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Mars: History of Climate Change and Evolution of the Water Cycle (Runcorn-Florensky Medal Lecture)

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Atmospheric general circulation models are becoming more and more sophisticated and can now be analyzed at various scales, and include variations in atmospheric water vapor content, orbital parameters and surface properties. A wide variety of geological evidence indicates that the climate on Mars has changed during its past history. We are now approaching the time when synergism is developing between studies of the observed geological record and predictions and results of climate models. Geological evidence for climate change ranges in physical scale from layering in the polar caps and sediments, to meters-thick ice-rich layers extending from high to mid-latitudes, to kilometers-thick polar and circumpolar deposits. Clear temporal changes in the mineralogy and alteration style of surface and subsurface materials signal long-term climate change. Evidence is found throughout the geologic record of Mars, ranging from interpreted Amazonian tropical mountain glaciers to much longer term trends implied by the temporal distribution of geological features such as valley networks and outflow channels. Furthermore, there is strong evidence for changes in the hydrological cycle of Mars that reflect long-term climate change. For the last $\sim$80% of its history (the Hesperian and Amazonian) Mars appears to have been a very cold, hyper-arid polar desert, similar to the McMurdo Dry Valleys of Antarctica. During this time, the hydrologic system on Mars has been horizontally layered, with the near-surface hydrologic cycle involving water movement between the atmosphere, polar caps, the surface and regolith at various latitudes; variations in spin-axis orbital parameters caused significant surface redistribution of ice and dust, and abundant ice has been sequestered beneath glacial debris-cover in the mid-latitudes for several hundred million years. Existing groundwater is sequestered below a globally continuous cryosphere; liquid water occasionally emerged to the surface during magmatic events that cracked or melted the cryosphere, forming outlet channels. In contrast, many believe that Mars was "warm and wet" during the first 20% of its history (the Noachian); in this scenario, there was no global cryosphere, and the hydrological cycle was vertically integrated. Geological evidence for this includes extensive valley network systems, hundreds of closed-basin and open-basin lakes, depositional fans and deltas, and integrated systems that extend for thousands of kilometers across the surface. Major outstanding questions include the causes and the duration of these more clement conditions in the Noachian, whether they led to the formation and evolution of life, why they changed in the late Noachian-Hesperian, the duration of the change, how the climate stabilized to its current state, whether any early-evolving life could survive this transition, and if so, where such life might reside today. The questions raised by the long-term climate history of Mars provide a compelling framework for future robotic and human exploration.