CONTROLS ON PRECIPITATION AND ARIDITY FOR ANCIENT MARS.

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Introduction: The purpose of this abstract and presentation is to explore the climatic controls on precipitation and aridity applicable to ancient Mars. What do we know about ancient Mars and where do these constraints come from? The starting point is the idea that Mars has lost a significant fraction of its atmosphere and that "early" in Martian history, it may have enjoyed a much thicker and warmer atmosphere. Constraints come from reflections on what controls aridity on the Earth, climate model simulations for ancient Mars, and simplified conceptual models of atmospheric water mixing and reservoir stability. We especially want to emphasize the importance of not simply asking "is the global mean temperature above 273 K?" While useful, the question is worn. And in any case, the unavoidable spatial non-homogeneity of water reservoir distribution and atmospheric transport, and the role of the latitudinal distribution of surface heating will greatly reduce the degree to which the global "273" number is useful in determining how "wet" given places on the planet would have been (specifically in terms of the geologically interesting issues of the activity, extent, and distribution of precipitation).

But it is important not to take relativism too far. Many an appeal can made to microclimates or local meteorological effects, but it is important to recognize that the availability of water substance at a given location is as important as meeting thermal requirements. Further, the atmosphere provides a short circuit between climatically active water reservoirs that is extremely rapid and has enormous carrying capacity integrated over geological time scales. No microclimate that is in contact with the atmosphere can be sealed from the global climate system. This is one of the most important reasons why liquid water is so difficult to conceive of for the current Martian climate: while daytime temperatures at many locations regularly exceed 273 K, the fact that the atmosphere is always in contact with 148 K dry ice deposits and sometimes with a ~210 K water ice cap means that the atmosphere carries only O(0.01-0.1) Pa partial pressure of water vapor and thus locations experiencing ground temperatures exceeding 273 K were generally long since desiccated.

We briefly review what kinds of climates Mars may have enjoyed, and then move on to examine what these states would have implied regarding location and state of water reservoirs. We examine the process responsible for precipitation and examine what determines aridity on the Earth. Using information about evaporation and precipitation for the Earth, we speculate about the importance of interconnected water bodies and the extent of "dry land." Examining the most extreme case of warm and wet early Mars, we further speculate on the precipitation volumes and patterns we would expect even in the case of a Mars with oceans and fully Earth-like climate.

What Kind(s) of Climate(s) Might Early Mars Have Enjoyed?: How warm Mars might have been in the past depends largely on how thick of an atmosphere Mars had, and also upon composition. It is usually assumed that the bulk atmosphere would have been CO_2, with traces of other gases, including relatively short lived sulphur species. Water vapour would almost certainly have been present, but just as for the Earth, atmospheric vapour abundance is largely determined by reservoir temperatures (*i.e.* it is not determined by planetary water inventory, unless the planet is water starved, in which case it would be a non-condensable trace atmospheric gas). CO_2, SO_2, and H_2O are important because they are active in the infrared (*i.e.* they are "greenhouse" gases).

A major challenge has been in contriving an early atmosphere that is both thick enough to yield mean temperatures above 273 K in the face of lower early solar luminosity, and yet would trend over geological time scales to the current (admittedly poorly constrained) carbon inventory. Given only the currently observed or easily inferred CO_2 inventory, the problem remains unsolved. However, if we assume a major buried carbon reservoir in the form of carbonates finely accumulated on subsurface rock pore walls (maybe as the result of ground water flow-through) then maybe the inventory constraint is moot and early very warm atmospheres are possible. It has also been suggested that for geologically transient periods, enhancement of atmospheric SO_2 due to volcanic activity could greatly warm climate (even for cases where the CO_2 abundance by itself would yield a Mars generally below 273 K). Sufficed to say, there is sufficient wiggle room with trace gases and hidden reservoirs that one can construct hypothetical warm (mean above 273K) and cool (near but below 273 K) early climates.

What Controls the Distribution of Water Reservoirs (and Why Do We Care)?: The distribution of water reservoirs ends up being critical to determining how humid the atmosphere is. For example, the relative humidity in the current Martian atmosphere in the lowest scale height is generally much lower than that on the Earth (and very far from saturation). A major reason for this is that the dominant source of water vapour is the northern residual ice cap, with few other seasonally active reservoirs on the planet. Thus, it doesn't matter how warm it gets at the equator – the temperature determining atmospheric vapour abundance is that of the northern ice cap. Conversely on the Earth, over the ocean, the local temperature of the sea surface plays a very large role in determining the humidity of the overlaying atmosphere. A very short distance away from the ocean (as one moves inland), the humidity can fall dramatically – try driving from Santa Monica to Pasadena and then out to Redlands in August.

