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Extrapolating future Arctic ozone losses

B. M. Knudsen[1], S. B. Andersen[1], B. Christiansen[1], N. Larsen[1], M. Rex[2], N. R. P. Harris[3], and B. Naujokat[4]

[1]Danish Meteorological Institute, Denmark
[2]Alfred Wegener Institute for Polar and Marine Research, Germany
[3]European Ozone Research Coordinating Unit, United Kingdom
[4]Free University of Berlin, Germany

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Correspondence to: B. M. Knudsen (bk@dmi.dk)

Abstract

Future increases in the concentration of greenhouse gases and water vapour are likely to cool the stratosphere further and to increase the amount of polar stratospheric clouds (PSCs). Future Arctic PSC areas have been extrapolated using the highly significant trends in the temperature record from 1958–2001. Using a tight correlation between PSC area and the total vortex ozone depletion and taking the decreasing amounts of ozone depleting substances into account we make empirical estimates of future ozone. The result is that Arctic ozone losses increase until 2010–2020 and only decrease slightly up to 2030. This approach is an alternative method of prediction to that based on the complex coupled chemistry-climate models (CCMs).

1. Introduction

The success of the Montreal Protocol and its amendments should lead to decreasing amounts of ozone depleting substances in the future. This in turn would lead to decreased ozone depletion if other factors remained unchanged. However, the stratosphere has been cooling for decades and some measurements suggest that the amount of water vapour in the stratosphere is increasing. Both these factors would tend to increase the ozone depletion in the Arctic vortex. Predicting the future ozone layer therefore involves a delicate balance between competing processes.

The tools used to predict future ozone depletion are chemistry-climate models (CCMs). These CCMs, while physically based, parameterise many important processes affecting the ozone layer, and do not include others. There is no agreement between models as to whether ozone will increase or decrease in the future. One of the reasons is that the current CCMs have difficulty in calculating correct polar temperatures, which are essential for determining the amount of ozone depletion. The range of model predictions of Arctic temperatures is currently too wide to make reliable predictions of future Arctic ozone losses, even given the large interannual variability in the

Arctic (WMO, 2003).

CCMs also have difficulties in representing two other important processes for polar ozone loss: the increase in stratospheric water vapour and the formation mechanism for solid type polar stratospheric clouds (PSCs). The observed increase in water vapour (Oltmans et al., 2000; Rosenlof et al., 2001) may have contributed substantially (Forster and Shine, 2002) to the observed cooling in the stratosphere (Ramaswamy et al., 2001; WMO, 2003). Yet, current CCMs include little more than that ∼1/3 of the trend in water vapour, which is due to increasing methane (WMO, 2003). In fact current chemistry-climate models do not reproduce either today's amounts of Arctic PSCs or the large increase since the 1960s (Austin et al., 2003; WMO, 2003; Pawson and Naujokat, 1997, and updates). Even if analysed temperatures are used in state-of-the-art chemical transport models the observed ozone depletion is not modelled correctly (Guirlet et al., 2000; Rex et al., 2004). This may be due to the fact that the formation of solid type PSC's is not well understood (Tolbert and Toon, 2001), making it difficult e.g. to model denitrification due to sedimentation of PSC particles, which can increase ozone depletion substantially (Waibel et al., 1999).

We thus have limited confidence in the predictions of future Arctic ozone losses made with even the best present day CCMs. Therefore, we have developed an alternative approach based on the observed behaviour of the stratosphere over the past 40–50 years. We base this approach on the tight correlation between PSCs and the total vortex ozone depletion observed by Rex et al. (2004). We do the extrapolation into the future using the highly significant increase in PSC occurrence (due to cooling in the Arctic vortex) from 1958–2001, taking into account the decreasing amounts of ozone depleting substances in the future. In this simplistic approach the water vapour trend and denitrification is included implicitly. Although such simple extrapolations have large associated uncertainties, these may not be larger than the uncertainties connected to CCMs. These extrapolations thus represent a useful alternative prediction to present day CCMs.

2. Data

2.1. Temperatures and calculation of PSC area

The Free University of Berlin (FUB) has made historical wintertime analyses of the NH stratosphere, which primarily use radiosonde data, from July 1965 to June 2001 (Labitzke et al, 2002; Pawson and Naujokat, 1997). They are available in a 10° latitude-longitude grid. Since 1977 a 5° grid was used, but for consistency the data set was thinned to the 10° grid.

The ECMWF 40 year reanalyses (ERA40) (Simmons and Gibson, 2000) covers the period 1957–2002. It uses a 3D variational analysis at T159 resolution and 60 levels in the vertical. The data were extracted in a 5° lat-lon grid from T21 truncated fields. These data were then thinned to the 10° FUB grid.

