TWO-DIMENSIONAL SIMULATIONS OF MARTIAN MESOSCALE CIRCULATION PHENOMENA: A REVIEW AND FUTURE ROLE.

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1 Introduction and background

The University of Helsinki's 2-D Mesoscale Circulation Model (MCM) [1] was adapted for Martian conditions in early 1990s [2] to create the University of Helsinki (UH), Division of Amospheric Sciences (ATM) 2-D Mars MCM (MMCM). The model has subsequently been used and developed at both UH/ATM and Finnish Meteorological Institute (FMI), Geophysical Research (GEO) to study a number of martian mesoscale circulations, especially so-called *surface-induced* phenomena. Among the forcing and circulation types are slope and (CO_2 and H_2O) ice edge winds, winds driven by variations in albedo and thermal inertia and horizontal dust optical thickness. Influences of large-scale flows, *e.g.*, those due to polar CO_2 sublimation, have also been studied [2–5].

It is obvious, that with the 3-D mesoscale models already in research use or in implementation phase [6–9], 2-D models and modelling — with the inherent limitations — will have very different yet significant role(s) and niche(s) in the future. The purpose of this paper is to review recent work carried out with the model as well as assess its strengths, weaknesses and potentially relevant future uses.

2 Description of the model

A fairly comprehensive description of the model can be found in, *e.g.*[10], some of the key features are listed below, nevertheless.

The model has the vertical dimension and a horizontal dimension. The horizontal coordinate system is cartesian x and the vertical a terrain-following coordinate $\sigma = (p-p_t)/(p_s-p_t)$, where p_t is pressure at the fixed top level of the model grid. The grid size and extent vary from 40–120 points and 500–2000 km, $\Delta x = 2.5 - 30\ km$ in the horizontal, 20–40 points and 10–30 km with denser grid spacing (as low as 0.33 m) near the surface in the vertical.

Predicted variables are the horizontal wind components (u, v), potential temperature (Θ), ground temperature (T_g), surface pressure (p_s) and H_2O mass fraction q. T_g — a key variable for studies of surface-induced circulations — is predicted using a combination of the two-level *Force-restore* scheme for CO_2 ice-free regolith and of saturation temperature formula for CO_2 covered surfaces. An alternate multi-level *Crank-Nicholson* scheme will be added in the future.

Surface characteristics are described using — typically idealised, smooth — profiles $p(x)$, where p can be surface height/topography, albedo, thermal inertia, surface roughness or CO_2 ice fraction, and (available) mass fraction of H_2O in the surface layer. Water ice coverage is denoted not with a separate quantity, but with mass fraction, high thermal inertia and intermediate (between regolith and CO_2 ice) albedo.

Radiative transfer includes dust and H_2O in the solar, CO_2 and H_2O in the thermal part of the spectrum. Dust is described as a temporally constant quantity, which *can* be set to vary horizontally ($\tau(x)$). The model does hence not currently include dust transport features (*see* section 4.1 below).

3 Phenomena studied recently

3.1 Northern polar circulations and water transport

Most effort has been allocated to the study of surface-induced mesoscale circulations of the martian northern polar region. The mesoscale circulation regime includes several types of surface-induced forcings:

1. Slope forcing due to the elevated topography of the cap region and its interior.

2. Sea-breeze type forcings caused by contrasts and variations in ice coverage, in surface albedo and in the thermal inertia of the near-surface layers.

3. Valley flows resulting from the complexity of the polar cap topography, *e.g.*, canyons and valleys such as the Chasma Borealis.

The sloping and ice-covered topography gives rise to Antarctic-type, predominantly katabatic slope flows. These flows are modified, *e.g.*, by other mesoscale forcings — by ice edge circulations occurring above the interfaces and transition regions of ice-free regolith, H_2O ice and CO_2 ice. The patterns of these circulations vary seasonally not only due to varying insolation, but also due to the expansion and contraction of the seasonal polar cap leading to substantial variation in CO_2 ice coverage. These circulation components have been simulated both separately and in combinations with the UH/ATM 2-D MMCM at different locations along the circumference of the polar cap and at some seasons.

The larger scale sublimation and condensation flows also interact with the mesoscale circulations and obviously also correlate with the evolution of the seasonal ice cap. Sublimation/condensation flow has been included in the model and the simulations in a coarsely approximative way [4, 5, 10], but condensation flow simulations have not yet been carried out.

