MYRIAM
Open-source software to estimate torque variations associated with plate-motion temporal changes

User manual

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Version released on DATE

Contents

1 Introduction

MYRIAM [Espinoza et al., 2023a] is a software that links, in a computationally inexpensive way, temporal changes in the motion of plates to the torque variations responsible for such changes. The theory behind it stems from the plate torque-balance equation, and is described in detail in Espinoza et al. [2023b].

2 Download and installation

MYRIAM is written in C#, and hosted at https://github.com/ValeEspinozaF/MYRIAM as open-source repository. Both source files and pre-compiled executables can be found in the repository.

2.1 Executable Files

To download a pre-compiled version of MYRIAM, go to the ”Releases” tab and select the latest version. Under the ”Assets” section, download the appropriate zipped file for your operating system (Windows, macOS, or Linux). Once the download is complete, unzip the file in the desired location. No further installation is required: the executable file can be run from any terminal window, as explained in Section 5. Alongside the executable file named MYRIAM, you will notice two accompanying folders, labeled as ”samples” and ”assets”. The ”samples” folder contains all necessary files to run the example described in Section 7. The ”assets” folder includes shapefiles and Python files that are required for generating output figures, which are optional. More detailed information about these outputs can be found in Section 6.2.

2.2 Source code

To clone the latest version of MYRIAM, you need to have Git installed. Make sure you do, and copy the following commands into a terminal:

```
cd 'path-to-desired-directory'
git clone https://github.com/ValeEspinozaF/MYRIAM.git
```

You can also download the latest version of MYRIAM as a ZIP file from the GitHub repository. Click on the blue button ”Code” and select ”Download ZIP” from the drop-down menu. Once the download is complete, unzip the file in the desired location.

Since MYRIAM's source code is written in C# as .NET application, generating an executable file requires ”building” the solution (.snl file in the main directory). To this end, we recommend the dedicated interface of Microsoft Visual Studio. To our knowledge, this software is only reliably available for Windows, thought the command-line ”build” fundamentals are available for all platforms (https://learn.microsoft.com/en-us/dotnet/core/install/). Both paths are a little more tech-invested, so unless you which to make changes to the code, we strongly suggest sourcing the pre-compiled executables.

If you run into any problem or have further questions, please do not hesitate to contact the authors via email (Valentina Espinoza, vf@ign.ku.dk).

3 Algorithm

MYRIAM builds upon inferences derived in previous studies about the torque variations required to produce known (i.e., inferred from observations) changes in the kinematics of tectonic plates [e.g., Busse et al., 2006; Iaffaldano & Bunge, 2015; Stotz et al., 2018]. This approach takes into account the viscous resistance that arises from the underlying mantle, which opposes any motion changes experienced by the plate. Consequently, the required torque variation depends on the size of the plate at its base as well as the rheology of the low–viscosity layer beneath. See Espinoza et al. [2023b], and references therein for a comprehensive mathematical description of the algorithm used.

At its simplest, MYRIAM's basic functionality requires two vectors describing the angular motion of a tectonic plate at two different points in time. The software then calculates an ensemble of motion change vectors, determines the depth-averaged viscosity of the underlying asthenosphere, and ultimately calculates the torque variation necessary to produce the observed kinematic change.

4 Input parameters and files

Executing MYRIAM requires the user to set some input parameters. These are declared on a plain–text input file, whose path is passed on to MYRIAM as a single input. An example file may be found inside the directory `samples` under the name `INPUT_FILE_EXAMPLE.txt`. It is important to note that parameters may be declared as:

- **Given:** The parameter is declared in the input text file, and a value is assigned to it.
- **Empty:** The parameter is declared in the input text file, but no value is assigned to it. In most cases, default values will be assigned to empty parameters, while in others the user will be prompted with an error message (see parameter details in Section 4.1).
- **Omitted:** The parameter is absent in the input text file. There are two ways of omitting a parameter: (i) erasing in the input file the text line containing the parameter, or (ii) commenting out the text line of the parameter by using a leading exclamation sign ("!"), which serves as comment delimiter. Omitting a parameter may result in using default values or triggering different options/methods within the program.