There are no long term observational records of PSCs suitable for this analysis. Accordingly the PSC area is defined here as the area where the temperature is below the nitric acid trihydrate condensation temperatures (T_{NAT})(Hanson and Mauersberger, 1988). The quality of the predicted temperatures below T_{NAT} has been assessed by comparison of both the analyses and the first guess fields (i.e. the 6-h forecasts from the last analysis, which is independent from individual radiosondes) to radiosondes. The extent of such low temperatures at 50 hPa was 6–10 and 1–2% lower than the radiosonde extent in 1995/1996 and 1996/1997 (Knudsen, 2003), respectively. The NH winter averaged PSC extent using FU-Berlin data is 11 and 5% higher than the ERA-40 PSC extent in 1995/1996 and 1996/1997, respectively. Thus, the both the ERA40 and the FU-Berlin PSC extent agrees well with observations. The ERA-15 reanalysis (Gibson et al., 1997), which has also been used, does not have a comparable accuracy of temperatures (Knudsen, 1996).

The FUB data are valid for 0:00 UT, whereas the ECMWF data are calculated for 12:00 UT. Tests show that this has only a minor effect on the PSC areas. The same is true for PSC areas calculated at higher resolution.

Changes in the observation system influence the quality of the meteorological analyses. In 1957, the International Geophysical Year, the number of radiosondes became comparable to the current number. In 1964 the former Soviet Union started supplying radiosonde data above 100 hPa and in 1979 satellite data became available. However, the averaged PSC area over the whole winter is a relative robust quantity, which does not depend on small errors. The FU-Berlin analyses have remained almost unchanged during the period and should thus be well suited for trend studies.

2.2. Water vapour

Following Forster and Shine (2002), we have adopted a homogeneous H_2O trend of 0.05 ppmv/year. The reference point is the UARS 1992–1998 HALOE+MLS climatology for February (http://code916.gsfc.nasa.gov/Public/Analysis/UARS/urap/home.html) at 70° N equivalent latitude. With this trend the 50 hPa H_2O mixing ratios (T_{NAT}) are 4.40 ppmv (195.0 K) in 1995, 3.65 ppmv (194.3 K) in 1980, 2.85 ppmv (193.2 K) in 1964 and 2.55 ppmv (192.8 K) in 1958. The nitric acid mixing ratio used is the LIMS January value at 76° N of 9 ppbv. In the SH the 70 hPa 64° S value of 6 ppbv was chosen in May, before denitrification and dehydration sets in. The SH H_2O mixing ratio in May at 70 hPa and 70° S is also 4.4 ppmv.

3. PSC trends

Figure 1 shows the mid December to end of March mean 50 hPa PSC area for FUB and ERA-40 analyses. The FUB and ERA40 data agree quite well in most years. One exception is in 2000, where large temperature biases occurred over the poles in the ERA40 data (Knudsen, 2003). When this figure was prepared the ERA40 reanalyses had not yet been completed. We have therefore used a combined data set with ERA40 data 1958–1965 and FUB data afterwards (solid line).

In the absence of a trend in H_2O, T_{NAT} would be constant and the PSC areas would follow the dashed black line. The linear regression line though all points, which are independent, is the solid red line. The PSC areas increase with more than 99.9% confidence (4σ) during the period (von Storch and Zwiers, 1998, Sect. 8.3.7).

The Arctic winter stratosphere is sometimes disrupted by major stratospheric warmings, which usually bring an end to the PSC season and limit the ozone loss. The largest ozone losses occur in the cold uninterrupted winters. To examine this group of winters separately, the maximum PSC areas in successive 5-year intervals (2001–1997, 1996–1992, etc.) are extracted (large squares)(Rex et al., 2004). The first interval (1958–1961) is only 4 years long. Linear regression reveals a highly significant (more than 99.99% confidence (8σ)) upward trend in these 9 maximum PSC areas. Such PSC areas are expected statistically only every fifth winter, so we have also examined the trends of the largest half of the PSC areas in 6-year intervals (squares; 2001–1996, 1995–1990, etc.) which are expected statistically every second winter. These trends are the main focus of this paper.

The first interval (1958–1959) is only 2 years long, and the larger of these two PSC areas is included in the trend calculations. In fact it would also have been chosen in the 6-year interval from 1958–1963. Again highly significant upward trends are obtained (8σ). Sensitivity studies reveal that going to 8-year intervals or starting the intervals in 1958 (both for 6 and 8 year intervals) changes the calculated trend by a factor ranging from 0.95–1.04. Going to 4-year intervals changes the calculated trend by a factor of 0.85 and decreases the significance of the trend substantially. This is due to inclusion of the small PSC area in 2001.

