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Cosmic Dust and the Earth's Atmosphere (Vilhelm Bjerknes Medal Lecture)

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Cosmic dust particles are produced in the solar system from the sublimation of comets as they orbit close to the sun, and also from collisions between asteroids in the belt between Mars and Jupiter. Dust particles enter the atmosphere at hyperthermal velocities (11 – 72 km s^{-1}), and ablate at heights between 80 and 120 km in the mesosphere/lower thermosphere (MLT). The resulting metallic vapours (Fe, Mg, Si and Na etc.) then oxidize and recondense to form nm-size particles, termed "meteoric smoke particles (MSPs)". MSPs are too small to sediment downwards and so are transported by the general circulation of the atmosphere, taking roughly 4 years to reach the surface. Smoke particles play a potentially important role as condensation nuclei of noctilucent ice clouds in the mesosphere, and polar stratospheric clouds in the lower stratosphere, where they also facilitate freezing of the clouds. There are also potential implications for climate, as the input of bio-available cosmic Fe in the Southern Ocean can increase biological productivity and stimulate CO_2 drawdown from the atmosphere. However, current estimates of the magnitude of the cosmic dust mass input rate into the Earth's atmosphere range from 2 to over 200 tonnes per day, depending on whether the measurements are made in space, in the middle atmosphere, or in polar ice cores. This nearly 2 order-of-magnitude discrepancy indicates that there must be serious flaws in the interpretation of observations that have been used to make the estimates. Furthermore, given this degree of uncertainty, the significance of these potential atmospheric impacts remains speculative.
In this lecture I will describe the results of a large study designed to determine the size of the cosmic dust input rate using a self-consistent treatment of cosmic dust from the outer solar system to the Earth's surface. An astronomical model which tracks the evolution of dust from various sources into the inner solar system was combined with a chemical ablation model to determine the rate of injection of metallic vapours into the atmosphere. Constraining these coupled models with lidar measurements of the vertical fluxes of Na and Fe in the MLT, and the rate of accretion of cosmic spherules at the South Pole, indicates that about 40 tonnes of dust enters the atmosphere each day, of which $\sim$18% ablates. The subsequent atmospheric chemistry of the ablated metallic vapours is then examined using the Whole Atmosphere Community Climate Model (WACCM), coupled with the aerosol microphysics model CARMA to treat the interplay of meteoric smoke particles with the stratospheric sulphate layer. While the optical extinction of meteoric smoke in the lower mesosphere, and of refractory material in polar stratospheric clouds is satisfactorily modelled, two problems remain. First, the injection rate of Na and Fe atoms is too large (by a factor between 5 and 10) for WACCM to replicate the observed metal atom layer densities in the MLT. It appears that vertical transport by eddy diffusion has to be significantly supplemented by chemical transport produced by unresolved (sub-grid) gravity waves (this process will significantly affect the transport of other species such as atomic O through the MLT). The second problem is that the rate of deposition of MSPs at polar latitudes is substantially underestimated by the model, indicating that there may be an efficient process for removing particles directly from the lower stratospheric winter polar vortex to the surface.
Underpinning the model development are three novel experimental systems developed at Leeds: a Meteor Ablation Simulator, which measures the evaporation of metals from cosmic dust particles that are flash heated to over 2800 K; a Time-of-Flight mass spectrometer with laser photo-ionization which is used to study the reactions of neutral metallic compounds in the gas phase; and a flowing afterglow experiment to study the dissociative recombination of metallic ions with electrons.