AIRBORNE POLAR EXPERIMENT GEOPHYSICA AIRCRAFT IN ANTARCTICA (APE-GAIA)

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INTRODUCTION

APE-GAIA (Airborne Polar Experiment – Geophysica Aircraft In Antarctica, Carli et al. 1999) has obtained interesting new information on the stratospheric chemistry and transport during the transition of the southern polar vortex from the ozone depletion to the recovery phase. The mission with the high-altitude aircraft M55 Geophysica took place in the period from 15th September to 15th October 1999 during which five scientific flights were performed from Ushuaia (Argentina, lat. 55°S, long. 68°W), the southernmost city of the world. A comprehensive payload of remote-sensing and in-situ instruments monitored an essentially unexplored altitude range of the vortex. Flying southward over the Antarctic Peninsula at latitudes up to 70°S and at altitudes from 14 to 20 km, while probing the vertical distribution with remote sensing techniques and occasional 'dives' (once even down to 10 km), allowed to investigate the main targets of the mission (Carli and Blom, 1997):

(i) the chemical composition of the Antarctic lowermost stratosphere during the transition phase,
(ii) the mixing of mid-latitude and polar air masses, and
(iii) the re-activation of chlorine over the Palmer peninsula

The scientific planning of the flights was first based on the relevant scientific objectives (M. P. Chipperfield and G. Redaelli, 1999). Individual flight plans were then finalised in the field using detailed forecasts. These forecasts includes standard output from global numerical weather prediction models, as well as high resolution trajectory/contour advection models (to identify filaments), lee wave models (to identify mountain wave PSCs) and global chemistry transport models. Use was also made of near real-time TOMS column O_3 data.
The M55-Geophysica aircraft has become available for scientific purposes in the frame of a co-operation between the Italian National Programme for Antarctic Research (PNRA)

and the Russian Myasishchev Design Bureau (MDB), AviaEcoCenter (AEC), and Central Aerological Observatory (CAO) of Moscow. A first mission (APE-POLECAT) was based out of Rovaniemi, Finland, in Winter 1996/97 (Stefanutti et al., 1998). More recently, the Geophysica was used in the APE-THESEO campaign (MacKenzie et al., 2000) to study transport and clouds at the tropical tropopause.

With respect to these missions APE-GAIA deployed a new payload that combined for the first time several instruments for the study of atmospheric chemistry.

The earlier US-American ER-2 deployments AAOE (Tuck et al., 1987) and ASHOE (Tuck et al., 1997) demonstrated the importance of high-altitude aircraft for research in and around the southern polar vortex.

The large payload capacity of the Geophysica, as well as its operational flexibility and manoeuvrability have offered, however, a new opportunity for observations above Antarctica. The capability for housing relatively large and heavy sensors (up to a maximum weight of 1500 kg and to a volume larger than 11 m^3) has allowed the deployment of a large payload of remote-sensing and in-situ instruments aboard of a single stratospheric aircraft. This, along with the fact that the Geophysica is able to fly at various altitudes, within cold air masses (temperature around –90°C), with deep dives, and to operate despite difficult ground conditions (strong cross wind), significantly advanced the scientific output of APE-GAIA.

In this paper a short description of the campaign and some preliminary results are presented.

INSTRUMENTATION

The scientific payload of the M55 aircraft during the Antarctic campaign is summarised in Table 1. The payload includes remote sensing and in-situ equipment for gaseous trace compounds, instruments aimed at characterising aerosols and cloud particles, and devices for radiation measurements.

The remote sensing chemistry instruments are the core of this payload as they provide simultaneous measurements of a large suite of chemical species. The two Fourier Transform Spectrometers MIPAS-STR and SAFIRE-A make limb and upward soundings to obtain column amounts above the aircraft and profiles below. Together they cover the main components of the Cl_y family (ClO, HCl and $ClONO_2$), MIPAS-STR almost covers the entire the NO_y family, whereas SAFIRE-A obtains information on Br_y. GASCOD-A uses the DOAS technique and measures total amounts of the trace constituents at zenith and nadir in the case of high sun, and vertical profiles in the case of sunrise and sunset. Important active species observed by this instrument are OClO and BrO.

The three instruments also observe several long-lived source gases. Their redundant measurements allow validation of the individual measurements and thus to improve the quality and reliability of the APE-GAIA data.

