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# Interannual variability of ozone and UV-B ultraviolet exposure

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**Abstract.** Zonal averages of annual and seasonal averages of ozone amounts from Nimbus 7/TOMS (1979–1992) have been examined to estimate the systematic interannual variability of UV-B (290–320 nm) exposure to solar radiation between  $\pm 60^\circ$  latitude. As shown from statistical modeling, clear-sky interannual UV-B changes can be ascribed mainly to the quasi-biennial oscillation (QBO) driven by stratospheric winds. The QBO oscillations can cause interannual changes in UV-B exposure of  $\pm 15\%$  at 300 nm and  $\pm 5\%$  at 310 nm at the equator and at middle latitudes. In addition to QBO effects, there are larger interannual changes in ozone and UV-B associated with dynamical effects at higher latitudes. When UV-B attenuation from clouds is included, the general latitudinal structure of the interannual variability is maintained. At the equator the interannual variability of ozone amounts and UV exposure caused by the combination of the 2.3 year QBO and annual cycles implies that there is about a 5 year periodicity in UV-B variability caused by dynamical effects. At higher latitudes the appearance of the interannual UV-B maximum is predicted by the QBO but without the regular periodicity. The QBO effects on UV-B irradiance are larger than the long-term changes caused by the decrease in ozone amounts.

## 1. Introduction

Increases in the amount of UV radiation reaching the Earth's surface is a major concern for human health and for environmental impact. This is especially true at lower latitudes ( $30^\circ\text{S}$  to  $30^\circ\text{N}$ ) during the summer, where the amount of noon-time UV radiation is the largest because of smaller solar zenith angles. The amount of ultraviolet radiation penetrating to the Earth's surface with wavelengths shorter than 320 nm (UV-B) is reduced by ozone absorption, aerosols, clouds, and Rayleigh scattering in the atmosphere. UV-A irradiances (320–400 nm) are not significantly affected by ozone changes because of their small ozone absorption coefficients  $\alpha_\lambda$ . After the solar zenith angle the second largest cause of daily variability, seasonal variability, and geographic distribution of UV irradiance is from clouds [Herman *et al.*, 1999]. Analysis of the ozone-amount time series [Stolarski *et al.*, 1991; Herman *et al.*, 1991] has shown that the major persistent sources of ozone variability are the annual cycle, the 2.3 year quasi-biennial oscillation cycle (QBO) [e.g., Bowman [1989], and the 11.5 year solar cycle [Hood, 1997; Zerefos *et al.*, 1997; Calvo *et al.*, 1995, and references therein]. A similar analysis for cloud and scene reflectivity shows that there is a moderate effect from QBO or ENSO (El Niño Southern Oscillation), and a significant 11.5 year solar-cycle effect [Herman *et al.*, 2000]. Other sources of ozone variability arise from volcanic aerosol effects [Solomon *et al.*, 1996], and the ENSO effect, and shorter-period perturbations of the atmosphere [Randel and Cobb, 1994].

In this paper, ozone and reflectivity data (for cloud trans-

mittance of UV radiances) from Nimbus 7/TOMS (1979–1992) are used to obtain the interannual variability of ozone and ultraviolet irradiances (300 and 310 nm) at the ground as a function of latitude. The results for 300 and 310 nm irradiances are compared with statistical time series analysis to validate the identification of the main variability with the QBO. Using radiative transfer solutions for clear and cloudy atmospheres, the variability of annual UV-B exposure is derived for  $60^\circ\text{S}$  to  $60^\circ\text{N}$  zonal means in  $2.5^\circ$  latitude bands. This study shows that the largest source of midlatitude interannual variability for UV-B and ozone comes from the QBO effect, driven by atmospheric winds in the 30–50 hPa ( $\sim 21$ –25 km) altitude range.

## 2. Data and Methodology

UV irradiances are determined from multiple-scattering radiative transfer calculations [Dave, 1965] using total column ozone values  $\Omega$  obtained from TOMS-measured radiances  $I_\lambda$  and cloud reflectivities  $R_{380}$ , within a Rayleigh-scattering atmosphere over a low-reflectivity surface [Herman and Celarier, 1997]. The attenuation of the surface radiation by clouds is estimated using the simplified cloud-transmittance model of Eck *et al.* [1995]. Defining  $CF$  as the ratio of cloudy-sky to clear-sky transmittance  $T_{\text{CLOUD}}/T_{\text{CLEAR}}$ , the Eck *et al.* [1995] model is given in (1).

$$\begin{aligned} CF &= [1 - (R_{380} - 0.05)/0.9] & R_{380} \leq 0.5, \\ CF &= 1 - R_{380} & R_{380} > 0.5. \end{aligned} \quad (1)$$

More accurate cloud transmittance models could be used without affecting the results of this study [Krotkov *et al.*, 1999; Herman *et al.*, 1999]. Since all of the results are based on zonally averaged ratios of radiances from different years, seasonal solar-zenith angle errors and ground reflectivity differences [Herman and Celarier, 1997] approximately cancel.