These three parameter declarations are exemplified in Figure 1:

The following section explains in detail the behavior of every individual parameter when it is given, empty or omitted. Please read carefully all parameters descriptions. If there is no specific behavior described for an omitted or empty parameter, such declarations will trigger an error in MYRIAM, preventing it from completing the calculation.

4.1 Main parameters

The main parameters required by MYRIAM are the following:

1. **`DIR_OUTPUTS`**: Path to an existing directory where all the output folders and files will be stored.
2. **`OUTPUT_LABEL`**: General label set by the user that is added to all output directories and input report file, to help the user distinguishing outputs from different calculations. This is particularly relevant to avoid output overwriting if the same primary input parameters of a

```
!-Viscosity average value for the asthenosphere [Pa*s]
muA = 5e19


!-Viscosity average value for the upper mantle [Pa*s]
muM =


!-Geographic region for viscosity averaging [degrees]
!REGION_muA_LV =
```

Figure 1: Example of parameters in a input textfile. `muA` is given, `muM` is empty, and `REGION_muA_LV` is omitted (note leading “!”).

previous run are used. If MYRIAM finds existing folders with the same label, it will prompt the user to confirm whether they wish to potentially overwrite the files or abort the run. To omit this inquiry and permit overwriting, the user may add an exclamation sign (‘!’) at the end of the label (e.g., `OUTPUT_LABEL = "test1"!`).

3. **`PLT_LABEL`**: Plate identification label added to all output directories and file names. While this label may consist of any string of characters[a], labels included in Table 1 allow MYRIAM to use built–in plate contours coordinates taken from the work of Matthews et al. [2016] (see parameter `CTR_PATH`).

4. **`STG_IDXs`**: Two integers, separated by a comma, which serve as indexes to identify the two specific time stages used. These are utilized for file labeling in order to prevent overwriting, e.g., when using the same plate but different Euler vectors. By convention, they point to the old and young time stages, respectively.

5. **`EVy_PATH`**: Path to a 3–column plain–text file containing an ensemble of sampled Cartesian values (ω_x, ω_y, ω_z) of the younger Euler vector, expressed in deg/Myr (degrees per million year). Alternatively, MYRIAM can sample its own ensemble from a single Euler vector stage. In this case, a 10–column single line input is expected: [1–2] Euler pole longitude/latitude in degrees East/North, [3] angular velocity in deg/Myr, [4–9] elements of the covariance matrix associated with the Euler vector uncertainty[b], in rad^2/Myr^2, and [10] size of the ensemble.

   If, instead, a 4-column single line input is provided, elements [1–3] are the same as before, but element [4] corresponds to the size of the ensemble. In this case, MYRIAM will automatically calculate the covariance elements by assuming that i) the off–diagonal elements are zero, ii) the diagonal entries are equal to the square of 5% of the angular–velocity value. To illustrate how these calculations are made, let us start by assuming that the plate’s angular velocity (AV) is equal to 1 deg/Myr. Firstly, we need to convert this value into rad/Myr, which results

[a]except for strings including any of the following characters: <, >, :, ”, /, \, |, ?, *.

[b]elements are c_{xx}, c_{xy}, c_{xz}, c_{yy}, c_{yz}, c_{zz} for a matrix constructed as follows:

$$\mathbf{C} = \begin{bmatrix} c_{xx} & c_{xy} & c_{xz} \\ c_{xy} & c_{yy} & c_{yz} \\ c_{xz} & c_{yz} & c_{zz} \end{bmatrix} \tag{1}$$

in $\sim 1.7 \cdot 10^{-2}$ rad/Myr. Then, for calculating the diagonal elements of the covariance matrix, we obtain the 5% of the value and then square it, so that:

