Detecting the recovery of total column ozone

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Abstract. International agreements for the limitation of ozone-depleting substances have already resulted in decreases in concentrations of some of these chemicals in the troposphere. Full compliance and understanding of all factors contributing to ozone depletion are still uncertain; however, reasonable expectations are for a gradual recovery of the ozone layer over the next 50 years. Because of the complexity of the processes involved in ozone depletion, it is crucial to detect not just a decrease in ozone-depleting substances but also a recovery in the ozone layer. The recovery is likely to be detected in some areas sooner than others because of natural variability in ozone concentrations. On the basis of both the magnitude and autocorrelation of the noise from Nimbus 7 Total Ozone Mapping Spectrometer ozone measurements, estimates of the time required to detect a fixed trend in ozone at various locations around the world are presented. Predictions from the Goddard Space Flight Center (GSFC) two-dimensional chemical model are used to estimate the time required to detect predicted trends in different areas of the world. The analysis is based on our current understanding of ozone chemistry, full compliance with the Montreal Protocol and its amendments, and no intervening factors, such as major volcanic eruptions or enhanced stratospheric cooling. The results indicate that recovery of total column ozone is likely to be detected earliest in the Southern Hemisphere near New Zealand, southern Africa, and southern South America and that the range of time expected to detect recovery for most regions of the world is between 15 and 45 years. Should the recovery be slower than predicted by the GSFC model, owing, for instance, to the effect of greenhouse gas emissions, or should measurement sites be perturbed, even longer times would be needed for detection.

1. Introduction

Significant changes have been observed in the stratospheric ozone layer since the 1970s [*World Meteorological Organization (WMO)*, 1995, 1999; *Farman et al.*, 1985]. International legislation in response to these changes calls for a reduction in ozone-depleting substances. Observations indicate the first signs of a reduction in ambient concentrations of these substances [*Montzka et al.*, 1996]; however, ozone levels continue

to decrease and may decrease further over the next few years. The magnitude of the decline in ozone has not been the same at all locations around the world, with the equator showing very small trends and the polar regions showing the greatest change. Similarly, the recovery of the stratospheric ozone layer is not expected to be the same in all areas. Statistical detection of ozone layer recovery will be an important step toward verification that all relevant processes in ozone destruction have been identified and that appropriate measures have been taken to assure the ozone layer's health. We estimate here the time required to detect ozone layer recovery using assessments of natural variability from past ozone measurements to assess the natural variability and predictions for the recovery of the ozone layer from the Goddard Space Flight Center (GSFC) two-dimensional (2-D) model [*Jackman et al.*, 1996]. Locations at which the recovery may be detected first are also reported. Figure 1 shows the expected recovery of ozone through 2050 based on GSFC 2-D model predictions for total column ozone levels at 45°S. This figure shows that the recovery rate is expected to be nearly linear and roughly independent of season. In this paper we address the question of how long it will take to detect the predicted trends given the natural variability in ozone concentrations.

Recovery is likely to appear first as a lessening of the downward trend in ozone, followed by an increase in ozone, and finally, it is hoped, the full recovery of ozone to unperturbed levels. Indeed, the term recovery can be used to refer to any of

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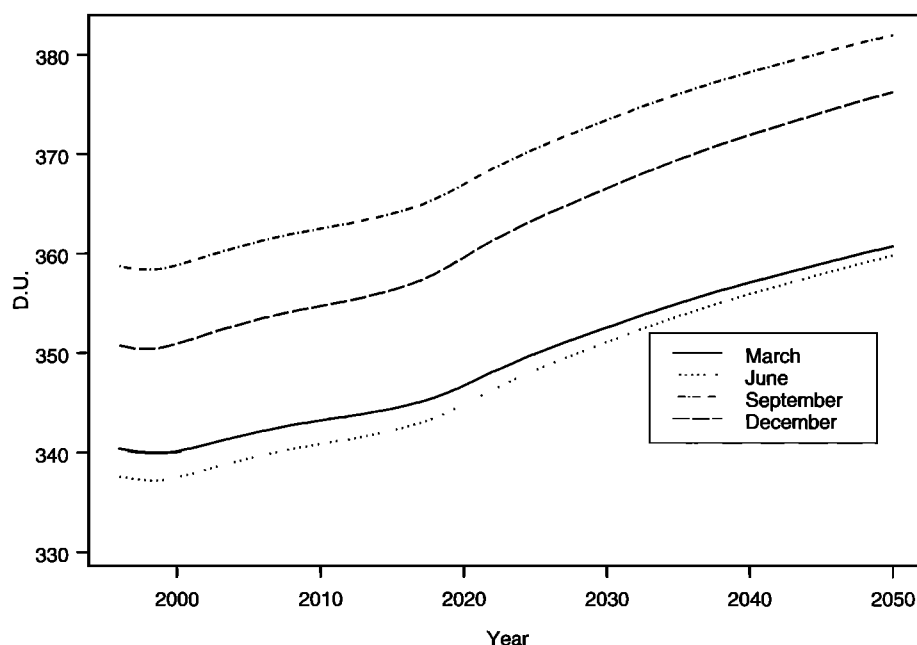
Figure 1. The predicted ozone concentrations in Dobson units based on the Goddard Space Flight Center (GSFC) two-dimensional (2-D) model for 4 months. The model predictions include estimates of future emissions of ozone-depleting substances but do not include the effect of stratospheric temperature changes due to increased greenhouse gas concentrations. Estimates of time to detect the predicted trends presented in this paper are based on linear trends derived from the predicted levels at each latitude for the years 2000–2020.

these three phases. For this paper we consider the question of how long it will take to detect a statistically significant positive trend in total column ozone and use the term recovery to refer to the process of increasing total column ozone levels. Available 2-D chemical models indicate that total column ozone should be starting to recover now; however, the influence of a cooling stratosphere due to greenhouse gas emissions may seriously slow or delay this phase [*Shindell et al.*, 1998; *Dameris et al.*, 1998]. Because the most severe depletion has been observed in seasonal and ozone profile trends, it is possible that these data will show convincing evidence for ozone recovery earlier than the total column ozone levels [*Miller et al.*, 1995, 1997; *Logan*, 1994; *Hofmann et al.*, 1997; *DeLuisi et al.*, 1994]. However, the most important effect of ozone depletion, the increase of UV radiation to the surface of the Earth, depends primarily on the total column ozone recovery [*Weatherhead et al.*, 1997], making the results presented here particularly important to environmental concerns.

