Variability of total ozone at Arosa, Switzerland, since 1931 related to atmospheric circulation indices

S. Brönnimann, J. Luterbacher, C. Schmutz, H. Wanner
Institute of Geography, University of Bern, Switzerland

J. Staehelin
Institute for Atmospheric Science, Swiss Federal Institute of Technology, Zurich, Switzerland

Abstract. Atmospheric circulation determines to a considerable extent the variability of lower stratospheric ozone and can modulate its long-term trends in Europe and the North Atlantic Region. Due to dynamical stratosphere-troposphere coupling, important features of the variability of the surface pressure field are reflected in the long-term total ozone record from Arosa, Switzerland. Significant (p<0.01) correlations between total ozone and different atmospheric circulation indices (NAOI, AOI, EU1, EU2) are found in all months except for April, June, July, and November for the period 1931 to 1997. An analysis of geopotential heights for the period 1958 to 1997 shows that these circulation anomaly patterns have upper tropospheric features over the North Atlantic-European sector that are consistent with a dynamical influence on total ozone.

Data and methods

NAO and AO represent the most prominent anomaly circulation patterns in the Northern Hemisphere [Hurrell, 1995; Thompson and Wallace, 1998] and also influence European climate. The so-called East Atlantic/West Russia pattern referred to as the Eurasia-2 pattern (EU2) [Barnston and Livezey, 1987] and an European continental scale circulation index (EU1) [Luterbacher et al., 1999] represent the meridional circulation over western Eurasia and central Europe, respectively. The NAOI, according to Hurrell [1995], was recalculated using station data from Ponta Delgada and Reykjavik. The AOI is defined as the score of the leading empirical orthogonal function (EOF) of Northern Hemisphere SLP anomalies poleward of 20° N, weighted by area [Thompson and Wallace, 1998]. We used two EU indices which are defined as the standardized SLP difference between the average of four grid points (5° × 5°) over Great Britain minus four points northwest of the Black Sea (EU1) and close to the Caspian Sea (EU2), respectively [Luterbacher et al., 1999]. The indices from 1931 to 1947 were calculated with gridded monthly mean SLP data from the National Center for Atmospheric Research (NCAR) [Trenberth and Paolino, 1980] and from 1948 to 1997 with the more homogeneous NCEP/NCAR reanalysis SLP data [Kalnay et al., 1996], interpolated on a 5° × 5° grid. The standardization period of the indices was 1901 to 1980 for NCAR and 1951 to 1990 for NCEP data. Values of EU1 calculated using each of these two data sources for the 1948 to 1995 period are correlated with one another at R=0.97. For EU2, the correlation is R=0.98. All indices are available from August 1931 to December 1997 (AOI until April 1997). Monthly mean homogenized total ozone values measured at Arosa from August 1931 to 1997 were taken from Staehelin et al. [1998a].

Dynamical interpretation is based on monthly GP fields on a 2.5° × 2.5° grid from 1958 to 1997 from the NCEP reanalysis data set. In addition to monthly analysis, a winter (November to April) and a summer season (May to October) were defined for analysis of month-to-month (using monthly anomalies) and interannual (seasonal averages) variability. To address the dynamical contribution to total ozone variations we correlated Arosa total ozone with different upper level meteorological variables for the gridpoint closest to Arosa for the period 1958 to 1997. Then we investigated...
Plate 1. Correlation coefficients between GP and A300, NAOI, and AOI for winter and A300, EU1, and EU2 for summer monthly anomalies. Note that the signs for EU1 and EU2 are inverted. Left, middle and right figures represent 300 hPa GP, a zonal (longitude-height) cross-section at 47.5° N, and a meridional (latitude-height) cross-section at 10° E, respectively. “A” marks the location of Arosa. The 99% significance level is around ±0.17.
how the latter are connected to the atmospheric circulation and established a relation between anomalies of total ozone at Arosa and atmospheric circulation indices for the longer period from 1931 to 1997.

