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The effect of atmospheric pressure on the dispersal of pyroclasts from martian volcanoes

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ABSTRACT

A planetary global circulation model developed by the Laboratoire de Météorologie Dynamique (LMD) was used to simulate explosive eruptions of ancient martian volcanoes into paleo-atmospheres with higher atmospheric pressures than that of present-day Mars. Atmospheric pressures in the model were varied between 50 mbar and 2 bars. In this way it was possible to investigate the sensitivity of the volcanic plume dispersal model to atmospheric pressure. It was determined that the model has a sensitivity to pressure that is similar to its sensitivity to other atmospheric parameters such as planetary obliquity and season of eruption. Higher pressure atmospheres allow volcanic plumes to convect to higher levels, meaning that volcanic pyroclasts have further to fall through the atmosphere. Changes in atmospheric circulation due to pressure cause pyroclasts to be dispersed in narrower latitudinal bands compared with pyroclasts in a modern atmosphere. Atmospheric winds are generally slower under higher pressure regimes; however, the final distance traveled by the pyroclasts depends greatly on the location of the volcano and can either increase or decrease with pressure. The directionality of the pyroclast transport, however, remains dominantly east or west along lines of latitude. Augmentation of the atmospheric pressure improves the fit between possible ash sources Arsia and Pavonis Mons and the Medusae Fossae Formation, a hypothesized ash deposit.

1. Introduction

Explosive eruptions into the atmosphere of Mars throughout its history are important because of their ability to deposit large quantities of fine particles across large areas, to release significant quantities of water vapor and other volcanic volatiles, and to induce short-term climate changes. Several authors have simulated explosive eruptions into the martian atmosphere, modeling the interactions between volcanic plumes and the atmosphere and estimating the height to which the plumes can rise convectively (Wilson and Head, 1994, 2007; Glaze and Baloga, 2002). Recent work has been done to apply what has been learned from convective plume modeling to the large-scale deposition of far-field ash by releasing ash into a Mars global circulation model (GCM) developed by the Laboratoire de Météorologie Dynamique (LMD) (Forget et al., 1999; Kerber et al., 2011, 2012). Tests were performed to ascertain the sensitivity of the model to parameters such as eruption strength (i.e. mass flux), season of eruption, grain size of pyroclasts, density of pyroclasts, and planetary obliquity. Simulated ash dispersal patterns from major martian volcanoes were compared to mapped extents of friable layered deposits on the martian surface in order to determine whether these deposits could have feasibly been emplaced by explosive volcanic eruptions (Kerber et al., 2012). It was determined that the variability in the final ash emplacement patterns due to differences in starting atmospheric and volcanic parameters was significant, but constrained. For example, the extent and thickness of ash emplacement from any single eruption depended greatly on the proposed grain size distribution and the height from which the pyroclasts escaped from the plume. However, the directionality of the plume was limited by strong atmospheric winds which tended to distribute pyroclastic material to the east and/or west of the erupting edifice regardless of other atmospheric parameters. Using these results it was possible to determine that some of the friable layered deposits (such as those in the basin of Argyre, or those in Arabia Terra) would have been difficult or impossible to emplace from known martian volcanoes, whereas others (such as the Medusae Fossae Formation) showed good matches under a variety of atmospheric and volcanic scenarios (Kerber et al., 2012). These simulations were performed under current martian atmospheric conditions (Kerber et al., 2011, 2012). However, many of the explosive volcanic centers on Mars can be

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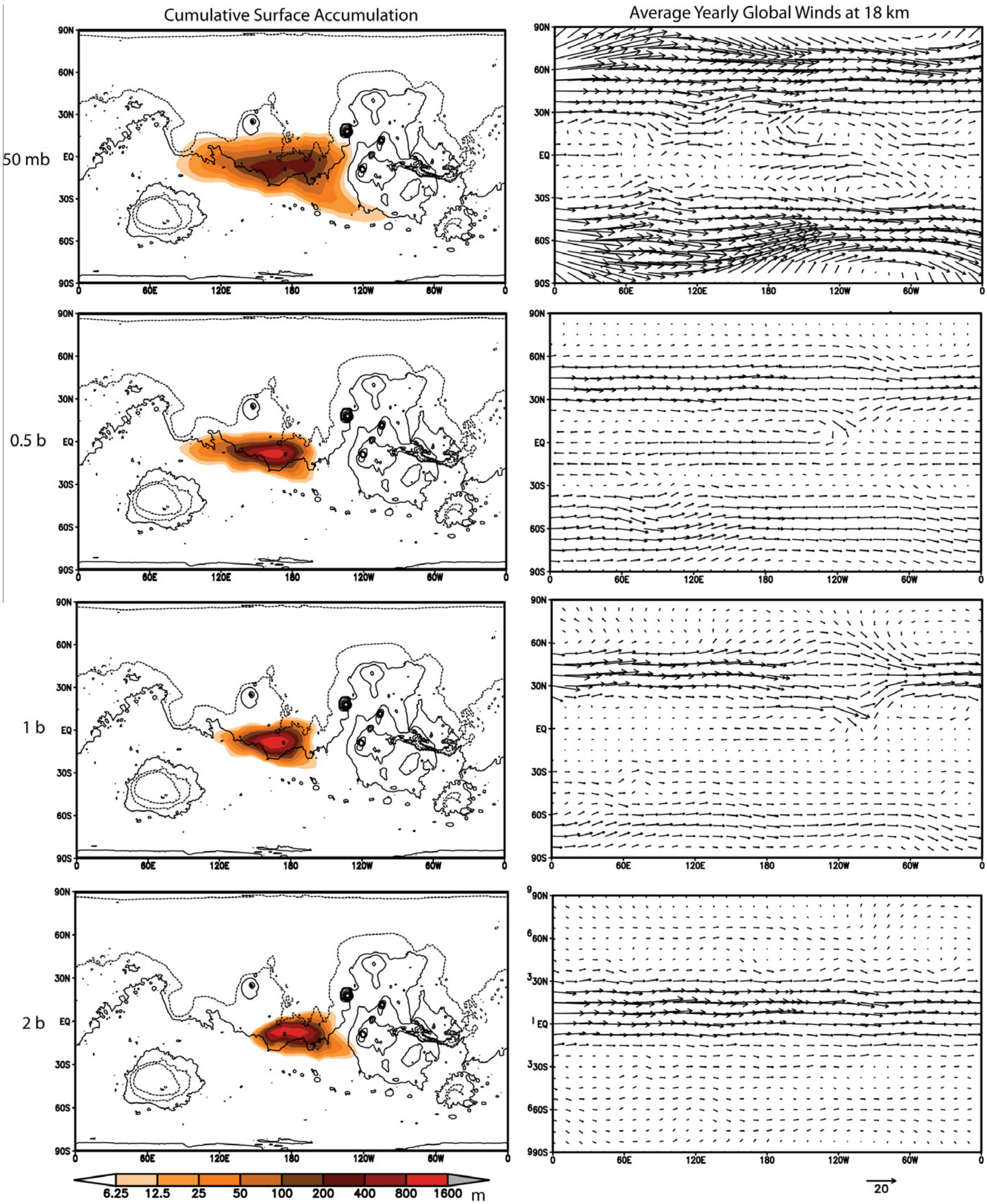

