Comparative Planetary Climate Studies

A White Paper for the Planetary Sciences Decadal Survey

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Introduction

With a broad scientific consensus on the reality of anthropogenic climate change [1], and the recognized need for more research on the consequent magnitude, mechanisms and potential for future societal disruption, NASA's crucial and highly visible role in our understanding of the Earth system has become increasingly clear. Much of the attention and discussion of this has focused on the obvious importance of remote sensing observations from Earth orbit and the further development of NASA-supported Earth science modeling efforts.

It is the purpose of this White Paper to draw attention to, and summarize, the important role that planetary exploration, and research with a comparative planetology focus, have played and should continue to play in our understanding of climate, and climate change, on Earth.

Venus is Earth's closest planetary neighbor, and a near twin in terms of overall properties such as mass and size. Their bulk densities and inventories of carbon and nitrogen are similar, suggesting similar primordial volatile inventories. Mars, Earth's next nearest neighbor, has surface conditions most closely resembling Earth's and a wide range of meteorological and geological phenomena that are recognizable as variations on familiar terrestrial themes. Current understanding of planetary formation, volatile accretion, isotopic signatures, and the well-preserved ancient geological record of Mars all suggest that these triplet planets started out with more closely comparable surface environments, geological processes, and atmospheric compositions. Yet, despite their close proximity and similar origins, these three planets have evolved into very different states. Rotation rates, magnetic fields, surface temperatures and pressures, atmospheric inventories of radiatively active gasses, total water inventories, polar deposits, and global patterns of geological activity are among the properties that differ dramatically.

An understanding of the evolutionary histories and current states of the Venus and Mars climates is directly relevant for studies of the past, present and future climates of Earth[1]. As extreme examples of very different climate on otherwise similar and nearby planets, Venus and Mars provide opportunities to improve and validate our knowledge of planetary climate data and modeling. For example, Venus can provide a test bed for an extreme case of global warming where nonlinear effects have evidently played an important and irreversible role in climate evolution. In addition to providing an instructive and fruitful challenge for understanding the terrestrial climate, Venus also serves as a model for the long term fate of Earth's climate, under the future influence of a warming sun. Mars has also experienced irreversible climate change from a more biologically clement surface environment, as well as a climate history where "Milankovich cycles on steroids" have resulted in a history of extreme climate variations from quasi-periodic changes in obliquity [2] [3] [4] [5] [6].

This synergism between Venus, Earth, and Mars goes both ways: Our understanding of Venus and Mars would benefit greatly from use of the best Earth observations and models along with engagement and expertise of the larger community of Earth scientists. Although such efforts are to some degree hampered at present by limitations in the data available for Venus and Mars,

[1] Although, intellectually, there are good arguments for also including Titan in a broad program of comparative climate research, because the purpose of this paper is to provide input to the Planetary Sciences Decadal Survey largely for the purposes of prioritizing missions to the inner solar system in the next decade, we have decided to restrict the current discussion to comparative climate studies of Venus, Earth and Mars.

much deeper understanding of these very different global climate systems should be possible, given the techniques developed to understand climate change on Earth. At the same time, these extreme cases can help to validate the crucial ability of terrestrial models to correctly predict climate on Earth forced by variations from the current atmospheric composition, increase the ability of Earth modelers to work with unforeseen climate feedbacks, and expose potential weaknesses or limitations in our current generation of Earth climate models. One of the most vexing problems of current terrestrial climate studies is separating anthropogenic from natural signals. Our neighboring terrestrial planets provide examples, devoid of human interference, that can help us with the important work of untangling these signals.

Even while representing very different evolutionary paths for Earthlike planets, Venus and Mars provide our closest analogs for many important processes and planetary mechanisms operating on Earth. This unique combination of similar initial conditions and bulk properties, with radically divergent evolutionary outcomes, makes Venus-Earth-Mars comparative studies a uniquely fruitful area for expanding and testing our knowledge of planetary system science and global change.

Comparative Climatology

Climate is a result of the interaction of atmospheric, solar and geological processes. All planetary climates evolve over time, and these changes often involve interactions between different components of the planetary system resulting in nonlinear feedbacks. Both modeling and laboratory studies can contribute to understanding the present-day climates of the terrestrial planets. However, compared to Earth our observational data sets of the atmospheres of Venus and Mars are quite crude. New missions will be required to fully capitalize on the potential of comparative climate studies. A comparative climatology research program should focus on the science described in Table 1, with notations indicating which objectives in each of the MEPAG Goals (M1, M2, M3) [7] and VEXAG Goals (V1,V2, V3) [8]documents are addressed.

