ATM Research and Action plan 2014-2019

Name of the Centre of Excellence: ‘Centre of Excellence in Atmospheric Science – From Molecular and Biological processes to The Global Climate’ Acronym: ATM

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1 Background to the research and previous research

The atmosphere forms a major part of the environment to which life on Earth is sensitively responsive. The atmosphere closely interacts with the biosphere, hydrosphere, cryosphere and lithosphere on time scales from seconds to millennia (Wanner et al., 2008). Changes in one of the components are directly or indirectly communicated to the others via intricately-linked processes and feedbacks. In recent years, a lot of research has been motivated by the importance of atmospheric aerosols to the global radiation budget, cloud formation, and human health. The concentrations of reactive gases, greenhouse gases (GHGs) and atmospheric aerosols are tightly connected with each other via physical, chemical and biological processes occurring in the atmosphere, biosphere and at their interface (Arneth et al. 2010, Carslaw et al. 2010, Mahowald 2011). Human and societal actions, such as emission policy, forest management and land use change, as well as various natural feedback mechanisms involving the biosphere and atmosphere, have substantial impacts on the complicated couplings between atmospheric aerosols, trace gases, GHG, air quality and climate (Arneth et al. 2009, Raes et al. 2010, Shindell et al. 2012).

COBACC hypothesis. Anthropogenic emissions of GHGs have increased substantially during the past century. Elevated concentrations of CO$_2$ and methane are the most important forcing agents causing global warming (IPCC, 2007). However, it is not straightforward to attribute or predict the climate change in detail, as the internal variability of climate is only partially understood, aerosol forcings are still highly uncertain, and there are many feedback mechanisms that are difficult to quantify. It has been recognized for decades that the biosphere plays an important role in climate. For example, Kulmala et al. (2004) suggested a negative climate feedback mechanism whereby higher temperatures and CO$_2$-levels boost continental biomass production, leading to increased biogenic secondary organic aerosol (BSOA) and cloud condensation nuclei (CCN) concentrations, tending to cause cooling. This COBACC (COntinental Biosphere-Aerosol-Cloud-Climate) feedback (Fig. 1), is similar to the so-called CLAW-hypothesis by Charlson et al. (1987) which connects the ocean biochemistry and climate via a negative feedback loop involving CCN production due to sulfur emissions from plankton (e.g. Quinn & Bates, 2011).

The COBACC feedback (Fig. 1) has two major overlapping feedback loops, both initiated by increased CO$_2$ concentrations (Kulmala et al., 2013a). The focal points of these two loops are ambient temperature and plant gross primary production (GPP). The loops are closely tied with aerosol-cloud interactions and with the atmospheric carbon sink, and both tend to act toward suppressing global warming. The feedback loops combine physical, chemical and metabolic phenomena. Thus we have to investigate very versatile processes simultaneously, and to integrate the obtained results to cover all the relevant features. Nucleation, condensation and atmospheric reactions together with metabolism of vegetation and microbes generate concentration, temperature and pressure differences that give rise to material and energy flows within and between the atmosphere, vegetation and soil. We apply our comprehensive approach to study the complete system and analyze the feedback loops generated by the material and energy flows. In this way, we can utilize the knowledge of different disciplines in our research team and take a full advantage of our versatile team. It is important to point out that many of
the quantities and processes related to these feedback loops are affected by human activities, and that there are many other feedback mechanisms that affect some sub-group of the relevant quantities. With that in mind, the COBACC feedback can be considered as a broad framework which connects the human activities, the continental biosphere, and the changing climate conditions.

**Figure 1.** The two feedback loops associated with the COBACC feedback. BVOC=biogenic volatile organic compounds, SOA=secondary organic aerosol, CS=the condensation sink, \( A_{\text{tot}} \)=total aerosol surface area, \( V_{\text{tot}} \)=total aerosol volume, CCN=cloud condensation nuclei, CDNC=cloud droplet number concentration, and GPP=Gross Primary Productivity, which is a measure of ecosystem-scale photosynthesis.

**Previous research as FCoE (2002–2007 and 2008–2013).** During the recent years, “The Finnish CoE in Physics, Chemistry, Biology and Meteorology of Atmospheric Composition and Climate Change” has taken the world leading position in building up scientific understanding related to the global climate change, particularly the dynamics of aerosols, ions and neutral clusters in the lower atmosphere and their linkages to biosphere-atmosphere interactions, biogeochemical cycles, GHGs and trace gases. This work has led to 16 published papers in *Nature* and 12 published papers in *Science* categorized as follows:

- **atmospheric chemistry and atmospheric oxidation:** *Nature* 488, 193 (2012).
- **effect of secondary biogenic aerosols on global aerosol load:** *Nature* 416, 497 (2002); *Nature* 417, 632 (2002); *Nature* 433, E13 (2005); *Nature* 461, 381 (2009); *Science* 326, 1525 (2009);
- **air pollution-climate interactions:** *Science* 326, 672 (2009); *Science* 337, 1078 (2012).

As a recognition of the scientific excellence of the consortium, M. Kulmala and S. Zilitinkevich were granted the ERC-Advanced Grants, and H. Vehkamäki and I. Riipinen the ERC-Starting Grants. The total number of the peer-reviewed publications produced by the ATM scientists is >1000 in the last 10 years. Two Finland Distinguished Professors (FiDiPro), Worsnop and Chandrasekar, have been appointed to our research team.

The key strength of the previous FCoE approach has been a successful combination of innovative method and instrument development, and the interplay between the comprehensive multidisciplinary measurements and advanced modeling, which have been capitalized to improve fundamental process understanding and up-scaled to clarify the implications of the processes.
Challenges in the assessment and prediction of climate change. In spite of the current success in the understanding of the aerosol formation processes, in the related dynamics as well as in the biosphere-atmosphere-climate interactions, there is still a great challenge in the assessment and prediction of climate change and in the analysis of related processes on a global scale. There has been criticism that the description of processes, and hence parametrizations, in the ESMs is based on insufficient knowledge of physical, chemical and biological mechanisms involved in the climate system, and that the resolution of known processes is insufficient (e.g. Ghan & Schwartz 2007, Grewe et al., 2012). For example, precipitation is a critical component of the hydrological cycle influencing ecosystem properties, a major source of energy for driving atmospheric circulation, and the main sink for aerosol particles and most atmospheric trace gases. Particularly the aerosol-cloud interactions and atmospheric dynamics leading into precipitation are not well described or parameterized. Due to the complexity of different feedback mechanisms that link the global climate, aerosols, trace gases and precipitation, global climate models are unable to reliably predict precipitation patterns and their changes (Rosenfeld et al. 2008, Li, 2011).

Many open questions are also related to emissions and atmospheric chemistry of biogenic volatile organic compounds (Grote & Niinemets 2008, Mauldin et al., 2012), subsequent aerosol formation (Tunved et al. 2006; Kulmala et al. 2011a) and aerosol-cloud interactions (McComiskey & Feingold 2012; Penner et al., 2012). It is essential to quantify the range of emissions and fluxes from different types of ecosystems and environments, including forests, peatlands and lakes, and their links to the ecosystem productivity, and also to take into considerations the previously unknown sources and processes (Su et al. 2011, Kulmala and Petäjä, 2011, Bäck et al 2010).

New openings of the ATM. Although our previous work was related to the COBACC hypothesis, it concentrated on the boreal forest environment and covered only some parts of the main feedback loops (Fig. 1). In the ATM, we will expand our approach in two complementary ways: i) by considering a full set of feedback loops associated with COBACC including all the relevant processes and biogeochemical cycles, and ii) by covering all the major continental regions. This will be possible with a help of continuous and comprehensive in situ observations in various environments and ecosystems e.g. Arctic, Antarctic, Siberia, high Alpine (Jungfraujoch, Hohenpeissenberg), Mediterranean (Crete), Coastal Atlantic (Ireland), tropical and subtropical (China, South Africa, Amazonas), complemented with ground- and satellite-based remote sensing and targeted laboratory experiments. Multi-scale modeling (from molecular dynamics to ESMs) with the improved conceptual understanding will be an essential part of our approach. Earth Observation techniques (space-borne remote sensing) will provide spatially continuous, frequent observational data sets that can be applied to the evaluation and further development of large-scale models, to analyses of trends in essential ecosystem and climate variables, and to analyses of spatially-distributed processes. A major new initiative coordinated by M. Kulmala is the Pan Eurasian Experiment (PEEX) which is a multidisciplinary climate change research project focusing on the Northern Eurasian region of Arctic and boreal zone.

