Study of water and ozone concentrations from MIPAS and SMR data

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Contents

1 Introduction

Continual monitoring of the global climate and atmosphere is vital for:

- Prediction of weather
- Improvement of current atmospheric models
- Understanding mechanisms involved in climatic change
- Understanding the influence of human activities on the abundance of trace gases and its contribution to the greenhouse effect and global warming

Remote measurements made using instruments on satellites are very useful as they enable continuous global coverage, which cannot be obtained from ground-based instruments, balloons or aircraft.

The atmosphere emits, absorbs and scatters electromagnetic radiation. As the emission spectra will depend on the the molecules present, its measurement can be used to determine atmospheric structure and composition.

In this project I will be using the data from the MIPAS instrument on the ENVISAT and SMR instrument on ODIN to investigate the atmospheric composition of water and ozone.

The specific aims of this project are to:

- Give some background on the instruments from which the data are retrieved
- Give some background to ozone and of water and their role in the atmosphere
- Compare profiles of O_3 and of H_2O as obtained from MIPAS data and as obtained from SMR data for one day in the year

2 The instruments

2.1 Michelson Interferometer for Passive Atmospheric Sounding (MIPAS)

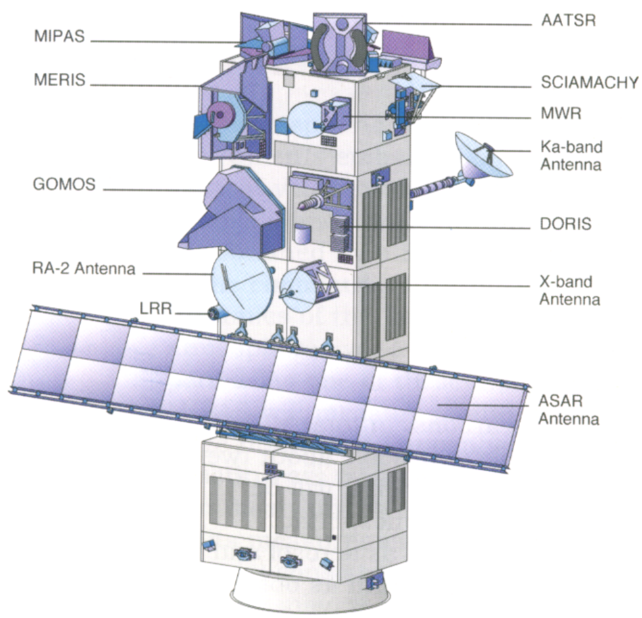

Figure 1: ENVISAT spacecraft (6)

The Michelson Interferometer for Passive Atmospheric Sounding is one of the nine instruments on the European Space Agency's ENVIronmental SATellite (ENVISAT), which was launched on the 1st March 2002 (see figure 1). ENVISAT is a polar-orbiting Earth observation satellite, with a sun-synchronous orbit. The mean altitude of the orbit is 800 km, and the satellite crosses the equator in a southerly direction at 10.00 am local time. This orbit gives a 35 day repeat cycle. Its mission is to provide measurements of the atmosphere, ocean, land and ice over its five year lifetime, thus improving upon the modeling and prediction of environmental and climatic changes made from the current European Earth observation program. The MIPAS instrument uses **limb scanning**, which views the atmosphere tangentially, allowing it a field of view of 3 km (see figure 2). ENVISAT orbits the Earth around 14 times a day, and in each orbit, around 70 complete limb scans are made. Therefore we expect 980 profiles per day from the MIPAS instrument. However not all these scans are successful.

The objectives of MIPAS are:

- Measurements of geophysical parameters in the middle atmosphere;
  Stratospheric chemistry: O_3, H_2O, CH_4, N_2O, NO_2, and HNO_3; and
  Climatology: Temperature, CH_4, N_2O, O_3 ;

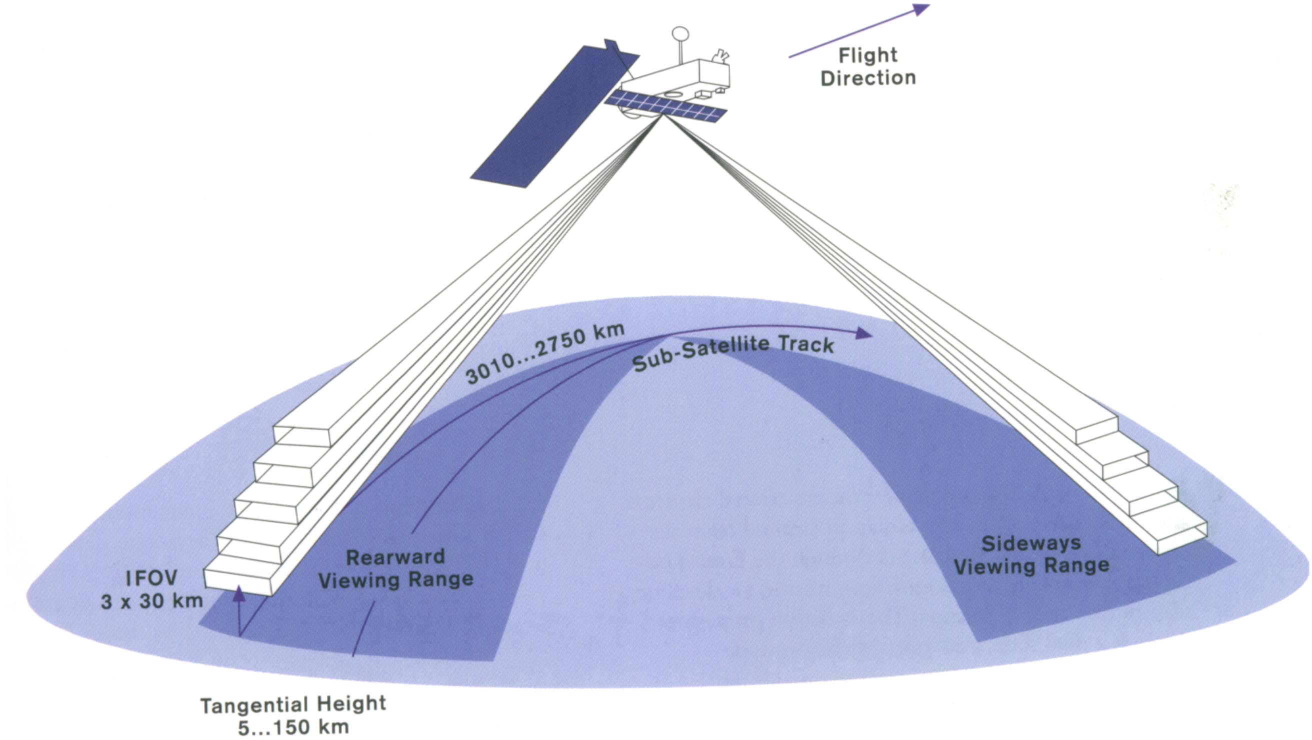

Figure 2: Limb scanning (5)

- Study of chemical composition, dynamics, and radiation budget of the middle atmosphere;
- Monitoring of stratospheric O_3 and CFCs.

As a unique feature of MIPAS, the atmospheric parameters are determined:

- simultaneously as collocated profiles
- with complete global coverage
- during day and night time conditions (allowing observations of the diurnal variation of trace species), and
- throughout its mission duration of four years.

The MIPAS instrument is a **Fourier transform spectrometer** (shown in figure 3) measuring the infrared atmospheric limb emission spectra from 685-2410 cm^{-1} (wavelengths of 14.5-4.1 μm) over an altitude range of 6-68 km. It works by division of input amplitude, and produces an interferogram, which is a Fourier transform of the spectrum of the incoming radiation. The interferograms in addition with other satellite and instrument data will contain all the required information to obtain the measured radiance spectra. The retrieval

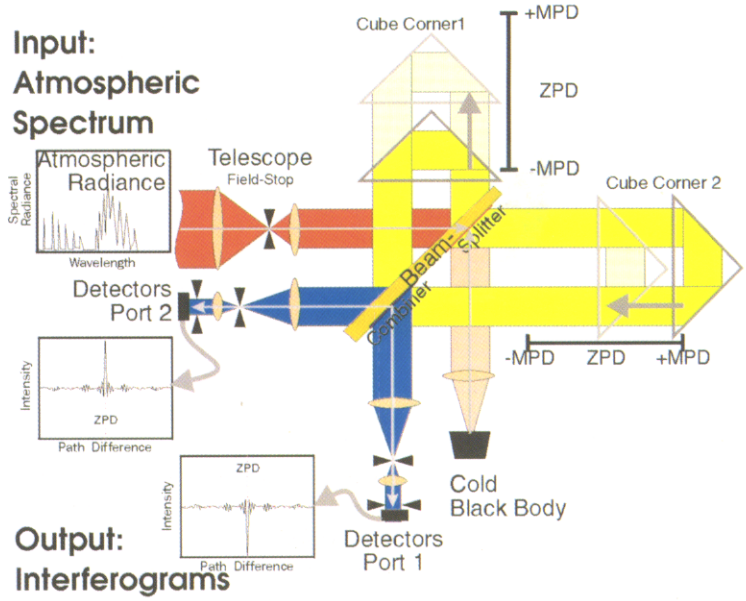

Figure 3: Fourier transform spectrometer on MIPAS (6)

of atmospheric compositions from the raw data involves a number of steps making a *data processing chain*, which is defined in terms of product levels:

- **Level 0:** Reformatted, time-ordered satellite data, in computer-compatible format
- **Level 1A:** Reconstructed interferograms
- **Level 1B:** Radiometrically and spectrally calibrated geolocated spectra
- **Level 2:** Profiles of atmospheric pressure, temperature and trace species.

