ArcRisk

Arctic Health Risks: Impacts on health in the Arctic and Europe owing to climate-induced changes in contaminant cycling

- Project Outline –

1 Concept and objectives of the ArcRisk Project

1.1 Concept and objectives

Background for an integrated climate-contaminants-health research initiative with a focus on the Arctic

The Arctic is contaminated by chemicals released as a result of both human activities and natural processes. Despite the fact that most of these substances have few, if any, sources within the region, these chemicals reach the Arctic from distant sources via the atmosphere and via northerly flowing rivers and ocean currents.

Although no longer pristine, Arctic (abiotic) environments generally exhibit lower levels of contamination than those found in regions closer to major sources, such as most of Europe. However, certain characteristics of the Arctic (cold, ice and snow cover, extended periods of darkness) mean that the Arctic has the potential to accumulate certain globally transported environmental contaminants, including a number of Persistent Organic Pollutants (POPs) and mercury. Processes that affect contaminant movement within and between different environmental compartments—and thereby determine to a large degree their transport pathways—are complex. These processes and pathways are influenced by a number of physical factors, such as temperature, precipitation, winds, ocean currents, and snow and ice cover, all of which are subject to climate-related perturbations.

At the same time, the Arctic possesses unique food webs, including a number of key species that utilize fat reserves for energy storage and insulation. Throughout history, Arctic human populations have relied on these natural resources for foods that form the basis of their 'traditional diets'. This combination of factors has resulted in a paradox whereby, despite generally low levels of contamination in air, soils or water, Arctic species high in the food-chains—polar bears, seals and toothed whales, certain seabirds, and predatory fish—accumulate very high concentrations of certain contaminants. As these species also form part of the traditional diet of Arctic peoples, certain Arctic populations receive greater exposures to specific contaminants than people anywhere else on the Earth. Many of these contaminants are toxic, with known potential to adversely affect the health of animals and humans. In some cases, evidence exists of direct health effects resulting from exposure to contaminants in general (i.e., non-occupationally exposed) population groups in some Arctic countries. As with the physical factors that influence contaminant transport pathways, ecosystems are also subject to climate-related perturbations that can alter food webs through a range of mechanisms and thus alter contaminant exposure in various parts of the system.

Until recently, information about Arctic pollution issues has received limited attention outside of the region; however, climate change has added a new dimension, increasing the relevance of this information for people both within and also outside the Arctic region. Change is occurring in the

Arctic more rapidly than elsewhere, and the effects are being felt sooner. There is increasing realization that the Arctic and global systems are integrally linked, and that what happens now in the Arctic may happen later elsewhere. The Arctic is increasingly being viewed as the 'canary in the mine'—providing lessons and early warning for possible effects on other regions.

Concept of a proposed integrated climate-contaminants-health research initiative with a focus on the Arctic

The brief background presented above provides a clear indication of the complex interactions that exist in the processes connecting contaminants released into the environment through their transport in abiotic systems, to their uptake in food-webs, and ultimately to human exposure and potential for causing adverse health effects in human population groups. And beyond this, is the recognition that these inherently dynamic processes are now being influenced by climate change, which is both changing and accelerating some of the natural processes in ways that are extremely difficult to predict. Assessing the impact of climate change is one of the greatest challenges for the scientific community today.

Clearly, any research initiative aiming to study the potential impact of exposure to persistent environmental contaminants on human health against the backdrop of climate change needs to adopt an integrated approach which addresses all components in the chain. This is a core part of the ArcRisk project concept—not only to consider contaminants, or health, or climate, but to attempt to link them in a meaningful way.

Equally obvious are the limitations of what can be accomplished within the resources available for project implementation. For this reason, a second element in the project concept is to squarely place the ArcRisk project within a framework of other relevant initiatives—to closely coordinate with these initiatives to maximize benefits to all parties, achieve cost-effective solutions, avoid duplication, and generally to produce an outcome that 'exceeds the sum of the parts'. The ArcRisk project will exploit, in particular, the work conducted under the Arctic Monitoring and Assessment Programme (AMAP), and the ongoing international research efforts under the International Polar Year (IPY), and at the same time produce information that will contribute to these parallel initiatives. In this respect, a close collaboration with AMAP is seen as a key element for a project addressing the ENV.2008.1.2.1.2 call in order to make use of the extensive datasets that have been compiled by AMAP over many years. These datasets represent a key resource that will be used extensively in the ArcRisk project, freeing up the limited resources available to the project group to concentrate on work to analyse and interpret available data. In addition, established linkages with other relevant EU projects, e.g., PHIME, NoMiracle, DROPS, EUROLIMPACS and CLEAR, will be maintained and strengthened.

The focus of the research on the Arctic has a number of advantages: the strong climate signals that exist in the Arctic present opportunities to investigate climate influences on key physical processes. The isolated communities of the Arctic provide a potential for elucidating health effects in a way that is not possible in more dynamic and complex societies. At the same time, these Arctic communities can be related to specific European population groups, for example, groups consuming large amounts of marine foods that are found throughout Europe from the Mediterranean to the Baltic, and thus provide potential for comparative studies.

