Examination of ozonesonde data for trends and trend changes incorporating solar and Arctic oscillation signals

Alvin J. Miller,[1] Airong Cai,[2] George Tiao,[3] Donald J. Wuebbles,[4] Lawrence E. Flynn,[5] Shi-Keng Yang,[1] Elizabeth C. Weatherhead,[6] Vitali Fioletov,[7] Irina Petropavlovskikh,[6] Xiao-Li Meng,[8] Serge Guillas,[9] Ronald M. Nagatani,[1,10] and Gregory C. Reinsel[11,12]

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[1] One major question that arises with the implementation of the Montreal Protocol and its subsequent conventions is our ability to determine that an ozone "recovery" is in process. Toward this we have utilized a statistical model suggested by Reinsel et al. (2002) that utilizes the idea of a trend and a trend change at a specific time and applied it to 12 ozonesonde stations in the midlatitudes of the Northern Hemisphere. The lower stratosphere, in particular, is of significance as this is where the ozone concentration is a maximum and also where heterogeneous ozone losses have been noted. This statistical methodology suffers, however, from the ambiguities of having to select a specific time for the ozone trend to change and the fact that the Mt Pinatubo volcanic aerosols impacted the ozone amount. Within this paper, we analyze the ozonesonde station data utilizing the above model but examine the statistical stability of the computed results by allowing the point of inflection to change from 1995 through 2000 and also exclude varying amounts of data from the post-Pinatubo period. The results indicate that while the impacts of deleting data and changing the inflection point are nontrivial, the overall results are consistent in that there has been a major change in the ozone trend in the time frame of 1996 and that a reasonable scenario is to utilize a change point in 1996 and exclude 2 years of data after the 1991 Mt. Pinatubo eruption. In addition, we include a term for the Arctic oscillation within the statistical model and demonstrate that it is statistically significant.

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1. Introduction

[2] With the adoption of the Montreal Protocol in 1987, along with its follow-up conventions, the scientific and political communities have been sensitive to the issue as to when we would observe the possible impacts of their implementation. As an example of the expectation, we present in Figure 1, the yearly average results from the University of Illinois two-dimensional model forecasts for total ozone averaged over the domain 30°N–50°N for the period 1975–2050 [*Wei et al.*, 2002] along with the data from the Dobson/Brewer network since 1964 [*Fioletov et al.*, 2002]. The units are ozone change, in percent, from 1979. Both the starting point and the area (30°N–50°N) was selected so that we would be comparable with the Solar Backscatter Ultraviolet Ozone Sensor (SBUV/(/2) satellite observations which begin in 1979. Note that the ozonesondes generally begin about 1970 and we plot a vertical dashed line at that point. In addition we plot a dashed vertical line for January 1979. There are several particular points we wish to emphasize from this diagram; (1) the general agreement between the data and the UIUC model and (2) the data indicate that the change in ozone from 1970 to 1979 is considerably less than from 1979 to 1996. The former point provides some confidence in utilizing the numerical model as guidance; the latter point will be emphasized below when we examine the representativeness of the ozonesonde data and the impact of the initial timing of the observations.

[3] While independent models show variations about the model results [e.g., *World Meteorological Organization* (*WMO*), 2003], the essence of the results is that based on the model scenario "Ab" of *WMO* [2003], we should expect total ozone values to return to their pre-1979 levels

[1]NOAA/NWS/NCEP/Climate Prediction Center, Camp Springs, Maryland, USA.
[2]Department of Information and Decision Sciences, University of Illinois at Chicago, Chicago, Illinois, USA.
[3]Graduate School of Business, University of Chicago, Chicago, Illinois, USA.
[4]Department of Atmospheric Sciences, University of Illinois, Champaign, Illinois, USA.
[5]NOAA/NESDIS, Camp Springs, Maryland, USA.
[6]Cooperative Institute for Research in the Environmental Sciences, University of Colorado, Boulder, Colorado, USA.
[7]Environment Canada, Toronto, Ontario, Canada.
[8]Harvard University, Cambridge, Massachusetts, USA.
[9]Georgia Institute of Technology, Atlanta, Georgia, USA.
[10]Retired.
[11]Department of Statistics, University of Wisconsin, Madison, Wisconsin, USA.
[12]Deceased May 2004.

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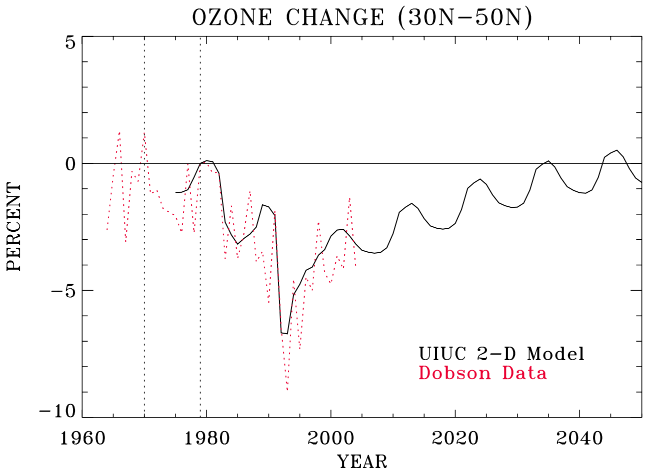

Figure 1. Percent ozone change for the region 30°N–50°N from the University of Illinois Urbana Champaign two-dimensional chemical transport model since 1975 and the Dobson network since 1964. Both data sets have been normalized to 1979 as the base period.

in approximately 2050. This, in turn, implies a rate of recovery that can be examined independently within the data and tested for statistical significance.

[4] The actual details of the recovery process and timing are obscured, however, by the impacts of the Mt. Pinatubo eruption in 1991 with effects lingering for several years depending on latitude. From our current perspective in 2005, with limited data beyond the Pinatubo eruption, our ability to state that the data agree with the models in terms of the rate of recovery is hindered by how well we consider the effects of the Pinatubo eruption as well as the other parameters that impact the interannual variability such as the solar cycle and dynamic influences.

[5] One method suggested by *Newchurch et al.* [2003] is to examine the cumulative sums of the departures of the data from a hypothetical scenario of continued trend. This methodology, while powerful, can be limited. First, one has to be sure to include all of the terms for expected deviations in the extrapolated model. Second, the methodology provides specific information, in the cumulative sense, that shows that the data do not agree with the underlying hypothesis, e.g., a continuing linear trend. Once it is demonstrated that the underlying hypothesis is false, adding additional years become somewhat redundant. One has to develop a different hypothesis to test against, e.g., invoking a change in trend.

