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

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

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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_y), 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

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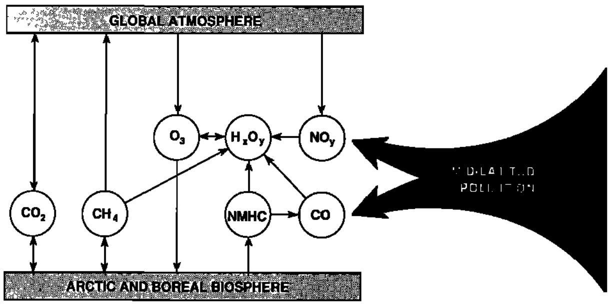

Fig. 1. A schematic illustration of interactions of the biosphere, climate, and long-range transport of pollutants as sources and/or sinks for atmospheric trace gases in northern high-latitude regions.

include detrimental effects on Arctic ecosystems. Or increased deposition of nitrogen could enhance biosphere-atmosphere gas exchange with subsequent effects on atmospheric gases like CO_2 and CH_4. Another concern is changes in the chemistry of "baseline" Arctic air, which is a major source region for north-to-south flow across North America and other regions. Thus, information on Arctic and sub-Arctic air chemistry is essential to resolving controversial issues like natural versus human contributions to acid rain and ozone pollution in the mid-latitudes.

Chemistry-Climate Connection

The ABLE 3A program was focused on high-latitude (>50°N) regions because almost all climate models and paleoenvironmental studies indicate that these regions are especially sensitive to climatic change. Several review papers have appeared recently which provide excellent summaries of the theoretical basis for predicting a tropospheric warming trend in response to increasing atmospheric trace gas concentrations [e.g., *Dickinson*, 1986; *Ramanathan et al.*, 1987]. There are also some empirical data which indicate increasing permafrost temperatures [*Lachenbruch and Marshall*, 1986], suggesting that certain regions of the high-latitude biosphere may be experiencing the early stages of a warming. Biospheric responses to a variable climate are feedback processes which could accelerate or modulate rates of climate change. Examples of potential feedbacks have been documented by direct measurement of trace gas exchange rates in response to seasonal climate changes, and by inference from correlations of trace gas concentrations and isotopically derived temperature records in ice cores. For example, studies of variations of trace gases of biospheric origin such as CO_2 and CH_4 in ice cores suggest that atmospheric composition has been closely coupled to atmospheric temperature in polar regions for at least the past 160,000 years [e.g., *Raynaud et al.*, 1988; *Chappellaz et al.*, 1990].

A more direct indication of initial feedbacks to climate change can be derived from field and experimental studies of CH_4 exchange rates between northern peatland soils and the atmosphere in response to seasonal variations in soil temperature and moisture. In both tundra and boreal environments CH_4 flux to the atmosphere has been shown to be sensitive to seasonal climatic variations [e.g., *Sebacher et al.*, 1986; *Moore and Knowles*, 1987; *Crill et al.*, 1988; *Whalen and Reeburgh*, 1988; *Bartlett et al.*, this issue]. Methane flux increases in response to increasing soil temperatures in water-saturated organic soils. Soil drying decreases CH_4 emissions. Experimental studies on tundra soil cores indicate the opposite behavior for CO_2 flux; aerobic decomposition which produces CO_2 is the dominant process in dry soils [e.g., *Billings*, 1987]. Thus, a warmer, wetter climate might enhance CH_4 flux from northern peatland environments. A warmer, dryer climate might result in reduced CH_4 emissions and enhanced CO_2 flux.

Potential trace gas feedbacks to climate change in northern tundra environments can be expected to operate on at least three time scales: (1) Changes in CH_4 flux from the near-surface "active" soil layer in response to seasonal or interannual climate variations will be the initial signal of a biospheric feedback. (2) Gradual climate change on decadal to century time scales could alter permafrost, a warming trend would release trapped CH_4 from the permafrost and increase the depth of the seasonal active layer. (3) A long-term dramatic warming of the Arctic (e.g., an ice-free condition) could lead to a release of CH_4 from presently frozen methane hydrates found at considerable depth below the surface. The ABLE 3 is focused on understanding the "early warning" response of the near-surface, organic active layer to climate variability.

