Orbital Effects on the Climates of Terrestrial Planets. A. P. Zent, NASA Ames Research Center, Moffett Field, CA 94035; Aaron.P.Zent@nasa.gov.

Introduction: Compelling evidence that the climate of northern Europe has evolved in the geologically recent past was first noted in the 1800's, as relict landforms that were reminiscent of glacial processes: moraines, erratics, till and fossilized patterned ground. Subsequent investigations have added geochemical, paleontological and other lines of evidence that confirmed the cyclic nature of terrestrial climate change.

Just as the driver for that change was being firmly tied to orbital oscillations[1] in the 1970's, the first spacecraft observations of the martian surface were also providing geomorphologic evidence that the martian climate might vary with time as well. Initially limited to the polar layered terrains[2,3] the evidence for variable climate on Mars now includes recent and active gullies and slope linea[4,5], mantling deposits[6], evidence of tropical alpine glaciers[7], excess ground ice[8], and diagnostic freeze-thaw signatures such as sorted stone circles[9].

Astronomical Cycles: For both Earth and Mars, the orbital elements involved in climatic variation are the obliquity, eccentricity and argument of perihelion; the semi-major axes are essentially invariant. *Obliquity* variations determine the annual range of subsolar latitudes, as well as the magnitude of the seasons. It varies from 22.5° to 24.5° with a period of 4.1×10^4 yrs for Earth, and currently from 15° to 35° for Mars, with periods of 1.2×10^5 and 1.3×10^6 yrs. Prior to 5×10^6 yrs ago, the average obliquity was ~10° greater. *Eccentricity* variations determine the annual range of heliocentric distance, and the hemispheric seasonal asymmetry. It ranges from 0.0 to 0.05 for Earth, with periodicities of 1×10^5 and 4×10^5 yrs, and from, 0.0 to 0.13 for Mars, with periodicities of 9.6×10^4 and 2×10^6 yrs. The *Argument of Perihelion* controls the phasing of seasonal asymmetries, and has periods of $\sim 2 \times 10^4$ years on Earth, and 1.75×10^5 years on Mars. Mars' orbital excursions are thus substantially greater but slower than those of Earth.

Climate Change on Earth: Variations in $\delta^{18}O$ (proxy for global ice abundance) and microfossil populations (proxy for Sea Surface Temperature (*SST*)) have shown distinct periodicity corresponding to the dominant periods in Earth's solar orbit. The 100 ka eccentricity has dominated large-amplitude glacial cycles recorded in the high-latitude North Atlantic over the last 800 ka. Earlier, climatic variations in this region were lower in amplitude and concentrated mainly at the 41 ka rhythm of orbital obliquity[10], with large ice volumes corresponding to periods of higher obliquity.

During the past 800 ka, ice sheets have taken about 90 ka to grow, and only 10 ka to collapse. Eccentricity has only a weak effect on insolation however, so the dominance of a 100 ka cycle is perplexing. Likewise, it is unclear why the rates of ice sheet growth and collapse have become asymmetrical.

The presence of Earth's oceans increases the complexity of the climate feedback cycles by acting as a heat sink, as a heat transport mechanisms, and importantly as a sink for both sediments and CO_2. The upper layers of the ocean are wind-driven, involving such major features as the Gulf Stream and the Circumpolar Current. Circulation at high latitudes generally contain a downward mass flux that is associated, at least loosely, with regions of severe heat loss to the atmosphere. In these regions, the fluid becomes dense and convectively unstable; the downward flux and subsequent lateral flow constitute a defining component of the thermohaline circulation.

The thermohaline circulation plays an important role in supplying heat to the polar regions, and thus in regulating the amount of sea ice. Changes in the thermohaline circulation have significant impacts on the Earth's radiation budget. Insofar as the thermohaline circulation governs the rate at which deep waters are exposed to the surface, it may also play an important role in determining the concentration of carbon dioxide in the atmosphere.

