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The North Atlantic Oscillation and the occurrences of ozone miniholes

Yvan J. Orsolini

Norwegian Institute for Air Research (NILU), Kjeller, Norway

Varavut Limpasuvan

Dept. of Chemistry and Physics, Coastal Carolina University, USA

Abstract. The North Atlantic Oscillation (NAO) induces a clear signature on synoptic-scale ozone fluctuations over the Euro-Atlantic sector, as revealed by a band-pass filtering analysis of the Total Ozone Mapping Spectrometer (TOMS) satellite observations over a 20-year period. Low-ozone episodes, or miniholes, appear more frequent over the Euro-Atlantic sector in the high NAO phase, when the prevailing, upper tropospheric westerly jet is displaced poleward and acquires a stronger northward tilt relative to climatology. Thus, the tendency of the NAO to remain in its high phase in late eighties and nineties accounts for recent observations of more frequent minihole conditions and episodes of low-latitude, ozone-poor intrusions into high-latitude region of this sector.

1. Introduction

Very low total column ozone values were observed in late November and early December of 1999 over a large sector of the eastern North Atlantic and northern Europe. Over Oslo and in southern Scandinavia, satellite and ground-based observations recorded readings in the range of 160-180 Dobson Units (DU). Such concentration was the record low for the entire 1999-2000 winter-spring period despite the occurence of pronounced and widespread ozone depletion over the northern high latitudes later that Spring [Sinnhuber et al., 2000]. In fact, the low values briefly observed near December 1, 1999 in southern Scandinavia were some of the lowest readings ever recorded in the Northern Hemisphere (NH) during the cold season.

Although short-lived episodes of ozone thinning occur in the extratropics of both hemispheres during the Winter, particularly strong (and even extreme) events tend to occur over the North Atlantic. These low-ozone episodes have been termed "miniholes" [Newman et al., 1988; Mckenna et al., 1989; James, 1998; Orsolini et al., 1998; Vigliarolo et al., 2001]. They are of particular interest as the associated low total column ozone amount and anticyclonic conditions imply enhanced penetration of UV radiation toward the ground.

The connection between column ozone fluctuations on a time scale of a few days and synoptic weather systems is well established. The column ozone basically varies in response to vertical and meridional motions near the tropopause and in the lower stratosphere. While tropopause undulation can readily induce column ozone fluctations, meridional advection contributes strongly toward the ozone decrease during the observed, strong minihole events through poleward injection of ozone-poor, low-latitude air [Orsolini et al., 1995; Hood et al., 1999]. Preferred regions of ozone variability on synoptic time scales (2-10 days) lie in the storm track regions as demonstrated by Orsolini et al. [1998]. They band-pass filtered satellite observations of column ozone over the NH using a 10-year data set from the TOMS instrument. They further showed that variability over the Atlantic storm track is climatologically stronger than over the Pacific storm track, and that the enhanced variability is governed by the occurrence of low-ozone episodes, or miniholes.

What factors govern interannual, or month-to-month variability in the occurrence of ozone miniholes over the Atlantic and Europe? We hypothesize that the North Atlantic Oscillation (NAO) plays a significant role in controling the tendencies or low frequency changes of the ozone miniholes. The NAO is the leading mode of the year-to-year and month-to-month wintertime variability in the Euro-Atlantic sector. While often characterised in terms of meridional sea-level pressure (SLP) gradient across the Atlantic, the NAO affects the troposphere as a whole, and influences many meteorological parameters, such as surface temperature or precipitation over Europe. The NAO phenomenon embodies the changes in the direction and intensity of the dominant westerly tropospheric jet stream over the Atlantic. In particular, Lau [1988] showed that the NAO is the main governor of storm track interannual variability over the Atlantic throughout the cold season. Because these low-ozone episodes are intimately linked to the transient eddy activity in the troposphere, such a principal mode of variability of the tropospheric circulation should play an important role in the minihole variability.

