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COMMENTARY
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This article is a comment on Wu et al. (2021), https://doi.org/10.1029/2020JE006752.

Key Points:

- A recent study reports unprecedented turbulence-resolving numerical simulations for Mars
- A dustier Martian atmosphere may result in stronger turbulence in Mars' planetary boundary layer
- This has many implications for future studies of Mars' meteorology and climatology

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Turbulence in the Lower Atmosphere of Mars Enhanced by Transported Dust Particles

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Abstract

A recent article by Wu et al. (2021, https://doi.org/10.1029/2020JE006752) reports unprecedented turbulence-resolving numerical simulations for Mars, in which the radiative impact of suspended dust particles transported in convective circulations is resolved for the first time. Those simulations demonstrate that in certain conditions, a dustier Martian atmosphere may result in stronger turbulence and mixing in Mars' planetary boundary layer, as a result of the inhomogeneity in the distribution of dust particles being reinforced by turbulent convective cells. This effect competes with what was hitherto thought to dominate in a dustier atmosphere, that is, a turbulence weakening related to surface shading by suspended dust particles. Wu et al. (2021 https://doi.org/10.1029/2020JE006752)'s work has many implications for future studies of Mars' meteorology and climatology.

Plain Language Summary

Near the surface of Mars, the air is strongly turbulent in daytime as a result of the warm surface heated by sunlight. Before Wu et al. (2021, https://doi.org/10.1029/2020JE006752)'s study, more dust in Mars' air was thought to lead to weaker turbulence because the added dust particles shade the surface. On the contrary, using unprecedented computer simulations calculating the turbulent motions of Martian near-surface air and of the dust particles it carries, Wu et al. (2021, https://doi.org/10.1029/2020JE006752) showed that more dust in Mars' air could lead to *stronger* turbulence because dust particles locally warm the upward turbulent plumes in which they concentrate. This new result changes the way scientists may view Mars' weather and climate in the future.

Dust is for weather on Mars what water vapor is for weather on Earth: dust particles suspended in the Martian atmosphere are a key source of meteorological and climatological variability. It is not entirely out of chance that terms inherited from terrestrial moist convection studies are borrowed by Martian scientists (Heavens et al., 2019) to designate observed or modeled dust storms on Mars: for example, hurricanes (Rafkin, 2009), cumulonimbus (Spiga et al., 2013), and mesoscale textures (Guzewich et al., 2015; Heavens, 2017). Airborne dust particles suspended in the Martian atmosphere are crucial ingredients of radiative forcing on Mars, given their absorption of incoming sunlight in visible wavelengths as well as their contribution to radiative fluxes in thermal infrared wavelengths (Kahre et al., 2017; Määttänen & Savijärvi, 2004; Madeleine et al., 2011). Local-to-regional dust storms on Mars (Battalio & Wang, 2021; Cantor, 2007; Määttänen et al., 2009) are the main source of interannual variability and their triggering, growth, and decay are still an active topic of research given the complex radiative-dynamical feedbacks that govern their evolution.

How dust particles get lifted from Mars' surface then suspended in Mars' atmosphere depends critically on winds and circulations developing in the atmospheric layers a couple of kilometers above the surface, the so-called planetary boundary layer (see, for Mars, Petrosyan et al., 2011 for an expert-level review, and Spiga, 2019 for a review aimed at non-expert audience). Mars is an environment known since the Viking era (Sutton et al., 1978) for its very active turbulence in the planetary boundary layer, especially in the daytime. This strong turbulence activity has been experienced by all the in-situ spacecraft that touched down the surface of Mars (see e.g., the review of in-situ observations by Martínez et al., 2017) and its impact on the thermal structure and volatile mixing have been detected by many orbital spacecraft (Fenton et al., 2016; Hinson et al., 2008; Malin & Edgett, 2001; Stanzel et al., 2008). For readers not expert of Martian weather, it might be deemed surprising that the cold Martian environment would be prone to such a strong near-surface atmospheric turbulence. Nevertheless, more than the absolute temperature, what matters in driving atmospheric turbulence in the near-surface environment is the contrast between surface and atmospheric temperature and this contrast is particularly strong in the thin Martian atmosphere. The daytime turbulence on Mars is actually even stronger than expected solely from this temperature contrast, because of near-surface infrared absorption of incoming surface radiation by CO_2 (the main component of the Martian atmosphere) and, to lesser extent, by dust particles (Haberle et al., 1993; Savijärvi, 1999; Spiga et al., 2010). In other words, the Martian planetary boundary layer is much more radiatively controlled than its terrestrial counterpart (Spiga, 2011).

