Seasonal and long-term variations of PMSE from VHF radar observations at Andenes, Norway

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Abstract

The observation of polar mesosphere summer echoes (PMSE) with VHF radars is an important possibility for the investigation of the polar mesospheric region during summer. This region is characterized by the lowest temperatures in the Earth’s atmosphere and the existence of mesospheric ice clouds, observed visually or by lidars as noctilucent clouds (NLC). Using measurements at 53.5 MHz in Andenes, Norway, with the ALOMAR SOUSY radar between 1994-1997 and with the ALWIN radar between 1999-2001 mean seasonal, solar cycle and long-term variations of PMSE have been derived. The seasonal variation of PMSE is characterized by a strong increase during end of May/beginning of June, a rather high level in June and July, and a more gradual decrease during August. The occurrence rate of PMSE is strongly positive correlated with the mesospheric ionization level mainly caused by solar cycle variations of the solar Lyman-∀ radiation and also by the flux of precipitating high energetic particles. Long-term trends of PMSE are only very small and not significant due to the limited data series.

1. Introduction

Polar mesosphere summer echoes (PMSE) are unexpected strong radar echoes from mesospheric heights which are regularly observed during summer season at polar latitudes. First PMSE have been detected with the 50 MHz radar at Poker Flat in 1979 [Ecklund and Balsley, 1981]. But later on PMSE have also been observed at other frequencies, in the upper VHF range with the 224 MHz EISCAT radar [Hoppe et al., 1988], in the UHF range at 933 MHz [Röttger et al., 1990] and even at 1.29 MHz [Cho et al., 1992b]. There are also indirect indications of PMSE-like structures in the MF range near 2.78 MHz [Bremer et al., 1996]. Most PMSE measurements, however, have been carried out at frequencies near 50 MHz.
Radar waves in the VHF range are backscattered by irregularities of the electron density with spatial scales of about half the radar wavelength as recently confirmed by Blix et al. [2002] from simultaneous rocket and radar observations. As such small irregularities (about 3 m at 50 MHz observations) are normally in the viscous subrange of the neutral turbulence and should be destroyed by viscous forces. An effective mechanism is therefore necessary to prevent the destruction of these irregularities. After suggestions of Kelley et al. [1987] and Cho et al. [1992a] large aerosols or ice particles could play an essential role by an effective reduction of the electron diffusivity. The existence of such particles is supported by low temperatures observed during summer months at polar mesospheric heights [Lübken, 1999], the observations of noctilucent clouds (NLC) consisting of small ice particles and normally occurring in the lower part of the PMSE structures [von Zahn and Bremer, 1999] as well as the by rocket measurements of charged aerosol particles during PMSE with a particle detector [Havnes et al., 1996, 2001]. A review about observational results and theoretical investigations can be found in Cho and Röttger [1997].

During the last 20 years a lot of PMSE observations with different radars have been carried out at different places mainly at northern polar latitudes but also in the southern hemisphere [Woodman et al., 1999]. Often these observations were however limited in time, and the investigations were restricted to special campaigns or single events. Therefore we will present in this paper the results of PMSE observations carried out at Andenes, Norway (69.3°N; 16.0°E) during the summer months of two extensive periods, from 1994 until 1997 with the ALOMAR SOUSY radar and from 1999 until 2001 with the ALWIN radar. After a brief description of these radars in section 2 the mean seasonal variation of the occurrence rate of PMSE is presented in section 3. In section 4 long-term changes of PMSE are investigated, including solar cycle changes as well as long-term trends. A summarizing discussion of the PMSE variations is given in section 5.

2. Brief description of the VHF radars at Andenes

PMSE observations at Andenes, Norway (69.3°N; 16.0°E) have been carried out with the ALOMAR SOUSY radar in co-operation between the Leibniz-Institute of Atmospheric Physics (IAP), Kühlungsborn and the Max-Planck-Institute of Aeronomy, Katlenburg-Lindau from 1994 until 1997. Since 1999 the PMSE investigations in Andenes have been continued with the ALWIN radar of the IAP. In this paper we use the data derived up to 2001. In Tab. 1 the most important technical parameters of both radars are summarized. In most parameters both equipments are very similar, only the effective mean power differs by about 3 dB taking into account the differences in the peak power, the duty cycle and the losses in the cables connecting the antenna system with the
transmitter and receiver units. The data of the antenna beam width given in Tab.1 are estimated for two way transmission, for one way the corresponding values are 6.5° for the ALOMAR SOUSY radar and 6.0° for the ALWIN radar. Further details of the radars can be found in Singer et al. [1995] for the ALOMAR SOUSY radar and in Latteck et al. [1999] for the ALWIN radar. In this paper we only use the signal-to-noise-ratio (SNR) derived from the vertical beam of the radars for the description of PMSE.

