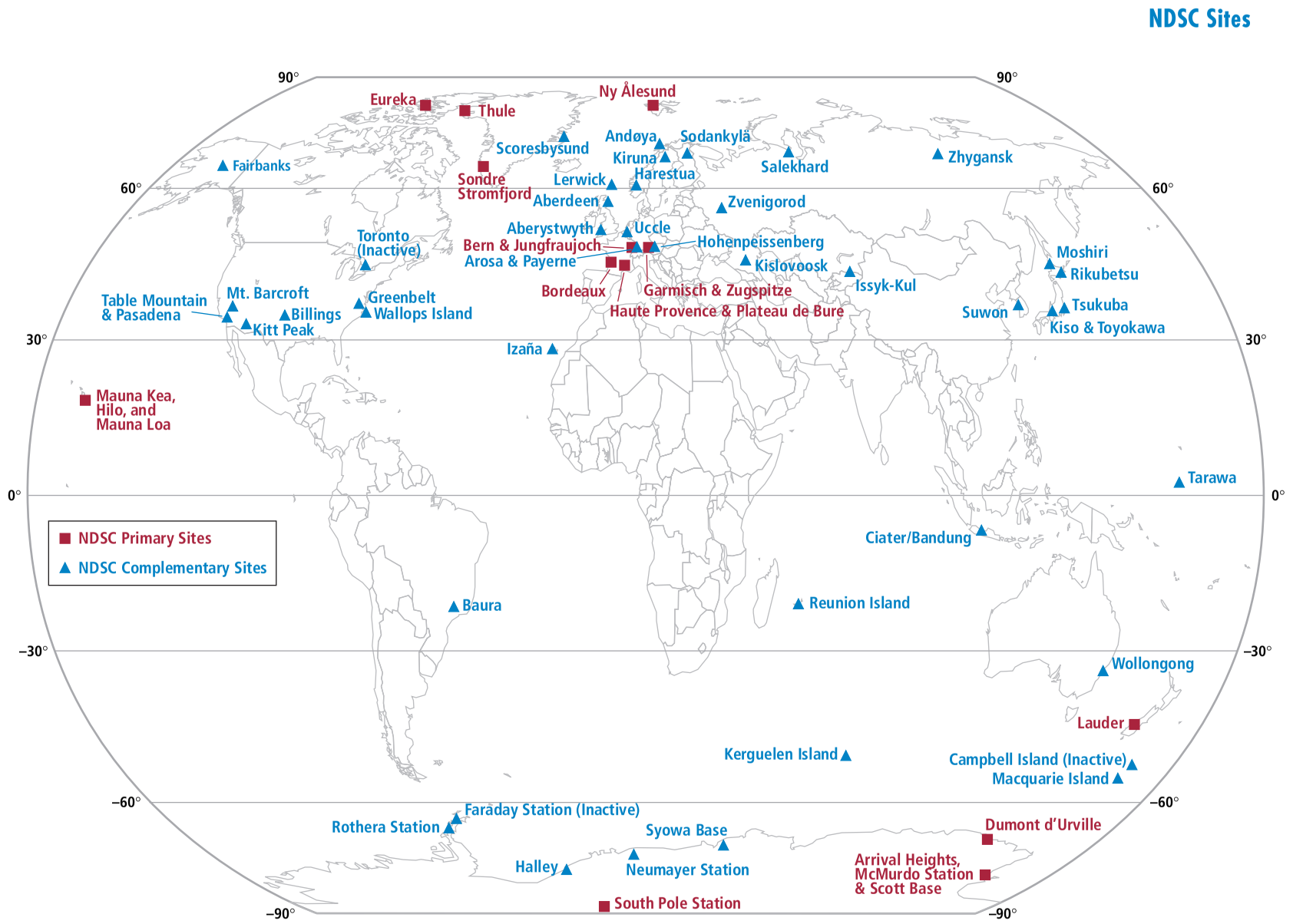
# Network *for the* Detection *of* Stratospheric Change

A long-term international scientific investigation of the ozone layer and its links to global climate

**Cover photo** shows the laser beam of the aerosol lidar instrument at Ny Ålesund, Spitsbergen, measuring polar stratospheric clouds and sulfuric acid aerosols during the polar night.



## Summary

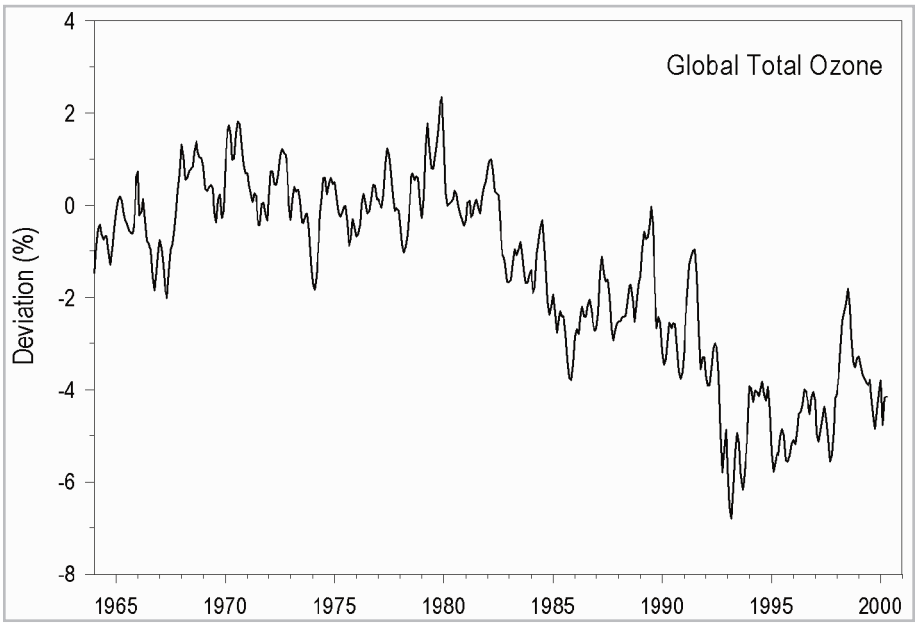
The atmosphere has undergone considerable change due to human influences over the last 30 years. Perhaps the most spectacular is the formation of the Antarctic ozone hole. Ozone depletion in the stratosphere, with harmful consequences for life, alerted the world community to the fragility of the atmospheric environment. This resulted in the signing of the Montreal Protocol and its Amendments and Adjustments to restrict the release of ozone-destroying industrial chemicals into the atmosphere. Evidence of ongoing atmospheric change has led to important questions for policymakers and the world community. *How will stratospheric ozone respond as the abundance of ozone-destroying chemicals decreases? How will atmospheric composition respond to and influence climate?* In this regard, comprehensive yet focused atmospheric research has never been more vital.

The international Network for the Detection of Stratospheric Change (NDSC) was formed to provide a consistent, standardized set of long-term measurements of atmospheric trace gases, particles, and physical parameters via a suite of globally distributed sites. Such measurements constitute the scientific bedrock upon which sound policy decisions are based. Since its creation 10 years ago, the NDSC has contributed to the understanding of stratospheric ozone depletion at the poles and midlatitudes, and documented the increase and leveling-off of ozone-depleting chemicals in the atmosphere and the continued growth of greenhouse gases. The NDSC is supported by national and international agencies.