Results and Discussion

Table 1 shows the correlations between monthly anomalies of total ozone at Arosa and different upper level meteorological variables at the gridpoint 10° E / 47.5° N (80 km NE of Arosa) for summer and winter from 1958 to 1997. The correlations with GP are similar between 500 and 200 hPa, strongest at 300 hPa in both seasons. Correlations with temperature in the upper troposphere are somewhat weaker than with GP, but are reasonably high also at 30 hPa, in agreement with Petzoldt [1999]. Moreover, total ozone is strongly related to thickness [Wege and Claude, 1997]. For the interannual variability in winter, the relations are similar as for the month-to-month variability. In summer, the interannual variability of total ozone is strongly related to the lower stratospheric variables, while tropospheric variables are somewhat less important compared to the month-to-month variability. Nevertheless, highly significant correlations between upper tropospheric variables and total ozone are found for both seasons and both variability time scales.

The 300 hPa GP close to Arosa, hereafter denoted as A300, is suggested as a proxy for the dynamically induced total ozone variability.

To study the relation between A300 and the atmospheric circulation over the North Atlantic-European sector we correlated A300, NAOI, and AOI (for winter, month-to-month) and A300, EU1, and EU2 (summer) with GP anomalies from 1958 to 1997. Plate 1 displays the correlations on the 300 hPa level and in zonal and meridional cross-sections. The 300 hPa pattern for A300 in winter shows positive correlations around Arosa and an area of negative correlation over the northern North Atlantic and the near East. It is comparable to the one for AOI, but shows stronger zonal differences in the zonal cross-section. The meridional structure reveals a northward sloping of the correlation field with height. The winter patterns of the 300 hPa GP for AOI and NAOI resemble those published by other authors for tropopause pressure [Thompson and Wallace, 1998; Appenzeller et al., 2000].

Table 1. Correlation coefficients between wintertime and summertime monthly anomalies (Win-M, Sum-M) or seasonal averages (Win-S, Sum-S) of total ozone at Arosa and upper level meteorological variables (Var) at the gridpoint (10° E, 47.5° N) from 1958 to 1997. Anomalies refer to the 1958 to 1997 long-term monthly mean values. Coefficients are given as $p < 0.01$. T = temperature, TH = thickness.

<table>
<thead>
<tr>
<th>Level</th>
<th>Var</th>
<th>Win-M</th>
<th>Sum-M</th>
<th>Win-S</th>
<th>Sum-S</th>
</tr>
</thead>
<tbody>
<tr>
<td>30 hPa</td>
<td>GP</td>
<td>*</td>
<td>0.247</td>
<td>*</td>
<td>0.390</td>
</tr>
<tr>
<td>50 hPa</td>
<td>GP</td>
<td>-0.112</td>
<td>*</td>
<td>0.300</td>
<td></td>
</tr>
<tr>
<td>100 hPa</td>
<td>GP</td>
<td>-0.497</td>
<td>-0.408</td>
<td>-0.559</td>
<td>*</td>
</tr>
<tr>
<td>200 hPa</td>
<td>GP</td>
<td>-0.676</td>
<td>-0.585</td>
<td>-0.774</td>
<td>-0.354</td>
</tr>
<tr>
<td>300 hPa</td>
<td>GP</td>
<td>-0.657</td>
<td>-0.571</td>
<td>-0.809</td>
<td>-0.422</td>
</tr>
<tr>
<td>500 hPa</td>
<td>GP</td>
<td>-0.498</td>
<td>0.444</td>
<td>0.624</td>
<td>0.280</td>
</tr>
<tr>
<td>30 hPa</td>
<td>T</td>
<td>-0.529</td>
<td>-0.486</td>
<td>-0.523</td>
<td>*</td>
</tr>
<tr>
<td>30/100 hPa</td>
<td>TH</td>
<td>0.616</td>
<td>0.546</td>
<td>0.739</td>
<td>0.694</td>
</tr>
<tr>
<td>300/850 hPa</td>
<td>TH</td>
<td>-0.657</td>
<td>-0.598</td>
<td>-0.754</td>
<td>-0.342</td>
</tr>
</tbody>
</table>

The pattern for AO shows a strong meridional structure at all heights. It can be considered as the surface signature of the polar vortex [Thompson and Wallace, 1998]. The summer 300 hPa pattern for A300 is similar to the one for winter, but the anticorrelation with the North Atlantic area is weaker. Zonal differences in the circulation field, which are also present in the A300 pattern, are captured by EU1 and EU2. For both patterns the upper level structure is displaced northwestward with respect to the surface pressure anomalies.