That study motivated our investigation of the NAO influence on ozone synoptic variability, despite the limited record (20 years) of global satellite ozone observations. A recent study by Appenzeller et al. [2000] investigated the signature of the NAO on local column ozone at Arosa (Switzerland), using a long time series extending back to the 1930's. Our study differs from the above-mentioned study in that we investigated ozone transients over the globe, rather than local winter-mean ozone and its decadal trend. We show that ozone miniholes tend to be frequent when the NAO is in its high phase. During such phase, the jet tilts poleward across the North Atlantic toward Scandinavia, and is more intense than in the low phase, when a more zonally oriented jet is found further equatorward, over the Mediterranean region.

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2. Description of the data

The climatological signature of the storm tracks on ozone is diagnosed by band-pass filtering the daily ozone measured by TOMS for each month for the November-to-April period (extended wintertime). The monthly variability is characterized in terms of the mean absolute deviation (M.A.D.) of the local time series band-passed for periods between 2 and 10 days [Orsolini et al., 1998]. The 20-year period of observations by TOMS Nimbus 7 (1979-93), Meteor (1993-94) and Earth-Probe (1996-2000) was segmented in monthly datasets as in Lau [1988]. The ensemble of 120 monthly sets is then large enough to be amenable to a statistical analysis. Short sequences of missing data occurred on several occasions, in January-February 1994, and December 1998 and 1999. The filtered ozone time series vanish during these missing days.

The NAO index was made available electronically by the Climate Unit of the University of East Anglia (UK). Normalised, monthly-mean sea level pressure differences between Gibraltar and Iceland, were used in the calculation of the NAO index. In addition, the daily-averaged SLP data from the National Center for the Environmental Protection and National Center for Atmospheric Research (NCEP/NCAR) reanalyses of observation [Kalnay et al., 1996] was employed to compute a daily NAO index (see section 4).

3. Signature of the NAO on ozone tracks

Maps of the band-passed column ozone M.A.D. have been calculated for each month throughout the 20-year observed period. Fig. 1 shows the winter-mean (Nov.-Apr.) climatological M.A.D. over the NH. Two regions of enhanced deviation appear over the storm tracks, peaking over 18 DU. They are referred to as the "ozone tracks" to emphasize their

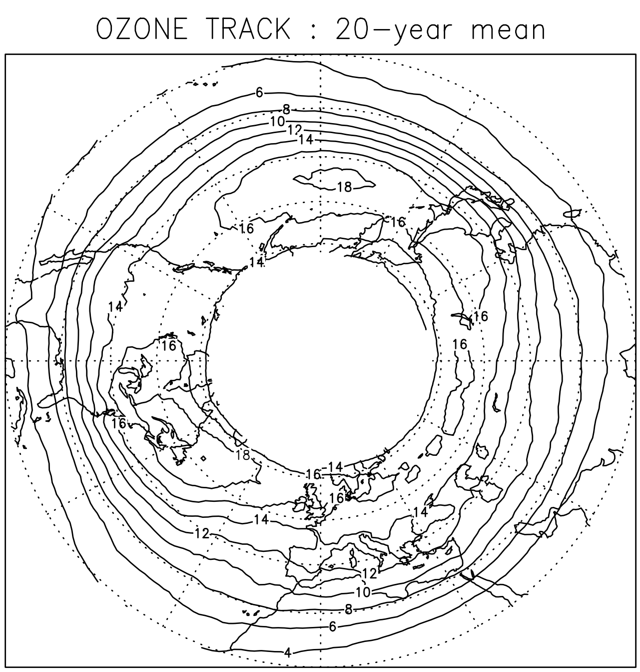

Figure 1. Climatological map of mean absolute deviation, or M.A.D., of the filtered ozone time series for the cold season (Nov-to-Apr) in DU, showing enhanced ozone synoptic variability over the storm tracks, especially over the Atlantic.

