### The Arctic Boundary Layer Expedition (ABLE 3A): July–August 1988

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The Arctic Boundary Layer Expedition (ABLE 3A): July–August 1988

R. C. Harriss, 1 S. C. Wofsy, 2 D. S. Bartlett, 1 M. C. Shippam, 3 D. J. Jacob, 2 J. M. Hoell, Jr., 3 R. J. Bendura, 3 J. W. Drewry, 3 R. J. McNeal, 4 R. L. Navarro, 5 R. N. Gidge, 5 and V. E. Rabine 5

The Arctic Boundary Layer Expedition (ABLE 3A) used measurements from ground, aircraft, and satellite platforms to characterize the chemistry and dynamics of the lower atmosphere over Arctic and sub-Arctic regions of North America during July and August 1988. The primary objectives of ABLE 3A were to investigate the magnitude and variability of methane emissions from the tundra ecosystem, and to elucidate factors controlling ozone production and destruction in the Arctic atmosphere. This paper reports the experimental design for ABLE 3A and a summary of results. Methane emissions from the tundra landscape varied widely from $-2.1$ to $426$ mg CH$_4$ m$^{-2}$ d$^{-1}$. Soil moisture and temperature were positively correlated with methane emission rates, indicating quantitative linkages between seasonal climate variability and soil metabolism. Enclosure flux measurement techniques, tower-based eddy correlation, and airborne eddy correlation flux measurements all proved robust for application to methane studies in the tundra ecosystem. Measurements and photochemical modeling of factors involved in ozone production and destruction validated the hypothesized importance of low NO$_x$ concentrations as a dominant factor in maintaining the pristine Arctic troposphere as an ozone sink. Stratospheric intrusions, long-range transport of mid-latitude pollution, forest fires, lightning, and aircraft are all potential sources of NO$_x$ and NO$_y$ to Arctic and sub-Arctic regions. ABLE 3A results indicate that human activities may have already enhanced NO$_y$ inputs to the region to the extent that the lifetime of O$_3$ against photochemical loss may have already doubled. A doubling of NO$_x$ concentration from present levels would lead to net photochemical production of O$_3$ during summer months in the Arctic (Jacob et al., this issue (a)). The ABLE 3A results indicate that atmospheric chemical changes in the northern high latitudes may serve as unique early warning indicators of the rates and magnitude of global environmental change.

INTRODUCTION

The Arctic Boundary Layer Expedition (ABLE 3A) was conducted in Arctic and sub-Arctic regions of North America and Greenland during July and August 1988. This was the first comprehensive investigation of the sources, sinks, and distribution of trace gas and aerosol chemical species in a northern high-latitude region during summer months. The ABLE 3A experimental design placed emphasis on the role of biosphere-atmosphere interactions in determining the chemical composition of the troposphere and on processes which influence the tropospheric O$_3$ budget (Figure 1). The suite of chemical species measured included the following gases: methane (CH$_4$), carbon monoxide (CO), carbon dioxide (CO$_2$), nonmethane hydrocarbons (NMHC), acetic acid (HA), formic acid (HFO), nitric oxide (NO), nitrogen dioxide (NO$_2$), total "reactive" nitrogen gas (NO$_x$), nitric acid (HNO$_3$), peroxyacetyl nitrate (PAN), peroxypropionyl nitrate (PPN), ozone (O$_3$), and aerosol chemical composition and size distribution.

The ABLE 3A is a component of the NASA Global Tropospheric Experiment (GTE) sponsored by the NASA Tropospheric Chemistry Program [McNeal et al., 1983]. Previous ABLE expeditions have reported on the chemistry of North African dust and marine air over the tropical Atlantic [e.g., Ferek et al., 1986; Talbot et al., 1986] and on air chemistry over the tropical rain forests of Guyana and Brazil [e.g., Gregory et al., 1986; Harriss et al., 1988, 1990]. A second expedition to the northern high latitudes (ABLE 3B) was conducted jointly with the Canadian Northern Wetlands Project during July–August 1990.

This paper reports the overall experimental design for ABLE 3A and includes a brief overview of results. A following series of papers report the detailed results of individual studies.