[6] With this in mind, Gregory Reinsel, who was a coauthor on the paper with *Newchurch et al.* [2003], has proposed an alternative statistical technique that employs a trend beginning at an initial point and a trend change at a denoted time [*Reinsel et al.*, 2002, 2005]. While this methodology includes techniques to quantify the effects of outside influences and nonindependence of the data, it suffers from several ambiguities; (1) the effect of the ozone decrease after the Mt. Pinatubo eruption on the statistics denoting a change in ozone after the event, as well as (2) having to denote a specific time for the inflection or trend change to occur.

[7] While the discussion to this point has centered on total column ozone, how the ozone changes are distributed in the vertical is also important in that there is a bimodal distribution of ozone change with altitude in the middle and high latitudes [*WMO*, 1998]. One region of ozone depletion has been observed at about 40 km related to homogeneous chemistry and a second at about 15 km related to heterogeneous effects and possibly other influences such as dynamic changes [e.g., *Weiss et al.*, 2001].

[8] Within this paper, we utilize the method outlined by *Reinsel et al.* [2002, 2005] to examine the ozonesonde data for temporal changes within the lower stratosphere. As part of the process, we will specifically examine the effects of changing the date of the inflection point as well as removing data as a way to account for the impacts of the Mt. Pinatubo eruption.

[9] As an indicator of the basic issues for the region 30°N–50°N (the basic region of the ozonesonde stations), we present in Figure 2 the yearly average SBUV/(2) [*Miller et al.*, 2002] data for this region depicted as the percent change since 1979. We use SBUV/(2) as it offers more complete coverage of the zone than the ground-based data, though it does begin at a later date. *Miller et al.* [2002] discuss the issues of intersatellite calibration as well as comparisons with available ground-based data. Within this diagram we have plotted as triangles the averages for the years 1991–1994 as the years most likely impacted by the Pinatubo eruption. The major points are as follows.

[10] 1. The data since 2000 are at approximately the same level as for 1985. The data do not indicate a continuing downward trend. The refined statistical mechanisms are, basically, quantifying this notion.

[11] 2. If we did nothing to the data, the trend (and standard error) computation from 1979 to 1996 would be heavily influenced by the very low observed values in 1993. As part of our results we will consider this by removing data for periods 0 to 4 years and examine the sensitivity of the results.

[12] 3. We also see that as discussed above, there is no clear point of demarcation of change in trend. Hence we

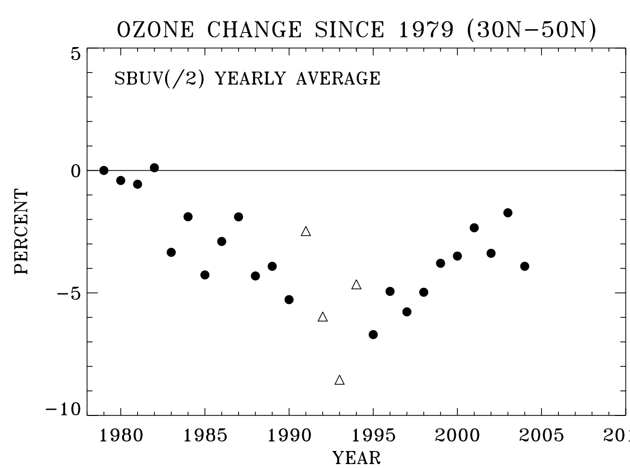

Figure 2. Ozone change since 1979 for region 30°N–50°N derived from the SBUV/(2) satellite data.

Table 1. List of Stations Used in the Study, Their Periods of Record, and the Instruments Used in Taking Their Measurements

Station	Latitude	Data Span	Method of Measurement
Resolute	74N	Feb. 1970–May 2003	BM, ECC (12/79)
Churchill	59N	Nov. 1973–June 2003	BM, ECC (09/79)
Edmonton	54N	Nov. 1973–Dec. 2003	BM, ECC (01/80)
Goose	53N	Mar. 1970–Dec. 2003	BM, ECC (01/81)
Wallops Island	38N	May 1970–Dec. 2002	ECC
Lindenberg	52N	Jan. 1975–Dec. 2003	East European BM, ECC
Uccle	51N	Jan. 1970–Dec. 2003	BM, ECC (04/97)
Hohenpeissenberg	48N	Jan. 1970–Dec. 2003	BM
Payerne	47N	Jan. 1970–Dec. 2003	BM
Sapporo	43N	Jan. 1970–Dec. 2003	KC
Tateno	36N	Jan. 1970–Dec. 2003	KC
Kagoshima	32N	Jan. 1970–Dec. 2003	KC

will also present the sensitivity of the results to changing the inflection point to various years from 1995 to 2000.

2. Data

[13] The list of stations and time periods employed in this study is presented in Table 1. Of the 12 stations, 11 fall within the latitude band 30°N–60°N. The one exception is Resolute at 74°N. The time period generally begins in 1970 and extends to 2003. For Lindenberg, the OSE type ozonesondes were used from 1975 to 1992. This sonde was manufactured in the former German Democratic Republic and was very similar to the Brewer-Mast sonde. A set of parallel measurements by OSE and ECC sondes was performed in 1992. From these tests, a correction procedure was established and the OSE data were reprocessed and resubmitted to the WOUDC. All data were obtained from the World Ozone and Ultraviolet Data Center in Toronto Canada, except Wallops Island which was obtained directly from Francis Schmidlin of the NASA Goddard Space Flight Center, Wallops Island Facility. Finally, on the basis of the recommendation of Samuel Oltmans of the NOAA Climate Monitoring and Diagnostic Laboratory, we have opted to not include the data from Boulder, Colo. within this study as the amount of data from 1979–1984 at Boulder is very limited with many months having only one sounding and many months of missing data.

[14] A discussion of some of the common problems encountered in dealing with ozonesonde data as well as the altitude sensitivity is found in the work of *WMO* [1998], *Logan* [1994], and *Logan et al.* [1999]. This includes the change of equipment from the Brewer-Mast sonde to the electrochemical concentration cell (ECC) sonde as well as changes in procedures during the years. We note that data for Uccle has been corrected for the BM-ECC difference [*Lemoine and De Backer*, 2001]. Most stations making sonde measurements scale the ozone profile to an independent measurement of the total column by Dobson or Brewer instruments. This is called the "correction factor." The procedure and problems associated with this practice for the purposes of detecting ozone trends have been delineated by *Logan et al.* [1999] and will not be repeated here. One major point of concern is that some of the station correction factors indicate a change in time unto themselves. This, in turn, can result in a trend not "observed" by the sonde but forced through the corr factor at a specific station. As *Logan et al.* [1999] have shown, however, this effect tends to be averaged out over the stations and the collective results, either when the factors are used or removed, are quite similar. Hence we will present here only the results for the data with the correction factor included. In addition, the correction factors are also used as an individual sonde quality control by using data selection criteria in which the correction factors are within the range 0.9–1.2 for the Brewer-Mast sonde and 0.9–1.15 for the ECC and Japanese sondes [*Tiao et al.*, 1986; *Miller et al.*, 1995]. On average, about 9% of the soundings were removed by this quality control process.

