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North Atlantic Oscillation modulates Total Ozone Winter Trends

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Abstract. The North Atlantic Oscillation (NAO) is modulating the Earth's ozone shield such that the calculated anthropogenic total ozone decrease is enhanced over Europe whereas over the North Atlantic region it is reduced (for the last 30 years). Including the NAO in a statistical model suggests a more uniform chemical winter trend compared to the strong longitudinal variation reported earlier. At Arosa (Switzerland) the trend is reduced to −2.4% per decade compared to −3.2% and at Reykjavik (Iceland) it is enhanced to −3.8% compared to 0%. The revised trend is slightly below the predictions by 2D chemical models. Decadal ozone variability is linked to variations in the dynamical structure of the atmosphere, as reflected in the tropopause pressure. The latter varies in concert with the NAO index with a distinct geographical pattern.

Introduction

The thickness of the Earth's ozone shield significantly decreased over the last three decades not only over polar regions but also over mid-latitudes [*Harris et al.*, 1997; *Stolarski et al.*, 1992]. The observed decrease in total ozone is qualitatively consistent with the expected effect of the increase in anthropogenically released chemicals, that are known to destroy ozone. It is also roughly consistent with the calculated trend from two-dimensional photochemical models, that predict negative ozone trends with increasing latitudes. However in certain periods the observed amplitude in Europe was considerably larger than the one expected [*Jackman et al.*, 1996]. In addition large longitudinal variations were observed. In general European ground-based measurements showed evidence of strongly negative trends (e. g. as much as −6% for certain periods), whereas measurements over the Atlantic region at Reykjavik (Iceland), although at higher latitude, showed negligible or even increasing trends.

Combined vertical ozone profiles [*SPARC*, 1998] at mid-latitude show a relative trend maximum at ≈ 40 km, in the region where chemistry is expected to play a dominant role, and another one at ≈ 15 km, in the lower stratosphere. In the latter region the photochemical life-time of ozone is long compared to the dynamical life-time. Thus, possible changes in the atmosphere's dynamics for example by natural or anthropogenic influence might substantially alter the observed trend magnitude [*Steinbrecht et al.*, 1998; *Peters and Entzian*, 1996; *Hood and Zaff*, 1995].

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Total ozone and tropopause pressure

Over mid-latitudes strong variability in total ozone occurs with the passage of low and high pressure systems. Due to the dynamical constraints on the large- scale flow, a surface low/high pressure system is associated with a distinct structure in the upper-troposphere lower-stratosphere. As shown in Figure 1 this includes an enhanced/reduced potential vorticity anomaly, a warm/cold potential temperature anomaly and a tropopause pressure higher/lower than normal [*Hoskins et al.*, 1985]. Similar to the surface pressure the tropopause pressure is an integral measure of the flow changes. Within a positive/negative potential vorticity anomaly vertical vortex tubes are stretched/shrinked and hence due to mass conservation the total mass (and similar total ozone mass) above a unit square is increased/reduced as reflected in an enhanced/reduced tropopause pressure (compare the tubes in figure 1). Hence from dynamical constrains one expects a simple linear relation between variability in tropopause pressure and total mass of ozone in the lower stratosphere (which contributes substantially to the total ozone value). A correlation between total ozone and tropopause variability has been documented for example by [*Schubert and Munteanu*, 1988; *Steinbrecht et al.*, 1998; *Vaughan and Price*, 1991], the one between total ozone and other lower-stratospheric upper-tropospheric atmospheric parameters e. g. by [*Ziemke et al.*, 1997].

This relation also holds for multi-annual or decadal variability in total ozone as shown in Figure 2 A, where winter mean total ozone measured over Arosa (46.78N, 9.68E), Switzerland [*Staehelin et al.*, 1998a] and the corresponding tropopause pressure calculated from the NCEP reanalysis data [*Kalnay et al.*, 1996] are shown. About half of the total variance (53%) can be explained with a simple linear relation (Table 1). Figure 2 B shows the same analysis for tropopause pressure and total ozone measured over Reykjavik (64.13N, 21.9W), Iceland. Since at Reykjavik sun photometric measurements are sparse during the December January period the winter mean was restricted to a February-March (FM) mean. In addition only 25 of 41 possible winters had more then 15 measurements per month and were used to calculate the FM mean values. At Reykjavik even a higher amount (67%) of the total variability can be explained with a linear relationship between total ozone and tropopause pressure.

