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THE DETECTION AND INTERPRETATION OF LONG-TERM CHANGES IN OZONE FROM SPACE

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ABSTRACT

Long-term measurements of backscattered ultraviolet radiances, now being acquired by orbiting monochromators, will provide the basis for seeking trends in atmospheric ozone. The unambigious detection of ozone trends on decadal time scales demands a data set that is essentially free of instrument drifts. Periodic flights of an ultraviolet monochromator on the space shuttle will provide an independent means of evaluating the long-term stability of identical instruments operating on free-flying satellites. A successful calibration of the free-flying sensors using the shuttle instrument places strict demands on calibration repeatability from one flight to the next. In addition, spatial and temporal variability in cloud cover could pose further complications in carrying out these in-flight calibrations.

INTRODUCTION

The unambiguous detection of long-term changes in the earth's ozone layer has remained a high scientific priority since the middle of the last decade. Space-borne instruments provide the only practical means of obtaining global scale data sets for use in trend detection. Yet, recent experience has demonstrated the difficulties inherent in identifying small changes in ozone from earth-orbit. The problems fall into two broad categories, being (1) instrument characterization and (2) geophysical interpretation of measured signals.

Instrument characterization consists of defining a set of quantitative relationships which, when applied to sensor outputs (level 0 data), yield calibrated radiances (level 1 data). The algorithms required in this activity are based on knowledge of instrument design and on tests performed both in the laboratory and during flight. These evaluations can be "internal," using capabilities built into the instrument, or they can be "external," using an independent measurement system.

The geophysical interpretation of measured signals must be based on a firm theoretical understanding of how the quantity of interest, here the ozone abundance, is related to the measured radiance. Often more than one independent variabile influences the measurement, and it is necessary to isolate only the influence of the desired atmospheric property. To use the case studied in this paper, the backscattered ultraviolet radiance observed by an orbiting monochromator varies with the ozone amount (the property of interest), the solar zenith angle, and, at some wavelengths, the nature of the lower boundary of the atmosphere, particularly the presence of cloud cover.

Central issues in the detection of decadal ozone trends involve ensuring stability of a long-term level 1 data base and the unambiguous separation of a signal related to changes in ozone from other sources of variability in the radiances. This paper considers several issues related to each of these topics.

THE LONG-TERM OZONE MEASUREMENTS EFFORT

The system now in use by the United States' ozone monitoring program is an advanced version of the backscatter ultraviolet instrument flown originally on the Nimbus 7 satellite /1/. The first of the operational Solar Backscatter Ultraviolet Spectral Radiometers/Model 2, was launched on the NOAA-9 satellite in late 1984. A series of identical instruments will follow on upcoming operational satellites until the middle-to-late 1990s at which time an infrared radiometer will come into use. Frederick et al /2/ described the level 0 outputs from the SBUV/2 instruments and their conversion to calibrated level 1 radiances. Experience shows that the optical properties of SBUV-type instruments change slowly over time. Past approaches to long-term instrument characterization have utilized checks internal to the instrument to detect and remove these drifts.

The continuation of such efforts is essential to maintaining the stability of the SBUV/2 data base. However, regular flights of the space shuttle can now provide an alternate approach for the characterization of sensors carried on free-flying satellites.

The program for long-term monitoring of the ozone layer includes the Shuttle Solar Backscatter Ultraviolet (SSBUV) Spectral Radiometer. The backscattered radiance measurements made by SSBUV are directly comparable, wavelength by wavelength, to those from the SBUV/2 instruments. The shuttle will carry SSBUV on approximately one flight every eight months. Over a time period of three days in orbit, the SSBUV and SBUV/2 instruments will view the same location on the earth within one hour of each other on roughly 30 occasions. The shuttle orbit restricts these observations to within 30 degrees latitude of the equator. Figure 1 illustrates the measurement concept. A comparison of backscattered radiances made by the two independent instruments provides the basis for detecting and removing long-term drifts in the free-flying SBUV/2 using SSBUV as a radiance standard. Hilsenrath et al /3/ have presented details of the SSBUV effort, including a discussion of the instrument and the laboratory calibration.

CONSIDERATIONS INVOLVING AN IN-ORBIT CALIBRATION

The performance of in-orbit calibrations is complicated by factors which we categorize as (1) geophysical and (2) instrumental. Ideally, both SSBUV and SBUV/2 would be exposed simultaneously to the same solar irradiance $F(\lambda)$ and backscattered radiance $I(\lambda)$, at wavelength λ viewed in the nadir. The instruments observe 12 wavelengths which lie between 252 and 340 nm. In the case of solar irradiance, a lack of exact simultaneity poses no problem, although such is not the case for the backscattered radiance. Since the derivation of ozone abundances is based on the ratios $A(\lambda) = I(\lambda) / F(\lambda)$, we will work in terms of this quantity which we name the "backscatter ratio."

