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Total columns of H_2O measured from the ground and from space at Observatoire de Haute-Provence in France (44° N)

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Abstract

In this work, we compare vertical column density of water vapour measured at Observatoire de Haute-Provence, Southern France (5° 42′ E, +43° 55′ N). Data were obtained by three satellite sensors, GOME, GOME 2 and SCIAMACHY, and by two ground-based spectrometers, Elodie and SAOZ. These five instruments are able to measure total column density of water vapour in the visible and have different principles of observation. All these instruments reproduce the total column water vapour with good accuracy. The mean difference between the satellite measurements, ground-based measurements, and between both types, are quantified. The diurnal cycle of water vapour above the station and its variability with latitude have been investigated. The differences between these data sets are due sometimes to the differences in the time of the measurements, or to the differences in the geometry of observations, or also due to both effects. The effect of land and sea and the effect of the season on the total column water vapour has been analysed. The global agreement between our data sets range from 10 % in summer to 25 % in winter, improved significantly when observations are closer in time and location.

1 Introduction

Water vapour is an atmospheric constituent that has a determinant effect on the climate and on the weather. It represents two-thirds of the greenhouse gases, and is mostly located in the troposphere. It is the key element of the hydrological cycle, conditioned by exchanges between its three phases in the atmosphere, the ocean and the continents, and also directed by the transport of energy between the surface and the atmosphere, by evaporation and condensation (Ramanathan, 1988). However, because of its large temporal and spatial variability, the measure of this component is a demanding task. For this reason, many different well-known techniques, such as GPS (Bastin et al., 2007; Yunck et al., 2000); radio sondes (Elliott and Gaffen,

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1991; Soden and Lanzante, 1996); lidars (Hoareau et al., 2009); microwave radiometers (Scheiben et al., 2010), as well as less-known techniques such as balloon-borne, near-infrared InGaAs laser diodes (Durry and Megie, 1999); UV-visible MAX-DOAS spectrometry (Wagner et al., 2013); and astronomical telescopes (Sarkissian and Slusser, 2009) from the ground, in-situ or from space as the ones presented in this work have been developed to estimate water vapour in the atmosphere. Also, the accuracy of the measurements' changes from one instrument to another as the mode of observation, the period of observation, the condition of measurement, and the retrieval method are different between them. Note that these instruments were not initially dedicated to water vapour measurements and the extraction of H_2O was not the principle objective. This paper compares measurements of total vertical column density (VCD) of water vapour, i.e. the amount of water vapour in a vertical atmospheric column, obtained above Observatoire de Haute-Provence (OHP), Southern France (5° 42′ E, +43° 55′ N) from five different instruments. This work compares results from two ground-based and three satellite instruments: the SAOZ (système d'analyse par observation zénithale) an automated UV-VIS spectrometer; Elodie, a cross-dispersed echelle spectrograph and its 1.92 m telescope; SCIAMACHY, a scanning imaging absorption spectrometer for atmospheric cartography; GOME, a nadir-scanning ultraviolet and visible spectrometer for global monitoring of atmospheric ozone; and GOME2, a second generation of GOME. The objective of this comparison was to build up continuous decadal series of H_2O data. This challenge was first tested using similar methods, showing that some differences need to be explored. Promising infrared techniques (e.g. MERIS, IASI) could be used in the future, however, the differences about techniques, characteristic, and algorithms will be a next step used beyond the scope of this study. This article is structured as follows: Sect. 2 presents a description of these instruments; Sect. 3 describes the method used to select the satellite measurements above OHP considered for comparisons; Sect. 4 presents the results and the comparison between the different data sets, as well as a quantification of their differences; Sect. 5 outlines the interpretation of the differences followed by Sect. 6, the conclusion and final remarks.

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2 Instruments

2.1 SAOZ

SAOZ (Pommereau and Goutail, 1988) is a ground-based zenith-sky UV-visible spectrometer. Water vapour total columns are obtained from twilight measurements at 592 nm using the differential optical spectroscopy method, averaged over 30–40 individual measurements taken from 86° SZA (Solar Zenith Angle) up to 91° SZA. Line-of-sight values of individual observations are divided by the air-mass factor of the observation, the coefficient needed to obtain vertical amounts. This technique is the same as the one used to measure stratospheric constituents like ozone and NO_2 but extended for tropospheric constituents like water vapour. Note that multi-scattering effects are enhanced at twilight and cannot be easily evaluated, and therefore the AMF corrected accordingly. Because the SAOZ operates permanently and observations are possible even during bad weather conditions (rain, clouds, etc.) data are available twice daily, morning (here and after a.m. values) and evening (p.m.) averages, all year round, depending on technical problems. Note that H_2O data presented here are preliminary real-time data, as they were not validated before in peer-reviewed publication. One of the objectives of this publication is therefore to bring quality feedback from the community about this data set and therefore to change its status and fill up the corresponding SAOZ database.

