Modelling the conceptual feasibility and impact of future artificial warming of Mars using manufactured aerosols

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Background:

While most proposals for humans living on Mars envision small, enclosed and controlled habitats, bolder plans have involved artificially modifying, or 'terraforming' Mars [1,2]. The most ambitious concepts involve importing volatiles to Mars from asteroids that are impacted into the surface [3,4], more moderate concepts envision enabling a diverse biosphere supported by photosynthesis using resources currently on Mars. In this view, the first step in terraforming Mars would be to warm the planet sufficiently to have small regions with seasonal temperatures warm enough to melt ice, at which point 'pioneer' species of micro-organisms may be established to start producing an atmosphere rich in oxygen [5,6].

Early work suggested that artificial warming of Mars sufficient to re-enable meltwater would be unfeasible [7-9] given the resources available on Mars to add to the required greenhouse effect. However, recent work proposes other methods of warming that appear more promising, for instance by using mirrors as solar sails [10] or by generating a solid-state greenhouse effect [11]. A positive result for global Mars warming would have a major impact not only on the sustainability of human engagement with Mars, but also on our knowledge of the reversibility of Mars' long-term climate evolution from an episodically warm and wet planet [12, and references therein] to the cold and dry planet we observe today, and also shed light on the future evolution of the climate over billions of years as the Sun brightens [13]. However, going beyond research to deployment in creating sustainable habitats and ecosystems on Mars would raise various practical, ethical and governance questions [6,14-16] about the responsible modification of what is currently a quasi-pristine environment, with potential externalities including the disruption of existing reservoirs of water ice that could be of astrobiological interest or that could provide a scientific record of past climate evolution on Mars. We must therefore assess each method not only according to its ability to warm Mars, but also according to criteria of controllability, reversibility and preservation of resources that could be useful for future generations.

Here, we focus on the feasibility of warming through 'engineered' aerosols that have high transparency to incoming solar radiation while backscattering and absorbing as much outgoing longwave radiation as possible. One such study estimated that a column density of 160 mg/m^2 of cylindrical 9×0.16×0.16 μm aluminium nanoparticles [17] – a mass loading equivalent to only a few years' worth of sustained emission – would induce the seasonally warm temperatures desired for liquid water. The proposed nanoparticles would be manufactured from Martian regolith which is rich in aluminium [18]. Another study [19] suggested that a mixture of 250 nm and 1000 nm diameter disks of graphene could be 10 times more effective at providing the required warming for a given mass loading. Both studies neglected the radiative effect of the water cycle, with the release of water vapour into the atmosphere through the seasonal sublimation of the polar ice caps adding to the greenhouse effect while water ice cloud condensation could produce either a greenhouse or anti-greenhouse effect [20-22].

Here, we further discuss timescales of warming as a function of dry deposition using preliminary results without water cycle feedbacks. We will also investigate a) the ability for warming to be regionally localized, b) the reversibility of any warming on Mars and c) the lifetime of engineered aerosols in the atmosphere and where they are deposited onto the surface. Ongoing work will then build on these results to assess the change in surface temperatures due to the radiative effects of the water cycle.

Model:

We use the Mars version of the planetary Weather and Research Forecasting (MarsWRF) 3-D global climate model [23,24]. The model is run on a 60×36 spatial grid with the atmosphere split into 52 vertical layers extending up to approximately 65 km from the surface. We model a dynamically and radiatively active background dust scenario as in [19] based on a non-global dust storm scenario from the Mars Climate Database [25-27]. We initialize the model at $L_s = 0°$ with surface albedo and thermal inertia as for current Mars. We then impose constant engineered aerosol release from a single point source on the surface; global mixing is fast relative to aerosol mass loading timescales so that the location of release has little impact on the resulting surface temperature distribution. In this abstract, we release 60 l s^{-1} of radiatively active cylindrical aluminium nanoparticles of dimension 8×0.06×0.06 µm as the warming agent (details in [19]). Aerosol settling speeds are calculated according to an analytical approach [28]. To assess the sensitivity of the model with respect to dry deposition, we model two scenarios: one, excluding the effect of dry deposition entirely (as in, only taking into account gravitational settling), and the other with a constant dry depositional velocity from the bottom layer of the atmosphere set to 0.03 cm s^{-1} (as in [19]) to simulate impaction and Brownian diffusion into the regolith from Brownian motion. We assume that the engineered aerosols would be designed to prevent self-aggregation, or 'clumping', as clumping would result in larger particles that have different optical properties and shorter atmospheric lifetimes.

