NASA-CR-191248

p. 27

Final Report

to

National Aeronautics and Space Administration

by

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November, 1992

Grant No: NAGW-2057

Period of Research: July 1, 1990 - June 30, 1992

Title: Statistical Analysis of Stratospheric Temperature and Ozone Profile Data for Trends and Model Comparison

(NASA-CR-191248) STATISTICAL ANALYSIS OF STRATOSPHERIC TEMPERATURE AND OZONE PROFILE DATA FOR TRENDS AND MODEL COMPARISON Final Report, 1 Jul. 1990 - 30 Jun. 1992 (Chicago Univ.) 27 p

N93-12877

Unclas

G3/46 0130528

1. Introduction

This final report describes work performed during the project period July 1, 1990 to June 30, 1992 on the statistical analysis of stratospheric temperature data, rawinsonde temperature data and ozone profile data for the detection of trends. Our principal topics of research are:

- Trend analysis of NOAA stratospheric temperature data over the period 1978-1989
- Trend analysis of rawinsonde temperature data for the period 1964-1988
- Trend analysis of Umkehr ozone profile data for the period 1977-1991
- Comparison of observed ozone and temperature trends in the lower stratosphere.

The main findings are summarized below:

- Analysis of NOAA stratospheric temperature data indicates the existence of large negative trends at 0.4 mb level, with magnitudes increasing with latitudes away from the equator.
- Trend analysis of rawinsonde temperature data over 184 stations shows significant positive trends about 0.2°C per decade at surface to 500 mb range, decreasing to negative trends about -0.3°C at 100 to 50 mb range, and increasing slightly at 30 mb level. There is little evidence of seasonal variation in trends.
- Analysis of Umkehr ozone data for 12 northern hemispheric stations shows significant negative trends about -.5% per year in Umkehr layers 7-9 and layer 3, but somewhat less negative trends in layers 4-6. There is no pronounced seasonal variation in trends, especially in layers 4-9.
- A comparison has been made of empirical temperature trends from rawinsonde data in the lower stratosphere with temperature changes determined from a one-dimensional radiative transfer calculation that prescribed a given ozone change over the altitude region, surface to 50 km, obtained from trend analysis of ozonsonde and Umkehr profile data. The empirical and calculated temperature trends are found in substantive agreement in profile shape and magnitude.

2. Trend Analysis of NOAA Satellite Temperature Data

This section reports the findings of a statistical trend analysis of stratospheric temperature data from National Oceanic and Atmospheric Administration (NOAA) satellites for the 11-year period from October 1978 through December 1989. The data consist of monthly average temperatures measured at 8 pressure levels (70, 50, 30, 10, 5, 2, 1 and 0.4 mb) for 36 latitude zones (0° N to 85° N and 0° S to 85° S at 5° intervals). A very small number of missing observations occur in the time series at particular pressure levels and certain latitudes (never more than 2 missing observations for any series), and in all instances, missing values were substituted by interpolated values from a preliminary fitting of the regression-time series model considered below.

Inspection of the temperature time series shows that they are highly seasonal and, generally, the magnitudes of seasonal fluctuations of the data become larger as one moves from the tropical zones towards the polar zones. A strong downward trend is evident in the time series for most latitudes at the 0.4 mb pressure level, although for many latitudes the prominent feature at 0.4 mb is more of a sudden drop in the mean level in early 1985 rather than a persistent downward linear trend. This phenomenon of a sudden dip in 1985 at 0.4 mb raises the question whether there is some intervention during this period or there is actually a downward trend exhibited in these time series. A slight downward trend is also observed in the data at the 2 mb and 5 mb pressure levels for the tropical zones. Further, by removing seasonal components with periods 12, 6 and 4 months, one can observe occasional occurrence of sharp peaks and dips in the deseasonalized data, particularly in the north polar region after 1985. This is a warning for caution against potential outliers.

Let $y_t, t = 1, \ldots, 135$, denote the time series of monthly average temperatures at a particular pressure level and a specific latitude. For the assessment of trends and the relationship between temperature and solar cycle activity, we consider regression time series models of the form

$$y_t = \mu + S_t + \omega x_t + \gamma z_t + N_t \tag{1}$$

where μ is an overall mean level, S_t is a seasonal component consisting of sinusoidal terms of fundamental period 12 months and their harmonics (6, 4 and 3 months), x_t is a linear trend and z_t is the series of f10.7 solar flux measurements. N_t is a "noise" term which is modeled as a second order autoregressive process, AR(2),

$$N_t = \phi_1 N_{t-1} + \phi_2 N_{t-2} + \epsilon_t \tag{2}$$

where ϵ_t is a white noise sequence of random variables with mean zero and constant variance. Models of the form (1)–(2) were estimated for each of the 36 x 8 time series for the different latitudes at the various pressure levels (36 latitudes by 8 pressure levels). Figures 1(a) and 1(b) display the trend estimates (in degrees per decade) obtained over the 8 pressure levels and the various latitude zones, with trend results displayed in latitude groups for the tropical (0°-25°), temperate (30°-55°) and polar (60°-85°) zones in the northern and southern hemispheres separately. The means of the trend estimates for each of the 6 latitude groups at each pressure level are presented in Table 1. For convenience, approximate standard errors of the mean trend estimates for each latitude group were calculated assuming that the correlation between the time series for any two latitudes in the same group is equal to one. This approximation is conservative, yet is found to be fairly accurate through some preliminary numerical investigations.

The prominent feature of the temperature trend results in Table 1 is the existence of large negative trends at 0.4 mb, with magnitudes increasing with increasing latitude away from the equator. Also, there are slightly significant negative trends at the 2 mb level in the tropics and at the 5 mb level in the tropical and the south temperate latitude groups. For the south polar region, a slightly significant positive trend occurs at 5 mb while a slightly significant negative trend occurs at the 1 mb level. In addition, below 10 mb the trends are generally slightly negative at all latitude groups except for the south polar region, where they tend to be positive. As always, when attempting to interpret trend results from model (1)–(2) over a relatively short time period such as 11 years, one must be aware of the partial confounding between trend and possible solar cycle or other natural variations.