[15] With respect to the sondes used in Japan, there are three types of Japanese ozonesondes KC-68, KC-79, and KC-96, that were in use in 1968–1979, 1979–1997, and after mid-1997, respectively. As reported by *Harris et al.* [1998], the Japanese sonde was modified in 1979 to include the radiosonde and ozonesonde in a single integrated package. The construction of the sensor may also have changed at this time from a double- to single-cell design. No apparent change in sonde performances was noted with these changes. However, there were some changes in the radiosonde and a radiation correction was applied to temperature sensors since 1979. This may have caused an altitude shift in the measurements. In 1996, the ozonesonde instrument was developed and *Fujimoto et al.* [2000] also mentioned improvements in the processing algorithm of KC-96 to address issues pointed out by *Smit and Kley* [1998]. They introduced new pump corrections and additional memory effect correction. This potentially could affect ozone trend estimations. Fortunately, the turning point of our trend calculations is 1996, i.e., almost at the same time when the switch to KC-96 occurred (mid-1997). Therefore the effect on trends should be relatively small. In addition, all Japanese data are normalized to total column ozone.

[16] The original ozonesonde data are reported in partial pressures, but they are integrated into 15 fractional Umkehr layers in the same manner as described by *Tiao et al.* [1986]. The layers and their altitude equivalent are given in Table 2.

[17] In addition to the above ozonesonde data, we also utilize the total ozone provided with the individual sondes as well as the monthly average zonal mean total ozone derived from the SBUV/(2) data. The latter is based on the

Table 2. Altitude, km, of the Ozonesonde Umkehr Layers

Layer	Altitude, km
1a	4.2
1b	6.8
1c	9.2
1d	11.4
2a	13.6
2b	15.8
3a	18.0
3b	20.2
4a	22.5
4b	24.7
5a	27.0
5b	29.3
6a	31.7
6b	35.2

method of *Miller et al.* [2002] and the total ozone data from both sources is utilized as a test of the zonal representativeness of the sonde data. Finally, as ancillary variables, we use the f10.7 cm solar flux as a proxy for the solar signal and the Arctic oscillation (AO) as a possible indicator of a troposphere-stratosphere dynamic linkage [*Appenzeller et al.*, 2000; *Baldwin and Dunkerton*, 1999, 2001; *Thompson and Wallace*, 1998, 2000; *Weiss et al.*, 2001]. The Arctic oscillation is defined as the amplitude of the first empirical orthogonal function of the 1000 hPa geopotential height computed from the NCEP/NCAR reanalyses [*Kalnay et al.*, 1996], often referred to as the loading pattern. As *Appenzeller et al.* [2000] have noted, a positive AO is associated with a lower tropopause pressure in midlatitudes which, in turn, is associated with lower ozone. Hence we anticipate a negative correlation between the Arctic oscillation and ozone in the lower stratosphere. Finally, we note that we do not include any terms to represent the quasi-biennial oscillation as previous work has indicated that the effect on the trends and the residual errors at the latitudes discussed here is quite minimal [*Tiao et al.*, 1986].

3. Statistical Model

[18] Many of the trend studies on ozone have assumed a linear decrease in ozone or a linear decrease after a certain date. As indicated above, *Reinsel et al.* [2002, 2005] has suggested an alternate approach that seeks to answer whether or not we can ascribe a change in the ozone trend beginning on a certain date. From Figures 1 and 2 we see that such an exact date probably does not actually exist but rather stretches out over a period of time. To help define the value of this statistical approach, we examine the statistics with a change date of January 1995, 1996, 1998, and 2000.

[19] The other aspect that must be considered is the effect of the Mt. Pinatubo eruption. As has been described by *Solomon et al.* [1998] and *WMO* [1998], the sharp decrease of total ozone during the winter of 1992–1993 has been ascribed to the combination of increased aerosols, the chlorine/bromine levels, and the relatively cold temperatures during this particular period. Following this, there should be a recovery from the Pinatubo effect that can be colinked with a general recovery of ozone due to decreased chlorine levels. To help ascertain the magnitude of this effect, we redo the statistics removing 2 years after the Pinatubo eruption, 3 years, and 4 years and compare the results with those whe ata are excluded.

[20] The statistical model is a linear regression model with first-order autoregressive errors, based on *Reinsel et al.* [2005] and is depicted pictorially within Figure 3. The first part from the initial data point has a computed trend of ω_1. At the inflection point a new slope is computed such that a change in slope ω_2 is provided. The mathematics of these calculations has been provided by *Reinsel et al.* [2005] and need not be repeated here. As discussed above, in addition to the trend components, the ancillary variables of f10.7 solar radio flux and Arctic oscillation are also included. In addition, an intervention term to account for the shift of instruments from the Brewer-Mast sonde to the Electrochemical Concentration Cell was also included [e.g., *Tiao et al.*, 1986]. The magnitude of the calculated shifts was compared with overlap comparisons of the two instrument types [*WMO*, 1994] and the two are in quite good agreement. Finally, it is noted that both the solar term and the AO term were included with no lead/lag effect. The latter was specifically examined for possible lead/lag with none detected.

[21] What is important to point out is that with data extending only to 2003, any movement of the inflection point closer to the end of the data reduces the certainty of the calculations. Within Figure 3, the question mark reflects the uncertainty of the actual date of the inflection point.

4. Results

[22] This section will discuss the results of the trend analysis performed on the Northern Hemisphere midlatitude ozonesonde data set and its sensitivity to the inflection point and removal of several years of data after the Mt. Pinatubo eruption.

