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Total Ozone Measurements in Cloudy Weather

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Abstract – Obtaining an accurate value for total ozone under a cloudy sky, especially when the sun is not high, is a major remaining problem associated with total ozone measurements. The Toronto spectrophotometer has been designed with this in mind. It has been fitted with a polarizing prism, and measures light at four wavelengths simultaneous which makes it possible to obtain two independent double ratios. Clouds produce two effects on ozone measurements; the first is purely an optical effect which causes an apparent increase in ozone, the second is most likely a real increase in ozone associated with large cumulus-type clouds. By considering the three following points it is possible to distinguish between these two cloud effects and probably measure the true total ozone for solar zenith angles less than 80°: 1. The multiply scattered component of polarized light is used to reduce optical cloud variance. This makes all skies appear like thick clouds. 2. A double difference similar to the AD method is used but the two ratios of the double difference are weighted inversely with $\Delta\beta$ ($\Delta\beta = \beta_1 - \beta_2$ for a pair). This further reduces the optical effects of clouds. 3. Real ozone increases due to large clouds are verified by comparing the increase of ozone obtained from one double difference to that of another. Differences between this multiply polarized curve and the direct sun curve will be given, and a technique to obtain an accurate value of total ozone under all sky conditions, provided that the solar zenith angle is less than 80°, will be given.

Introduction

Perhaps the last major problem associated with ground-based measurement of total ozone is the interference caused by clouds on the observations. Those of us who are familiar with total ozone measurements are well aware of the problems caused by clouds. Results of measurements made at Toronto, Canada (44° N, 79° W), suggest that there are two cloud effects. The first effect is purely optical which is a result of the clouds integrating and scrambling the light from the sun and sky above. This optical effect is called the 'Small Cumulus Effect' and causes an apparent increase of ozone of about .020 cm (Dobson [2]). The second effect is almost certainly a real increase of ozone which is associated with larger cumulus clouds and is called the 'Cumulus Effect'. We have observed increases as large as .300 cm ozone. An increase of .200 cm is common (Dobson *et al.* [3]). The distinction between these two types of cloud effects has never really been clear and the picture has been confused because usually only the optical effect is present and sometimes both effects are present. We have developed a means of eliminating the optical effects of clouds and thereby making it possible to identify real ozone increases.

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Elimination of optical cloud effects

The optical cloud effects are illustrated in Fig. 1, which is a plot of zenith sky observations for the variably cloudy day of 25 November, 1971. The top two curves are the logs of ratios of wavelength pairs and the bottom curve is the log of their double

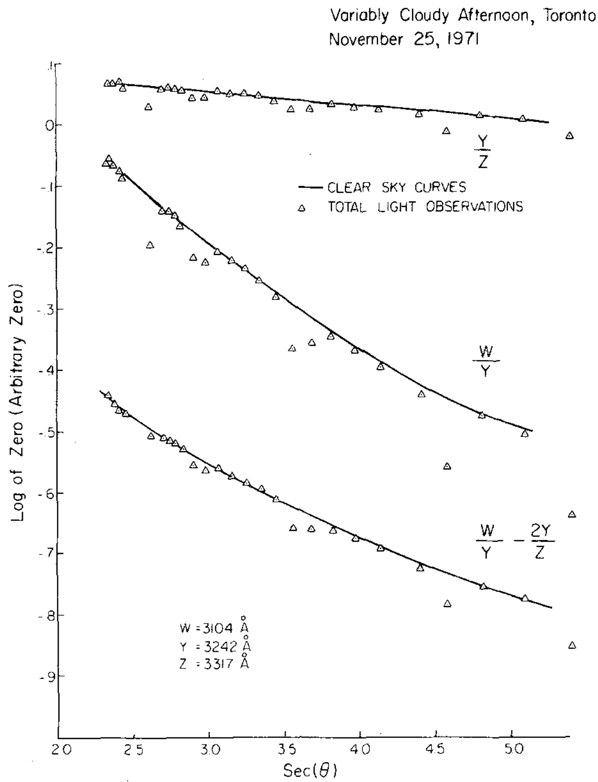

Figure 1
Zenith sky observations for the variably cloudy day of 25 November, 1971. The two single ratios are significantly influenced by passing clouds and the conventional double ratio cloud correction method partially reduces cloud effects

ratio, similar to the Dobson AD double ratio but weighted inversely with $\Delta\beta$ ($\beta =$ Rayleigh scattering coefficient). A cloud on a single ratio causes a lowering of the ratio which implies an apparent increase in ozone for all solar zenith angles. The double ratio reduces the variability due to clouds especially when the sun is high (DOBSON [2]). However, when the sun is lower ($\sec\theta \gtrsim 3$) the double ratio fails to correct for clouds. The situation is more serious when the ozone absorption is larger. This is why the Dobson CD is more successful than the AD when the sun is low. The double ratio cloud correction method is far from perfect, but it has been the best tool available to deal with the cloud problem.

