WATER AND CLIMATE ON THE TERRESTRIAL PLANETS, AND IMPLICATIONS FOR LIFE ELSEWHERE. B. M. Jakosky\textsuperscript{1} and Roger J. Phillips\textsuperscript{2}. \textsuperscript{1}Laboratory for Atmospheric and Space Physics and Dept. of Geological Sciences, Univ. of Colorado, Boulder, CO 80309-0392, email bruce.jakosky@lasp.colorado.edu, and \textsuperscript{2}Dept. of Earth and Planetary Sciences, Washington University, St. Louis, MO 63130.

Introduction. We do not at present understand how rocky planets work. This makes it very difficult to try to extrapolate from our solar system to Earth-like planets around other stars. In particular, Earth, Venus, and Mars are three examples of terrestrial planets in our solar system that have substantial atmospheres that have interacted with the surface and interior, that have or likely have had liquid water at the surface at some time, and that have undergone climate change over the last four billion years. The role that the atmosphere has played in their histories is very different for each of these planets. The nature of the climate and of climate change, including both the processes involved and the end results, is very different. And, the nature of interactions between the atmosphere and the interior, whether by outgassing, ingassing, or a combination, is very different.

We wish to examine the histories of the terrestrial planets in our solar system as a way of understanding general issues about how planets work and what the interactions are between the atmosphere and climate on the one hand and the surface and interior on the other hand. Remarkably, nature has given us an excellent set of natural experiments in these three planets that elucidate the roles of different processes. The results will help us to understand the relationship between planetary evolution and the boundary constraints on planets such as size, distance from star, nature of tectonic and geological processes, and so on. In turn, this will feed back to understanding the controls on the behavior and history of the atmosphere and climate, the history of water, and the potential for life to originate or to exist for long periods.

Earth. We know the most about the Earth and can most convincingly discuss the connections between the atmosphere and interior. Climate is controlled by the presence of life (and the consequent stripping out of C from CO\textsubscript{2} to leave an O\textsubscript{2}-rich atmosphere), the presence of a hydrological cycle and an ocean (and the resulting ability to remove CO\textsubscript{2} from the atmosphere at a rate that depends on a wide variety of processes), and the occurrence of global-scale plate tectonics (which provide a means by which sediments can be injected back into the upper mantle and by which, when subducted, the entrained volatiles can be released back into the atmosphere).

The combination of processes leads to a coupled upper-atmosphere/atmosphere/surface/interior system that appears to be very efficient at regulating surface temperature in a manner that allows temperatures to be moderate and liquid water to remain stable at the surface. These characteristics have allowed liquid water to have been present at the Earth’s surface since prior to 4 billion years ago and life to have existed continuously since about that same time. Major climate variations, such as the warm Cretaceous epoch, can be understood in terms of variations in the rate of creation and subduction of oceanic plates, along with non-steady-state aspects of a complex, non-linear system.

Venus. Venus differs from the Earth by a small amount in mass and size, by being closer to the Sun, by having no global-scale plate tectonics, by having a thick atmosphere consisting predominantly of CO\textsubscript{2}, and by having very little water in the atmosphere or, presumably, in the interior. The difficult part is separating out cause and effect in this complicated natural experiment. The gases are present in the atmosphere because they are not stable in other forms on the surface. The water inventory is small presumably because of loss of substantial quantities of water to space (as evidenced by the enhanced D/H ratio in the atmosphere). Presumably, Venus has experienced a runaway greenhouse, as a consequence of which most of the water that has been lost to space and all of the CO\textsubscript{2} now resides in the atmosphere.

Water and other gases still can be released from the interior, despite the absence of plate tectonics, as a result of volcanism (for which there is evidence over the last billion years). However, the absence of liquid water and the unstable nature of sediments that could contain water or CO\textsubscript{2} on the surface preclude the removal of volatiles into a surface sink; the absence of global-scale plate tectonics precludes injection back into the mantle, if anything could reside on the surface. Ironically, the absence of water to weaken lithosphere faults is probably the chief reason for the lack of plate tectonics on Venus.

Thus, while Venus appears to lie outside of the habitable zone in our solar system at present, it may have harbored life in the past. It is not clear what processes maintain its present atmospheric greenhouse and inhospitably high surface temperatures. There may be scenarios that would lead to a lessened greenhouse, but we do not understand the necessary mechanisms; e.g., the role of lithospheric recycling and the rate of volcanic outgassing.
**Mars.** Mars is half the radius and a tenth the mass of the Earth, has an atmosphere with pressure about 1/100 that of the Earth and made primarily of CO₂. It presently does not have global-scale plate tectonics nor does it provide any strong evidence that this process operated in the past (although it has been geologically active for its entire history and has local and regional tectonic activity). Despite this, it shows geomorphological evidence for having had vigorous hydrological activity both throughout its entire history and in recent times. The early atmosphere probably was thicker than the present one, in order to produce sufficient greenhouse warming to have allowed liquid water to have been more stable at the surface than it is today. Convincing evidence exists for loss of CO₂ from the early atmosphere to the crust in forming carbonate minerals, to space by ejection by impact, and to space by stripping by the solar wind; unfortunately, there is as yet insufficient data to tell us what the relative importance of each of these processes was.

Recycling of volatiles on Mars may not have been as efficient as it is on the Earth. While sediments may form from and incorporate CO₂ and water from the atmosphere, recycling of these sediments is problematic. Over much of the history of Mars, there appears to be no Earth-like plate-tectonic conveyor belt that takes sediments and thrusts them deep enough into the mantle to allow heating to release the volatiles back into the atmosphere. Volcanism can bury materials as well as provide heat, but the declining rate of volcanism over the last few billion years suggests that this would not be an efficient process.

Despite the problems, Mars appears to have had liquid water throughout its entire history—at the surface early in history, and within the crust throughout subsequent epochs and even at the present.

**Discussion and conclusions.** The emphasis on the history of water is appropriate for a discussion of the terrestrial planets. Not only does it have a direct influence on the climate and atmosphere through its radiative and physical effects, but it is an excellent indicator of the nature of the atmosphere and the status of evolutionary processes. In addition, water appears to be a necessary ingredient for an origin or a continued existence of life, and tracking the water is a legitimate way of tracking planetary habitability.

With three of the terrestrial planets in our solar system, nature has done an experiment in which the boundary conditions have been varied. Planet size, composition, volatile inventory, and distance from the Sun are different for each. These have affected the resulting history of the deep interior, the surface, the atmosphere, and the interactions with the solar wind, and have resulted in very different planetary outcomes.

Our interest in understanding whether Earth-like planets around other stars can support life requires a detailed knowledge of what makes a planet habitable and what makes a planet non-habitable. That is, we must understand the processes that control the outcome of planetary evolution and how they play out under different starting conditions. Clearly, we do not as yet understand how these processes operate in our own backyard, so that extrapolation to putative Earth-like planets elsewhere is difficult at best.

A discussion of the distribution of life in the galaxy depends on knowing what determines planetary outcomes, whether there is life elsewhere in our solar system, and how general the example of our solar system is in understanding the formation and evolution of solar systems elsewhere.