Table 1. Averages of Trend Estimates (in degrees per decade) over 5° latitude zones within each of six latitude groups and each pressure level, using NOAA temperature data from Oct. 1978 through Dec. 1989.

	60–85°S	30–55°S	0–25°S	0–25°N	30–55°N	60–85°N
Pressure (in mb)	est se	est se	est se	est se	est se	est se
0.4	-10.00 (2.82)	-5.47 (1.17)	-2.20 (1.27)	-2.03 (1.23)	-5.29 (2.14)	-8.35 (1.84)
1	-2.95 (1.83)	0.37 (1.33)	-0.71 (0.74)	-0.96 (0.74)	0.19 (1.05)	-0.52 (1.97)
2	1.45 (1.38)	0.42 (1.09)	-1.56 (0.67)	-1.61 (0.75)	1.06 (0.87)	1.94 (1.59)
5	2.99 (1.49)	-1.79 (0.92)	-1.31 (0.70)	-1.07 (0.69)	-0.48 (1.43)	0.04 (1.12)
10	0.36 (1.91)	-0.38 (1.28)	0.12 (1.87)	0.80 (1.43)	0.73 (0.83)	0.47 (0.85)
30	1.07 (1.22)	-0.85 (0.64)	-0.58 (0.64)	-1.09 (0.50)	-0.40 (0.43)	-0.13 (0.64)
50	0.62 (1.05)	-0.97 (0.56)	-0.58 (0.72)	-1.43 (0.56)	-0.55 (0.43)	-0.06 (0.61)
70	0.28 (1.04)	-1.01 (0.54)	-0.46 (0.70)	-0.49 (0.71)	-0.60 (0.40)	-0.09 (0.59)

Approximate standard errors of average trend estimates are given in parentheses.

3. Trend Analysis of Rawinsonde Temperature Data

This section presents a statistical trend analysis of rawinsonde temperature data.

$$\begin{cases} y_t = \mu + \beta_1 \sin(\frac{\pi t}{6}) + \beta_2 \sin(\frac{\pi t}{3}) + \beta_3 \cos(\frac{\pi t}{6}) + \beta_4 \cos(\frac{\pi t}{3}) + \beta_5 x_t + \gamma f_t + \beta_6 z_t + N_t \\ N_t = \phi N_{t-1} + \epsilon_t \end{cases} \quad (3)$$

where μ is a constant or mean level term. The sine and cosine terms are annual and semi-annual sinusoidal components. $\{x_t\}$ is a linear ramp function of the form $x_t = t/12$, f_t is the solar flux series, and ϵ_t's are independent and normally distributed with mean zero and possibly different variances in different months. For series having a level shift, an intervention term $\beta_6 z_t$ is included, where z_t is an indicator variable of the form:

$$z_t = \begin{cases} 0 & \text{before the beginning date of level shift} \\ 1 & \text{after the beginning date of level shift} \end{cases}$$

We include a second intervention term for stations which have another level shift.

The trend term $\beta_5 x_t$ in model (3) assumes that the trend is uniform over all 12 months. To account for possibly different monthly trends, we consider the following monthly trend regression time series model,

$$\begin{cases} y_t = \Sigma_{i=1}^{12} \mu_i I_i(t) + \Sigma_{j=1}^{12} \beta_j I_j(t) x_t + \gamma f_t + \beta_6 z_t + N_t \\ N_t = \phi N_{t-1} + \epsilon_t \end{cases} \quad (4)$$

where μ_i and β_i are the ozone mean level and trend in month i, respectively, $I_i(t)$'s are monthly indicator variables, and x_t, f_t, z_t, and ϵ_t are the same as in the annual trend model.

Annual Trend Estimates Results

For each of the 10 pressure levels at the 184 stations, the regression time series model (3) is fitted to data from January 1964 to December 1988. At pressure levels 30 mb and 50 mb, many stations do not have sufficient quantity of data to obtain reliable trend estimates, where the data have either a short record or a large number of missing values. Only maximum likelihood estimates with more than 50 observations are reported. The estimates are given in units of Celsius degree per decade.

Figure 3 shows histograms of the annual trend estimates against the 10 pressure levels. Also shown are the means of the trend estimates over all the stations for the 10 pressure levels and associated standard errors. It is seen that the averages of estimates show significant positive trends on the order of 0.2°C per decade at the surface level to 500 mb altitude range, then decreasing gradually to significant negative trends about -0.3°C per decade at the 100 mb and 50 mb range and finally increasing slightly again at the 30 mb level.

The Monthly Trend Estimates

Model (4) is fitted to monthly time series for each of the 10 pressure levels of the 184 stations. The monthly trends are also estimated by the maximum likelihood (ML) method. As mentioned before, at pressure levels 30 and 50 mb, many stations do not have sufficient quantity of data to obtain reliable trend estimates where the data have either a short record or a lot of missing values. Provided a series at a particular level of a specific station has more than 100 observations and at least three observations for each month, the trend estimates for the series will be reported.

Figure 4 shows, for each month, the medians of the trend estimates over all the 184 stations against the 10 pressure levels. We can see that the median trend estimates for each month basically have the same pattern as the annual trend estimates shown in Figure 3, i.e., positive trends on the order of 0.2°C per decade at the surface level to 500 mb range, then decreasing gradually to a negative trend of about -0.3°C per decade at the 100 mb to 50 mb range, and then increasing above the 50 mb level. There seems to be no apparent seasonal differences in the trend estimates.

Further details of the trend findings for the rawinsonde temperature data will be given in a technical report under preparation.

