

Aerosol over New Zealand in relation to other sites

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Abstract. Aerosol optical depth at Lauder in Central Otago, New Zealand, is amongst the lowest measured at the Earth's surface. The monthly mean Lauder values at 500 nm are in the range 0.02-0.05, whereas measurements at clean low-altitude sites globally are mostly at least twice as large in corresponding seasons. The maximum at Lauder is in springtime, under the influence of tropical biomass burning. At 300 nm, the daily mean aerosol optical depth can be up to 0.3, but this is still much less than the effect of molecular scatter. For much of the globe, UV irradiance is significantly reduced by aerosols, and the measured extent of this reduction suggests that UV absorption by aerosols may be substantial.

Atmospheric Optical Depth

When a parallel beam of radiation traverses a scattering or absorbing medium, its intensity falls exponentially with distance, or the optical density, according to the Beer-Lambert-Bouguer law. Optical depth is the exponent (base e) for normal incidence; for oblique incidence there is an additional factor for path length. The law extends easily to attenuation in a series of homogeneous layers, which is an adequate model of Earth's atmosphere for cloud-free conditions. If refraction can be ignored, the air mass factor for each layer, scatterer, and wavelength is just the slant path length $\sec \theta$, and we have the simple form:

$$I(\lambda, \theta) = I_0(\lambda) \exp(-\tau(\lambda) \sec \theta) \quad (1)$$

where λ is the wavelength
 θ is the solar zenith angle
 I_0 is the incident intensity
 I is the transmitted intensity
 τ is optical depth

Total optical depth τ is a sum of components due to molecular (Rayleigh) scatter τ_R , absorption by gases τ_g , and aerosol scatter and absorption τ_a : The first term is given to good accuracy from theory, and absorption spectra for atmospheric gases contributing to τ_g are well known, being the basis for remote measurement of many species including ozone. Aerosol optical depth τ_a is highly variable, and much less understood than the other terms. At wavelengths with little gaseous absorption, τ_a can be derived if τ can be measured to sufficient accuracy. Absolute calibration of sun photometers by standard lamps or relative to reference instruments can barely achieve the required accuracy and is unstable over time. The Langley technique, measuring I for varying θ , provides both τ and I_0 (intrinsic calibration) to the requisite accuracy if the sky is cloud-free and the optical depth is constant over several hours [Forgan, 1994]. Changes in I_0 over time, corrected for variation in the earth-sun distance, measure drift in photometer calibration, and if smooth it

can be interpolated to all clear sky data. This expands the set of usable measurements of optical depth, and it also yields statistics on their variability, which is otherwise assumed to be zero within a single Langley analysis.

Measurements at Lauder

From February 1996 to May 1997, an aureole sun photometer at Lauder (45° S, 170° E, 370 m altitude) measured direct solar radiation through filters centred at 368, 500, 674, and 776 nm [Forgan and Liley, 1997]. Installation in August 1999 of an SPO2 sun photometer has continued the data series with measurements centred on 412, 500, 610, and 778 nm. In addition, the solar tracking system itself measures at 862 nm, though with larger uncertainty. Stability of the SPO2 calibration in particular has been excellent, allowing the use of constant calibration coefficients for the data presented here. The 610 nm channel was an exception, with much higher noise apparently due to misalignment. These data are excluded from the present analysis, as are the 862 nm data after the initial (1996/7) measurement period.

Figure 1 shows monthly means of τ_a calculated from the selected data. At 500 nm and 776/778 nm, monthly means can be combined for the whole period, giving the mean annual cycle shown as dotted lines for 1998.

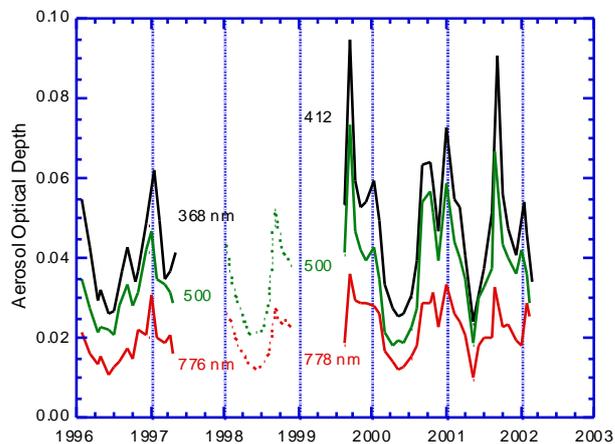


Figure 1. Monthly mean aerosol optical depth at Lauder, Central Otago, NZ.

The earlier data series shows a clear annual cycle, with a maximum in summer. For the later series there is a pronounced peak in springtime, but for the rest of the year values are similar to the earlier set. Analysis of data from balloon-borne instruments [Liley et al., 2001] shows that in the upper troposphere over New Zealand aerosol from tropical biomass burning occurs regularly in springtime.

