Monitoring of the middle atmosphere: Grille spectrometer experiment results on board SPACELAB 1 and scientific program of ATLAS 1 mission

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ABSTRACT

Measurements of atmospheric trace gases have been performed during the first Spacelab mission on board the Space Shuttle. The principle of the observations is infrared absorption spectroscopy using the solar occultation technique. Infrared absorption spectra of NO, CO, CO_2, NO_2, N_2O, CH_4 and H_2O have been recorded using the Grille spectrometer developped by ONERA and IASB. From the observed spectra, vertical profiles for these molecules have been derived.

The present paper summarizes the main results and compares them with computed vertical profiles from a zonally averaged model of the middle atmosphere. The scientific objectives of the second mission, Atlas 1, planned for 1990 are also presented.

1. INTRODUCTION

The actual vertical distribution profiles of trace molecules are the result of the dynamical, chemical and radiative processes in the Earth's atmosphere. Strongly coupled cycles such as the interaction of chlorine or nitrogen compounds with stratospheric ozone are influenced by sources and losses taking place at much higher or lower altitudes while the penetration of photochemically active radiation depends on the vertical distributions of all atmospheric constituents.

It has now been demonstrated that infrared absorption spectroscopy using the solar occultation technique is a powerful tool to observe trace molecules. The largest possible optical depth is obtained using the limb viewing mode; with the sun as a source the best sensitivity and precise information on the vertical distribution is provided if high spectral resolution is achieved. A great deal of information has already been gathered from aircraft and balloons. An orbiting spacecraft provides access to higher altitudes and allows a global coverage. For this purpose, the Grille spectrometer has been developed for flights on the space shuttle jointly by the Office National d'Etudes et de Recherches Aérospatiales in France and the Belgian Institute for Space Aeronomy.[1,2]

Measurements of atmospheric trace gases have been performed with this spectrometer during the first Spacelab mission in November 1983. Infrared absorption spectra of NO, CO and CO_2 have been obtained for the first time at high altitude. From the observed spectra, vertical profiles for these molecules have been derived as well as for NO_2, N_2O, CH_4 and H_2O.[3]

A second mission is planned for 1990, during the Atlas 1 mission. The autonomy of the cryogenic device used to maintain the detector at liquid nitrogen temperature which was the main constraint limiting the number of observations during the Spacelab 1 mission has now been increased by a factor of five. The expected new measurements will hopefully confirm and extend the previous vertical profiles.

The present paper summarizes the main results obtained during the first mission and compares them with computed vertical profiles derived from a zonally averaged model of the middle atmosphere.[4,5] Finally, the scientific objectives of the Atlas 1 mission are presented.

2. OBSERVATION AND INVERSION OF THE SPECTRA OBTAINED DURING SPACELAB 1 MISSION

The Grille spectrometer observes the absorption of solar radiation by the Earth's atmosphere during sunrise and sunset. The instrument and its operation during the Spacelab 1 flight have already been described.[1,2]

Essentially the instrument is a scanning infrared spectrometer with a spectral resolution slightly lower than 0.1 cm^{-1}, and designed to cover spectral intervals in the 2 - 10 μm range. In order to achieve good altitude resolution, a selected interval limited to a few wavenumbers is continuously scanned at fast rate. The possibility exists to change from one interval to another at 12 different limb altitudes according to a preplanned sequence.

During the flight, actual scientific data were obtained for 19 occultations. Twelve of them occured at sunset, seven at sunrise. Due to the launch date and orbit inclination, sunset occultations were all observed at middle northern latitudes, between 23°N and 43°N while sunrises were observed at high southern latitudes around 68°S. About 6000 spectra were recorded from the lower stratosphere to the lower thermosphere (20 - 130 km) providing spectral information on 10 different species namely H_2O, CO, CO_2, CH_4, N_2O, NO, NO_2, HF, HCℓ and O_3. Table 1 presents the spectral intervals which are scanned and consequently used to retrieve vertical concentration profiles.

An automatic retrieving technique[6,7] was used in which an inversion algorithm compares the computed transmittances with the observed ones in a given spectral interval and minimizes the residual error (root mean square of the difference taken every 0.01 cm^{-1}) between observed and synthetic spectra.

Species	Event	Spectral domain (cm^{-1})	SS/SR	Latitude	Z (km)
N_2O	5	2205 - 2211	SS	43°N	30 - 50
CH_4	14	3010 - 3020	SS	27°N	30 - 70
	15	2974 - 2982	SS	27°N	30 - 70
H_2O	6	1914 - 1918	SR	68°S	30 - 80
	13	3811 - 3825	SS	35°N	30 - 80
	21	3812 - 3825	SS	24°N	30 - 80
NO	6	1914.5 - 1918	SR	68°S	20 - 95
NO_2	6	1595 - 1598.5	SR	68°S	20 - 45
CO	3	2117 - 2123	SS	44°N	40 - 125
	16	2117 - 2123	SS	26°N	40 - 130
	17	2154 - 2162	SR	68°S	40 - 110
	20	2154 - 2162	SR	68°S	30 - 130
CO_2	14	{2341 - 2348 {2356 - 2365	SS	31°N	50 - 90 90 - 130
	18	{2341 - 2348 {2356 - 2365	SS	28°N	50 - 90 90 - 130
	21	2356 - 2365	SS	28°N	30 - 130

Table 1
Main characteristics of the observations. The altitudes indicated correspond to the ranges where vertical distributions could be inverted (SS = sunset, SR = sunrise).