4. Trend Analysis of Umkehr Ozone Profile Data

A statistical trend analysis of stratospheric Umkehr ozone profile data over the period January 1977 through June 1991 for Umkehr layers 3-9 (approximately 15 to 49 km in altitude) from 12 Northern Hemisphere Umkehr stations has been performed. The correction method used in the analysis to adjust the Umkehr measurement data for errors caused by volcanic aerosols associated with El Chichon is the empirical method based on use of optical thickness time series data, similar to the method described in Reinsel et al. (1989). The optical thickness data that have been considered in the analysis uses aerosol data obtained from the SAGE II satellite for the period Oct. 1984 through Nov. 1990 combined with the pre-1984 composite optical thickness series derived from ground-based lidar data measurements. The SAGE II data for 1984-1990 used in the analysis were constructed by performing a quadratic interpolation of the optical thickness readings (above 15 km) from the three wavelengths 1020, 525, and 453 nm, to obtain optical thickness values appropriate for 694.3 nm (the wavelength used for ground-based lidar measurements) for each month. These were constructed separately from the SAGE II aerosol zonal series for each of the latitude zones 20°N, 30°N, 40°N, and 50°N. (The resulting SAGE II zonal series were found to be reasonably compatible with the ground-based lidar data for the period 1984-1990, so the SAGE II data were directly combined with the earlier lidar data for the trend analysis.) The SAGE II latitudinal zonal aerosol series were separately combined with the earlier pre-1984 composite optical thickness series derived from ground-based lidar data measurements (with a time lag in the lidar-based composite data series suitable to the latitude zone of the SAGE II data). For the trend analysis of the Umkehr data from any particular station, the appropriate combined lidar-SAGE II aerosol data series is used according to the latitude and location of the station.

Linear trend models which also include the $F_{10.7}$ solar flux term to account for solar cycle variations in the Umkehr data were estimated for the Umkehr data at each of the 12 stations using the empirical-model aerosol error correction method. (Umkehr data during a portion of 1982-1983 where the aerosol data values were most extreme, approximately the period from November 1982 through June 1983, were omitted in the estimation of the trend model.) The trend model used for each individual Umkehr station monthly ozone series Y_t at each Umkehr layer is

$$Y_t = \mu + S_t + \omega X_t + \gamma_1 Z_{1,t} + \gamma_2 Z_{2,t} + N_t , \tag{5}$$

where S_t represents the sinusoidal terms for the seasonal component, X_t denotes a linear trend function, ω denotes the trend or change in ozone, $Z_{1,t}$ denotes the 10.7 cm solar flux series, $Z_{2,t}$ denotes a transformation ($Z_{2,t} = e^{-\tau_t} - 1$) of the optical thickness series τ_t , which we refer to as the transmission series, and N_t is a residual noise series modeled as a first-order autoregressive (AR(1)) model, $N_t = \phi N_{t-1} + e_t$, where e_t is a white noise sequence with constant variance. Intervention mean level shift terms were also included in model (5) for the stations Kagoshima and Sapporo, to account for a possible effect of change from the Japanese-type Dobson instruments to Dobson instruments during 1989, and for the station Lisbon, to account for a possible effect due to instrument repairs and recalibration during 1987-1988.

The trend estimates obtained from model (5) for each of the 12 Umkehr stations and for each Umkehr layer 3-9 are presented in Figure 5. The overall estimates for trend obtained by combining estimation results over the 12 Umkehr stations, are presented in Table 2(a) for each Umkehr layer 3-9, with associated 95% confidence limits. The results indicate a significant overall negative trend, exclusive of trend variations associated with solar flux variations, of the order of -0.5% per year in Umkehr layers 7-9 over the period 1977-1990. Trend results in layers 5-9 for the period 1977-1990 are similar to previous results for the period 1977-1987 reported in Reinsel et al. (1989). However, the trend in layer 4 is somewhat more negative for the extended period (-0.35% per year for the 1977-1990 period compared with -0.19% per year for 1977-1987), and the trend estimate in layer 3 for 1977-1990 was also significantly negative, -0.59 $\pm$ 0.49 % per year. Note that this negative trend in layer 3 (15-19 km) for recent Umkehr data is reasonably consistent with trend results for that altitude region as obtained from ozonesonde data by Tiao et al. (1986, and updated in the recent WMO Ozone Assessment Report (1989).

Analysis of Umkehr Ozone Profile Data for Seasonal Trends

A preliminary seasonal trend analysis of Umkehr ozone profile data has also been performed. To investigate the nature of ozone trends in the Umkehr station ozone profile data, as a function of Umkehr layer (altitude) and the four different seasons of the year (Winter-December, January, February; Spring-March, April, May; Summer-June, July, August; Fall-September, October, November), the seasonal trend model used for each individual Umkehr station monthly ozone series Y_t at each Umkehr layer is

$$Y_t = \mu + S_t + \Sigma_{m=1}^{4} \omega_m I_{mt} X_t + \gamma_1 Z_{1,t} + \gamma_2 Z_{2,t} + N_t, \tag{6}$$

where μ denotes an overall level term, S_t denotes a seasonal component consisting of sinusoidal terms of fundamental period 12 months, 6 months, 4 months and 3 months, $I_{mt}, m = 1,..., 4$, denotes an indicator series for the mth season of the year which equals 1 if t corresponds to season m of the year and 0 otherwise. X_t denotes a linear trend function, ω_m denotes the trend or change in ozone for season $m, Z_{1,t}$ denotes the 10.7 cm solar flux series, $Z_{2,t}$ denotes a transformation ($Z_{2,t} = e^{-\tau_t} - 1$) of the optical thickness series τ_t, which we refer to as the transmission series, and N_t is the residual noise series modeled as a first-order autoregressive (AR(1)) model, $N_t = \phi N_{t-1} + e_t$. Hence the seasonal trend model (6) is an expanded form of the (nonseasonal) trend model (5) in which the trend in ozone is permitted to be different for each different season of the year (and also the seasonal mean structure in (6) is slightly more general than in (5)). As in (5), intervention mean level shift terms were also included in model (6) for the stations Kagoshima and Sapporo, to account for a possible effect of change from the Japanese-type Dobson instruments to Dobson instruments during 1989, and for the station Lisbon, to account for a possible effect due to instrument repairs and recalibration during 1987-1988.

The annual trend (defined as the average of the seasonal trends over the four seasons) estimates from the seasonal model (6) were combined over the 12 Umkehr stations, and these overall estimates are tabulated in Table 2(b) together with associated 95% confidence limits. These overall estimates for annual trend are seen to be very similar to the corresponding overall estimates in Table 2(a) from the nonseasonal trend model (5).

