

of craters larger than 20 km in diameter — and crustal porosity. They also find a positive correlation between the spatial densities of impact basins larger than 200 km in diameter and crustal porosity. Huang et al. propose that the lunar highland's bulk crustal porosity was generated by large impacts and subsequently declined progressively due to later smaller impacts and compaction from overburden pressure. The derived quantitative relationship between crustal porosity evolution and impact sizes partly reflects how the impact process affects regolith, with large impacts breaking up competent bedrocks and increase porosity and small impacts acting to close pores in mature regolith⁷.

Huang and colleagues constructed an analytical model to simulate the crustal porosity for the entire Moon, assuming an initial porosity of 10% immediately after formation of the South Pole–Aitken basin 4.3 billion years ago. By adjusting the relative formation sequences of the modelled basins, they were able to produce a crustal porosity map for the lunar highland that is very similar to estimates based on GRAIL observations. The preferred formation sequence of impact basins estimated from crustal porosity is generally consistent with previous studies², with additional constraints on the formation ages of basins including Nubium, Humboltianum, and Crisum. The findings suggest that the bulk porosity of lunar crust formed very soon after the

solidification of the lunar magma ocean, and it has been decreasing ever since.

The approximate match between the observed crustal porosity from GRAIL gravity data and that modelled by Huang and colleagues is impressive. Such a porosity-based approach has potential applications to understanding the early impact history and crustal evolution of other inner solar system bodies. However, the porosity model of Huang and colleagues does not include the physics of porosity generation and reduction processes, and crater densities predicted from GRAIL-derived crustal porosity contain unknown contributions of overburden pressure to pore compaction. Therefore, the crater densities predicted by Huang et al. may be overestimates of the craters that have actually accumulated in various terrains.

Interestingly, reported model ages for the proposed sequence of impact basins suggest that most of the Moon's 77 impact basins formed over an interval of 200 million years, between about 4.3 to 4.1 Ga, with the exception of several younger basins such as Moscovine, Imbrium and Orientale (Fig. 1b). This interpreted impact history is akin to a cataclysm bombardment, but one that occurred earlier than the traditional lunar cataclysm scenario⁸. The clustered model ages, however, were predicted from the accretionary tail scenario³, which implies that the pre-4.31 Ga impact flux may have been even larger — intriguing for

understanding the role of large impacts in the evolution of the newborn Moon and the lifetime of the lunar magma ocean⁹. However, the porosity model ages are dependent on the impact flux model employed.

Nevertheless, the work by Huang and colleagues³ reveals that the Moon's crustal porosity records the impact history of the lunar surface, suggesting that geophysical observations can be an important tool in unravelling the geologic evolution of the Moon. □

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Competing interests

The author declares no competing interests.

AIR POLLUTION

A step forward to mitigate ozone

For decades, ozone pollution mitigation efforts relied on two chemical regimes. A global modelling analysis has revealed a third regime involving aerosols that would help with the concurrent control of both ozone and particulate pollution.

Audrey Gaudel

In the upper layers of the atmosphere, ozone protects life from harmful ultraviolet radiation. However, closer to the Earth's surface, ozone contributes to global warming and is detrimental to human health and vegetation. Cleaning the air can be achieved by reducing emissions at the source for pollutants directly emitted into the atmosphere, but ozone is not directly emitted. Near-surface ozone is formed by complex chemical reactions of precursor

gases, mainly volatile organic compounds (VOCs) and nitrogen oxides ($\text{NO}_x = \text{NO} + \text{NO}_2$), in the presence of sunlight.

In ozone mitigation efforts, these reactions are typically considered within two regimes called “ NO_x -limited” and “VOC-limited”. The NO_x -limited chemical regime describes conditions in which NO_x emissions reductions are most beneficial to reduce ozone, while the VOC-limited regime represents situations where lowering

emissions of organic compounds would be most effective. Writing in *Nature Geoscience*, Ivatt et al.¹ show a third chemical regime, named “aerosol-inhibited”, under which the reduction of particulate pollution can lead to an increase of ozone if the emissions of the two main ozone precursors, NO_x and VOCs, are not sufficiently reduced simultaneously.