The impact of airborne dust particles on atmospheric turbulence is thought to be fairly straightforward in most existing studies. Owing to absorption by suspended dust particles, dusty conditions on Mars are expected to cause a shading of incoming sunlight at the surface, hence a decrease of the strength of turbulence in the planetary boundary layer, and a subsequent negative feedback for dust lifting (Kahre et al., 2006; Newman et al., 2002). Nevertheless, a handful of studies argues for a possible enhancement of convective structures in the planetary boundary layer by transported dust particles (Daerden et al., 2015; Fuerstenau, 2006; Heavens et al., 2011; Rafkin, 2012; Spiga et al., 2013). No existing study proposes, however, the kind of advanced numerical simulations that Wu et al. (2021) carried out to advance significantly the knowledge on the impact of suspended dust particles on Mars' convective turbulence in the planetary boundary layer.

The numerical modeling approach that Wu et al. (2021) used is named large-eddy simulations. This technique is used on Earth to explore turbulence in the planetary boundary layer: large-eddy simulations are fine-scale simulations in which only the largest turbulent eddies a couple of tens of meters across, responsible for most of the mixing in the planetary boundary layer, are explicitly resolved (Couvreux et al., 2010; Giersch et al., 2019; Klose & Shao, 2013; Lilly, 1962; Mason, 1989). Large-eddy simulations provide fruitful insights in the case of the Martian atmosphere too (Odaka et al., 1998; Rafkin et al., 2001), to understand convective vortices (Kanak, 2006; Nishizawa et al., 2016; Toigo et al., 2003) leading to dust devils (Lorenz et al., 2016; Spiga et al., 2016), to assess the horizontal and vertical structure of the convective planetary boundary layer (Fenton & Michaels, 2010; Michaels & Rafkin, 2004; Richardson et al., 2007; Sorbjan, 2007; Spiga et al., 2010), to determine the atmospheric dynamics encountered by landers and rovers during their Entry, Descent, and Landing (Rafkin & Michaels, 2003; Tyler et al., 2008), to make sense of turbulence observations by spacecraft visiting Mars (Davy et al., 2010; Gheynani & Taylor, 2011; Spiga et al., 2021), and to explore the possibility of radiatively controlled turbulent convection in Mars' nighttime water-ice clouds (Spiga et al., 2017).

The study of Wu et al. (2021) proposes, for the first time, large-eddy simulations of the dusty Martian atmosphere where dust particles are not being simply used to compute radiative forcings in the atmosphere, but are also actively transported in the turbulent motions resolved by their model. What Wu et al. (2021) basically do is to introduce an additional level of complexity (i.e., explicitly resolving the dust-related radiative-dynamical feedbacks related to turbulence on Mars) to reach a more realistic representation of Mars' dusty atmosphere in turbulence-resolving models and to conduct unprecedented numerical experiments, akin to laboratory experiments with brand new instruments. This is obviously a risky strategy, involving time-consuming model development and validation, but possibly a highly fruitful approach.

The new simulation pathway proposed by Wu et al. (2021)—coupling turbulence-resolving simulations to radiatively active transported dust particles–allows them to discover that, contrary to what has been thought thus far, a dustier Martian atmosphere could be, in certain conditions, *more* turbulent than a clear Martian atmosphere (Figure 1). A preliminary to those new results is first to check that, in known case studies, their model used for large-eddy simulations are consistent with existing spacecraft observations (Hinson et al., 2008) and previously published large-eddy simulations (Spiga et al., 2010). Wu et al. (2021) also confirm that the configuration adopted by existing large-eddy simulations, that is, a fixed dust distribution, yields the result previously considered as the consensus—that is, an increase in atmospheric dust opacity causes a weakening of turbulent convection owing to reduced sunlight reaching the surface. After this thorough validation, Wu et al. (2021) report their new, unprecedented large-eddy simulations using interactive transport of dust particles that show that, contrary to the fixed distribution case, convection may be stronger in dustier cases. This results from the horizontal structure of turbulent circulations (in particular cellular structures akin to Rayleigh-Bénard convection cells) causing an inhomogeneous spatial distribution of dust particles, which are primarily concentrating in updrafts (upwelling convection plumes). Consequently, the

