Arctic Oscillation–induced variability in satellite-derived tropospheric ozone

John K. Creilson,[1,2] Jack Fishman,[1] and Amy E. Wozniak[1,2]

Received 17 March 2005; revised 3 June 2005; accepted 21 June 2005; published 27 July 2005.

[1] The Arctic Oscillation (AO) has been identified as the dominant mode of near-surface climate variability in the Northern Hemisphere. In this study, we examine the interaction between the AO and the distribution of tropospheric ozone derived from satellite observations. Our analysis shows that there is a statistically significant correlation between the AO and the springtime tropospheric ozone distribution over the northeastern Atlantic, but not over the Pacific. This finding is consistent with our understanding of the differing effect that the AO has on the Atlantic versus Pacific basins and the strong influence that the El Niño phenomenon has in the Pacific. The insight gained from this study will contribute to the growing use of teleconnections as a forecast tool, providing insight into the interaction between prevailing meteorological conditions and the formation of significant pollution events.
Citation: Creilson, J. K., J. Fishman, and A. E. Wozniak (2005), Arctic Oscillation–induced variability in satellite-derived tropospheric ozone, *Geophys. Res. Lett.*, *32*, L14822, doi:10.1029/2005GL023016.

1. Introduction

[2] The Arctic Oscillation (AO) is a term used to identify the seesaw of atmospheric mass between the polar cap and the middle-latitudes in both the Atlantic and Pacific Oceans, including the adjacent land masses. Until recently, the AO, also known as the Northern Hemisphere Annular Mode (NAM), was thought to be predominantly a European and Atlantic sector phenomenon [*Hurrell et al.*, 2003]. However work done primarily by Thompson and Wallace [*Thompson and Wallace*, 1998, 2000; *Thompson et al.*, 2000; *Thompson and Wallace*, 2001] demonstrated that the impacts of the AO extend beyond this region and impact the Northern Hemisphere at all longitudes; and that it has been determined to be the most dominant influence in Northern Hemisphere near-surface climate. This teleconnection has both a warm and a cool phase. The warm phase (i.e., positive phase) is characterized by lower than normal atmospheric pressure over the Arctic and higher pressures centered on 45°N, leading to stronger westerly winds in the middle and upper troposphere at northern latitudes [*Thompson and Wallace*, 1998, 2001]. Over the last 25 years, the AO has been trending in a positive direction [*Thompson et al.*, 2000], indicative of a strengthening of the wintertime polar vortex from sea level to the upper troposphere/lower stratosphere. Some researchers have speculated that this upward trend, which has coincided with a cooling of the lower stratosphere and strengthening of the polar vortex, has been driven by ozone depletion in the lower stratosphere and increasing greenhouse gas concentrations in the troposphere [*Thompson and Wallace*, 1998; *Deser*, 2000; *Thompson et al.*, 2000; *Weiss et al.*, 2001].

[3] In this study, we examine the 1979–2000 interannual relationship between the AO and springtime satellite-derived tropospheric column ozone in the mid-latitudes over both the Atlantic and Pacific basins. Tropospheric ozone is of particular interest because of its importance in controlling the troposphere's oxidizing capacity, its detrimental role as a pollutant and its links with climate [e.g., *Fishman et al.*, 1979; *Fishman*, 2003; *Gauss et al.*, 2003]. Earlier studies have revealed distinct interannual variability in observed tropospheric ozone associated with the El-Niño Southern Oscillation (ENSO) [*Ziemke and Chandra*, 1999; *Thompson et al.*, 2001] and the North Atlantic Oscillation (NAO) [*Li et al.*, 2002; *Creilson et al.*, 2003]. More recently, *Lamarque and Hess* [2004] discovered a strong lagged relationship between the January–February–March (JFM) AO and North American springtime tropospheric ozone below 500hPa as determined from ozonesonde measurements.

[4] This analysis expands on these previous studies, particularly *Creilson et al.* [2003] whose focus was solely on the North Atlantic region and an analysis of its seasonality as it relates to the NAO, by examining how tropospheric ozone fields derived from satellite measurements relate to the interannual variability of both the AO and Southern Oscillation Index (SOI, defined as the surface pressure difference between Tahiti and Darwin) across the Atlantic and Pacific basins. In addition, we compare our findings with Northern Hemisphere temperature and geopotential fields for the same period since these variables have also been shown to be correlated with the AO. Our goal is to gain insight into the controlling factors that determine this trace gas's abundance and distribution so that seasonal predictive relationships between prevailing meteorology and pollution amounts can be identified and used to help forecast elevated pollution events.

