databases created (Drozdov et al., 2015) and results of latest complex monitoring of the Arctic territories were reported (Moskalenko et al., 2012; Matyshak et al., 2015; Melnikov et al., 2016; Drozdov et al., 2017; Vasiliev et al., 2017).

Added value of consortium collaboration. The project is genuinely cross-disciplinary, linking the physics of climate with ecology and biogeochemistry. Sub-project 1 PI (S.Z.) is among the world leaders in PBL physics whose recent research is focused on PBL as a physical entity "hosting" microclimate. Sub-project 2 PI (J.B.) has long experience on ecophysiology in both Arctic and boreal ecosystems, especially focusing on terrestrial ecosystem-climate feedbacks and developing efficient research infrastructure collaborations for promoting multidisciplinary research. The main focus of the Russian partners is to study thermal regime of permafrost in dominant ecosystems and CO_2 and CH_4 content in the cryogenic soils and ground.

Relevance to the Call and ARKTIKO Academy Programme. The project develops cross-disciplinary research collaboration between UH and FMI (both Finland) and UT (Russia) on the theme "Ecosystem adaptation to the rapidly changing Arctic". The collaboration grows from involvement of all PIs in Pan-Eurasian Experiment (PEEX) – international program started in 2012 (Lappalainen et al., 2016; www.atm.helsinki.fi/peex/). ClimEco responds to PEEX research agenda (Lappalainen et al., 2015). PEEX, targeted for 2013-2033 (& continuing until 2100), provides systematic framework for ClimEco collaboration. This project, addressing the chain *climate-change → microclimate → vegetation*, provides essential knowledge also for "Changing Arctic climate, changing diseases". The project meets all the three main objectives of the ARKTIKO Programme:

- The project is essential for achieving a breakthrough in understanding of ecosystem transitions and multidimensional changes unfolding in the Arctic under the global warming: we will produce new knowledge on coupling and feedback mechanisms supporting the observed recent advance of alternative, more productive terrestrial ecosystems (Objective 1).
- The project will strengthen cross-disciplinary and problem-based research addressing biological and physical aspects of the Arctic environmental change: it will resolve the long-standing problem with dynamic vegetation schemes in climate models, currently unable to reproduce realistic distribution and multi-decadal dynamics of the Arctic vegetation types (Objective 2).
- The project will disseminate its outcomes to support decision-makers and stakeholders: see 3B and 3C (Objective 3).

Contributing to other ARKTIKO goals the project will:

- Collect in-situ data and compile it with remotely sensed products for answering urgent research questions on climate-ecosystem change in Arctic from several most established sites in:
  - Russia: Nadym, Marre-Sale and Tiksi (permafrost),
  - Finland: Värriö Subarctic Research station/SMEAR I subarctic forest, Pallas wetland and Sodankylä forest (no permafrost).
- Boost Finnish-Russian networking in Arctic research acting as a catalyst for expansion of Finnish SMEAR[1] super-site infrastructure to Russia: the bilateral ClimEco project will facilitate the formulation of research agenda for the first Russian SMEAR-type station, being constructed in Sabetta, Yamal Peninsula.

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[1] Stations for Measuring Ecosystem – Atmosphere Relationships (SMEAR) measure fluxes, storages and concentrations in the land ecosystem – atmosphere continuum in the boreal climate zone (Hari & Kulmala, 2005). SMEAR stations are managed jointly by the Department of Forest Sciences and the Department of Physical Sciences at UH and form the foundation for PEEX in-situ network.

3. Objectives and expected results

3 A Objectives of the research

The ClimEco aim is to principally improve modern knowledge of mechanisms, feedbacks and pathways of the Arctic ecosystems response and their adaptation to the Arctic warming and, thus, to advance scientific background and tools for projecting current and future changes in Arctic ecosystems and microclimates. Such projections will be done for selected sites in Subarctic Finland and North-West Siberia, where the main drivers for ecosystem change and adaptation are the Arctic warming and land-use/cover disturbances caused by human activities.

