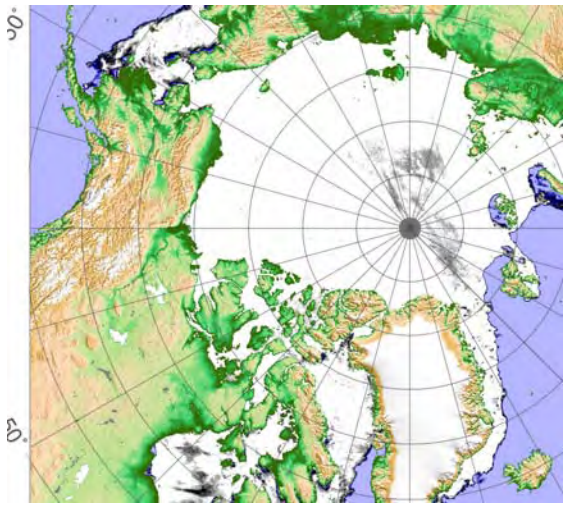
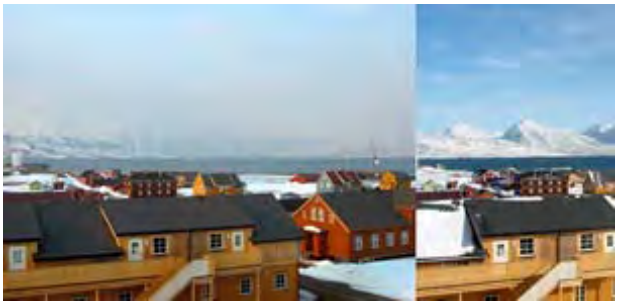
ARCPAC: Aerosol, Radiation, and Cloud Processes affecting Arctic Climate

Science and Implementation Plan





http://www.esrl.noaa.gov/csd/ARCPAC/

A Project of NOAA's Climate Forcing and Air Quality Programs for the International Polar Year 2008

June 2007

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A NOAA Climate Forcing Program Project for the International Polar Year 2008

I. Background

Introduction

Global temperature records show a statistically significant warming in the last century, with most of the change attributed to anthropogenically emitted greenhouse gases and associated climate feedbacks (Fig. 1). Temperature increases in the Arctic exceed the global annual average (Fig. 2), with maximum warming occurring in winter and spring.

Closely linked to the observed and modeled warming is an observed decrease in seasonal Arctic sea ice coverage and thickness. The minimum summertime extent of sea ice is decreasing significantly (Fig. 3; Comiso, 2006), and this reduction now clearly exceeds that expected from natural oceanographic and meteorological oscillations (Johannessen et al., 2004; Francis and Hunter, 2006). Some models predict a fully ice-free summertime Arctic Ocean (Winton, 2006), with attendant disruptions to Arctic ecosystems, ocean circulation, and global climate. However, modeling of the Arctic climate system is difficult due to complex and sensitive feedbacks (Serreze and Francis, 2006a,b) and many climate simulations struggle to replicate historical precipitation, cloudiness, and sea ice properties (Walsh et al., 2002). Simulations of future climates result in substantial model-to-model variability in Arctic climate parameters such as sea ice extent and thickness, indicating that some important processes are not being adequately described or simply are not included in the simulations (Winton, 2006).

Analyses of observations and recent climate simulations suggest that, in addition to greenhouse gas-induced warming and feedbacks, Arctic warming may also be caused by shorter-lived climate forcing agents. In particular, four processes have been postulated to contribute significantly to observed atmospheric warming in the Arctic and reductions in sea ice there. These processes include:

1) direct warming of the lower troposphere by the absorption of solar radiation and IR emission by aerosol particles from anthropogenic and biomass burning sources (e.g., Treffeisen, 2005; Ritter et al., 2005),

2) changes in snow melt due to deposition of soot (light-absorbing carbon) to the surface in springtime (Hansen and Nazarenko, 2004; Flanner et al., 2007),

3) increases in IR emissivity of wintertime and springtime clouds in the Arctic due to the effects of anthropogenic aerosol particles on cloud properties (Lubin and Vogelmann, 2006; Garrett and Zhao, 2006), and

4) direct radiative effects of tropospheric ozone in the Arctic (Mickley et al., 1999; Hansen et al., 2005).

During the International Polar Year of 2008, NOAA will engage in an airborne field measurement campaign targeted at improving understanding of these four climate-relevant processes. This effort will be focused on direct measurements of properties and processes that can be used to reduce uncertainty in radiation and climate models. The measurements will be made in the Alaskan Arctic to closely coordinate with remote-sensing and in situ observations planned for aircraft and ground sites in the vicinity of Barrow, Alaska.

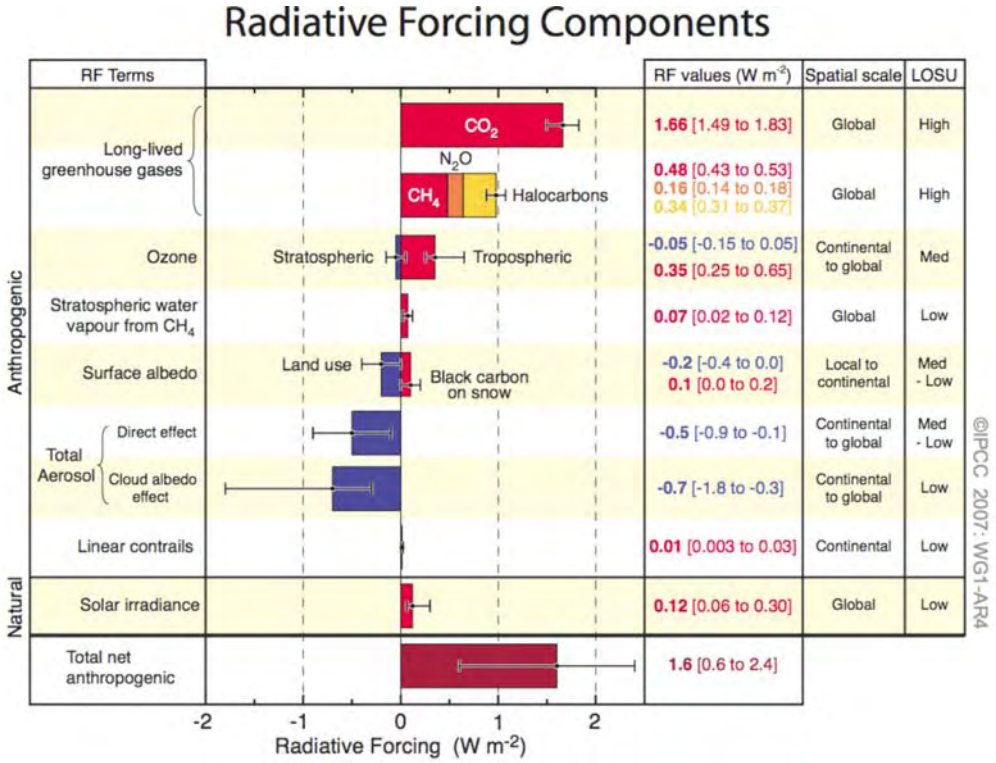

Figure 1. Global-average radiative forcing (RF) estimates and ranges in 2005 for anthropogenic forcing agents, the typical geographical extent of these forcings, and the level of scientific understanding, LOSU (Intergovernmental Panel on Climate Change, 2007).