Fig. 1. Left column: The dispersal of pyroclasts from Apollinaris Mons, Mars, under different atmospheric pressure regimes (50 mbar, 0.5 bars, 1 bar, and 2 bars). Right column: Yearlong average of wind patterns at the height of release of the pyroclasts, ~18 km. Winds are stronger in lower pressure atmospheres. The distance that a pyroclast will travel depends greatly on the latitude of the erupting volcano.

dated to the Hesperian period of martian history (Scott and Tanaka, 1986; Greeley and Guest, 1987), when it is possible that the atmospheric pressure was higher than it is at present (see discussion in Forget et al., 2012, in press). Higher atmospheric pressure would affect both the height to which the plume could convect and the subsequent dispersal of the pyroclasts. Higher pressure would

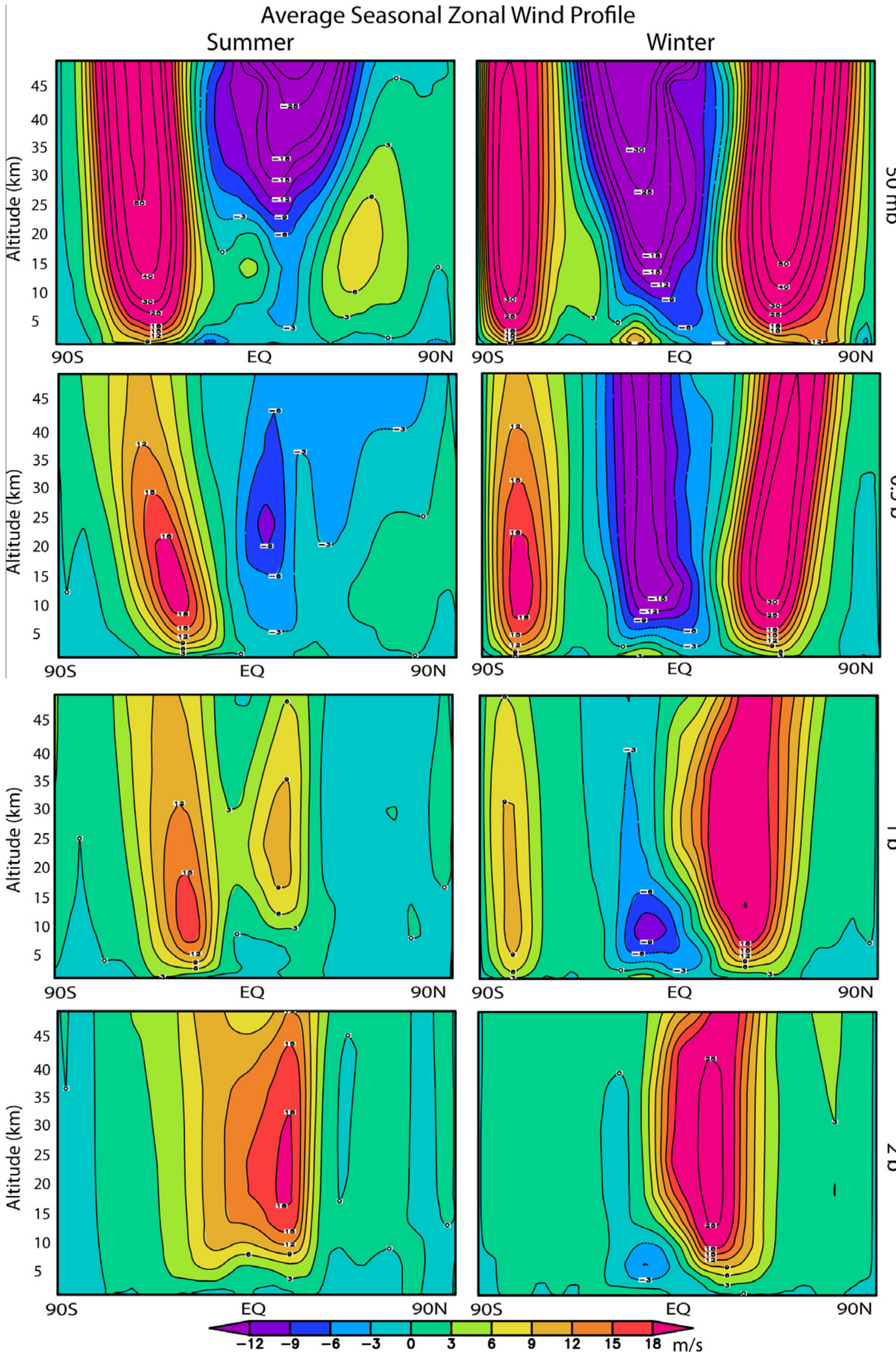

Fig. 2. Summer and winter seasonal averages of zonal winds according to altitude. Zonal winds are shown for atmospheric pressures of 50 mbar, 0.5 bars, 1 bar, and 2 bars. As pressure increases, winds slow and the prograde northern hemisphere winter jet moves towards the equator. Positive values indicate prograde winds, negative values indicate retrograde winds.