ARCTIC AND BOREAL REGION AIR

Arctic and boreal regions (>50°N) are uniquely important to tropospheric chemistry for at least two reasons: (1) these regions include approximately 27% of the world’s soil carbon [Post et al., 1982]. The exchange of this carbon between soils and the atmosphere, as CO$_2$ and CH$_4$, is influenced by climate variability [e.g., Billings, 1987]. In a “global warming” era these environments may be “feedback” regions which influence rates of climatic change. (2) Even the most remote wilderness areas of the region are showing indications of air pollution derived from long-range transport from mid-latitude source emissions. During late winter and early spring, meteorological conditions are particularly favorable for midtropospheric air masses to track across industrialized regions and into the Arctic (see Barrie [1986] for a review). It is particularly important to understand both direct and indirect impacts of long-range transport of pollutants on the chemistry of high-latitude air masses. Direct impacts could
Methane flux increases in response to increasing soil temperature and moisture. In both tundra and boreal environments, changes can be derived from field and experimental studies of atmosphere in response to seasonal variations in soil temperature has been closely coupled to atmospheric composition has been closely coupled to atmospheric chemistry [e.g., Hameed and Cess, 1983; Khalil and Rasmussen, 1989]. These studies also indicate that climate-induced feedbacks from natural soils could potentially influence the global CH₄ budget.

The ABLE 3A has obtained regional-scale empirical data on trace gas exchanges between northern ecosystems and the atmosphere, which will permit a more detailed analysis of potential biosphere-atmosphere feedback processes in response to climate variability. Three independent approaches to CH₄ flux measurement were used to define the characteristic temporal and spatial variability for the Yukon-Kuskokwim tundra ecosystem, Alaska. Ground-based enclosure and eddy correlation measurements were used to characterize temporal variability, individual landscape elements as sources or sinks, and integrated flux from the local area. An airborne eddy correlation measurement program was used to characterize spatial variability in CH₄ flux at the regional scale.

**High-Latitude Air Pollution: Magnitude and Impacts**

The large-scale pollution of the Arctic troposphere by long-range transport of pollutants from industrial regions during late winter and early spring months is well documented [e.g., Schnell, 1984; Barrie, 1986; Stonehouse, 1986; Lowenthal and Rahn, 1985]. During these “Arctic haze” pollution events the buildup of aerosol constituents, sulfur dioxide, and PAN has been observed [e.g., Barrie and Hoff, 1985; Bottenheim et al., 1986]. At the time of Arctic sunrise, significant perturbations in the chemistry of the boundary layer have been observed: O₃ concentrations decrease, gaseous halogens increase, and aerosol pollutant species decrease [Barrie et al., 1989]. To date, there have been no comprehensive studies of the chemistry of the Arctic troposphere during summer months. Observations during the summer are critical to an assessment of the full impact of the accumulated winter/spring pollutant loadings, and to determine if significant long-range transport and injection of pollutants occur during these months.
Observations at a few ground-based monitoring sites have indicated that concentrations of aerosols are at a minimum during summer periods [e.g., Bodhaine, 1986]. However, ground-based monitoring stations at Arctic sites are influenced by frequent stratus cloud cover and may not be a good indicator of overall tropospheric air chemistry. Evidence gathered in ABLE 3A indicates that the stratus cloud decks common over the Arctic during summer months may filter out soluble aerosol species before they reach ground level [e.g., Talbot et al., this issue].

The observation of a possible increasing trend in surface \( \mathrm{O}_3 \) at Barrow, Alaska [Oltmans and Komhyr, 1986] is a potential indicator of an increasing degree of Arctic pollution. However, the \( \mathrm{O}_3 \) concentration at any individual site will be influenced by a variety of meteorological and chemical factors. The ABLE 3A placed special emphasis on identifying the range of variables which might have a significant influence on the tropospheric \( \mathrm{O}_3 \) budget in the Barrow region during the summer period.