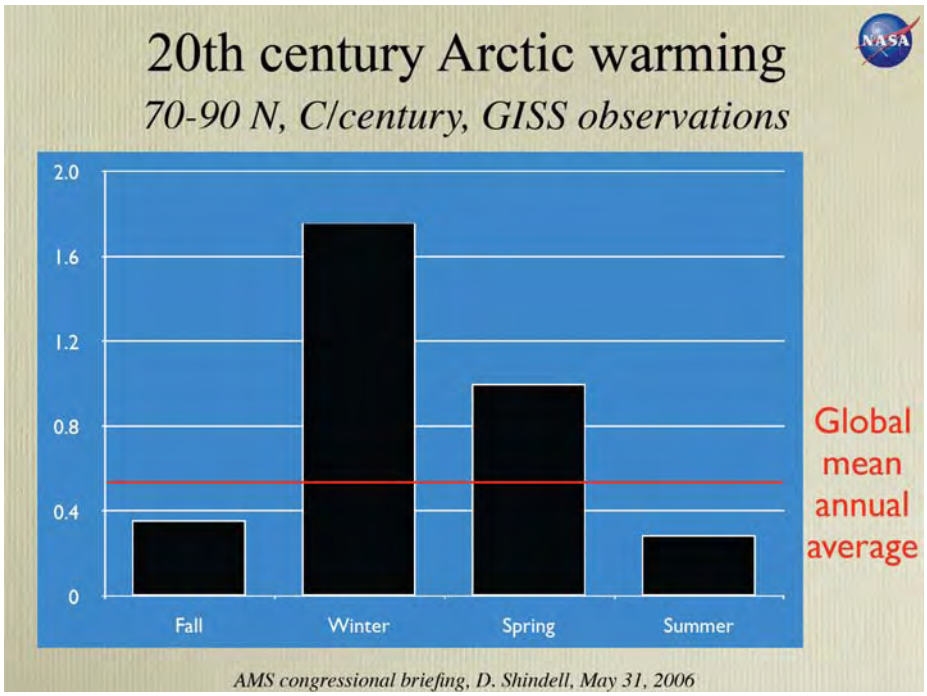

Figure 2. Seasonally separated measured rate of change of 2-m atmospheric temperatures from 70-90 ^{o}N and the global mean change (horizontal line). From Shindell et al., 2006.

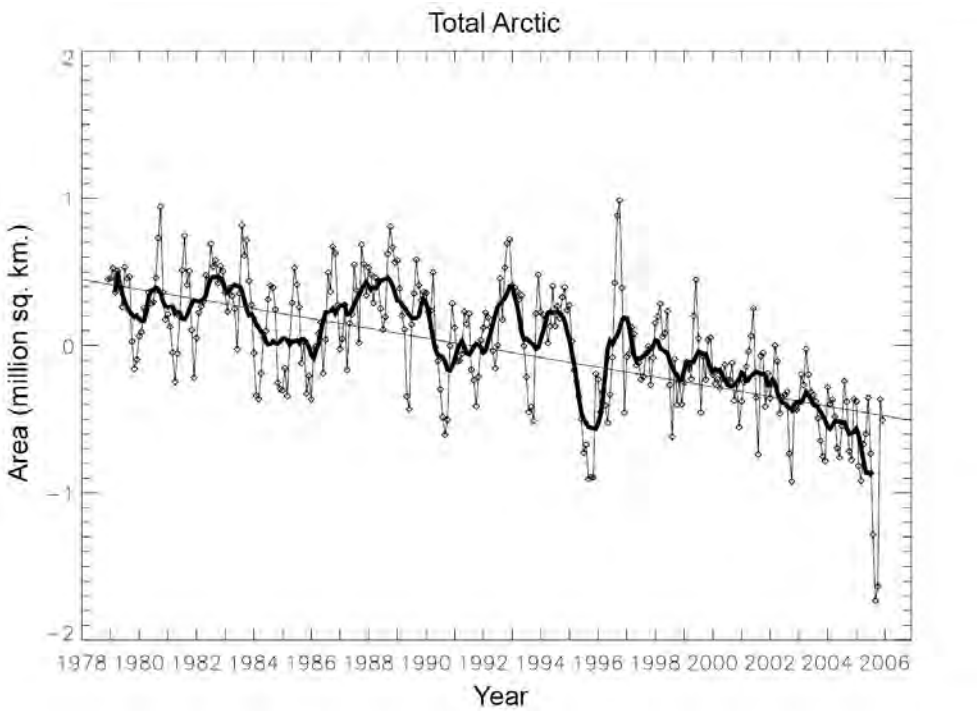

Figure 3. Monthly anomalies of the area of minimum extent of Arctic sea ice from 1978 to 2005. Thick line is 12-month running mean; thin straight line is least-squares linear fit. From Serreze and Francis, 2006a, courtesy of National Snow and Ice Data Center, Boulder, CO.

Climate processes in the Arctic

The Arctic undergoes significant annual changes in its energy budget which are driven largely by the seasonal cycle in solar radiation, surface sensible energy fluxes, and albedo. Surface energy fluxes are controlled in part by the presence and extent of a layer of sea ice and surface snow that partially insulate the Arctic Ocean from the overlying atmosphere in winter and spring. During summer the snow melts, and the sea ice retreats in extent, thickness, and areal density, allowing significant sensible and latent energy fluxes between the ocean and atmosphere. Snow on top of sea ice is prevalent throughout the late fall, winter and spring, but is especially important radiatively during the springtime months when it increases surface albedo and prevents the relatively dark, underlying sea-ice from absorbing solar radiation as the sun begins to rise. Also driving tropospheric energetics, and coupled with the sea ice annual cycle, are variations in lower tropospheric clouds. These clouds warm the surface in the dark winter months by IR absorption and re-emission, and cool the surface in the summertime by reflection of solar radiation.

When coupled with ocean circulations, atmospheric dynamics and meteorology, sea ice physics and wind forcings on sea-ice movement, the climate system in the Arctic is seen to be a dynamic and complex system with many potential nonlinear feedbacks both within the Arctic and with the global climate system. These feedbacks will modify the climate effects of the well-documented phenomenon of large-scale air pollution within the northern polar regions, known as Arctic haze.