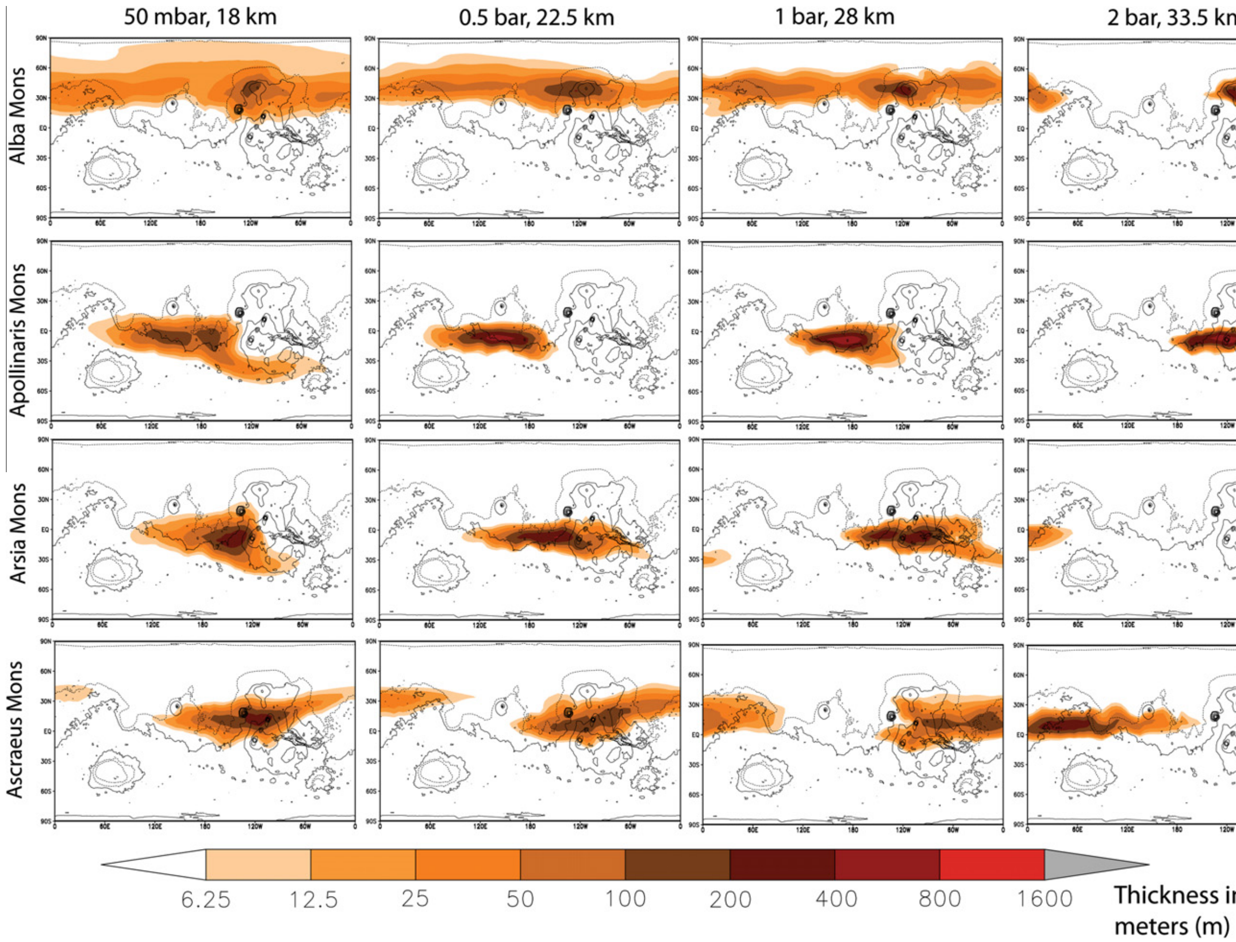

Fig. 3. Pyroclastic ash distribution patterns for major martian volcanoes in meters of surface accumulation. Each simulation represents a year-long eruption with a total erupted volume of 1.4×10^6 km^3.

mute the initial inertial volcanic blast from the vent (due to drag) (Wilson and Head, 1994, 2007), but could ultimately allow a plume in the convective regime to rise higher (due to the availability of atmospheric gas for entrainment) (Glaze and Baloga, 2002). In addition to these direct effects on the rise of the ash plume, there will be changes in atmospheric circulation which will affect the strengths and directions of the winds that the pyroclasts encounter as they fall. It is therefore important to compare the results obtained using the modern martian atmosphere with higher pressure simulations in order to test the sensitivity of the model results to different pressure regimes and to explore whether predictions made using the lower pressure model would be invalidated if the atmospheric pressure were higher at the time of eruption.