In situ instruments provide measurements of ozone, water vapour and long-lived tracers at flight altitude with high spatial resolution. From these measurements vertical distributions can be observed during dives of the aircraft. The horizontal variability of the atmospheric composition and the dynamics of the mixing can be derived during flights at constant

altitude ensuring an important synergy with the more extended vertical maps that the remote observations obtain on the basis of the assumption of horizontal homogeneity.
Aerosols and PSC particles are detected and characterised by lidars and scatterometers pointing at different directions and operating with different ranges and different longitudinal resolutions. Correlation of PSC detection with the measurements of atmospheric composition simultaneously made by the "chemistry payload" provides an opportunity for the direct analysis of the effects of PSC formation (denitrification, dehydration, heterogeneous chemistry).
Finally, two instruments provide measurements of radiation fluxes for a more precise quantification of photochemical parameters.

Table 1 – APE-GAIA payload

	Instrument	**Type**	**Measurement**
Remote-sensing chemistry	GASCOD-A	UV – Visible Spectrometer	Vertical profiles and column of stratospheric constituents
	MIPAS-STR	Mid-Infrared Fourier Transform Spectrometer	Vertical profiles and column of stratospheric constituents
	SAFIRE-A	Far-Infrared Fourier Transform Spectrometer	Vertical profiles and column of stratospheric constituents
In-situ Chemistry	ECOC	Electrochemical Ozonometer	Ozone
	FISH	Stratospheric Hygrometer	Water vapour
	FLASH	Stratospheric Hygrometer	Water vapour
	FOZAN	Chemiluminescence Ozone analyser	Ozone
	HAGAR	2-channel gas chromatograph + IR-analyser for CO_2	CFC-11, CFC-12, H-1211, N_2O, SF_6, CO_2
Microphysics	ABLE	Lidar	Particle backscatter and related properties below the aircraft from 300 m. to ground level and surface reflectivity
	MAL 1 and MAL 2	Microjoule lidar	Particle density up to 2 km from the aircraft (upward and downward)
	MAS	Multi-wavelength aerosol Scatterometer	Particles density and optical properties
Radiation	GASCOD-A/4π	UV – Visible spectroradiometer	Actinic fluxes
	SORAD	Radiometer	Broad-band flux

SCIENTIFIC FLIGHTS

Fig. 1 shows a map of the five scientific flights performed from Ushuaia during the campaign. The flight route and timing of each flight were determined on the basis of stratospheric meteo forecast complemented by high resolution reverse domain filling trajectories (RDFT) maps (Sutton et al., 1994) and MM5 mesoscale fields (Ferretti et al. 2000) and were verified with an early alert of the flight opportunities made possible by ground weather forecast.

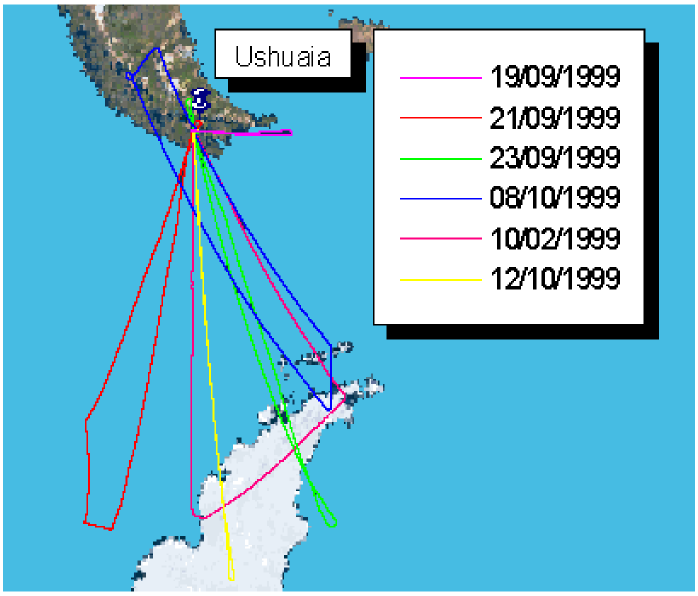

Figure 1
Map of the test flight and the five scientific flights performed by the M55-Geophysica from the base of Ushuaia (Argentina) during the APE-GAIA mission

The modelling activity provided, in forecast mode, accurate information about location of the boundaries of the polar vortex, as well as about occurrence of lee waves and formation of filaments eroded from the vortex edge. Three flights aimed at entering as deep as possible inside the polar vortex and at performing dives inside, one of them reaching down to almost the tropopause. This type of flight was repeated more than once in order to study the chemistry of the polar air and the mixing between polar vortex and middle latitude air at different times as a function of the season and with slightly different vertical coverage. One flight was performed inside a major event of lee wave formation over the Antarctic Peninsula and one flight crossed twice a filament eroded from the vortex edge.
The flight planning was focused around these specific objectives, but took into account also the requirements of the different instruments, such as night time versus day time preference, constant versus variable altitude and solar blinding effects. A compromise was always found and the heterogeneous character of the techniques allowed the simultaneous measurement of many different parameters with a major enhancement of the acquired information, even if some instrument with specific requirements was not always able to perform measurements during the whole flight.