Anthropogenic activity has caused significant changes in the stratospheric ozone layer. Plate 1 shows ozone depletion from 1978 through 1998 based on observations from three separate satellites. Considerable efforts have resulted in an understanding of the processes that govern ozone production and destruction and influence these changes. Long-term monitoring and modeling efforts as well as measurement campaigns are devoted to furthering this understanding for prediction of future ozone levels. Current predictions indicate a slow ozone recovery, which will not occur uniformly over the globe.

Detecting the recovery in nonpolar regions, as with detection of downward trends, depends on the magnitude of the trend as well as the magnitude and autocorrelation of the unexplained portion of the noise. Estimates are made of the number of years required to detect a fixed change in ozone as

well as the expected change predicted by the GSFC 2-D model. This work shows that the time periods to detect the expected change differ significantly by location.

Past and future changes are often approximated by a linear term. For this study we adopt the commonly used decision rule that a real trend is considered to be detected when the estimated trend is more than two standard deviations from zero. As was most recently shown by *Weatherhead et al.* [1998], the ability to detect trends in environmental data depends critically on three factors: the size of the trend to be detected; the random variability (or noise) in the data; and the autocorrelation of the noise in the data. The first two factors may be considered intuitive: It is easier to detect a trend when it is large and/or when the natural variability is low. The autocorrelation of the data refers to the relationships within the data set, for example, that this month's measurement is highly correlated with last month's measurement. Such a tendency reduces the number of independent pieces of information from which to estimate a trend, thus increasing its uncertainty. All three of these factors vary significantly with geographic region. Expected ozone trends have previously been observed to vary with location [*WMO*, 1995, 1999]. It has also been observed that noise is lowest, but autocorrelation is highest, in the equatorial region. This paper estimates the number of years required to detect ozone trends with a given confidence around the globe, incorporating information on variability and autocorrelation of noise from Nimbus 7 ozone records.

A variety of issues, besides statistical factors, affect the detection of ozone trends. Quality of data, which can be difficult to describe and often varies during the time period of analysis, can have an overwhelming influence on trend detectability. For ozone records the ground-based Dobson network has served as a primary reference for stability of most satellite-based ozone
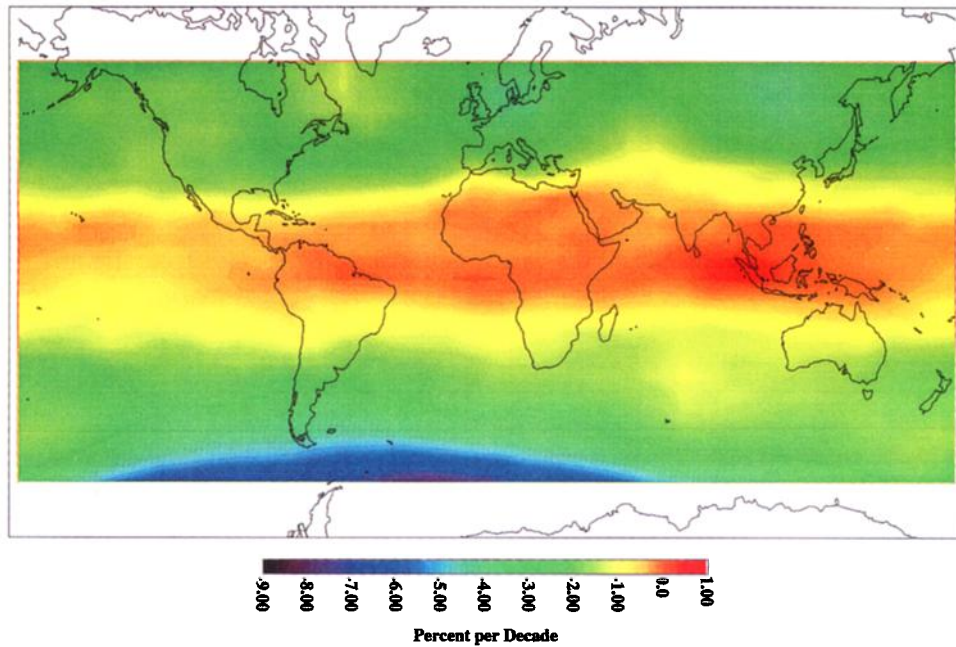
Percent per Decade

Plate 1. Observed ozone depletion 1978–1998 from Nimbus 7 Total Ozone Mapping Spectrometer (TOMS), Meteor 3 TOMS, and ADEOS TOMS. Trends are based on monthly averaged data.

measurements. Sudden changes, such as those that occurred with the eruptions of Mount Pinatubo, and changes in satellites and instruments can further confound trend results. Many of these factors cannot be predicted, and virtually all add to the uncertainty in estimated trends obtained from statistical analysis of ozone data. Nonetheless, there is value in assessing a minimal detection time of ozone trends, based on the assumption that no interfering problems occur. Because we cannot incorporate unforeseen problems into the analysis, this work estimates the number of years required to detect a trend under the best of circumstances.

A number of studies, including *Reinsel et al.* [1994] and *Stolarski et al.* [1991, 1992], have looked for trends in existing ozone records. *Miller et al.* [1992] examined trends in stratospheric ozone and temperature. More recently, *Weatherhead et al.* [1998] showed that ozone, among several examined environmental parameters, is particularly good for the detection of trends because of its relatively low noise and autocorrelation when compared with parameters such as relative humidity and ultraviolet radiation. The recovery of the Antarctic ozone hole was addressed by *Hofmann* [1996], who considered the question in terms of variability but did not examine recovery at midlatitudes.