Atmospheric Dynamics and Chemistry

Ideally terrestrial GCMs are based on “first principles”, applying the laws of physics to well sampled sets of atmospheric data, correctly simulating atmospheric motions in the current climate regime and accurately predicting such motions in future regimes of altered atmospheric composition. Unfortunately, the limitations of current simulation techniques and technologies requires that many convenient simplifications and hard-coded ad hoc assumptions are included in such models. Due to the great complexity of modern GCMs and their heritage as products of many researchers over many years, the users of these models are often not completely aware of some of the simplifications and assumptions embedded within. This has been made abundantly clear by early efforts to use terrestrial GCMs to simulate the very different climates of Venus and Mars. If these models were simply based on first principles, then such applications should merely require changes in input data such as solar insolation, rotation rate, axial tilt, atmospheric pressure and abundances, radiative time constants, dust loading, and various boundary conditions such as the presence or absence of an ocean and surface topography. In reality terrestrial codes, as written, do not work with such altered conditions because of the many simplifications and hard coded assumptions that are exposed when such efforts are made. Exposing and overcoming these limitations of terrestrial GCMs can also help to improve the ability to accurately predict future climate on Earth. (e.g. [9] [10, 11] [12]).

Table 1. Proposed Comparative Climatology Research Program

Proposed Comparative Climatology Research Program	M1	M2	M3	V1	V2	V3
Identifying the responses to short and long-term changes in solar forcing on Venus, Mars and Earth (uncovering responses to the faint young sun, understanding the role of solar forcing in recent climate changes, and predicting future climate under the bright aging sun) [13] [14] [15].	A B	B	A B	1	1 4	1 2 3
Studying the influence of clouds on radiative balance, including microphysics, cloud morphology, dynamics and cloud coverage on Venus, Mars and Earth. (e.g. [16] [17] [18] [19] [20, 21] [22] [23].		A C			3 4	1
Elucidating the role of volcano-climate interactions on Venus, Mars and Earth. [24] [25].	A B	B	A B	2	1,2 3,4	1 3
Studying the role of dust in climate stability on Mars & comparing to the effects of volcanic, impact, industrial and 'nuclear winter' aerosols on Earth (e.g.[26] [27] [28] [29] [30] [31]).	A B	A B				
Comparing the role of sulfuric acid clouds and hazes on Venus, Earth and early Mars (e.g. [32] [33] [34] [35] [36], [37]).	A B	B	A	1 3	1 3 4	1 3
Studying complex nonlinear global systems theory through Venus, Mars and Earth climate feedbacks.	B	A,B C	A B	2	3 4	1,2 3
Contrasting the role of water in the terrestrial planets, including climate, geology (rheology and composition), plate tectonics, and interior dynamics, structure, and habitability	A B C	A B C	A B	1 2 3	1 2	1 2 3
Modeling Venus as an extreme case of global warming [38] [39] [40].				1,2 3		1,2 3
Refining the history of the runaway greenhouse on Venus and comparing to worst case scenarios of anthropogenic global warming on Earth (e.g. "The Venus Syndrome" in [41]).				1	1 3 4	1
Developing fast, accurate radiative transfer models that would be valid for dense CO_2-H_2O atmospheres, including Venus and early Earth/Mars, to improve upon past 1-D calculations and include in 3-D GCMs.	A B	B		1	4	1 2
Studying the role of obliquity cycles in the climate histories of Mars and Earth.	A B	A,B C	A			
Validating techniques and models used for terrestrial climate predictions, including testing for imbedded assumptions, implicit simplifications, or vestigial "black box code" in current Earth climate models.		A B C			4	1
Measuring and modeling the abundances and isotopic ratios of noble gases to understand how similar or diverse were the original states of Venus, Earth and Mars and the coupled evolution of their interiors and atmospheres.		B	B	1 2 3	1 2 3 4	2 3
Measuring and modeling the stable isotopes of C, H, O, S and N as tracers of atmospheric sources and sinks, and as markers of potential ancient biospheres.	A B C	A B C	A B	1 2 3	1,2 3,4	2 3
Comparing the internal, tectonic and volcanic evolution of Venus, Earth and Mars as functions, size, composition and interaction with evolving atmospheres.		B	A B	1 2	3	1 2 3
Exploring the implications of Venusian and Martian climatic and tectonic evolution for the future of Earth.		B	A B	1 2	2 3	1 3

Insights into terrestrial dynamics can come from applying theory and models developed for understanding terrestrial dynamics to extraterrestrial atmospheres. Similarly, important insights into terrestrial atmospheric chemistry have been gained from studying the chemistry of our planetary neighbors. One important historical example of this is the application of models developed to study the role of chlorine in catalytically destroying oxygen compounds in the upper atmosphere of Venus to the problem of modeling the role of industrially produced chloroflourocarbons in eroding stratospheric ozone on Earth [42] [43].