Arctic haze

Pilots and surface sites in the Arctic have long reported the annual occurrence of visibility-reducing aerosol hazes in the Arctic in springtime. An extensive literature has documented the chemical and optical characteristics of these hazes, and a climatology of some key parameters extending more than 20 years has been developed for a few Arctic sites (e.g., Quinn et al., 2007). The aerosol is composed predominantly of sulfate and sea salt, with lesser contributions from nitrate, soot, soil and trace elements, and organic compounds (e.g., Quinn et al., 2002). There is a pronounced seasonal cycle to both intensive (e.g., type, size, composition) and extensive (e.g., mass loading, number

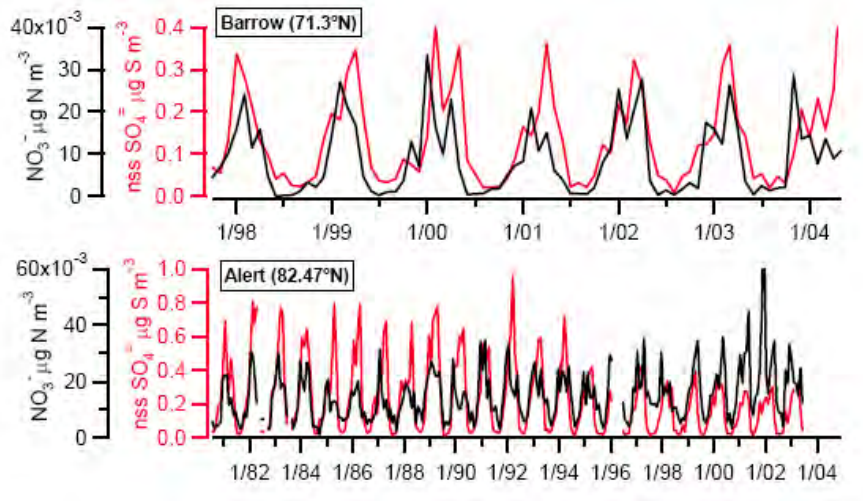

Figure 4. Time series of monthly averaged particulate nitrate and non-sea-salt sulfate concentrations in µg S m^{-3} and µg N m^{-3}, respectively, for a) Barrow, Alaska and b) Alert, Canada (from Quinn et al., 2007, data courtesy of the Canadian National Atmospheric Chemistry (NAtChem) Database and Analysis System and NOAA PMEL (http://saga.pmel.noaa.gov/data/)).

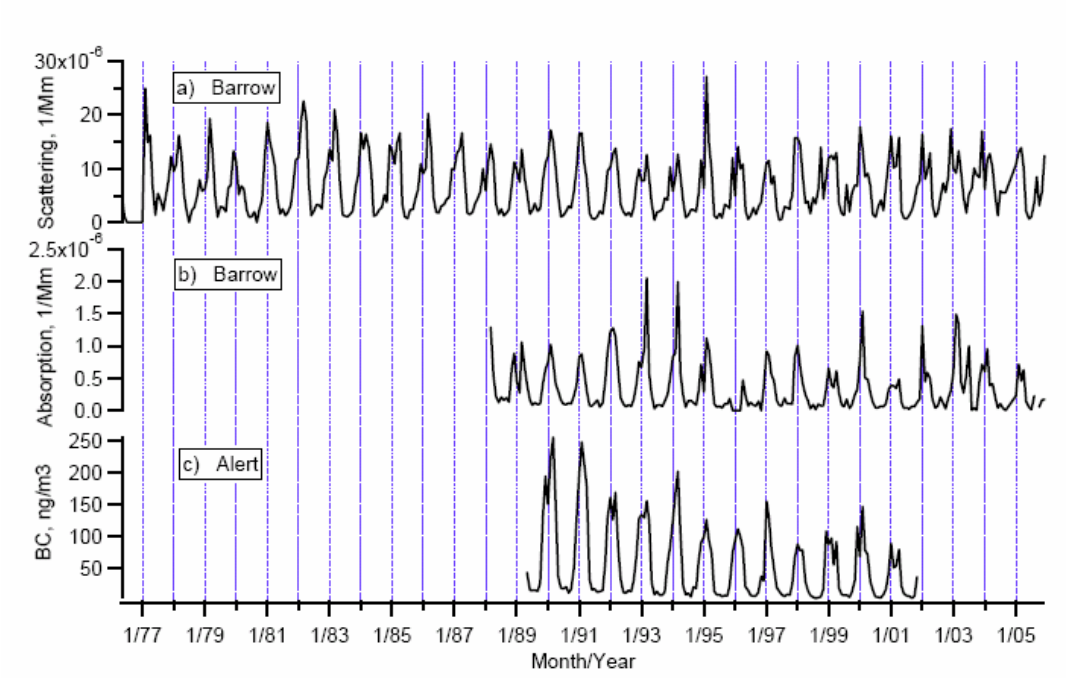

Figure 5. Monthly averaged a) light scattering and b) absorption at 550 nm by sub-10 micron aerosol at Barrow, Alaska (Mm^{-1}) and c) black carbon mass concentration (ng m^{-3}) at Alert, Canada (from Quinn et al., 2007, data courtesy of NOAA GMD and the Canadian National Atmospheric Chemistry (NAtChem) Database and Analysis System).

concentration) aerosol properties at surface sites throughout the Arctic (Figs. 4, 5). During the time of maximum mass concentration—the late winter and early spring—much of the aerosol is anthropogenic. There is some more limited evidence for a slightly different seasonal cycle to Arctic haze properties aloft, with higher concentrations occurring aloft later in the spring than at the surface (Scheuer et al., 2003). In addition, aerosol layers associated with biomass burning sources have been observed in the Arctic middle and upper troposphere in summer (Brock et al., 1989; Stohl, 2006).

By argument of isentropic transport, as well as more sophisticated analyses, the dominant sources of the springtime surface aerosol maximum are seen to lie poleward of the Arctic front (Fig. 6). On average, the largest contributions are believed to come from northern Europe and the Russian Arctic, where large industrial complexes have long operated (Sharma et al., 2006; Stohl, 2006). With declines in former Soviet Union emissions, soot concentrations have fallen in the Arctic in springtime (e.g., Fig. 5, Quinn et al., 2007). Because most industrial sources in North America lie southward of the mean position of the Arctic front, and since advection from these sources to the Arctic involves transport through the meteorologically active North Atlantic region,