Several preliminary modeling studies have also been conducted to explore potential interactions between climate change and 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 CH_4 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 CH_4 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 CH_4 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: O_3 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 O_3 at Barrow, Alaska [*Oltmans and Komhyr*, 1986] is a potential indicator of an increasing degree of Arctic pollution. However, the 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 O_3 budget in the Barrow region during the summer period.

A component of ABLE 3A O_3 studies was to determine the sources of nitrogen oxides (NO_x) and total reactive nitrogen (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 NO_x and NO_y. Under natural conditions, the Arctic region should be an important low-NO_x region for testing photochemical theory on the role of NO_x in 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 NO_x to influence photochemical 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 CO_2 and 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 nonmethane hydrocarbon species which are important in O_3 chemistry. As a long-term strategy, the ABLE missions are designed to study O_3 production and destruction processes in atmospheric boundary layer environments which have characteristics of low NO_x/low NMHC (tundra), low NO_x/high NMHC (boreal forest), low NO_x/high NMHC (wet season tropical forest), intermediate NO_x/high NMHC (dry season, unpolluted tropical forest), high NO_x/high NMHC (polluted tropical and boreal forests), and high 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 Biospherics 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 CH_4, CO, and 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 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-

TABLE 1. Principal Investigators Participating in ABLE 3A

Investigator	Institution	Investigation
	Tropospheric Chemistry Program	
John Barrick	NASA Langley Research Center	Airborne meteorological/position data (a)
John Bradshaw	Georgia Institute of Technology	Nitric oxide, nitrogen dioxide, NO_y (a)
Edward V. Browell	NASA Langley Research Center	Aerosols, ozone profiles (a)
David R. Fitzjarrald	State University of New York at Albany	Micrometeorological studies (s)
Gerald L. Gregory	NASA Langley Research Center	Ozone, aerosol size (a)
Robert C. Harriss	NASA Langley Research Center	Carbon dioxide/Mission Scientist (a)
Paul Kebabian	Aerodyne Research, Inc.	Methane (s)
Enio Pereira	Instituto de Pesquisas Espaciais, Brazil	Radon (a)
John Ritter	NASA Langley Research Center	Eddy correlation flux (CO, CH_4, O_3, H_2, H_2O) (a)
F. Sherwood Rowland	University of California at Irvine	Nonmethane hydrocarbons (a)
Glen W. Sachse	NASA Langley Research Center	Carbon monoxide, methane (a)
Hanwant Singh	NASA Ames Research Center	PAN, PPN, CCl_4 (a)
Robert W. Talbot	NASA Langley Research Center	Aerosol composition, nitric and organic acids (a)
Steven C. Wofsy	Harvard University	Carbon dioxide (a)
		Nitrogen species (NO, NO_2, NO_y) (s)
		Eddy correlation flux (O_3, CO_2, NO_y) (s)
	Biospheric Research Program (s)	
David S. Bartlett	NASA Langley Research Center	CO_2 exchange/Mission scientist
Michael Hardisky	University of Scranton	Below-ground biomass/radar
Karen B. Bartlett	College of William and Mary	Methane flux
Mark Hines	University of New Hampshire	Sulfur flux
Gary King	University of Maine	Methane oxidation
Vic Klemas	University of Delaware	Below-ground biomass/radar
Christopher Martens	University of North Carolina	Radon/CH_4 Isotopes
	Interdisciplinary Program (s)	
Patrick Crill	University of New Hampshire	Methane flux

(a), airborne; (s), surface.

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 5*a* and 5*b*).