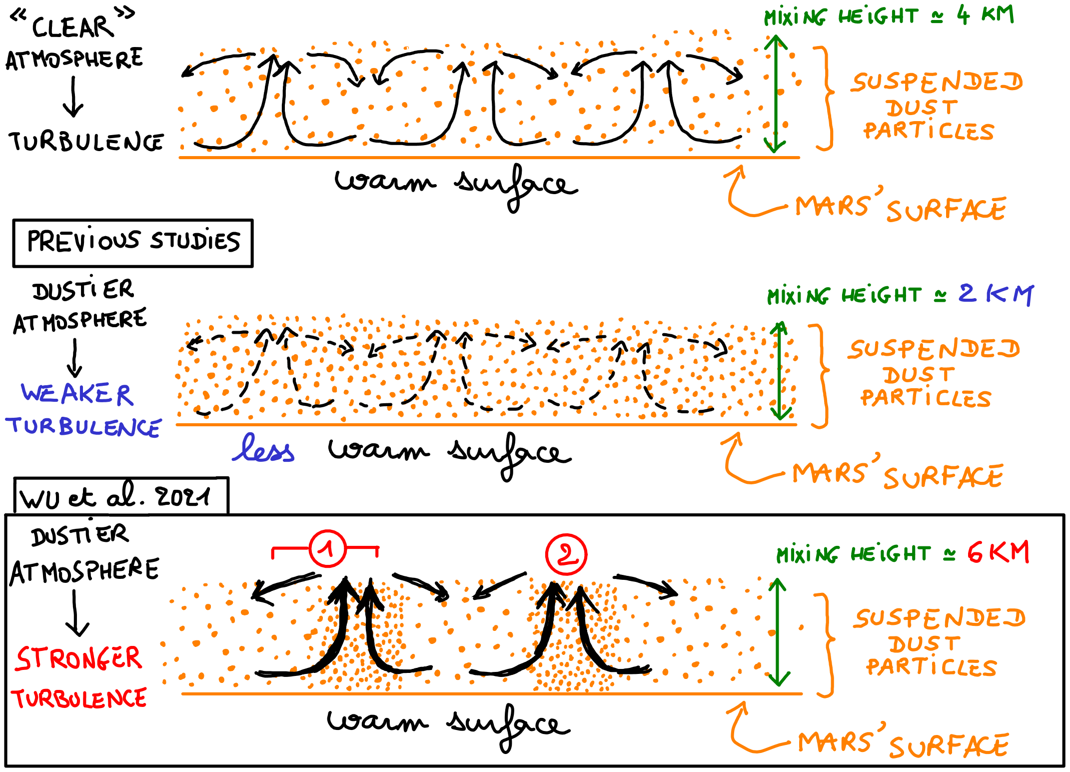

Figure 1. Schematics describing the interplay in Mars' atmosphere between daytime turbulence in the planetary boundary layer (black arrows) and the amount of suspended dust particles (orange dots). The top panel shows the regular situation where the atmosphere of Mars is not very dusty: the surface is warmed by incoming sunlight and turbulence is active. The middle and bottom panels show the case when/where the atmosphere of Mars is dustier than usual. In the middle panel, according to previous studies, more suspended dust particles means enhanced surface shading compared to the top panel situation (because part of the sunlight is absorbed by dust particles). As a result, turbulence on Mars is systematically weaker in a dustier atmosphere than in a clear atmosphere, with a lower mixing height from the surface. In the bottom panel, according to the new study by Wu et al. (2021), dust particles are transported by turbulent convective cells and concentrate within upward plumes where they warm locally the atmosphere. Consequently, more suspended dust particles mean (a) stronger horizontal temperature differences and (b) stronger buoyancy. As a result, contrary to what was previously thought, turbulence on Mars could be stronger in a dustier atmosphere than in a clear atmosphere, with a larger mixing height from the surface meaning that dust particles and chemical species could be transported higher than previously thought. The situation described in the middle panel remains valid when the atmosphere of Mars is homogeneously very dusty.

absorption of incoming sunlight by dust particles is enhanced in turbulent updrafts, which has two effects (see Figure 1) simultaneously acting to reinforce convective motions: (1) in the horizontal dimension, thermal contrasts in the CBL are stronger and (2) in the vertical dimension, buoyancy production is larger. In other words, in addition to the already-known stabilizing effect of atmospheric dust loading (by shading of the surface), Wu et al. (2021) demonstrate with their new modeling approach that there is a competing destabilizing effect of atmospheric dust loading related to the concentration of dust particles in upwelling plumes. Wu et al. (2021) identify that only certain combinations of atmospheric dust loading (total optical depth) and spatial dust inhomogeneity—for instance a moderate increase in dust loading with active areas of dust lifting—leads to the destabilizing effect to dominate the stabilizing effect, thereby causing the dustier atmosphere to exhibit stronger turbulence in the planetary boundary layer; in other circumstances, in particular, when the atmosphere is homogeneously very dusty, the stabilizing effect dominates and this corresponds to the regime known before Wu et al. (2021)'s study.