1.1 Objectives, innovativeness and expected results of the research.

The main scientific objective of ATM is to quantify the COBACC feedbacks in changing climate. In order to do this, we will:

(i) find out and quantify the main climatic feedbacks and forcing mechanisms related to aerosols, clouds, precipitation, biosphere-atmosphere and cryosphere-atmosphere interactions,
(ii) develop, refine and utilize the newest measurement techniques and modeling tools scaling from quantum chemistry to global Earth System Observations and Models,
(iii) create a deep and quantitative understanding on the role of atmospheric clusters and aerosol particles in local and global biogeochemical cycles of water, carbon, sulfur and nitrogen and their linkages to the atmospheric chemistry, and
(iv) integrate the results in the context of regional and global scale Earth system understanding.

The four sub-objectives also present in the research Work Packages 1–4 enfold the planned six-year period of the ATM. The innovativeness is related to the development of new instruments, data analysis/mining and modeling tools reaching across the spatial and temporal scales in a coordinated
research chain and network optimized to have a clear impact on society. By addressing these questions of high relevance for both the science and for the society, and by tightly linking theory and experiments, we will contribute in solving the urgent issues related to the climate change.

It is already known that feedback mechanisms are crucial factors in climate dynamics, and thus their understanding is essential for predicting the changing climate. Here we assume that by addressing quantitatively the COBACC feedbacks, we are able to predict the future climate much more accurately than is possible with current knowledge. Atmospheric cluster formation, nucleation and growth of newly formed particles are strongly coupled with biosphere processes (both above- and belowground). We anticipate that by understanding the dynamics, concentrations and composition of the atmospheric clusters together with the process level insight, we will be able to quantify and assess the biogeochemical couplings between the ecosystems, atmosphere and climate.

**Expected results.** We expect to unravel quantitatively the COBACC feedback loops and cluster dynamics. Therefore our results will help predicting future climate and also enables us to give clear outlines for climate mitigation and adaptation, including scientific assessment of potential benefits and drawbacks of geoengineering. We also expect to have several scientific breakthroughs, potentially all of them published in Nature or Science.

1.2 On significant research results, breakthroughs, promoting science, its capacity for renewal, potential risks

**Potential for achieving scientifically significant results.** The evaluation report (Sep. 2011) of previous CoE Scientific Advisory Board (Profs. R. Jaenicke, N. Donahue, P. Kabat, M. Sutton), states “The Finnish CoE in “Physics, Chemistry, Biology and Meteorology of Atmospheric Composition and Climate Change” is on track being an extraordinary success. The FCoE funding serves a unifying purpose, helping to bring the team together and facilitate a more cohesive research programme. The number of publications in high ranking journals, including Nature and Science, is impressive. In brief, the advisory board feels that the FCoE is in outstanding excellent shape”. In the recent evaluation of Physics Research in Finland (2012), it is said “The centre of atmospheric physics is found in Helsinki. Here, the synergies evolving from co-location on one campus of the Div. Atmospheric Sciences at the Dept. Physics, Univ. Helsinki, and the FMI allowed for creation of a world-renowned centre of excellence.” All these evaluations support us in our on-going research direction and in the future research goals and plans.

**Scientific breakthroughs.** When working toward our objectives, we expect to make several scientific spearheading advances associated both with high risk and high gain, leading to potential publications in Nature or Science. The most plausible topic areas for the breakthroughs are:

1) Atmospheric oxidation, the role of Criegee radicals originating from atmospheric oxidation of biogenic organic compounds,
2) Cluster dynamics and composition particularly in sizes between 0.5 – 5 nm, including neutral and ion cluster formation pathways, coagulation, growth and deposition,
3) Aerosol dynamics, including aerosol formation, growth, deposition, phase and phase transitions in aerosol particles,
4) Cloud condensation nuclei formation, cloud microphysics and precipitation formation including warm, mixed and ice clouds,
5) Ice nucleation and freezing in the atmosphere,
6) Phase transitions in vegetation, including cavitation, freezing and ice nucleation in the trees and their effects on water transport and VOC production within trees,
7) Seasonal variation of snow and ice cover as well as frost/permafrost distributions and their changes in the decadal scale together with secondary satellite data products combining vegetation, aerosols, clouds, radiation and atmospheric chemistry data,
8) Synthesis of BVOCs and organic nitrogen in various environments, including soils, lakes/rivers, peat lands, forests and cryosphere all around the world,
9) Atmospheric turbulence and its effect on atmospheric fluxes of clusters and their precursors including BVOCs, amines, sulfur compounds, atmospheric oxidants, HONO and carbonyl sulfide (COS),
10) Atmospheric boundary layer dynamics and its interactions with GHG fluxes and biogeochemical cycles of water, carbon, nitrogen and sulfur,
11) Quantification of COBACC feedback loops, and
12) Global and regional importance of the COBACC feedback loops including the effects of changing biosphere and cryosphere.

Atmospheric oxidation, aerosol chemistry and physics, clustering and aerosol formation are central to the carbon, nitrogen and sulfur cycles of the Earth-atmosphere system. By quantitative analysis of the initial phase transitions from gas molecules to clusters, we can gauge the atmosphere-ecosystem exchange processes of carbon, nitrogen and sulfur. The ATM aims to describe these complex processes and their feedbacks, starting from mesoscopic clusters and their growth to cloud condensation nuclei sizes, their activation into cloud droplets and ultimately formation of precipitating clouds. The process-level understanding and mathematically robust descriptions will be applied to reveal the global consequences and feedbacks between the sub-systems. The ATM contributes its scientific findings directly to the international assessments, e.g. IPCC assessment reports as well as to international climate negotiations.

Promoting the progress of science and its capacity for renewal. During the recent years we have promoted the development and visibility of atmospheric sciences in national, Nordic, European and global levels (Fig 2.). In ATM we aim to further enhance our international leadership via several initiatives, including EINAR (European Institute of Atmospheric Sciences and Earth System Research), PEEX (Pan Eurasian Experiment), European ESFRI Research Infrastructures. ICOS head office is hosted by ATM, tentatively also ACTRIS, and Climate Change Initiative by the European Space Agency. The ATM has a critical mass and proven leadership to promote atmospheric sciences globally. Fig. 2 summarizes our present activities and leadership in international research and infrastructure developments. Here the joint international efforts and continuously renewed scientific approaches are needed in order to contribute to the solution of the Grand Challenges (like climate change and air quality). Our approach in quantifying the processes from molecular to global scale including various ecosystem components, their feedbacks and linkages is motivated by the close relationships in biogeochemical cycles between the atmosphere and ecosystems. This is manifested e.g. in the important role of ecosystem processes in producing volatile organic carbon and nitrogen compounds, central to aerosol formation and atmospheric oxidation capacity. With the multidisciplinary team structure and comprehensive measurement and modeling tools, ATM is one of the few groups in the World capable of efficiently combining the climate change, greenhouse gases, trace gases, aerosol processes and vegetation processes.