The research components of the ArcRisk proposal are organized around three main work packages comprising (WP2) the utilization of models to investigate contaminant transport under present and future climate scenarios, (WP3) process studies to investigate key parts of the chain linking environmental contamination to human exposure under climate-mediated influences, and (WP4) the investigation of available epidemiological databases and human health statistics, in particular those based on cohort studies in both the Arctic and selected areas of Europe, to attempt to resolve the influences on health of contaminants and climate change from the many other determinants of health. The potential influence of climate variability and global climate change will be studied using emissions and climate scenarios for the first half of the 21st century and up to the year 2100.

Two important additional work packages address the integration of the overall results of the work and elucidation of their policy implications (WP5) and the necessary stakeholder/communications issues (WP6) that are considered essential to the implementation of the planned programme of work and the dissemination of key findings for broader use, including in policy-making.

The proponents of the ArcRisk project are conscious of the fact that the planned work involves a large number of consortium members—this being necessary to cover the range of expertise required to successfully carry out a project with such a broad scope. Consequently, a strong project management structure has been designed by including experienced project management capability at the work package level in addition to the overall project management within WP1.

In addressing the issues covered in this project, it is envisaged that the key concerns and threats posed by chemical pollutants to a future 'warmer' Arctic will be identified and recommendations can be given with the aim of reducing human exposure and risk to Arctic populations. The results will also be relevant to EU policies in relation to chemical legislation and risk assessment as well as to international conventions aimed at the use of POPs and of persistent chemicals subject to long-range transport.

The main objectives of ArcRisk are to:

1. Describe, using selected climate change and chemical usage scenarios, the changing routes and mechanisms by which persistent chemical pollutants and air pollutants are delivered to the Arctic and the possible role of climate variability and global climate change on the processes influencing pollutant transfer and distribution;
2. Quantify the deposition and accumulation of selected persistent chemical pollutants on snow/ice and on ice-free surfaces, their geochemical fate in the seasonal snow pack, and their transfer to aquatic food chains with melt-water runoff;
3. Determine the transfer of pollutants from the abiotic Arctic environment into the base of food chains and to higher trophic level organisms (e.g., fish, marine mammals, reindeer) consumed by humans and the possible role of climate variability and global climate change on these processes, including bioaccumulation and biomagnification factors of select 'emerging' contaminant groups in specific food webs and organisms relevant to human diet;
4. Compare the role of climate change on the transport, fate and food web transfer of pollutants in the Arctic to the situation in relevant selected areas with exposed local populations in the EU;
5. Identify and quantify the current main health outcomes in relation to exposure to 'legacy' contaminants in selected populations in the Arctic and exposed local populations in the EU;
6. Establish geographical and temporal trends in the distribution of health impacts associated with contaminants (both legacy and emerging) in several areas of the Arctic and selected areas of Europe;
7. Develop projections for the effects of climate change on the 'legacy' contaminant exposure and health effects/outcomes in the selected populations in the Arctic and in exposed local populations in the EU and develop scenarios of potential future health risks induced by climate-mediated changes in exposure to contaminants;

8. Prepare strategies for adaptation and for the prevention of adverse health outcomes related to climate-mediated changes in exposure to pollutants in populations in the Arctic and in Europe.

1.2 Progress beyond the state-of-the-art

There have been a large number of studies of the transport of contaminants to the Arctic; the concentrations of contaminants in Arctic environmental media, organisms, and humans; the health of Arctic populations and potential impacts of contaminants on health; and the impacts of climate change. Much of this work has been coordinated by the Arctic Monitoring and Assessment Programme (AMAP) and the results published in major assessment reports (e.g., AMAP, 1998, 2002, 2003a, 2003b, 2004a, 2004b, 2004c, 2009; ACIA, 2005), which, together with associated AMAP databases and the results of recent and on-going projects in the Arctic (e.g., relevant International Polar Year (IPY) projects), provide an extensive foundation for further work on these issues. To date, AMAP has provided the most thorough, comprehensive assessments of the state of the Arctic environment with regard to a large number of pollutants, with data from all the circumpolar nations compiled under the umbrella of AMAP. Therefore, it is vital to involve the AMAP network and its information base in addressing EU call ENV.2008.1.2.1.2 and thus build on its vast accumulated knowledge and experience.

Substantial research has been carried out in the EU on the mechanisms and effects of environmental contaminants. Nevertheless, it is still unclear to what extent and/or in what situations and population sub-groups environmental contaminants may represent a significant, long-term health risk, particularly for populations living in the cold northerly fringes of Europe, where the cold conditions combined with a traditional diet of fish and marine mammals serve to enhance human exposure to contaminants.

Given the particular sensitivity of the Arctic to climate change and the clear impacts of climate change that are already being observed, it is timely to investigate the potential climate-mediated changes that may occur in the long-range transport of pollutants, including air pollutants, to the Arctic from regional and global sources and the ways in which climate variability and global climate change will affect the mobilization and transfer of pollutants in the Arctic environment and their uptake into living organisms, particularly those in food webs leading to species consumed by humans. These potential climate-induced changes in bioaccumulation and bioavailability of contaminants in human food species, such as fish, marine mammals, and reindeer in the Arctic, further may affect the health of their human consumers, in addition to the other potential health impacts of climate change. To provide a broader perspective, comparisons will be made with the potential impact of climate change on contaminant exposure and effects on human health in several areas of Europe with exposed local populations.