A component of ABLE 3A \( \mathrm{O}_3 \) studies was to determine the sources of nitrogen oxides (\( \text{NO}_x \)) and total reactive nitrogen (\( \text{NO}_y \)) to the Arctic troposphere. Previous studies indicated that primary production in many biological environments in the Arctic is limited by inadequate levels of available nitrogen during summer months [e.g., Van Cleve and Alexander, 1981]. These results suggest that surface environments should be a net sink for \( \text{NO}_x \) and \( \text{NO}_y \). Under natural conditions, the Arctic region should be an important low-\( \text{NO}_x \) region for testing photochemical theory on the role of \( \text{NO}_x \) in \( \mathrm{O}_3 \) production and destruction processes. However, the alternate possibility existed that a reservoir of atmospheric reactive nitrogen accumulated during winter and spring months from mid-latitude pollution sources could provide a source of \( \text{NO}_x \) to influence photochemical \( \mathrm{O}_3 \) chemistry during summer months. Enhanced deposition of nitrogen to the Arctic biosphere from mid-latitude pollution sources could also stimulate primary production and alter biosphere-atmosphere exchange rates of other trace gases like \( \text{CO}_2 \) and \( \text{CH}_4 \).

Another characteristic of the Arctic tundra ecosystem important to ABLE 3A objectives is the paucity of plant species known to emit isoprene and other reactive non-methane hydrocarbon species which are important in \( \mathrm{O}_3 \) chemistry. As a long-term strategy, the ABLE missions are designed to study \( \mathrm{O}_3 \) production and destruction processes in atmospheric boundary layer environments which have characteristics of low \( \text{NO}_x \)/low NMHC (tundra), low \( \text{NO}_x \)/high NMHC (boreal forest), low \( \text{NO}_x \)/high NMHC (wet season tropical forest), intermediate \( \text{NO}_x \)/high NMHC (dry season, unpolluted tropical forest), high \( \text{NO}_x \)/high NMHC (polluted tropical and boreal forests), and high \( \text{NO}_x \)/low NMHC (polluted tundra environments). Results from several of these categories are reported in ABLE 2 publications (Journal of Geophysical Research, volume 93, pages 1349-1624, 1988; and volume 95, pages 16,721-17,050, 1990) and in the present issue.

**Approach**

The scientific objectives of ABLE 3A were accomplished through a coordinated program of chemical and meteorological measurements at surface sites in Alaska and on the NASA Lockheed Electra research aircraft. The expedition was conducted during July and August 1988. A complimentary program of surface-based biogeochemical studies, termed the Biospheric Research on Emissions from Wetlands (BREW), supported by the NASA Biospheres Research Program, was conducted in Bethel, Alaska, during the period of the ABLE 3A. Investigators sponsored by the NASA Interdisciplinary Program also participated in the expedition. A list of principal investigators, institutions, and measurements is presented in Table 1.

**Aircraft Experiments**

The centerpiece of ABLE 3A was a series of research flights with the instrumented NASA Electra (Figure 2). The flights were divided into four generic types of experiments: (1) Boundary layer survey studies determined the regional horizontal and vertical distribution of trace gas and aerosol species over tundra environments to explore the qualitative effects of biosphere-atmosphere exchange versus atmospheric transport processes on the chemical composition of the atmospheric mixed layer and overlying free troposphere. (2) Flux measurements were conducted over tundra environments to quantify exchange rates for \( \text{CH}_4 \), \( \text{CO} \), and \( \mathrm{O}_3 \) at incremental scales of approximately 50-150 km over a total of up to 2000 km per experiment. (3) Several missions were devoted to determining the large-scale distribution of gas and aerosol species over ice and oceanic environments upwind of tundra, with flight lines along a sea or ice to land gradient. These missions also provided an excellent qualitative indication of gas and aerosol source/sink processes associated with different surface environments. (4) Several missions, and transit flights between bases, were devoted primarily to characterizing mid-tropospheric variability of gas and aerosol species for investigation of long-range transport of pollutants to the study regions and tropospheric photochemical processes. A schematic illustration of these generic flight patterns is shown in Figure 3.

The areas studied by intensive aircraft missions are shown in Figure 4. The characteristics of each mission are summarized in Table 2.

In situ measurements of most of the trace gas and aerosol chemical species discussed in the above sections are available for all of the flights listed in Table 2. The two-dimensional distribution of aerosol and \( \mathrm{O}_3 \) from the surface to the tropopause was measured along each flight path using a UV Differential Absorption Lidar (DIAL) described by Browell et al. [this issue]. The UV DIAL also provides information on cloud distribution and on mixed layer dynamics.

