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Chicago, Illinois USA

TECHNICAL REPORT NO. 13

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DYNAMICAL CONTRIBUTIONS**

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February 2002  
Revised: February 2005



Although the research described in this article has been funded wholly or in part by the United States Environmental Protection Agency through STAR Cooperative Agreement #R-82940201 to The University of Chicago, it has not been subjected to the Agency's required peer and policy review and therefore does not necessarily reflect the views of the Agency, and no official endorsement should be inferred.

February 18, 2004; revised Oct. 30, 2004; revised Feb. 1, 2005

## **Trend analysis of total ozone data for turnaround and dynamical contributions**

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**Abstract.** Statistical trend analyses have been performed for monthly zonal average total ozone data from both TOMS and SBUV satellite sources and ground-based instruments over the period 1978–2002 for detection of a ‘turnaround’ in the previous downward trend behavior and hence evidence for the beginning of an ozone recovery. Since other climatic and geophysical changes can impact ozone behavior and can influence the detection of turnaround and recovery, we also focus on accounting for ozone variations that may be ascribed to various physical and chemical influences. Thus we include in the statistical trend modeling and analysis the effects of various dynamical and circulation variations in the atmosphere, including those associated with the quasibiennial oscillation (QBO), Arctic oscillation (AO) and Antarctic oscillation (AAO), and Eliassen-Palm (EP) flux influences, as well as influences of solar cycle. A notable result of the analysis is that for latitude zones of 40° and above in both hemispheres, large positive and significant estimates of a change in trend (since 1996) are obtained (on the order of 1.5 to 3 DU per year). The dynamic index series, AO/AAO and EP flux, are found to have a substantial influence on total ozone for these higher latitudes, and significant influences of lesser magnitude are also found for lower latitudes. The feature of positive significant change in trend in total ozone over recent years, however, is obtained both without and with the dynamical index terms included in the statistical models.

### **1. Introduction**

Current numerical models indicate that atmospheric ozone at midlatitudes should begin to show a recovery and that we should start seeing a change or lessening in ozone depletion rates given the implementation of international controls on ozone depleting chemicals [*WMO*, 1999, 2003]. Consequently, there is considerable interest in detecting various stages of ozone recovery. The role of dynamics, climate change, atmospheric conditions, and CH<sub>4</sub>, H<sub>2</sub>O, and NO<sub>x</sub> chemistry as well as uncertainties in predicting and determining the peak abundances of ozone depleting substances all complicate the timing of ozone recovery. These factors add considerable uncertainty to determining a possible turnaround or change in ozone trends.

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A fundamental question to address using the available ozone data is how soon might we be able to detect, in a statistically significant manner, that a leveling off or a turnaround in ozone trend is occurring. The statistical factors and data characteristics that affect the ability to detect trends in environmental variables and length of data requirements for detection were addressed in a general sense by *Tiao et al.* [1990] and *Weatherhead et al.* [1998], and more recently with a particular focus on total ozone data by *Weatherhead et al.* [2000] and *Reinsel et al.* [2002]. In particular, *Reinsel et al.* [2002] advanced the statistical techniques to incorporate a turning point or change point in trend and look for a change, or lessening, in the negative trend in ozone. They differentiated between the detection of a change in downward trend (slowdown or turnaround) and the detection of a positive trend (recovery) after the change. Their findings showed that detection of a change in trend might be possible with considerably fewer years of data after the change (on the order of 7 years required) than the number of years required for detection of a positive trend after the change (on the order of 20 years). *Reinsel* [2000] reported the first evidence of a positive change in trend in upper stratospheric (35-45 km) ozone measured at three ground-based stations, and more recently, *Newchurch et al.* [2003] applied related statistical techniques to upper stratospheric ozone data from SAGE and HALOE to find evidence for a slowdown in upper stratospheric ozone losses globally.

In this study, we first briefly review the statistical model that incorporates a change in trend, and then apply the statistical techniques to analysis of two satellite total ozone data sets, as well as ground-based total ozone data, to address changes in rate of decline in total column ozone. Since ozone trend behavior may be affected by further natural dynamical and chemical influences, inclusion of various additional explanatory factors to account for such influences is also considered with an attempt to ascribe the ‘overall trend’ variations of ozone to contributions from various sources.

## 2. Basic Statistical Model and Analysis for Detecting a Change in Trend

As reported by *Reinsel et al.* (2002), changes in environmental variables are commonly modeled as being a smooth change, and many statistical trend analyses of available data typically represent the change as linear or piecewise linear [e.g., *Stolarski et al.*, 1992; *Reinsel et al.*, 1994]. Although this may never be the actual case, it allows a simple approximation of the direction and magnitude of changes in the data. For ozone, a lessening in the decline and eventual increase in total column levels (relative to current depleted levels) is expected to have started beginning in the late 1990s and hence we expect a change in trend from the declining values which have occurred in prior years. Thus, our focus is to investigate the detection of a trend, or detection of a change in trend, when there is a turning point in the linear trend behavior. The statistical model used in this process is described in detail in *Reinsel et al.* (2002) and can be summarized as follows.

Suppose we wish to detect such a possible change in linear trend based on  $T$  observations, with  $T_0$  consecutive observations obtained starting from some initial time  $t = 1$  prior to the specified change date, and  $T_1$  consecutive observations from  $T_0$  onwards ( $T = T_0 + T_1$ ). The piecewise linear trend model is written as

$$Y_t = \mu + S_t + \omega_1 X_{1t} + \omega_2 X_{2t} + N_t, \quad t = 1, \dots, T \quad (1)$$

and described by *Reinsel et al.* (2002). Here,  $t$  is in months,  $Y_t$  denotes the monthly average measurement of the geophysical or environmental variable of interest, either on its original scale or after a transformation (most often a log transformation),  $\mu$  is a baseline constant or mean level term, and  $S_t$  is a seasonal component that can often be represented as

$$S_t = \sum_{j=1}^4 [\beta_{1j} \sin(2\pi j t / 12) + \beta_{2j} \cos(2\pi j t / 12)],$$

containing four cosine and four sine waves.  $X_{1t} = t/12$  is a linear trend function,  $\omega_1$  represents a linear trend beginning at time  $t = 0$ , and  $\omega_2$  represents the magnitude of a possible *change* in trend at time  $t = T_0$ . That is,

$$X_{2t} = \begin{cases} 0, & 0 < t < T_0, \\ (t - T_0)/12, & T_0 < t \leq T. \end{cases}$$

The model contains the unexplained noise term,  $N_t$ , most often assumed to be autoregressive with a time lag of 1 month. That is,  $\{N_t\}$  satisfies  $N_t = \phi N_{t-1} + \varepsilon_t$ , where the  $\varepsilon_t$  are independent random variables with mean 0 and common variance  $\sigma_\varepsilon^2$ . It is also assumed the autocorrelation,  $\phi$ , is between -1 and 1 so that the process  $\{N_t\}$  is stationary, with  $\text{Var}(N_t) = \sigma_N^2 = \sigma_\varepsilon^2 / (1 - \phi^2)$ .

Under the statistical model in (1), we can estimate the trend  $\omega_1$  and change in trend  $\omega_2$  by maximum likelihood or equivalently generalized least squares (GLS) estimation. Expressions for the standard deviations of the corresponding GLS estimates  $\hat{\omega}_1$  and  $\hat{\omega}_2$  can be derived, and are provided by *Reinsel et al.* [2002], as a function of  $\phi$ ,  $N$ ,  $T_0$ , and  $T$ . *Reinsel et al.* [2002] also provided several numerical illustrations of the number of years of data required for detecting that a positive change in trend (i.e., ‘turnaround’ or change point) occurs after  $T_0$ ,  $\omega_2 > 0$ , and for detecting that a positive overall trend (i.e., ‘recovery’) occurs after  $T_0$ ,  $\omega = \omega_1 + \omega_2 > 0$ .

### 3. Analysis of Merged TOMS/SBUV Satellite Zonal Total Ozone Data

We first consider analysis of zonal monthly averages of a merged TOMS/SBUV satellite total ozone data set (Stolarski and Hollandsworth Frith, see [http://code916.gsfc.nasa.gov/Data\\_services/merged](http://code916.gsfc.nasa.gov/Data_services/merged) for details), over the period November 1978 through December 2002, to illustrate the detection of a possible change in trend. Estimation results will be presented for zonal average data from twelve 5° latitude bands over the range of 65°S–65°N. The deseasonalized zonal average values of these merged satellite data for twelve 5°-latitude zones from 65°S–65°N are displayed in Figure 1. The plots show that there is considerable variability at time scales longer than one month. Some of this variability can be statistically explained with the dynamical indices shown in Section 3.1. Figure 1 also shows that the magnitude of the downward trend and more recent indications of recovery are more visually observable for some latitude bands.

