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Atmospheric Chemistry and Physics Discussions

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Interactive Comment

Interactive comment on "Synoptic influences on springtime tropospheric O_3 and CO over the North American export region observed by TES" *by* J. Hegarty et al.

J. Hegarty et al.

Received and published: 22 December 2008

Response to Editorial Comments: by J. Hegarty et al.

This review is by Owen Cooper, editor of this manuscript.

Received and published: 20 November 2008

This paper describes the relationship between synoptic circulation patterns over the western North Atlantic Ocean during spring (2005-2006), and TES measurements of tropospheric O3 and CO. I think that the purpose of the paper is sound (although as described below the purpose needs to be more clearly stated), as is the classification of the various synoptic patterns. However I have major concerns regarding the high

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Discussion Paper

level of speculation about the actual pollutant transport patterns associated with each synoptic type. Much more back trajectory analysis needs to be conducted to reduce the level of speculation and lend confidence to the transport pathways. Also improvements are required of the PV analysis, and greater consideration needs to be given to the impact of clouds. My current opinion of this paper is that it needs a major revision before it can be published in ACP, as described in my comments below. I am posting my comments now so that the authors have plenty of time to conduct further analyses and respond to my comments. I have not yet had the benefit of reading the comments of the two anonymous referees and their opinions will have a major influence on my final decision as to whether the paper can be published on the ACP website.

Main concerns: 1) Pollution is often hidden in clouds as described by: Crawford J. et al., Clouds and trace gas distributions during TRACE-P, JGR, 108, D21 Article Number: 8818 Published: NOV 4 2003

How are your composites affected by cloud? i.e. how strong is the bias towards clear sky conditions and how much pollution is missed by TES? It would be very helpful to the analysis for you to show a plot for MAM1 with the number of observations per cell and the percent of observations that had to be excluded for cloud.

Clouds reduce the sensitivity of TES to trace gas and other atmospheric parameters below the cloud. Simulations suggest that the sensitivity to O3 below a cloud with an optical depth of 1.0 is reduced to 30

If necessary we can include plots of the number of observations per cell for MAM1 and all the map types as supplementary material or incorporated into the main body of the revised manuscript.

2) What is the main purpose of the paper? The conclusion seems to imply that it is to show that TES can detect trace gas distributions that are caused by synoptic disturbances, i.e. a verification study. Or is the purpose to more broadly demonstrate the type of trace gas distributions due to cyclones, with TES just being a convenient

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tool? If this is the point then in the Introduction please present a clear scientific question that you are trying to answer, such as: What are the ozone and CO distribution across the western North Atlantic Ocean and how are they controlled by synoptic weather patterns?

The main point of the paper is the former. TES has the unique capability of providing tropospheric profiles of O3 and major precursors and as a newer instrument (only in operation since the latter half of 2004) it has undergone only a limited amount of verification mainly focused on global error characteristics and the variability of the seasonal mean global distributions which are possibly highly influenced by the a priori. Relatively little has been done to verify whether TES can capture the more subtle variability caused by synoptic circulation patterns in the mid-latitudes. We feel that this is a critical first step which will help researchers understand, among other things, the real impact of the assimilation of these observations into chemical transport models.

3) Much of the transport description is purely speculative. A much more rigorous back trajectory analysis is required, to provide better estimates of the pollution transport pathways and origins. The specific comments below indicate the points in the paper that I think are too speculative. I suggest you run back trajectory clusters for each TES measurement and then build composite trajectory plots for features of interest in Figures 6 and 8. Then you can state with some certainty what the general transport pathway is for each feature rather than speculating or relying on just one or two cases. A sample trajectory composite plot can be found in Figure 5 in: Cooper et al., Trace gas composition of mid-latitude cyclones over the western North Atlantic Ocean: A seasonal comparison of O3 and CO, JGR, 107, D7, 10.1029/2001JD000902, 2002.

Per your suggestion we recently performed a more systematic back trajectory analysis and have produced composite trajectory analyses for all of the map types at the 681 hPa level. We composited back trajectories for all of the corresponding O3 and CO observations for each map type in Region 1, and for selected map types in the other regions based on the relevant features in the O3 and CO composites. We also created

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trajectory composites for the 316 hPa level in regions of interests.

