

# Arctic Research of the Composition of the Troposphere from Aircraft and Satellites (ARCTAS)

A NASA contribution to the International IGAC/POLARCAT Experiment  
For the International Polar Year 2007-8

White paper prepared by

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## 1 INTRODUCTION

The Arctic is a beacon of global change. It is where warming has been strongest over the past century, accelerating over the past decades. It is an atmospheric receptor of pollution from the northern mid-latitudes continents, as manifested in particular by thick aerosol layers (“arctic haze”) and by accumulation of persistent pollutants such as mercury. It is increasingly beset by emissions from massive forest fires in boreal Eurasia and North America. Perturbations to the arctic environment trigger unique regional responses including melting of ice sheets and permafrost, decrease in snow albedo due to deposition of black carbon, and halogen radical chemistry from sea salt aerosols deposited to the ice. These responses make the Arctic a particularly vulnerable place, subject to dramatic amplification of environmental change with possibly global consequences. The urgent need for research to better understand changes in arctic atmospheric composition and climate is discussed by the Arctic Climate Impact Assessment (<http://amap.no/acia/>) and the U. S. Global Change Research Program (<http://www.usgcrp.gov>). Major research activities to address this need will take place in 2007-2008 under the auspices of the Third International Polar Year (IPY; <http://www.ipy.org/>).

NASA has the opportunity to play a leadership role in arctic atmospheric research during IPY through the unique and timely vantage point offered by its polar-orbiting satellites (Terra and the A-train). These satellites observe the long-range transport of mid-latitudes pollution and its seasonal accumulation in the Arctic, enabling a better understanding of pollution sources, transport pathways, and radiative implications. They detect fires and the associated smoke plumes. They measure aerosol optical depths and other aerosol properties, and the concentrations of gas-phase species such as ozone, CO, NO<sub>2</sub>, and BrO that are important drivers of arctic chemistry. The Arctic is a vast, remote, sparsely sampled place, and the information available from space-based sensors has unique potential to advance our understanding.

The NASA ARCTAS aircraft mission described in this document will unleash the potential of NASA space-based observations for Arctic research by providing retrieval algorithm validation and correlative information uniquely accessible from aircraft platforms (Figure 1). Satellite retrievals in the Arctic must deal with reflective, cold surfaces, low sun angles, seasonal darkness, and extensive cloud cover. Targeted retrieval algorithm development and validation using aircraft observations is essential. Beyond validation, the supplemental information available from aircraft can deliver considerable added value for extrapolating the satellite observations and improving their integration with models. Much of pollution transport in the Arctic takes place in the lower troposphere, where satellites have limited sensitivity; in addition, many species of environmental interest (e.g., mercury) are not directly observable from space. The correlative information and error characterization available from ARCTAS aircraft measurements will enable effective assimilation of the space-based observations into Earth science models including chemical transport models (CTMs), general circulation models (GCMs), and Earth system models (ESMs). Developing the capability to integrate measurements from diverse platforms into

Earth science models for societal benefit is a key issue facing the U.S. Group on Earth Observations (<http://usgeo.gov/>). ARCTAS will provide an important demonstration of current capability with regard to USGEO goals for assessing and forecasting air quality ([http://usgeo.gov/docs/nto/Air\\_Quality\\_NTO\\_2006-0925.pdf](http://usgeo.gov/docs/nto/Air_Quality_NTO_2006-0925.pdf)).

The ARCTAS mission will provide a critical link to enhance the value of NASA satellite observations for Earth science models. The modeling and satellite communities will be involved at all stages of mission design and execution to ensure that the data are collected optimally to serve model needs. Only through Earth science models can one predict how the arctic environment will respond to future perturbations under different scenarios of global environmental change. NASA has been a leader in the development of these models, and this end-to-end approach has served it extremely well for identifying priority measurements from space and for maximizing scientific return from the measurements. Aircraft missions of the NASA Tropospheric Chemistry Program over the past 15 years have focused on continental outflow and intercontinental transport in the tropics (TRACE-A, PEM-Tropics) and northern mid-latitudes (PEM-West, TRACE-P, INTEX-A and -B), and they have considerably improved the relevant capabilities of CTMs. The TRACE-P and INTEX missions of the EOS era involved increasing partnerships with EOS satellite science teams for instrument validation and for integrated applications to source characterization and intercontinental transport at northern mid-latitudes. It is time to turn our attention to the Arctic, particularly in the context of the opportunity offered by IPY. In doing so, ARCTAS will build on previous U.S. aircraft missions to the Arctic including the NASA ABLE-3 and SOLVE missions and the NSF TOPSE mission.

ARCTAS will take place as two 3-week aircraft deployments, in April and July 2008. It will involve the NASA DC-8 as an in situ platform for detailed atmospheric composition. To focus more closely on aerosols and radiation, two smaller aircraft may be involved. One would serve as a remote sensing platform generally flying constant altitude transects in the middle to upper troposphere. The other would be a profiling aircraft for examining radiative fluxes and in situ aerosol properties. The spring deployment will target anthropogenic pollution including arctic haze, stratosphere-troposphere exchange, and sunrise photochemistry including halogen radicals. The summer deployment will target boreal forest fires, stratosphere-troposphere exchange, and summertime photochemistry. ARCTAS will be part of the international IPY/POLARCAT arctic field program for atmospheric composition (<http://zardozi.nilu.no/~andreas/POLARCAT/>), which involves a consortium of countries (United States, Canada, Germany, France, Norway, Russia...) and agencies (including NSF, NOAA, and DOE for the United States), and an ensemble of aircraft, surface, and ship-based measurement platforms. Table 1 gives a list of currently planned POLARCAT activities, and Figure 2 shows how POLARCAT will link with other IPY activities in the arctic. ARCTAS will be a leading partner of POLARCAT through its deployment of a high-altitude, long-range aircraft and complementary specialized aircraft, its link to satellite observations, and its engagement of models in mission design and execution. Taken together with the ensemble of POLARCAT and broader IPY activities, ARCTAS offers an unprecedented opportunity for NASA to contribute to an integrated

arctic research program. Such an opportunity is unlikely to present itself again within the next 30 years.

## 2 SCIENTIFIC THEMES OF ARCTAS

ARCTAS has four major scientific themes, on which we elaborate below:

1. **Long-range transport of pollution to the Arctic** including arctic haze, tropospheric ozone, and persistent pollutants such as mercury;
2. **Boreal forest fires** and their implications for atmospheric composition and climate;
3. **Aerosol radiative forcing** from arctic haze, boreal fires, surface-deposited black carbon, and other perturbations;
4. **Chemical processes** with focus on ozone, aerosols, mercury, and halogens.

### 2.1 Long-range transport of pollution to the Arctic

The arctic troposphere in winter-spring is heavily polluted by long-range transport from northern mid-latitudes continents. This pollution has a number of environmental consequences. Radiative forcing from thick aerosol layers (“arctic haze”) and black carbon deposition to snow modify regional and global climate. Seasonal build-up of tropospheric ozone and its precursors affects the ozone budget on a hemispheric scale. Deposition of mercury transported from mid-latitudes is a recognized threat to arctic ecosystems. The Arctic may further be an important route for intercontinental transport of aerosol pollution at northern mid-latitudes. There remain large uncertainties regarding the transport pathways from mid-latitudes to the Arctic, and the relative contributions of different source regions to arctic pollution. Integration of satellite and aircraft observations with models through ARCTAS provides a means to address this issue.

Polar orbiting satellites, having dense spatial coverage in polar regions, offer a unique vantage point for observing the transport of northern mid-latitudes pollution to the Arctic. Space-based observations of CO (TES, AIRS, MOPITT), ozone (TES, OMI, MLS, HIRDLS), and aerosols (CALIPSO, OMI, MODIS, MISR) are of particular interest. They can characterize synoptic transport events, the seasonal build-up of pollution during winter-spring and its ventilation to mid-latitudes in spring-summer, and the interannual variability driven by climatological features such as the Arctic Oscillation (AO). This capability is illustrated by TES arctic observations of CO in March and July 2006 (Figure 3) and of seasonal variations of tropospheric ozone and CO (Figure 4). TES provides correlative information on ozone and CO vertical profiles that can be particularly useful to relate ozone enhancements to anthropogenic influence.

The augmentation of satellite observations with aircraft measurements during ARCTAS will enhance considerably the value of the satellite data for improving understanding of pollution transport to the Arctic, not just for the duration of the mission but for the longer term. The aircraft will observe transport at different altitudes, complementing the coarser vertical resolution available from satellites. The extensive chemical payload aboard the aircraft will enable extrapolation of the satellite observations to a wide range of correlated species. Tracer measurements on the aircraft (e.g., halocarbons) will provide signatures to separate contributions from North America, Europe, and Asia. Coordination with other POLARCAT sampling platforms in Table 1 will provide additional information. Surface measurements will be particularly valuable to link the pollution layers observed from aircraft to their manifestations at ground level.

A major focus of ARCTAS will be to evaluate chemical transport model (CTM) simulations of source-receptor relationships for pollutants in the Arctic. Modeling the long-range transport of mid-latitude pollutants to the Arctic is a challenge because of the complexity of the transport patterns involved, the paucity of meteorological data, the stratification of the atmosphere, uncertain chemistry and surface interactions, and numerical filtering necessary for pole-converging Eulerian grids. Arctic atmospheric observations to test the CTMs have mainly been limited to long-term time series at a small number of surface sites, but this is grossly inadequate as the long-range transport processes are known to be decoupled from the surface. The TOPSE aircraft mission was a milestone in that regard but still provided only limited geographical coverage. The linked aircraft and satellite observations during ARCTAS will provide critical information for CTM testing and improvement, and greatly increase confidence in the application of these models to develop strategies for protecting the arctic environment.