This report will only deal with the Level 2 products, i.e. the profiles of atmospheric trace species.

2.2 Sub-Millimetre Radiometer(SMR)

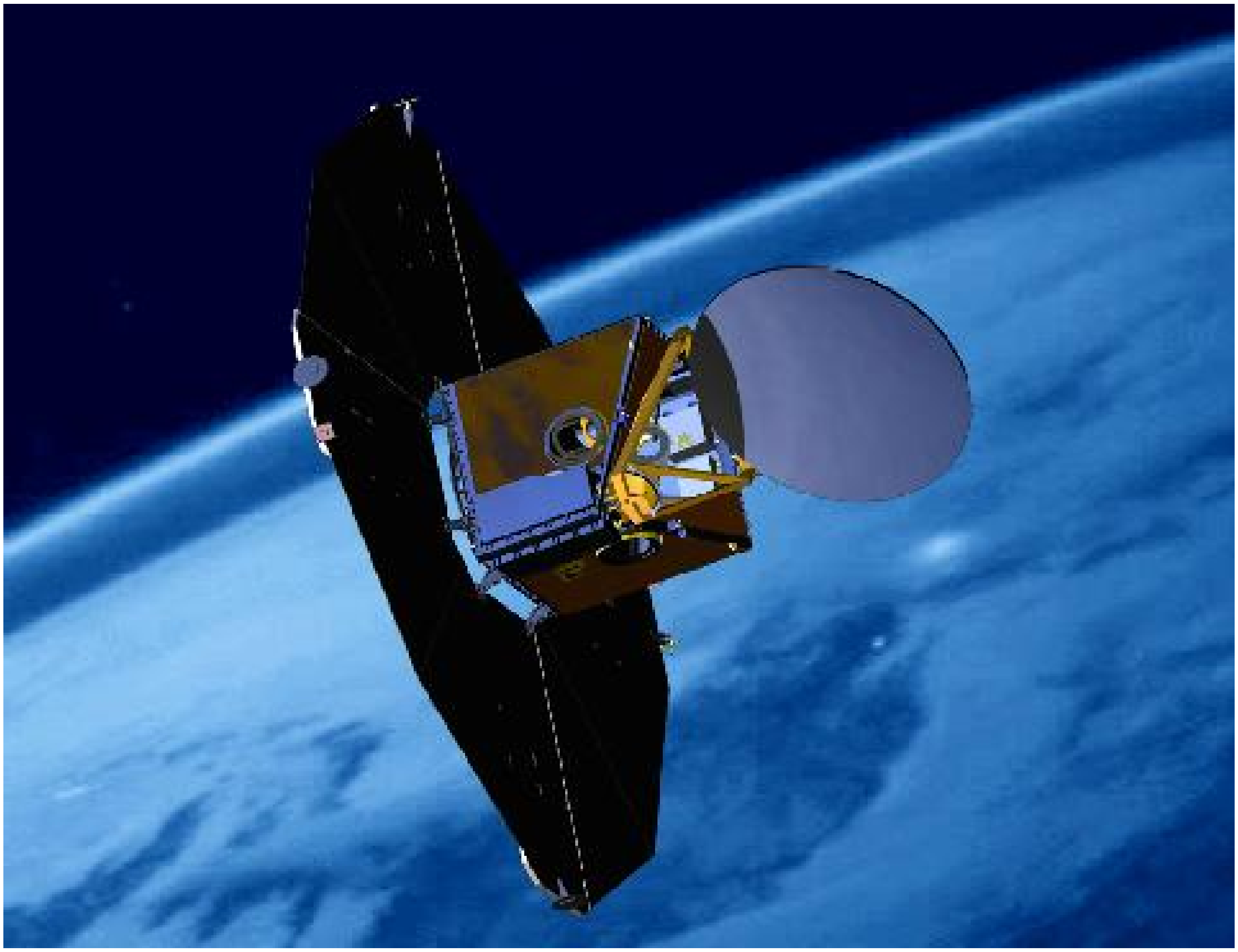

Figure 4: ODIN spacecraft (10)

The Sub-Millimetre Radiometer is one of two instruments on the Swedish Small Satellite Project for Astronomical and Atmospheric Research (ODIN) (see figure 4). The other instrument is the OSIRIS, an optical spectrometer. The ODIN satellite was launched on February 20, 2001 and is used to conduct research in two areas:

- **Astronomy**: The main objective here is to perform detailed studies of the physics and the chemistry of interstellar medium by observing emission from bodies such as comets, planets and galaxies.

- **Aeronomy**: This research will make measurements of various trace species in the stratosphere and mesosphere. In summary the objectives are:

  - *Stratospheric ozone science*: To extend understanding on the mechanisms responsible for ozone depletion in the ozone layer, and how widespread it is, and to study dilution effects due to sulphate aerosols.

- *Mesopheric ozone science*: To establish the relative role of odd hydrogen chemistry and the effects of ordered and turbulent transport and corpuscular radiation.
- *Summer mesopheric science*: To establish the variability of mesopheric water vapour including an assessment of the required fluxes for aerosol formation in the polar mesosphere.
- *Coupling of atmospheric regions*: To study some of the mechanisms that provide coupling between upper and lower atmosphere, for example downward transport of aurorally enhanced NO with its effects on ozone photochemistry and the vertical exchange of minor species such as odd oxygen, CO and H_2O.

Aeronomy is the area in which we will be interested in. For this the SMR instrument views the Earth's limb (as does MIPAS), scanning the atmosphere up and down from 15 to 120 km at a rate of up to 40 scans per orbit. Therefore as the satellite makes about 14 orbits a day, we would expect about 560 profiles for each species a day. Again, as with MIPAS, all these scans may not be successful every time.

ODIN works with wavelengths of around 0.5 mm and 3 mm. There is also complementary information on the atmosphere from spectral lines at ultraviolet and optical wavelengths.

The SMR instrument has one receiver at a wavelength of 3 mm and four in the submillimetre band ($1 \geq 0.5$ mm).

3 Background on ozone and water and the atmosphere

3.1 The atmosphere

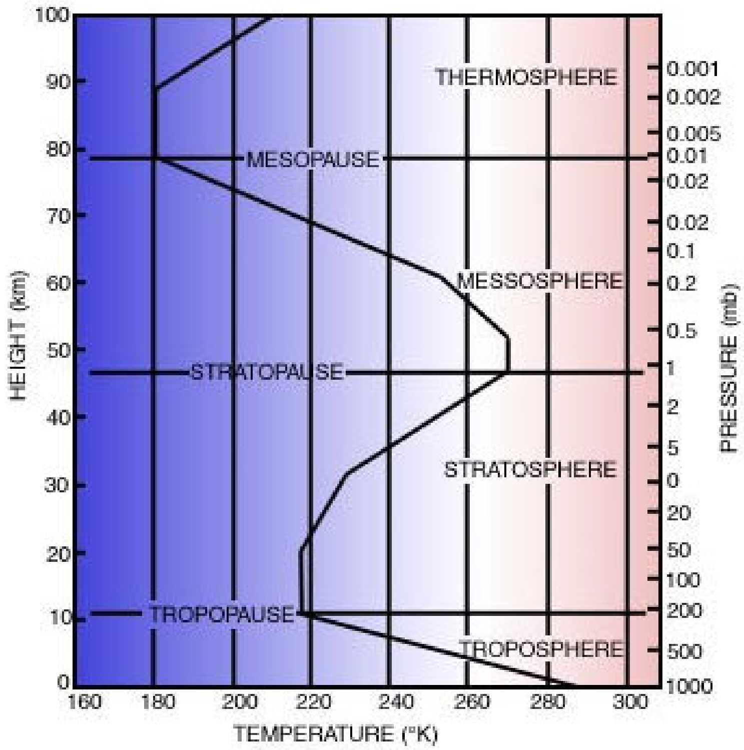

Figure 5: Typical vertical structure of atmospheric temperature/K (3)

The Earth's atmosphere consists of a mixture of ideal gases, consisting mainly of oxygen, O_2 and nitrogen, N_2. However the minor constituents (often referred to as the *trace gases*) play crucial roles. The two gases that we are looking at, ozone and water vapour, are two of these trace gases.