Since 1984 the FUB data over data-sparse regions have been supplemented by satellite derived data. We have therefore calculated the trends of the 50% largest PSC areas for the period 1984–2001. The slope is 0.063±0.032%NH/year (1σ) and is significant at the 90% confidence limit, when the small numbers of data points are taken into account (von Storch and Zwiers, 1998, Sect. 8.3.7). As seen in the figure the 1984–2001 trend is close to the trend over the whole period.

4. Correlation between PSC area and ozone depletion

Vortex averaged ozone depletions in the Arctic from 400–550 K potential temperature have been calculated by Rex et al. (2004), and they form probably the most accurate and consistent data set for Arctic vortex ozone depletions. Although there are certain assumptions involved in this method, it does give a correct depletion in the winter 1999/2000 (Lait et al., 2002; Schoeberl et al., 2002). It has been shown that mixing ideally should be taken into account at the bottom of the vortex and below (Knudsen et al., 1998) and in some years even above (Grooß and Müller, 2002).

Rex et al. (2004) found a high correlation between mean PSC volume and mean end-of-winter column ozone depletion. To be able to use the FUB data we here use 50 hPa PSC areas instead, and to compare with the Antarctic ozone hole the total vortex depletion in Mt is used instead of the column depletion. Another advantage of using the total vortex depletion in Mt is that this quantity determines how large an influence the vortex depletion has on ozone levels at mid-latitudes after break-up of the vortex (Knudsen and Grooß, 2000; Knudsen and Andersen, 2001). The edge of the vortex used to calculate the vortex area is the position of largest gradient in 475 K PV. The vortex area was averaged in the period mid December to end of March, in which the PSC areas were calculated. In 1997 and 1999 the vortex did not establish at 475 K before around 8 January, so the vortex areas are calculated as of this date.

Figure 2 shows the remarkably good correlation (correlation coefficient 0.96) of the total depletion with the PSC area for the period 1992–2000 for the NH. Also shown are the 68% confidence limits on the 50% largest PSC areas for 2030. One question is whether this correlation can be extended to these larger PSC areas expected in a future colder stratosphere, as it is possible that we have reached some kind of saturation where larger PSC areas do not lead to larger ozone losses. To investigate this we turn to the SH, where larger PSC areas do occur. The SH temperatures are taken from the ERA-15 reanalyses from 1979–1993. Earlier years have not been used because the lack of satellite data is a serious problem for SH analyses (A. Simmons, personal communication). Later years have been omitted because then ERA-15 data would not be available and adding more points in the upper right corner of the plot would not be of any help. The only exception is the year 2002, which was unusually warm with PSC areas close to the NH values.

Possibly the best available estimate of the long-term ozone vortex depletion in the SH is the October mean column ozone from Halley (76° S, 26° W) (WMO, 1995, updated courtesy J. D. Shanklin) minus the 1956–1959 mean (310 DU). The column ozone at Halley is of course lower than in the vortex mean, but so is the climatological mean at Halley.

Model calculations (Sinnhuber et al., 2002) show that the ozone loss is proportional to the equivalent effective stratospheric chlorine (EESC) loading, which incorporates bromine. Figure 3 shows that this is a fair assumption for the Antarctic ozone losses. In order to compare to the current NH depletions we have scaled the SH depletions up to the 1992–2000 halogen loading. This is done by dividing the SH depletions by the fraction of EESC in each year relative to the 1992–2000 average. The period during which the average PSC area is calculated is mid July to end of October. This is one month later in the season than in the NH because the SH vortex is much more pole-centred and sunlight reaches Halley later than it reaches the NH vortex. In the SH the PSC areas before mid July would not add to the ozone depletion since dehydration and denitrification would occur anyway. The level used is 70 hPa because the ozone depletion in the SH vortex occurs lower than in the NH. The vortex area used is 12.5% of the SH (61° S equivalent latitude) taken from the 550 K 1979–2000 mean (WMO, 2003). Figure 2 justifies the assumption that further increases in the NH winter averaged PSC areas would lead to further ozone loss.