For the higher latitudes, these plots suggest that total ozone values may have been slightly increasing or at least leveling off over the past few years. Therefore, for purposes of exploring the possible ozone turnaround and illustration of the statistical methodology and related issues, we consider estimation of a trend model similar to (1), which includes a change in trend at time  $T_0$ ,

$$Y_t = \mu + S_t + \omega_1 X_{1t} + \omega_2 X_{2t} + \gamma_1 Z_{1,t} + \gamma_2 Z_{2,t+k} + N_t, \quad 0 < t \leq T, \quad (2)$$

where  $X_{1t}$  and  $X_{2t}$  are trend functions as defined in model (1),  $Z_{1,t}$  is the f10.7 cm solar radio flux series,  $Z_{2,t+k}$  is the 50 mb equatorial QBO wind series at Singapore lagged  $k$  months, and  $N_t$  is the unexplained noise term assumed to be an AR(1) (Box et al. 1994) process as in model (1). We, in fact, also allow for one further modification to this model, in which the QBO wind term is allowed to have coefficients which are seasonally dependent, that is, the term  $\gamma_2 Z_{2,t+k}$  in the statistical model (2) is replaced by  $[\gamma_{2,0} + \gamma_{2,1} \sin(2\pi t/12) + \gamma_{2,2} \cos(2\pi t/12)] Z_{2,t+k}$ . This modification to

the QBO factor seems to be useful primarily for latitudes between about 10° and 50° in both hemispheres.

Based on a casual inspection of the deseasonalized monthly ozone values in Figure 1, the date  $T_0$  of change in trend is specified as January 1996. A precise change date is difficult to determine. Analyses, similar to those reported by Newchurch et al. (2003), indicate that the results presented here are not sensitive to changing this date by as much as two years. This specified statistical model in (2), with linear trend, change in trend, solar flux and lagged (seasonally dependent) QBO wind terms included, was estimated over 1979–2002 for total ozone series for each of the 5° latitude zones in 65°S–65°N. To somewhat lessen the possible impact of the abnormally low ozone values during the winter-spring of 1993 (e.g., see Figure 1), related to the Pinatubo volcanic eruption, in our analyses we have omitted data for the six-month period December 1992 through May 1993. While there is direct evidence that aerosols from Pinatubo remained in the stratosphere for considerably longer than this time period, omitting larger time spans did not noticeably change the derived trends.

In the statistical model (2), only solar and QBO terms are included as explanatory factors to represent certain types of chemical and dynamical influences on total ozone. We now also consider additional factors that might explain other particular influences on ozone variations. One factor is the large-scale dynamical circulation processes, which are reflected in climate patterns such as the North Atlantic Oscillation (NAO) or the Arctic Oscillation (AO), for the Northern Hemisphere, and the Antarctic Oscillation (AAO), for the Southern Hemisphere. For the Northern Hemisphere, these have also been shown to be correlated with tropopause pressure [Appenzeller et al., 2000; Weiss et al., 2001]. Another factor relates to energy-exchange between the troposphere and stratosphere, represented as lower stratosphere Eliassen-Palm (EP) flux terms in both the Northern and Southern Hemispheres. Another possible factor relates to stratospheric aerosols resulting from volcanic eruptions, as increased amounts of aerosol loading in the stratosphere can cause enhancement of ozone destruction through chemical reactions on the surfaces of the aerosol droplets.

In addition to the basic model (2) that includes trend, solar flux, and QBO wind terms, we estimate and present results for an additional regression-time series model fitted to the total ozone zonal series. This model includes Arctic/Antarctic oscillation (AO/AAO) index terms and EP flux terms to account for dynamical effects on ozone. More specifically, the Arctic oscillation (AO) index series for the Northern Hemisphere and Antarctic oscillation (AAO) index series for the Southern Hemisphere,  $Z_{3t}$ , used in the statistical model are climatic variables similar to that considered by Thompson and Wallace [1998]. The AO series is calculated at 1000 hPa and the AAO series at 850 hPa due to the height of the Antarctic continent. The series may be interpreted as a signature of modulation in the strength of the polar vortex, and has recently been considered in ozone trend studies of the Payerne balloon soundings data by Weiss et al. [2001]. The AO and AAO index series, as well as smoothed ‘trend’ curves obtained by local temporal averaging, are plotted in Figure 2a-b. For higher latitudes, we find that ozone is related to the AO/AAO index series  $Z_{3t}$  contemporaneously and also with time lags of a few months. Therefore, the general AO/AAO term included in the statistical model is of the form  $\gamma_{3,0}Z_{3,t} + \gamma_{3,1}Z_{3,t-1} + \gamma_{3,2}Z_{3,t-2}$ .

Similarly, we include the lower stratosphere EP flux series,  $Z_{4t}$ , in the model with time lags, so that the general term in the statistical model is of the form  $\gamma_{4,0}Z_{4,t} + \gamma_{4,1}Z_{4,t-1} + \gamma_{4,2}Z_{4,t-2}$ . The EP flux dynamical time series are calculated as eddy heat flux at 100 hPa and area-averaged over 30°–90° latitude in each hemisphere, and are similar to those used recently by Randel et al. [2002] in their study of correlations between total ozone and lower stratosphere EP flux (also see Fusco and Salby [1999]). The EP flux series may serve as a useful dynamical proxy variable for upwelling

planetary wave activity. The deseasonalized EP flux time series used in the analysis for Northern and Southern Hemispheres are plotted in Figure 2c-d. Ideally, it might also be desirable to include some explanatory factor in the model to account for ‘special’ effects on ozone from stratospheric aerosols, perhaps using a proxy variable based on stratospheric optical thickness measurements. The volcanic effects would be most prominent during the period related to the Mount Pinatubo volcanic eruption. In lieu of attempting to formulate such an explanatory factor, as noted previously, we have simply estimated the statistical model with ozone data omitted for the period of six months, from Dec. 1992–May 1993, the period most severely affected as a result of Pinatubo.

Figure 3 shows the resulting trend estimates  $\hat{\omega}_1$ , change in trend estimates  $\hat{\omega}_2$ , overall trend estimates  $\hat{\omega} = \hat{\omega}_1 + \hat{\omega}_2$ , autocorrelation estimates  $\hat{\phi}$ , and noise standard deviation estimates  $\hat{\sigma}_N$  versus the middle latitude of each zone for 65°S–65°N. The merged TOMS/SBUV estimation results for zones in 25°–55°N are also displayed in Table 1. The solar coefficient estimates are generally at least slightly statistically significant over a large number of the latitude bands and the QBO effect estimates are highly statistically significant across nearly all latitude bands. As is well known, the pre-turnaround trend estimates  $\hat{\omega}_1$  for higher latitudes (e.g., above about 25°) in both hemispheres are highly negative and statistically significant, and increase in magnitude with increasing latitude. Quite large positive (and statistically significant) estimates  $\hat{\omega}_2$  of the change in trend, as well as large estimates  $\hat{\omega}$  of the overall trend, are found in the merged TOMS/SBUV data for latitudes of 40°N and above in the Northern Hemisphere and 45°S and above in the Southern Hemisphere.

We emphasize, however, that these estimates of change in trend  $\hat{\omega}_2$  and overall trend  $\hat{\omega}$  for the higher latitudes are more positive than would be expected from physical model considerations [e.g., Andersen *et al.*, 2003] that account only for changes in atmospheric concentrations of ozone-depleting compounds. The estimates therefore need to be interpreted with much caution and cannot be viewed with high reliability. The results depend on the presumption that the observed short-term tendency over the past several years (since 1996) is consistent with an “actual” longer-term trend behavior. The very recent ozone trend behavior is also probably influenced to an extent by the meteorological conditions of the past few years. Hence the positive change in trend estimates, while suggestive, are based on a relatively short data record since 1996 and might not be viewed at this time as clear evidence of an ozone turnaround.

**Table 1.** Results of trend estimation, change in trend, and overall trend from statistical model (2), with data omitted during Dec. 1992–May 1993, based on monthly zonal average merged TOMS/SBUV total ozone data in 5° latitude bands over 25°–55°N for the period Nov. 1978–2002.

Zone	Trend $\hat{\omega}_1$	Change $\hat{\omega}_2$	Overall $\hat{\omega}$	Solar $\hat{\gamma}_1$	QBO	$\hat{\phi}$	$\hat{\sigma}_N$
50°–55°N	-1.12(0.22)	3.03(0.79)	1.91(0.64)	-0.16(1.56)	0.96(0.30)	0.659	7.567
45°–50°N	-1.08(0.20)	2.81(0.71)	1.73(0.57)	-0.45(1.45)	1.13(0.27)	0.634	7.074
40°–45°N	-0.92(0.19)	2.13(0.67)	1.21(0.54)	-0.12(1.36)	1.08(0.25)	0.644	6.594
35°–40°N	-0.69(0.19)	1.30(0.68)	0.61(0.55)	1.50(1.24)	1.17(0.23)	0.712	6.046
30°–35°N	-0.48(0.18)	0.64(0.64)	0.15(0.51)	3.18(1.09)	1.17(0.20)	0.740	5.404
25°–30°N	-0.34(0.16)	0.52(0.58)	0.18(0.47)	3.38(0.92)	1.12(0.17)	0.771	4.657

Trend and change in trend estimates in DU per year, solar estimate in DU per 100 solar flux units, and QBO estimate in DU per 10 knots wind. Standard errors of estimates are given in

parentheses. The standard error takes into account the uncertainty due to both the magnitude of variability and the autocorrelation.

Further estimation results for the expanded regression-time series model that includes the AO/AAO index and EP flux terms are obtained for the merged TOMS/SBUV zonal total ozone data. The resulting estimation results are displayed in Figure 3, along with results for the previous model without AO/AAO and EP flux terms for comparison. For ease of comparison, merged TOMS/SBUV results with the AO/AAO index terms and EP flux terms included as explanatory factors are also displayed in Table 2 for the same latitude zones as in Table 1.