Preliminary results without active water feedbacks:

The time at which the global aerosol inventory is equally distributed between the atmosphere and the surface, and hence the point at which the temperature of the atmosphere stabilises, occurs after approximately 6-7 Martian years without dry deposition and after just one Martian year including dry deposition (Fig. 1). At this stage, a no dry deposition scenario would result in large portions of the equatorial lowlands having diurnal average temperatures above 273 K all year round, never going below freezing even at night and reaching temperatures of 350 K during the day at perihelion season (Fig. 2). This heating can be reversed by ceasing the emission of aerosols, at which point the atmospheric aerosol loading immediately decreases with an e-folding timescale of 4 Martian years. Even small amounts of dry deposition, however, would drastically reduce the lifetime of aerosols in the atmosphere, with an equivalent e-folding decay timescale of 400 days, and thereby halve the global average warming for a given aerosol release. Nonetheless, annually averaged temperatures near freezing could be reached within just 1-2 Martian years at low latitudes, with seasonally-averaged temperatures above freezing in the mid-latitudes where subsurface ice is observed to be more concentrated [29]. This might be sufficient to establish pioneer species.

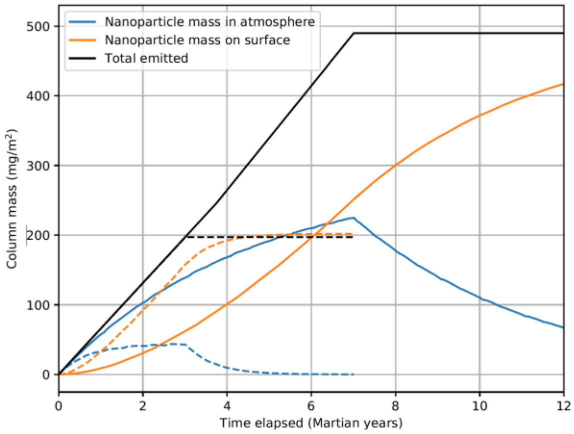

Fig 1: Total global column mass of engineered aerosols in the atmosphere and surface as a function of time since start of release. Solid lines indicate the scenario without dry deposition while dashed lines indicate the scenario with 0.03 cm/s of dry deposition. Aerosol release was ended after 7 years (for the non-dry deposition scenario) and 3 years (for the dry deposition scenario) and the aerosols allowed to settle out of the atmosphere.