4.1. Annual Results

[23] We begin our discussion with presentation in Figure 4 of the annual results, computed as above, for the case with 2 years of data removed beginning in June 1991 and the inflection point at January 1996. For the computations, each station was done separately and the overall averages and standard deviations then calculated. As discussed above, we

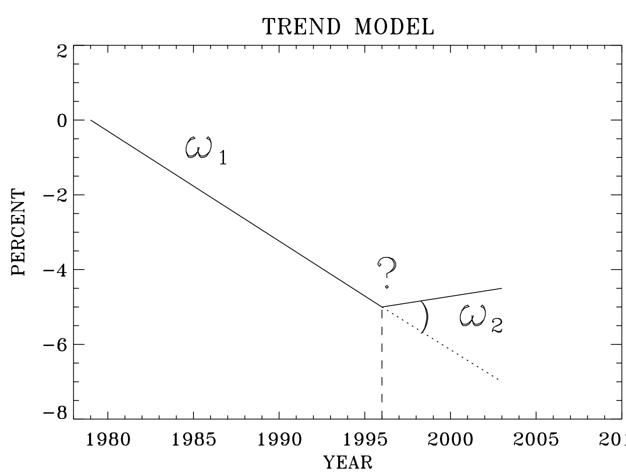

Figure 3. Pictorial diagram of the statistical trend and trend change model. The "?" indicates that the actual point of inflection to be used is somewhat uncertain.

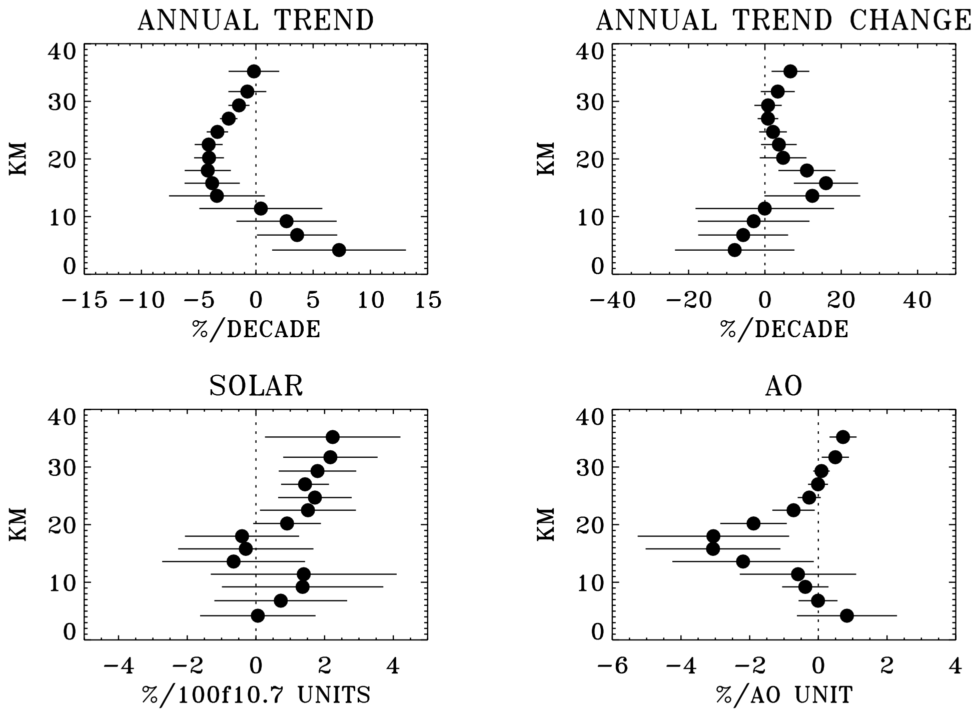

Figure 4. Average trend, trend change, solar coefficient, and AO coefficient derived from the 12 ozonesonde stations as a function of altitude. Horizontal bars represent the 95% confidence limits. Results shown for 12 stations computed, individually, and then averaged.

will examine the ramifications of this set of criteria in detail below. The results are presented for the trend (1970–1996), the trend change at 1996 and the amplitude of the solar and AO component as a function of altitude. The solid horizontal lines represent the 95% statistical confidence limits. We see that the trend in the lower stratosphere is about −4%/decade and statistically significant which is in good agreement with previous calculations [e.g., *Logan et al.*, 1999]. The trend change is statistically significant and positive, about +10–15%/decade, over the general domain from 13 to 18 km. The solar coefficient exhibits an interesting pattern in that the coefficient becomes negative in the middle to upper troposphere, though it is not statistically significant. This point will have to be examined further with other data to see if it is supported. Finally, we note that the AO coefficient for the lower stratosphere is negative and statistically significant indicating a possible linkage between troposphere and stratosphere. On the other hand, the data do not indicate a clear transmittal mechanism as a function of height.

[24] Two points raised in review are the explained variance of the statistical model and the fact that we chose not to include terms for the quasi-biennial effect. To answer the latter question, we redid the analyses for Hohenpeissenberg, as an example, for layer 3B where the negative trend is a maximum. The impact on the trend and trend-change terms and their associated 95% confidence limits for layer 3B was as follows: trend without qbo, −4.2 ± 1.7%/decade; trend with qbo, −4.1 ± 1.5%/decade; trend change without qbo, 7.0 ± 8.3 %/decade; trend change with qbo, 6.1 ± 7.0%/decade. Thus the impact of the qbo on the trend and trend change is very small at these latitudes and altitudes, especially compared with t fidence limits.

[25] To examine the AO relationship further, we look at the individual station AO coefficients at 18 km. Within Figure 5 we present the AO loading pattern along with the location of the individual stations used within this analysis (red stars). We see that the locations are well distributed with respect to the variations of the EOF such that we would anticipate a negative relationship. Figure 6 illustrates the results for Layer 3A (18 km) where we plot the annual AO coefficient versus the loading factor. The individual stations have a strong negative correlation, r = −0.83, suggesting a true physical relationship between AO and ozone. On the basis of this, all computations presented here include the AO term as an ancillary variable.

[26] We now return to the question of the explained variance, and in Table 3 we provide the value for each station and each layer. For all computations, the data have been deseasonalized first as the ability to model, statistically, the seasonal variations overwhelms the trend and trend change aspects. We see that the variations between stations and with layers are quite extensive and that the overall average explained variance is about 38%. The only general pattern that is discernable is a relative minimum in explained variance from layers 1D–3B that is about 33%.

[27] Within Figure 7 we indicate, as an example, the monthly deseasonalized data, in Dobson Units, for Payerne, Layer 3A as a function of time (blue) as well as the statistically modeled fit (red). From Table 3, the explained variance is 0.33 which is about average for the layer. From the figure we see several interesting aspects. First, of course, is the trend in the earlier part of the record followed by the leveling off after 1996. In addition, we gain an appreciation of the month-to-month variability in the data along with the ability of the inclusion of the AO term to account for it.