2. Methods

Unlike the thin modern martian atmosphere, higher pressure atmospheres require a generalized radiative-transfer scheme to model effects such as collision-induced absorption and Rayleigh scattering accurately. For this reason, a generalized planetary model was developed by the LMD in order to model the early martian atmosphere and the atmospheres of exoplanets (Wordsworth et al., 2011, 2013; Forget et al., 2012, in press). This new advance in modeling infrastructure has made it possible to explore ash dispersal in higher pressure atmospheres on Mars.

For this investigation, the pressure in the model was varied between 50 mbar and 2 bars. In the modern (~6 mbar) martian atmosphere, the convection height of volcanic plumes is limited by the atmospheric pressure: above around 20 km, there is too little atmospheric gas to entrain, and the plume cannot buoyantly rise any higher (Glaze and Baloga, 2002). The combination of high subsurface driving pressures and low ambient atmospheric pressures could create strong inertial plumes that would carry pyroclasts to heights in excess of 20 km; however, their horizontal motion while in the higher parts of the atmosphere would be small (3–50 km) compared with their horizontal motion at heights less than 20 km (100 s of km) (Wilson and Head, 2007). Convecting plumes would reach a neutral buoyancy height at 20 km or lower. In a thicker atmosphere, the basal inertial parts of plumes would extend for a smaller vertical distance (due to drag) but would entrain more atmosphere, so that the upper, convecting parts of the plumes could extend to greater heights. Glaze and Baloga (2002) calculated a limit of 31 km for ancient martian plumes into a 1-bar atmosphere, assuming high mass rate eruption conditions identical to their 20-km modern plume. For the current study, plumes erupting into atmospheric pressures of 50 mbar, 0.5 bar, 1 bar and 2 bars were investigated. The height of release of the pyroclasts were interpolated from the results of Glaze and Baloga (2002) to the nearest GCM level. To provide consistency with earlier studies (Kerber et al., 2011, 2012), Apollinaris Mons was used as a test case. The simulations were run for one year as a way of averaging out the effects of seasonal winds (see Kerber et al., 2012). The one-year eruption is therefore a proxy for dozens of shorter eruptions of equal strength that might have taken place over hundreds to millions of years during random seasons. As a