2. Tropospheric Column Ozone Data

[5] *Fishman et al.* [2003] present a summary of the global distribution of TOR using coincident measurements from the Total Ozone Mapping Spectrometer (TOMS) and Solar Backscattered Ultraviolet (SBUV) instruments from 1979–2000. During this period, nearly eighteen years of monthly averages over most of the globe from 50°N to 50°S have been calculated (http://asd-www.larc.nasa.gov/TOR/

[1]NASA Langley Research Center, Hampton, Virginia, USA.
[2]Also at Science Applications International Corporation, Hampton, Virginia, USA.

0094-8276/05/2005GL023016$05.00

data.html). A description of this technique is given by *Fishman and Balok* [1999] and *Fishman et al.* [2003]. Due to the data density provided by the 1° latitude × 1.25° longitude pixel (TOMS grid size), the regional aspect of both monthly and seasonal tropospheric ozone features are seen in the TOR data set.

[6] Tropospheric ozone data utilized in this study are defined for regions that encompass both the Atlantic (~80W to 15E) and the Pacific (~110E to 110W) basins poleward of 20°N. These regions are chosen to diagnose their relationship with the AO, which has been shown to have a level of teleconnectivity in these basins [*Deser*, 2000]; and also to look at the processes that may be impacting tropospheric ozone formation or accumulation in these areas. Our focus is on the spring season (March–April–May (MAM)) from 1979 to 2000, and is driven by both the stronger impact of the AO during this time of the year and because the other seasons lacked the same strong continental correlative signature. The years 1994 through 1997 are not included due to issues with the satellites and/or instruments (details about this are given by *Fishman et al.* [2003]).

3. Springtime Relationship Between the Arctic Oscillation and Tropospheric Ozone

[7] In Figure 1, we present an analysis of the correlations between the TOR and the AO across both the Atlantic (top panel) and Pacific (bottom panel) basins, respectively, for MAM 1979–2000. Both the TOR and AO (http://www.cpc.ncep.noaa.gov/) data sets were normalized and binned into seasonal time periods. By doing so, we identify the fraction of the tropospheric ozone variations that can be explained by the modulations in the AO over this time period. The strongest correlations are found over the north-

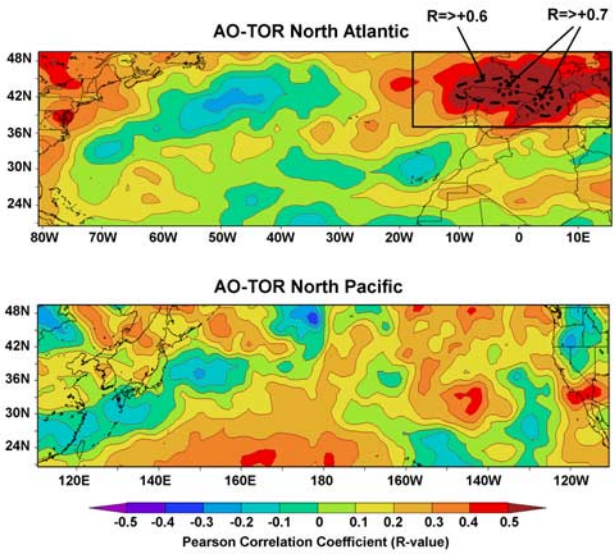

Figure 1. 1979–2000 MAM correlations between the AO and the TOR across (top) the North Atlantic and (bottom) the North Pacific. Statistically significant correlations >0.5 (.05 level) are highlighted.

