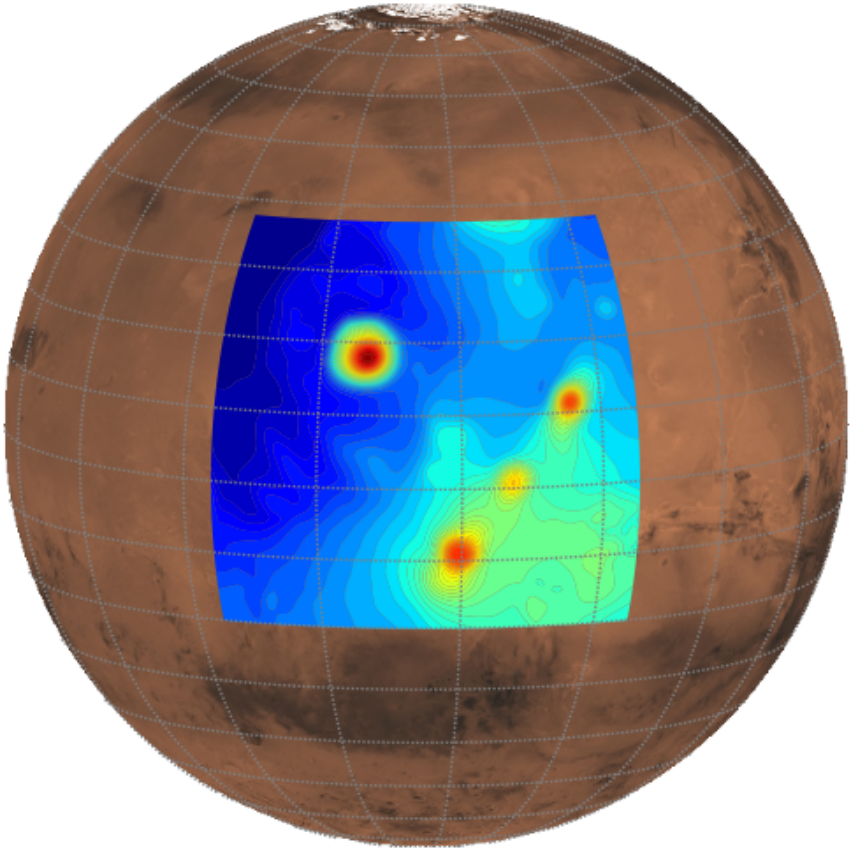
LMD Martian Mesoscale Model
User Manual



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Foreword

Welcome! This manual describes how to use the Laboratoire de Météorologie Dynamique (LMD) Martian Mesoscale Model. Many thanks for looking forward to using this model which development required countless hours of hard work! A significant part of the model development and validation have been funded by ESA and CNES which are acknowledged here.

Contact The main contact to reach at LMD to become an user of the model is Aymeric SPIGA (main developper, `aymeric.spiga@upmc.fr`). Alternative contacts at LMD for mesoscale modeling inquiries are Ehouarn MILLOUR `ehouarn.millour@lmd.jussieu.fr` or François FORGET `francois.forget@lmd.jussieu.fr`. We are open to questions and suggestions on new scientific collaborations, teaching/outreach actions or contractual proposals.

Chapter 1

What is the LMD Martian Mesoscale Model?

This chapter comprises slightly edited excerpts from *Spiga and Forget* [2009], dedicated to a general scientific and technical description of the LMD Martian Mesoscale Model, of its design and capabilities. Further details can be found in the reference *Spiga and Forget* [2009] paper and subsequent papers about mesoscale applications: e.g., *Spiga and Lewis* [2010] and *Spiga et al.* [2011]. Figure 1.1 summarizes the main points detailed in this introduction. This chapter is intended both for beginners and advanced users of the LMD Martian Mesoscale Model.

1.1 Dynamical core

The numerical integration of the atmospheric fluid dynamic equations is performed in meteorological models by the dynamical core. The LMD Martian Mesoscale Model dynamical core is based on the stable and carefully tested, fully parallellized, Advanced Research Weather Research and Forecasting model (hereinafter referred as ARW-WRF) [*Skamarock et al.*, 2005, 2008], developed for terrestrial applications at NCEP/NCAR (version 2.2.1 - November 2007).

The ARW-WRF mesoscale model integrates the fully compressible non-hydrostatic Navier-Stokes equations in a specific area of interest on the planet. Since the mesoscale models can be employed to resolve meteorological motions less than few kilometers, a scale at which the vertical wind acceleration might become comparable to the acceleration of gravity, hydrostatic balance cannot be assumed, as is usually done in General Circulation Models (GCMs).

Mass, momentum, entropy, and tracer conservation are ensured by an explicitly conservative flux-form formulation of the fundamental equations, based on mass-coupled meteorological variables (winds, potential temperature, tracers). Alternatively, these variables are recast into a reference profile plus a perturbation to reduce truncation errors [*Skamarock et al.*, 2008]. Tracer transport can be computed by an additional forward-in-time scheme based on the Piecewise Parabolic Method [*Carpenter et al.*, 1990], with positive definite and monotonic properties [*Skamarock et al.*, 2006].

In the vertical dimension, the equations are projected, as suggested by *Laprise* [1992], on terrain-following mass-based coordinates ("eta levels"): $\eta = (\pi - \pi_t)/(\pi_s - \pi_t)$ where π is the hydrostatic component of the pressure, π_s the value at the surface and π_t the (constant) upper boundary value. As shown in *Laprise* [1992] and *Janjic et al.* [2001], the choice of such vertical coordinates enables the integration of the ARW-WRF equations either in full non-hydrostatic mode

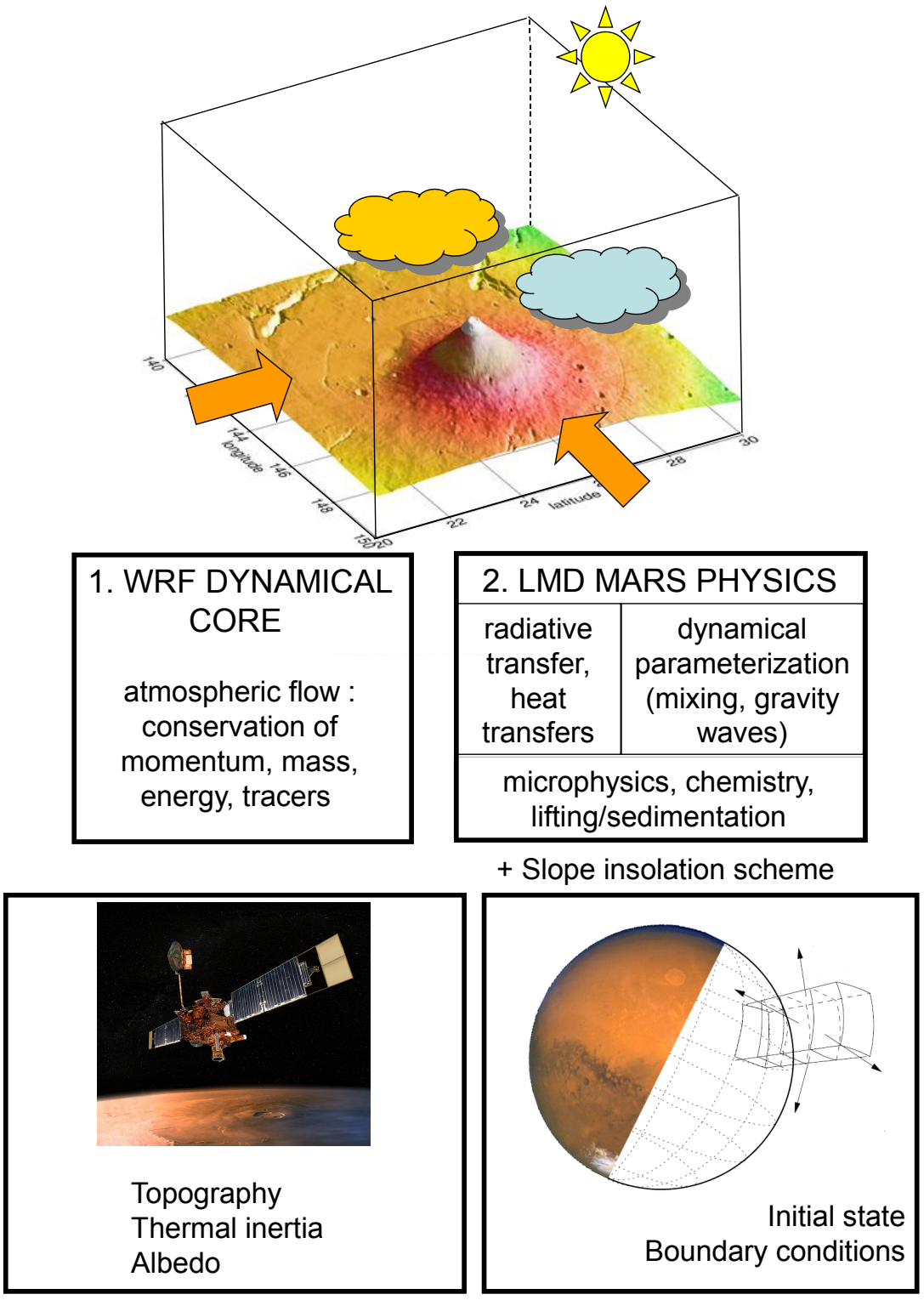

Figure 1.1: An illustration of the LMD Martian Mesoscale Model design and capabilities.

or under the hydrostatic assumption. At the top of the domain, a free relaxation condition to zero vertical velocity is imposed (gravity wave absorbing layers can be defined as well).

In the horizontal dimension, the dynamical solver is available with three possible projections on the planetary sphere: Mercator (suitable for equatorial regions), Lambert Conformal (for mid-latitudes), and Polar Stereographic (for high-latitudes). Projections are defined by map scale factors, ensuring a regular computational grid whatever the map projection should be. Polar simulations are therefore devoid of any pole singularity, an usual drawback of the GCMs that requires the use of additional filtering. The spatial discretization is an Arakawa C-grid, where normal velocities are staggered one-half grid length from the thermodynamic variables [*Arakawa*, 1966].

In the temporal dimension, a third-order Runge-Kutta integration scheme is employed for improved numerical accuracy and stability: the maximum stable Courant Friedrichs Lewy (CFL) numbers for advection are increased by a factor of two compared to the regular leapfrog integration scheme [*Skamarock et al.*, 2008]. A time-splitting integration technique is implemented to prevent the meteorologically insignificant acoustic motions from triggering numerical instabilities [*Klemp et al.*, 2007]. Additional filters for acoustic external and internal modes damp residual instabilities possibly arising in the acoustic step integration.

In the ARW-WRF Runge-Kutta time-integration scheme, while pressure gradient and divergence terms are simply second order and centered, spatial discretizations of the advection terms for momentum, scalars and geopotential are 2nd through 6th order accurate [*Wicker and Skamarock*, 2002]. Martian simulations are performed with a 5th order discretized advection. One peculiarity of the odd-order advection discretization is the inherent inclusion of a dissipation term [*Hundsdorfer et al.*, 1995] with a coefficient proportional to the Courant number.

However, as was pointed out by *Knievel et al.* [2007], this odd-ordered implicit scheme is not diffusive enough in low-wind or neutral/unstable stratification, and numerical noise in the wind fields might reach amplitudes comparable to the simulated winds. Such noise was found to be significant in the Martian case under near-surface afternoon superadiabatic conditions. The standard Martian simulations thus include the additional 6th order diffusion scheme developed by *Knievel et al.*, with a removal parameter set for Martian applications to 20% of the $2\,\Delta x$ noise in one timestep. While reducing the numerical noise near the surface to almost undiscernable amplitudes, the additional Knievel diffusion has little effect on the simulated meteorological fields.

Particular adaptations were required to use the ARW-WRF dynamical solver in the Martian environment. Physical constants, such as the acceleration of gravity and the planetary rotation rate, were converted to the Martian values. Vegetation and ocean-related variables were not used, and replaced with variables more suitable for the Martian applications (e.g., thermal inertia). Martian dates are given by the aerocentric solar longitude L_s, which indicates the position of Mars with respect to the Sun (0, 90, 180, 270 degrees are, respectively, the beginning of the northern hemisphere spring, summer, fall and winter). The terrestrial calendar was thus replaced with the LMD-GCM Martian calendar built on 669 Martian sols split in 12 "aerocentric longitude"-based months (each of them is $L_s = 30°$ long, and thus encloses an irregular number of Martian sols due to the high eccentricity of the orbit), and one hour was defined as 1/24 sol.

1.2 Martian physics

In any meteorological model, the 3D dynamical core is coupled with parameterization schemes (most often 1D) to compute at each grid point of the simulation domain the particular physics of the considered planetary environment: diabatic forcing of the atmospheric circulation (radiative transfer, soil thermal diffusion); sub-grid scale dynamical parameterizations (Planetary Boundary Layer [PBL] diffusion and mixing, convective adjustment); tracer sources and sinks (microphysical processes, chemistry, dust sedimentation and lifting). The LMD-MGCM complete physical parameterizations are interfaced with the adapted ARW-WRF dynamical core, described in the previous section, by a new "driver" that is built on the same principles as the ARW-WRF terrestrial parameterization schemes, which are all switched off for the Martian applications. Thus, the

LMD Martian Mesoscale Model shares the same comprehensive physical parameterizations as the LMD-MGCM, in order to simulate the Martian dust, CO_2, H_2O and photochemistry cycles [*Forget et al.*, 1999; *Montmessin et al.*, 2004; *Lefevre et al.*, 2004].

1.2.1 Physical parameterizations

The radiative transfer in the model accounts for CO_2 gas infrared absorption/emission [*Hourdin et al.*, 1992] and visible and infrared dust absorption, emission and diffusion [*Forget et al.*, 1998, 1999]. Description of the CO_2 condensation processes in the model can be found in *Forget et al.* [1998b]. Thermal conduction in the soil is simulated by the 11-layer soil model developed by *Hourdin et al.* [1993] for Mars (soil density and soil specific heat capacity are set as constants). Turbulent closure is based on turbulent viscosity with coefficients calculated from the "2.5-order" scheme by *Mellor and Yamada* [1982], improved by *Galperin et al.* [1988]. In the case where vertical mixing is handled in the independent 1D physical packages, the native vertical mixing schemes in the ARW-WRF dynamical core are switched off, and the most appropriate choice for explicit horizontal diffusion is the built-in ARW-WRF scheme based on horizontal deformation [*Smagorinsky*, 1963].

Recent improvements on the radiative transfer computations [*Dufresne et al.*, 2005], on the slope irradiance estimations [*Spiga and Forget*, 2008], on the dust lifting and sedimentation [*Forget et al.*, 1999b; *Newmann et al.*, 2002], on the water cycle and water ice clouds [*Montmessin et al.*, 2004], and on the photochemical species [*Lefevre et al.*, 2004], particularly ozone [*Lefevre et al.*, 2008], are also natively included in the LMD Martian Mesoscale Model. The non-local thermodynamic equilibrium (NLTE) parameterizations for thermosphere applications [*González-Galindo et al.*, 2005] as well as estimations of the atmospheric exchanges with the Martian regolith [*Böttger et al.*, 2005], are also available in the model.

Two physical parameterizations of the LMD-MGCM, specifically designed for synoptic-scale meteorological applications, are not used in the mesoscale applications.

Firstly, in the mesoscale domain, the topographical field is described with horizontal resolutions from tens of kilometers to hundreds of meters. The *Lott and Miller* [1997] subgrid-scale topographical drag parameterization and the *Miller et al.* [1989] gravity-wave drag scheme can thus be switched off, as the topographical influence on the atmospheric flow is computed by the dynamical core at the chosen mesoscale resolutions.

Secondly, in order to ensure numerical stability, and to account for subgrid-scale mixing processes insufficiently handled in the PBL scheme, it is usually necessary to modify any unstable layer with negative potential temperature gradients (an usual near-surface situation during Martian afternoons) into a neutral equivalent [*Hourdin et al.*, 1993]. As pointed out by *Rafkin* [2003b], the use of such an artificial convective adjustment scheme might be questionable in Martian atmospheric models, should they be GCMs or mesoscale models. Since numerical stability is ensured in the LMD Martian Mesoscale Model by choosing the appropriate dynamical timestep with respect to the CFL condition, and using the aforementioned ARW-WRF nominal filters and diffusion schemes, the convective adjustment scheme used in the LMD-MGCM can thus be switched off in the LMD Martian Mesoscale Model.

1.2.2 Physical timestep

Invoking physical packages often with respect to the dynamical computations was found to be necessary to accurately account for near-surface friction effects where the wind acceleration is particularly high, typically in regions of strong Martian topographically-driven circulation. In such areas, if the ratio between the physical timestep and the dynamical timestep is above ~ 5, the model predicts winds spuriously increasing with the chosen ratio and varying with the horizontal resolution. On the contrary, if this ratio is less than ~ 5, the simulated winds neither vary significantly with the chosen ratio nor with the horizontal resolution.

A ratio equal to 1 is chosen in the standard LMD Martian Mesoscale Model simulations. This choice is in conformity with the strategy adopted in the terrestrial ARW-WRF model. Besides,

computing the physical parameterizations at the same frequency as the dynamical integration is profitable to some physical parameterizations, such as the formation of clouds (which is sensitive to rapid temperature change). Note that radiative transfer computations are usually carried out less often to save computational time.

When the ratio between the physical timestep and the dynamical timestep is superior to 1, two distinct strategies could be adopted. Interestingly, we found that splitting the physical tendency in equal parts and blending it with the dynamical tendency at each dynamical timestep computation is slightly more stable (understand: allows for higher dynamical timesteps) than applying the whole physical tendency when the physical parameterizations are computed, and letting the dynamical core naturally evolve until the next physics call. However, an analysis of the simulated meteorological fields in both cases does not reveal significant differences.