The atmosphere is conventionally divided into layers in the vertical direction, according to the variation of temperature with height. This is shown in figure 5 The temperature decreases with height up to about 15 km altitude. This layer is called the *troposphere* and it is bounded above by the *tropopause*. The layer from the tropopause to about 50 km altitude, in which the temperature rises with height is called the *stratosphere*. This is the layer that we will be interested in in this project and it corresponds to a pressure of about 100 mbar to 1 mbar (where the bottom of the troposphere is at a pressure of 1000 mbar). The stratosphere is bounded by the *stratopause*. Then the layer from this to about 85-90 km, where the temperature again falls with altitude, is called the *mesosphere* and it is bounded by the *mesopause*. Above this is the *thermosphere*, where the temperature again increases with height.

The troposphere is also called the *lower atmosphere*, and it is here where most weather phenomena occur. The stratosphere and mesosphere make up the *middle atmosphere* and above this is the *upper atmosphere.*

3.2 Ozone

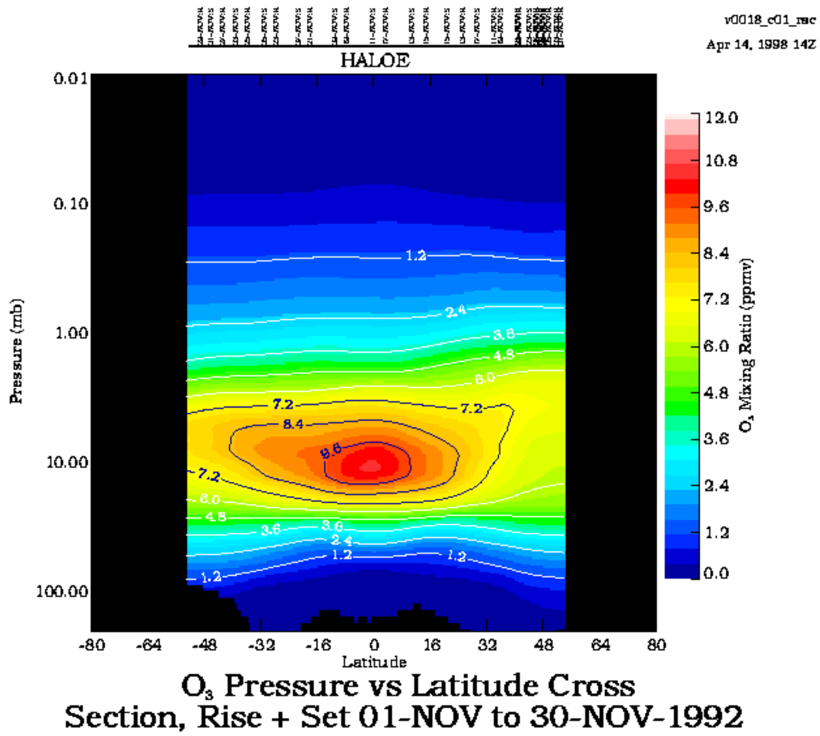

Figure 6: Zonal mean volume mixing ratio of O_3 as measured by HALOE November 1992 (4)

The stratosphere contains the bulk of ozone molecules, and is therefore loosely known as the *ozone layer.* The distribution of ozone in the atmosphere obtained by HALOE (HALogen Occulation Experiment) is shown in figure 6. This was launched on the UARS (Upper Atmosphere Research Satellite) on September 12, 1991 as part of the Earth Science Enterprise (ESE) Program. HALOE is a reliable source of data because it has been running for much longer than the MIPAS and SMR instruments, so the data will have had more time for validation.

The production of ozone (O_3) molecules occurs through photochemical processes that involve the absorption of ultraviolet photons from radiation from the Sun by O_2 molecules in the atmosphere. Three O_2 molecules combine to form two O_3 molecules. This absorption of ultraviolet radiation is what causes the temperature of the atmosphere to increase with height in the stratosphere. It also is important as it protects humans and animals on the Earth from high exposure to it. Therefore understanding the mechanisms which govern the creation and destruction of ozone in the stratosphere is crucial.

The concentration of ozone can be measured in terms of ozone number density or *volume mixing ratio* (VMR), which is the number density of the constituent divided by the total number density of the air. This is the measure used in this project as it has the useful property of being constant for a moving mass of air (unlike the number density), where there is not chemical production and loss processes.

3.3 Water Vapour

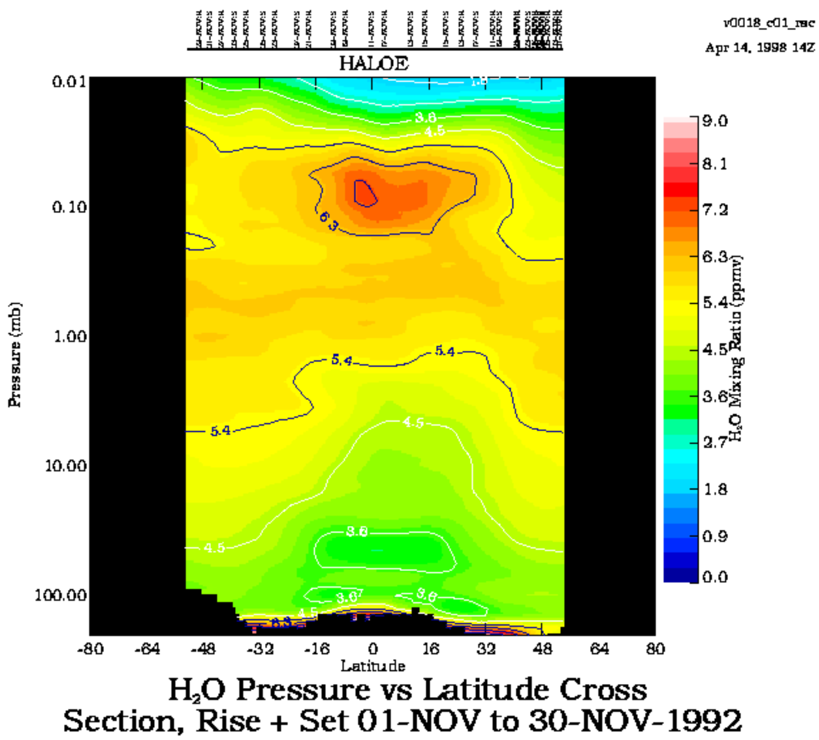

Figure 7: Zonal mean volume mixing ratio of H_2O as measured by HALOE November 1992 (4)

Water vapour is a minor constituent of the atmosphere, but it has a strong influence on weather and climate processes. It is responsible for rain and snow (precipitation) and the formation of polar stratospheric clouds, play an important role in ozone depletion.

Water vapour is also a greenhouse gas. Therefore changes in its concentrations would have serious ramifications in the greenhouse effect and subsequently global warming.

4 Comparison of data from SMR and MIPAS instruments for water vapour and ozone

4.1 Method

The data from the SMR and MIPAS instruments were processed using the programming language **IDL (Interactive Data Language)**. Programs to read the original binary data files into structures were already written by Reinhold Spang from the University of Leicester for MIPAS (program is called *F_MIP_L2RD*) and by Joachim Urban from Chalmers University for SMR (program is called *read_l2p_hdf*). The source code for the routines written using these programs can be found in the appendix A.

Sub-routines were written for each instrument (see appendix A.1 and appendix A.3) that used the two programs created by Spang and Urban to read the data for each instrument into a structure. The data from these structures were then put through loops selecting only the 'good' data (i.e. the data that passed certain quality indices). This 'good' data was then interpolated onto a *standard pressure grid* with 201 levels, created at the beginning of the subroutine. This was done because the pressure levels used by each instrument were not the same. By carrying out this interpolation, the species concentrations measured by each instrument could be compared at the same standard pressure levels. These new interpolated data were then put into a new structure for each instrument as well as appropriate tags such as latitude, longitude, species, scan number, orbit number and date. This was done for all the orbits in one day for the MIPAS instrument, and for all the orbits for the same day and the next day for the SMR instrument (each SMR data file contained data for two consecutive days).