Aircraft research missions were conducted from bases in Barrow, Alaska (flights 6–12), Bethel, Alaska (flights 14–21, 25–26), Cold Bay, Alaska (flights 22–24), and Thule, Greenland (flight 29). Flights 30–33 from Thule, Greenland, to Wallops Island, Virginia, on August 15–16, 1988, included vertical profiles along the flight track to determine latitudinal distributions of trace gas and aerosol species as a function of altitude. Flights 1–5 were constant altitude transits between Wallops Island, Thunder Bay, Churchill, Thule, Fairbanks, and Barrow (Figure 4).

**Ground-Based Experiments**

The extensive peatland environments in the Yukon-Kuskokwim Delta region of Alaska, overflown during mis-
sions conducted from Bethel, were selected for detailed ground-based studies of trace gas exchange between the biosphere and the atmosphere. The region includes approximately 9 million hectares of lowland tundra, underlain by permafrost, and containing a large number of shallow lakes. Vegetated areas are covered by a moss/lichen/dwarf shrub community on relatively well-drained soils and by a herbaceous community on wet soils (Figures 5a and 5b).

Data on the distribution of vegetation types and other environmental characteristics were available at a number of spatial scales. Land cover of the entire delta region has been mapped at 80-km resolution by the U.S. Geological Survey using Landsat imagery. More detailed characterization of local areas was conducted during the analysis of ABLE 3A data using System Probatoire d’Observation de la Terre (SPOT) imagery, which has 15-m resolution.

The two major components of the ground-based research program were (1) measurements of fluxes, total storage, and isotopic characteristics of biogenic trace gases using enclosures and soil sampling techniques. (2) Flux and ambient atmospheric concentrations of trace gases were also measured using micrometeorological and eddy correlation techniques to obtain time series of surface/atmosphere exchange.

The objective of enclosure measurements was to quantify relationships of biogenic gas sources and sinks along major environmental gradients representative of the Yukon-Kuskokwim tundra. Topography and resulting surface and soil water conditions exert major controls over vegetation and soil composition (Figure 5a). These relationships were also hypothesized to mediate trace gas fluxes. Satellite remote sensing of the spatial distribution of surface environments was used to extrapolate point measurements of flux to the regional tundra environment [e.g., Bartlett et al., this issue; Whiting et al., this issue]. Relationships of flux with important physical variables such as temperature and light level were also studied. The trace gas species examined were CH₄ [Bartlett et al., this issue], CO₂ [Whiting et al., this issue], and several sulfur compounds [Hines and Morrison, this issue]. Soil profiles and depth to permafrost along selected transects were obtained using ground-penetrating radar techniques by Doolittle et al. [1990]. Studies were conducted in undisturbed sites accessible by road from Bethel, and in the area of the ABLE 3A micrometeorological tower.

The ABLE 3A micrometeorological tower facility is shown in Figure 6. The tower was located approximately 50 km WNW of Bethel (61°N, 162.5°W) and was accessible by float plane. Climatological data were used to site the tower in a location which would be subject to minimal local pollution effects.

Ground-based measurements were carefully coordinated with aircraft overflights to provide data for comparing estimates of CH₄ emissions from local to regional scales based on enclosure, tower, and airborne eddy correlation methods.

In addition to ABLE 3A investigators, the ground-based program included investigators sponsored by BREW and the NASA Interdisciplinary Research Program (Table 1).

### METEOROLOGICAL MEASUREMENTS

Meteorological forecasts during the ABLE field expedition were provided by a team of meteorologists stationed at the Anchorage National Weather Service Office. The Anchorage office receives extensive data, including both GOES and NOAA 9 polar orbiter imagery, all National Weather Service products, statewide surface observations, and a host of specialized computer-generated products tailored to the Alaska region.
In addition, a Micro-VAX-II computer from NASA was used to receive domestic, international, and model data through a satellite downlink from Zephyr Weather, Inc. This allowed a host of additional products to be generated and stored in near real time, including soundings, potential temperature time-height cross sections, and 12- to 48-hour forecast wind fields. All generated products were faxed to the aircraft location on a twice daily basis. Forecasts were updated via telephone and were available on an as needed basis.