THE VORTEX EDGE

Fig. 2 shows an example of observations made by the *in-situ* instruments during the flight of 23rd September 1999. As shown by the top plot, the altitude was about 17 km in the forward (southbound) leg. While maintaining the southbound direction, a dive was performed down to 14 km. After regaining altitude the reverse (northbound) flight was performed, with two steps at 18 km and at 19 km, in the north direction. The first part of the flight is at night time and the second part is at day time with sunrise occurring during the dive.

Most species were observed by a single instrument, but in the case of ozone (bottom plot) two independent measurements are superimposed and show very good agreement.

Ozone, water vapor and most tracers have very similar variations both in the general shape of the curves as well in some of the small features. The event of a rapid drop of concentrations synchronously observed for most species can be considered to identify the crossing of the vortex edge. From the figure one infers that during this particular flight the vortex edge was situated at a latitude of 60°S on the forward leg (17 km altitude), but at 62°S during the return leg (19 km altitude). The different location and gradient of the vortex edge as a function of altitude was also observed during other flights.

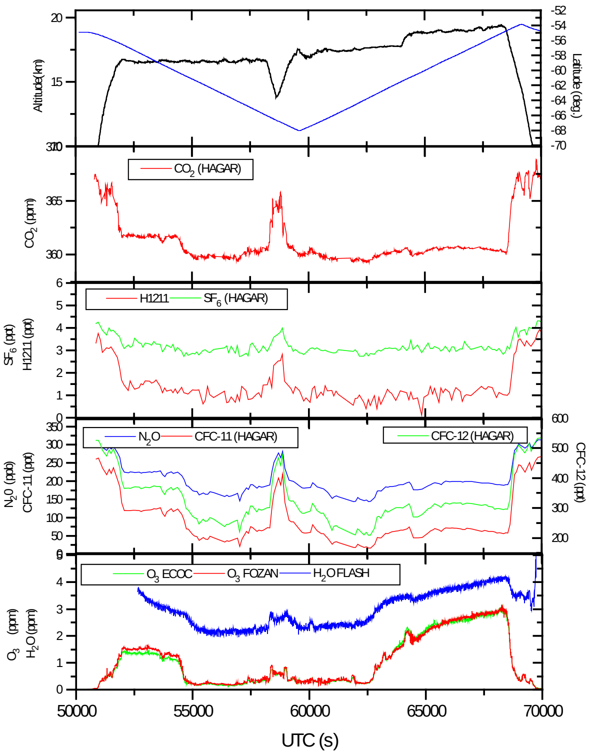

Figure 2

Altitude, latitude and in-situ measurements of minor constituents acquired during the flight of 23rd September 1999. The measurements are preliminary

Together with the in-situ measurements shown in Fig. 2, during the same flight vertical profiles of several minor constituents were observed as a function of latitude by the remote sensing instruments. For instance, a clear anti-correlation is observed by SAFIRE-A between ozone and ClO, the latter being detected only in the reverse leg in daytime. A comprehensive analysis is still in progress. As an example of the detail of the information and of the remaining data analysis activity required for the remote sensing instruments, Fig. 3 shows a comparison between the measurements of HNO_3 made with SAFIRE-A and with MIPAS-STR. Colour-contour plots are used for the comparison of the two measurements performed on different grids in the altitude-latitude domain. Both measurements have several preliminary features: a simplified and possibly incomplete spectroscopic data base is used in the case of SAFIRE-A and temperature profiles provided by models instead of those directly measured by the instruments are used in the case of MIPAS-STR. Furthermore some gaps are present in the data acquisition of the two instruments during this particular flight and different regularisation and determination of the distribution above flight altitude are operated in the two retrievals.

