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LETTER

"Ultraviolet spring" and the ecological consequences of catastrophic impacts

Charles S. Cockell[1,3] and Andrew R. Blaustein[2]
[1]*M/S 239–20, NASA Ames Research Center, Moffett Field, CA 94035–1000, USA. E-mail: ccockell@mail.arc.nasa.gov*
[2]*Department of Zoology, Oregon State University, Corvallis, OR 97331–2914, USA*
[3]*Current address: British Antarctic Survey, High Cross, Madingley Road, Cambridge, CB3 0ET, UK*

Abstract

Asteroid and comet impacts cause ozone depletion. For the first time, we have quantified the photobiological characteristics of these events and speculate on some of the associated ecological consequences. Following the clearing of stratospheric dust after "impact winter", levels of damaging UVB radiation (280–315 nm) could increase by at least 100%, resulting in an "ultraviolet spring". Many of the taxa stressed by the cold and dark conditions of impact are the same that would be stressed by large increases in UVB radiation. Furthermore, depletion of dissolved organic carbon (DOC) by impact-induced acid rain would increase UVB penetrability into freshwater systems. Although an increase in UVB radiation is an attractive hypothesis for exacerbating the demise of land animals at the Cretaceous-Tertiary (K/T) boundary, e.g. dinosaurs, our calculations suggest the impact into rare sulphate-rich target rock may have prevented an ultraviolet spring in this case. If the K/T impact event had occurred in any other region on Earth, the stress to the biosphere would probably have been considerably greater.

Keywords

Asteroid, comet, extinction, global change, impact events, UV radiation.

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INTRODUCTION

Sudden increases in ultraviolet radiation B at the surface of the Earth caused by catastrophic and natural ozone depletion events could potentially have disastrous consequences for the biosphere (Cockell 1999). Increases in UVB radiation suppress photosynthesis, the base of most of the world's food chains, as well as increasing DNA damage (Holm-Hansen *et al.* 1993). UVB radiation increases the incidence of cataracts in many animals, as well as deformities and mortality (Jose & Pitts 1985; Blaustein *et al.* 1994). Because some species are more affected than others by increased levels of ambient UVB radiation (Blaustein *et al.* 1999), significant changes in community are likely. Ozone loss is predicted to occur following impact events (Turco *et al.* 1982; Zahnle 1990; Toon *et al.* 1997). We examine the photobiological effects of ozone loss and some of its ecological consequences.

METHODS

We conducted a series of radiative transfer calculations to quantitatively estimate the levels of UVB radiation that would be expected following a large-scale impact event. UVB flux at the surface of the Earth was calculated using a δ-2 stream Delta-Eddington approximation as described previously (Haberle *et al.* 1993). In our calculations we included an impact generated dust cloud with an initial loading of 1 g cm^{-3}, the estimate for a K/T sized event ($\sim 10^8$–10^9 Megatons) (Pollack *et al.* 1983), as shown in Fig. 1(a). The destruction of ozone and subsequent recovery is more difficult to predict. It will depend upon the loading of the atmosphere by NO, its latitudinal distribution, and the rate of its rain-out as nitrous and nitric acid (Toon *et al.* 1997). We have used the ozone depletion data of Whitten *et al.* (1975), who use a one-dimensional model to calculate the ozone depletion and recovery expected from a 10^4 Megaton (Mt) nuclear war. The maximum ozone depletion occurs after approximately 50 days and recovery of ozone is approximately 1% every 20 days.

For large body impacts ($\sim 10^8$ Mt), initial NO concentrations might be on the order of 10^2–10^3 times greater than previous estimates of a large-scale nuclear war and 10^3–10^4 times greater than those estimated for Tunguska (zonally distributed between 55 and 65°N) (Turco *et al.* 1982). However, since the present calculations estimate maximum ozone depletion at nearly 90%,