Potential risks. The main risk is that our research consortium developed in the last decade starts to collapse due to insufficient funding or without the coherent leadership provided by the CoE program. There are always risks due to several technical, practical and bureaucratic problems to fail in e.g. international campaigns. It is also very challenging to renew model frameworks and conduct experiments over spatial and temporal scales of more than 25 orders of magnitude. Specific examples of such challenges are construction of new Earth System Model components and utilising Earth observations in complementary ways. Risks associated with Earth system modeling include insufficient description of subgrid-scale processes (partly addressed by integrated development together with Large Eddy Simulation models) and potentially the complex nature of atmosphere-ecosystem-climate system which is challenging for quantifying the feedbacks robustly. The use of satellite data implies a risk of instrument malfunctioning resulting in loss of data.
2 Implementation of the research plan

2.1 Research methods, schedule and materials management plan

Our Scientific Approach is to combine i) continuous and comprehensive in situ observations in different types of environments or ecosystems and platforms, ii) ground- and satellite-based remote sensing, iii) targeted laboratory experiments and iv) multi-scale modeling efforts, in order to provide improved conceptual understanding over the relevant spatial and temporal scales (Fig. 3).

Concerning atmospheric aerosols, we start from quantum chemistry and from molecular dynamic simulations incorporating the first principles of physics in order to understand molecule-molecule interactions, cluster formation and dynamics, nucleation and aerosol thermodynamic processes (McGrath et al. 2012). The next steps are to understand the aerosol formation and growth, aerosol dynamics as a whole, and the processes dictating the aerosol chemical composition (Kulmala et al., 2013b). Significant advances in instrumentation, data storage and utilization and modeling techniques are being developed.

In order to connect the aerosol system with precursor formation from biogenic emissions, we will investigate vegetation processes, including photosynthesis, assimilate and water transport, freezing in
trees, soil dynamics and synthesis of volatile organic compounds in many scales with enclosure and ecosystem flux measurements (Kolari et al., 2012). Fundamental aerosol and carbon cycle processes need to be understood in order to quantify aerosol radiative properties and the influence of aerosols on cloud microphysics and dynamics at the scale of individual clouds. These cloud processes are in turn modifying the carbon uptake dynamics of ecosystems.

At larger scales, advances in the understanding of boundary layer meteorology are needed to clarify atmospheric aerosol transport, trace gas and water vapor exchange and deposition processes. The boundary layer studies form a link to regional-scale processes and further to global-scale phenomena (Kulmala et al. 2011a). In order to simulate global climate and air quality, the most recent progress on this chain of processes must be compiled, integrated and implemented in climate change and air quality numerical models via novel parameterizations. The COBACC feedbacks and their overall effects are studied using global station network, active and passive remote sensing and ESMs.

Figure 3. The ATM Multi-Scale approach and methodologies from molecular dynamics to integrated ESMs, and their connection to the WPs. The science conducted by the PIs interconnects, forming a seamless network reaching across the scales of the atmosphere-biosphere continuum. Prof. Kulmala is involved in all the scales.

We have divided the work into 4 Work Packages (WP) which cover the relevant temporal and spatial scales. A wide variety of tools and methodologies (Fig. 3) across the scales are utilized to gauge the atmosphere-ecosystem continuum. At the scientific core of ATM is the global relevance of biogeochemical cycles (Fig. 4) and COBACC feedback, connecting the two main cooling agents, carbon sink and aerosol source, to each other (Fig 1.). The nanoclusters and aerosol particles formed in various locations and environments are the focal point as they reflect the intricate connections between nitrogen, carbon and sulfur compounds due to their transient nature, both in terms of concentrations and composition (Zhang et al., 2012). The comprehensive observations and hierarchical modeling tools together with open data archives used in an integrative manner in combination with global GHG, aerosol and ecosystem networks enable us to study the different cycles and feedbacks.
Figure 4. Connections between the COBACC feedback and the biogeochemical cycles of carbon, sulfur, nitrogen and water. ATM focuses on: (i) the processes linking carbon, nitrogen, sulfur and water cycles and (ii) feedbacks between the aerosol formation and the biogeochemical cycles. The research openings are related to the development of comprehensive observations systems and to the enhancement and utilization of open data archives in an integrative manner to study the different cycles and feedbacks. VOC = volatile organic carbon, HONO = nitrous acid, sCl = Stabilized Criegee intermediates, CCN = cloud-condensation-nuclei.

WP1: From nano to micro scales

This WP approaches the COBACC hypothesis at the smallest spatial and temporal scales. The method development includes advances in environmental measurements, in theoretical methods (particularly quantum chemistry and molecular dynamics) and in nanoscale models. The WP1 is dependent on WP3 for directing the efforts towards the most relevant processes for the ESM system, and on WP2 for determining the sources of precursors and for down-scaling the effects from the mid-scale to the nanoscale.

Task 1.1 Atmospheric oxidation. This includes development of methods and techniques critical for advancing the process level understanding of atmospheric oxidation, in particularly the role of Criegee intermediates. The task develops novel quantified mass spectrometric techniques and nanocluster and particle physical and chemical characterization. These will provide quantified data on ppq-level mixing ratios of trace gases and oxidants relevant to aerosol formation and growth. Instrumental methods connecting carbon, nitrogen and sulfur cycles (carbonyl sulfide, amines, organosulfates, organonitrates) will also be developed. Involved PIs: Sipilä, Riekkola, Vehkamäki, Hartonen, Kerminen, Petäjä, Worsnop.

Task 1.2 Phase transitions in the vegetation and in the atmosphere: Cavitation, freezing, nucleation and ice nucleation. The task involves measurements and models describing the tree functions with respect to light, water and essential nutrients, freezing of cells, and emissions of biogenic volatile compounds, and chemical composition of 1–3 nm clusters and ions. This task determines the role of organic molecules (e.g. amines) in atmospheric new-particle formation based on evaporation rates and stabilities of the clusters with variable atmospheric trace gas mixing ratios. We determine chemical and physical properties and the phase-state of biogenic SOA particles, and their importance on aerosol-cloud interactions and ice nucleation potential. Involved PIs: Vehkamäki, Bäck, Kerminen, Virtanen.

Task 1.3 Cluster dynamics and composition – Experimental and modeling approaches to nanoparticles. Modern and efficient methods and tools for chemical analysis of atmospheric ultrafine aerosols and gaseous emissions from the biosphere, novel environmental process models based on gas phase precursors marker compounds. The task reaches from the field applications to generation of true nano-materials in the laboratory and utilization of the atmospheric mass spectrometric methods for air/water/environmental quality/human health diagnostics. Involved PIs: Kulmala, Riekkola, Sipilä, Hartonen, Petäjä, Worsnop, Vehkamäki.
WP2: Canopy, local and regional scale processes

The medium-scale is crucial for the COBACC hypothesis, bridging the gap between the short process times of oxidation, mixing and removal of organic compounds and aerosols and many biosphere processes to the canopy and regional scales, thus enabling the up-scaling to Earth system behavior. The WP uses new parameterizations from WP1 to up-scale the processes for larger scales and different environments. A key part is the revolutionary contributions to the development of the aerosol measurement techniques and their further refinement by the ATM (Kulmala et al., 2012) and the benchmarking, long-term measurements of ecosystem properties and fluxes of elements and energy. New parameterizations for large-scale modeling frameworks will be developed and evaluated. As a whole, these developments open a new area in understanding and quantifying the processes relevant for the regional and Earth system scales.

Task 2.1. Aerosol dynamics in the atmosphere. The task evaluates the processes driving formation and dynamics of atmospheric clusters and the compounds participating in aerosol formation and growth. The role of atmospheric ions and galactic cosmic rays will be determined. The work includes development of measurement techniques for aerosol particle characterization and aerosol-cloud interaction studies and development of measurement platforms (aircrafts, tall towers, atmospheric soundings, satellites). These will provide quantified data on particle physical and chemical properties relevant to climate, such as the aerosol phase state and its effect on cloud condensation and ice nuclei activation and changes in the particle chemical composition due to the cloud processing. These processes are then studied in detail in intermediate scale models, generalizing the results for the global scale. Involved PIs: Kerminen, Boy, Korhonen, Lihavainen, Petäjä.

