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FINAL REPORT

"Possible Dynamical Mechanisms for the Martian Polar Warming Phenomenon"

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1. Brief Summary of Research

The research performed under NAGW-727 falls into three major categories: dynamical modeling of the Martian polar warming phenomenon, studies of dust and water transport associated with a Martian polar warming, and studies of the possible effects of breaking gravity waves on the Martian atmospheric circulation. The work carried out in each of these three areas is briefly summarized below. Background material relevant to these studies has been provided in both the original research proposal and the renewal proposal for NAGW-727, and thus is not given here.

Polar Warming Dynamics

Early in the project it was decided that the dynamical studies would focus upon a planetary wave mechanism for the Martian polar warming phenomenon. The strong observational similarities to terrestrial sudden stratospheric warmings (as noted by previous investigators) had a major influence on this choice. In addition, it was decided that it would be appropriate (as well as most direct) to employ a relatively simplified model to make a preliminary examination of the viability of such a mechanism. The simplest model capable of simulating the essential aspects of a sudden polar warming as induced by vertically propagating planetary waves is a β-plane wave-mean flow model. Such a model has been utilized by several workers to study the basic dynamics of sudden stratospheric warmings. A version of this kind of model was already in hand (it had been developed and used previously in connection with another project); only relatively minor modifications were required in order to make it suitable for the polar warming studies. The model development work and the subsequent numerical studies were carried out with the assistance of Jeffery L. Hollingsworth, a Graduate Research Assistant in the Department of Atmospheric Sciences at Oregon State University.

Various numerical experiments (some 40 in number) were performed to examine a planetary wave mechanism for the Martian polar warming phenomenon. These were designed to assess the basic viability of such a mechanism and to study the dependence of it upon several important factors. The latter included the wave forcing amplitude and scale, the vertical profile of the zonal-mean flow, the strong radiative damping in the Martian atmosphere, and the nature (mechanical or thermal) of the wave forcing. A set of diagnostic calculations and associated graphical products was designed and developed to aid in the interpretation of the model simulations. This included various dynamical quantities of relevance to the so-called "transformed Eulerian mean" system. The dynamics of a sudden polar warming are simpler and more understandable in fundamental terms when viewed in this modified system, of which extensive recent use has been made in studies of the terrestrial atmosphere.

The numerical studies of a planetary wave mechanism for a Martian polar warming culminated in the preparation of a journal article, which has been published in *Icarus*. This article ("Dynamical Modeling of a Planetary Wave Mechanism for a Martian Polar Warming", J.R. Barnes and J.L. Hollingsworth - a reprint is attached to this report) presents the results of the planetary wave warming study in detail. The most important conclusion that came out of this study is that a planetary wave mechanism is indeed a very viable one for the Martian polar warming phenomenon. It is capable of producing a polar warming with the observed magnitude (more than 40°K at the pole, at the 25 km altitude level) and rapid development (one to three weeks). The wave forcing may be either mechanical (topographic) or thermal in nature, but must be of very large scale (corresponding to planetary wavenumber one). The required forcing amplitude is fairly large (but plausible) in the simplified model - and is very sensitive to the strength of the radiative damping. There are reasons to think that the necessary forcing amplitude might be smaller in a more realistic model (one incorporating spherical geometry). A final point about the results of the dynamical study is that they provide a very good opportunity for comparative planetary dynamics. Comparisons of the results obtained for Mars with previous results from terrestrial studies proved to be quite interesting, and hopefully helped to broaden our understanding of sudden stratospheric warmings on Earth.

The dynamical modeling work performed under NAGW-727 has set the stage for future efforts in this area, by establishing the basic viability of a planetary wave mechanism and by pointing out the remaining key questions and issues. Among these are the effects of latitudinal wave propagation and changes in the latitudinal structure of the zonal flow; a model with fully spherical geometry is required to properly investigate these dynamical processes. The amplitude and latitudinal structure of the wave forcing is a crucial area for further work. It should be noted that the dynamical studies of the Martian polar warming phenomenon are continuing, under a new NASA grant (NAGW-1127). They are proceeding with the development of more realistic models (incorporating spherical geometry).