There are several geophysical reasons why the backscatter ratios sensed by SSBUV will differ from those obtained by SBUV/2. Even if the data were acquired simultaneously, the altitude of the shuttle orbit, approximately 300 km, implies a much smaller viewing area projected onto the earth's surface for SSBUV than for SBUV/2, which is roughly 800 km high. Horizontal variations in atmospheric and surface properties over length scales of several tens of kilometers will influence the backscattered radiances and lead to true differences between simultaneous SSBUV and SBUV/2 measurements. In the case of ozone, horizontal variations are expected to be small, less than 1%, particularly at the tropical latitudes of the space shuttle orbit. However, when the observations extend to wavelengths longer than 295 nm, the influence of the ground albedo and cloud cover becomes significant. Reflection from clouds at these wavelengths could provide substantial variations in radiance within the SBUV/2 field of view.

Differences in scene between SBUV/2 and SSBUV take on enhanced importance when one considers the lack of exact simultaneity. In practice, a "coincidence" is defined as both instruments passing over the same point on the earth within one hour of each other. Here an additional correction must be made for the changing solar zenith angle. This poses no theoretical problems, and the required adjustments can be determined in the same analysis that treats the potentially more important issue of variations in cloud cover.

Instrument performance is the major factor that determines the quality of an in-orbit calibration based on SSBUV. Even if SSBUV and SBUV/2 viewed the same area on the earth simultaneously, the measured backscatter ratios would not be identical. These differences arise in part from a lack of exact repeatability in the measurements. The same input signal does not consistently produce the same output owing to a small noise component in the data. This is a random error that can be minimized by obtaining a large number of measurements.

Biases in absolute radiometric calibration are potentially far more important than random errors and are of several types. First, biases can exist in the SBUV/2 measurements as a consequence of the original laboratory calibration as well as a trend associated with changes in optical or electronic components. The detection and removal of this instrument trend is the objective of the SSBUV program. The SSBUV instrument will be calibrated immediately before and after each flight. However, each calibration will be subject to biases, and great care must be taken to keep these to a minimum. The duration of a shuttle mission is sufficiently short that drifts in calibration should be negligible during a single flight. Stability of the SSBUV level 1 data set over this short time period is essential if SSBUV is to be useful as a calibration standard. The success of an in-orbit calibration requires that the SSBUV bias vary no more than $\pm$ 1% between shuttle missions. A rigorous statistical examination of these requirements and the manner in which SSBUV data can be combined with the long-term SBUV/2 measurements will be the topic of a separate study.

THE INFLUENCE OF CLOUD COVER ON BACKSCATTER RATIOS

Models based on gas phase chemistry predict the largest percent changes in ozone, related to CFC release, to occur near 40 km in altitude. The full vertical width of the depletion should grow over time and is of the order of an atmospheric scale height. This altitude region, from 35 to 45 km, is where SBUV-class instruments have their greatest sensitivity to ozone, and there is little conceptual problem in interpreting a change in backscatter ratio in terms of a change in ozone, provided instrument stability is assured /4/. Recently, however, there is increased concern over long-term trends in lower stratospheric ozone. The most dramatic example of this is the Austral spring ozone depletion over Antarctica. Also of great interest is an apparent small decrease in total column ozone over the northern hemishpere during the past decade /5/.

The backscatter ratios obtained by an SBUV-class instrument contain information on ozone in the lower stratosphere, although the inference of an ozone profile here is much more dependent on a-priori information than is the case above 30 km. The limitations on information content arise from multiple Rayleigh scattering and the consequent broadening of contribution functions. Any use of the SBUV/2 data set to seek ozone trends in the lower stratosphere must account for these issues, in addition to meeting the long-term stability requirements that apply to wavelengths that sense higher altitudes.

When one considers wavelengths that carry information on lower stratospheric ozone, an additional complication appears in the use of SSBUV for in-orbit calibrations of the SBUV/2. Clouds reach high altitudes at the tropical latitudes of a shuttle orbit, and column ozone amounts are relatively small. The broad contribution functions imply that wavelengths which penetrate the lower stratosphere also carry information on cloud albedos. Variations in tropical cloud cover over short times and small spatial scales constitute a potential obstacle to an in-orbit calibration of SBUV/2.