Valley flows as well as channeling of slope flows are expected to occur, but are inherently 3-D phenomena and can not be comprehensively simulated with a 2-D model. Some aspects of, *e.g.*, the Chasma Borealis circulation regime can, however, be investigated, as the chasm is partly almost parallel to the latitude circles. The 2-D grid has been in some of our simulations placed *across* the valley to simulate cross-sectional components of the circulations.

In all these simulations a partial water cycle and transport description has been included and has given a semi-quantitative picture of the regional water transport. This aspect of the model will be improved in the future.

3.2 Mesoscale circulations in the NetLander Hellas landing site area

Most recently a study on the circulations occurring in the northern edge of the Hellas basin using the UH/ATM 2-D MMCM has been initiated and is ongoing at the time of writing. This study is motivated by a planned *NetLander* landing site in the region. Due to the steep slope of the northern rim of the basin and *e.g.*, the condensation flow down the rim in the southern spring and winter, this area is potentially conducive to the occurrence of *downslope windstorms* [5]. Other interesting aspects to study include surface stress τ_0 generated by the local circulations and its correlations to dust lifting, as well as the extent the late-winter CO_2 ice coverage on the basin floor influences the circulation patterns in this area. Initial simulation results indicate that the influence is not observed at the planned nominal *NetLander* site at 27°S.

3.3 Advantages and disadvantages between 2-D and 3-D models

It is obvious that the 3-D models describe the real world with much greater fidelity than a 2-D model assuming semi-infinite domain in, *e.g.*, one horizontal direction. This improved realism is of course achieved at much higher computational expense: the UH/ATM 2-D MMCM simulations can currently be run in reasonable wall-clock time even on a modern laptop computer, whereas similar throughput times require at least cluster architectures or other high-performance computing platforms. Alternatively, the wall-clock times are of the order of several hours, up to days. Hence the practical possibilities of performing various kinds of sensitivity studies as well as testing of new algorithms and computational schemes are hampered and slowed by the computational expense. Consequently, the current level of achievable temporal durations and spatial resolutions are much coarser with the 3-D models.

Hence, the key advantage and provider of a niche for the 2-D model(s) is the considerably lesser computational cost. This implies and points to certain — albeit a bit more limited — tasks and roles for 2-D models in the near future. These are discussed and evaluated in section 4.

4 Future prospects

4.1 Testbed for new schemes and algorithms

The model palette available at UH/ATM and FMI/GEO includes a 1-D column boundary layer model. The model has been used extensively to study, develop and test model algorithms and schemes subsequently implemented in the 2-D MMCM and the 3-D Mars Limited Area Model (MLAM) [11–13]. The 1-D model is obviously limited to phenomena and schemes which are vertical in nature. Hence the 2-D model is a good supplementary tool for initial and pilot studies of multidimensional phenomena, such as horizontal variations and transport.

4.2 Simulation of spatial gradients and interfaces

The 2-D MMCM has been used extensively to study circulations driven or influenced by spatial gradients and interfaces, some of the types of variations are outlined in section 1. These studies have been of idealised nature and have hence provided cleaner insights into the characteristics of these phenomena, useful for interpretation of the results generated by more complex and realistic models. The 2-D MMCM remains useful in this role and the model can be adapted to study of gradients in other, so far less studied variables, *e.g.*, the surface roughness z_0.

4.3 Parameter-space mapping and pilot studies of ensemble-type approaches

Ensemble-type approaches have been and are being introduced to operational numerical weather prediction systems in the recent years. In these approaches a set of simulations with varied initial or boundary conditions is run and the forecast is derived from the set of results using, *e.g.*, statistical analyses. These approaches, however, multiply the requirements for computational resources and are in many cases prohibitively costly, even in terrestrial applications. For an introduction of the ensemble approaches, *see*, *e.g.*, the Web site (and links and references therein) of the European Centre for Medium-range Weather Forecasts (ECMWF) at `http://www.ecmwf.int/`.

For Mars research purposes the 3-D MMCMs are in the foreseeable future computationally too expensive for such statistical studies. The lesser computational cost of the 2-D MMCM in comparison to 3-D models renders the 2-D MMCM, however, a much more feasible tool for use in studies using *parameter space mapping* and *ensemble*-type approaches with reasonable set or sample sizes. Parameter space mapping would imply a set of simulations run using, *e.g.*, systematically and deterministically varied initial or boundary values of some parameters (essentially using a parameter space grid) to investigate and analyse — also with statistical methods — the domain and range of the results. Ensemble-type approach includes in addition or in stead introduction of random variations in selected parameters, creating essentially a Monte-Carlo type approach.

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