Modeling the Atmospheric Structure and Dynamics of the Martian Atmosphere. R.M. Haberle, NASA/Ames Research Center, MS 245-3, Moffett Field, CA 94035. e-mail: bhaberle@mail.arc.nasa.gov.

Introduction: Models of the general circulation and climate system of Mars have reached a high level of maturity, but observations to validate them have lacked the kind of global and temporal coverage required. However, we are now on the verge of a new era in Mars exploration as Mars Global Surveyor, and the now enroute Mars Climate Orbiter, will provide daily global coverage of the atmosphere for two Mars years. In the coming years, data from these missions will test the predictions of general circulation models (GCM's) whose results have perhaps become too accepted as truth. This talk will review what GCM's tell us about Mars, what their weaknesses are, and what the latest results imply for their future.

Models: A general circulation model uses numerical methods to solve the "primitive" equations. Broadly speaking, these equations have two parts: a "dynamical core" (adiabatic part), and a "physics package" (diabatic part). While there are many different kinds of dynamical cores, they generally give the same results. Instead, it is the physics package which has the greatest affect on a GCM's output. Included in the physics package are radiative heating, boundary layer mixing, and other subgrid scale processes. For Mars, none of these processes are as well characterized as we would like. Suspended dust particles, for example, have a major effect on the radiation field, yet their optical properties in the visible and infrared are not yet well constrained. And at the time of this writing, we do not yet have a well constrained topography data set. Topography is a major boundary condition for GCM's and the community is looking forward to MOLA results on this issue.

The General Circulation: The models tell us that the general circulation on Mars is like the Earth's in that it has Hadley cells, winter time traveling weather disturbances, and topographically generated stationary waves. Yet unlike the Earth, Mars has enormous thermal tides and a seasonal net mass flow to and from the poles that accounts for a 25% fluctuation in global mean surface pressure. According to the models, seasonal variations are much more pronounced on Mars [1]. At the solstices, the Hadley circulation is dominated by a single cross equatorial cell, while at the equinoxes two less intense cells emerge. And the winter midlatitude weather systems completely disappear in summer. But does this really happen?

Topography plays a big role. It modulates the Hadley circulation, winter traveling waves, and the thermal tides. Because of the large topographic relief of the Martian surface, the Hadley cells are longitudinally asymmetric, particularly the lower branch which funnels most of the air it transports into narrow currents along the western slopes of major topographic provinces [2]. Does this also occur on Mars? And the midlatitude winter weather systems, in the models, are stronger in the north than they are in the south. The reason appears to be related to topography: zonal asymmetries in southern hemisphere topography stabilizes the eddies [3]. Is this really the case? Are the southern hemisphere weather systems really that much weaker than their northern hemisphere counterparts?

Not only is there a pronounced hemispheric asymmetry in the strength of simulated traveling weather systems, there is also a pronounced longitudinal dependence. "Storm Zones" are simulated by the models [4]. These are regions of especially intense activity. They exist during northern winter and are found in the plains of Arcadia, Acidalia, and Utopia. Do storm zones also exit on Mars?

Topography modulates the thermal tides by inducing eastward components which can interfere with the sun-following westward modes. Zonal variations in surface properties and/or atmospheric dust loading can have a similar effect. The models suggest such an interaction is needed to explain the observed surface pressure tidal signatures [5]. If atmospheric dust is preferentially concentrated over the upland regions at northern summer solstice, the models can reproduce the observations. Does the circulation on Mars organize itself in such a way to produce such a distribution?

Of course, dust is a major driver of the circulation. Its presence increases the solar heating rates. In large amounts, such as those observed during the first year of the Viking mission, dust can broaden, deepen, and greatly intensify the Hadley circulation. This intensification is now believed to be the explanation for the so called winter "polar warming" phenomenon observed during the second global dust storm of 1977 [6]. The rising and sinking branches of an angular-momentum conserving cross-equatorial solsticial Hadley circulation are extended the poles. Adiabatic heating in the sinking branch raises polar temperatures. During such periods, does the Hadley circulation really extend from pole-to-pole?

One area where the models have great difficulty is in reproducing the temperature tidal signature of the Viking 15 micron IRTM brightness temperatures when the atmosphere is relatively clear and the surface is relatively hot (daytime during northern summer) [7]. The data suggest a temperature wave at altitude that is in phase with that at the surface; the models show a significant lag. How can this be reconciled? One suggestion is that the IRTM data are biased due to a spectral leak, and that when this corrected for, they give results more in line with the models [7]. The corrected data also move the IRTM measurements closer to the Earth-based microwave data which have generally showed a colder clearer Mars than was seen during the Viking mission. Are the IRTM data really biased during these times, or are the models simply missing something?