Task 2.2. Cloud condensation nuclei formation, cloud microphysics and cloud processes. This task clarifies the biogenic and anthropogenic contribution to the formation, chemical composition and physical phase of atmospheric SOA particles based on cloud-resolved modeling, in-situ observations and active remote sensing. Role of meteorology, cloud microphysics and aerosol-cloud interactions (size, chemistry, phase) will be quantified in warm, mixed and ice clouds. The effect of these changes in cloud droplets are further evaluated by an array of cloud models and compared to cloud in-situ and remote sensing datasets. Involved PIs: Moisseev, Chandrasekar, Romakkaniemi, Laaksonen.

Task 2.3. Seasonal variation of snow and ice cover including frost/permafrost distributions. The task analyzes short and long term variability of surface albedo, reflected radiation, near-surface heat transport and the effects of aerosol particles, concentrations, cloud cover and properties and changes in precipitation on radiation balance on lakes and rivers. Improved understanding on spatial variability of the cryosphere-atmosphere and cryosphere-biosphere interactions based on integrated ground-based remote sensing measurements (tower based surface albedo, microwave emission and backscattering observations) and observations from the satellites will be acquired. Involved PIs: Pulliainen, de Leeuw.

Task 2.4 Production of aerosol precursors by biosphere processes in various environments. The task includes quantitative analysis and models of biosphere processes in vegetation growth, nutrient and water use, and in the effects of stress factors modifying the plant performance and the synthesis of volatile organic carbon and nitrogen compounds, specifically interactions between below and above ground compartments. The approach includes field measurements of processes and fluxes from rural (forest, peatland and freshwater), and urban ecosystems and ecosystem-atmosphere interface, experimental work on plant-soil-atmosphere interfaces and process-based modeling. Involved PIs: Bäck, Pumpanen, Vesala, Mäkelä.

Task 2.5 Atmospheric turbulence, fluxes of clusters, GHGs, BVOCs, amines, sulfur compounds, oxidants, HONO, COS. The task quantifies the emissions and fluxes of inorganic reactive gases (HONO, HNO₃, NH₃) and biogenic volatile organic compounds (terpenoids, amines, oxygenated compounds) using in-situ ion chromatography and mass spectrometry with enclosure, gradient and eddy covariance techniques over different environments taking into account the oxidation within the canopy. The task improves estimates of the magnitude and variability of ecosystem-scale photosynthesis, respiration and transpiration with novel tracers such as stable isotopes and carbonyl sulfide sinks in ecosystems. Involved PIs: Vesala, Petäjä, Bäck, Hakola. Zilitinkevich.
**Task 2.6 Boundary layer dynamics and interactions with biochemical cycles of water, carbon, nitrogen and sulfur.** The task quantifies the links between ecosystem hydrological cycle, BVOC production and aerosol processes in the boundary layer including the effect of boundary layer height to trace gas and aerosol concentrations via the sensible heat flux and evapo-transpiration. We will apply zero-dimension process models and incorporate them into large eddy simulations to account for the meteorology, and develop capabilities to up-scale the cluster-scale processes to regional and global models. We will develop ecosystem models including a description of forest growth processes important for the regional atmospheric properties. *Involved PIs: Vesala, Mäkelä, Aalto, Zilitinkevich, Boy.*

**WP3: Synoptic scales and beyond**

Although this WP is strongly dependent on the processes and parameterizations derived in other WPs, it does contribute directly to the WPs 1-2 via determination of the relevant processes that strongly affect the Earth system. This WP uses (regional and global) general circulation, vegetation, chemical transport and ESMs, aided by satellite and long-term in-situ datasets.

**Task 3.1. Sensitivity to the key processes of COBACC feedback.** We will identify the key feedback mechanisms in the Earth System by comprehensive multi-scale and multi-platform data integration, including in-situ concentrations, fluxes, emissions and both active and passive remote sensing. The existing data provide us the possibility to probe into the inter-annual variability of the relevant quantities in the regional and global spatial scales. *Involved PIs: Kerminen, Bäck, Petäjä, Räisänen, Hakola, Pulliainen, de Leeuw, Vesala, Korhonen.*

**Task 3.2. Global and regional importance of the COBACC feedbacks.** We aim to quantify the linkages between the major aerosol precursor compounds, gas-to-particle conversion process, aerosol-cloud interactions, and precipitation formation, and air quality-climate interactions utilizing comprehensive in-situ, airborne and active remote sensing from the ground and from the satellites in connection with a hierarchy of models. The assessment of the model performance by direct comparison of the in-situ observation network and satellite and ground-based remote sensing data, using both data assimilation and statistical methods will be conducted. We implement the improved process understanding and new COBACC parameterizations to ESMs in order to create a more thorough representation of the feedbacks and biogeochemical cycles. We will assess the overall role of COBACC in the climate different time scales, in the past, current and future climate conditions and potential geo-engineering efforts. *Involved PIs: Laaksonen, Kerminen, Hämeri, Järvinen, Korhonen, Kulmala.*

**WP4: Integration between the scales**

Synthesis and integration is done in WP 4 (see Figure 4). Here we also prepare actions towards beyond-state-of-the-art integrative Earth System understanding based on ESM and comprehensive Earth Observations (EO).

**Task 4.1 Up/downscaling of the processes.** Development effort is mobilized to bridge the gap between aerosol-cloud processes at the microphysical level and sub-grid scale effects of aerosols and clouds in ESMs, including existing and new aerosol and cloud-activation sub-grid schemes. The observed and simulated aerosols and clouds will be analyzed to evaluate the sub-grid scale process representations performance, providing information on the uncertainties related to the closure parameters of cloud-aerosol parameterizations. As a common denominator, aerosol data assimilation is developed to properly interface observations and models. Improved modeling of ecosystem productivity and up-scaling from individual tree/stand to regional scale will be contributing to better understanding of feedbacks mediated through land use changes (Valentine & Mäkelä 2012). *Involved PIs: Laaksonen, Mäkelä, Vesala, Kerminen, Öster, Järvinen, Viisanen.*

**Task 4.2 Derivation of proxy variables.** The task will derive descriptive proxy variables for the feedback mechanisms and essential climate variables from the space-borne EO data with a global view. This activity enables us to generalize the data from the state-of-the-art measurement networks, remote sensing and modeling frameworks for assessing the role of the feedback mechanisms both in different future climate scenarios over decadal and centennial scales and in the past changes over millennia scales. In order to extract the full information content of the past and future measurements, latest data analysis methods incl. Extended Kalman Filter, will be implemented to “re-analyze” the field.
measurements. We comprehensively integrate the EO from the world-wide network of in-situ and active and passive remote sensing stations. With this re-analysis data we will provide microphysical state estimates with appropriate error bars, opening new opportunities to retrospective studies of existing data. We also improve the retrieval algorithms for atmospheric state from the satellites (Kulmala et al. 2011b).

Involved PIs: Kulmala, Pulliainen, de Leeuw, Järvinen, Petäjä, Kerminen.

WP5: Coordination, training and dissemination
The management of ATM is described in Section 2.2.

Methodological problems and alternative methods. We identify and to prioritize key gaps in the poorly understood or unknown processes in the atmosphere-biosphere continuum and expand our activities to many measurement sites. To the extent possible we will approach all the research questions using a combination of continuous, multidisciplinary and intensive in situ field measurements, modeling frameworks covering different spatial and temporal scales, active and passive remote sensing, and targeted laboratory experiments. With this approach, problems in a single or even several methods will not hinder us investigating and addressing the research questions.

Schedule of the research. The four objectives are addressed in scientific work packages (WP1-4). The WP5 is coordinating the work. Each of the WPs tackles particular questions and tasks aiming towards comprehensive scientific breakthroughs. A detailed implementation plan for the first 3 years of the ATM is depicted by the tasks of each WP with the schedule is presented in Figure 5.

Fig. 5. The cross-cutting WPs continue throughout the project period while the tasks have estimated start and end times. The detailed work is scheduled for the first 3 years with a strong vision extending beyond.