2.2 Elodie

Total column water vapour were obtained using observations of astronomical objects made between July 1994 and December 2004 with the 193 cm telescope and Elodie high-resolution spectrometer (spectral domain: 385 nm to 680 nm, sampling: 0.005 nm, Resolution: 0.0065 nm). H_2O is measured visibly at 592 nm on individual spectra obtained when the source is close to the meridian, i.e. at higher possible elevation from the horizon. The air mass of the observation is then between 1 when the source is

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at zenith and 2 when the source is 30° above the horizon. Vertical amounts of H_2O are averaged over 20–40 individual measurements taken during the entire clear night (Sarkissian and Slusser, 2009). Monthly averages of Elodie data are available regularly, as it is rare to have heavy cloudy skies rending astronomical observations not possible all night, but spectrometric observations are still possible when cirrus clouds are present for example. It is also rare to have more than 15 fully cloudy nights a month at OHP and this is the reason we used this limit for acceptable monthly averages. Note that sometimes for technical reasons the telescope is stopped during relatively long periods for failures or maintenance. Elodie short-term observations have been compared and was used previously to validate using lidar data at OHP (Hoareau et al., 2009).

2.3 Sciamachy

SCIAMACHY (SCanning Imaging Absorption spectroMeter for Atmospheric CartographY) is a passive remote-sensing spectrometer observing backscattered, reflected, transmitted or emitted radiation from the atmosphere and the earth's surface, in the wavelength range between 240 and 2380 nm. The instrument flies on board ENVISAT, which was launched on 1 March 2002.

The primary scientific objective of SCIAMACHY is the global measurement of various trace gases in the troposphere and stratosphere, which are retrieved from the solar irradiance and the earth's radiance spectra. The large wavelength is also ideally suited for the determination of aerosols and clouds. Validation of SCIAMACHY is essential to ensure the quality of these derived products.

SCIAMACHY measures total columns of H_2O on nadir mode in the visible part of the spectrum using AMC-DOAS method (Noel et al., 2004).

2.4 GOME

GOME (Global Ozone Monitoring Experiment) is a nadir-scanning ultraviolet and visible spectrometer for global monitoring of atmospheric ozone. GOME spectral domain

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is from 240 to 790 nm with a spectral resolution of 0.2 to 0.4 nm, and a spatial resolution of 40 km × 320 km, indicating a global cover within 3 days and 43 orbits. H_2O is retrieved using the AMC DOAS method in the visible part of the spectrum. GOME 1 (GOME, hereafter) was launched on the ERS2 platform, and GOME 2 on the METOP platform in October 2006 with the same spectral resolution of GOME1, but the spatial resolution is much better with a ground-pixel size of 80 km × 40 km. Since summer 1996, ESA has been delivering users three-day GOME global observations of total ozone, nitrogen dioxide, and related cloud information via CD-ROM and internet. A key feature of GOME is its ability to detect other chemically active atmospheric trace gases as well as aerosol distribution (Noel et al., 1999).

3 Selection method of satellites measurements at the OHP

Each satellite measurement corresponds to a location on the surface of the earth that can be determined by the four sides of a quadrangle bounded by latitudes and longitudes ranges. Collocated measurements corresponding to ground-based observation are selected for latitude and longitude ranges that contains the coordinates of OHP. The optimal choice for these ranges corresponds to a compromise between the highest correlation between the satellite VCD and SAOZ am (measurements closest in time) and a sufficient number of observations for performing representative monthly means that are determined to be at least 100 measurements. Table 1 gives a selection of results of these correlations, varying the latitude and longitude ranges around OHP. Hereafter, correlation coefficients were calculated using the Pearson method, ranging from −1 (opposite direction) to +1 (same direction), with an alpha coefficient of 0.05 (2-tailed). Then, the optimal quadrangle corresponding to the data selection area around OHP was founded different for each satellite, as illustrated in Fig. 1.

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4 Results and discussion

For this study we analysed and compared two VCD data sets of H_2O above OHP. The satellites data sets are issued from SCIAMACHY, GOME and GOME2. The ground-based instruments are Elodie and SAOZ. Table 2 presents the temporal coverage for these data sets for each instrument.

We must indicate that data are available in various temporal and geographical samplings and for this study the comparison has been made in making monthly averages first, to maximise the number of coincidences that satisfy the temporal and spatial collocation criteria (as indicated for all instruments in Sect. 3) and then compare together the monthly means of each instrument.