The results of a series of Umkehr measurements made at Toronto led to the discovery that polarized light from the zenith sky could be used to minimize cloud effects. It was found that light from the zenith sky polarized parallel to the plane of scattering is less affected by the presence of clouds than is light polarized perpendicular to this plane. Figure 2 shows the difference in variability between the two types of polarization measurements for the single ratio of a wavelength pair. These results may be explained

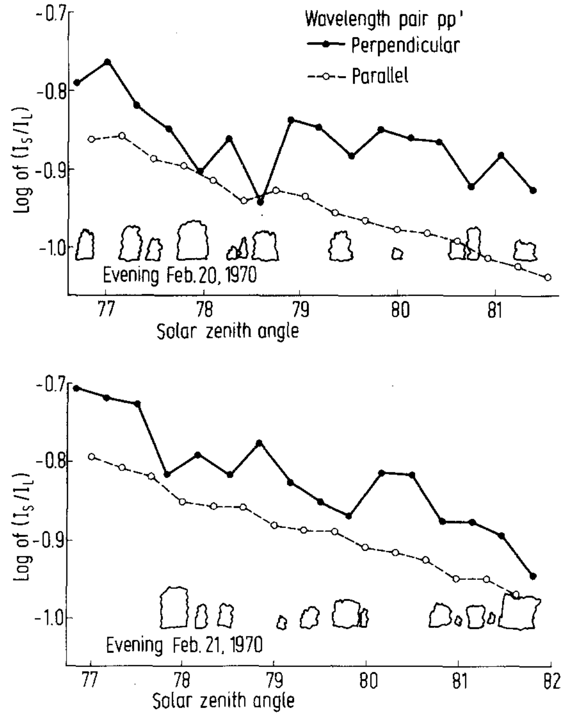

Figure 2
Zenith sky observations on two variably cloudy evenings for light polarized parallel and perpendicular to the plane of scattering. The reduced variability on the parallel light is evident

by considering the nature of the polarized light from the zenith sky. Most of the primary scattered light is polarized perpendicular to the plane of scattering, hence we have called this plane the primary plane of polarization. Most of the light polarized parallel to the plane of scattering is light which has been multiply scattered and this plane is called the multiple plane of polarization. Light leaving the base of a cloud has been scattered several times within the cloud and one would expect this light to be similar to the light in the multiple plane. The observations in Fig. 2 of polarized light during variably cloudy weather confirm this idea.

The Toronto spectrophotometer was used to take further polarization observations at Toronto. These observations have led to a method which apparently eliminates the optical effects of clouds. Figure 3 is a plot of the zenith blue sky curves for the clear morning of 21 January, 1972, showing direct sun, primary, and multiply polarized light for single and double ratios. These curves are typical of a clear day. It may be seen that the multiple curve contains more ozone than the primary curve. This is expected because the multiply scattered light has followed a less direct path through the atmosphere than the primary scattered light. The multiple scattered curve also

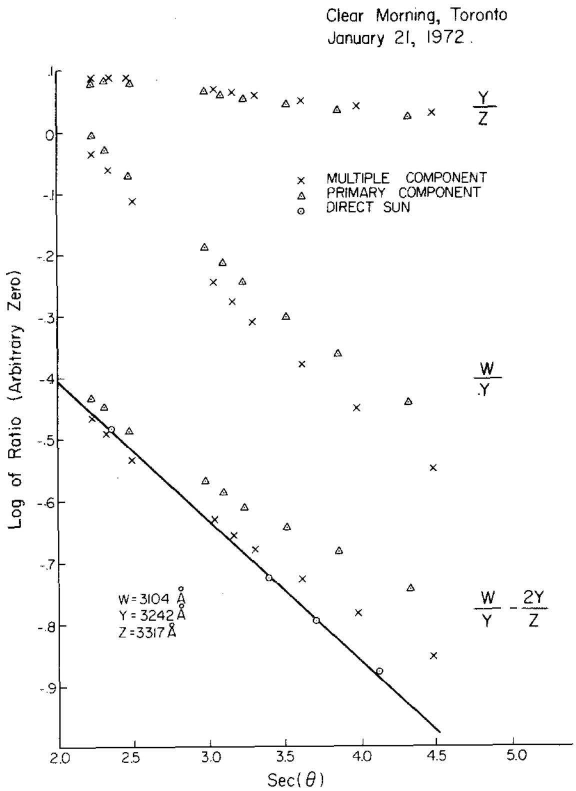

Figure 3
Zenith sky observations for the clear morning of 21 January, 1972. These curves are typical of a clear sky

follows closer to the direct sun on the double ratio than does the primary scattered curve.