5. Future ozone losses

The linear regression lines in Fig. 1 have been extended to 2030, giving our best estimate of the future PSC areas. By combining these with the correlation between PSC area and ozone depletion from Fig. 2 and scaling the results by the fraction of EESC relative to the 1992–2000 average (WMO, 2003) to allow for decreasing EESC we obtain the future predictions of the ozone losses in Fig. 4. The dashed lines give 68% confidence intervals for the means at each year (Von Storch and Zwiers, 1998, Sect. 8.3.10) taking only the uncertainties in the PSC area regressions into account (note that this does not mean that 68% of the depletions will lie within the dashed lines, because individual depletions have a larger variation than the mean). Almost the same confidence intervals for the future parts of the lines are obtained by using lines crossing the regression line at the central year (1979.5) in Fig. 2 with the slope of the regression line ± the standard deviation of the slope. To get 95% confidence limits the line spacing would have to be approximately doubled. Due to the small number of points, the line spacing for the maximum PSC area in 5-year intervals would, however, increase by a factor of 2.14 instead of 2.

The largest PSC areas in 5-year intervals lead to the largest ozone depletion in the future, but such depletion is only expected statistically every 5th year. Generally, we predict that the ozone depletion will increase, reach a maximum between 2010 and 2020, and then decrease slightly before 2030. For comparison, the CCMs do not agree on whether or not ozone depletion will increase in the future and show a substantial recovery by 2030 (Austin et al., 2003; WMO, 2003). It should be noted that by 2030 uncertainties are quite large in any prediction and in particular in our extrapolation.

While the ozone depletion in the Arctic vortex might match the amount of ozone depletion in the SH in the warmest years of the 1980s (without the scaling to the 1992–2000 mean EESC), there is no indication that it will ever reach current levels of total depletion (in Mt) in the Antarctic ozone hole. The Antarctic column depletions (in DU) during the warmest years in the 1980's were already surpassed in the Arctic in 1996.

We have performed a sensitivity study of what could influence the future predictions for the case with the 50% largest PSC areas. As shown in Fig. 5, using only the FUB data (black line) would increase the predicted ozone loss. The reasons why this might give a better prediction are a better consistency of the data and the fact that former

Soviet Union radiosonde temperatures above 100 hPa are only available since 1964. Further, radiosondes might have had difficulties in observing very low temperatures in the early years (Pawson and Naujokat, 1997). However, the FUB period may be biased by 5 out of the first 6 years being warm. It is informative to calculate how often such an event occurs. If the chance of a "warm" winter is $\frac{1}{2}$, the chance of at least 5 out of 6 winters being warm is $7\times(\frac{1}{2})^6=0.11$. Such an event is therefore expected every 55 years.

The H_2O trend is not fully explained. Scaife et al. (2003) showed that part of the trend is due to the upward trend in the Southern Oscillation Index (SOI). It is not known, whether the change in the SOI is a temporary natural variation or a more permanent change due to increased greenhouse gases. We have therefore tried to look at the effect on the future predictions if the trend slows down. About 35% of the H_2O trend is due to the trend in methane, which is thought to continue in the future (WMO, 2003). The levelling off of the methane trend in recent years might be due to decreased fossil fuel burning in the former Sovjet Union (Dlugokencky et al., 2003).

Because of the uncertainties about the H_2O trend (SPARC, 2000) we have studied the sensitivity of the future predictions on the trend. If the H_2O trend is not taken into account in the calculation of the PSC areas, Fig. 5 shows that less ozone depletion would be expected (green dashed line). The prediction based on FUB data only is not as sensitive to the H_2O trend (black dashed line). The best-documented part of the trend goes back to 1980 (Oltmans et al., 2000). The cyan dotted line shows that using this part of the H_2O trend still gives less depletion.

The 1980–2000 trends in H_2O, greenhouse gases, and stratospheric ozone are estimated to have caused a mid December to mid March 50 hPa high-latitude NH cooling of about 1.1, 0.2, and 0.6 K, respectively (Forster and Shine, 2002; Rosier and Shine, 2000; WMO, 2003). This is quite consistent with the fact that the trend in T_{NAT} needed to offset the FU-Berlin 50 hPa PSC trend is 1.0 K/decade. If the H_2O trend is anthropogenic, then the PSC trend thus seems to be attributable to anthropogenic changes and not to long-term natural variations.

Since our results indicate that the future trend of ozone is close to zero, we would expect the temperature trend to decrease by about 1/3, which would lead to future ozone depletions close to the green dashed line. If the non-methane related part of the H_2O trend were to stop the remaining temperature trend would be about half the 1980–2000 trend. Figure 5 shows that this would lead to a faster recovery of the ozone layer (magenta dash-dotted line). In the last years H_2O has decreased (Rosenlof et al., 2003), but this may be related to changes in the SOI (Scaife et al., 2003). It should be noted that there is no consensus about the attribution of the observed downward trend of the Arctic winter temperatures to the trends in ozone, greenhouse gases, and water vapour (WMO, 2003). If ozone plays a larger role for the decreasing temperatures the future ozone depletions would become smaller, whereas a smaller role for water vapour would increase the confidence in the future predictions.