The implications of Wu et al. (2021)'s work are broad and diverse. An example of possibly crucial implication is related to the growth of dust storms on Mars. The possible positive feedback between atmospheric dust loading and the vigor of turbulence in the daytime planetary boundary layer is interesting, because a more vigorous turbulence means more powerful wind gusts, henceforth enhanced lifting, injection, and mixing of dust particles from the surface to the overlying atmosphere. This is a possible mechanism to explain the growth of a local dust storm toward a larger regional dust storm. The fact that this positive feedback may only exist in a certain range of atmospheric dust loading and dust inhomogeneity is an additional interesting perspective to explain why only certain local dust storms grow into larger dust storms while others do not (Toigo et al., 2018). Another possible great implication of this work is the exploration of various mechanisms for regional and seasonal variability of the strength of mixing in Mars' planetary boundary layer. Dust loading now comes—and in a subtle way, since this depends on both total dust loading and dust inhomogeneity—in addition to incoming sunlight, topography (Hinson et al., 2008; Spiga et al., 2010), and slope winds (Hinson et al., 2019) as potential causes for spatial and seasonal variability of mixing in the near-surface atmosphere. This could be key to understand how aerosols, volatiles, and chemical species are mixed and transported in the Martian atmosphere, from the near-surface to the upper atmosphere. The results of Wu et al. (2021) could imply that in a season and/or region with a dustier atmosphere, the vertical transport and mixing of species from the surface to the upper atmosphere is underestimated in global circulation models not resolving the intimate coupling between dust particles and turbulent motions. Thus, a related outcome of the turbulence-resolving simulations by Wu et al. (2021) is that the parameterizations of subgrid-scale mixing by turbulence in global climate models (e.g., Colaïtis et al., 2013) will need to be upgraded to account for those new effects. A last implication is a fact that the future robotic and human exploration of Mars calls for an improved understanding of Martian weather to reach a better level of predictability. Getting a view on new potential feedback mechanisms as exhibited in Wu et al. (2021) for the crucial dust-related processes on Mars allows the Martian community to be in a better place to fulfill this goal.

An obvious future line of research is that, as both thought-provoking and convincing as those new results of Wu et al. (2021) are, these are based on modeling and need to be validated by observations in future work. This constructive dialogue between observations and modeling that underlies the contemporary Martian atmospheric science is the best proof of its maturity and also the best pathway for future progress. The confirmation of the modeling results by Wu et al. (2021) may lie in existing in-situ and orbital data set already acquired on Mars, or could require additional measurement campaigns. For instance, a fascinating possibility is that the mechanism depicted by Wu et al. (2021) could explain the observed strong enhancement of vortex-induced pressure drops during the "dusty" season by both Curiosity (Ordonez-Etxeberria et al., 2018; Newman et al., 2019) and InSight (Chatain et al., 2021). On this topic, the future in situ atmospheric measurements by Perseverance and Zhurong, at different locations than Curiosity and InSight, will be particularly interesting. Another great perspective to build on Wu et al. (2021)'s modeling work is to explore whether an enhanced planetary boundary layer mixing in dusty conditions could be evidenced in existing (or future) temperature profiling acquired by thermal infrared spectrometers and radio occultations. At any event, future innovative measurements will also be needed to better understand Mars' planetary boundary layer, the part of the atmosphere crucial to both human/robotic exploration and surface-atmosphere interactions. The modeling study by Wu et al. (2021) underlines the need for a significant leap in the techniques deployed to profile Mars' planetary boundary layer, for instance by combining instrumentation never sent to Mars—like sonic anemometers, wind/aerosols LIDAR, dust flux experiments—on board a new generation of Martian spacecraft, for example, a global network of fixed weather stations, associated with instrumented aerial explorers building on the successful demonstration flights of NASA's Ingenuity helicopter. The experience coming from terrestrial experts on this endeavor will be particularly crucial.

Data Availability Statement

Data were not used, nor created for this research.

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