The trajectory composites were in good qualitative agreement with our map typing analysis and in general supported our hypotheses concerning the factors contributing to the features of the O3-CO composites. We would be happy to include them as supplementary material or incorporate them into the main body of the revised manuscript.

4) The PV analysis needs to be improved. The upper tropospheric TES retrievals are centered at 316 hPa while PV is shown for 400 hPa, a full km lower in altitude than the center of the TES retrieval. PV can vary dramatically over just a short vertical distance and all of your PV analysis is biased low in altitude in comparison to the TES retrievals. The PV analysis is also limited because you use a fairly coarse PV product (2.5 by 2.5 degrees and only 6 or 7 levels in the troposphere), that is then interpolated to pressure surfaces. Why interpolate the PV values to 400 hPa and not 316 hPa? Or why not just calculate PV yourself using the GFS data which have a much higher vertical and horizontal resolution? Using the GFS vorticity, temperature and wind fields you can use the method of Bluestein [1992] to calculate PV directly on pressure surfaces (I will send this formula to Dr. Hegarty in a separate e-mail). It may take a day or two to write the code to perform the calculations, but once the code is written the calculations should be more efficient than conducting a 3 dimensional interpolation. Bluestein, H., Synoptic-driven meteorology in mid-latitudes, 431 pp. Oxford University Press, New York, 1992.

The PV analysis of Figure 3 is a plot of the 2005 -2006 mean 400 hPa PV for each map type and not for any individual case. As such much of the added detail gained by an increase in resolution would likely be smoothed out. Therefore we used the available NCAR/NCEP 2.5 X 2.5 degree analysis.

We chose a level lower than 316 hPa to identify potential areas of deeper penetration of stratospheric air to lower altitudes. Given that these are mean plots if the 400 hPa PV analysis indicated stratospheric air in a given location, it is highly likely that it would

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indicate air of similar or greater stratospheric characteristics directly above it at 316 hPa.

Specific comments:

Section 2.3 Please provide some information on the transport patterns that were not classified. Do the ozone and CO distributions from the non-classified data look different from Figure 4? Are you ignoring some important transport events?

The non-classified data are included in the seasonal mean plots of Figure 4. Since these are random events with a wide variety of circulation types a composite of all of these observations should resemble the seasonal mean. However, because these are unclassified by circulation type it is not possible to gain further insight into the impacts of common transport pathways on the O3-CO distributions by examining the composites. To do so would require an event by event analysis and this could be an entirely different study. This isn8217;t to say that there are no important transport events on unclassified days, but just that the circulation types for these events do not occur frequently according to our classification procedure.

page 3 line 71 change to synoptic-scale mid-latitude cyclone;

Changed in manuscript.

page 3 line 76, change to; causing ground-level O3 mixing ratios to rise, but so far this has only been observed at high elevation sites in the Alps;

Changed in manuscript.

page 4 line 82 change to: distribution of O3 and its precursors as well as the air mass transport history are required;

Changed in manuscript.

line 85 ITCT-2K2 is a west coast inflow study and not relevant to N. American outflow.

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Removed ITCT-2K2 item from list in manuscript.

line 120 Please be specific as to the region you are referring to in terms of the decrease in mid-latitude cyclones. They clearly decrease over the southeast US where the Bermuda high shifts them further northwards in summer. But does the frequency actually decrease over the northeast USA in summer?

Yes there is a decrease in cyclone activity in the mid-latitudes during the summer months and this includes the northeastern U.S. (See Ziska and Smith, 1980 reference in manuscript for plot showing cyclone frequency in January and July manuscript). We will also include citations for Bell and Bosart 1989, 8220;A 15-Year climatology of Northern Hemisphere 500 mb Closed Cyclone and Anticyclone Centers8221;, MWR, 117 and Serreze et al., 1997, 8220;Icelandic Low Cyclone Activity: Climatological Features, Linkages with the NAO, and Relationships with Recent Changes in the Northern Hemisphere Circulation8221; , J. Climate, 10, which show frequency plots of all 4 seasons.

line 301 The comment about continuous vertical mixing producing a well-mixed atmosphere seems overstated. What is the mechanism for this continuous vertical mixing? Stationary lows are not features isolated from the surrounding air masses. There is always air transported in, through and out of a stationary low. Well-mixed implies little variation of ozone and CO with altitude and a smooth moist adiabatic lapse rate. I can8217;t think of any measurements that show such profiles in mid-latitude cyclones as there always seems to be some layering due to differential horizontal advection. Please be more specific.