Accordingly, in the ArcRisk project, the influence of climate change on contaminant transport and the resultant risk to human populations in the Arctic and other areas of Europe will be studied with special focus on:

1) the ways in which climate change will affect the long-range transport and fate of selected groups of contaminants, and possible implications for the re-distribution of contaminants (geographically and between relevant environmental media), involving modelling utilizing the existing information base on the distribution of relevant contaminants in the Arctic and other areas of Europe;
2) the impacts that climate change will have on contaminant transfer and fate in aquatic and terrestrial environments and on contaminant uptake and transfer within food webs, leading to foods consumed by humans, as determined in experimental work and process studies;

3) determining how climate-mediated changes in the environmental fate of selected groups of contaminants will result in changes in exposure of human populations, in the Arctic and in selected areas of Europe, and the implications of this for the direct and indirect effects of contaminants on human health, as based on meta-data analysis of large numbers of health studies and several relevant cohort studies.

The work in these three areas of focus will be integrated, ensuring the exchange of results among the various aspects of the project, as needed. Based on the results of these three main components, an overall integration and assessment will be produced regarding the potential pollutant-related health impacts of global climate change and suggestions will be developed regarding possible adaptation strategies.

The results of ArcRisk will provide information relevant to EU policies in relation to the Environment and Health Action Plan, the REACH (Registration, Evaluation, Authorization and Restriction of Chemicals) process, and the development of strategies for adaptation to climate change. It will also contribute to the work of Member States and others in relation to international commitments such as the Stockholm Convention on Persistent Organic Pollutants and the UNECE Convention on Long-Range Transboundary Air Pollution.

Given the wide range of scientific issues covered in this project, the state-of-the-art will be described for each of the three major aspects of the work: 1) modelling the transport of pollutants to, their distribution within, and fate in the Arctic, including in the food web, and the possible influence of climate variability and change; 2) experiments to determine key fluxes and processes of contaminant loading and transfer that will be affected by climate change; and 3) current evaluations of the direct and indirect impacts of contaminants on human health in the Arctic and selected exposed populations in Europe and projections of the potential influence of climate change. Much of the work will be based on the large accumulation of data and information on so-called 'legacy' contaminants: persistent organic pollutants (POPs) including PCBs and organochlorine pesticides; however, where possible, new data will be obtained on new 'emerging' contaminants, such as polybrominated diphenylethers (PBDEs), perfluoroalkylated substances (PFAS), and others. The contaminants to be studied will be determined in selection procedures early in the project and at least several contaminants will be included in all components of the project.

Modelling pollutant transport to, fate in, and interaction with the Arctic and the possible role of climate variability and global climate change on these processes

State-of-the-art. Current understanding of the potential effects of climate change on the transport, fate, and food-web transfer of chemical pollutants is mostly qualitative by nature (e.g., see review by Macdonald et al., 2005; AMAP, 2004a). There have been limited attempts to use models to determine the effects of climate change and climate variability on chemical fate, transport, and exposure to pollutants (e.g., McKone *et al*., 1996; MacLeod *et al*., 2005; Valle *et al*., 2007). The change of transport patterns in air and water under climate change has been studied (e.g., ACIA, 2005) but not with regard to pollutant transport. Chemical fate and exposure vary with latitude as a result of changing temperature and other climate parameters and their variability (Wania, 2006). Similar to the physical effects, it is hypothesized that the effects of climate change on chemical fate will be different and more pronounced in the Arctic compared to at lower European latitudes. Particularly climate-sensitive processes of chemicals cycling are sea-ice and snow melting, precipitation patterns, and ocean primary productivity. These have not been addressed by modelling so far.

Models of chemical fate, transport, and bioaccumulation make a quantitative link between physical-chemical properties and emission estimates of chemical contaminants, and concentrations measured in the environment. They thus provide insight into the chemical, biological, and physical factors that determine how chemical pollutants behave, and are the only available tools to budget contaminants on large spatial and temporal scales and predict environmental fate under climate change. Multimedia mass balance models (MMMs) represent the environment as a set of connected well-mixed compartments (i.e., air, water, soil, sediments and biota). They are widely used for describing global chemical fate and transport because they are flexible, easy to handle, and computationally cheap. MMMs are suitable for explaining differences in environmental fate and transport between chemicals in a defined environment, and exploring the influence of variable environmental factors on chemical fate and transport. There has only been a limited effort to date to model human exposure from pollutants originating from wildlife food webs in the Arctic. Food web models developed to describe the uptake and bioaccumulation of pollutants by single organisms and in aquatic food webs are used to investigate the phenomenon by which pollutants present at low concentrations in the abiotic environment become concentrated by many orders of magnitude in biota as well as in humans.