1.3 Initial and boundary conditions

1.3.1 Starting state and horizontal boundaries

Mesoscale simulations can be performed in a limited domain anywhere on the planet. Thus, boundary conditions for the main meteorological fields (horizontal winds, temperature, tracers) have to be provided during the simulations, in addition to an atmospheric starting state. Idealized simulations usually require the use of periodic, symmetric or open boundary conditions, whereas real-case simulations need specified climatologies at the boundaries.

The specified boundary conditions and the atmospheric starting state are derived from previously performed $64 \times 48 \times 25$ (i.e., horizontal resolution of $5.625°$ in longitude and $3.75°$ in latitude, model top $\sim$ 80 km altitude) LMD-MGCM simulations which have reached equilibrium, typically after $\sim$ 10 simulated years. GCM results are often used every Martian hour to constrain the mesoscale model at the domain boundaries. Temporal interpolations to each mesoscale timestep and spatial interpolations on the mesoscale domain are performed from the LMD-MGCM inputs. A relaxation zone of a given width (user-defined, usually 5 grid points) is implemented at the boundaries of the ARW-WRF domain to enable both the influence of the large-scale fields on the limited area, and the development of the specific mesoscale circulation inside the domain. The interpolations and the use of a relaxation zone prevent the prescribed meteorological fields at the lateral boundaries from having sharp gradients and from triggering spurious waves or numerical instabilities (the situation where the relaxation zone crosses steep topographical gradients should however be avoided).

1.3.2 Nesting or single-domain strategy ?

The model includes one-way and two-way (or "feedback") nesting capabilities. The nested simulations feature two kinds of domains where the meteorological fields are computed: the "parent" domain, with a large geographical extent, a coarse grid resolution, and specified boundary conditions, and the "nested" domains, centered in a particular zone of interest, with a finer grid resolution, and boundary conditions provided by its parent domain.

The nesting capabilities can be used only if deemed necessary, and single-domain simulations may be the primary type of run performed.

Firstly, employing the same physical parameterizations in the mesoscale model computations and in the GCM simulations defining the boundary and initial conditions, ensures a very consistent meteorological forcing at the boundaries of the mesoscale domain. This assumption was not denied by further examination of the performed simulations: mesoscale predictions are not unrealistically departing from the LMD-MGCM prescribed fields at the boundaries, and the mesoscale influence naturally adds to the synoptic (large-scale) tendency communicated at the boundaries.

Secondly, the single-domain approach is appropriate as long as the variations of near-surface winds, pressure and temperature induced by "passing" thermal tides through the east-west boundaries are not unrealistic. This criterion is specific to Martian mesoscale modeling and was described

by *Tyler et al.* [2002]. In the various simulations performed with the LMD Martian Mesoscale Model, a likely spurious influence of the passing thermal tides was only detected in the near-surface meteorological fields calculated at the ~ 5 near-boundaries grid points. The amplitudes of the departures were negligible ($\delta T \lesssim 3$ K; $\delta u, \delta v \lesssim 5\%$) and did not require the use of domains nested inside one semi-hemispheric parent domain [*Tyler et al.*, 2002]. However, the analysis of the simulated fields at the near-boundaries grid points should be carried out with caution when choosing the single-domain approach. A practical solution to this drawback is to define a large domain, centered on the chosen area of interest, with a sufficient number of grid points (75×75 being a minimal requirement).

Thirdly, *Dimitrijevic and Laprise* [2005] showed, by the so-called "Big Brother" approach, that the single-domain approach yields unbiased results when the boundary forcing involves a minimum of $\sim 8-10$ GCM grid points. Thus, given the resolution of the GCM fields used to constrain the LMD Martian Mesoscale Model, single-domain simulations with, for instance, a horizontal resolution of 20 km shall be performed on at least 133×88 grid points. *Antic et al.* [2006] found that the "$8-10$ grid points" limit can be lowered in situations of complex topography, because the dynamical influence of these mesoscale features is responsible for the larger part of the mesoscale circulation in the domain. Such situations are rather common on Mars, and the aforementioned "minimal" grid can be of slightly smaller horizontal extent in areas such as Olympus Mons or Valles Marineris.

Thus the sizes of the simulation grids have to be chosen in order to ensure the applicability of the single-domain approach. The nesting technique is used only when defining a single domain with sufficient geographical extent would have required too many grid points to handle the computations within reasonable CPU time. For instance, with "64×48" GCM simulations as boundary conditions, the use of the single-domain strategy to model the Arsia Mons circulation at 5 km resolution imposes a simulation grid of at least 531×354 points. The nesting technique is more suitable for this kind of simulation.

1.3.3 Surface fields

Surface static data intended for the mesoscale domain are extracted from maps derived from recent spacecraft measurements: 64 pixel-per-degree (ppd) MOLA topography [*Smith et al.*, 2001], 8 ppd MGS/Thermal Emission Spectrometer (TES) albedo [*Christensen et al.*, 2001], 20 ppd TES thermal inertia [*Putzig and Mellon*, 2007]. A smoother composite thermal inertia map derived from *Palluconi and Kieffer* [1981], *Mellon et al.* [2000] and *Vasavada et al.* [2000] can be alternatively used for better continuity with LMD-MGCM simulations. Except for CO_2 ice covered areas, emissivity is set to 0.95. The roughness length z_0 is set to the constant value of 1 cm, but further versions of the model will use spatially-varying z_0 [*Hébrard et al.*, 2007]. Initial values for time-varying surface data, such as CO_2 and H_2O ice on the surface and soil temperatures, are derived from the GCM simulations. The latter initialization reduces the spin-up time for surface temperature to roughly one simulated sol.

The LMD Martian Mesoscale Model has the complete ability to simulate the dust cycle (lifting, sedimentation, transport). However, the high sensitivity of the results to the assumptions made on threshold wind stress and injection rate [*Basu et al.*, 2004] leads us to postpone these issues to future studies. Instead, similarly to the reference LMD-MGCM simulations, dust opacities are prescribed in the mesoscale model from 1999-2001 TES measurements, thought to be representative of Martian atmospheric conditions outside of planet-encircling dust storm events [*Montabone et al.*, 2006]. In the vertical dimension, as described in *Forget et al.* [1999], and in accordance with the general consensus of well-mixed dust in equilibrium with sedimentation and mixing processes [*Conrath*, 1975], dust mixing ratio is kept constant from the surface up to a given elevation $z_{\max}$ above which it rapidly declines. Both in the nominal GCM and mesoscale simulations, $z_{\max}$ as a function of areocentric longitude and latitude is calculated from the "MGS scenario" [*Forget et al.*, 2003].

1.3.4 Vertical interpolation

In the process of initialization and definition of boundary conditions, the vertical interpolation of GCM meteorological fields to the terrain-following mesoscale levels must be treated with caution. While deriving the near-surface meteorological fields from GCM inputs, one may address the problem of underlying topographical structures at fine mesoscale horizontal resolution, e.g., a deep crater that is not resolved in the coarse GCM case.

A crude extrapolation of the near-surface GCM fields to the mesoscale levels is usually acceptable for terrestrial applications. On Mars, owing to the low density and heat capacity of the Martian atmosphere, the surface temperature is to first order controlled by radiative equilibrium, and thus it is left relatively unaffected by variations of topography [e.g. *Nayvelt et al.*, 1997]. A practical consequence, which renders an extrapolation strategy particularly wrong on Mars, is that the near-surface temperature and wind fields vary much more with the distance from the surface than with the absolute altitude above the areoid (or equivalently with the pressure level). Initial tests carried out with the extrapolation strategy showed that differences between temperatures at the boundaries and temperatures computed within the mesoscale domain close to these boundaries often reach $20-30$ K near the surface. An interpolation based only on terrain-following principles solves this problem near the surface but was found to lead to numerical instabilities at higher altitudes during the mesoscale integrations.

Therefore, input meteorological data need to be recast on intermediate pressure levels P' with a low level smooth transition from terrain-following levels (for the near-surface environment) to constant pressure levels (for the free atmosphere at higher altitude). We thus have $\mathrm{P}'(x,y) = \alpha + \beta\,\mathrm{P}_s(x,y)$, P_s being the surface pressure at the resolution of the GCM simulations. To ensure a realistic low-level transition, the technique described in *Millour et al.* [2008], based on high-resolution GCM results, is employed to calculate the P' levels. The mesoscale surface pressure field p_s is an input parameter of the method, since the near-surface adiabatic cooling over mountains and warming within craters are taken into account. Note that $p_s(x,y)$ is calculated from $\mathrm{P}_s(x,y)$ on the basis of the high-resolution topography of the mesoscale domain $z(x,y)$ by

$$p_s(x,y) = \mathrm{P}_s(x,y)\, e^{\frac{g\,[\mathrm{Z}(x,y)-z(x,y)]}{\mathrm{R}\,\mathrm{T}(x,y)}}$$

where $\mathrm{Z}(x,y)$ is the topography at the resolution of the GCM simulations, R the gas law constant, g the acceleration of gravity, and $\mathrm{T}(x,y)$ the temperature predicted by the GCM 1 km above the surface (see *Spiga et al.* [2007]). Without reinterpolating the data, the intermediate pressure P' levels are then simply converted into their mesoscale counterparts p' by substituting p_s for P_s in the formula $\mathrm{P}'(x,y) = \alpha + \beta\,\mathrm{P}_s(x,y)$. Finally, the built-in ARW-WRF vertical interpolation onto the final mesoscale terrain-following levels can be performed, as the problem of extrapolation is solved by the use of the intermediate pressure levels p'.

The initial atmospheric state obtained through this "hybrid" method ensures low-amplitude adjustments of the meteorological fields by the mesoscale model at the beginning of the performed simulations (i.e., in the first thousands of seconds). Furthermore, the continuity between the large-scale forcing and the mesoscale computations near the limits of the domain, as well as the numerical stability of the simulations, appear as significantly improved compared to methods either based on extrapolation (especially in areas of uneven terrains) or terrain-following interpolation.

Chapter 2

Installing the model

This chapter is meant for first time users of the LMD Martian Mesoscale Model. We describe how to install the model on your system. Experience with either the terrestrial WRF mesoscale model or the LMD Martian GCM is not absolutely required, although it would help you getting more easily through the installation process.

2.1 Prerequisites

2.1.1 General requirements

In order to install the LMD Martian Mesoscale Model, please ensure the following prerequisites:

- your computer is connected to the internet;
- you have `200 Mo` free disk space available;
- your OS is Linux [1] with a decent set of basic commmands (`sed`, `awk`, ...);
- `bash`, `m4` and `perl` are installed on your computer;
- at least one of the following Fortran compilers is installed on your computer
  - Portland Group commercial compiler `pgf90`
  - G95 free compiler [2] `g95`
  - Intel commercial compiler `ifort`
- your C compiler is `gcc` and C development libraries are included;
- `netCDF` libraries [3] have been compiled *on your system with the Fortran compiler suite you aim to use to compile the model.* Three environment variables associated with the `NETCDF` libraries must be defined with the following commands [4]:

```
declare -x NETCDF=/disk/user/netcdf
declare -x NCDFLIB=$NETCDF/lib
declare -x NCDFINC=$NETCDF/include
```

☞ If you want the environment variables to be persistent in your system, please copy the `declare` command lines spread in this user manual in your `.bashrc` or `.bash_profile`.

1. The model was also successfully compiled on MacOSX; "howto" information is available upon request but could have become obsolete on recent versions of Apple hardware and software. It is probably possible to compile the model on Windows using Cygwin but this has not been implemented nor tested. This could work, but we recommend instead to install a Linux distribution on your computer (e.g. Ubuntu, Debian, Fedora, ...).
2. Sources and binaries available on `http://www.g95.org`
3. The outputs from model computations are in netCDF format. This is a convenient self-describing file format widely used in atmospheric science and data analysis. Further information and downloads can be found in `http://www.unidata.ucar.edu/software/netcdf`.
4. All command lines proposed in this document are defined in `bash` script language

☞ You might also find useful – though not mandatory – to install on your system:

- `ncview`[5]: tool to visualize the contents of a netCDF file;
- `nco`[6]: tools to manipulate and modify netCDF files;
- `epd`[7]: the python distribution suite packaged by Enthought, including many librairies for plotting, scientific computations, data analysis...

2.1.2 Compiling the terrestrial WRF model

The LMD Martian Mesoscale Model is based on the terrestrial NCEP/NCAR ARW-WRF Mesoscale Model. As a first step towards the compilation of the Martian version, we advise you to check that the terrestrial model compiles on your computer with either `g95` or `pgf90` or `ifort`. On the ARW-WRF website `http://www.mmm.ucar.edu/wrf/users/download/get_source.html`, you will be allowed to freely download the model after a quick registration process (click on "New users"). Make sure to download the version 2.2 of the WRF model and copy the `WRFV2.2.TAR.gz` archive to your current working directory. Then please extract the model sources and configure the compilation process:

```
tar xzvf WRFV2.2.TAR.gz
cd WRFV2
./configure
```

The `configure` script analyzes your architecture and proposes you several possible compilation options. Make sure to choose the "single-threaded, no nesting" option related to either `g95` (should be option 13 on a 32 bits Linux PC) or `pgf90` (should be option 1 on a 32 bits Linux PC) or `ifort`. The next step is then to compile the WRF model by choosing the kind of simulations you would like to run. A simple and direct test consists in trying to compile the idealized case of a 2D flow impinging on a small hill:

```
./compile em_hill2d_x > log_compile 2> log_error &
```

☞ In case you encounter problems compiling the ARW-WRF model, please read documentation on the website `http://www.mmm.ucar.edu/wrf/users`, contact the WRF helpdesk or search the web for your error message. Our team will not be able to offer support for the LMD Martian Mesoscale Model if the ARW-WRF model does not compile and run on your system.

If the compilation is successful, the file `log_error` should be empty or only reporting few warnings. In the `main` folder two executables `ideal.exe` and `run.exe` should be found, which allows you to run[8] the test simulation:

```
cd test/em_hill2d_x
./ideal.exe
./wrf.exe
```

During the simulation, the time taken by the computer to perform integrations at each dynamical timestep is displayed in the standard output. The simulation should end with a message `SUCCESS COMPLETE WRF`. The model results are stored in a `wrfout` netCDF data file you might like to browse with a `NETCDF`-compliant software such as `ncview`, or read with your favorite graphical software. Once you have checked the WRF terrestrial model compiles and runs well on your system, you can delete all files related to the operations done in this section 2.1.2.

5. `http://meteora.ucsd.edu/~pierce/ncview_home_page.html`
6. `http://nco.sourceforge.net`
7. `http://www.enthought.com/products/getepd.php`. A complete version is available free of charge for students and employees at degree-granting institutions. A limited version with essential librairies is available free of charge for any user (but e.g. cartography and `netCDF` python packages are not included in this free version).
8. If you compiled the model with `g95`, `ideal.exe` will possibly complain about an error reading the namelist. Please move the line `non_hydrostatic` below the line `v_sca_adv_order` in the `namelist.input` file to solve the problem.

2.2 Main installation of the model sources

Method 1: You were given a `LMD_MM_MARS.tar.gz` archive Please set the environment variable `$MESO` to point at the directory where you will install the model, and set the environment variable `$MMM` as `$MESO/LMD_MM_MARS`. Copy the `LMD_MM_MARS.tar.gz` file in the `$MESO` directory and extract the files. Then execute the `prepare` script that would perform all installation tasks [9]:

```
declare -x MESO=/disk/user/MODELS
declare -x MMM=$MESO/LMD_MM_MARS
cp LMD_MM_MARS.tar.gz $MESO
cd $MESO
tar xzvf LMD_MM_MARS.tar.gz
cd $MESO/LMD_MM_MARS
ln -sf ./SRC/SCRIPTS/prepare .  ## not needed if script already in LMD_MM_MARS
./prepare
```

Method 2: You were given a `SVN` link `THE_LINK` *You must have Subversion (**svn**) installed on your system to follow this method.* Please use the name of our server repository combined to an `svn checkout` command to get the model sources [10]. Please also set the environment variables `$MESO` and `$MMM` as is detailed below. The first download of the model sources could be a bit long. Compared to method 1, this method 2 using `svn` would allow you to easily get the latest updates and bug fixes done on the LMD Martian Mesoscale Model by the development team [11].

```
svn checkout the_link -N the_name_of_your_local_destination_folder
cd the_name_of_your_local_destination_folder
svn update LMDZ.MARS MESOSCALE
cd MESOSCALE
declare -x MESO=$PWD  ## put absolute link in your .bashrc
declare -x MMM=$MESO/LMD_MM_MARS
    ## to get latest updates later on
    cd the_name_of_your_local_destination_folder
    svn update LMDZ.MARS MESOSCALE
    svn log | more
```

2.3 Parallel computations (optional)

Parallel computations with the Message Passing Interface (MPI) standard are supported by the LMD Martian Mesoscale Model. If you want to use this capability, you would have to add the installation of MPICH2 as a additional prerequisite. Once the installation is completed, it is required to define the environment variable `$WHERE_MPI` to point in your MPICH `bin` directory, even if you added the `$your_software_dir/MPI/mpich2-1.0.8/bin` directory to your `$PATH` variable.

☞ Here is a brief "how-to" to install MPICH2, although this surely does not replace reading carefully installation notes and choosing which installation suits best your system. Please download the current stable version of the sources (e.g. we choose here an old version `mpich2-1.0.8.tar.gz` for the sake of illustration) on the MPICH2 website `http://www.mcs.anl.gov/research/projects/mpich2` and install the MPICH2 utilities by the following commands:

```
mkdir $your_software_dir/MPI
mv mpich2-1.0.8.tar.gz $your_software_dir/MPI/
cd $your_software_dir/MPI
tar xzvf mpich2-1.0.8.tar.gz
cd mpich2-1.0.8
./configure --prefix=$PWD --with-device=ch3:nemesis > conf.log 2> conferr.log &
# please wait...
make > mk.log 2> mkerr.log &
declare -x WHERE_MPI=$your_software_dir/MPI/mpich2-1.0.8/bin
```

9. Deflate the various compressed archives contained into `LMD_MM_MARS`, download the ARW-WRF sources from the web, apply a (significant) "Martian patch" to these sources and build the structure of your `LMD_MM_MARS` directory

10. At this stage, it is essential to have registered to the WRF website (see foreword) because our server contains some part of the ARW-WRF sources.