This comment was included to make a distinction between the more uniform air mass characteristics expected for MAM1 and other map types featuring younger and more mobile cyclones which are associated with greater spatial inhomogeneity and we feel it is essentially correct. We would like to make the following points.

1. Many studies have shown that cyclones transport lower tropospheric air upward and

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poleward while at the same time transporting upper tropospheric and stratospheric air downward and equatorward thereby effectively mixing previously distinct air masses. Simulations of idealized cyclones have indicated that the distinction in the free troposphere between air masses originating in the stratosphere and boundary layer almost completely disappears after several days of being continuously mixed by cyclone air streams (see Polvanni and Esler et al., 2007, reference in manuscript)

2. We dispute the suggestion that moist adiabatic lapse rates are rare in mid-latitude cyclones as we found several profiles indicating moist adiabatic rates extending through large depths of the troposphere just by briefly examining the latest cyclone event here in the Northeastern U.S. on December 15-16, 2008. For example see soundings for Grey, ME 00 UTC December 16, 2008, and Maniwaki, QC, (CWMW), Grey, ME (KGYX), and Buffalo, NY (KBUF) for 1200 UTC December 15, 2008. Also you could look at Detroit, MI (KDTX) at 12 UTC on December 15, 2008 which is just post frontal and features a shallower elevated moist adiabatic layer. You can plot these soundings from the Plymouth State Weather Center archive (http://vortex.plymouth.edu/u-make.html).

3. Our composite of 4-day back trajectories near the center of MAM1 cyclones showed that the majority of trajectories continuously circulated around the system and had undergone at least one descent-ascent cycle while only about 25

To be more general however we will change text to read 8220;Could subject the troposphere to continuous mixing thereby reducing the spatial variability of constituents8221;

line 310 and Section 4.1 Here you imply that elevated ozone at 681 hPa is related to the stratospheric influence at 400 hPa. This would require the stratospheric intrusions to be almost vertical, while they actually slope downward and equatorward, so you would expect the lower tropospheric ozone enhancement to be further south than the upper troposphere enhancement. Please run back trajectories to explore the possibility of an intrusion.

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As implied in the text we believe it is a combination of factors that contributed to the enhanced 681 hPa O3 retrievals in this region including the intrusion of stratospheric air to below 400 hPa and the upward shift of the peak in the TES averaging kernels to between 400 and 500 hPa. The shift in the averaging kernels would imply that large increases in O3 at those levels would be reflected in the 681 hPa values even if the enhanced O3 didn8217;t extend all the way down to the 681 hPa level. The composite 4-day back trajectory analysis showed that only approximately a third of the back trajectories from 681 hPa descended from above 400 hPa.

line 325-328 This transport pathway is also described by Owen et al. [2006] with regards to transport to the Azores.

Statement and citation added to manuscript.

line 335-336 The DA always has some portion that is of a lower stratospheric origin. The sentence should be reworded to: ...because it transports drier air from the upper troposphere and lower stratosphere to the mid-troposphere with some strong systems allowing for direct transport to the lower troposphere.

Change made to manuscript.

line 341 change to: ...were mainly due to the position...

Change made to manuscript.

line 350 It8217;s not clear which cyclone in MAM4 you are referring to. The cyclone in the northeast of the figure is outside of the classification box so it is not likely part of the classification. The cyclone to the west is upwind of the western Atlantic so its DA cannot be influencing the study region. Is MAM4 the result of the position of the cyclones, or more the result of the large anticyclone over the western Atlantic?

