Intercontinental transport of tropospheric ozone: A study of its seasonal transport and variability across the North Atlantic utilizing tropospheric ozone residuals

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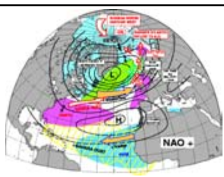
Why is this important?

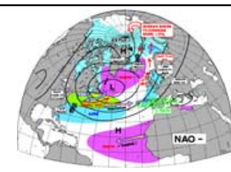
Long-range transport of atmospheric pollution has been identified in numerous aircraft campaigns in recent years. Interpretation of these measurements using global and regional chemical transport models can be a complex task. In this study, we present an analysis that utilizes satellite data to help provide the context in which the integrated result of intercontinental transport and in situ photochemical production is observed. This becomes especially important in terms of a region's ability to meet its ozone standards and the potential impact on human health. Our study also shows that the distribution of tropospheric ozone over the North Atlantic exhibits a degree of interannual variability that is not only linked to prevailing circulation features across the North Atlantic, but also to large-scale modes of climate variability, such as the North Atlantic Oscillation.

North Atlantic Circulation and the North Atlantic Oscillation



Positive Phase of the NAO

In the mid-latitudes, the large-scale circulation over the North Atlantic is primarily governed by three features: 1) the Icelandic low, 2) the Bermuda-Azores high, and 3) the northeasterly trade winds (see figure at left). Generally, there are three mechanisms for the movement of anthropogenic pollution from North America to the North Atlantic: 1) frontal lifting via the warm conveyor belt, 2) convection over continental areas that is lifted to the free troposphere and transported via the westerlies, and 3) direct westerly movement of boundary layer air from eastern North America to the North Atlantic (Carlson, *Mid-Latitude Weather Systems*, 1998). Once the pollution gets transported out over the North Atlantic, the large scale features help determine its fate. Linked with these large scale features is the North Atlantic Oscillation (NAO). In the midlatitudes, the NAO is the leading mode of variability across the North Atlantic. The (Hurrell) NAO index is determined by taking the pressure difference between Portugal and Iceland. During a positive phase of the NAO (left figure), the Azores high and the Icelandic low both become stronger and an enhanced zonal (west to east) flow sets up. This zonal flow coupled with a strong pressure gradient causes air to move quickly across the North Atlantic without much obstruction. During a negative phase (right figure), the Azores high and/or the Icelandic low weaken causing the circulation across the North Atlantic to be altered (i.e., less zonal, more meridional). Studies of the NAO's influence have primarily focused on the winter and spring when the westerlies are faster and its relationship to changes in North American and European climate have been noted. However, the NAO displays considerable monthly and interannual variability and its effects have been witnessed in all seasons. (Figures depicting the positive and negative NAO phases are courtesy of Dr. R. Dickson, CEFAS)



Negative Phase of the NAO

Introduction

The tropospheric ozone residual (TOR) technique utilizes concurrent observations from the Total Ozone Mapping Spectrometer (TOMS) and Solar Backscattered Ultraviolet (SBUV) instruments to generate daily maps of the integrated amount of ozone in the troposphere. In this study, empirically-corrected monthly and seasonal values of the TOR are used to investigate the seasonal and interannual variability of tropospheric ozone from 1979-2000 over the North Atlantic. In addition, its relationship with the North Atlantic Oscillation (NAO) and the Arctic Oscillation (AO) is analyzed to help determine potential transport mechanisms and synoptic conditions favorable for photochemical production.

North Atlantic Study Area

Figure 1. North Atlantic Study Area (8th Oxford Atlas of the World, 2000). The following are the five numbered regions shown in study area above: 1) Wallops Island, VA (USA), 2) Bermuda (UK), 3) Azores (Portugal), 4) Lisbon (Portugal), and 5) Biscarrosse (France).