11. If you are not interested by this feature, please replace the command line featuring `svn checkout` by the command line `svn export the_link/LMDZ.MARS the_link/MESOSCALE`

Chapter 3

Compiling the model and running a test case

This chapter is meant for first time users of the LMD Martian Mesoscale Model. We describe how to compile the program and run a test case. We start with important basics about how the model works and how it is organized.

3.1 Basics

3.1.1 Necessary steps to run a simulation

Any simulation that will be carried out with the LMD Martian Mesoscale Model comprises the five following steps. More details are given on these steps in the following chapters, but it is important at this stage to have this structure in mind.

- **Step 0** Compiling the model.
- **Step 1** Running the LMD Global Circulation Model (GCM) to provide initial and boundary conditions for the mesoscale model.
- **Step 2** Choosing the mesoscale limited-area domain of simulation. Running preprocessing programs to horizontally interpolate GCM meteorological fields and static data (topography, soil properties) to the chosen simulation domain.
- **Step 3** Running preprocessing programs to vertically interpolate GCM meteorological fields and generate the initial and boundary conditions directly used by the mesoscale model.
- **Step 4** Running the LMD Martian Mesoscale Model.

In this chapter, the general method to perform steps 0 and 4 is reviewed. Other steps are reviewed in chapter 5; here the model is compiled and run for a test case with precomputed sample files for preprocessing steps 1, 2, 3.

3.1.2 Structure of the `LMD_MM_MARS` directory

Please take the time to check the contents of the `LMD_MM_MARS` directories [1] and sub-directories through the following command lines:

```
ls $MMM ; ls $MMM/*
```

1. If you used method 2, you will probably notice that other directories than `LMD_MM_MARS` are present in `$MESO`, but those are not important at this stage.

Contents of `LMD_MM_MARS` directory:

- `makemeso`: this is the `bash` script to compile the model.
- `SRC`: this is a directory containing the model sources.
- `SIMU`: this is a directory containing scripts and files for an advanced use.
- `WPS_GEOG`: this is a directory containing static data used in step 2.

Contents of `LMD_MM_MARS/SRC` subdirectory:

- `SCRIPTS`: this is a directory containing useful `bash` scripts for installation.
- `WRFV2`: this is a directory containing main model sources (modified WRF dynamics + LMD physics in `mars_lmd*`).
- `PREP_MARS`: this is a directory containing sources for the last part of step 1.
- `WPS`: this is a directory containing sources for step 2.
- `POSTPROC`: this is a directory containing postprocessing sources.
- `PYTHON`: this is a directory containing `python`-based graphical scripts.
- `LES` and `LESnophys_`: these are directories containing sources for Large-Eddy Simulations.

Contents of `LMD_MM_MARS/SIMU` subdirectory:

- `dustopacity.def`, `namelist.input_full`, `namelist.input_minim`, `namelist.input_nests`, `namelist.input_les`, `run.def`, `namelist.wps`, `namelist.wps_les`: these are useful template files to guide you through setting up your own parameters for the LMD Martian Mesoscale Model simulations.
- `calendar`: this is a text file containing time management information in the model.
- `runmeso`: this is a `bash` script that can be used once the model and preprocessing systems are installed; it prepares and runs a mesoscale simulation by going from step 1 to 4.
- `RUN`: this is a directory containing various files and scripts useful for advanced simulations.
- `DEF`: this is a directory containing many examples of parameter files for simulations.

☞ In pre-2011 versions of the model, the contents of the various directories listed here might differ. This has probably no impact on your use of the model if you ensure the following files and directories are present in `LMD_MM_MARS`:

- `makemeso`, `prepare`, `prepare_ini`, `copy_model`
- `SRC/WRFV2`, `SRC/PREP_MARS`, `SRC/WPS`
- `SIMU/runmeso`, `SIMU/calendar`
- `WPS_GEOG`

3.2 Main compilation step

3.2.1 Description of the `makemeso` script

The `bash` script which allows you to compile the LMD Martian Mesoscale Model is `makemeso`. It is an automated script which performs the following serie of tasks:

- ask the user about compilation settings;
- retrieve some additional information about the system;
- create a directory `$MESO/LMD_MM_MARS/your_compdir` which name depends [2] on the kind of compiler you are using, on whether your system is 32 or 64 bits, on whether sequential or parallel computations are planned and on the kind of simulations (idealized or real-case);
- generate with `copy_model` a directory `your_compdir/WRFV2` with links to `SRC/WRFV2` sources [3];
- execute the WRF `configure` script with the correct options;
- tweak the resulting `configure.wrf` file to include a link towards the Martian physics and various patches and specific compilation options;
- calculate the total number of horizontal grid points handled by the LMD physics;
- duplicate LMD physical sources if nesting is activated;

2. For example, a `your_compdir` directory named `g95_32_single` is created if the user requested a `g95` compilation of the code for single-domain simulations on a 32 bits machine.

3. A note to developers: this method ensures that any change to the model sources would be propagated to all the different `your_compdir` installation folders.

- compile the LMD physical packages with the appropriate `makegcm` command and collect the compiled objects in the library `liblmd.a`;
  - ☞ This step could be a bit long, especially if you are defining more than one domain. The `makemeso` script provides you with the full path towards the text file `log_compile_phys` in which you can check for compilation progress and possible errors. In the end of the process, you might find at the end of `log_compile_phys` an error message associated to the generation of the final executable. Please do not pay attention to this, as the compilation of the LMD sources is meant to generate a library of compiled objects called `liblmd.a` instead of an executable.
- compile the modified Martian ARW-WRF solver and include the `liblmd.a` library;
  - ☞ When it is the first time the model is compiled, this step could be quite long. The `makemeso` script provides you with a `log_compile` text file where the progress of the compilation can be checked and a `log_error` text file listing errors and warnings during compilation. A list of warnings related to `grib` utilities (not used in the Martian model) may appear and have no impact on the final executables.
- change the name of the executables in agreement with the settings provided by the user.

3.2.2 Use of the `makemeso` script

To compile the model, change directory to `$MMM` and execute the `makemeso` command:

```
cd $MMM
./makemeso
```

You are asked a few questions by the `makemeso` script (see the list below) then it compiles the model for you. The script outputs a text file named `last` in which your answers to the questions are stored, which allows you to re-run the script without the "questions to the user" step through the `makemeso < last` command line. In what follows, the answers given in brackets are the ones you want to use so that you will be able to run the test case proposed in the next section.

1. **choice of compiler** [4]
1.bis (mpi-based compilation) number of processors to be used
2. **number of grid points in longitude** [5] [61]
3. **number of grid points in latitude** [61]
4. **number of vertical levels** [61]
5. **number of tracers** [1]
6. **number of domains** [1]

A key question that often arises when using the LMD Martian Mesoscale Model is: when does the model has to be recompiled? The set of questions asked by `makemeso` give some hints about this. Suppose you compiled a version of the model for a given set of parameters 1 to 6 to run a specific compilation. If you would like to run another simulation with at least one of parameters 1 to 6 subject to change, the model needs to be recompiled [6] with `makemeso` (cf. also chapter 4).

Note that the `makemeso -h` command lists the various options that can be used in the `makemeso` script. Most options should be used only by advanced users and some of them will be described in the following chapters. At this stage, the only option of `makemeso` which can be useful to you is `-f` which forces the model to be recompiled from scratch. If you already compiled the model

4. We advise you to compile the model on the same kind of system (computer + operating system + librairies) as the one you plan to use to run the model.

5. When you use parallel computations, please bear in mind that with 2 (respectively 4, 6, 8, 12, 16, 20, 24, 32, 64, 128) processors the whole domain would be separated into 1 (resp. 2, 2, 2, 3, 4, 4, 4, 4, 8, 8) tiles over the longitude direction and 2 (resp. 2, 3, 4, 4, 4, 5, 6, 8, 8, 16) tiles over the latitude direction. Thus make sure that the number of grid points minus 1 in each direction could be divided by the aforementioned number of tiles over the considered direction. For instance a 82×109 horizontal grid is compliant with the use of 12 processors.

6. This necessary recompilation each time the number of grid points, tracers and domains is modified is imposed by the LMD physics code. The WRF dynamical core alone is more flexible.

succesfully, but the model fails to compile a few days later for reasons unrelated to your operations on your system or on the model file, we recommend you to use the `-f` option in `makemeso` to try to recompile the model [7].

```
[output of makemeso -h]
# Use:
#
# makemeso                    ## basic use (real-case configuration)
#
# makemeso -d                 ## no compilation, just check the name of the compile folder
#
# makemeso -c ideal           ## idealized mode (convective cell, mountain wave, etc...)
# makemeso -c les             ## large-eddy simulations mode based on WRFV3
#
# makemeso -n                 ## do not recompile LMD physics (must have been compiled before)
#
# makemeso < last             ## basic use + skip questions [! script must have been executed at least once]
# makemeso -r < last          ## basic use + skip questions + only known config
# makemeso -nr < last         ## basic use + skip questions + only known config + no LMD phys recompile
#
# makemeso -j                 ## just compile the LMD physics
#
# makemeso -g                 ## debug mode
#
# makemeso -h                 ## display options
#
# makemeso -p                 ## with new LMD physics
#
# makemeso -f                 ## fresh start [clean -a]
#
# makemeso -s storm           ## a specific scenario, you need a corresponding mars_lmd_... (only for newphys)
#
# makemeso -x                 ## a case with no LMD physics included
```

3.3 Running a simple test case

We assume here that you had successfully compiled the model with `makemeso` at the end of the previous section and you had based your answers to the `makemeso` script on the indications in brackets. You should then find in the `your_compdir` directory the `real_x61_y61_z61_d1_t1_p1.exe` and `wrf_x61_y61_z61_d1_t1_p1.exe` executables.

In order to test the compiled executables, a ready-to-use test case (with pre-generated initial and boundary conditions) is proposed in the `LMD_MM_MARS_TESTCASE.tar.gz` archive that you can download in the following FTP site `ftp://ftp.lmd.jussieu.fr/pub/aslmd/LMD_MM_MARS_TESTCASE.tar.gz`. This test case simulates the hydrostatic atmospheric flow around Arsia Mons (Figure 3.1) during half a sol in springtime with constant thermal inertia, albedo and dust opacity [8].

To launch the test simulation, please type the following commands, replacing the `g95_32_single` directory with its corresponding value on your system. In the end, the model should run and output the computed meteorological fields in netCDF files named `wrfout*`. Feel free to browse those files with `ncview` or your favorite graphical tool to check if the simulated fields looks reasonable.

```
cp LMD_MM_MARS_TESTCASE.tar.gz $MMM
tar xzvf LMD_MM_MARS_TESTCASE.tar.gz
cd TESTCASE
ln -sf ../g95_32_single/wrf_x61_y61_z61_d1_t1_p1.exe wrf.exe
nohup wrf.exe > log_wrf &
```

7. A more extreme solution if `makemeso -f` does not solve your problem is to remove the corresponding `your_compdir` directory. See chapter 9

8. Though the simulation reproduces some reasonable features of the mesoscale circulation around Arsia Mons (e.g. slope winds), it should not be used for scientific purpose, for the number of grid points is unsufficient for single-domain simulation and the integration time is below the necessary spin-up time.

The files contained in `TESTCASE` prior to launching the simulations with the `wrf.exe` command illustrate which files are needed to perform step 4, i.e. running a LMD Martian Mesoscale Model simulation [9].

- `namelist.input`: text file containing parameters for the dynamical core
- `callphys.def`: text file containing parameters for the physics parameterizations
- `wrf.exe`: the model executable (or a link to it) as compiled by `makemeso`
- `wrfinput_d01` and `wrfbdy_d01`: data files containing initial and boundary conditions

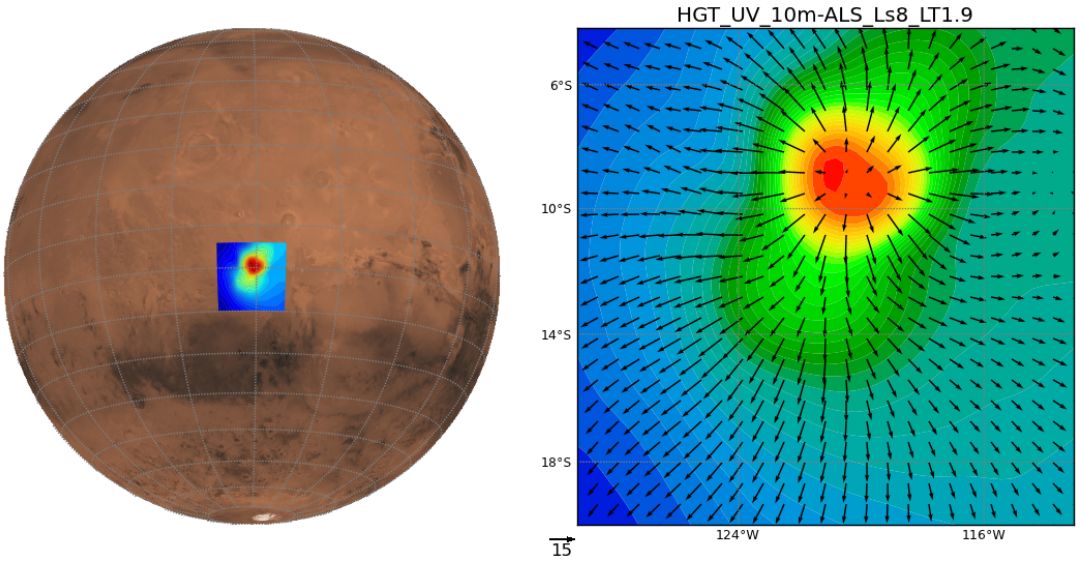

Figure 3.1: [Left plot] Simulation domain defined in the test case proposed as a demonstrator for running the LMD Martian Mesoscale Model. [Right plot] Nighttime winds predicted by the model 10 m above the surface. Both plots have been generated by command-line scripts written in `python + numpy + matplotlib` (see chapter 8).

☞ If you compiled the model using MPICH2, the command to launch a simulation is slightly different:

```
[simulation on 4 processors on 1 machine]
mpd &      # first-time only (or after a reboot)
           # NB: may request the creation of a file .mpd.conf
mpirun -np 4 wrf.exe < /dev/null &      # NB: mpirun is only a link to mpiexec
tail -20 rsl.out.000?     # to check the outputs

[simulation on 16 processors in 4 connected machines]
echo barry.lmd.jussieu.fr > ~/mpd.hosts
echo white.lmd.jussieu.fr >> ~/mpd.hosts
echo loves.lmd.jussieu.fr >> ~/mpd.hosts
echo tapas.lmd.jussieu.fr >> ~/mpd.hosts
ssh barry.lmd.jussieu.fr   # make sure that ssh to other machines
                           # is possible without authentification
mpdboot -f ~/mpd.hosts -n 4
mpdtrace
mpirun -l -np 16 wrf.exe < /dev/null &   # NB: mpirun is only a link to mpiexec
tail -20 rsl.out.00??     # to check the outputs
```

9. For the test case presented here, a file named `dustopacity.def` is needed because for the sake of simplicity of this test case, we set idealized uniform dust opacity. The file `namelist.wps` is included in the `TESTCASE` folder for further reference but not needed at this stage.

Chapter 4

Setting simulation parameters

Here we describe how to set the parameters defining a simulation with the LMD Martian Mesoscale Model. As it was detailed in 3.3, two main parameter files are needed to run the model. Many examples of such files for martian mesoscale simulations can be found in `$MMM/SIMU/DEF`:

1. The parameters related to the dynamical part of the model (dynamical core) can be set in the file `namelist.input` according to the ARW-WRF namelist formatting.
2. The parameters related to the physical part of the model (physical parameterizations) can be set in the file `callphys.def` according to the LMD-GCM formatting.

4.1 Dynamical settings

4.1.1 Description of `namelist.input`

The file `namelist.input` controls the behavior of the dynamical core in the LMD Martian Mesoscale Model. This file is organized as a Fortran namelist with explicitely named categories:

- `time_control`: set simulation start/end time and frequency of outputs;
- `domains`: set the extent and grid spacing of the simulation domain(s) in the horizontal and vertical dimension, as well as the timestep for numerical integration;
- `physics`: set parameters related to the dynamics / physics interface;
- `dynamics`: set parameters controlling dynamical integrations (accuracy, diffusion, filters);
- `bdy_control`: set parameters related to boundary conditions and relaxation rows between model integrations and boundary conditions;
- `grib2`, `fdda`, `namelist_quilt`: not relevant for Mars, only present for continuity.