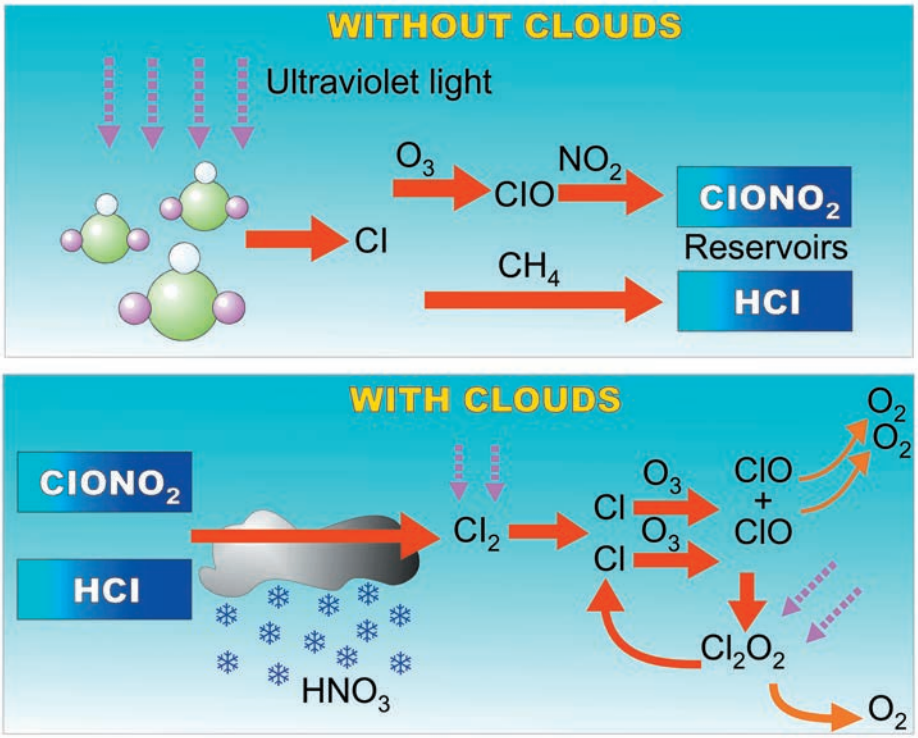
## Introduction

The stratosphere, which spans from about 10 to 50 km altitude, is a key component of the interactive global system that determines atmospheric composition and climate. It is the location of the ozone layer, which both absorbs ultraviolet (UV) radiation harmful to the biosphere and is itself a contributor to the greenhouse effect. Many long-lived gases, both natural and man-made, are broken down in the stratosphere and destroy ozone. In addition, some of these gases also contribute to the greenhouse effect. Stratospheric aerosols are important in determining the chemical composition and radiative balance of the stratosphere. Through the absorption of solar radiation and mixing with the air above and below it, the stratosphere influences the composition of the entire atmosphere. The stratosphere has undergone significant changes over the last 30 years due to human influences. Such changes are expected to continue for decades before they eventually decline. It is vital that scientists document and understand these changes and further our capability to forecast the future state of the atmosphere.

The Network for the Detection of Stratospheric Change (NDSC) was established to help meet these research needs. It is based on a set of high-quality, remote-sensing research stations for observing and understanding the physical and chemical state of the stratosphere and for assessing the impact of changes in the stratosphere on the underlying troposphere and on global climate. The measurement priorities include ozone, key parameters such as temperature and aerosols that affect the ozone layer, and tracers of chemistry and atmospheric motions. The current NDSC operates at more than 60 locations worldwide and is supported by ozone soundings, satellite measurements, and other existing ground-based monitoring networks. Over 250 scientists from at least 20 countries are currently




Deviations from the 1964–1980 level for global total ozone estimated from ground-based measurements




Simplified chemistry scheme showing the activation of stratospheric chlorine with and without the presence of polar stratospheric clouds

involved with NDSC research activities, funded by national and international agencies.

The NDSC formally began operation in January 1991, following five years of planning, instrument design, and implementation. There have been a number of important scientific and policy developments since its inception—in particular, the identification of the deepening and widening of the Antarctic ozone hole and the similar, although less-pronounced, ozone loss over the Arctic; the detection of evidence for worldwide ozone decreases at midlatitudes; the implementation of the Montreal Protocol on Substances that Deplete the Ozone Layer and its Amendments and Adjustments; and the negotiation of the Kyoto Protocol to the UN Framework Convention on Climate Change. These developments have all served to emphasize the importance of a high-quality, long-term monitoring network focusing on stratospheric changes. The NDSC was in place to contribute to the quantification and understanding of such changes, and it will play an equally important role in the detection of the future stabilization and recovery of the ozone layer.

The NDSC is a major component of the international atmospheric research effort and has been endorsed by national and international scientific agencies, including the United Nations Environment Programme (UNEP) and the International Ozone Commission of the International Association of Meteorology and Atmospheric Sciences. Since 1993, the NDSC has been a contributing part of the World Meteorological Organization (WMO) Global Atmosphere Watch (GAW) Programme, and the WMO considers NDSC participation to be an important complementary component.

This publication summarizes the current status of the NDSC and provides an overview of some typical activities. More information can be found on the NDSC Web site (www.ndsc.ws).

## Table 1 Measurement Priorities

| *Measurement* | | *Instrument Types* | *Rationale* |
|---|---|---|---|
| $O_3$ total column | | Dobson; Brewer; other UV/Visible spectrometers | Controls penetration of UV radiation to troposphere and ground |
| $O_3$ profile | 0–18 km<br>15–60 km<br>12–65 km<br>0–32 km | DIAL[(1)] ($\lambda$<300 nm)<br>DIAL ($\lambda$>300 nm)<br>μwave[(2)] radiometers<br>ozonesondes | Determines stratospheric temperature structure; influences circulation and climate; important greenhouse gas in the troposphere |
| Temperature | 15–35 km<br>30–95 km | Raman lidars<br>Rayleigh lidars | Determines rates of chemical reactions and dynamics of stratosphere; controls vertical transport and $H_2O$ content near tropopause; influenced by greenhouse gases |
| ClO profile | 25–45 km | μwave radiometers | Catalyzes $O_3$ destruction |
| $H_2O$ profile | 0–15 km<br>0–30 km<br>40–80 km | Raman lidars<br>hygrometer sondes<br>μwave radiometers | Controls radiative and chemical balance of the stratosphere; tracer of troposphere/stratosphere exchange; main source of OH in the stratosphere; affects climate |
| Aerosol distribution | 0–30 km | backscatter lidars<br>backscatter sondes | Influences climate; initiates heterogeneous processes in particular at high latitudes; affects optical sensor data reduction |
| $NO_2$ stratospheric column | | UV/Visible and FTIR[(3)] spectrometers | Provides catalytic control of $O_3$ coupling of $NO_X$, $HO_X$ and $Cl_X$ cycles |
| HCl and $ClONO_2$ columns | | FTIR spectrometers | Main inorganic chlorine (Cl) reservoirs of key relevance in stratospheric heterogeneous activation processes |
| $N_2O$, $CH_4$, and CFCs columns and stratospheric profiles | | FTIR spectrometers<br>μwave radiometers | Tracers of atmospheric transport; provide reference systems for interpretation of ozone changes; important greenhouse gases |
| $HNO_3$ and NO columns | | FTIR spectrometers | Important compounds of the $NO_y$ family |
| HF and $COF_2$ columns | | FTIR spectrometers | Main inorganic fluorine (F) species in the stratosphere |
| Other species (OH, $HO_2$, OCS, ...) | | UV fluorescence lidars; μwave radiometers, FTIR spectrometers | Regulate stratospheric oxidation capacity, sulfate aerosol loading |
| UV radiation at the ground | | UV spectroradiometers | Increases as $O_3$ decreases; affects oxidation capacity of troposphere and thus lifetimes of greenhouse gases, adverse effects on humans and biosphere |