TOR Distribution over the North Atlantic

The following figure shows the seasonal TOR distributions for the study area shown in Figure 1. Each 1° latitude x 1.25° longitude pixel (TOMS grid) shown in each seasonal climatology represents an average of ~1600 points (~90 days x ~18 years). This density of data points is able to show the seasonal variability of tropospheric ozone across the North Atlantic. Strong seasonality is evident and regional features can be seen that might be linked to in-situ production by or transport into a region.

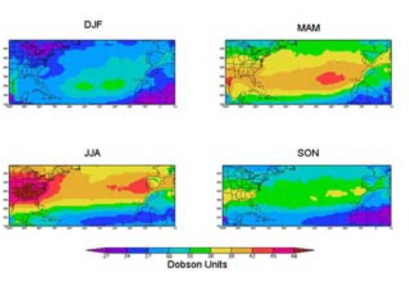


Figure 2. Seasonal depiction of the 1979-2000 TOR climatology over the North Atlantic. The domain of this region is 15°N to 50°N latitude and 100°W to 10°E longitude.

Tropospheric Ozone Residual Data by Region

The following table (Table 1) and figure (Figure 3) show the seasonal TOR values and the monthly TOR variability, respectively, for each region highlighted in Figure 1. The seasonal values for each region shown in the table consist of an areal averaging of the TOR data for each and are defined by 81 TOMS grid points (1° latitude x 1.25° longitude) centered on each named location. Regions were chosen because of their proximity to ozonesonde measurement sites. Figure 4 shows the relationship between the TOR at Wallops Island and the ozonesonde measurements taken at Wallops Island.

December-February

	Wallops	Bermuda	Azores	Lisbon	Biscarrosse
Mean TOR	26.4	27.8	30.8	30.0	28.7
Range-High	30.5 (1979)	30.1 (1979)	34.9 (1989)	33.7 (1990)	31.5 (1992)
Range-Low	22.5 (1999)	25.4 (1987)	28.1 (1999)	26.4 (1980)	26.2 (1982)
R:TOR-NAO	-0.21	0.27	**0.49**	0.38	0.14
R:TOR-AO	-0.17	0.41	**0.51**	**0.59**	**0.46**

March-May

	Wallops	Bermuda	Azores	Lisbon	Biscarrosse
Mean TOR	37.9	39.3	39.0	37.6	33.6
Range-High	41.5 (1998)	42.7 (1991)	42.8 (1999)	42.4 (1991)	38.0 (1990)
Range-Low	34.7 (1983)	36.1 (1985)	36.0 (1979)	34.7 (1980)	28.9 (1980)
R:TOR-NAO	0.20	0.01	0.22	0.30	**0.61**
R:TOR-AO	0.32	0.02	0.18	0.39	**0.71**

Strongest NAO relationship

June-August

	Wallops	Bermuda	Azores	Lisbon	Biscarrosse
Mean TOR	45.1	40.8	41.8	41.7	38.1
Range-High	47.2 (1980)	42.6 (1998)	44.9 (1999)	44.3 (1999)	41.5 (1999)
Range-Low	42.9 (1997)	35.5 (1997)	37.6 (1992)	39.5 (1989)	35.0 (1997)
R:TOR-NAO	-0.08	0.12	-0.09	0.41	0.35
R:TOR-AO	0.21	0.22	0.13	0.18	-0.03

September-November

	Wallops	Bermuda	Azores	Lisbon	Biscarrosse
Mean TOR	33.7	34.3	34.9	34.6	31.0
Range-High	39.0 (1998)	38.5 (1990)	37.8 (1990)	37.3 (1998)	34.3 (1992)
Range-Low	31.4 (1999)	32.1 (1987)	31.4 (1985)	32.2 (1983)	29.0 (1987)
R:TOR-NAO	0.09	0.40	-0.28	0.03	0.13
R:TOR-AO	-0.25	0.03	-0.04	-0.34	0.03

Table 1. Seasonal mean TOR, range, and R-values for the five regions shown in Figure 1. The climatology was constructed from the 1979-2000 TOR data set. The R-values show the relationship between the 1979-2000 TOR (at those sites) and the NAO and Arctic Oscillation (AO) index for the same season. Statistically significant correlations (levels of significance exceeding 0.10) are highlighted. (NAO data courtesy of J. Hurrell, NCAR); AO data courtesy of Climate Prediction Center)

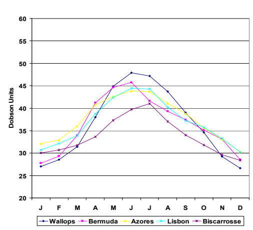


Figure 3. Monthly climatological TOR variability for the five regions shown in Figure 1.