4.1 Inter-comparison of ground-based measurements

Monthly averages of the total column water vapour measured by SAOZ and Elodie, from 1995 to 2004 above OHP, both exhibit a clear annual variation (Fig. 2). SAOZ can measure H_2O even in the presence of clouds, in contrast to Elodie which measures only by clear skies. SAOZ values are then expected to be slightly larger in comparison with Elodie because of the higher occurrence of cloudy days (i.e. days with more H_2O in the atmosphere) in the SAOZ series. For this reason, we have only selected the daily measurements of SAOZ that also exist in the Elodie data set (clear night conditions). In taking into account the coincident daily measurements, we have eliminated most of the cloudy days in the SAOZ data set.

The measurements of Elodie and SAOZ have trapped similar annual behaviours (Fig. 2), however, with small differences which appear sometimes during maximum or minimum values. The correlation coefficient is $R = 0.8$, and indicates a high correlation between the two types of measurements. We can see also note that for the year 2003 in the SAOZ dataset, the maximum of the seasonal cycle of this year is low relative to other years, due to a change in the absorption cross section (convolution) and the spectrum of reference for this year (problem in the spectrometer slit).

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4.2 Inter-comparison of satellite measurements above OHP

In this section, satellite products are inter-compared using SCIAMACHY measurements as reference because it covers the longest period covering the measurement periods of the two other instruments. The monthly mean of the VCD of H_2O derived from the satellite SCIAMACHY, GOME for the years 2002–2004 and SCIAMACHY, GOME2 for the years 2007–2009 above OHP (Fig. 3).

Despite the small difference observed, we can conclude that the measurements of the three satellites agree well over the OHP, with a correlation coefficient between GOME and SCIAMACHY of 0.97, and 0.98 between GOME2 and SCIAMACHY having been compared. This good agreement can be attributed to the fact that these three instruments (SCIAMACHY, GOME, GOME2) have almost the same design, and use the same algorithm (AMC-DOAS) to achieve H_2O, and also that the three instruments have low offset between their overpass times above OHP.

4.3 Comparison between ground-based and satellite measurements at OHP

In order to examine the representation of the satellite estimates of H_2O above OHP compared to the ground-based measurements, we compared the two types of data sets. As we mentioned above, the three satellites of this study utilise the AMC-DOAS algorithm to retrieve the VCD.

An air-mass correction factor in the algorithm effectively removes overly cloudy scenes, then the AMC-DOAS products are cloud-cleared Mieruch et al. (2008). To make the comparison between the satellites and SAOZ measurements, we selected only the morning measurements of SAOZ that also existed in the satellites data sets, as it is the nearest period of their measurements.

In Fig. 4, we compared the monthly averages of VCD obtained by Elodie, GOME from 1995 to 2004, Elodie, SCIAMACHY from 2002 to 2004, SAOZ, GOME from 1995 to 2004 and SAOZ, SCIAMACHY from 2002 to 2009.

From these figures we can conclude that:

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– The measurements of GOME and SAOZ are in good agreement with a correlation of high-order (0.8) and a difference appears sometimes between their maximum values, as in the year 1998, or between their minimum values as in 2000.

– The measurements of SCIAMACHY and SAOZ are also in good agreement, with a maximum in SCIAMACHY higher than SAOZ for most of the year and a moderate correlation (0.77).

– The comparison between the measurements of Elodie and the satellites GOME and SCIAMACHY shows that those of SCIAMACHY and Elodie ($R = 0.91$) are in similar agreement than those of GOME with Elodie ($R = 0.90$), with a slightly better agreement for SCIAMACHY.

4.4 Quantification of the differences between the measurements

According to the figures previously shown, which compare the monthly averages of H_2O VCD provided by our instruments, it is obvious that the periods of minimum and maximum are in phase, but the amplitude of these minimum and maximum differ. For this reason we have used this difference as a criterion for the next study.

The following table shows an estimate of the mean difference that may exist between the various measures of our instruments at OHP. To compute the difference between the measurements from both instruments, data have been selected during periods that do not exhibit any technical or data processing issues.

The quantification in Table 3 shows that the differences between the measurements of the three instruments oscillates between 0.45×10^{22} molecules cm^{-2} and 2.1×10^{22} molecules cm^{-2} where the difference between Elodie and SAOZ is the highest, the difference between GOME and Elodie is higher than those amongst SAOZ/GOME and SAOZ/GOME2. Note that 1×10^{22} molecules cm^{-2} corresponds to 20 % of the average value. However, the difference between SCIAMACHY and Elodie is smaller than that between SAOZ and SCIAMACHY. We also found that the differences

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between satellite measurements themselves are not very large and less than those already shown.