2. Statistical Techniques

General time series analysis and, specifically, trend analysis are covered in a variety of textbooks [e.g., *Box et al.*, 1994]. The question of how many years of data are needed to detect a trend of a given magnitude has been studied in detail by *Tiao et al.* [1990] and more recently by *Weatherhead et al.* [1998]. Such estimates can be used to understand where changes are likely to be detected first and can also be used to establish reasonable expectations for length of time needed to detect the expected changes. Many statistical analyses of ozone data [e.g., *Reinsel et al.*, 1994] employ the following statistical model:

$$Y_t = \mu + S_t + \omega X_t + \gamma QBO_{t-k} + \kappa SOL_t + N_t, \qquad (1)$$

where Y_t is the time series of monthly ozone data; μ is the overall mean; S_t is a seasonal mean component, which can often be represented as $S_t = \Sigma_{j=1}^{4} [\beta_{1,j} \sin (2\pi jt/12) + \beta_{2,j} \cos (2\pi jt/12)]$; ω represents the trend or rate of change; X_t is a linear trend function, $X_t = t/12$, where $t = 1, 2, 3, \ldots$; and γQBO_{t-k} is the component of ozone that is directly related to variability in the quasi-biennial oscillation (QBO), where the QBO effect is proxied by winds lagged by k months [*Ziemke and Stanford*, 1994]. Here κSOL_t represents the effect of the 11-year solar cycle [*Chandra and McPeters*, 1994; *Hood et al.*, 1993; *McCormack and Hood*, 1996]. N_t is the unexplained noise term, most often assumed to be autoregressive with time lag of 1 when monthly data are considered and has mean 0 and standard deviation σ_N. That is, $N_t = \phi N_{t-1} + \varepsilon_t$, where ε_t is a sequence of independent random variables with mean 0 and variance σ^2, and hence $\sigma_N^2 = $ Var $(N_t) = \sigma^2/(1 - \phi^2)$. Analysis of ozone in terms of such a model allows for estimation of the time needed for future trend detection.

We now outline the argument presented by *Tiao et al.* [1990] and recently developed further by *Weatherhead et al.* [1998] for determining the number of years of data needed to detect, with a specified degree of certainty, a true trend ω of a given magnitude when the data are assumed to follow the model in (1). Let $\hat{\omega}$ be the estimate of the unknown trend ω and let $\sigma_{\hat{\omega}}$ be the associated standard error of $\hat{\omega}$. The standard error $\sigma_{\hat{\omega}}$ is a function of the autocorrelation ϕ, the noise variance σ_N^2, and the length of the data record. Clearly, as the data span increases, $\sigma_{\hat{\omega}}$ will decrease and the chance of detecting a real trend of specified value will increase. Because we cannot increase the data span indefinitely, we must set up some criteria to obtain the number of years of data needed for trend detection. Within the trend detection analysis, we must consider both the error that occurs when we reject the test hypothesis of
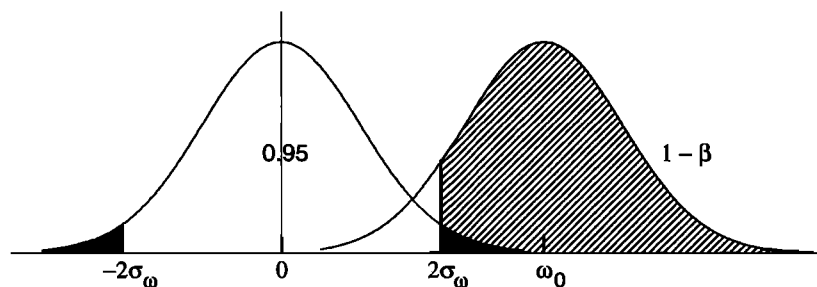
Figure 2. Probability distributions of trend estimate $\hat{\omega}$, under $\omega = 0$ (left curve) and $\omega = \omega_0$ (right curve), with illustration of probability of detection, $P(\hat{\omega} > 2\sigma_{\hat{\omega}} | \omega = \omega_0) = 1 - \beta$, under specified true trend value ω_0.

zero trend when it is actually true and the error that occurs when we accept the hypothesis of zero trend when it is actually false. Therefore we need (1) to formulate a decision rule for trend detection that controls the probability of the first type of error and (2) to prescribe an acceptable degree of certainty that a nonzero trend of specified value will be detected by the rule (equivalently, prescribe an acceptable probability for the second type of error). For point 1 we adopt the rule commonly used in scientific investigation that a real (nonzero) trend is indicated, with 95% confidence or 5% error rate, if the magnitude of the estimate $\hat{\omega}$ is greater than 2 times its standard error, i.e., $|\hat{\omega}| > 2\sigma_{\hat{\omega}}$. For point 2 it seems reasonable to require that there should be (at least) a 50% chance that a specified nonzero trend value is detected by this rule, but higher probabilities of detection could also be entertained.

The situation is depicted in Figure 2. The left curve shows a normal distribution for the estimate $\hat{\omega}$ centered at 0 (representing the case for a true trend of zero) with $\pm 2\sigma_{\hat{\omega}}$ limits marked, and the right curve shows the distribution of $\hat{\omega}$ centered at a specified true trend value ω_0 ($\omega_0 > 0$) with the same standard error $\sigma_{\hat{\omega}}$. Note that there is a 5% error rate, equivalently, a 95% confidence level, that a trend will be indicated by the rule, i.e., that $|\hat{\omega}| > 2\sigma_{\hat{\omega}}$, when the true trend is in fact zero. On the other hand, the shaded area in the right curve gives the probability that a trend will be detected by the rule when the true trend is the specified value ω_0. (The unshaded portion under the right curve thus gives the probability of the second type of error, that a trend will not be indicated by the rule, i.e., that $|\hat{\omega}| < 2\sigma_{\hat{\omega}}$, when the true trend is ω_0.) From Figure 2 we can infer that as the number of years of available data increases, (1) the left curve will become more concentrated around 0 and the $\pm 2\sigma_{\hat{\omega}}$ limits will accordingly shrink toward 0, and (2) the right curve will get more concentrated about ω_0 and consequently the shaded area (probability of detection) will become larger.