So what handle do we have on where reservoirs could have been on ancient Mars? Let's start with some simplified cases. If the surface were impermeable, if there were an initial water inventory available above this impermeable barrier, and if the planet experienced equator-to-pole heating contrasts (*i.e.* the radiative time constant is less than a year or so), but the annual mean equatorial heating exceeded that of the pole (*i.e.* the obliquity is less than about 40°-50°), then polar deposits would form. These deposits would be ice if the temperatures at the pole were low enough, or some combination of ice and liquid, or simply liquid, at higher temperatures. The volume of water in the system would determine how extensive the water deposits would be. Assuming no change in the spin axis, the Martian topography means that while caps could form at either pole, large liquid water deposits could only form in the north, or in the Argyre or Hellas basins in the south. Above about 40°-50° obliquity, the water would be deposited at the equator if cold enough for ice. However, if the planet were warm enough that only liquid exists, we would have our first non-thermal argument: the fact that liquid flows down hill means that even at high obliquity, the water would tend to remain as "seas" in the topographic lows of the northern pole and high latitudes, and again also in the major topographic depressions of the south.

In the limiting case of very thick atmospheres (which may never have been plausible for Mars), the elimination of the seasonal thermal cycle due to very long radiative time scales would mean that obliquity would cease to matter for water stability (ground temperatures would vary very little – such as Venus and Titan currently), and the liquid water would tend to sit in topographic lows, with the relative humidity roughly uniform and high – a kind of global Atlanta in August.

The surface is of course not impermeable, and the ability of water to fill the interconnected free space inside of the fractured regolith is critical. In the case of large water inventory, the system tends to the "impermeable" cases already described: being fully saturated, the subsurface effectively becomes sealed to climatically active water. However, given the topographic dichotomy, this would require a vast amount of water, since a saturated regolith in the southern highlands corresponds to a water table top that has much of the northern plains covered by kilometers of surface water. This would be the most Earth-like of scenarios, with a large fraction of the planet covered by oceans. Though how Earth-like even this lush scenario would be, we will discuss below.

Let's say we don't have quite that much water. If the southern highlands tend to drain surface water to the north due to topographic heat (large scale ground water flow), then the upper several hundred meters to kilometers of the southern highlands may remain dry. A fixed water table geopotential would have water on the surface in the north. This is not a balanced situation, though. The exposed water would tend to create a humidity that is near to saturation in the high latitudes (actually near the equatorward edge of the ocean or ice sheet). Some amount of water will be transported into the opposite hemisphere and any amount of rainfall or snowfall onto the desiccated regolith will tend to remove water from the atmosphere. This will cause a north-to-south atmospheric water pump. The system would only come into equilibrium when this atmospheric transport is balanced by groundwater flow. Given how slow the ground water pathway is, it seems plausible that a northern ocean in this scenario would dessicate in "trying" to fill the southern highlands to create the balancing return flow. In this case, liquid water would exist within a tilting water table, with evaporation of the water occurring under the surface of the northern plains. This is an arid limit for the system, and decreases of water inventory from this point simply further reduce the rates of evaporation and precipitation.

Precipitation and Aridity: In the "wet" limit, what determines precipitation and aridity? This is the weather forecasting problem and it comes down to two factors: water availability (humidity) and upward vertical motion. Much of terrestrial weather forecast thus comes down to predicting vertical motion and the vapour transport.

Some terrestrial regional climates illustrate the issues. The desert southwest of the US sits inland and downwind of the relatively cool eastern Pacific ocean. It also sits downwind of a series of north-south running mountains that tend to rain and snow out the modest amount of vapour that does arise from the ocean. Only major winter storms originating from the higher latitudes, or summer extreme north and westward penetration of humid air from the relatively warm Gulf of

Mexico tend to bring rain. Conversely, the near permanent upwind presence of the warm Gulf of Mexico explains the humidity of the US southeast.

The Atacama desert in South America extends all the way to the coast, as does the Namib in southern Africa and the northwest Sahara in northern Africa. Rain shadow is not an issue here, but the combination of cool ocean temperatures and a location in the generally downwelling subtropics leads to the desert climate of this region.

In central Asia, the Gobi desert is located near about 40° latitude (*i.e.* poleward of the subtropical descent associated with the tropical overturning circulation ("Hadley" circulation)). The aridity of the Gobi results from the great distance of the central Asian heartland from the nearest major body of water (over 1600 km). This continental "water source distance" aridity ties into ideas of why the Triassic has left such a large amount of evidence for extensive aridity when the continental land mass was accumulated into the extensive Pangaea supercontinent and centered near the equator.

Why is There So Much Rain in Brazil When it's so Cold at the Poles?: Charts of precipitation minus evaporation (P-E) for the zonal mean for the Earth show positive numbers in the high latitudes and in the tropics. The high tropical rainfall enables the rain forests of South America, Africa, and Asia. Much of this rainfall is recycled water: the very wet surface yields high humidity immediately above the forest and when combined with perturbation upwelling, convective rain results that puts the water back on the surface. But for the Brazilian example, we know that there is net flow of water out of the rain forest in the form of the Amazon, and other smaller rivers (all manifestations of water runoff). This water has to be resupplied or else the rain forest would rapidly dry. Indeed, this balancing resupply is from vapour transported to the west by the trade winds, and originating from evaporation of the warm western tropical South Atlantic ocean.

