CLIMATE, PRECIPITATION, AND ARDITY ON THE TERRESTRIAL BODIES. M. I. Richardson[1], Claire E. Newman[1], and A. S. Soto[1,2], [1] Ashima Research (600 S. Lake Ave., Suite 104, Pasadena, CA 91106, {mir,claire}@ashimaresearch.com) [2]Colorado School of Mines, Department of Geophysics.

Introduction: The 'hydrological' cycle is often the piece of the planetary climate of most widespread interest. 'Hydrological' is in quotes since the 'working substance' need not necessarily be water – on Titan it is methane. Hydrological cycles are of great interest from a climate dynamics perspective as they tend to involve increasingly numerous and complex dynamical feedback systems as the abundance of the 'working substance' increases and especially as abundant liquid is available. From an integrated hydrological perspective, the climatic branch of the hydrological cycle tends to be the fastest (as opposed to ground water flow or tectonic cycling). As such, the mean fluxes resulting from the 'fast' component of the hydrological system must be understood or bounded in order to understand the evolution of 'slow' inventories and specifically how very deep, slow inventories influence the surface and near surface environment.

Three primary factors dominate the distinction between the fast hydrological cycle on planetary bodies: the planetary rotation rate, the surface temperature relative to the triple point of the 'working substance', and the available inventory of the 'working substance' relative to the reservoir sites it may fill.

Rotation rate sets the nature of the atmospheric circulation and specifically the fraction of the surface entrained in 'tropical' versus 'extratropical' systems. Titan's low rotation rate creates a system in which much of the planet is tropical, from a meteorological perspective, creating distinctive patterns of cloud and rainfall [1]. This distinction revolves around the degree to which the mean overturning circulation (MOC) can extend in latitude: higher rotation rates tending to limit this extent and allowing storms associated with a strong zonal jet to push to lower latitudes.

Surface temperatures determine whether the 'working substance' can exist near its triple point. Conditions on Earth and Titan allow this situation for water and methane, respectively. Evidence on Mars suggests that conditions were sufficient to allow this for water in the distant past. It should be noted here that the surface temperatures of relevance to the global climate system are globally representative temperatures, not extremum local temperatures. Given the current state of the Martian climate system and the geological evidence for active liquid water, almost all work on ancient Martian climate dynamics has focused on the 'early warm Mars' problem: how to make the planet warm enough for liquid water to exist in abundance.

Working fluid inventory has received much less attention but is no less critical. On the Earth, the ability to produce copious precipitationat at most locations results directly from the availability of moisture at the surface at all latitudes (*i.e.* the presence of globally interconnected oceans). The challenge on the Earth is to understand how certain locations can be dry (*e.g.* the Sahara, Gobi, *etc*.) and to determine what factors cause precipitation rates at a given location to vary over time (*e.g* the current versus the 6,000kya 'green' Sahara). Oceans exist on the Earth because sufficient water exists to saturate much of the subsurface and to 'saturate' the ice sheet reservoirs, and then to fill the extensive interconnected oceanic basins. Both Titan and Mars currently have substantially smaller relative 'working substance' inventories than the Earth. The result is vastly more arid worlds.

The Cup Runneth Over: Without evaporative supply from the oceans at low latitudes, tropical rainfall would decrease dramatically and climatically-active water would migrate poleward. This is inspite of the fact that most moisture in tropical convective precipitation is locally recycled. Small losses poleward still occur and without oceanic resupply the system would run dry. Given the presence of oceans, the challenge of understanding precipitation and aridity on Earth comes down to understanding vapor source strengths, vapor transport pathways, and locations of upwelling (atmospheric vertical motions) [*e.g.* 2].

The importance of the *vapor source strength* can easily be illustrated by consideration of deserts that abut the sea (*e.g.* the Atacama and Namib deserts). In these cases, low sea surface temperatures associated with the Peru and Benguala currents yield low relative humidity when the air is transported over land. Conversely, Florida is bathed in a warm water setting, especially during the summer.