6. Comparison to models

Rex et al. (2004) show that the SLIMCAT CTM does not reproduce the observed increase in ozone depletion with increasing PSC areas and this is likely to apply to CCMs as well. In Fig. 6 we show a prediction of the vortex ozone losses based on the 50 hPa PSC areas from CCM calculations (Austin et al., 2003). These CCM PSC areas equal the average area of temperatures below 195 K and are November–March averages, so our predicted PSC areas have been calculated for this period rather than the mid-December to end March period shown earlier. The red line shows the resulting prediction of the ozone depletion, while the red dashed lines give the 68% confidence limits. The black line shows the predicted ozone depletion in individual years based on the actual PSC extent instead of the trend. The CCMs all use an old halogen scenario (WMO, 1999), which predicted larger concentrations and therefore more ozone depletion in the future as seen in the figure (red dash-dotted line) for our predictions. Only results from CCMs that reproduce the past PSC areas are shown, since Rex et al. (2004) and the present study indicate that this is crucial for calculations of vortex ozone depletion. For example, the European Centre Hamburg (ECHAM) models have too large areas with $T<195$ K due to the common cold-pole problem, but in the ozone depletion calculations this is resolved by using a nucleation barrier for PSC formation. The ECHAM models predicts a warming of the Arctic vortex in the future due to increased planetary wave activity (Schnadt et al., 2002), while the opposite is the case for the University of L'Aquila (ULAQ) and Goddard Institute for Space Studies (GISS) models. This is the main reason for the large differences in the predictions of the future ozone between CCMs.

The results from the ULAQ model (Pitari et al., 2002) are in good agreement with observed PSC areas in 1990 and also with the extrapolated results for 2030. The ULAQ model predicts a slight increase in the March-April minimum total ozone in the Arctic from 1990 to 2030 (Pitari et al., 2002, and personal communication) contrary to our prediction in Fig. 6 based on the ULAQ PSC areas only (blue crosses). The results of the Unified Model with Eulerian TRansport And Chemistry (UMETRAC)(Austin and Butchart, 2003) moderately underestimates observed past PSC areas and does not capture the increase since 1975 (dashed magenta line). This may be connected to incorporation of only the methane related part of the H_2O trend and not the (controversial) remaining part. For reference our prediction without a H_2O trend in the PSC thresholds is shown in Fig. 6 as the red dotted line. From the UMETRAC PSC area calculations we predict much smaller ozone depletions in the future in agreement with their predictions of the March-April minimum total ozone in the Arctic (Austin et al., 2003).

Of the other 3-D CCMs in WMO (2003) and Austin (2003) the GISS model showed much more ozone depletion than our results by 2010–2020, whereas the remaining models showed substantially less depletion. For the GISS model no PSC areas were available. The GISS model has been criticized for its coarse resolution and simple dynamics, but this may in fact be less important than other model features such as gravity-wave parameterisations (Shindell, 2003).

Most models used in WMO (2003) predict considerable ozone recovery by 2030 contrary to our results. Danilin et al. (1998) also predicted little recovery by 2030 in idealized air parcels using a chemical box model forced by a cooling of 1 K/dec. Waibel et al. (1999) found ozone recovery to be substantially delayed due to extensive denitrification caused by a cooling of 5 K. Tabazadeh et al. (2000) argue that severe denitrification in the Arctic is possible in the future with a cooling of 4 K and could enhance ozone loss by up to 30%.

7. Conclusions

Using the tight correlation observed between PSC areas and total vortex ozone depletion and taking into account the decreasing amounts of ozone depleting substances, we predict ozone losses in the future. Ozone depletions are predicted to increase until 2010–2020, and decrease slightly afterwards as shown in Fig. 4. The confidence limits shown in the figure just give the formal extrapolation errors based on the existing data. They do not include uncertainties in the predicted chlorine loading and the conversion from PSC areas to ozone depletion. Further, predicting the future is always uncertain. Future massive volcanic eruptions would temporarily increase the ozone depletion substantially (Tabazadeh et al., 2002), while a decrease in the H_2O trend would lead to less ozone depletion as shown in Fig. 5. Despite these uncertainties, we think our empirically based approach is a valuable alternative predictive tool which complements the chemistry-climate models.