**Table 2.** Results of trend estimation, change in trend, and overall trend from statistical model (2), with data omitted during Dec. 1992–May 1993, and with Arctic and Antarctic oscillation terms and EP flux terms using lags up to 2 months included, based on monthly zonal average merged TOMS/SBUV total ozone data in 5° latitude bands over 25°–55°N for the period Nov. 1978–2002.

Zone	Trend $\hat{\omega}_1$	Change $\hat{\omega}_2$	Overall $\hat{\omega}$	Solar $\hat{\gamma}_1$	QBO	Arctic	Phi $\hat{\phi}$	$\hat{\sigma}_N$
50°–55°N	-0.92(0.19)	2.31(0.68)	1.38(0.55)	1.58(1.39)	0.90(0.26)	-4.911	0.641	6.629
45°–50°N	-0.87(0.17)	2.01(0.60)	1.14(0.48)	1.48(1.24)	1.16(0.23)	-5.671	0.625	5.930
40°–45°N	-0.78(0.17)	1.56(0.60)	0.77(0.48)	1.31(1.22)	1.21(0.23)	-4.771	0.642	5.846
35°–40°N	-0.64(0.19)	1.08(0.67)	0.43(0.54)	1.97(1.21)	1.17(0.23)	-2.315	0.715	5.853
30°–35°N	-0.50(0.18)	0.70(0.65)	0.19(0.52)	3.01(1.10)	1.15(0.20)	-0.329	0.749	5.404
25°–30°N	-0.39(0.17)	0.70(0.59)	0.30(0.48)	2.97(0.91)	1.10(0.17)	0.621	0.786	4.624

Trend and change in trend estimates in DU/yr, solar estimate in DU/100 flux units, QBO estimate in DU/10 knots. Overall AO estimate, in DU/index unit, is sum of 3 coefficient terms. Standard errors of estimates are given in parentheses.

The results in Figure 3 suggest that the AO/AAO coefficient terms at time lags 0, 1, and 2 months are negative and highly significant for latitudes from 35°N–60°N and 40°S–60°S, and positive at lag 0 for 65°N and 65°S. The EP flux coefficient terms are most significant at time lag 1 month for all latitudes. For latitudes of 50°N and above for the Northern Hemisphere and 40°S and above for the Southern Hemisphere, this effect of EP flux on total ozone is positive and relatively large in magnitude; for lower latitudes in both hemispheres, the effect is negative and smaller in magnitude, although statistically significant. The effects on total ozone due to AO/AAO and to EP flux influences both show rather strong symmetry between the Northern and Southern Hemispheres. Inclusion of the AO/AAO and EP flux terms has substantial impact in reducing the magnitude of the noise standard deviation  $\sigma_N$  for higher latitudes (40° and above). For these higher latitudes, values of  $\sigma_N^2$  are reduced by 20% to 30% which means that the AO/AAO and EP flux terms are explaining about 20–30% of the remaining month-to-month variance of the noise  $N_t$  in total ozone (after accounting for influences of linear trend, solar flux, and QBO).

Inclusion of AO/AAO and EP flux terms also mildly decreases the magnitude of the pre- turnaround trend  $\hat{\omega}_1$ , by about 0.2 DU/yr, and substantially reduces the magnitude of the change in trend estimate  $\hat{\omega}_2$ , by about 0.6 DU/yr, for the 35°–65°N latitude zones. In percent terms, magnitudes of the trend estimate  $\hat{\omega}_1$  are reduced by about 15% to 20% and magnitudes of  $\hat{\omega}_2$  are reduced by 20% to 25%, so one can interpret that approximately these percentages of the long-term total ozone trend in 35°–65°N may be accounted for by the contributions from AO and EP

flux behavior. An additional impact of the inclusion of the AO terms in the model for these latitude zones is that it substantially increases the solar effect estimates to more positive values, due to the mild positive correlation (equal to about 0.15) between the AO and f10.7 solar time series. For lower latitude zones, although the AO/AAO and EP flux coefficients show some statistical significance, inclusion of these terms has little impact on trend or other estimates for these latitudes.

Thus, in summary, we note the following general features that result from inclusion of the AO index and EP flux terms as additional explanatory factors in estimation of the expanded model, mainly for latitude bands above 35°N:

- (i) substantial magnitude of coefficient estimates for overall AO index and EP flux effects on ozone for latitudes above 35°N, with largest effects in the 40°N to 55°N range for AO (negative) and 50°N to 65°N range for EP flux (positive),
- (ii) decrease in magnitudes of  $\hat{\sigma}_N$ , with associated decreases in standard errors for regression parameter estimates,
- (iii) small decrease in magnitude of ‘pre-turnaround’ trend estimate  $\hat{\omega}_1$ ,
- (iv) reduction in magnitude of the change in trend estimate  $\hat{\omega}_2$ ,
- (v) increase in magnitude of the solar effect estimate,  $\hat{\gamma}_1$ ,
- (vi) stability of the QBO effect estimate over different models.

A graphical example to illustrate the various explanatory factors to the overall behavior of total ozone is provided in Figure 4 for 40°–45°N. The deseasonalized merged TOMS/SBUV total ozone series for 40°–45°N is presented in the top panel. The combined effect of the explanatory components (including linear trend terms) is represented in the next panel, and the remaining noise series  $N_t$  is shown in the bottom panel. The vertical scale used in Figure 4 is the same, in DU, for all panels. We see that for 40°–45°N the AO index and QBO terms make substantial contributions to total ozone behavior, with much lesser contributions from the EP flux terms and the solar component. Overall we find that the explanatory components (including trend) in the statistical model can account for about two-thirds of the variance of the deseasonalized total ozone series for the 40°–45°N latitude series.

#### 4. Analysis of SBUV(/2) Satellite Zonal Total Ozone Data

We also consider analysis of zonal monthly averages of a cohesive SBUV(/2) total ozone data set from NOAA satellites [Miller *et al.*, 2002], for the latitude range of 70°S–70°N, over the period November 1978 through December 2002. Again, we entertain the fitting of the statistical model (2), which includes a change in trend, to the SBUV(/2) total ozone data, using the same date of January 1996 for the change date  $T_0$ . The deseasonalized zonal average values of these SBUV(/2) total ozone data for the 10-degree latitude zones in 70°S–70°N are displayed in Figure 5. As with the merged TOMS/SBUV data analysis, in the analysis of the SBUV(/2) data the seasonally-dependent QBO terms are included in model (2), as additional explanatory factors for total ozone, and data during Dec. 1992–May 1993, which may be influenced by the Pinatubo volcanic eruption, have been omitted. Similar to Figure 1, the data are presented for all latitudes to show the variability, trends and changes in trends by latitude.

The statistical model (2) was estimated for the 10-degree latitude zones in 70°S–70°N, and estimation results for all latitude zones are depicted in Figure 6, in similar style to those in Figure 3 for the merged TOMS/SBUV data. Estimation results for the four latitude zones 20°N–60°N are also presented in Table 3 for comparison with previous results from merged TOMS/SBUV total ozone data. We also derive estimates using the more general model, which includes the AO/AAO index terms,

$$\sum_{j=0}^2 \gamma_{3,j} Z_{3,t-j}$$

and EP flux terms,

$$\sum_{j=0}^2 \gamma_4 Z_{4,t-j}$$

The estimation results of this expanded model for the SBUV(/2) data are depicted in Figure 6 for all latitudes in 70°S–70°N, and are also summarized in Table 4 for the four latitude zones in 20°N–60°N. Fairly similar features are found in these model estimation results, relative to model results without the AO/AAO and EP flux terms included, as were seen in the merged TOMS/SBUV data results. In particular, magnitudes and general features of the estimated AO/AAO and EP flux effects on total ozone as a function of latitude are comparable with those obtained from the merged TOMS/SBUV data analysis. In addition, the inclusion of AO/AAO and EP flux terms has comparable effects on the magnitudes of the trend, change in trend, and solar estimates, as well as on reducing the noise variance  $\sigma_N^2$  in higher latitudes.

For the analyses both without and with the AO/AAO and EP flux terms included, however, we find that in the higher latitudes (above 20°) the pre-turnaround trend estimates  $\hat{\omega}_1$  are somewhat more negative for the SBUV(/2) data relative to the merged TOMS/SBUV data, and the change in trend estimates  $\hat{\omega}_2$  are more positive. Differences in the pre-turnaround trend estimates  $\hat{\omega}_1$  between SBUV(/2) and merged TOMS/SBUV data are on the order of -0.3 DU/year, and differences in the change in trend estimates  $\hat{\omega}_2$  are on the order of 0.6 DU/year, for the higher latitudes. The SBUV(/2) data also give somewhat less positive (more negative) estimates of the solar effect than merged TOMS/SBUV data in the higher latitudes of both hemispheres, with differences on the order of -1.1 DU/100 flux units.

**Table 3.** Results of trend estimation, change in trend, and overall trend from statistical model (2), with data omitted during Dec. 1992–May 1993, based on 50°–60°N, 40°–50°N, 30°–40°N, and 20°–30°N monthly zonal average SBUV(/2) total ozone data for period Nov. 1978–2002.

