The statistical distribution law of relative humidity in the global tropopause region

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Abstract

Cloud cleared Microwave Limb Sounder (MLS) data of upper tropospheric humidity are evaluated in order to determine the global statistics of relative humidity with respect to ice, $R_{Hi}$. The evaluation is performed for the 215 hPa level, in order to compare the results with earlier results from the Measurement of ozone by Airbus in-service aircraft (MOZAIC) project. In agreement with the earlier study we find that in the lowermost stratosphere the probability to get a certain value of relative humidity decreases exponentially with the relative humidity. In the Antarctic data class (data south of 55°S, mainly winter data) we also find an exponential distribution for $R_{Hi}$ but with less steep slope. There is no change in the slope of the exponential distribution function at ice saturation. In the upper troposphere there are corresponding exponential distributions for $R_{Hi}$ in ice-supersaturated regions and in subsaturated regions (for 20% < $R_{Hi}$ < 100%), however with different slopes, viz. a steeper one in ice-supersaturated regions. In the cases of the tropospheric and antarctic data there is no indication of homogeneous ice nucleation at high humidities of $R_{Hi}$ > 150%, and the exponential distributions extend without change of slope up to 180–200%. Such extreme humidity events occur mostly in the tropics and at the edge of Antarctica, and could result from incidental lack of aerosol.

1 Introduction

Relative humidity is a field quantity that usually displays a very intricate structure in space and time. Since it depends on both absolute humidity and temperature, fluctuations of both these fields translate into relative humidity fluctuations. Even instantaneous fluctuations on a scale of 300×300 km$^2$ (which is a typical grid size for general circulation models) can be quite large; the statistical distributions of these fluctuations are heavy-tailed (GIERENS et al., 1997). Under these circumstances it is at first surprising that by and large the relative humidity in the lowermost stratosphere and in ice-supersaturated regions in the upper troposphere seems to obey a very simple statistical law (GIERENS et al., 1999): Three years of data obtained by the Measurement of ozone by Airbus in-service aircraft (MOZAIC) project (MARENCO et al., 1998) revealed (1) for the lowermost stratosphere that the probability to find a certain relative humidity value decreases exponentially with this value, and (2) for tropospheric ice-supersaturated re-
gions that the probability to find a certain degree of supersaturation decreases exponentially with the supersaturation. Expressed by formulae, this reads:

\[ P_{RH}(u) = a \exp(-au) \]  
(lowermost stratosphere) \hspace{1cm} (1.1)

\[ P_{S}(s) = b \exp(-bs) \]  
(tropospheric supersaturation), \hspace{1cm} (1.2)

where \(a, b\) are constants, \(RH\) is relative humidity, \(S\) is supersaturation with respect to ice, and \(u, s\) are variables on the \(RH\) and \(S\) axes, respectively. \(P\) means probability density.

Although the MOZAIC data is an extremely useful data set for studies like the ones mentioned above, it has a weak point, that is its lack of global coverage. The MOZAIC data are obtained during daily commercial flights, and therefore the data base is restricted to common international flight routes. Additionally some biases due to habits of commercial flying cannot be excluded (e.g. to avoid storms etc.). Therefore it is desirable to have another global data set of relative humidity that does not suffer from these restrictions. Fortunately, such a data set is at hand with the Microwave Limb Sounder (MLS) data (READ et al., 1995, 2001), obtained on board the Upper Atmosphere Research Satellite (UARS).

In the present paper we use the information on water vapour contained in the 203 GHz channel of the MLS to study the statistics of relative humidity on a global basis. We use those data that refer nominally to the 215 hPa pressure level, although one must concede that the field of view of MLS has a vertical extension of about 3 km at the tangent point. Since we are dealing with the upper troposphere, we use the relative humidity with respect to ice, \(RHi\), for this study. Our treatment of the MLS data is described in the next section. In Section 3 we present results and a discussion. Conclusions are drawn in Section 4.