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 5*a*). 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 CH_4 [*Bartlett et al.*, this issue], CO_2 [*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 CH_4 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 orbitor imagery, all National Weather Service products, statewide surface observations, and a host of specialized computer-generated products tailored to the Alaska region.

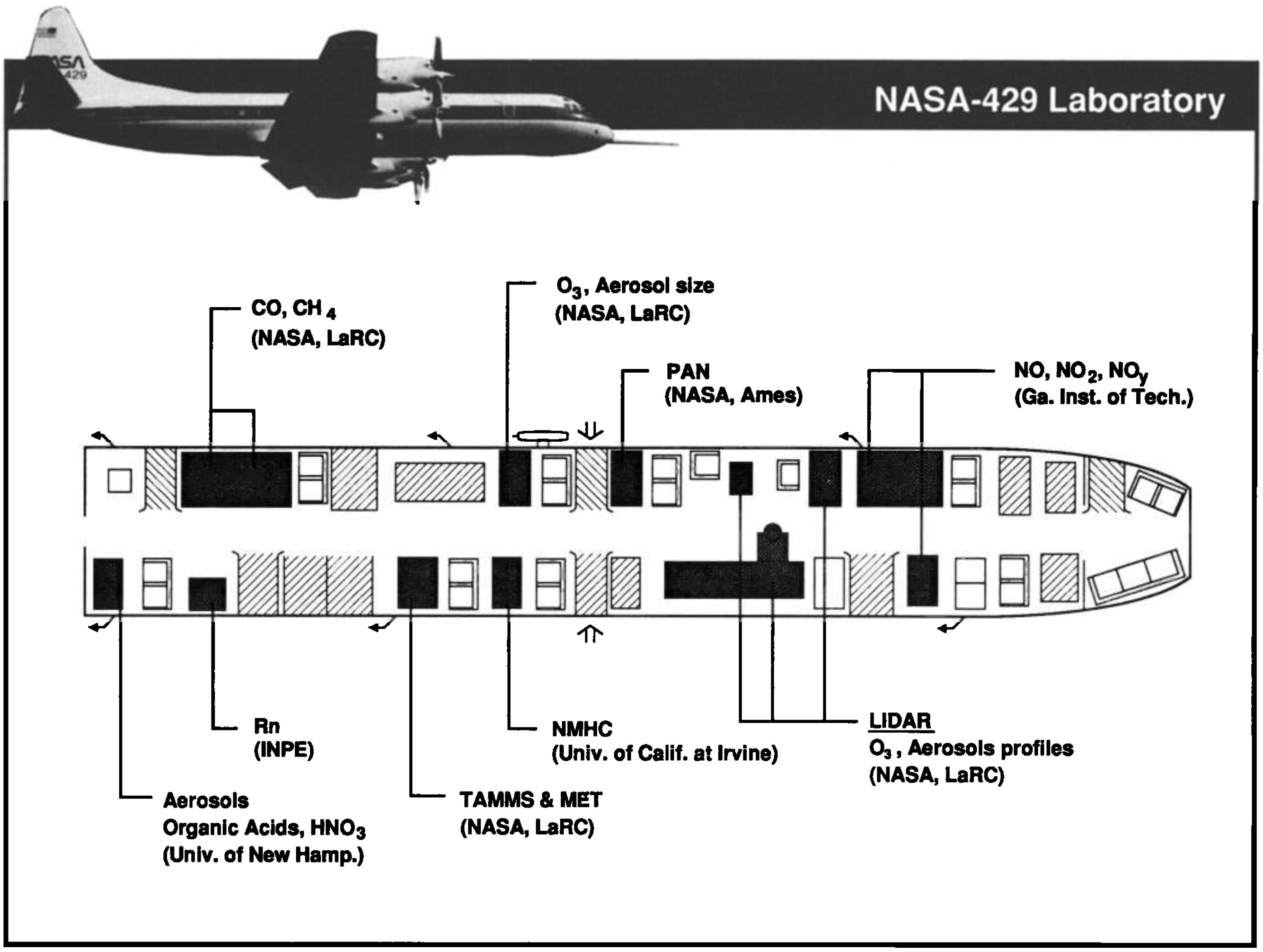

Fig. 2. The NASA Electra research aircraft and a diagram of the location of instrumentation during ABLE 3A.