In our analyses, we proceed from the physical entity holding and controlling both local ecosystem and microclimate, the atmospheric PBL (Zilitinkevich et al., 2015). Here, ecosystems essentially control the energy and matter exchange through plant evapotranspiration and CO_2 assimilation, regulated at leaf-scale through stomata, thus bridging physical processes in the atmosphere and soil and linking the entire PBL-microclimate system. Our tools include i) ecophysiological and micrometeorological analysis of ecosystem structure and exchange processes in the Arctic, ii) new turbulence-closure theory (Zilitinkevich et al., 2013) and concept of long-lived PBLs typical of polar winter or summer, distinct from usual mid-latitudinal PBLs; and iii) new knowledge of climate-Arctic ecosystem feedbacks based on unique data from sites in Finland and Arctic Russia. Special emphasis is on improving the conventional methodology of calculation of surface drag, heat transfer and evapotranspiration, now based on the concept of roughness lengths as empirical parameters defined once and for all. This approach is irrelevant to multi-scale, deep and flexible vegetation canopies but yet employed widely, for lack of alternative. Our theoretical analyses and direct numerical simulation (DNS) of interactions between turbulent and molecular transports at the air-plant interface, combined with experimental studies of heat/mass transfer over natural ecosystems are able to explain and quantify real variability of roughness lengths.

The ecosystem responses to micro-scale changes/disturbances will be examined through analysis of species and population dynamics and ecosystem scale flux measurements in sites varying in permafrost, land-cover and microclimate. Our approach implies integration of all these features of patchiness in the framework of PBL dynamics and aims to improve understanding of the ecosystem resilience/sensitivity to anthropogenic and natural disturbances and consequently, to quantify their adaptation to climatic changes.

Summing up, ClimEco methodology includes:
(i) Satellite remote sensing products - to locate disturbance patterns and related persistent surface temperature anomalies and ecosystem properties (plant functional types, species abundance, coverage, LAI) at regional scale; (ii) In situ data and new observations on microclimate, ecosystem structure and functions (productivity)/experiments - to refine the links between properties of ecosystems and microclimates and to allow pairwise comparisons between disturbed-undisturbed and micro-climatically different sites; (iii) Downscaling from global climate changes to microclimates via advanced PBL models, and further from microclimate to ecosystem via advanced heat/mass transfer models, accounting for microscale (stomatal level) physical processes; (iv) Seamless modelling to clarify the nature of anomalies and their effects on essential climate variables.

We anticipate a breakthrough beyond purely statistical climate-ecosystem studies, currently not able to capture the patchiness in ecosystems to PBL models. Our expectation is underpinned by recent advances in physics of atmospheric PBLs (Zilitinkevich 2012, 2013; Zilitinkevich et al., 2012, 2013 (EFB)); physics and DNS of surface drag and heat/mass transfer (Zilitinkevich et al., 2001, 2006, 2008; Druzhinin et al., 2016a,b; Troitskaya et al., 2017), understanding of PBL control of microclimates (Zilitinkevich and Esau, 2009; Zilitinkevich et al., 2015) and by progress in turbulence modeling, data collection and analysis (Zilitinkevich et al., 2013; Baklanov et al., 2017). The expected quantification of PBL feedbacks between ecosystems and climate will add new links to the feedback loop presented by Kulmala et al. (2004, 2014). Importantly, it allows obtaining advanced understanding on disturbance-flux relationships in the Arctic regions, caused by pressures by anthropogenic (industrial activity, e.g. building or roads and pipelines) or natural (permafrost, warming) drivers.

ClimEco specific objectives are:

- To integrate historical and newly obtained in-situ and remote-sensing data for demonstrating and quantifying parallel ongoing changes in climate and ecosystems over the territories addressed in the project: Northern Finland and North-Western Siberia (WP1)
- To identify and specify by field observations and experiments in different ecosystems (mires, shrublands tundra and forest, permafrost and non-permafrost) concrete responses of Arctic ecosystems to climate warming and land-use disturbances at small scales (WP2)
- To advance conventional concept and methods of calculation of Arctic PBLs and heat/moisture exchange between the atmosphere and selected Arctic ecosystems, towards better understanding and forecasting of local Arctic climate-biosphere systems (WP3)

Hypotheses

Our hypothesis is that instantaneous transitions from one microclimate-ecosystem equilibrium to another are based on the feedback between partitioning of the surface energy budget among turbulent fluxes of sensible and latent heat, on the one hand, and changes in structure and functioning of ecosystems, on the other hand. In particular, we will quantify how anthropogenic and natural degradation of the present Arctic vegetation cover and alternative succession of communities responds to the reduced latent heat flux causing higher surface air temperature, better near-surface ventilation, and deeper active soil layer.