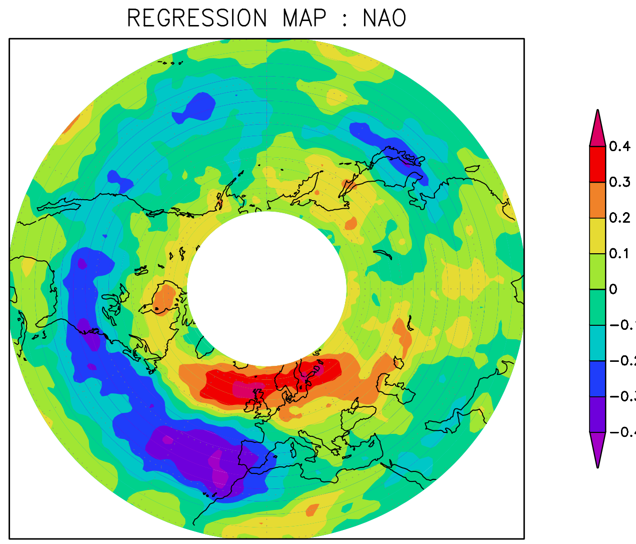

Figure 2. Correlation map of monthly ozone M.A.D. against the monthly NAO index, for the 20 years of TOMS observations in the extended winter (Nov-to-Apr).

close association with the storm tracks [Orsolini et al., 1998]. A stronger and more widespread ozone track is evident over the North Atlantic.

To examine how the Atlantic ozone track varies with the NAO, the monthly column ozone M.A.D. anomalies (i.e. departure from their monthly climatology) were correlated with the NAO monthly index. The correlation map (i.e. the local, normalized correlation coefficient as a function of latitude and longitude) is shown in Fig. 2. The lobe with positive correlation values over the North Atlantic and Europe mirrors the northward shift and tilt of the jet stream in association with the high phase of the NAO [Lau, 1988]. This anomalous jet stream pattern fosters a northwesterly shift of synoptic eddy activity and concomittant ozone fluctuations. In the low NAO phase, the ozone fluctuations are found southward and are directed toward the Mediterranean region; the associated jet stream is more zonal along the 40°N latitude circle.

4. Signature of the NAO on low-ozone episodes

The amplitude of the ozone tracks is heavily influenced by episodes of low column ozone amount [Orsolini et al., 1998] and, as shown above, the Atlantic ozone track is constrained largely by the jet stream position associated with the NAO. In this section, we demonstrate that a similar relationship exists between the episodes of low ozone amount and the NAO.

To facilitate the study, an index measuring the size, or "volume", of the negative ozone fluctuations over the North Atlantic is formulated using the daily band-pass filtered time series. The index is the product of the areal fraction (in percent) of the North Atlantic sector (48°N-60°N and 30°W-60°E) where the band-pass filtered fluctuations are negative, multiplied by the mean (negative) amplitude over that area. This index has units of DU. A uniform fluctuation of -40 DU over half of the North Atlantic sector would have an index of -2000 DU. Daily time series of this index from November to

April and for the 20-year period of TOMS observations are shown in Fig. 3. Months during which the NAO index is positive are underlined (thick line). A large-amplitude negative index would correspond to an ozone minihole event, such as the late November 1999 event (marked by the arrow on Fig. 3). A weakly negative index indicates that no low-ozone episode is occurring in the North Atlantic sector.