Materials management plan. ATM is pioneering comprehensive continuous observations and observation networks. The material and data operate under a common management infrastructure and with a common user experience throughout the ATM. This means that the raw data, data analysis, different datasets and publications are stored and shared via a common data platform. With this approach the materials produced are more easily available, and have a reproducible analysis trail with version control and full data information including metadata. The “research data systems” project (TTA) of the Finnish Ministry of Education provides the necessary infrastructure for the planning of the ATM material storage. As a part of the TTA project, a pilot data infrastructure on storing the environmental research data from ATM SMEAR stations started in 2012 (SMEAR-data). It will be in operation by the end of 2013. The key design criteria are: data long-term storage, accessibility, citability, and openness. The methodologies, work flow and storage of the SMEAR-data project for all the data streams will be used in a joint manner for the ATM data as well as for ICOS (GHGs), ACTRIS (aerosols, trace gases, clouds) data, and all the climate relevant parameters defined by IPCC.

The data will be stored in the Finnish IT Centre for Science (CSC) operated IDA permanent storage platform. This ensures long-term security of the datasets, including version control and secure backups. To ensure accessibility of the data, a complete descriptive metadata is stored together with the datasets and made available in the global metadata repositories. The ATM datasets will be made
publicly available after quality control, with specific monitoring data submitted as near real time data. By 2016, most of the ATM data (including the earlier datasets) will be available in similar format and stored permanently in national IDA archive.

All satellite and other remote sensing data and products are freely available for the project team and other collaborators and to any other external research group. Simulation data from all scales will be stored locally on a data archive where it will be available for research purposes during the project. All final evaluated results will be stored in the archive permanently and will be available for scientific use for the GLOMAP, MPI-ESM and other research communities. Parameterizations developed during the ATM will be published under Gnu Public License (GPL) and will be openly available to the scientific community. The freely available CMIP5 multi-model archive of climate simulations (http://cmip-pcmdi.llnl.gov/cmip5/) will be used to put our own ESM simulations in a perspective. Intellectual Property Rights, in case needed, will be agreed upon in the Consortium Agreement between UHEL, FMI and UEF.

2.2 Structure and organization of the ATM, distribution of work

The ATM consortium consists of UHEL Phys (coordination) and four other partners: UHEL Chem, UHEL For, UEF and FMI. Work is organized into four scientific WPs described above and into a management WP 5.

WP 5: Management. The ATM is managed by three bodies: the FCoE director, the Steering Committee (SC) and the Advisory Board (AB). The ATM director Prof. M. Kulmala is responsible for the coordination, science plan implementation, project reporting, financial control and signing the contracts. M. Kulmala as a consortium director has a top-down management approach to ensure that, when necessary, decisions are made rapidly and acted upon. He will be the chair of the SC. Project vice-director Prof. T. Vesala will support M. Kulmala in his tasks. The day-to-day management of the ATM including dissemination and public outreach is overseen by Research Coordinator Dr. Hanna Lappalainen and the education by Teaching Coordinator Dr. Antti Lauri. The Steering Committee consists of ATM director (SC chair), team leaders and research coordinator (SC secretary). The Advisory Board consists of Academy appointed external evaluators.

Budget. The budget breakdown (Table 1) and overall budget for ATM (Table 2) in MEUR.

Table 1. Budget breakdown (2014-2019)

<table>
<thead>
<tr>
<th>Item</th>
<th>Budget (2014-2019)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Salaries</td>
<td>90,0</td>
</tr>
<tr>
<td>Infrastructure, new instruments</td>
<td>9,0</td>
</tr>
<tr>
<td>Infrastructure, maintenance</td>
<td>6,0</td>
</tr>
<tr>
<td>Consumables</td>
<td>7,0</td>
</tr>
<tr>
<td>Travel</td>
<td>8,0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>120,0</strong></td>
</tr>
</tbody>
</table>

Table 2. Overall ATM budget (2014-2019)

<table>
<thead>
<tr>
<th>Fund</th>
<th>Budget (2014-2019)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Direct CoE Funding (Academy of Finland)</td>
<td>14,0</td>
</tr>
<tr>
<td>European Commission</td>
<td>28,0</td>
</tr>
<tr>
<td>UHEL</td>
<td>20,0</td>
</tr>
<tr>
<td>UEF</td>
<td>6,0</td>
</tr>
<tr>
<td>FMI</td>
<td>14,0</td>
</tr>
<tr>
<td>Other Academy Funding</td>
<td>18,0</td>
</tr>
<tr>
<td>Other international funding</td>
<td>10,0</td>
</tr>
<tr>
<td>Private foundations</td>
<td>4,0</td>
</tr>
<tr>
<td>Private companies</td>
<td>6,0</td>
</tr>
<tr>
<td><strong>TOTAL</strong></td>
<td><strong>120,0</strong></td>
</tr>
</tbody>
</table>

Budget justifications for the period 2014-2016: Coe funding from Academy of Finland:

Salaries: PhD students 33 person-years (salary level ca. 2500 €/mo), post docs 30 person-years (salary level ca. 3500 €/mo), researchers 20 person-years (5*3yr + 1*2 yr; (salary level ca. 4500 €/mo)), professors 1.5 person-years (salary level ca. 7000 €/mo).

Materials: 60 000 eur/yr., Services: 14 000 eur/yr (auditing), Travel expenses 55-63 000 eur/yr

2.3 Ethical issues and research permits or the application for permits

The proposed plan does not involve other ethical issues besides those involved in normal scientific research. We follow the codes of conduct in ethics of research, publication, and recruitment of researchers outlined by Academy of Finland and European Commission.
3. Competence of the director, vice director and team leaders

3.1 The publication history, the merits and expertise of the director and vice director

ATM Director Academy Prof., ERC AdG holder, Markku Kulmala: is the world leading scientist in the area of atmospheric nucleation and related biosphere-atmosphere interactions. Prof. Kulmala has published over 700 peer-review papers (9 in Nature, 11 in Science and 7 in Phys. Rev. Lett.). He is 1st in the Citation Rankings in Geosciences (ISI Web of Knowledge, since 1.5.2011), H-index is 68 (>19000 cit.). Prof. Kulmala is one of the founders of “terrestrial ecosystem meteorology”. His works cover theoretical and experimental physics, atmospheric chemistry, observational chemical meteorology, biophysics and, in particular, biosphere-aerosol-cloud-climate interactions. He has received many international and national prizes and awards.

ATM Vice Director Prof. Timo Vesala: published over 230 peer-reviewed papers, of which 4 in Nature, and 1 in Phys. Rev. Lett. (H-index 43, >7100 cit.). His work covers exchange of GHGs and other trace gases in various ecosystems and aerosol particle deposition, long-term field measurements, modeling of boundary-layer flows, and biogeochemical cycles of N and C. He has received the Väisälä Award and the Norbert Gerbier-MUMM International Award.

Publication history and the merits and expertise of the team leaders

(i) Prof. Markku Kulmala: Atmospheric aerosol-team: see Sect.3.1 and Sect. 3.4.
(ii) Assoc. prof. Annele Virtanen: Aerosol-Cloud Interactions & Cloud Microphysics - team: she has 38 peer-reviewed publications, 1 in Nature as a first author (H index 14, 672 cit.). She is expert in particle characterization methodology (phase state of particles) and incorporates this to aerosol particle-cloud interaction studies, enabling new scientific breakthroughs and insights into the processes determining the indirect effects of the atmospheric particles.
(iii) Prof. Timo. Vesala: Meteorology-team: See Section 3.1 and Sect. 3.4.
(iv) Prof. M-L. Riekkola: Analytical chemistry-team: she is internationally recognized scientist in the field of separation science (miniaturization, multidimensional chromatography, capillary electromigration, field-flow-fractionation and on-line coupled techniques) with over 300 peer-reviewed publications (H index 41, > 6000 cit.). She received Magnus Ehrnrooth prize in chemistry in 2008.
(v) Adj. Prof. Jaana Bäck: Ecosystem processes-team: she has published 46 peer-review papers (1 in Science) (H index 16, >780 cit.). Her expertise is in ecophysiological methods on analyzing the feedbacks between biosphere and atmosphere, in particular the tree gas exchange and biosynthesis and emissions of biogenic volatile organic compounds.
(vi) Director Yrjö Viisanen: FMI Department of Research and Development -team: is the research director of Finnish Meteorological Institute since 2004. He has 93 peer-reviewed publications, 1 in Nature and 1 in Science. (H index 26, > 2700 cit.). His special expertise lies in aerosol science, experimental nucleation and condensation studies and their applications to atmospheric processes; monitoring of climatically active species.