Expected progress. ArcRisk for the first time offers the opportunity to investigate the influence of changing conditions in the physical environment on different classes of pollutants. Due to the application of novel modelling tools, contaminant transport to, spreading in, and interaction with the Arctic environment and Arctic food webs will be addressed more realistically than previously possible. Models are the only tools to provide physically consistent scenarios of present and future climate states. Relevant climate variables will be extracted from the most recent IPCC integrations (AR4) for different future greenhouse gas emission scenarios and, where necessary, downscaled from the global scales to the regional scales. Which results will be taken into account will depend on the models' performance in northern high latitudes (see, e.g., Gerdes and Köberle, 2007). These results will be used as forcing functions for the transport and fate models linked to food web transfer models. A hierarchy of numerical models will be used in WP2 encompassing multimedia mass balance models (MMMs) and atmospheric and oceanic chemistry transport models. This enables the simulation of the environmental (climate) parameters and their variability and trends using the most comprehensive, state-of-the-art modelling tools and at the same time to explore the sensitivity of pollutant paths in the environment and in food webs with appropriately versatile tools. ArcRisk will employ the BETR Global MMM to investigate the impact of climate variability on contaminant concentrations in the Arctic. ArcRisk will also use the Danish Eulerian Hemispheric Model (DEHM) to study the effect of climate variations and climate change on air transport of contaminants, and the NAOSIM (North Atlantic/Arctic Ocean Sea Ice Model) GCM for coupled ice-ocean simulations. In the framework of ArcRisk, NAOSIM will be amended with modules describing the behaviour of suspended matter, relevant for particle-reactive pollutants. A multimedia GCM model, comprising a coupled atmosphere-ocean GCM, will also be used. This model is unique and presently the most comprehensive multimedia model existing. It is applicable to both hydrophobic and hydrophilic POPs and captures the influence of the particle phases in seawater and air on transport and fate and POPs concentration at the base of the marine food chain.

All key processes of environmental cycling of chemicals under climate change conditions will be captured, some of them more comprehensively than ever. These include: 1) exchange between air and sea-ice, 2) variability of contaminant concentrations in time and space, 3) partitioning to and sinking with various classes of marine particles, and 4) entry of pollutants into marine and terrestrial food chains. A key area of investigation is the retreat of sea-ice cover, which acts as a barrier for air-sea exchanges and as a transport medium and secondary source for deposited pollutants. Changes in seasonal ice coverage, age and thickness distribution, and drift patterns will have significant influence on physical processes relevant for pollutant transfer, such as surface water exposure times, melt-water input patterns and timing, atmospheric deposition targets (ice vs. ocean), Polynya distributions, and dense water formation. Process studies undertaken in WP3 on air-sea exchange will provide an important means of evaluating the models' predictive capabilities. The model hierarchy will be used for late 20th century baseline simulations and a set of climate change scenario simulations. In addition to information on changes and variability of the physical environment relevant for pollutant transfer, these models will be used for dispersion studies for a set of 'legacy' as well as 'emerging' persistent pollutants. Model intercomparison will be an integral part of the model quality assurance process, as will comparison of model results with monitoring data and process studies in WP3. In particular, the effects of climate change on the transport, fate, and food-web transfer of pollutants in the Arctic will be compared with selected areas of Europe (e.g., Baltic).

Process studies on the influence of climate change on contaminant transfer in the Arctic

State-of-the-art. Understanding the transfer of persistent organic pollutants (POPs) and mercury (Hg) both to and within the Arctic and their uptake and accumulation in food webs has, to date, focused chiefly on 'legacy' contaminants (AMAP, 2004a, 2004b, 2004c). These surveys have been supported by numerous field-based campaigns to establish information on concentrations of these contaminants and, to a limited extent, understand their behaviour in different abiotic and biotic matrices. Importantly, long-term atmospheric monitoring programmes in both the Canadian and Norwegian Arctic have provided systematic POPs and Hg air concentrations since the early 1990s, with weekly resolution (e.g., Berg *et al*., 2004; Hung *et al*., 2005; Becker *et al*., 2006). These datasets provide a unique tool with which to assess long-range atmospheric transport to the Arctic and provide insights into temporal trends (Hung *et al*., 2002), their geographical distribution (Su *et al*., 2006) and, recently, evidence of newer contaminants entering the Arctic environment (e.g., polybrominated diphenylethers (PBDEs): Su *et al*. 2007; perfluoroalkylated substances (PFAS): Stock *et al*., 2008).

Processes governing the contaminant transfer from the atmosphere into vulnerable Arctic food webs are an area that is not well understood, notably for the newer, emerging contaminant groups. In particular, the role of snow in scavenging, storing, and releasing contaminants to fresh/marine waters is uncertain, and yet precipitation as snowfall is projected to increase in most regions of the Arctic under climate change scenarios (ACIA, 2005).

Current studies on contaminant accumulation in snow reveal that Hg and semi-volatile chemicals have a tendency to re-evaporate following snowpack ageing and melt (e.g., Aspmo *et al*., 2006; Herbert *et al*., 2006). Chemicals such as deca-BDE and PFAS have now been detected in snow (Muir and Zheng, 2007; Young *et al*., 2007), but their tendency to re-evaporate from snow is likely to be considerably less than that of the semi-volatile legacy POPs, and the concern now is that winter snow and summer drizzle will provide a highly efficient delivery mechanism of these chemicals to Arctic habitats.

Retreating sea ice will strongly influence contaminant dynamics and food-web uptake in the marine environment. For 'legacy' contaminants, such as polychlorinated biphenyls (PCBs), a compilation of data from surveys detailing concentrations in marine and freshwater biota exists under the auspices of AMAP (see AMAP, 2004a). However, the role of abiotic-biotic interactions at the base of the marine and freshwater food webs is poorly understood, and processes resulting in bioaccumulation require investigation, particularly if climate change impacts on contaminants pathways into biota are to be understood. For example, it has been recently demonstrated that PCB bioaccumulation factors (BAFs) for plankton studied in Arctic marine waters show considerable variation, with recent field studies demonstrating much higher values than those obtained in earlier studies and also calculated based on physical-chemical properties (i.e., Kow) (Borgå *et al*., 2005). This calls into question the operational definition of 'dissolved' concentrations, and raises the possibility of high uncertainties for standardized methods used for the previous determination of PCBs in Arctic surface waters (e.g., see Gustafson *et al*., 2005; Sobek *et al*., 2006) as well as the bioaccumulation potential of emerging contaminants.