Coupling to the Seasonal Cycles: The present Martian climate system is often characterized in terms of the seasonal cycles of dust, CO_2, and water. These cycles are coupled by the general circulation. The strongest coupling is with the dust cycle because of the feedback between dust lifting and the intensity of the circulation. Major dust lifting events, called global dust storms, occur as the planet nears perihelion which occurs near the beginning of northern winter solstice at the present epoch. However, the observations show that such global dust storms do not occur every Mars year as was evidently the case when MGS arrived at Mars in late 1998. (A regional storm, however, was observed). What is the cause of this interannual variability?

The low thermal inertia of the Martian climate system (atmosphere and surface) render its "memory" quite short so that the general circulation should very closely repeat (statistically) from year to year. Indeed, the models do show this to be the case. Even when run in fully interactive mode (radiative feedbacks + self consistent surface lifting) they tend to repeat from year-to-year, i.e., the models have not yet produced any significant interannual variability. One possible explanation for interannual variability is that the frequency of major dust lifting events is controlled by the supply of mobile surface materials in the prime dust raising regions [8]. Thus far, the models have been run assuming an infinite supply of dust at the surface at all locations. A finite reservoir is more realistic, but is the supply that limited? Certainly the models appear capable of scouring a great amount of material, but can the real Mars wind systems strip the surface clean?

The dust cycle also feeds back onto the CO2 cycle - at least in principle it should. The dustiest time of year occurs when the north cap is growing. Hence, we expect the north cap to be darker than the south cap. This does appear to be the case for the residual caps, but we're really not certain if this is the case for the seasonal caps. According to the models, the seasonal CO2 cycle is best reproduced for seasonal cap albedos that are either the same in each hemisphere [9], or in which the north cap is actually brighter than the south cap [10]. How can this be? None of the models gives a good fit for the case where the north cap is darker than the south cap as would be expected.

Finally, the water cycle. Perhaps one of the most interesting results from GCM simulations of the water cycle is that without a regolith, the planet would become covered with ice in a matter of years - a result obviously not consistent with observations [11]. This result is based on simulations which assume a permanent source of water at the north pole, and a permanent sink at the south pole. In these simulations there is a net annual loss of water from the north pole that is not completely taken up by gains at the south pole. Instead, water accumulates in the atmosphere which eventually saturates forcing ice onto the surface. The only way to mitigate this is to include and adsorbing regolith. This reduces atmospheric humidities, and allows mass balance between the poles to be established. But is a regolith really required? Are their alternative transport scenarios that can explain the observations without invoking a regolith?

Data Assimilation: Data assimilation is a technique that combines a GCM with observations to provide a complete picture of the state of the atmosphere. Several groups will be attempting assimilation with MGS data. The main issue here is how to ingest asynoptic data into a model in a meaningful way. In principle, the data acquired by MGS can be readily assimilated. In addition to giving a more complete picture of the atmosphere, data assimilation can also provide a forecast.

Latest Results and Implications: Perhaps MGS's most important finding thus far is the extent to which aeolian processes have modified the surface. Everywhere MOC looks at the surface there is evidence for atmosphere-surface interactions, e.g., dunes. Some of these features are indicative of the present climate regime, while others appear to be the result of past climates [12]. Thus, we can look forward to having a data set that can shed light on the present as well as earlier climates.

Another nearly ubiquitous feature of MGS observations are water ice clouds. To be sure, these are thin in comparison with Earth's clouds, but they appear in many of the TES observations and seem to be everywhere. This is consistent with HST observations and the long observing sequence of microwave observations. The radiative effects of water ice clouds have been ignored in GCM's, but this will have to change if recent simulations suggesting that their nighttime cooling can be quite significant are correct. These clouds may also play a vital role in controlling the vertical distribution of dust through radiative feedback effects [13]. Thus, this is an area future GCM's must address.

TES observations of the north polar region during winter region show it to possess a strong, stable, polar vortex. The structure of this vortex is best simulated with models having a clear polar atmosphere. However, MOLA data is showing reflections off fairly high altitude clouds in the polar atmosphere which are likely to be CO2 ice clouds. If these are CO2 ice clouds, how do their dust nucleation centers get past the polar vortex? Perhaps the dust is brought in very high and gets nucleated very quickly to form the clouds. Full-up 3-D transport calculations with coupled CO2 ice cloud microphysics is needed to address this issue.

Radio occultation data from the radio science experiment appear to be confirming the existence of low level westerly jets near the subsolar point. The data show a thermal structure which from gradient wind balance produces a jet-like near-surface feature. In the models, these features form at the solstices when the rising branch of the Hadley cell is well off the equator, and angular momentum conservation spins up the westerlies as the flow progresses poleward.

A major surprise regarding the upper atmosphere has been the apparent detection from accelerometer data of a stationary zonal wave 2-3 at about the 120 km level. This feature appears in a region where models and data indicate easterly winds. Is this feature forced by topography, and if so how do waves propagate through easterlies? Present theory forbids wave propagation through easterlies. On the other hand, could it be the result of an in-situ instability? Some preliminary modeling does show strong stationary wave activity in this region - even in the presence of easterly winds. However, further analysis is needed to understand what it is and how it got there.

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