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Abstract

We present vM21 MIPAS temperatures from the lower stratosphere to the lower thermosphere, which cover all optimized resolution measurements performed by MIPAS in the Middle Atmosphere, Upper Atmosphere and NoctiLucent Cloud modes during its lifetime. i.e., from January 2005 to March 2012. The main upgrades with respect to the previous version of MIPAS temperatures (vM11) are the update of the spectroscopic database, the use of a different climatology of atomic oxygen and carbon dioxide, and the improvement of important technical aspects of the retrieval setup (temperature gradient along the line of sight and offset regularizations, apodization accuracy). Additionally, an updated version of ESA calibrated L1b spectra (5.02/5.06) is used. The vM21 temperatures correct the main systematic errors of the previous version because they on average provide a 1–2 K warmer stratopause and middle mesosphere, and a 6–10 K colder mesopause (except in high latitude summers) and lower thermosphere. These lead to a remarkable improvement of MIPAS comparisons with ACE-FTS, MLS, OSIRIS, SABER, SOFIE and the two Rayleigh lidars at Mauna Loa and Table Mountain, that, with few specific exceptions, typically exhibit differences smaller than 1 K below 50 km and than 2 K at 50–80 km in spring, autumn, winter at all latitudes, and summer at low to mid-latitudes. Differences in the high latitude summers are typically smaller than 1 K below 50 km, smaller than 2 K at 50–65 km and 5 K at 65–80 km. Differences with the other instruments in the mid-mesosphere are generally negative. MIPAS mesopause is within 4 K of the other instruments measurements, except in the high latitude summers, where it is within 5–10 K of the other instruments, being warmer than SABER, MLS and OSIRIS and colder than ACE-FTS and SOFIE. The agreement in the lower thermosphere is typically better than 5 K, except for high latitudes during spring and summer, where MIPAS usually exhibits larger vertical gradients.

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1 Introduction

The Michelson Interferometer for Passive Atmospheric Sounding (MIPAS) (Fischer et al., 2008) globally measured onboard EnviSat (Environmental Satellite) the day and night limb emission from atmospheric constituents from July 2002 to April 2012, when contact to the satellite was lost. MIPAS spectra cover wavelengths from 4.3 to 15.6 μm with a resolution of 0.035 cm^{-1} (unapodized; full resolution) from 2002 to 2004 and 0.0625 cm^{-1} (unapodized; reduced resolution) onwards. MIPAS was in a sun-synchronous orbit, with ascending/descending nodes at 10:00/22:00 LT. MIPAS almost continuously measured in its nominal (NOM) mode (6–68 km) but used special modes to expand its measurements to the mesosphere and lower thermosphere (MLT) during around ten 2–3 full days campaigns in 2005 and 2006 and on a regular basis (every 10 days) starting in March 2007. These special modes of operation are the Middle Atmosphere mode (MA; covering 18–102 km, in 3 km vertical steps), the Upper Atmosphere mode (UA; covering 40–102 km, in 3 km steps, and 102–170 km, in 5 km steps) and the NoctiLucent-Cloud mode (NLC; covering 39–102 km, in 3 km steps except at 78–87 km, where 1.5 km vertical steps were used ; this mode was only used for 3 day campaigns in the solstices) (Oelhaf, 2008).

The MA, NLC and UA mode measurements are currently used to derive kinetic temperature, ozone, water vapor, methane, carbon monoxide, nitric oxide, nitrous oxide, nitrogen dioxide and ice volume density in the MLT. The retrieval of temperature and line of sight vertical pointing information (TLOS) is the first one in this chain since TLOS is needed for all other retrievals. Thus, assuring a high quality TLOS is essential. TLOS is retrieved from the CO_2 atmospheric emission measured by MIPAS around 15 μm up to the lower thermosphere, which, in contrast to the retrievals from measurements in the NOM mode (von Clarmann et al., 2003), needs the inclusion of a non-Local Thermodynamic Equilibrium (non-LTE) model since the atmospheric infrared emissions at those altitudes are generally affected by these effects (López-Puertas and Taylor, 2001). García-Comas et al. (2012) (GC2012 hereafter) documented the first release

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of temperatures in the MA, UA and NLC modes (vM11, where $M = 5, 6, 7$ stands for MA, UA and NLC, respectively). Those versions included measurements from 2005 to 2009. GC2012 made a comprehensive description of the retrieval setup, the mechanisms considered in the non-LTE model, and compared the results with measurements from other instruments. The spectra provided by the European Space Agency (ESA) used to generate that TLOS version was version 4.61/4.62.

MIPAS L1b spectra in the version 4.61/4.62 are not available for measurements made after 2009 but the updated version 5.02/5.06 is provided from then on. Changes from the former version to the latter in engineering altitude and in radiance, due to a new calibration, non-linearity corrections of the detectors and a better treatment of the forward/reverse problem, are significant. That implies that a uniform MIPAS dataset covering all MIPAS MA, UA and NLC temperature measurements using vM11 is not possible. Fortunately, 5.02/5.06 L1b spectra version was released for all measurements made by MIPAS during its lifetime. These two facts motivated us to generate a new version of TLOS using 5.02/5.06 spectra. Since the comparisons of temperature with other instruments in GC2012 showed systematic differences, we also modified the retrieval setup with the aim of addressing their causes.

We present for the first time a complete MIPAS reduced resolution (January 2005–March 2012) MA/UA/NLC temperature dataset in versions v521, v621 and v721 (vM21, hereafter). We describe the improvements introduced in these retrievals, their impact on MIPAS temperatures and the retrieved temperature fields in Sect. 2. In order to assess the quality of these new versions, we compare these temperatures with measurements from five satellite instruments and two lidars. A short summary of each of these instruments is presented in Sect. 3. Section 4 describes the results of the comparisons from 20 to 100 km, including a discussion on the differential behavior in the different modes of observations and in the two hemispheres. Section 6 summarizes our findings.

2 The temperature retrieval: Improvements in version vM21

The retrieval of temperature, line of sight (LOS) altitude information and temperature horizontal (mainly latitudinal) gradients in versions vM21 is done from measurements of the CO₂ atmospheric radiance at 15 μm for each MIPAS single limb scan. The scheme of the setup follows that described in detail for vM11 by GC2012, which in turn is an extension of the retrieval in the MIPAS NOM mode (von Clarmann et al., 2003) with the GRANADA non-LTE model described in Funke et al. (2012). We note that vM21 uses the same microwindows as vM11 (see Table 1 in GC2012) and the same retrieval altitude grid (1 km below 50 km and 2 km above; we note that the forward calculations are performed using the finer grid (1 km) up to 88 km). The main upgrades introduced in the retrieval version vM21 and their impact on the retrieved temperatures with respect to version vM11 are:

- MIPAS L1b spectra: VM21 retrievals use calibrated spectra as supplied by ESA in version 5.02/5.06. The effect on retrieved temperatures, compared to results using the previous 4.61/4.62 spectra, is smaller than 1–2 K below 90 km (when affected, that difference is generally positive) and temperature decreases above, exhibiting the maximum difference (in absolute value) at 95 km (–10 K). That occurs at all latitudes and seasons except for the summer at latitudes larger than 70°. At the latter conditions, the changes are more pronounced. The effect is smaller than 1–2 K only below 75 km, the temperature increases 4 K around 75 km and at the mesopause, and it decreases above, with the maximum change at 95 km (–15 K).
- Atomic oxygen climatology: the role of the atomic oxygen in MIPAS temperature retrievals is crucial at and above the mesopause. Atomic oxygen efficiently quenches the vibrationally excited CO₂ molecules there, where it is more abundant, and, thus, it is needed to calculate the populations of the emitting CO₂(v₂) levels with the non-LTE model. Consequently, changes in the atomic oxygen concentration affect temperatures retrieved from measurements of atmospheric 15 μm emissions.