## **2.2 Boreal forest fires**

Summertime boreal fires are a major atmospheric perturbation to the Arctic. Smoke emissions have a direct influence on the radiation budget and exert indirect influence through impact on cloud processes. Deposition of pyrogenic black carbon to snow and ice surfaces decreases surface albedo and may accelerate melting. Chemistry in the fire plumes leads to formation of tropospheric ozone, which exerts a significant climate forcing in the Arctic. When transported to lower latitudes, boreal fire emissions contribute to poor air quality and exacerbate pre-existing air quality problems. Pyroconvective events can inject fire emissions to the lowermost stratosphere with possibly long-lasting implications for radiation and for stratospheric chemistry. The potential for a positive feedback between climate change and fire emissions is highlighted by the recent increase in extreme fire seasons in Siberia, Alaska, and Canada associated with warm and dry years (Figure 5).

NASA satellites can play a critical role for improving our understanding of boreal fire emissions and their impacts. CALIPSO provides unprecedented resolution of the vertical distribution of smoke plumes while other aerosol sensors (OMI, MISR, MODIS) and CO sensors (TES, MOPITT, AIRS) provide horizontal mapping of the regional extent

of fire influence (Figure 6). MISR can determine fire injection heights from its multiangle view of the fresh plumes (Figure 7) while the combination of OMI and CALIPSO can be used to estimate the strength of particle absorption. Pyroconvective injection of CO is observable by MLS and TES. Tropospheric ozone enhancements associated with the fires should be observable from TES and OMI, and may contribute to the high June-July ozone concentrations seen by TES in Figure 4.

Combination of aircraft and satellite observations during ARCTAS will both verify the utility and improve the interpretation of the satellite observations. The DC-8 payload will have the capability to observe the detailed chemical composition and aerosol properties of fire plumes. This is critical to examine how the aging of gases and aerosols is influenced by plume composition, altitude, transport path, etc. Aerosol and radiation measurements on the smaller aircraft will focus on determining aerosol types, optical properties, and radiative effects as the fire plumes evolve. ARCTAS will complement the DLR and Canadian aircraft to be deployed in summer 2008 with focus on pyroconvective injection of fire plumes (Table 1).

Integration of the ARCTAS observations into CTMs and climate models will enable better understanding of the perturbation to the arctic environment from boreal forest fires, and provide a foundation for study of positive feedbacks between fires and arctic climate change. The testing of satellite capabilities for observing fire injection heights will enable development of process models to predict these heights as a function of fire intensity and local meteorological stability. The combination of satellite and aircraft observations will improve constraints for inverse models used to derive fire emission estimates from satellite observations of CO, and allow extrapolation of these emission estimates to a wide range of species on the basis of the enhancement ratios measured by the aircraft.

### **2.3 Aerosol radiative forcing**

The Arctic is a region of particular interest for radiative forcing of climate, in part because of the rapid pace of arctic climate change and in part because of the unique radiative environment. Low solar elevation angles and highly reflective surfaces increase slant optical depths and associated radiative effects of both scattering and absorbing particles and gases. Arctic haze in spring and smoke from boreal forest fires in summer are easily detectable from space and represent large perturbations to the regional radiative budget. High-latitude clouds are modified by aerosols in a number of ways, thereby extending aerosol radiative forcing to IR wavelengths.

NASA and other polar-orbiting satellites bring a wealth of capabilities to the study of aerosol radiative forcing in the Arctic. Complementary techniques of UV/Vis/IR reflectances, multi-angle sensing, lidar, and radar are available from sensors presently in space including MISR, MODIS, OMI, CALIPSO, CloudSat, and POLDER. The Glory Aerosol Polarimetry Sensor (APS) to be launched in December 2008 into the A-train orbit will provide NASA's first polarimetry measurements of Earth from space; airborne simulation of APS measurements during ARCTAS will provide valuable preparation.

Determination of aerosol radiative forcing on the basis of satellite measurements alone is difficult, due to lack of information on aerosol optical and chemical properties as well as surface reflectances. This lack of information also compromises efforts to synthesize the different spaceborne measurements into a more comprehensive characterization of the aerosol. Considerable added value can be provided by aircraft measurements of aerosol optical depth, radiative fluxes, radiances (including polarized radiances), and in situ vertical profiles of the aerosol size distribution, composition, mixing state, phase, extinction, absorption, and scattering phase function. Aircraft measurements of radiant flux and radiance can characterize surface albedo and the bidirectional reflectance distribution function (BRDF) to improve satellite aerosol retrievals. ARCTAS will attempt to coordinate with the DOE aircraft mission in April 2008 over Alaska focused on aerosol-cloud radiative interactions (Table 1).

Radiative forcing by black carbon due to its deposition to arctic ice and snow has received much attention recently. Observing this forcing from space is difficult because other variables, such as snow grain size and melting state, also affect snow and ice albedo. Low-altitude mapping of UV/Vis./NIR surface albedo and (polarized) BRDF during ARCTAS will provide unique information that, in co-ordination with surface measurements of ice and snow properties and black carbon concentration, can be used to evaluate the potential of satellite measurements to map black carbon deposition and the resulting albedo effect in the Arctic.

There is controversy as to whether the major sources of black carbon to the Arctic are from fossil fuel combustion (and if so, whether from Europe, Asia, or North America) or from biomass burning (and if so, whether from tropical or boreal fires). Aerosol observations from CALIPSO, MODIS, MISR, and OMI, together with aircraft in situ characterization of aerosol plumes, will greatly help to constrain source-receptor relationships. Aircraft measurements will also provide information on the evolving mixing state of the black carbon aerosol prior to deposition, and how this mixing state varies with source type and source region.

## **2.4 Chemical processes**

The arctic troposphere is a very reactive environment despite its high latitude. Seasonal accumulation of PAN in winter, followed by decomposition to  $\text{NO}_x$  in the spring, is a driver for fast ozone production and likely contributes to the observed springtime maximum in tropospheric ozone. Extremely high acidities in arctic haze aerosol could drive fast heterogeneous chemistry. Reactive nitrogen and organic species deposited to the ice drive photochemical emission of  $\text{NO}_x$  and of a variety of oxygenated organics. Sunrise photochemistry involving sea salt deposited to sea ice is a major source of halogen radicals; the resulting Cl and Br atoms provide a fast oxidation sink for hydrocarbons transported from mid-latitudes, as well as a catalytic loss mechanism for ozone that frequently drives concentrations to sub-ppbv levels. Fast oxidation of elemental mercury by Br atoms leads

to “mercury depletion events” where the resulting Hg(II) deposits rapidly, causing accumulation of mercury in arctic ecosystems.

Current understanding of Arctic air chemistry has mostly relied on surface observations. Two past aircraft missions have significantly added to that understanding: the NASA/ ABLE-3 missions in the summers 1990 and 1992 and the NSF/TOPSE mission in Feb-May 2000. ARCTAS observations will expand considerably on these missions not only through a larger ensemble of instrumentation and geographical coverage, but also through the link with satellite observations and the ensemble of other POLARCAT surface and airborne platforms.

Joint satellite-aircraft observations will be of particular importance for improving understanding of halogen radical chemistry, with implications not only for arctic spring but also for the global troposphere. Satellite observations of BrO tropospheric columns by solar backscatter, first from GOME and subsequently from SCIAMACHY and OMI (Figure 8), have played a crucial role in demonstrating the importance and widespread nature of this radical chemistry in the Arctic. They suggest, as shown in Figure 8, a more widespread geographical importance of bromine radical chemistry (“bromine cloud”) than is apparent from the limited surface data. In the absence of a satisfactory process-based understanding of the mechanisms for BrO generation in the arctic troposphere, satellite observations have been widely used as direct constraints in CTMs to calculate ozone and Hg(0) loss rates. But they have never been validated and they offer no information on the vertical distribution of BrO in the troposphere. ARCTAS will address these issues.

A high priority for ARCTAS will be to include in situ measurements of BrO on the DC-8, depending on available technology. Vertical profiles in bromine-enhanced regions (as determined from the satellite observations) will validate the satellite data under a range of conditions and determine whether the halogen radical chemistry is confined to the near-surface air or extends throughout the troposphere. Correlations with ozone and mercury measured on the aircraft will help to develop better understanding of halogen-driven depletion events. Combination of the information from the aircraft and from space will enable the development and testing of models including process-based representation of halogen chemistry for application not just to the Arctic but to the global troposphere.

ARCTAS will also provide an opportunity to better understand the tropospheric chemistry of hydrogen oxide radicals ( $\text{HO}_x \equiv \text{OH} + \text{H} + \text{peroxy radicals}$ ), with particular focus on the hydroxyl radical OH, the main tropospheric oxidant. Tropospheric OH cannot be measured directly from space, but could be inferred from measurements of species that regulate its abundance (ozone, water vapor, CO,  $\text{NO}_2$ ) if the underlying chemistry is understood. A focus of ARCTAS will be to help develop this capability. Tropospheric OH measurements from aircraft have so far mainly been made by two methods, Chemical Ionization Mass Spectrometry (CIMS) and Laser-Induced Fluorescence (LIF). These two techniques have never been flown on the same aircraft, and intercomparisons between different aircraft have been inconclusive. Recent NASA tropospheric aircraft missions have found large discrepancies between observed  $\text{HO}_x$  concentrations and the values simulated by locally constrained photochemical models. This implies either instrument errors or fundamental flaws in current understanding of tropospheric  $\text{HO}_x$  chemistry. ARCTAS will



consider the possibility of deploying two HO<sub>x</sub> airborne instruments using different techniques to address this issue.

Stratosphere-troposphere exchange (STE) may play an important role in the budget of tropospheric ozone in the Arctic at all times of year, and simulation of this process in CTMs is notoriously difficult. Achieving a better understanding of STE at high northern latitudes will be an important objective of ARCTAS. Satellite observations from HIRDLS provide global mapping of ozone vertical distributions with ~ 1-km resolution in the tropopause region. These will be validated with the DC-8 aircraft in regions of tropopause folds. The possibility of significant HNO<sub>3</sub> input to the Arctic troposphere in spring from sedimentation of arctic polar stratospheric clouds (PSCs) will also be investigated.