Now the seasonal trend estimates obtained from fitting of model (6) exhibit considerable variation over the 12 Umkehr stations in all the Umkehr layers. The overall seasonal rend estimates were obtained for each season and each Umkehr layer by combining trend estimation results over the 12 Umkehr stations, and these are presented in Table 3. Now, in any attempt to interpret these seasonal trend results as a function of season of the year and altitude (Umkehr layer), it must be cautioned that these overall seasonal trend estimates have a substantial degree of uncertainty (because of the relative shortness of the data period, 14 and one-half years). Nevertheless, there is a general impression given by Table 3 that the seasonal trends in the upper layers, 5-8, do not exhibit any pronounced pattern over the seasons of the year. However, in the lower layers, 3 and 4, there are some patterns suggested in the seasonal trends. The trends in layer 3 seem to have seasonal features most similar to those of total ozone, (see Bojkov et al. (1990)), with rather substantial negative trends on the order of -7% per decade in winter and spring, slightly less negative trends of about -5% per decade in summer and about -3% per decade in fall. The trends in layer 4 have similar features over the seasons to those in layer 3, but the differences among seasonal trends are smaller, with winter and spring trends of about -4% per decade and summer and fall trends of about -3% per decade. For layer 9, the trend in fall (about -6% per decade) is less negative than the trends in the other three seasons (about -8% per decade), but the uncertainty in these overall seasonal trend estimates is relatively large for this layer.

Overall, on the basis of percentage change in ozone, the pattern in seasonal trends over the altitude region of Umkehr layers 3-9 shows the greatest amplitude of variation over the seasons occurring for Umkehr layer 3, with somewhat less variation in the seasonal trends in layer 4, and little or no variation in the layers 5-8.

Table 2. Overall Trend Estimates (in Percent per Year), Exclusive of Trend Due to Solar Cycle Effect, From 12 Umkehr Stations for the Period January 1977 Through June 1991, Using the Empirical Correction Model for Aerosol Effects With Data Deletions in 1982-1983, and Using the Combined Lidar-Sage II Aerosol Data Set.

(a) From Nonseasonal Trend Model Analysis

Layer	Trend
9	(−0.70 ± 0.31)
8	(−0.46 ± 0.21)
7	(−0.54 ± 0.17)
6	(−0.22 ± 0.15)
5	(−0.13 ± 0.11)
4	(−0.35 ± 0.17)
3	(−0.59 ± 0.49)

(b) From Seasonal Trend Model Analysis

Layer	Trend
9	(−0.67 ± 0.28)
8	(−0.47 ± 0.18)
7	(−0.53 ± 0.17)
6	(−0.21 ± 0.12)
5	(−0.13 ± 0.12)
4	(−0.32 ± 0.18)
3	(−0.52 ± 0.36)

Table 3. Overall Seasonal Trend Estimates (in Percent per Year) from 12 Umkehr Stations for the Period January 1977 Through June 1991. Based on the Seasonal Trend Analysis Model.

Layer	Winter	Spring	Summer	Fall
9	(−0.84 ± 0.42)	(−0.81 ± 0.32)	(−0.80 ± 0.29)	(−0.56 ± 0.31)
8	(−0.55 ± 0.21)	(−0.50 ± 0.21)	(−0.52 ± 0.19)	(−0.43 ± 0.20)
7	(−0.58 ± 0.19)	(−0.49 ± 0.19)	(−0.50 ± 0.20)	(−0.56 ± 0.23)
6	(−0.20 ± 0.15)	(−0.22 ± 0.12)	(−0.20 ± 0.14)	(−0.25 ± 0.14)
5	(−0.11 ± 0.13)	(−0.18 ± 0.12)	(−0.17 ± 0.14)	(−0.15 ± 0.11)
4	(−0.43 ± 0.25)	(−0.38 ± 0.18)	(−0.30 ± 0.19)	(−0.25 ± 0.20)
3	(−0.70 ± 0.57)	(−0.70 ± 0.34)	(−0.48 ± 0.40)	(−0.28 ± 0.49)
Total Solution	(−0.26 ± 0.12)	(−0.27 ± 0.10)	(−0.19 ± 0.12)	(−0.11 ± 0.12)

5. Comparison of Observed Ozone and Temperature Trends in the Lower Stratosphere

This section reports a comparison of empirical temperature trends with changes in temperature determined from a one-dimensional radiative transfer calculation that prescribed a given ozone change over the altitude range from the surface to 50 km (Miller et al., 1992).

In Tiao et al. (1986) a detailed statistical trend analysis of monthly averages of balloon ozonesonde readings from 1970 through 1982 was given. These results were updated through 1986 in the WMO Ozone Assessment Report (WMO, 1989) with very similar results.

The statistical regression model used was

$$Y_t = a + S_t + cX_t + dU_t + N_t \tag{7}$$

where Y_t is the monthly average value of ozone for month t, a is a constant or mean level term, S_t is a seasonal component consisting of annual and semi-annual sinusoidal terms, cX_t is a linear trend term, dU_t is a level shift term and the residual series N_t is an autoregressive process AR(1). The level shift term is included to account for discontinuities in the observed data that result from factors such as changes in instrumentation or movement of station location. It is represented by a time series, U_t, consisting of 0's up to the discontinuity and 1's afterward and the statistical procedure estimates the magnitude, d, of the shift.

The trend estimate results of this statistical analysis for the ozonesonde data are depicted in Figure 6. In the lower troposphere the evidence is for positive ozone change although except for the lowest layer the results are not statistically different from zero. In the upper troposphere and lower stratosphere the results are negative and statistically significant, peaking at about -6% per decade at about 20 km. While the latitudinal extent of the ozonesonde stations is limited to mid-latitudes of the Northern Hemisphere, the pattern of ozone loss in the lower stratosphere is supported by the results from the satellite measurements of the Stratospheric Aerosol and Gas Experiment (SAGE) (WMO, 1989;

McCormick et al., 1992).

Within this framework, then, two questions are posed for this study:

1. What signal might we expect in the temperatures

   and

2. Does evidence exist in the available global rawinsonde data base of this signal?

Radiative Transfer Model

The model calculations of expected temperature change for this study were determined from a one-dimensional radiative transfer calculation that prescribed a given ozone change over the altitude range from the surface to 50 km. This is very similar to the approach utilized in WMO (1988). Above about 22 km the results of the ozone change as determined from Umkehr observations are merged (DeLuisi et al., 1989; Reinsel et al., 1987; WMO, 1989) and are also depicted in Figure 6.