$c_{xx} = c_{yy} = c_{zz} = (\frac{5}{100} \cdot \mathrm{AV}_{\mathrm{rad/Myr}})^2 = (\frac{5}{100} \cdot 1.7 \cdot 10^{-2})^2 = 7.6 \cdot 10^{-7}\ \mathrm{rad}^2/\mathrm{Myr}^2$

In order not to impose arbitrary off-diagonal elements, which would result in speculative shapes for the 3D uncertainty ellipsoids associated with the Euler vectors, we take a more conservative approach and set the off-diagonal elements to zero, so that: $c_{xy} = c_{xz} = c_{yz} = 0$

6. **`EVo_PATH`** (*optional*): Similar to **`EVy_PATH`**, but for the Euler vector of the older stage. This input is *optional*: when omitted, MYRIAM assumes that `EVy_PATH` (whether input as ensemble, or as nominal value with associated covariances) is the vector difference between two Euler vectors at two particular stages (i.e., $\Delta\omega_x$, $\Delta\omega_y$, $\Delta\omega_z$).

7. **`CTR_PATH`** (*optional*): Path to a 2–column plain–text file containing the longitude and latitude coordinates of the plate contour, expressed in degrees-East and -North, respectively. If omitted, MYRIAM will search for the appropriate plate contour coordinates within the built–in data set from Matthews et al. [2016]. Using these requires the parameter `PLATE_ID` to be a three–capital–letter identifier for the desired plate (see Table 1). Note that we provide some additional pre-processing scripts in the MYRIAM repository, which offer Python tools for e.g. extracting the geometry of a feature inside a GPlates file (.gpml), and create MYRIAM-compliant input files using the feature's contour coordinates.

8. **`GRID_RES`** (*optional*): Value of the grid resolution of the plate's base, expressed in degrees – i.e., the longitudinal/latitudinal spacing of the grid. Each grid point represents a fraction of the plate's basal area, used to compute the operator $\mathbf{P}$ (see equations in Espinoza et al. [2023b]). If omitted, MYRIAM will use a grid resolution of 1 degree. Users should be aware that, while it may require more computational resources, maintaining a sufficiently dense grid is crucial for obtaining accurate torque-variation results (refer the Supplementary file in Espinoza et al. [2023b]).

9. **`HL_km`** (*optional*): Value of the average lithosphere thickness, expressed in kilometers. This value can also be regarded as the depth of the lithosphere–asthenosphere boundary (LAB). If omitted, MYRIAM will use a lithosphere thickness of 180 km.

10. **`muA`** (*optional*): Value of the average asthenosphere viscosity, expressed in $\mathrm{Pa \cdot s}$. This value is used to calculate the lateral variations of asthenosphere viscosity within the region constrained by `REGION_muA_LV`, following the methodology described in Espinoza et al. [2023b]. If the setting of `REGION_muA_LV` dismisses lateral variations (i.e., is empty), this value then denotes the laterally-uniform viscosity of the asthenosphere. If `muA` is omitted, MYRIAM will use an average asthenosphere viscosity of $5 \cdot 10^{19}$ $\mathrm{Pa \cdot s}$.

11. **`muM`** (*optional*): Value of the average viscosity of the sub-asthenospheric mantle (i.e., the lower part of the upper mantle), expressed in $\mathrm{Pa \cdot s}$. This value is used alongside `muA` to calculate an average thickness for the asthenosphere, following the inference of Paulson & Richards [2009]. If omitted, MYRIAM will use an average upper–mantle viscosity of $1.5 \cdot 10^{21}$ $\mathrm{Pa \cdot s}$.

12. **`REGION_muA_LV`** (*optional*): Vector defining the rectangular (in equirectangular projection) geographic region of the asthenopshere where the laterally-varying viscosity features an average equal to `muA`. This vector consists of four elements representing the geographic coordinates of the region boundaries, expressed in degrees East/North: [1] minimum longitude, [2] maximum longitude, [3] minimum latitude, and [4] maximum latitude. If this parameter is omitted,

MYRIAM will use the whole asthenosphere – i.e., geographic region with longitude between $-180°$ and $180°$, and latitude between $-90°$ and $90°$). Alternatively, if the parameter is empty, a laterally-uniform asthenosphere viscosity equal to `muA` will be used.