5 Interpretation

5.1 Interpretation of the difference between the various measures of water vapour total column at the OHP

After quantifying the average difference between the measurements, the origin of these differences have been investigated. To reach this objective, we have analysed the effect of time of measurement and of the geometry of the observation.

5.2 Period of measurements

Table 4 presents the time of measurements for each instrument in summer and in winter. According to this table we can see that there is a significant discrepancy between the time of measurements of ground-based instruments and the overpass times of the satellites above OHP, but also between the measurements of ground-based instruments themselves. The difference is negligible between satellites themselves.

How can these gaps in time contribute to the difference between their measurements?

To answer this question, we looked at the diurnal cycle of H_2O VCD above OHP provided by OPERA. The OPERA data are derived from operational analysis from 2002 to 2011 by the ECMWF (European Center for Medium Range Weather Forecast). These measurements were obtained every 6 h from January 2002 to April 2011.

Figure 5 shows the daily variations of H_2O VCD above OHP by OPERA 1–6 January. According to the evolution of these variations, we cannot see any systematic diurnal periodicity, as the hour corresponding to the minimum or to the maximum varies from one day to another. For example, on 1 January the maximum is observed at 18 h and

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the minimum at 12 h and on 6 January the maximum is observed at 00 and the minimum at 18 h.

However, the amplitude of these variations oscillates between 0.3 and 1.6×10^{22} molecules cm^{-2}, and thus by averaging over several days, this difference can be of the order of 1×10^{22} molecules cm^{-2}. The same study is done on the diurnal cycle in summer, where we found the same amplitude for the difference. Also, the diurnal cycles of water vapour can be caused by the influence of large-scale synoptic flows. These flows have a strong impact on the content of moisture in the lower part of the troposphere after the examination of the effect of these flows on the diurnal cycle of total column water vapour over Marseille (a city in the south of France near to the OHP) by looking at the vertical profiles of water vapour and winds measured over this city. Finally we can say, in the case of instruments which measure the total column vapour at OHP at different times differences in the value of water vapour can be obtained on average of the order of 1 approximately.

An alternative approach has been made during the recent DEMEVAP (Development of Methodologies for Water Vapour Measurement, Octobre 2011 at OHP) inter comparison campaign with lidars, GPS and radiosondes, showing a relatively good agreement between all instruments (for example 3 % between GPS and selected UV-visible spectrometers; Bock et al. (2013)). This approach was possible only because GPS instruments measure every 5 min, i.e. with a much better temporal resolution than other instruments.

5.3 Geometry of the observation

We know that the daily variation of the total column vapour is different from one region to another. For example, Bastin et al. (2007) examined in their article the diurnal cycle of total column water vapour over two GPS stations (one located in the centre of Marseille at an altitude of 131 m, and one north of the latter at an altitude of 314 m during the period from 21 to 26 June 2001), where they found non-regular differences between them for this period. These differences are mainly due to the location of the two stations

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where the topography is different. However in our case, our instruments do not measure the water vapour in the same location because their modes of viewing are different.

Figure 6 shows the different path of sight for the instruments of this study where we can see that Elodie and SAOZ do not observe the water vapour at the same location: Elodie observes above the OHP as the stars are often observed toward the south by 60° of elevation, and the impact point of the line of sight is just located a few kilometres (less than 10 km) of the instrument.

For the SAOZ, however, which looks at the solar radiation scattered at the zenith at the sunset and sunrise, the line of sight across the troposphere is tangential to the surface of the earth and the impact point is located around 180 km for a 10 km-thick atmosphere, and at 50 km for a 2 km-thick atmosphere. H_2O being a tropospheric constituent, its impact point for the SAOZ line-of-sight is in between these values.

For the satellites, Fig. 1 presents the location of the footprint of the measurement zones considered for each of the three satellites. We notice that the rectangles of GOME and GOME2 are located more on land, but the rectangle of SCIAMACHY is divided between the land and the sea, with the greater part being over the sea. In Fig. 6 the red rectangle contains the combination of these three areas.