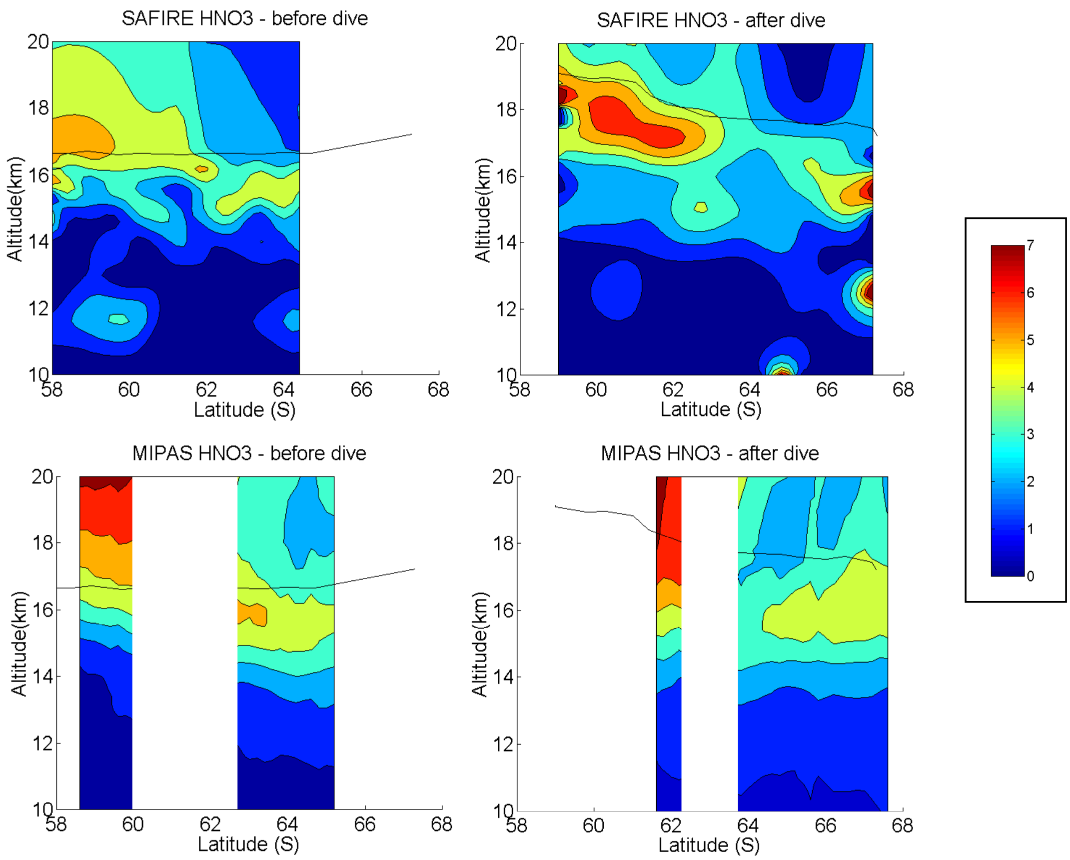

Figure 3

The volume mixing ratio [ppb] of nitric acid as a function of altitude and latitude is shown for the two remote sensing instruments and the two legs of the same flight of 23rd September 1999. The continuous line shows the flight altitude. The measurements are preliminary.

Despite the fact that some differences are observed both between the two instruments and between the forward and reverse leg of each instrument, the overall features of the observed distributions are quite consistent. At latitudes below 63° HNO_3 is mainly observed at altitude above 16 km, there is a reduction of HNO_3 concentration around 64° latitude and a distribution peaked at 16 km at latitudes above 65°. The lowering of the altitude of the peak of concentration with increasing latitude is in agreement with the expected effect of a sedimentation process.
The differences observed between the forward and the reverse leg could also be due to the atmospheric variability since the aircraft flew along the same track in the two legs and the remote instruments looked on the two sides at air masses that are up to 500 km apart.
A detailed analysis of the results obtained by the two instruments will validate the observed differences and provide a better understanding of the atmospheric variability.

LEE WAVES AND FILAMENTS

With an alert of about 36 hours, model forecast predicted lee wave formation over the Antarctic Peninsula for the 2nd of October 1999. A flight was accordingly planned with a flight route aimed at probing the temperature oscillations and observing the induced effects in the atmosphere. A measurement made during that flight is shown in Fig. 4, which displays a comparison of the back-scattering signal measured above the aircraft by MAL-1 and the local temperature as function of time. The back-scattering signal is corrected by the aircraft altitude and is located at the correct relative position in the atmosphere. The very low temperature experienced by the aircraft caused a partial loss of the engine efficiency which made it difficult for the aircraft to maintain a constant altitude.
The temperature profile along the flight track shows clearly several temperature oscillations, at different frequencies, with the major amplitudes well matching in time and space with the forecasted temperature fields. PSCs occurrence is also well correlated with local temperature minima.