Temperature changes were calculated for the scenario with CO_2 increasing from 325 to 345 ppmv (the approximate change from 1970 to 1986) and the ozone changes described above. For further details, see Miller et al., (1992). Results are shown in Figure 7 (0's). We see that a temperature decrease of about -0.8 degrees C is calculated for the lower stratosphere in direct response to the presumed ozone decrease. Above and below [illegible] until the mid-stratosphere where the are the station network utilized by Angell (1988). For some pressure levels at several stations, especially the surface level, the temperature data show a discontinuity which has been incorporated in the statistical procedures outlined in model (3). The average value of the estimated trends in temperature over all stations and 95% confidence intervals are plotted in Figure 8 as a function of altitude. We see that a positive trend, on the order of 0.3 degrees C per decade, exists in the surface to 5 km range and that the trend decreases gradually to a negative trend of about -0.4 degrees C per decade at 16 km and 20 km and becomes less negative above. These results differ slightly from those of Angell (1986, 1988), most likely due to our use of pressure level information as distinct from thicknesses and a more complex statistical model.

Comparison of Theory with Observed Trends

Comparing the results of the rawinsonde trends with those of the radiative model calculations, we see that the shape of the two profiles is quite similar, but that the rawinsonde trends in the 15 to 20 km region are less negative than those calculated in the model. In addition, we included a term for the solar flux variation, the F10.7 cm flux, but found essentially no impact of this effect on our calculations. Finally, we examined the trend results for a latitudinal effect and found no generally discernible pattern with latitude.

Thus, the pattern of temperature trend with height in the upper troposphere and lower stratosphere is consistent with that calculated from a model incorporating the observed ozone changes. The magnitude of the observed temperature decrease, however, is less than that determined from the numerical model. This issue needs to be considered further both from the data and theoretical points of view. For further discussion, see Miller et al. (1992).

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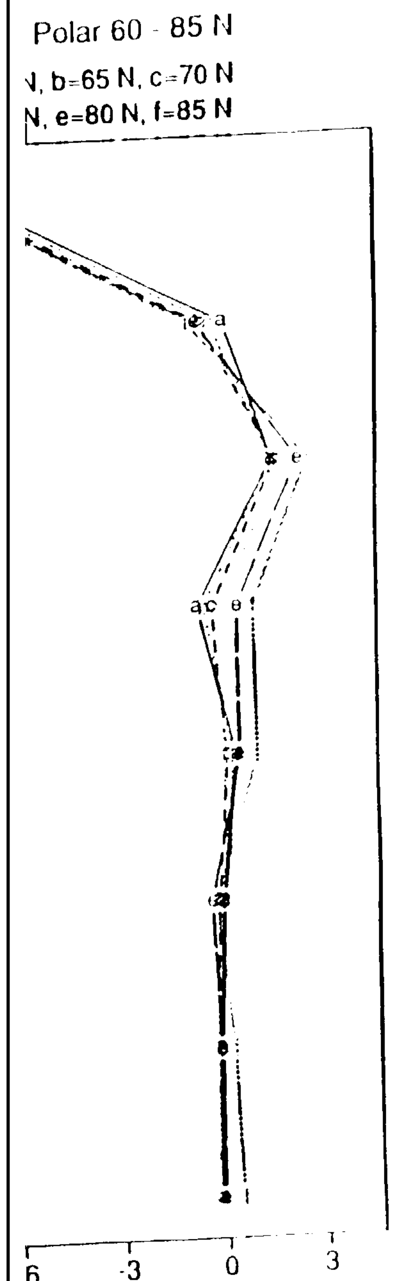
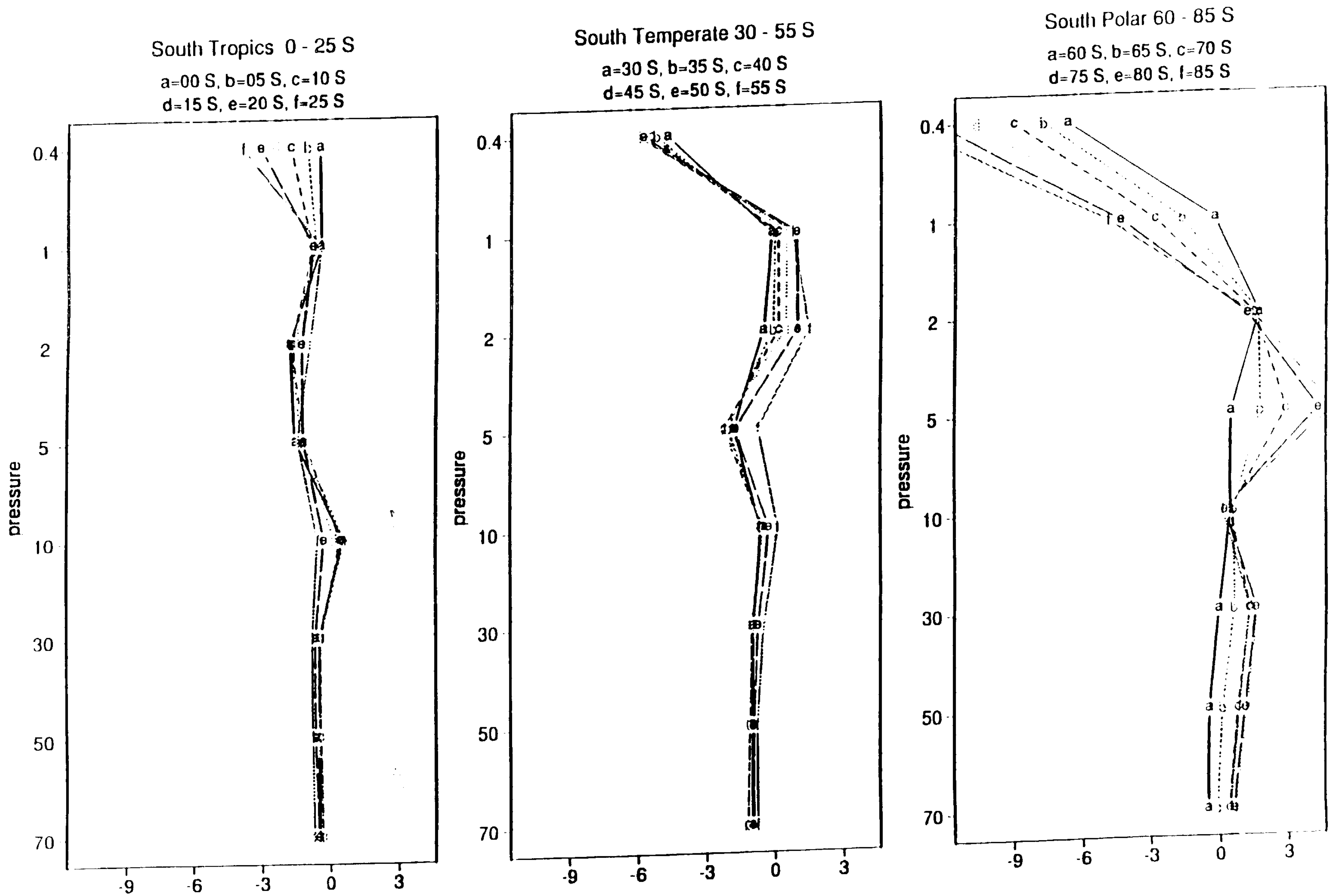