During the afternoon of the same day the weather became cloudy with a light to moderate snowfall. Figure 4 shows smooth curves fitted to the clear morning zenith blue sky observations together with the afternoon observations on the cloudy sky. Clouds cause an apparent increase of ozone for both the primary and multiple light on the single ratios, however, the effects are not as large with the multiple light as with the primary light. The double ratio primary light also has an apparent increase of ozone with clouds, however, the double ratio multiple light is virtually unaffected by the clouds.

We have shown that the optical effects of clouds can be eliminated by the following two procedures:

1) use a double ratio weighted inversely with $\Delta\beta$,
2) use the multiply scattered component of zenith sky light.

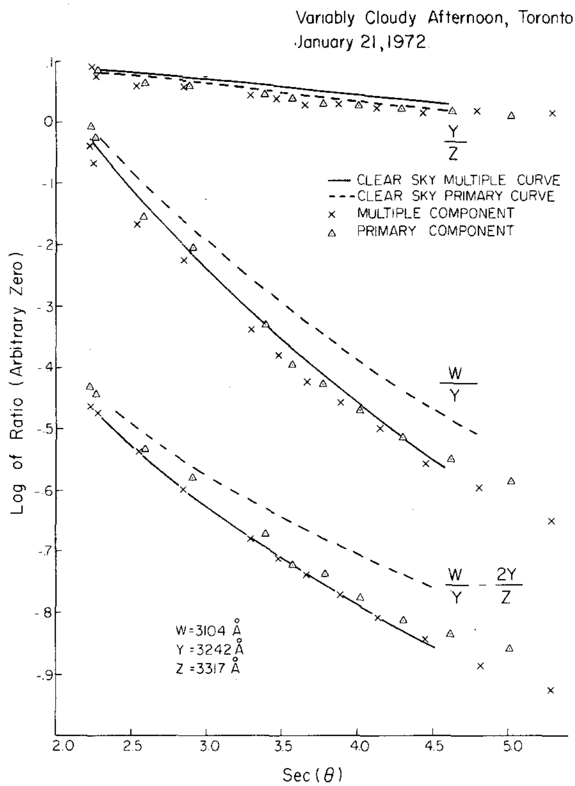

Figure 4
Zenith sky curves for the afternoon of the same day as in Fig. 3. The afternoon was cloudy with a light to moderate snowfall. The double ratio multiply polarized light is unaffected by clouds

The advantages of using these two procedures are summarized in Table 1. The observations from 21 January, 1972, have been fitted to a smooth curve, in this case the first three terms of a Taylor series expansion about $\mu - 1$. The standard deviation of the observations from this smooth curve will give us a good measure of the variability of a particular type of measurement. The table shows the variation from a smooth curve for both multiple and primary scattered light on single and double ratios. It may be seen that the double ratio of the multiple scattered light gives by far the least variation from a smooth curve and is therefore the most successful means to eliminate optical effects of clouds.

Table 1

Variations from a smooth curve for different types of observations on the variably cloudy day of 21 January, 1972. The multiply polarized double ratio shows by far the least variation due to clouds

Ratio	Polarization	Variation from a smooth curve
$\frac{W}{Y}$	Primary (⊥) Multiple (II)	.0317 .0163
$\frac{Y}{Z}$	Primary (⊥) Multiple (II)	.0041 .0082
$\frac{W}{Y} - \left(\frac{Y}{Z}\right)^2$	Primary (⊥) Multiple (II)	.0260 .0027

It is of interest to compare our polarized zenith sky curves to more conventional curves which are obtained using unpolarized light. An unpolarized curve on the zenith blue sky would lie between the primary and multiple component curves shown in Fig. 3 but closer to the primary curve because the primary component contains most of the light. The unpolarized zenith cloud curve would follow the multiple component curve because the light from the base of a thick cloud is unpolarized and the multiple component is the same as the primary component on a cloudy sky as shown in Fig. 4. For measurements using unpolarized light there is a distinct difference between the zenith blue and zenith cloudy sky. This difference would be about .020 cm ozone because the separation between the blue sky primary and blue sky multiple double ratio curves corresponds to about .025 cm using Vigroux's absorption coefficients (VIGROUX [4]). The difference between the blue sky primary and multiple light accounts for the observed difference of .020 cm ozone on small cumulus clouds.