It follows that the probability of detection under a true specified (positive) trend ω_0 is

$$P(|\hat{\omega}| > 2\sigma_{\hat{\omega}} | \omega = \omega_0) \approx P\left(\frac{\hat{\omega} - \omega_0}{\sigma_{\hat{\omega}}} > 2 - \frac{\omega_0}{\sigma_{\hat{\omega}}}\right)$$

$$\equiv P\left(Z > 2 - \frac{\omega_0}{\sigma_{\hat{\omega}}}\right),$$

and the probability that a standard normal random variate $Z = (\hat{\omega} - \omega_0)/\sigma_{\hat{\omega}}$ will be greater than $2 - \omega_0/\sigma_{\hat{\omega}}$. If we require that a trend of given magnitude ω_0 should be detectable with a prescribed probability equal to $1 - \beta$, then we require a sufficient number of years of data so that $P(Z > 2 - (\omega_0/\sigma_{\hat{\omega}})) \geq 1 - \beta$. This is equivalent to $P(Z < 2 - $

$(\omega_0/\sigma_{\hat{\omega}})) \leq \beta$ or $2 - (\omega_0/\sigma_{\hat{\omega}}) \leq -z_\beta$, where $-z_\beta$ is the lower β-percentile of the standard normal distribution, such that $P(Z < -z_\beta) = \beta$. Thus we require length of data sufficiently large so that $\sigma_{\hat{\omega}} \leq \omega_0/(2 + z_\beta)$. Then, from the form of $\sigma_{\hat{\omega}}$ presented by *Weatherhead et al.* [1998], where

$$\sigma_{\hat{\omega}} \approx \frac{\sigma_N}{n^{3/2}} \sqrt{\frac{1 + \phi}{1 - \phi}},$$

it directly follows that the number of years n^* required to detect a real trend of specified magnitude $|\omega| = |\omega_0|$, with at least $1 - \beta$ probability, is

$$n^* \approx \left[\frac{(2 + z_\beta)}{|\omega_0|} \sigma_N \sqrt{\frac{1 + \phi}{1 - \phi}}\right]^{2/3}. \tag{2}$$

Here σ_N is the month-to-month variability in the noise (expressed in Dobson units (DU)), ϕ is the month-to-month autocorrelation in the noise, and ω_0 is the expected or specified trend (in DU yr^{-1}). Specifically, if $1 - \beta = 0.50$ probability of detection is prescribed, as seems reasonable, then $z_\beta = z_{.50} = 0$ so that $2 + z_\beta = 2$ in (2). For another example, if a much higher $1 - \beta = 0.90$ probability of detection is desired, then $z_\beta = z_{.10} \approx 1.3$ so that $2 + z_\beta = 3.3$ in (2). As was mentioned above, we will adopt the 0.50 probability of detection and hence use the number of years for detection as

$$n^* \approx \left[\frac{2\sigma_N}{|\omega_0|} \sqrt{\frac{1 + \phi}{1 - \phi}}\right]^{2/3}.$$

The more exact formula [see *Weatherhead et al.*, 1998], for which this is an approximation, has been used to determine the number of years to detect a 1 DU yr^{-1} trend in ozone data. The results are presented in Table 1 for a range of values of σ_N and ϕ. The values in Table 1 show that for typical ranges of autocorrelation and noise variance, the number of years to detect a 1 DU yr^{-1} trend can vary from less than 10 years to more than 20 years. While it may not be appropriate to refer to changes in short time series (less than 10 years) as trends, the numbers are offered here for comparative purposes. *Weatherhead et al.* [1998] also discuss the uncertainty in the estimate of the number of years n^* for trend detection, formed from (2) when ϕ and σ_N need to be estimated from the data.

3. Data Used in This Study

To assess the magnitude of variability and especially the autocorrelation of ozone data, a long, continuous data set is needed. The Nimbus 7 Total Ozone Mapping Spectrometer (TOMS) gridded data provide a relatively long time span of data (from 1979 through 1993) as well as high-quality assur-

ance [*McPeters and Labow*, 1996]. The data are gridded in 1° latitude by 1.25° longitude areas and have been intercompared with the ground-based Dobson network. The effects of any undetected small problems of drifts or level shifts on estimates of noise and autocorrelation are likely to be very small, in part because this analysis removes any trend or seasonal bias before estimating the noise parameters.

Plates 2 and 3 show estimates of the standard deviation (σ_N) and the autocorrelation (ϕ) of the noise derived from the TOMS gridded data. Plate 2 shows the distribution of the standard deviation of the ozone noise for the time period of 1979 through 1993. The results are shown in Dobson units and represent the month-to-month variability in the Nimbus 7 ozone record after accounting for the seasonally expected mean as well as the effects of QBO, linear trend, and 11-year solar cycle. Plate 2 shows that the data are least variable at the equator, with higher variability near the poles. There is also some longitudinal variation: Even in the tropics the magnitude of the noise can vary considerably, from 3.3 to 6.6 DU.

The autocorrelation in Plate 3 ranges from near zero to almost 0.9, with the highest values at the equator. This range of autocorrelation values makes trends more difficult to assess when all other factors are equal. The strong latitudinal dependence of the autocorrelation is accompanied by some longitudinal variations, particularly in the subpolar regions. The magnitude and autocorrelation of the noise as shown in Plates 2 and 3 will be used to determine the detectability of trends in ozone over different locations around the globe.

Both the magnitude and autocorrelation of the noise are influenced by sampling size. Each grid represents an averaging of the individual satellite measurements within that area. The physical size of the grids varies with latitude, and thus some bias may be introduced when comparing grids of different sizes. To assess the impact of the grid sizes, the ozone data are averaged for a 2° × 2.5° grid area, effectively quadrupling the area for which satellite scans are used. The estimates of magnitude and autocorrelation of noise for these larger grids are compared with the estimates from the original grids. Only very small differences are observed when the areal size is quadrupled. Thus the differences in physical grid size with latitude introduce only a minor bias in interpreting the data.