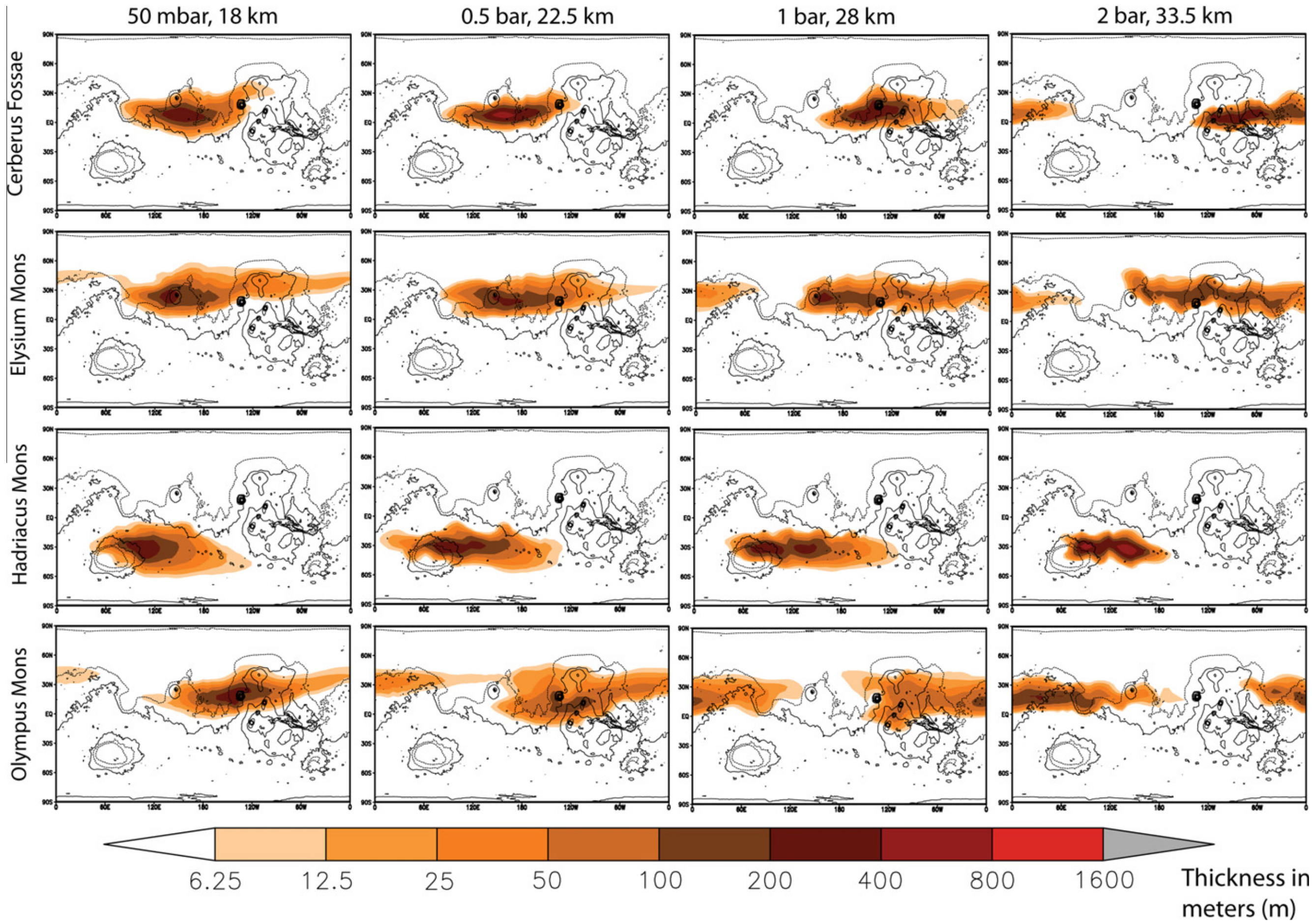

Fig. 4. Pyroclastic ash distribution patterns for major martian volcanoes in meters of surface accumulation. Each simulation represents a year-long eruption with a total erupted volume of 1.4×10^6 km^3.

point of reference, the total volume of the eruption was taken to be the volume of the Medusae Fossae Formation (1.4 million cubic kilometers, Bradley et al., 2002), which has been hypothesized to be a pyroclastic airfall deposit (Scott and Tanaka, 1986; Tanaka, 2000; Hynek et al., 2003) and for which evidence suggests Apollinaris Mons may be a source (Kerber et al., 2011). A variety of ash particle sizes, taken from a theoretical ash distribution calculated by Wilson and Head (1998) was explored in Kerber et al. (2012). The pyroclasts dispersed in the current simulations are 35-μm in radius, representative of small, far-field ash. Larger pyroclasts produced by the volcano would accumulate closer to the source. For example, most of the pyroclasts erupted from Apollinaris Mons larger than about 200 μm would fall on the roughly 40,000 km^2 area of the edifice itself. These distributions shown here thus represent the maximum expected areal extent of ash. Pyroclasts in this study were not themselves radiatively active. Finally, the simulations were repeated for the other major martian volcanoes to determine the applicability of the Apollinaris results globally and to determine the sensitivity of the dispersal results reported in Kerber et al., 2012 to the ambient atmospheric pressure at the time of eruption.

3. Results

The results of simulated eruptions from Apollinaris Mons into atmospheres of varying pressure are shown in the first column of Fig. 1. To isolate the effect of pressure from the effect of release height, all pyroclasts were released at a GCM pressure level roughly equivalent to ~18 km (±1 km). Depending on the atmospheric pressure, there is a change in the number of pyroclasts that are emplaced east or west of the edifice. The differences are driven by changes in the number and strength of zonal wind bands, shown for the release height (18 km) in the second column of Fig. 1. Faster winds at lower pressures cause the dispersal in the 50 mbar atmosphere to be wider. In addition, the pyroclasts sample a seasonal wind which transports them to the southeast of where they are seen in other regimes. The wind maps in Fig. 1 show a simplified view of the dispersal-controlling winds, however, since they only sample one atmospheric level and because they are year-long averages. A more comprehensive view of ash-dispersing winds is provided in Fig. 2, which shows longitudinally averaged zonal winds depending on altitude at different pressures. The winds shown were averaged over the summer and winter seasons for pressures of 0.05, 0.5, 1 and 2 bars. In the winter hemisphere, the circulation is characterized by a prograde jet located where the latitudinal temperature gradient is at a maximum: at the edge of the overturning Hadley cell. The hemispheric temperature contrast (and thus the extension of the Hadley cell) decreases with increasing atmospheric thickness. This decrease explains the shift of the winter jet toward the equator with increasing pressure. In the summer hemisphere a weaker prograde jet can also exist, depending on the temperature contrast and the interaction of the mean flow with planetary waves induced by the topography. The behavior of the wind in the equatorial regions above 10 km appears to be especially complex. At low pressures, as found on Mars today, the conservation of angular momentum in