In addition, a Micro-VAX-II computer from NASA was used to receive domestic, international, and model data through a satellite downlink from Zeypher 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].

OVERVIEW OF RESULTS

In this brief overview of results, we highlight selected findings from individual investigations which relate directly to the primary objectives of the expedition. It is hoped that this summary will serve the reader who may not be able to pursue study of the entire collection of ABLE 3A papers. 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 CH_4 in the Arctic and sub-Arctic landscapes studied in ABLE 3A. Dry tundra soils can reduce CH_4 concentrations below ambient concentrations in the atmospheric mixed layer, acting as a weak sink for tropospheric CH_4 [*Whalen and Reeburgh*, 1990]. In the Yukon-Kuskokwim Delta environments studied in ABLE 3A, CH_4 exchange rates ranged widely from -2 mg m^{-2} d^{-1} (net consumption of atmospheric CH_4) to net emissions as high as 400 mg m^{-2} d^{-1} [*Bartlett et al.*, this issue].

A synthesis of published CH_4 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 CH_4 from the global tundra ecosystem. Scaling up the CH_4 flux data from the ABLE 3A micrometeorological tower produced an estimate of approximately 11 Tg CH_4 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

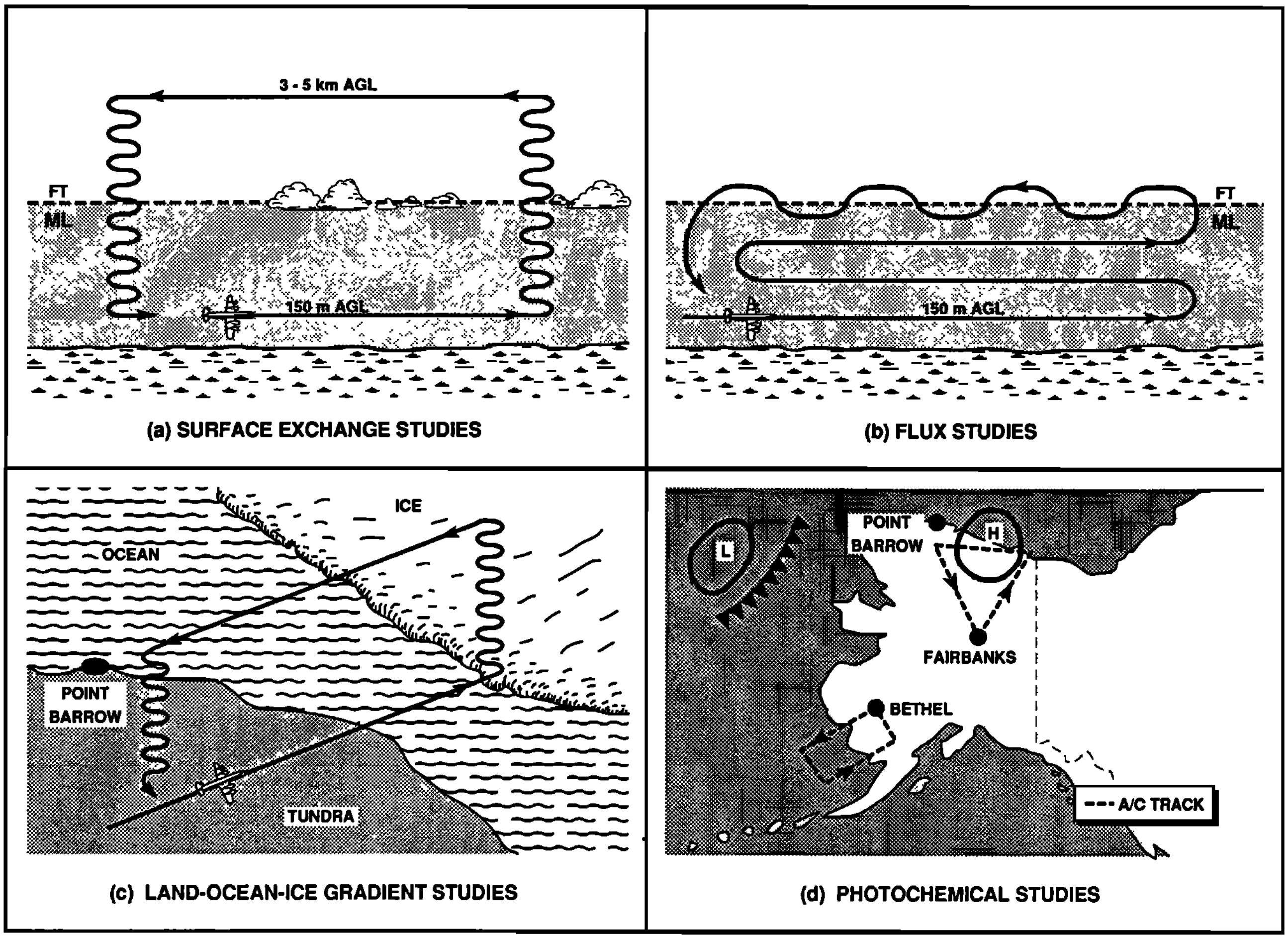

Fig. 3. Simplified illustrations of flight profiles used in ABLE 3A.

note that these new, lower estimates of the tundra CH_4 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 CH_4 flux were soil moisture and soil temperature. Water-saturated soils typically emitted CH_4 at rates more than an order of magnitude greater than dry soils (Figure 7). The sensitivity of CH_4 flux rates from both saturated and moist

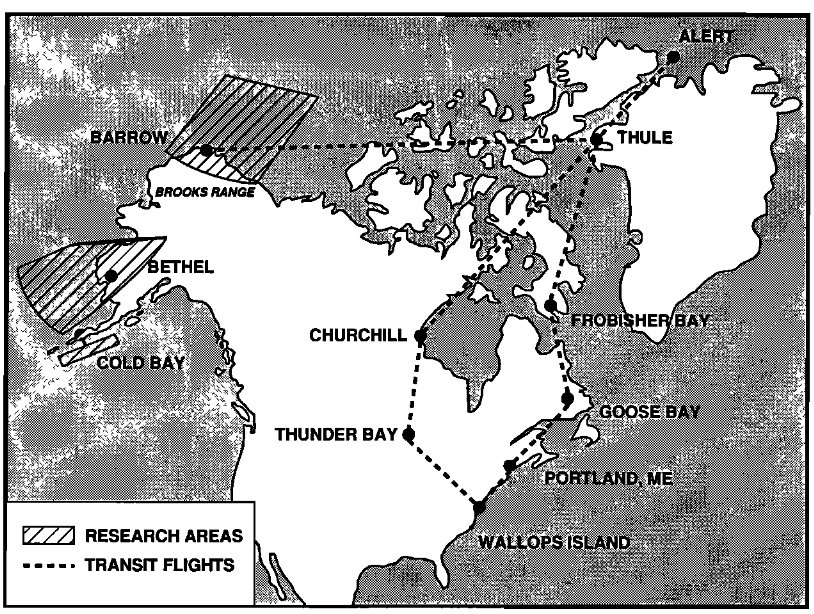

Fig. 4. Map of the regions studied by ABLE 3A.