*(1) differential absorption lidar; (2) microwave; (3) Fourier transform infrared*

## Principal Goals *of the* NDSC

The initial goals of the Network have been expanded to address the broader scope of atmospheric change and related concerns. The current objectives of the NDSC are

- to study the temporal and spatial variability of atmospheric composition and structure in order to provide early detection and subsequent long-term monitoring of changes in the physical and chemical state of the stratosphere and upper troposphere; in particular, to provide the means to discern and understand the causes of such changes;
- to establish the links between changes in stratospheric ozone, UV radiation at the ground, tropospheric chemistry, and climate;
- to provide independent calibrations and validations of space-based sensors of the atmosphere and to make complementary measurements;
- to support field campaigns focusing on specific processes occurring at various latitudes and seasons; and
- to produce verified data sets for testing and improving multidimensional chemistry and transport models of both the stratosphere and troposphere.

Water vapor microwave instrument operating at Mauna Loa, Hawaii

## Measurement Priorities *and* Rationale

The objectives of the NDSC require high-precision, state-of-the-art measurements of not just ozone but also of a broad range of chemical species and long-lived tracers that influence ozone and climate. Such measurements are needed to determine whether stratospheric changes are due to chemistry or to atmospheric transport and dynamics. Table 1 lists the measurements of highest priority to the NDSC. These priorities are based on the assumption of continued satellite measurements as well as ground-level monitoring of ozone and long-lived source gases by existing networks. Remote-sensing instruments were selected for their capability for continuous, long-term field operation, potentially in isolated locations. The aim is to equip the primary NDSC stations with the full set of instruments listed in Table 1, subject to specific site characteristics such as geography and meteorology, in order to make the most complete and internally consistent set of measurements. The current measurement capabilities at NDSC sites and stations are listed on the NDSC Web site.

## Table 2 Location of Primary Stations

| | *Latitude* | *Longitude* | *Altitude (m asl)** |
|---|---|---|---|
| **Arctic Stations** | | | |
| Eureka, Canada | 80.1° N | 86.4° W | 610 |
| Ny Ålesund, Spitsbergen | 78.9° N | 11.9° E | 15 |
| Thule, Greenland | 76.5° N | 68.8° W | 30–220 |
| Sondre Stromfjord, Greenland | 67.0° N | 50.6° W | 180–300 |
| **Alpine Stations** | | | |
| Garmisch/Zugspitze, Germany | 47.5° N | 11.1° E | 734/2,964 |
| Bern, Switzerland | 47.0° N | 7.5° E | 550 |
| Jungfraujoch, Switzerland | 46.5° N | 8.0° E | 3,580 |
| Observatoire de Bordeaux, France | 44.9° N | 0.5° W | 73 |
| Plateau de Bure, France | 44.6° N | 5.9° E | 2,550 |
| Observatoire de Haute Provence, France | 43.9° N | 5.7° E | 650 |
| **Hawaii Stations** | | | |
| Mauna Kea, Hawaii | 19.8° N | 155.5° W | 4,204 |
| Hilo, Hawaii | 19.7° N | 155.1° W | 11 |
| Mauna Loa, Hawaii | 19.5° N | 155.6° W | 3,397 |
| **New Zealand Station** | | | |
| Lauder, New Zealand | 45.0° S | 169.7° E | 370 |
| **Antarctic Stations** | | | |
| Dumont d'Urville | 66.7° S | 140.0° E | 20 |
| Arrival Heights | 77.8° S | 166.7° E | 250 |
| McMurdo Station | 77.9° S | 166.7° E | 10 |
| Scott Base | 77.9° S | 166.8° E | 22 |
| South Pole Station | 90.0° S | — | 2,835 |

**m asl*, meters above sea level.

## Network Deployment *and* Station Considerations

In order to provide early identification of changes in the stratosphere and upper troposphere, the locations of NDSC stations have been selected to provide as much latitudinal coverage as possible, given the obvious constraints of funding and resources. A minimal operational network should consist of seven fully equipped primary stations: polar, midlatitude, and tropical in both hemispheres, plus an equatorial station. It is desirable that the

NPL-NIWA FTIR intercomparison, Lauder, New Zealand

monitoring stations be located at relatively dry, pollution-free sites. For some instruments, it also is important to operate at a high elevation (>2,000 m asl, or even higher in the tropics) in order to minimize the interfering effects of low-altitude water vapor and aerosols. The goal of understanding the cause of changes, rather than merely detecting them, requires that the instruments be colocated to an extent consistent with the temporal and spatial requirements of the measurements and the realities of site availability. Where it was not feasible to colocate instruments on the same site, a composite station has been formed with instruments at different sites within reasonable distances.

The NDSC currently comprises the five primary stations listed in Table 2, most of which are composite sites. The geographic coverage of the Network is enhanced by more than 40 other sites where complementary measurements of one or more of the parameters of interest are performed. The full network of sites currently affiliated with the NDSC is shown on the map on the inside front cover. More sites will be added to the Network when they meet the NDSC protocols and data-quality criteria. Particular efforts are being made to identify facilities and involve groups in Asia, Africa, and South America.

The complementary site at the Ile de la Réunion (21.8° S, 55.5° E) is expected to develop into the primary Southern Hemisphere subtropical station, as a counterpart to the Hawaiian station in the Northern Hemisphere subtropics. The Table Mountain Facility in the United States (34.4° N, 117.7° W) acts as an intercomparison and test research site for many of the primary instruments. No equatorial station has been selected yet; possible sites are being evaluated in Africa, South America, and the central Pacific.

## Organization

Measurement and analysis activities within the NDSC are conducted by a science team composed of all the instrument Principal Investigators (PIs). Activities are coordinated through Working Groups organized by instrument type and by relevant activities such as satellites, theory and modeling, data archiving, or network interactions.




A Eureka, Canada

B Thule, Greenland

C Ny Ålesund, Spitsbergen

D Jungfraujoch, Switzerland

E Zugspitze, Germany

F Plateau de Bure, France

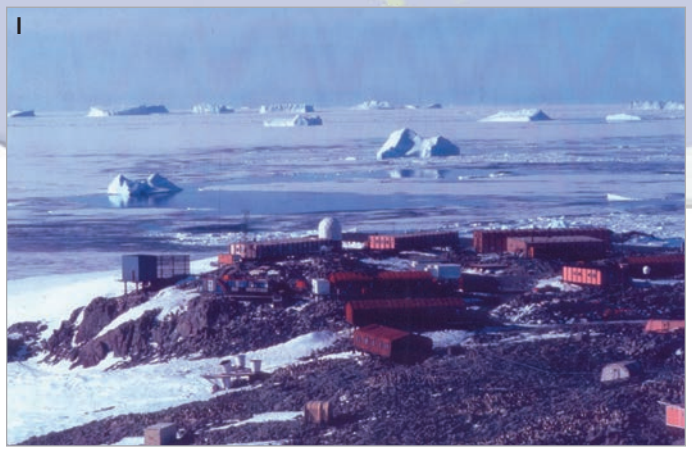
G Observatoire de Haute Provence, France