Then main routines were written for each instrument (see appendix A.2 and appendix A.4 using these sub-routines. The comparison between the MIPAS and SMR instruments of individual profiles for O_3 and H_2O at specific locations is still not possible, even though they were interpolated onto the same standard pressure grid because the latitude-longitude co-ordinates of individual profiles from the different instruments are not the same. The concentrations of O_3 and H_2O are expected to vary with longitude, but not significantly with latitude. Therefore the data for each orbit and for each species was split into 10 degree latitude bins so that the zonal profiles for the gases form each instrument could be compared. The routine then selects the profiles for which the volume mixing ratio (VMR) is greater than zero and averages them over all the orbits in that day for each pressure on the standard pressure grid, at each latitude. The data from the SMR instrument however had to first be split into the two days (as each file contained data for two days) before the averaging was carried out. These zonal mean profiles were then put into arrays. The routines then made contour plots for O_3 and for H_2O for each instrument displaying the zonal mean profiles, with pressure as the y-axis (a log axis) and latitude as the x-axis. A colour program was called in the routines to fill in the contours, and a colour bar created on the left of the contour plot as to indicated the concentration levels that the colours correspond to.

A routine was then made (see appendix A.5) that created contour plots of the difference in the zonal mean profiles as a percentage of the MIPAS zonal mean profiles (MIPAS is the instrument we are checking the validity of), with pressure again as the y-axis and latitude as the x-axis. This routine uses a different colour program to fill in the contours. With a symmetrical range of values set for the z-axis, regions of white signifies areas of 0% difference, red signifies areas of (+)ve difference and blue signifies areas of (-)ve difference. This contour plot therefore will make any differences between the data from each instrument very clear.

The five contour plots created as a result of these routines were used to compare the SMR data for O_3 and for H_2O with the MIPAS data. The day studied in this project is 22nd

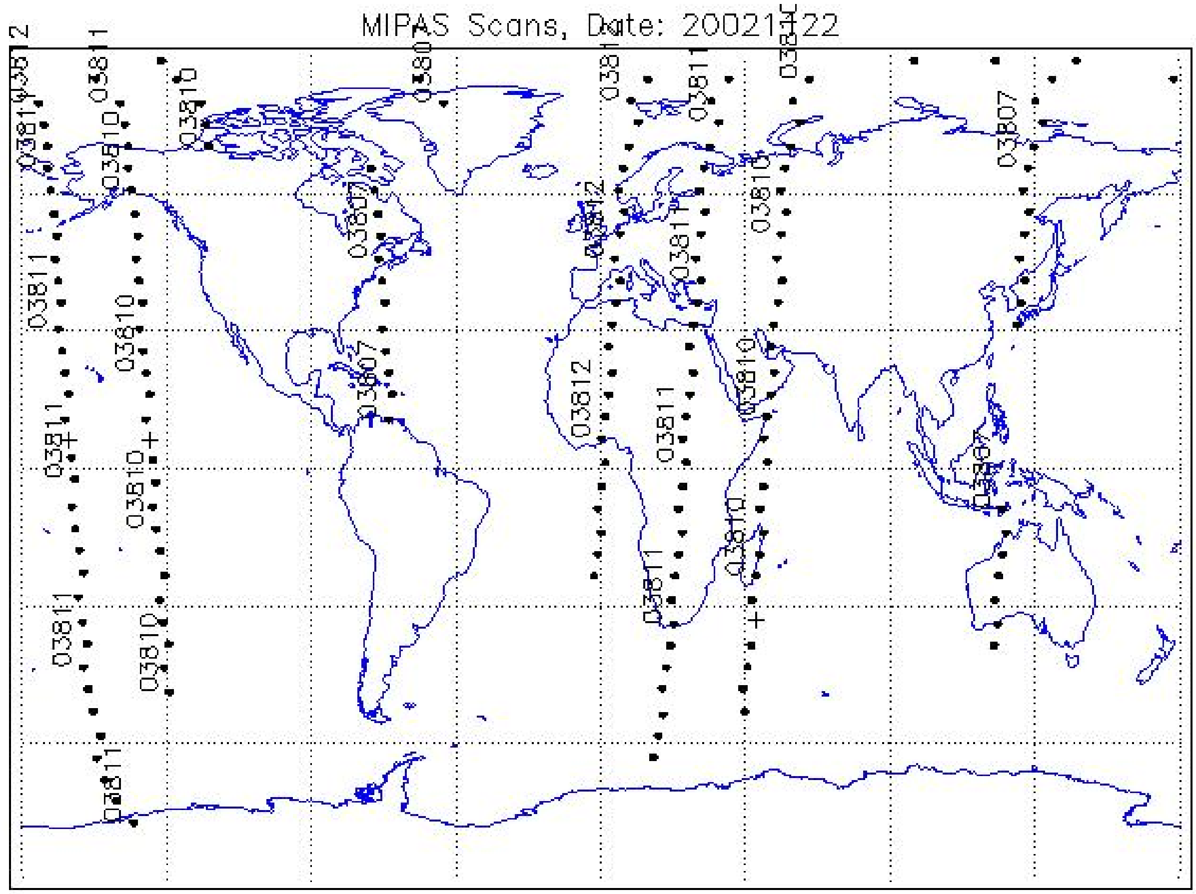

Figure 8: MIPAS coverage plot for 22nd November 2002 (8)

November 2002. Figure 8 shows the coverage plot (i.e. the profiles collected) for MIPAS for this day.

4.2 O_3 comparison

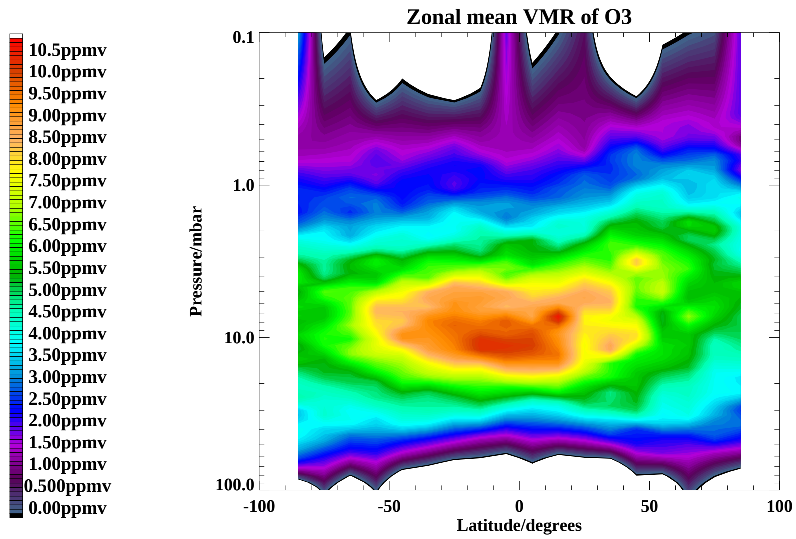

Figure 9: Zonal mean VMR of O_3 as measured by SMR for November 22nd 2002

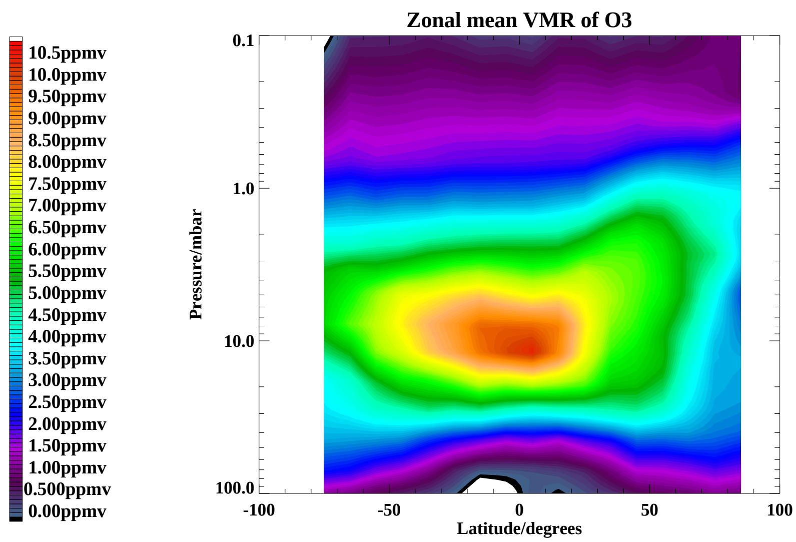

Figure 10: Zonal mean VMR of O_3 as measured by MIPAS for November 22nd 2002

Figure 9 and figure 10 show the zonal mean distributions for O_3 for November 22nd 2002 as measured by the SMR and MIPAS instruments respectively. They both show regions of high ozone concentration of up to about 11 ppmv between pressures of 4 and 20 mbar (corresponding to an altitude range of about 30 to 40 km, the top half of the stratosphere) and centred on the zero degree latitude (which is over the equator). This agrees with the literature (see section 3.2), which states that the stratosphere could be loosely called the 'ozone layer'. Both plots show a steady decrease in ozone VMR towards the North and South Poles and for pressures and altitudes outside the range of high ozone concentrations.