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VM21 uses an atomic oxygen climatology from the WACCM model (Garcia et al., 2007) in its specified dynamics (SD) configuration. WACCM-SD (or WACCM4) constrains the meteorological fields in the troposphere and stratosphere with observations (Lamarque et al., 2012). The model is free-running above. We recall that vM11 used atomic oxygen mixing ratios from the NRLMSISE-00 model (Picone et al., 2002). Differences between NRLMSISE-00 and WACCM-SD atomic oxygen depend on altitude, latitude and season, leading to corresponding dependencies in the retrieved temperature. Induced changes on MIPAS retrieved temperature are less than 1 K below 80 km at high latitudes ($> 50^\circ$) and below 95 km elsewhere. In the summer high latitudes, WACCM-SD atomic oxygen is 2–3 times larger than NRLMSISE-00 at the mesopause (87 km), leading to 5–6 K larger temperatures, and it is 4–5 times larger from 95 to 100 km, leading to 10 to 20 K lower temperatures, respectively. WACCM atomic oxygen in the winter and equinox high latitudes is up to 3 times larger than NRLMSISE-00 at 85 km, causing only 1 K temperature decrease at that altitude, and slightly changes at 100 km, producing there an unnoticeable effect. At low latitudes, WACCM-SD atomic oxygen is larger than NRLMSISE-00 above 95 km by a maximum factor of 1.5, which decreases temperature by 3 K at 100 km.

- Carbon dioxide climatology: MIPAS TLOS is derived from measurements of emission in carbon dioxide spectral lines using prior knowledge of CO_2 abundance. Changes of that CO_2 concentration influence the TLOS retrieval. VM21 uses a carbon dioxide climatology from the WACCM-SD model. The WACCM-SD CO_2 trend correction takes into account the observed emission growth. VM11 used a trend-corrected 2000–2003 WACCM3 (free-running) composite monthly mean climatology. Retrieved temperature variations due to the change from WACCM3 to WACCM-SD CO_2 are -1 K at low- and mid-latitudes and 2–3 K in the winter high latitudes above 85 km, 2–6 K in the summer high latitudes above 90 km, and smaller than 0.5 K elsewhere.

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1–2 K around 85 km in the summer high latitudes. It also increases 2–3 K between 90 and 100 km at all latitudes, except around 95 km at latitudes higher than 70° during the summer, where it increases 8 K. In general, the temperature of the mesopause at all latitudes is 1–3 K larger. In the polar summer, additionally, its altitude is 3–4 km lower.

- a priori: we now use a more realistic temperature-pressure a priori, which is a merging of ECMWF high resolution operational data assimilation and forecasting system temperatures for pressures larger than 0.1 hPa and NRLMSISE-00 otherwise. We note that, given the first order difference Tikhonov regularization used, the a priori temperatures do not substantially influence the retrieved temperatures directly but constrain predominantly the vertical temperature gradients. This upgrade leads to changes of ± 1 K affecting temperatures above 70 km, except for summer latitudes between 50 and 70°, where the changes are slightly larger (reaching -2 K around 75–80 km).
- Horizontal gradients within non-LTE populations: the atmosphere changes along the line of sight, particularly when the poles are intercepted during the solstices, and so do the populations of the emitting states. These populations are now corrected for the simultaneously retrieved temperature gradient along the LOS using a significantly improved approach. This results in 1 K changes affecting latitudes from 50° to 70° above 80 km during the summer.
- H₂O and O₃ joint fit: water vapor and ozone contribute to atmospheric radiance around 15 μ m in the lower stratosphere. VM11 modeled these contribution using H₂O and O₃ abundances from climatologies. Following the retrieval scheme used for the TLOS retrieval in the NOM mode, we now jointly retrieve the water vapor and ozone in order to account for differences between climatological H₂O and O₃ and the abundances prevailing in the measurements. The average changes in temperature are small above 20 km (i.e., in the MA, UA and NLC temperatures) due to the minor contribution of H₂O and O₃ in the microwindows used.

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– Field of view: instead of using three pencil beams for the numerical integration of the signal over the field of view above 40 km, we now use five for the whole altitude range. This change does not significantly affect the retrieved kinetic temperature but leads to a larger convergence ratio in vM21.

5 Other important aspects of the retrieval, including non-LTE collisional rate constants, are set as in the previous vM11 version (refer to GC2012 for more details) with some (minor) non-LTE updates as described in (Funke et al., 2012)

Using this retrieval setup, we derived temperatures, line of sight and temperature horizontal gradients for all MIPAS MA, UA and NLC measurements in the optimized resolution, i.e., from January 2005 to April 2012. Figures 3–5 show seasonal altitude-latitude zonal means of the retrieved temperatures for the MA, UA and NLC modes, respectively, the corresponding vertical resolutions and the difference with version vM11 temperatures. The MA and UA modes cover the four seasons, which include measurements taken during December-January-February (DJF), March-April-May (MAM), June-July-August (JJA), and September-October-November (SON), and the NLC mode cover two seasons, which include measurements taken in January and June. The averages shown in these figures contain measurements extending only from 2005 to 2009 but they are representative of the complete period. This has been done for the sake of compatibility with vM11 averages, since the latter were done from 4.61/4.62 spectra, only available for 2005–2009. Our Fig. 3 left and central panels are thus directly comparable to those in Fig. 2 in GC2012.

25 The latitude-altitude temperature distributions behave similarly in the three modes of observation. The vertical resolution is however slightly (1–2 km) better in the NLC mode from 75 to 90 km, where it decreases with respect to the MA and UA mode due to the finer NLC mode vertical sampling. The mesopause is also slightly colder and the lower thermosphere slightly warmer in the summers in the NLC mode. The higher vertical resolution in the 80–90 km region accounts for up to 3–4 K lower NLC temperatures (in the polar summer mesopause). The remaining differences exist because the NLC measurements are taken closer to the solstices whereas the MA and UA measurements are

taken regularly through DJF or JJA, i.e., the summers in Fig. 5 show a more extreme scenario than in Figs. 3 and 4.

The vM21 estimated systematic and random temperature errors remain similar to those of versions vM11 (cf. Table 2 of GC2012). The sources of systematic errors considered are the uncertainties in non-LTE errors collisional rates, atomic oxygen abundance, CO₂ abundance, CO₂ spectroscopic properties (strength, position and width of spectral lines), gain calibration, instrument line shape and spectral shift (see further details on error sources included in GC2012). Systematic errors depend on latitude and season but are typically smaller than 1 K below 70 km, 3 K at 85 km and 10 K at 100 km. For summer high latitudes, these values are larger in the upper mesosphere and above, reaching 6 K in the mesopause (88 km) and 30 K at 100 km. VM21 random errors are mainly caused by the instrumental noise and are smaller than 0.5 K below the stratopause and 7 K at the mesopause. The vertical resolution is barely affected by the version used.

VM21 temperature differences with respect to vM11 are important, particularly, above 80 km (see Figs. 3–5). The latitude-altitude distribution of the vM21–vM11 temperature difference remains almost invariant with mode in all seasons. The differences in each mode do not significantly vary with season at low latitudes (< 30°) but they do at higher latitudes. Beyond 30° N/S, differences are larger during solstice than equinox and slightly larger above 80 km during JJA (or only June in NLC) than during DJF (or only January in NLC). The latter is explained by inter-hemispheric differences in the temperature itself. Temperatures during JJA show sharper structure (colder mesopauses and warmer lower thermospheres at all latitudes). In general, those translate in a larger sensitivity to some of the main changes introduced in vM21 retrievals: atomic oxygen, because of the larger non-LTE effects in more extreme atmospheres, or temperature horizontal gradient regularization, because of the larger gradients along the line of sight.

Overall, the effects of these new retrieval setups sum up to a 1–2 K increase right above the stratopause (maximum in the polar summers), mainly driven by the updated

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decrease around 100 km at high latitudes is -15 K in the austral summer and -20 K in the boreal summer, mainly due to the atomic oxygen and the L1b spectra version, but also to the temperature horizontal gradient regularization and the CO_2 abundance (effects are larger than 3 K , in absolute value).

3 Instruments used for comparison

In order to assess the quality of the MIPAS temperatures derived using vM21 retrievals, we compare our results with close-to-simultaneous remote measurements from seven instruments. Besides the comparison with two lidars on ground, we include five other satellite instruments that, together with MIPAS, are the only ones that provided temperature in the MLT (as of the time of this publication) on a regular basis in long periods (longer than 5 years) between January 2005, when the vM21 retrievals start, until April 2012, when MIPAS stopped operations.