Zone	Trend, $\hat{\omega}_1$	Change, $\hat{\omega}_2$	Overall, $\hat{\omega}$	Solar $\hat{\gamma}_1$ ,	QBO	Phi, $\hat{\phi}$	$\hat{\sigma}_N$
50°–60°N	-1.61(0.25)	3.84(0.90)	2.23(0.72)	-1.43(1.71)	1.10(0.32)	0.690	8.291
40°–50°N	-1.39(0.21)	3.51(0.76)	2.11(0.61)	-2.05(1.47)	1.11(0.28)	0.680	7.137
30°–40°N	-0.83(0.19)	1.38(0.69)	0.55(0.56)	1.42(1.15)	1.06(0.21)	0.755	5.733
20°–30°N	-0.49(0.16)	0.76(0.56)	0.27(0.45)	2.24(0.88)	1.00(0.16)	0.773	4.474

Trend and change in trend estimates in DU per year, solar estimate in DU per 100 solar flux units, and QBO estimate in DU per 10 knots wind. Standard errors of estimates are given in parentheses.

**Table 4.** Results of trend estimation, change in trend, and overall trend from statistical model (2), with data omitted during Dec. 1992–May 1993, and with Arctic and Antarctic oscillation terms and EP flux terms using lags up to 2 months included, based on 50°–60°N, 40°–50°N, 30°–40°N, and 20°–30°N monthly zonal average SBUV(/2) total ozone data for period Nov. 1978–2002.

Zone	Trend $\hat{\omega}_1$	Change $\hat{\omega}_2$	Overall $\hat{\omega}$	Solar $\hat{\gamma}_1$	QBO	<i>Arctic</i>	Phi $\hat{\phi}$	$\hat{\sigma}_N$
50°–60°N	-1.45(0.22)	3.26(0.80)	1.82(0.64)	-0.04(1.57)	1.07(0.29)	-3.934	0.672	7.516
40°–50°N	-1.23(0.18)	2.82(0.64)	1.59(0.51)	-0.51(1.24)	1.19(0.23)	-5.616	0.676	5.945
30°–40°N	-0.82(0.19)	1.30(0.68)	0.48(0.55)	1.57(1.13)	1.05(0.21)	-1.445	0.757	5.582
20°–30°N	-0.54(0.16)	0.94(0.56)	0.40(0.45)	1.89(0.86)	1.00(0.16)	0.804	0.785	4.387

Trend and change in trend estimates in DU/yr, solar estimate in DU/100 flux units, QBO estimate in DU/10 knots. Overall AO estimate, in DU/index unit, is sum of 3 coefficient terms. Standard errors of estimates are given in parentheses.

A main source of the differences between SBUV(/2) and merged TOMS/SBUV trend results becomes somewhat evident from examining plots of differences between the SBUV(/2) and merged TOMS/SBUV monthly zonal average data. From these plots it is found that during the period from roughly 1989 to 1993, the SBUV(/2) values have substantially lower levels relative to the merged TOMS/SBUV data, for a majority of latitude zones in both the Northern and Southern Hemispheres. This feature is consistent with findings by *Fioletov et al.* [2002] which, in comparisons among different satellite data sets and ground-based Dobson total ozone data for zonal aggregates of 35°–60°N and 60°S–60°N, indicated that merged TOMS/SBUV data were consistently higher than Dobson data while SBUV(/2) data were consistently lower than Dobson data over this period.

Other types of differences also exist, of course, between the merged TOMS/SBUV and SBUV(/2) data sets but the differences during 1989–1993 appear to be the largest in magnitude. These data features apparently enhance the magnitude of both the negative pre-turnaround (before 1996) trend estimates and the positive change in trend estimates (after 1996) for the SBUV(/2) data. For higher latitudes these relative features of the data also seem to have the impact of giving somewhat less positive (more negative) estimates of the solar effect for SBUV(/2) data than for merged TOMS/SBUV data.

### 5. Analysis of Ground-Based Total Ozone Data

We also consider similar trend analysis of ground-based total ozone data for comparison with the satellite data analysis results. We focus on the region of the Northern Hemisphere midlatitudes, 20°–60°N, as total ozone ground stations are predominantly located within this region. For convenience of comparison with satellite data results, the analysis is based on aggregate ground-based total ozone series for four latitude zones. The four series formed are averages of ground-based total ozone data in the latitude regions of 50°–60°N (11 stations), 40°–50°N (11 stations), 30°–40°N (10 stations), and 20°–30°N (7 stations). The stations involved use primarily Dobson instruments, but also include a small number of sites using Brewer instruments and filter ozonometers. All stations included have long running data records of at least 20 years, and the data are complete through the end of 2002 (or nearly so) for almost all the stations.

The same statistical model (2), both without and with the AO and EP flux dynamical terms, was applied to the four zonal ground-based total ozone series over the period 1978–2002. For brevity,

estimation details of only the model with dynamical terms included are presented for the four zonal series, with the results given in Table 5. (The statistical model was also used in analysis of the total ozone data at each individual station, and overall results from that estimation give similar findings as the analysis of the four zonal aggregate series.) In general, we find that estimation results for the ground-based total ozone data in 20°–60°N are comparable to those from the satellite data sources, with a few modest differences. For instance, in the 40°–50°N latitude zone the ground station data seem to give somewhat less positive change-in-trend estimate  $\hat{\omega}_2$  and somewhat more positive solar effect estimate than the satellite data.

**Table 5.** Results of trend estimation, change in trend, and overall trend from statistical model (2), with data omitted during Dec. 1992–May 1993, and with Arctic oscillation terms and EP flux terms using lags up to 2 months included, based on 50°–60°N, 40°–50°N, 30°–40°N, and 20°–30°N monthly zonal average ground-based total ozone data for period 1978–2002.

Zone	Trend $\hat{\omega}_1$	Change $\hat{\omega}_2$	Overall, $\hat{\omega}$	Solar $\hat{\gamma}_1$	QBO	Arctic	Phi $\hat{\phi}$	$\hat{\sigma}_N$
50°–60°N	-1.14(0.19)	2.30(0.70)	1.16(0.56)	1.86(1.68)	0.77(0.31)	-4.238	0.398	9.082
40°–50°N	-0.93(0.16)	1.14(0.58)	0.21(0.47)	2.84(1.36)	0.97(0.25)	-4.832	0.474	7.061
30°–40°N	-0.65(0.15)	0.30(0.56)	-0.36(0.45)	1.98(1.15)	1.30(0.21)	-1.864	0.639	5.584
20°–30°N	-0.16(0.10)	0.35(0.38)	0.19(0.31)	2.21(0.82)	1.11(0.15)	0.874	0.602	4.030

Trend and change in trend estimates in DU/yr, solar estimate in DU/100 flux units, QBO estimate in DU/10 knots. Overall AO estimate, in DU/index unit, is sum of 3 coefficient terms. Standard errors of estimates are given in parentheses.

## 6. Concluding Remarks

We have considered trend analysis, including a change point or change in trend feature (assumed to start in 1996), of monthly average total ozone data through 2002 for latitude zonal averages from both merged TOMS/SBUV and SBUV(/2) satellite sources, as well as from ground stations. Different statistical modeling approaches were considered, to allow for effects of various explanatory factors on ozone behavior. The analysis presented in this paper establishes a clear depiction of the influence of the dynamic factors, Arctic/Antarctic oscillation index and EP flux, on total ozone variations as a function of latitude. The results remained consistent among analysis of the different data sets and using different statistical techniques. When analyzing whether a change in trend is detectable, only a relatively short period of data, seven years, are available after the presumed change point. Although the work of *Reinsel et al.* [2002] indicates that change in trend in total ozone of the magnitudes that are projected to occur may be statistically detectable in theory with such a modest length of data after the change point, such estimates of the change in trend are necessarily somewhat unreliable and need to be interpreted cautiously in practice. For example, they depend to some extent on the assumption of a simple *linear* change in trend at a specified change point. Nonetheless, based on several different statistical modeling approaches, a robust feature that emerges is the substantial positive and statistically significant estimates of change in trend (assumed to start in 1996) in ozone for latitudes of 40° and higher in both hemispheres, which might be interpreted as the first evidence of an early signal of a turnaround in total ozone trends. Indications of a turnaround in total ozone trends are also found at lower latitudes, in the form of positive estimates of changes in trends. Although the changes are of smaller magnitudes and less statistical significance, the results still suggest the potential beginning of a turnaround in total ozone, at least from a statistical viewpoint. The especially large positive change in trend estimates for the higher latitudes of the Southern Hemisphere (above 50°S) may be mildly impacted by unusually high ozone values of late 2002. However, SBUV/2 data for 2003 show ozone values for these latitudes that are similar

to the levels in 2000 and 2001. Thus, the trend analysis through 2003 continues to support the feature of a highly significant positive change in the total column ozone trend.

**In Memoriam.** Greg Reinsel's professional expertise and personal dedication in applying advanced statistical techniques to environmental questions spanned three decades. His initial efforts to apply robust statistics to the analysis of environmental data were published in 1984 (Reinsel et al., "Analysis of upper stratospheric Umkehr ozone profile data for trends and the effects of stratospheric aerosols." *J. Geophys. Res.*, 89, 4833-4840). His work has stood the test of time and his techniques have been broadly adopted in the environmental sciences community. It is with great sadness that we, his co-authors and collaborators, say good bye to Greg and acknowledge the many contributions he has made to this field and the personal loss we each feel.

**Acknowledgements.** The research described herein has been funded in part by the Center for Integrating Statistical and Environmental Science at The University of Chicago through United States Environmental Protection Agency STAR Cooperative Agreement #R-82940201-0; although it has not been subjected to the Agency's required peer and policy review and therefore does not necessarily reflect the views of the Agency, and no official endorsement should be inferred.