Altogether we have 7 years PMSE observations at the same place in Andenes. Whereas the measurements during the years 1997 and 1999 until 2001 are nearly continuous during the PMSE season, during the earlier years some data gaps occurred. In 1994 the observation started only on 24 July and in 1995 and 1996 some data gaps occur due to technical problems with the radar.

3. Mean seasonal variation of PMSE

To illustrate the mean seasonal variation of PMSE at northern polar latitudes in Tab. 2 the first and last days of PMSE appearance are shown together with corresponding values of NLC observations. The PMSE dates were mainly derived from radar observations at Andenes, only for the year 1998 data of the Esrange MST radar at Kiruna [www.irf.se] have been used. The NLC dates were taken from a compilation of von Cossart et al. [1999b] updated by von Zahn [private communication, 2002]. Most of the NLC dates were derived from measurements with the ALOMAR RMR lidar, some were got from lidar observations by K. H. Fricke of the University Bonn [UB] at Andenes or Kiruna. The dashed lines in Tab. 2 indicate that during the critical periods the corresponding instrument was not in operation. Values in brackets characterize the first or last day of operation of the instrument with PMSE or NLC occurrence. Neglecting the doubtful dates in brackets we estimated the median values of the first and last day of PMSE and NLC occurrence. After that the mean PMSE season at Andenes starts near 19 May and lasts until 28 August whereas the NLC season starts about 20 days later (8 June) and ends about 15 days earlier (13 August).

The seasonal variation of PMSE is shown for the years 1999, 2000, and 2001 in more detail in Fig. 1. Here the daily occurrence rates OR have been calculated for an SNR>10 dB. To reduce the strong interdiurnal variation the daily values have slidingly averaged over ten days. The main characteristics of the seasonal variation of PMSE are the steep increase during end of May/beginning of June, a rather high level near 90 % in the middle of June until the middle/end of July, and a more gradual decrease during August. The gradient of the increase of the occurrence rate OR is markedly more pronounced than the gradient of the decrease. This feature is found in all years investigated and can be seen by the straight regression lines in Fig. 1 with the corresponding gradients
printed there. The errors of these gradients have been calculated after Taubenheim [1969] for a statistical reliability of 95%.

In Fig. 1 the occurrence rate has been estimated for an SNR>10 dB. It is however also possible to use another threshold value. In Fig. 2 the mean occurrence rate has been derived for different time intervals (15 June – 15 July, 1 June – 31 July and 19 May – 28 August) of the year 2000 in dependence on the threshold SNR$_{\text{min}}$. As to be expected after the results presented in Fig. 1 the OR values in Fig. 2 are most pronounced during the period between 15 June until 15 July whereas the values derived for the whole PMSE period between 19 May and 28 August are markedly smaller. As also to be expected the occurrence rate decreases with increasing SNR$_{\text{min}}$ values. The same behaviour were derived also for the other years investigated.

As remarked in section 2 the PMSE investigations at Andenes consist of two parts, the first with the ALOMAR SOUSY radar between 1994 and 1997 and a second with the ALWIN radar between 1999 and 2001. In Fig. 3 the mean seasonal variations of the PMSE occurrence rate are presented for both periods. Due to the differences of the available mean power of both radars different SNR-thresholds have to be used with 7 dB and 10 dB. Now both curves should be comparable. The general behaviour of both curves is similar, however, their absolute levels are quite different. Whereas the maximum occurrence rate during 1994-1997 is about 70%, in 1999-2001 it is more than 90%. The reason of this difference will be investigated in the next section.