The map type MAM4 is really a result of all these features including both cyclones and anticyclone. Even though the eastern cyclone center is to the east of the map typing domain, the primarily east-west pressure gradient in Figure 2 would suggest a cyclone

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to the east with a strong meridional component to the surface flow.

line 386-395 In comparing the ozone/CO slopes between this study and earlier studies you need to be very careful that you account for changing emissions of NOx and CO in North America. As described by: Parrish, DD, Critical evaluation of US on-road vehicle emission inventories, ATMOS. ENVIRON. Volume: 40 Issue: 13 Pages: 2288-2300. 2006 and Kim, SW, et al., Satellite-observed US power plant NOx emission reductions and their impact on air quality, GEOPHYSICAL RESEARCH LETTERS Volume: 33 Issue: 22 Article Number: L22812, 2006 The older O3/CO slopes are the result of NOx and CO emissions ratios that no longer exist. So we shouldn8217;t expect the later TES values to exactly match the older estimates

That is true, but in our manuscript we were mainly concerned with whether or not our O3/CO slopes fell within the range of the older measurements. We will add a statement acknowledging the changes on U.S. emissions and their implications for O3/CO slopes.

line 424-425 Please explain why the averaging kernels shift upwards.

The averaging kernel represents the sensitivity of the retrieval at a given level to the true value at that level and all other levels. The shape of the averaging kernel vector for a given parameter can be influenced by meteorological factors such as the temperature, water vapor, and cloud profiles as well as the vertical profile of the trace gas being measured. For example, a high concentration of O3 in the middle or upper troposphere will reduce the sensitivity to O3 in the lower troposphere and the retrieved values in the lower troposphere will become more dependent on correlations in the a prior constraint with adjacent levels above than on the actual O3 concentrations in the lower troposphere.

line 461 do you mean westerly to southwesterly flow?

Yes, this has been corrected in the manuscript.

line 510 What do you mean by significant upper level CO features? Statistically sig-

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nificant, or simply elevated? Also when discussing upper tropospheric CO you need to make sure you aren8217;t really looking at lower stratospheric CO. As shown in Cooper et al 2002, CO in the vicinity of 316 hPa with values of 100-110 can easily be in the lower stratosphere where aged CO can accumulate. Cooper et al., Trace gas composition of mid-latitude cyclones over the western North Atlantic Ocean: A seasonal comparison of O3 and CO, JGR, 107, D7, 10.1029/2001JD000902, 2002.

We actually mean simply elevated or enhanced. We have changed the wording in the manuscript to 8220;features of enhanced upper level CO in the composites8221;.

The areas of high CO at 316 hPa generally did not correspond to areas of high O3 or PV which would suggest that the air was not of stratospheric origin. In addition our new composite back trajectories for these features seem to imply that for most cases the transport was from the lower troposphere to the south and west rather than from the lower stratosphere. We will include these trajectories in the revised manuscript.

Section 4.3 The inland cyclone for MAM4 likely has nothing to do with the CO in the Atlantic, which is likely to be aged. So which cyclone transports the CO to the Atlantic? What do back trajectories show?

Because of the low frequency of this case and poor data coverage we could not conclusively identify the transport mechanism for every feature of this map type particularly those well out into the Atlantic which likely were influenced less by the map type. However, back trajectories in this region suggested that the cyclone to the east may have incorporated pollutants from North America as well as those from further east (origin unknown) into its WCB.

On line 525 you speculate that high ozone and low CO indicate a stratospheric origin. But what do the back trajectories show?

The composite trajectories for MAM5 indicate mainly transport from the upper troposphere and lower stratosphere in a general north-south direction in this region. How-

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ever, approximately 25-30

On line 532 you state that the averaging kernel shifted upwards to 500-550 hPa, so if it is centered on the mid-troposphere, wouldn8217;t the retrieval have equal influence from both the upper and lower troposphere?

Yes this is true. However, in the context of the manuscript the statement meant that compared to MAM1 the retrievals of high O3 levels at 681 hPa were more likely to be due to high O3 in the lower free troposphere, not that they were entirely due to high O3 in the lower free troposphere.

lines 538-541 The discrepancy between the ozone and PV is likely due to the vertical separation. Another potential problem is that PV is not well conserved once it enters the troposphere. If the intrusion is more than a couple of days old the PV values can diminish while the ozone values stay fairly high.

We will add this explanation to the manuscript.

Line 551-552 I am skeptical that the inland cyclone in MAM4 is responsible for the ozone and CO south of 40 N in the western Atlantic. The cyclone seems to be too far away and this pollution could have been left behind by the downstream cyclone. Back trajectories would make this more clear.

Yes, we now believe this to be true since our back trajectories for this map type seem to suggest flow around the back side of the departing cyclone further east. We have rewritten the statements in Section 4.3 to reflect this newer finding.