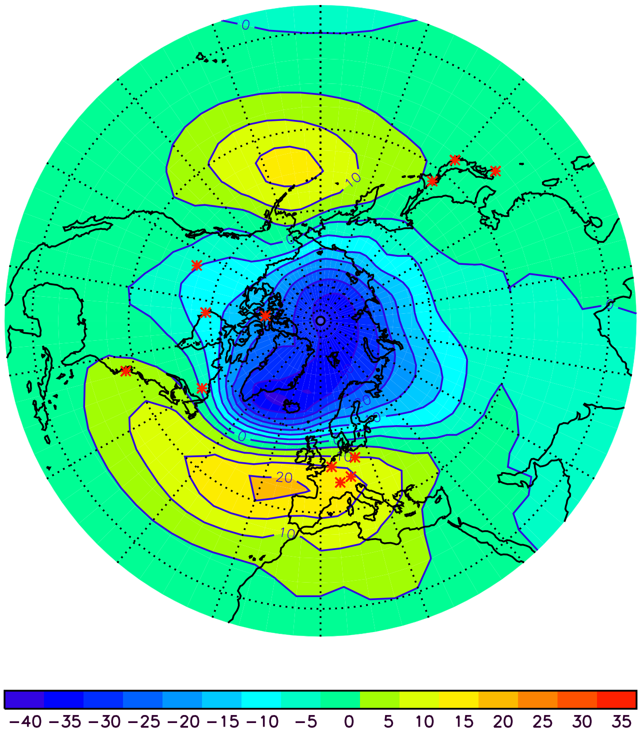

Figure 5. Arctic oscillation pattern–empirical orthogonal function 1 of monthly height anomalies (m) at 1000 hPa. Asterisks mark locations of ozonesonde stations used in the study.

While the statistical estimation technique clearly does not capture the extremes in the data, we are able to perceive that the AO term is associated with the monthly variability.

4.2. Seasonal Results

[28] The above results are for the annual computations. As has been shown previously, [e.g., *Logan et al.*, 1999; *Tiao et al.*, 1986] there is a strong seasonality to the trends and within Figure 8a we present our seasonal trend results for the period 1970–1996. Consistent with the previous authors, the trends in spring indicate the maximum negative trend in the lower stratosphere with values about −7%/decade. For illustrative purposes, the 95% confidence limits are presented for the spring values. The greatest difference between the current results from those cited above are for winter which does not indicate as large a negative trend as previous. This appears to be due to the fact that we have removed the 2 years following the Pinatubo eruption which, for these latitudes, makes the winter trends more positive (e.g., Figure 2, first three triangle points). In addition, we note that the inclusion of the AO term within the statistics may also influence the trend results. *Appenzeller et al.* [2000] and *Weiss et al.* [2001], for example, show strong influence of the AO term on individual station trends. However, when we examined this aspect for the overall zonal average ozone, we found that the AO influence to be less important. This appears to be associated with very low values of the AO coefficient in 1989–1990 which are not associated with observed changes in ozone. This is an area that requires further analysis but is beyond the scope of this current work.

[29] Within Figure 8b we present the results for the trend change (note the different abscissa scale from Figure 8a) and we see that for the lower stratosphere the spring values are about 20%/decade and statistically significant. For these latitudes, then, the trend plus trend change in the lower stratosphere is positive, indicating an increase in the ozone amount since 1996 which is in overall agreement with the picture of total ozone presented in Figure 2.

[30] For both the trend and trend change, the question is how much of the observed changes are explainable by current understanding, both chemical and dynamic. As indicated above, the results are very seasonally dependent and, ultimately, we will have to do a complete analysis as a function of season and compare the results with both chemical models and dynamic forcing factors. For this paper the principal question is the sensitivity of the results to the inherent assumptions and the utility as a methodology. Once this is determined, we can build on the results within an appropriate statistical framework.

[31] This leads to the next question concerning our statistical method which is how sensitive are the results to the specific assumptions concerning removal of data post-Pinatubo and the specific date of the ozone inflection point.

4.3. Statistical Uncertainty

[32] To examine the statistical uncertainty of the assumptions utilized in the above results, we focus on layer 3A or 18 km and examine the trend, trend change, solar coefficient, and AO coefficient using multiple scenarios. Within Figures 9a–9d, we divide the results into four sections which correspond to removing 48, 36, 24, and 0 months following the eruption of Mt. Pinatubo in June 1991. These sections are marked at the top of each figure. Within each section we then plot results using January 1995, 1996, 1998, and 2000 as the inflection point. These are marked on the bottom of the first column. For illustrative purposes, we add the 95% confidence limits to the results with 24 months removed and inflection point in January 1996. We point out that the aerosol data from satellite and ground-based data [e.g., *Thomason*, 1991; *Russell et al.*, 1996] indicate that the aerosols are near background levels within about 3 years of

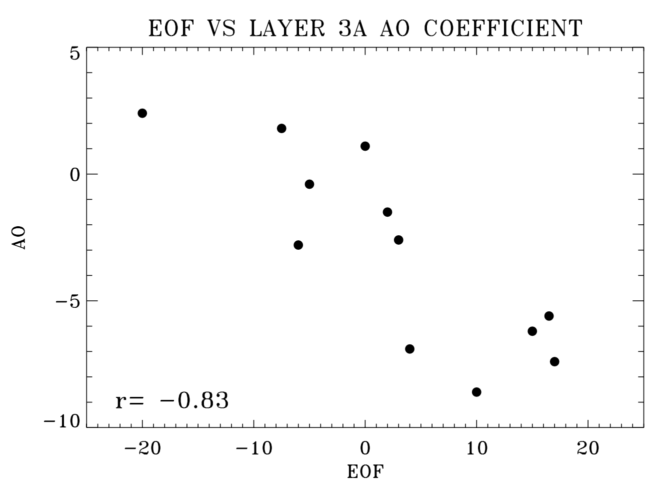

Figure 6. Plot of Layer 3A Arctic oscillation (AO) coefficient as a function of the EOF loading factor at the 12 ozonesonde stations.