H Lauder, New Zealand

I Dumont d'Urville, Antarctica

J South Pole, Antarctica

K Mauna Loa, Hawaii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D


F


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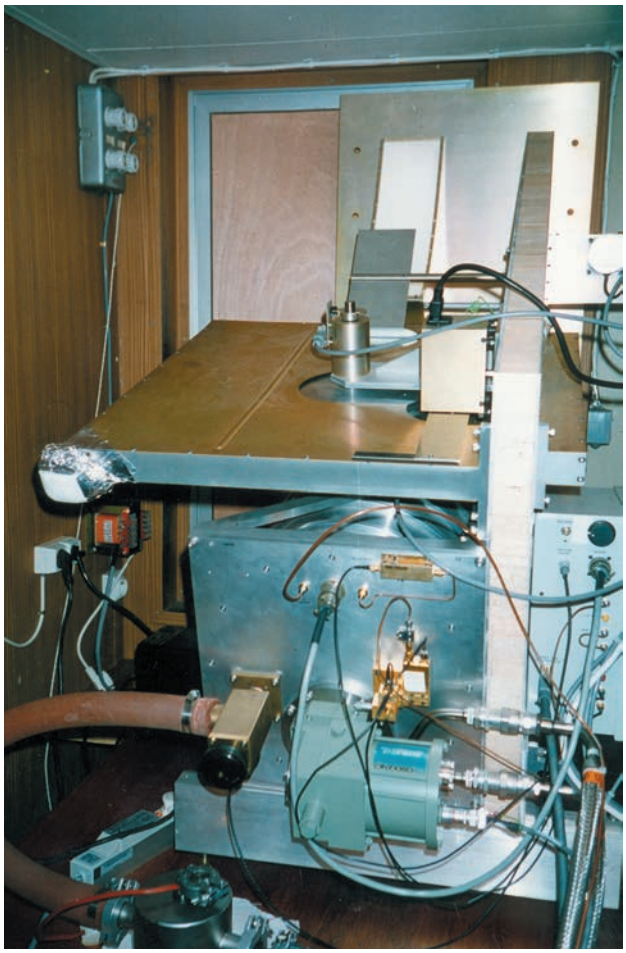
H

The NDSC Steering Committee consists of two co-chairs, pairs of PIs representing each of the Working Groups, independent scientists who are appointed to act as peer reviewers, and ex-officio members from important NDSC funding agencies and supporting institutions. As the primary managerial body for the NDSC, the Steering Committee has responsibility for internal operational oversight, scientific oversight, and the recommendation of implementation and funding actions. The Steering Committee meets annually. The names of the current Steering Committee members are listed on the inside back cover and the list on the NDSC Web site is updated as necessary.



ClO microwave radiometer operating at Plateau de Bure in the French Alps

## Operations: Quality Control *and* Data Archiving

Optimum operation of the NDSC requires international collaboration, both scientifically and managerially, with numerous national funding cosponsors. There is no central NDSC funding. The participation of the broader, international scientific community in the activities of the NDSC through complementary measurements, theory, modeling, and data analysis is also important to its long-term success. Commitment to data quality is essential to achieving the goals of the Network and, thus, it is necessary for complementary measurements to meet the same standards as the primary stations. Quality control procedures have been implemented to achieve this by rigorous calibration measures and regular intercomparisons. To ensure quality and consistency of NDSC operations and products, a number of protocols have been formulated covering such topics as primary and complementary measurements, data, instrument intercomparisons, theory and analysis, and validation. The protocols can be accessed from the NDSC Web site.

The Network's data lie at the heart of its contribution to understanding atmospheric changes and links to climate. The nature of the measurement of long-term trends requires these data to be fully verified before they can be used for comparison with models or to assess trends and correlations. It is the spirit and purpose of the NDSC to foster the broadest possible collaboration among all interested scientists as quickly as possible. However, as with any

good research, the PIs bear the ultimate responsibility for data quality. In order to achieve a verifiable data set, sufficient time is needed to collect, reduce, analyze, test, and intercompare the streams of continuous preliminary data from each of as many as five primary stations and potentially 40-plus complementary locations. The NDSC data protocol is aimed at achieving the twin goals of excellent data quality and ready data access. After a two-year period to allow for verification by the PIs and their coworkers, data are made available to the public through centralized archiving and distribution facilities (from NOAA at www.ndsc.ws and from NILU at www.nilu.no) that are accessible by anonymous FTP. More immediate access can be arranged by contacting the appropriate PI(s). For details on data access, consult the NDSC Web site.

## Examples *of* Network Activities

The range of NDSC capabilities is illustrated below with brief descriptions of some results produced during the past years of successful network operation, including examples of some of the many intercomparisons that have been carried out thus far. For more complete and up-to-date information, the reader should consult the list of publications available on the NDSC Web site or contact the responsible PIs directly.

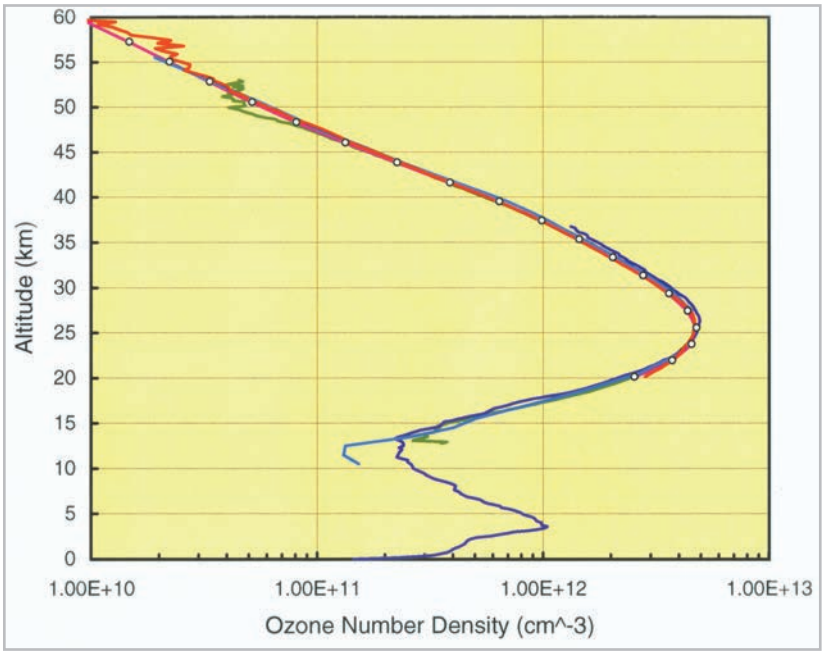



**Figure 1** MLO3 intercomparison. Mean profiles in ozone number density

### *Total column ozone*

The total integrated column of ozone is monitored at NDSC sites by ground-based Dobson and Brewer instruments, as well as numerous UV/Visible and FTIR spectrometers. Measurement of the total column serves as a quality control for the lidar, microwave, and ozonesonde profile measurements, since the integrated ozone profiles should be consistent with the total column measurements at the same location. Each summer the world standard Dobson spectrophotometer is operated at Mauna Loa Observatory, Hawaii, for about two months, providing a check on the long-term stability of other NDSC ozone column measurements which, in turn, contribute to the validation of satellite-based monitoring instruments.