The ClimEco will answer the following research questions in four WPs (see Fig. 2):

Q1: How heterogeneity of the surface temperature and moisture affects the ecosystem composition and productivity at regional (10^5 m), PBL/microclimate (10^3 m) and local (10^1 m) scales? Which specific ecosystem changes develop within patches of warm microclimate in tundra and forest-tundra ecotones? How are ecosystems and microclimates co-evolving? (WP1)

Q2: Which functional-structural properties and physiological processes support adaptations and alternative successions in–warmer or degraded environments? How alternative ecosystems modify their physical environment? (WP2)

Q3: How turbulent mixing in PBL and heat/mass transfer processes at the atmosphere-ecosystem boundary interplay with the surface energy and matter exchange, surface temperature, and surface humidity? How the properties and replacement of ecosystems are linked to partitioning of turbulent fluxes? (WP3)

We expect that our project will contribute to extending the current strategy of research on adaptation of Arctic ecosystems from paleo-proxy evidence, model simulations and statistical regressions, towards integrated observational and modelling studies of co-evolution of ecosystems, microclimate and PBL, based on advanced physics of both the Arctic PBLs and the near-surface heat-mass exchange, and with due regard to heterogeneity of Arctic landscapes. We anticipate a **breakthrough** in comprehending and calculating the energy and matter exchange between the Arctic PBLs and selected Arctic ecosystems. By this means, we will quantify the major ecosystem-microclimate feedbacks and, thus, open prospects for better-grounded seamless climate-biosphere modelling and projections of ecosystem replacement under the warming Arctic climate. Better understanding of heat-mass transfer over alternative ecosystems and thawing soils will serve for reassessment of the water and carbon cycles in the changing Arctic.

Effects and impact beyond academia: The project will provide a fundamental understanding of proliferating alternative ecosystems and plant successions in the Arctic, in relation to microclimate.

Results can be applied in selecting tools for restoration of destroyed ecosystems in the Arctic, i.e. in planning of management after forest fire or rehabilitation of abandoned industrial areas. They will be of immediate use for the technologies to reduce the surface erosion. In long-term, the improved climate projections for the Arctic will help to assess the impact of warming, its diverse pathways and to design proper adaptation and mitigation measures. The results will also be useful in assessing the consequences of rates of loss, degradation, and fragmentation of natural Arctic habitats (Aichi Target 5).

Publication plan: All results will be published rapidly and in open access journals (the golden open access route, publication fees budgeted in project costs) as joint research papers, and each task produces, at least, one presentation and a peer-review paper. Both high-impact international peer-reviewed journals covering specific areas and in multidisciplinary journals will be selected for publication fora. All partners will participate in international conferences and workshops. Collaboration with WMO and IIASA will serve for dissemination of the results and new knowledge to the global community. PEEX network will serve as a dissemination channel aimed at potential end-users (environmental administrations, industry, in particular, oil and gas companies engaged in the Arctic exploitation, etc). Besides, the consortium will communicate the results to national media in Finland and Russia, and to international media where appropriate. Web pages and social media will be utilised to reach the public audience.

4. Research methods and material, support from research environment

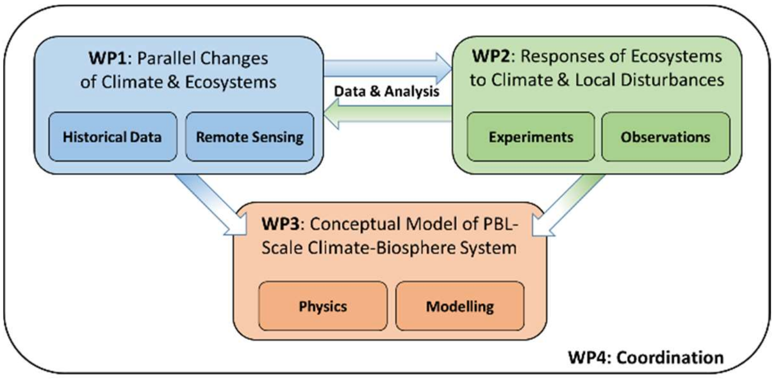

Figure 2. Schematic structure of the ClimEco project WPs and their linkages

WP 1: How ecosystems affect climate in the Arctic? (Leaders: Prof. Vladimir Melnikov, UT, Russia; Dr. Alexander Mahura, UH, Finland)

Objective: To collect historical / in-situ ground-based and remote-sensing data to show contemporary parallel changes of climate and ecosystems over the Northern Finland and North-Western Siberia territories.

Methods: Collection, processing and multi-scale statistical analysis of the combined in situ ground-based and remote sensing long-term comprehensive data to investigate the mechanisms and processes shaping the ecosystem responses in different micro-climates of the Sub-Arctic and Arctic sites as well as to provide observational constraints for the land surface models improvements.