Many parameters in the `namelist.input` file are optional in the Martian version [1] and their default values are defined in the file `$MMM/SRC/WRFV2/Registry/Registry.EM` [2]. The only mandatory parameters in `namelist.input` are within the `time_control` and `domains` categories. The minimal version of the `namelist.input` file corresponds to standard simulations with the model [3]:

1. E.g., in the `namelist.input` file associated to the Arsia Mons test case presented in the previous chapter, the parameter `non_hydrostatic` is set to false to assume hydrostatic equilibrium, whereas standard simulations are non-hydrostatic. Compared to the file the ARW-WRF users are familiar with (see generic description in `$MMM/SRC/WRFV2/run/README.namelist`), typical `namelist.input` files for LMD Martian Mesoscale Model simulations are much shorter.
2. Changing default values in `$MMM/SRC/WRFV2/Registry/Registry.EM` should be avoided even if you are an advanced user.
3. You may find the corresponding file in `$MMM/SIMU/namelist.input_minim`.

```
&time_control
start_year       = 2024,
start_month      = 07,
start_day        = 01,
start_hour       = 06,
end_year         = 2024,
end_month        = 07,
end_day          = 02,
end_hour         = 06,
history_interval    = 37,
frames_per_outfile  = 24,
restart          = .false.
restart_interval = 8880
io_form_history  = 2
io_form_restart  = 2
io_form_input    = 2
io_form_boundary = 2
debug_level      = 0
/

&domains
time_step   = 30
dx = 20000,
dy = 20000,
e_we   = 61,
e_sn   = 61,
e_vert = 61,
p_top_requested = 5
/

&physics
/

&dynamics
/

&bdy_control
/

&grib2
/

&fdda
/

&namelist_quilt
nio_tasks_per_group = 0,
nio_groups = 1,
/
```

A more detailed description of the `namelist.input` file is given in what follows [4], with all available (mandatory or optional) parameters to be set by the user. Each parameter is commented to understand its impact on the mesoscale simulations. Optional parameters are given with their default values. We have adopted labels to describe the specifics of each parameter with respect to the 5 steps detailed in section 3.1.1 (compilation, preprocessing, run):

- `(r)` indicates parameters which modifications imply a new compilation [5] of the model using `makemeso` (step 0);
- `(p1)`, `(p2)`, `(p3)` mention parameters which modification implies a new processing of initial and boundary conditions (see chapter 5), corresponding respectively to step 1, 2, 3; `(p1)` means the user has to carry out again steps 1 to 3 before being able to run the model at step 4; `(p2)` means the user has to carry out again steps 2 to 3 before model run at step 4;
- no label means once you have modified the parameter, you can simply start directly at step 4 (running the model);
- `(*d)` denotes dynamical parameters which modification implies non-standard simulations – please read `$MMM/SRC/WRFV2/run/README.namelist` and use with caution, i.e. if you know what you are doing; after modifying those parameters you can simply start at step 4.
- `(*)` denotes parameters not to be modified;
- `(n)` describes parameters involved when nested domains are defined (see chapter 7.1).

4. You may find the corresponding file in `$MMM/SIMU/namelist.input_full`.
5. A full recompilation using the option `makemeso -f` is not needed here.

```
&time_control
start_year       = 2024,    !! (p1) Start Martian Year (20XX for MY XX)
start_month      = 07,      !! (p1) Start Martian Month
start_day        = 01,      !! (p1) Start Martian Day
start_hour       = 06,      !! (p1) Start Martian Hour (at longitude 0)
end_year         = 2024,    !! (p1) End Martian Year (20XX for MY XX)
end_month        = 07,      !! (p1) End Martian Month
end_day          = 02,      !! (p1) End Martian Day
end_hour         = 06,      !! (p1) End Martian Hour (at longitude 0)
history_interval    = 37,   !! Frequency of outputs (37 --> 3700s = 1 Martian hour)
frames_per_outfile  = 24,   !! Size of time dimension in files
restart          = .false.  !! (*) Output restart files ?
restart_interval = 8880     !! (*) Frequency of output restart files ?
io_form_history  = 2        !! (*) Choice of NETCDF for ouputs
io_form_restart  = 2        !! (*) Choice of NETCDF for ouputs
io_form_input    = 2        !! (*) Choice of NETCDF for ouputs
io_form_boundary = 2        !! (*) Choice of NETCDF for ouputs
debug_level      = 0        !! (*) Verbose level
!!!!! OPTIONAL !!!!!!!!!!!!!!!
interval_seconds = 3700     !! (p2) Frequency of large-scale fields update (s)
input_from_file = T,        !! (n)(p2) Initialize a given domain with an input file
/

&domains
time_step   = 30            !! Dynamical timestep
dx = 20000,                 !! (p2) Horizontal resolution
dy = 20000,                 !! (p2) Horizontal resolution (should be equal to dx)
e_we   = 61,                !! (r)(p2) Number of longitude grid points
e_sn   = 61,                !! (r)(p2) Number of latitude grid points
e_vert = 61,                !! (r)(p2) Number of vertical levels
p_top_requested = 5         !! (p3) Chosen value of pressure at the top of the model
!!!!! OPTIONAL !!!!!!!!!!!!!!!
time_step_fract_num = 0     !! Additional fraction to time_step: numerator
time_step_fract_den = 1     !! Additional fraction to time_step: denominator
num_metgrid_levels = 26     !! (p1) Number of vertical levels in GCM inputs (+1)
force_sfc_in_vinterp = 8    !! (p3) Number of levels hardwired in the PBL
                            !!      NB: decrease this parameter if low p_top_requested
max_dz = 1500.              !! (p3) Maximal interval (m) between vertical levels
eta_levels = -1.            !! (p3)  Specify a list of e_vert eta levels
max_dom = 1                 !! (r)(n)(p2) Total number of domains
grid_id                = 1, !! (n)(p2) Identification of the domain
parent_id              = 0, !! (n)(p2) Associated parent domain
i_parent_start         = 0, !! (n)(p2) x-position of the bottom-left nest corner
j_parent_start         = 0, !! (n)(p2) x-position of the bottom-left nest corner
parent_grid_ratio      = 1, !! (n)(p2) Ratio of horizontal resolution parent/nest
parent_time_step_ratio = 1, !! (n) Ratio of time step parent/nest
feedback               = 0  !! (n) Define one-way nesting [0] or two-way nesting [1]
smooth_option          = 2  !! (n) Smoothing option for parent domain (feedback=1)
                            !!     0: none; 1: 1-2-1 smooth; 2: smooth-desmooth
blend_width            = 5  !! (n) Extent of blending zone for parent/nest boundaries
/

&physics
!!!!! OPTIONAL !!!!!!!!!!!!!!!
radt = 1,                   !! Ratio between physical and dynamical time step
                            !! ... 1 is recommended, >5 is not recommended
mars =  0,                  !! (r)(p2) Configuration of tracers:
                            !!        0: no tracers, 1: water vapor + ice, 2: dust
init_TI = 0.,               !! Define constant thermal inertia value
init_AL = 0.,               !! Define constant albedo value
init_U = 0.,                !! (p3) Define constant ini/bdy zonal wind value
```

```
init_V = 0.,                !! (p3) Define constant ini/bdy meridional wind value
init_WX = 0.,               !! (p3) \  Ini/bdy wind profile is everywhere equal to
init_WY = 0.,               !! (p3) /  the wind profile @ grid pt (init_WX,init_WY)
init_MU = 0.,               !! (p3) Multiply ini & bdy zonal wind by init_MU
init_MV = 0.,               !! (p3) Multiply ini & bdy meridional wind by init_MV
num_soil_layers = 10.       !! (r)(p1) Number of layers in soil model
/

&dynamics
!!!!! OPTIONAL !!!!!!!!!!!!!!!
time_step_sound = 6,        !! Ratio of time step dynamic/acoustic integration
                            !!   NB: an increase could help solve instabilities
non_hydrostatic = T,        !! Integrate in non-hydrostatic/hydrostatic mode
pd_scalar = T,              !! Positive-definite advection scheme for tracers
tiso = 140.,                !! (p3) Temperature at which base profile is isotherm
!!
diff_opt = 1                !! (*d) Diffusion option [set to 0 if GCM-like]
km_opt = 4                  !! (*d) Eddy coefficient option
diff_6th_opt = 2,           !! (*d) Knievel numerical diffusion
diff_6th_factor = 0.2,      !! (*d) Knievel numerical coeff. [set to 0.5 if GCM]
smdiv = 0.1,                !! (*d) Divergence damping
emdiv = 0.01,               !! (*d) External-mode filter for mass coord. model
epssm = 0.1,                !! (*d) Time off-centering for vertical sound waves
h_mom_adv_order = 5,        !! (*d) Horizontal momentum advection order
v_mom_adv_order = 3,        !! (*d) Vertical momentum advection order
h_sca_adv_order = 5,        !! (*d) Horizontal scalar advection order
v_sca_adv_order = 3,        !! (*d) Vertical scalar advection order
/

&bdy_control
!!!!! OPTIONAL !!!!!!!!!!!!!!!
specified = T,              !! (n)(p3) Boundary conditions specified by GCM
nested = F,                 !! (n)(p3) Boundary conditions from parent domain
periodic_x = F,             !! (p3) Periodic boundary conditions over x
periodic_y = F,             !! (p3) Periodic boundary conditions over y
open_xs = F,                !! (p3) Open boundary conditions @ western boundary
open_xe = F,                !! (p3) Open boundary conditions @ eastern boundary
open_ys = F,                !! (p3) Open boundary conditions @ southern boundary
open_ye = F,                !! (p3) Open boundary conditions @ northern boundary
spec_bdy_width = 5          !! (p3) Width of transition zone with specified=T
                            !!      (spec_bdy_width must be equal to relax_zone+1)
relax_zone = 4              !! (p3) Width of relaxation zone with specified=T
/

!!!!! DO NOT MODIFY !!!!!!!!!!
&grib2
/

&fdda
/

&namelist_quilt              !! (*)
nio_tasks_per_group = 0,     !! (*)
nio_groups = 1,              !! (*)
/                            !! (*)
!!!!! DO NOT MODIFY !!!!!!!!!!
```

4.1.2 Advice on filling `namelist.input`

Test case An interesting exercise is to analyze comparatively the `TESTCASE/namelist.input` file (cf. section 3.3) with the reference `namelist.input_full` given above, so that you could understand which settings are being made in the Arsia Mons test simulation. Then you could try to modify parameters in the `namelist.input` file and re-run the model to start getting familiar with the various settings. Given that the test case relies on pre-computed initial and boundary conditions, not all parameters can be changed in the `namelist.input` file at this stage.

Syntax Please pay attention to rigorous syntax while editing your personal `namelist.input` file to avoid reading error. If the model complains about this at runtime, start again with the available template `$MMM/SIMU/namelist.input_full`.

Time management Usually the user would like to start/end the mesoscale simulation at a given solar aerocentric longitude L_s or a given sol in the Martian year [6]. In the `namelist.input` file, start/end time is set in the form year / month / day with each month corresponding to a "slice" of 30° L_s. The file `$MMM/SIMU/calendar` (reproduced in appendix) is intended to help the user to perform the conversion prior to filling the `namelist.input` file. In the above example of `namelist.input_minim`, the simulation with the LMD Martian Mesoscale Model takes place on month 7 and day 1, which corresponds, according to the `calendar` file, to $L_s \sim 180°$. In the Arsia Mons test case, the simulation with the LMD Martian Mesoscale Model takes place on month 1 and day 17, which corresponds, according to the `calendar` file, to $L_s \sim 8°$.

4.2 Physical settings

The file `callphys.def` controls the behavior of the physical parameterizations in the LMD Martian Mesoscale Model. Modifying `callphys.def` implies to recompile the model only if the number of tracers has changed. This file is organized very similarly to the corresponding file in the LMD Martian GCM, which user manual can be found at `http://web.lmd.jussieu.fr/~forget/datagcm/user_manual.pdf`. Here are the `callphys.def` contents with typical mesoscale settings:

```
General options
~~~~~~~~~~~~~~~
tracer    (Run with or without tracer transport ?)
F
diurnal   (Diurnal cycle ?  if diurnal=F, diurnal averaged solar heating)
T
season    (Seasonal cycle ? if season=F, Ls stays constant like in "start")
T
lwrite    (want some more output on the screen ?)
F
stats     (Saving statistics in file "cumul" ?)
F
calleofdump (Saving EOF profiles in file "profiles" for Climate Database ?)
F
Dust scenario. Used if the dust is prescribed (i.e. if tracer=F or active=F)
~~~~~~~~~~~~~
iaervar  (=1 Dust opt.deph read in startfi; =2 Viking scenario; =3 MGS scenario
4        (=4 Mars Year 24 from TES assimilation)
iddist  (Dust vertical distribution: =0: old distrib. (Pollack90)
3       (=1: top set by "topdustref"; =2: Viking scenario; =3 MGS scenario )
topdustref (Dust top altitude (km). Matter only if iddist=1)
55.
```

6. Information on Martian calendars: `http://www-mars.lmd.jussieu.fr/mars/time/solar_longitude.html`.

```
Physical Parameterizations :
~~~~~~~~~~~~~~~~~~~~~~~~~~
callrad   (call radiative transfer ?)
T
callnlte (call NLTE radiative schemes ?   matter only if callrad=T)
F
callnirco2 (call CO2 NIR absorption ?   matter only if callrad=T)
T
calldifv  (call turbulent vertical diffusion ?)
T
calladj   (call convective adjustment ?)
F
callcond  (call CO2 condensation ?)
T
callsoil  (call thermal conduction in the soil ?)
T
calllott  (call Lott's gravity wave/subgrid topography scheme ?)
F
Radiative transfer options :
~~~~~~~~~~~~~~~~~~~~~~~~~~
iradia    (the rad.transfer is computed every "iradia" physical timestep)
10
callg2d   (Output of the exchange coefficient mattrix ? for diagnostic only)
F
rayleigh  (Rayleigh scattering : should be =F for now)
F
Tracer (dust water, ice and/or chemical species) options (use if tracer=T) :
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
dustbin    (DUST: Transported dust ? (if >0, uses q(1) to q(dustbin))
0
active     (DUST: Radiatively active dust ? (uses q(1) to q(dustbin))
F
doubleq    (DUST: needs dustbin=1, use mass q(1) and nb q(2) mr to predict dust size ?)
F
lifting    (DUST: lifted by GCM surface winds ?)
F
dustdevil  (DUST: lifted by dust devils ?)
F
scavenging (DUST: Scavenging by CO2 snowfall ?)
F
sedimentation (DUST/WATERICE: Gravitationnal sedimentation ?)
F
iceparty   (WATERICE: Water cycle includes water ice mixing ratio q(nqmx-1))
F
activice   (WATERICE: Radiatively active transported atmospheric water ice ?)
F
water      (WATER: Compute water cycle using q(nqmx) )
F
caps       (WATER: put the current permanent caps at both poles)
F
photochem  (PHOTOCHEMISTRY: chemical species included)
F
Thermospheric options (relevant if tracer=T) :
~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~~
callthermos  (call thermosphere ?)
F
```

```
thermoswater  (WATER: included without cycle only if water=F)
F
callconduct  (call thermal conduction ?     matter only if callthermos=T)
F
calleuv  (call EUV heating ?                matter only if callthermos=T)
F
callmolvis  (call molecular viscosity ?     matter only if callthermos=T)
F
callmoldiff  (call molecular diffusion ?    matter only if callthermos=T)
F
thermochem  (call thermospheric photochemistry ?  matter only if callthermos=T)
F
solarcondate (date for solar flux calculation: 1985 < date < 2002))
1993.4       (Solar min=1996.4 ave=1993.4 max=1990.6)
```

- ☞ In the provided example, convective adjustment `calladj`, gravity wave parameterization `calllott` and non-local thermodynamic equilibrium schemes `callnlte` are turned off, as is usually the case in typical Martian tropospheric mesoscale simulations (see chapter 1).
- ☞ `iradia` sets the frequency (in dynamical timesteps) at which the radiative computations are performed. To obtain the interval in seconds at which radiative computations are performed, one simply has to multiply `iradia` to the value of `time_step` in `namelist.input`.
- ☞ `iaervar=4` and `iddist=3` defines the standard "Mars Global Surveyor" dust scenario (see chapter 1). It is the recommended choice.

Chapter 5

Preprocessing utilities

In this chapter, we describe the installation and use of the preprocessing tools to define the domain of simulation, calculate an initial atmospheric state and prepare the boundary conditions for the chosen simulation season and time of day. This corresponds to steps 1,2,3 as defined in section 3.1.1. These operations would eventually allow you to run your own simulations at the specific season and region you are interested in, with a complete ability to modify any of the parameters in `namelist.input`, including the ones labelled with `(p1)`, `(p2)` or `(p3)`.

5.1 Installing the preprocessing utilities

The compilation operations indicated here need to be done only once on a given system.

5.1.1 Prerequisites

First and foremost, since the preprocessing utilities could involve files of quite significant sizes, it is necessary to define a directory where these files would be stored. Such a directory (e.g. `/bigdisk/user`) must be linked with the name `TMPDIR` as follows. In addition, three directories `GCMINI`, `WPSFEED`, `WRFFEED` have to be created in `$MESO/TMPDIR` as indicated below.

```
ln -sf /bigdisk/user $MESO/TMPDIR
mkdir $MESO/TMPDIR/GCMINI
mkdir $MESO/TMPDIR/WPSFEED
mkdir $MESO/TMPDIR/WRFFEED
```

A second prerequisite to the installation of the preprocessing tools is that the LMD Martian Mesoscale Model was compiled at least once. If this is not the case, please compile the model with the `makemeso` command described in section 3.2. The compilation process created an installation directory adapted to your particular choice of compiler+machine (what we named `your_compdir` in section 3.2, which could be for instance `g95_32_single`). The preprocessing tools will also be installed in this directory. Please type the following commands:

```
cd $MMM/your_compdir
ln -sf ../SRC/SCRIPTS/prepare_ini .
./prepare_ini
echo $PWD
```

5.1.2 Compiling preprocessing utilities

The script `prepare_ini` plays for the preprocessing tools a similar role as the `copy_model` with the model sources: files are simply linked to their actual location in the `SRC` folder. Once you have executed `prepare_ini`, please check that two folders were generated: `PREP_MARS` and `WPS`. In the `PREP_MARS` directory, please compile the programs `create_readmeteo.exe` and `readmeteo.exe`, using the compiler mentioned in the name of the current installation directory. In the `WPS` directory, please compile the programs `geogrid.exe` and `metgrid.exe`. Here are the useful commands:

```
cd your_compdir/PREP_MARS/
./compile_pgf [or] ./compile_g95 [or] ./compile_ifort
ls -lt create_readmeteo.exe readmeteo.exe
cd ..
cd WPS/
./configure     ## select your compiler + 'NO GRIB2' option
./compile
ls -lt geogrid.exe metgrid.exe
```

Apart from the executables just compiled, the preprocessing utilities include `real.exe`, which was compiled by the `makemeso` script along with the mesoscale model executable `wrf.exe` [1]. `real.exe` should be copied or linked in the simulation directory (e.g. `TESTCASE` for the Arsia Mons test case) to be at the same level than `namelist.input`.