TABLE 2. Summary of the Flights Conducted During the ABLE 3A Expedition

Mission Number	Flight Date	Departure Time	Departure Location	Arrival Time	Arrival Location	Purpose
1	July 7	1312	NASA Wallops Island	1700	Thunder Bay	Mid-troposphere distributions
2	July 7	1813	Thunder Bay	2108	Churchill	Mid-troposphere distributions
3	July 8	1356	Churchill	1845	Thule	Mid-troposphere distributions
4	July 9	1250	Thule	1844	Fairbanks	Mid-troposphere distributions
5	July 10	1951	Fairbanks	2329	Barrow	Mid-troposphere distributions
6	July 12–13	2332	Barrow	0304	Barrow	Correlations
7	July 13–14	1945	Barrow	0043	Barrow	Boundary layer composition
8	July 15–16	2033	Barrow	0046	Barrow	Boundary layer composition
9	July 17	1756	Barow	2309	Barrow	Vertical distributions
10	July 18–19	1925	Barrow	0048	Barrow	Flux measurements
11	July 19–20	2024	Barrow	0153	Barrow	Vertical distributions
12	July 21–22	2303	Barrow	0349	Barrow	Vertical distributions
13	July 24	1801	Barrow	2343	Bethel	Mid-troposphere distributions
14	July 26–27	2007	Bethel	0033	Bethel	Vertical distributons
15	July 27–28	2351	Bethel	0503	Bethel	Vertical distributions/correlations
16	July 28–29	1955	Bethel	0107	Bethel	Flux measurements
17	July 29–30	1859	Bethel	0016	Bethel	Land-sea interface
18	July 31	1707	Bethel	2214	Bethel	Flux measurements
19	Aug. 2–3	1855	Bethel	0010	Bethel	Land-sea interface
20	Aug. 3	1800	Bethel	2220	Bethel	Vertical distributions
21	Aug. 4	0001	Bethel	0404	Bethel	Vertical distributions
22	Aug. 7	1902	Bethel	2157	Cold Bay	Mid-troposphere distributions
23	Aug 7–8	2329	Cold Bay	0419	Cold Bay	Vertical distributions
24	Aug. 8	2206	Cold Bay	2331	Bethel	Mid-troposphere distributions
25	Aug. 9	0131	Bethel	0645	Bethel	Land-sea interface
26	Aug. 9–10	2057	Bethel	0156	Bethel	Flux measurements
27	Aug. 11–12	2136	Bethel	0015	Barrow	Mid-troposphere distributions
28	Aug. 12	1723	Barrow	2224	Thule	Mid-troposphere distributions
29	Aug. 13	1330	Thule	1836	Thule	Mid-troposphere distributions
30	Aug. 15	1200	Thule	1636	Frobisher Bay	Mid-troposphere distributions
31	Aug. 15	1719	Frobisher Bay	2108	Goose Bay	Mid-troposphere distributions
32	Aug. 16	1333	Goose Bay	1750	Portland	Mid-troposphere distributions
33	Aug. 17	1340	Portland	1708	NASA Langley	Mid-troposphere distributions

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 CH_4 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 CH_4 concentrations. A long-term monitoring program for ambient CH_4 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

