

concern in the development of cataracts is the cumulative lifetime exposure to UV-B radiation.

### c. Effects on the Immune System

Information on the effects of UV-B radiation on the immune system comes primarily from laboratory animal studies. High doses of UV radiation cause a depression in systemic hypersensitivity reactions, whereas relatively lower doses cause a depression in local contact hypersensitivity. Both of these immunosuppressive effects of UV radiation have been found to reside almost entirely in the UV-B portion of the solar spectrum (U.S. EPA, 1987, ES-39).

Information about the effects of UV radiation on the human immune system, however, is very limited. Without more complete information from laboratory or epidemiological studies, the nature of an exposure of concern cannot be estimated. Immunologic studies have not assessed the effects of long-term, low-dose UV-B irradiation, such that the magnitude of risk from this type of exposure cannot be assessed (U.S. EPA, 1987, ES-40).

## 2. Relationship Between Ground-level O<sub>3</sub> and UV-B Radiation Exposure

### a. Relevant Atmospheric Factors

The relationships between ground-level O<sub>3</sub> and UV radiation occur in the context of a much larger dynamic of the earth's atmospheric systems. The sun is, of course, overwhelmingly the main source of a wide band of electromagnetic radiation, including the ultraviolet. The total atmosphere blocks a significant portion of the range of this incoming solar radiation before it reaches ground level, including much of the more energetic wavelengths that are shorter than visible light (400–900 nm). The UV spectrum (100–400 nm) is comprised of UV-C (100–280 nm), UV-B (280–320 nm), and UV-A (320–400 nm). Ultraviolet-B radiation is efficiently but not completely absorbed by total column O<sub>3</sub>. Wavelengths above 350 nm, including visible light, are not absorbed by oxygen (O<sub>2</sub>) or O<sub>3</sub> (U.S. EPA, 1987, ES 35). Because the amount of atmospheric O<sub>3</sub> traversed by sunlight varies with the sun angle, atmospheric absorption is more complete in winter months and both early and late in the day, as compared to the absorption around mid-day near the summertime solar zenith. Therefore, a decrease in total column O<sub>3</sub> from naturally occurring conditions is of greater concern during times of higher sun

angles, and for the more energetic portion of the UV-B range.

The underlying annual and diurnal patterns of UV-B penetration to the ground layer are driven primarily by three factors: (1) The change in apparent sun angle with the surface that occurs as the earth travels around the sun; (2) the diurnal change in apparent sun angle caused by the earth's rotation; and (3) the solar/meteorologically driven annual change in the amount of O<sub>3</sub> in the stratosphere. Stratospheric O<sub>3</sub> over U.S. latitudes shows a characteristic peak in the spring months, falling steadily thereafter through summer and fall (Fishman *et al.*, 1990; Frederick *et al.*, 1993). The combination of the annual sun cycle and the stratospheric O<sub>3</sub> cycle means that peak UV-B radiation reaching the troposphere tends to occur in late June to early July, and falls steadily thereafter (Frederick *et al.*, 1993). The annual peak in ground-level O<sub>3</sub> concentrations, which extends in most areas from May through September, generally overlaps the UV-B radiation peak (e.g., U.S. EPA, 1996a, Figure 4–23). Diurnal patterns of ground-level O<sub>3</sub> vary, but in urban areas, summertime peaks tend to occur between noon and 4 pm (U.S. EPA, 1996a, section 4.4). This obviously overlaps with peak incoming UV-B radiation. The pattern of vertical mixing in the atmosphere is such that morning ground-level measurements probably do not accurately reflect “mixing-layer” concentrations (U.S. EPA, 1996a, p. 3–44).<sup>50</sup>

The relationship between ground-level O<sub>3</sub> and solar radiation, including UV-B radiation, is complex and mediated by a number of atmospheric factors. It is not limited to the simple absorption of energy. At a fundamental level, the variation in apparent solar radiation is a primary cause of meteorological fluctuations that strongly influence the build-up and transport of anthropogenic air pollution. Further, as discussed in Chapter 3 of the Criteria Document, UV-B radiation that penetrates the stratosphere to the mixing layer plays a key role in the processes leading to the formation of photochemical smog, including the formation of ground-level O<sub>3</sub>. In fact, increased penetration of UV-B radiation to the troposphere due to stratospheric O<sub>3</sub> depletion would likely increase ground-level concentrations of O<sub>3</sub> in most urban and many rural areas of the U.S. (U.S. EPA, 1996a, p. 3–5). The chain of indirect events triggered by

increased penetration of UV-B radiation can result in both increases and decreases in aerosol and acid rain formation (U.S. EPA, 1996a; pp. 3–38 to 39), with attendant further feedbacks through heterogeneous chemistry and aerosol scattering of UV-B radiation. All of these complex processes could, under varying conditions, increase or decrease the amount of UV-B radiation that actually reaches ground level relative to an unperturbed case. The reactions can further affect the concentrations of radiatively important substances such as methane, O<sub>3</sub>, and particles, and could affect local, regional, and global climate.

Setting aside the direction and magnitude of these complex indirect effects of UV-B radiation penetration on ground-level air pollution, and assuming appropriate sun angles and cloud density, the marginal effect of ground-level O<sub>3</sub> on the absorption of UV-B radiation by the earth's atmosphere can be considered separately. Because of increased scattering of incident UV-B radiation by the denser layer air molecules, droplets, and particles nearer the surface, tropospheric O<sub>3</sub> can absorb somewhat more UV-B radiation than an equal amount of O<sub>3</sub> in the stratosphere (Brühl and Creutzen, 1989). The extent to which this increase in unit effect occurs depends on the relative concentrations and character of aerosols in the troposphere as compared to the stratosphere.

A further consideration is the relative effectiveness of ground-level O<sub>3</sub> in absorbing those spectra of UV-B radiation wavelengths most likely to cause health effects. The “effective dose” of UV-B radiation can be expressed as a function of two factors, the intensity of radiation (by wavelength) reaching the earth's surface and the action spectrum. The wavelength-dependent effect of O<sub>3</sub> on reducing the intensity of radiation in the UV-B range is summarized above. The action spectrum describes how effective radiation at particular wavelengths is at causing a particular biological effect or a response in an instrument. Action spectra allow the estimation of the potential effects of simultaneously changing radiation at different wavelengths by different amounts, as happens with changing O<sub>3</sub> levels. Laboratory and field studies have been used to estimate and adopt action spectra conventions for various biological endpoints (e.g., Madronich, 1992). As noted above, uncertainty exists about the action spectra as well as how to specify appropriate dose metrics for particular health endpoints. Even estimates of the range of wavelengths

<sup>50</sup> The mixing layer (relevant to the vertical “thickness” of ground-level O<sub>3</sub>) develops and grows in height through the day.