To determine the magnitude of scattering by clouds on the backscatter ratio at each wavelength, we fit the regression model of equation 1 to portions of the Nimbus 7 SBUV data set. The model is:

$$A(\lambda) = a_0(\lambda) + a_1(\lambda)\Theta + a_2(\lambda)R \qquad (1)$$

where $A(\lambda)$ is the backscatter ratio at wavelength, λ, Θ is the solar zenith angle, and R is the effective surface albedo derived from radiances at a wavelength of 339.8 nm /6/. The effective surface albedo, R, supplied with the SBUV data set, includes all reflections from the earth and atmosphere other than Rayleigh scattering. A large effective surface albedo arises from snow or ice-covered ground and from clouds, where only the latter need be considered at the latitudes observed by SSBUV. The linear dependence of $A(\lambda)$ on Θ used in equation 1 is accurate given the fixed local noon orbit of Nimbus 7 so long as the analysis considers data restricted to a 10 degree wide latitude zone over a time interval of one month.

The coefficient $a_0(\lambda)$ is a mean backscatter ratio appropriate to an overhead sun and an effective surface albedo of 0.0. It is convenient to express results in terms of the parameter $\alpha(\lambda)$, where:

$$\alpha(\lambda) = 100\ a_2(\lambda)/a_0(\lambda) \tag{2}$$

Physically, $\alpha(\lambda)$ is the percent change in backscatter ratio in response to a change in effective surface albedo from R = 0.0 to R = 1.0. At the shortest wavelengths one would expect the derived values of $a_2(\lambda)$ to be zero. Radiances which emerge from the atmosphere at wavelengths less than approximately 290 nm are strongly attenuated by ozone and presumably have not penetrated to the cloud tops. As wavelength increases, clouds exert a growing influence on the signals which emerge to space, and longward of 330 nm changes in effective surface albedo should dominate the variance in backscatter ratio.

Figure 2 presents $\alpha(\lambda)$ as a function of λ for the latitude band 0 - 10°N during the months of January and April. Points on each curve indicate the discrete wavelengths at which SBUV obtains data. Wavelength, increasing downward on the vertical scale, is an indicator of the altitude at the peak of each contribution function. However, the breadth of the contribution functions implies that there is no simple one-to-one mapping between wavelength and altitude. Values of $\alpha(\lambda)$ in excess of 10% exist longward of 297 - 298 nm, while $\alpha(\lambda)$ exceeds 100% between 300 and 303 nm depending on the case examined.

An unexpected result in Figure 2 is the behavior of λ at wavelengths shorter than 295 nm. The values of $a_2(\lambda)$ in equation 1 remain statistically significant to the 5% level or better for all wavelengths and consistently show a positive relationship between $A(\lambda)$ and R, even at the shortest wavelengths. Furthermore, the minimum value of $\alpha(\lambda)$ occurs between 283 and 293 nm and increases slightly toward shorter wavelengths. If aerosols were present in the upper stratosphere, then the additional scattering might provide a source for the observed behavior. Such scattering would be implicit in the effective surface albedo. However, we regard an instrumental origin as a far more likely explanation for the correlation between $A(\lambda)$ and R at $\lambda < 290$ nm. Scattering of light within the monochromator or a finite time response in the detector system could result in the observed behavior. The light level at 339.8 nm exceeds that at 283.0 nm by several orders of magnitude, and the effective surface albedo is a measure of the signal at the longer wavelength. If (1) the SBUV detector response did not come into equilibrium with the rapidly changing light levels during an observing sequence or (2) a small amount of long wavelength light were scattered within the instrument and contaminated the short wavelength measurements, then the correlation of Figure 2 would result.

This analysis implies that changes in tropical cloud cover should be considered when attempting to remove drifts in the SBUV/2 backscatter ratios using SSBUV as a calibration standard. Data from the operational SBUV/2 on NOAA-9 were not available when this study was completed. However, given the relationships which exist in the Nimbus 7 SBUV data base, it is essential that the regression model of equation 1 be applied to the SBUV/2 data base before attempting an in-orbit calibration using SSBUV. The SBUV/2 backscatter albedos must be adjusted to refer to the solar zenith angles and effective surface albedos of the SSBUV measurements before one attempts to detect long-term instrument drifts.