3.3 Complementarity of the expertise of the director, vice director and team leaders

The fundamental principle in the team structure is multidisciplinarity, which ensures utilization of up-to-date methods, wide and integrative scientific approach and has yielded fruitful scientific collaboration in the former periods of CoE funding. The complementary expertise of the teams is demonstrated in Fig. 3. Prof. Kulmala’s expertise extends all the scales related to the atmospheric research topics of the ATM approach. The ATM includes six research teams as follows:

1. Atmospheric aerosols: PI: M. Kulmala (Subteam-PIs: V-M. Kerminen, H. Vehkamäki, T. Petäjä, D. Worsnop, P. Öster, K. Hämeri, M. Boy),
5. Ecosystem processes: PI: J. Bäck (A. Mäkelä, J. Pumpanen),
3.4 The leadership skills of the director and vice director.

**Director, Academy Prof. Markku Kulmala** has led 2 national and 2 Nordic CoEs and the NordForsk Graduate School. The research unit consists currently of > 150 scientists. He has participated in >35 EU-projects, four as coordinator and in 30 as a PI. He coordinates also the SMEAR stations, PEEX and EINAR initiatives and is the Chair of national climate panel. His coordination network can be seen in Figure 2.

**Vice-Director, Prof. Timo Vesala** has been Vice-Director in the 2 previous national CoEs and participated in 2 Nordic CoEs. He is leading the European ESFRI Integrated Carbon Observation System (ICOS) Head Office, and is the chair of ICOS-Finland. He has coordinated 3 international projects and acted as a PI in 10 EU projects.

4. Research environment and cooperation

4.1 Support of the host organisations for the ATM

UHEL will support ATM in-kind by funding personnel (11 professors + 5 University lecturers) and SMEAR infrastructures (see Table 2). In addition, UHEL has reserved a special budget for its CoEs. This funding will be distributed when the Academy of Finland has decided which applications are selected for the CoE 2014–2019 programme. FMI will support ATM with funding of personnel (5 professors) and use of infrastructures: Pallas GAW stations, Sodankylä Observatory (remote sensing). UEF is committed to support with the funding personnel (2 professors and 2 univ. lecturers) and use of aerosol physics laboratory. As a joint activity of the host institutes, the Centre of Atmospheric Research was established in 1.1. 2013, which will act as the core of European Institute of Atmospheric and Earth System Research (EINAR, Fig. 2).

Compatibility of the ATM research with the strategies of the host organisations. The ATM directly supports the strategic aims of the host organizations. The research approach strengthens the active role of the Universities and FMI in the research on climate change and air quality topics by distributing scientific knowledge via national and international publications, assessment reports, participating on expert panels (IPCC) and public discussion.

The UHEL strategy for 2013-16 states that the University aims at ranking among the 50 leading universities in the world. The ATM aims for the high quality and high impact research including publications in the leading journals. This aim will be achieved by international and multicultural collaboration within the global scientific network. Top quality science will help university towards the strategic goal of being within top 50 universities globally. UHEL will also actively promote discussion and communicate its expertise in resolving global challenges, assume a responsible role in selected ESFRI projects and increase incentives for the shared use of infrastructures. Resources will be systematically directed to both the focus areas and to the new initiatives. One of the strategic key research areas at UHEL is climate, environment and natural resources, and the ATM is fully embedded in this focal research area. The highest level atmospheric science is also at the core of FMI strategy. According to the strategy of UEF, “Forests and the environment” is one of the three areas of expertise of the university. The UEF targets significant strategic resources to the areas of expertise which enhance the university’s profile. The research and collaboration in ATM ties up excellently with the strategies of UEF, FMI and UHEL.

As a summary, the ATM will support visibility of the universities and FMI as an active player in the national and international research policy and maintains the position of Universities of Helsinki and Eastern Finland in the frontline in climate change research and training of multi-talented environmental and atmospheric experts.

Research infrastructures. Comprehensive field and laboratory measurements are essential for our research. The ATM research infrastructure has the following main components, described in detail in the electronic form: (i) field station network (ii) laboratories, (iii) modeling & super-computer capacity, (iv) remote sensing data, (v) airborne measurements.

(i) Field station network:

**Finland.** The research unit operates five field stations in Finland: GAW (Global Atmosphere Watch) station in Pallas-Sodankylä and the four SMEAR (Station for Measuring Forest Ecosystem Atmosphere Relations) stations. The **SMEAR II** is the world leading station due to its comprehensive
research program and due to its unique time series of aerosol formation and biogeochemical fluxes (Hari & Kulmala, 2005).

Global coverage. We analyze data from several field sites in “climate space” to identify and prioritize key gaps in understanding of global features in the climate change. In addition to Finnish SMEAR –station network, our teams will be intensively involved with a super-site concept development in Europe and outside Europe; many of the collaborations established already. SMEAR-type stations have been established in China (Nanjing), Estonia (Järvselja), South Africa (Welgegund), Italy (San Pietro Capofiume), India (Gual Pahari) and Saudi Arabia (Jeddah). The long-term atmospheric datasets will be obtained from the Arctic (Nordic CoE CRAICC stations) and Amazonas regions as well. FMI is establishing a long term measurement station to Siberia (Tiksi) in co-operation with Russian research organizations particularly for year-round observations of important climate forcing agents. PEEX will provide a unique set of data to be utilized for the ATM research. The use of EU-FP6-EUCAARI data will enhance the global perspective of the analysis as the EUCAARI instrumentation has been running continuously from 2009 (Kulmala et al. 2011a).

(ii) Laboratories:

Aerosol Particle Laboratory (UHEL): mass spectrometers, particle generators, aerosol, cluster and ion spectrometers, and equipment for analyzing the hygroscopic properties and volatility of aerosol particles, characterization of novel instrumentation, calibration, optimization.

Ecophysiological laboratory (UHEL): growth chambers, mini-rhizotrons, physiological measurement systems with stable isotope equipment.

Viikki Urban tree laboratory (UHEL): continuous observations of tree growth, water relations and vitality in an urban setting.

Laboratory of Analytical Chemistry (UHEL): a suite of commercial and self-modified/self-constructed instruments, incl. aerosol mass spectrometry, portable gas chromatography-mass spectrometry, multidimensional chromatographic techniques, size-selective sampling, combination of mass spectrometry and chromatography.

Aerosol Physics Laboratory (UEF): composition of cloud condensation nuclei, cloud forming ability of the particles, particle phase studies plant/smog/reaction chambers, aerosol phase studies.

FMI aerosol and analytical laboratories: formation and growth of aerosol particles through nucleation of different atmospherically relevant gas phase species in different environmental conditions. In-situ measurements are performed using chromatographic techniques (ion-chromatographs for inorganic aerosol and gas measurements, MARGA), on-line gas-chromatographs with mass- and FID- detectors and gas- ion- and liquid-chromatographs.

CERN Cloud Chamber: located in a beam-line T11 at the CERN Proton Synchrotron accelerator is built to the highest technical standards of cleanliness and performance (Kirkby et al. 2011). The use of CERN facilities is allowed via the FP7-CLOUD-TRAIN project partnership.

Leibniz-Institute for Tropospheric Research Laminar Flow Tube: atmospheric chemical processes and initial steps of new particle formation, instrumentation for detecting particles, clusters or cluster/particle precursors including sulfuric acid, oxidized organics and amines (Sipilä et al. 2010).

Plant and reaction chamber facility (Kiendler-Scharr et al. 2009) at Forschungszentrum Jülich, Germany, response of plants to changing environmental variables (heat stress, drought), controlled reaction chamber. Access is provided by existing collaboration.