Expected progress. Important new information on the deposition and runoff (melt-water) for a range of chemicals including emerging contaminant groups will be obtained in view of a 'changing' Arctic. The current International Polar Year (IPY) is providing the impetus to study detailed transfer processes in the field and new databases on emerging contaminant groups in both abiotic and biotic matrices will be compiled. Importantly, new quantitative information will be obtained on:

- transport pathways of POPs and mercury to the Arctic and their lifetimes in snow and ice matrices, utilizing data from on-going campaigns such as COPOL, OASIS, ATMOPOL, ARCPOP, and the Canadian Flaw-Lead system (CFL) project in 2007–2008 (http://www.ipy-cfl.ca/) available to ArcRisk. Atmospheric deposition will be measured at sites in southern Norway (Birkenes), northern Sweden, and Finland (Pallas) in conjunction with study sites in Svalbard to assess the role of long-range atmospheric transport and provide 'ground-truth' fluxes for the models in WP2;
- contaminant concentrations in surface waters and the assessment of contaminant uptake into the lower food web, drawing on datasets acquired through ongoing and planned marine fieldwork (see CFL above);
- specific air-water transfer for 'emerging' contaminant groups. This will improve the spatial assessment of air-water exchange as a route of entry for these contaminants into 'ice-free' marine waters (e.g., see Weber *et al*., 2006), with renewed focus on the European Arctic. Comparisons to biological uptake in well-studied, high-altitude freshwater systems in temperate mountain areas will provide a useful means with which to assess biological uptake for 'emerging' contaminant groups such as the PBDEs (e.g., Gallego *et al*., 2007);
- spatially resolved data for 'emerging' contaminants such as deca-BDE and the PFAS in select biota. This will fill a major knowledge gap with regard to contaminant levels in a variety of food webs that provide 'country foods' to indigenous communities in the European Arctic, particularly in select coastal regions and terrestrial areas of Norway/Northern Finland and Russia. New quantitative analytical methods utilizing chiral tracer compounds, including organochlorine pesticides and PCBs, will provide knowledge on the selective uptake and bioavailability of persistent contaminants under various climate-related regimes (Kallenborn and Hühnerfuss, 2001; Bidleman *et al*., 2007).

Effects of contaminants on human health and the influence of climate change

State-of-the-art. Individuals and populations are exposed in their everyday lives to a large number of environmental contaminants occurring in many different combinations, and they have complicated effects on physiological functions in the body, e.g., hormone balance and on human health. Body burdens of contaminants vary with the source and level of contamination, exposure paths (including life-style factors), and genetic background of individuals (Pelkonen *et al.*, 2003; Aylward *et al.*, 2005; Sergent *et al.*, 2008), which are the basis for most of the inter-individual variations in tissue concentrations of contaminants seen in population studies. In particular, tissue concentrations of POPs differ greatly according to gender, age, race, and population (Needham, 2008).

Environmental contaminants may cause several adverse health outcomes, and in epidemiological studies increased risks for congenital abnormalities, chronic diseases, and cancers have been observed. Especially the perinatal period is particularly critical for the developing fetus and advance developmental effects may be a result of the exposures of both parents before and during pregnancy (Needham *et al*., 2005); they also depend on the timing of the exposure during the pregnancy (Barr, 2005). The adverse effects of the contaminants depend greatly on their fate in the human body, which is a function of contaminant toxicokinetics, metabolism, and cell transporter functions; during metabolic processes, the xenobiotic chemicals may become even more toxic, mutagenic, or carcinogenic products.

Maternal blood and urine samples and cord blood have been used to assess *in utero* exposures (Barr, 2005; Lallas, 2001; Carrizo *et al*., 2007). Several relevant prospective cohort studies have investigated neurobehavioural function during infancy and childhood. In Canadian Arctic population studies, it was observed that concentrations of different environmental pollutants in maternal blood were associated with specific neurobehavioural disturbances of infants and children (Despres *et al*., 2005). However, other studies have found no correlation between levels of contaminants in mother's blood, placenta or breast milk and the prevalence of diseases or abnormalities in their children (Main *et al*., 2007). These discrepancies between results of human epidemiological studies have also led to suggestions that the reason for the differences may be due to the combined exposure of contaminants (e.g., PCB and MeHg) (Grandjean *et al*., 2001).

Health outcomes that have been investigated include maternal health, placenta function, incidence of spontaneous abortions, altered sex ratios, premature deliveries, low birth weight, malformations, and perinatal mortality and morbidity. Maternal exposure to high levels of PCBs during pregnancy may cause growth retardation of children (Rylander *et al*., 2000), while congenital cryptorchidism has been observed after exposure to PBDEs during pregnancy (Main *et al*., 2007).

Environmental contaminants, including endocrine disrupters, may lead to increased risk of chronic disease, and even at low exposure levels have been found to cause epigenetic effects (Hanson and Gluckman, 2008; Cordier, 2007; Hansen *et al*., 2008). High body burdens of mercury may be a risk factor for acute coronary events (coronary heart disease and infarction) in middle-aged men (Virtanen *et al*., 2005) and increased incidence of cancers has been found after paternal exposure to chemicals (Cordier, 2008).