To highlight the effect of the different observation modes of our instruments on their measurements we propose the following method (see Fig. 6):

- determine the zone that contains all the locations of the measurements of our instruments that are between 3–5° in longitude and 40–48° in latitude;
- divide this zone into 35 sub-zones, 19 zones above the OHP and 16 zones below the OHP;
- we can see that most of the sub-zones above the OHP are located rather on the land, but the ones below are rather on the sea;
- retrieve the measurements of the total column water vapour corresponding to each of these zones of global measures of GOME, which are available over the period from 1995 to 2004;

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- as the difference between the measurements of our instruments appears more clearly between the summer or winter most of the time (maximum and minimum values respectively), we have selected only the measurements of total column water vapour corresponding to these two seasons for each sub-area;
- these selected measurements are averaged over ten years;
- calculate the distance in km of each OHP sub-zone;
- present the averages over the ten years calculated for the summer and the winter of each sub-zone as a function of the distance of these sub-zones from OHP.

The result of this method is presented in the Fig. 7, which shows the gradient in the total column amount of water vapour according to the latitude around OHP, as the red points represent the summer measurements for each sub-area, and the blue ones those of winter.

This figure shows that the amount of total column water vapour decreases from south to north. The rate of the decline is stronger in summer than in winter, and the variability of the measurements between the sub-zones is more remarkable in summer than in winter, but also over the zones of the north than those of the south of OHP.

In another way, we can say that in summer the total column water vapour over the sea is systematically higher than over the land, where the difference between the southern and the northern boundaries presented in Fig. 7 is 1.8×10^{22} molecules cm^{-2}. In contrast, in winter the difference is less remarkable between the two boundaries and equal to 0.3×10^{22} molecules cm^{-2}.

In Fig. 7 we have also determined the position of the measurements for each instrument used in this study, which allows us to determine the order of magnitude of the differences arising from the variation of mode of observation between these instruments. Results are presented in Table 5.

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5.4 Interpretation and quantification

Based on the study performed in Sect. 5, the source of the bias can be explained (Table 4). The differences between the measurements between the different satellites correspond to the difference of the selected area of measurements chosen, as the overestimation of VCD measured by SCIAMACHY is due to geographical area covered that often include a significant portion of the sea, while those for GOME and GOME2 cover mainly the land.

However, the difference between Elodie and SCIAMACHY is due only to the difference in their measurement times. In contrast, the discordance in measurement times and in geometry of observation between GOME and Elodie contributes together to the observed differences in the estimation of VCD. This is also the case for SAOZ/satellites and SAOZ/Elodie.

6 Conclusions

In this work we have analysed and compared H_2O VCD above OHP obtained by various instruments including ground-based instruments and satellites ones. A good agreement is found between all these measurements over OHP. However, differences in the estimation of the maximum and minimum values appear between these different data sets, where the magnitude of differences varies according to the both instruments, as the differences between the satellite data sets is smaller than those observed between the satellites and the ground-based measurements, as well as between the ground-based measurements themselves. After the analyses of the diurnal variations of atmospheric water vapour over OHP and the variability of the VCD with latitude around OHP, we have shown that the differences observed between our instruments are due to the differences in their mode of observations and in their time of measurements. In another way, these instruments do not observe the water vapour in the same location and are not making their measurements at the same times.

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We found that these two reasons contribute to the mean difference between SAOZ/Elodie, SAOZ/satellites and GOME/Elodie, but the difference detected between the measurements of the satellites are mainly due by the difference of their geographic domain chosen. Also, the mean difference between Elodie and SCIAMACHY measurements are caused by the differences in their measurement times.

This study allows us to draw several conclusions about the comparisons of the total column water vapour in the region of OHP:

- The diurnal variations of total column water vapour above OHP is not systematic and varies from day to day and also from one season to another.
- In summer and in winter the amount of total column water vapour over the sea is systematically higher than over the land, indicating that the level of difference is also higher in summer than in winter.
- Variations of the total column water vapour with latitude is more important in summer. In contrast, the amplitude of these variations is very low in winter.
- This data analysis shows that the values of the total column water vapour over OHP, in summer and winter seems to exhibit a transition zone that separate the amount of water vapour in two levels: the first level south of OHP is characterised by higher values less variable with latitude, and the second level north of OHP is characterised by lower values more variable with latitude. The variations between these two domains is stronger during summer. This difference can be due to land/sea differences or can also be caused by air drying during the passage over the mountains as well as the effect of altitude in the presence of mountain (not low layer).

Future works will consist in studying climatological variability of atmospheric water vapour above Mediterranean locations with satellite thanks to this validation study using OHP ground-based data.

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Table 1. Selection of tests conducted for the size of the quadrangle around OHP.