5.1.3 Preparing input static data

All the static data (topography, thermal inertia, albedo) needed to initialize the model are included in the `$MMM/WPS_GEOG` directory. By default, only coarse-resolution datasets [2] are available, but the directory also contains sources and scripts to install finer resolution datasets: 32 and/or 64 pixel-per-degree (ppd) MOLA topography (`mola_topo32` and `mola_topo64`), 8 ppd MGS/Thermal Emission Spectrometer (TES) albedo (`albedo_TES`), 20 ppd TES thermal inertia (`thermal_TES`). The role of the `build_static` script is to automatically download these datasets from the web (namely PDS archives) and convert them to an acceptable format for a future use by the preprocessing utilities:

```
cd $MMM
ln -sf SRC/SCRIPTS/build_static .
./build_static
```

- ☞ Please install the `octave` free software [3] on your system to execute the `build_static` script [4].
- ☞ Building the MOLA 64ppd database can be quite long; hence this is not performed by default by the `build_static` script. If you would like to build this database, please remove the `exit` command in the script, just above the commands related to the MOLA 64ppd.
- ☞ If you do not manage to execute the `build_static` script, ready-to-use datafiles can be found in the link `ftp://ftp.lmd.jussieu.fr/pub/aslmd` and must be extracted in `$MMM/WPS_GEOG`.
- ☞ The resulting `WPS_GEOG` directory can reach a size of several hundreds of Mo. You might move such a folder in a place with more disk space available and define a link `WPS_GEOG` in `$MMM`.

1. Even though the name of the executable reads e.g. `real_x61_y61_z61_d1_t1_p1.exe`, such program is not related to the specific `makemeso` parameters – contrary to the `wrf.exe` executable. We just found that renaming the (possibly similar if the model sources were not modified) `real.exe` executable was a practical way not to confuse between executables compiled at different moments.

2. These coarse-resolution datasets correspond to the fields stored in the file `surface.nc` known by LMD-MGCM users: `http://web.lmd.jussieu.fr/~forget/datagcm/datafile/surface.nc`

3. Available at `http://www.gnu.org/software/octave`

4. Another solution is to browse into each of the directories within `WPS_GEOG/res`, download the data with the shell scripts and execute the `.m` scripts with either `octave` or the commercial software `matlab` (just replace `#` by `%`).

5.1.4 Compiling the GCM for initial and boundary conditions

The LMD Martian GCM needs to be run to compute meteorological fields that will be used as initial and boundary conditions each one or two Martian hours by the limited-area LMD Martian Mesoscale Model. Hence the LMD Martian GCM must be compiled in your system (see the LMD-MGCM user manual for further details `http://web.lmd.jussieu.fr/~forget/datagcm/user_manual.pdf`). If you did not get the model using the `svn` method, please request us to send you an archive containing the LMD-MGCM named `LMDZ.MARS.meso.tar.gz`, to be extracted in the `$MESO` directory. If you got the model using `svn`, you do not have to request this file. In the `$MESO/LMDZ.MARS` directory, a script named `compile` can be found and must be used *on the system you plan to run the mesoscale model on* to compile the GCM. The `compile` script is actually just a wrapper for the `makegcm` script which compile the GCM for you; the default `makegcm` script only works with Portland Group Fortran compiler `pgf90` but scripts to compile the model using other Fortran compilers (including `g95` or `ifort`) are also available. The following commands should yield the compilation of two executables `newstart.e` and `gcm.e`:

```
cd $MESO/LMDZ.MARS
[edit $MESO/LMDZ.MARS/libf/phymars/datafile.h & fill absolute link $MMM/WPS_GEOG]
./compile
```

The other necessary operation to prepare the LMD-MGCM for step 1 is to store a set of initial states for the LMD-MGCM to start with, based on previous typical LMD-MGCM runs having reached equilibrium after ten years of integration. A reference database can be found in the following online archive `ftp://ftp.lmd.jussieu.fr/pub/aslmd/STARTBASE_64_48_32_t2.tar.gz`. This archive must be extracted somewhere on a disk that would be accessible to the system you plan to run the mesoscale model on. A link named `startbase` towards the `STARTBASE_64_48_32_t2` directory must be created in the directory `$MESO/LMDZ.MARS/myGCM`. If those operations went well, please try the command line `echo 22 | launch_gcm` in this directory, which should launch the GCM integrations on your system.

5.2 Running the preprocessing utilities

5.2.1 General overview

When you run a simulation with `wrf.exe` (e.g. section 3.3), the program attempts to read the initial state in `wrfinput_d01` and the domain boundary conditions in `wrfbdy_d01`. The whole chain of data conversion and interpolation needed to generate those files is summarized in the diagram on Figure 5.1. Three distinct preprocessing steps are necessary to generate the final files (steps are numbered 1,2,3 as in section 3.1.1). Figure 5.1 helps to better understand the labels `(p1)`, `(p2)`, `(p3)` used to describe `namelist.input` parameters in chapter 4. For instance:

- ☞ changing the season of simulation implies to re-run the LMD Mars GCM for this specific season to prepare initial and boundary conditions for the mesoscale model. Hence e.g. `start_month` is labelled with `(p1)` because changing this in `namelist.input` requires a complete reprocessing from step 1 to step 3 to successfully launch the simulation.
- ☞ changing the number of horizontal grid points for the mesoscale domain implies to interpolate the static and GCM fields to the new domain, while no new computations on the GCM side are needed. Hence e.g. `e_we` is labelled with `(p2)` because changing this in `namelist.input` requires a reprocessing from step 2 to step 3 to successfully launch the simulation (and also for this specific parameter recompiling with `makemeso` is needed).
- ☞ changing the position of model top implies to interpolate initial and boundary conditions to the new vertical levels, while no horizontal re-interpolations are needed. Hence e.g. `p_top_requested` is labelled with `(p3)` because changing this requires a reprocessing of step 3.
- ☞ changing the timestep for dynamical integration does not require any change in initial and boundary conditions. Hence e.g. `time_step` is not labelled with `(p1)`, `(p2)` or `(p3)`.

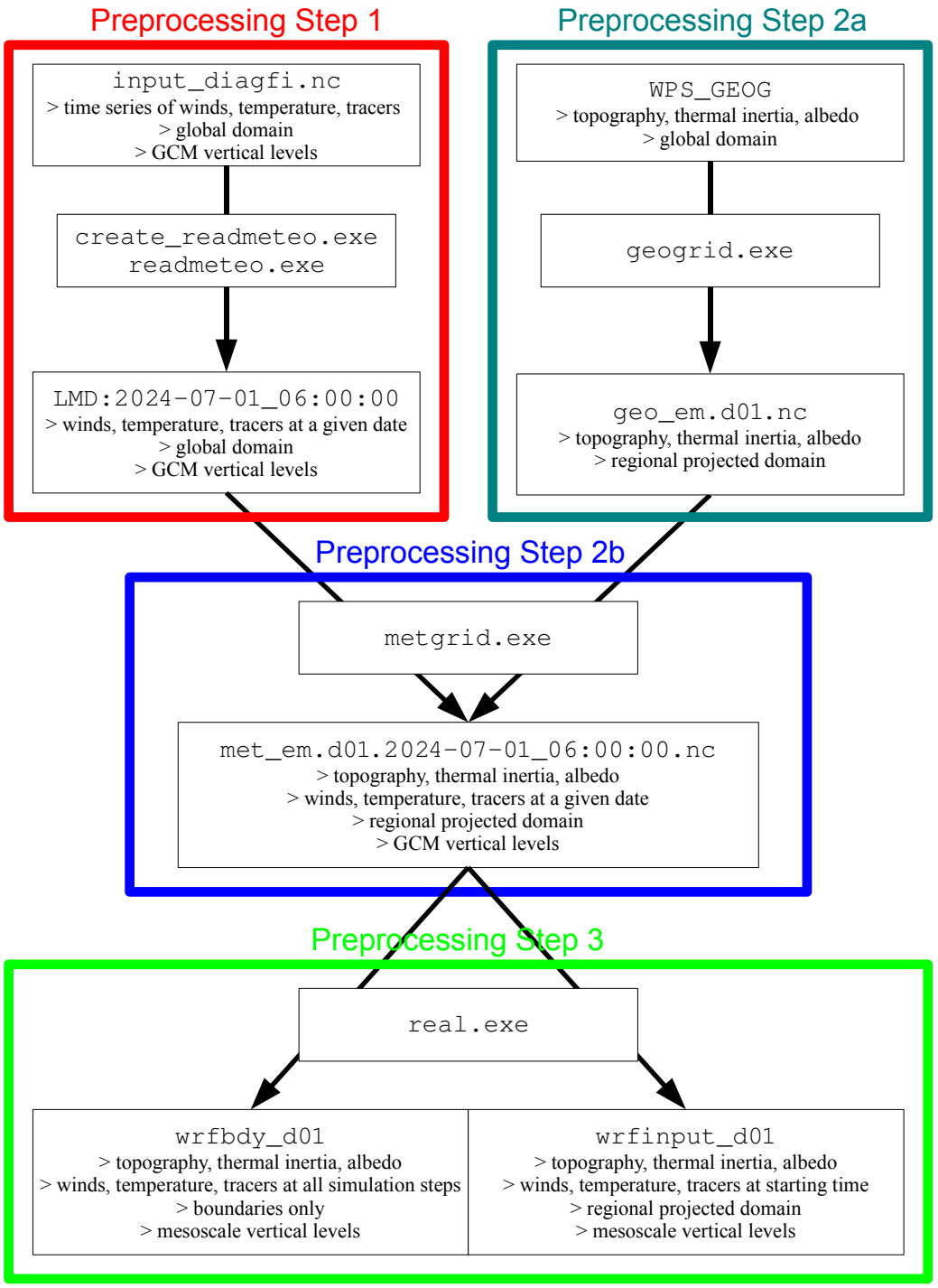

Figure 5.1: The details of preprocessing steps and their related software and inputs/ouputs

5.2.2 Step 1: Running the GCM and converting data

Here we assume that the user has chosen a given Martian sol or L_s on which to start the mesoscale simulation. As already mentionned in section 4.1.2, the file `$MMM/SIMU/calendar` reproduced in appendix can help with this choice (i.e. sol→L_s→mesoscale date and vice-versa). In addition, the user has to check in the `calendar` file which sol is before the one wanted for simulation start and has 99 in the first column: such sols are the ones for which an initial starting file for the GCM is available. Then the number of GCM simulated days `nday` in `$MESO/LMDZ.MARS/myGCM/run.def` must be set accordingly: suppose you want to start a mesoscale simulation at sol 9 during 4 sols, then according to the `calendar` file, sol 8 is the closest file before sol 9 to be in the database, so `nday` must be at least 5. For optimal forcing at the boundaries, we advise you to write the meteorological fields to the `diagfi.nc` file at least each two hours, or ideally each hour, i.e. `ecritphy` is respectively 80 or 40 in `$MESO/LMDZ.MARS/myGCM/run.def`. Eventually the GCM run can be launched using the following commands and should produce a netCDF data file named `diagfi.nc`:

```
cd $MESO/LMDZ.MARS/myGCM
./launch_gcm    ## answer: your desired starting sol for the simulations
```

Once the GCM simulations are finished, programs in the `PREP_MARS` directory allow the user to convert the data [5] from the NETCDF `diagfi.nc` file into separated binary datafiles for each date contained in `diagfi.nc`, which follows the formatting needed by the preprocessing programs at step 2. These programs can be executed by the following commands; if everything went well with the conversion, the directory `$MESO/TMPDIR/WPSFEED` should contain files named `LMD:*`.

```
cd $MMM/your_install_dir/PREP\_MARS
echo 1 | ./create_readmeteo.exe     # drop the "echo 1 |" if you want control
./readmeteo.exe < readmeteo.def
```

5.2.3 Step 2: Interpolation on the regional domain

Step 2a In the `WPS` directory, the `geogrid.exe` program allows you to define the mesoscale simulation domain, to horizontally interpolate the topography, thermal inertia and albedo fields at the domain resolution and to calculate useful fields such as topographical slopes. Please execute the commands:

```
cd $MMM/your_install_dir/WPS
ln -sf $MMM/TESTCASE/namelist.wps .   # test case (or use your customized file)
./geogrid.exe
```

The result of `geogrid.exe` – and thus the definition of the mesoscale domain – can be checked in the NETCDF file `geo_em.d01.nc` (using for instance `ncview`, or your favorite graphical interface for netCDF files, or python-based scripts as in section 8). If you are unhappy with the results or you want to change the location of the mesoscale domain on the planet, the horizontal resolution, the number of grid points ..., please modify the parameter file `namelist.wps`, content thereof is reproduced/commented on the next page, and execute again `geogrid.exe`.

- ☞ No input meteorological data are actually needed to execute `geogrid.exe`. This step 2a can be achieved/prepared e.g. before step 1. It is probably a good idea to prepare step 2 by choosing the mesoscale simulation domain while GCM computations being performed done during step 1.
- ☞ More details about the database and more options of interpolation could be found in the file `geogrid/GEOGRID.TBL` (for advanced users only).
- ☞ Two examples of `namelist.wps` parameters are given in Figure 5.2 with resulting domains.

5. If the fields `emis`, `co2ice`, `q01`, `q02`, `tsoil` are missing in the `diagfi.nc` file, those are replaced by respective default values 0.95, 0, 0, 0, tsurf.

```
&share
 wrf_core = 'ARW',                   !!   [do not modify: choice of dynamical core]
 max_dom = 1,                        !! number of simulation domains
 start_date = '0000-00-00_00:00:00'  !! YYYY-MM-DD_HH:mm:ss start date
 end_date   = '1111-11-11_11:11:11'  !! YYYY-MM-DD_HH:mm:ss end date
 interval_seconds = 3700             !! frequency of GCM updates [1 Mars hour = 3700 s]
 io_form_geogrid = 2,                !!   [do not modify: choice of NETCDF outputs]
 debug_level = 0,                    !! verbose level of the programs
 opt_output_from_geogrid_path='./'   !! location of the geogrid outputs
/

&geogrid
 parent_id         =   1,        !! number identifying the related parent domain
 parent_grid_ratio =   1,        !! ratio between parent and nested domains
 i_parent_start    =   1,        !! x-position of the southwest corner of nest
 j_parent_start    =   1,        !! y-position of the southwest corner of nest
 e_we              =  61,        !! number of longitude grid points
 e_sn              =  61,        !! number of latitude grid points
 geog_data_res     = 'gcm'       !! static data sources: '64ppd','32ppd',... cf.GEOGRID.TBL
 dx = 20000,                     !! resolution (meters) in the x-dimension
 dy = 20000,                     !! resolution (meters) in the y-dimension
 map_proj = 'mercator',          !! map projection: 'mercator', 'lambert' or 'polar'
 ref_lat   =  -12.,              !! north latitude of the center of the domain
 ref_lon   =  239.,              !! east longitude of the center of the domain
 truelat1  =  0.0,               !! (lambert or polar) lat position of projection cone
 truelat2  =  0.0,               !!   [do not modify]
 stand_lon =  0.0,               !! (lambert or polar) lon position of projection cone
 geog_data_path = './WPS_GEOG',  !!   [do not modify: symbolic link in the WPS folder]
/

&metgrid
 fg_name = './WPSFEED/LMD'       !!   [do not modify: symbolic link in the WPS folder]
 io_form_metgrid = 2,            !!   [do not modify: choice of NETCDF outputs]
 opt_output_from_metgrid_path='./WRFFEED/current'  !!   [do not modify: symbolic link]
/
```

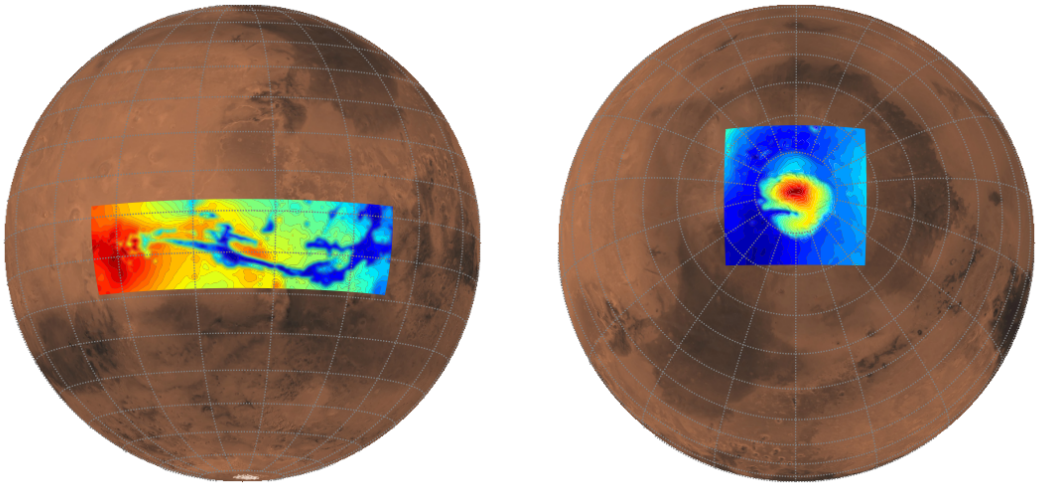

Figure 5.2: (Left plot) An example of mercator domain in the Valles Marineris region as simulated by *Spiga and Forget* [2009, their section 3.3]: relevant parameters in `namelist.wps` are: `e_we = 401`, `e_we = 121`, `dx = 12000`, `dy = 12000`, `map_proj = 'mercator'`, `ref_lat = -8`, `ref_lon = -68`. (Right plot) An example of north polar domain with stereographical projection: relevant parameters in `namelist.wps` are: `e_we = 117`, `e_we = 117`, `dx = 20000`, `dy = 20000`, `map_proj = 'polar'`, `ref_lat = 90`, `ref_lon = 0.1`, `truelat1 = 90`, `stand_lon = 0.1`.