Postmission meteorological analyses included a comparison of weather during the study period to climatological means, calculation of isentropic trajectories for air mass flow and source regions associated with each aircraft mission, and compilation of the active forest fires in Alaska during ABLE 3A. A summary of meteorological methods and results for ABLE 3A is provided by Shipham et al. [this issue].

This summary also serves as a guide to individual papers, which discuss the details of specific factors controlling the distribution of any particular trace gas or aerosol constituent.

Methane Sources and Sinks

Water-saturated soils and lake sediments are the primary sources of CH₄ in the Arctic and sub-Arctic landscapes studied in ABLE 3A. Dry tundra soils can reduce CH₄ concentrations below ambient concentrations in the atmospheric mixed layer, acting as a weak sink for tropospheric CH₄ [Whalen and Reeburgh, 1990]. In the Yukon-Kuskokwim Delta environments studied in ABLE 3A, CH₄ exchange rates ranged widely from -2 mg m⁻² d⁻¹ (net consumption of atmospheric CH₄) to net emissions as high as 400 mg m⁻² d⁻¹ [Bartlett et al., this issue]. A synthesis of published CH₄ flux data from high-latitude tundra sites by Bartlett et al. [this issue] was used to calculate an annual flux of approximately 11 ± 4 Tg CH₄ from the global tundra ecosystem. Scaling up the CH₄ flux data from the ABLE 3A micrometeorological tower produced an estimate of approximately 11 Tg CH₄ yr⁻¹ from global tundra [Fan et al., this issue]. Most previous estimates centered between 20 and 40 Tg yr⁻¹ [e.g., Sebacher et al., 1986; Whalen and Reeburgh, 1988]. It is significant to
note that these new, lower estimates of the tundra CH₄ source are very compatible with the preferred estimate derived with a global modeling technique [Fung et al., 1991]. The dominant factors determining the magnitude of CH₄ flux were soil moisture and soil temperature. Water-saturated soils typically emitted CH₄ at rates more than an order of magnitude greater than dry soils (Figure 7). The sensitivity of CH₄ flux rates from both saturated and moist
TABLE 2. Summary of the Flights Conducted During the ABLE 3A Expedition

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Time is GMT.

tundra to variations in soil temperature are also shown in Figure 7. In wet meadow tundra a 2°C increase in temperature at 10- to 20-cm soil depth increases the CH4 flux to the atmosphere approximately 120%. These results together with similar characterizations at other Arctic and boreal sites [e.g., Crill et al., 1988; Whalen and Reeburgh, 1988] indicate that a warming of several degrees centigrade during summer months in northern high latitudes could possibly produce a detectable increase in regional tropospheric ambient CH4 concentrations. A long-term monitoring program for ambient CH4 at sites downwind of extensive tundra could possibly provide an "early warning" of climate change effects in the Arctic.

Sources and Chemistry of Nitrogen Gases

The ABLE 3A results indicate that pollutant emissions from human activities in mid-latitude regions and emissions

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Fig. 5a. Schematic cross section of the type of environments studied by aircraft and ground-based investigations in the Yukon-Kuskokwim Delta region of Alaska during ABLE 3A.
Fig. 5b. An aerial perspective of the Yukon-Kuskokwim Delta, including the ABLE 3A ground site.
from sub-Arctic forest fires are sources of reactive nitrogen gases to the sub-Arctic and Arctic troposphere during summer months. The tundra ecosystem is a net sink for atmospheric nitrogen species. A brief synthesis of the ground and airborne nitrogen measurements is presented here as a guide to the detailed results presented in other papers in this issue [Bakwin et al., this issue; Sandholm et al., this issue; Jacob et al., this issue (a); Singh et al., this issue (a, b); Talbot et al., this issue; Wofsy et al., this issue].