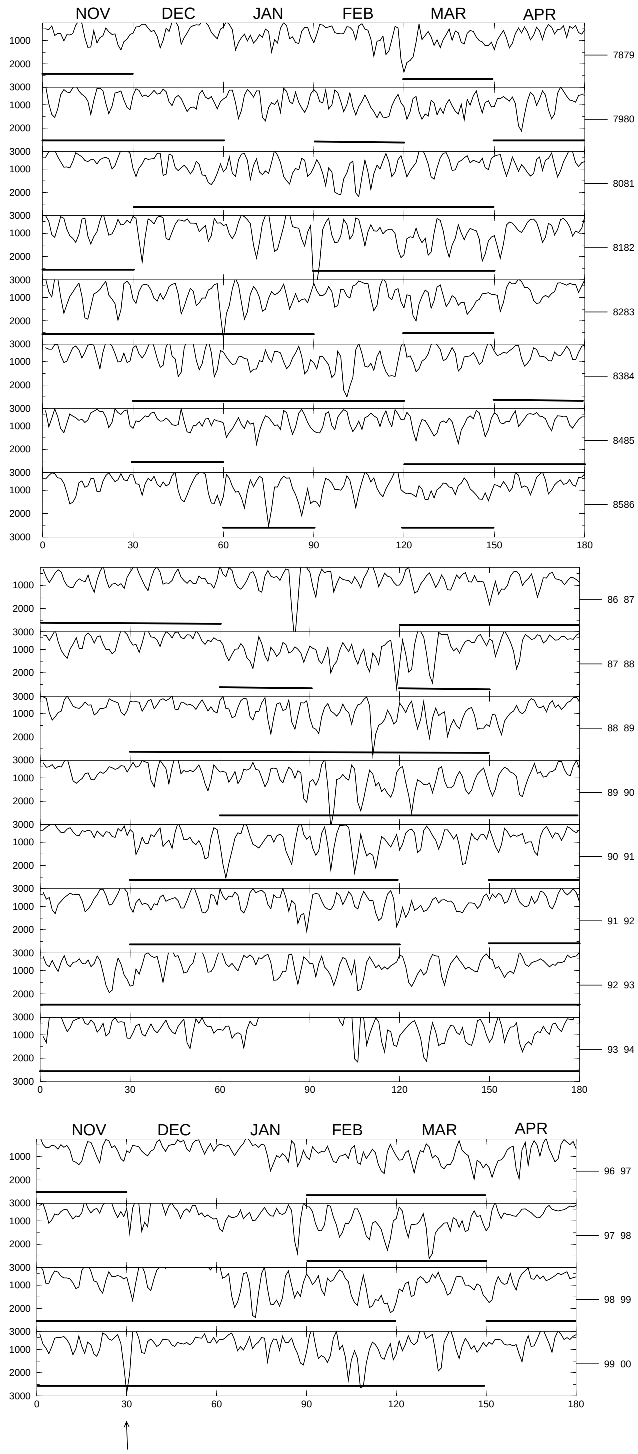

Figure 3. Index of occurrences of the North Atlantic ozone miniholes for 20 extended winters of TOMS observations. Months during which the NAO index is positive are underlined (thick line).

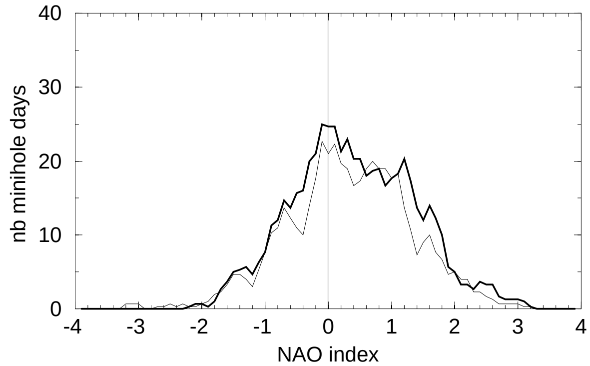

Figure 4. Number of days satisfying a minihole criterion, based on the North Atlantic minihole index, and binned according to the daily NAO index (bold line). The skew of the distribution indicates more minihole days for positive NAO. Similar curve (dashed line) using the band-pass filtered, local TOMS observations over Oslo (Scandinavia).

Visual inspection of Fig. 3 indicates that minihole events tend to occur primarily in the high NAO phase.