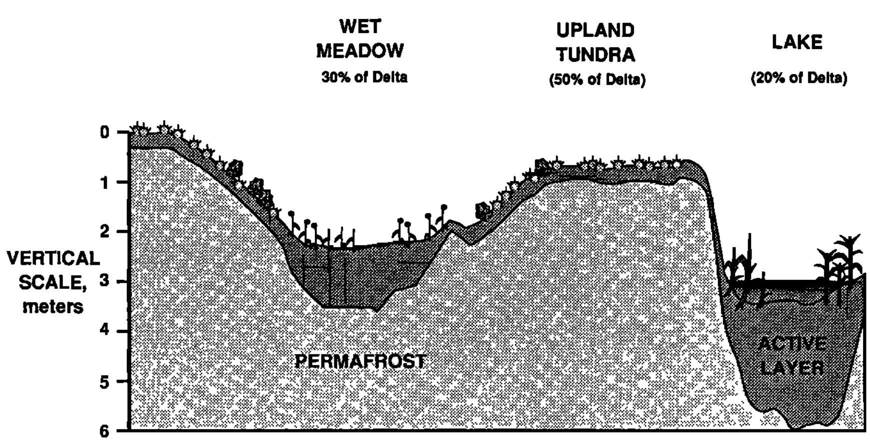

Fig. 5*a*. Schematic cross section of the type of environments studied by aircraft and ground-based investigations in the Yukon-Kuskokwim Delta region of Alaska during ABLE 3A.

Fig. 5*b*. An aerial perspective of the Yukon-Kuskokwim Delta, including the ABLE 3A ground site.