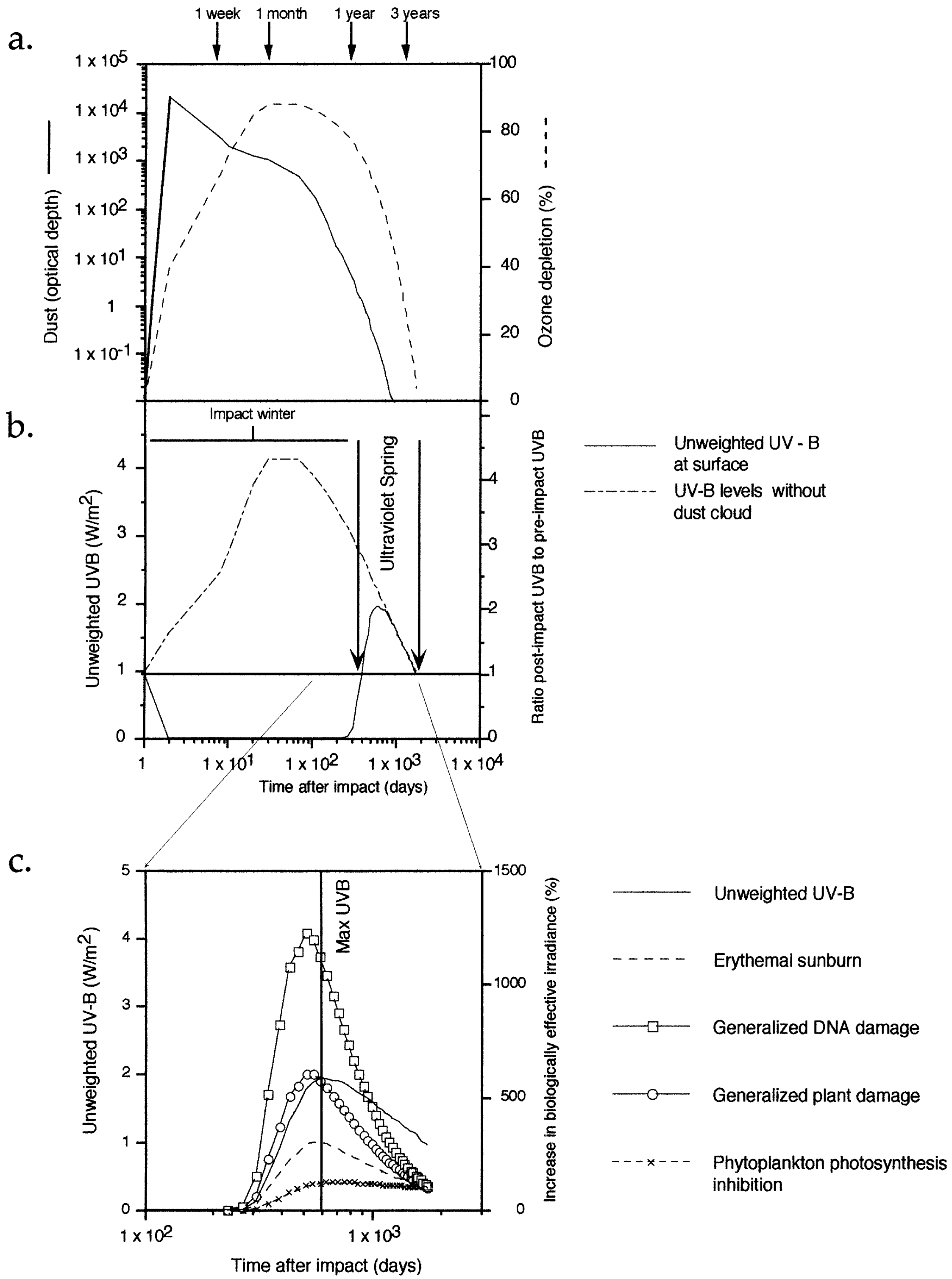

Figure 1 (a) Levels of dust loading and ozone depletion used in the radiative transfer models to calculate effects of ultraviolet spring. Dust loading is taken from ref. (4) and ozone depletion and recovery data are extrapolated from Tunguska and nuclear weapons detonations as explained in the text. (b) Increases in UVB associated with a large scale impact event with an initial dust loading of 1g cm^{-3}. Data are provided for zenith angle = 40°. Impact occurs on day 1. Levels of UVB that would be experienced at the Earth's surface in the absence of a dust cloud are also shown. (c) Increases in biologically weighted irradiances for given increase in total UVB flux during an ultraviolet spring following a K/T sized impact.

greater levels of NO loading will not alter maximum levels of ozone depletion, but they might extend the period over which large scale ozone depletion occurs. The effect of this would make our data an underestimate of the importance of UVB radiation following impact events, but it would not change the qualitative conclusions.