The input datasets for topography and soil properties can be set in `namelist.wps` through the keyword `geog_data_res`. Possible choices are:

- `'gcm'`: coarse-resolution datasets;
- `'32ppd'`: coarse-resolution datasets, but 32ppd MOLA topography;
- `'64ppd'`: fine-resolution datasets: TES albedo & thermal inertia, 64ppd MOLA topography;
- `'64ppd_noHRti'`: fine-resolution datasets, but coarse-resolution thermal inertia;
- `'32ppd_HRalb'`: fine-resolution albedo, coarse-resolution thermal inertia, 32ppd topography.

STEP 2B Once the `geo_em` file(s) are generated, the `metgrid.exe` program performs a similar horizontal interpolation of the meteorological fields to the mesoscale domain as the one performed by `geogrid.exe` for the surface data (interpolation options can be modified by advanced users in `metgrid/METGRID.TBL`). Then the program writes the results in `met_em` files and also collects the static fields and domain parameters included in the `geo_em` file(s). If everything went well with the commands below, the directory `$MESO/TMPDIR/WRFFEED` should contain `met_em.*` files.

```
cd $MMM/your_install_dir/WPS
mkdir WRFFEED/current
./metgrid.exe
```

5.2.4 STEP 3: VERTICAL INTERPOLATION ON MESOSCALE LEVELS

The last preprocessing step before being able to run the mesoscale simulation at step 4 is to execute `real.exe` to perform the interpolation from the vertical levels of the GCM to the vertical levels defined in the mesoscale model. This program also prepares the final initial state for the simulation in files called `wrfinput` and the boundary conditions in files called `wrfbdy`. To successfully execute `real.exe`, you need the `met_em.*` files and the `namelist.input` file to be in the same directory as `real.exe`. Parameters in `namelist.input` which controls the behavior of the vertical interpolation are those labelled with `(p3)` in the detailed list introduced in chapter 4.

```
cd $MMM/TESTCASE   ## or anywhere you would like to run the simulation
ln -sf $MESO/TMPDIR/WRFFEED/met_em* .
./real.exe
```

The final message of the `real.exe` should claim the success of the processes and you are now ready to launch the integrations of the LMD Martian Mesoscale Model again with the `wrf.exe` command as in section 3.3.

☞ **When you modify either `namelist.wps` or `namelist.input`, make sure that the common parameters are exactly similar in both files (especially when running nested simulations) otherwise either `real.exe` or `wrf.exe` command will exit with an error message. Also, obviously the dates sent to `launch_gcm` and written in both `namelist.input` and `namelist.wps` should be consistent.**

Chapter 6

A quick guide to running a complete mesoscale simulation

In this chapter, we assume that the user has followed all the installation/compilation steps in the previous chapters. Probably it was a bit of an effort to do so; now the reward is that complete mesoscale simulations, i.e. all steps referred to in section 3.1.1, can be run. This chapter is thus meant to be a permanent reference for users once all tasks described in the previous chapters have been successfully achieved.

6.1 A summary of the complete set of commands to run a mesoscale simulation

It is assumed here that the user is working in a directory named `/a_place/MY_SIMU` mounted on a disk with enough free space to host the `wrfout*` output files.

Prerequisites Prepare parameter files (copy templates or pre-existing files); Edit those files; Use `$MMM/SIMU/calendar` (or cf. appendix) to choose simulation dates and fill the namelists; Pay attention to correspondances between `namelist.input` and `namelist.wps`. See 4 and 5.2.3 for further details.

```
cd /a_place/MY_SIMU
cp $MMM/SIMU/namelist.input_minim namelist.input
cp $MMM/SIMU/callphys.def .
cp $MMM/SRC/WPS/wps_mars/namelist.wps_TEST namelist.wps
[edit those three files and set your parameters]
```

Step 0 Compile the model. See 3.2 for further details.

```
cd $MMM
makemeso
[answers to the questions must be compliant with information in namelist.input]
[check in your_compdir that executables real.exe and wrf.exe are here]
cd /a_place/MY_SIMU
ln -sf $MMM/your_compdir/wrf_suffix_reflecting_your_choices.exe wrf.exe
ln -sf $MMM/your_compdir/real_suffix_reflecting_your_choices.exe real.exe
[NB: executables can be copied instead of linked]
```

Step 1 Run the LMD Global Circulation Model (GCM) to provide initial and boundary conditions for the mesoscale model. See 5.2.2 for further details.

```
cd $MESO/LMDZ.MARS/myGCM
launch_gcm
[answer: sol number corresponding to chosen dates (use $MMM/SIMU/calendar)]
[wait for GCM simulation to end]
cd $MMM/your_compdir/PREP_MARS
[check that the link input_diagfi.nc points toward the GCM output diagfi.nc]
echo 1 | create_readmeteo.exe
readmeteo.exe < readmeteo.def
[check that WPSFEED contains data files which prefix is LMD:]
```

Step 2 Create the mesoscale limited-area domain of simulation. Run preprocessing programs to horizontally interpolate GCM meteorological fields and static data (topography, soil properties) to the chosen simulation domain. See 5.2.3 for further details.

```
cd $MMM/your_compdir/WPS
geogrid.exe
[check that geo_em* netCDF files are created in the current directory]
mkdir WRFFEED/current
metgrid.exe
[check that met_em* netCDF files are created in the WRFFEED/current directory]
```

Step 3 Run preprocessing programs to vertically interpolate GCM meteorological fields and generate the initial and boundary conditions directly used by the mesoscale model. See 5.2.4 for further details.

```
cd /a_place/MY_SIMU
ln -sf $MMM/your\_compdir/WPS/WRFFEED/current/met_em* .
real.exe
[check that wrfinput* wrfbdy* netCDF files are created]
```

Step 4 Run the LMD Martian Mesoscale Model. See 3.3 for further details.

```
cd /a_place/MY_SIMU
wrf.exe [or use a MPI instance for parallel computations]
[check that wrfout* netCDF files are created and filled by simulation results]
[once wrf.exe is running met_em* links can be deleted]
```

6.2 The runmeso script

The serie of commands detailed in section 6.1 has to be repeated each time the user would like to run a new simulation with the LMD Martian Mesoscale Model. This is usually simple if the user simply want to change, e.g., the integration timestep, because only the few commands detailed at step 4 have to be used. On the contrary, if the user wants to run a new simulation in which, e.g., both the simulated season and the number of grid points are changed, every step from 0 to 4 have to be repeated (see e.g. section 5.2.1). Not only it can be tedious to type all commands again and again, but there is a quite high probability that the user (even the most experienced one) will face one or several of the following problems, which would waste the user's time, or prevent the simulation from running correctly, from running at all, or from computing reasonable results:

- A parameter labelled `(r)` in `namelist.input` (see chapter 4) is changed, but the sources have not been recompiled accordingly;
- The answers to `makemeso` are not compliant with information in `namelist.input`;
- The common information in `namelist.input` and `namelist.wps` are inconsistent;
- The input sol in `launch_gcm` does not correspond to the dates in `namelist.input` and `namelist.wps` (in accordance with the `calendar` table, cf. appendix);
- One or several of the various files used as input/output in step 1, 2, 3 are not correctly linked;
- The wrong executable is used because the right model executables are not correctly linked;
- Large domain simulations yield long computations of step 2 and 3, so the user have to wait a long time between each commands to type.

In those circumstances, using the `bash` script `runmeso` located in `$MMM/SIMU` is probably a good idea when the commands listed in section 6.1 has been successfully followed *at least once*. The purpose of the `runmeso` script is to perform all commands and tests about links, executables, etc... described in section 6.1. To put it in a nutshell, after all the efforts made in the previous chapters to install, compile, test the LMD Martian Mesoscale Model and its initialization routines, the user can now rely on `runmeso` to easily launch a simulation with the LMD Martian Mesoscale Model! The serie of commands listed in the previous section 6.1 is replaced by a simple user-friendly method:

- set a simulation directory containing the parameter files `namelist.input` and `callphys.def`;
- edit the `namelist.input` file with your settings;
- edit the `callphys.def` file with your settings;
- run the `runmeso` script in the simulation folder by typing `$MMM/SIMU/runmeso` (or only `runmeso` if you add `$MMM/SIMU` in your `PATH` environment variable);
- make a choice about which step to start with.

When executing the `runmeso` script, useful information about the simulation, and the system in which you plan to run it, are prompted before an invitation appears about the choice of step(s) to process with:

```
********************************************
**** LMD Martian Mesoscale Model launcher ****
********************************************
** User                  >>> aymeric
** Hostname              >>> aymeric-laptop
** Hardware              >>> i686
** Processor             >>> unknown
********************************************
** Simulation directory  >>> /home/aymeric/Science/MODELES/MESOSCALE/LMD_MM_MARS/TESTCASE
** Start date            >>> 2024-01-17 [sol=16, Ls=8.102209]
** End date              >>> 2024-01-17 [sol=16, Ls=8.102209]
** Domain(s)             >>> 1
** Tracer(s)             >>> 1
** Grid points           >>> 61 x 61 x 61
** Horizontal resolution >>> 20000
********************************************
** The runmeso script does it for you !
********************************************
** Step 0: compile the model if not done yet
** Step 1: run GCM and prepare inputs
** Step 2: interpolate on domain horizontal grid
** Step 3: interpolate on chosen vertical levels
** Step 4: run the model
************************ Please make a choice
 1 --> Perform steps 0 1 2 3 4  [ -1: step 0 skipped]
 2 --> Perform steps 0 2 3 4    [ -2: step 0 skipped]
 3 --> Perform steps 0 3 4      [ -3: step 0 skipped]
 4 --> Perform steps 0 4        [ -4: step 0 skipped]
11 --> Perform steps 0 1 2 3    [-11: step 0 skipped]
12 --> Perform steps 0 2 3      [-12: step 0 skipped]
13 --> Perform steps 0 3        [-13: step 0 skipped]
 0 --> Perform step  0 only
99 --> Oops ! Exit now please.
********************************************
What is your choice?
```

- ☞ A first test of `runmeso` can be carried out with the test case of section 3.3. Please create a directory (e.g. `test`) and copy the files `namelist.input`, `callphys.def` and `namelist.wps` referring to this Arsia Mons test case in this directory. Then run `runmeso` and make choice 1, i.e. going through all steps detailed in 3.1.1 and 6.1.
- ☞ The execution of `runmeso` stops if an error is encountered: e.g., the environment variable `MESO` is not defined, one of the two files `namelist.input` or `callphys.def` are not present in the working directory, etc...
- ☞ If `namelist.wps` is not present in the simulation directory, the `runmeso` script will propose to create it and will prompt 4 additional questions about map projection, data source, latitude for center of domain, longitude for center of domain. The remaining information to be set in `namelist.wps` (cf. section 5.2.3) is then copied from `namelist.input` to ensure all common parameters between the two files are the same. The program `geogrid.exe` is then run and, if `ncview` is installed on your system, this program is prompted so that you can explore the file `geo_em.d01.nc` file to check the newly created domain.
- ☞ An `xeyes` session is prompted when the `runmeso` script has finished processing required steps.
- ☞ If `runmeso` went well through steps 1 and 2, but encountered an error in 3, once the error has been corrected `runmeso` is not required to perform steps 1 and 2 again and can be started directly at step 3 (by typing 3, see possible choices above).
- ☞ The `LMD:*` files created by a `runmeso` call which features step 1 are kept in `WPSFEED` (located in `$MESO/TMPDIR`). Those files will be overwritten by subsequent calls to `runmeso` if you choose to re-run the GCM at similar dates.
- ☞ The `met_em*` files created by a `runmeso` call which features step 2 are kept in a directory in `WRFFEED` (located in `$MESO/TMPDIR`) which name refers to precise date and time, so that it will not be overwritten by subsequent calls to `runmeso` for other simulations. In the simulation directory `runmeso` creates a `met_em` directory which contains links towards the `met_em*` files.
- ☞ The contents of directories in `$MESO/TMPDIR` (i.e. `GCMINI`, `WPSFEED`, `WRFFEED`) might grow large as you launch more and more simulations with `runmeso`. It is probably a good idea to clean up from time to time files referring to old obsolete simulations.

Chapter 7

Advanced simulations

In this chapter, advice to perform more sophisticated simulations is provided to advanced users.

7.1 Running nested simulations

Preparing namelist.input For simulations with `max_dom` nested domains, `max_dom` parameters must be set wherever there is a "," in the `namelist.input_full` template in chapter 4. Specific parameters for nested simulations are labelled with `(n)` in this `namelist.input` template (see e.g. categories `&time_control`, `&domains` and `&bdy_control`). To help you with filling the `namelist.input` file for a nested simulation, a commented example is given below

```
&time_control
start_year         = 2024, 2024, 2024,   !! Any information about dates have to be duplicated for each nest
start_month        =   10,   10,   10,   !! ..
start_day          =   03,   03,   03,   !! ..
start_hour         =   06,   06,   06,   !! ..
end_year           = 2024, 2024, 2024,   !! ..
end_month          =   10,   10,   10,   !! ..
end_day            =   07,   07,   07,   !! ..
end_hour           =   06,   06,   06,   !! ..
history_interval   =   37,   37,   37,   !! Any information about model outputs have to be set for each nest
frames_per_outfile =   24,   24,   24,   !! ... NB: could be different for each nest
restart            = .false.
restart_interval   = 8880
io_form_history    = 2
io_form_restart    = 2
io_form_input      = 2
io_form_boundary   = 2
debug_level        = 0
/

&domains
time_step              =     40    !! This is time_step for the parent nest
p_top_requested        =     10
force_sfc_in_vinterp   =      5
num_metgrid_levels     =     33
max_dom                =      3               !! Set number of nests here
grid_id                =      1,     2,    3,  !! Identify each grid by a number
parent_id              =      0,     1,    2,  !! Identify parents for each nested domain
                                              !! ....(two nested domains can have the same parent)
parent_grid_ratio      =      1,     3,    3,  !! "Zooming" ratio between nests. 3 is a good choice.
 !! WARNING: parent_grid_ratio must divide e_we - s_we plus 1
parent_time_step_ratio =      1,     2,    3,  !! Time step ratio between nests.
i_parent_start         =      0,    40,   40,  !! \  Those subscripts are used to place the nested
j_parent_start         =      0,    40,   40,  !! /  domains with respect to their respective parents.
e_we                   =    117,   121,  121,  !! IMPORTANT: e_we[parent domain] = e_we[child domains] - 4
e_sn                   =    117,   121,  121,  !! IMPORTANT: e_sn[parent domain] = e_sn[child domains] - 4
 !! WARNING: number of processors must divide e_we minus 1 and e_sn minus 1
e_vert                 =     61,    61,   61,  !! Vertical levels must be duplicated
dx                     =  63000, 21000, 7000,  !! Compute dx[child] with parent_grid_ratio and dx[parent]
dy                     =  63000, 21000, 7000,  !! .... (keep 10^-2 accuracy if result of division is not int)
```

```
 feedback              =      1               !! Set 0 for 1-way nesting / 1 for 2-way nesting
 smooth_option         =      2               !! We recommend using smooth_option = 2
 blend_width           =      5               !! We recommend using blend_width = 5
 /

 &physics
 /

 &fdda
 /

 &dynamics
 tiso = 100.
 non_hydrostatic  =   F, F, F,       !! We recommend using hydrostatic integration in all nests
                                     !! .... (non-hydrostatic nested runs might be unstable)
 /

 &grib2
 /

 &bdy_control
 specified        =   T, F, F,       !! Only the parent domain has specified GCM boundary conditions
 nested           =   F, T, T,       !! ... the child domains are nested within the parent domain
 /

 &namelist_quilt
 nio_tasks_per_group = 0,
 nio_groups = 1,
 /
```

Preparing namelist.wps As is the case for single-domain simulations, the common parameters in the two files `namelist.input` and `namelist.wps` must be exactly similar. Similarly to single-domain simulations, an automated generation of `namelist.wps` from `namelist.input` is provided in the `runmeso` script. If you do not use `runmeso` to generate the `namelist.wps` file, please bear in mind that in this file, dates are different for the parent domain and the child domains, since boundary conditions are needed only for the parent domain while initial conditions are needed for all domains. The `namelist.wps` file associated to the previously described `namelist.input` file is given below and corresponds to a nested simulation in the Hellas Planitia region (Figure 7.1). Note that map projection is similar in all nests.

```
&share
 wrf_core         = 'ARW'
 max_dom          = 3
 start_date = '2024-10-03_06:00:00','2024-10-03_06:00:00','2024-10-03_06:00:00'
 end_date   = '2024-10-07_06:00:00','2024-10-03_06:00:00','2024-10-03_06:00:00'
 interval_seconds = 3700
 io_form_geogrid  = 2
 debug_level      = 0
 opt_output_from_geogrid_path='./'
/

&geogrid
 parent_id         =      0,    1,    2,
 parent_grid_ratio =      1,    3,    3,
 i_parent_start    =      0,   40,   40,
 j_parent_start    =      0,   40,   40,
 e_we              =    117,  121,  121,
 e_sn              =    117,  121,  121,
 dx = 63000,
 dy = 63000,
 geog_data_res     = '64ppd', '64ppd', '64ppd'
 map_proj = 'lambert'
 ref_lat   =  -35.
 ref_lon   =  50.
 truelat1  =  -35.
 truelat2  =  0.0
 stand_lon =  50.
 geog_data_path = './WPS_GEOG'
/

&metgrid
 fg_name = './WPSFEED/LMD'
 io_form_metgrid = 2,
 opt_output_from_metgrid_path='./WRFFEED/current'
/
```

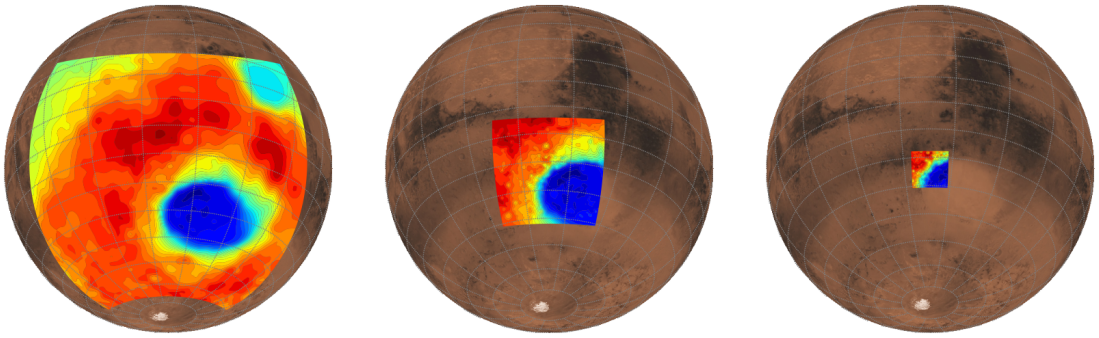

Figure 7.1: Domains for a nested mesoscale simulations in Hella Planitia defined by `namelist.wps_nests`. From left to right, "parent" domain i.e. nest number 1 (horizontal resolution 63 km), "child" domain i.e. nest number 2 (horizontal resolution 21 km), "grandchild" domain i.e. nest number 3 (horizontal resolution 7 km).