Polar 60 - 85 N
N, b=65 N, c=70 N
N, e=80 N, f=85 N
6
-3
0
3

Fig 1(b). NOAA Temperature Data Trend Estimates (in C per decade), within latitude groups, for period Oct. 1978 - Dec. 1989 with AR(2) noise model--Southern Hemisphere




0
150
180
90
60
30
0
30
60
90
120
150
180

Figure 3: Histograms of Rawinsonde Temperature Trend Estimates VS Pressure Levels.

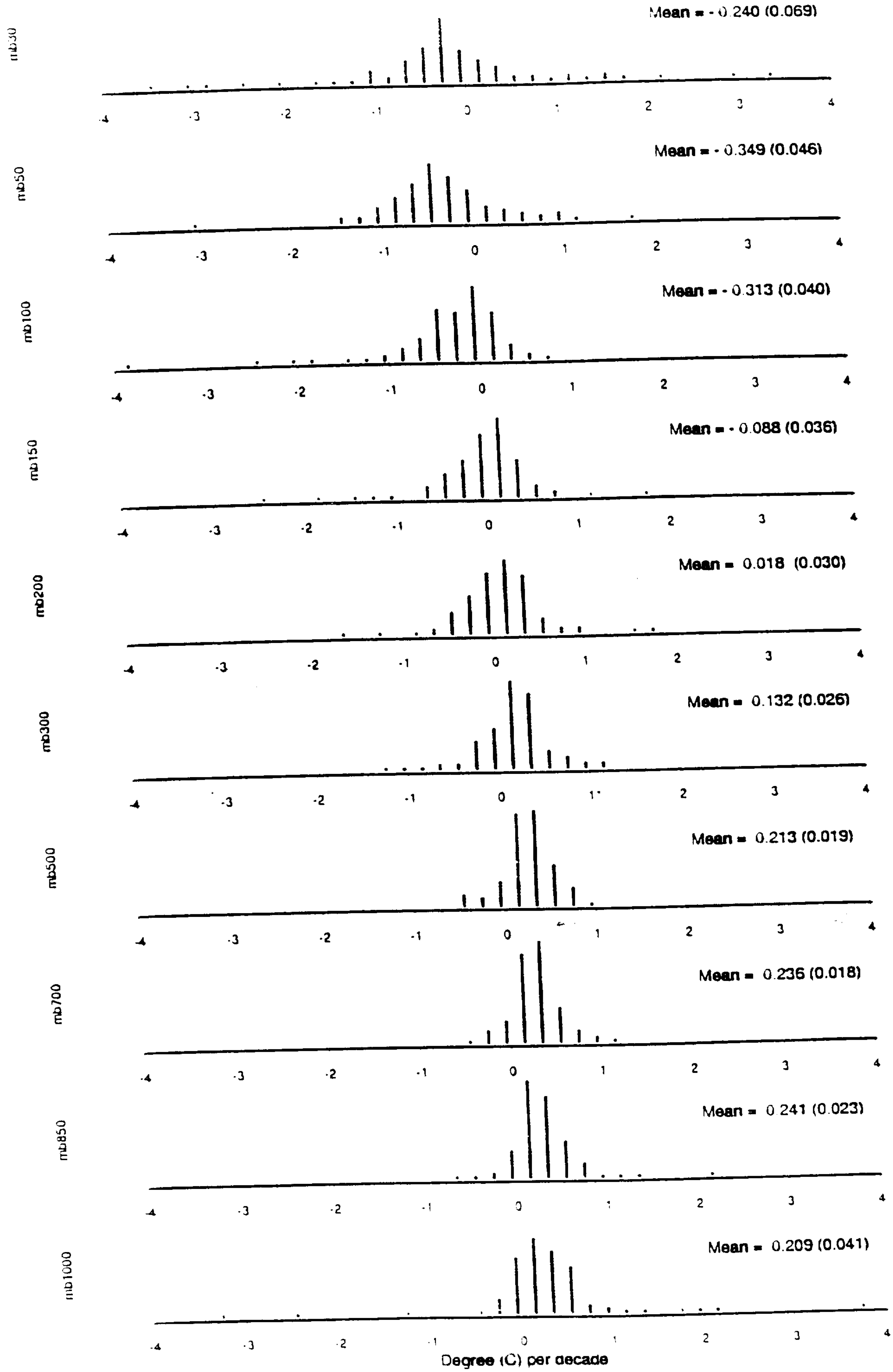


Figure 4: Median of Estimated Rawinsonde Temperature for Each Month VS Pressure Level (All 184 stations)