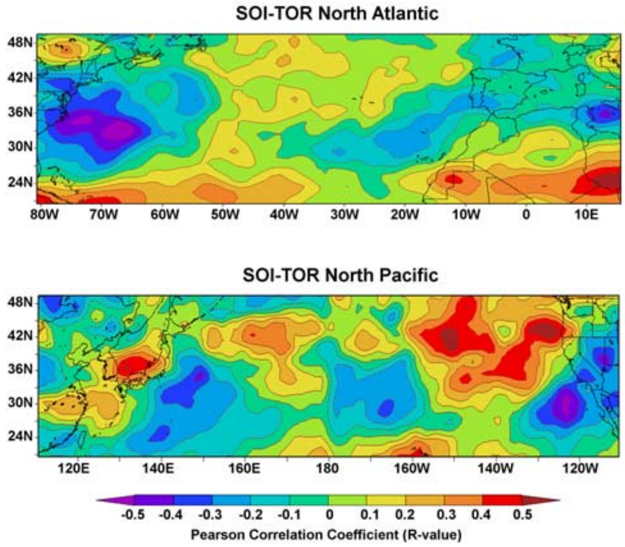

Figure 2. 1979–2000 MAM correlations between the SOI and the TOR across (top) the North Atlantic and (bottom) the North Pacific.

eastern Atlantic Ocean/western Europe region (top panel). Within this region, that encompasses significant positive correlations (R-values) of >0.5 (brownish-red colored area), are correlations that exceed 0.6 (dashed area) and 0.7 (dotted area). Correlations, that have an R-value greater than 0.5, equate to a level of significance that exceeds .05, while the areas that include 0.6 and 0.7 equate to a level exceeding.01. In the bottom panel, the strongest correlation (R = ~0.4–0.5) is not statistically significant and does not exhibit any real structure. The difference in correlation distributions across the North Atlantic and North Pacific corroborates work done by *Deser* [2000], who found, during an analysis of the teleconnectivity of the AO across both these basins, that the temporal coherence between the Arctic and mid-latitudes is strongest over the Atlantic sector. This finding, which is partially due to the fact that the Pacific sector is more strongly influenced by the ENSO phenomenon, is also seen when we correlate the TOR and SOI (http://www.cpc.ncep.noaa.gov/) over this same time period and same region. Figure 2 is similar to Figure 1, except the analysis is performed with the TOR and the SOI. From Figure 2, we find that the mid-latitude TOR-SOI correlations are stronger for the Pacific sector (bottom panel) than for the Atlantic (top panel). Even though the correlations are only marginally significant at the.05 level, we feel it is important to note the stronger mid-latitude reflection in the Pacific and is a potential subject of future research.

[8] Figure 3 is a time series of the normalized TOR over the area that exhibits the highest correlation (boxed area shown in top panel of Figure 1) compared with the AO index; the TOR data are averaged over a 9 × 9 pixel region centered on 44°N latitude, 1°W longitude. The strong interannual variability of the AO is captured in the TOR (actual anomalies range from −4.8 DU to +4.3 DU) resulting in a highly significant relationship between the two (R = +0.71), with >50% of the variance in the TOR being

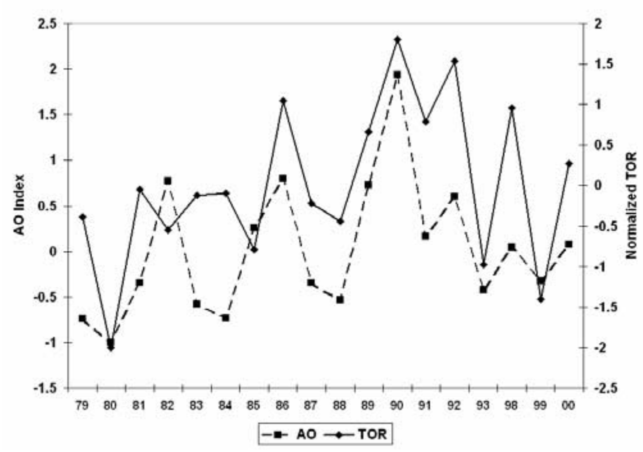

Figure 3. 1979–2000 time series of the interannual variability between the MAM AO and the TOR.

explained by the AO. An analysis of MAM ozonesonde data for Hohenpeissenberg (V. Brackett, NASA Langley Research Center, personal communication, 2005) from 1979–2000 shows that there is a similar positive interannual correlation (R = +0.55; ρ = .05) between the amount of ozone in the troposphere and the AO.

4. Discussion

[9] Elevated amounts of tropospheric ozone over western Europe during a positive AO can be attributed to several factors: 1) in situ production, 2) transport (either horizontal or vertical) into this region of either ozone or its precursors, or 3) a combination of both. In this section, we examined both processes to provide insight into the climatological characteristics of the region identified in Figure 1.