Both contour plots show strong similarities with the HALOE contour plot (also for November; see figure 6), which also shows a maximum concentration of about 10 - 11 ppmv around the region of 0 degrees latitude and 10 mbar pressure. The HALOE contour plot also shows a steady decrease in ozone VMR outside this region of maximum concentration. The HALOE contour plot is also very smooth, like the MIPAS plot. The SMR plot is much less smooth, which might indicate problems in the data retrieval process. To gauge the dif-

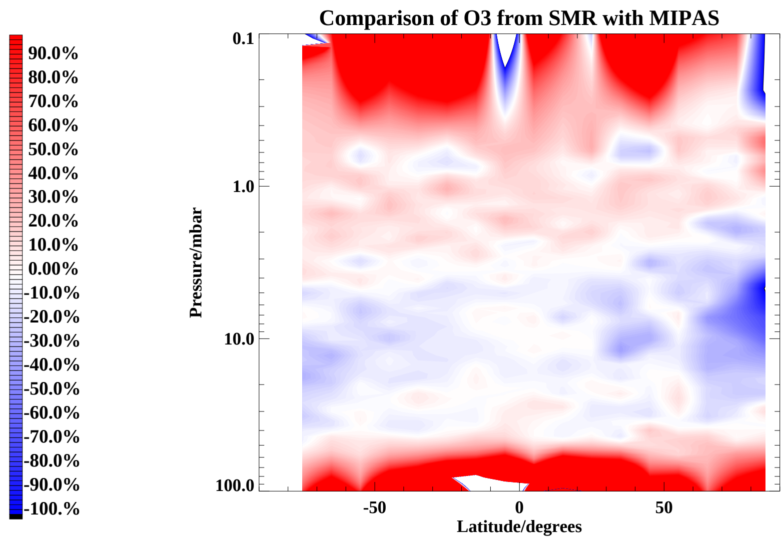

Figure 11: Comparison contour plot for O_3 for November 22nd 2002

ferences between the data from the two instruments more closely, a contour plot was made of the difference in the VMR from the two instruments of ozone for the same pressure and latitude, as a percentage of the MIPAS VMR (as this is the instrument that we are checking the validity of). This plot is shown in figure 11. The white regions on the plot show where the instruments agree. The more red the region, the higher the MIPAS data is compared with the SMR data, while the more blue the region, the higher the SMR data is compared with the MIPAS data.

This contour plot shows that the instruments are most in agreement at pressures between 0.8 mbar and 50 mbar, which corresponds to the region where the ozone concentrations are highest. This is to be expected as any errors made with higher concentrations will be a smaller fraction of the total concentration, and higher concentrations of gas are easier for the instrument to detect. In this region, the MIPAS data is generally lower than the SMR data by about 20% between pressures of 50 mbar and 5 mbar, but there is an area at the North Pole extending between about 5 mbar and 20 mbar pressure, where the MIPAS data gets up to 70% lower than the SMR data. There seems to be an abrupt change at pressures between 0.4 mbar and 5 mbar, where the MIPAS data is generally higher than the SMR data by about 10%. At pressures below 0.4 mbar and above 50 mbar, the MIPAS data becomes over 90% higher than the SMR data. These percentage differences have a significantly high magnitude, as the data from both instruments is expected to be accurate to within 10%.

4.3 Water vapour comparison

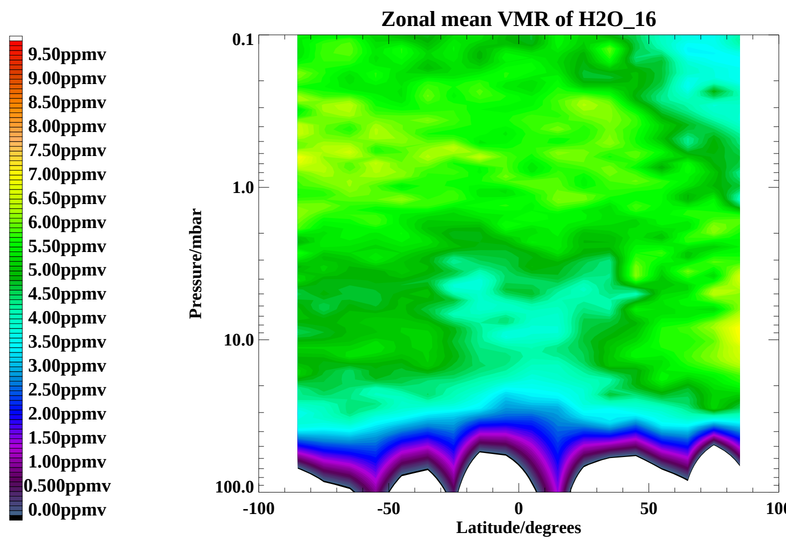

Figure 12: Zonal mean distribution for H_2O as measured by SMR for November 22nd 2002

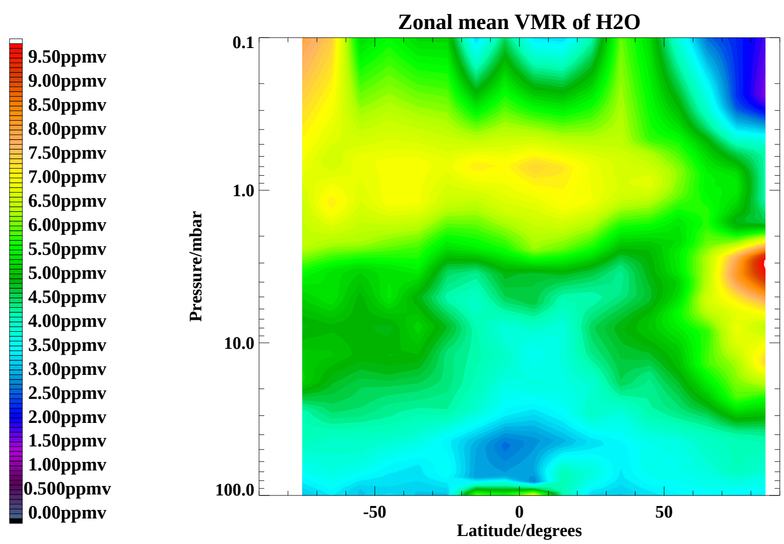

Figure 13: Zonal mean distribution for H_2O as measured by MIPAS for November 22nd 2002

Figure 12 and figure 13 show the zonal mean distributions for H_2O for November 22nd 2002 from the SMR and MIPAS instruments respectively. Both plots show that the upper half of the stratosphere (from 10 to 1 mbar) and the lower half of the mesosphere (from 1 mbar downwards) have higher concentrations of water vapour in general than at higher pressures (i.e. the lower altitudes), at around 6 ppmv on the SMR plot and about 7 ppmv on the MIPAS plot. This shows that the VMR values from MIPAS data are slightly higher in general than those from the SMR. The SMR VMR values for water are also generally more even, while the MIPAS shows specific areas where the concentration of water is significantly higher than the surrounding area. Most prominently, the MIPAS plot shows a considerably higher VMR of about 10 ppmv or higher at the North Pole at a pressure of about 3 mbar. There is also a region at about 0 degree latitude and 0.7 mbar pressure, and at the South Pole between 0.1 mbar and 0.3 mbar, where the concentration of water on the MIPAS plot reaches about 8 ppmv. These three regions do not really shows up on the SMR plot.