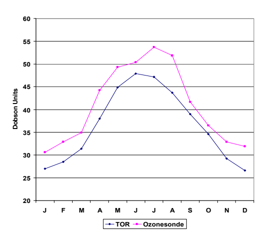


Figure 4. Relationship between TOR at Wallops and ozonesonde at Wallops (R=.97) (ozonesonde data courtesy of V. Brackett, NASA Langley).

Discussion and Work Remaining

- Strong seasonality evident in distribution of tropospheric ozone across the North Atlantic with highest amounts in the spring and summer seasons.
- Statistically significant positive relationship discovered between TOR off the west coast of southern France and the NAO during the spring.
- Similar relationship has been seen between surface ozone at Mace Head Ireland and NAO in the spring (Li et al, *JGR*, 10.129/2001JD001422, 2002).
- Increase in spring tropospheric ozone during positive phase of NAO could be due to transport via the westerlies over the northern edge of the strong Azores high. The positive phase of the NAO has also been linked to warmer than average surface temperatures in Europe (Hurrell, *Science*, **269**, 676, 1995), possibly increasing in-situ production of tropospheric ozone.
- However, influx of stratospheric ozone into the troposphere can take place at this latitude during the spring. Further work into identifying whether the increase in ozone is due to transport across the North Atlantic, in-situ generation, or stratospheric intrusion is currently on-going.
- Further the ozonesonde validation to include other regions.
- Extend NAO analysis to the AO.

Relationship between the TOR and NAO

In the midlatitudes, the North Atlantic Oscillation (NAO) is the leading mode of variability across the North Atlantic. Several researchers have shown linkages between transport of atmospheric constituents and the phase of the NAO. From Table 1, the strongest TOR-NAO relationship (level of significance exceeding .01) shown is between the TOR off the west coast of southern France (Biscarrosse) in the spring and the positive phase of the NAO in the same season. A further look into this relationship follows.

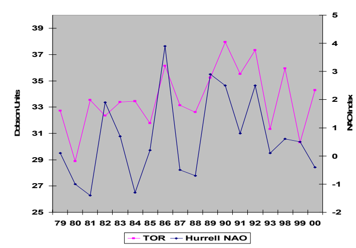
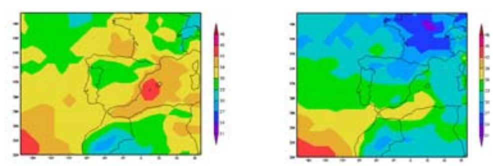


Figure 5. 1979-2000 time series of spring-time TOR over Biscarrosse and NAO (R=0.61).



Spring 1992 - Positive NAO **Spring 1980 - Negative NAO**

Figure 6. Depiction contrasting the amount of tropospheric ozone during a positive NAO year (1992) versus a negative NAO year (1980).