(iii) Modeling & super-computing capacity:

The available models establish a hierarchy reaching across the scales of ATM research, e.g. ECHAM-HAM, SALSA, MALTE, JSBACH, GLOMAP, MPI-ESM (listing of models in the e-forms). The model framework gives us an opportunity to develop and combine models operating at different spatial and temporal scales. IT Center for Science Ltd (CSC) as a workflow and computing infrastructure topics partner, has an active role in the ESM and Large Eddy Simulations.

(v) Remote sensing data (FMI and UHEL): Global / large scale climate data records on selected essential climate variables, weather/cloud radar and other ground-based remote sensing observations from a suite of instruments. The Sodankylä-Pallas super-site, designed for EO satellite calibration and validation purposes, is a globally unique testbed in the boreal forest/sub-arctic zone
providing integrated observations on soil-snow-vegetation-atmosphere system (including CO₂/CH₄ fluxes of different ecosystems), combined with monitoring data from ground-based reference systems of satellite-borne instruments.

(vi) **Aircraft data (FMI and UHEL):** 1) SHORT SC-7 Skyvan aircraft, operating distance 1370 km and 3 km altitude. Automated inlet system for particle aerodynamic diameters < 10 μm, versatile payload according to research needs. 2) CESSNA 172 aircraft instrumented to probe in to spatial and vertical variability of aerosol particles at < 3.5 km altitude (Schobesberger et al. 2013).

### 4.2 Major national and international research collaboration

The extent of our international collaboration can be seen in Figure 2 and in the listed active collaborators (137). The ATM predominantly acts as a coordinating body in the research activities taking the lead in directing the science, e.g. within ICOS, PEEX and EINAR.

**Links to industry.** The link from the ATM scientific breakthroughs towards innovations is established via a close co-operation with SMEs, especially with Airmodus Ltd., which is a university spin off company providing aerosol particle counters and mass spectrometer products. Furthermore, FMI and UHEL have a strategic partnership with Vaisala Ltd and have close connections to other companies, e.g. Space System Finland. UHEL and FMI are partners in Cluster for Energy and Environment research consortium, CLEEN Ltd and contribute to the CLEEN research programs.

### 5. Significance of the ATM for researcher training and promotion of the research career

#### 5.1 Objectives and resources to supervise and support doctoral and postdoctoral research careers

Objectives of the training and promotion of the research career:

(i) to educate a next generation of researchers and specialists in atmospheric research,

(ii) to establish future collaboration between PhD students with national and international parties involved in atmospheric / Earth system research and technology,

(iii) to provide transversal training addressing all aspects of the atmospheric and Earth system observation, from instrument development, data provision to data application in numerical models,

(iv) to provide transferable skills applicable on a wide range of scientific and expert tasks in the society.

The doctoral training in ATM is organized through the national doctoral programme “Atmospheric Composition and Climate Change: From Molecular Processes to Global Observations and Models” (ACCC). ATM and ACCC have recognized the importance of career development, and together with Nordic partners introduced an education structure covering all the academic levels from master students to professors, thus also involving the idea of lifelong learning.

**Figure 6.** The positive feedback loop associated with the education, life-long learning and peer support in ATM.

The actions supporting the creation and existence of the positive feedback loop (Fig 6.) in education include: (i) guidance groups involving both students, post-doctoral researchers and professors meeting regularly to discuss about advances and bottlenecks (currently 13 groups operating;
each student has 2-3 supervisors from the pool of > 50 docent-level supervisors); (ii) cross-supervision involving supervisors from two or more research groups (currently >40% of students participate in the cross-supervision); (iii) organizing annually several joint, international courses and workshops to directly support the students’ research, and providing both core and transferable skills (>30 courses and workshops in 2010-2012); and (iv) a dedicated mentoring programme. The specific transferable skills provided to both the students and postdoctoral researchers include e.g. skills in working with the field measurements; instrument technology; data analysis, data mining, modeling, presentation, teaching and knowledge transfer, project management; public outreach; commercialization of scientific ideas; and entrepreneurship.

**Integration of research and education activities into larger frameworks.** ATM will promote and strengthen the productive supradisciplinary research environment while being an active player in science policy by deepening the scientific understanding of the multi-scale concept and participating in the construction of European environmental research infrastructures with an open data access and visualization of data. A very important aim is that in future all the graduates will be employed immediately after graduation either to public or to private sectors. A specific aim of ATM is to enhance the employment into the private sector after obtaining a PhD degree. This is realized e.g. in collaboration with the FiDiPro Professors. Furthermore, ATM is actively proposing and participating in European level initiatives on doctoral training, e.g. Erasmus Mundus programmes and FP7 Marie Curie Initial Training Networks (CLOUD-ITN, CLOUD-TRAIN, HEXACOMM).

**Promotion of researcher mobility.** Mobility both nationally and internationally is done on four levels: (i) between ATM/ACCC sites; (ii) between research fields (ecology-physics-technology-chemistry-meteorology-geography, in situ observations–remote sensing observations); (iii) between research methodologies (theory-modeling-experiments-observations); and (iv) between universities, research institutes and business. The mobility is carried out by organizing joint courses and workshops, and through researcher secondments.

**6. Societal impact of the ATM activity**

ATM creates a new innovative working environment to meet the global grand challenges like climate change and air quality via several new and unique approaches particularly materializing strategic innovativeness. One example is Pan Eurasian Experiment (PEEX, Kulmala et al 2011c). ATM will, with the Russian, EU and Chinese collaborators, establish the PEEX activity in 2013. PEEX is the next generation research infrastructure in boreal and Arctic regions, focusing on in the high latitudes of Arctic, where climate change is proceeding the fastest as the near-surface warming has been about twice the global average during the recent decades.

The ATM research agenda contributes to the global challenges and integrates the scientific results into policy making. The ATM PIs are key figures in international scientific organizations and networks such as IPCC, IGAC/IGBP and iLEAPS/IGBP. The iLEAPS (Integrated Land Ecosystem-Atmosphere Processes Study) has its international project office in Helsinki. The iLEAPS can bring visibility to ecosystem-atmosphere interactions research at an international policy level. Via the iLEAPS, ATM responds to the Future Earth initiative that will re-organise ICSU’s global environmental change (GEC) programmes closer to social science and economics. They will be indispensable partners for natural sciences on the road to solve the equation of one Earth and a growing human population.

The ATM research contributes to socioeconomic issues related to global sustainability and land-atmosphere-society interactions. Research programmes such as PEEX, iLEAPS, and Forests and Climate Change concentrate on the effects of climate change on the environment and agriculture, forestry, energy consumption, urban planning, and extreme events. ATM is equipped to deal especially with questions such as sustainable managed environments and the mixed anthropogenic and biogenic input to cloud and aerosol processes. The ATM research is applied to socioeconomic issues also via the National Climate Panel chaired by Prof Kulmala; via the ATM’s membership of the Forum of Environmental Information that produces scientific information for policy-making; and via Future Earth, the international initiative on global sustainability led by ICSU, ISSC, and UN.
Applicability and potential for applications. The scientific outcome of the ATM will be a combination of new methods, instrument development and comprehensive measurements, and improved process understanding and novel parameterizations of the ESMs. This will be achieved by answering the main objectives and research questions. Scientific breakthroughs of the methods and instrument development can be applied across fields of applications: generation of true nanomaterials in the laboratory, utilization of mass spectrometric methods for air, water, environment quality and human health diagnostics, as well as assessment of geoengineering. The commercial exploitation of the results includes new techniques, methods, designs on (i) online mass spectrometry methods, (ii) new satellite remote sensing instrumentation for atmospheric measurements, (iii) cloud property measurement instrumentation system, (iv) high-frequency instrumentation for flux measurements and (v) quality controlled laser trace gas monitors for studying the carbon cycle. ATM contributes also in air quality issues via EMEP acitivities.