### **3 AIRCRAFT PLATFORMS, PAYLOADS, AND DEPLOYMENTS**

#### **3.1 Platforms**

ARCTAS will include the NASA DC-8 aircraft as its in situ sampling platform, and may include other smaller platforms focused on aerosols and radiation. These aircraft would coordinate closely in flights targeted at the aerosol radiative forcing theme of the mission. This coordination is described in section 4.5. The DC-8 will also have broader regional and chemical objectives that take advantage of its endurance and payload.

The DC-8 has a ceiling of 39-41 kft, an endurance of 10 hours (12 hours with augmented flight crew), and a cruising speed of 450 kts. It has the range needed for targeting regional opportunities (fires, pollution events, BrO hot spots, etc.), and for validating satellite data under a wide range of conditions. Its ceiling is adequate for complete vertical profiling of the arctic troposphere, extending to the lowermost stratosphere.

The small profiling aircraft would focus on remote sensing of the shortwave radiative effects of atmospheric constituents (aerosols, water vapor, clouds, ozone), in situ aerosol properties, and possibly surface albedo including the BRDF. The constant-level, remote-sensing aircraft would focus primarily on targeted opportunities to sample pollution and fire plumes coincident with A-train satellite overpasses.

#### **3.2 Payloads**

The DC-8 will include a comprehensive chemical payload targeted at aerosol formation, tropospheric ozone, pollution sources, radical chemistry, and mercury. Table 2a lists priority species. Table 2b outlines desired observations for the two smaller aircraft focused on aerosols and radiation.

#### **3.3 Deployments**

We anticipate two 3-week ARCTAS deployments, in April and July 2008. April is the peak in seasonal accumulation of northern mid-latitudes pollution in the Arctic (Figure

4), and the seasonal onset of solar radiation results in significant radiative forcing from arctic haze and black carbon. This is also the time of year when high-BrO events are regularly observed (Figure 9), presumably reflecting sunrise photochemical effects on sea salt accumulated over the sea ice during winter. July is a photochemically active period and the most likely time for large boreal forest fires (Figure 10). Stratosphere-troposphere exchange will be of interest in both spring and summer.

The spring deployment will be based at North American and/or European arctic/subarctic sites. Candidate bases for the DC-8 are limited by availability of a sufficiently long runway. They include Anchorage, Fairbanks, Thule, Winnipeg, Cold Lake, and Kiruna. Figure 11 shows the ranges accessible from these and a few other bases. The two smaller aircraft have more flexibility in terms of operational bases. Selection of the bases and of operating areas will draw upon analyses of (1) CTM hindcasts and satellite data from previous years; (2) logistics and costs; and (3) linkages with other POLARCAT elements. An attractive possibility would be to base the DC-8 for 1-2 weeks in Kiruna followed by 1-2 weeks in Fairbanks, with the smaller aerosol platforms remaining in Fairbanks.

The summer deployment will be based at North American arctic/subarctic sites. The Canadian POLARCAT sub-component will operate out of Yellowknife but the runway there is too short for the DC-8. Fairbanks, Cold Lake, Churchill, and Thule are attractive possibilities. Base selection will rely on analyses similar to those for the spring deployment.

## **4 FLIGHT PLANNING: INTEGRATION WITH SATELLITES AND MODELS**

### **4.1 General approach**

ARCTAS is an integrated satellite-aircraft mission where the focus of the aircraft is to add value to the satellite observations for facilitating their exploitation by atmospheric Earth science models, in particular CTMs and GCMs. Satellite and model science teams will be involved at all stages of pre-mission flight planning, flight execution, and post-mission data interpretation. Development of a flight menu prior to the mission will rely heavily on hindcast CTM simulations and analyses of satellite observations for previous years. Specific pre-mission questions to be addressed using a combination of literature, satellites, and models include:

1. What are the dominant pathways and receptor regions for transport of northern mid-latitudes pollution to the Arctic?
2. How are the transport pathways for arctic haze expected to differ from those for long-lived gases and ozone?
3. Where are forest fires most likely to occur and where are the plumes most likely to be transported?

4. What are typical cloud frequencies and cloud types during the deployment months and around candidate deployment bases? How do clouds typically vary with time of day, frontal passages, inflows from lower latitudes, etc.?

Day-to-day flight planning during the mission will involve meteorological and chemical forecasts from several modeling teams, analyses of near-real-time satellite data and satellite validation needs, inputs from the aircraft science teams, and reviews of progress in meeting mission objectives. The modeling and satellite instrument science teams will be present in the field, and discussions will be conducted in an open and inclusive manner at daily flight planning meetings. This will follow the successful procedure used in past NASA aircraft missions, notably INTEX-B. In what follows we describe nominal flight menus for the individual aircraft and then discuss the coordination between the three aircraft in the field.

## 4.2 DC-8

The DC-8 will have a flight allocation of 140 hours for the mission (70 hours for each deployment). Flights will typically be long (~9 hours) to take advantage of the aircraft range. Each deployment will include 8 flights, taking place every 2-3 days, for a total of about 3 weeks in the field. The DC-8 will conduct a number of different flight patterns over the course of the mission (Figure 12). Brief descriptions of these patterns are given below. A given flight will typically involve a combination of several patterns, depending on the opportunities offered by weather conditions, satellite overpasses, and other factors. Coordination with the smaller aircraft is described in section 4.5.

1. **Nadir satellite instrument validation.** This involves vertical spirals coincident in time and space with the satellite overpass.
2. **Limb satellite instrument validation.** This involves “crenellated” flights along the orbit track extending vertically over the depth of the limb measurement.
3. **Pollution and boreal fire plumes.** Typical flight pattern includes lidar detection of the altitude and thickness of the plumes, vertical profiling through the plumes, and level legs inside the plumes.
4. **Arctic haze.** This involves in situ characterization of the chemical and optical properties of the aerosols, as well as lidar remote sensing of the aerosol layers. “Wall” flight patterns with level legs above, within, and below the layers may be most appropriate.
5. **Background air composition and chemical processes.** This entails extensive vertical profiling through a wide range of air masses and extending from the boundary layer to the lowermost stratosphere.

6. **Linkages and intercomparisons with other POLARCAT platforms.** Formation flying with other POLARCAT aircraft (wingtip-to-wingtip if possible) and fly-bys of surface sites.

#### 4.3 Smaller profiling aircraft

Each 3-week deployment will have a flight allocation of 65 hours. Flight durations are expected to average ~3 hours, thus allowing for about 20 flights. The key flight patterns (Figure 13) are:

1. **Survey vertical profile.** Often flown when first arriving at a measurement site, this spiral pattern provides profiles of AOD, aerosol extinction, column water vapor (CWV), and water vapor density. 5-min transects at profile top and bottom provide radiant flux and radiance measurements describing the surface and the atmospheric column.
2. **Minimum-altitude transect.** Usually flown at or near satellite overpass time, this transect provides AOD and CWV measurements of the full column viewed by the satellite while radiometers measure the surface. Long transects can measure gradients and other spatial structure in the satellite scene.
3. **Stepped profile** (also called “parking garage”). This includes horizontal legs and linking ramps. The horizontal legs permit measurements of radiative fluxes and radiances describing selected aerosol layers, at altitudes chosen on the basis of the survey vertical profile.
- 3'. **Stepped profile orbit.** This provides radiance measurements to characterize surfaces and aerosols.
4. **Above-cloud transect.** This provides measurements of AOD spectra and CWV above cloud, plus radiometric measurements of cloud properties.
- 4'. **Above-cloud orbit.** This provides radiance measurements to characterize clouds.
5. **Linkages and intercomparisons with other POLARCAT platforms.** This involves spirals and transects within lidar curtains of other aircraft, and fly-bys of surface sites (including AERONET sun/sky radiometers).

#### 4.4 Smaller constant-level aircraft

This platform will have a flight allocation of 140 hours for the mission (70 hours for each deployment) allowing for up to 18 flights (including transits) for each deployment. Depending on the primary airfield location and the range needed to reach areas of interest, many of the flights can be expected to last ~7 hours with a refueling stop. Extending the range of this platform might be possible through overnight stays at distant airfields. Some

portion of flights will be associated with satellite validation (e.g., CALIPSO, MODIS, MISR). Flights will also be conducted in concert with the profiling aircraft and DC-8 to more fully characterize the morphology and composition of arctic haze and boreal fire plumes.

#### 4.5 Coordination between the three aircraft

The three aircraft will operate out of a common base for at least part of each deployment and will conduct several coordinated flights addressing the aerosol radiative forcing theme of the mission. We envisage two types of coordinated flight patterns involving the three aircraft (Figure 14):

- 1. Development and validation of satellite retrieval algorithms.** This will focus on improving and verifying the capabilities of MODIS and MISR for observing aerosol optical depths, and of CALIPSO for physical and optical characterization of aerosol layers; it will also provide pre-mission test scenes for APS aboard Glory. Construction and testing of aerosol retrieval algorithms for space-based sensors requires 3-D information on the physical, chemical, and optical properties of the aerosol over the field of view (viewing scene) of the sensor. The three ARCTAS aircraft will work together to achieve this 3-D characterization; the profiling and constant-level aircraft will horizontally survey the scene with back-and-forth, criss-cross, or L-shaped patterns, while the DC-8 will conduct one vertical profile through the scene. The profiling aircraft will provide reflectance information at different altitudes, separating in particular the contributions from the surface and from the aerosol to the reflectances observed from space. Remote sensing from the constant-level aircraft will provide information on the vertical distributions and properties of the aerosol layers in the scene. Vertical profiling with the DC-8 will provide a large ensemble of in situ data on aerosol properties.
- 2. Characterization of the radiative effects of fire and pollution aerosol layers and their evolution with time.** Characterization of the radiative effects of an aerosol layer, and how these effects depend on the composition and other properties of the aerosol, will involve ‘parking garage’ legs by the DC-8 through the aerosol layer, level legs below and above the aerosol layer by the smaller profiling aircraft, and remote sensing by the constant-level aircraft flying above the aerosol layer (Figure 14). This type of coordinated flight pattern will be carried out for a number of different types of aerosol layers, of different ages, to provide a better understanding of the radiative forcings associated with different aerosol sources.