Contamination of dietary intake provides the most extensive exposure to POPs and most heavy metals, and is the main source of exposure in Arctic populations (AMAP, 2003a). In particular, Arctic populations have a higher exposure to POPs than other European populations owing to the high levels of POPs in Arctic marine mammals and some fish species that are consumed as part of the traditional diet. With regard to fish, nutrients in seafood may modify the toxicity of contaminants and research is needed on fish-eating populations. Fatty fish are high in omega-3 polyunsaturated fatty acids (PUFAs), which are believed to be beneficial to health, but frequent fish consumption includes the risk of exposure to POPs (Wilson, 2004). However, adverse effects of exposure to these chemicals are still limited while the health benefits of eating fish are clear, and prenatal maternal PUFAs may act as protective factors against foetal neurotoxicity owing to environmental chemicals (Domingo *et al*., 2007).

Expected progress. In the ArcRisk project, the comprehensive data from recent and on-going AMAP assessments concerning adverse health outcomes induced by contaminants will be combined with data from a large number of publications and on-going research projects in the Arctic to provide a picture of baseline health status in the Arctic; this will establish geographical and temporal trends in the distribution of health impacts of contaminants in the Arctic. After a critical evaluation of the long-term time series of environmental and epidemiological data, ArcRisk will indicate the detection potential of these databases. Multivariate incorporation of climate change factors, food strategies, and environmental exposures in human risk assessment models and benchmarking the weight of these factors among different regions should provide the basis for comparison among the regions studied. After data analysis, a comprehensive project database (see below) will be developed in cooperation with WP5 for further use beyond the project.

ArcRisk will provide an excellent opportunity to assess the variability of health status in different populations in the Arctic and in selected exposed populations in Europe and to project threshold values in relation to environmental metadata compiled in other aspects of the project (WP2 and WP3). Based on the results of the application of climate change scenarios to contaminant transport and distribution pathways and changes in the food webs (WP2 and WP3), scenarios will be developed to project future human exposure and health impacts associated with these climate-induced changes in dietary contaminant exposures.

The extensive database regarding health outcomes in relation to contaminant exposure established in this project will also provide an opportunity to identify particular combinations of different contaminants that deserve further research in the light of their implications for human health. This will be further developed in modelling based on the thirty-year follow-up trend study of blood levels of classical and emerging contaminants in the general population of Northern Norway (The Tromsø Study) that is integrated into WP4.

Synthesis of results and policy implications

Many different sources are available for the synthesis of information on contaminant transport in the environment, human exposure to contaminants, and their impacts on human health in the Arctic. Several assessment reports on various environmental topics have been prepared by the Arctic Monitoring and Assessment Programme (AMAP), including on heavy metals, persistent organic pollutants, human health, and climate change. A large quantity of information on these topics is also available in the open scientific literature.

In this project, a dedicated approach will be devised for providing answers to the main question of the project: how will climate change affect the transport of contaminants both to and within the Arctic, as well as their human health impacts in the Arctic in relation to exposed local populations in Europe.

A **project evaluation system** will be used as a systematic tool for identifying relevant information and to ensure that this information can be extracted from the project activities. A process evaluation plan will be developed based on the WP descriptions whereby key events and results are identified. Mid-term evaluations of the work performed in WP2, WP3, and WP4 will be conducted based on the specifications in the process evaluation plan. This will give insight into the overall work progress and will enable partners to make proper re-directions, harmonization, adaptation, collection of additional information, etc., if needed. A pre-synthesis evaluation of the work of WP2, WP3, and WP4 will be performed before concluding the work in the scientific WPs. The primary aim is to ensure that key messages can be extracted from the results, and that they are useful in the context of the overall assessment and policy development. The project evaluation system will also form the basis for the development of a project database. The database will consist of aggregated information on relevant parameters such as: spatial and temporal trends of contaminant concentrations in relevant parts of the Arctic ecosystem and as relevant to human exposure, as well as data on climate change influences on contaminant transport, transformations, and exposure. This database will form the basis for the dissemination performed in WP6 and also for a general summary and synthesis of information on the influence of climate change and climate variability on emissions and transport of selected contaminants, and exposure of humans to these contaminants. Finally, a compilation and evaluation of European policies related to contaminants and their human health impacts will be made. Results of the project will be used to assess options for strategies for adaptation and abatement.

The policy evaluation will include comparisons of contaminant levels and human exposures in the Arctic with information on risk assessment used in these policies, such as evaluation methods applied in the REACH (Registration, Evaluation, Authorisation and Restriction of Chemicals) regulation and Environmental Quality Standards defined in the Water Framework Directive (WFD) and related work of the Nordic Council of Ministers (Nordic Chemical Group) and the OECD. Other policies and international agreements whereby contaminants including POPs are controlled owing to their potential for long-range atmospheric transport include the Stockholm Convention on POPs (Persistent Organic Pollutants) and the 1998 Aarhus protocols on Persistent Organic Pollutants (POPs) and Heavy Metals (HMs) of the 1979 Geneva Convention on Long-Range Transboundary Air Pollution (LRTAP).