3.1 Lidars

We use for our comparisons measurements from the two NASA Jet Propulsion Laboratory Rayleigh and Raman Differential Absorption Lidars: one located at the Table Mountain Facility (34° N , 118° W) and the other one at the Mauna Loa Observatory (20° N , 156° W). They provide nighttime temperatures from 12 km to 80–85 km with a 300 m vertical sampling, and a vertical resolution of 1–2 km from 10 to 65 km and 2–4 km from 65 to 80 km. Temperature precision is better than 1 K below 55 km and 5 K at 80 km. Systematic errors are 4 K below 25 km, less than 1 K at 30–60 km and 10 K at 80 km (Leblanc et al., 1998).

3.2 ACE-FTS

FTS (Fourier Transform Spectrometer) flies onboard the Canadian-led scientific satellite SciSat-1 (also known as ACE, the Atmospheric Chemistry Experiment). It is a solar

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occultation high resolution (0.02 cm^{-1} , unapodized) instrument, covering daily a narrow range of latitudes, which depend on season, but achieving near-global coverage over the course of a year. ACE-FTS provides temperature from CO_2 transmittance measurements from 15 to 125 km. Non-LTE effects are not considered in these retrievals but the selection of microwindows was done to minimize these effects: the microwindows above 70 km cover absorption lines from common lower state (ground level) vibrational bands. The vertical sampling ranges typically from 1 km in the mid-troposphere to 3–4 km above the mid-stratosphere and the vertical resolution is limited to 3–4 km (Boone et al., 2013). We use here v3.0 temperatures. There are no estimates of the systematic errors currently available.

3.3 MLS

The Microwave Limb Sounder (MLS), launched on the NASA Aura satellite in 2004, provides daily nearly global (82° N – 82° S) profiles of temperature and trace gases from 316 to 0.001 hPa from observations of the atmospheric limb at millimeter and submillimeter wavelengths. Retrieved temperature is derived primarily from oxygen emission at 118 and 239 GHz, and is not impacted by cirrus ice, aerosols or effects of non-LTE. We use here version v3.3 of MLS temperature, which is similar to v2.2 described in Schwartz et al. (2008) (differing in the number of stratospheric retrieval levels and reduced vertical smoothing in the mesosphere and lower thermosphere). Vertical resolution is 5 km from 261 to 100 hPa, 3.6 km at 31.6 hPa, 4.3 km at 10 hPa, 6 km at 0.1 hPa and ≈ 10 km at 0.001 hPa. Precision is generally better than 1 K at retrieval pressures above 1 hPa and degrades from 1 to 3 K between 1 and 0.001 hPa. In the stratosphere, MLS has a 1 K mean low bias with additional oscillatory structure of order ± 1 K compared to correlative data. Biases are more poorly characterized, but generally negative in the mesosphere/lower thermosphere.

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3.4 OSIRIS

OSIRIS (Optical Spectrograph and InfraRed Imaging System) is onboard the Odin satellite, launched in 2001, and observes the Earth's limb between 7 and 110 km with a 1.5 km vertical sampling and covers latitudes smaller than 82° in both hemispheres. Its spectral resolution is 1 nm. Temperatures are derived from measurements of the Rayleigh scattered sunlight at 318.5 nm from 45 to 72 and 347.5 nm from 72 to 85 km, and from the measurements of the O₂ A-band airglow at 762 nm from 85 km to 105 km. Systematic errors are less than 2 K below 72 km, less than 3 K at 72–77 km and 8 K around 85 km (Sheese et al. (2012), and references therein). Measurements are affected by mesospheric cloud contamination but these are filtered out. Odin is in a sun-synchronous orbit, with ascending/descending nodes at 06:00/18:00 LT.

3.5 SABER

SABER (Sounding of the Atmosphere using Broadband Emission Radiometry) onboard NASA's TIMED (Thermosphere Ionosphere Mesosphere Energetics Dynamics) satellite is a broadband radiometer measuring temperature from 20 to 120 km since 2002. SABER measures day- and night-time temperatures almost globally (52–82°), alternating every two months between northern (52° S–82° N) and southern (82° S–52° N) almost-polar coverage. As vM21 MIPAS temperatures, SABER's are derived from measurements of the CO₂ limb radiance at 15 μm, needing also from non-LTE calculations in the retrievals. SABER vertical grid is 400 m and its vertical resolution is 2 km. Typical SABER estimates of v1.07 temperature random errors are < 0.5 K below 55 km, 1 K at 70 km, 2 K at 85 km and 7 K at 100 km and systematic errors are < 1.5 K below 55 km, 0.5 K at 70 km, 4 K at 85 km and 5 K at 100 km (Remsberg, 2008; García-Comas et al., 2008). We use here SABER v2.0 temperatures. A thorough validation of these temperatures is not published yet nor the differences of the v2.0 temperatures with version v1.07. Nevertheless, the v2.0 estimated systematic and random errors are not expected to change much from v1.07 since the uncertainty of their sources are the

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smooth lidars, SABER, SOFIE, and OSIRIS profiles in their comparisons with MIPAS, and MIPAS in its comparison with MLS. Given their similar vertical resolution, we do not smooth MIPAS nor ACE-FTS profiles in their comparison. We use altitude as the vertical coordinate for all comparisons except for those between MIPAS and MLS, for which we use pressure.

We calculated the temperature difference for each pair of profiles and, then, their yearly averages for co-locations within 20° wide latitude boxes for four periods: DJF, MAM, JJA and SON. We then calculated the mean for each season and latitude box. The spring averages encompass the measurements during MAM in the Northern Hemisphere (NH) and SON in the Southern Hemisphere (SH), autumn during SON in the NH and MAM in the SH, summer during JJA in the NH and DJF in the SH, and winter during DJF in the NH and JJA in the SH.

Figures 6–9 show the average seasonal differences for the four seasons in the MA mode and Figs. 10 and 11 for summer and winter in the NLC mode. Note that, even if we determined the differences as a function of pressure in the MIPAS vs. MLS comparison, we plot them as a function of MIPAS altitude for the sake of simplicity. Results for the comparisons of co-located measurements in the UA mode (see Supplementary Material) are almost identical to those in the MA mode. The figures also include the estimated MIPAS temperature systematic errors and the number of coincidences for each hemisphere. Using only MIPAS errors represents a pessimistic scenario because, strictly speaking, the temperature differences should be compared with the combined systematic errors for each instrument pair, which necessarily have larger values than the shading in the figures. Differences in temperatures of the stratopause (point in the temperature-altitude average profile with maximum temperature in the stratosphere and lower mesosphere region) and mesopause (point with minimum average temperature in the upper mesosphere and lower thermosphere region), even if they are located at different altitudes in each pair of instruments, are also plotted using symbols at their corresponding mean altitudes in MIPAS co-located profiles. When these symbols are

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exactly over the difference profiles, this indicates that the two instruments under consideration located the strato- and/or the meso-pauses at the same altitude.

4.1 From the lower stratosphere to the middle mesosphere

MIPAS temperatures, typically, differ from measurements from the other instruments on satellites and the lidars less than 1 K in the stratosphere at all latitudes and seasons (Figs. 6–9). The altitudes of MIPAS and the other instruments stratopauses do not differ significantly. The stratopause temperature differences are, normally, less than 1 K. Differences at 50–80 km are, typically, less than 2 K at latitudes lower than 50° for all seasons and at higher latitudes during spring, autumn and winter. At the summer high latitudes (> 50°), differences are, in general, smaller than 2 K at 50–65 km and 5 K at 65–80 km. The differences in the middle mesosphere are generally negative (except for some comparisons during winter), i.e., MIPAS sees a slightly colder middle mesosphere. Besides the polar summer above 40 km, these values are within MIPAS systematic error estimates.

Exceptions to the typical behavior described above occur:

- Around 20 km, in all comparisons with SABER and at 70–90° in comparisons with SOFIE: MIPAS temperatures are there 2 K lower than these other two instruments. We do not assign these differences to a bias in MIPAS temperatures because they had been previously reported in SABER v1.07 comparisons with other instruments (Remsberg, 2008) and they persist in v2.0 (used here). SOFIE behaves as SABER at 70–90° at these altitudes.
- Around 20 km, in comparisons with ACE-FTS in the winter at 70–90°, where MIPAS provides 5 K lower temperatures. This behavior is persistent mostly in SH observations, for all years where coincidences are available, and also in the NH in 2011.