## 5 POST-MISSION DATA ANALYSIS

The post-mission data analysis will focus on the science themes described in section 2, integrating the information from the aircraft with satellites and models, and enabling development of the next generation of models to improve our understanding of arctic atmospheric composition and climate. Results will be presented at special sessions of AGU meetings and published in special issues of journals such as the *Journal of Geophysical Research*. We expect publication of a wide range of studies drawing on diverse results from the mission and involving different levels of integration between the aircraft data, satellite data, and models. Some of the types of publications expected to emerge within a few years of ARCTAS execution include:

- **Satellite validation papers** using the aircraft data to assess the quality of satellite sensors for the unique conditions of the arctic environment. We expect that cross-sensor validation of aerosol products and validation of tropospheric BrO will be of particular interest.
- **Satellite interpretation papers** using the aircraft observations to confirm and model studies to interpret features of the satellite observations. An example would be satellite identification of events of long-range transport of pollution or fire plumes, combined with detailed chemical characterization of these events using the aircraft observations.
- **Aerosol radiative forcing papers** using satellite measurements together with aircraft remote and in situ measurements of aerosol, cloud, and surface properties and radiative effects to better quantify aerosol radiative forcing from different source regions and source types.
- **Process papers** using the aircraft observations to improve our understanding of chemical and aerosol processes. An example would be the intercomparison of HO<sub>x</sub> measurements and their comparison with photochemical models.
- **Source attribution papers** using CTMs evaluated with the combination of aircraft and satellite observations to quantify source-receptor relationships for pollution in the Arctic and make projections for the future.
- **Climate modeling papers** using radiative constraints from the satellite and aircraft observations to improve the representation of arctic aerosol and tropospheric ozone radiative forcings in GCMs, and assess the implications for arctic climate change.
- **Data assimilation papers** using the information from the aircraft to evaluate and improve the assimilation of satellite observations into CTMs, GCMs, and ESMs. An example would be the construction of improved error covariance matrices for satellite observations based on the detailed data provided by the aircraft.

This brief list is no more than an illustrative sample of the richness of the ARCTAS data set and its expected use by the atmospheric composition and climate research communities. The data collected in ARCTAS are certain to provide a major reference and anchor in the decades ahead for our understanding of arctic environmental change.

Table 1. U.S. and international POLARCAT activities during IPY

| Agency/Country         | Platform                             | Location                    | Focus   | Duration              | Status                    | Contact                                  |
|------------------------|--------------------------------------|-----------------------------|---|-----------------------|---------------------------|--|
| NASA                   | DC-8, and two smaller aircraft       | TBD (see section 3.3)       | pollution transport, fires, radiative forcing, regional chemistry                         | Apr and Jul 08        | pending                   | J.H. Crawford, NASA; D.J. Jacob, Harvard |
| NOAA                   | WP-3D aircraft                       | Iqaluit                     | N American export of pollution, aerosol-cloud interactions                                | Apr 08                | tentative                 | C. Brock and M. Trainer NOAA             |
| NOAA                   | R/V Ron Brown                        | Arctic cruise               | gas and aerosol chemistry   | Feb-Mar 08            | funded                    | T. Bates, NOAA                           |
| NSF-ATM, NSF-OPP       | Surface                              | Summit                      | radical chemistry, ice interactions   | Apr 07 – Aug 08       | funded                    | J.E. Dibb, U. New Hampshire              |
| DOE                    | aircraft                             | Alaska North Slope ARM site | aerosol-cloud interactions and radiative forcing  | Apr-May 08            | funded                    | S. Ghan, DOE                             |
| Russia, France, Norway | Antonow aircraft                     | Russian Arctic              | General   | TBD                   | funded                    | K. Law, CNRS                             |
| France (CEA)           | AN-30 aircraft                       | TBD                         | C cycle   | TBD                   | funded                    | P. Ciais, CEA                            |
| Germany (DLR)          | Falcon aircraft                      | NE Canada                   | pollution transport, satellite validation, heterogeneous chemistry, UT/LS, pyroconvection | Mar-Apr 07, summer 08 | funded (07), pending (08) | H. Schlager, DLR                         |
| Canada                 | 3 aircraft                           | Yellowknife                 | pyroconvection  | Jun-Jul 07 and 08     | pending                   | B.J. Stocks                              |
| Russia, Norway         | Train (TROICA instrumented carriage) | Transsiberian               | fires, arctic haze  | spring and summer 08  | funded                    | B. Belan and N. Elansky, Russia          |
| Norway                 | surface, Lagrangian balloons         | Spitsbergen                 | fires, mid-latitudes pollution, albedo effects, POLARCAT coordination                     | 2007-2009             | funded                    | A. Stohl, NILU                           |
| Canada, Europe, Russia | Surface sites                        | Arctic                      | regional chemistry, C cycle, ice interactions   | IPY                   | funded                    | various investigators                    |

Table 2a. DC-8 priority measurements in ARCTAS.

| Species/Parameter  | Priority <sup>1</sup> | Detection Limit                          | Desired Resolution |
|--|-----------------------|--|--------------------|
| <b>Gas phase in situ</b>   |                       |  |                    |
| O <sub>3</sub>   | 1                     | 3 ppb                                    | 1 s                |
| H <sub>2</sub> O   | 1                     | 10 ppm                                   | 1 s                |
| CO   | 1                     | 3 ppb                                    | 1 s                |
| NO <sub>2</sub>  | 1                     | 10 ppt                                   | 30 s               |
| NO   | 1                     | 5 ppt                                    | 5 s                |
| OH/HO <sub>2</sub> /RO <sub>2</sub>                                    | 1                     | .01/0.1 ppt                              | 30 s               |
| BrO  | 1*                    | 1 ppt                                    | 1 min              |
| CO <sub>2</sub>  | 2                     | 0.5 ppm                                  | 1 s                |
| CH <sub>4</sub>  | 2                     | 10 ppb                                   | 1 s                |
| Speciated NMHC   | 2                     | 5 ppt                                    | 1 min              |
| Oxygenated VOCs  | 2                     | 10 ppt                                   | 2 min              |
| Halocarbons  | 2                     | 5 ppt                                    | 2 min              |
| HNO <sub>3</sub>   | 2                     | 5 ppt                                    | 1 min              |
| PAN, PPN, MPAN, etc.   | 2                     | 5 ppt                                    | 1 min              |
| HO <sub>2</sub> NO <sub>2</sub>  | 2                     | 10 ppt                                   | 1 s                |
| HCHO   | 2                     | 50 ppt                                   | 30 s               |
| H <sub>2</sub> O <sub>2</sub>  | 2                     | 15 ppt                                   | 30 s               |
| CH <sub>3</sub> OOH  | 2                     | 25 ppt                                   | 30 s               |
| HCN/CH <sub>3</sub> CN   | 2                     | 10 ppt                                   | 2 min              |
| SO <sub>2</sub>  | 2                     | 10 ppt                                   | 1 s                |
| Hg(0)  | 2 *                   | 0.2 ng m <sup>-3</sup>                   | 5 min              |
| Reactive gaseous mercury (RGM)   | 2 *                   | 20 pg m <sup>-3</sup>                    | 60 min             |
| Total particulate mercury  | 2 *                   | 20 pg m <sup>-3</sup>                    | 60 min             |
| HOBr, ClO, HOCl  | 2 *                   | 1 ppt                                    | 5 min              |
| N <sub>2</sub> O   | 3                     | 1 ppb                                    | 10 s               |
| RONO <sub>2</sub>  | 3                     | 10 ppt                                   | 30 s               |
| NO <sub>y</sub>  | 3                     | 5 ppt                                    | 1 s                |
| NH <sub>3</sub>  | 3*                    | 30 ppt                                   | 1 min              |
| Organic acids  | 3                     | 10 ppt                                   | 1 min              |
| <b>Aerosol in situ</b>   |                       |  |                    |
| Aerosol number   | 1                     | NA                                       | 1 s                |
| Aerosol size distribution  | 1                     | NA                                       | 10 s               |
| Optical properties (scattering/absorption)                             | 1                     | NA                                       | 1 s                |
| Aerosol volatility   | 2                     | NA                                       | 1 s                |
| Aerosol hygroscopicity, f(RH)  | 2                     | NA                                       | 10 s               |
| Aerosol composition, inorganic   | 2                     | 50 ng m <sup>-3</sup>                    | 5 min              |
| Aerosol composition, OC and BC   | 2                     | 100/50 ng m <sup>-3</sup>                | 5 min              |
| Size-resolved aerosol composition                                      | 2                     | 100 ng m <sup>-3</sup>                   | 5 min              |
| Droplet size distribution (and phase)                                  | 3                     | NA                                       | 5 s                |
| Condensed water content  | 3                     | NA                                       | 5 s                |
| CCN  | 3                     | NA                                       | 5 s                |
| Radionuclides ( <sup>222</sup> Rn, <sup>7</sup> Be, <sup>210</sup> Pb) | 3                     | 1/100/1 fCi/m <sup>-3</sup>              | 5 min              |
| <b>Remote Sensing</b>  |                       |  |                    |
| O <sub>3</sub> (nadir/zenith)  | 1                     | 5 ppb                                    | Z < 500 m          |
| Aerosol extinction (nadir/zenith)                                      | 1                     | NA                                       | Z < 100 m          |
| BrO (zenith column)  | 1*                    | 3x10 <sup>13</sup> molec/cm <sup>2</sup> | 5 min              |