The multiple component observation has not yet been tried using the Dobson spectrophotometer. There is no reason to believe that our method will fail to correct for clouds on the Dobson, however, there are a few problems which may be encountered. Firstly, the intensity of light is reduced when one component of polarization is filtered out. This would result in a reduction of accuracy of the measurements. Another problem is that the Dobson spectrophotometer is sensitive to polarized light. This may be overcome, as we do, by fixing the polarizer to the instrument and rotate the entire instrument to follow the sun. Fitting the Dobson spectrophotometer with a polarizer would be a profitable experiment and would most likely reduce the effects of clouds on the routine zenith sky measurements.

Having eliminated the optical effects of clouds, it is possible to distinguish between real and apparent ozone increases caused by clouds. There have been speculations that the ozone increases associated with large cumulus type clouds occur either within the clouds or above the clouds in the stratosphere. It is now possible to obtain a clearer picture of these real ozone increases and we hope to determine their cause. Observers have been discouraged from taking ozone measurements under dark clouds or heavy rain (DOBSON [2]). We feel that there is something to be learned about the convective patterns in the troposphere and stratosphere if ozone measurements are taken through large cumulus and cumulo-nimbus clouds. For example, we have some evidence that ozone increases associated with thunderstorms in the tropics are not as large as those observed at mid-latitudes. Further studies of this and other ideas would give us a better understanding of the tropospheric–stratospheric interactions during stormy weather.

Determination of total ozone from zenith sky measurements

Determining total ozone from a cloudy sky is now not much different than determining total ozone from a clear blue sky. It is evident from our results, as well as DOBSON's [2], that in mid-latitudes the uncertainty of a total ozone measurement obtained from the zenith sky as compared to that obtained from the direct sun is approximately 4μ m atm cm, where μ is the pathlength. Thus at $\mu = 4$, for example, there is an uncertainty in a zenith sky measurement of 16 m atm cm. This uncertainty is most likely caused by variations of the height of the ozone and by horizontal gradients. If differences in height of the ozone cause noticeable variations on the measurements it should be possible to measure the height of the ozone and therefore correct for the height on a total ozone measurement.

We hope to make it possible to determine the height and total amount of ozone by the following procedure. Our results, together with computer model calculations similar to those of DAVE and FURUKAWA [1], indicate that zenith sky curves such as in Fig. 3 may be very well approximated by an equation of the following form, provided the sun is not too low and the absorption is not too strong.

$$N_{z.s.} = A - B(\mu - 1) + C(\mu - 1)^2, \qquad (1)$$

where $N_{z.s.}$ is the zenith sky observation minus the instrumental constant and A, B, C are functions of total ozone and/or ozone height.

These are the first three terms in a Taylor series expansion about $\mu - 1$. We have fitted our measurements to curves of this type and compared them to the computed output. Having analyzed our results, we can make the following conclusions:

1) A in equation (1) above is probably of the form $-\Delta\Delta\alpha X(1 + \bar{p})$, where $\Delta\Delta\alpha$ is the double difference in absorption for a triplet, X is the total ozone and $\bar{p}$ represents the mean height of the ozone in atmospheres.
2) B is apparently equal to $\Delta\Delta\alpha X(1 + \bar{p})$. Figure 5 is a plot of the B coefficient in (1) for zenith blue curves of individual intensities on the clear day of 16 February, 1972, versus ozone absorption coefficients as measured in the laboratory. The linear relation of B to αX is quite evident.
3) C is linearly proportional to $\alpha X\bar{p}$.

If we substitute these values for A, B, and C we obtain, for a double ratio such as shown in Fig. 3,

$$N_{z.s.} = -\Delta\Delta\alpha X(1+\bar{p}) - \Delta\Delta\alpha X(1+\bar{p})(\mu-1) + \Delta\Delta\alpha X\bar{p}(\mu-1)^2. \quad (2)$$

It is evident from equation (2) that $N_{z.s.}$ is proportional to $\Delta\Delta\alpha X$. This implies that two measurements using two wavelength triplets are, unfortunately, not independent and X and $\bar{p}$ cannot be solved.