2 Data reduction and cloud clearance

The retrieval method and validation of UARS MLS upper tropospheric humidity is described in detail elsewhere (READ et al., 2001). The microwave limb sounder allows retrieval of upper tropospheric humidity at pressure levels 147 hPa, 215 hPa, 316 hPa and 464 hPa with vertical resolution of about 3 km. Globally about 1318 profiles are measured per day, the data are available from 1277 days, from 18 September 1991 to 14 June 1997; there are some wider gaps since October 1994. For this study we use the level 2-ASCII-files with data version 4.90, individually described in READ et al. (2001). We only use data from the pressure level 215 hPa to compare the results with MOZAIC-measurements in a pressure range 200±25 hPa (GIERENS et al., 1999). The total uncertainty of the MLS retrieval for the 215 hPa level is 22% \(RHi\) in terms of accuracy and 10% in terms of precision (random error component) according to READ et al. (2001). These figures include uncertainties on limb tangent pressure, temperature, radiance noise, and background constituents (e.g. ozone).

MLS has the advantage that measurements are also possible when clouds are present. The retrieval is not directly affected by clouds because the microwave sounder is about a factor of 2 less sensitive to ice than to water vapour per mass. But certainly some of the data may be affected by cloud contamination, even in the subsaturated range. Therefore some cloud clearance measures have been taken following the recommendations of READ et al. (2001), viz.:

1. Bad data, flagged with a minus sign in front of the uncertainty value, are discarded;
2. Measurements with \(RHi(215 \text{ hPa}) > 230\%\) are discarded;
3. Measurements at 215 hPa are discarded, when simultaneously \(RHi(147 \text{ hPa}) > 230\%\);
4. Thick cirrus is diagnosed when the calculated radiance (i.e. the radiance that best fits the relative humidity profile neglecting ice scattering) at the lowest altitude of a limb scan is more then 10 Kelvin warmer than the measured radiance; these measurements are discarded.

READ et al. (2001) recommend to remove all measurements with \(RHi > 120\%\) because at such high supersaturations it is not possible to clearly distinguish in the MLS signal between contributions from vapour or from small ice crystals (diameter < 100 \(\mu\)m) that do not scatter microwave radiation. However, there is now plenty of evidence from several measurement campaigns with various types of instruments that such high supersaturations do occur in regions without detectable cirrus formation (e.g. JENSEN et al., 1998; VAY et al., 2000, OVARLEZ et al., 2000). Therefore, and because the MOZAIC data show the existence of cloud free ice-supersaturated regions we use measurements with \(RHi > 120\%\), although we cannot be certain which effect thin clouds have on the derived distribution of \(RHi\). This is discussed further in the next section. Finally, we use the temperature profiles of the National Centers for Environmental Prediction (NCEP) to determine whether a certain MLS measurement at 215 hPa occurred in the troposphere or in the stratosphere. For the sake of simplicity and because of the low vertical resolution we take the standard pressure level where the temperature is minimum as the tropopause. If this turns out to be 200 hPa, the tropo-/stratosphere assignment is considered uncertain and we do not use the measurement for the evaluation. It must be noted that the data assigned as “stratospheric” here refer to the lowermost stratosphere and may be influenced by the upper troposphere, since the low resolution of MLS does not allow a clearer attribution of the data.
Table 1: Exponents $b$ for the frequency distribution law $\ln[N(RHi)] \propto -b \cdot RHi$ as obtained from straight line fitting to the distributions of relative humidity with respect to ice, $RHi$, shown in Figs. 1 and 2. The standard deviations $\sigma_b$ for the determined values for the fits are given additionally. Corresponding data for MOZAIC are given for comparison. All values of $b$ and $\sigma_b$ are multiplied by 100 for easier reading.