<sup>1</sup> Priority code: 1 = top priority; 2 = high priority; 3 = medium priority. Asterisks recognize exploratory, high-risk measurements – at least one of these will be included in the payload.



|                                       |   |                                      |             |
|---------------------------------------|---|--------------------------------------|-------------|
| Aerosol depolarization (nadir/zenith) | 2 | NA                                   | $z < 100$ m |
| UV spectral actinic flux ( $4\pi$ sr) | 2 | $10^{-5} \text{ s}^{-1} \text{ J's}$ | 10 s        |

Table 2b. Priority measurements for the smaller aerosol and radiation platforms in ARCTAS

| Measurement type              | Detail  |
|-------------------------------|---|
| Optical depth spectra         | Near-UV→Vis→Near-IR   |
| Radiative flux spectra        | Upwelling and downwelling, Near-UV→Vis→Near-IR              |
| Radiance spectra              | Angular scanning, Near-UV→Vis→Near-IR, preferably polarized |
| Lidar backscatter coefficient |   |
| Lidar extinction coefficient  |   |
| Lidar aerosol depolarization  |   |
| In situ aerosol properties    | See Table 2a  |

Satellites: CALIPSO, CloudSat, OMI, TES, HIRDLS, MLS, ACE, MODIS, AIRS, MISR, MOPITT

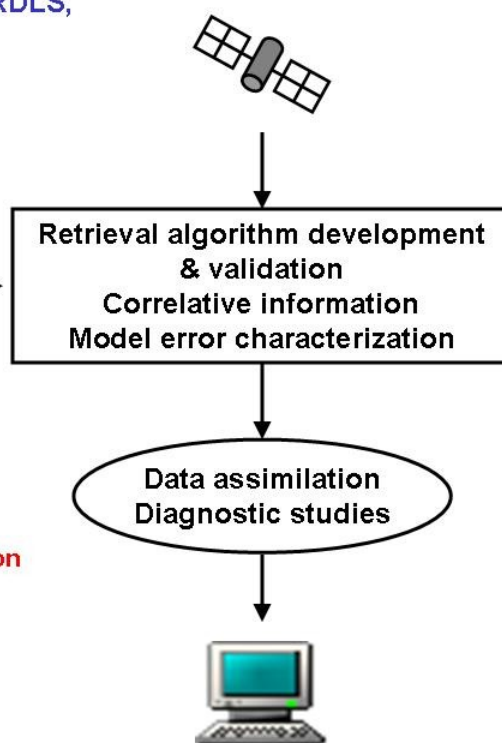
- Aerosol optical depth, properties
- CO, ozone, BrO, NO<sub>2</sub>, HCHO

Aircraft: DC-8 and smaller platforms

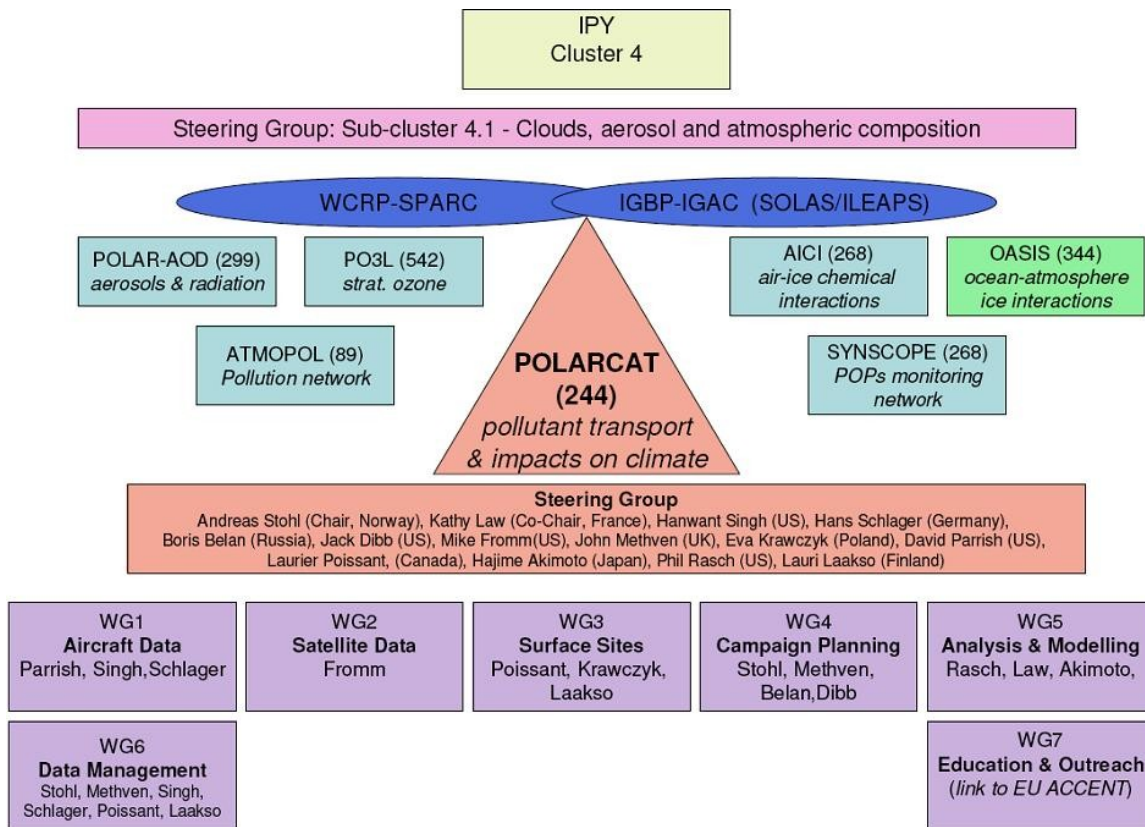
- Detailed in situ chemical and aerosol measurements
- Remote sensing of ozone, aerosol, surface properties

Models: CTMs, GCMs, ESMs

- Source-receptor relationships for Arctic pollution
- Effects of boreal forest fires
- Aerosol radiative forcing
- Arctic chemistry

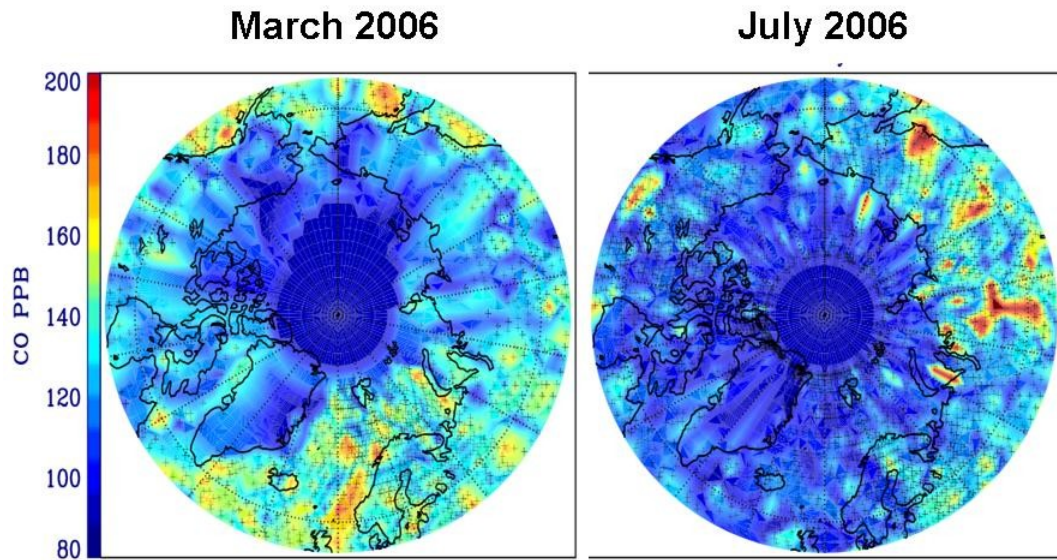


**Figure 1.** ARCTAS strategy for enabling exploitation of NASA satellite data to improve understanding of arctic atmospheric composition and climate

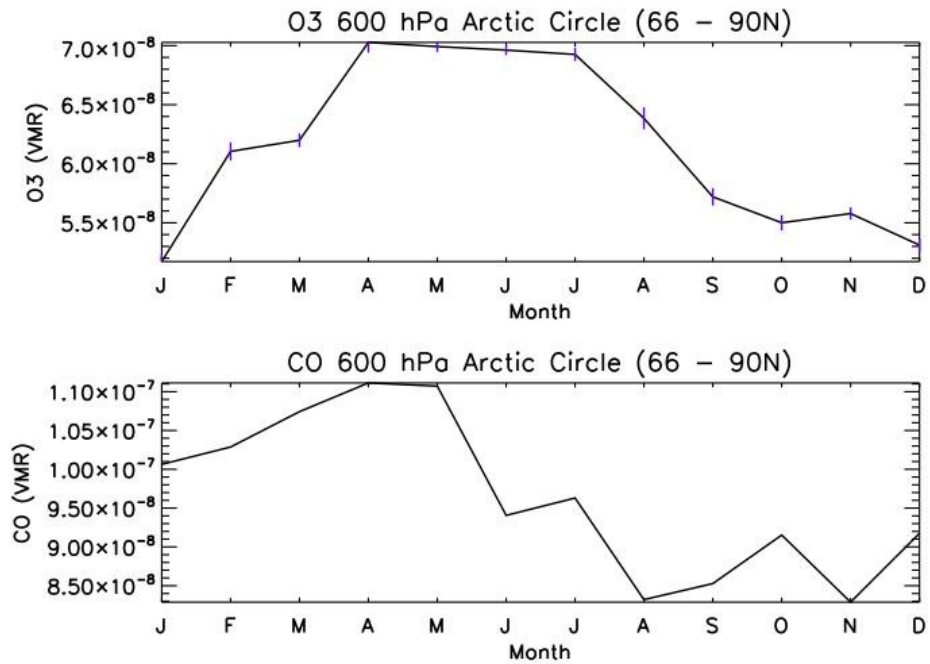


**Figure 2.** POLARCAT as an element of the IPY cluster "Clouds, aerosols, and atmospheric composition". Major partner activities are identified.