## References

- Andersen, S. B., et al., in Quandrenniel Ozone Symposium, 2004 (Kos, Greece).
- Appenzeller, C., A. K. Weiss, and J. Staehelin, North Atlantic Oscillation modulates total ozone winter trends, *Geophys. Res. Lett.*, 27, 1131–1134, 2000.
- Box, G., G.M. Jenkins, and G.C. Reinsel, "Time Series Analysis: forecasting and control," Third edition, Prentice Hall, 592 pp., 1994.
- Fioletov, V.E., G.E. Bodeker, A.J. Miller, R.D. McPeters, and R. Stolarski, Global and zonal total ozone variations estimated from ground-based and satellite measurements: 1964–2000, *J. Geophys. Res.*, 107(D22), 4647, doi:10.1029/2001JD001350, 2002.
- Fusco, A. C. and M. L. Salby, Interannual variations of total ozone and their relationship to variations of planetary wave activity, *J. Climate*, 12, 1619–1629, 1999.
- Miller, A. J., R. M. Nagatani, L. E. Flynn, S. Kondragunta, E. Beach, R. Stolarski, R. McPeters, P. K. Bhartia, M. DeLand, C.H. Jackman, D.J. Wuebbles, K.O. Patten, and R.P. Cebula, A cohesive total ozone data set from the SBUV(2) satellite system, *J. Geophys. Res.*, 107(D23), 4701, doi:10.1029/2001JD000853, 2002.
- Newchurch, M. J., et al., Upper-stratospheric ozone trends 1979-1998, *J. Geophys. Res.*, 105, 14,625–14,636, 2000.
- Newchurch, M. J., E.-S. Yang, D. M. Cunnold, G. C. Reinsel, J. M. Zawodny, and J. M. Russell III, Evidence for slowdown in stratospheric ozone loss: First stage of ozone recovery, *J. Geophys. Res.*, 108(D16), 4507, doi:10.1029/2003JD003471, 2003.
- Randel, W. J., F.Wu, and R. Stolarski, Changes in column ozone correlated with the stratospheric EP flux, *J. Meteorol. Soc. Japan*, 80, #4B, 849–862, 2002.

- Reinsel, G. C., Trend analysis of upper stratospheric Umkehr ozone data for evidence of turnaround, *Geophys. Res. Lett.*, 29(10), 1451, doi:10.1029/2002GL014716, 2002.
- Reinsel, G. C., G. C. Tiao, D. J. Wuebbles, J. B. Kerr, A. J. Miller, R. M. Nagatani, L. Bishop, and L. H. Ying, Seasonal trend analysis of published ground-based and TOMS total ozone data through 1991, *J. Geophys. Res.*, 99, 5449–5464, 1994.
- Reinsel, G. C., E. C. Weatherhead, G. C. Tiao, A. J. Miller, R. M. Nagatani, D. J. Wuebbles, and L. E. Flynn, On detection of turnaround and recovery in trend for ozone, *J. Geophys. Res.*, 107(D10), 10.1029/2001JD000500, 2002.
- Stolarski, R. S., R. Bojkov, L. Bishop, C. Zerefos, J. Staehelin, and J. Zawodny, Measured trends in stratospheric ozone, *Science*, 256, 342–349, 1992.
- Thompson, D. W. J., and J. M. Wallace, The Arctic Oscillation signature in the winter time geopotential height and temperature fields, *Geophys. Res. Lett.*, 25, 1297–1300, 1998.
- Tiao, G. C., G. C. Reinsel, D. Xu, J. H. Pedrick, X. Zhu, A. J. Miller, J. J. DeLuisi, C. L. Mateer, and D. J. Wuebbles, Effects of autocorrelation and temporal sampling schemes on estimates of trend and spatial correlation, *J. Geophys. Res.*, 95, 20,507–20,517, 1990.
- Weatherhead, E. C., G. C. Reinsel, G. C. Tiao, X.-L. Meng, D. Choi, W.-K. Cheang, T. Keller, J. DeLuisi, D. J. Wuebbles, J. B. Kerr, A. J. Miller, S. J. Oltmans, and J. E. Frederick, Factors affecting the detection of trends: Statistical considerations and applications to environmental data, *J. Geophys. Res.*, 103, 17,149–17,161, 1998.
- Weatherhead, E. C., et al., Detecting the recovery of total column ozone, *J. Geophys. Res.*, 105, 22,201–22,210, 2000.
- Weiss, A. K., J. Staehelin, C. Appenzeller, and N. R. P. Harris, Chemical and dynamical contributions to ozone profile trends of the Payerne (Switzerland) balloon soundings, *J. Geophys. Res.*, 106, 22,685–22,694, 2001.
- World Meteorological Organization, Scientific assessment of ozone depletion: 1998, *Rep. 44*, WMO Global Ozone Res. and Monit. Proj. Geneva, 1999.
- World Meteorological Organization, Scientific assessment of ozone depletion: 2002, *Rep. 47*, WMO Global Ozone Res. and Monit. Proj. Geneva, 2003.

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### List of Figure Captions

**\*NOTE TO EDITORS: PANEL (B) OF FIGURE 4 SHOULD BE ELIMINATED AS BELOW.**

**Figure 1.** Deseasonalized merged TOMS/SBUV version 7 satellite total ozone series, 1979–2002. The data are shown for various latitude bands as past depletion has been latitudinally dependent and causes of ozone depletion are likely to be latitudinally dependent. At the time this paper was written, version 8 TOMS was in progress but not yet released. Comparison of the monthly means of ozone from version 7 and version 8 indicates that the results are not likely to be significantly different. The long-term mean of the dataset is preserved and only the seasonal component is removed.

**Figure 2.** AO and AAO index series, and deseasonalized EP flux for Northern Hemisphere and Southern Hemisphere, and smooth “trend” curves, 1979–2002. (Circles are original index, solid curve is lowest smoother with  $f = 0.05$ .)

**Figure 3.** Estimation results for zonal ( $5^\circ$ ) merged TOMS/SBUV total ozone, 1979–2002. Error bars indicate a one sigma confidence level. Calculations of trends are presented both with and without AAO/EP indices used as explanatory variables. For both cases, the high northern latitudes show an overall increase in ozone which is statistically significant at the two sigma level. Note that the AAO has a strong influence for 40–60N and very little influence near the equator. All of these results refer to analysis based on Equation 2.

**Figure 4.** Merged TOMS/SBUV total ozone data and explanatory components for  $40^\circ$ – $45^\circ$ N. The first plot shows the original deseasonalized data. The second plot shows the ozone levels which can be explained by the statistical model (Equation 2) including Solar, QBO, AO and EP flux. The final plot shows the unexplained portion of the data. Note that the variability is reduced by almost one half by using the solar, QBO, AO and EP flux terms.

**Figure 5.** Deseasonalized SBUV(/2) satellite total ozone series, 1979–2002. As in Figure 1, the long-term mean is preserved and only the seasonal component is removed. Differences between the available datasets are discussed in the text. The additional data in most cases add to the confidence in turnaround results.

**Figure 6.** Estimation results for zonal ( $10^\circ$ ) SBUV(/2) total ozone, 1979–2002. As with the TOMS/SBUV merged dataset, the turnaround is most significant north of 40N, with the AAO and EP indices indicating larger trends when included in the analysis.

Figure 1. Deseasonalized Merged TOMS/SBUV Satellite Total Ozone Series, 1979-2002

