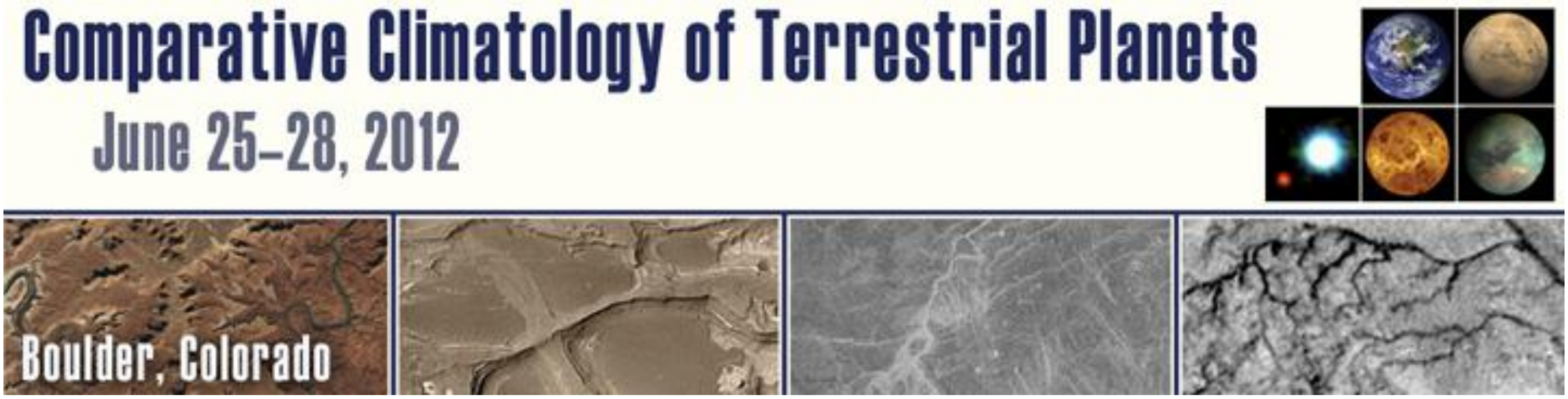

Executive Summary

The *Comparative Climatology of Terrestrial Planets* (CCTP) was convened by scientists from the planetary and Earth sciences as well as heliophysics and astrophysics. This multidisciplinary approach caught the interest of a wide range of scientists, bringing them together for discussions that resulted in cross fertilization between these fields. Indeed, CCTP, which was supported by NASA's Science Mission Directorate, was the first conference to be jointly convened and funded by all four science divisions and NASA's Chief Scientist.

The *Comparative Climatology of Terrestrial Planets* conference began on June 25, 2012 in Boulder, Colorado, and was attended by more than 120 scientists. The purpose of the conference was to identify and explore physical and chemical climate processes that are shared among rocky planets with atmospheres, in order to advance scientific progress through detailed comparisons. To this end, invited speakers and poster contributors were asked to present results on investigations that rely on comparisons between Earth, Mars, Venus, Titan, and terrestrial planets around other stars. The conference consisted of 40 invited, 30 minute talks, 60 poster presentations, and three panel discussions. An edited volume, *Comparative Climatology of Terrestrial Planets*, to be published by the University of Arizona Press' Space Science Series, is in preparation and will become available in the autumn of 2013.

'Climatology' in the context of this meeting means the full range of planetary process that affect the climates of terrestrial worlds. Besides the obvious comparisons of the energy balance of planetary atmospheres and climate forcing by the Sun or parent star, presenters discussed results of comparative investigations in photochemistry, clouds and aerosols, exospheric processes, magnetic fields, surface-atmosphere interactions, atmospheric dynamics, geology, mantle convection, and impacts. What was notable was the wide range of scientific problems that can benefit from insights generated by comparing similar processes in different planetary contexts.

Purpose

The purpose of comparative climatology is to develop an understanding of the most fundamental rules that govern planetary climates. Foremost, the observation of similar processes on two or more planets permits a comparison of physical laws operating in different contexts. Mathematical models that simulate the chemistry and physics of climate can be verified and their limits understood by comparing the outcomes of numerical experiments for different planets. Where numerical models fail to explain observations, a comparison of the physics and chemistry operating under different conditions offers an opportunity to fundamentally improve the predictive power of these models.