These contour plots do not bear the same degree of similarity with the HALOE plot (see figure 7, as the ozone contour plots did. The HALOE plot does also show that the concentration of water is higher in the upper half of the stratosphere and going into the mesosphere (around 6 ppmv), but there is a much more pronounced gradation in concentration over the latitudes and pressures. There is a maximum concentration around 0 degree latitude and 0.1 mbar pressure (which could correspond to the region of higher concentration on the MIPAS plot at 0 degree latitude, but around a higher pressure of 0.7 mbar), where the concentration reaches a value of about 7.5 ppmv. Away from this region, there is a steady decrease in the concentration.

Again the MIPAS plot, like the HALOE plot is considerably smoother than the SMR plot. To have a closer look at the differences, a contour plot was made of the difference

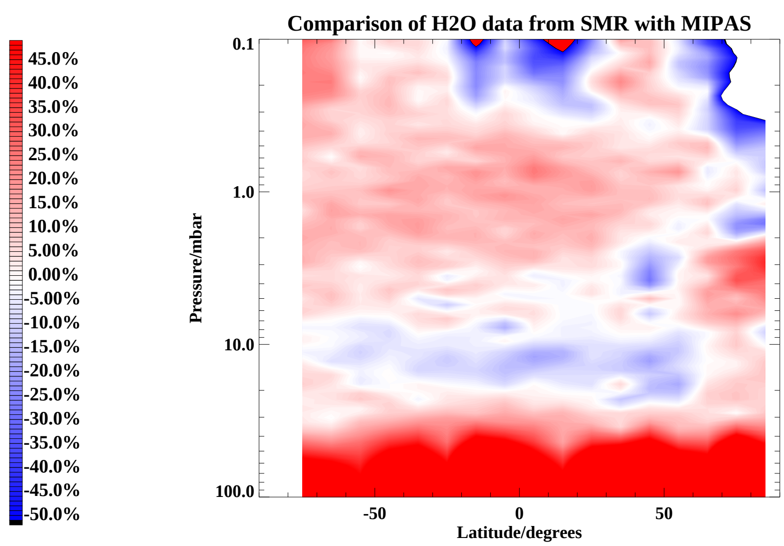

Figure 14: Comparison contour plot for H_2O for November 22nd 2002

between the data as a percentage of the MIPAS data. This is shown in figure 14. This plot is much more illuminating. It shows that the MIPAS data is generally higher than the SMR data by about 15%. There is a small region however across the latitudes between pressures of about 6 mbar and 20 mbar, where the SMR data is about 10 to 15% higher than the MIPAS data. In the boundaries between these two regions, the two instruments more or less agree. These percentage differences again lie outside the 10% error associated with the data from the instruments.

Above a pressure of 40 mbar, the MIPAS data goes above 50% higher than the SMR data, while below 0.3 mbar, around 0 degree latitude and the North Pole, the SMR data goes to about 30% higher than the MIPAS data.

5 Conclusions and Further Work

For November 22nd 2002:

- For pressures between 5 mbar and 50 mbar, the SMR data is significantly higher than the MIPAS data for O_3, but for pressures below 5 mbar and 50 mbar, MIPAS data is significantly higher.
- Both instruments showed variation in O_3 with latitude and pressure in a similar pattern to that in the literature.
- The MIPAS data for H_2O is significantly higher than SMR data in most regions.
- The pattern of variation for H_2O for both instruments was not as well pronounced as suggested by the literature.
- The MIPAS plots are much smoother than the SMR plots. Both plots are expected to be smooth however as zonal means have been taken over about 14 orbits for both instrument, so small fluctuations should be washed out.
- In general the differences between the data from the instruments have a higher magnitude than the 10% error associated with the data. This means that one of the datasets is not reliable, but it cannot be said which, unless further work is carried out.

If more time was available, the following suggestions could be carried out to validate and extend the conclusions made above:

- The size of the differences between MIPAS and SMR could be compared quantitively with the size of the errors on the zonal means.
- Different days could be investigated, and perhaps zonal means over a month calculated.
- More extensive validation could be carried out for each instrument with one such as HALOE which, has been running for a lot longer, and therefore should have more reliable data.
- Other species could be investigated to provide a more thorough report on a comparison between the two instruments.

References

[1] David G. Andrews. *An Introduction to Atmospheric Physics*. Cambridge University Press, 2000

[2] http://www.cpc.ncep.noaa.gov/products/stratosphere/SMDBA/fig3e.gif

[3] http://www.met-office.gov.uk/education/images/atmosf1.jpg

[4] http://haloedata.larc.nasa.gov/home.html

[5] IGACtivities: Newsletter of the International Global Atmospheric Chemistry Project, December 2001, Issue 25

[6] ENVISAT: http://envisat.esa.int/instruments/mipas

[7] IPAS: http://www.atm.ox.ac.uk/group/mipas

[8] http://www.atm.ox.ac.uk/group/mipas/L2/20021122map.jpg

[9] DIN: http://www.ssc.se/ssd/ssat/odin.html

[10] http://www.ssc.se/ssd/ssat/odinny.jpg

A Source Code

A.1 vmrinterpol_mipas.pro

```
PRO vmrinterpol_mipas, norbit, specnam, nscan, nswp, nzm, nspec, orbit

; Set path to pick up L2 utility procedures

!PATH = '/home/crun/eodg/mipas/L2/util:' + !PATH
!PATH = '/home/crun/eodg/mipas/L2/util/read:' + !PATH
FORWARD_FUNCTION F_MIP_L2RD   ; Forces F_MIP_L2_RD to be recognised as a
; function

root = '/home/crun/mipas/L2/NL/20021122/*.N1'

SPAWN, 'ls ' + root, LV2FIL

norbit = N_ELEMENTS(LV2FIL)

specnam = ['H2O', 'O3']
nspec = N_ELEMENTS(specnam)

; Define standard pressure grid
zm_levels = DINDGEN(201)/2
zm_levels[0] = 0.01
zm_levels = 10.^double(round(100.*alog10(1000.*exp(-zm_levels/7.)))/100.)

nzm = N_ELEMENTS(zm_levels)

; Define structure 'orbit', which will contain the interpolated data
intscan = REPLICATE({gas:REPLICATE({vmr:FLTARR(nzm)}, nspec), lat:FLTARR(17), $
lon:FLTARR(17), pres:FLTARR(nzm)}, 73)

orbit = REPLICATE({intscan:intscan}, norbit)

FOR iorbit = 0, norbit - 1 DO BEGIN

; Read data into the structure, smr, for each orbit
l2s = F_MIP_L2RD(LV2FIL(iorbit), /SCAN)

; Find out number of scans and number of sweeps in the file
nscan = N_ELEMENTS(l2s.scan.lat(0))
nswp = (N_ELEMENTS(l2s.scan.lat))/nscan
```

```
goodspec = FLTARR(nswp,nscan,nspec)   ; Array for good measurments
goodpre = FLTARR(nswp,nscan,nspec)   ; Pressure array for good measurements

FOR iscan = 0, nscan - 1 DO BEGIN

   ; Define entries in 'orbit' structure by looping over data in all the orbits
   orbit(iorbit).intscan(iscan).pres = zm_levels
   orbit(iorbit).intscan(iscan).lat = l2s.scan(iscan).lat
   orbit(iorbit).intscan(iscan).lon = l2s.scan(iscan).lon

    FOR ispec = 0, 1 DO BEGIN

   ; Define good data
goodval = $
        WHERE (l2s.scan(iscan).gas(ispec).vmr GT 0, $
      ;AND l2s.scan(iscan).ptflag NE 0, $
      count)
          IF count NE 0 THEN BEGIN
               goodspec(goodval,iscan,ispec) = $
       l2s.scan(iscan).gas(ispec).vmr[goodval]
       goodpre(goodval,iscan,ispec) = $
       l2s.scan(iscan).pres[goodval]

; Interpolate onto standard pressure grid to get improved vmr values
x = ALOG10(goodpre(goodval,iscan,ispec))
v = goodspec(goodval,iscan,ispec)
u = ALOG10(zm_levels)
orbit(iorbit).intscan(iscan).gas(ispec).vmr = $
INTERPOL(v, x, u)

          ENDIF   ; goodval

    ENDFOR   ; ispec

  ENDFOR   ; iscan

ENDFOR   ; iorbit

END
```