Line 570 Here you are assuming that the intrusions extend straight down rather than sloping to the south. What do back trajectories indicate?

Back trajectories indicated northwesterly descent from over Central Canada and the upper Midwest from levels between 450 8211; 350 hPa, which may have been in the lower stratosphere.

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line 647-648 Please describe how this case study differs from the similar mechanism described by Owen et al., 2006.

This case is generally similar to Event 2 described in Owen et al., 2006. The main difference seems to be in the mean storm track which is somewhat further north in Owen et al., 2006. However, this may be due in part to the fact that a secondary system developed along the Mid-Atlantic coast in our case but did not seem to in Event 2 of Owen et al., 2006. We will add statements citing this case to the revised manuscript.

line 659 Please elaborate on what you mean by loss rate. Are you saying that CO is oxidized and/or diluted?

Ozone continued to be produced while CO was diluted and photochemically processed/ oxidized and this lead to O3 decreasing more slowly to the east than CO.

line 664-666 The speculation on the transport pattern could be confirmed or rejected with the use of back trajectories.

Composite trajectories for MAM2 and MAM3 showed both a direct west 8211; east transport pattern in the lower troposphere as well as transport from the upper troposphere/lower stratosphere from the north.

line 684 Here you state that the exported pollution was undoubtedly from North America, but the back trajectories on May 14 do not support this statement as they don8217;t reach the polluted North American boundary layer. Also the ozone mixing ratio of 70 ppbv and the CO mixing ratio of 110-115 ppbv could just be air transported downwards from the mid- or upper troposphere.

The trajectories on the 15th clearly did reach the polluted boundary layer of the U.S. and we were attempting to show the variety of transport pathways to this region as another way of justifying the dilution of CO. We have changed the word 8220;undoubtedly8221; to 8220;may have8221; in the manuscript.

line 693-698 This transport pattern is similar to the one described by Owen et al. [2006]

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that transports pollution to the Azores at low altitude. Some comparison between the two studies would be useful.

We did not find a single common or dominant transport mechanism for this region, which was far removed from the east coast of North America and therefore not as strongly influenced by the map type. Instead as discussed in the manuscript we found several mechanisms that seemed equally possible some at low altitude, while others feature lofting and then descent. The larger variety compared to Owen et al., 2006 may be due in part to seasonal differences since we are looking at spring and Owen et al., 2006 focused on summer. We will elaborate on this point in the revised manuscript.

lines 701-703 This sentence makes it sound like there are only 6 possible transport patterns, when really there were many more, they were just not very clear.

We have revised the sentence to read ;

8220;The springtime tropospheric O3 and CO distributions constructed using the 2005 and 2006 TES measurements were dependent on the atmospheric circulation and exhibited substantial variability between 6 predominant map types (MAM1 8211;MAM6).8221;

References Please check that all recent JGR papers in the reference section have the correct citation. For example I noticed that the correct citation for Cooper et al. 2002 should be: Cooper O. R., et al., (2002), Trace gas composition of midlatitude cyclones over the western North Atlantic Ocean: A conceptual model, J. Geophys. Res., 107 (D7), doi:10.1029/2001JD000901.

We will make that change to the manuscript and check all of the references.

Figures: Figure 1 What does the kink at the top of the DA arrow indicate? Is this supposed to describe a real feature? Because the WCB rises above the CCB, please overly the red arrow on top of the green arrow.

The kink is a drawing mistake that will be corrected in the revised manuscript. We will

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overlay the WCB over the CCB.

Figures 2, 3, 6, 8 Please label each panel with the corresponding map types. Figure 3: to be more relevant to the analysis replace PV at 400 hPa with PV at 316 hPa, or 300 hPa. Figure 5 make the axes the same in both panels Figure 9 make the axes the same in both panels Figure 10 make the SLP contours darker make the text larger and darker in the trajectory plot, as much of it is illegible. Why are the CO observations offset slightly to theright? Figure 11 and 13 in both figures make the SLP contours darker and increase the size and darkness of the text in the trajectory plots

We will make all of these changes to the figures in the revised manuscript.

Interactive comment on Atmos. Chem. Phys. Discuss., 8, 19743, 2008.

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