CONCLUSIONS

The unambiguous detection of long-term trends in atmospheric ozone requires great care both in instrument characterization and in the physical interpretation of measured radiances. Periodic flights of the SSBUV instrument on the space shuttle will allow in-orbit calibration updates of optically identical sensors, the SBUV/2 series, carried on free-flying satellites. The quality of this in-orbit procedure depends heavily on the flight-to-flight calibration repeatability in SSBUV. Given accurate measurements of the backscattered radiance, it is still necessary to account for differences in solar zenith angle and effective surface reflectivity between the SBUV/2 and shuttle observations. An analysis of Nimbus 7 SBUV measurements reveals significant correlations between the backscatter ratio and effective surface reflectivity at all wavelengths. For $\lambda < 290$ nm, this relationship is likely of instrumental, rather than geophysical, origin. When seeking long-term trends in ozone it is essential to account for all factors that influence the measured radiances; such as the correlation between backscattered radiance and cloud cover.

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LIST OF FIGURES

Fig. 1 Schematic of the in-orbit calibration of a free-flying SBUV/2 instrument by the shuttle-borne SSBUV monochromator

Fig. 2 Relation between backscatter ratios and effective surface reflectivity as a function of wavelength. The parameter ALPHA is 100 $a_2(\lambda)/a_0(\lambda)$ where a_0 and a_2 are the regression coefficeints of equation 1 in the text.