To determine if the autocorrelation estimates are consistent over time, the 14-year TOMS data set is divided into two time periods, 1979–1985 and 1986–1992. The autocorrelation and magnitude of noise are estimated for each of these two time periods and compared with the estimates when the entire set of data is used. While small differences appear in these two time periods, the general pattern of the magnitude of the noise both for latitudinal and longitudinal variations remains the same. Some differences are noted in the longitudinal patterns of the autocorrelation values for the different time periods; however, the general patterns for the gross features remain the same. We conclude therefore that the eruptions of Mount Pinatubo in June 1991 and El Chichon in March–April 1982, while having a direct impact on the ozone concentrations, do not have as large an impact on the fundamental parameters of autocorrelation or variance. We assume in our predictions for detectability therefore that these quantities will remain stable over the next several decades. If the magnitude of variability or the autocorrelation increases, then the predictions for the number of years to detect a change presented in this paper may be considered to be a lower estimate of the actual number of years needed.

Table 1. Number of Years of Monthly Data Needed to Detect a Trend of 1 Dobson Unit per Year at a 95% Confidence Level for Selected Values of Autocorrelation (ϕ) and Standard Deviation (σ_N) of the Noise

σ_N	Value of ϕ									
	0.0	0.1	0.2	0.3	0.4	0.5	0.6	0.7	0.8	0.9
2	2.5	2.7	2.8	3.0	3.2	3.5	3.8	4.1	4.6	5.2
3	3.3	3.5	3.7	4.0	4.3	4.6	5.0	5.5	6.2	7.3
4	4.0	4.3	4.5	4.8	5.2	5.6	6.1	6.7	7.7	9.2
5	4.6	4.9	5.3	5.6	6.0	6.5	7.1	7.9	9.0	10.9
7	5.8	6.2	6.6	7.1	7.6	8.2	9.0	10.0	11.4	14.0
10	7.4	7.9	8.4	9.0	9.7	10.5	11.4	12.8	14.7	18.2
15	9.7	10.3	11.0	11.8	12.7	13.8	15.1	16.8	19.4	24.3
20	11.7	12.5	13.4	14.3	15.4	16.7	18.3	20.5	23.7	29.7
25	13.6	14.5	15.5	16.6	17.9	19.4	21.3	23.8	27.6	34.7
30	15.3	16.4	17.5	18.8	20.2	21.9	24.1	26.9	31.2	39.4

The standard deviation σ_N of the noise is expressed in Dobson units of variability in the month-to-month data.

4. Detecting a Fixed Trend

The estimates of autocorrelation and magnitude of noise derived from the Nimbus 7 TOMS data are used to estimate the number of years to detect a fixed linear trend of 1 DU yr^{-1} in total column ozone using the result of (2). While such a trend is not expected uniformly around the world, the analysis shows, to some extent, the ability to detect trends in different locations. The results of this section may be extrapolated to other size trends: If one area is better for detecting a trend of 1 DU yr^{-1}, it will also be better for detecting a trend of any fixed magnitude. In section 5, more realistic, geographically specific trends will be considered.

Plate 4 shows the number of years to detect a trend of 1 DU yr^{-1} in total column ozone. The numbers range from about 4.3 years to just over 20 years. Quite interestingly, within the tropical region the trend detectability changes markedly between the equator and 10° off the equator. At 10° off the equator, less than 5 years of data are needed to detect a trend of 1 DU yr^{-1}, while directly on the equator more than 8 years of data are needed. These latitudinal variations in the tropics seem to be quite independent of longitude. Because trends in the tropics are expected to be very small, these results could be important in setting up tropical monitoring stations for trend detection of ozone. Additionally, recent record low levels of ozone observed in the tropics (P. K. Bhartia, personal communication, 1998) have brought new concern to monitoring ozone in this region. Plate 4 also shows that from a purely statistical viewpoint, monitoring stations in Hawaii are not at the most advantageous location for detecting small tropical ozone trends. However, as discussed in the introduction, other factors are relevant for choosing optimal locations for long-term monitoring.

To determine if the areas of high and low detectability are extremely sensitive to the data available, the Nimbus 7 TOMS data used to determine the autocorrelation and noise levels are again divided into two time periods: 1979–1985 and 1986–1992. The same general patterns exist in both time periods. Specifically, the levels of high sensitivity to trend detection at approximately 10° off the equator are prominent in both time periods. The high similarity in the results for both subsets of data, during times when significant perturbations to the natural ozone layer took place, suggests that these areas will likely persist as areas of high or low detectability for future ozone changes.
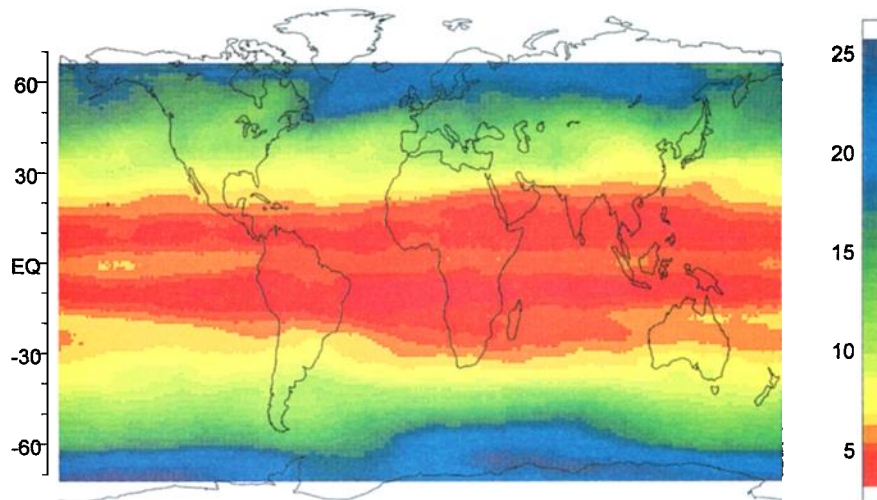
Plate 2. The observed variation in Dobson units of the monthly averaged ozone record with seasonal variability, quasi-biennial oscillation (QBO), linear trend, and 11-year solar cycle effects removed. Areas of high variability are areas where large deviations in ozone make trend detection difficult.
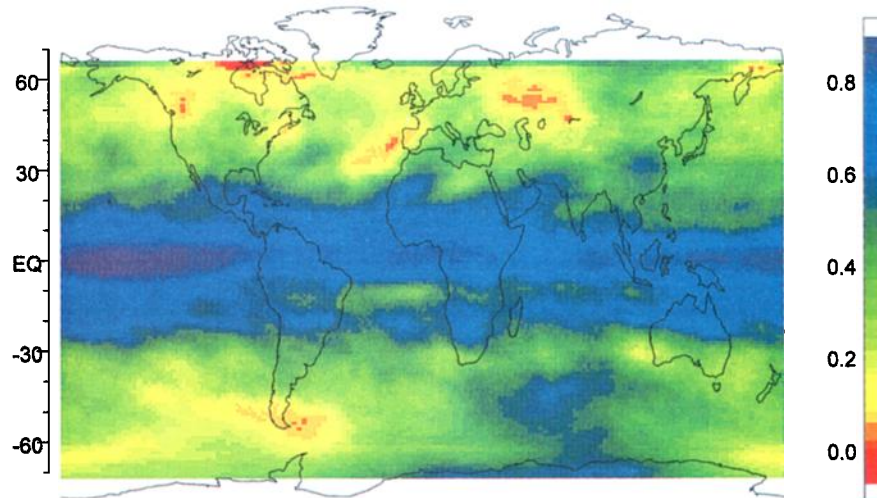