RESULTS AND DISCUSSION

Figure 1(b) shows the results of the radiative transfer model for a large-body impact. The data presented is for a zenith angle of 40° and an initial ozone column abundance of 350 Dobson units (9.41×10^{18} cm^{-2}). This provides typical average values of UVB radiation increases at midday in spring and summer in mid-latitude regions. A point is reached approximately 390 days after impact at which the dust loading exactly balances the ozone depletion and total UVB radiation levels are similar to preimpact levels. After this point, dust clearing continues until maximal UVB flux is reached approximately 600 days after impact. Beyond this point, ozone recovery occurs and UVB flux begins to decrease. The rate of decrease will depend upon the total NO loading and consequent ozone recovery. We estimate the maximum UVB flux would be at least 100% greater than preimpact levels across most latitudes assuming even distribution of ozone depletion and the total length of the ultraviolet spring (the period when average levels of UVB radiation are higher than preimpact levels) could be 4 years.

To understand the biological consequences, the absolute UVB radiation levels must be biologically weighted. The biological weighting is determined by multiplication of the incident irradiance with a known action spectrum. The action spectrum specifies the relative biological effect of different wavelengths of radiation. In Fig. 1(c). we calculated the change in the weighted biologically effective irradiance for a diversity of biological processes (Green *et al.* 1974; McKinlay & Diffey 1987; Cullen *et al.* 1992). Although the total UVB flux reaches a maximum after 600 days, the maximum biological stress for many organisms will be 100 days earlier. This is because although the total UVB flux is less due to attenuation by the impact generated dust cloud, the greater ozone depletion skews the UVB radiation that does reach the ground towards more biologically damaging shorter wavelengths. Biological damage that has a higher sensitivity to short wavelength UVB radiation (such as DNA damage) will be expected to reach a maximum sooner after exit from impact winter compared with processes than have a greater UVA (315–400 nm) weighting (such as photosystem damage). The balance between dust loading and ozone depletion will thus generate a well-defined temporal sequence of photobiological damage in the biosphere. The biospheric trauma is substantial. DNA damage increases by over a 1000 times and generalized plant damage by up to 500 times compared with preimpact levels.

We recognize three important photobiological synergisms associated with large body impacts. First, many of the taxa expected to be stressed by an increase in UVB radiation would also be stressed by a drop in temperature and irradiance during impact winter (Cockell 1999). This includes shallow water and photic zone taxa, exposed terrestrial taxa, large terrestrial animals and particularly organisms in equatorial regions where the UVB dose is acquired in a few hours around midday rather than over a longer period as for high latitude polar regions. Second, many species and particularly phototrophic microbial communities that survive impact winter, will not have received the UVA and B required to induce UV-protecting compounds. They will be relatively UV sensitive. Third, substantial acid rain generation is suggested for large body impacts (Prinn & Fegley 1987; Toon *et al.* 1997). Nitrous and nitric acid rain-out from stratospheric NO_x may acidify lakes and rivers, thus reducing concentrations of dissolved organic carbon, the primary UV absorber in freshwater systems. Acidification has already been demonstrated to greatly increase the UVB penetrability of lakes with the associated biological consequences (Schindler *et al.* 1996; Yan *et al.* 1996). Thus, although increases in acidity may directly affect some freshwater ecosystems, increases in UVB radiation could, through synergistic interactions with acid rain, be a significant contributory factor to biospheric crises.

We repeated the calculations for the Tunguska meteor fall, which was approximately a 10^1 Mt event, possibly seven to eight orders of magnitude less energetic than a K/T size event (Toon *et al.* 1997). Turco *et al.* (1982) present data on the levels of ozone depletion expected from this event. It is estimated that the dust loading may have had an optical depth of 0.05. In the case of the hemispherical distribution of impact generated NO, the increase in UVB radiation compared with preimpact levels is approximately 100%, similar to our estimates for a 10^8 Mt impact (Fig. 2).