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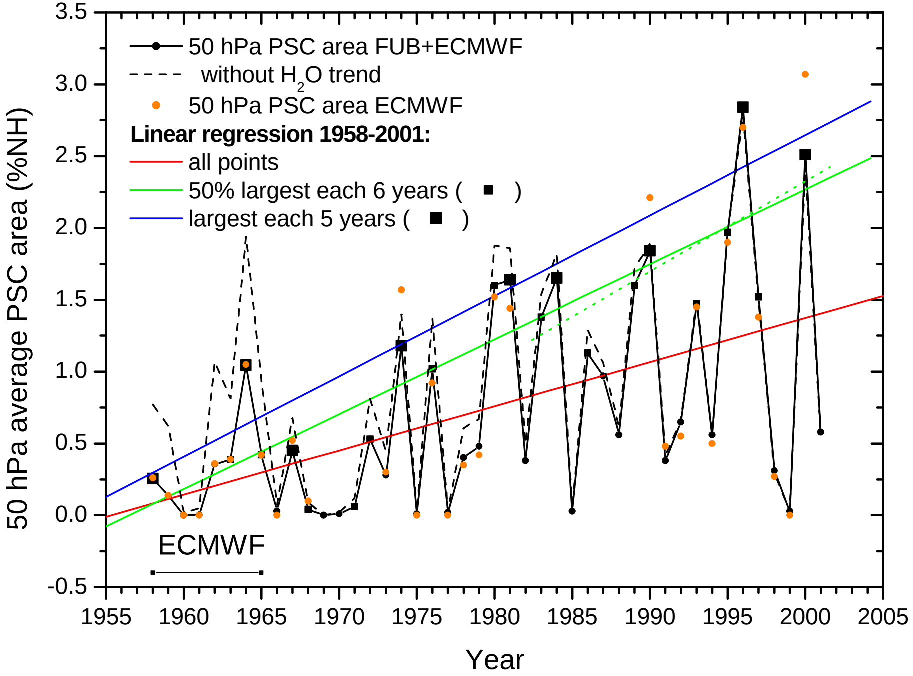

Fig. 1. Mid December to end of March mean NH 50 hPa PSC areas based on FUB and ECMWF analyses with (solid) and without (dashed) incorporation of the observed H_2O trend. Linear regression lines using all points (red), the 50% largest PSC areas in 6-year intervals (green) for 1958–2001 (solid) and 1984–2001 (dotted), and using the largest PSC areas in 5-year intervals (blue) are shown.

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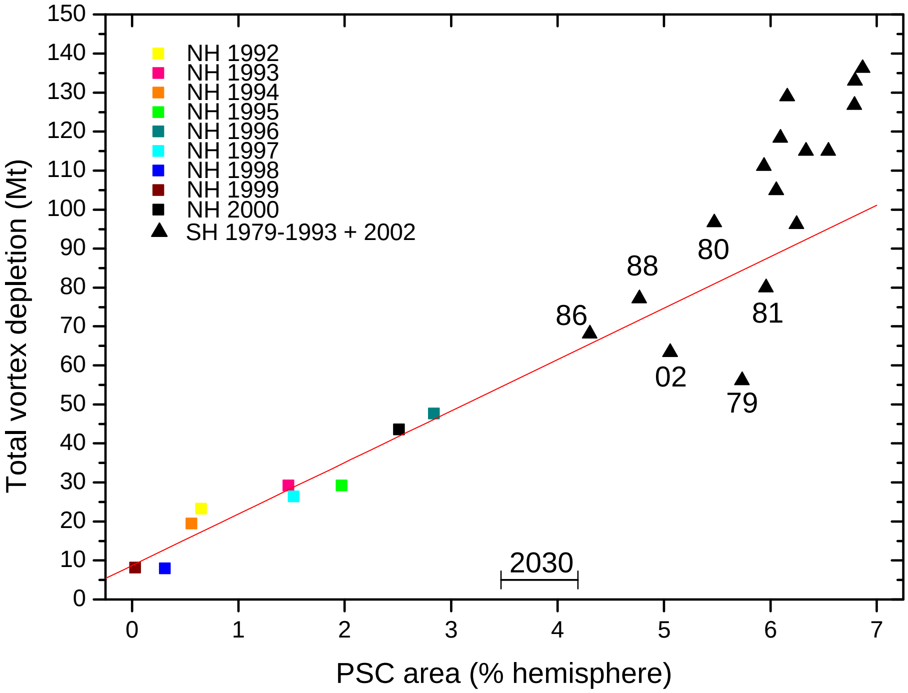

Fig. 2. Total NH vortex ozone depletions 1992–2000 as a function of average PSC areas (squares) and the corresponding regression line (red). SH results are shown with triangles and the year is given for the warmest winters.