Plate 3. The autocorrelation of the monthly averaged ozone record with expected seasonal variability, QBO, linear trend, and 11-year solar cycle effects removed. Areas of high autocorrelation are areas where deviations in ozone may last several months, making trend detection difficult.
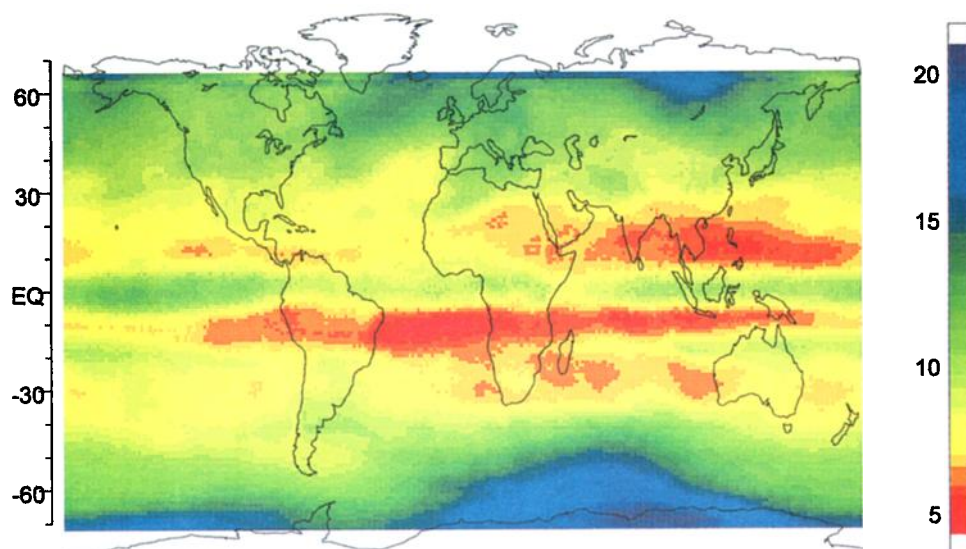
Plate 4. The expected number of years to detect a trend of 1 DU yr^{-1} in total column ozone records. The estimates assume that a trend is detected at the 95% level. The estimates make use of the magnitude of variation and autocorrelation of the noise in the ozone record presented in Plates 2 and 3.

5. Detection of Expected Trends

Past ozone trends have not been uniform throughout the world. Similarly, ozone recovery is not expected to be uniform or even directly related to past decreases. Because future trends are predicted to vary geographically, the results in section 4 addressing the issue of fixed trends may not be directly applicable to present scientific concerns. In this section the magnitude and latitudinal dependence of expected ozone trends from the GSFC 2-D model are used along with the estimates of the variability and autocorrelation of TOMS data to determine locations at which the expected recovery is likely to be detected earlier. Verification of the recovery is critical for determining if current understanding of ozone depletion and the international response are sufficient for global recovery of the ozone layer.

5.1. Expected Trends

All dynamical and chemical models evaluated for the WMO Scientific Assessment of Ozone Depletion 1998 [*WMO*, 1999] predict that the largest trends for stratospheric ozone recovery will occur in the polar regions. For this study the GSFC 2-D chemistry and transport model is used to predict future ozone trends by latitude. This model showed the fastest recovery time of all 10 models examined for the WMO Scientific Assessment of Ozone Depletion 1998 [*WMO*, 1999]. Should other models prove to be more accurate, longer times than estimated here will be needed for the detection of these trends. The model run used here is the same as reported by WMO (model A-3). It assumes no direct temperature changes due to greenhouse gas emissions but does allow for expected changes in gases relevant to ozone depletion, including methane. The GSFC 2-D model run shows that the largest trends are expected in the Southern Hemisphere and at the polar regions (Figure 3). These trends are expected to be close to linear for the next 50 years, with the trends becoming stronger during the latter period. For the purposes of this study, trends were derived using the first 20 years of predicted ozone levels. These trends should be more difficult to detect than the slightly larger trends derived using the full 55 years of predicted levels.

5.2. Results for Detecting Expected Trends

We estimate the number of years of data needed to detect the trends predicted for WMO by the GSFC 2-D model using monthly and latitudinally averaged past ozone data. The results, shown in Figure 3, indicate that the Southern Hemisphere midlatitudes should be one of the first places where recovery will be detected. However, a closer examination of the data reveals that there may be considerable longitudinal variations in the length of time required to detect recovery at a single location. Plate 5 shows the number of years of monthly averaged data needed to detect the expected trends in ozone. These results show that the expected trends are not likely to be detected in most parts of the Northern Hemisphere for at least 25 years. Notably, three areas of high detectability exist: the areas around New Zealand/eastern Australia, around southern South America, and around southern Africa. Should the trends predicted by the GSFC 2-D model occur, they are likely to be detected in approximately 15 years in these three areas. These areas show a combination of moderate noise characteristics and trends, resulting in high detectability. It is interesting that none of these areas of high detectability for the GSFC predicted trends is an area of lowest noise characteristics or an area of highest expected trends.

