ATMOSPHERIC SCIENCE

Smoke above clouds

Aerosols in the atmosphere alter the radiative balance of the Earth by reflecting or absorbing solar radiation. Space-borne measurements of clouds and aerosols advected over the southeastern Atlantic Ocean indicate that the greater the cloud cover below the aerosols, the more likely the aerosols are to heat the planet.

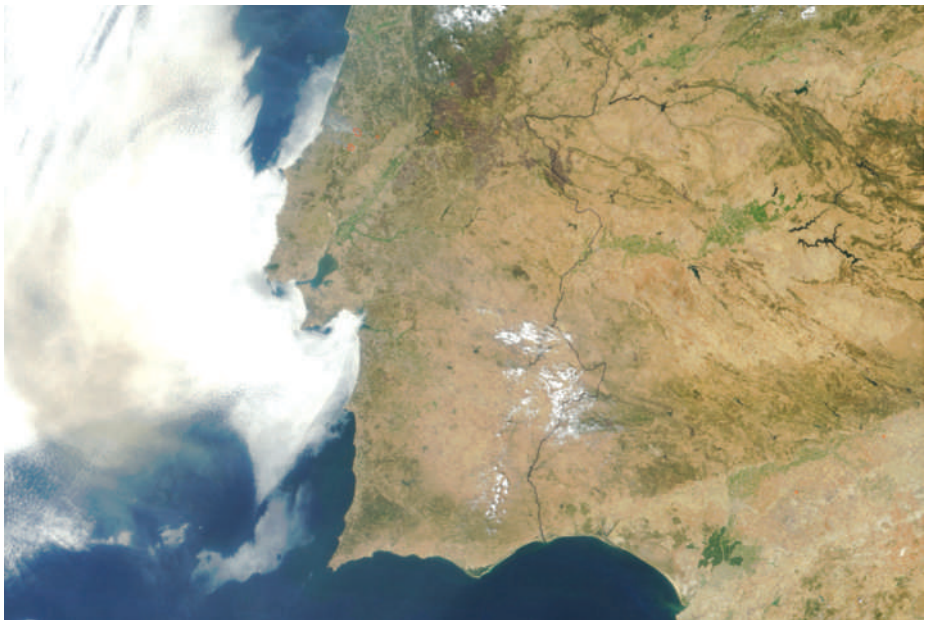
Lorraine A. Remer

Many of the processes that emit carbon dioxide and other greenhouse gases into the atmosphere, such as the burning of fossil fuels and agricultural waste, also emit smoke and particles. Like greenhouse gases, these particle pollutants — collectively known as aerosols — alter the radiative energy balance of the Earth[1,2]. However, greenhouse gases heat the planet by trapping outgoing terrestrial radiation, whereas aerosols can both heat and cool the planet by absorbing solar radiation, shading the Earth's surface and altering the reflectivity of the Earth as seen from space[3]. Whether aerosols exert a net warming or a net cooling effect depends, in part, on the reflectivity of the underlying surface[4]. On page 181 of this issue, Chand and colleagues[5] show that the radiative forcing potential of aerosols, that is their ability to heat or cool the planet, is primarily controlled by the fractional coverage of underlying clouds.

Clouds are an important determinant of the Earth's radiative balance. Looking down at Earth from space, bright white clouds dominate our view. These brilliant surfaces reflect light back to space (Fig. 1). However, when dark smoky aerosols overlie these cloud decks, they darken the scene. This increases the amount of incoming solar radiation absorbed by the atmosphere and decreases the amount of solar radiation reflected back to space[6]. In this scenario, aerosols will warm the planet. In contrast, on clear, cloudless days, the presence of aerosols in the atmosphere will often lighten the view from space, increasing the amount of solar radiation reflected out of the Earth system and cooling the planet. In this way, low-level clouds can exert a critical control on the radiative effect of aerosols that are higher up in the atmosphere.

Despite its importance, quantifying the effect of low-level cloud cover on aerosol forcing has proved tricky. Until recently, satellites were only able to measure the concentration of aerosols in cloud-free conditions, owing to the use of passive aerosol sensors, which rely on the reflection of natural sunlight from aerosol surfaces and are unable to directly measure the altitude at which a signal (be it cloud or aerosol) is generated (for example, see ref. 7). This made it impossible to resolve the spatial position of aerosols with respect to clouds, and vice versa. Thus, measurements of aerosol forcing have largely been confined to cloud-free conditions, and quantification of the impact of low-level cloud cover on aerosol forcing has relied on model simulations. These simulation studies indicate that low-level clouds can increase the warming potential of overlying aerosols by as much as 2.5 Wm^{-2} (ref. 6), which is equivalent to the magnitude of the total global forcing generated by greenhouse gases[8].

Chand *et al.*[5] provide long-awaited observational verification of these model results. Using a space-based lidar — Cloud Aerosol Lidar and Infrared Pathfinder Satellite Observation, or CALIPSO[9] for short — they measured the amount of radiation scattered by aerosols that were advected over the partly cloudy surface of the southeastern Atlantic Ocean during July–October of 2006 and 2007. Unlike passive aerosol sensors, the lidar sends out its own signal, allowing it to measure the time until the reflection returns, and thus the altitude of the cloud or aerosol that is in the way. This allows the lidar to measure the properties of aerosols even on a cloudy day, as long as the aerosol layer is situated above the clouds. Combining the lidar data with satellite-derived measurements of regional cloud cover, from the Moderate Resolution Imaging Spectroradiometer (MODIS), they show that the more cloudy it is below the aerosols, the greater the aerosol-induced warming.