PREPARING CALLPHYS.DEF If you run a simulation with, say, 3 domains, please ensure that you defined three files `callphys.def`, `callphys_d2.def` and `callphys_d3.def` (one per nest). If needed, different settings for physical parameterizations can be made in each nest; usually all settings in these files are similar, except `iradia` (so that differences in dynamical timesteps between nests can be potentially impacted to `callphys*.def` in order to synchronize radiative transfer call).

COMPILING Use the command `makemeso` and specify the number of domains and dimensions set in `namelist.input` (as far as the horizontal grid is concerned, answers to `makemeso` shall refer to the values of `e_we` and `e_sn` for the parent domain). This is done automatically of course if you use `runmeso` which reads the information in `namelist.input`.

RUNNING If grid nesting and parallel computing are used, no more than 4 processors can be used. If the nested simulation is unstable, try a single-domain simulation with the parent domain and choose best parameters for stability (e.g., `time_step`), then add a first nested domain, and start again stability tests and investigations, etc.

INPUTS/OUTPUTS Defining several domains yield one output per domain: e.g. for three domains `geogrid.exe` yields `geo_em.d01.nc`, `geo_em.d02.nc`, `geo_em.d03.nc`...; `real.exe` yields `wrfinput_d01`, `wrfinput_d02`, `wrfinput_d03`, ...; `wrf.exe` yields `wrfout_d01*`, `wrfout_d02*`, `wrfout_d03*`, ...

USEFUL REMARKS The model presently supports 3 nests, but more nests can be included by adaptating `runmeso` and the following files:

```
$LMDMOD/LMD_MM_MARS/SRC/WRFV2/call_meso_inifis3.inc
$LMDMOD/LMD_MM_MARS/SRC/WRFV2/call_meso_physiq3.inc
$LMDMOD/LMD_MM_MARS/SRC/WRFV2/mars_lmd/libf/duplicate3
$LMDMOD/LMD_MM_MARS/SRC/WRFV2/mars_lmd/libf/generate3
$LMDMOD/LMD_MM_MARS/SRC/WRFV2/mars_lmd/makegcm*  ## search for 'nest'
```

7.2 RUNNING SIMULATIONS WITH TRACERS

PREPARING NAMELIST.INPUT The default behavior of the model is to include no transported tracer by the dynamics. This corresponds to `mars=0` in `namelist.input` (or the absence of parameter `mars` from the user's namelist). To compute the water cycle in the LMD Martian Mesoscale

Model, simply set `mars=1` in `namelist.input` (category `&physics`). This will add one tracer for water vapor and one tracer for water ice in the model's computations and outputs. To compute a mesoscale simulation with one simple transported dust bin (with typical characteristics), set `mars=2` in `namelist.input`.

GCM INPUTS For water cycle simulations (`mars=1`), the GCM runs used to build initial and boundary conditions for the mesoscale model must also include water tracers. This is done by default in parameter files in `$MESO/LMDZ.MARS/myGCM`, compiler wrapper `$MESO/LMDZ.MARS/compile` and the database of start files `STARTBASE_64_48_32_t2`.

PREPARING CALLPHYS.DEF It is important to set `callphys.def` in accordance with the option chosen for the keyword `mars` in `namelist.input`. For instance, for water cycle simulations (`mars=1`), the following settings must be changed in `callphys.def`: `tracer`, `sedimentation`, `iceparty`, `water` shall be `T`.

COMPILING It is key to recompile the LMD Martian Mesoscale Model with `makemeso` each time the number of transported tracers has changed, which would most often be the case if you modify `mars` in `namelist.input`. The right number of tracers corresponding to the `mars` case you are setting must be specify when answering questions to the `makemeso` script. This is done automatically of course if you use `runmeso` which reads the information in `namelist.input`.

INPUTS/OUTPUTS Additional fields corresponding to tracer mixing ratios (e.g. `QH2O` for water vapor) are automatically output in `wrfout*` files if a different option than `0` is used for the `mars` keyword. Note that when a large number of tracers is set, output files might grow very large quickly after the mesoscale simulation is launched.

TEST CASE A good test case consists in coming back to the Arsia simulation described in section 3.3 and activate the water cycle. Add `mars=1` to `namelist.input`, change `callphys.def` as described previously. Launch `runmeso` and choose `3` (i.e. recompile the model, run `real.exe` so that initial and boundary conditions for water are included, eventually run `wrf.exe`). Check for tracer fields in output files `wrfout*`.

7.3 Running Large-Eddy Simulations

PREREQUISITES Large-Eddy Simulations are very specific applications of the LMD Martian Mesoscale Model which allow the user to simulate boundary layer turbulent convection in idealized conditions at fine spatial and temporal resolution. We recommend to read section 3.4 of *Spiga and Forget* [2009] and the first three sections of *Spiga et al.* [2010].

PREPARING NAMELIST.INPUT A typical parameter file `namelist.input_les` is given in what follows (and could be found in `$MMM/SIMU`). Settings specific to Large-Eddy Simulations are referred to as `LES`. The main differences with regular mesoscale simulations are the following:

- the duration of simulation is specified in seconds,
- model top is specified as altitude above surface,
- the dynamical timestep and the spatial resolutions are much smaller,
- an additional `isfflx` keyword defines surface forcings (`1` is recommended),
- albedo and thermal inertia have to be set with uniform user-defined values,
- idealized wind profile is often assumed,
- `&dynamics` keywords are adapted to small-scale diffusion,
- periodic boundary conditions are set for the horizontal grid.

```
 &time_control
 run_seconds         = 37000   !! Duration of simulation                      [LES: !=0]
 history_interval_s  = 100     !! Frequency of outputs in seconds             [LES: !=0]
 frames_per_outfile  = 37      !! Size of time dimension in files
 start_year          = 9999    !! Idealized simulation                        [LES: 9999]
 end_year            = 9999    !! Idealized simulation                        [LES: 9999]
 restart             = .false. !! (*) Output restart files ?
 restart_interval    = 8880    !! (*) Frequency of output restart files ?
 io_form_history     = 2       !! (*) Choice of NETCDF for ouputs
 io_form_restart     = 2       !! (*) Choice of NETCDF for ouputs
 io_form_input       = 2       !! (*) Choice of NETCDF for ouputs
 io_form_boundary    = 2       !! (*) Choice of NETCDF for ouputs
 debug_level         = 0       !! (*) Verbose level
 /

 &domains
 ztop                = 12000.  !! Altitude above ground of model top          [LES: !=0]
 time_step           = 0       !! Dynamical timestep
 time_step_fract_num = 3       !! Additional fraction to time_step: numerator
 time_step_fract_den = 4       !! Additional fraction to time_step: denominator
 dx                  = 50      !! (p2) Horizontal resolution
 dy                  = 50      !! (p2) Horizontal resolution (should be equal to dx)
 e_we                = 145     !! (r)(p2) Number of longitude grid points
 e_sn                = 145     !! (r)(p2) Number of latitude grid points
 e_vert              = 201     !! (r)(p2) Number of vertical levels
 /

 &physics
 isfflx              = 1       !! 0 : UST/HFX from tke_... namelist values
                               !! 1 : UST/HFX from LMD physics
                               !! 2 : UST from LMD / HFX from namelist.input
 init_TI             = 50.     !! Define constant thermal inertia value       [LES: !=0]
 init_AL             = 0.3     !! Define constant albedo value                [LES: !=0]
 !!
 !! OPTIONAL
 !!
 radt                = 40      !! Ratio between physical and dynamical time step
 mars                = 0       !! (r)(p2) Configuration of tracers:
                               !!         0: no tracers, 1: water vapor + ice, 2: dust
 init_MU             = 0.01    !! (p3) Multiply ini & bdy zonal wind by init_U
 init_MV             = 0.01    !! (p3) Multiply ini & bdy meridional wind by init_V
 /

 &dynamics
 diff_opt            = 2       !! (*d) Diffusion option                       [LES: 2]
 km_opt              = 2       !! (*d) Eddy coefficient option                [LES: 2]
 diff_6th_opt        = 0       !! (*d) Knievel numerical diffusion            [LES: 0]
 mix_full_fields     = T       !! (*d) Set true if mixing ref + pert profiles [LES: T]
 !!
 !! OPTIONAL
 !!
! c_k                   = 0.10     !! Mixing coefficient constant for km_opt=2 [default: 0.15]
! c_s                   = 0.18     !! Mixing coefficient constant for km_opt=3 [default: 0.25]
! pd_tke                = T        !! Positive definite advection of tke
! tke_heat_flux         = 1.       !! Constant surface thermal flux (H/(rho*cp), K m/s)
! tke_drag_coefficient  = 0.0025,  !! Constant surface drag coefficient (Cd, dimensionless)
! mix_upper_bound       = 100.     !! Non-dimensional upper limit for diffusion coeffs
! mix_isotropic         = 1        !! 0=anistropic vertical/horizontal diffusion coeffs, 1=isotropic
! pert_coriolis         = T        !! Coriolis only acts on wind perturbation (idealized)
 /

 &bdy_control
 periodic_x          = T       !! (p3) Periodic boundary conditions over x     [LES: T]
 periodic_y          = T       !! (p3) Periodic boundary conditions over y     [LES: T]
 /

 &grib2
 /

 &fdda
 /

 &namelist_quilt              !! (*)
 nio_tasks_per_group = 0,     !! (*)
 nio_groups = 1,              !! (*)
 /                            !! (*)
```

PREPARING CALLPHYS.DEF It is essential that `calldifv` is set to `T` and `calladj` is set to `F` for Large-Eddy Simulations. Generally `iaervar` is set to `1` so that the (uniform) opacity in the domain can be set by creating a text file named `dustopacity.def` with the chosen value for opacity in it.

COMPILING The dynamical core used for Martian Large-Eddy Simulations is different than usual mesoscale simulations; it is based on WRF v3 instead of WRF v2. The first time the model is compiled, the user has to install it by typing the following commands:

```
cd $MMM/SRC/LES
./LMD_LES_MARS_install
cd $MMM
```

The compilation of the Large-Eddy Simulations model is carried out through the command:

```
makemeso -c les
```

This creates a new compilation folder with prefix `les` in which the executables can be found once the model is compiled. Answers to `makemeso` must be compliant with settings in `namelist.input`.

INPUTS/OUTPUTS Large-Eddy Simulations need four input files `input_coord`, `input_sounding`, `input_more`, `input_therm` which define initial pressure, temperature, density, winds profiles at the location/season for which simulations are run, along with information about this location/season. Typical files are available upon request, or you might simply build your own profiles using the Mars Climate Database (see the sample `scilab` script `wrf_sounding.sci` in `$MMM/SIMU/RUN`). Examples for `input_*` files are provided in `$MMM/SIMU/DEF/LMD_LES_MARS_def` and correspond to the cases run in the study by *Spiga et al.* [2010].

- `input_coord` contains longitude, latitude, L_s and local time;
- `input_sounding` contains (first line) near-surface pressure (mbar), potential temperature, a dummy value; and (subsequent lines) altitudes above MOLA zero datum, potential temperatures, dummy value, zonal wind component, meridional wind component;
- `input_more` contains on the same line altimetry and surface temperature;
- `input_therm` contains lines with corresponding values for (from left column to right column) R, c_p, pressure, density, temperature.

RUNNING Large-Eddy Simulations are not supported by `runmeso`. After compiling the model with the command `makemeso -c les`, please copy the executables `ideal.exe` and `wrf.exe` from the compilation directory `$MMM/les*` towards your simulation directory where the `input_*` files are located. Running `ideal.exe` would generate the initial state `wrfbdy_d01` from the profiles provided in the `input_*` files, then running `wrf.exe` would launch the model's integrations.

Chapter 8

Post-processing

In this chapter, the user is introduced to the principles of choosing the outputs of the LMD Martian Mesoscale Model. Elements about post-processing (interpolation, graphics) are also proposed here, although it is obviously left to the user to choose and develop its own tools to analyze the results of LMD Martian Mesoscale Model computations.

8.1 Controlling which fields to output in `wrfout` files

All non-local variables communicated within subroutines and functions in the WRF dynamical core are declared in a text file named `Registry.EM` located in `$MMM/SRC/WRFV2/Registry`. In this file, each useful variable is declared through a one-line instance organized as follows:

```
state  real  PSFC  ij  misc  1  -  i01rh  "PSFC"  "SFC PRESSURE"  "Pa"
```

The fields which appears in `wrfout*` output files feature an `h` (which stands for history) in the 8th column. If you do not want the field to appear in `wrfout*` files, simply remove the letter `h` from the group of letters in the 8th column. If you want the field to appear in `wrfout*` files, simply add the letter `h` in the group of letters in the 8th column.

It is also possible to output fields which are present only in the physical computations, i.e. appearing in `$MMM/SRC/WRFV2/mars_lmd/libf/phymars/physiq.F`. The method is simple. Assume you would like to output in the `wrfout*` files a 3D field named `zdtnirco2` and a 2D field named `qsurfice` in `physiq.F` with the new names `HR_NIR` and `QSURFICE`. All you have to do is add the following lines to `Registry.EM` (see also examples around lines `75-120`. For 2D [3D] files the 4th column must be `ij` [`ikj`] and the 12th column `#SAVEMARS2` [`#SAVEMARS3`].

```
state  real  HR_NIR  ikj  misc  1  -  rhd  "HR_NIR"  "HEATING RATE nirco2"  "K/s"  #SAVEMARS3  zdtnirco2
state  real  QSURFICE  ij  misc  1  -  rhd  "QSURFICE"  "WATER ICE AT SURFACE"  "kg m-2"  #SAVEMARS2  qsurfice
```

Each change in `Registry.EM` must be followed by a complete recompilation because the model variables have changed. Whether you use `makemeso` or `runmeso`, use the option `-r` to force recompiling with a new/updated list of variables.

☞ IMPORTANT: Each compilation directory `your_compdir` in `$MMM` (e.g. `g95_32_single`) has its own copy of `Registry.EM` in `your_compdir/WRFV2/Registry`. This is the file that has to be modified. The file `$MMM/SRC/WRFV2/Registry/Registry.EM` should not be modified: it is the reference file that is copied when the compilation directory is built by the `copy_model` script (cf. section 3.2).

8.2 Interpolating outputs on altitude and pressure levels

The fields output in `wrfout*` files are given for each grid point and model level. A vertical interpolation has to be performed to get those fields either in altitude or pressure levels. In addition, perturbation potential temperature `T`, x-component wind `U` and y-component `V` are output instead of the more informative (meteorogically-speaking) temperature `tk`, zonal wind `Um` and meridional wind `Vm`. This is why we developed a program named `api` (Altitude and Pressure Interpolator) which performs the tasks to convert the netCDF `wrfout*` files into another netCDF file featuring more useful fields to make plots and analyze the Martian mesoscale meteorology.