Task 1.1. Processing local scale site related ground-based observations. We will collect and analyse available series of meteorological, hydrological, land-cover/use, landscape, physiographical, geobotanical, ecosystem, etc. data from the Arctic and Subarctic Russian sites (Nadym, Marre-Sale, Tiksi) and Finnish (Pallas, Sodankylä, Värriö) sites as well as multi-year time-series observations at WMO stations in studied regions; integration all observations into GIS and in-depth statistical analysis are planned together with students' training on existing sites.

Task 1.2. Processing regional coverage/ scale related satellite observations. We will process remote sensing data - MODIS products (NDVI - 0.25 km, LST - 1 km), LandSAT8 (hi-res - 0.03 km) based on analysis of satellite data (30 years) for identification of micro-climatic surface temperature heterogeneity, warming micro-climate hot spots and the corresponding changes in the soil moisture and ecosystem productivity characteristics; identify where and which ecosystems are affected by a different degree of the surface warming over the past decades. The NDVI changes disclose the phenological shifts, summer maximum biological productivity and LAI of the ecosystems in question. Statistical multi-factoral analysis of these biological variables in connection with physical micro-climate variables will establish the long-term tendencies in the Arctic biota.

Task 1.3. Links for climate and land surface changes. We will perform the combined statistical analysis to link changes in climate conditions and land surface properties and characteristics; multi-scale complex analysis of all collected information; consideration of additional sources of influence (populated areas, hydrological objects) on ecosystems and permafrost; historical zoning of the investigated territories; physical properties of the lower atmosphere corresponding to diverse microclimates and ecosystems will be determined; construction of models of landscape and ecosystem transformation from Arctic territories in focus; work will use input from T1.1-1.2 & WP2.

M1.1: Processing completed for local and regional scale data (M18)

M1.2: Analysis finalised for climate and land surface changes links (M21)

D1.1: Local scale changes in Arctic: data analysis of long-term measurements at sites (Article/M12/ Resp. – UT; Contrib - UH, FMI & collabor)

D1.2: Remote sensing and analysis of hot-spots, land-cover/landscape changes in the Arctic regions (Article/M18/ Resp. – FMI; Contrib - UH, UT & NERSC)

D1.3: Links for climate and land surface changes in the Russian and Finnish Arctic territories (Article/M21/ Resp. - UT; Contrib - FMI, UH & collabor)

Outputs: regional and local/ sites climate changes overview; refining climate databases; vegetation, land-cover, landscape changes description; local and regional scale maps of ecosystems and their changes and quantitative assessments of impacts on climate change (to WP2); estimates of average annual heat sources in soil; data on permafrost dynamics; hints for land surface models improvements; links for climate change and land surface change (to WP3).

WP2: How climate affects ecosystems in the Arctic? (Leaders: Prof. Jaana Bäck, UH, Finland; Prof. Dmitry Drozdov, UT, Russia)

Objective: To identify and specify structural and functional responses of the Arctic ecosystems (treeless wetlands, tundra, shrublands and subarctic forests, with or without permafrost) and their adaptation to climate and local disturbances

Methods: Linking measured material and energy flows and abiotic (climate, soil) and biotic (vegetation) factors to describe the differences in the ecosystem structure and function in micro-sites differing in climatic and permafrost conditions.

Task 2.1. Vegetation coverage and structural analysis: species-level data for statistical analysis of site-specific patterns in functional plant traits. Ground vegetation survey (% cover of each species, specific plant traits) is done in sample plots (Vanha-Majamaa et al., 2000; Chapin et al., 1996) in already established sites, and in newly selected sites at all six field stations. A number of sub-plots will be located in disturbed or degraded ecosystems (fire, industry, roads, etc.), defined by analysis of the remote sensing data ('hot spots') and local expertise. Albedo measurements will be performed at each site. The data is pooled together to search for site-specific patterns in functional plant groups (graminoids, bryophytes, lichen, woody plants) and functional traits in the current situation, and data from previous analysis used as a comparison.

Task 2.2. Ecosystem scale fluxes of mass and energy as an indicator for climate acclimation.

We combine all available meteorological and ecosystem scale data on primary production, CO_2 emissions, transpiration and CH_4 exchange using EC technique with the vegetation coverage, functional types and functional plant traits (Task 2.1) at the study sites. The dataset will include several years of data on subsites from treeless wetlands and tundra to subarctic forests with varying

LAI, ground water table, permafrost and climatic conditions. We will use the dataset to model the rates of different fluxes using the optical (T1.1.), biotic (T2.1) and abiotic factors (mainly temperature and ground water table/permafrost) as inputs in order to estimate how the predicted changes in these could reflect to the BDL fluxes at each site.