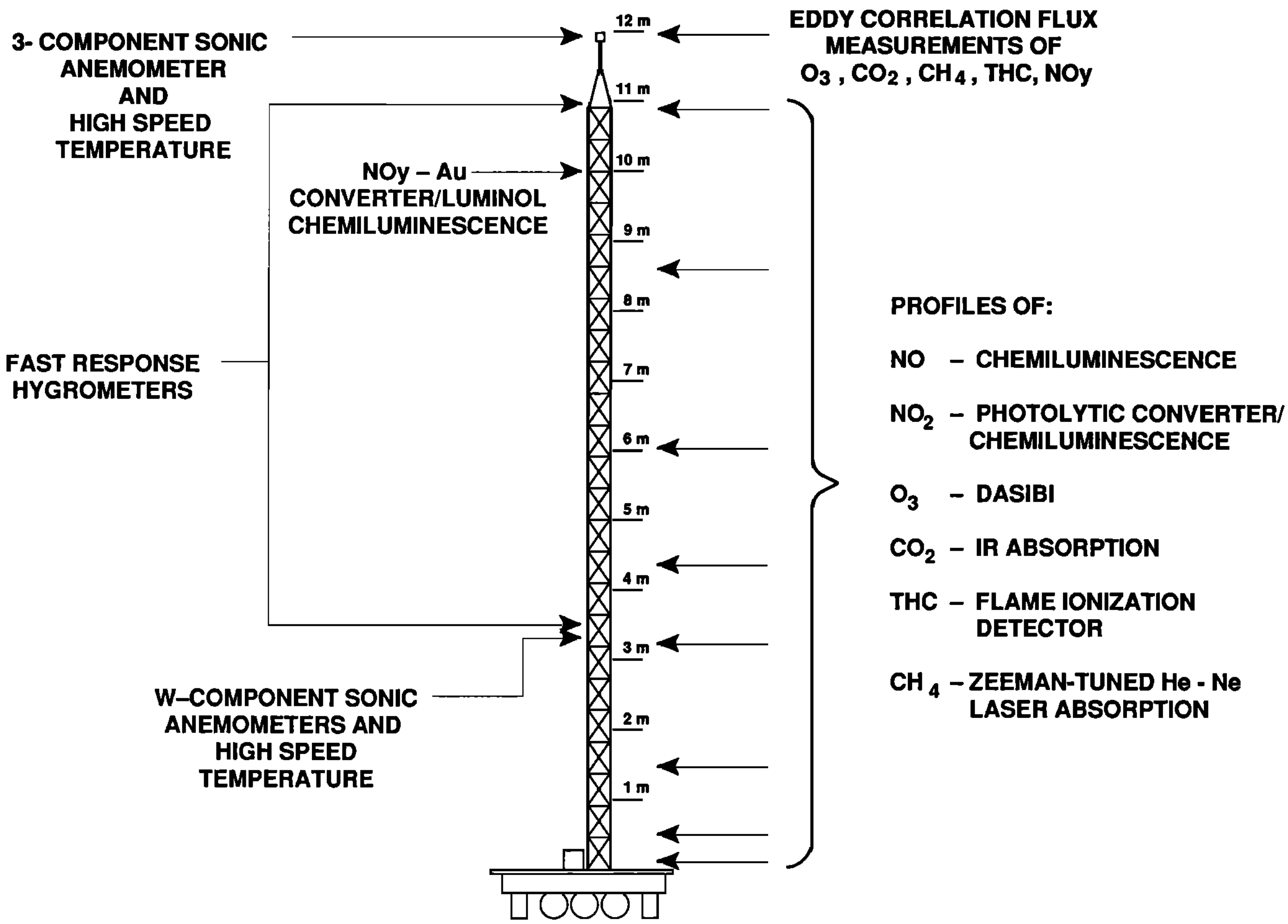

Fig. 6. Ground-based micrometeorological tower used for conducting flux measurements in a tundra environment near Bethel, Alaska.

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

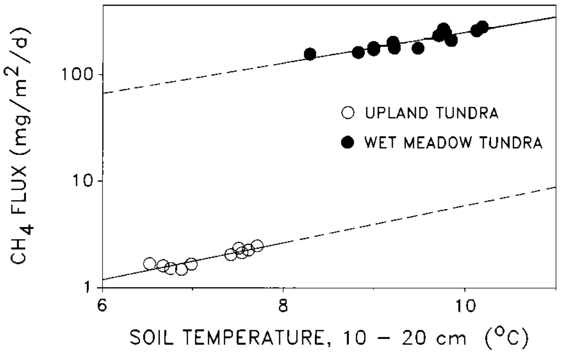

Fig. 7. Fluxes of methane from two ABLE 3A study sites [*Bartlett et al.*, this issue].

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, NO_2, and total NO_y measurements at the Lake ABLE ground site for July and August. The fluxes of NO_x and NO_y determined from these data indicate an emission rate for NO from the tundra surface to the atmosphere of 0.17 ($\pm$.10) $\times$ 10^9 molecules cm^{-1} s^{-1}. The mean dry deposition of NO_y to the tundra was 2.0 ($\pm$1.0) $\times$ 10^9 molecules cm^{-1} s^{-1}. The mean wet deposition rate for NO_3^- to the Lake ABLE region during the ABLE study period was approximately 3.9 $\times$ 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 NO_x and NO_y 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 NO_x levels associated with emissions from forest fires were often greater than 30 pptv, a level which would promote photochemical O_3 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_y 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 (alkylnitrates 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 6×10^{21} molecules m^{-2}. Using the deposition flux average measured at the Lake ABLE tower of -1.1×10^{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).

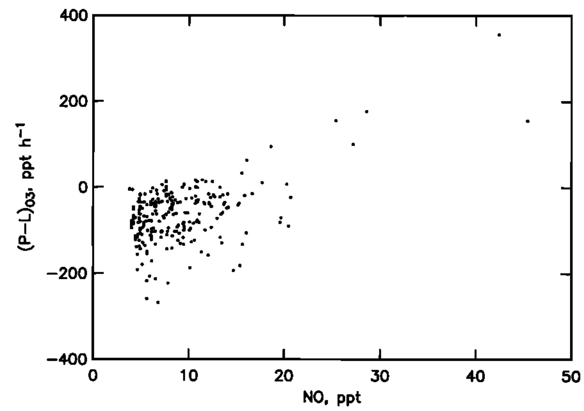

Fig. 8. Photochemical production minus loss rate of O_3, $(P - L)_{O3}$, as a function of NO concentration. Results are shown for 475 individual points from flights 11–25 where detailed aircraft measurements of atmospheric composition are available. The rates were obtained using a photochemical model [*Jacob et al.*, this issue (*a*)]. The ensemble of points covers the altitude range 0.1–6.2 km and the temporal range 0600–1915 solar time.

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_2SO_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_y 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 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_y 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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