NASA/GSFC

Figure 1 | Aerosols advected over the Atlantic Ocean following wildfires in Portugal in 2008. The dark smoke can be seen on the left side of the image; as it passes over the brighter cloud deck, it darkens the scene, reducing the clouds' ability to reflect sunlight back to space. In contrast, over the darker cloud-free ocean, the smoke appears brighter than the background, increasing the ocean's ability to reflect sunlight back to space. Chand and colleagues[5] use space-borne measurements of aerosols and cloud cover to show that low-level clouds can alter the radiative impact of aerosols. Image: Jacques Descloitres, MODIS Rapid Response Team, NASA/GSFC obtained through NASA's Visible Earth.

The linearity of the relationship between cloud cover and aerosol forcing makes it possible to define a critical cloud fraction at which aerosols switch from exerting a net cooling to a net warming effect. The average cloud cover in the southeastern Atlantic Ocean between July and October exceeded this critical threshold, suggesting that the net effect of aerosols in this region, at least at this time, will be to warm the atmosphere. Indeed, using their cloud and aerosol retrieval data, they calculated that aerosols will exert a positive radiative forcing of roughly 2.4 Wm^{-2}. However, when they ran the calculations assuming that the spatial pattern of aerosols was independent of the clouds, regional warming was reduced threefold, to 0.8 Wm^{-2}. The data indicate that spatial co-variation between lofted aerosols and low-level cloud cover is a critical control on aerosol forcing.

The Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC)[8] estimates that the direct radiative forcing associated with aerosols is -0.5 ± 0.4 Wm^{2}. That is, globally aerosols are expected to cool the planet. This aerosol induced cooling is roughly 20% of the magnitude of present-day greenhouse-gas-induced warming, providing a significant counterbalance to a mostly positive forcing. However, the results of Chand *et al.* indicate that aerosols may in fact warm the tropical Atlantic Ocean, despite the negative global mean. This suggests that IPCC global estimates are unable to account for the complexity of aerosol forcing, which will vary regionally, seasonally and with cloud cover[10].

The work of Chand *et al.*[5] would not have been possible without the CALIPSO lidar and the MODIS imager, demonstrating the need for continued and comprehensive measurements of aerosol and cloud properties using both passive and active satellite sensors, supplemented by focused suborbital campaigns and long-term surface stations. Without these measurements, determining the climatic influence of particulate matter in the atmosphere, in a shifting hydrologic regime, will not be possible. ❐

References

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Lorraine A. Remer is at Laboratory for Atmospheres, Code 613.2, NASA Goddard Space Flight Center, Greenbelt, Maryland 20771, USA. e-mail: Lorraine.a.remer@nasa.gov

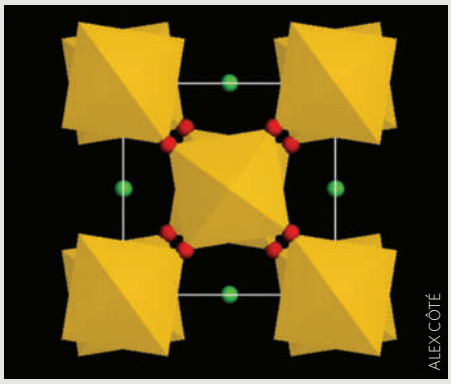
MANTLE MINERALOGY

Deep heat

When compared with the Earth's compositionally diverse crust, the planet's lower mantle might seem a dull place: it is dominated by only a few main elements, namely oxygen, silicon, magnesium and subsidiary iron. Yet, this deep and unseen part of the Earth is also thought to contain minor amounts of other elements, such as calcium, aluminium and even uranium. In fact, previous work indicates that almost half of Earth's inventory of uranium may lie in the lower mantle. This element can generate substantial amounts of heat by radioactive decay.

Exactly where uranium sits in the lower mantle is not clear. One possibility suggested by laboratory work is that this element is incorporated in the crystal structure of a relatively common lower-mantle mineral known as aluminous calcium perovskite, by replacing some of the calcium atoms that have a similar atomic size. To further clarify how uranium enters the structure of this mineral, Steeve Gréaux and colleagues conducted additional laboratory experiments (*Phys. Earth Planet. Inter.* doi:10.1016/j.pepi.2008.06.010; 2009).

They synthesized aluminium-bearing calcium perovskite and mixed it with natural uranium oxide under



the conditions thought to occur in the deep Earth: crushing pressures scarcely imaginable and temperatures of 1,700 °C or more that can easily melt iron. The results show that as the perovskite crystals grow, uranium finds its way into the crystal structure by diffusion. Although pressure is known to reduce the efficiency of diffusion, the researchers found that the positive effect of temperature on this process far outweighed any adverse effects of the high pressure.

Interestingly, aluminium seems to have an important role in the diffusion of uranium into calcium perovskite — in experiments with an aluminium-free form, the mineral did not allow uranium into its crystal structure. Apparently, when aluminium replaces the silicon that is otherwise incorporated in the perovskite, the crystal structure is altered subtly in such a way that uranium can squeeze in too. Furthermore, the incorporation of uranium, in addition to the presence of aluminium, has a marked effect on the compressibility of calcium perovskite and could affect the physical properties of the lower mantle.

Pressures in the deepest parts of the mantle are thought to be even higher than those in the experiment. However, the researchers argue that additional pressure should not have a marked effect on the structure of the perovskite. In light of its abundance and capacity to accommodate uranium in its structure, this mineral may be the most important repository of uranium in the deep Earth. Moreover, if there are regions in the lower mantle with higher than average concentrations of the mineral, the decaying uranium could provide enough heat to generate the buoyant upwellings that have been detected by seismic techniques.

NINAD BONDRE