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systematic error and thus the difference is almost within MIPAS and OSIRIS combined error. Note that Sheese et al. (2012) also found these differences in OSIRIS-SABER comparisons. Note also that, except for the summer 70–90° box, MIPAS and SABER are within 1 K at these altitudes.

- Around 80 km in the summer in comparisons with ACE-FTS, where the negative difference is significantly larger than in comparisons with the other instruments and reaches 10 K. A warm bias in ACE-FTS summer temperatures was already reported in Sica et al. (2008) for v2.2 temperatures.

It is important to highlight the excellent results that the comparisons between MIPAS and SABER show. Differences in temperatures measured by these two instruments are smaller than 1 K below 80 km all year round, except for the lowermost altitudes (–1–2 K) and the mesosphere only during summer at latitudes larger than 70° (–3 K) and winter at 50–70° (+2 K). This behavior, significantly improved with respect to the previous comparisons in GC2012, where MIPAS vM11 was compared with SABER v1.7, and persistent in almost all seasons and latitudes, demonstrates the excellent performance of both instruments and their temperature retrievals.

The differences with most instruments present a narrow (10 km) oscillation centered around 75 km with 1–2 K temperature amplitude and which shows up in comparisons with all instruments and corresponds to an oscillation of the same characteristics which systematically appears in vM21 temperatures. This small oscillation is more prominent during the summers.

The following two aspects related to comparisons with ACE-FTS are noteworthy. First, even within the limits detailed above for the high latitudes, the differences between MIPAS and ACE-FTS temperatures in the lower mesosphere ($z < 70$ km) are 1–2 K larger (in absolute value) at 50–70° than at higher latitudes (70–90°) all year round, which is not the general behavior in MIPAS comparisons with other instruments.

Second, we have paid special attention to a potential change of the behavior of the differences after October 2010, date from which ACE-FTS v3.0 temperature profiles

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might be affected by problems related to the pressure registration around 15 km (taken from the Canadian Meteorological Center), which may have lead to a maximum altitude offset of the order of 1 km. We found co-locations with MIPAS after then only during spring in the 50–70° N latitude box and during spring and winter in the 70–90° N box.

The differences with MIPAS do not change significantly for the former case with respect to previous springs. They do for the latter case but only in the lower stratosphere, where ACE-FTS temperatures are 4–5 K warmer than on average. Above the mid-stratosphere, the differences for these season-latitude boxes do not differ significantly from the average difference.

4.2 From the upper mesosphere to the lower thermosphere

Differences at altitudes above 85 km are more variable, and depend on instrument, season and latitude.

At latitudes smaller than 50°, MIPAS mesopause temperatures are 1–2 K lower than SABER's (except for winter in the MA mode, when their temperatures coincide on average) and the mesopause is located at the same altitude in winter and summer but not in spring and autumn (where MIPAS mesopause is slightly lower; 2–3 km). It is 2–3 K warmer than MLS's and located at the same altitude. It is 1 K colder than OSIRIS's in spring and autumn and 3 K warmer in summer, although not many coincidences were found then, due to the difference in the ascending/descending local times of the two instruments. Above 95 km, MIPAS is usually 0–4 K warmer than the other instruments at these latitudes, except in comparisons with MLS and OSIRIS in the summer, where the two latter exhibit significantly smaller temperature vertical gradients than the rest, leading to differences of up to 10 K.

Leaving the summer high latitudes aside, MIPAS mesopause temperatures at latitudes larger than 50° lie between the measurements from the other instruments. MIPAS mesopauses are within 2 K of those of SABER (colder in winter and warmer in autumn), within 3 K of those of OSIRIS (warmer in spring and colder in autumn), 1–4 K colder than ACE-FTS, 3–5 K warmer than MLS, and 4–5 K colder in spring and winter

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and 7–10 K warmer in autumn than SOFIE. Except for few cases (some spring comparisons with ACE-FTS and SOFIE, autumn with SOFIE or MLS or winter with ACE-FTS), MIPAS mesopauses are located at altitudes differing less than 1–2 km. Note that ACE-FTS mesopause in winter is located 6 km higher although its temperature is the same as in MIPAS. Except for SABER in autumn and spring, MIPAS temperatures around 85 km at these latitudes are generally from 2 to 5 K warmer (OSIRIS and SOFIE present slightly larger differences). Except in comparisons with OSIRIS and SABER in spring, MIPAS temperatures in the lower thermosphere are 1–7 K warmer than the other instruments.

As for altitudes below 85 km, comparisons between SABER and MIPAS are also particularly good above that altitude, showing differences smaller than 2 K at 80–95 km except during summer at high latitudes.

Differences above 85 km in the summer high latitudes are larger than under any other conditions examined. MIPAS mesopause (≈ 88 km) temperatures also lie within the other instrument measurements but the differences (in absolute value) reach significantly larger values around the poles. On average, they are 7–12 K warmer than MLS, SABER and OSIRIS, and 5 and 14 K colder than SOFIE and ACE-FTS, respectively. Results from previous comparisons with other instruments from SOFIE and ACE-FTS (Stevens et al., 2012; Sica et al., 2008) resulted in reported likely positive biases for them around the mesopause. MIPAS temperatures in the polar summer mesopause would better agree with those measured by MLS, SABER and OSIRIS if an atomic oxygen concentration smaller than that of WACCM-SD were used in MIPAS retrievals in that region. Nevertheless, the altitude of the mesopause is very similar for all instruments (≈ 88 km).

The differences above 90 km are positive, except for SABER comparisons, and generally larger than 15 K, except for OSIRIS comparisons. The differences in the lower thermosphere increase with altitude, reflecting a larger temperature vertical gradient in MIPAS (and particularly SABER) measurements.

4.2.1 NLC mode temperature differences

We examine in detail here the comparisons with other instruments in the NLC mode and their differences with respect to the comparisons in the other modes, that have a coarser vertical sampling in the upper mesosphere.

5 Temperature differences with the other instruments in summer and winter in the NLC mode (Figs. 10 and 11) show a similar behavior to those in the MA mode (Figs. 8 and 9), and also in the UA mode, particularly in its vertical shape. The magnitude of temperature differences at all altitudes is generally similar in all modes at all latitudes and seasons, except at the mesopause and at all altitudes at 50–70° in the summer.

10 Note also that the comparisons with ACE-FTS in the winter around the stratopause (although there were only 27 coincidences, all of them in 2005) and with OSIRIS in the summer around 80 km exhibit differences slightly larger (in absolute value) in the NLC mode comparisons.

15 The NLC temperatures in the summer 50–70° comparisons seem to be affected by biases similar (although slightly smaller) to those found in the 70–90° MA (and UA) full summer season temperature comparisons. Therefore, the same conclusions described in the previous section apply. That happens because the NLC measurements are taken very close to the solstices (and so are the co-locations found), when the atmospheric conditions at 50–70° are more extreme, which generally translates in larger differences with the other instruments. In other words, the MA and UA temperatures at 50–70° also have larger differences with the other instruments close to the solstices than on average from the early to the late summer.

25 MIPAS NLC summer mesopause temperature comparisons with SABER, OSIRIS and MLS improve with respect to those of the MA and UA modes by around 2 K at 70–90° latitudes. The better vertical resolution of the NLC temperatures does not explain that improvement because the mode characteristic vertical resolution is accounted for when applying the averaging kernels. Different atmospheric conditions, like a more extreme temperature profile, are not the cause either. Indeed, when restricting the MA

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co-locations to measurements taken the closest days before and after NLC measurements, similar 2 K mesopause differences are found (see example of summer solstice comparisons with SABER in Fig. 12 at 70–90° latitudes, where differences at 88 km are 7 K in the MA mode and 5 K in the NLC mode). Therefore, the most likely cause is the narrower vertical sampling performed in this mode (1.5 km instead of 3 km in MA and UA) that, concomitant with the MIPAS 3 km field of view, is able to obtain a less biased measurement in the coldest point in the region in v721. This might be explained by the non-linearity effects, for example, in non-LTE radiative transfer.