Total ozone and NAO

On multi-annual time scales European winter climate is strongly linked with the North-Atlantic Oscillation which is

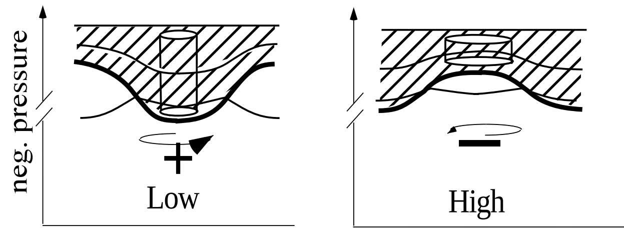

Figure 1. Stretching/shrinking of a tube of air in the lower stratosphere associated with a surface low/high pressure system [*Hoskins et al.*, 1985]. Stratospheric air (high potential vorticity) is hatched, the tropopause is given as a thick line, potential temperature surfaces as thin lines and ± indicate sense of vorticity.

typically measured with an index representing the strength of the meridional surface pressure difference across the North-Atlantic e. g. between Ponta Delgada (Azores) and Stykkisholmur (Iceland) [*Hurrell*, 1995]. NAO-like variability occurs in a large number of atmospheric and oceanic key climate variables [*Wallace and Gutzler*, 1981; *Hurrell*, 1995] and others and encompasses the entire troposphere-stratosphere system [*Perlwitz and Graf*, 1995; *Thompson et al.*, 1998]. Figure 4 shows results of a correlation analysis between winter mean NAO index and winter mean tropopause pressure over the North Atlantic European region. Both the tropopause data and the NAO index for the period 1958 to 1998 were calculated from NCEP reanalysis data [*Kalnay et al.*, 1996]. The correlation pattern shows a clear tri-pole pattern. During positive NAO phases tropopause pressure is higher at high latitudes and lower at mid-latitudes, as would be expected from an enhanced Icelandic low and Azores high pressure system. The sub-tropical band with positive correlation is not directly associated with a surface feature. It is shifted towards the end of the Atlantic storm-track region and coincides with the location where stratospheric streamers and cut-off lows are frequently observed, e. g. [*Appenzeller et al.*, 1996].

Since tropopause pressure variations are proportional to total ozone variations one expects a similar space dependent correlation between NAO and total ozone. Figure 3 shows that during positive NAO phases winter mean total ozone is reduced at Arosa whereas over Iceland (Figure 2 C) total ozone values are enhanced as expected from Figure 3. At both stations a linear relation explains roughly one third of the total variance (Table 1). This result is also stable when the Arosa winter mean time series (1932 to 1998) is split into two equal parts, with the first part not disturbed by any trend or possible anthropogenic influence.

From the 60's to the early 90's the NAO index showed a continuing increase towards positive values with the exception of the winter 1996. This positive bias over the last 30 years had a direct impact on a large number of climate variables e. g. [*Hurrell*, 1996; *Thompson et al.*, 1999]. Since total ozone is varying in concert with the NAO index one might speculate that a similar bias occurred in the observed total ozone trends. This hypothesis can be supported using a linear statistical trend model with the NAO index as additional explanatory variable.

Total ozone trend model

An earlier trend analysis for the winter mean total ozone measurements at Arosa [*Staehelin et al.*, 1998b] showed that