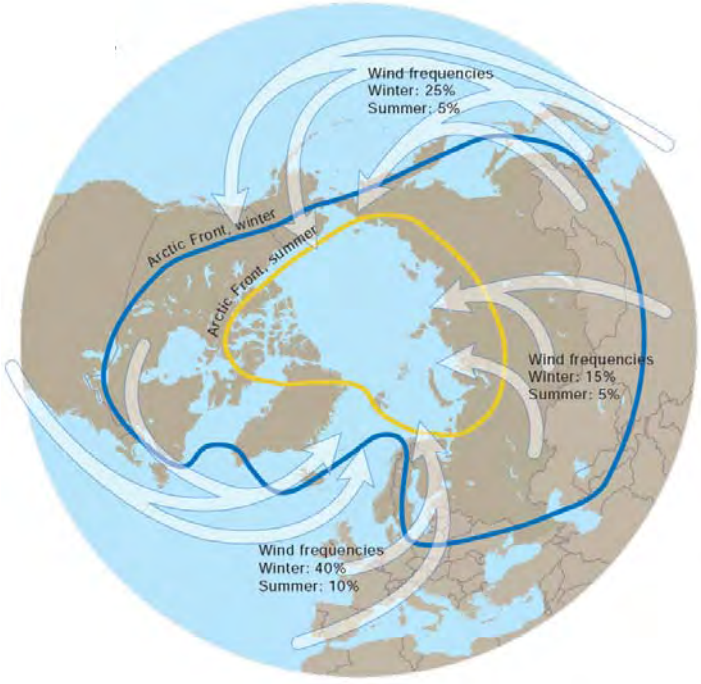

Figure 6. Map showing mean positions of Arctic front in winter and summer, and main transport pathways for pollution from the midlatitudes to the Arctic (Arctic Monitoring and Assessment Programme, 2006).

North American sources are not believed to contribute more than occasionally to Arctic haze (Stohl, 2006). Koch and Hansen (2005) suggest a significant contribution to springtime Arctic soot loadings from industrialized regions of northeastern China, but Stohl (2006) found this source region to be only a small contributor to the Arctic soot budget.

II. Major uncertainties regarding atmospheric climate forcing in the Arctic

Model sensitivity studies indicate that, in addition to long-lived greenhouse gases (LLGG), short-lived pollutants may play an important role in climate forcing in the Arctic. However, despite more than 30 years of study of the sources and chemical characteristics of Arctic haze, the climate-relevant properties of the aerosol are inadequately characterized. As a consequence, climate models are not well constrained, and major uncertainties remain in the magnitude of direct and indirect forcing by aerosols in the Arctic and which anthropogenic sources contribute most to those forcings. As noted previously, there are four primary processes not associated with LLGG that have been identified as being possibly significant to Arctic climate.

Direct radiative forcing by aerosol particles

Direct radiative forcing refers to perturbations to the climate caused by the interaction of aerosol particles with visible radiation. The direct radiative effects of Arctic aerosols depend strongly on the single scatter albedo of the particles. Arctic haze aerosol particles contain significant concentrations of carbon soot (Fig. 4), which is the principal absorber of visible solar radiation, and which leads to a particle single scatter ing albedo (ratio of scattered light to scattered and absorbed light) of ~0.94 (Delene and Ogren, 2002). Quinn et al. (2007) calculated a net radiative heating of 1.6 W m^{-2} in an Arctic haze layer, with a surface cooling of 0.9 W m^{-2} due to the presence of the scattering and absorbing haze above the high-albedo surface. The haze layer was calculated to warm by 0.25 K day^{-1}, which is consistent with other recently determined heating rates of 0.1-0.5 K day^{-1} (Treffeissen et al., 2005). Heating of the surface by

infrared emission from the warmer atmosphere was not considered by Quinn et al., but may compensate for some of the surface cooling (Ritter et al., 2005).

The infrared and dynamical consequences of atmospheric heating by an absorbing aerosol will depend in part on the vertical distribution of the aerosol, which is poorly characterized in the Arctic. Repeated vertical profiles during the NSF-sponsored TOPSE project (Scheuer et al., 2002), and SAGE-II and -III satellite-based extinction observations in the middle and upper Arctic troposphere (Treffeisen et al., 2006) suggest that hazes aloft may be more prevalent later in the Arctic spring, while surface hazes may dominate during winter and early spring. This shift in vertical structure may reflect a shift in source region, with more southern sources at higher potential temperatures contributing to the higher layers (Stohl, 2006). A seasonal change in removal processes may also be a factor, as near-surface clouds and precipitation become more prevalent as springtime progresses. As a consequence, the optical properties of the hazes may differ both seasonally and with altitude.

The single scattering albedo of the Arctic haze aerosol has been reported from the NOAA ESRL/GMD site at Barrow, Alaska since 1988 (Delene and Ogren, 2002; Quinn et al., 2007). During the January-April peak haze season, monthly median single scatter ing albedos ranged from 0.93 to 0.96, indicating a significant absorbing component to the particles. However, these measurements were obtained at relative humidities <40%, and do not reflect possible ambient enhancements in both scattering and absorption due to the hygroscopic growth of particles under ambient conditions. Measurements of the dependence of aerosol light scattering on relative humidity began at the NOAA Barrow ground site in 2006 and will continue during and after the IPY. Aerosol measurements at the NOAA Barrow observatory will be further enhanced in 2007 with the addition of instruments for measuring the number concentration of cloud condensation nuclei as a function of water supersaturation, and of the size distribution of particles in the range of 15-800 nm diameter.

The geographical source of the carbon soot that causes the observed optical absorption is in question. Koch and Hansen (2005) used a general circulation model to determine that industrial emissions and biofuel combustion in southern Asia are a major source of soot to the Arctic. This finding has been disputed by Stohl (2006), who used a

particle dispersion and emission inventory model to identify Europe and northern Asia as the main source of Arctic soot in springtime, both at the surface and aloft. There are only a few Arctic sites at which regular measurements of aerosol absorption are made, with those at the Barrow observatory (Quinn et al., 2007) and the Canadian Arctic site of Alert (Sharma et al., 2004; 2005) having the longest records. To our knowledge there is no information in the Arctic on the soot mass absorption cross-section (MAC, absorption per unit mass of soot), which is necessary to relate modeled soot mass concentrations to optical absorption. The state of understanding of the MAC is poor (Bond et al., 2006), and new measurement techniques need to be applied to determine its mean value and variability in the atmosphere.

Soot deposition to snow

Small reductions in the albedo of Arctic snow to solar radiation are calculated to have globally significant climate effects (Fig. 1). Analysis of light absorbing material in remote Arctic snow samples indicates that soot (light absorbing carbon) particles are sufficient to reduce snow albedo by several percent (Warren and Wiscombe, 1980). A recent global climate simulation of the atmospheric transport and deposition of soot to Arctic snow was coupled with a detailed snow physics and radiation model (Flanner et al., 2007). The perturbations to Arctic climate included shifting the peak in the snowmelt season to almost a month earlier in springtime, limited primarily by available sunlight. As a result of earlier snowmelt, the Arctic sea-ice underneath absorbed more solar radiation and melted earlier, with resulting Arctic-wide temperature increases of >2 K.