5 Differences in temperature inter-hemispheric asymmetries

The understanding of atmospheric variable inter-hemispheric differences, commonly known as inter-hemispheric asymmetries, is an important topic that is currently often addressed in atmospheric studies. Studies based on differences are usually more reliable than those dealing with absolute values because the persistent (in time and/or place) systematic errors may cancel out. That is not the case if artificial spatial and temporal inhomogeneities in the measured atmospheric variables (that may be due to several aspects such as dependence of the retrievals to atmospheric conditions, dependence of the observations and/or inversions on the time or location, etc.) are present. A correct interpretation of inter-hemispheric asymmetries relies on the ability of the measurements to homogeneously reproduce the atmospheric state fields. Temperature inter-hemispheric asymmetries are widely used, for example, in polar mesospheric cloud studies (Winkler et al., 2012), for which a differential behavior in the two hemispheres occurs.

Our goal here is to assess MIPAS ability to measure temperature and altitude inter-hemispheric asymmetries or, in other words, detect differences between NH and SH measurements not originated by the real atmospheric state. Note that the difference between instruments in hemispheric asymmetry of certain observable is equivalent to the hemispheric asymmetry in the observable difference between instruments. That is,

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the resulting differences in temperature inter-hemispheric asymmetry also reflect deviations between NH and SH MIPAS temperature differences with the other instruments.

We compare the temperature and altitude inter-hemispheric asymmetries measured by MIPAS in the stratopause and the mesopause with those from the other five satellites. In order to avoid sampling effects (in location and/or time) as much as possible, we determined the inter-hemispheric asymmetries for each instrument from the set of co-located measurements. We also used the full season co-location set instead of selected periods, which assures a large number of co-locations for all instruments in each hemisphere (plus a north and south pole coverage by SABER, which alternates their observation every two months) and, thus, a representative result.

Figure 13 shows the difference between MIPAS average NH–SH asymmetries and those from co-located measurements from the other instruments in the stratopause and the mesopause, for the summer and winter seasons and at 70–90° and 50–70° latitudes. The x-axes show the difference between instruments in the temperature asymmetry and the y-axes show the difference between instruments in the altitude asymmetry. We represent in those plots the absolute values of the asymmetry differences and assign a negative sign only when MIPAS asymmetry has the opposite sign than that from the other instrument (that is, if MIPAS measured a larger temperature in one hemisphere but the other instrument measured it in the other hemisphere). In other words, a positive/negative value indicates an agreement/disagreement in the sign of the asymmetry.

During summer, differences between MIPAS and the other instruments stratopause temperatures NH–SH asymmetry are smaller than 1 K for both latitude boxes. It is worth noting that, in several cases, that value is significantly smaller than the corresponding absolute difference between the stratopause temperature measured by each instrument, as shown in Fig. 8. The difference of the MIPAS stratopause altitude NH–SH asymmetry from the other instruments is smaller than 1 km and within MIPAS vertical resolution at the corresponding altitude. MIPAS comparisons with MLS, SABER and SOFIE for winter stratopause temperature and altitude inter-hemispheric asymmetries

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are very good (smaller than 1 K and 2 km, respectively) both at 70–90° and 50–70° latitudes, but there is a 4 K deviation with respect to the asymmetry measured by ACE-FTS at 70–90°. All instruments detect the same sign for the stratopause temperature hemispheric differences.

Differences between MIPAS summer mesopause temperature and altitude NH–SH asymmetries and the corresponding asymmetries measured by the other instruments are smaller than 2 K and 2 km, respectively, except for the comparison with OSIRIS at 50–70° and MLS. That 2 K temperature asymmetry difference is significantly smaller than the corresponding temperature absolute difference between the instruments at the mesopause (see Fig. 8). MLS exhibits a persistent deviation in its temperature hemispheric asymmetry of 10 K (70–90°) and 15 K (50–70°). The negative sign shown in the plot additionally indicates that MLS temperature inter-hemispheric asymmetry has a different sign from those of all other instruments (in particular, MLS NH summer mesopause is warmer than in the SH, opposite to the behavior measured by the other instruments). OSIRIS temperature NH–SH asymmetry difference from the other instruments is also large (7 K), but has the same sign.

The comparisons of inter-hemispheric asymmetries in the winter mesopause are more variable. MIPAS NH–SH temperature asymmetry difference with SABER at 70–90° is there only 1 K and both instruments show the same sign. MIPAS and SABER winter temperature asymmetries at these latitudes are reversed with respect to the other instruments (see negative sign in Fig. 13). MIPAS temperature asymmetry differences are 7 K (SOFIE), 10 K (MLS) and 13 K (ACE-FTS); note that these values coincide with the hemispheric asymmetries in MIPAS temperature differences with those instruments. The winter comparisons improve in general at 50–70°, where MIPAS temperature asymmetry has the same sign as ACE-FTS, MLS and SABER and is 2–4 K larger. The temperature asymmetries they all measure there have opposite sign to that measured by SOFIE. MIPAS and SOFIE temperature asymmetry difference is 5 K. The MIPAS altitude NH–SH asymmetry in winter is within 2 km of those measured by the other instruments except ACE-FTS (4 km and different sign).

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6 Summary

We present vM21 MIPAS temperatures, the latest version of temperatures retrieved in the 20–102 km altitude range from the MA, UA and NLC modes, that measured the carbon dioxide emissions in the 15 μm region from January 2005 to March 2012. This version introduces the following updates with respect to the previous version vM11: HITRAN 2008 spectroscopic database, a climatology of atomic oxygen and carbon dioxide from WACCM-SD, version of ESA calibrated L1b spectra (5.02/5.06), and improvement of technical aspects of the retrieval setup, such as temperature gradient along the line of sight regularization, offset regularization, apodization accuracy, a priori, correction of CO_2 non-LTE populations along the line of sight, H_2O and O_3 joint fit, and FOV radiance calculations.

The vM21 temperature, as compared to vM11, increases, on average, 1–2 K in the stratopause and 0–2 K around 75 km, mainly due to effects from the version of the spectroscopic database and L1b spectra, although those from changes of the offset and temperature horizontal gradient regularizations at all latitudes, and also of the apodization accuracy and the a priori in the polar summer, are not negligible.

Except for the summer high latitudes, vM21 temperatures from 80 to 100 km are smaller than in vM11, with a maximum 15 K decrease at the mesopause, mainly due to the L1b spectra version and with smaller effects caused by (in this order) the up-graded temperature horizontal gradient regularization, the atomic oxygen abundance, the offset regularization, the apodization accuracy and the carbon dioxide concentration. In the summer high latitudes, the mesopause is 2–4 K warmer than in version vM11, primarily due to the atomic oxygen but partially compensated by the effect of the improved offset and temperature horizontal gradient regularizations. Temperature at 90 km decreases 4 K due to the spectra version, the temperature horizontal gradient and offset regularizations, and the CO_2 abundance. Although the causes for the temperature changes above 95 km are the same as at other latitudes, their effects are amplified in the polar summer and temperature decreases up to 20 K at 100 km.

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The vM21 changes in temperature correct the main biases found from the lower stratosphere to the lower thermosphere in the comparisons of the previous temperatures (vM11) with other instruments, except around the mesopause during the high latitude summers. Indeed, comparisons of the vM21 temperatures with measurements from ACE-FTS, MLS, OSIRIS, SABER, SOFIE and the two Rayleigh lidars at Mauna Loa and Table Mountain show, in general, significantly smaller differences (note that new versions are also used for ACE-FTS, MLS and SABER).

Except for the higher altitudes (above 80 km), the MLO and TMF lidar measurements and MIPAS vM21 temperatures are within 2 K. An exception occurs in the summer above 70 km in the comparisons over MLO, where MIPAS temperatures are up to 5 K colder.

MIPAS and ACE-FTS comparisons are very good, except in the summer. Their temperatures are within 1–2 K below 80 km and 2–4 K above 80 km in spring, autumn and winter (except for a narrow region around 80 km in the spring at 50–70°). In the summer, MIPAS (and the rest of the instruments) on average measure a 3 K (5 K) warmer stratopause and a more than 15 K (20 K) colder mesopause.