4. Long-term variation of PMSE

In Fig. 4 the variation of the mean occurrence rate of PMSE for three different time intervals are shown in dependence on time. As explained above different SNR$_{\text{min}}$ values (7 dB and 10 dB) have been used for both radars. The accuracy of the values for 1994 and 1995 is somewhat reduced due to some gaps in the data series. The general behaviour of the long-term variation, however, is not influenced by these gaps as confirmed by the very similar variation of the three curves using different time intervals.

If the long-term variation of the occurrence rate OR of PMSE is caused by the changing ionization level in the polar mesopause region than a connection between OR and the ionizing solar wave and/or particle radiation should be exist. Therefore, in Fig. 5 the variation of OR (using now the time period between 19 May and 28 August) is shown together with the solar Lyman $\forall$ radiation and the solar 10.7 cm radio flux as well as the geomagnetic $\Gamma K$ index of Tromsø and the global geomagnetic Ap index. The Lyman $\forall$ flux is a very important solar wave radiation ionizing nitric oxide, the most important ionizing process in the undisturbed mesosphere region [Brasseur and Solomon, 1984]. The Ly$\forall$ data are taken from the recently updated SOLAR2000 model.
Another index describing the solar wave radiation is the 10.7 cm radio flux from Ottawa/Penticton. Geomagnetic indices are indicators for precipitating particle fluxes which may especially at polar latitudes be important for the ionization of the mesosphere. In Fig. 5 the global geomagnetic Ap index is shown together with the more local index $\Gamma_K$ derived at the Auroral observatory Tromsø [http://geo.phys.uit.no/].

Comparing the different curves in Fig. 5 some similarities seem to exist. The connection between the occurrence rate of PMSE and the solar Ly$\alpha$ flux and the geomagnetic $\Gamma K$ index (both calculated for the same interval as for the OR values) is shown in Fig. 6 together with the corresponding regression lines and the estimated correlation coefficients. Especially the correlation between OR and Ly$\alpha$ is very strong and significant with more than 99 % reliability [Taubenheim, 1969], a similar correlation was derived between OR and F10.7. The correlation between OR and $\Gamma K$ is also positive, but not significant due to the small number of data available. The correlation between OR and the global Ap index is slightly smaller than with $\Gamma K$, an indication that the precipitation of high energetic particles can better be described by a local geomagnetic index. The same conclusion was also found in Bremer et al. [2001]. Summarizing it can be stated that an essential part of the long-term variation of PMSE is caused by changing ionization in the mesosphere due to solar cycle changes of solar wave and particle fluxes.

We also tested if there is a long-term variation in PMSE possibly connected with trends in the mesospheric temperature or water vapour content. Using the data OR, Ly$\alpha$, and $\Gamma K$ presented in Fig. 5 we estimated the following twofold regression equation

$$ OR(\text{th}) = a + b \cdot \text{Ly}\alpha + c \cdot \Sigma K $$

and calculated the difference between the experimental OR values and theoretical values after equation (1) according to $\Delta OR = OR(\text{exp}) - OR(\text{th})$. By this procedure the solar and geomagnetic influence on the PMSE occurrence rate is eliminated. The $\Delta OR$ values are shown in Fig. 7 in dependence on time. The estimated linear trend is with 0.3%/year markedly smaller than its mean error (+/-2.1%/year) calculated for a statistical reliability of 95 % [Taubenheim, 1969]. Therefore, we can conclude that possible long-term trends in the occurrence rate of PMSE are very small in comparison with the strong solar and geomagnetic influence. We also got similar results for investigations of other time periods of the yearly occurrence rates (15 June - 15 July, 1 June - 31 July).

5. Discussion
First results of the seasonal variation of PMSE have been found by the VHF radar observations at Poker Flat [Ecklund and Balsley, 1981; Balsley et al., 1983]. Later Kirkwood and Rechou [1998] and Kirkwood et al. [1998] reported about seasonal variations measured in Kiruna with the ESRAD VHF radar. Results obtained with the ALOMAR SOUSY radar during the years 1994-1997 in Andenes were presented by Hoffmann et al. [1999]. These different results agree in general with the seasonal variations of the PMSE in Andenes presented in Fig. 1 for the years 1999 until 2001. This can be confirmed by the mean curves of Fig. 3 at least for the observations in Andenes. For the year 1997 the seasonal PMSE variation in Kiruna [Kirkwood and Rechou, 1998; Kirkwood et al., 1998] is very similar to the results at Andenes with the steep increase of PMSE in May/beginning of June as well as the more gradual decrease in August. Therefore, we believe that the mean seasonal variation derived from 7 years PMSE observations at Andenes is characteristic for polar latitudes, at least northern polar latitudes. At the southern hemisphere probably less PMSE are observed [Balsley et al., 1995; Huaman and Balsley, 1999; Woodman et al., 1999] and no detailed information about seasonal variations are available until now.