As already noted for the case of direct radiative forcing by aerosols, the soot budget in global chemical transport and climate models is poorly constrained (Bond et al., 2004). The extreme stability of the Arctic lower troposphere further complicates the linkage between soot mass concentrations in air and those in snow. Cloud nucleation/ precipitation scavenging is the primary mechanism that removes soot from the atmosphere to the snow surface under the stable meteorological conditions prevalent under the Arctic (Noone and Clarke, 1988). If soot is present in particles that are effective ice nuclei (IN), it may be preferentially present in cloud ice particles. However, measured concentrations of IN are a few to a few tens per liter of air, indicating that

incorporation of additional soot into snowfall by cloud droplet riming or aerosol scavenging is necessary to achieve observed concentrations of soot in snow of tens to hundreds of ppbm. These processes are dependent upon the phase of the cloud particles (liquid water, ice, or a mixture of the two), details of the soot size distribution, and the inclusion of the soot in cloud droplets or ice crystals during formation.

Indirect aerosol forcing

The aerosol indirect effect on clouds typically causes a cooling of the Earth's surface by increasing the reflection of visible solar radiation. The potential indirect effect in the Arctic is especially large because of the significant cloud radiative couplings with energetics and dynamics (e.g., Vavrus, 2004). Strong surface temperature inversions in the Arctic persist throughout the diurnal cycle, producing a unique situation for cloud radiative effects. When low clouds are warmer than the surface, then infrared radiation from the clouds warms the surface. Measurements in the Arctic can therefore provide significant tests of the infrared portion of the indirect effect.

Low-level boundary layer clouds are typical in the Arctic for all seasons [*Curry et al*., 1996]. Despite the cold temperatures in the Arctic these clouds are typically mixed-phase, even in winter and spring [*Pinto*, 1998; *Intrieri et al*., 2002]. The phase distribution of condensed water is a fundamental microphysical property that affects the radiative properties of Arctic clouds; detailed cloud-resolving model studies have shown that by increasing IN number density by 2-3 times, a largely liquid stratus deck can be transformed into a broken, optically-thin ice cloud system [*Harrington et al.*, 1999; *Jiang et al*., 2000; *Harrington and Olsson*, 2001]. The resulting ice cloud has a much lower number density of particles; these sparse, relatively large ice crystals reduce the cloud emissivity, which decreases the cloud's warming potential, and settle relatively rapidly, thereby initiating precipitation and reducing the lifetime of the cloud. *Lynch et al*. [1995] found that including an IN parameterization increased precipitation by as much as 50% and cooled the surface air temperature by up to 5^{o}C over the baseline simulation without ice microphysics.

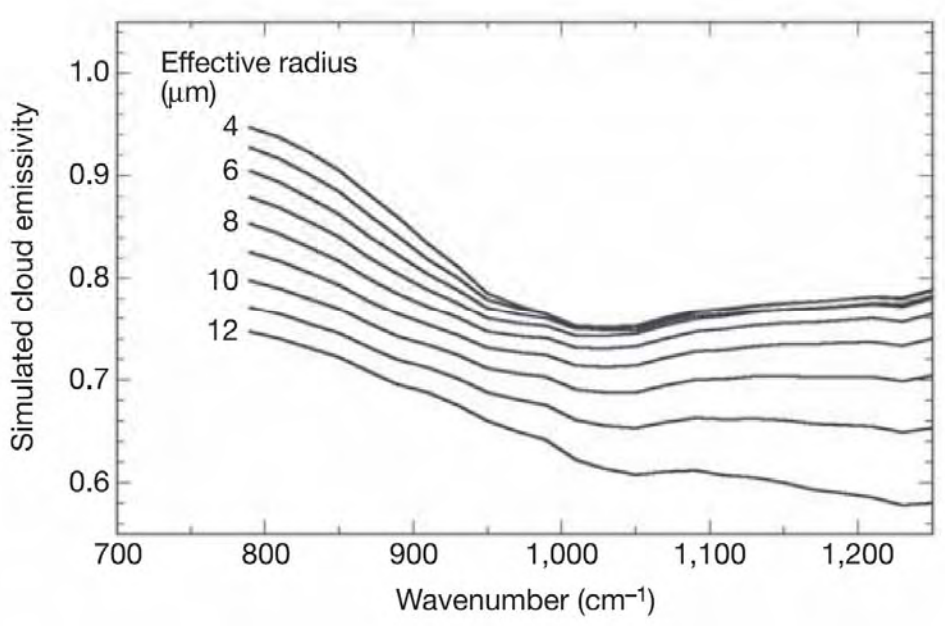

Figure 7. Spectral emissivity from a radiative transfer calculation for an Arctic cloud with constant liquid water content and variable effective radius (Lubin and Vogelmann, 2006).

Clouds in the springtime lower Arctic troposphere are often optically thin and have low droplet number concentrations (<30 cm^{-3}, Garrett and Zhao, 2006). Arctic haze has been shown to increase the number density of these supercooled liquid cloud droplets and decrease the droplet effective radii, thereby increasing the cloud longwave emissivity (Fig. 7, *Lubin and Vogelmann*, 2006). However, the Arctic haze may also contribute more (or less) IN, increasing (decreasing) the rate of cloud glaciation, which reduces (increases) cloud longwave emissivity. To unravel this complexity we must be able to describe the relative fractions of CCN and IN in the aerosol population for a given water vapor supersaturation; this ratio may vary significantly as it is sensitive to the distribution and mixing state of the particle chemical composition, which is constantly evolving as the aerosol population ages and interacts with fresh emissions, both in and out of cloud.

Processes governing ozone abundance

Depletion of ozone in the arctic boundary layer occurs when bromine compounds are activated by sunlight in the spring. The duration and extent of these events may change with a changing climate and provide a feedback to ozone radiative forcing (Fig. 8). A full study of ozone production and loss rates is beyond the scope of this study.

Instead, the focus will be to improve the understanding of halogen initiated photochemistry that destroys ozone. Although these events have been regularly observed (e.g. Ridley et al., 2003), uncertainties remain regarding the source of the halogen radicals and their transport (Simpson et al., 2007). Furthermore, vertically resolved measurements have not been achieved for most of the halogen species involved in spring time arctic boundary layer catalytic ozone destruction. Fast response measurements of halogen species will be used to determine their vertical distribution. These measurements can then be compared with model results (e.g. Lehrer et al, 2004) to test the understanding of ozone depletion events and their possible relationship to radiative forcing.

The combination of sea salt (Quinn et al, 2002) and conditions favorable to N2O5 formation (Tie et al, 2003) in the spring time arctic may make ClNO2, which can be formed from reactions of N2O5 on chloride-containing aerosol particles, important to polar boundary layer ozone. The specific halogen chemistry that we will examine follows from the conversion of N_2O_5 to $ClNO_2$. $ClNO_2$ is photolyzed relatively rapidly (0.5 to 1 hr lifetime), even under Arctic springtime conditions, to form NO_2 and gas-phase Cl atoms. This Cl is highly reactive towards VOCs and O_3, forming either HCl or ClO. The ClO radical reacts with HO_2 producing HOCl, which is soluble and will be taken up on aerosol particles and in droplets. Aqueous HOCl can further react with Cl^- and Br^- to produce the volatile compounds Cl_2 and BrCl. BrCl can be photolyzed in the gas phase, generating Cl and Br atoms, which cycle through the above chemistry again, catalytically destroying ozone. The HOBr produced in the reaction of BrO with HO_2 is also soluble and will produce Br_2 upon reaction with Br^-. The species $ClNO_2$, Cl_2, BrCl, Br_2, and BrO, along with the extensive aerosol and O_3 measurements that will be made on the WP-3D, will give us the ability to assess the role of $ClNO_2$ in initiating this ozone destruction chemistry over a wide geographic area.