Satellite	Latitude °N	Longitude °E	Correlation	Year
GOME2	42–44	5–7	0.92	2008
GOME2	42–44	5–10	0.91	2008
GOME2	43–44	5–6	0.91	2008
GOME2	43–45	5–7	0.93	2008
GOME2	43–46	5–8	0.92	2008
GOME2	43–47	5–9	0.77	2008
GOME	42–44	5–7	0.82	1996
GOME	42–44	5–10	0.83	1996
GOME	43–44	5–6	0.77	1996
GOME	43–45	5–7	0.83	1996
GOME	43–46	5–8	0.85	1996
GOME	43–47	5–9	0.85	1996
GOME	43–48	5–10	0.88	1996
SCIAMACHY	42–44	5–7	0.95	2007
SCIAMACHY	42–44	5–10	0.94	2007
SCIAMACHY	43–44	5–6	0.96	2007
SCIAMACHY	43–45	5–7	0.96	2007
SCIAMACHY	43–46	5–8	0.95	2007
SCIAMACHY	43–47	5–9	0.94	2007
SCIAMACHY	43–48	5–10	0.94	2007
SCIAMACHY	40–45	3–8	0.97	2007
SCIAMACHY	42–48	4–10	0.95	2007

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Table 2. Temporal coverage of the datasets of water vapour measurements obtained by the instruments.

Instruments	Temporal coverage
Elodie	July 1994–November 2004
SAOZ	June 1992–now
SCIAMACHY	July 2002–now
GOME	June 1995–December 2004
GOME2	March 2007–now

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Table 3. Quantification of differences between water vapour measurements obtained by our instruments.

Instruments	Year	Difference 10^{22} molecules cm^{-2}	Standard Deviation 1σ
Elodie-SCIAMACHY	2003–2004	0.3	1.0
Elodie-GOME	1996–2002	1.1	1.6
SAOZ-SCIAMACHY	2007–2009	−0.8	1.6
SAOZ-GOME	1999–2002	−0.2	1.6
SAOZ-GOME2	2007–2009	−0.2	1.1
SAOZ-Elodie	1999–2002	−0.5	2.1
SCIAMACHY-GOME	2002–2004	0.6	0.3
SCIAMACHY-GOME2	2007–2009	0.5	0.4

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Table 4. Observation time of our instruments.

Instrument	Time of measurement in winter at OHP	Time of measurement in summer at OHP
SCIAMACHY	between 10:30 and 11:50	between 11:30 and 12:50
GOME	between 11:00 and 12:15	between 12:00 and 13:15
GOME2	between 09:45 and 11:40	between 10:45 and 12:40
SAOZ	Morning: between 07:00 and 08:00 Evening: between 16:00 and 18:00	Morning: between 06:00 and 07:00 Evening: between 20:00 and 21:00
Elodie	from 18:00 to 07:00	from 21:00 to 04:00

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Table 5. Order of magnitude of differences arising from the variation of mode of observation between our instruments.

Instruments	Difference in summer 10^{22} molecules cm^{-2}	Standard Deviation 1σ
SCIAMACHY – SAOZ	0.5	0.6
SCIAMACHY – Elodie	0	0.6
SCIAMACHY – GOME	0.6	0.2
SCIAMACHY – GOME2	0.3	0.3
SAOZ – GOME	0.1	0.8
GOME2 – SAOZ	0.2	0.4
Elodie – GOME	0.6	0.8
Elodie – SAOZ	0.5	n.a.

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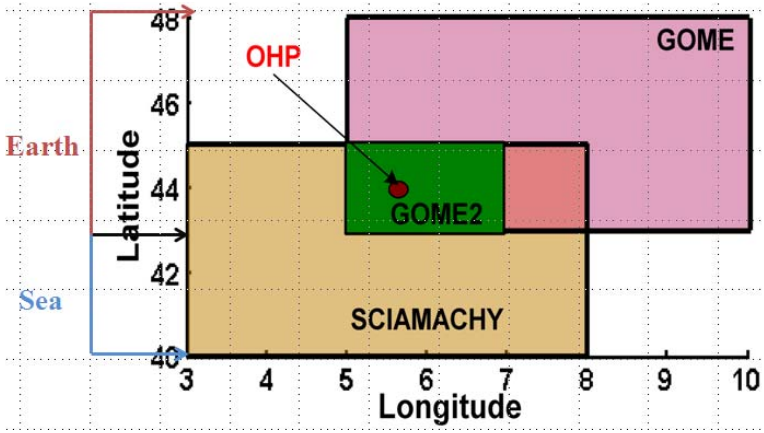

Fig. 1. The dimensions of the quadrangles used to extract measurements of the total column water vapour above OHP from the global measurements of our satellites.