## *Vertical profiles of ozone*

Three complementary measurement techniques are used within the NDSC to obtain ozone profiles from the ground up to altitudes of 65 km. Balloon-borne ECC sondes measure ozone from the ground up to the burst altitude of the balloon, which is typically around 32 km. Below approximately 20 km, ECC measurements are very reliable but their uncertainty increases at higher altitudes. DIAL systems can provide ozone measurements from close to the ground up to about 50 km altitude. DIAL measurements are usually made only at night and under cloud-free conditions, and they have the advantage of high sensitivity and good altitude resolution. Microwave radiometers are also used to determine ozone from 12 to 65 km altitude. These instruments have the advantage of operating almost continuously and with minimal operator attention. Whereas their altitude resolution is not as good as the DIAL systems and sondes, their response time is fast.

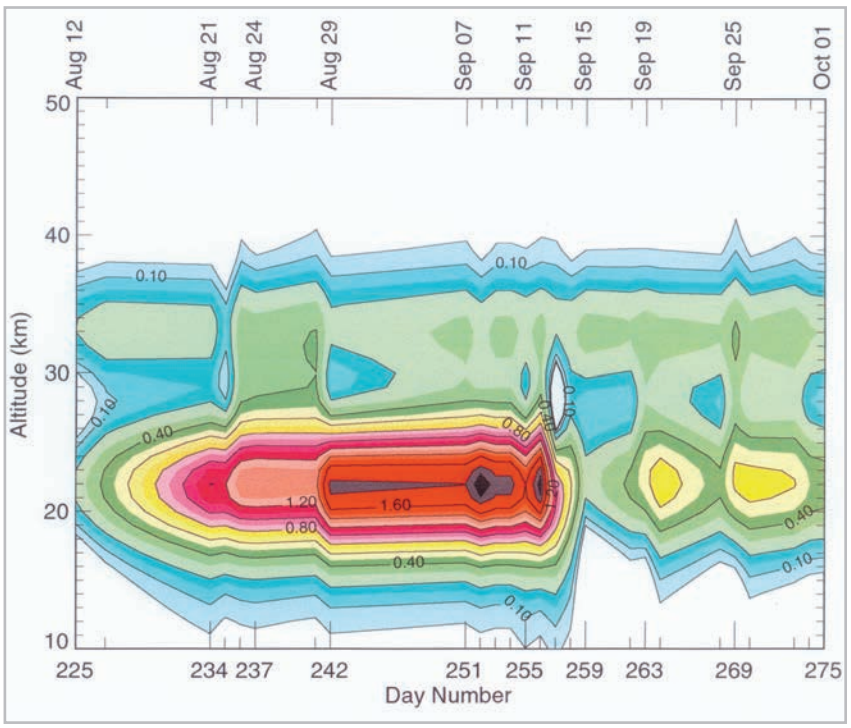



**Figure 2** Contour plot of ClO mixing ratio obtained with the Stony Brook microwave instrument at Scott Base, Antarctica, during the 1996 Antarctic spring, showing the increase in ClO in the lower stratosphere due to heterogeneous chemistry in polar stratospheric clouds which leads to the ozone hole

Figure 1 shows an example of ozone profiles obtained by these three techniques during the MLO3 intercomparison campaign that was held at the Mauna Loa Observatory in 1995. The agreement between the different measurements in altitude regions where overlap occurs is clearly demonstrated. This figure also includes an ozone profile from the SAGE II satellite instrument and shows the agreement between the NDSC and satellite measurements, exemplifying the capability of the Network to provide verification of satellite results.

## *Vertical profiles of temperature*

Temperature maps for the entire globe are retrieved by the National Centers for Environmental Prediction using the vertical sounders on polar orbiting satellites, radiosondes, and ground-based operational systems. From these retrievals, profiles are produced consisting of temperature values at a set of standard pressure levels from the ground to about 55 km. These temperatures are interpolated to the NDSC site locations for validation purposes through intercomparisons with local measurements from

lidar systems that are capable of measuring temperature profiles from about 15 up to 95 km, depending on the power of the instrument. The lower altitude limit is related to the presence of aerosols and water vapor. Special techniques have been implemented to retrieve temperatures below the tropopause when aerosols are at or near background levels.

The 1995 MLO3 campaign also allowed an intercomparison of four lidar temperature profiles that showed relative variations of only about ±1K at the stratopause. Comparison of lidar temperature data at selected altitudes with ozone data from a colocated microwave instrument provides a good example of the benefits of the NDSC concept; such measurements taken at the Lauder, New Zealand, site during the Austral winter of 1994 clearly showed the anti-correlation of ozone with temperature above about 50 km.

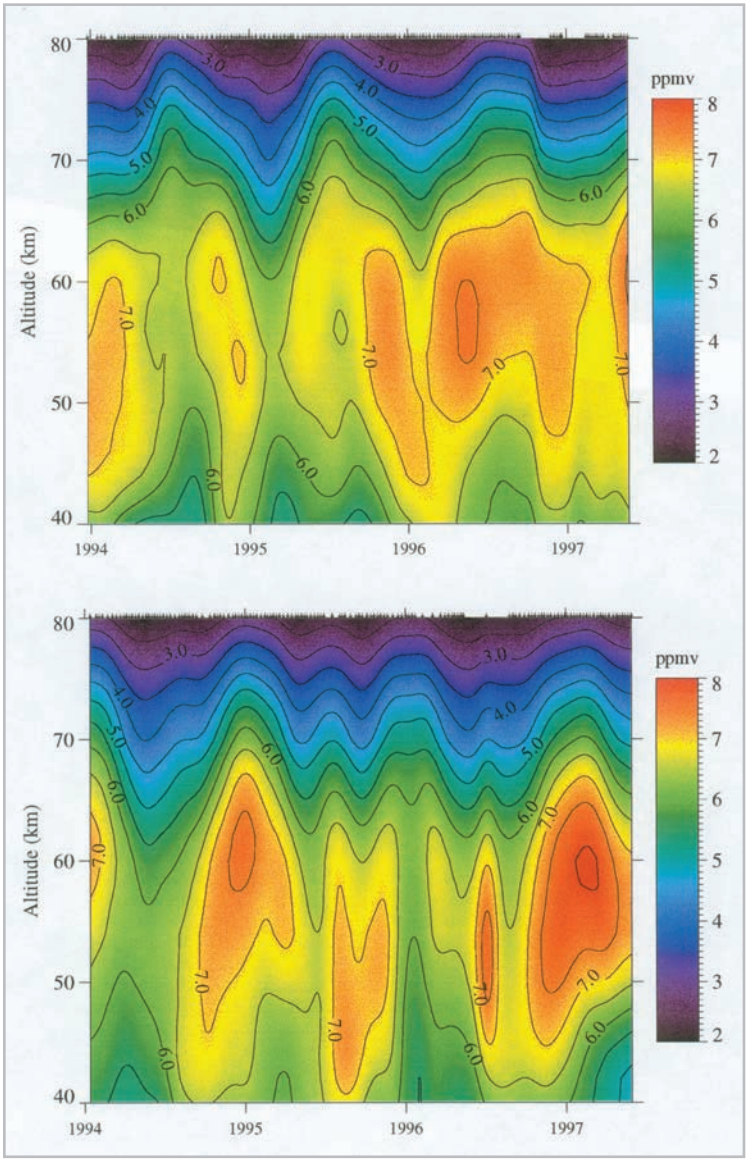



**Figure 3** Water vapor mixing ratio measured by microwave spectrometry at Table Mountain,California (top, 34.4°N) and Lauder, New Zealand (bottom, 45.0°S)

## *Vertical profiles of ClO*

The NDSC microwave ClO instruments operate at either the 204-GHz or the 278-GHz ClO emission lines. Zenith and horizon data are accumulated separately and subtracted to cancel out instrumental effects. These measurements permit the recovery of the spectrum as it would be observed at the zenith from above the troposphere. Interfering ozone lines are removed from the spectrum by one of several methods, leaving the pressure-broadened ClO line-shape from which the altitude distribution of ClO can be obtained. Because of the weakness of the ClO signal under normal background conditions, up to several days' data must be averaged together to produce a spectrum with a signal-to-noise sufficient for successful deconvolution. Representative data showing the evolution of lower stratospheric ClO over Antarctica are shown in Figure 2.