Both ground and airborne measurements indicate that the sub-Arctic tundra ecosystem is a net sink for atmospheric nitrogen species. Bakwin et al. [this issue] report a near-continuous time series of NO, NO2, and total NOy measurements at the Lake ABLE ground site for July and August. The fluxes of NOx and NOy determined from these data indicate an emission rate for NO from the tundra surface to the atmosphere of 0.17 (+0.10) x 10^9 molecules cm^-1 s^-1. The mean dry deposition of NOy to the tundra was 2.0 (+1.0) x 10^9 molecules cm^-1 s^-1. The mean wet deposition rate for NOy to the Lake ABLE region during the ABLE study period was approximately 3.9 x 10^9 molecules cm^-1 s^-1 [Talbot et al., this issue]. Thus, the tundra was a net sink for atmospheric nitrogen species during this summer period.

Enhanced NOx and NOy concentrations observed at the Lake ABLE ground site during the study correlated with the long-range transport of emissions from forest fires into the Yukon-Kuskokwim Delta region. Forest fire emissions polluted a significant portion of the tropospheric column during episodes of westerly flow from the areas of active burning which were centered around the Yukon Flats region north of Fairbanks [Wofsy et al., this issue; Shipham et al., this issue; Harriss et al., this issue; Bakwin et al., this issue (a)].

The NOx levels associated with emissions from forest fires were often greater than 30 pptv, a level which would promote photochemical O3 production [Jacob et al., this issue; Singh et al., this issue (b)]. However, studies of haze...
layers derived from biomass burning indicate a relatively rapid conversion of NO$_x$ to PAN in the Alaska troposphere, with consequent low O$_3$ enhancements compared to tropical haze layers [Jacob et al., this issue (a); Wofsy et al., this issue].

The vertical distributions of PAN, NO, NO$_2$, HNO$_3$, and NO$_y$ indicate that the primary sources of these gases to the North American sub-Arctic and Arctic troposphere are a combination of stratospheric intrusions, long-range transport of pollutants from mid-latitude sources, and warm season biomass burning in sub-Arctic environments. The concentration of PAN increases with altitude, with highly variable concentrations above 3 km (e.g., <50 to >700 ppt). Singh et al. [this issue (a)] attribute the origin of PAN to a group of diverse sources, including injections of mid-latitude pollution during winter-spring "Arctic haze" events, forest fires, and stratospheric intrusions. It is likely that lightning and aircraft are also potentially significant sources of NO$_x$ to this region. The relative stability of PAN in the cold middle and upper Arctic troposphere promotes accumulation and a lifetime determined primarily by the dynamics of downward transport. In the atmospheric mixed layer (0-3 km), PAN concentrations are typically 0-50 ppt. PAN, and an as yet unidentified suite of organic nitrate gases (alkyl nitrites and pernitrates?), has the potential to control the summer NO$_x$ availability in the high-latitude troposphere and thus to determine O$_3$ concentrations and distribution [Singh et al., this issue (b); Jacob et al., this issue (a)]. Photochemical modeling indicated that decomposition of PAN alone could account fully for the NO$_x$ concentrations observed at 0- to 2-km altitude, but for only 20% of the NO$_x$ at 5-6 km.

**Ozone: Distribution and Variability**

The stratosphere was the dominant source of O$_3$ to lower tropospheric altitudes in the ABLE 3A study regions. Well-defined intrusions of O$_3$-rich air from the upper troposphere and stratosphere were directly observed with remote sensing to influence O$_3$ concentrations at altitudes of 1 km and lower [Browell et al., this issue]. The dynamical characteristics of stratosphere/troposphere exchange at high latitudes has been discussed by several authors [e.g., Gidel and Shapiro, 1980; Shapiro, 1980; Shapiro et al., 1987; Raatz et al., 1985].