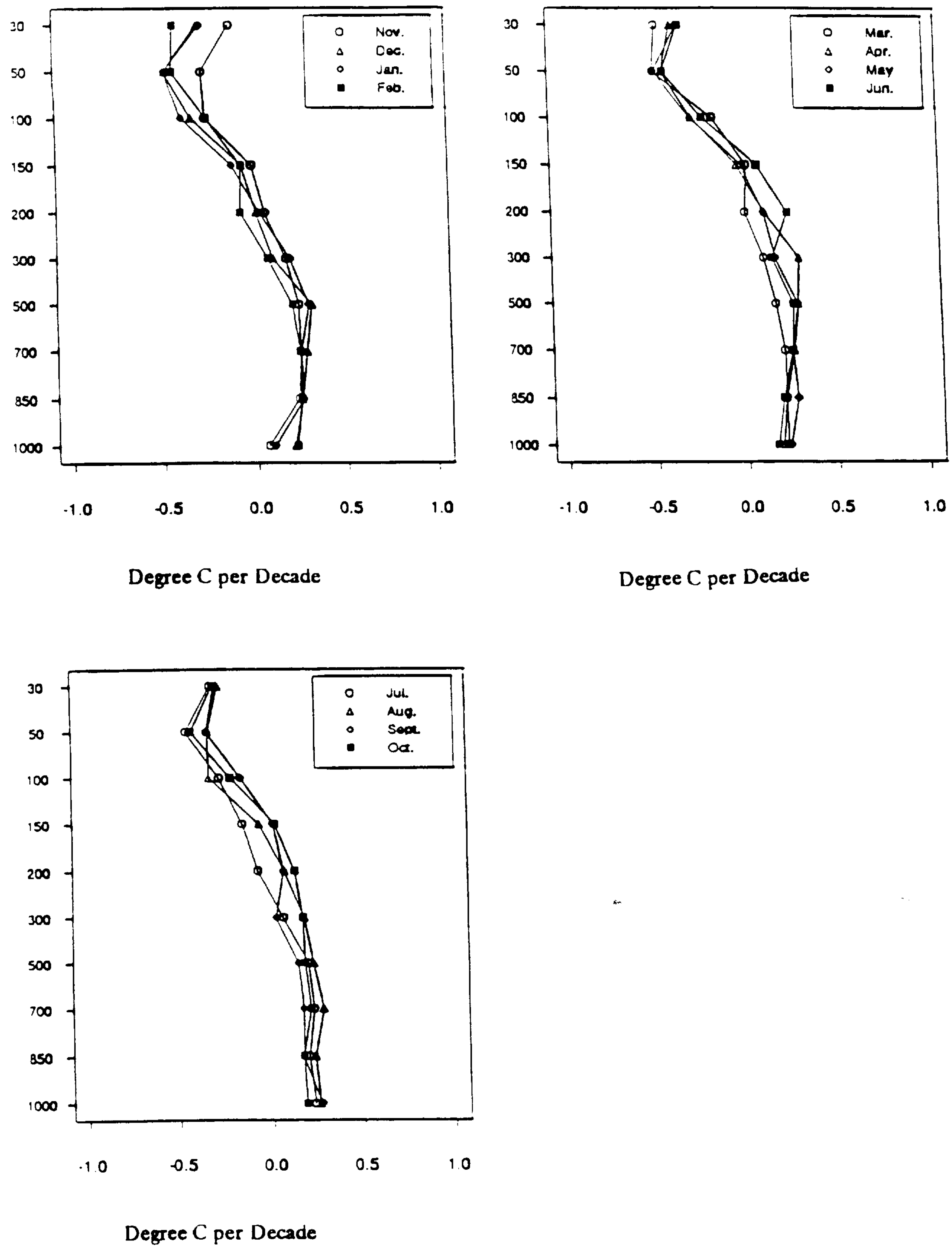


Fig. 5. Umkehr Trend Estimates. Jan. 1977 - Jun. 1991
for 12 Northern Hemisphere Stations (in % per year)

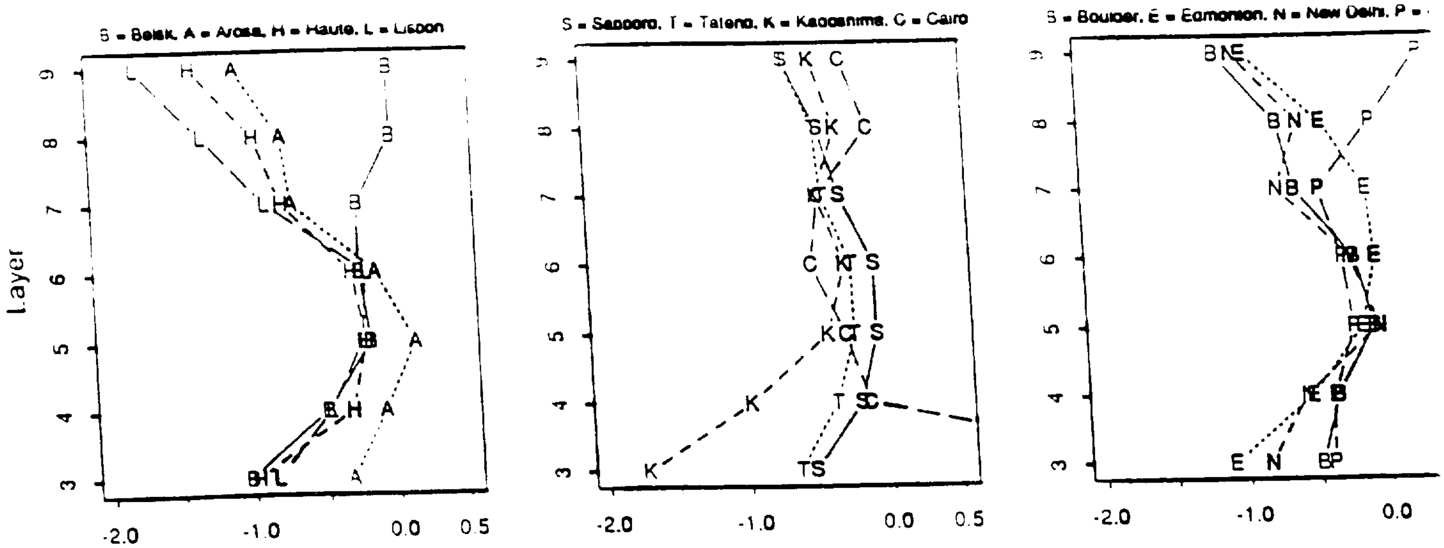


Fig. 6. Ozonesonde trend estimates as a function of height, X's. (Tiao et al., as reported in WMO,1989) and Umkeher trend estimates, 0's. (DeLuisi et al., 1989). Horizontal lines represent 95% confidence limits of trend estimates.