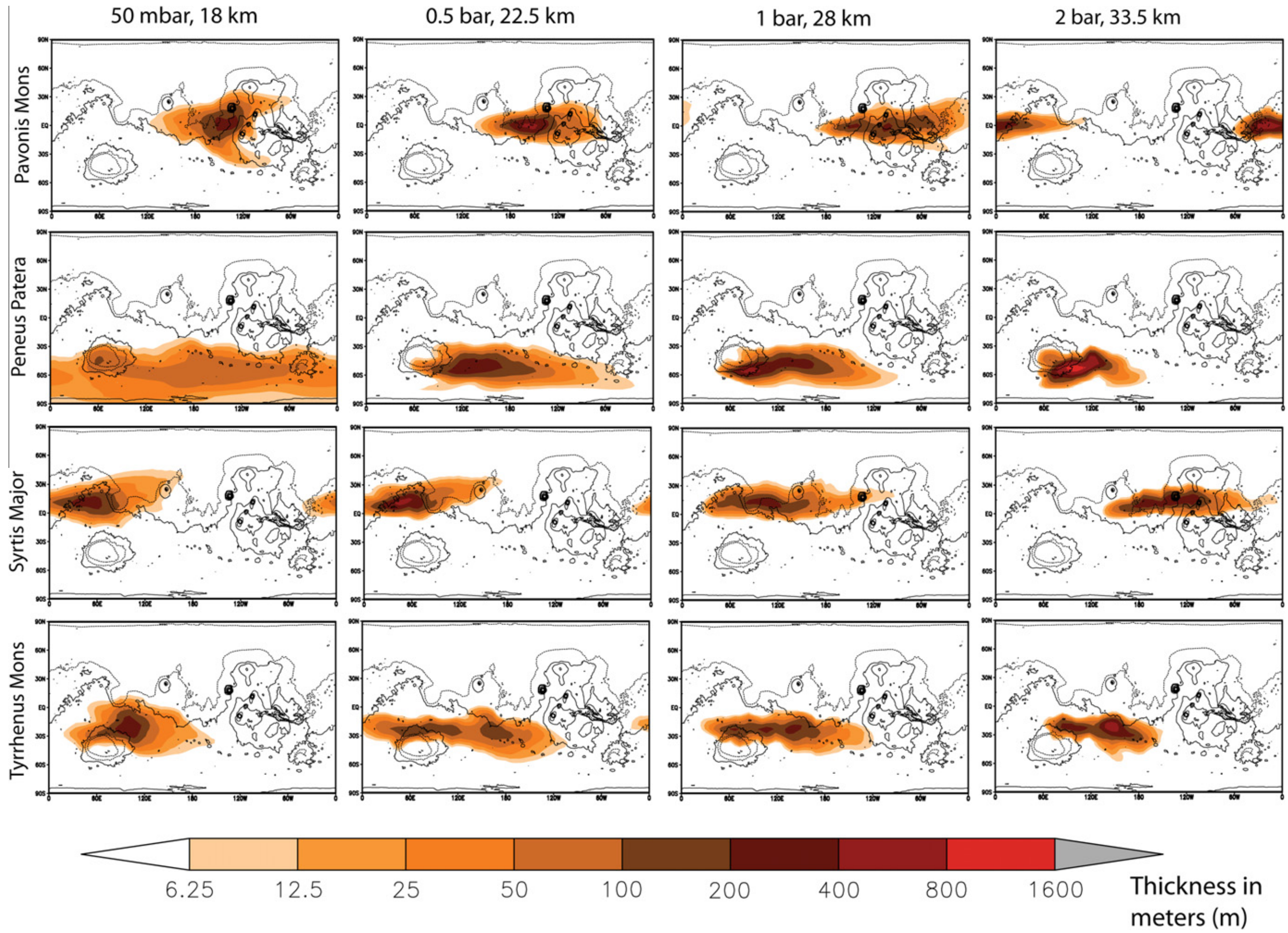

Fig. 5. Pyroclastic ash distribution patterns for major martian volcanoes in meters of surface accumulation. Each simulation represents a year-long eruption with a total erupted volume of 1.4×10^6 km^3.

the cross-equatorial Hadley circulation and the wave-mean flow interaction with thermal tides both tend to create a retrograde jet (Forget et al., 1999). Above 1 bar, equatorial waves are able to create a prograde jet, especially during northern summer. Preliminary analysis suggests that, unlike the winter jets, the behavior of this equatorial circulation is sensitive to the model parameters, and its actual behavior in the martian past is difficult to predict. In any case, however, the equatorial winds remain strongly zonal and are able to carry particles both eastward and westward depending on the period of the year.

From this view it can be seen that the strong winds near the height of release will tend to dominate the ash dispersal, and that eruptions taking place in different seasons will be affected by different winds. Despite these differences, however, since pyroclast dispersal is dominated by high-level zonal winds, they will therefore still be dominantly emplaced along a latitudinal line east or west of the source volcano. Pyroclasts emitted due to large eruptions of martian volcanoes would not be expected to travel predominantly north or south. The sensitivity of the result to pressure alone is similar to the sensitivity of the result to season of eruption or obliquity (Kerber et al., 2012).

From the second column of Figs. 1 and 2, it can be seen that volcanoes at some latitudes would be more strongly affected by changes in circulation due to pressure than others. For example, many of the volcanoes on Mars are located between the latitudes of 30 and 60N and are thus exposed to strong westerlies in many pressure regimes.

As the atmosphere thickens, the theoretical limit for plume height convection should increase. More specifically, Glaze and Baloga (2002) predicted modern volcanic plumes to be limited to less than 20 km and average ancient plumes into a 1-bar atmosphere to be limited to about 31 km. Additional simulations were therefore run releasing pyroclasts at ~18 km in the 50 mbar atmosphere, ~28 km in the 1-bar atmosphere, and interpolated heights based on these two end members for the pressures not modeled by Glaze and Baloga (2002). Pyroclasts were released at ~22.5 km for the 0.5-bar atmosphere and ~33.5 km for the 2-bar atmosphere (all heights are approximate as they are based on pressure levels rather than strict altitudes). Figs. 3–5 shows the results for the major martian volcanoes, using pressure-dependent ash-release heights as described above. As the atmospheric pressure increases, the center of greatest accumulation tends to move further down wind because the particles have further to fall. This effect is especially apparent for volcanoes located in the windiest part of the 2-bar atmosphere, where major accumulation takes place far to the east of the source volcano (Fig. 3–5).