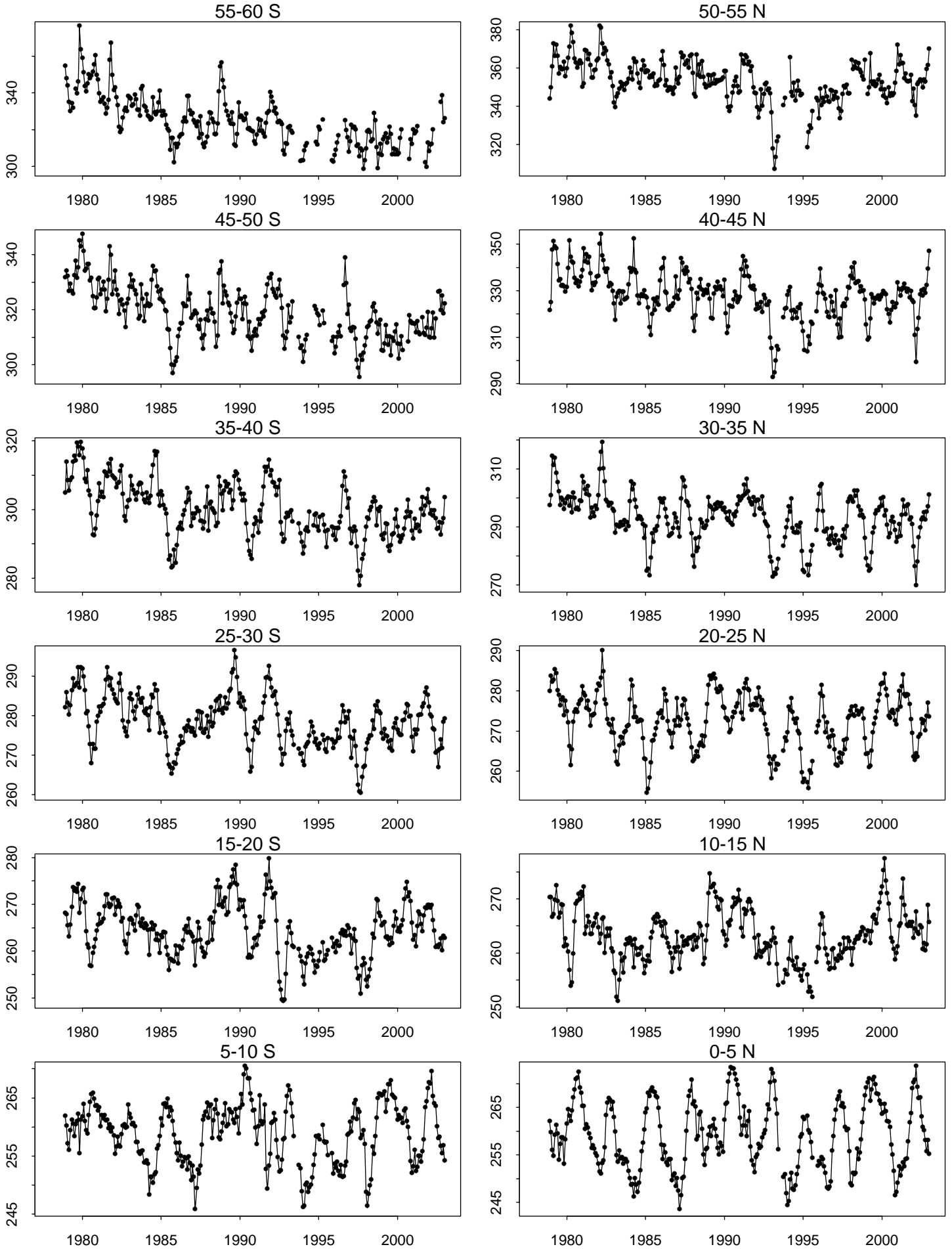


Figure 2. AO and AAO Index Series, and Deseasonalized EP Flux for NH and SH, and Smooth "Trend" Curves, 1979-2002  
Circles are Original Index, Solid Curve is Lowess Smoother with  $f=0.05$

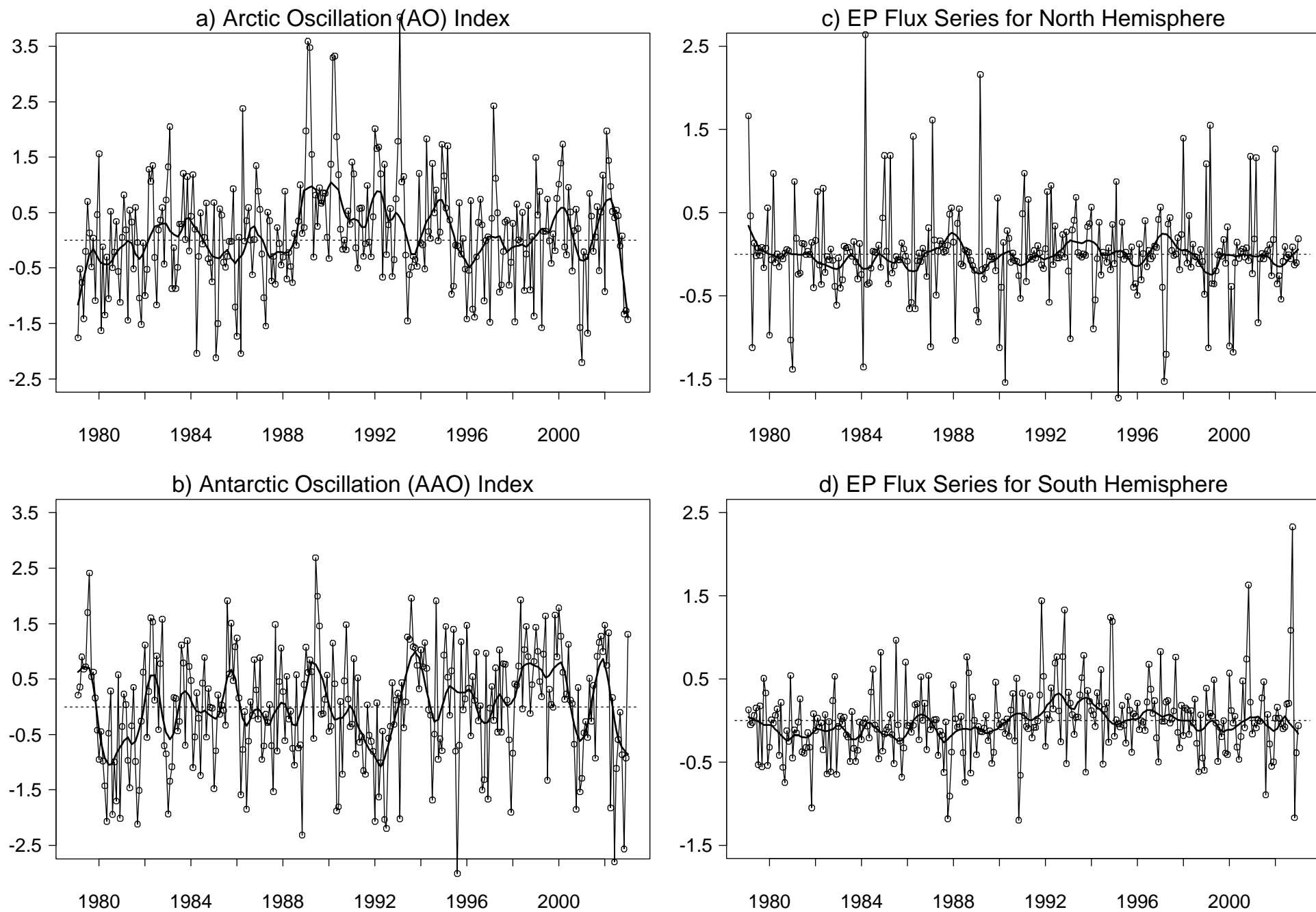


Figure 3. Estimation Results for Zonal ( $5^\circ$ ) Merged TOMS/SBUV Total Ozone, 1979-2002

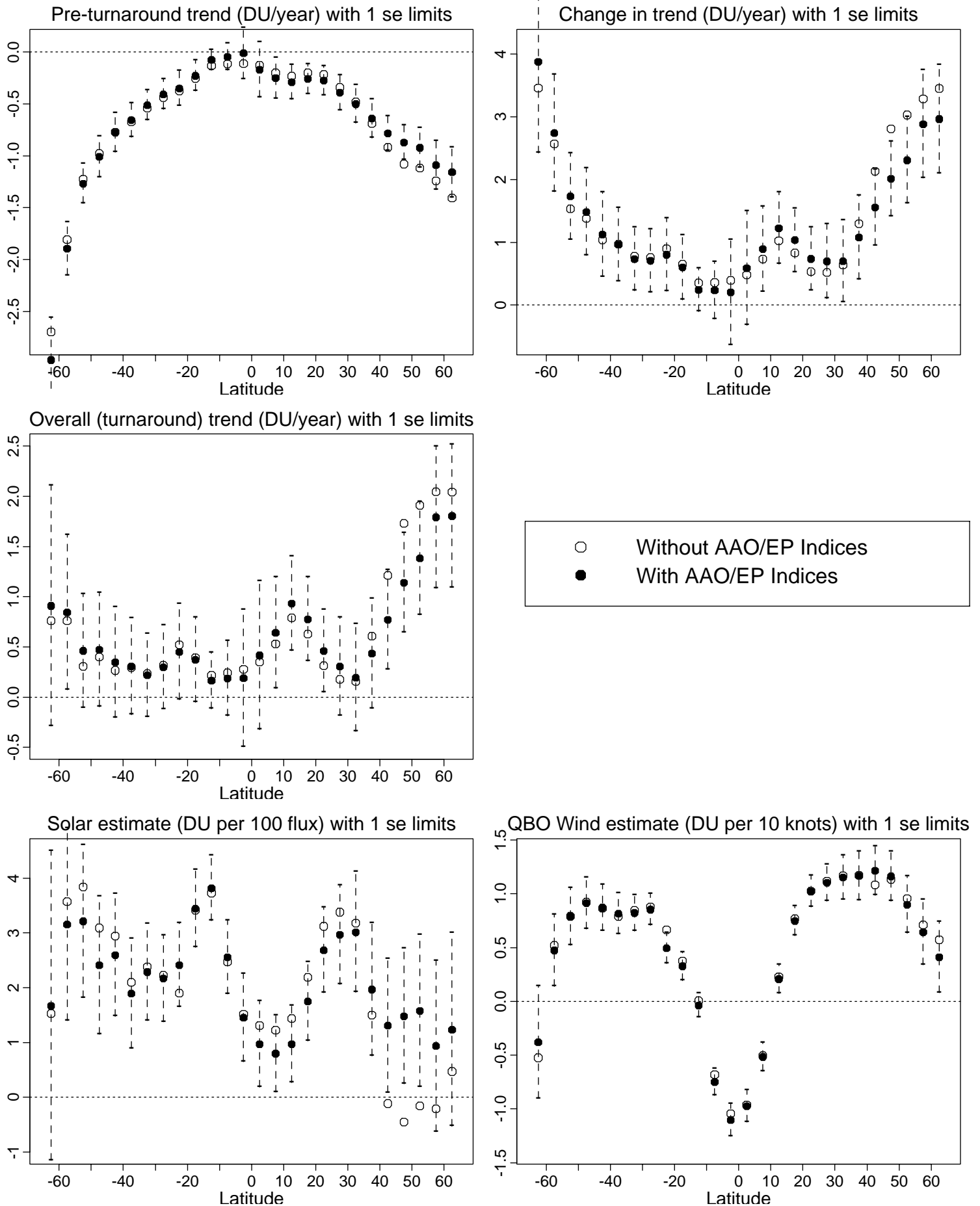


Figure 3. Estimation Results for Zonal ( $5^\circ$ ) Merged TOMS/SBUV Total Ozone, 1979-2002