Comparative climatology has the potential to improve the fundamental understanding and mathematical treatment of climate processes on Earth, Venus, Mars and Titan. However, it is also extremely useful for interpreting the growing data on planets around other stars. To the extent that improved understanding leads to a general theory of planetary climate, it will be possible to more accurately envision and model the atmospheres of terrestrial exoplanets. As the observational data become more accurate and diverse, it may eventually be possible to predict whether any given rocky planet around another star is habitable.

The CCTP conference showed that there is a recognized need for a comparative cross-disciplinary approach to understanding terrestrial planet climates, and the ability of Earth to support life. We have outlined specific focus areas and strategies that hold the potential for such an approach to solve complex problems in climate studies. Many consensus findings were culled specifically to address those which, by their interdisciplinary nature, might not reach their full potential under funding from existing specific SMD areas.

Relationship to the 2010 SMD Science Plan and NASA's 2011 Strategic Plan

Comparative climatology is a new way to investigate the Science Questions of SMD's 2010 Science Plan and to meet its Science Objectives, as summarized in its Appendix 1. Progress in meeting all four of the Science Goals can be made, particularly where they overlap and require an interdisciplinary perspective. For example, the frontiers of climate research are at or near the boundaries of the existing disciplinary structure of Research and Analysis programs at NASA. Comparative Climatology attempts to bridge some of those gaps with a common theme of understanding terrestrial climate systems. Two of the Earth Science Questions, *What are the sources of change in the Earth system and their magnitudes and trends (Understand)*, and *How will the Earth system change in the future? (Predict)* can benefit from the methods of comparative climatology. Of the Earth Science Area Objectives, Objectives 1, 5, and 6 are multidisciplinary in nature and amenable to progress by comparing physical and chemical processes on different planets. One of the Heliophysics Science Questions can be addressed: *How do the Earth and Heliosphere respond?*, and Heliophysics Objectives 1 and 2 can be met through comparative climatology. All of the Planetary Science Questions and all five of the Planetary Science Objectives can best be addressed through comparative climatology. In Astrophysics, the Science Question, *What are the characteristics of planetary systems orbiting other stars, and do they harbor life?* is fundamentally a comparative question, and Astrophysics Science Objectives 2 and 3 will ultimately be met with the involvement of comparative climatology.

The execution of NASA's mission is discussed in the 2011 Strategic Plan. Space and Earth exploration at NASA are highly mature, and the science questions facing society are complex and evolving. Much of the basic understanding of climate was acquired decades ago, and the science problems to be solved are difficult and complex. Comparative Climatology is the kind of 'out-of-the-box' thinking that is required to make progress on the most difficult scientific issues. For this reason, the interdisciplinary nature of comparative climatology makes it highly relevant to NASA's top level strategic goals. Specifically, comparative climatology will figure in meeting NASA's Strategic Goals 1,2,5, and 6.

Recommended Next Steps

1. Maintain an ad-hoc CCTP steering committee.
2. CCTP steering committee will work with Analysis Groups (AGs) and other committees that report to the NASA Advisory Council.
3. Publish University of Arizona book, *Comparative Climatology of Terrestrial Planets*, Fall 2013.
4. Exploit unique opportunities in comparative climatology to interest and excite the public and students from a different perspective (e.g. FameLab, Earth & Planetary science summer school programs).
5. Create a new Comparative Climatology ROSES element to tackle how terrestrial planetary climates work. This would fund interdisciplinary PI-led projects that must have a comparative aspect. They could include Earth-planet comparisons, exoplanets, and planet-star interactions, for example. Non terrestrial planet processes should be included if they have relevance to terrestrial climate problems.
6. There is a need for long-term, continuous, observations/measurements of solar system terrestrial planets. CCTP can move forward with NASA's continuing support for observations of solar system planets using orbiting telescopes, high altitude balloons, and sounding rockets.
7. Investigate the possibility of a joint interdisciplinary comparative climatology program between NASA SMD and the NSF.
8. Organize and sponsor the follow-up CCTP2 meeting in 2015.