[10] In situ production is typically associated with increased photochemistry brought on by a persistent dome of high pressure, anomalously warmer temperatures, and abundant precursors. Previous studies of the interannual variability between MAM air temperature over Europe and the JFM AO found a strong relationship between the positive phase of the AO and warmer conditions over Europe [*Buermann et al.*, 2003], while also showing that the correlative spatial patterns between the AO and seasonal temperature anomalies likely influence NH surface temperatures, especially in winter and spring. Figure 4a shows the correlation between the 1979–2000 temperature anomalies for Europe and the MAM AO. A strong positive correlation is evident over western Europe, including a large area that is significantly correlated, indicating that during anomalously warmer springs, the AO is positive. Coupled with this temperature anomaly is a similar depiction showing the MAM correlation between sea level pressure (SLP) and the AO from 1979–2000 (Figure 4b). Both figures, when taken together, highlight a persistent dome of high pressure that sets up over this region. In addition to the strong correlations seen with the AO-SLP relationship, the similarity in the spatial patterns between Figures 1 (top) and 4b is particularly striking. Further analysis showing both strong negative 700 hPa specific humidity anomalies and 500 hPa ridging (not shown) support the existence of strong positive sea level pressure anomalies over the same region shown in Figures 4a and 4b during a positive AO, leading to conditions where descending air under a dome of high pressure is dominant.

[11] The second factor to consider is transport, either advection from another source region or the occurrence of stratosphere-troposphere exchange (STE). A 5-year (1993–1997) simulation using the GEOS-CHEM model examined the transatlantic transport of air pollutants and its relationship with surface ozone in Europe [*Li et al.*, 2002] and found that ozone transport during the spring across the North Atlantic was strongly correlated with the NAO, leading to higher surface ozone concentrations at Mace Head Ireland (53°N, 10°W). The study also determined that the transport occurred in both the boundary layer and the free troposphere. An analysis of the 1979–2000 correlation between the 500 hPa zonal wind and the AO shows that the

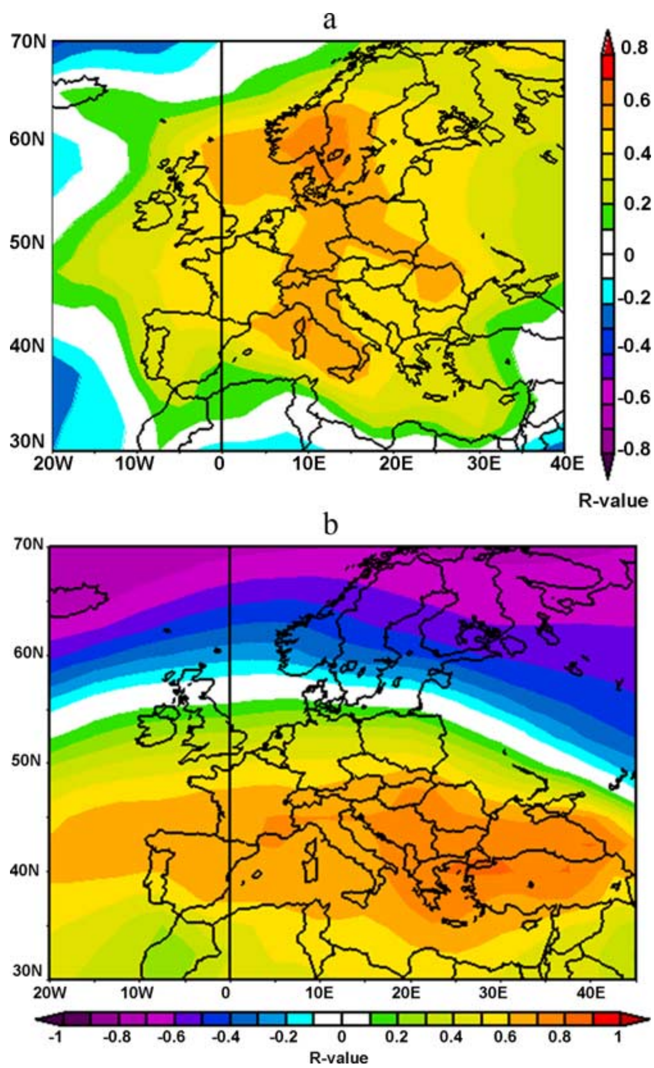

Figure 4. (a) 1979–2000 MAM correlations between surface air temperature and the AO over Europe; (b) 1979–2000 MAM correlations between sea level pressure anomalies and the AO over Europe (R-value > 0.5 equates to.05 level of significance); data courtesy of NCEP/NCAR Reanalysis [*Kalnay et al.*, 1996].