The comparisons with MLS are good in the stratosphere but MLS exhibits a colder upper stratosphere and smaller temperatures than MIPAS (and the other instruments) at 55–75 km (0–5 K) and at the mesopause (3–10 K). MLS also differs from the other instruments in the temperature inter-hemispheric asymmetry because, opposite to them, it measures a (significantly) colder summer mesopause in the Southern Hemisphere.

The differences between MIPAS and OSIRIS below 85 km are smaller than 2 K in spring, and 4 K in autumn and summer, with MIPAS temperatures being colder. Differences at 85–90 km are generally larger and reach 10 K in the summer high latitudes (mesopause) or 7 K (right below the mesopause) in other conditions. The difference at 95 km is reduced to 2–4 K.

Comparisons with SABER are remarkably good, bringing differences smaller than 2 K at all altitudes and seasons, except for high latitude summers above 65 km. That means that average MIPAS-SABER differences between previous versions have been

eliminated or significantly reduced in most conditions. The only exception occurs during the polar summer, where they are 3–4 K at 65–80 km (MIPAS colder) and 5–7 K around the mesopause (MIPAS warmer).

MIPAS and SOFIE differences are smaller than 2 K in the stratosphere. SOFIE stratopause is generally 3 K colder than MIPAS and, in general, than the other instruments. Their temperatures in the mesosphere are within 1–3 K, MIPAS being generally colder. Except for autumn, MIPAS mesopause is 3–5 K colder than SOFIE.

Overall, MIPAS vM21 temperature comparisons exhibit typical (with few specific exceptions) differences smaller than 1 K below 50 km and than 2 K at 50–80 km in spring, autumn and winter at all latitudes, and summer at low to mid-latitudes. Differences between MIPAS and the other instruments in the summer high latitudes are typically smaller than 1 K below 50 km, smaller than 2 K at 50–65 km and 5 K at 65–80 km. The differences in the mid-mesosphere are generally negative. MIPAS mesopause temperature lies within the other measurements. It is generally within 4 K, except in the high latitude summers, where it is within 10 K. The polar summer comparisons with SABER, MLS and OSIRIS point to a too warm MIPAS mesopause, whereas those with ACE-FTS and SOFIE to a too cold mesopause. The agreement in the lower thermosphere is typically better than 5 K, except for high latitudes during spring and summer, where MIPAS usually exhibits larger vertical gradients.

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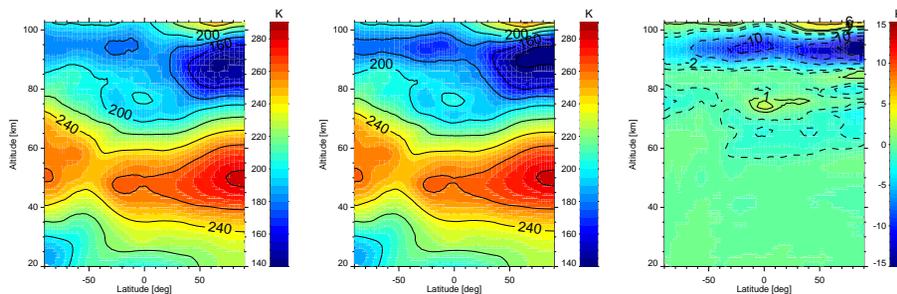


Figure 1. Zonal mean vM21 temperature for 3 June 2010 retrieved considering (left) and not considering (center) temperature gradients along the line of sight and difference between both (right). The gradients used for the calculations are those simultaneously retrieved in vM21 TLOS retrievals.

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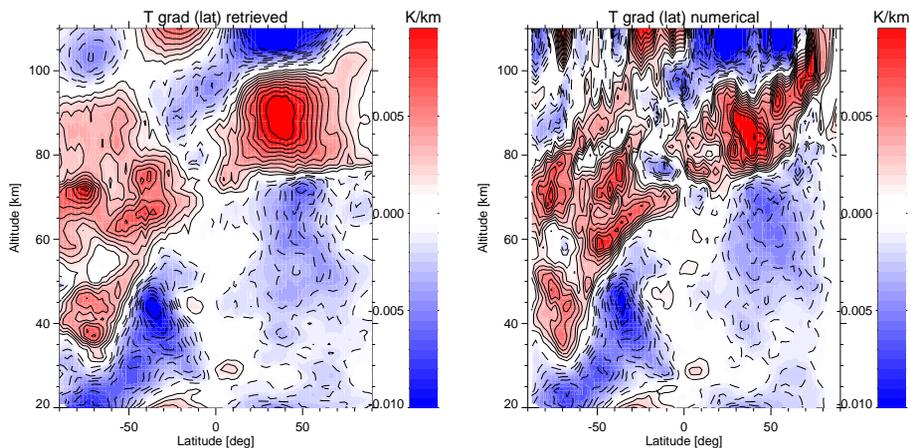


Figure 2. Latitude-altitude cross sections of v521 zonal means of MIPAS kinetic temperature horizontal (meridional) gradients for the 15 July 2009. Left panel: directly retrieved; right panel: produced using the retrieved temperature fields.

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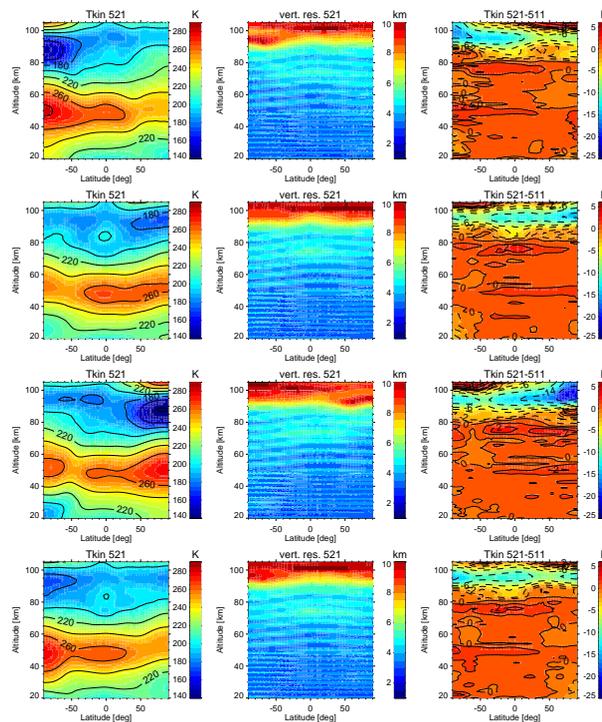


Figure 3. Latitude-altitude cross sections of v521 zonal means of MIPAS MA kinetic temperature (left), its vertical resolution (center) and its difference with version v511 (right; contours at -22 , -18 , -14 , -10 , -6 , -4 , -2 , -1 , 0 , 1 , 2 , 4 , and 6 K) during, from top to bottom, the boreal winter (December-January-February; DJF), vernal equinox (March-April-May; MAM), austral winter (June-July-August; JJA) and autumnal equinox (September-October-November; SON). Only measurements from 2005 to 2009 are included for direct comparison with results in García-Comas et al. (2012).

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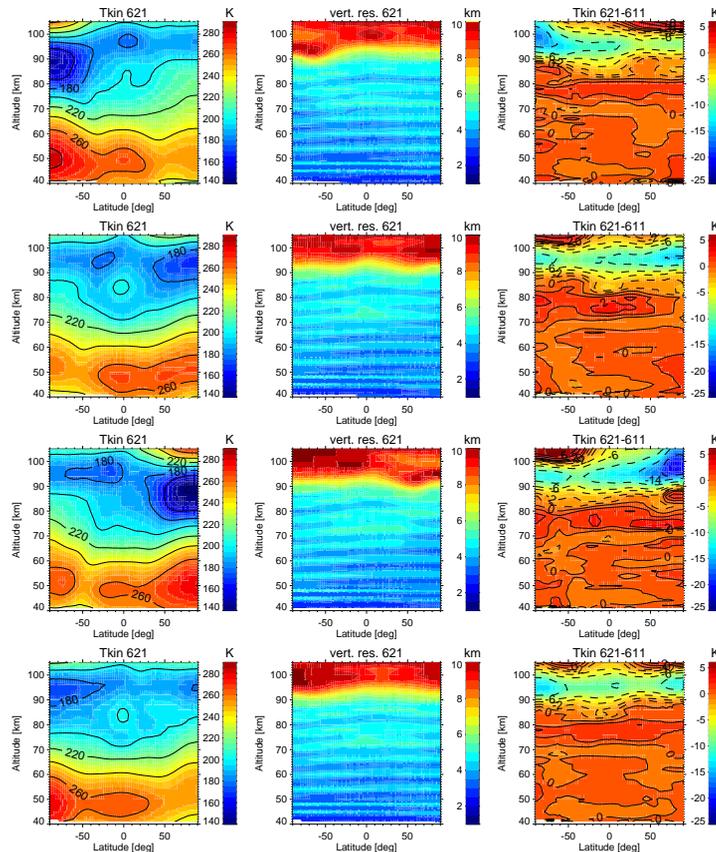


Figure 4. Latitude-altitude cross sections of v621 zonal means of MIPAS UA kinetic temperature (left), its vertical resolution (center) and its difference with version v611 (right) during, from top to bottom, the boreal winter (DJF), vernal equinox (MAM), austral winter (JJA) and autumnal equinox (SON).