Task 2.3. Impacts of disturbances and warming on ecosystems. We will collect data from past and ongoing field campaigns and create an online GIS tool for analysing the data. In addition, emerging alternative ecosystems of the disturbed land patches around Nadym will be studied in student expeditions/workshops (2019, see Mobility), complementing the earlier studies in the area. To further parameterise the PBL models, vegetation structure at specific degraded sites will be analysed in more detail in the third year; these will be identified from results of the first two years of the project. To study adaptation of vegetation to climate warming, passive open top chambers will be used in Pallas wetland and Sodankylä pine forest, where also disturbance caused by reindeer grazing pressure is studied. The effect of moderate warming (about 2°C) on the development of vegetation and CO_2 and CH_4 fluxes will be measured during the project.

M2.1: Vegetation analysis finalised for all 6 sites (M20)
M2.2: Dataset on flux measurements finalized (M36)
D2.1: Impact of disturbances on Arctic vegetation adaptation capacity (Article/M20/ Resp. – UT; Contrib - UH, FMI & collabor)
D2.2: Vegetation traits and changes in functionality in micrometeorological hot-spots in the Arctic (Article/M30/ Resp. – UH; Contrib - UT, FMI & NERSC)
D2.3: Impacts of experimental warming on Arctic vegetation (Article/M36/ Resp. - FMI; Contrib - UH & collabor)

Output: Dataset on responses of vegetation structure, functional traits and groupings, and material and energy flows to changes in ecosystem structure in sites differing in abiotic factors and disturbance (to WP1); improved parameterisations of disturbed ecosystems for PBL models (to WP3).

WP3: Conceptual model of Arctic climate-ecosystem interactions via PBL dynamics (Leader: Prof. Sergej Zilitinkevich, FMI, Finland)

Objective: To develop conceptual model of the PBL-scale climate-biosphere system accounting for specific features of energy and matter exchange at the atmosphere-plant interface and specific nature of long-lived Arctic PBLs; and to use it for analysing and seamless modelling of microclimate-ecosystem interaction.

Methods: Theoretical analysis and topical DNS (using INM-RAS code) of turbulent exchange processes in specific condition of Arctic PBLs and ecosystem canopies, meteorological and soil data analyses, and seamless climate-ecosystem modelling.

Task 3.1. New framework for comprehending and parameterizing the surface layer turbulence. We will revise Monin-Obukhov similarity theory of atmospheric surface layer with due regard to the recently revealed self-control of shear-generated turbulence in stable stratification and self-organisation of convective turbulence in unstable stratification; develop advanced theory of the surface-layer turbulence consistent with new experimental evidence; and create novel theoretical framework for calculation of turbulent fluxes linking the atmosphere with underlying Earth's surface in any stratification.

Task 3.2. Refined physics and parameterization of the drag and heat/mass transfer at the atmosphere-Earth's surface interface for selected Arctic ecosystems. Conventional parameterization of the surface drag and heat / mass (water vapour) transfer is based on the widely recognised vision of land-surface roughness lengths (for momentum and scalars) as empirical parameters given once and for all. This is wrong, especially for deep and multi-scale vegetation canopies, where roughness lengths strongly depend on intensity of turbulence and hence on wind speed and static stability (e.g., Zilitinkevich, 2013). We will account for these dependence and develop semi-empirical formulation of roughness lengths for tundra and forest ecosystems.

Task 3.3. Improved methodology for calculation of surface fluxes over selected Arctic ecosystems. Improved methodology for calculation of turbulent fluxes of energy and matter over tundra and forest will be created based on advanced theory of the surface-layer turbulence (Task 3.1) and new formulation of roughness lengths and displacement heights as dependent of wind speed and static stability (T3.2). We will validate this methodology against observations in Arctic sites.

Task 3.4. Empirical study of patches of warmer microclimates in relation to changing ecosystems. We will employ new vision of the surface-layer turbulence and advanced methodology for calculation of surface fluxes (T3.3) from massive available meteorological, hydrological and soil data, by this means quantify partitioning of turbulent fluxes of heat and moisture (Bowen ratio) and thus refine relations between warmer microclimates and successive ecosystems.