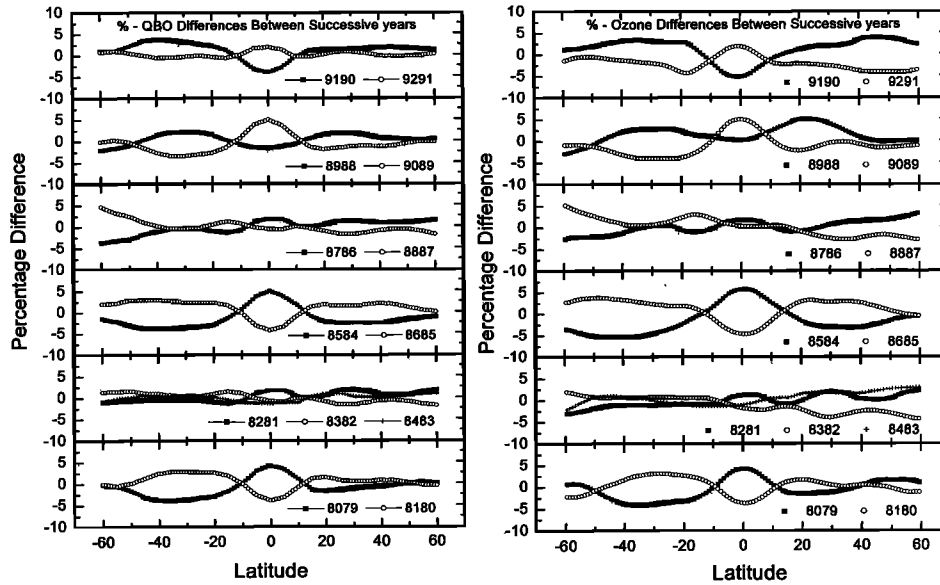
The UV exposure  $E$  is defined as the integral over daylight hours of the UV irradiance at the Earth's surface. Because of

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**Figure 1.** Differences for successive years between zonally averaged annual averages of ozone amounts for the years 1979–1992 (right-hand panel) and the QBO term from a statistical fit to the ozone data (left-hand panel). The darker curve in each frame represents the earlier pair of years. The caption within each frame indicates the years entering into the differences. The symbol 8079 means  $100[\text{O}_3(1980) - \text{O}_3(1979)]/\text{O}_3(1979)$ .

the exponential decrease in the intensity of the primary solar-flux beam with increasing solar-zenith angle  $\theta$  during the day, the main contribution to the exposure comes from times near noon. A first-order approximation to the percent changes in exposure with percent changes in ozone amount is similar to the definition of the radiation amplification factor (RAF) for irradiances given by Madronich [1993]

$$\frac{\Delta E}{E} = -K \frac{\Delta \Omega}{\Omega}, \quad (2)$$

where  $\Omega$  is the total ozone amount and  $K$  is a positive proportionality constant for a given wavelength or wavelength range. For irradiance,  $K = \alpha_\lambda \Omega \sec(\theta)$ , while for exposure,  $K(300 \text{ nm}) \sim 3 \sec(\theta_{\text{Noon}})\Omega/300$  and  $K(310 \text{ nm}) \sim \sec(\theta_{\text{Noon}})\Omega/300$ , where  $\alpha_\lambda$  is the ozone absorption coefficient. Because of this relationship the changes in UV-B exposures are expected to inversely track the changes in ozone amount.