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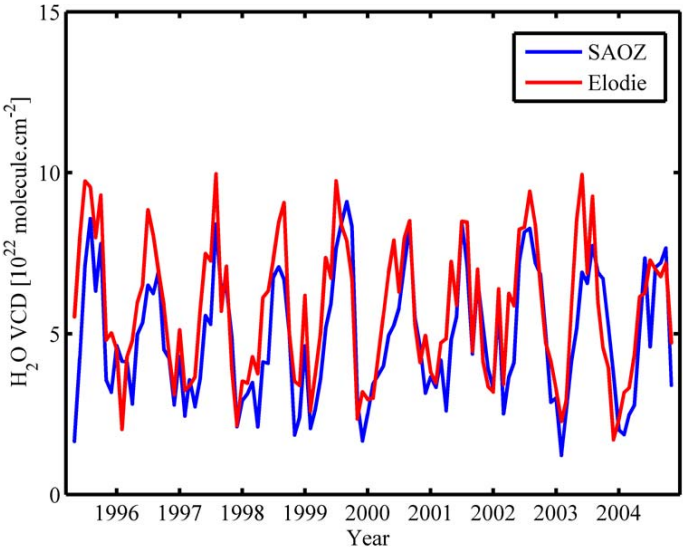

Fig. 2. Comparison of monthly averages of H_2O at OHP measured by Elodie and SAOZ from 1995 to 2004.

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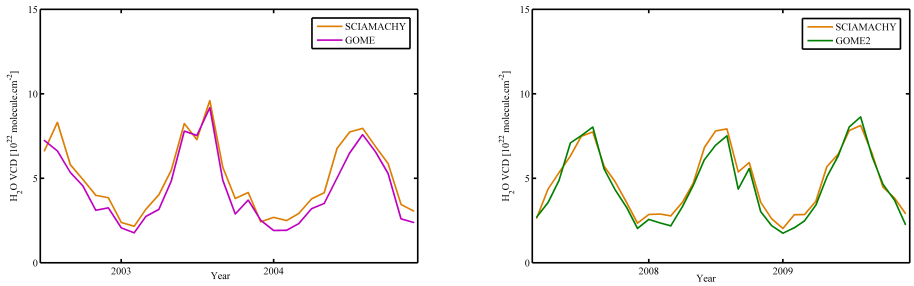

Fig. 3. Comparison of the monthly average of H_2O obtained by SCIAMACHY, GOME and GOME2 above OHP.

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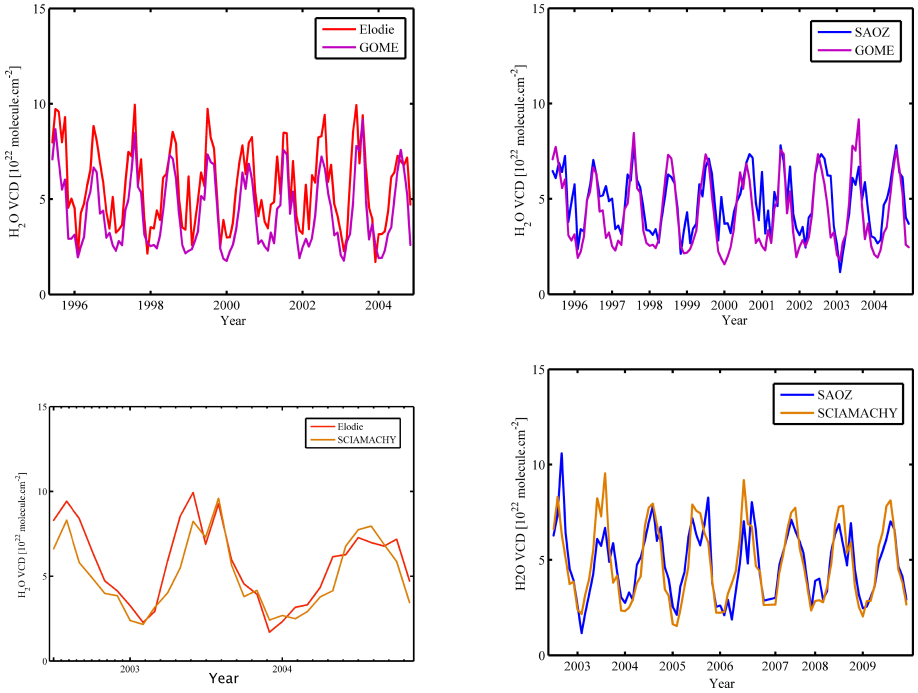

Fig. 4. Comparison of monthly average of H_2O obtained by ground-based SAOZ, Elodie and satellites GOME, SCIAMACHY above OHP.