Task 3.5. Numerical experimentation on sensitivity of microclimate to ecosystem through seamless modelling using Enviro-HIRLAM model. We will adapt Enviro-HIRLAM to specific conditions of the Arctic; incorporate new surface-flux scheme based on results from T3.1-3.3; perform high-resolution (1-2 km) simulations driven by past/ current/ and possible future data on vegetation, land-cover and ecosystem changes from T1.1-1.3, 2.1-2.2 & 3.4; analyse variability in key meteorological parameters due to changes in vegetation; estimate interactions and feedbacks between meteorological and ecosystem changes.

M3.1: Tools for improving the calculation of surface fluxes ready (M18)
M3.2: Dataset on surface fluxes calculated using the improved methodology (M32)
D3.1: Improved understanding of interaction and feedbacks between microclimate and pristine/disturbed ecosystems (Article/M8/ Resp. - FMI; Contrib - collabor)
D3.2: New formulation of land-surface roughness lengths for momentum and scalars as dependent of wind speed and static stability (Article/M18/ Resp. - FMI; Contrib - collabor)
D3.3: Novel methodology for description of atmosphere/land-surface interaction in seamless climate-ecosystem modelling (Article/M24/ Resp. - UH; Contrib - FMI & collabor)
D3.4: Patchiness of microclimates in relation to Arctic ecosystems accounting for local differences in sensible and latent heat fluxes (Article/M32/ Resp. - FMI; Contrib - UT, UH)
D3.5 Meteorological vs. ecosystem changes in the Arctic - sensitivity studies with seamless high resolution modelling (Article/M36/ Resp. - UH; Contrib - FMI & collabor)

<u>Output:</u> Refined concept and methodology of calculation of surface-layer turbulence, surface drag and heat/mass transfer with application to selected Arctic ecosystems; refined knowledge of climate-biosphere feedbacks at the PBL scales.

WP4: Coordination, research training and dissemination (Leaders: Prof. J. Bäck, UH, Finland & Prof. S. Zilitinkevich, FMI, Finland)

<u>Objective:</u> To coordinate and direct the project activities to fulfil the multidisciplinary goals, periodic assessments and modifications to plans if needed, dissemination and reporting of results and organizing the mobility and researcher training activities.

Task 4.1. Project coordination and interactions between partners
M4.1, M4.2: Kick-off and final meeting
Task 4.2. Dissemination and reporting
M4.3: Signing data usage agreement, M4.4.: project Web pages published
D4.1: Web-page, D4.2-4.4 Annual and final reports
Task 4.3. Research training and mobility
M4.5-M4.7: Workshop on the topic, research visits, expeditions

The kick-off meeting will be held in Mar 2018 at the Hyytiälä research station (Finland). The exact time will be chosen so that PhD students can participate in the Winter school organized by UH. The course is based on intensive work in small groups, with MATLAB used for statistical analysis. In Sum 2019, UT will arrange a workshop, including expert lectures and practical fieldwork on taxonomy and functional traits of Arctic vegetation, flux measurement and PBL modeling. The final project meeting will be held in Nadym (Russia) in Oct 2019.

The research will receive tangible support from the international PEEX community (https://www.atm.helsinki.fi/peex). NERSC will collaborate in analysis of the remote sensing data. MSU (Konstantinov) will collaborate in analysis of the temperature data from the WMO weather stations and the AUHICHN network in Nadym/Novy Urengoy (Yamalo-Nenets Autonomous Okrug, YNAO, Russia). UH recently established INAR (Institute for Atmospheric and Earth System Research), leading the Consortium and providing in-kind support in the form of infrastructures (data and instruments, operating personnel) and research services. Internationally, the project links to European RIs ACTRIS, ICOS, eLTER and AnaEE. In Tiksi, measurements are conducted by Arctic and Antarctic Research Institute (Makshtas) and FMI; both collaboratively will analyze the results. The research utilizes both remote sensing data and in situ data from several field stations (see Fig. 3). The Russian sites are operated by TSU (Nadym), by TSU and HydroSpetsGeology (Marre-Sale) and by Melnikov Permafrost Institute, Roshydromet (Tiksi).

Figure 3. Geographical locations of ClimEco sites: subarctic region in Northern Finland (Värriö, Sodankylä and Pallas), Yamal-Nenets Autonomous okrug (Nadym and Marre-Sale) and Sakha Republic (Tiksi) of the Russian Arctic.