The importance of *water transport pathways* can be illustrated with the Gobi desert. The Gobi sits deep in the Asian continental interior. Not only is the distance to ocean water sources long, but mountain ranges (the Himalayas and Tien Shan amongst them) along this 'reach' tend to rather effectively dessicate the air before its arrival in central Asia. Another example is provided by the Fennoscandian ice sheet, which varied greatly in extent from limited Scandinavian mountain glaciers during interstadials to the vast sheet extending to England during the last glacial maximum (LGM). At the LGM, the ice sheet deflected the meridional thermal contrast to the south and in doing so also deflected the westerly jet and vapor transport (and also winter storms). Thus while during relatively warm interstadials, humidity and precipitation in central Europe may have been similar today, at the LGM Europe north of the Alps was a dry polar desert, the moisture instead being ducted to the south yielding higher winter rainfall in the mountains of the Mediterrainean [*e.g.* 3]

Given an ample supply of vapor, *upwelling* determines rainfall. The global distribution of annual mean rainfall rate amply demonstrates this, with a distinct band near the equator corresponding to the intertropical convergence zone (ITCZ). The ITCZ is the upwelling branch of the MOC and is located near the peak of atmospheric heating by the solar heating of the surface / ocean. Over the oceans, the ITCZ remains close to the equator due to thermal inertia, however, if sufficient low thermal inertia surface is present in the tropics, as obtains with India, then a monsoon circulation can develop, where the ITCZ detaches from the equator and transitions towards the tropic. The ITCZ over Africa during northern summer is near the threshold for this transition. For current orbital conditions, the ITCZ is closer to the equator, leaving downwelling and aridity over the Sahara. However, only 6-10 kya the argument of perihelion placed more insolation in northern hemisphere summer. The increased forcing (and related changes in Atlantic sea surface temperatures) tended to favor the tropical position of the northern summer ITCZ and much stronger northern summer monsoon patterns developed, resulting in the “green Sahara” evident from lake records, spaceborne radar observations of river beds, and Paleolithic art such as the Cave of the Swimmers [4]. In more poleward climes, upwelling is primarily provided in storms resulting from baroclinic instability of the winter thermal front. Thus rainfall tends to map to storminess given adequate vapor supply.

Tropical World: Titan is a low ‘working substance’ inventory body with a low planetary rotation. Low rotation rates places most of the planet in the tropical regime with an extensive MOC, while the low inventory of methane means that the surface is ocean-free and low thermal inertia, resulting in strongly monsoonal patterns of ITCZ switching between hemispheres (almost pole-to-pole). The poles remain annually the coolest locations on the planet, and thus methane is most stable on the surface there. The seasonal migration of the ITCZ tends to provide a seasonal migration of cloudiness and rainfall, with more clouds when the ITCZ is located nearer the poles (with lower air temperatures and consequently higher relative humidity). The mixing induced by the ITCZ passage in the presence of a global thermal gradient inevitably leads to a pumping of methane from the lower latitudes and into the poles, dessicating the lower and mid-latitudes [1]. The very low abundance of methane means that cloudiness and rainfall are very limited. Indeed, only the tendency of the thick atmosphere and tropical circulation to homogenize meridional temperatures allows relative humidity sufficient for sporadic cloud and rainfall away from the poles.

Paradise Lost: Mars currently lacks abundant climatically-available water and is too cold for liquid water except for in the most extreme circumstances. The current ‘fast’ hydrological cycle is dominated by transport pathways from the small permanent cap in northern summer and from transient seasonal caps. With consequent very low near-surface relative humidity over much of the planet, precipitation (fine snow and direct surface deposition) tends to occur over the seasonal CO_2 ice caps. Slow interaction with an adsorptive regolith source is also possible. The tendency to dessicate the equatorial and mid-latitudes is even greater than on Titan, since the effectiveness of the polar cold traps is much greater due to the larger pole-to-equator temperature contrasts.

Orbital changes in the recent to intermediate history of Mars will tend primarily to have moved around the permanent water ice sheet. Precesssion will tend to have switched the ice sheet from north to south, favoring the longer, cooler summer, much as it likely has moved the location of stable polar lake deposits on Titan. At higher obliquity, the ice sheet locations move from the poles to the equatorial region, with mountain ice sheets being the first seed locations.

The question of how the hydrological cycle would have functioned in the ancient past depends on two factors: warmth and availability of water. Martian climate dynamics has tended to fixate only the former, but it should be easy to see that a planet with Earth-like warmth but lacking climatically-available water would be vastly drier than the Atacama or Gobi via the operation of the mechanisms discussed in the section on the Earth. In the absence of a vast ocean, the question of rainfall comes down to how effectively ground water recharge and sporadic events (like outflows) can fill lakes. In reality, very little work has been done in assessing the likely distribution and degree of precipitation and aridity for a putative ancient warm Mars, yet much of the climate dynamical understanding to do this already exists.

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