A.2 interpol_mipas.pro

```
PRO interpol_mipas, specnam, prearr, specarr, latarr, plotlat
```

```
vmrinterpol_mipas, norbit, specnam, nscan, nswp, nzm, nspec, orbit

maxval = [10.0, 11.0]

prearr = FLTARR(nzm,18,nspec)    ; Set up pressure array
specarr = FLTARR(nzm,18,nspec)    ; Set up species array

; Looping the program over the two different species
FOR ispec = 0, 1 DO BEGIN

!P.FONT = 0
!P.MULTI = 0
region = [.2, 0.05, 0.95, 0.95] ;  Region of page to place plot on
!P.REGION = region

SET_PLOT, 'PS'
DEVICE, /COLOR, /ENCAPSULATED, XSIZE = 31, YSIZE = 22
DEVICE, SET_FONT = 'Times-Bold', FONT_SIZE = 24

colour_ps

; In order to produce a contour plot with latitudinal variation, have to put
; everything into latitude bins

latbounds = FLTARR(19)
FOR ilat = 0, 18 DO latbounds(ilat) = -90 + 10*ilat

; Array to keep track of number of profiles in each latitude bin
numprof = FLTARR(18)

FOR ilat = 0, 17 DO BEGIN

FOR iorbit = 0, norbit - 1 DO BEGIN

nscan = N_ELEMENTS(orbit(iorbit).intscan)

  FOR iscan = 0, nscan - 1 DO BEGIN

    FOR iswp = 0, nswp - 1 DO BEGIN

      IF (orbit(iorbit).intscan(iscan).lat(iswp) GE latbounds(ilat) ) $
        AND (orbit(iorbit).intscan(iscan).lat(iswp) LE latbounds(ilat+1) ) $
        THEN BEGIN
 goodval = $
```

```
 WHERE ((orbit(iorbit).intscan(iscan).gas(ispec).vmr), count)
 IF count GT 0 THEN BEGIN
          specarr(goodval,ilat,ispec) = specarr(goodval,ilat,ispec) + $
      orbit(iorbit).intscan(iscan).gas(ispec).vmr[goodval]
          numprof(ilat)= numprof(ilat) + 1
          prearr(goodval,ilat,ispec) = prearr(goodval,ilat,ispec) + $
      orbit(iorbit).intscan(iscan).pres[goodval]

         ENDIF ; goodval

      ENDIF   ; latitude bins

    ENDFOR   ; iswp

  ENDFOR   ; iscan

ENDFOR ; iorbit

; Take an average of pressure and vmr values over latitude bins for each day
prearr(*,ilat,ispec) = prearr(*,ilat,ispec) / (numprof(ilat))
specarr(*,ilat,ispec) = specarr(*,ilat,ispec) / (numprof(ilat))

ENDFOR   ; ilat

; Set up latitude array (10 degree latitude bins)
latarr = FLTARR(nzm, 18)
FOR ilat = 0, 17 DO latarr(0,ilat) = -85.0 + 10*ilat
FOR ilev = 0, N_ELEMENTS(latarr(*,0))-1 DO latarr(ilev,*) = latarr(0,*)

; In case orbit has not completed: check for latitude bins that don't
; contain anything.  Only plot the latitudes that have data in them
plotlat = WHERE (numprof NE 0, countlat)

DEVICE, FILE = 'vmr_mipas_' + specnam(ispec) + '_' + '20021122' + '.eps'

; Define data arrays to be plotted
specplot = FLTARR(nzm,18)
latplot = FLTARR(nzm,18)
preplot = FLTARR(nzm,18)

specplot = specarr(*,plotlat,ispec)
latplot = latarr(*,plotlat)
preplot = prearr(*,plotlat,ispec)
```

```
; Set levels for the contours
minlev = 0
maxlev = maxval(ispec)
nlev = 100
step = (maxlev - minlev)/nlev
contlev = FLTARR(nlev)
FOR ilev = 0, nlev - 1 DO contlev(ilev) = minlev + ilev*step

; Plot contour
IF ispec EQ 0 $
      THEN BEGIN
  CONTOUR, specplot, latplot, preplot, $
       TITLE = specnam(ispec) + '/ppmv*1e-06', $
       XTITLE = 'Latitude/degrees', $
       YTITLE = 'Pressure/mbar', $
       LEVELS = contlev, /YLOG, /FOLLOW, /FILL, $
       CHARSIZE = 0.75, CHARTHICK = 3, $
       XRANGE = [-90,90], $
       YRANGE = [1e2, 0.1], $
    XSTYLE = 1
    YSTYLE = 1
ENDIF ELSE BEGIN
  CONTOUR, specplot, latplot, preplot, $
       TITLE = specnam(ispec) + '/ppmv*1e-06', $
       XTITLE = 'Latitude/degrees', $
       YTITLE = 'Pressure/mbar', $
       LEVELS = contlev, /YLOG, /FOLLOW, /FILL, $
       CHARSIZE = 0.75, CHARTHICK = 3, $
       XRANGE = [-90,90], $
    YRANGE = [1e2, 0.1]
    XSTYLE = 1
    YSTYLE = 1
      ENDELSE

; Set colour bar position and draw the color bar
     col_region=[0.015,0.1,0.03,0.9]
     xc1=col_region(0)
     xc2=col_region(2)
     yc1=col_region(1)
     yc2=col_region(3)
labelbary,xc1,xc2,yc1,yc2, contlev,label = ' '

ENDFOR   ; ispec
```

```
DEVICE, /CLOSE

END
```

A.3 vmrinterpol_FM_08.pro

```
PRO vmrinterpol_FM_08, norbit, specnam, nscan, nswp, nzm, nspec, orbit

!PATH = '/home/crun/mipas/L2/ODIN/odin/pro:' + !PATH

root = '/home/crun/mipas/L2/ODIN/FM_08/*.DATA'

SPAWN,'ls ' + root, filename

norbit = N_ELEMENTS(filename)

datafile = STRARR(norbit)
FOR iorbit = 0, norbit - 1 DO $
datafile(iorbit) = STRMID(filename(iorbit),0,STRLEN(filename(iorbit))-5)

specnam = ['H2O', 'O3', 'H2O_16', 'H2O_18']
nspec = N_ELEMENTS(specnam)

; Define standard pressure grid
zm_levels = DINDGEN(201)/2
zm_levels[0] = 0.01
zm_levels = 10.^double(round(100.*alog10(1000.*exp(-zm_levels/7.)))/100.)

nzm = N_ELEMENTS(zm_levels)

; Define structure 'orbit', which will contain the interpolated data, and days
intsmr = REPLICATE({species:REPLICATE({profile:FLTARR(nzm)}, nspec), $
latitude:0.0, longitude:0.0, $
zpt:REPLICATE({profile:FLTARR(nzm)}, 3)}, 31)

orbit = REPLICATE({intsmr:intsmr, day:0}, norbit)

FOR iorbit = 0, norbit - 1 DO BEGIN

; Read data into the structure, smr, for each orbit
read_l2p_hdf, datafile(iorbit), smr
nscan = N_ELEMENTS(smr.latitude)
nswp = N_ELEMENTS(smr(0).zpt(1).profile)
```

```
goodspec = FLTARR(nswp,nscan,nspec)   ; Array for good measurments
goodpre = FLTARR(nswp,nscan,nspec)   ; Pressure array for good measurements

  FOR iscan = 0, nscan - 1 DO BEGIN

   ; Define entries in 'orbit' structure by looping over data in all the orbits
   orbit(iorbit).intsmr(iscan).zpt(1).profile = zm_levels
   orbit(iorbit).intsmr(iscan).latitude = smr(iscan).latitude
   orbit(iorbit).intsmr(iscan).longitude = smr(iscan).longitude
   orbit(iorbit).day = smr(0).day

    FOR ispec = 1, nspec - 1 DO BEGIN

   ; Define good data (i.e., greater than zero, with quality zero and
   ; measurement response greater than 0.9)
goodval = $
        WHERE (smr(iscan).species(ispec).profile GT 0 AND $
      FLOAT(smr(iscan).quality) EQ 0 $
      AND smr(iscan).species(ispec).measresp GT 0.9, $
      count)
          IF count NE 0 THEN BEGIN
               goodspec(goodval,iscan,ispec) = $
       smr(iscan).species(ispec).profile[goodval]
       goodpre(goodval,iscan,ispec) = $
       smr(iscan).zpt(1).profile[goodval]

; Interpolate onto standard pressure grid to get improved vmr values
x = ALOG10(goodpre(goodval,iscan,ispec))
v = goodspec(goodval,iscan,ispec)
u = ALOG10(zm_levels)
orbit(iorbit).intsmr(iscan).species(ispec).profile = $
INTERPOL(v, x, u)

          ENDIF   ; goodval

    ENDFOR   ; ispec

  ENDFOR   ; iscan

ENDFOR   ; iorbit

END
```