The lower times to detect recovery in the Southern Hemisphere than in the Northern Hemisphere are due strictly to the faster recovery rates predicted for the Southern Hemisphere. The ozone recovery rates in models depend on many factors, including assumptions made about future emissions of halocarbons, methane, nitrous oxide, and sulfate aerosols, plus changes in temperature and meteorological fields, including influences from climate change. All 10 models examined for the WMO Scientific Assessment of Ozone Depletion 1998 [*WMO*, 1999] do not include all of these factors, but all of the models do predict a quicker recovery in the Southern Hemisphere than in the Northern Hemisphere. This difference is
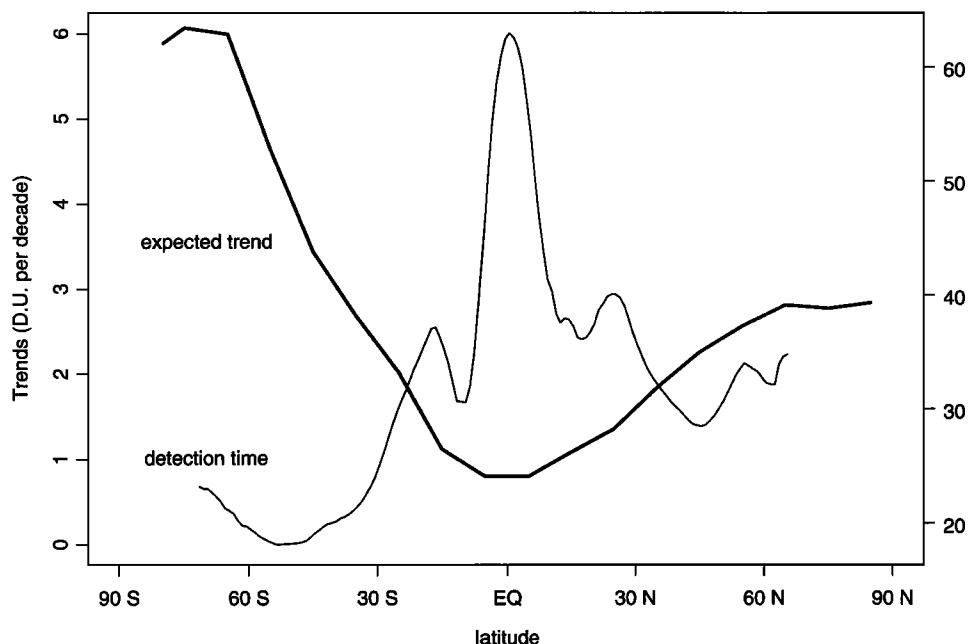
Figure 3. The predicted future changes in ozone based on the GSFC 2-D model for 2000–2020 are presented by latitude. The lengths of time estimated to detect these trends are also presented by latitude. The areas of largest trends are not the areas in which it will be easiest to detect predicted changes because these are also the areas of large variability.

noted for all latitudes, not just the polar regions. The decrease in ozone in the Southern Hemisphere has been much larger than that in the Northern Hemisphere due to the effects of heterogeneous chemistry on polar stratospheric clouds over Antarctica, causing what is referred to as the Antarctic ozone hole. These effects have spread depleted ozone levels into other latitudes in the Southern Hemisphere, adding to any loss due to halogen-related chemistry at these latitudes [*Prather et*

al., 1990]. Because the ozone loss in the Antarctic ozone hole is nonlinearly sensitive to the amount of reactive chlorine, a more rapid response to reduction in emissions of CFCs and other halocarbons should be expected in the Southern Hemisphere, even outside of the Antarctic ozone hole, than in the Northern Hemisphere, where much less of the nonlinear processing on polar stratospheric clouds occurs. There is some concern that the predicted differences in Northern and South-
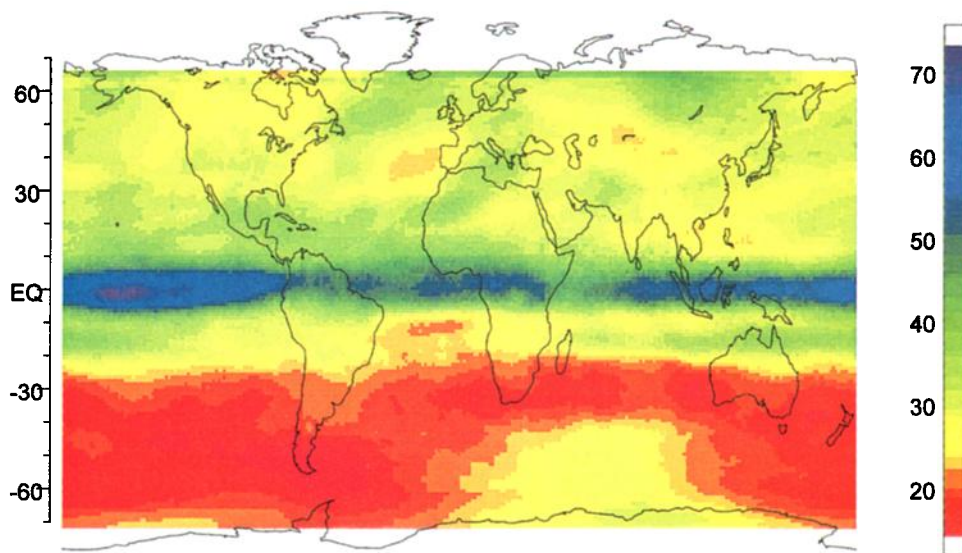

Plate 5. The expected number of years to detect the predicted trend for ozone. Estimates assume that a trend is detected at the 95% confidence level. The estimates make use of the magnitude of variation and autocorrelation of the noise as well as the magnitude of the predicted trends in ozone. The predicted trends are based on the GSFC 2-D model as reported in the WMO Scientific Assessment of Ozone Depletion 1998 [*WMO*, 1999]. The estimates for the magnitude and autocorrelation of noise in the ozone signal are based on the Nimbus 7 TOMS ozone record.

ern Hemisphere recovery from the 2-D models may be too large. Should this be the case, the detection times for the two hemispheres will be more similar in magnitude.