For large impacts, the global ozone depletion will be greater, but the dust cloud will ameliorate the immediate effects of ozone depletion. For some large impact events, wash-out of the NO_x may even have a chance of occurring prior to the dissipation of the dust cloud. Furthermore, if substantial wildfires occur, a long-term smoke haze may help ameliorate the UV exposure over a long period. For many smaller events, ozone depletion will be less extreme, but the lower dust loading associated with these events will provide less protection. Thus, in some cases, because of the lack of a dust cloud, smaller impacts may actually

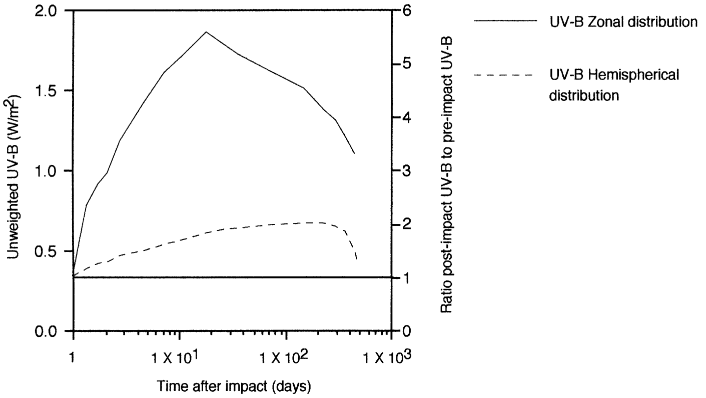

Figure 2 Increases in UVB radiation following the Tunguska meteor explosion of 1908 based on the ozone depletion estimates of Turco *et al.* (1982) and taking an optical dust loading of 0.05 and a zenith angle of 40°. Data are shown for ozone depletion from 55 to 65°N (zonal distribution) as well as distribution throughout the northern hemisphere.

cause greater UV damage. Clearly the composition of the impactor is also a factor that will cause variability in results (Toon *et al.* 1997). Impactors that may disintegrate more easily, such as comets, will break up higher in the atmosphere and may deliver more of their energy into the stratosphere causing ozone depletion.

The K/T impact event was a special case since the impact occurred in anhydrite ($CaSO_4$) rich target rock that may have resulted in a long-term (9–12 years) sulphate haze (Pope *et al.* 1994). We repeated the calculations presented above with a haze that we assumed reduced light transmission to 0.15 times preimpact levels (Pope *et al.* 1994). Only a small increase in UVB (25%) occurs over a period of 2–3 months. If ozone depletion was greatly extended by the NO loading, then there may have been a more pronounced increase in the UVB flux. However, since the sulphate haze is predicted to have lasted for 9–12 years, it is likely that the impact into sulphate rich target rock (which covers less than 1% of the Earth's surface) fortuitously prevented the stress of an ultraviolet spring at the K/T boundary.

Whether evidence for a lack of a UV effect could be found is equivocal. In the case of the K/T extinctions some organisms survived relatively well, e.g. amphibians (Archibald 1996). Yet, extant salamanders whose embryos develop in shallow, open water exposed for less than 3 weeks to ambient UVB radiation (5–26 $\mu W\ cm^{-2}$ at 45°N latitude in Oregon) exhibit severe deformities and significant mortality (Blaustein *et al.* 1994). This amount of radiation is far less than amphibians would have encountered during an ultraviolet spring. Present levels of ambient UVB radiation damage the eggs and larvae of several amphibian species with low DNA repair capacity and may be contributing to their population declines (Blaustein *et al.* 1997). Indeed, ambient levels of UVB radiation, much lower than those during the ultraviolet spring, contribute to severe retinal damage in basking diurnal frogs (Fite *et al.* 1998).

Given that even Tunguska sized impacts are predicted to occur at least every 1000 years (Toon *et al.* 1997), impact-induced increases in UVB radiation may be quite regular through geological time. The rare impact into anhydrite rock 65 million years ago may, however, have saved many organisms at the K/T boundary from the effects of an ultraviolet spring.

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BIOSKETCH

Charles Cockell is a biologist based at the British Antarctic Survey with specialisation in photobiology, polar biology and exobiology. He was formerly at the NASA Ames Research Center, California studying evolutionary photobiology.

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