III. A NOAA-sponsored airborne campaign to investigate climate-relevant atmospheric processes in the Arctic

Scientific questions to be addressed

NOAA will undertake a airborne field experiment, the Aerosol, Radiation, and Cloud Processes affecting Arctic Climate (ARCPAC) in Alaska in late March and April of 2008 to address the four major areas of non-greenhouse-gas atmospheric climate

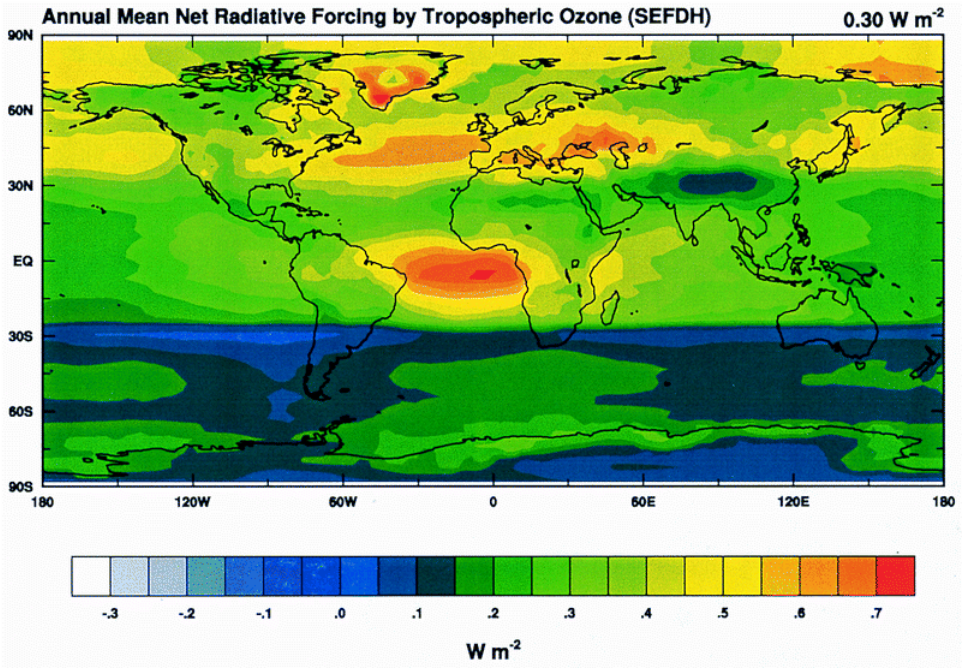

Figure 8. Model predictions of annual mean net radiative forcing by tropospheric ozone (Kiehl et al., 1999).

processes in the Arctic. A NOAA WP-3D aircraft will be used for this experiment and will be based at Fairbanks, Alaska (Fig. 9). This experiment will be coordinated with the POLARCAT activity of the IPY, with the NOAA baseline climate research station at Barrow, Alaska, and with the intensive operations period executed at the DOE-sponsored Atmospheric Radiation Measurement site adjacent to NOAA's Barrow site. Specific scientific questions to be addressed are listed below.

Q1: What are the chemical, optical, and microphysical characteristics of aerosols in the Arctic in springtime?

- What is the solar extinction and absorption of the aerosol, and how do these properties vary with relative humidity?
- What is the mass concentration and size distribution of soot?
- To what extent are soot particles coated with other materials, and do such coatings influence the radiative and cloud-nucleating properties of the soot particles?
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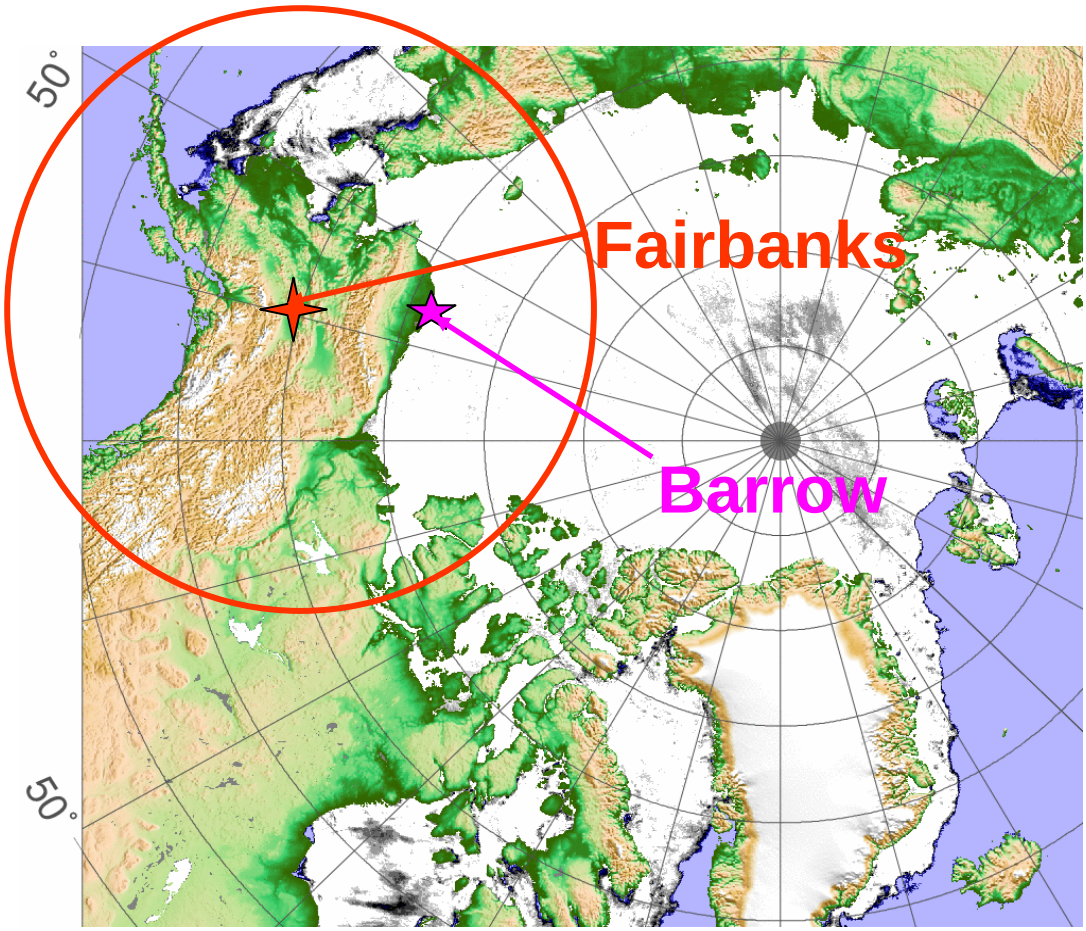

Figure 9. Map showing the area of operaton for ARCPAC. The WP-3D aircraft will be based in Fairbanks, Alaska. The typical out-and-return range of the aircraft is shown by the red circle.