As discussed in the introduction PMSE are strongly coupled with small charged particles. These particles may be small ice particles as suggested by the observed good correlation between PMSE and NLC found in simultaneous and common-volume radar and lidar measurements [von Zahn and Bremer, 1999]. The existence of ice particles markedly depends on the degree of saturation \( S = w \theta p / p_s \) where \( w \) is the water vapor mixing ratio, \( p \) the atmospheric pressure, and \( p_s \) the saturation pressure of water vapor. \( p_s [N/m^2] \) can be calculated by the following equation [Marti and Mauersberger, 1993]

\[
\log p_s = -2663.5/t + 12.537
\]

with the temperature \( t [K] \). In the lower part of Fig. 8 the mean occurrence rate OR of PMSE is presented. This curve has been derived from the data sets of PMSE observations at Andenes from 1994-1997 and 1999-2001 shown in Fig. 3. The degree of saturation \( S \) has been estimated for an altitude of 85 km from experimental temperature data of Lübken [1999] and model results of the water vapor mixing ratio \( w \) [Körner and Sonnemann, 2001] both to be seen in the upper part of Fig. 8. Whereas the temperature data were derived from falling sphere experiments at Andenes (Andoya Rocket Range) and Kiruna (Esrange) during the years 1987-1997, the water vapor mixing ratio \( w \) has been derived from model calculations with two coupled three-dimensional models, the dynamic model COMMA-IAP [Berger and von Zahn, 1999] and a chemical model [Sonnemann et al., 1998]. The model results of \( w \) agree rather well with experimental results obtained at Andenes by Seele and Hartogh [1999] from microwave radiometer measurements and by von Cossart et al. [1999a] from 3-color lidar observations. During the time interval between the end of May and middle of August the degree of saturation \( S \)
is greater than one. A value $S > 1$ is a necessary condition for ice particles to exist or to grow. Therefore, it is reasonable to assume that at least during this interval ice particles occur in the polar mesosphere between about 80 and 90 km. This conclusion is supported by the fact that during the main part of this time interval also NLC are observed, characterized by the straight line in the lower part of Fig. 8. For the time periods in May and in the second half of August we assume that the conditions for the existence of ice particles are at least partly be fulfilled. There are two possible scenarios to be discussed. We can assume that the water vapor mixing ratio $w$ is markedly higher than assumed after the model results shown in the upper part of Fig. 8. But we need values of $w$ markedly higher than 10 to get at the mean dates of the beginning and end of the PMSE season (19 May and 28 August, see Table 2) the condition $S = 1$. Such high values of $w$ near 85 km altitude have never been observed or modelled and are therefore extremely unrealistic. More reasonable, however, is to assume wave induced temperature variations (gravity waves or tides). Waves with amplitudes in the order of 5-10 K would induce $S$ values greater than one. Therefore, during the mean PMSE season the condition of $S \exists 1$ should be fulfilled at the beginning and end of this period only partly, during the middle part however nearly continuously. Some questions concerning the seasonal variation of PMSE, as e. g. its asymmetric behaviour with the strong increase end of May/beginning of June and the more gradual decrease in August, cannot be explained only by the variation of $S$ shown in the lower part of Fig. 8 and needs further investigations. One essential problem is the source of electron irregularities necessary to create the mesospheric radar scattering. As discussed in Cho and Röttger [1997] different mechanisms have been proposed but until now no final decision is possible. Seasonal variations of this source may also contribute to the observed seasonal PMSE variations.