Table 3. Values of R^2 for Each Station and Each Layer[a]

	Chur	Edmo	Goos	Hohe	Kago	Lind	Paye	Reso	Sapp	Tate	Uccl	Wall	AVG
1A	0.42	0.44	0.44	0.40	0.66	0.19	0.54	0.45	0.58	0.40	0.64	0.41	0.46
1B	0.50	0.47	0.32	0.61	0.54	0.23	0.58	0.34	0.52	0.38	0.33	0.33	0.43
1C	0.49	0.59	0.37	0.58	0.44	0.32	0.51	0.38	0.47	0.20	0.41	0.31	0.42
1D	0.31	0.46	0.23	0.11	0.33	0.20	0.19	0.38	0.43	0.13	0.34	0.50	0.30
2A	0.28	0.44	0.20	0.16	0.39	0.19	0.15	0.37	0.33	0.24	0.31	0.35	0.28
2B	0.44	0.50	0.28	0.23	0.50	0.33	0.24	0.44	0.42	0.19	0.31	0.33	0.35
3A	0.37	0.43	0.26	0.22	0.42	0.31	0.33	0.44	0.38	0.21	0.34	0.33	0.34
3B	0.38	0.62	0.30	0.27	0.32	0.21	0.25	0.65	0.36	0.29	0.36	0.26	0.36
4A	0.49	0.59	0.40	0.35	0.36	0.29	0.38	0.63	0.52	0.46	0.33	0.40	0.43
4B	0.47	0.52	0.44	0.46	0.42	0.31	0.41	0.45	0.61	0.55	0.30	0.54	0.46
5A	0.37	0.51	0.39	0.38	0.45	0.16	0.35	0.30	0.52	0.51	0.28	0.46	0.39
5B	0.28	0.48	0.26	0.28	0.33	0.22	0.36	0.34	0.48	0.22	0.28	0.34	0.32
6A	0.36	0.61	0.27	0.33	0.41	0.29	0.37	0.32	0.61	0.37	0.38	0.48	0.40
6B	0.38	0.58	0.18	0.46	0.50	0.28	0.44	0.24	0.53	0.46	0.37	0.46	0.41
AVG	0.40	0.52	0.31	0.35	0.43	0.25	0.36	0.41	0.48	0.33	0.36	0.39	0.38

[a]Data have been deseasonalized and 2 years deleted after the eruption of Mt. Pinatubo. Averages are the linear averages down columns and across rows.

the Pinatubo eruption so that our choice of inflection points should be effective in removing the impact.

[33] Examining the results for the trend (Figure 9a), we see several points. Not removing any data results in the largest negative trend for each inflection point with the differences up to about 1% per decade. For each inflection point, the impact of removing 24 versus 48 months appears to be relatively minor. The impact of changing the inflection point within each category with data removed is about 1 to 1 1/2% per decade with the tendency for the later inflection points to be less negative than the earlier ones. This is consistent with the notion advanced previously that the data are not continuing with the same negative trend and quantifies the effect. All results are within the 95% confidence limits of the data.

[34] Looking next at the trend change coefficient, Figure 9b (note the different ordinate scale from Figure 9a), we see a quite similar overall effect though the magnitudes are quite different. With no data removed the trend changes are quite large and include the recovery from the Pinatubo eruption. The results for the same inflection point, but with the various data sets removed, are relatively consistent and are within about 1% per decade. Within each category of data removal, however, the effect of the change in inflection point is up to about 5% per decade with the inflection point in 2000 being the most positive within the groupings. This inflection point has, of course, the least amount of data following the date of inflection. If we restrict consideration of the change in inflection point to the period 1995–1998, the effect is lessened to about 2% per decade. The confidence limits of the data are about 6% per decade so that all results are not statistically apart.

[35] The solar coefficients are plotted within Figure 9c. For this case the 95% confidence limits are about 1 1/2

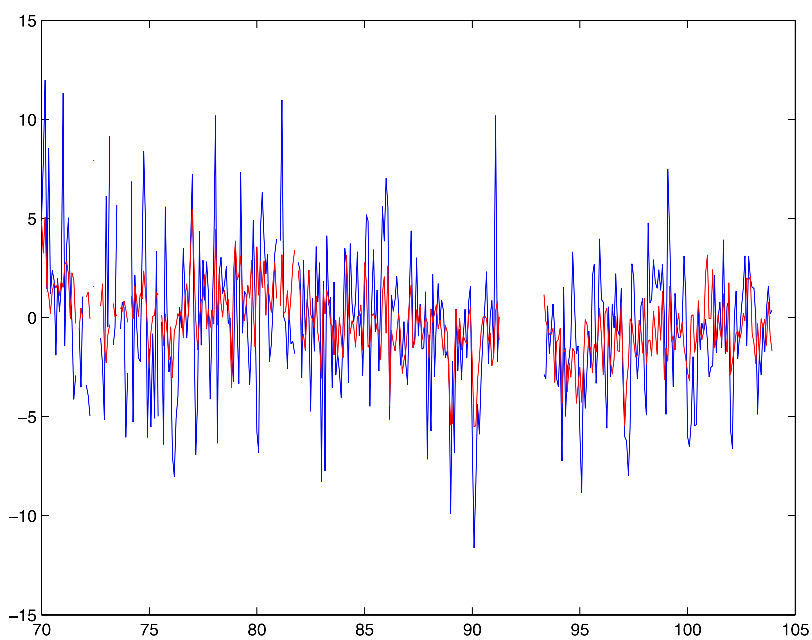

Figure 7. Plot of ozone anomalies as function of time at Payerne for Layer 3A. Blue line represents the data and the red line represents the regression fit to the data. In the abscissa, 70 refers to 1970 and 100 refers to 2000. : Dobson Units.

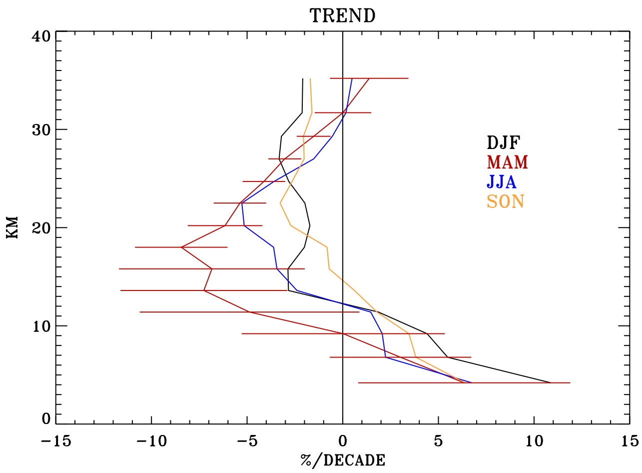

Figure 8a. Average computed trends as a function of altitude for each season. Winter is defined as DJF, Spring is MAM, Summer is JJA, and Fall is SON.