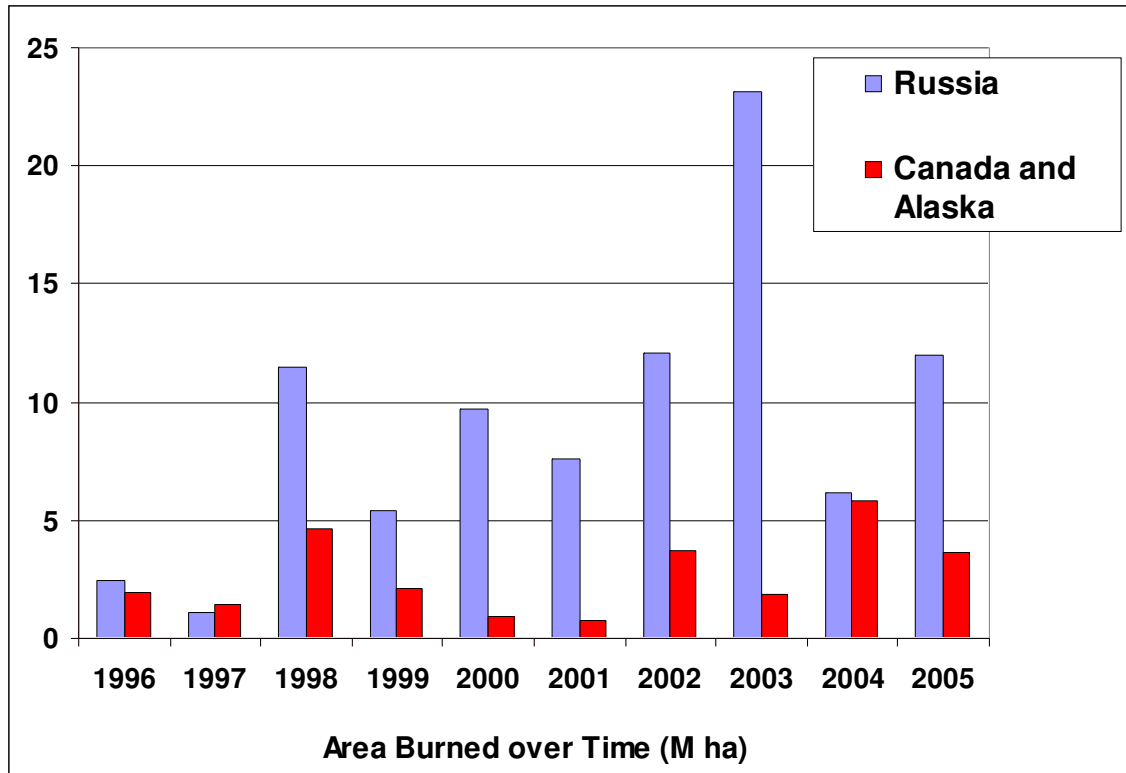
### TES CO at 600 hPa



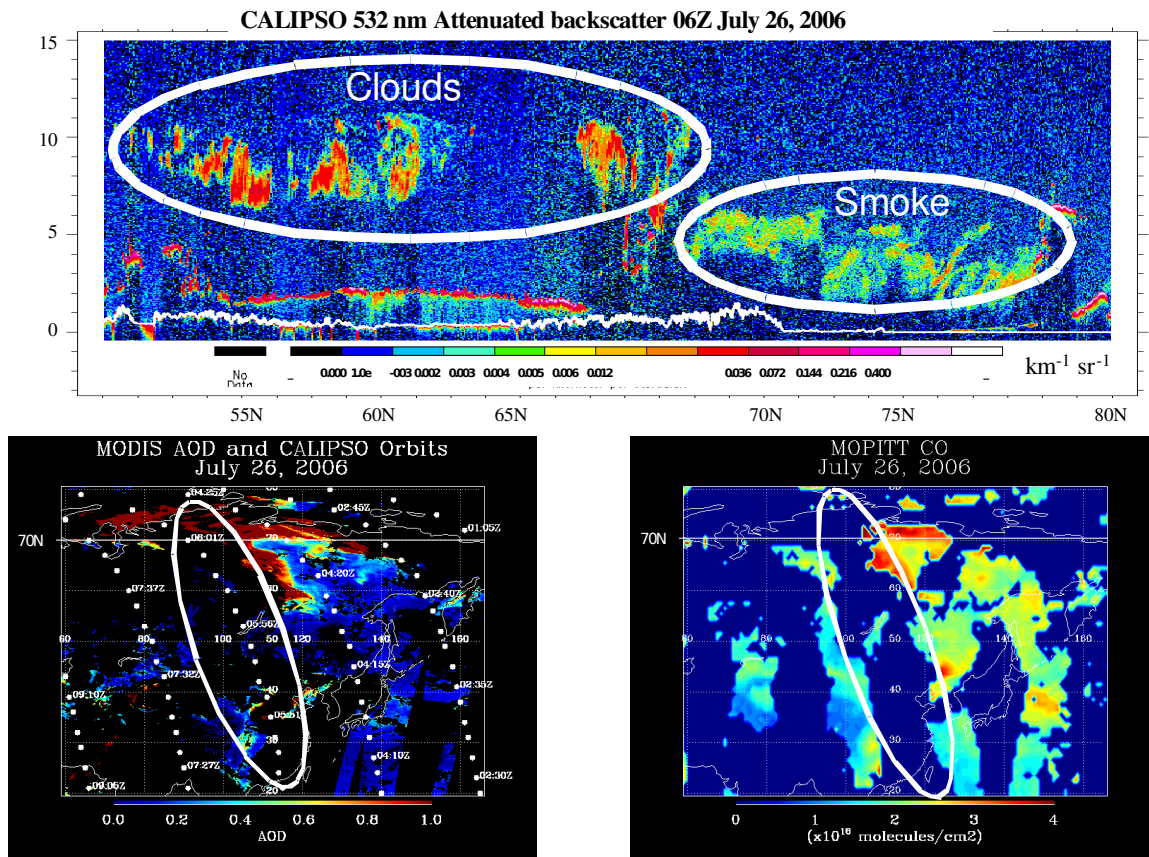
**Figure 3.** TES observations of arctic CO concentrations at 600 hPa. Values are monthly means for March and July 2006. Observations are marked by crosses. There are no observations above 82°N because of the inclination of the Aura satellite. (John Worden, TES Science Team).



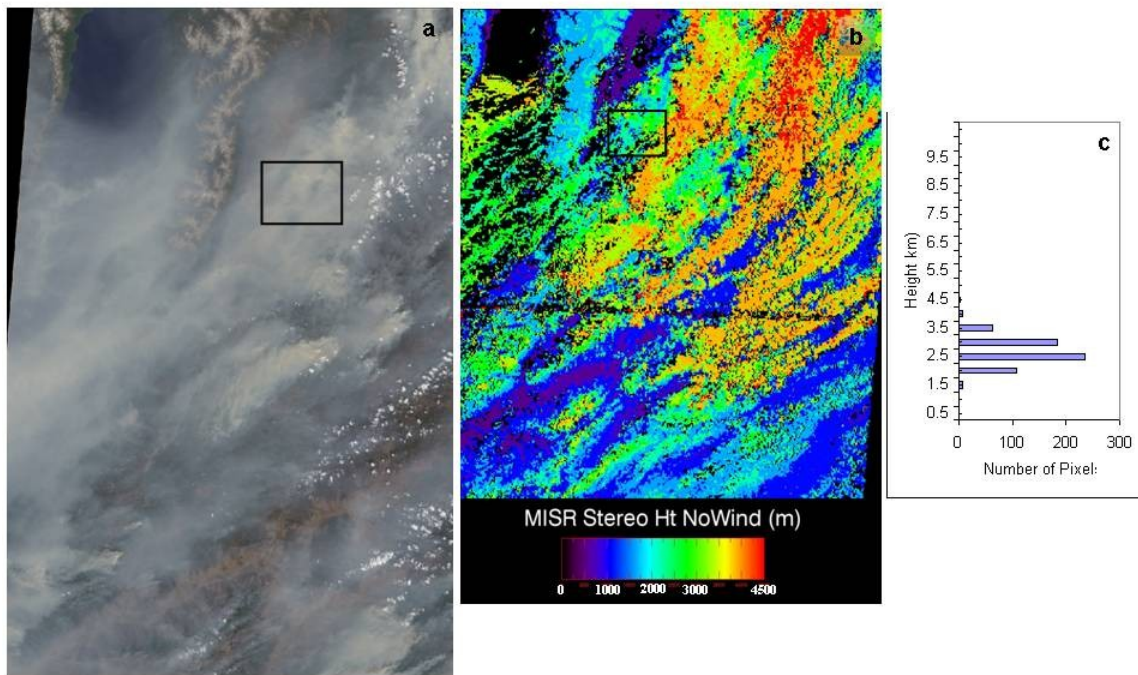
**Figure 4.** Seasonal variations of ozone and CO concentrations at 600 hPa over the Arctic as observed by TES. The error bars represent the errors on the mean monthly values which do not include sampling error. The errors on the CO mean values are too small to show. (John Worden, TES Science Team)