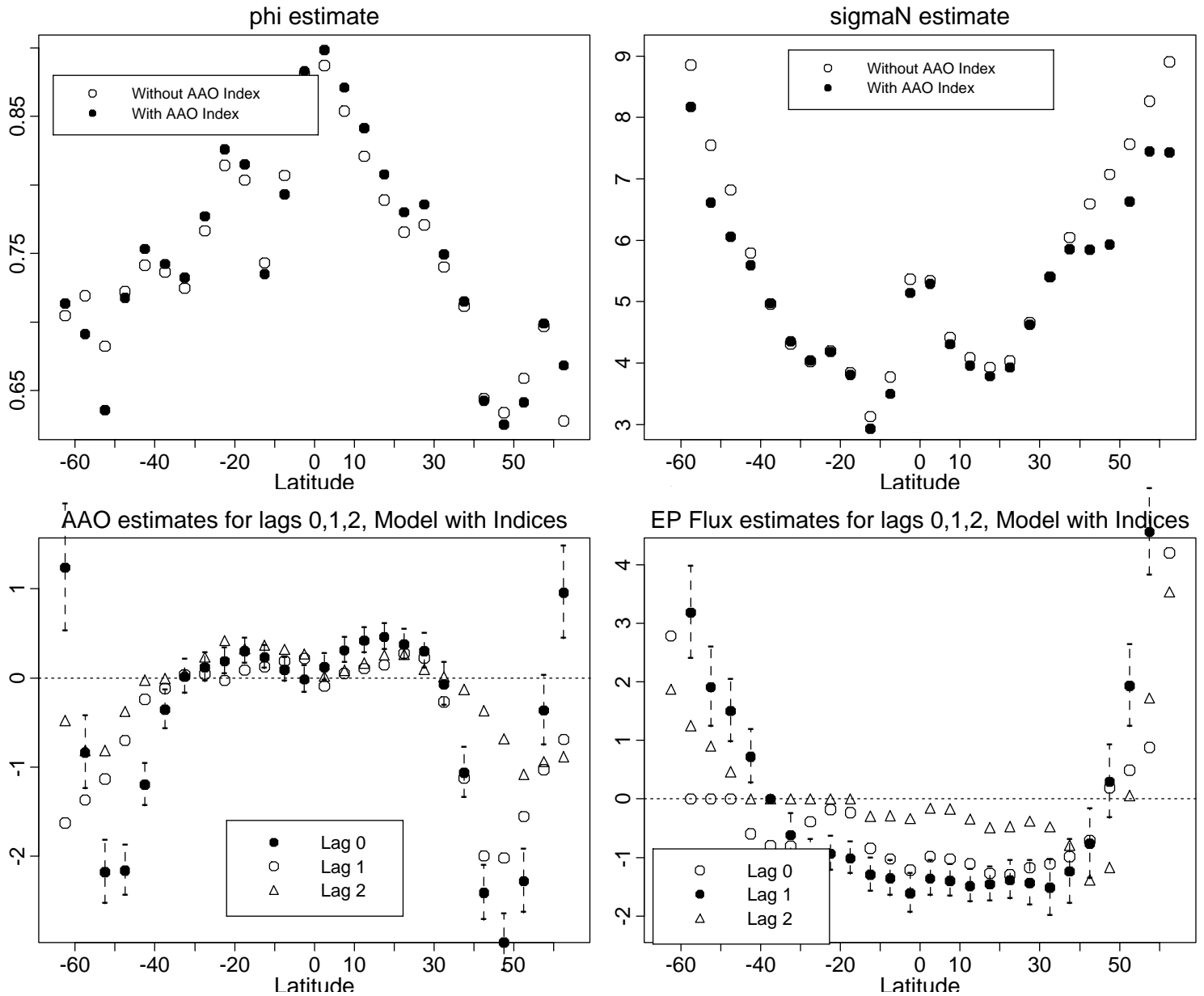
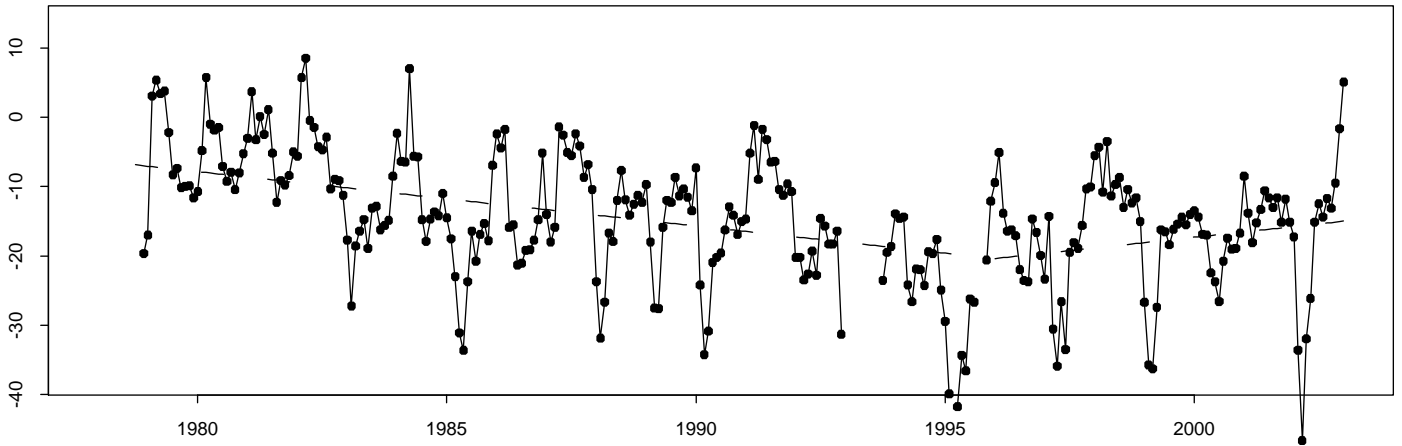
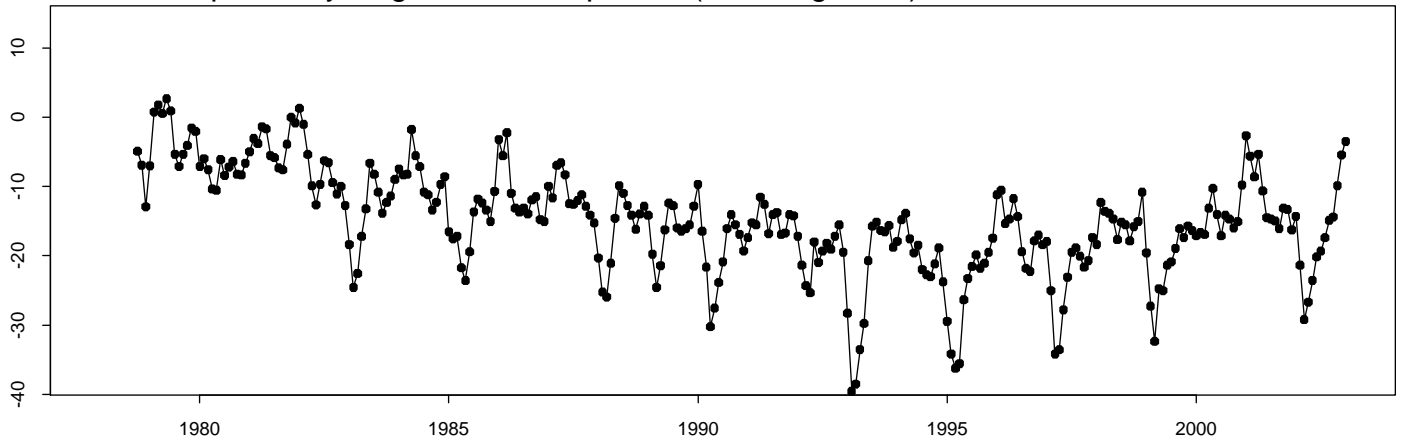


Figure 4. Merged TOMS/SBUV Total Ozone and Explanatory Components for 40-45 N  
Deseasonalized Total Ozone, 40-45 N (with trend component indicated)



Overall Explanatory Regression Component (including trend) for Deseasonalized Total Ozone



Noise Component  $N(t)$ , Deseasonalized Total Ozone Adjusted for Explanatory Components