## *Vertical profiles of $H_2O$*

Continuous monitoring of middle atmosphere water vapor profiles from 25 to 80 km

altitude from the NDSC sites at Mauna Loa, Lauder, and Table Mountain is provided by millimeter-wave spectrometers. Observations generally show an increase in water vapor with increasing altitude in the stratosphere where methane is converted to water, and then a decrease in the mesosphere due to photodissociation. These photochemical processes compete with transport processes and allow the shape of the water-vapor altitude profile to be used as a tracer for atmospheric transport. At Mauna Loa, the maximum is generally observed at higher altitudes than at the two midlatitude sites, which is consistent with upward transport of water vapor near the equator. The seasonal variations in water vapor at the two midlatitude sites show a predominantly annual cycle, with upward motion being observed in the summer hemisphere (Figure 3). A secondary semiannual cycle, thought to be the result of variations in transport, is also observed at the midlatitude sites. Raman lidars can provide water vapor profiles in the free troposphere but are limited to altitudes below the hydropause (tropopause).

## *Vertical distribution of aerosols*

Stratospheric aerosols affect the global radiative balance both directly by scattering and absorption processes and indirectly by converting inactive chlorine reservoirs such as $ClONO_2$ and HOCl into active chlorine forms that destroy ozone. Sources of sulfur compounds, the main constituents of aerosols in the stratosphere, are global volcanism and biogenic, oceanic, and various anthropogenic emissions.

Aerosol loadings after the two major volcanic eruptions of the past two decades—at El Chichon in 1982 and Mt. Pinatubo in 1991—were described and quantified by remote sensing (lidar) and *in situ* (backscatter sonde) measurements at NDSC stations. Figure 4 shows profiles of the scattering ratio from 1992 to 1998 as observed by lidar measurements at the northern midlatitude primary NDSC station in Garmisch-Partenkirchen. It was possible to follow the decay of the Mt. Pinatubo perturbation from its maximum in 1992 to the formation of a new background level after 1997. The formation of polar stratospheric clouds (PSCs) has been observed by lidar in winter at NDSC stations located in polar regions.

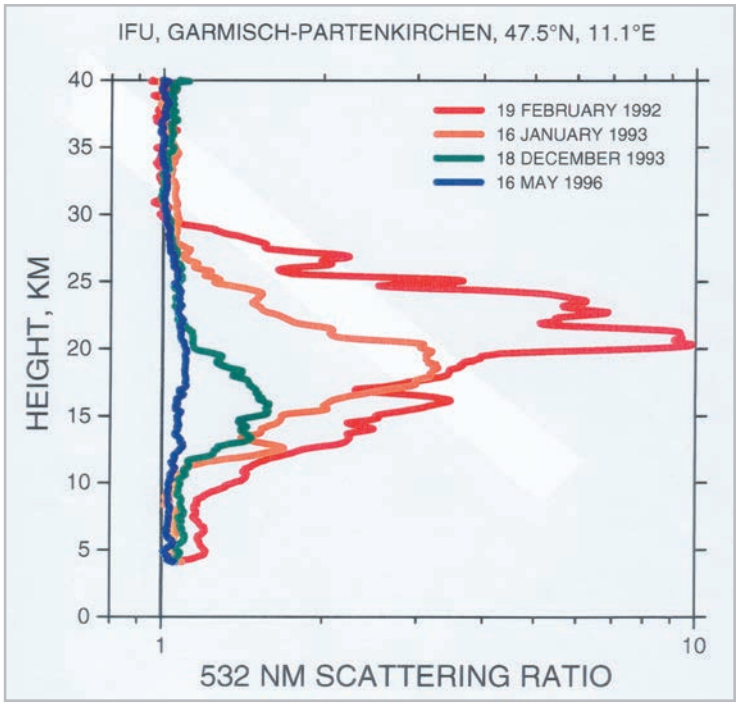



**Figure 4** Profiles of the lidar scattering ratio describing the perturbations in the aerosol layer in the northern midlatitude stratosphere following the eruption of Mt. Pinatubo

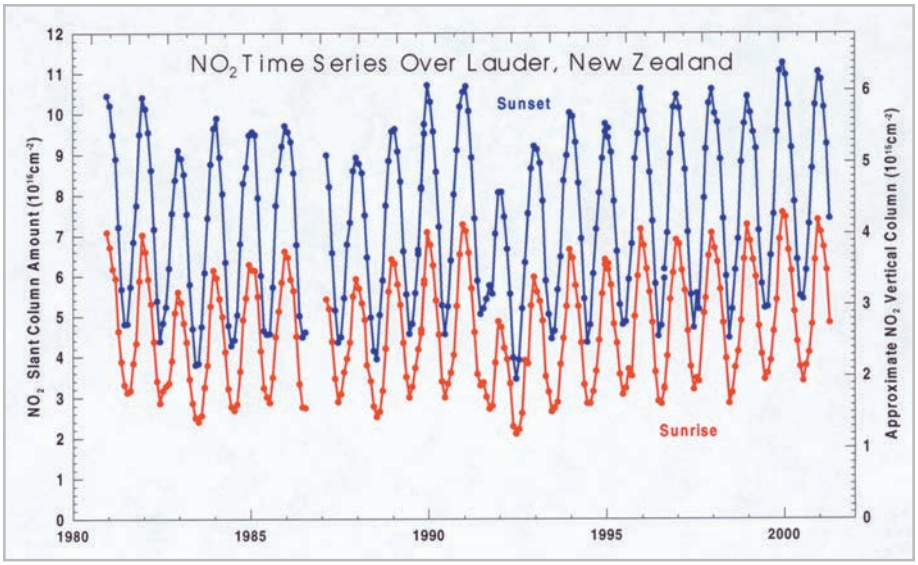



**Figure 5** Monthly means of sunset and sunrise slant column $NO_2$ measurements at Lauder (45°S, 170°E) by UV/Visible spectrometry

## *Nitrogen species in the stratosphere*

As well as being directly responsible for the catalytic control of ozone, $NO_2$ plays a vital role in coupling the $NO_X$ ($NO$ and $NO_2$), $ClO_X$ ($Cl$ and $ClO$), and $HO_X$ ($OH$ and $HO_2$) families, leading to key stratospheric reservoir species such as $ClONO_2$ and $HNO_3$. Figure 5 shows monthly mean slant column measurements of $NO_2$ monitored by UV/Visible spectrometry at the primary NDSC station in Lauder, New Zealand, from 1981 to 1999. Diurnal (A.M. versus P.M. solar zenith angles), seasonal (minimum in winter, maximum in summer), and long-term changes can be assessed from such observational databases. The influence of major volcanic eruptions such as El Chichon and Mt. Pinatubo on stratospheric $NO_2$ burdens can also be seen, with substantially reduced $NO_2$ columns measured in the years following these eruptions.