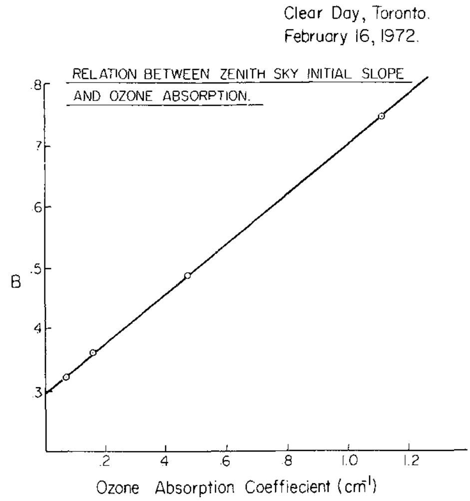

Figure 5
A plot of B coefficient in equation (2) versus laboratory measured ozone absorption coefficients. The coefficients were obtained for individual intensity measurements on the clear day of 16 February, 1972

There is, however, a strong natural correlation between $\bar{p}$ and X, that is, when total ozone is large, the mean height of the ozone is low, and when total ozone is small, the mean height is high. This correlation is illustrated in Fig. 6 which is a plot of the B coefficient versus C in equation (1). This graph does not pass through (0, 0) which would occur if the height remained constant and only the total ozone varied. The best line shown on the graph relates $\bar{p}$ to X in the following manner for the wavelength triplet in Fig. 3:

$$\bar{p} = -\frac{.029}{X} + .181. \ (X \text{ in atmo. cm.}) \quad (3)$$

Equations (2) and (3) may now be solved for X. The total ozone given by these equations is the same as that which would be obtained from a well-constructed sky chart which could extend to $\mu = 6$ and still obtain reliable results. It may be noticed that this result is obtained from measurements made at both Kingston, Jamaica, and Toronto, which vary significantly in both height and amount of zone. The scatter of the points in Fig. 6 suggests that the error of a zenith sky measurement due to height variations is about $\pm 2\mu$ m atm cm.

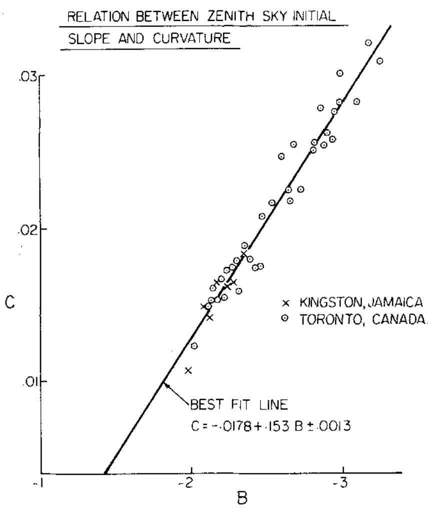

Figure 6

A plot of B versus C in equation (2). Each point is a full day's observations on both cloudy and clear days

There are three possible methods to measure both the total ozone and the ozone height.

1) Measure at two different values of μ which would give two equations of type (2). Both $\bar{p}$ and X could then be solved. It is important that the ozone remains constant between the two measurements.
2) Measure both the direct sun and the zenith sky. Total ozone is obtained from the direct sun reading and equation (2) could be used to determine $\bar{p}$ from the zenith sky reading. It is important that the ozone is horizontally uniform.

Table 2

Estimated accuracy for various types of ozone measurements using the Toronto spectrophotometer

Measurement		Errors (m.a. cm)		Height accuracy	Counts	
		Poisson	Due to ht uncertainty			
Total O_3, no ht	$\mu = 1$	1.2	2		all $\approx 10^7$	
	$\mu = 6$	1.5	12		all $> 10^5$	Usually obtainable in 1 min
Total O_3, plus ht	two μ's 4, 6	3		10%	all $> 10^5$	No O_3 changes while μ changes
	d.s. + z.s.	3		10%	all $> 10^6$	No O_3 gradients

3) Measure when the solar zenith angle is at about 85°. When μ is larger than about 6 equation (2) breaks down and higher order terms in αX become significant. We believe it may be possible to use two independent triplets at about $\mu = 10$ and measure both total ozone and ozone height to useful accuracy.

Table 2 is a summary of the different types of total ozone and/or ozone height measurements. The errors given in the chart are our estimates of the capabilities of the Toronto spectrophotometer.

Summary

We have presented a means by which it is possible to eliminate the optical effects of clouds. This is done by measuring only the multiply polarized component of scattered light from the zenith sky which makes all skies appear like thick clouds. With the elimination of optical cloud effects, the largest remaining error associated with zenith sky measurements is that due to variations in the height of the ozone layer. This error can be greatly reduced by the natural relation between total ozone and ozone height and as a result the errors in total ozone are acceptable provided μ is less than 6. For greater solar zenith angles it may be possible with a single four-wavelength observation to deduce the height and hence improve the accuracy of total ozone measurements.

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