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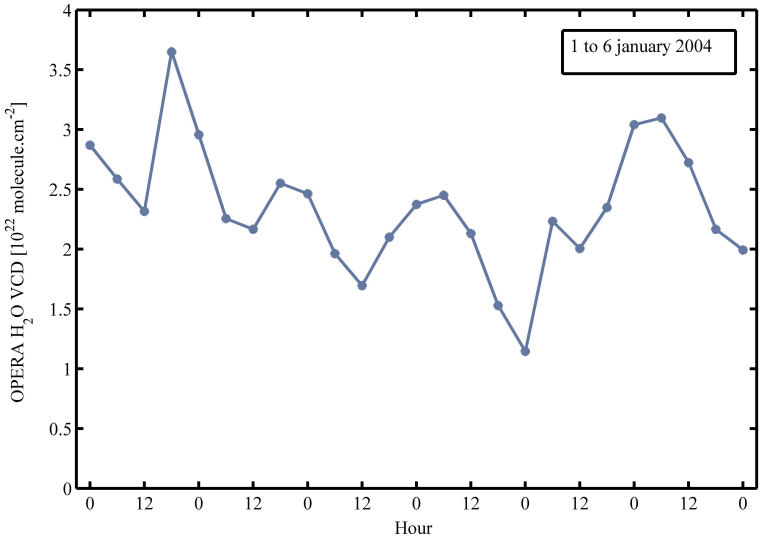

Fig. 5. Daily variations of the total column water vapour obtained over OHP from 1–6 January 2004 by OPERA.

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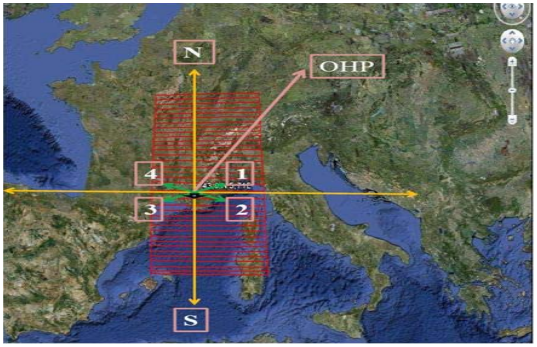

Fig. 6. Direction of the impact point of the line-of-sight of the different instruments of this study. The numbers 1, 2, 3 and 4 present the line-of-sight of the SAOZ oriented toward the sun at sunrise or at sunset, which correspond to the azimuth 55, 123, 236, and 305°, respectively. 1: morning, summer; 2: morning, winter; 3: evening, winter; 4: evening, summer. The little blue arrow oriented towards the south presents the direction of Elodie line-of-sight.

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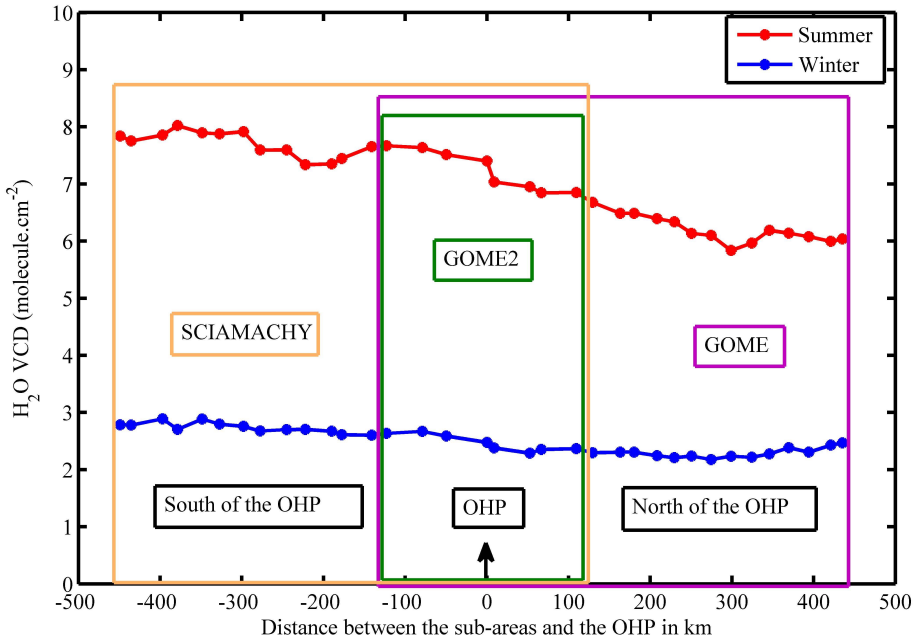

Fig. 7. Gradient with latitude of total column water vapour around OHP measured by GOME.

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