The results from this project will also be important within the marine conventions of OSPAR and HELCOM and the Marine Strategy Framework Directive, described in "Communication from the Commission to the Council and the European Parliament—Thematic Strategy on the Protection and Conservation of the Marine Environment, COM(2005) 504 final, Commission of the European Communities, Brussels, 24.10.2005" and "Proposal for a Directive of the European Parliament and of the Council establishing a Framework for Community Action in the field of Marine Environmental Policy (Marine Strategy Directive), COM(2005) 505 final, Commission of the European Communities, Brussels, 24.10.2005". In particular, paragraph 42 of the preamble to the Marine Strategy Framework Directive specifically notes "The serious environmental concerns, in particular those due to climate change, relating to Arctic waters, a neighbouring marine environment of particular importance for the Community, need to be assessed by Community institutions and may require action to ensure the environmental protection of the Arctic."

One of the main aims of this project is to generate scientific results that are relevant to policies dealing with contaminants and health on European, pan-Arctic and also global scales. In order to fulfill this aim, the project needs not only to generate results of high scientific quality but also to communicate these results to relevant stakeholders in an appropriate manner. These activities are focused in WP5 and WP6 but will be integrated into all activities and involve all participants.

To facilitate the transfer of project results to relevant policy-makers and other stakeholders, specific efforts will be made to synthesize and disseminate policy-relevant results. An important part of the communication strategy that will be developed under WP6 will therefore be to identify communication pathways to organizations (relevant EU bodies and agencies, authorities, international bodies, NGOs) involved in establishing, implementing, and evaluating policies on contaminants and health.

Communication will be achieved by preparing and distributing project overviews where the results are summarized and evaluated in relation to policy issues and through direct communication with policy-makers and stakeholders at workshops, expert meetings, and symposia. The mid-term and final project meetings will be of particular importance in this respect. If feasible, these events will be arranged in conjunction with other relevant stakeholder meetings or as joint events with other EU projects (e.g., the CLEAR project) in order to maximize the attendance of stakeholder representatives.

The results of ArcRisk will be highly relevant to Arctic populations, and in particular to Arctic indigenous peoples, some of whom receive some of the highest exposures to contaminants of any people on the planet due to their traditional diets and lifestyles. A special awareness and understanding of the lifestyles and cultures of Arctic indigenous peoples is required to ensure an appropriate communication of scientific results to these groups. For this reason, the ArcRisk communication strategy will include consultation with organizations representing the Arctic indigenous populations, to ensure that the dissemination of project results to this particular group of stakeholders is managed in a responsible manner.

1.3 Scientific methodology and associated work plan

Overall strategy of the work plan

The strategy of the work plan is to adopt an integrated approach to studying the potential influence of climate change on long-range contaminant transfer, passage through the food chain and accumulation in species consumed by humans, and their ultimate effects on human health. The focus of the approach will be on the Arctic, with comparisons to exposed populations in Europe, e.g., with respect to significant consumption of fish. The work plan addresses all components in this chain: contaminants, human health, and climate change.

The work plan is organized into six interdependent work packages, three of which cover the three main scientific aspects of the project: 1) modelling long-range transport of contaminants to the Arctic, their cycling and uptake in food chains, and climate change impacts on these mechanisms (WP2); 2) process studies to validate model results and investigate the influence of climate change on critical contaminant transfer processes in the Arctic (WP3); and 3) investigations of human health outcomes in relation to contaminants based on analyses of large compilations of data from Arctic and European studies and cohort studies, and projections of future health outcomes under climate change based on WP2 results. A process evaluation system will be developed to support the flow of results among the WPs and provide a framework for the overall integration and synthesis of results, including policy implications, (WP5), which will ultimately be used to prepare products for dissemination to the EC, stakeholders, and the public (WP6). WP6 will also coordinate project activities with other networks, e.g., AMAP, IPY. The overall work plan will be managed in WP1. An outline of the tasks and their interactions is as follows:

WP1: Project coordination and management

WP1.1: Management of the project, including overall coordination of activities and implementation of project strategy

WP1.2: Establishment of the ArcRisk website, facilitation of internal communications within the project, and provision of relevant information on the project implementation status for external communication under WP6

WP2: Modelling pollutant transport to, fate in, and interaction with the Arctic and the impact of global climate change on these processes

WP2.1: Select chemicals to be studied in the project, together with WP3 and especially WP4

Select climate scenarios and emissions scenarios for use in WP2

WP2.2: Modelling of atmospheric transport and fate of contaminants in Arctic (compare with results in WP3.1 and WP3.2)

WP2.3: Modelling of contaminant transport in food chains (compare with results in WP3.1 and WP3.2; provide results to WP4.2)

WP2.4: Compare contaminant transport with another European region

WP2.5: Synthesis of all modelling work (provide to WP5 for overall integration and synthesis)

WP3: Process studies on contaminant transfer in the Arctic

WP3.1: Studies of bulk deposition on land and contaminant fate and release with snowmelt (compare with results of modelling in WP2.2)

WP3.2: Studies to assess air-water transfer and contaminant fate in seawater snowmelt (compare with results of modelling in WP2.2)

WP3.3: Biological uptake in marine and terrestrial food webs: routes of human exposure (using model scenarios in WP2; provide results to WP4.2)

All WP3 results to WP5 for overall integration and synthesis

WP4: Effects of contaminants on human health and the influence of climate change

WP4.1: Estimation of the effects of contaminants on human health in the Arctic (data management and development of database)

WP4.2: Comparison of effects of contaminant exposure of selected populations in the Arctic and selected areas of Europe under climate change (using results from WP4.1, WP2.3, and WP3.3)