From the findings above it is expected that total ozone over the North Atlantic-Eurasian sector is related to atmospheric circulation indices in all seasons. Table 2 gives the correlation coefficients between total ozone at Arosa and the atmospheric circulation indices from 1931 to 1997. The NAOI shows strongest correlations with total ozone in February and March. This relation can be explained by a displacement of the tropopause [Appenzeller et al., 2000]. The AO displays a more consistent winter pattern with high correlations from December through March. A positive AOI represents a strong vortex, which is accompanied by a high tropopause at Northern midlatitudes [Thompson et al., 2000]. Significant correlations between EU1 and total ozone are found in late summer and autumn and are almost as strong as those for the winter indices (NAOI and AOI). The correlation is weaker for EU2, in agreement with the location of Arosa with respect to the patterns shown in Plate 1. Apart from the vertical motion associated with trough/ridge patterns, horizontal advection in the presence of a meridional ozone gradient could also contribute to the total ozone - EU1 relation [Hood et al., 1997; Greisiger et al., 1998]. On the interannual scale, the variability in winter is similar as for the month-to-month scale but somewhat less so in summer. Still, the correlation between EU1 and total ozone for summer seasonal averages is highly significant.

Conclusions

Our results reveal a strong relation between total ozone at Arosa and important atmospheric circulation indices. The
zonal NAO and AO patterns dominate the relation in winter, while EU1 and EU2 are more important in summer. Between 12% and 35% of the total ozone variance is shared by the strength of one dominating large-scale SLP anomaly pattern in all months except for April, June, July, and November. This is roughly half as is obtained with the best local predictor in the upper troposphere/lower stratosphere directly above Arosa (Table 1). Moreover, other influences are known to play a role (CFCs, aerosols, solar cycle, QBO). Total ozone is expected to bear similar signatures of the interannual to interdecadal circulation variability as the indices. Positive trends of the NAOI and AOI in the last decades suggest that circulation changes most probably have contributed to the observed winter trend of total ozone [Appenzeller et al., 2000; Thompson et al., 2000]. EU1 and EU2 have only small trends since about 1970. Furthermore, total ozone trends in summer are much smaller than in winter [Staehelin et al., 1998b].

The close relation between total ozone time series and the atmospheric circulation at different height levels suggests that it might serve, together with meteorological time series, as an important predictor for reconstructing GP fields over the North Atlantic-European sector beyond the period of currently available data.

Acknowledgments. We wish to thank David Thompson for providing AOI data. Nicolas Schneider and Dimitrios Gyalistras developed some of the computer programs. NCEP Reanalysis data were provided by the NOAA-CIRES Climate Diagnostics Center, Boulder, Colorado. The Climate Research Unit, Norwich, U. K., provided the station data from Ponta Delgada and Reykjavik.

References


S. Brönnimann, J. Luterbacher, C. Schmutz, H. Wanner, Institute of Geography, University of Bern, Hallerstr. 12, CH-3012 Bern, Switzerland, e-mail: broen@giub.unibe.ch. J. Staehelin, Institute for Atmospheric Science, Swiss Federal Institute of Technology (ETH), Hönggerberg, CH-8093 Zurich, Switzerland.

(received September 9, 1999; revised November 24, 1999; accepted April 4, 2000.)

This preprint was prepared with AGU’s LATEX macros v4, with the extension package ‘AGU++’ by P. W. Daly, version from .