Atmospheric general circulation models argue that the North American ice sheet directly controls North Atlantic surface-ocean responses via strong cold winds that are generated on the northern ice-sheet flanks and blow out across the ocean, chilling its surface. Surface buoyancy boundary conditions strongly influence the transport of heat and salt, because the fluid must become dense enough to sink, but these boundary conditions do not actually drive the circulation.

The composition of the atmosphere is likewise variable on the same timescales. Bubbles of air trapped in ice cores show that CO_2 and CH_4 contents of the atmosphere were low during glacials and high during interglacials

Multiple feedback mechanisms are understood to operate across the climatic cycles. For example, a positive feedback exists between sheet ice and surface albedo. Biological processes are often invoked to explain apparent pumping of CO_2 into the deep oceans during glacial intervals, possibly as a result of additional feedback mechanisms such as shelf nutrient or Fe fertilization.

Climate Change on Mars: Observational evidence for variations in the Martian climate have accumulated steadily in the last few decades, along with considerable theoretical advances in understanding likely drivers and responses.

It is likely that there was a substantial secular shift in the planet's average obliquity ca. 5 Ma bp[11], with more recent obliquity averaging some 10° lower. Earlier planetary obliquities varied chaotically, making statistical treatment of the climate history obligatory. Fourier analysis of the vertical sequences in the polar layered deposits has revealed a characteristic and repetitive wavelengths in some sections of the sequence, but absent from others[12]. Unconformities at the base of the NPLD, with sandy material below and essentially pure H_2O-rich materials above[13] to a depth of ~ 1.8 km suggest the absence of polar layered deposits in the not-too-distant past, with subsequent accumulation of the current deposits.

Improved imaging resolution has permitted mapping of lobate debris aprons and dusty, water-ice-rich mantling deposits that are layered, meters thick and latitude dependent, occurring in both hemispheres from mid-latitudes to the poles[6]. It appears that these deposits are currently being eroded and reworked. Likewise, evidence for cold-based tropical alpine glaciers throughout the Tharsis montes have revealed large-scale redistribution of H_2O.

The major driver to variations in the martian climate system is generally understood to be the orbital obliquity. Models of the climate are consistent with the observational data outlined above in that they predict that polar H_2O caps destabilize at high obliquities, with consequent transport of H_2O to low latitude, high elevation sites[14], or perhaps into mid-latitude deposits that are subsequently mantled. Global mean surface temperatures and pressures decline with increasing obliquity due to the increasing extent of the winter polar caps. The seasonal CO_2 cycle and intensity of the solstice circulation amplify considerably with increasing obliquity such that global dust storms are likely at both solstices. The dust lifting potential increases sharply with obliquity and is greatest at times of high obliquity when perihelion coincides with northern summer solstice.

The discovery of abundant, recent, and indeed currently active flow features[5] argues that substantial volatile reservoirs, likely emplaced at higher obliquities, remain out of equilibrium with their expected distribution, and that the consequences for climate variations and their geologic signatures must consider non-equilibrium processes.

At low obliquities, the atmospheric pressure is reduced by the presence of stable CO_2 caps. H_2O is transported to higher latitudes – perhaps precipitating out as ice-rich materials that subsequently become mantled. Dust lifting is suppressed due to the lower atmospheric pressures.

Even in the simpler martian climate system, feedbacks between atmospheric pressure, atmospheric aerosols and dust, atmospheric circulation and cap thermophysical and radiative properties are certain to play a role in generating non-linear climate responses to continuous variations in a limited set of orbital drivers.

Summary: The cautions that pertained to similar discussions 20 years ago[15] remain applicable to our current, fragmentary understanding of the complex relationship between orbit and climate, " The difficulty of climate modeling for the Earth, and the similarity of the martian problem should not be underemphasized…. Considering the wealth of information available for Earth… it is sobering to consider both how far our understanding of martian climate has advanced and how much remains to be learned".

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