$N_2O$ is the main source of stratospheric $NO_X$. The steady increase of $N_2O$ during the recent industrial era (by about 0.2 percent per year) should lead to a similar increase in $NO_X$. This has partly been offset during the last decades by the increase of $ClONO_2$. FTIR spectrometers are able to measure the stratospheric loading of the most important nitrogen species simultaneously, as shown in measurements made at the NDSC site at the Jungfraujoch, Switzerland station (Figure 6).

## *Inorganic halogens in the stratosphere*

The ultimate reservoirs of inorganic stratospheric chlorine and fluorine atoms resulting from the breakdown of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) are HCl and HF, respectively. The presence of HCl in the stratosphere was discovered in 1975 through infrared airborne measurements, and its detection from the ground was demonstrated soon afterwards, based on high-resolution IR solar observations at the Jungfraujoch station and at Kitt Peak National Observatory in the United States. Since then, the monitoring of the vertical column abundance of HCl, along with another important stratospheric chlorine reservoir,

$ClONO_2$, has been pursued and has become a priority task for ground-based FTIR measurements within the framework of the NDSC. The pink frames in Figure 6 reproduce portions of the HCl and $ClONO_2$ databases gathered at the Jungfraujoch station during recent years. These time series indicate that the rate of change of inorganic Cl in the stratosphere mirrors very closely the evolution of the tropospheric loading of organic chlorine bound in the most important CFCs and HCFCs. Correlative monitoring of HF (as shown in the bottom frame of Figure 6) along with HCl helps to distinguish between natural and anthropogenic loading of Cl in the atmosphere. Recent inter-comparisons between remote and *in situ* ground-based and remote space-based observations show that the chlorine loading has started to decrease in the troposphere and to stabilize in the stratosphere. This is as expected, resulting from the phase-out of chlorine-containing source gases under the Montreal Protocol and its Amendments and Adjustments.

## *Vertical profiles of $CH_4$ and $N_2O$*

$CH_4$ and $N_2O$ are included in routine NDSC monitoring activities because both are gases with long stratospheric lifetimes and simple removal mechanisms (reaction with the OH radical for $CH_4$ and photolysis for $N_2O$), making them ideal tracers of atmospheric motions. Short-term changes in both their vertical distributions and total column abundances are indicative of atmospheric dynamic processes (meridional circulation as well as subsidence in polar regions) that also affect the ozone field. Long-term changes in the $N_2O$ source strengths at the ground (primarily anaerobic processes in soils and oceans) will impact the ozone layer because $N_2O$ is the major source of stratospheric $NO_X$. The reaction of $CH_4$ (whose main sources include wetlands, rice paddies, animal husbandry, and fossil fuel production and use) with the OH radical has a direct impact on the oxidizing capacity of the troposphere and has an indirect effect on the lifetimes of various chlorine-bearing hydrogenated compounds. Both $CH_4$ and $N_2O$ are radiatively important gases, and increases in their atmospheric

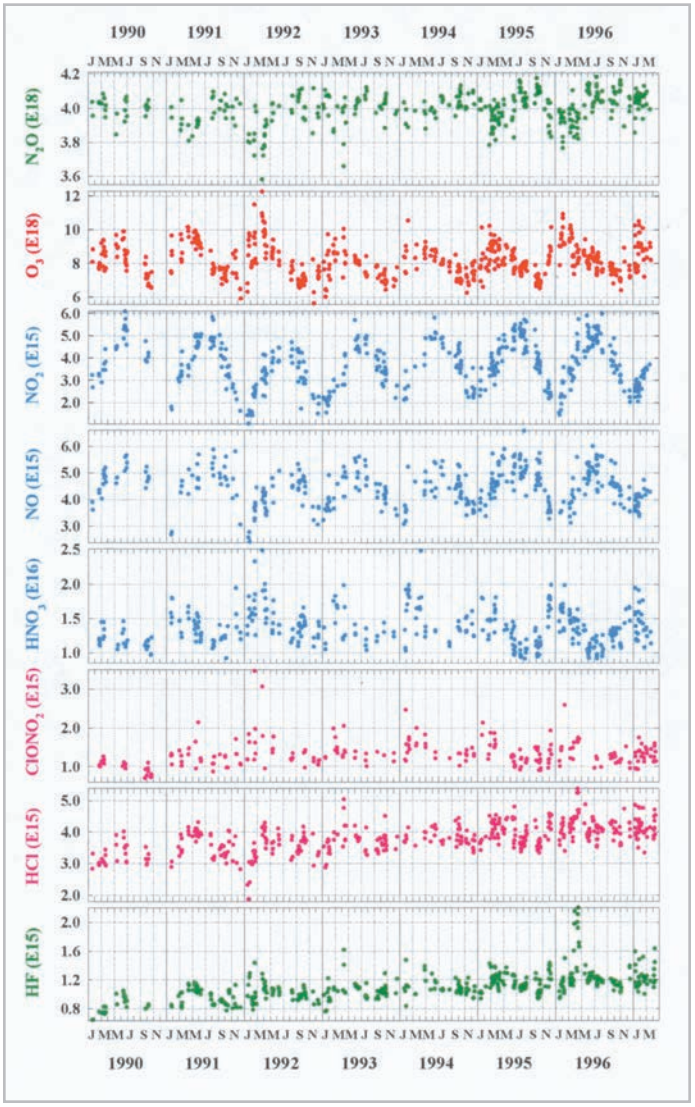



**Figure 6** NDSC-related FTIR measurements made at the Jungfraujoch station

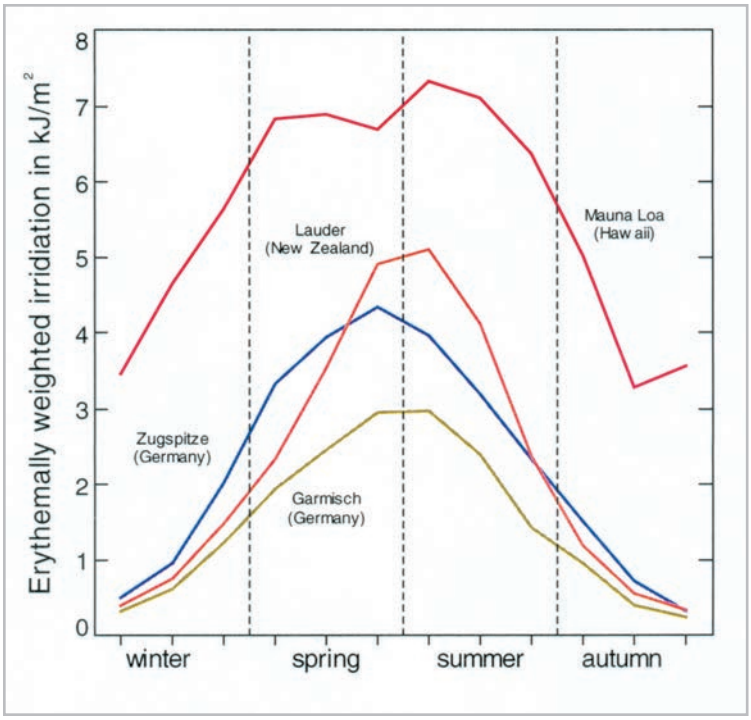



**Figure 7** Erythemally weighted UV irradiation at four locations

concentrations contribute to an enhanced greenhouse effect.