Future Possibilities

1. Funding of small interdisciplinary working groups with 10-15 Co-Is. A relevant model is the Swiss International Space Science Institute (ISSI). This program mainly funds travel to meetings for team members with individual science funded through existing programs.
2. Create an Interplanetary Climate Model Intercomparison Program (ICMIP) for comparing model results and for helping create a modular infrastructure for modeling planetary climates with a unified interface.

Key Future Science Focus Areas

- Improve the microphysics and chemistry of cloud and aerosol modeling, and their radiative effects in Earth and planetary GCMs. This would include a more fundamental understanding of cloud condensation nuclei, particle shapes, dust, convection and advection.
- Develop standard comparisons and testing of components of Earth and planetary GCMs through a formal intercomparison project (see ICMIP, Future Possibilities point 2).
- Laboratory-driven acquisition of spectral line data relevant to planetary and exoplanetary environments is needed. This includes laboratory studies of temperature regions that have not typically been funded, i.e. between 500 and 3000 K. Spectroscopic data in the thermal IR, near IR, and visible wavelength regions, as well as UV cross sections are fundamental for interpreting ground and space-based telescopic data of exoplanet atmospheres.
- Laboratory studies of gas phase and heterogeneous reaction thermodynamics and kinetics in the temperature range of 500 to 3000 K are needed for the understanding of processes occurring in the atmospheres, clouds, and at the surface of exoplanets. Reactions of sulfur gas species in particular under these conditions are relevant.

- Common physical data repositories, such as the Virtual Atomic and Molecular Data Centre (VAMDC), should be utilized as a standardized framework for model parameterizations and as a means to identify physical data gaps or needs
- Long term continuous measurement of the Earth's albedo is critical for Earth climate modeling.
- Long term continuous monitoring of the albedos of Mars, Venus, and Titan would provide the most fundamental data for testing of planetary climate models.
- The impact of solar flares on the Earth and inner solar system planets, and the impact of stellar flares on terrestrial exoplanet atmospheres should be studied. The habitability of exoplanets around stars that are more active than the sun needs to be understood, since these stars are far more numerous than G-type (i.e. solar type) stars.
- The role of planetary magnetic fields on the long term evolution of planetary climate is poorly understood. Comparative studies of magnetospheres, ionospheres, and thermospheres, are needed.
- Transit and occultation observations of the Earth and Venus as analogs to exoplanet observations are extremely revealing. The high fidelity understanding of the atmospheres of these two planets will enable more informed interpretation of transit and occultation data of exoplanets taken at different phase angles.
- The climates of terrestrial planets are largely influenced by volatiles that undergo phase changes and transport in these environments. Comparative studies of volatile budgets and their role in the climates of terrestrial planets are necessary for a more fundamental understanding of climate evolution.
- Volatiles in terrestrial planets are in part responsible for the transport of heat, atmospheric dynamics, clouds, geology, and even plate tectonics. Theories of the role of volatiles in the evolution of all aspects of climate on terrestrial planets can be placed on a more fundamental footing by comparing processes on two or more planets.
- Earth climate models include the interaction of the atmosphere, ocean, land surfaces, and biosphere. The role of interior processes such as mantle convection and tectonic plate subduction are less well understood. Climate models for terrestrial planets, including terrestrial exoplanets should study the chemical and physical interactions between the interior, surface, and atmosphere.
- Large scale changes in climate could be accompanied by perturbations in surface pressure. Evidence for this kind of change is seen on Mars and possibly on Venus. The effects of surface pressure on past climates of Earth and terrestrial planets require investigation.
- Impacts of asteroids and comets are known to have caused changes in the Earth's climate. Because impacts, both large and small, are experienced by all the inner planets and the moon, their effects on climate are best studied through comparative studies.
- Changes in atmospheric composition are recorded in the stable isotopes of the atmosphere and surface. Studying these effects on all the terrestrial planets will enable a more general understanding of the processes at work in modifying atmospheric composition over time.
- The Earth, Mars, Venus and Titan are only four examples of terrestrial planets that most likely number in the billions in the Milky Way galaxy. Observations and modeling of exoplanet atmospheres, in increasing detail, will be required for a more general and powerful understanding of planetary climate.