From high resolution RDFT fields, a filament was forecasted for the 8th of October 1999, between Argentina and the Antarctic Peninsula. The signature of the filament was already clearly present in the RDFT forecasted products since 96 hours in advance. In order to verify and study the occurrence of this structure a flight was planned, with a four legs track on two isentropic surfaces: 390K and 450K. As forecasted, while flying quasi isentropically at 450 K, the aircraft has observed an intense and localised variation of the measured tracers, that is supposedly related with the sampling of the vortex filament structures along the flight track. Also, high resolution RDFT products (not shown here) picture a three-dimensional filament with a strong horizontal gradient, a deep vertical shape and a high resolution internal structure that seems to correspond well with the preliminary analysis of the time series of experimental data. Further analyses, involving the complete set of tracers data available from onboard instrumentation, is needed to have a more complete understanding of this case.

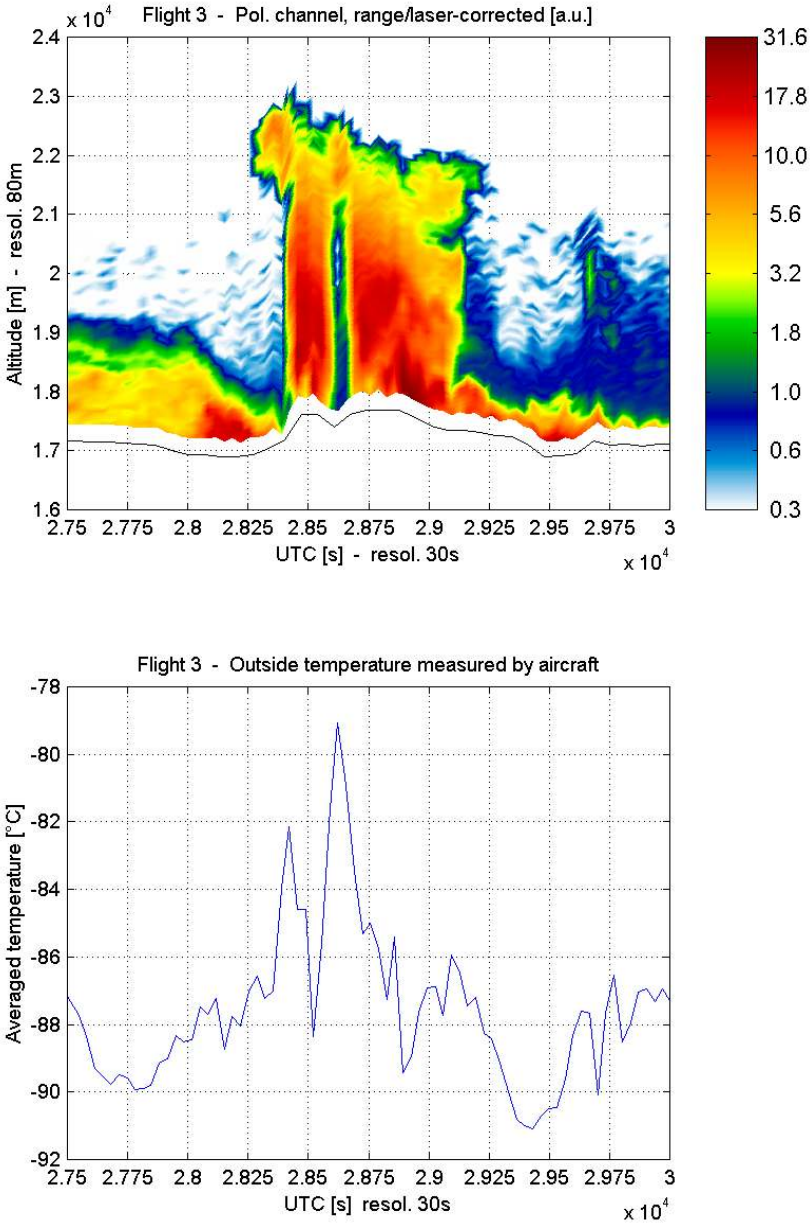

Figure 4

Observations of the MAL instrument during the flight of 2nd of October 1999 in the area in which lee wave formation was forecasted. The upper panel presents the altitude profile of the back-scattering signal, the lower panel presents the temperature of the atmosphere at flight level.