- What is the contribution of organic material to the optical and chemical properties to the aerosol?
- How do aerosol concentrations, composition, optical properties, and cloud nucleating properties above the surface relate to values measured at the surface?
- What is the radiative forcing and resulting atmospheric heating rates due to the aerosol, and how do these values compare with those derived from spaceborne lidar, surface lidar, and surface aerosol measurements?
- How do the composition and hygroscopic properties of aerosols relate to chemical processing estimated from trace gases?

Q2: What are the source types (industrial, urban, biomass/biofuel, dust, sea-salt) of the aerosol components, and the absorbing components in particular?

- What are the correlations between aerosol components and trace gases?
- How does the composition of the aerosol and trace gases compare to that expected from transport and emission models such as FLEXPART?

- Does the vertical distribution of aerosol properties reflect differences in source region, transport, and removal?
- What are the major sources that contribute to atmospheric and surface soot during the critical springtime warming period?

Q3: What are the microphysical and optical characteristics of optically thin clouds in the lower Arctic troposphere in springtime, and do pollution particles affect these cloud properties?

- What is the number density of CCN present in aerosol layers and in clean air, and is there closure between the predicted CCN, from the observed aerosol composition and size distribution?
- How does the number concentration of CCN, as a function of water supersaturation, vary as a function of altitude?
- Is the cloud droplet number concentration in liquid clouds consistent with that predicted from the observed CCN and cloud cooling rate?
- What is the relationship between measured IN concentrations and cloud ice number concentrations and size?
- What are the measured solar reflectance and transmission, the IR radiance, and the effective radius of Arctic clouds, and how do these values vary with CCN and IN concentration?
- How do directly measured and derived cloud properties compare with remotely measured and derived parameters at the DOE ARM site?

Q4: What are the concentration of particles that serve as ice nuclei (IN) in background and polluted air?

- What is the number density of IN present in aerosol layers and in clean air?
- What are the geographic sources of the IN in the Arctic?

Q5: Is soot present in particles that serve as IN and CCN?

- Is soot efficiently scavenged by cloud droplet nucleation, ice crystals, and snowfall?
- What role do coatings on soot particles play in nucleation scavenging and removal of soot?

Q6: What halogen chemistry is occurring during Arctic spring?

- What is the distribution of gas phase chlorine and bromine compounds, especially $ClNO_2$?
- What is the vertical distribution of sea-salt aerosol and what chemical processing has it undergone?
- What is the relative importance of the sources of O_3 in the Arctic and subArctic lower troposphere in springtime (production vs. stratospheric vs. long-range transport)?

Measurement requirements

The six science questions lead to specific measurement requirements:

R1) The stratified nature of the Arctic lower stratosphere requires airborne and remote-sensing measurements so that the properties and processes occurring in and near radiatively important haze layers and stratiform clouds can be investigated.

R2) Because of the vertically stratified and spatially non-uniform distribution of Arctic haze, fast-response in situ gas- and aerosol-phase instruments are required.

R3) The climatic importance of aerosol optical properties and soot number and mass require accurate and fast-response measurements of these parameters, along with measurements of the variation in optical properties with relative humidity.

R4) Because of the strong potential climate interaction between aerosols and cloud microphysical and radiative properties, detailed cloud microphysical and visible and infrared radiation measurements are needed. Modeling is essential to interpret the aerosol, cloud and radiation observations and extrapolate them to climate-relevant scales.

R5) Improving understanding of halogen photochemistry in the Arctic requires accurate measurement of gas phase halogen species and their vertical distribution, as well as measurements of ozone and photolytic fluxes.

R6) Transport, chemistry, and climate models are needed to relate the observed aerosol and gas-phase characteristics to sources and transport mechanisms and to evaluate their importance.

R7) Because ground sites are essential for developing climatologies and for understanding the temporal changes in atmospheric processes in the Arctic, short term airborne studies should be made at locations and times that can be linked to the surface sites.

Based on scientific questions Q1-Q6 and the measurement requirements R1-R7 that logically follow, NOAA will operate a WP-3D aircraft in the Alaskan Arctic in spring of 2008 as part of the International Polar Year (IPY). NOAA's Earth System Research Laboratory (ESRL) and extramural colleagues have developed a powerful set of precise and accurate gas- and particle-phase instruments for airborne investigations of air quality and climate-relevant chemical and microphysical processes ranging in scale from tens of meters to intercontinental distances. In particular, NOAA has developed new, sensitive instruments for determining aerosol optical properties, including a cavity ringdown method for directly measuring aerosol extinction at multiple wavelengths and its variation with relative humidity.

ESRL scientists have also substantially modified, evaluated, tested, and operated on aircraft a recently developed commercial instrument that measures the number and mass of individual soot particles and that can determine the amount of condensed coating on them. NOAA has also developed an unique instrument for measuring the composition of single aerosol particles and the residue from evaporated cloud particles, and has optimized a commercial aerosol mass spectrometer for airborne non-refractory aerosol composition measurements. In addition, the NOAA Aircraft Operations Center has recently purchased a set of state-of-the-art cloud probes for measuring the number, size, and shape of cloud and precipitation particles. With the addition of well-tested gas-phase and radiometric measurements, this payload is ideal for addressing the climate-relevant scientific questions outlined above (Table 1).

The diverse objectives of the ARCPAC project cannot be met without the experimental and scientific talents of non-NOAAcolleagues. In particular, measurements of IN, CCN, bulk aerosol composition, solar spectral irradiance and infrared irradiance, VOCs, and transport and chemical-transport modeling require equipment and expertise from researchers from universities, other governmental laboratories, and international research organizations.

Coordination with other IPY activities

The atmospheric measurement portion of the IPY is coordinated under the Polar Study Using Aircraft, Remote Sensing, Surface Measurements and Models of Climate, Chemistry, Aerosols, and Transport (POLARCAT) program (http://zardoz.nilu.no/~andreas/POLARCAT/). This program links a large number of atmospheric measurements ranging across the Eurasian, Canadian, and Alaskan Arctic together with transport, chemistry, and climate models. A partner in POLARCAT is the Indirect and Semi-Direct Aerosol Campaign (ISDAC) sponsored by the U. S. Department of Energy. ISDAC is an intensive cloud and aerosol observing program that will be based at the Atmospheric Radiation Measurement (ARM) site near Barrow, Alaska during April 2008, and which will involve detailed surface remote sensing and airborne measurements of aerosol and cloud properties. Adjacent to the Barrow ARM site is the NOAA ESRL/GMD baseline monitoring station. This site will operate a variety of instruments

Table 1. Priority instruments for the WP-3D aircraft during ARCPAC.