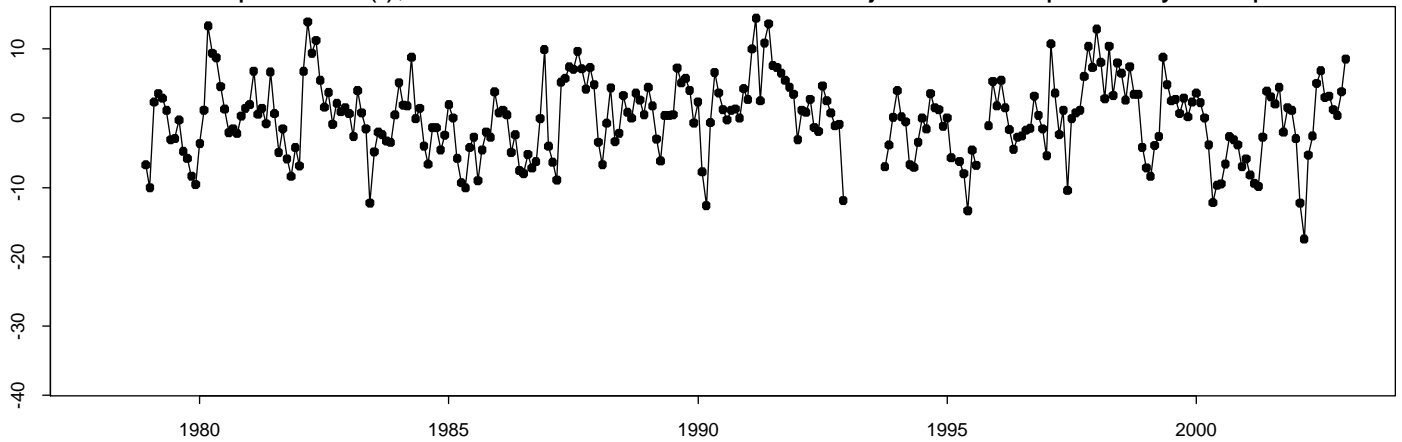


Figure 5. Deseasonalized SBUV(/2) Satellite Total Ozone Series, 1979-2003

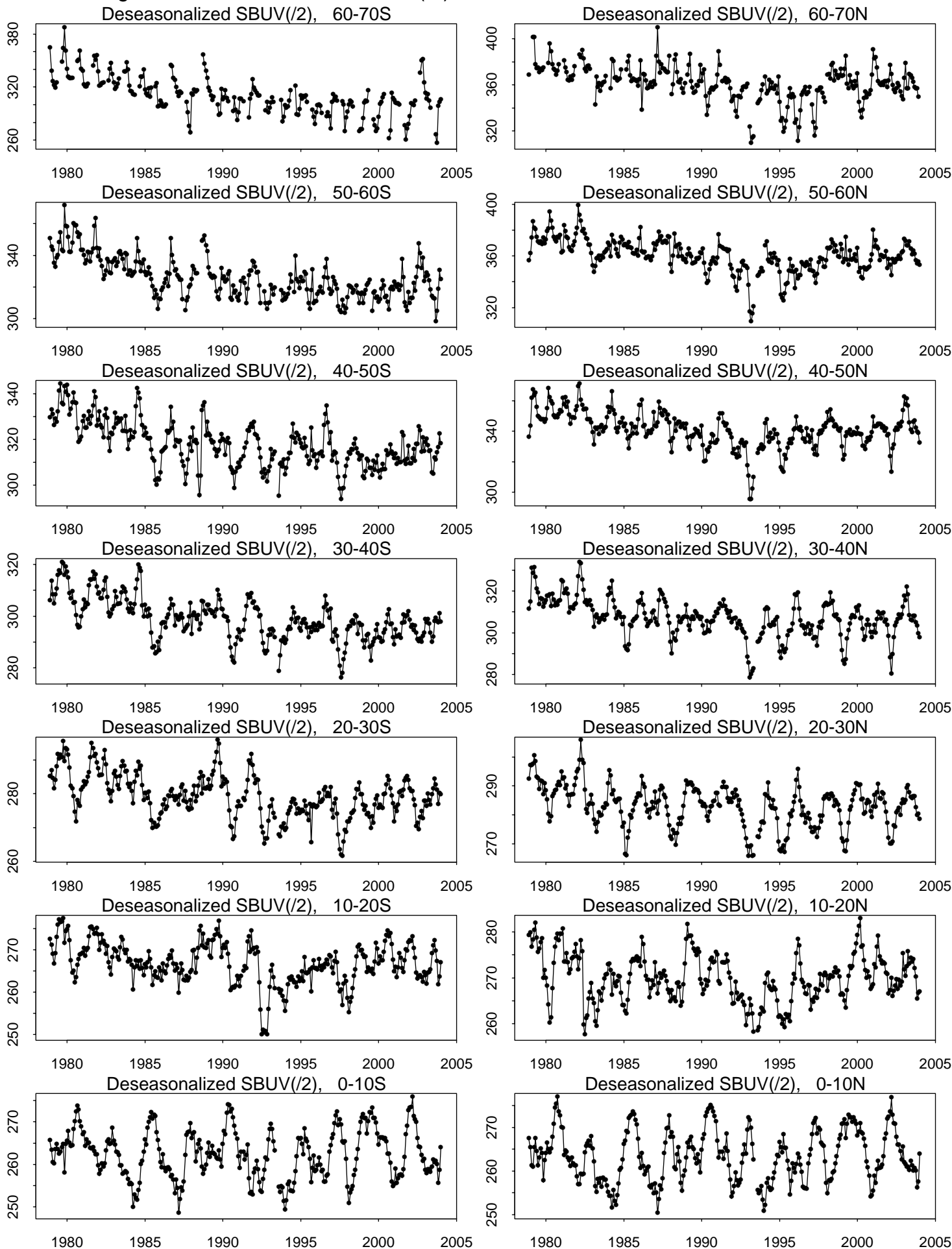


Figure 6. Estimation Results for Zonal ( $10^{\wedge}0$ ) SBUV(/2) Total Ozone, 1979-2003

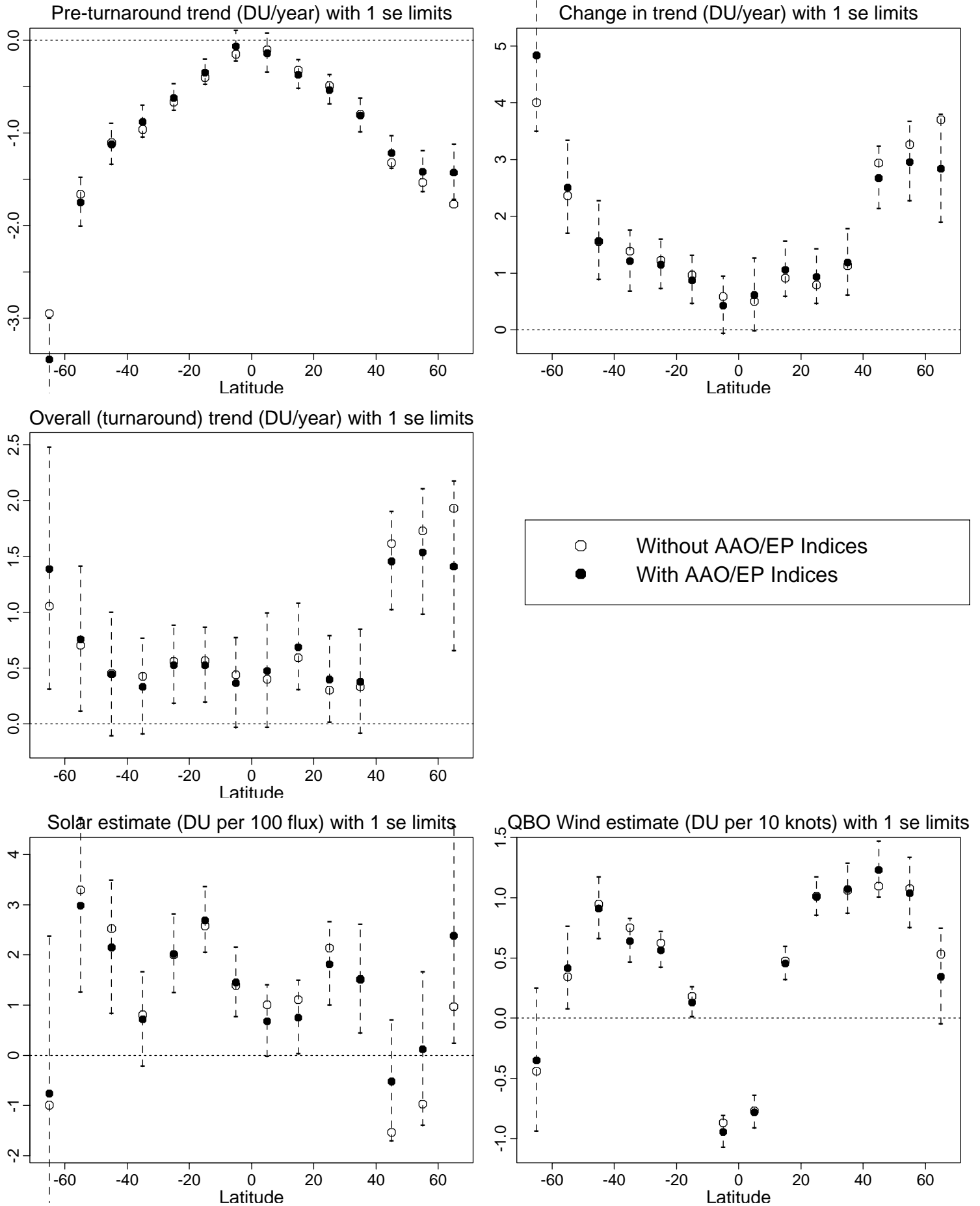


Figure 6. Estimation Results for Zonal ( $10^{\wedge}0$ ) SBUV(/2) Total Ozone, 1979-2003