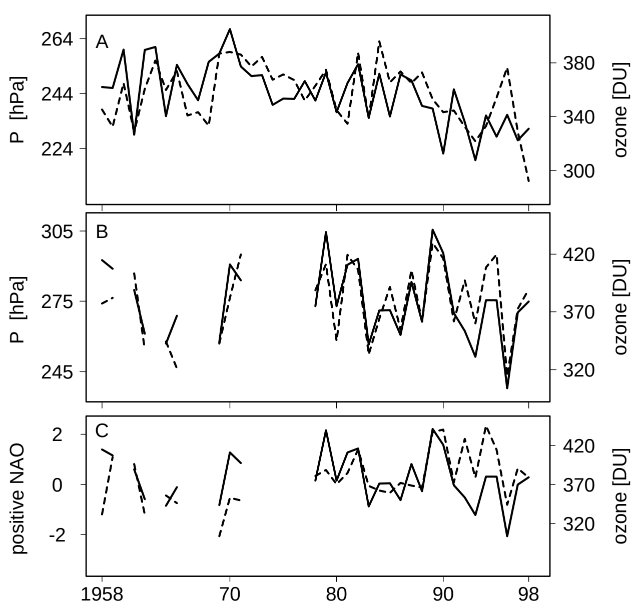

Figure 2. Panel A: February-March (FM) mean total ozone (solid line, in Dobson units) and tropopause pressure derived from NCEP reanalysis data (dashed line, in hPa) for the period 1958 to 1998, over Arosa, Switzerland. Panel B: As Panel A, but for Reykjavik, Iceland. Panel C: As Panel B but December to March means, and instead tropopause pressure with NAO index (dashed line) based on NCEP reanalysis data.

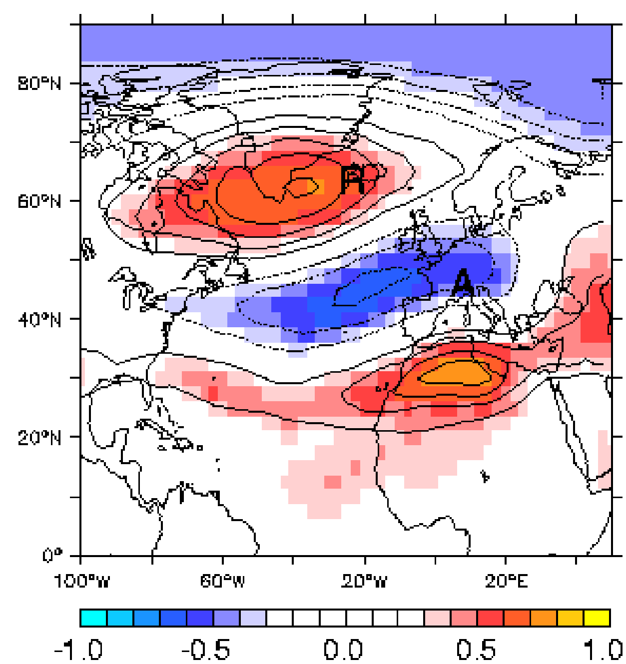

Figure 3. Cross correlation map (in colors) between winter mean (December to March) tropopause pressure and NAO index both derived from NCEP reanalysis data for the period 1958 to 1998. Only correlation coefficients above/below ±0.3 are shown. Contours indicate tropopause pressure variation associated with +1 SD in NAO index. Contour interval is 2 hPa, zero line omitted. (A) location Arosa and (R) location Reykjavik.

Table 1. Total ozone winter trends with and without considering NAO or tropopause pressure (P-tropo)

Ozone model	with(out)	% $Trend_{with}$	% $Trend_{without}$	[DU]/ unit NAO	[DU]/ hPa	R^2_{with}	$R^2_{without}$
Arosa DJFM	NAO	-2.4 ± 0.5	-3.2 ± 0.6	-7.8 ± 1.2		70	47
Arosa FM	NAO	-2.8 ± 0.8	-3.6 ± 0.8	-7.6 ± 2.9		50	39
Reykjavik FM	NAO	-3.8 ± 1.4	not sign.	18 ± 5		39	8
Arosa FM	P-tropo	-3.2 ± 0.8	-3.6 ± 0.8		0.9 ± 0.3	53	39
Reykjavik FM	P-tropo	-2.7 ± 1.0	not sign.		1.1 ± 0.2	67	8

Trend estimates in % per decade, based on a linear regression model (1). DJFM denotes December-March, FM February-March average. Full model is used for Arosa DJFM with data from 1932-1996 for comparison with literature [*Staehelin et al.,* 1998a]. All other models with FM means are calculated from 1958-1998, without SF and AOD as not significant variables for this series. Highly aerosol disturbed data (AOD> 0.02) were excluded. R^2 is total explained variance in %.