Jan 30.1		Feb 30.8		Mar 31.8		Apr 33.7		May 37.4		Jun 39.8		Jul 41.0		Aug 37.1		Sep 34.2		Oct 31.7		Nov 29.7		Dec 28.5	
1989	35.0	1992	36.7	1981	35.4	1992	41.3	1990	42.7	1979	48.4	1990	44.4	1983	41.1	1989	41.2	1992	39.1	1991	34.6	1990	30.6
1990	33.0	1998	34.8	1992	34.7	1990	38.3	1986	41.4	1999	45.6	1985	44.4	1988	40.7	1981	35.7	1991	34.0	1980	34.6	1979	30.4
1979	32.9	1986	34.4	1990	34.4	1989	38.1	1998	41.3	1992	42.1	1998	43.7	1999	40.2	1992	35.4	1979	33.7	2000	34.6	1986	30.3
1992	31.8	2000	33.1	1983	34.3	1987	37.0	2000	40.3	1981	40.8	1999	43.2	1982	40.0	1991	35.3	1982	32.5	1992	31.8	1992	30.2
1982	31.5	1987	32.4	1998	34.2	1984	35.5	1984	40.0	1984	40.6	1987	43.0	1998	38.6	1988	35.1	2000	32.2	1999	30.5	1989	29.8
1983	31.4	1983	31.7	1986	34.1	1999	35.4	1982	39.1	1988	40.5	1979	42.4	1984	38.5	1982	34.7	1981	32.1	1989	30.2	2000	29.3
1985	30.8	1990	31.0	1985	33.3	1988	34.8	1989	38.9	1982	40.4	1992	42.4	1986	38.3	1990	34.5	1980	31.8	1990	30.1	1988	29.0
1991	30.4	1985	31.0	2000	33.3	1998	34.8	1992	38.7	1987	39.9	1988	41.3	1990	37.6	1986	34.3	1990	31.7	1985	29.7	1980	29.0
1984	30.3	1989	30.3	1987	32.6	1983	33.6	1991	38.4	1985	39.5	1991	40.9	1979	37.5	1997	34.0	1984	31.7	1986	29.4	1999	28.9
1987	29.9	1988	30.2	1989	32.4	1979	33.6	1988	37.4	2000	39.3	2000	40.6	1981	37.5	1985	33.8	1998	31.5	1979	28.5	1987	28.7
2000	29.8	1993	29.9	1993	31.0	1981	32.3	1985	36.4	1990	38.4	1980	40.2	1992	36.7	1979	33.8	1989	31.1	1988	28.1	1991	28.5
1988	29.3	1979	29.9	1979	30.1	1991	31.4	1979	35.7	1989	37.7	1981	39.3	1980	36.4	1983	33.5	1986	31.0	1981	28.1	1997	28.1
1986	28.2	1984	29.7	1984	29.0	1986	31.4	1981	35.5	1983	37.6	1986	39.2	1997	35.6	1984	33.3	1985	30.9	1987	27.8	1985	27.9
1999	28.2	1999	29.6	1982	28.9	1980	30.8	1983	34.8	1986	37.4	1984	38.3	1989	34.6	1987	33.3	1983	30.7	1984	27.3	1983	27.4
1993	27.6	1980	28.7	1980	27.8	1993	30.4	1980	32.2	1998	36.7	1983	38.2	1987	34.5	1998	33.3	1997	30.3	1983	26.9	1982	26.8
1998	27.6	1991	28.6	1988	27.4	1982	29.7	1987	32.1	1991	36.7	1982	37.9	2000	34.0	1999	32.9	1999	30.0	1982	26.5	1984	25.4
1980	27.1	1981	26.7	1999	27.0	1985	29.4	1999	31.3	1980	34.7	1989	37.8	1985	33.3	1980	31.2	1988	29.0	1997	25.7	1981	24.1
1981	26.6	1982	25.4	1991		2000	28.9	1993		1993		1993		1991	32.6	2000	30.3	1987	28.1	1993		1993	

Table 2. Monthly TOR values at Biscarrosse ranked from years of greater tropospheric ozone to years of lesser tropospheric ozone. Highlighted in magenta is a positive NAO year (1992) and highlighted in blue is a negative NAO year (1980). 1992 was the year of the greatest average amount of TOR and 1980 was the year of the least.

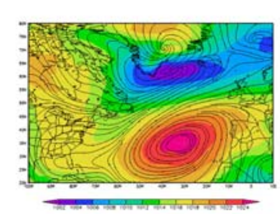


Figure 7. 1992 March-April-May sea level pressure and boundary layer winds over the North Atlantic. The streamlines shows the trajectory of the low-level westerly winds around the Azores high during a positive phase of the NAO, and is one example of a potential transport pathway for pollutants to cross the North Atlantic. (Data courtesy of NCEP/NCAR Reanalysis)

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