Publication of the research results. All the key results are published in high-impact fora, such as Nature, Science, Nature Climate Change, Nature Geoscience, Atmospheric Chemistry and Physics, Biogeosciences etc. In addition to international peer-reviewed journals, scientific results are published in various reports, newsletters, conference publications and short popular scientific articles.

Dissemination of research results to end-users:

(1) To scientific community. The direct beneficiaries of the results, e.g. atmospheric and climate modeling communities will get access to our results via the efficient collaborators network as well as via the strong role of ATM members in the IPCC process. We have an active Mobility program, and participation in international conferences and short- and long-term research visits are strongly encouraged. We strongly emphasize open access publishing of results.

(2) To policy makers. The ATM research contributes directly to the current debate on climate change and air quality issues by delivering state-of the art data for science policy and policy making processes (e.g. Kulmala is acting as a chair of National Climate Panel). PI-scientists involved in ATM are key players in international scientific organisations and networks such as ICOS (Vesala), IPCC (Vesala, Kerminen, Räisänen), IGAC/IGBP and iLEAPS/IGBP (Kulmala) and ANAEE (Bäck).

(3) To European ESFRI process. The ATM reinforces the internationally acknowledged Finnish atmospheric and ecosystem science research infrastructures. The National Survey of Research Infrastructures in Finland in 2008 placed our measurement sites on the list of nationally important research infrastructures and on the priority list of Finnish RI roadmap. They are also the fundamental elements of several European ESFRI Research Infrastructures, such as ICOS, LifeWatch and ANAEE. There is a momentum for the ATM research agenda to reinforce the ACTRIS (aerosols-trace gases – cloud) to be part of the ESFRI process and to support the Finnish aerosol community to take the leading role in Europe in this effort.

(4) To private sector. ATM has close connections with several private enterprises including the CLEEN Ltd. ATM is also a member of “Business from the innovation pipeline – commercialization of cleantech innovations” -project, which is aiming for commercialized know-how, new enterprises and jobs. Helsinki Univ. and FMI have ongoing collaboration with private sector e.g. Vaisala Oyj, Space Systems Finland Oy, and Airmodus Oy, which is a spin-off company. This provides a forum for a combination of research and business needs: a network for effective product development also after ATM and for the future jobs for the ATM PhDs.

(5) To general public. The results are informed using distributed written material and press conferences, which generates interviews and articles in popular science magazines and in domestic and international newspapers as well as in the TV and radio. ATM results will be distributed via several platforms incl, Hiukkastieto (www.hiukkastieto.fi/), Ympäristötiedon foorumi (www.ymparistotiedonfoorumi.fi) and Hiilipuu (www.hiilipuu.fi). A ‘Climate Whirl’ will be developed for introducing the facts about climate change phenomena to wide audience by the means of modern interactive web-based technology. Members of ATM are already working also in close co-operation with elementary and high schools to familiarize pupils and students with analyses of
environmental data and the scientific world and take actively part to the social discussion via the blog: 
http://blogs.helsinki.fi/atmscience/

7. Added value generated by the ATM activity

The ATM has multiple ways to add value to the research conducted by its members: 1) steering the Finnish global change research towards global sustainability science co-designed by funders, scientists, and policy-makers: Prof Kulmala has been elected to chair the new Finnish Global Change National Committee that will lead this development; 2) advancing major global observation infrastructures such as the SMEAR and ICOS networks where the ATM has a leading coordinative and research role; 3) the uniquely multidisciplinary composition of the group also allows a systems approach to land-atmosphere interactions from soil to vegetation and to atmospheric chemistry and cloud processes. Examples include recent findings of the role of soil reactive nitrogen in atmospheric chemistry (Kulmala & Petäjä 2011, Science) and the new role of forests in atmospheric oxidation (Mauldin III et al 2012, Nature).

Scientific added value. Our approach enables a true multiscale approach from molecular level processes to global Earth System in both modeling and in advanced observational and experimental research. The next step is to fully integrate and interlink the experimental work and observational databases with theoretical frameworks and multiscale modeling in a coherent manner and by taking full advantage of the synergy of multidisciplinary research groups. Only the multidisciplinary ATM-teams can provide a critical mass, scientific expertise, and especially the research infrastructures needed for this type of approach. In separate projects these ambitious goals would be impossible to achieve and the recent progress would be distributed into too small units and the momentum in research would be lost.

Promotion of multidisciplinary research & Structural benefits. ATM has provided integration of GHG- aerosol - bioscience (ecosystem process studies) research communities at national level and will make it at Nordic and European level (see also Figure 2). ATM is currently building integrated atmospheric observation systems in Europe via its leading role in ICOS and ACTRIS. ICOS provides independent GHG data to help improve emission inventories, for monitoring the applications of international conventions like Kyoto protocol and climate negotiations.

Actually without ATM, the fragmentation of the atmospheric sciences would increase in all geographical levels. ATM is a European level node for building multidisciplinary science and enabling crossing over disciplinary borders among science communities. ATM has critical mass to build real integration of observations, modeling and developing theories, as an outcome new science results but also new ways of working and operating. Therefore ATM is benchmarking many work processes, leadership and scientific work culture: ATM is in evolution phase (service level) and the size of the ATM enables not only it to adapt to the changes in the science policies / program topics or societal demands but ATM has the capacity to change and influence the science policies and the societal dialogue, the evolution phase of the organization and the critical mass also enables a creation of strategic and management level innovation together with the technical and scientific innovations.

In order to raise quality, international competitiveness and visibility, ATM will promote the establishment of the European Institute of Atmospheric Sciences and Earth System Research (EINAR). Europe a research body that has the capacity to integrate, upscale and synthesize the observations and process-understanding in the global scale, produce state-of-the-art research knowledge for policy making, and has a long-term strategy and funding. Furthermore, the ATM research agenda consolidates the role of Finland as one the leading countries in global initiatives such as IGBP and Future Earth. ATM is crucial to promote and materialize Pan Eurasian Experiment, PEEX, which can be listed as one of the most potential experiment initiatives providing new data on the climate change problematics related to the cryosphere and to the Arctic areas. ATM will promote the societal impact of research and supports the work towards sustainable adaptation and mitigation of climate change, to disseminate of research findings (for policy making processes) and focus on training of multi-talented environmental and atmospheric experts.

New researcher training opportunities. The ATM brings together the added value both at national and international scales. At the national scale it brings together the next generations of interdisciplinary atmospheric scientists from different backgrounds (chemistry, physics, forest ecology,
meteorology, geography-remote sensing). Internationally the ATM’s added value materializes in its international networks, capable of providing access to the best available research infrastructures like CERN Cloud Chamber laboratory (Kirkby et al. 2011).

**More efficient use of research infrastructures.** ATM reinforces and stabilizes the development of ICO S, ACTRIS, ANAEE research infrastructures. It will consolidate the operation of the ICOS Head Office in Helsinki and promotes the possibility to establish ACTRIS Head Office also in Helsinki. The overall impact is expected to strengthen the funding inflows to research to maintain high international level of infrastructures and other resources. ATM new component, the satellite and remote sensing technology, will enable the efficient participation in the global scale environmental challenges.

8. **The position of the ATM in respect to the world leaders in its field/s**

The ATM has obtained a world leading position in: (i) formation of atmospheric aerosols and in the biogenic background processes leading to aerosol formation and (ii) measuring fluxes of GHGs, aerosol particles and their precursors. The leading competitors are: 1) Climate - biosphere interactions: Max Planck Institutes Mainz, Hamburg, Jena, Germany, Prof. M.O. Andreae; 2) Atmospheric aerosol research & instrument development: High Temperature and Plasma Laboratory, University of Minnesota USA, Prof. P.H. McMurry; 3) Atmospheric chemistry: Max Planck Institute for Chemistry, Mainz, Germany, Prof. J. Lelieveld; 4) Biogeochemical cycles: CEA-CNRS, France, Prof. P. Ciais. Our strategy towards the most important competitors is joint research and instrument development projects.

**REFERENCES**

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