**Figure 5.** Boreal fire trends over the past decade (Amber Soja, NASA/LaRC)

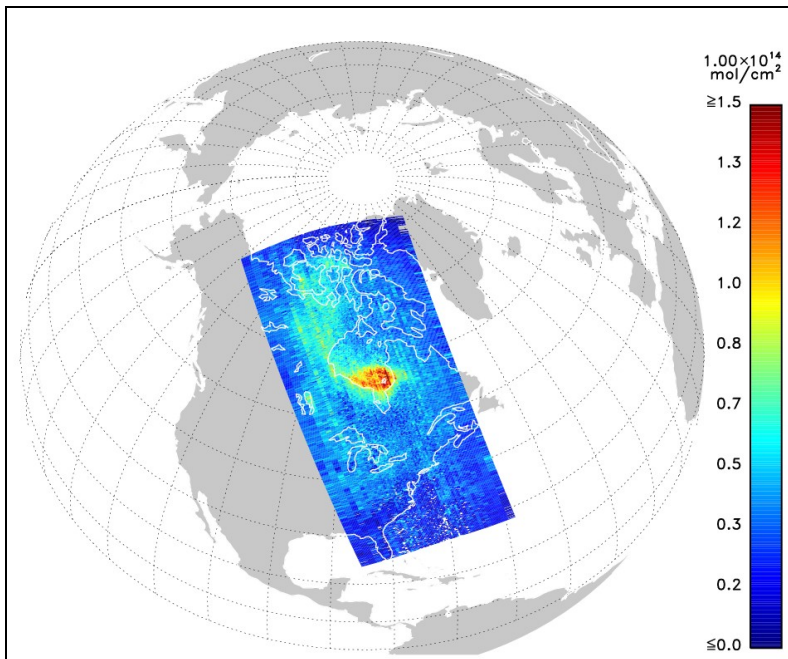


**Figure 6.** Concurrent views of Siberian boreal fire activity on July 26, 2006 by multiple satellites: CALIPSO observations of smoke (top), MODIS AOD (bottom left), and MOPITT CO (bottom right). CALIPSO provides information on the altitude of fire emissions while MODIS and MOPITT observations offer a view of the regional extent of elevated AOD and CO downstream of fires.

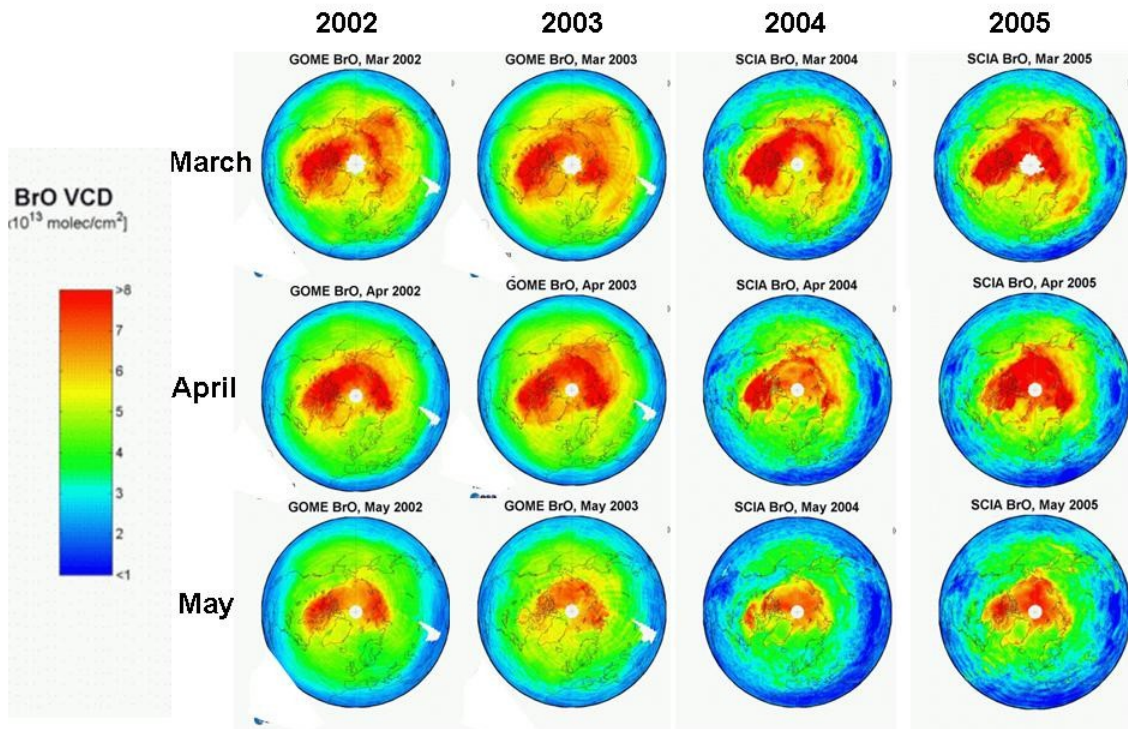


**Figure 7.** MISR plume height analysis for the June 11, 2003 boreal fire in the Siberian taiga near Lake Baikal (51-54° N, 110-112° E), Orbit 18506, Path 130, Blocks 47-49. (a) MISR true-color nadir image with black box marking the study patch. (b) MISR Stereo Height product (Version 13, without wind correction), for the region shown in (a). (c) Plume height histogram from the MISR Standard Stereo Height product, for the study patch.

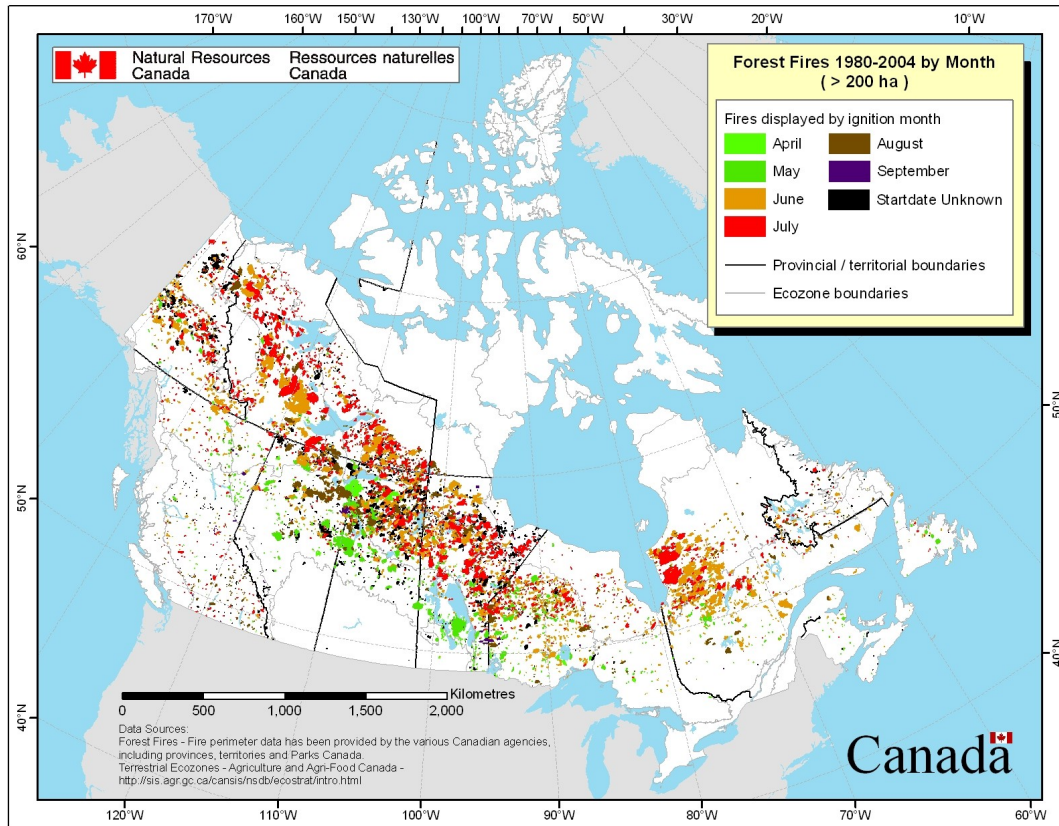




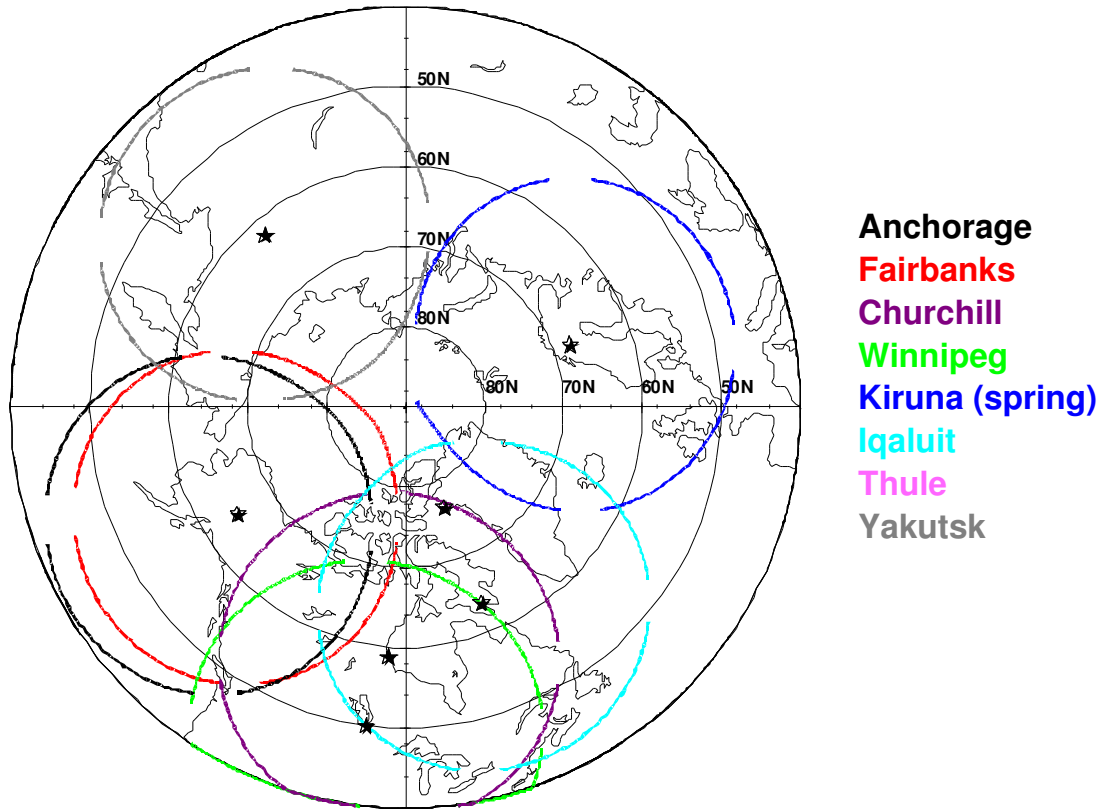
**Figure 8.** Tropospheric BrO column observed by OMI on March 11, 2005 (Thomas Kurosu, OMI Science Team)