To identify the sources of interannual variability, we incorporate a regression trend model similar to that used by Stolarski et al. [1991] but include an additional total ozone dynamical surrogate  $P(t)$ :

$$\Omega(t) = \alpha + \beta t + \gamma Q_{\text{QBO}}(t) + \delta S_{\text{solar}}(t) + \varepsilon P(t) + R(t). \quad (3)$$

In (3),  $t$  is the month index ( $t = 1, 2, \dots, 168$ ),  $\alpha$ ,  $\beta$ ,  $\gamma$ ,  $\delta$ , and  $\varepsilon$  are time-dependent regression coefficients, each one given as a constant plus 12, 6, and 4 month cosine and sine harmonic series as defined by Randel and Cobb [1994]. The error in this model is the residual series  $R(t)$ ,  $\alpha$  is the seasonal fit, and the ozone trend is given by the coefficient  $\beta$ .  $Q_{\text{QBO}}(t)$  in (3) is the quasi-biennial oscillation proxy derived from Singapore ( $1^\circ\text{N}$ ,  $140^\circ\text{E}$ ) zonal winds using the method of Randel et al. [1995]. Their representation of  $Q_{\text{QBO}}(t)$  involved the empirical orthogonal function (EOF) approach introduced by Wallace et al. [1993].  $S_{\text{solar}}(t)$  represents the solar proxy (10.7 cm solar-flux series). In this study, deseasonalized and linearly detrended global brightness temperatures from the microwave

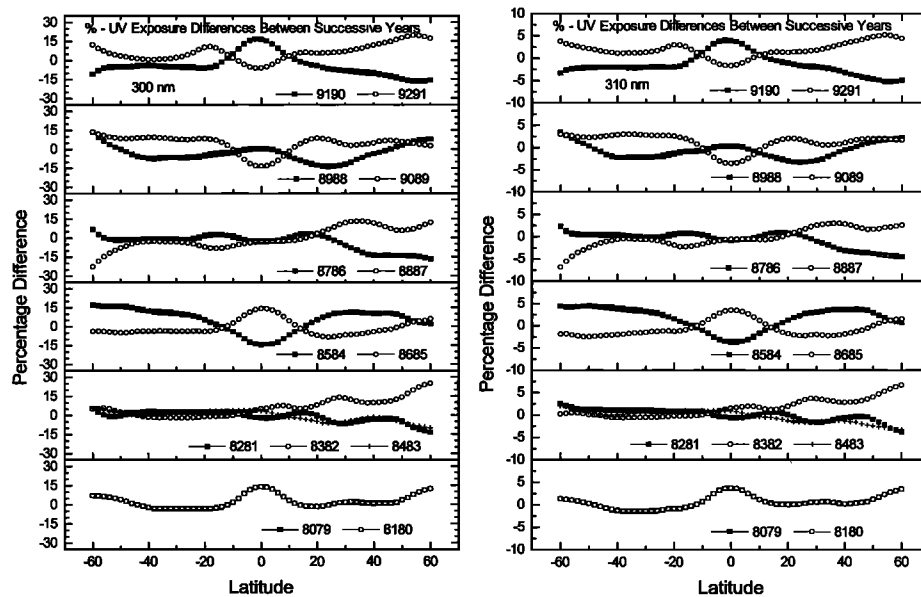
sounding unit channel 4 (MSU4) (half vertical weighting function response near 40 and 150 hPa, mean near 90 hPa) were used for the optional surrogate  $P(t)$ .

The major components contributing to ozone interannual variability can be obtained by systematically subtracting the 14-year average annual cycle from each year's ozone time series, removing the linear trend, subtracting a solar cycle term modeled on the 10.7 cm solar flux, and then removing the QBO variability modeled from Singapore zonal winds [Herman et al., 1991]. This can be done sequentially for each component or simultaneously [Stolarski et al., 1991] as in the present study by a statistical least squares fit to variations in the ozone data (see (3)).

### 3. Interannual Ozone Variability

Year-to-year variability in ozone amounts can be obtained directly by subtracting each year's ozone amounts from the preceding year, as a function of latitude, longitude, and time. In Figure 1 the results are summarized in zonal and annual averages of the differences (see the right-hand panel of Figure 1). As shown in the left-hand panel of Figure 1, the QBO term from the model described in (3) accounts for most of the interannual variability up to latitudes of about  $55^\circ$ .

At the equator the interannual difference is positive whenever the QBO westerlies overlie easterlies (westerly shear) from 10 to 70 hPa for the first half of the QBO cycle and easterlies lie above westerlies for the second half. The westerly shear results in downward secondary circulation along the equator (increasing ozone), and the easterly shear causes upward secondary circulation (decreasing ozone). At subtropical and middle latitudes the secondary circulation is reversed, causing the opposite effect in total-ozone amount. The secondary circulation pattern reverses approximately every 2.3 years, producing a reversal in the ozone percent differences shown in Figure 1. During the years 1981–1984 and 1986–1988, percent



**Figure 2.** Percent differences for successive years of 300 and 310 nm UV annual exposure for clear-sky conditions. The UV-exposure data for 1979 is missing because it contains too many missing days.

differences in low latitudes were either weak or not synchronized with the annual cycle.