The concentrations of NO$_x$ in the region studied were sufficiently low that photochemical processes were typically a net sink for tropospheric O$_3$ [Sandholm et al., this issue; Jacob et al., this issue (a)]. The extensive biomass burning in Alaska during summer 1988 had little impact on the observed tropospheric O$_3$ distributions [Gregory et al., this issue; Browell et al., this issue; Jacob et al., this issue (a); Wofsy et al., this issue]. Long-range transport of photochemically derived O$_3$ from the mid-latitudes into the study area was difficult to detect due to the relatively high "background" of O$_3$ derived from upper atmospheric sources. Jacob et al. [this issue (b)] combined the aircraft O$_3$ measurements to estimate an average 0- to 7-km O$_3$ column of approximately $6 \times 10^{11}$ molecules m$^{-2}$. Using the deposition flux average measured at the Lake ABLE tower of $-1.1 \times 10^{11}$ molecules cm$^{-2}$ s$^{-1}$ an O$_3$ lifetime of 8 months was calculated. If the time scale for ventilation of air north of 60°N is 2-3 months the Arctic cannot be viewed as an ultimate sink for O$_3$.

If the PAN and organic nitrates which decompose to produce NO$_x$ in the Arctic are derived, in part at least, from human activities, the lifetime of O$_3$ against photochemical loss may have already increased significantly. Increased NO$_x$ inputs would further reduce the capacity of the Arctic as a region for O$_3$ destruction; in particular, a doubling of NO$_x$ concentrations from present levels would lead to net O$_3$ photochemical production in the Arctic (Figure 8).

**Acidic Gases, Aerosols, and Precipitation**

The Arctic and sub-Arctic tropospheric regions studied during ABLE 3A were acidic. Formic and acetic acids were the principal acidic gases, the aerosol acidity was due to the presence of "excess" sulfate [Talbot et al., this issue]. The rainwater-free acidity (average pH = 4.69) in the Bethel area was derived from the carboxylic acids and H$_2$SO$_4$. Sources of these acids included marine and continental biogenic emissions, forest fires, and to a lesser extent, long-range transport of industrial pollutants.

Nitric acid is a major component of the nitrogen cycle in the boundary layer. Decomposition of PAN and biogenic emissions of NO are precursors for HNO$_3$ production, biomass burning, and long-range transport of industrial pollutants to the region contribute to episodic increases [Talbot et al., this issue; Bakwin et al., this issue; Jacob et al., this issue (a); Singh et al., this issue (a, b)]. The results of photochemical model simulations predict an HNO$_3$ concentration of 50 ppt for the boundary layer [Jacob et al., this issue (a)], the measured mean concentration was 59 ± 25 ppt [Talbot et al., this issue]. Nitric acid is the primary component of NO$_x$ dry deposition to the tundra ecosystem [Bakwin et al., this issue].

**Implications for Future Studies**

The results of ABLE 3A confirmed two major hypotheses which generated the study. First, emissions of CH$_4$ from the tundra ecosystem are sensitive to changes in climate variables such as soil moisture and temperature. Enclosure flux measurements, eddy correlation flux measurements from a ground-based tower, and airborne eddy correlation tech-
techniques for CH$_4$ flux measurement, all proved to be robust for use in studying emissions from the tundra landscape. Airborne flux measurements are most useful for surveying large areas to characterize relationships between major ecosystem parameters (e.g., distribution of vegetation type) and CH$_4$ flux. Tower-based eddy correlation and enclosure flux techniques can be best used to quantify specific response functions relating changes in CH$_4$ emissions to changes in soil climate.

Second, concentrations of NO$_x$ are critical to O$_3$ production/destruction processes in the relatively pristine high-latitude regions studied. At present, O$_3$ destruction processes dominate; however, NO$_x$ pollution from mid-latitude sources may have already reduced the capacity of the region to act as an O$_3$ sink [Jacob et al., this issue (a)].

These ABLE 3A results indicate that atmospheric chemical changes in the Arctic environment may serve as a unique early warning indicator of global change. If northern hemisphere NO$_x$ emissions continue to increase, particularly in the newly industrializing nations (e.g., Korea, China, India), Arctic O$_3$ levels could increase rapidly with significant implications for the northern hemisphere and, perhaps, the global environment. Future studies should emphasize determining the pathways and mechanisms of the transport and fate of NO$_x$ to the Arctic from mid-latitude pollution sources.

Methane flux from tundra environments may be one of the most sensitive, integrative indicators of climate change effects on the Arctic biosphere. A long-term monitoring program of CH$_4$ flux at a network of sites in the tundra ecosystem, in combination with enhanced monitoring of ambient air CH$_4$ trends, could contribute to early detection of climate change effects in the Arctic.

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