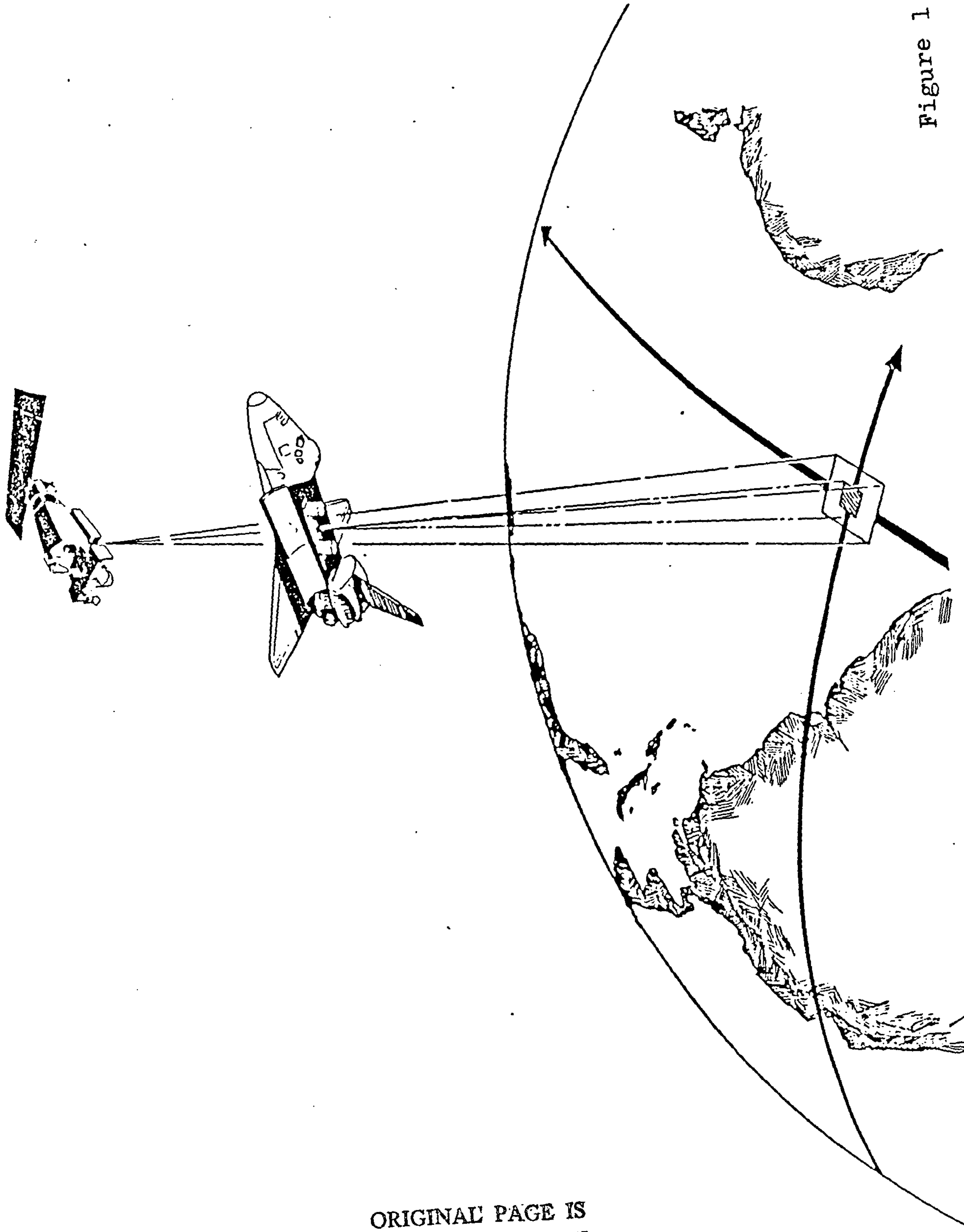

Figure 1

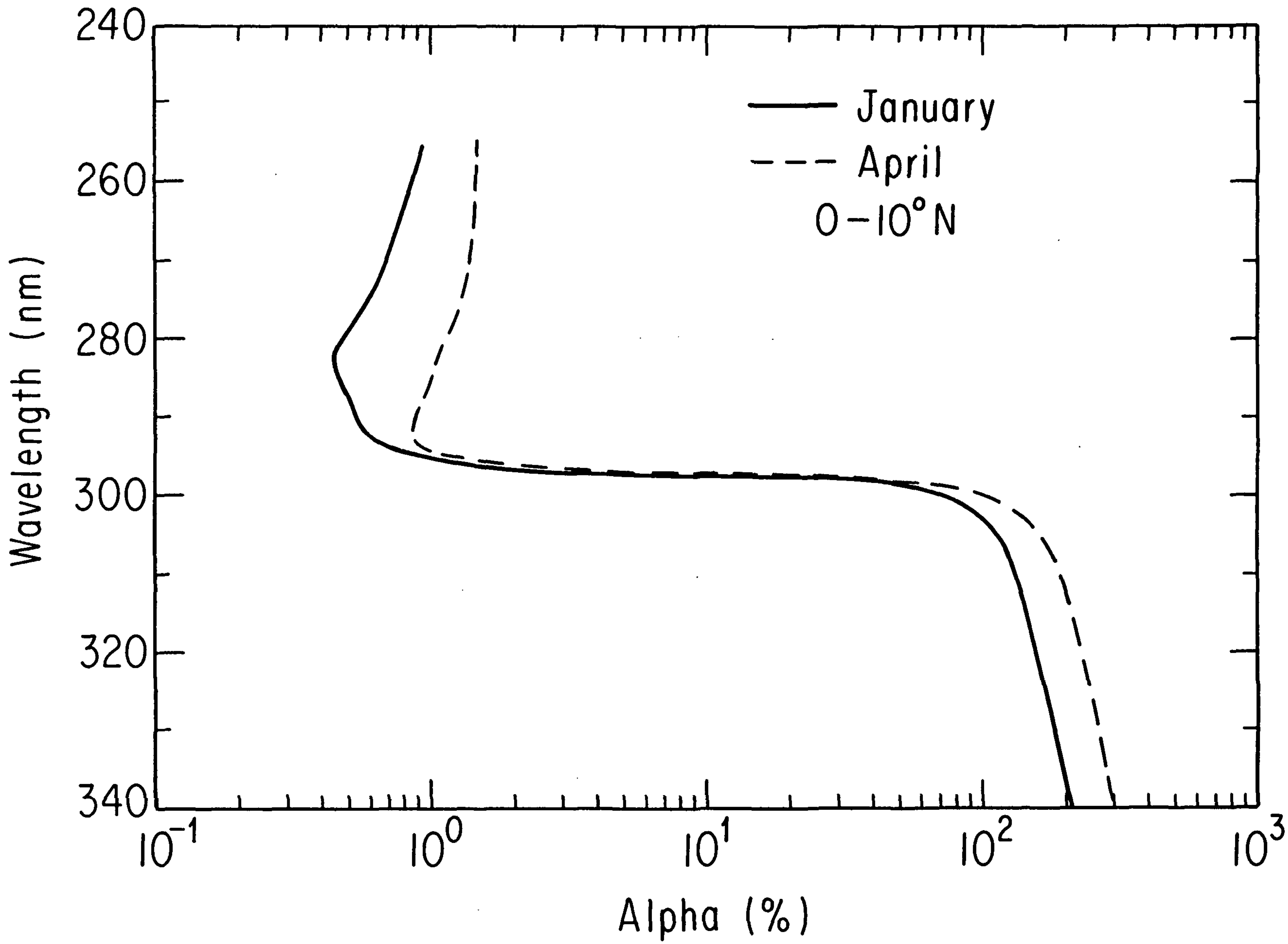
January
April
0-10°N
240
260
280
300
320
340
Wavelength (nm)
10^-1
10^0
10^1
10^2
10^3
Alpha (%)

Figure 2