Dust Transport

A major objective was to investigate the implications of the dynamical processes occurring during a Martian polar warming for the transport of dust and water into the north polar region. Such transport could be of considerable possible significance for the dust and water cycles, and could be of central importance for the question of the formation of the polar layered terrains.

In order to enable a quantitative examination of the possible transports of dust and water, a tracer transport model was developed and employed in a series of numerical experiments. This model is a β-plane wave-mean flow model, essentially analogous to the dynamical model utilized in the warming studies. It was developed to be run "off-line" from the dynamical model, reading in history tapes produced in previous simulations with that model. Thus, the transport experiments were strictly passive in nature - the transport having no feedback upon the dynamical motions. In order to allow an examination of deposition, in the case of dust transport, sedimentation and vertical mixing processes were incorporated in the transport model.

The numerical experiments performed with the transport model were primarily directed at dust transport, since dust is much more nearly a conservative tracer (apart from sedimentation and deposition) than water (vapor) is. A variety of experiments were carried out, to look at the dust transport and deposition associated with a planetary wave-induced polar warming event. The sensitivity of the transport to the initial distribution of dust, as well as to the details of the warming dynamics, was a primary area of investigation for the numerical experimentation. Experiments both with and without dust sedimentation were conducted. In the latter type of simulation, the effect of latitudinally and vertically dependent sedimentation (largest at higher latitudes and low levels) was examined with the model. Such a dependence could result from "condensation scavenging" of dust particles, a process that has been suggested as being active in the north polar region of Mars (and of importance for the formation of the polar layered terrains). Finally, several experiments aimed at water transport (in which no condensation was allowed to occur) were performed.

The chief result of the transport studies is that substantial amounts of dust, and water, could be rapidly transported to very high north polar latitudes in association with a planetary wave polar warming event - given that large quantities of these substances are present in northern low and middle latitudes during the early stages of global dust storm development. Substantial amounts of dust could be deposited in very high northern latitudes, especially if condensation scavenging is an active process. The amount of dust transported and deposited at very high polar latitudes depends strongly upon the amounts of dust "resupplied" to low and middle latitudes during a global storm, something that can only be simulated rather artificially in the simple β-plane transport model. Amounts of deposited dust corresponding to layers as thick as ≈15 μm were obtained in experiments with plausible initial optical depths and resupply source strengths. Amounts of this magnitude or larger are invoked in theories of the formation of the polar layered terrains. Very significant amounts of water could also be transported to high polar latitudes during a planetary wave polar warming event, if condensation and fall-out of large quantities of water in sub-polar regions does not take place. The very high temperatures that prevail in the polar atmosphere (except at relatively low levels) during a warming event are conducive to keeping water in the vapor phase.

While the studies of dust and water transport were focused upon a planetary wave polar warming event (in light of the results of the dynamical modeling studies), there was also consideration given to transport in a more general context. The fundamental dynamics of a warming are such as to produce poleward transport of a "tracer" (e.g., dust or water) which is initially concentrated largely equatorward of the polar region, even if the specific dynamical mechanism differs from the planetary wave one. It seems almost certain that significant quantities of dust and water are transported into the north polar region of Mars during a global dust storm polar warming event. The actual amounts of transport and deposition, and the latitudinal distribution of the deposition, are rather uncertain at this point. To the extent that the planetary wave dynamical mechanism is essentially the correct one, then the simulations carried out with the simple β-plane models should provide at least an indication of the specifics of the transport and deposition.

A paper summarizing the work on dust and water transport ("Transport of Dust into High Northern Latitudes During a Polar Warming in the Atmosphere of Mars", J.R. Barnes) is presently being prepared, and will be submitted to *Icarus* for publication. The transport research had previously led to several papers which were presented at MECA Workshops (see the Bibliography for these references; copies are attached to this report).

Gravity Wave Studies

The third major area of research conducted under NAGW-727 concerned the possible effects of breaking internal gravity waves on the circulation of the Martian atmosphere. It is known that such waves are of considerable importance for the circulation of the Earth's middle atmosphere, and they might be expected to be significant for the Martian atmosphere also - at least at relatively high altitudes, and perhaps especially in the winter hemisphere (where they should be strongly forced by flow over topography). Recent Earth-based temperature measurements of the 50-80 km region in the Martian atmosphere (obtained using heterodyne spectroscopy) have provided an indication that temperatures at high winter latitudes may be substantially in excess of radiative equilibrium. Breaking internal gravity waves could possibly act to produce such warm temperatures. They also could conceivably be of importance for the polar warming phenomenon, in which substantial warming occurs at somewhat lower levels (20-30 km) in the Martian atmosphere.