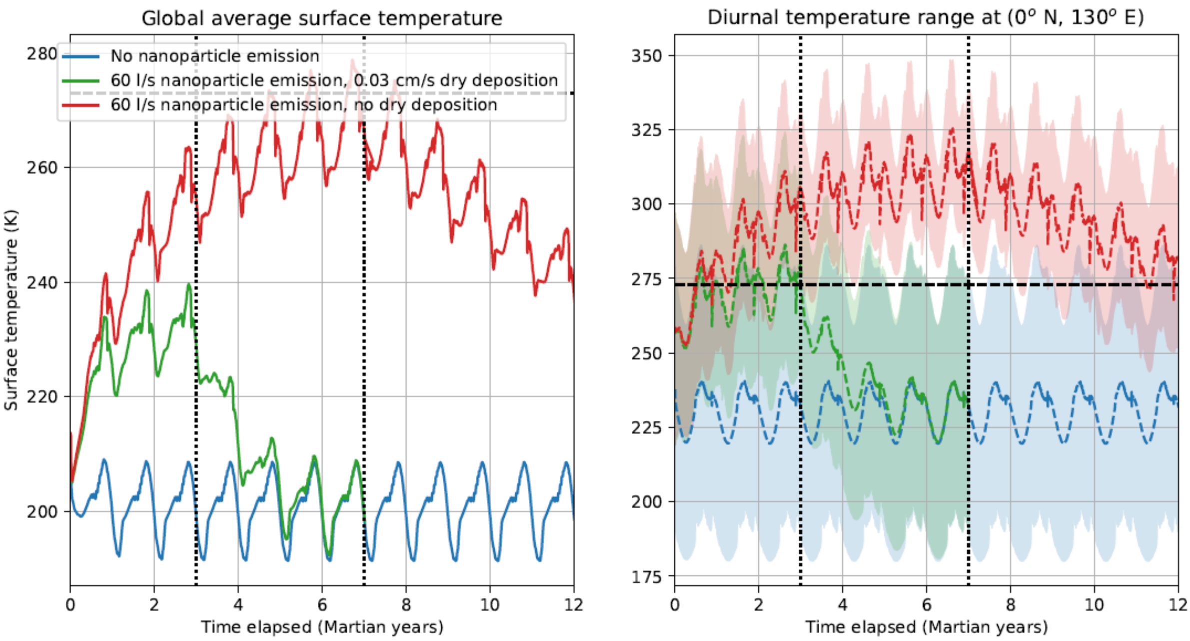

Fig. 2: (Left) Global average surface temperatures for the two aerosol release scenarios compared with a control scenario without aerosol release, (right) surface temperatures at the aerosol release location with diurnal variations shaded. Vertical black dotted lines indicate termination of aerosol release at 7 years (for no dry deposition scenario) and 3 years (for dry deposition scenario).

Although aerosol release results in significant warming of low latitudes, the enhanced greenhouse effect is less effective at high latitudes, especially in the winter hemisphere (Fig. 3). Sustained and moderated annually-averaged warming therefore requires less aerosol loading to achieve in the equatorial lowlands, where no near-surface water ice has been confirmed [29], than in lowland regions at southern mid-latitudes such as the Hellas Basin, where near-surface water ice is more abundant but which would undergo dramatic swings in temperature over the year. Since heating can be focused on lower and mid-latitudes, winter temperatures could be maintained below the frost point of CO_2 at the South Pole, and so the continued seasonal deposition and sublimation of CO_2 ice - a key and unique feature of the Martian climate that sets it apart from other planets in the Solar System – would continue. It would also preserve layered deposits of water ice that provide a scientifically valuable record of climate cycles in Mars' recent history [30]. Engineered aerosol release could therefore permit the establishment of pioneer species in mid-latitude regions where substantial warming is encountered seasonally in regions of abundant near-surface water ice, while also preserving polar deposits.

Over time, the Hadley Cell circulation would result in the seasonal redistribution and concentration of