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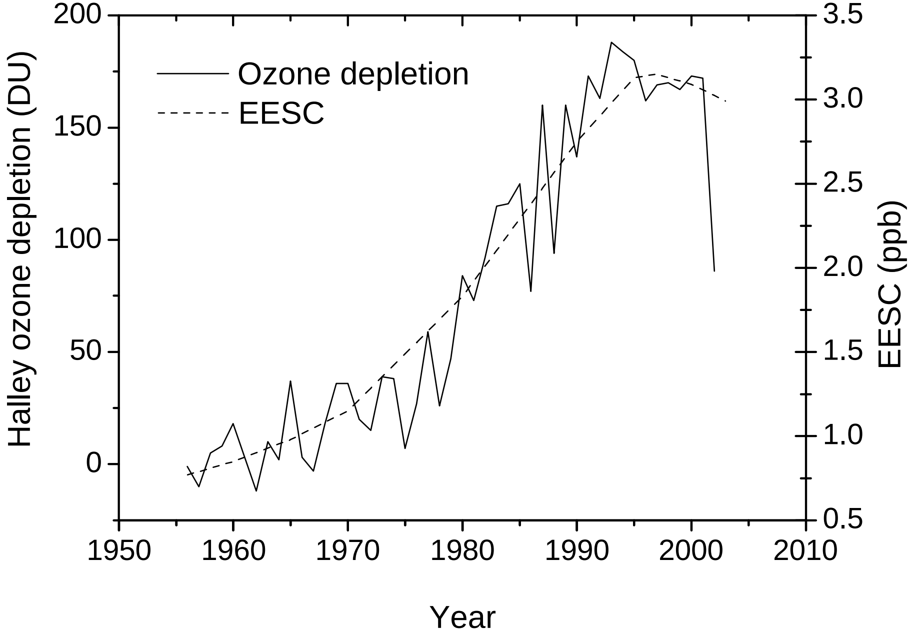

Fig. 3. Development of the column ozone depletion inferred from Halley data and the EESC.

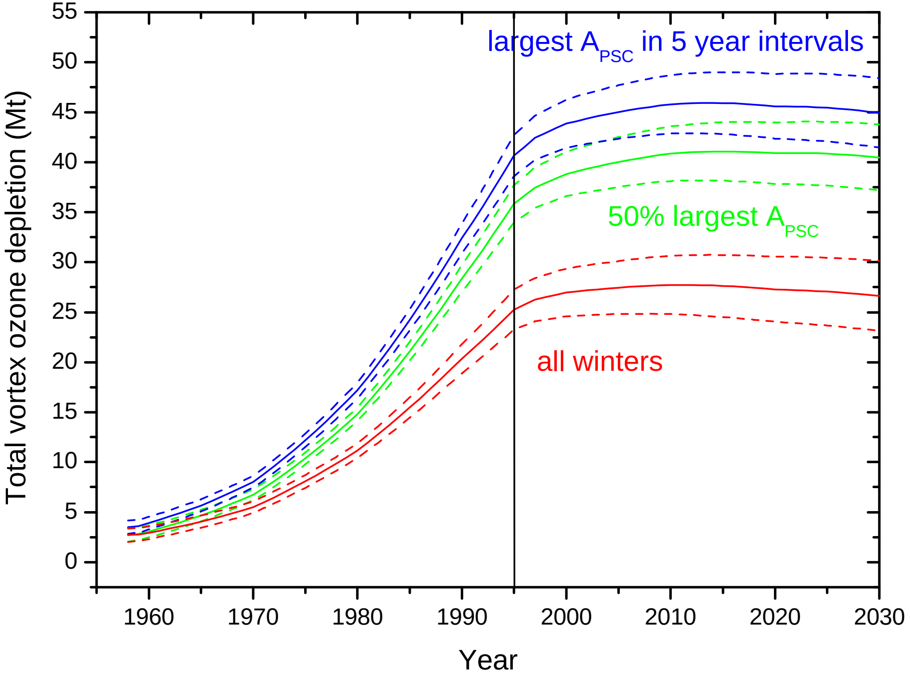

Fig. 4. Future predictions of the ozone depletion using PSC trends for all winters (red), the 50% largest PSC areas in 6-year intervals (green), and using the largest PSC areas in 5-year intervals (blue). 68% confidence limits of the PSC extrapolations are shown with the dashed lines.