The effects of breaking gravity waves were investigated using a simple β–plane dynamical model (very similar to that employed in the polar warming studies, but without a large-scale wave), to which a gravity wave parameterization was coupled. The gravity wave parameterization employed is essentially like one previously developed and used in studies of the terrestrial middle atmosphere. It represents the effects of one or more gravity wave "modes", determining the breaking level(s) and the stresses and mixing induced above the breaking level(s). These quantities are strong functions of the zonal flow, so the coupled mean flow-gravity wave model is highly nonlinear. The model is run in a time integration mode, until a steady state is attained.

After development and testing of the gravity wave model was completed, a series of numerical experiments were performed. These were directed at the effects of breaking gravity waves in the winter hemisphere of Mars, where relatively strong westerly flow over topography should provide ample forcing (of stationary waves able to propagate in the westerly flow) and the highly statically stable atmosphere should promote vertical propagation. As noted above, Earth-based measurements indicate that temperatures in the 50-80 km region may be well above radiative equilibrium at high winter latitudes; during a polar warming event they are greatly elevated, at much lower altitudes.

The experiments with the gravity wave model have shown that breaking internal gravity waves could produce very warm temperatures in the winter polar region, between 50-80 km. For a "nominal" set of gravity wave parameter values, there is a peak warming (above radiative equilibrium) in the 60-70 km region (the gravity wave breaking level is 78 km for this case) of some 40-50°K. For this case, maximum westerly zonal winds are found at about the 45 km level. There is very little warming below 30 km. For different choices of some of the gravity wave parameters (in particular, larger amplitude and more "active" breaking) larger warming can be produced below 30 km. Relatively long wavelengths are required to produce these kind of effects, wavelengths of at least 100 km or so. Shorter waves are vertically trapped well below their breaking levels (and thus do not reach large amplitudes). It appears quite likely, based on the results obtained with the simple β-plane model, that breaking gravity waves are of substantial importance for the circulation of the wintertime Martian "middle atmosphere". Their effects may be of significance for the circulation at relatively lower levels as well. However, they do not appear to be a strong candidate mechanism for the polar warming phenomenon, as observed to occur in the 20-30 km altitude region. Changes in the zonal-mean circulation appropriate to dust storm conditions, in particular stronger thermal forcing and zonal flow, do not favor the induction of large polar warming at low levels by breaking gravity waves. Increases in sources of wave dissipation (both thermal and mechanical), that almost certainly characterize dust storm conditions, also do not favor strong low-level warming effects. Fairly large warming at lower levels can be produced in the simple gravity wave model under dust storm conditions, but very long wavelengths (as long as 1000 km) and large wave amplitudes seem to be required. It is not apparent that there are any plausible gravity wave sources having such properties.

Preparation of a manuscript summarizing the gravity wave work is commencing; it is anticipated that the paper will be submitted to *Icarus* when completed. An abstract based upon this research ("Possible Role of Breaking Gravity Waves in the Winter Circulation of the Middle Atmosphere of Mars", J.R. Barnes) was submitted for the 1987 DPS Meeting in Pasadena, and was presented as an exhibit.

2. Bibliography

1987: Dynamical modeling of a planetary wave mechanism for a Martian polar warming. *Icarus, 71, #2*, 313-334 (J.R. Barnes and J.L. Hollingsworth).

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1985: Dynamical modeling of a Martian polar warming. *Bull. Am. Astron. Soc.*, *17*, *No. 3*, 733 (J.R. Barnes and J.L. Hollingsworth).

1985: Transient baroclinic eddies in the atmospheres of Mars and Earth. *IAMAP/IAPSO Joint Assembly Abstracts*, p. 95 (J.R. Barnes).

3. Attachments

(i) Reprint of polar warming article in *Icarus*

ii) Copies of MECA papers

(iii) Copy of 1987 DPS Meeting Abstract