core of the strongest positive correlations is centered on ~55°N, consistent with the work of *Li et al.* [2002], while negative correlations were evident south of 45°N, indicating that the faster zonal flow brought on by the positive AO was centered to the north, which was conducive for the formation of a dome of high pressure (i.e., anticyclonic flow) being established further south of this enhanced flow. In terms of a potential STE influence, we examined both total ozone and cross-tropopause exchange. A 1979–2000 correlation analysis between TOMS total ozone and the AO over the same region and time period as the top panel in Figure 1 does not show the same strongly positive correlation, but rather a slightly negative one, a finding consistent with *Thompson and Wallace* [2000]. In addition, *Sprenger and Wernli* [2003] analyzed the climatological Northern Hemisphere cross-tropopause exchange from 1979–1993 and showed that less STE occurs during anticyclones and that there is a higher frequency of anticyclones associated with the positive phase of the NAO. Thus, the significant tropospheric ozone relationship seen in Figure 1 during a positive AO is independent of the variability in total ozone, which primarily reflects the amount of ozone in the stratosphere as well as the dynamical processes that are responsible for bringing more ozone into the troposphere from the stratosphere.

[12] As discussed earlier, correlations across the Pacific were stronger with the SOI (Figure 2) than with the AO (Figure 1). An analysis of the prevailing meteorology over the Pacific does not show the similar significant surface temperature and pressure correlations and 500 hPa flow relationships coincident with the strongest correlations. A review of 500 hPa flow patterns across the North Pacific shows that the core of the strongest anomalies are located to the north of our study area and also to the south where the influence of ENSO is strongest, suggesting that enhanced tropospheric ozone in the eastern Pacific/western United States is due to a different set of processes and relationships not discussed here.

5. Conclusion

[13] In this study, we correlated the springtime TOR north of 20°N in both the Atlantic and Pacific basins with the AO and the SOI. Strong positive TOR-AO correlations over the northeastern North Atlantic and western Europe are identified, but no discernible mid-latitude correlative pattern between the TOR and AO is evident in the Pacific. The statistically significant relationship (R = +0.71) between the interannual variability of the TOR over western Europe and the positive phase of the AO has been shown to coincide with positive sea level pressure anomalies and negative 500 hPa zonal wind anomalies across this region. It has also been previously shown that the faster zonal flow and subsequent transport of pollution to the north of our region has caused an increase of tropospheric ozone at Mace Head. Thus, the increase in tropospheric ozone observed over western Europe during a positive AO can be attributed to a greater amount of in situ production coincident with warmer, drier (and less cloudy) air associated with the subsidence within the dome of high pressure, or by entrainment into this dome of high pressure of pollution transported from the north, or both. A logical next step should be a modeling effort to examine the relative impact of these two sources.

[14] The stronger TOR-SOI relationship in the Pacific and the lack of a distinctive TOR-AO Pacific pattern is believed to be due to the dominance of the ENSO phenomenon over the AO in that region. Overall, the Pacific basin relationship shows stronger links during both La Niña and El Niño than during either phase of the AO.

[15] The resultant statistically significant relationship of the AO with the TOR within the Atlantic basin is one of many emerging monthly and seasonal relationships between climate indices and greenhouse gases. The eventual goal of such research is implementing a practical use of satellite data to improve the capability of understanding why regional-scale concentrations are elevated and thus more likely to define conditions that result in the generation of widespread air pollution episodes.

[16] **Acknowledgments.** We thank and appreciate the referee comments and recommendations. Collectively, these suggestions resulted in an improved article. This work was supported through NASA's Atmospheric Chemistry, Modeling, and Analysis Program.

References

Buermann, W., B. Anderson, C. J. Tucker, R. E. Dickinson, W. Lucht, C. S. Potter, and R. B. Myneni (2003), Interannual covariability in Northern Hemisphere air temperatures and greenness associated with El Niño-Southern Oscillation and the Arctic Oscillation, *J. Geophys. Res.*, *108*(D13), 4396, doi:10.1029/2002JD002630.