This tendency is demonstrated by comparing the daily minihole index with a "daily" NAO index. In order to define such a daily NAO index, we constructed the spatial map of the NAO showing the SLP difference on a hemispheric scale by regressing the monthly SLP anomalies at every grid point with the monthly NAO index. We then projected the resulting map onto the daily NCEP/NCAR reanalyses SLP anomalies map, yielding a daily time series that basically describes how the SLP anomaly maps at each day resemble the NAO pattern. The resulting series was then normalised. Note that the monthly-mean NAO index derived from this daily time series can differ from the more local monthly-mean NAO index derived monthly-mean SLP difference between Gibraltar and Iceland.

We then defined a suitable threshold for defining an ozone minihole. We consider extreme, low-ozone events when the index falls below a threshold value of -1200. Such a choice for the index nicely captures some of the minihole events that have been studied in the literature, for example in late January 1992 [Orsolini et al., 1995], or February 1989 [McCormack and Hood, 1997]. Note that unlike the present study, that uses the band-pass filtered ozone, some authors define a minihole as an event during which column ozone dropped below a given absolute threshold (e.g. 300 DU). We calculated the number of days when the minihole criterion is fullfilled, throughout the extended winters from 1978 to 1998. The results binned according to the NAO index (Fig. 4, bold curve) show a histogram skewed toward positive NAO. Hence, one finds a higher number of minihole days (meaning more frequent minihole conditions) during the positive NAO phase, when the NAO index is greater than +1. A similar histogram was obtained using local, filtered ozone values at the closest grid point to Oslo (Scandinavia), instead of the area-weighted North Atlantic minihole index (Fig. 4, dashed curve). The minihole events were then defined as local, negative fluctuations in excess of -20DU.

5. Summary and Discussion

We have established a relationship between the NAO phase and the occurrence of ozone miniholes over the North

Atlantic during the cold season. Such a statistical relationship holds true from month to month and links the tendency of the observed ozone miniholes to the high phase of the NAO when the storm track and the prevailing westerly jet tilts northward.

Because of the current tendency of the NAO to be preferentially in a high phase (see Fig. 3), this relationship then suggests that observations of more frequent ozone miniholes in recent years is connected the well-known modulation of the tropospheric storm tracks by the NAO. For example, McCormack and Hood [1997] examined minihole events in February over the Atlantic sector (908°E-908°W; 408°N-608°N) in the 15-year record of TOMS Nimbus-7 observations (1978-1993). They found an increasing number of days when minihole conditions were observed in the late eighties and early nineties, especially from 1988 to 1990, and 1993. Recently, Hood et al. [1999] examined the link between monthly-mean ozone trends in February and March in the NH and trends in lower stratospheric circulation. They found that enhancement of the mean anticyclonic shear of the zonal circulation throughout recent years (1979-1998) favoured poleward breaking of Rossby waves. The more frequent transport of low-latitude ozone-poor air to high latitudes hence depressed the monthly-mean ozone. Examining ozonesonde data at several central European locations, Reid et al. [2000] further observed that the number of ozone-poor low-latitude intrusions, diagnosed as minima in the ozone profile, increased in the early nineties.

Recent studies have viewed the NAO to be a local representation of a more global picture of NH winter climate variability referred to as the Arctic Oscillation or the Northern Hemisphere Annular Mode (NAM), whose patterns show strong zonally symmetric component that extends well into the stratosphere [Thompson and Wallace, 1998; Limpasuvan and Hartmann, 1999; 2000]. In particular, the meridional shifting of the storm tracks appears in correspondance with the strenghtening and weakening of the polar vortex during the cold season [Baldwin and Dunkerton, 1999; Limpasuvan and Hartmann, 2000]. The synoptic ozone fluctuations over the Atlantic investigated in this paper, which are mostly influenced by upper troposphere-lower stratosphere dynamics, seem to be adequately described in terms of the regional NAO.

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Yvan J. Orsolini, Norwegian Institute for Air Research (NILU), Kjeller, Norway (e-mail: orsolini@nilu.no)

Varavut Limpasuvan, Dept. of Chemistry and Physics, Coastal Carolina University, Conway, SC, USA (e-mail: var@coastal.edu)

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