Faster recovery rates are expected if one derives expected recovery rates from the model predictions for the years 2000–2050 rather than the years 2000–2020. Estimates for the length of time to detect the changes over the 2000–2050 time period, rather than over the 2000–2020 time period, are similar to those shown in Plate 5. The differences are negligible at the equator, where approximately 2% less time is needed to detect the longer-term trends. However, approximately 30% less time is needed at the midlatitudes and approximately 40% less time is needed in the high latitudes. The time-for-detection estimates using both the shorter- and longer-term estimates of trends show that the areas around New Zealand/eastern Australia, southern Africa, and southern South America appear as the areas likely to show the detection of these longer-term trends earliest.

6. Regional Averages

For some discussions the most critical question is, What are the trends in large regions of the world, for instance, Northern Hemisphere midlatitudes? Regional trends offer a summary of changes in ozone that can be particularly useful for gauging the success of efforts to protect the ozone layer. For this reason, estimates have been made to determine how long it will take to detect the expected positive trends in ozone in several regions around the world. The expected trends for each region are determined by averaging the latitudinally dependent trends from the GSFC 2-D model predictions weighted by the area represented in each latitudinal band. For each region the magnitude of noise (σ_N) and autocorrelation (ϕ) are estimated using (1) from a single time series of the available gridded TOMS data, weighting each grid point by the area it represents. The results are presented in Table 2. The values presented represent the number of years to detect a trend with 0.50 probability, using a 95% confidence level decision rule. Therefore, should the predicted trends be accurate (and no large, confounding changes to the data records take place), there is an approximately 50% chance that the trends will be detected within the number of years shown in Table 2.

Notice that in comparison with typical values displayed in Plates 4 and 5, the numbers of years for trend detection for regions like 30°N–60°N, 0°–30°N, 0°–60°N, and 30°S–0° are not dramatically smaller than those obtained from corresponding individual grid points. In general, regional averages decrease the magnitude of noise but increase the autocorrelation estimates derived from the data. The most substantial reductions in the numbers of years for detection from regional analyses would appear to occur for the 60°S–30°S and 60°S–60°N regions.

7. Conclusion

International efforts to control ozone-depleting substances have been modified as our understanding of ozone depletion has improved. Full verification that our current understanding is sufficient and that international actions are appropriate will occur when the ozone concentrations have returned to unperturbed levels. However, before this takes place, the detection of the increase in ozone levels will be one of the most convincing arguments that current actions are working. Several net-

Table 2. Number of Years of Monthly Data Needed to Detect Trends for Selected Regions

Region	σ_N	ϕ	Years to Detect 10 DU per Decade	Expected Trend, DU per Decade	Years to Detect Expected Trend
30°N–60°N	6.31	0.82	11.5	2.1	32.4
0°–30°N	3.47	0.82	7.7	1.1	34.5
30°S–0°	3.08	0.77	6.5	1.4	24.5
60°S–30°S	5.20	0.81	9.8	3.6	19.4
0°–60°N	4.05	0.88	9.8	1.5	34.8
0°–60°S	3.23	0.84	7.6	2.3	20.2
60°S–60°N	1.91	0.82	5.0	1.9	15.0
20°S–20°N	2.74	0.74	5.8	1.0	27.0

works have been established and are being maintained to detect changes in total column ozone. It is likely that some of these locations will detect ozone recovery sooner than others. The ability to detect changes in spite of the local natural variability will be a limiting factor in detecting ozone recovery.

This analysis shows that natural variability makes it likely that predicted ozone trends will be most readily detectable around New Zealand/eastern Australia, southern South America, and southern Africa. It is particularly interesting to note that these areas are not where the largest trends are expected nor are they the areas where the background noise is most conducive to trend detection. However, the combination of moderate noise and signal indicate that these are the areas where the trends predicted by the GSFC 2-D model should be detected earliest.

As shown by *Weatherhead et al.* [1998], sudden changes in the data sets, such as instrumentation changes, local perturbations, or volcanic eruptions, can increase the number of years needed to detect a trend by as much as 50%. Thus it is critical for detection of ozone recovery that current monitoring stations be maintained through the expected recovery.

The GSFC 2-D model shows the fastest ozone recovery of all models examined for the WMO Scientific Assessment of Ozone Depletion 1998 [*WMO*, 1999]. Should the recovery be slower than predicted by the GSFC model, for instance, by the effect of greenhouse gas emissions, or should measurement sites be perturbed, even longer times would be needed for detection, and the geographic distribution of areas of high and low detectability may change.

However, the analysis also assumes that each gridded area will be analyzed in isolation from all other information. It is far more likely that the entire body of data will be analyzed, either from satellite information or from ground-based networks. The information from multiple regions, analyzed jointly, is likely to reduce the number of years to determine a statistically significant trend, but as illustrated by the results in section 6, the reductions due to regional analyses need not be substantial.

Some of the benefits of this type of analysis are outlined briefly here.

1. By establishing reasonable expectations of the number of years necessary to detect trends, the results of this study can be used to make judicious choices about continuation of existing monitoring. In particular, this work shows that improved monitoring of ozone in the Southern Hemisphere may be critical to determining the effectiveness of efforts to protect the ozone layer.

2. By determining areas of high likelihood for the detec-

tion of ozone recovery, this study will allow existing and future work to begin focusing on areas where scientific results are likely to be achieved earliest and therefore with least cost. Similarly, methods of analysis can be developed to exploit these differences in detectability.

3. By estimating now the number of years necessary for detection of recovery, this study will be useful for explaining why positive ozone trends may not be detected in the Northern Hemisphere in the next 20 years, despite the effectiveness of international treaties.

This study points to the importance of understanding reasonable expectations for ozone recovery. Continuation of existing monitoring stations and judicious placement of new instruments are critical for detecting the recovery of ozone. The ability to detect trends could be improved by use of ancillary data or by grouping data from different regions to identify average behavior over large spatial scales. Finally, one should note that long-term monitoring has value other than trend detection. The capability to identify unexpected, and perhaps large or abrupt, changes in the environment must be maintained.

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