The long-term variation of PMSE is mainly caused by changes of the ionization in the mesosphere due to changes of the solar wave radiation and particle precipitation as shown in Figs. 4-7. The influence of the ionization level on the diurnal variation of PMSE has been investigated by Bremer et al. [2000, 2001]. Here mainly precipitating particles characterized by geomagnetic indices or riometer data had a marked positive influence on the strength of PMSE whereas the effects due to solar radiation (Lyman $\alpha$ or 10.7 cm radio flux) were rather small. Investigating the diurnal variations during the year 2000, however, the influence of the wave radiation became markedly stronger. As discussed in detail by Rapp et al. [2002] a positive correlation between the mesospheric ionization level and the strength of the backscattered radar signals can be expected for normal changes of the ionization in the mesosphere (typically about 500 until 5x10$^4$ electrons/cm$^3$). In case of extreme high ionization levels (electron densities of about 10$^5$ cm$^3$, only during strong ionospheric disturbances as PCA) this positive correlation between PMSE and ionization level breaks down.
Significant long-term trends cannot be derived from the PMSE observations at Andenes. The estimated trends are with about 0.3%/year very small compared with the solar activity induced variations. There are hints of long-term trends in the occurrence rate of NLC in North-West Europe [Gadsden, 1990, 1998] which could be indications of negative temperature trends or positive trends of the mesospheric water vapor content. On the other hand, from rocket-borne temperature measurements in Northern Scandinavia Lübken [2000, 2001] found only small negative temperature trends in the NLC and PMSE region (-0.09 K/year at altitudes 75-85 km). The small positive PMSE trend in Fig. 7 is in qualitative agreement with small negative temperature trends and/or small positive trends in water vapor content. However, the PMSE-trends derived are not significant due to the limited data series. For more reliable results an essential longer time interval of PMSE observations is necessary. With the available data at Andenes only qualitative hints are possible about long-term trends until now.

6. Conclusions

VHF radar observations at 53.5 MHz have been carried at Andenes, Norway with the ALOMAR SOUSY radar during 1994-1997 and with the ALWIN radar between 1999-2001. Main aim of these measurements is the investigation of polar mesosphere summer echoes (PMSE). Basing on these observations the following results have been derived concerning their seasonal variations, solar cycle variations and long-term trends:

- The mean PMSE season at northern polar latitudes starts near 19 May and ends near 28 August. The seasonal variation is characterized by a strong increase during end of May/beginning of June, a rather high level in June/July and a more gradual decrease in August. The seasonal variation is strongly connected with the existence of small ice particles mainly caused by low mesospheric temperatures.

- The variation of PMSE is markedly controlled by the level of ionization in the mesosphere caused by solar cycle variations of the solar wave (mainly Lyman \( \alpha \) radiation) and precipitating high energetic particle fluxes.

- Very small positive long-term trends in the occurrence rate of PMSE are in qualitative agreement with NLC and temperature trends at polar latitudes. However, the PMSE trends are not significant due to the available limited observation interval.

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Aeronomy, Katlenburg-Lindau. SOLAR2000 Research Grade historical irradiances are provided courtesy of W. Kent Tobiska and SpaceWx.com. The historical irradiances have been developed with funding from NASA, UARS, TIMED, and SOHO missions.

References


Figure 1. Seasonal variation of the occurrence rate OR of PMSE with an SNR>10 dB after observations with the ALWIN radar in Andenes during the years 1999, 2000, and 2001. The straight lines mark the gradients at the beginning and end of the PMSE-seasons.

Figure 2. Variation of the occurrence rate of PMSE for three different time intervals after radar observations in Andenes during summer 2000 in dependence on the threshold value SNR_{min}.

Figure 3. Mean seasonal variation of the occurrence rate of PMSE after observations with the ALOMAR SOUSY radar during 1994-1997 and with the ALWIN radar during 1999-2001. Due to different effective powers of both radars different SNR_{min} values for both periods have been used.

Figure 4. Long-term variation of mean yearly occurrence rates of PMSE for three different time intervals after observations with two VHF radars in Andenes.

Figure 5. Comparison of long-term variation of yearly PMSE occurrence rates after observations with two VHF radars in Andenes (upper part) with corresponding variations of the solar wave radiation (Lyman $\forall$ and 10.7 cm radio flux in the middle part) and of geomagnetic activity (global Ap and local $\varepsilon$K index in the lower part).

Figure 6. Correlation of yearly PMSE occurrence rates (SNR_{min}=10 dB for years 1994-1997 and 7 dB for 1999-2001) for the time the interval between 19 May – 28 August with corresponding solar Lyman $\forall$ radiation data (upper part) and geomagnetic $\Gamma$K values (lower part).