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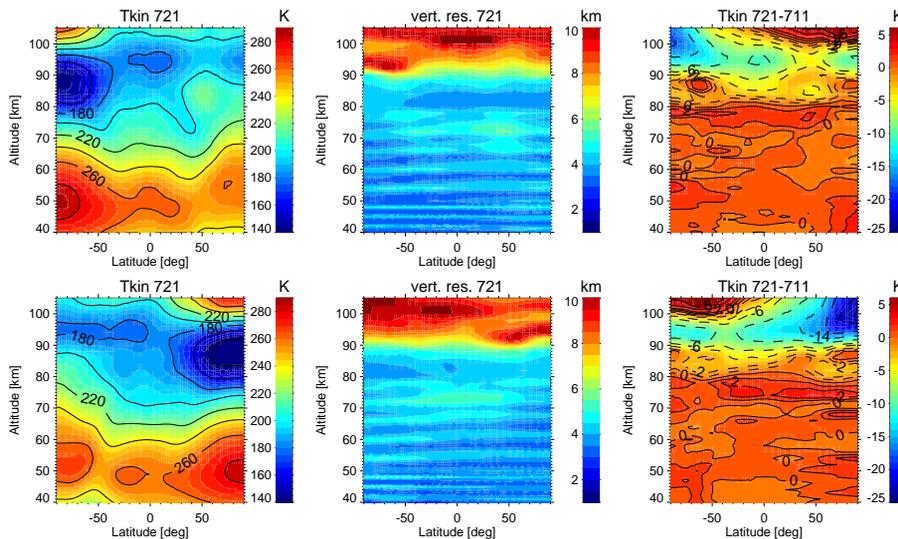


Figure 5. Latitude-altitude cross sections of v721 zonal means of MIPAS NLC kinetic temperature (left), its vertical resolution (center) and its difference with version v711 (right) during January (top) and July (bottom) (note that MIPAS measured in the NLC mode only around the solstices).

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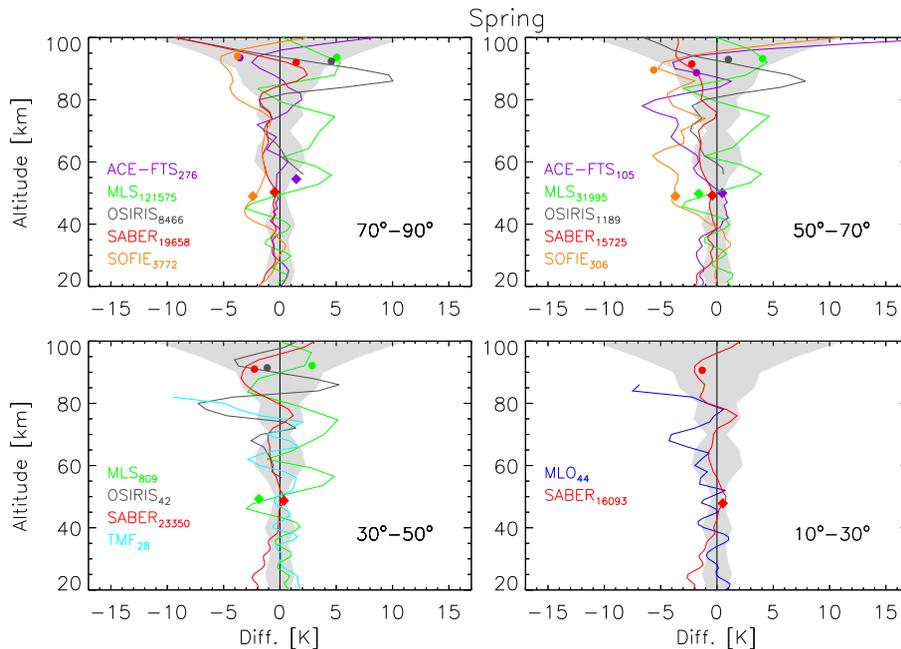


Figure 6. Spring (MAM for NH and SON for SH) mean temperature differences (MIPAS–instrument) between co-located pairs of measurements of MIPAS (MA mode) and ACE-FTS (purple), MLS (green), OSIRIS (grey), SABER (red), SOFIE (orange), and the Table Mountain (light blue) and Mauna Loa (dark blue) lidars. The number of MIPAS coincidences with each instrument within 2 h and 1000 km is indicated in the corresponding subscript. Difference in the stratopause (diamond) and mesopause (circle) temperatures at their corresponding altitude in MIPAS averaged co-located profiles are indicated. Shaded areas include MIPAS-only systematic errors.

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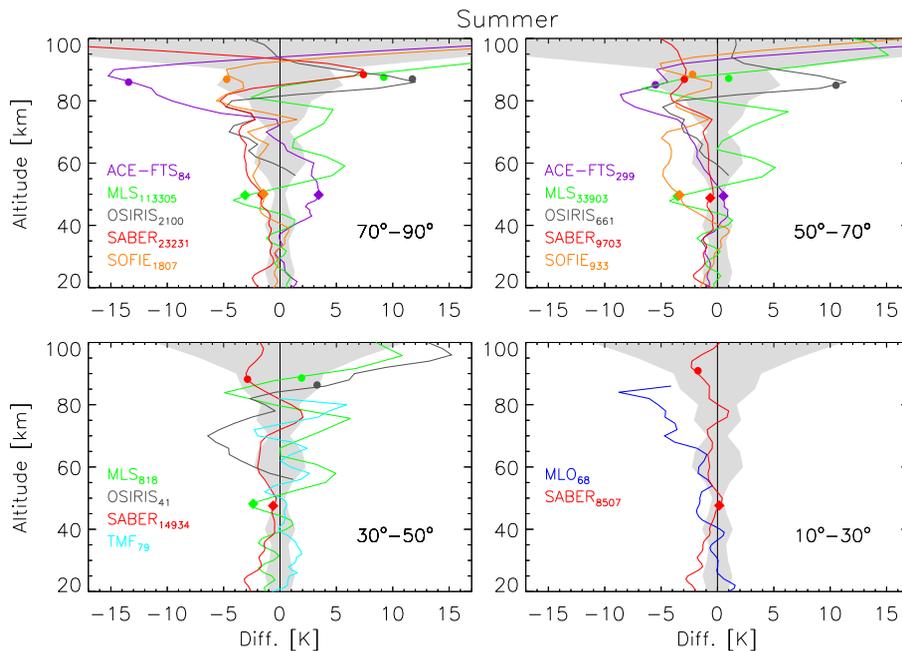


Figure 8. As in Fig. 6 but for summer (JJA for NH and DJF for SH) co-locations.