The production of ground-level ozone involves hundreds of non-linear



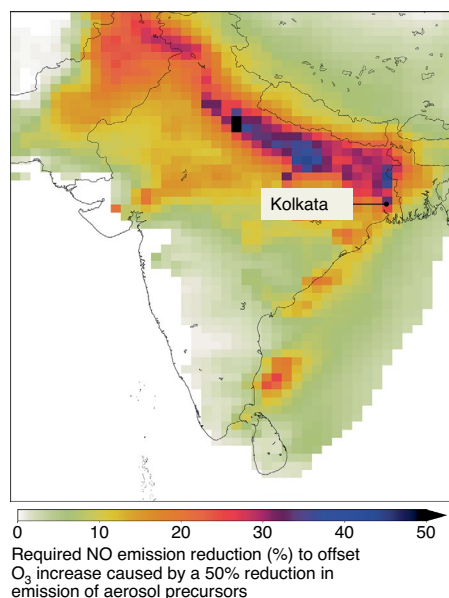


Fig. 1 | South Asia is a region where the aerosol-inhibited regime prevails. Kolkata, where PM_{2.5} and NO_x decreased by 41% and 26%, respectively, experienced a 12% increase in ozone in the lockdown months of 2020 compared to the period 2015–2019. The air might appear clearer but it does not always mean that it is cleaner. Figure reproduced with permission from ref. ¹, Springer Nature Limited.

photochemical reactions between NO_x and VOCs and intermediate chemical compounds. In mid-latitude regions, surface ozone is at a maximum in spring/summer when sunlight is prominent². One of the key reactions to produce ozone occurs between hydroperoxyl radicals and nitric oxide. Hydroperoxyl radicals, however, can be removed from the atmosphere at the same time by particulate matter with a diameter equal to or smaller than 2.5 μm (PM_{2.5}). Therefore, a decrease in PM_{2.5} causes less hydroperoxyl radicals to be removed and thus can lead to an increase in ozone.

This trade-off between O₃ and PM_{2.5} has recently been found to be an unintended consequence of air pollution control in China after the government implemented the Clean Air Action plan^{3–5}. Since the implementation of the policy, the ozone level has increased in summer over the

North China Plain, in association with a decrease in NO_x emissions, constant or an increase in VOC emissions, and a large decrease in PM_{2.5} levels. The lessons learned are that ozone mitigation is not as simple as considering NO_x-limited and VOC-limited regimes and the role of PM_{2.5} must also be considered.

Ivatt et al. incorporate the role of PM_{2.5} by defining the uptake of hydroperoxyl radicals onto the surfaces of particulate pollutants as the key component of a third chemical regime for ozone formation at a global scale. Using a global chemical model, Ivatt and colleagues compared the rate of the typical chemical reactions of the three regimes in the Northern Hemisphere for July 1750, 1970 and 2014. They find that regions where this aerosol-inhibited regime dominates have evolved with time. From 1970 to 2014, the percentage of the population in the Northern Hemisphere living in the aerosol-inhibited regime increased from 2% to 21%.

The authors find that in 1750, biomass-burning regions in North America and Northeast Asia were the most affected by the aerosol-inhibited regime. In 1970, the highly industrialized regions were most affected, including North America, Europe and parts of Asia. In 2014, South and East Asia had become the regions where the aerosol-inhibited regime dominated. South Asia (Fig. 1) is particularly affected by this aerosol-involved regime at present. It is estimated that a 40% reduction in NO_x emissions is required to offset the increase in surface ozone resulting from a 50% reduction in emissions of PM_{2.5} precursors.

The findings of Ivatt et al. are supported by observed changes in atmospheric chemistry during the COVID-19 lockdown in spring 2020. A drastic drop in economic activity led to a big decrease in emissions of air pollutants globally, especially NO_x, and also in PM_{2.5} levels. But changes of ozone varied by region, depending on local atmospheric chemistry conditions^{6,7}. Two cities in India represent a good example of this phenomenon: New Delhi saw a 24% decrease in ozone associated with a 48% decrease in PM_{2.5} and a 55% decrease in NO_x. In contrast, Kolkata, where PM_{2.5} and NO_x decreased by 41% and 26%,

respectively, experienced a 12% increase in ozone⁷.

In 2019, PM_{2.5} and ozone pollution are estimated to together cause 4.5 million global premature deaths⁸, of which PM_{2.5} accounts for more than 90%. Ozone also negatively impacts crop productivity as it oxidizes the leaves of the plants after being absorbed via the open stomatal pores, reducing photosynthesis that plants need in order to grow. For example, ozone pollution in South Asia during 2010–2012 led to crop yield losses, including 7% for maize, 5% for rice, 11% for wheat and 16% for soy beans⁹. Therefore, to maximize the benefits of air pollution control efforts, co-control of PM_{2.5} and ozone is important, especially for regions where the aerosol-inhibited regime dominates.

Ivatt et al. show that it is now possible to detect regions, such as South Asia, where the aerosol-inhibited regime prevails. The third chemical regime is bringing new understandings that are crucial to reduce ozone pollution. The reduction of emissions of O₃ precursors in tandem will avoid the trade-off between O₃ and PM_{2.5} and the resulting consequences for both vegetation and human health. If policymakers would like to control O₃, then they will have to consider the chemical aerosol-inhibited regime. □

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