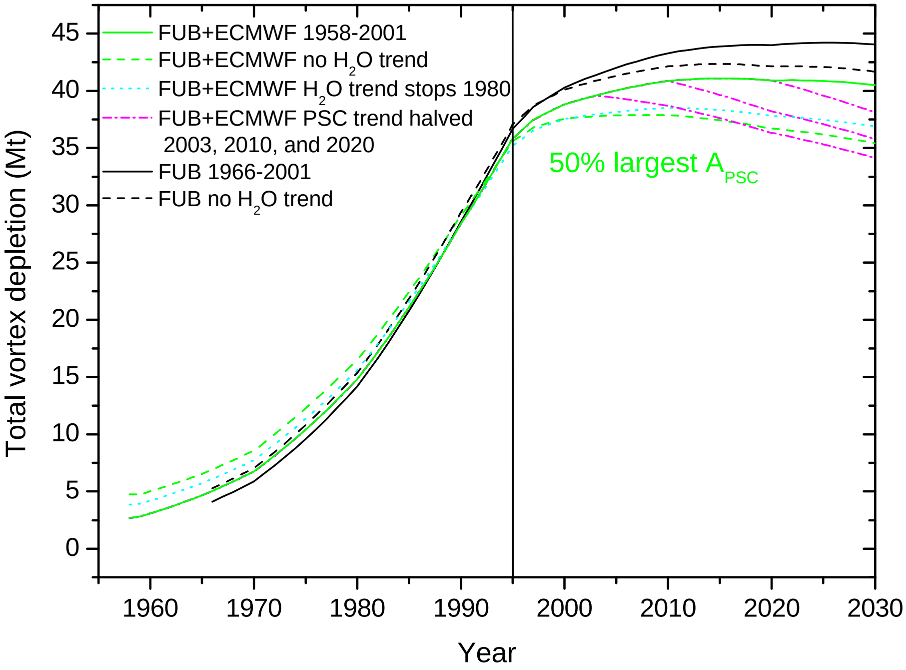

Fig. 5. Sensitivity study of the predicted ozone depletion. The depletions based on the largest 50% of FUB+ECMWF 1958–2001 PSC areas with (green solid line) and without the H_2O trend (green dashed line), if the H_2O trend stops 1980 (cyan dotted line) and if the PSC trend is halved 2003, 2010, or 2020 (magenta dash-dotted line) are shown. In black are shown the depletions based on FUB 1966–2001 trends with (solid) and without the H_2O trend (dotted).

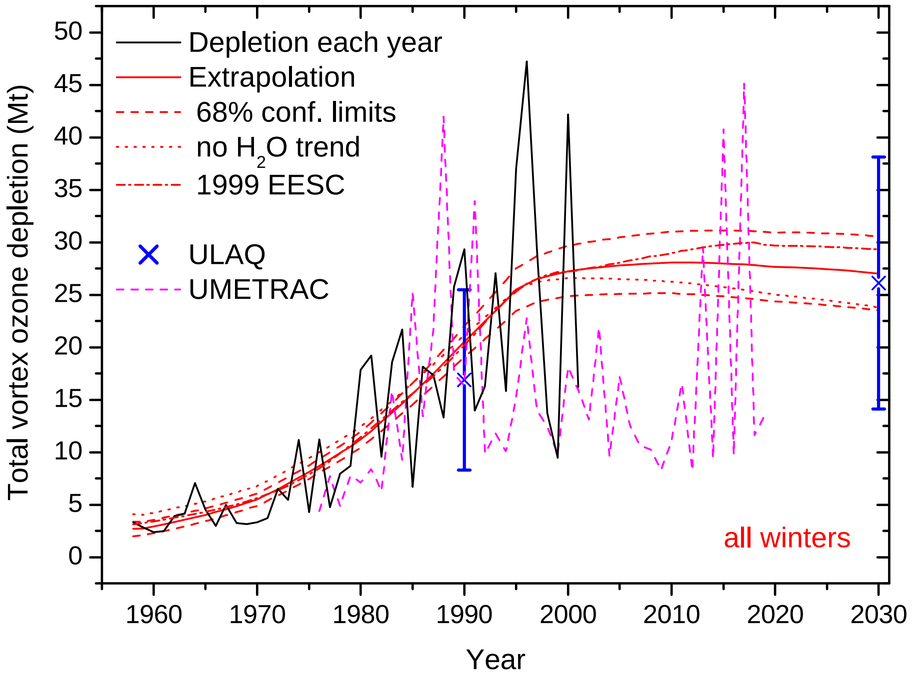

Fig. 6. Shows the future predictions using the extrapolations of PSC areas for all winters (red solid line) with 68% confidence limits (red dashed lines). Also calculations without using the H_2O trend in the PSC threshold temperatures (red dotted line) and using an old halogen scenario (WMO, 1999)(red dash-dotted line) are shown (red dotted line). The modelled depletions in individual years based on the PSC areas are also shown (solid black line). Ozone losses using PSC areas from the UMETRAC transient run (dashed magenta line) and the ULAC time slice runs (blue crosses) are also shown.