Creilson, J. K., J. Fishman, and A. E. Wozniak (2003), Intercontinental transport of tropospheric ozone: A study of its seasonal variability across the North Atlantic utilizing tropospheric ozone residuals and its relationship to the North Atlantic Oscillation, *Atmos. Chem. Phys.*, *3*, 2053–2066.

Deser, C. (2000), On the teleconnectivity of the "Arctic Oscillation", *Geophys. Res. Lett.*, *27*(6), 779–782.

Fishman, J. (2003), Tropospheric ozone, in *Handbook of Climate, Weather, and Water: Chemistry, Impacts and Applications*, edited by T. D. Potter and B. Colman, pp. 47–59, John Wiley, Hoboken, N. J.

Fishman, J., and A. E. Balok (1999), Calculation of daily tropospheric ozone residuals using TOMS and empirically improved SBUV measurements, *J. Geophys. Res.*, *104*(D23), 30,319–30,340.

Fishman, J., V. Ramanathan, P. J. Crutzen, and S. C. Liu (1979), Tropospheric ozone and climate, *Nature*, *282*, 818–820.

Fishman, J., A. E. Wozniak, and J. K. Creilson (2003), Global distribution of tropospheric ozone from satellite measurements using the empirically corrected tropospheric ozone residual technique: Identification of the regional aspects of air pollution, *Atmos. Chem. Phys.*, *3*, 893–907.

Gauss, M., et al. (2003), Radiative forcing in the 21st century due to ozone changes in the troposphere and lower stratosphere, *J. Geophys. Res.*, *108*(D9), 4292, doi:10.1029/2002JD002624.

Hurrell, J. W., Y. Kushnir, G. Ottersen, and M. Visbeck (Eds.) (2003), *The North Atlantic Oscillation Climatic Significance and Environmental Impact*, *Geophys. Monogr. Ser.*, vol. 134, 279 pp., AGU, Washington D. C.

Kalnay, E., et al. (1996), The NCEP/NCAR 40-year reanalysis project, *Bull. Am. Meteorol. Soc.*, *77*, 437–472.

Lamarque, J.-F., and P. G. Hess (2004), Arctic Oscillation modulation of the Northern Hemisphere spring tropospheric ozone, *Geophys. Res. Lett.*, *31*, L06127, doi:10.1029/2003GL019116.

Li, Q., et al. (2002), Transatlantic transport of pollution and its effects on surface ozone in Europe and North America, *J. Geophys. Res.*, *107*(D13), 4166, doi:10.1029/2001JD001422.

Sprenger, M., and H. Wernli (2003), A Northern Hemisphere climatology of cross-tropopause exchange for the ERA15 time period (1979–1993), *J. Geophys. Res.*, *108*(D12), 8521, doi:10.1029/2002JD002636.

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

Thompson, D. W. J., and J. M. Wallace (2000), Annular modes in the extratropical circulation, part I: Month-to-month variability, *J. Clim.*, *13*, 1000–1016.

Thompson, D. W. J., and J. M. Wallace (2001), Regional climate impacts of the Northern Hemisphere annular mode, *Science*, *293*, 85–89.

Thompson, D. W. J., J. M. Wallace, and G. C. Hegerl (2000), Annular modes in the extratropical circulation, part II: Trends, *J. Clim.*, *13*, 1018–1036.
Thompson, A. M., J. C. Witte, R. D. Hudson, H. Guo, J. R. Herman, and M. Fujiwara (2001), Tropical tropospheric ozone and biomass burning, *Science*, *291*, 2128–2132.
Weiss, A. K., J. Staehelin, C. Appenzeller, and N. R. P. Harris (2001), Chemical and dynamical contributions to ozone profile trends of the Payerne (Switzerland) balloon soundings, *J. Geophys. Res.*, *106*(D19), 22,685–22,694.
Ziemke, J. R., and S. Chandra (1999), Seasonal and interannual variabilities in tropical tropospheric ozone, *J. Geophys. Res.*, *104*(D17), 21,425–21,442.

J. K. Creilson, J. Fishman, and A. E. Wozniak, NASA Langley Research Center, MS 927, One Enterprise Parkway, Hampton, VA 23681-2199, USA. (j.k.creilson@larc.nasa.gov)