The latitudinal dependence of the interannual variability of ozone is quite similar to the QBO term obtained from the statistical model. Most of the features in the modeled ozone data are well reproduced except at high latitudes. In particular, reversal of the QBO effect in interannual ozone differences between low and midlatitudes is almost the same as shown in the ozone-amount data. This is also true for the effect during years when the QBO wind reversals were either weak or not synchronized with the annual cycle. The percent differences

between the observed interannual variability and the fraction arising from the QBO effect show that the other terms in (2) must be retained for a full description of ozone variability.

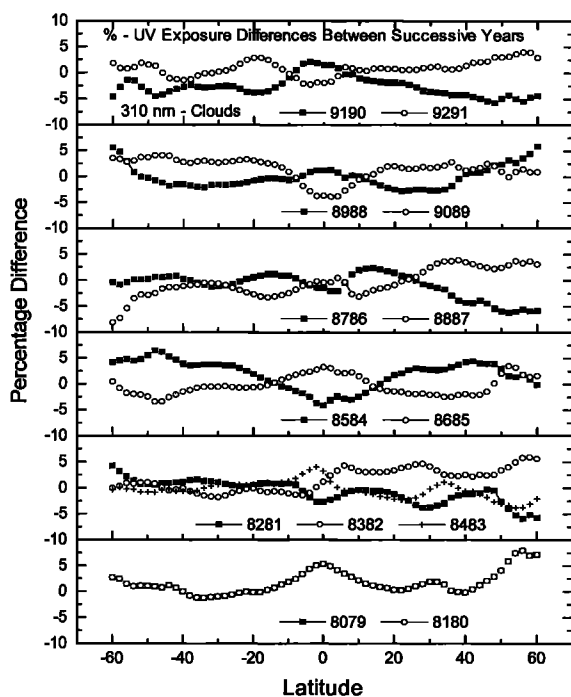
#### 4. Annual Variability of UV-B Exposure

At the equator and middle latitudes the average interannual ozone variation can amount to  $\pm 5\%$  between successive years. On the basis of the RAF factors for irradiances at moderate solar zenith angles the changes in 300 nm exposures are substantially larger than at 310 nm for a given change in ozone amount. This factor is approximately proportional to the ratio of the ozone absorption coefficients  $\alpha_{\lambda}(300)/\alpha_{\lambda}(310)$ . For the erythemally weighted exposure integrated from 290 to 400 nm, the sensitivity to ozone change is approximately the same as for 310 nm.

In Figure 2 the UV-B exposures are computed from solutions of the multiple-scattering radiative transfer equation [Dave, 1965], using ozone amounts and cloud reflectivities measured by TOMS and at every  $1^\circ$  latitude  $\times$   $1.25^\circ$  longitude grid point. Since the percent changes between successive years for the clear-sky 300 nm and 310 nm UV-B annual exposure (Figure 2) are modulated by ozone absorption, the changes are inverse to the changes in ozone amount (Figure 1), as indicated in (2).

For 310 nm the annual proportionality constant  $K$  (see (2)) for exposure change relative to ozone change is  $\sim 1$ , and for 300 nm,  $K$  is  $\sim 3$ . Shorter wavelengths will have  $K \gg 1$  and longer wavelengths,  $K \ll 1$ , roughly in proportion to the ozone absorption coefficient ratio to that at 310 nm. There is also a dependence on the noontime solar zenith angle for a specified latitude and season.

When the effects of cloud cover are included in the zonally averaged annual exposure estimate, based on the TOMS reflectivity measurements [Herman et al., 1996, 1999; Krotkov et al., 1999], the results are substantially the same (Figure 3). There are small percent differences caused by cloud cover variability between successive years that are less than the QBO effect. The effect of clouds is to reduce the daily and annual



**Figure 3.** Same as Figure 2 (zonal average and annual average) but with cloud effects included.

UV-B transmittance to the ground and increase its day-to-day variability. If the exposure is computed along a meridian, instead of a zonal average, then the cloud-induced differences between successive years are larger than for zonal averages. This is because cloud patterns are normally different at a given geographical location from year to year, causing substantial differences in surface UV-B flux. Examples of the local cloud-induced variability of UV irradiances are shown by *Herman et al.* [1999].