Figure 7. Long-term variation of yearly PMSE occurrence rates for the time interval between 19 May - 28 August after elimination of the solar and geomagnetically induced part. The straight line marks the linear trend.

Figure 8. Mean seasonal variation of the PMSE occurrence rate OR derived from radar observations at Andenes during 1994-1997 (SNR_{min}=10 dB) and 1999-2001 (SNR_{min}=7 dB) together with the degree of saturation S derived from experimental temperature data $t$ [Lübken, 1999] and theoretical values of the water vapor mixing ratio $w$ [Körner and Sonnemann, 2001].
**Table 1.** Compilation of technical parameters of the ALOMAR SOUSY radar and of the ALWIN radar during their operation at Andenes.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>ALOMAR SOUSY</th>
<th>ALWIN</th>
</tr>
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<tbody>
<tr>
<td>Frequency</td>
<td>53.5 MHz</td>
<td>53.5 MHz</td>
</tr>
<tr>
<td>Peak power /duty cycle</td>
<td>100 kW / 4%</td>
<td>36 kW / 5%</td>
</tr>
<tr>
<td>Pulse length</td>
<td>2:s</td>
<td>2:s</td>
</tr>
<tr>
<td>Range resolution</td>
<td>300 m</td>
<td>300 m</td>
</tr>
<tr>
<td>Antenna Elements</td>
<td>148 Yagi antennas</td>
<td>144 Yagi antennas</td>
</tr>
<tr>
<td>Antenna Beam Width</td>
<td>4.6°</td>
<td>4.3°</td>
</tr>
<tr>
<td>Antenna Beam Directions</td>
<td>Vertical, N, S, E, W</td>
<td>Vertical, NW, SE, NE, SW</td>
</tr>
<tr>
<td>Antenna Beam Angle</td>
<td>8°</td>
<td>7°, 14°, 21°</td>
</tr>
<tr>
<td>Altitude range</td>
<td>75 – 95 km</td>
<td>73.2 – 96.6 km</td>
</tr>
<tr>
<td>Method</td>
<td>Doppler Beam Swinging (DBS)</td>
<td>Doppler Beam Swinging (DBS)</td>
</tr>
</tbody>
</table>

**Table 2.** Dates of the first and last seasonal occurrence of PMSE and of NLC after observations with radars and lidars at Andenes or Kiruna (for details see text).

<table>
<thead>
<tr>
<th>Year</th>
<th>First PMSE</th>
<th>First NLC</th>
<th>Last NLC</th>
<th>Last PMSE</th>
</tr>
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<tbody>
<tr>
<td>1993</td>
<td>---</td>
<td>---</td>
<td>9 August [UB]</td>
<td>---</td>
</tr>
<tr>
<td>1994</td>
<td>---</td>
<td>---</td>
<td>17 August [UB]</td>
<td>(23 August)</td>
</tr>
<tr>
<td>1995</td>
<td>19 May</td>
<td>(4/5 July)</td>
<td>12/13 August</td>
<td>(2 August)</td>
</tr>
<tr>
<td>1996</td>
<td>(22 May)</td>
<td>29/30 Mai</td>
<td>(28 July)</td>
<td>(7 August)</td>
</tr>
<tr>
<td>1997</td>
<td>20 May</td>
<td>12 June</td>
<td>13/14 August [UB, Kiruna]</td>
<td>28 August</td>
</tr>
<tr>
<td>1999</td>
<td>18 May</td>
<td>4 June</td>
<td>13 August</td>
<td>4 September</td>
</tr>
<tr>
<td>2000</td>
<td>22 May</td>
<td>29 June</td>
<td>16 August</td>
<td>31 August</td>
</tr>
<tr>
<td>2001</td>
<td>11 May</td>
<td>8 June</td>
<td>10 August</td>
<td>23 August</td>
</tr>
<tr>
<td>Median</td>
<td>19 May</td>
<td>8 June</td>
<td>13 August</td>
<td>28 August</td>
</tr>
</tbody>
</table>
\[ \Delta \text{OR-[%]} \]

\[ \Delta \text{OR-trend} = 0.3 \pm 2.1 \text{ [%/year]} \]