Parameter	Method
Size-resolved non-refractory aerosol composition	Compact time-of-flight aerosol mass spectrometer
Single particle black carbon	Single particle soot photometer
Single particle composition	Laser mass spectroscopy
Bulk particle composition	Particle-in-liquid sampler, IC
Aerosol size distribution	Multiple CPCs, OPCs
Aerosol extinction (532, 1064 nm), f(RH)	Cavity ringdown
Filter-based aerosol absorption (467, 530, 660 nm)	Particle soot absorption photometer
Cloud condensation nuclei concentration	CCN counter
Liquid water content/Total water content	Hot wire probes
Cloud particle size distribution (0.5-50 μm)	Forward/back scattering-cloud and aerosol spectrometer
Cloud particle size distribution (2-50 μm)	Forward scattering-cloud droplet probe
Cloud particle size distribution (25-1550 μm), imaging/phase	Photodiode imaging-cloud imaging probe
Ice nuclei concentration	IN chamber with detector
Soot incorporation into IN	SP2 behind IN chamber in fuselage
Actinic fluxes (near 280-690 nm, ↑ and ↓)	Spectral actinic flux radiometer
Spectral irradiance (300-1700 nm, ↑ and ↓)	Solar spectral flux radiometer
IR irradiance (4.5-42 μm, ↑ and ↓)	Pyrgeometers
Ozone (O_3)	NO chemiluminescence
NO, NO_2, NO_y	O_3 chemiluminescence
Carbon dioxide (CO_2)	Nondispersive IR
Carbon monoxide (CO)	UV fluorescence
VOCs	Whole-air sampler
SO_2	UV fluorescence and chemical ionization mass spectrometry (CIMS)
HNO_3	CIMS
Peroxyacyl nitric anhydrides (PANs)	CIMS
Halogens ($ClNO_2$, Br_2, Cl_2, BrCl, BrO)	CIMS

Direct effect instruments
Indirect effect instruments
Tracer and halogen chemistry instruments

for measuring aerosol scattering, absorption, size distribution, CCN concentration, and composition. The intensive measurement campaigns planned for Barrow in April 2008 make this location a logical ground site with which to coordinate the WP-3D flights.

During the study period, the research vessel *Knorr* will be sponsored by the NOAA Marine Operations Center as the primary platform for the International Chemistry Experiment in the Arctic Lower Troposphere (ICEALOT) experiment http://saga.pmel.noaa.gov/Field/icealot/. Measurements of aerosol optical, micro-physical, cloud-activation and chemical properties, along with gas-phase, remote sensing, and meteorological variables, will be made in the North Greenland and Barents Seas. This region is one of the primary transport pathways from Europe to the Arctic (Stohl et al., 2006), and measurements in this area will provide information on the properties of relatively fresh anthropogenic pollution as it enters the Arctic. This information can be contrasted with the airborne measurements of more aged Arctic aerosols to improve understanding of transformation processes occurring during the aerosol's long lifetime in the Arctic.

During April of 2008 period, the NASA/University of North Dakota DC-8 aircraft, as well as remote-sensing airborne platforms, will operate as part of the Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS) program. This airborne and satellite remote sensing mission will focus on aerosol properties and ozone chemistry, and will be based at Kiruna, Sweden and Fairbanks, Alaska during this springtime period. The NOAA WP-3D measurements of reactive halogenated gas species will complement the more extensive DC-8 payload of HO_x and other species related to ozone production and loss rates.

Measurement location

Understanding of the context and representativeness of the WP-3D airborne measurements will be improved by connecting the measurements with those made by DOE and NOAA at their respective surface sites at Barrow, Alaska during the key springtime transition season of April (Fig. 9). Fairbanks, Alaska is the best location near Barrow for operating a large aircraft such as NOAA's WP-3D. The WP-3D has the appropriate range, endurance, altitude capability and payload for the investigations

outlined here. This aircraft is capable of operating safely in the demanding Arctic environment while performing multiple vertical profiles, long-ranging horizontal transects, and low-altitude sampling. With >8-hour endurance, a WP-3D can fly from Fairbanks to Barrow and conduct more than 4 hours of research in the vicinity before returning to Fairbanks (Fig. 9). The horizontal legs from Fairbanks to Barrow can provide additional information regarding the latitudinal gradient in aerosol properties across the mean position of the Arctic front.

Meteorology and modeling

The FLEXPART model will be used to identify specific regions of anthropogenic pollutants, and, with newly developed polar-orbiting satellite capabilities, guide the aircraft to regions likely to have aerosol-cloud interactions. The FLEXPART model couples transport simulations using forecast or analyzed meteorological fields and convective parameterizations with emission inventories to predict the locations and concentrations of specific trace species (Stohl, 2006). Post-flight verification and quantification of anthropogenic influence will utilize tracer species carbon monoxide (CO), CO_2, sulfur dioxide (SO_2), and soot.

The FLEXPART model will also be used to diagnose specific source regions of observed haze layers at different altitudes, and to estimate the length of time that air parcels have been within the Arctic region. These "polar age" estimates can be compared with hydrocarbon ratio measurements to improve understanding of transport and aging processes within the Arctic.

In addition to transport modeling, diagnostic cloud models are being developed to compare with the in situ and remote sensing observations of aerosol and cloud properties. The specific model-measurement comparisons (Table 2) should permit a thorough evaluation of the level of understanding of cloud droplet nucleation and growth, ice formation, aerosol scavenging, and IR emission within the mixed-phase clouds expected in the Arctic. The improvement in understanding of these key processes should lead to better parameterizations for the global climate models that are required to diagnose climate forcings and feedbacks between the atmosphere, sea ice, and ocean.

Table 2. Measurement and modeling comparisons.

Measurement	Model
In situ particle composition/size distribution, cloud condensation- and ice- nuclei spectra, cloud particle concentration, phase, size	Parcel model of cloud formation, ice nucleation and growth
In situ cloud dimension and up/downdraft velocity, cloud particle concentration, phase, size, solar and IR transmission/emission	Large eddy simulation (LES) with coupled cloud dynamics, microphysics, radiation in 3D Eulerian framework
Surface-based remote sensing measurements of cloud dynamics, phase, precipitation, radiative characteristics, particle size, phase	LES with coupled cloud dynamics, microphysics, radiation in 3D Eulerian framework
In-situ particle composition/size distribution near and below cloud.	LES with in- and below-cloud aerosol scavenging added
Surface measurements of soot concentration in newly fallen snow	LES with in- and below-cloud aerosol scavenging
Gas phase chlorine compounds, sea salt aerosol chemistry, actinic fluxes	Parcel model with heterogeneous chemistry

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