the solar radio flux (SF) at 10.7 cm (lagged by 32 months) and a measure for stratospheric aerosol loading (AOD) due to volcanic eruptions [*Sato et al.*, 1993] were statistically significant. The anthropogenically induced chemical ozone destruction was quantified using an artificial ramp (R) starting in January 1970. However, the error term (ε) was autocorrelated indicating that major influences were not accounted for. To be consistent with the earlier analysis a revised linear model for total ozone (N) is assumed

$$N = \bar{N} + c_1 NAO + c_2 R + c_3 SF + c_4 AOD + \varepsilon \qquad (1)$$

with the NAO index as additional explanatory variable (or alternatively the tropopause pressure $P - tropo$). $\bar{N}$ denotes the ozone mean.

For Arosa the dynamically corrected anthropogenic winter mean total ozone trend estimated from (1) is (-2.4 ± 0.5)% per decade. This corresponds to a reduction in trend amplitude of a quarter compared to analysis without considering the NAO (-3.2 ± 0.6)% or an other meteorological parameter representing the NAO behavior. The results of the best models found with stepwise linear regression are summarized in Table 1. In addition note the following two points. The inclusion of the NAO index removed the autocorrelation in the error term (ε) and resulted in better statistical model. Second the statistical significance of the lagged SF disappeared for the period when the Quasi Biennial Oscillation (QBO) data were included (available from 1954 onward) as was tested in a separate model run. The QBO accounted for much less variance then the NAO index and did not affect the trend analysis.

The same statistical modeling procedure was used for the Reykjavik total ozone measurements. Due to the sparse December - January ozone data coverage the analysis was again restricted to a February March (FM) average. The NAO index proved to be a significant variable explaining $\approx 30\%$ of the ozone variability. The dynamically corrected FM trend estimate is a negative trend of (-3.8 ± 1.4)% change per decade (compared to no trend without NAO contribution). The trend seems to be higher than the revised FM trend over Arosa (-2.8 ± 0.8)% as expected from 2D chemistry models (see also Table 1).

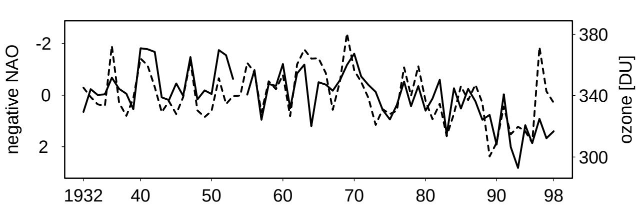

Figure 4. Total ozone (solid line, DJFM mean, in Dobson units) over Arosa and normalized NAO index (dashed line), scaled with -1.0, based on pressure data from Iceland and Azores for the period 1932 to 1996. Compare to Figure 2 Panel C.

Using directly tropopause pressure instead of the NAO index as explanatory variable leads to revised trend estimates that are comparable to the one described above (see Table 1). The tropopause pressure model setup performs even better than the one using the NAO index. This is consistent with the assumption that the changes in the dynamical structure of the atmosphere, as reflected in the tropopause pressure, are an immediate driving force for total ozone fluctuations, whereas the NAO is the climate oscillation associated with the observed multi-annual fluctuations.

Finally, note the following two points. First the apparent inconsistencies in total ozone trends in Western Europe and the North Atlantic are explained when allowance is made for the dynamical variability associated with the NAO. This effect is particularly strong for the TOMS period (1978 to 1994), where the revised trends are now consistent with, though slightly less than, those calculated using a 2D chemistry model [*Jackman et al.*, 1996; *Stolarski et al.*, 1992]. The revised trend for e.g., march ozone at Arosa is -2.2% instead -5%, for Reykjavik -5% instead 0% compared to -3 to -5% for 2D chemical models. Second, it has been suggested that the NAO can be considered as a sub-pattern of a hemispheric Arctic climate oscillation (AO) [*Perlwitz and Graf*, 1995; *Thompson et al.*, 1998]. The AO index is comparable to the NAO index and hence a similar statistical relation between total ozone and AO index is expected [*Thompson et al.*, 1999].

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References

Appenzeller, C., H. C. Davies, and W. A. Norton, Fragmentation of stratospheric intrusions, *J. Geophys. Res., 101,* 1435-1456, 1996.