<table>
<thead>
<tr>
<th>Region</th>
<th>MLS (Satellite)</th>
<th>MOZAIC (In situ)</th>
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<tr>
<td></td>
<td>$RHi[%]$</td>
<td>$b \times 100$</td>
</tr>
<tr>
<td></td>
<td>$\sigma_b \times 100$</td>
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<tr>
<td>Troposphere</td>
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<tr>
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<tr>
<td></td>
<td>20–80</td>
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<tr>
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<td></td>
<td>20–80</td>
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<td>20–150</td>
<td>2.03</td>
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The NCEP profiles often do not show any tropopause over Antarctica, in particular in southern winter months, when the thermal tropopause is not sharp (Zängl and Hoinka, 2001). Therefore we term data from this region ‘stratospheric’ only when a tropopause can be found in the corresponding NCEP profile. All other data from the Antarctic region (i.e. south of 55°S) are collected into a new class ‘Antarctic data’. Accordingly, most Antarctic data taken in local summer belong to the stratosphere class, whereas most winter data belong to the ‘antarctic’ class. It can be noted that the mean tropopause pressure in antarctic summer is around 300 hPa (Zängl and Hoinka, 2001) such that the 215 hPa level belongs mostly to the stratosphere.

As discussed in the next section this choice of a new data class seems to be reasonable.

3 Results and discussion

Fig. 1 shows the (non-normalised) frequency distribution of relative humidity with respect to ice, $N(RHi)$, as obtained from the MLS data for tropospheric air-masses on the 215 hPa level. The $RHi$ values are binned into 1% wide classes, ranging from 1 to 230%. The figure reveals three regimes: Between 1 and 20% the number of events is increasing with increasing humidity, from 20 to 100% (i.e. up to ice saturation) the number of events is decreasing with increasing humidity in an exponential fashion, and in the ice-supersaturated regime the number of events is also decreasing with $RHi$, again exponen-
tially, albeit with a steeper gradient than in the subsaturated regime.

Exponential distributions of the form \( f(u) = b \cdot \exp(-bu) \) can be fitted to the two latter regimes. For the subsaturated regime (fit range 20–80%) we find \( b = (2.08 \pm 0.06) \times 10^{-2} \) (statistical errors are 1σ_b values). For the supersaturated regime we use two fit ranges, 100–150%, and 100–200%. The corresponding exponents are \( b = (4.65 \pm 0.09) \times 10^{-2} \) (range 100–150%) and \( b = (4.59 \pm 0.04) \times 10^{-2} \) (range 100–200%), respectively. For the ice-supersaturated regions we can compare these values with the one determined from the MOZAIC data (at 200 hPa), which is \( b_{\text{MOZAIC}} = (5.8 \pm 0.1) \times 10^{-2} \). The difference between the values of \( b \) from MLS and MOZAIC is probably due to the different vertical resolution of the data (about 3 km for MLS, whereas each MOZAIC measurement refers to an exact pressure level), and due to undetected thin cirrus in the MLS field of view. The latter is discussed below.

When the tropospheric data are divided into Northern hemisphere (80°N–30°N), Southern hemisphere (30°S–55°S) and tropical data (30°N–30°S) for the same fit ranges as above (20–80%, 100–150%) we find slopes in the range \( (1.93 \pm 2.29) \times 10^{-2} \) (fit range 20–80%) and in the range \( (4.55 \pm 5.07) \times 10^{-2} \) (fit range 100–150%) respectively, so there is no significant difference to the distribution for the global range (80°N–55°S). All results mentioned here are compiled in Table 1.

GERENS et al. (1999), invoking a stochastic source-sink model, linked the observed exponents of the statistical humidity distribution laws to the rates of physical processes, that increase or decrease the number of H_2O molecules in the vapour phase of a system under consideration. The exponents for the subsaturated and supersaturated regions are significantly different, which points to different physical processes at work in these regions, which is plausible. However, it is astonishing that in the cloud cleared MLS data there is no significant change of the exponent in the supersaturated regime at least up to \( RHI \approx 180\% \), although we would expect a signature of cirrus formation at least from about \( RHI \approx 150\% \) on, as this is approximately (at the temperatures typical for the 215 hPa level) the threshold for homogeneous nucleation of micrometer sized aqueous solution droplets (KOOP et al., 2000). Because of this we expected that cloud clearance does not work at these high humidities, however, seemingly it does. For testing one can also consider the MLS data with less restrictive use of the cirrus clearance criteria. In such cases, one finds generally higher \( N(RHI) \) for high supersaturations as those shown in Fig. 1, which rendered it impossible to fit an exponential through the whole range 100–200%. Thus the cloud cleared data suggest that there are cloud free ice-supersaturated regions with very high humidities up to approximately 180%.