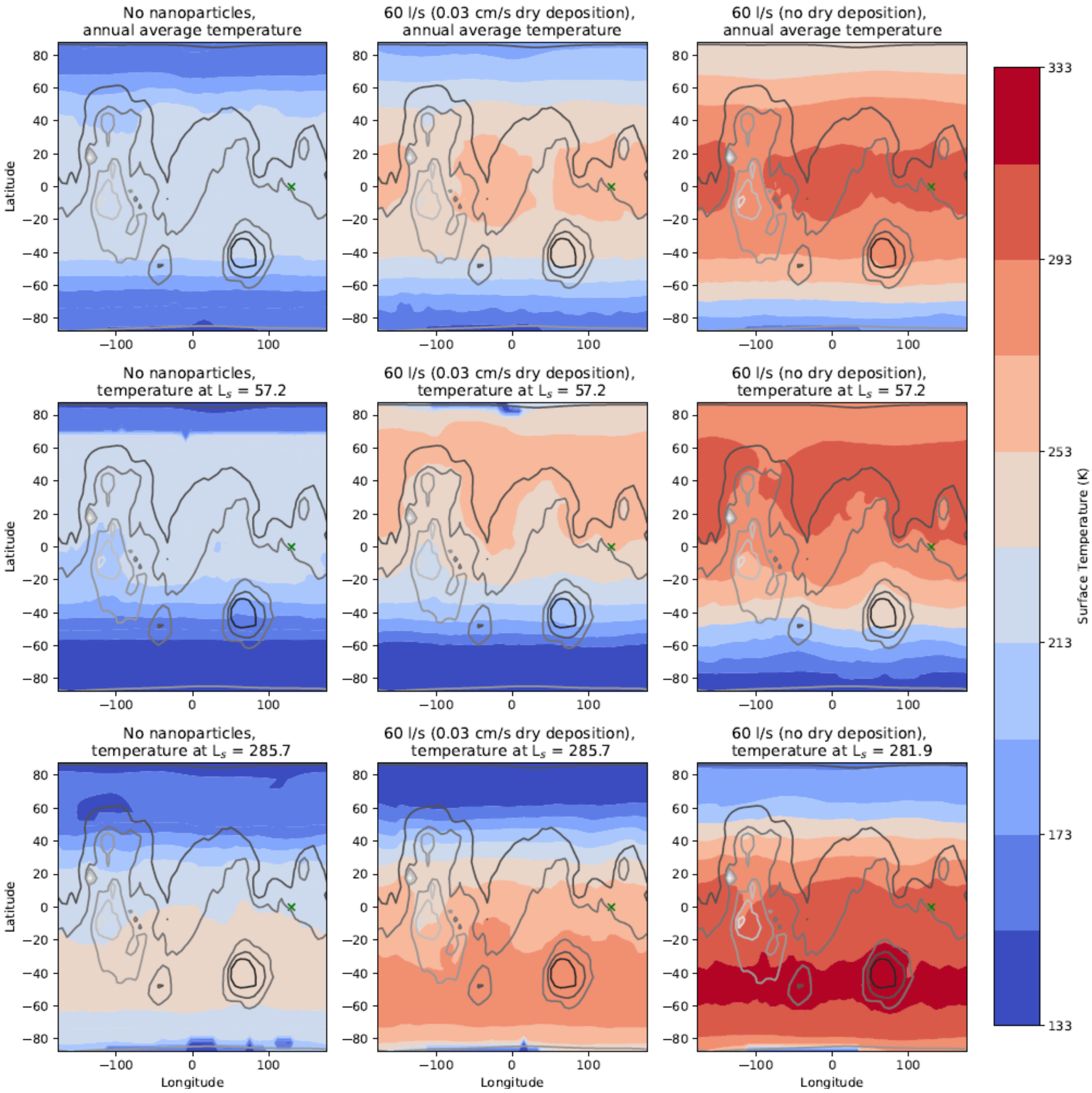

Fig 3: Diurnal average surface temperatures for each of the two dry deposition scenarios compared with a control scenario without aerosol release, (top) annual average surface temperatures, (centre) surface temperatures when the global average temperature is at its coldest (aphelion/early Northern summer), (bottom) surface temperatures in Southern summer during the peak of the dust season when global average temperatures are at their warmest. The green cross marks the aerosol release location at 0° N, 130° E.

aerosols within high latitudes, resulting in high rates of aerosol deposition over the poles (Fig. 4), assuming no further lofting of aerosols back into the atmosphere. These polar aerosol deposits, which are expected to oxidise back into aluminium oxide over timescales that are currently unknown, would significantly affect the surface albedo of polar ice, which we have not accounted for in our model. Future research on engineered aerosol candidates might therefore focus on regional warming using larger particles that sediment out of the atmosphere rapidly while minimizing their accumulation at the poles.

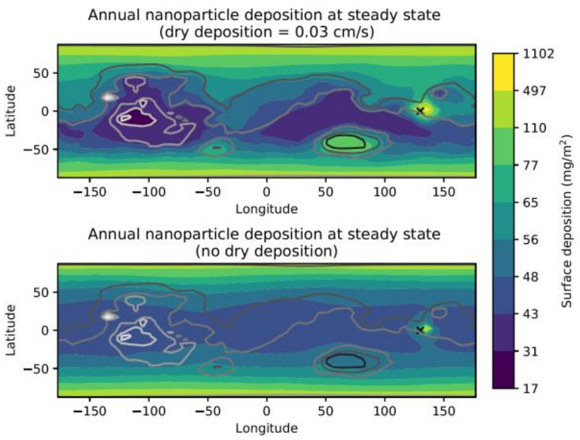

Fig 4: Annual nanoparticle surface deposition rates 2 years (with dry deposition) and 6 years (without dry deposition) following the start of aerosol release.

Perspectives:
Engineered aerosols are an effective warming agent on Mars that might allow for the establishment of pioneer species in near-surface ice. The small size of these aerosols allows for rapid global mixing and a residence time of one to several years in the atmosphere, resulting in a global warming effect that could potentially still preserve polar ice deposits. Climate feedbacks from the water cycle may amplify this effect further, but could also result in the redeposition of water ice in cold trap regions on the surface and so require additional investigation. However, if regional confinement is desired, aluminium nanoparticles are a poor candidate warming agent. Increased dry deposition can ensure a greater proportion of released aerosol is deposited close to the plume release site before spreading elsewhere on Mars. Further constraints are therefore needed on dry deposition velocities of submicron particles onto the Martian surface.

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