On the basis of the simulations performed by Kerber et al. (2012), it was concluded that while it was easy to distribute pyroclasts in the equatorial and mid-latitude regions, it was much more difficult to distribute material above 60°N. Fig. 6 shows the total ash accumulation that would be expected if all of the volcanoes on Mars erupted 1.4×10^6 km^3 of ash during their lifetimes. Higher pressure conditions tend to decrease the amount of volcanic ash that can reach the high northern latitudes, supporting the

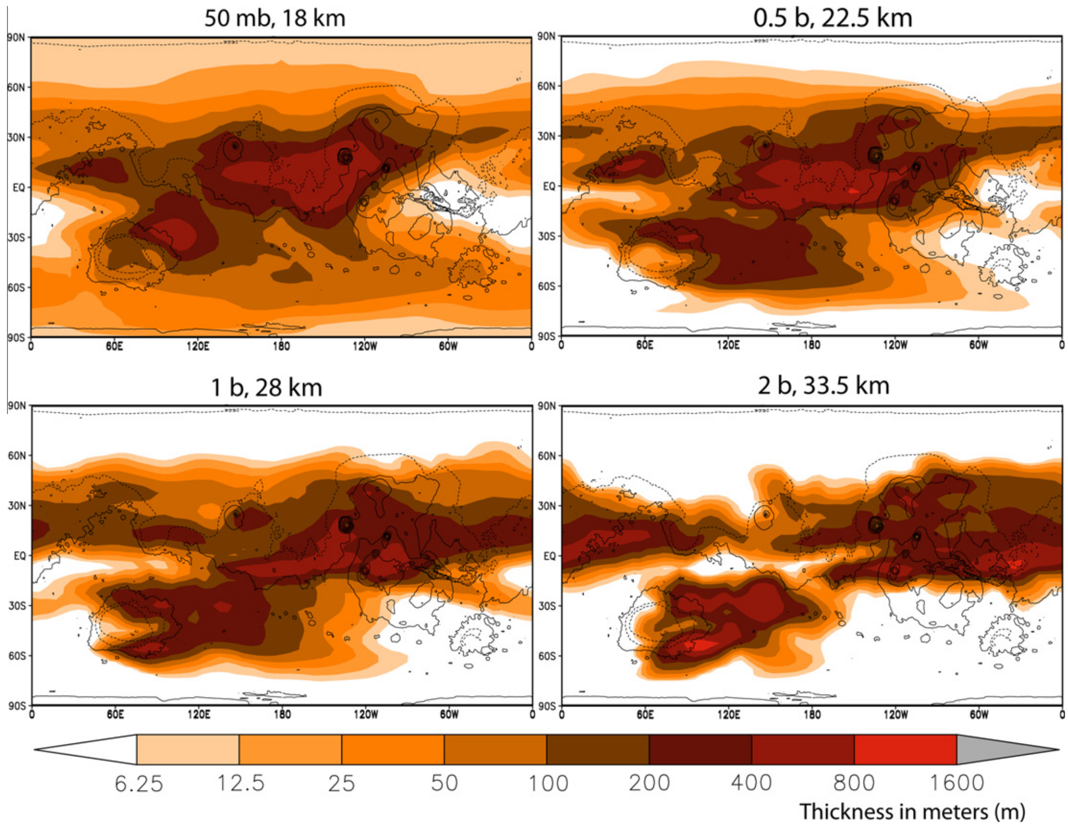

Fig. 6. Combined ash distribution patterns for all of the major volcanic centers on Mars, assuming that each of them erupted 1.4×10^6 km^3 of ash during their lifetimes. As the atmospheric pressure increases, the band of ash-covered latitudes becomes narrower.

conclusion that sediments found in the Vastitas Borealis are unlikely to be volcanic ash.

4. Conclusions

Martian volcanoes are capable of dispersing fine ash (pyroclasts ~35 μm) to great distances (>1000 km). However, the majority of this material will be emplaced either to the east or west of the vent. An augmentation of the atmospheric pressure causes the resulting dispersal pattern to narrow along the east–west direction and allows particles of a given size to fall out hundreds of kilometers further downwind, mostly due to the increased fall-out height of pyroclasts from the volcanic plume. This material may then be subject to reworking by aeolian processes. The differences in dispersal patterns due to pressure are similar in magnitude to the differences caused by season of eruption or obliquity shifts (Kerber et al., 2012), indicating that the conclusions regarding the provenance of the friable layered deposits that were drawn from the simulations of the modern atmosphere hold under past atmospheric conditions. The results provided by the newly generated ash dispersal maps do not overturn the conclusions reached by the earlier paper. Two conclusions that can be modified by the new, high pressure results are those regarding the eruption distribution patterns simulated for Arsia Mons and Pavonis Mons. At 0.5 bars, the patterns are much better matches for the Medusae Fossae Formation than those under modern pressure conditions. It was previously concluded that these volcanoes would make good sources for the Medusae Fossae Formation only under high obliquity conditions, but these recent simulations demonstrate that higher pressures at the time of eruption could also increase the likelihood that these two volcanoes contributed material to this deposit, as hypothesized by Hynek et al. (2003). During most of recent history, eruptions from Arsia and Pavonis Mons have been dominated by effusive activity (e.g., Tanaka et al., 1992), but evidence for explosive volcanic products has been reported near the summit of Arsia Mons on the basis of the discovery of fine-grained materials and the presence of pit craters (Mouginis-Mark, 2002) and several morphological and morphometric arguments have been advanced to support the designation of the Tharsis Montes as composite volcanoes (Head and Wilson, 1998). In this case, Arsia, Pavonis, or proto-volcanoes in the same area would have had to have been active during a time in martian history when the atmosphere was 0.5 bars. The source most favorably located to produce the Medusae Fossae Formation under the widest variety of conditions remains Apollinaris Mons (Kerber et al., 2011, 2012).