3. RESULTS AND ANALYSIS

3.1 Results

For all the retrievals a reference atmospheric temperature profile has been taken from US standard atmosphere 1976 for mid-latitude spring-fall conditions. The thermospheric temperature is relevant to a low solar activity observed during Spacelab 1, and corresponds to an exospheric temperature of 900 K.

The atmosphere was modelled using isothermal layers 3 km thick. The scanning rate was such that the number of observed spectra for a given occultation was at least equal to the number of atmospheric layers.

Table 1 shows for each species the altitude range for which vertical profiles have been determined. There are three groups of profiles: first, H_2O, CO, NO and NO_2 profiles measured in summer at high southern latitudes, second H_2O, CH_4, CO and CO_2 profiles at northern tropical latitudes and third H_2O, CO and N_2O profiles measured at northern midlatitudes in winter. Data concerning CO and H_2O provide a good opportunity for studying latitudinal variations.

The final results have been summarized recently.[3] The main characteristics of the observations are the following:

- H_2O: Latitudinal variations of H_2O have been noticed at high latitudes above 70 km with a higher mixing ratio in summer than in winter.[8]
- CO_2: The departure from the homospheric mixing ratio has been observed for two occultations with a decrease by about a factor 10 between 90 and 110 km.[9]
- CO: Carbon monoxide has been measured twice from 30 to 120 km. A large latitudinal variation has been observed from these data around 80 km. This is most probably related to the OH chemistry.[9]
- NO: For the first time, nitric oxide has been observed from the thermosphere to the low stratosphere in one shot by means of infrared absorption.[10]
- NO_2: This species is photochemically coupled with NO in the stratosphere. Both species were measured simultaneously at high southern latitude.[10]
- N_2O and CH_4: The profiles observed during Spacelab 1 are consistent with previous measurements (balloon, rocket, satellite) and extended to higher altitudes.[11]

3.2. Analysis

To analyse the results of the first flight and in the prospect of future experiments a zonally average model of the middle atmosphere has been developed[4,5] from the two dimensional stratospheric model of the french National Meteorological Office.[12] It covers the range of altitude between 0 and 140 km. 36 species including CO_2, H_2 are explicitly calculated as a function of latitude and season. Temperature and zonal mean vertical velocity fields are deduced from the LIMS[13] (Limb Infrared Monitoring of the Stratosphere) measurements. The model solves continuity equations for long-lived species or group of species. The concentrations of the short-lived species are updated every model-day and used to reevaluate the 24 hours averages of the production and loss rates of the long-lived species. The molecular diffusion fields including gravity waves.

One interesting molecule is CO which is very sensitive to transport in the mesosphere. In the lower thermosphere the source of CO is CO_2 photodissociation. On the other hand, the photochemical sink ($CO + OH > CO_2 + H$) reduces CO abundance, particularly in the summer mesosphere. As a result, its abundance in the mesosphere is a balance between photochemistry and downward transport from the thermospheric source region by general circulation and eddy mixing. The CO produced in the thermospheric source region in summer is transported by downward advection in winter to the mesosphere where its lifetime is relatively long.

Figure 1 shows the computed profiles of CO compared with the profiles deduced from the Grille spectrometer results at 68°S in summer and at 40°N in winter. In this figure, the previous results of Clancy[14] and Waters[15] as well the more recent ATMOS results[16] are also reported. The important hemispheric gradient is computed satisfactorily by the model.

An additional confirmation of this model can be found in the CO_2 observations. Figure 2 presents the CO_2 profiles deduced from Grille results together with the previous profiles of Trinks[17] and compares them with the computed profiles at 35°N. We can notice clearly the influence of the CO_2 photodissociation above 90 km.