The source files for `api` are located in `$MMM/SRC/POSTPROC/`. The program `api.F90` has to be compiled with the `comp_api` command (which must be edited first, to uncomment the line corresponding to the Fortran compiler you are used to). Then the user has to fill in the parameter file `namelist.api` before launching the interpolator through the command `api`. A commented template for `namelist.api` is given below (this examples and many others can be found in `$MMM/SRC/POSTPROC/`). The calculations might be long if you are asking for many fields and many interpolation levels. In the example below, temperature, meteorological winds and vertical velocity are interpolated at 50 m above the local surface. The results are output in a netCDF file having the same name as the input `wrfout*` files, with an additional suffix which depends on the chosen interpolation method.

```
&io
 path_to_input  = './'                            !! where input wrfout* files are located
 path_to_output = './'                            !! where output API files will be located
 input_name     = 'wrfout_d01_9999-09-09_09:00:00' !! input file to API (could be wrfout*)
 process        = 'list'                          !! [do not modify]
 fields         = 'tk,W,uvmet'                    !! a list of fields to interpolate
                                                  !! - either fields in wrfout*
                                                  !! - or tk for temperature
                                                         uvmet for meteorological winds
                                                         tpot for potential temperature
 debug          = .TRUE.                          !! [add this if you want more information on screen]
/

&interp_in
 interp_method = 4                !! 1 --> INTERPOLATION: PRESSURE [LINEAR in p]         output: wrfout*_p
                                  !! 2 --> INTERPOLATION: PRESSURE [LINEAR in log(p)]    output: wrfout*_p
                                  !! 3 --> INTERPOLATION: ALTITUDE ABOVE MOLA AREOID     output: wrfout*_z
                                  !! 4 --> INTERPOLATION: ALTITUDE ABOVE LOCAL SURFACE   output: wrfout*_zabg
 interp_levels = 0.050            !! Interpolation levels: - pressure in hPa for interp_method = 1 or 2
                                  !!                        - altitude in km  for interp_method = 3 or 4
                                  !!                        - [pressure shall be in decreasing order]
/
```

8.3 Generating maps for winds and meteorological fields simulated by the model

8.3.1 General remarks

This section does not replace the need for you to develop your own plotting tools to suit your needs, which should be not too difficult. The model outputs, as well as the results of `api` interpolations, are written using the netCDF format which can be read by most software with graphical capabilities. For a quick inspection of model results (especially for checking model outputs while the model is running), we recommend using `ncview`; for simple manipulations of netCDF files (e.g. concatenation, difference, extraction, ...), we recommend using commands from the `nco` package (see chapter 2 for website links). Graphical routines based on `idl` [1], `ferret` and `grads` can be made available upon request (as is, i.e. undocumented yet commented scripts). Successful

1. Most graphics in the published papers to date about the LMD Martian Mesoscale Model were made with this software

reading/plotting of the LMD Martian Mesoscale Model outputs on `matlab`, `octave`, `idv` are also reported. It is possible to import the model's outputs to Geographical Information System (GIS) such as `arcgis` [2].

8.3.2 Python scripts

Powerful scripts based on `python+numpy+matplotlib` have been developed to obtain plots from the mesoscale model outputs. All figures in this user manual are based on the scripts `domain.py` and `winds.py` (more scripts will be available in the future). Those scripts can be found in `$MMM/SRC/PYTHON`. It is required that `python` and numerical/graphical librairies (`numpy`, `scipy`, `matplotlib`, `basemap`, `netcdf` are installed on your system. Perhaps the simplest way to do so is to install the user-friendly complete python distribution `epd` (cf. link in chapter 2). One of the advantages of an approach using `python`, apart from its open-source philosophy and the abundant online documentation, is that in a common framework it allows for scripting with various options, integrating Fortran routines, manipulating arrays, making plots with various map projections. This is exemplified by the `winds.py` script. It can both perform interpolation with `api` for the level requested by the user then generate a map, all that in one simple command line. For instance, Figures 3.1 in chapter 3 has been generated by the following two commands:

```
domain.py -f wrfout_d01_2024-01-17_02:00:00
winds.py -f wrfout_d01_2024-01-17_02:00:00 -i 4 -l 0.01 -v HGT -n -1 -m -1500. -M 20000. -s 2
```

Many options can be used in our `python` scripts. The example of command `winds.py` at the time of writing is listed below; this information can be obtained by typing `winds.py -h`. This script can also be easily edited to suit your needs if the option you need does not exist.

```
-h, --help            show this help message and exit
-f NAMEFILE, --file=NAMEFILE  [NEEDED] name of WRF file (append)
-l NVERT, --level=NVERT       level (def=0)(-i 2: p,mbar)(-i 3,4: z,km)
-p PROJ, --proj=PROJ   projection
-b BACK, --back=BACK   background image (def: None)
-t TARGET, --target=TARGET    destination folder
-s STRIDE, --stride=STRIDE    stride vectors (def=3)
-v VAR, --var=VAR      variable color-shaded (append)
-n NUMPLOT, --num=NUMPLOT plot number (def=2)(<0: plot LT -*numplot*)
-i INTERP, --interp=INTERP    interpolation (2: p, 3: z-amr, 4:z-als)
-c COLORB, --color=COLORB     change colormap (nobar: no colorbar)
-x, --no-vect          no wind vectors
-m VMIN, --min=VMIN    bounding minimum value (append)
-M VMAX, --max=VMAX    bounding maximum value (append)
-T, --tiled            draw a tiled plot (no blank zone)
-z ZOOM, --zoom=ZOOM   zoom factor in %
-N, --no-api           do not recreate api file
-d, --display          do not pop up created images
-e ITSTEP, --itstep=ITSTEP    stride time (def=4)
-H, --hole             holes above max and below min
-S SAVE, --save=SAVE   save mode (png,eps,svg,pdf or gui)(def=gui)
-a, --anomaly          compute and plot relative anomaly in %
-w VAR2, --with=VAR2   variable contoured
--div=NDIV             number of divisions in colorbar (def: 10)
-F FIRST, --first=FIRST       first subscript to plot (def: 1)
```

☞ Please ensure that you have the rights to execute `domain.py` and `winds.py` (otherwise use the `chmod` command). It is also necessary to set the following environment variables to ensure the commands `winds.py` or `domain.py` would execute in any working directory

```
PYTHONPATH=$MMM/SRC/PYTHON/
export PYTHONPATH
PATH=$PYTHONPATH:$PATH
```

☞ The option `-i` in `winds.py` make use of the Fortran routine `api.F90` (and the routine `time.F` is also needed). The routines have to be converted to `python` commands using `f2py`. Please execute the script amongst `api_g95.sh`, `api_ifort.sh`, `api_pgf90.sh` which corresponds to the Fortran compiler installed on your system. Check for errors/warnings in the log files and ensure that the two files `api.so` and `timestuff.so` are generated.

2. `idl`, `matlab` and `arcgis` are neither open-source nor free.

Chapter 9

Frequently Asked Questions, Tips and Troubleshooting

Browse this chapter if you encounter problems or issues while using the LMD Martian Mesoscale Model. Before reading what follows, please ensure that:

- you made no errors in using the model;
- your problem is not addressed in the previous chapters;
- your operating system and machine are in good health.

You might also read this chapter out of curiosity: it might be useful for your experience as an user.

9.1 General questions

I don't know anything about mesoscale meteorology. Does that prevent me from becoming an user of your model?

☞ Not really. It is the purpose of this user manual to help you with running simulations with the LMD Martian Mesoscale Model. Now, you will probably not be able to interpret simulation results that easily, but we will then be happy to help you with our expertise on atmospheric science and to advise good books so that you learn more about this topic.

I don't have time, or feeling overwhelmed by learning how to use the model.

☞ There are particular cases in which our team might be able to run the simulation for your study. Or help someone you would hire to do the work with learning about how to use the model and answer to questions. We are open to discussion.

9.2 Compilation

The model compiled yesterday. Now, with no apparent changes, it does not compile.

☞ This is one of the most frustating situation. Remember though that there is 99% chance that the reason for the problem is either stupid or none of your responsability. Please check that:

- Disk quota is not exceeded;
- You are working on the same machine as the day before;
- No source file has been accidentally modified; no links broken;
- No updates has been performed on your system during the night;
- Recompiling with `makemeso -f` does not solve the problem.

The model is no longer compiling, after I abruptly stopped the `makemeso` script because I realized that I made a mistake (e.g. I was compiling on the wrong machine).

☞ Recompile the model from scratch by using the option `-f` to `makemeso`.

I am asking for compiling the model on a huge grid (e.g. over $200 \times 200 \times 100$ for a single-processor run). The compilation fails with "relocated fits" errors.

☞ Try to lower the number of grid points (either horizontal or vertical) or consider using parallel computations where computations over the model grid will be split over several processors.

I am afraid I explored a given compilation directory in `$MMM` (say `g95_32_single` and broke something, e.g. deleted or break some links. The model does not compile anymore.

☞ Delete the corresponding compilation directory. Since it is mostly filled with symbolic links, you will only lose the previously compiled executables and the (possibly modified) `Registry.EM` file. Save those files prior to deletion of the compilation directory if you would like to keep those. Then run again `makemeso` for the same combination of compiler/system and a new clean version of the compilation directory will reappear, while the model executables are recompiled from scratch.

I update the model's sources through `svn update` and the compilation failed with the new version

☞ It could happen (but this is not usual) that we move, create or delete some files in `$MMM/SRC` while developing new capabilities or bug fixes for the model – and commit the changes to the reference version of the model. Please apply the solution proposed in the previous point and the model can be compiled again (because our rule is to commit only versions of the model which could be compiled). Possible problems can be anticipated by having a look to commit log through the command `svn log`. The vast majority of our commits, and subsequent reference model changes, is perfectly transparent for the user.

I would like to learn more about the interface between the WRF dynamical core and the LMD Martian physical parameterizations.

☞ The program source that is responsible for the interface between the dynamical core and the physical parameterizations is `module_lmd_driver.F` in `$MMM/SRC/WRFV2/phys/`.

I think I found a bug in the model.

☞ This is not impossible! Please double check then contact us.

9.3 Preprocessing steps

I would like to have smoother surface properties.

☞ Increase the smoothing parameter `smooth_passes` in the file `WPS/geogrid/GEOGRID.TBL` for each field you would like to get smoother, then restart at step 2 (execution of `geogrid.exe`).

I would like to know more about customizing the calculations made by `geogrid.exe` and `metgrid.exe`.

☞ You probably want to know more about various settings in `WPS/geogrid/GEOGRID.TBL` and `WPS/geogrid/METGRID.TBL`. A detailed description can be found here `http://www.mmm.ucar.edu/wrf/users/docs/user_guide/users_guide_chap3.html` (some parameters are not relevant for Mars).

To speed up initializations, I would like to define GCM constraints at the domain boundaries each 6 Martian hours, instead of each one or two hours as it is usually done (cf. `interval_seconds = 3700`).

☞ It is not a good idea. Near-surface atmospheric fields undergo a strong daily cycle on Mars which you will not be able to capture if `interval_seconds` is higher than 7400 seconds (i.e. two Martian hours).

`real.exe` is sometimes crashing with certain (low) values of `p_top_requested`.

☞ The program `real.exe` attempts to come up with nice equally-spaced-in-altitude vertical levels above the boundary layer up to the model top. This is done by an iterating algorithm integrating the hydrostatic equation which sometimes does not converge if the model top is too high (typically for values of `p_top_requested` below 5 Pa). Try to lower `force_sfc_in_vinterp`, increase `max_dz`, or modify `tiso` to help the algorithm to converge.

I would like to define my own vertical levels.

☞ Create a file `levels` with all your mass-based model levels (see chapter 1) in it then add the optional setting in `&domains` in `namelist.input`

```
eta_levels =     1.000000,
                 0.000000
```

You might also want to use `eta_levels` to prescribe directly in `namelist.input` the list of your custom model levels. Please ensure that the lowermost model level is 1, the uppermost is 0 and vertical resolution is refined in the boundary layer ($\sim$ 8 vertical levels above surface).

9.4 Runtime

I would like to know how much time my simulation will last.

☞ Check the log information while `wrf.exe` is running. The effective time to realize each integrating or writing step is indicated. Hence you can extrapolate and predict the total simulation time. If you use parallel computations, have a look in `rsl.error.0000` to get this information.

With default settings, I have one `wrfout*` file per simulated day, each one of those containing fields hour by hour. I want to change this.

☞ If you want to have an output frequency higher [lower] than one per hour, decrease [increase] the parameter `history_interval` in `namelist.input` (remember that each unit of `history_interval` is 100 seconds). If you want to have more [less] data in each individual file, increase [decrease] the parameter `frames_per_outfile` in `namelist.input`.

Looks like in the model (cf. `namelist.input`, a Martian hour is 3700 seconds. The reality is closer to 3699 seconds.

☞ This is true, though obviously the `3700` figure is much more convenient and choosing this instead of 3699 has no impact whatsoever on simulations which last typically less than one month, and most often only a few days.

I want to know the local time for a given model output.

☞ Time management in the model, which includes the way output files are named, relates to UTC time, i.e. local time at longitude 0°. The time given in the name of each `wrfout*` file refers to the first frame written in the file – using `history_interval` allows you to infer universal time for all frames in the file. Another method is to look at the variable `Times` in `wrfout*`. Once you know about universal time, you can check the domain longitudes in `XLONG` to calculate local time at any location.

The executable `wrf.exe` crashes a few seconds after launching and I don't know why.

☞ Please check all outputs from `wrf.exe`: information log and `wrfout*` files. It is usually possible to find hints about the problem(s) which make the model become unstable or crash. Sometimes it is just one file that is missing. If `cfl` warnings are reported in information log, it is probably a good idea to lower the timestep, but this will not fix the problem all the time especially if there are wrong settings and subsequent physical inconsistencies. If everything looks fine in the information log, try to lower `history_interval` to 1 in `namelist.input` so that much frequent outputs can be obtained in the `wrfout*` files and the problem can be further diagnosed through analyzing simulated meteorological fields.

I don't know which timestep should I choose to prevent the model from crashing.

☞ The answer depends on the horizontal resolution according to the CFL condition – and whether the dynamical core is used in hydrostatic or non-hydrostatic mode, plus other factors (e.g. slopes, temperature gradients, etc...). Please refer to the table in *Spiga and Forget* [2009] for guidelines about timestep. A rule-of-thumb to start with is to set `time_step` to the value of `dx` in kilometers; this value can be sometimes raised to get faster integrations. If the `time_step` parameter is too large for the horizontal resolution `dx` and violates the CFL criterion, `wrf.exe` usually issues warnings about CFL violation in the first integration steps.

Looks like `wrf.exe` is crashing because there are dynamical instabilities on the lateral boundaries apparently close to a topographical obstacle.

☞ Check that no steep slope (mountain, crater) is located at the domain boundaries. Otherwise, change the domain's center so that no major topographical gradient is located close to the domain boundaries (in the relaxation zone). This is also true for nested simulations at the boundary between parent and nested domains.

Martian calendars

init --	GCM sol --	GCM ls --	LMD Martian Mesoscale Model
0	0	0.000000	2024-01-01_00:00:00
0	1	0.5125165	2024-01-02_00:00:00
99	2	1.024138	2024-01-03_00:00:00
0	3	1.534933	2024-01-04_00:00:00
0	4	2.044906	2024-01-05_00:00:00
99	5	2.554062	2024-01-06_00:00:00
0	6	3.062404	2024-01-07_00:00:00
0	7	3.569939	2024-01-08_00:00:00
99	8	4.076671	2024-01-09_00:00:00
0	9	4.582605	2024-01-10_00:00:00
0	10	5.087745	2024-01-11_00:00:00
99	11	5.592097	2024-01-12_00:00:00
0	12	6.095666	2024-01-13_00:00:00
0	13	6.598457	2024-01-14_00:00:00
99	14	7.100474	2024-01-15_00:00:00
0	15	7.601723	2024-01-16_00:00:00
0	16	8.102209	2024-01-17_00:00:00
99	17	8.601937	2024-01-18_00:00:00
0	18	9.100911	2024-01-19_00:00:00
0	19	9.599138	2024-01-20_00:00:00
99	20	10.09662	2024-01-21_00:00:00
0	21	10.59337	2024-01-22_00:00:00
0	22	11.08938	2024-01-23_00:00:00
99	23	11.58467	2024-01-24_00:00:00
0	24	12.07924	2024-01-25_00:00:00
0	25	12.57309	2024-01-26_00:00:00
99	26	13.06623	2024-01-27_00:00:00
0	27	13.55866	2024-01-28_00:00:00
0	28	14.05039	2024-01-29_00:00:00
99	29	14.54143	2024-01-30_00:00:00
0	30	15.03177	2024-01-31_00:00:00
0	31	15.52144	2024-01-32_00:00:00
99	32	16.01042	2024-01-33_00:00:00
0	33	16.49873	2024-01-34_00:00:00
0	34	16.98637	2024-01-35_00:00:00
99	35	17.47335	2024-01-36_00:00:00
0	36	17.95967	2024-01-37_00:00:00
0	37	18.44534	2024-01-38_00:00:00
99	38	18.93036	2024-01-39_00:00:00
0	39	19.41475	2024-01-40_00:00:00
0	40	19.89849	2024-01-41_00:00:00
99	41	20.38161	2024-01-42_00:00:00
0	42	20.86410	2024-01-43_00:00:00
0	43	21.34598	2024-01-44_00:00:00
99	44	21.82724	2024-01-45_00:00:00
0	45	22.30789	2024-01-46_00:00:00
0	46	22.78794	2024-01-47_00:00:00
99	47	23.26740	2024-01-48_00:00:00
0	48	23.74626	2024-01-49_00:00:00
0	49	24.22454	2024-01-50_00:00:00
99	50	24.70224	2024-01-51_00:00:00
0	51	25.17936	2024-01-52_00:00:00
0	52	25.65592	2024-01-53_00:00:00
99	53	26.13191	2024-01-54_00:00:00
0	54	26.60734	2024-01-55_00:00:00
0	55	27.08223	2024-01-56_00:00:00
99	56	27.55657	2024-01-57_00:00:00
0	57	28.03036	2024-01-58_00:00:00
0	58	28.50362	2024-01-59_00:00:00
99	59	28.97636	2024-01-60_00:00:00
0	60	29.44857	2024-01-61_00:00:00
0	61	29.92026	2024-02-01_00:00:00
99	62	30.39144	2024-02-02_00:00:00
0	63	30.86211	2024-02-03_00:00:00

```
 0          64    31.33229     2024-02-04_00:00:00
99          65    31.80197     2024-02-05_00:00:00
 0          66    32.27115     2024-02-06_00:00:00
 0          67    32.73986     2024-02-07_00:00:00
99          68    33.20808     2024-02-08_00:00:00
 0          69    33.67584     2024-02-09_00:00:00
 0          70    34.14313     2024-02-10_00:00:00
99          71    34.60995     2024-02-11_00:00:00
 0          72    35.07632     2024-02-12_00:00:00
 0          73    35.54224     2024-02-13_00:00:00
99          74    36.00772     2024-02-14_00:00:00
 0          75    36.47276     2024-02-15_00:00:00
 0          76    36.93737     2024-02-16_00:00:00
99          77    37.40155     2024-02-17_00:00:00
 0          78    37.86531     2024-02-18_00:00:00
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