Fig. 2 shows the (non-normalised) frequency distribution of relative humidity with respect to ice, \( N(RHI) \), as obtained from the MLS data when the 215 hPa level

is in the lowermost stratosphere. The binning is as in Fig. 1. We see that the stratospheric \( RHI \) distribution can be fitted with an exponential distribution through the whole range from 10 to 100%, without a kink, which was already found from the MOZAIC data. The value of \( b \) is \( b = (6.60 \pm 0.10) \times 10^{-2} \) (fit range 10–90%). The corresponding value from the MOZAIC data is \( b_{\text{MOZAIC}} = (3.9 \pm 0.3) \times 10^{-2} \) (see also Table 1). When the MLS data are divided into Northern (80°N–0°) and Southern hemisphere (0°–80°S) the corresponding slopes are not significantly different, namely \( (6.92 \pm 0.11) \times 10^{-2} \) for the Northern hemisphere and \( (5.83 \pm 0.14) \times 10^{-2} \) for the Southern hemisphere. The difference between the values of \( b \) from MLS and MOZAIC is probably due to the same reasons as above.

Fig. 2 also shows the (non-normalised) frequency distribution \( N(RHI) \) as obtained from the Antarctic data class. This distribution can be also fitted with an exponential distribution through the whole range from 20 to 150%, without a kink at saturation, similarly to the stratospheric distributions found from the MOZAIC data. But similarly to the tropospheric distribution described above there is no significant change of the exponent in the supersaturated regime up to \( \approx 180\% \). The slope is significantly different from the slopes of the stratospheric distributions found from MLS data, namely \( b = (2.03 \pm 0.03) \times 10^{-2} \), the MOZAIC slope (for the stratospheric distribution) lies between the values for the stratospheric data and the Antarctic data found from MLS data.

This again shows that Antarctica is a special region and it is justified to open a class of its own for the Antarctic data. The difference between the slopes for Antarctica on one hand and the Southern and Northern hemisphere lowermost stratosphere on the other hand shows that there are either different physical pro-
cesses acting in in- or decreasing the number of water molecules in the vapour phase, or the same processes are acting with different rates.

There are at least three tentative explanations for the seemingly missing cirrus formation at \( RHi \gtrapprox 150\% \). (i) It could be an error in the MLS retrieval: this is unplausible because we would not expect a perfect straight line arising from an erroneous retrieval. It can be mentioned here that the correlations between the fits and their respective underlying data measured by the Pearson correlation coefficient \( r \) are very well in any case, with \( |r| > 0.97 \). (ii) the \( RHi \)-product could be scaled wrongly, i.e. the measured \( RHi \) could be \( \lambda u \) where the true \( RHi \) is \( u \) with a constant \( \lambda > 1 \): this is also unplausible, since then the kink in the \( N(RHi) \) distribution would not occur at saturation, but at \( \lambda \times 100\% \). (iii) The lack of cirrus formation is true and it is a result of missing aerosol particles: we do not know whether there are volumes of the size of the MLS field of view in the atmosphere that are essentially free of aerosol, so this is speculation. But it is not contrary to physical laws, so it might be possible. It must be noted that only about 10% of the ice-super saturated region events reach relative humidities in excess of 150%, corresponding to about 0.5% of all data in Figs. 1 and 2. These measurements occur mostly in the tropics and over the edge of Antarctica and the temperatures where these measurements have been taken cluster around \(-50^\circ C\) and \(-70^\circ C\). At the lower of these, the threshold supersaturation for homogeneous nucleation is about 60% according to Koop et al. (2000). The very high \( RHi \) values over Antarctica could result from the cooling of the air during the polar winter, while the apparent lack of aerosols in the tropics could result from scavenging by sedimenting ice crystals.