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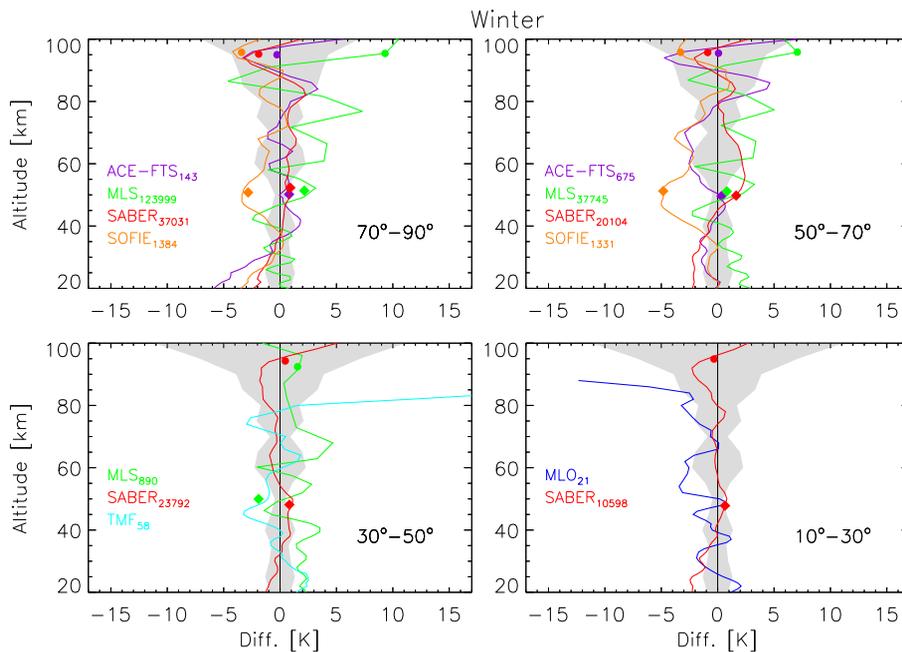


Figure 9. As in Fig. 6 but for winter (DJF for NH and JJA for SH) co-locations.

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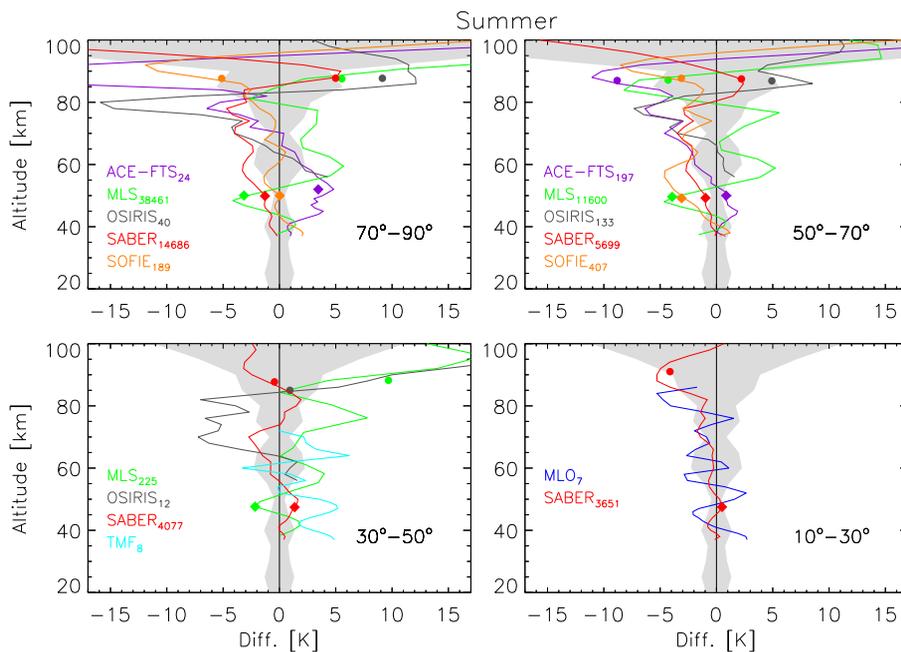


Figure 10. As in Fig. 6 but for summer (July for NH and January for SH) co-locations in the NLC mode.

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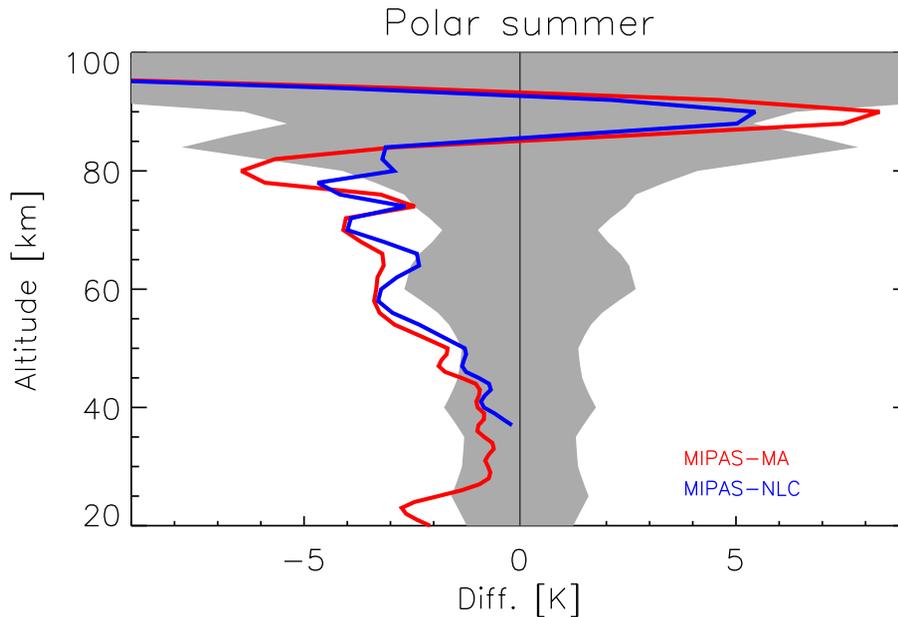


Figure 12. Average MIPAS NLC (blue) and MA (red) differences with SABER co-located measurements from 2008 to 2011 at 70–90° latitudes. NLC average include coincidences found in the three days of NLC measurements. MA average include co-locations found in the MA measurements taken the closest day after and the closest day before the NLC measurements.

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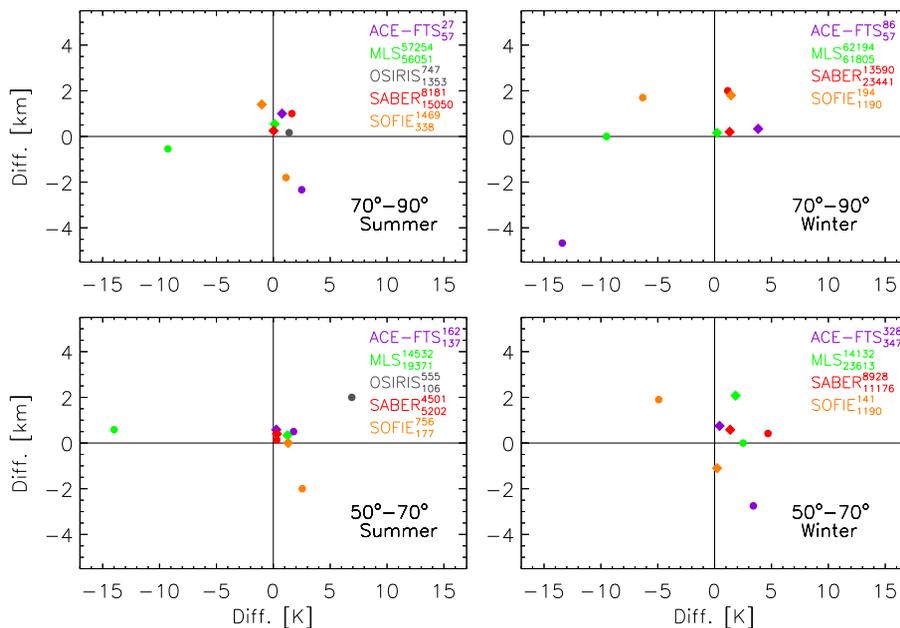


Figure 13. Deviation (in absolute value) between stratopause (diamonds) and mesopause (circles) interhemispheric temperature (x axis) and altitude (y axis) differences (NH vs. SH) measured by MIPAS and the satellite instruments indicated for summer (left) and winter (right) at 70–90° latitudes. A positive sign of the deviation indicates that the NH–SH difference has the same sign in both instruments (and vice versa). The number of MIPAS coincidences with each instrument in the northern and Southern Hemispheres are shown in the superscripts and subscripts, respectively.

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