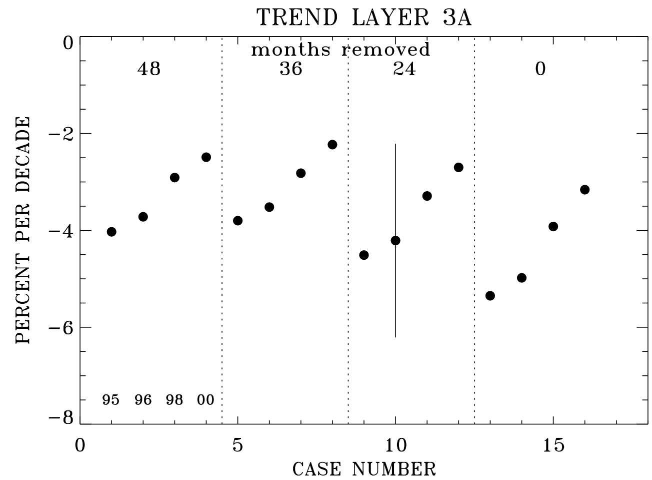

Figure 9a. Trend results plotted for Layer 3A (18 km) as a function of months removed and date of inflection point.

percent per 100 f10.7 units. The coefficients are generally negative for this layer, but the confidence limits are so large that there is little that can be stated with certainty. The results for the AO coefficient, Figure 9d, on the other hand, indicate that the results are quite consistent amongst all scenarios and are statistically different from zero.

[36] As a final comment within this section, we have computed the explained variance for the results for layer 3A and the case of removing 24 months with inflection point in January 1996. The explained variance tends to be about 28% for the solar and AO terms.

4.4. Spatial Representativeness

[37] The final question to be answered in this section is how representative are the results from the 12 stations compared to a zonal average. To help answer this question, we have utilized the total ozone associated with each ozonesonde profile and compared the statistics with those computed from the zonal average data derived from the SBUV/(2) instruments [*Miller et al.*, 2002]. As the SBUV/(2) data begin in 1979, as opposed to the ozonesonde data in 1970, this confuses the issue. Therefore we also plot the ozonesonde results with a start date of 1979 so that we can, in addition, ascertain the impact of beginning the time series in 1970 versus 1979.

[38] Figure 10a presents the results for the trend computations, as before, as a function of data removed and date of inflection point. For this case, we plot the 95% confidence limits computed from the satellite observations. Overall, we see the largest impact arises from the length of the data. Beginning the ozonesonde trends in 1970 shows virtually no impact of inflection point, but that the station results beginning in 1979 do indicate a trend that has a range of about 1% per decade. The comparison of the shorter-term satellite and station data indicate a similar behavior with inflection point and the trends are within about 0.5% per decade with the stations being more negative. These results are well within the approximate 1% per decade confidence limits of the satellite data.

[39] The total ozone trend change results presented in Figure 10b also indicate that the difference between the stations and the zonal average satellite observations is more a function of the start time of the series than the observation type. The satellite and station data beginning in 1979 agree

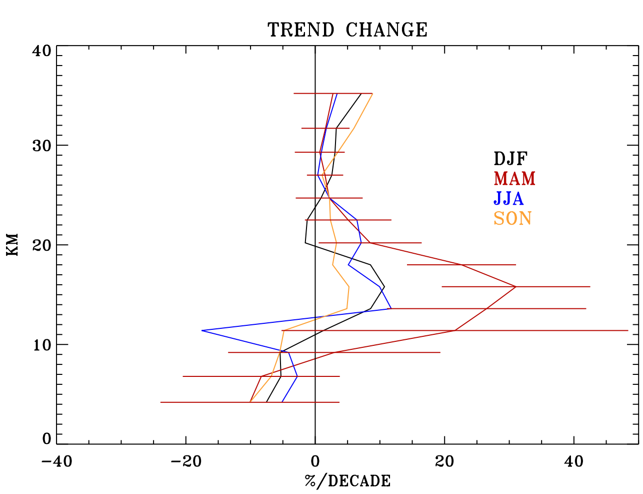

Figure 8b. Same gure 8a for trend change.

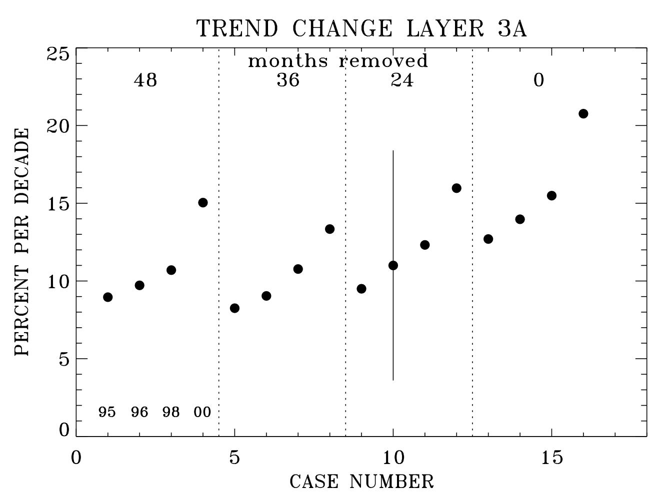

Figure 9b. Same as Figure 9a for trend change.

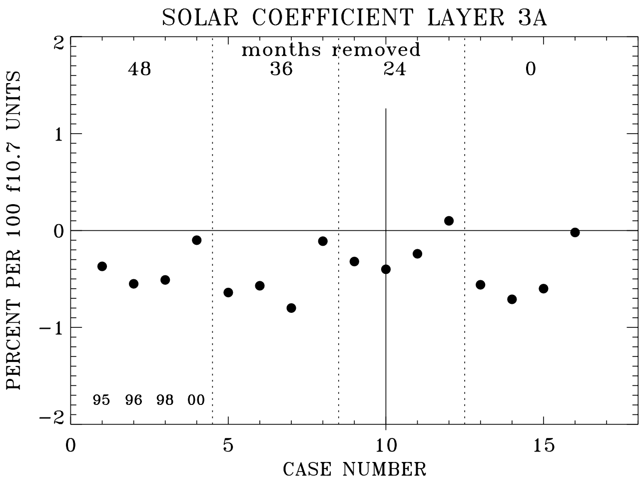

Figure 9c. Same as Figure 9a for solar coefficient.