The applied cloud clearance measures are not able to catch cirrus clouds with only small ice crystals of less than about 100 \( \mu m \) diameter (presumably thin cirrus), because small ice crystals do not scatter 203 GHz radiation. The emission of such ice clouds in the field of view therefore lead to higher retrieved \( RHi \) values. However, this effect can probably not explain the very high humidities found, since, as mentioned, per unit mass ice emits only half as much as vapour at 203 GHz. Thus, if we assume an ice cloud formed at 150% \( RHi \), giving at equilibrium (i.e. saturation) one unit of ice mass per two units of vapour mass, this would lead to a retrieved \( RHi \) of 125%. If we assume further uplifting of such a cloudy air mass, the vapour to ice mass ratio can eventually reach 1:2, which would give a retrieved \( RHi \) of 200%, if the ice crystals would not grow to sizes where they scatter microwave radiation. This, however, would require that the considered air parcel does not reach ice saturation until the temperature decreases to less than about \(-50^\circ C\) (giving low absolute humidity such that the growing ice crystals stay smaller than 100 \( \mu m \)), and then it would have to cool further by additional 10 K. Since the high \( RHi \) events cluster around \(-50^\circ C\) in the tropics, this process is unable to explain the tropical high \( RHi \) events. It might work for the polar, in particular the Antarctic, high \( RHi \) events, where the temperatures are about \(-70^\circ C\). However, for any such attempt of an explanation the question arises, why such cloud processes would not lead to stronger deviations from the observed exponential distribution.

Undetected, non-scattering ice clouds in the field of view probably change the slope of the exponentials, and could contribute to the differences between the slopes found from the MLS data and those found from the MOZAIK data. However, such clouds obviously do not alter the general character of the humidity distributions. The appearance of thin cirrus in the field of view must be a random event that is unconnected to the mean \( RHi \) over the field of view, which is plausible since during a certain MLS scan such a cloud can be in any stage of development. Otherwise we would not expect the distribution curves to be straight up to \( RHi \approx 180\% \).

4 Conclusions

We have evaluated cloud cleared data contained in the \( RHi \)-product of the microwave limb sounder (MLS) and determined globally the statistical distribution laws of relative humidity with respect to ice on the 215 hPa level. We found, that consistent with a similar earlier study using MOZAIK data (Gierens et al., 1999), the degree of supersaturation in tropospheric ice-supersaturated regions is exponentially distributed, i.e. the probability to find a certain supersaturation, \( S_i \), decreases exponentially with \( S_i \). The same type of statistical distribution, i.e. exponential, has been found for the relative humidity in the lowermost stratosphere and antarctic data class. On the global scale we also found an exponential distribution for \( RHi \) in subsaturated regions of the troposphere (for \( RHi > 20\% \)), but with a less steep slope than in ice-supersaturated regions. Thus we can state that the MLS data confirm on a global scale the more regional findings from the MOZAIK data. The slopes of the exponentials generally differ between the MOZAIK and the MLS data. Such differences could be simply due to the vertical resolution, but can also arise from undetectable signal contributions from thin ice clouds in the MLS data.

An amazing finding is that the distributions extend without any sign of cloud formation far beyond values of \( RHi \) where, according to theory, homogeneous nucleation should commence. Since the exponential fits are very good with linear correlation coefficients \( |r| > 0.97 \) we think that errors in the retrieval process that would pretend such high supersaturations are improbable. It might be possible that these rare events (about 0.5% of the analysed cloud cleared data) occur when there is a lack of aerosol particles in the MLS field of view. Most of these events are found in the tropics where aerosol could be washed out by sedimenting ice crystals, and at the edge of Antarctica, where cooling of polar air during polar winter could result in high relative humidities.
The frequent occurrence of ice-supersaturation in regions with no or only few ice crystals is currently ignored by all weather prediction models (as far as we know). This means that cirrus cloud formation, at least by homogeneous freezing, is not correctly represented by these models. The existence of such regions becomes evident to everybody in situations when there are persistent contrails in an otherwise clear blue sky. Efforts should therefore be undertaken at the weather prediction centres to change their cloud physics parameterisations in order to allow representation of these frequent phenomena.

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References