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AUXILIARY MEASUREMENTS

In parallel with the M55-Geophysica flights, a series of ground-based and balloon measurements were made from different sites located in Tierra del Fuego and on the Antarctic Peninsula, in order to correlate the observations conducted during the APE-GAIA campaign with the time series of ground measurements. Ground-based ozone, NO_2, SO_2 and UV radiation measurements were carried out from Ushuaia. On the Antarctic Peninsula, real-time measurements of total ozone and NO_2 were obtained from the base of the British Antarctic Survey in Rothera (67° 34’ S; Long. 68° 07’ W), along with radiosonde launches. ozone soundings, temperature, humidity and wind radiosondes. Total column ozone values were obtained from the Argentinean bases of Marambio (64°23' S, 56°72' W) and of Belgrano II (Lat. 77º 52' S; Long. 34º 37' W), the activity in the former base being performed in collaboration with the Finnish Meteorological Institute. From these two bases ozone and NO_2 measurements were also obtained by the INTA (Spain) and CNR-IFA (Italy).

A preliminary comparison of the ozone measurements made from Marambio and those made from the aircraft during a dive made nearby during the flight of 8[th] October 1999 show very similar shape, but some quantitative difference in the amplitude of the ozone variability.

The different resolution and coverage of aircraft and ground based observation makes the comparison of these observations difficult, but enlarges significantly the comprehensiveness of the acquired picture.

MEASUREMENTS DURING THE TRANSFER FLIGHT

A further opportunity offered by the APE-GAIA campaign was the possibility of carrying out scientific observations during the transfer flights of the M55-Geophysica from Europe to South America and reverse. This made it possible to explore the upper troposphere and

lower stratosphere over a wide range of latitudes, and to study the interactions between the polar vortex and the middle latitude stratosphere.
These measurements were very demanding from the logistical point of view. The limited range of the M55 required the transfer flights to be completed in four legs. However, access to the instruments was only possible at the intermediate airport of Recife (Brazil) where the aircraft stopped for three days. There was no access to the instruments during the other two stopovers at Porto Alegre and Sal Island where the aircraft stopped only for a few hours for refuelling and changing the pilot. For this purpose the instruments had to operate and store data for a period of 14 hours of unattended operation.
During the transfer flights auxiliary measurements were provided from Buenos Aires, Mar del Plata, Sal Island and Izaña (Canary Islands).

CONCLUSIONS

APE-GAIA has been a major international collaboration. About 70 among scientists, engineers and technicians worked in Ushuaia during the campaign, and almost as many at other locations were involved in APE-GAIA, contributing with models, data analysis, auxiliary measurements and logistic organisation. A total of nine countries (Italy, Russia, Germany, United Kingdom, Switzerland, Finland, Spain, Argentina, United States) participated in the project.
The M55 stratospheric aircraft operated successfully from the base of Ushuaia in Argentina with a payload that included a comprehensive set of new instruments. Thorough modelling allowed accurate forecasts for focused observations aimed at the exploration of the edge of the polar vortex, and the probing of lee waves and filaments. The timely operation of both the aircraft and the instruments completed the operative success of the campaign that acquired a significant amount of high quality data. The conflicting measurement requirements of the different observing methods have only marginally reduced the productivity of the single instruments while ensuring a unique wealth of complementary information.
The features of the vortex edge were probed at different altitudes with the simultaneous measurement of a large number of tracer species.
Maps of minor constituents distributions were observed as a function of altitude and latitude by the remote sensing instruments. An example has been shown in the case of HNO_3 in which strong indications of sedimentation effects are observed.
The formation of a dense clouds of ice particles was observed at 20 km altitude in the cold regions generated by orographic waves above the Antarctic mountains.
A filament of polar vortex air was forecasted and then sampled by the Geophysica.
The transfer flights from Moscow at 55° N to Ushuaia at 55° S and reverse were used to perform further scientific measurements that provide a continuous detailed monitoring over a very wide latitude range.
The majority of the data will require an elaborate analysis process. A complete assessment of the acquired information will involve comparisons between the instruments and testing of the consistency of the models with the observations. It is expected that the campaign will provide important new information on the dynamics of the vortex, on the processes

controlling ozone in the atmosphere and will improve our estimate of Antarctic ozone recovery time after the phasing out of CFCs .

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