The modeling of volcanic ash distribution can aid in determining the feasibility of a volcanic origin hypothesis for particular fine-grained units. In addition, if a particular unit was positively identified as volcanic by other means, a great deal of information could be gleaned by determining what volcanic and atmospheric conditions were necessary to create it. For example, the mound of materials in Gale Crater may be at least partially composed of Medusae Fossae Formation material (e.g., Thomson et al., 2011). In situ analysis of this deposit by the 2012 Curiosity rover may allow a more diagnostic determination of the composition of the Medusae Fossae Formation. Important measurements needed for the more detailed modeling of volcanic ash deposits on Mars include estimates for the thickness of these deposits (potentially derived from radar), average grain-size estimates (preferably as a function of distance from the source), and age estimates. Measurement of the density, shape, and composition of potential pyroclasts would also be useful in constraining their source and in modeling their radiative effects on the atmosphere.

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References

Bradley, B.A., Sakimoto, S.E.H., Frey, H., Zimbelman, J.R., 2002. Medusae Fossae Formation: New perspectives from Mars Global Surveyor. J. Geophys. Res. 107, E8.

Forget, F., Hourdin, F., Fournier, R., Hourdin, C., Talagrand, O., 1999. Improved general circulation models of the martian atmosphere from the surface to above 80 km. J. Geophys. Res. 104, 24155–24176.

Forget, F., Wordsworth, R., Millour, E., Madeleine, J.-B., Kerber, L., Leconte, J., Marcq, E., Haberle, R.M., 2012. 3D modelling of the early martian climate under a denser CO_2 atmosphere: Temperatures and CO_2 ice clouds. Icarus, in press.

Glaze, L.S., Baloga, S.M., 2002. Volcanic plume heights on Mars: Limits of validity for convective models. J. Geophys. Res. 107, 5086. http://dx.doi.org/10.1029/2001JE001830.

Greeley, R., Guest, J., 1987. Geologic Map of the Eastern Equatorial Region of Mars. USGS Misc. Invest. Ser. Map I-1802-B.

Head, J.W., Wilson, L., 1998. Tharsis Montes as Composite Volcanoes? 3. Lines of Evidence for Explosive Volcanism in Edifice Construction. Lunar Planet. Sci. 29. Abstract #1124.

Hynek, B.M., Phillips, R.J., Arvidson, R.E., 2003. Explosive volcanism in the Tharsis region: Global evidence in the martian geologic record. J. Geophys. Res. 108 (E9), 5111.

Kerber, L., Head, J.W., Madeleine, J.B., Forget, F., Wilson, L., 2011. The dispersal of pyroclasts from Apollinaris Patera, Mars: Implications for the origin of the Medusae Fossae Formation. Icarus 216, 212–220.

Kerber, L., Head, J.W., Madeleine, J.B., Forget, F., Wilson, L., 2012. The dispersal of pyroclasts from ancient explosive volcanoes on Mars: Implications for the friable layered deposits. Icarus 219, 358–381.

Mouginis-Mark, P.J., 2002. Prodigious ash deposits near the summit of Arsia Mons volcano, Mars. Geophys. Res. Lett. 29, 1768. http://dx.doi.org/10.1029/2002GL015296.

Scott, D.H., Tanaka, K.L., 1986. Geologic Map of the Western Equatorial Region of Mars. USGS Misc. Invest. Ser. Map I-1802-A.

Tanaka, K.L., 2000. Dust and ice deposition in the martian geologic record. Icarus 144, 254–266.

Tanaka, K.L., Scott, D.H., Greeley, R., 1992. In: Kieffer, H.H., Jakosky, B.M., Snyder, C.W., Matthews, M. (Eds.), Global Stratigraphy. Mars. Univ. of Arizona Press, Tuscon, AZ, pp. 345–382.

Thomson, B.J., Bridges, N.T., Milliken, R., Baldridge, A., Hook, S.J., Crowley, J.K., Marion, G.M., de Souza Filho, C.R., Brown, A.J., Weitz, C.M., 2011. Constraints on the origin and evolution of the layered mound in Gale Crater, Mars using Mars Reconnaissance Orbiter data. Icarus 214, 413–432.

Wilson, L., Head, J.W., 1994. Mars: Review and analysis of volcanic eruption theory and relationships to observed landforms. Rev. Geophys. 32, 221–263.

Wilson, L., Head, J.W., 2007. Explosive volcanic eruptions on Mars: Tephra and accretionary lapilli formation, dispersal and recognition in the geologic record. J. Volcanol. Geoth. Res. 163, 83–97.

Wordsworth, R., Forget, F., Selsis, F., Millour, E., Charnay, B., Madeleine, J.-B., 2011. Gliese 581d is the first discovered terrestrial-mass exoplanet in the habitable zone. Astrophys. J. Lett. 733, L48.

Wordsworth, R., Forget, F., Millour, E., Madeleine, J.-B., Charnay, B., Head, J., 2013. Global modelling of the early martian climate under a denser CO_2 atmosphere: Water cycle and ice evolution. Icarus 222, 1–19.