A.4 interpol_odin_FM_08.pro

```
PRO interpol_odin_FM_08, prearr08, specarr08, latarr08, plotlat08

vmrinterpol_FM_08, norbit, specnam, nscan, nswp, nzm, nspec, orbit

maxval = [8, 11.0, 10.0, 0.018]

prearr08 = FLTARR(nzm,18,2,nspec)   ; Set up pressure array
specarr08 = FLTARR(nzm,18,2,nspec)   ; Set up species array

; Looping the program over the last three species
FOR ispec = 1, nspec - 1 DO BEGIN

!P.FONT = 0
!P.MULTI = 0
region = [.2, 0.05, 0.95, 0.95] ;  Region of page to place plot on
!P.REGION = region

SET_PLOT, 'PS'
DEVICE, /COLOR, /ENCAPSULATED, XSIZE = 31, YSIZE = 22
DEVICE, SET_FONT = 'Times-Bold', FONT_SIZE = 24

colour_ps

; In order to produce a contour plot with latitudinal variation, have to put
; everything into latitude bins

latbounds = FLTARR(19)
FOR ilat = 0, 18 DO latbounds(ilat) = -90 + 10*ilat

; Array to keep track of number of profiles in each latitude bin
numprof = FLTARR(18,2)

day = [22,23]

FOR ilat = 0, 17 DO BEGIN

FOR iorbit = 0, norbit - 1 DO BEGIN

intscan = N_ELEMENTS(orbit(iorbit).intsmr)

FOR iday = 0, 1 DO BEGIN
```

```
 IF orbit(iorbit).day EQ day(iday) THEN BEGIN

  FOR iscan = 0, intscan - 1 DO BEGIN

   IF (orbit(iorbit).intsmr(iscan).latitude GE latbounds(ilat) ) $
     AND (orbit(iorbit).intsmr(iscan).latitude LE latbounds(ilat+1) ) $
     THEN BEGIN
goodval = $
WHERE ((orbit(iorbit).intsmr(iscan).species(ispec).profile), count)
IF count GT 0 THEN BEGIN
         specarr08(goodval,ilat,iday,ispec) = $
 specarr08(goodval,ilat,iday,ispec) + $
      orbit(iorbit).intsmr(iscan).species(ispec).profile[goodval]
         numprof(ilat,iday)= numprof(ilat,iday) + 1
         prearr08(goodval,ilat,iday,ispec) = $
 prearr08(goodval,ilat,iday,ispec) + $
      orbit(iorbit).intsmr(iscan).zpt(1).profile[goodval]

        ENDIF ; goodval

   ENDIF   ; latitude bins

  ENDFOR   ; iscan

 ENDIF   ; separating out orbits with days

ENDFOR   ; iday

ENDFOR ; iorbit

FOR iday = 0, 1 DO BEGIN

; Take an average of pressure and vmr values over latitude bins for each day
prearr08(*,ilat,iday,ispec) = $
prearr08(*,ilat,iday,ispec) / (numprof(ilat,iday))
specarr08(*,ilat,iday,ispec) = $
specarr08(*,ilat,iday,ispec) / (numprof(ilat,iday))

ENDFOR   ; iday

ENDFOR   ; ilat

; Set up latitude array (10 degree latitude bins)
latarr08 = FLTARR(nzm, 18)
```

```
FOR ilat = 0, 17 DO latarr08(0,ilat) = -85.0 + 10*ilat
FOR ilev = 0, N_ELEMENTS(latarr08(*,0))-1 DO latarr08(ilev,*) = latarr08(0,*)

date = ['20021122', '20021123']

FOR iday = 0, 1 DO BEGIN

; In case orbit has not completed: check for latitude bins that don't
; contain anything.  Only plot the latitudes that have data in them
plotlat08 = WHERE (numprof(*,iday) NE 0, countlat)

DEVICE, FILE = 'vmr_' + specnam(ispec) + '_' + date(iday) + '.eps'

; Define data arrays to be plotted
specplot = FLTARR(nzm,18)
latplot = FLTARR(nzm,18)
preplot = FLTARR(nzm,18)

specplot = (specarr08(*,plotlat08,iday,ispec))*1e06
latplot = latarr08(*,plotlat08)
preplot = prearr08(*,plotlat08,iday,ispec)

; Set levels for the contours
minlev = 0
maxlev = maxval(ispec)
nlev = 100
step = (maxlev-minlev)/nlev
contlev = FLTARR(nlev)
FOR ilev = 0, nlev - 1 DO contlev(ilev) = minlev + ilev*step

; Plot contour
CONTOUR, specplot, latplot, preplot, $
  TITLE = specnam(ispec) + '/ppmv*1e-06', $
  XTITLE = 'Latitude/degrees', $
  YTITLE = 'Pressure/mbar', $
  LEVELS = contlev, /YLOG, /FOLLOW, /FILL, $
  CHARSIZE = 0.75, CHARTHICK = 3, $
  XRANGE = [-90,90], $
  YRANGE = [1e2, 0.1]
  XSTYLE = 1
  YSTYLE = 1

; Set colour bar position and draw the color bar
     col_region=[0.015,0.1,0.03,0.9]
```

```
     xc1=col_region(0)
     xc2=col_region(2)
     yc1=col_region(1)
     yc2=col_region(3)
labelbary,xc1,xc2,yc1,yc2, contlev,label = ' '

ENDFOR   ; iday

ENDFOR   ; ispec

DEVICE, /CLOSE

END
```

A.5 comparison.pro

```
interpol_odin_FM_08, prearr08, specarr08, latarr08, plotlat08

interpol_mipas, specnam, prearr, specarr, latarr, plotlat

FOR ispec = 0, 1 DO BEGIN

!P.FONT = 0
!P.MULTI = 0
region = [.2, 0.05, 0.95, 0.95] ;  Region of page to place plot on
!P.REGION = region

SET_PLOT, 'PS'
DEVICE, /COLOR, /ENCAPSULATED, XSIZE = 31, YSIZE = 22
DEVICE, SET_FONT = 'Times-Bold', FONT_SIZE = 24
DEVICE, FILE = 'comparison_' + specnam(ispec) + '_' + '20021122' + '.eps'

colour_ps

minval = [-40.0, -110.0]
maxval = [50.0, 60.0]

; Set levels for the contours
minlev = minval(ispec)
maxlev = maxval(ispec)
nlev = 100
step = (maxlev - minlev)/nlev
contlev = FLTARR(nlev)
FOR ilev = 0, nlev - 1 DO contlev(ilev) = minlev + ilev*step
```

```
IF ispec EQ 0 THEN BEGIN
; Set up arrays to contain the difference in species data, pressure and lat
compplot = ((specarr(*,plotlat,ispec) - 1e6*specarr08(*,plotlat,0,2)) / $
   specarr(*,plotlat,ispec))*100
latplot = latarr(*,plotlat)
preplot = prearr(*,plotlat,ispec)

 CONTOUR, compplot, latplot, preplot, $
       TITLE = 'Comparison of ' + $
    specnam(ispec) + ' from SMR with MIPAS', $
       XTITLE = 'Latitude/degrees', $
       YTITLE = 'Pressure/mbar', $
       LEVELS = contlev, /YLOG, /FOLLOW, /FILL, $
       CHARSIZE = 0.75, CHARTHICK = 3, $
       XRANGE = [-90,90], $
       YRANGE = [1e2, 0.1], $
    XSTYLE = 1
    YSTYLE = 1

ENDIF ELSE BEGIN

; Set up arrays to contain the difference in species data, pressure and lat
compplot = ((specarr(*,plotlat,ispec) - 1e6*specarr08(*,plotlat,0,ispec)) / $
   specarr(*,plotlat,ispec))*100
latplot = latarr(*,plotlat)
preplot = prearr(*,plotlat,ispec)

 CONTOUR, compplot, latplot, preplot, $
       TITLE = 'Comparison of ' + $
    specnam(ispec) + ' from SMR with MIPAS', $
       XTITLE = 'Latitude/degrees', $
       YTITLE = 'Pressure/mbar', $
       LEVELS = contlev, /YLOG, /FOLLOW, /FILL, $
       CHARSIZE = 0.75, CHARTHICK = 3, $
       XRANGE = [-90,90], $
       YRANGE = [1e2, 0.1], $
    XSTYLE = 1
    YSTYLE = 1

ENDELSE

; Set colour bar position and draw the color bar
     col_region=[0.015,0.1,0.03,0.9]
```

```
     xc1=col_region(0)
     xc2=col_region(2)
     yc1=col_region(1)
     yc2=col_region(3)
labelbary,xc1,xc2,yc1,yc2, contlev,label = ' '

ENDFOR

DEVICE, /CLOSE

END
```