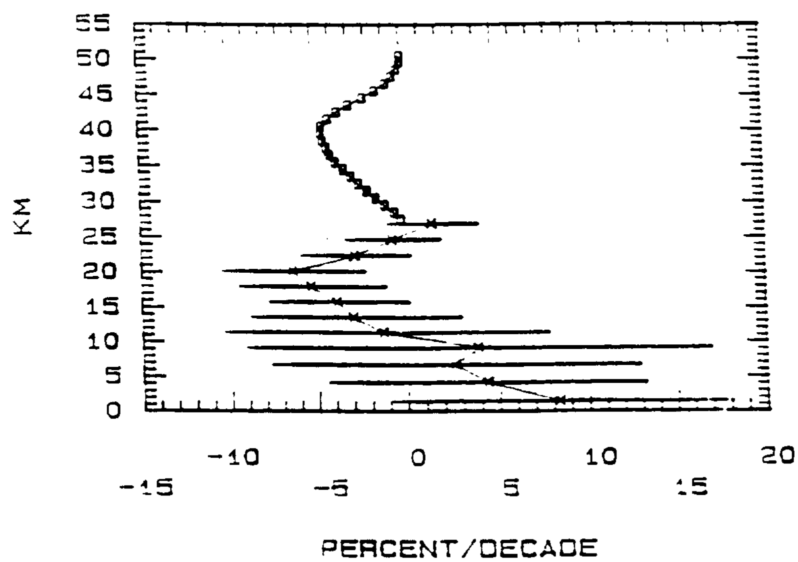


Fig. 7. Decadal temperature trend estimates derived from radiative transfer model using ozone change estimates of Figure 6. 0's are estimates with CO_2 changing through the period and the horizontal lines represent the 95% confidence limits. The curve represented by X's is for the calculation with CO_2 fixed at the 1970 value.

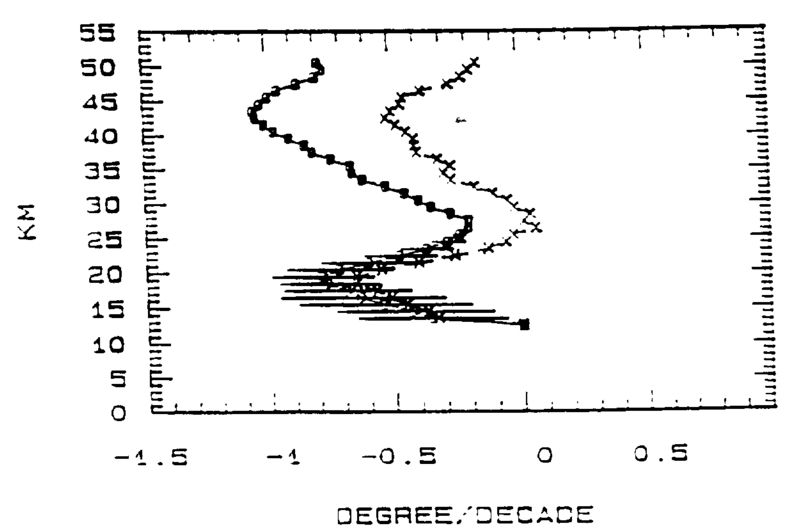
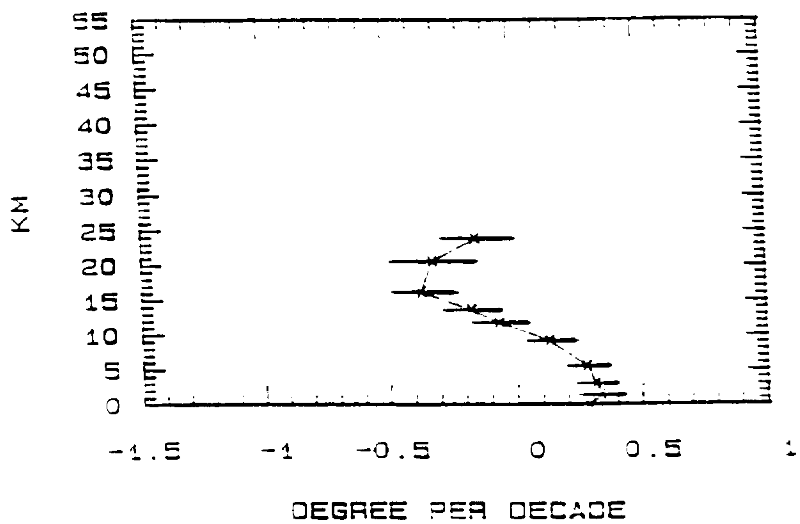


Fig. 8. Rawinsonde temperature trend estimates as a function of height. Horizontal lines represent 95% confidence limits of estimated trends. Units: Degrees per decade.



7. List of Journal Publications during the Period of Research

[1] Bojkov, R., L. Bishop, W.J. Hill, G.C. Reinsel and G.C. Tiao (1990). A statistical trend analysis of revised Dobson total ozone data over the northern hemisphere. *Journal of Geophysical Research*, 95, 9785-9807.

[2] 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 (1990). Effects of autocorrelation and temporal sampling schemes on estimates of trend and spatial correlation, *Journal of Geophysical Research*, 95, 20,507-20,517.

[3] Miller, A.J., R.M. Nagatani, G.C. Tiao, X.F. Niu, G.C. Reinsel, D. Wuebbles, and K. Grant (1992). Comparisons of observed ozone and temperature trends in the lower stratosphere, *Geophysical Research Letters*, 19, 929-932.

[4] Niu, X.F., J.E. Frederick, M.L. Stein, and G.C. Tiao (1992). Trends in column ozone based on TOMS data: Dependence on month, latitude and longitude,