Our understanding of, and ability to model, both dynamics and chemistry in the atmospheres of our neighboring planets are currently limited largely by limitations on the quality and spatial and temporal density of available data sets. Any successful long term program to increase understanding in these areas will require new missions to improve the quality and quantity of data. Research in comparative planetary dynamics and chemistry should focus on the science described in Table 2, with notations indicating which objectives in each of the MEPAG Goals (M1, M2, M3) [7] and VEXAG Goals (V1,V2, V3) [8]documents are addressed.

Table 2. Comparative Climatology: Dynamics and Chemistry

Comparative Climatology: Dynamics and Chemistry	M1	M2	M3	V1	V2	V3
Explaining Venus and Mars global circulation within the theoretical framework of modeling techniques developed for terrestrial GCMs.		A C			4	1
Studying the limitations of terrestrial GCMs revealed by these modeling programs.		A C			4	1
Studying atmospheric angular momentum and exchange with solid planet angular momentum on Venus and Earth, including, for example, ENSO-connected variations of Earth's rotation period.					4	1
Comparing Venus and Mars dynamical phenomena to Earth stratospheric Quasi-Biennial oscillation. (e.g. [44]).		A C			4	1
Characterize vorticity and storm morphology on Venus and Mars and comparing to Earth (e.g. [45]).		A C			4	1
Comparing the chemistry and dynamics of Venus and Mars middle atmospheres to Earth's middle atmosphere.		A			4	1
Comparing the photochemistry of Cl, O, and S on Venus, Mars and Earth.		A B			4	1
Characterizing Venus and Earth polar vortices.					4	1

Space Physics

The interaction of the uppermost atmospheres of each terrestrial planet with the space environment and the radiation and particle fluxes from the Sun is different, depending on the thickness and composition of the atmosphere, the strength of gravity and resulting escape velocity, the presence or absence, morphology and strength of an intrinsic magnetic field, and distance from the sun. The full range of these interactions and their varied responses to changes in the sun over different timescales provides valuable context for understanding sun-Earth interactions and their role in past, present and future climate change. Research in comparative planetary space physics should focus on the science described in Table 3, with notations indicating which objectives in each of the MEPAG Goals (M1, M2, M3) [7] and VEXAG Goals (V1,V2, V3) [8] documents are addressed.

Table 3. Comparative Climatology: Space Physics

Comparative Climatology: Space Physics	M1	M2	M3	V1	V2	V3
Studying the structures and variability of planetary magnetic fields and improving dynamo theories of field generation (e.g. [46]).			B	1	2	3
Modeling atmospheric escape on Venus, Mars and Earth, including present day escape and fractionations, and those in the early solar system under the influence of enhanced XUV and solar wind (e.g. [47] [48] [49, 50]).	A	B	B	1 3	1 4	1 2
Comparing the solar cycle responses of the upper atmospheres, exospheric escape fluxes and climates on all three planets.		A		1 3	1 4	1 2
Characterizing the space weather environments and the upper atmospheres of each of the planets (e.g. [51] [52] [53] [54]).		A		1 3	1 4	1 2
Using Venus and Mars as analogs for Earth during future and past magnetic field reversals.			A B	1	2	3

Recommendations

1) Scientific goals for the exploration of Mars and Venus are well defined in [7] and [8] and should be pursued by a diverse program of Discovery, New Frontiers, and Flagship spacecraft missions to both these planets.
2) Observations which will facilitate improved comparative climate modeling – in particular long term, high resolution observations of the upper, middle and lower atmospheres, should be a very high priority for missions to Venus and Mars in the coming decade.
3) To fully take advantage of the valuable research opportunities in this field which might otherwise "fall through the cracks" of separate programs organized by discipline or class of planetary object, NASA should fund a new program of Comparative Planetary Climate Research.
4) NASA's new Mars Climate Modeling Center should be expanded to a Comparative Planetary Meteorology Modeling Center, to allow for the important insights that only a program of comparative modeling including Venus, Earth (and ultimately Titan) GCMs and comparative climate investigations can produce. This center will also prove to be of great importance to modeling and interpreting observations of extrasolar terrestrial planets which are expected to become available in the coming decade.

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