The Nadym site (northern taiga) is located in the zone of the insular permafrost in the YNAO; in operation since 1971. It has long-term series of observations for air temperature, biota, soils, landscapes, CO_2 and CH_4 emissions, annual seasonal-thaw layer measurements. The Marre-Sale site (tundra) is located in the western Yamal. The meteorological observations are carried out since 1914, and for permafrost since 1978. The Tiksi site (Arctic tundra) is located in the northern part of the Sakha Republic; in operation since 1932 (climate) / 2010 (micrometeoroglogical fluxes). The micrometeorological fluxes and atmospheric and soil parameters are measured at several microsites representing the main soil-vegetation microsites around the flux tower. At the footprint area, there is a road and vehicle tracks through. The permafrost depth is more than 200, 100, and 800m (with active layer max depth up to 1, 1.8 and 0.4 m) for the Nadym, Marre-Sale and Tiksi sites, respectively.

Finnish partners have three highly instrumented subarctic sites differing in their land use and erosion intensity: Värriö Strict Nature Reserve & SMEAR I station (pristine subarctic forest, wetland and tundra) and two sites in Pallas (wetland) and Sodankylä GAW station (pine forest). All sites offer a possibility to analyse long-term vegetation patterns related to impacts from reindeer herding (exclusion fences have existed for decades), and comparisons with pristine and more developed touristic areas can be done. The sites have long-term measurements on meteorology and ecosystem structure and functions, including EC measurements of GHG exchange.

Critical points and risks; mitigation: The probability of failure is low due to already existing active collaboration between Finnish and Russian partners. The field sites and data are accessible through participating organisations. At the Russian sites we are dependent on the measurement and data transfer permissions by Special Services. Remote sensing datasets originate from Landsat and MODIS, and thus the datasets are complementary. In the case of unforeseen problems in the field measurements, data will be used from close-by sites or from satellite observations. In Task 3.2 we will attempt to develop a solid theory for calculation of heat/mass transfer at the atmosphere - Earth's surface interface, but success can't be guaranteed, as the problem remains unsolved for decades. Alternatively, we will develop semi-empirical formulation of roughness lengths for momentum and scalars, allowing better than now calculation of heat/mass transfer in tundra ecosystems.

5. Ethical issues

The proposal does not involve any ethical issues and does not require research permits in other places than in Värriö Strict Nature Reserve, where UH has an agreement with Finnish Forest Service in place. Licences and agreements are in place for the work in Russian sites. Work with databases, datasets, codes, and models will not cause any intellectual property infringement, as none of these are subject to official restrictions.

6. Implementation: schedule and distribution of work

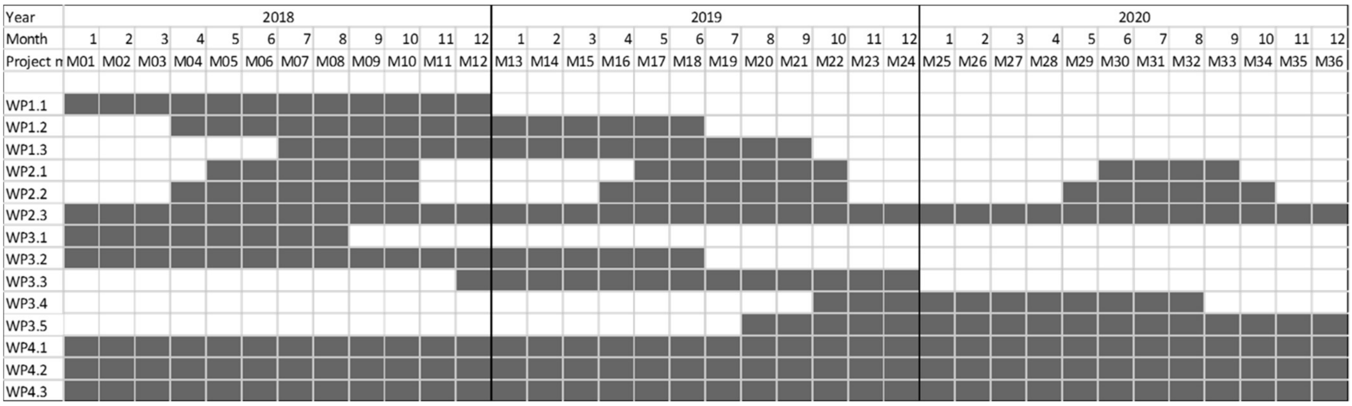

Table 1. GANTT chart for ClimEco divided by WPs and tasks.