## *Spectral UV radiation*

Measurements of solar ultraviolet radiation at the ground were added to the NDSC program in 1995. As a consequence of the decline in stratospheric ozone, it is expected that UV levels will increase at high and mid latitudes, leading to adverse effects on the biosphere (including terrestrial and aquatic ecosystems) as well as on human health. The anti-correlation between ozone and UV is partly masked by the variability in cloud cover, UV-scattering and UV-absorbing aerosols in the troposphere, tropospheric pollution, and the aerosol content of the stratosphere.

The NDSC UV instruments are designed to establish a UV climatology through long-term monitoring by a network of UV spectroradiometers, to detect spectrally resolved trends in global spectral UV irradiance, to provide data sets for specific process studies and for the validation of radiative transfer models as well as satellite-derived UV irradiance at the Earth's surface, and to understand geographic differences in global spectral UV irradiance. An example of the latter is shown in Figure 7. Monthly average daily erythemal doses for the year 1996 were measured at the primary NDSC stations at Garmisch-Partenkirchen, Zugspitze, Lauder, and Mauna Loa. At all four stations, UV doses generally increase with solar elevation. Mauna Loa has the highest doses due to the highest solar elevation, lowest total ozone, and highest altitude. The UV levels in Lauder (45°S) are generally higher than in Garmisch (47°N) because of lower total ozone overhead, less cloudiness, and fewer aerosols. The yearly dose at the Zugspitze is equal to Lauder's, and is about 50 percent higher than that at Garmisch (same latitude as Zugspitze, but lower altitude).

## *Intercomparisons and validations*

It is crucial that the measurements produced by the NDSC sites are internally consistent and as precise and accurate as possible in order to have the high quality necessary to meet the Network's objectives. An ongoing program of intercomparison and validation

is therefore part of the responsibility of the various instrument Working Groups.

A wide range of intercomparisons has already been completed and more are planned for the future. For instance, the NDSC UV/Visible Working Group organized its first formal intercomparison of the $NO_2$-measuring instruments at Lauder, New Zealand, in 1992, with seven groups participating from seven countries. The "blind" part of the campaign was supervised by a neutral referee and carried out according to rules discussed with and agreed to beforehand by the participants and the NDSC Steering Committee. The seven sets of measurements agreed to within ±10% of the mean on most days; however, the sensitivity of the individual instruments varied considerably. All groups benefited from their participation and most were subsequently able to further improve their measurement and analysis approaches.

Similar side-by-side instrument intercomparisons have been carried out by the Microwave, Lidar, FTIR and Spectral UV Working Groups. A total of 10 FTIR intercomparisons have been performed at both primary and secondary sites using a mobile instrument. Various intercomparisons such as the 1997 EC SUSPEN campaign in Greece, in which 19 spectroradiometers took part, have shown the high quality of the NDSC spectral UV instruments and their good agreement.

Other activities implemented to achieve NDSC data quality include algorithm intercomparison exercises to identify and eliminate inconsistencies in the data analysis process and ongoing scientific studies aimed at selecting the best spectroscopic parameters for remote atmospheric measurements.

## *Theory and models*

The analysis and modeling of NDSC observations is a key objective of the Network. Analysis of observations provides a link amongst the various Network components and to outside sources of observations such as satellite data. Comparison with models provides verification of our understanding of the dynamical and chemical processes in the atmosphere and their coupling. The NDSC Steering Committee encourages theoretical and analysis studies that both utilize NDSC observations and provide important feedback on the NDSC strategy. The NDSC currently provides data to projects dealing with (i) improvement of algorithms for the retrieval of vertical profiles and total column amounts of trace gases, (ii) linkage to trace-gas data from other monitoring networks and interpretation of such data using inverse methods and global

models, (iii) studies of trends in trace gases, and (iv) investigations utilizing global chemical transport models to compare with NDSC observations.

## Future Thrusts: The Role *of the* NDSC *on a* Broader Atmospheric Scale

During its first years of operation, the NDSC concentrated primarily on stratospheric research and, more specifically, on the erosion of the ozone layer and on identifying related causes and impacts. Results from the Network have made important contributions to various international reports issued by the Intergovernmental Panel on Climate Change and the European Commission, and, more recently, to the 1998 UNEP/WMO Scientific Assessment of Ozone Depletion. This Assessment identified the importance of the coupling of the ozone layer and the climate system. Potential future changes in gases such as $CO_2$, $N_2O$, $CH_4$, and water vapor, and in climate-influenced variables such as temperature will affect the recovery of the ozone layer. Moreover, there are aspects of ozone change such as those in the Arctic that are still not well understood.

The NDSC, with its ensemble of priority measurements, remains committed to monitoring the ozone layer through the predicted periods of stabilization and eventual recovery, and to assessing worldwide compliance with the UNEP Montreal Protocol and its Amendments and Adjustments. The NDSC Steering Committee has worked on ways to implement and enhance the capabilities of the Network by seeking additional expertise and affiliations to study and quantify the impacts of stratospheric changes on the underlying atmosphere. As a result, UV radiation measurements at the ground were added in 1995 and ozone profile and water vapor measurements in the lower atmosphere by ozonesondes and lidars have been increased and coordinated.

The flexible structure of the NDSC will enable it to continue to adapt to meet future challenges arising from advances in scientific understanding or political developments such as the implementation of the Kyoto Protocol on substances that alter the radiative forcing of the climate system and its interaction with the Montreal Protocol on ozone-depleting substances. The recently recognized variability of atmospheric circulation, the evolution of water vapor in the stratosphere and its link to troposphere/stratosphere exchange at low to mid latitudes, and the coupling of chemistry and climate are all important areas with which the NDSC will be dealing in the near future.

## Sponsors

From the inception of the NDSC in 1986, important organizational impetus and preliminary funding was provided by such scientific organizations as CNRS and INSU in France, NIWA in New Zealand, NASA and NOAA in the United States, and by the chemical industry. The European Commission, through its Research Directorate General (DG), has supported and coordinated European contributions to the NDSC since 1989 through its long-term, stratospheric research projects. Financial support for the implementation and continued operation of the NDSC has come from many national and international organizations, including

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| | | |
|---|---|---|
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| | R.J. Zander<br>*zander@astro.ulg.ac.be* | University of Liège, Belgium |

### *Science Team Representatives*

| | | |
|---|---|---|
| Dobson & Brewer | C.T. McElroy | Meteorological Service of Canada/Environment Canada |
| | S.J. Oltmans | National Oceanic and Atmospheric Administration (NOAA), Climate Monitoring and Diagnostics Laboratory, USA |
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| H. Fast | Meteorological Service of Canada/Environment Canada |
| G. Giovanelli | Instituto FISBAT, Italy |
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## Contacts

**For more information, please go to the NDSC Web site:** www.ndsc.ws

**or contact the co-chairs:**

Dr. Michael J. Kurylo

Headquarters, National Aeronautics and Space Administration

Code YS, Office of Earth Science
Washington, DC 20546-0001
USA

Tel: +1-202-358-0237

Fax: +1-202-358-3098

E-mail: *mkurylo@hq.nasa.gov*

Dr. Rudy J. Zander

Institute of Astrophysics and Geophysics
University of Liège

5 Avenue de Cointe
B-4000 Liège
Belgium

Tel: +32-4-254-7556

Fax: +32-4-254-7511

E-mail: *zander@astro.ulg.ac.be*

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