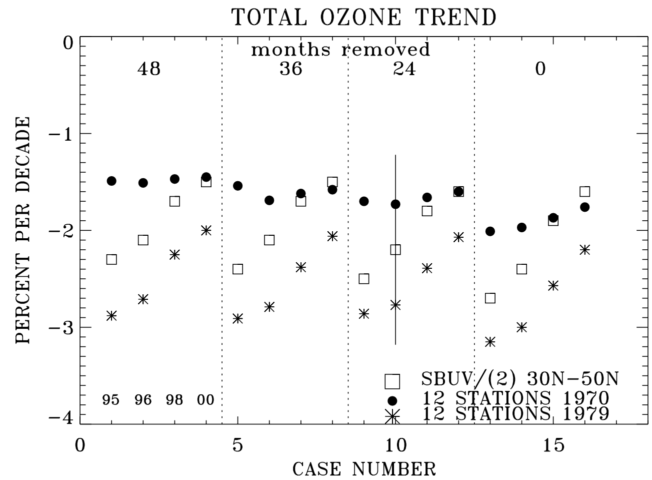

Figure 10a. Results presented as Figure 9a for total ozone trend derived from 12 stations beginning in 1970, the same stations beginning in 1979 and the SBUV/(2) satellite data beginning in 1979.

to within about 1% per decade (save for inflection point at year 2000 when it is about 2%) and show similar impacts of inflection point. The impact of changing the inflection point is to increase the trend change coefficient by about 3% per decade from 1995 to 2000. Overall, the notion of how large is the trend along with the trend change is very much a function of the length of record. This result agrees with the information provided in Figure 1 and also in Tables 4–7 of *WMO* [1998] which indicates an annual trend for the region 35°N–60°N of −2.3 % per decade for the period 1970–1997 and −3.7 % per decade over the period 1979–1997.

[40] All of the above argues that the 12 stations are quite representative of the zonal average. On the other hand, the impact of the length of time series is substantial and indicates that we must be very careful not to overinterpret the statistical results.

5. Concluding Remarks

[41] After examining the utilization of the trend and trend change methodology on the Northern Hemisphere midlatitude ozonesonde stations, along with the sensitivity of the assumptions, the results can be summarized for the lower stratosphere as follows.

[42] 1. The impacts of deleting up to 4 years of data and changing the inflection point from 1995 to 2000 are nontrivial, but that the overall results are consistent.

[43] 2. There has been a major change in the ozone trend within the time frame of 1996.

[44] 3. The ozone in the lower stratosphere has been increasing from that approximate time.

[45] 4. A reasonable scenario is to utilize a change point in 1996 and remove 2 years of data post Mt. Pinatubo eruption.

[46] 5. Including a term for the Arctic oscillation within the statistical model demonstrates that it is statistically significant. Thus inclusion of stratosphere-troposphere linkages is an important aspect that must be included within the physical models.

[47] 6. Comparison of the total ozone trend and trend change from the12 station average with the zonal average

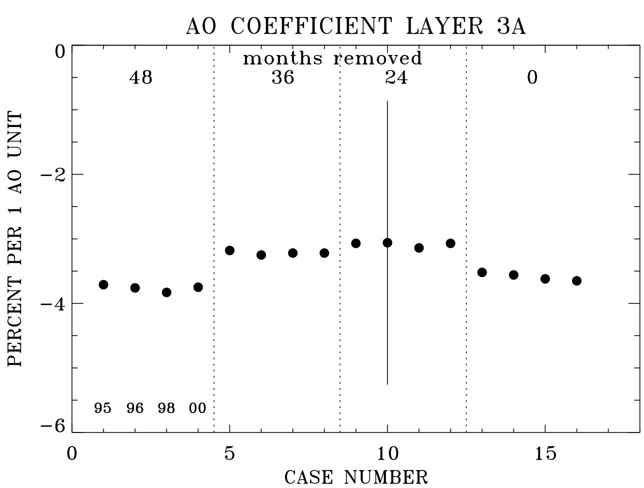

Figure 9d. Same ure 9a for AO coefficient.

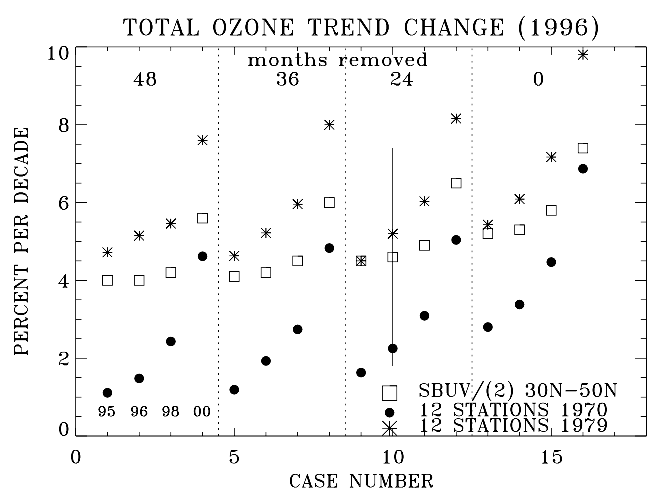

Figure 10b. Same as Figure 10a for total ozone trend change.

derived from satellite data indicates that the average of the 12 stations is quite representative of the zonal mean.

[48] 7. However, examination of the station results beginning in 1970 versus 1979 indicates substantial effects such that we must be very careful not to overinterpret the results.

[49] A major element of this paper has been the discussion of the sensitivity of the results using the particular statistical technique of trend and trend change to the assumptions invoked. What has not been included at this point is a comprehensive examination of attribution of cause and effect. How much of the observed changes can be explained by chemical theory and dynamic influences and how much remains to be explained? With our confidence in the methodology delimited, we can now extend this analysis utilizing the scenario of removing 2 years after Pinatubo and 1996 as the inflection point as the standard. From this, we will compare the results with available model computations as a function of season and also examine the impacts of several possible dynamic variables such as the Arctic oscillation and the Eliassen-Palm flux [e.g., *Guillas et al.*, 2004].

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A. Cai, Department of Information and Decision Sciences, University of Illinois at Chicago, Chicago, IL 60607, USA.

V. Fioletov, Environment Canada, Toronto, Ontario, Canada.

L. E. Flynn, NOAA/NESDIS, Camp Springs, MD 20746, USA.

S. Guillas, Georgia Institute of Technology, Atlanta, GA, USA.

A. J. Miller, R. M. Nagatani, and S.-K. Yang, NOAA/NWS/NCEP/Climate Prediction Center, Camp Springs, MD 20746, USA. (alvin.miller@noaa.gov)

X.-L. Meng, Harvard University, Cambridge, MA, USA.

I. Petropavlovskikh and E. C. Weatherhead, Cooperative Institute for Research in the Environmental Sciences, University of Colorado, Boulder, CO 80309, USA.

G. Tiao, Graduate School of Business, University of Chicago, Chicago, IL 60637, USA.

D. J. Wuebbles, Department of Atmospheric Sciences, University of Illinois at Urbana-Champaign, Champaign, IL 61801, USA.