7. Research team and collaborative partners

The project team will consist of the following (tasks) (FI), paid by the project or in-kind:

***Salaries*:** Postdoc Liisa Kulmala (UH): GPP and flux data and measurements; PhD student Laura Matkala (UH): vegetation analyses, flux measurements; senior scientist/ university researcher Alexander Mahura (UH): seamless modeling, meteorology, statistical analysis. Postdoc NN (FMI): ecosystem and flux measurements and analysis; Researcher Svyatoslav Tyuryakov (FMI): remote sensing and in-situ data processing and analysis; Postdoc Evgeny Kadantsev (FMI): PBL and heat/mass transfer modelling

In-kind contributions: Prof. Jaana Bäck (UH): Arctic ecology & ecophysiology; univ. researcher Hanna K. Lappalainen (UH): coordination with PEEX, metadata database for Arctic sites; Prof. Tuukka Petäjä (UH): PEEX infras, observational and modelling platforms; Prof. Sergej Zilitinkevich (FMI): theory of heat/mass transfer and PBL; senior researchers Tuomas Laurila and Mika Aurela (FMI): ecosystems, Pallas, Sodankylä and Tiksi

Russian project partner (UT): Prof. Vladimir. Melnikov and his research group: Vladimir Melnikov (UT): geocryology, modeling the impact of permafrost degradation; Prof. Dmitry Drozdov (UT): geocryology, zoning, mapping, GIS; Prof. Alexander Vasilev (UT); geocryology, research at the Nadym site; Prof. Elena Slagoda (UT): geocryology, research at the Marre-Sale site; Prof. Lyudmila Kalenova (UT): Arctic ecology and biology; 2 PhD students Jana Tihonravova and Anna Kuznecova: data collection, processing and analysis

External collaborators: The project is having extensive collaboration both nationally and internationally. The most important global collaborations are with the WMO and IIASA (meteorology, climate modeling), PEEX and ILTER (in situ observations) and GEO-GEOSS (remote sensing). Other highly relevant and important collaborations in various forms (data and site access, methodologies, etc) include e.g. AARI, ICOS ERIC, eLTER, AnaEE, NERSC, Max-Planck Institute, Obukhov Institute of Atmospheric Physics RAS, and Universities of Copenhagen and Delft (see collaborations list in application). The most important national collaboration in Finland is the Center of Excellence with >250 climate and ecosystem scientists.

8. Research careers, fulfilment of the mobility requirement and researcher training

ClimEco will advance the career and research training of several PhD students and PostDocs, and promote a multi-disciplinary approach. The project is oriented towards the young generation of researchers, and >10 students from the Finnish and Russian teams will be involved. MSc E. Kadantsev is expected to defend his PhD thesis at UH in spring 2018 and start his Postdoc career at FMI; S. Tyuryakov and L Matkala will prepare their PhD theses during the project. Research training will include mobility and participation of students in the fieldwork/expeditions as well as in the training course on modelling, observation and assessment for Arctic ecosystems including a series of lectures and practical exercises. Additionally, the involvement of the PEEX community partners/ organizations is expected. Such training events will contribute to building contacts and networking on multi- and interdisciplinary subjects. Learning experience, horizontal level of communication, better understanding of common and specific needs are envisaged. Student supervision will be done jointly by the researchers from the Finnish and Russian teams; and at least, 5 students are planned to be supervised. In addition, the outreach activities towards the university, school education and general public will be promoted with including research results, achievements and developments into lectures, presentations, demonstrations, website, etc.

ClimEco will encourage and support gender equality. Among the 13 persons involved directly in the project there are 9 male and 4 female researchers, including 4 young researchers and PhD students. The project personnel is recruited based on scientific merits and ability to complement the team with required expertise. In case of additional recruitment needed, the equal opportunities policy will apply.

9. Mobility plan for the funding period

The mobility plan includes research visits to and from Russia, practical training and scientific workshops/summer schools in methodological issues (surface flux measurements, vegetation analysis, modeling, PBL analysis). Particular emphasis is given to early career researcher mobility and knowledge exchange between Russia and the Finnish partners.

Spring 2018 - Research training/ mobility (from Russia to Finland) – participation/ learning/ visit programme to the SMEAR measurement station & meetings with Finnish researchers on theoretical, observations and modelling topics (2 weeks; contrib. to all WPs)
Summer 2019 - Research training/ mobility (from Finland to Russia) – participation in fieldwork/ summer 2019 expedition and training workshop in Yamalo-Nenets Autonomous okrug (1+ months; field measurements; contrib. to all WPs)
Spring 2020 – Research training course on modelling, observation and assessment for Arctic ecosystems (in Finland) – mobility/ funding for Russian students to attend the course (1 week; better understanding occurring processes, theoretical and model improvements for Arctic landscapes and ecosystems; analysis of observations for ecosystems; seamless, LES, ecosystem modelling and sensitivity studies on land-cover changes; contrib. to all WPs).

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