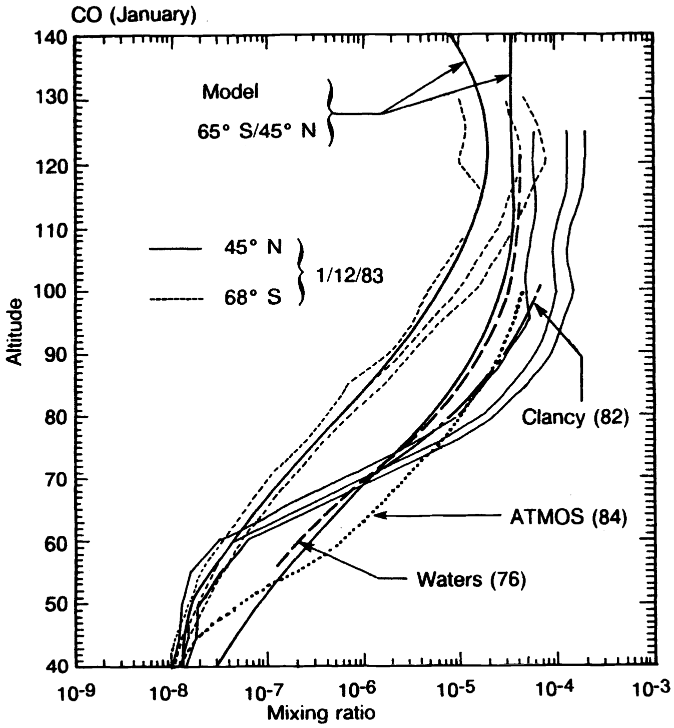

Figure 1
Comparison between CO profiles (retrieval with the envelopes due to inversion and noise errors) deduced from Grille spectrometer observations and calculated profiles obtained from a 2D model. Other experimental results are also reported for comparison.

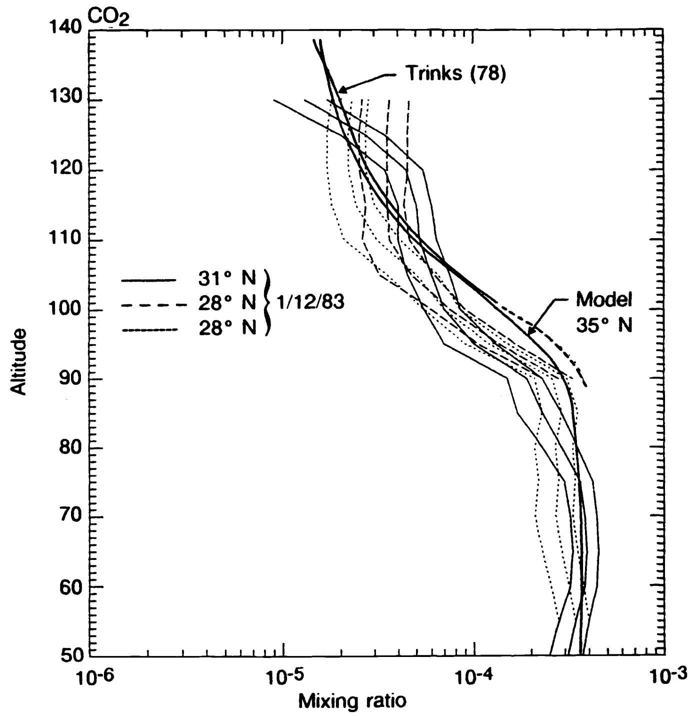

Figure 2
Comparison between CO_2 profiles (retrieval with the envelopes due to inversion and noise errors) deduced from Grille spectrometer observations and calculated profiles obtained from a 2D model. Observations by Trinks are also reported.

4. SCIENTIFIC OBJECTIVES OF THE ATLAS 1 MISSION

Though limited by the numbers of the occultations, the Spacelab 1 results are very significant due to the high level of confidence associated with the infrared absorption spectrometry in the solar occultation mode.

Owing to the increased autonomy of the cryogenic device available for the Atlas 1 mission, we expect a large amount of new data on at least ten species: O_3, NO, NO_2, H_2O, CO, CO_2, CH_4, N_2O, HCℓ, HF. As demonstrated by Spacelab 1 results the solar occultation technique allows measurements over a very large range of altitude. So for each species, this advantage will be emphasized and whenever possible continuous measurements will be performed over the whole middle atmosphere with the same spectral intervals.

More measurements of H_2O would improve the reliability of the previous findings and a more global mapping would allow to a better knowledge of the various processes involved (dynamics, chemistry), specially between 50 and 80 km.

Since CO_2 is a species which is very important to explain the thermal exchange in the mesosphere (radiative balance) it may also be possible to study the departure from Local Thermodynamical Equilibrium.

It is also important to measure CO and CO_2 simultaneously and to have more results for CO in order to study accurately CO variations with latitude and season. The chemistry of CO is well explained so that its global distribution in the mesosphere is a precise diagnostic of dynamical processes.

The Spacelab 1 flight has allowed to observe NO for the first time over a large altitude range with the same instrument. We can expect to record NO at higher altitude during Atlas 1 mission. As for CO, the vertical profiles obtained in this way will provide a good information on the independent stratospheric and thermospheric sources.

Much uncertainty remains on ozone in the photochemical equilibrium region requiring more observation specially in the mesosphere. They were not possible during Spacelab 1 because of the limited number of occultations.

Finally, very limited data have been obtained on HCℓ and HF during this first flight. The next mission would permit to obtain more complete HF and HCℓ profiles the ratio of which is of basic importance for the evaluation of human perturbations to the ozone layer.

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