**Figure 9.** Monthly mean March-May tropospheric BrO columns observed from space by GOME (2002-2003) and SCIAMACHY (2004-2005). Imagery from U. Bremen, <http://www-iup.physik.uni-bremen.de>



**Figure 10.** Seasonal distribution of large (>200 ha) Canadian fires in 1980-1994 (from Brian J. Stocks, Canadian POLARCAT White Paper)



**Figure 11.** Range of the DC-8 aircraft from candidate bases, based on 4 hours out and back with nominal vertical profiling.

## DC-8 FLIGHT STRATEGIES

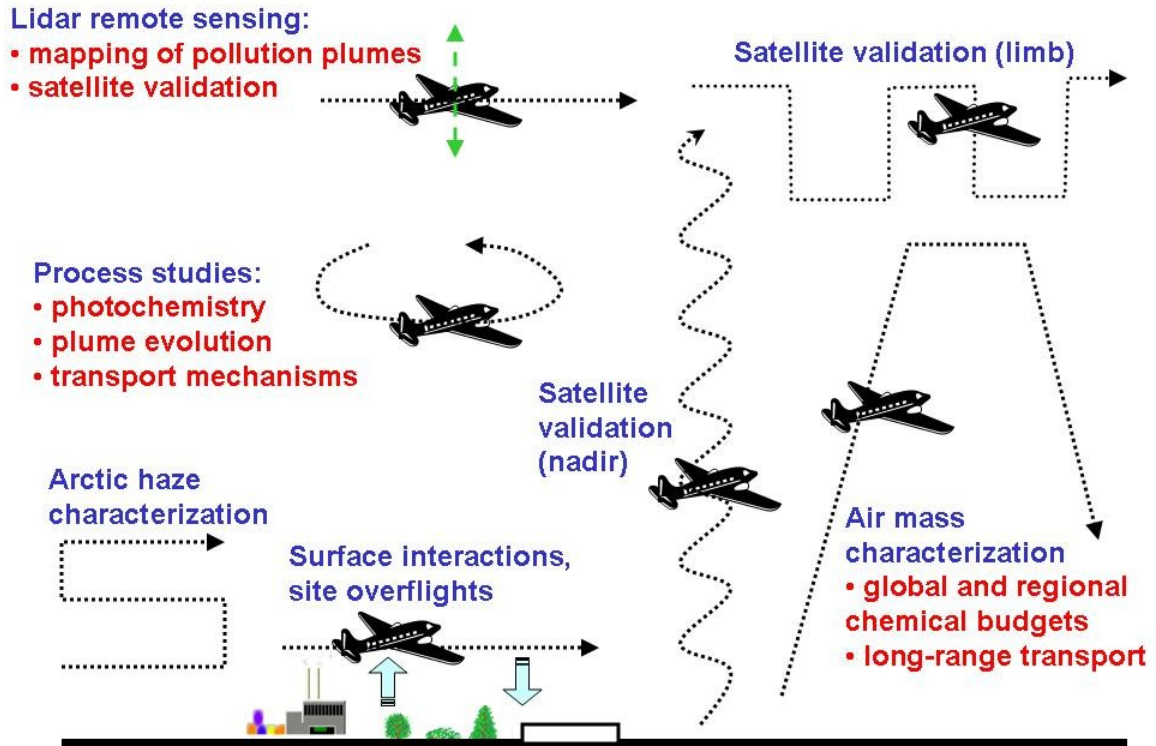
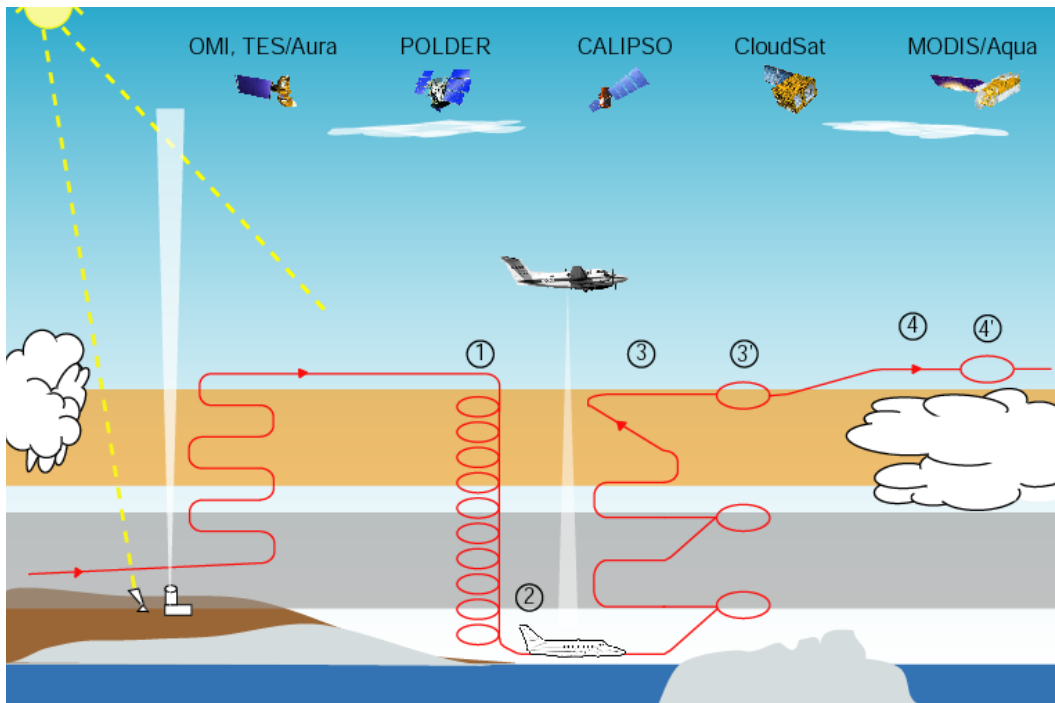
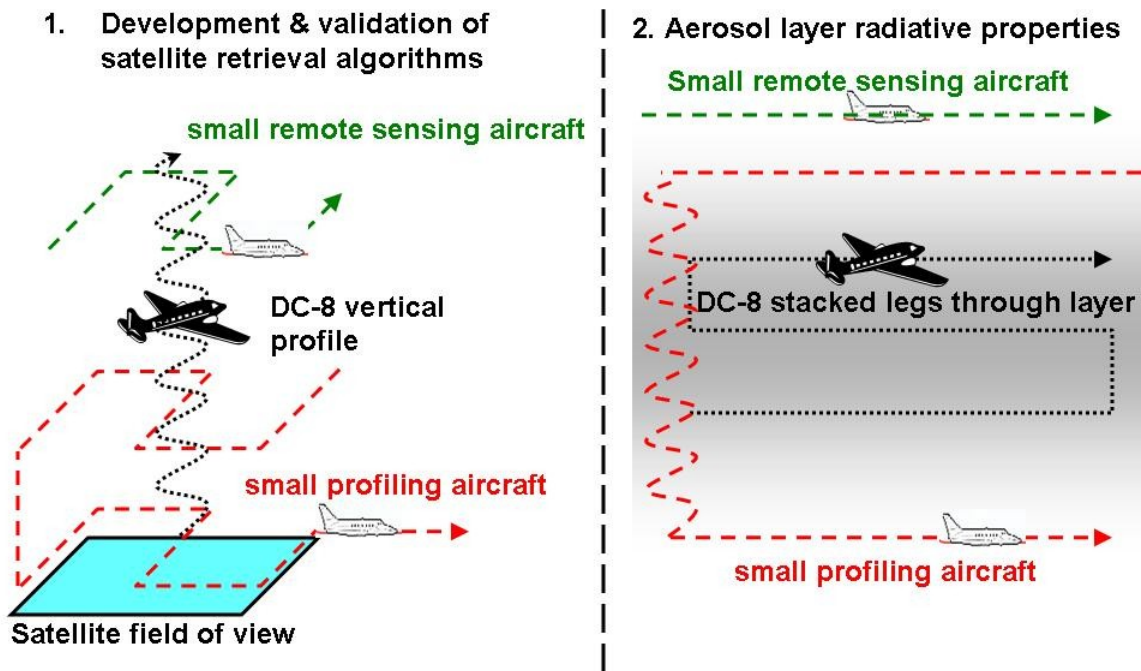


Figure 12. Nominal DC-8 flight patterns in ARCTAS



**Figure 13.** Flight patterns for studies of aerosol radiative forcing in ARCTAS. (1) Survey vertical profile. (2) Minimum-altitude transect. (3) Stepped profile (parking garage). (3') Stepped profile orbits. (4) Above-cloud transect. (4') Above-cloud orbit. See text for details.

## Coordinated flights of DC-8 and smaller aircraft for investigating aerosol radiative effects



**Figure 14.** Nominal patterns for coordinated DC-8 flights with smaller aircraft during ARCTAS.