The P-E chart for the Earth is actually somewhat puzzling in some senses. The evaporation is highest over tropics, but the P-E is actually positive near the equator. The peak near the equator results from covergence of water vapour in the inter-tropical convergence zone (ITCZ) where the peak "Hadley" cell upwelling occurs. A significant belt of negative P-E exists in the subtropics of both hemispheres – some good fraction of this excess evaporated water is required to sustain the equatorial P-E excess. The subtropics can of course only sustain the P-E hemorrhage of water because they are part of the globally connected ocean system – the loss is balanced by net inflow of more water as liquid. But what would happen if the tropics were completely filled with land? Or we could somehow stop the water from flowing? Say we had an Earth just like that of today, but with only a two-phase water cycle (ice-vapour). In that case – and not worrying about changes in the planetary moment of inertia or spin axis – we would progressively remove the subtropical water, initially piling it up near the equator and in the high latitudes. After the subtropics were depleted, however, the equatorial region would loose its poleward water supply and would start to compete with the poles, which having much lower evaporation rates would be in equilibrium with lower global humidity. The equatorial belt would thus also desiccate. On the real Earth, the tropics are moist because even though the poles are the most stable locations for water, being mostly liquid the darn stuff tends to fill in the topographically low regions, which in turn cross the equator.

What Would a Warm, Wet Early Mars Look Like?: Even with significant exposed surface water, Mars would not possess many pathways for getting water to the tropics. In this regard, Mars would provide a more extreme case than even the Triassic supercontinent climate: much of the Martian tropics and southern hemisphere may have resembled the Gobi desert. Rainfall in the northern mid-latitudes over the northern ocean would have been high, with extratropical storms creating ample upwelling and the ocean providing significant humidity to the atmosphere. Thus here, water would simply cycle from the ocean, up into the atmosphere, and then straight back as rainfall onto the ocean surface. However, it would certainly seem that supply of water to the ITCZ would have been substantially less than is supplied to the terrestrial tropics. Very little water would also have been supplied to the southern mid-latitudes. That is not to say that the southern hemisphere and tropics would have been completely dry or completely without rainfall. In the presence of diffusive atmospheric motions, some water vapour mixing must have occurred. And it also seems unavoidable that meteorological conditions would occasionally conspire to create rainfall even very deep into the tropics and southern hemisphere (as indeed occurs in the Gobi). The idea here is that even a very wet and warm Martian climate would likely not have corresponded to the kinds of high rates of precipitation that we are used to in the tropics and in the mid-latitudes of the Earth (again, except over the northern mid-latitude ocean).

What About Microclimates?: Appeals are sometimes made to the idea of local microclimates for extremes of precipitation. For example, if it is warm in Valles Marineris, might we have precipitation there even if the global Martian climate is relatively arid and cold? The interconnectedness of climate makes this problematic on any long term basis. Transient events obviously are very hard to rule out, especially as one moves the environment closer to liquid water stability. The major criteria is one of how would a microclimate vapour excess be sustained? For a transient event, a rapid release of water could put a very local and transient humidity excess in place, and could probably produce rain even today on Mars, very locally over the water eruption. But any sustained rainfall requires high mean humidity that cannot be sustained within the context of a dry global climate: the atmosphere would simply mix the vapour away on rapid time scales. To maintain high vapour abundances in this context, very high rates of resupply would be needed. Ground water flow seems wholly unable (by several orders of magnitude) to provide the kinds of rates of supply needed to balance evaporation in an arid climate.

Summary: This abstract presents speculation on the nature of precipitation for a putative warm early Mars. This speculation is based on ideas for what controls precipitation on the Earth, and also on basic climate dynamics concepts. It is clear, however, that the speculation needs in the future to be examined within the context of GCM-based climate dynamics models – a vital step that needs to be taken before significant weight can be applied to the suggestions.

Notwithstanding, two aspects of the Martian problem suggest some divergence from an Earth like pattern of precipitation. First, in the case of a poorly saturated regolith, surface water deposits may not be viable at all, with precipitation limited by relatively low global atmospheric humidity set by polar water deposits (in a low obliquity limit <~45°) or tropical deposits for high obliquity. For higher water abundance, such that the regolith is saturated, a northern ocean (as well as large seas in the southern basins) initially suggests more Earth-like precipitation. However, the location of almost all low land in the northern mid- and high-latitudes suggests that high tropical humidities seen on the Earth may not be viable for Mars. Akin to the Triassic Pangaea, tropical penetration of vapour over vast distances from evaporation of the northern ocean is likely suppressed. It is thus quite possible that an early Martian ITCZ would have seen very much less rain than the ITCZ of the Earth. Indeed, large precipitation rates may have been limited to the northern hemisphere extratropical storm tracks, simply recycling vapour back into the northern ocean. This relative suppression (but by no means prohibition) of rainfall over much of the tropics and southern hemisphere may explain how Mars could have had extensive surface water for prolonged periods and yet produced erosion rates on the southern highlands that are much lower than would be expected on the Earth.