The atmospheric optical depth due to Rayleigh scatter at wavelength λ (μm) is approximately:

$$\tau_R \approx 0.0086 \lambda^{-4} \quad (2)$$

At 500 nm, $\tau_R \approx 0.14$, more than four times the mean Lauder values of τ_a for this wavelength. In analogy to (2), the wavelength dependence of τ_a can be expressed as:

$$\tau_a \approx \tau_{a0} \lambda^{-\alpha} \quad (3)$$

The ('Ångstrom-') exponent α is in the range 1-1.5 for most aerosols, and indeed for the Lauder data both series give monthly mean values for α of 1.2 ± 0.1 . The highest values occur in springtime, coincident with the increase in optical depth, and the larger values of α imply a smaller mean size for these aerosols.

The light-scatter due to aerosol increases to shorter wavelengths, but by much less than Rayleigh scatter. At 300 nm, $\tau_R \approx 1.1$, whereas using (3) to extrapolate all data for Lauder gives $0.02 < \tau_a < 0.3$ at 300 nm, with monthly means in the range 0.03-0.13. For non-absorbing aerosols, most of the light is scattered forward, adding to the diffuse flux. We conclude that aerosols over Lauder, and presumably much of rural New Zealand, have minimal direct effect on total (direct plus diffuse) UV irradiance.

Measurements at Other Sites

Globally disperse measurement of τ_a has only been undertaken in recent years as improvements in instrument stability and reliability has enabled deployment in remote locations. One such project is AERONET, for which Holben *et al.* [2001] described results from 29 stations with at least three years reliable operation, and tabulated monthly mean values of τ_a . Their values are summarised in **Figure 2** by combining data from like sites.

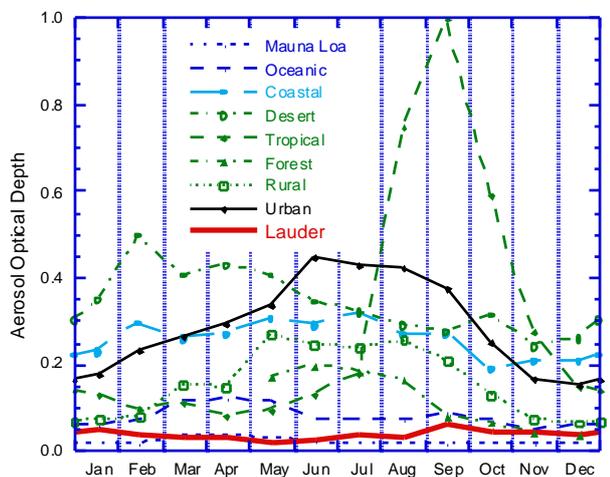


Figure 2. Monthly mean aerosol optical depth for 29 AERONET sites grouped by type, and for Lauder.

Mauna Loa is the benchmark site for instrument calibration, and at 3400 m above sea level it is above most of the global aerosol burden. For the 'oceanic' sites, at sea level in Hawaii and off the Californian coast, τ_a is much less than at the other sites, but still about twice that for Lauder in the corresponding season. The 'coastal' classification includes several island sites far from major land masses which nevertheless show strong continental influence. Together with the other extra-tropical sites, mostly in the northern hemisphere, they have a maximum in the summer. The very strong September peak in τ_a at

the tropical sites is due to seasonal burning. Its effect is diluted in transport to other sites, and it is readily apparent at Lauder only because the air is otherwise clear. Even with this peak, mean τ_a for Lauder is only twice that of Mauna Loa, with a six-month phase shift.

Aerosol Effects on UV

For much of the northern hemisphere, Figure 2 suggests a representative value $\tau_a = 0.3$ at 500 nm, and with $\alpha = 1.2$ this gives $\tau_a = 0.55$ at 300 nm. This could explain hemispheric differences in surface UV irradiance [Seckmeyer and McKenzie, 1992], and in satellite data veracity [McKenzie *et al.*, 2001], if half of the scattered UV flux were reflected back to space. Again, this is unlikely because aerosol scatter is peaked in the forward direction, and more so at shorter wavelengths. Scattering increases path lengths for absorption, such as by tropospheric ozone, but also the effect of surface albedo. Radiative transfer models suggest that scattering alone does not explain aerosol-related differences in surface UV.

In discussing optical depth we distinguished the effects of scattering and absorption for gases but not for aerosols. Though it has long been recognised that black carbon in aerosol is a major absorber of solar radiation, other aerosols have been assumed to absorb only very weakly (sea salt and sulphate) or with little spectral signature (e.g., desert dust). Recently, Jacobson [2001] has noted that many organic species absorb strongly in the UV, and that such species may constitute a substantial proportion of the aerosol in regions of continental influence.

While the Lauder data will be representative for much of rural New Zealand, urban areas will have some similarity to the NH sites discussed above. Tropospheric ozone concentrations are still low, and urban air pollutant ratios are different, so the implications for UV intensity in populated areas warrant further research

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