In the latitude range 40°S–40°N, year-to-year UV-B variabilities caused by cloudiness and the QBO are both larger than long-term (decadal) UV-B changes caused by decreases in ozone, since the start of the TOMS record. The decadal trend analysis of Nimbus-7/TOMS ozone data shows that there are no statistically significant (2 standard deviations) annual trends between  $\pm 40^\circ$  latitudes and especially no trends in the tropical region  $\pm 10^\circ$ , where UV exposure is a maximum. The interannual variability caused by the QBO effect in these regions can easily reach 10% at 310 nm between the maximum and the minimum exposure amounts for different years. The same magnitude of variability is calculated for the erythemal exposure. For the years corresponding to the maximum UV exposure the risk of biological damage is increased substantially. This effect is repeatable, occurring approximately every 5 years (e.g., 1981, 1986, 1991).

At higher latitudes the effect diminishes, going to zero at about  $\pm 10^\circ$  latitude and then increasing again into the middle latitudes. At middle latitudes the periodicity is less pronounced because of the interference of other dynamical effects mixed in with the QBO effect. The percent differences in midlatitude surface UV-B at 310 nm for successive years can be as much as 10%, because of the QBO and other interannual sources. The corresponding value for 300 nm is about 25%.

As shown by *Herman et al.* [1996], the largest decadal increases in exposure occur in the spring months, between latitudes 35° and 60° in both hemispheres, and amount to about +4% per decade at 310 nm. For 300 nm, exposure percent changes are larger by a factor of about 3. Trends in extratropical 300 nm UV-B exposures analyzed by *Herman et al.* [1996] were around +10% per decade during spring.

## 5. Seasonal Variability

Seasonal time series analysis shows that there is almost no interannual variability during the summer and autumn in both hemispheres, and there is maximum variability in the winter and spring. Within the equatorial region,  $\pm 10^\circ$ , the interannual variation in the seasonal ozone amounts can be as much as  $\pm 6\%$  with corresponding variations in the 310 nm irradiance and the erythemal exposure of about  $\pm 6\%$  and for 300 nm about  $\pm 22\%$ . The seasonal ozone and UV irradiance interannual variability within the equatorial zone is about the same as the annual averaged interannual variability. Because summer and autumn interannual variability is nearly zero, the annual average interannual variability mainly reflects the winter and spring interannual variability.

Determinations of clear-sky long-term changes from currently available well-calibrated ground-based measurements are made more difficult since QBO-driven changes in surface UV-B are larger than the UV trends expected from long-term changes in ozone amount. The monthly QBO effects must be removed from the data record available from ground-based measurements prior to the estimation of trends. Since the

calculated UV irradiance from TOMS ozone data spans 14 years (five QBO cycles), the annual cycle, QBO, and solar cycle effects are easily removed from long-term UV trends.

## 6. Summary

This study shows that the interannual variabilities in TOMS total ozone and derived UV-B exposure are dominated by the QBO with mean year-to-year percent differences as large as  $\pm 6\%$  in total ozone and as much as  $\pm 6\%$  for 310 nm and  $\pm 22\%$  for 300 nm exposures. The most important QBO-driven UV-exposure effect occurs in the equatorial regions where there is no decadal ozone trend since the beginning of TOMS measurements in November 1978. In the  $\pm 10^\circ$  equatorial region the interannual variability has an  $\sim 5$  year cycle caused by the interaction between the annual solar period and the 2.3 year QBO period. At middle latitudes the periodicity of the observed interannual variability in ozone amount, and therefore UV-B exposure is more variable than caused by just the QBO.

The interannual variabilities of ozone and UV-B exposure driven by the QBO are larger than the decadal trends caused by the long-term loss of ozone for equatorial and middle latitudes ( $0^\circ$  to about  $50^\circ$ ). For lower latitudes between  $0^\circ$  and  $30^\circ$ , where there are no statistically significant decadal decreases in ozone amounts since 1979, the QBO effect causes periodic increases in biologically important doses of UV-B radiation.

The interannual variability of clouds only produces a small perturbation on the overall effect caused by the QBO on zonally averaged UV exposure. At higher latitudes, cloud effects produce larger perturbations than at lower latitudes. In a few places there are quite large long-term reflectivity changes that have occurred at polar latitudes and in smaller midlatitude regions, such as on the western coast of Chile and Argentina [*Herman et al.*, 2000], causing long-term decreases in UV radiation.

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(Received February 25, 2000; revised July 7, 2000; accepted July 7, 2000.)