WP4.3: Assessment of health effects under different climate change scenarios (using results from WP4.1, WP4.2, and modelling results of WP2)

All WP4 results to WP5 for overall integration and synthesis

WP5: Synthesis and policy implications

WP5.1: Process evaluation system: in support of WP1 and integrating output of WP2, WP3, and WP4

WP5.2: Development of database: based on existing information and new results from WP2, WP3, and WP4. Data extraction tools and materials for dissemination will be prepared (in cooperation with WP6)

WP5.3: Summarizing and synthesizing information: Harmonization of results to ensure consistency and documentation, with subsequent storage in the database

WP5.4: Policy evaluation and strategies for adaptation and abatement: overall synthesis of results from WP2, WP3, and WP4 and preparation of project summaries for policy-makers for dissemination in WP6

WP6: Dissemination and communication

WP6.1: Communication of information about the project and its implementation status, and increasing stakeholder awareness (also linked to project website development under WP1)

WP6.2: Development of communication strategy, including stakeholder consultation, to maximize effective delivery of the project results

WP6.3: Dissemination of products of use for the scientific community (based on input from WP2 to WP5)

WP6.4: Dissemination of the results of the project to target audiences and key stakeholders (based on input from WP2 to WP5)

Graphical presentation of the components showing their interdependencies

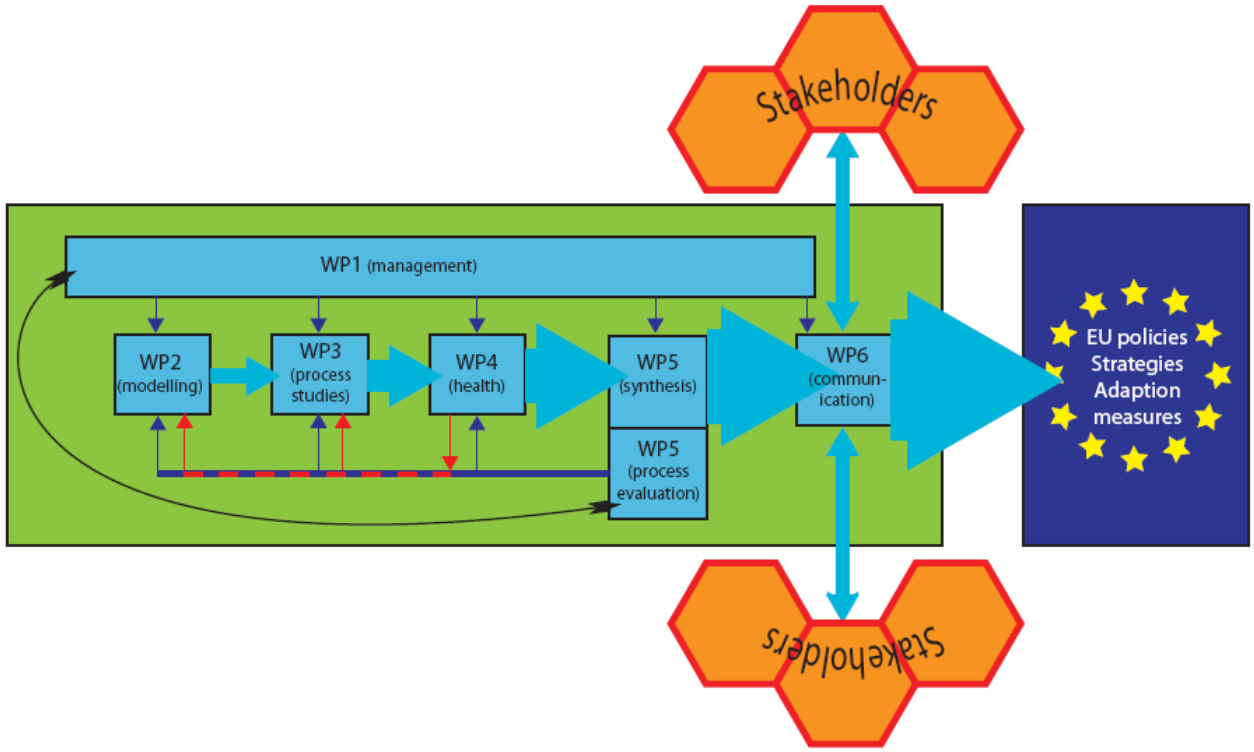

Figure 1. Graphical representation of the components of the ArcRisk project

Figure 1 shows the structure of the ArcRisk project with WP1 providing overall coordination and management of the project, assisted by the process evaluation system developed in WP5, which comprises a system for internal project evaluation to ensure that the project results are consolidated and relevant to the overall project aims. The figure shows the logical progression of work (light blue-shaded arrows) through the main science Work Packages (WP2, WP3, and WP4), with the key results for the project as a whole arising out of WP5 and WP6 (i.e., the dissemination of findings and recommendations on EU policies, etc.). Important feedback loops (red arrows) are shown between WP2, WP3, and WP4, whereby results and deliverables are fed from one WP to another. One example of this is that the results from WP3 (process studies) will feed key contaminant transfer information into WP2 (modelling), which in turn will predict and quantify contaminant exposure pathways for WP4 (health outcomes). WP4 has a feedback loop to WP2 and WP3 concerning which contaminants have been observed to show an influence on human health outcomes. All results feed into WP5 for overall integration and synthesis and the evaluation of policy implications, with ultimate communication and dissemination via WP6.

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