Harris, N. R. P. et al., Trend in stratospheric and free tropospheric ozone, *J. Geophys. Res., 102,* 1571-1590, 1997.

Hood, L. L., D. A. Zaff, Lower stratospheric stationary waves and the longitude dependence of ozone trends in winter, *J. Geophys. Res., 100*, 25'791-25'800, 1995.

Hoskins, B. J., M. E. McIntyre, and A. W. Robertson, On the use and significance of isentropic potential vorticity maps, Quart. J. Roy. Meteorol. Soc., *111*, 877-946, 1985.

Hurrell, J. W., Decadal trends in the North Atlantic oscillation regional temperatures and precipitation, Science, *269,* 676-679, 1995.

Hurrell, J. W., Influence of variations in extratropical wintertime teleconections on northern hemisphere temperature, *Geophys. Res. Lett., 23,* 665-668, 1996.

Jackman, C. H., E. L. Fleming, S. Chandra, D. B. Considine, and J. E. Rosenfield, Past, present, and future modeled ozone trends with comparisons to observed trends, *J. Geophys. Res., 101,* 28'753-28'767, 1996.

Kalnay, E. et al., The NCEP/NCAR 40 year reanalysis project, *Bull. Am. Meteorol. Soc., 77,* 437-471, 1996.

Perlwitz, J., and H. -F. Graf, The statistical connection between tropospheric and stratospheric circulation of the Northern Hemisphere in winter, Journal of Climate, *8,* 2281-2295, 1995.

Peters, D. and G. Entzian, January ozone anomaly over the North Atlantic-European region: Longitude dependent decadal change in total ozone during 1979-1992, Meteorolog. Zeitschr. NF, *5*, 41-44, 1996.

Sato, M., J .E. Hansen, M. P. McCormick, and J. B. Pollak, Stratospheric aerosol optical depth, 1850 - 1990, *J. Geophys. Res., 98,* 22'987-22'994, 1993.

Schubert, S. D., and M. -J. Munteanu, An Analysis of Tropopause Pressure and Total Ozone Correlations, Monthly Weather Review, 116, 569-582, 1988.

SPARC, Assessment of Trends in the vertical distribution of ozone, in WMO Ozone Research and Monitoring Project Report Nr. 43, edited by N. Harris, R. Hudson, and C. Phillips, pp.289, World Climate Research Progr., 1998.

Staehelin, J., A. Renaud, J. Bader, R. McPeters, P. Viatte, B. Hoegger, V. Bugnion, M. Giroud, and H. Schill, Total ozone series at Arosa (CH): Homogenization and data comparison, *J. Geophys. Res., 103,* 5827-5841, 1998a.

Staehelin, J., R. Kegel, and N. R. P. Harris, Trend analysis of homogenized total ozone series of Arosa (CH), 1926-1996, *J. Geophys. Res., 103,* 8389-8399, 1998b.

Steinbrecht, W., H. Claude, U. Köhler, and K. P. Hoinka, Correlation between tropopause height and total ozone: Implications for long-term trends, *J. Geophys. Res., 103,* 19'183-19'192, 1998.

Stolarski, R., R. Bojkov, L. Bishop, C. Zerefos, J. Staehelin, and J. Zawodny, Measured trends in stratospheric ozone, Science, *256,* 342-349, 1992.

Thompson, D. W. J., and J. M. Wallace, The Arctic Oscillation signature in the winter time geopotential height and temperature fields, *Geophys. Res. Lett., 25,* (9) 1297-1300, 1998.

Thompson, D. W. J., J. M. Wallace, and G. C. Hegerl, Annual modes in the extratropical circulation, Part II: Trends, Journal of Climate, submitted, 1999.

Vaughan, G., and J. D. Price, On the relation between total ozone and meteorology, Quarterly Journal of the Royal Meteorological Society, *117,* 1281-1298, 1991.

Wallace, J. M., and D. S. Gutzler, Teleconnections in the geopotential height field during the Northern Hemisphere winter, Monthly Weather Review,*109*, 784-812, 1981.

Ziemke, J. R., S. Chandra, R. D. McPeters, and P. A. Newman, Dynamical proxies of column ozone with applications to global trend models, *J. Geophys. Res., 102,* (D5) 6117-6129, 1997.

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