13. **`FRACTION_HA`** (*optional*): Value the vertical fraction – with a range (0,1] – used to define the depth–average viscosity of the asthenosphere. If the parameter is set to 1, MYRIAM will use the whole asthenosphere thickness (H_A) obtained from Paulson & Richards [2009]. If the parameter is set to a value smaller than 1, a shallow fraction of H_A is used. If this parameter is empty or omitted, MYRIAM will use a value of 1.

    The motivation behind adding this parameter lies in the fact that the calculated H_A may not always coincide with the one inferred from tomographic models [in this case, Priestley & McKenzie, 2013]. Consequently, portions of the more–viscous sub-asthenospheric mantle may be incorporated unintentionally into the calculation of the depth-averaged asthenosphere viscosity. Assessing whether this phenomenon happens or not in specific cases may be done with the aid of optional figure `MAP_muA_*.png`, which shows a map of the resulting asthenosphere depth-averaged viscosity (please note that the generation of this figure requires providing an `PYTHON_PATH` on the input file).

14. **`DEF_DISTANCE_km`**: This parameter allows to set up a buffer zone of deformation along the plate boundary. The input value expresses the width of such zone in kilometers. The rigidity of the plate is set to scale linearly from 0 to 1 across the buffer zone, where the least rigid area is the one located at the plate's boundary. If this value is set to 0 or it is omitted, no deformation buffer zone will be considered, meaning that the entire plate is deemed rigid.

4.2 Secondary parameters

Users can provide additional optional parameters, which mainly concern the visualization of the torque–variation ensemble statistics, such as (i) histograms of the torque-variation magnitude and (ii) maps tracing the confidence–contours of the torque-variation pole (intersection between the torque–variation vector and the Earth's surface). These figure files allow the user to make a preliminary visual inspection of the outputs. Note however, that these are not publication–quality figures, and we therefore do not recommend using them for that purpose. Also note that in using this option, MYRIAM calls the second-party software Python3 to perform the plotting (see secondary parameter 6, `PYTHON_PATH`)

1. **`DM_MAGHIST_BINS`** (*optional*): Value for the number of bins used to construct the histogram of the torque–variation magnitude. If this parameter is empty, MYRIAM will use 50 bins. If omitted, the calculation of torque–variation magnitude distribution is not performed (i.e., the output files `MAGHIST_*.txt` and `PLOT_MAGHIST_*.txt` are not generated).

2. **`DM_CNTR_BINS`** (*optional*): Vector of values used to constrain the spatial distribution of the torque–variation poles, and thus modify the resolution of the output pole confidence contours. The full array of values one may pass to MYRIAM via `DM_CNTR_BINS` is: [1] resolution of the 2-D histogram grid in degrees, [2-3] minimum and maximum longitude of the grid in degrees East, and [4-5] minimum and maximum latitude of the grid in degrees North. If the array passed consists of only one element instead of five, MYRIAM takes this value as the grid resolution ([1]), while the other parameters are constrained from the minimum and maximum values of the ensemble's longitude/latitude. If this parameter is empty, MYRIAM will use

the aforementioned grid extension and a resolution equal to 2% of the ensemble's extension. If this parameter is omitted, the calculation of torque–variation pole distribution is not performed (i.e., output files `CNTR*_*.txt`, `MAP_ROTATED_CNTR68.png` and `MAP_CNTR20c68_*.png` are not generated).

Note that a higher–resolution (i.e., small `DM_CNTR_BINS`[1] value) comes at a higher computational cost, whereas a lower–resolution could yield a rough pole–distribution estimate (i.e., jagged contours). Setting a more constrained rectangular geographic region (by changing `DM_CNTR_BINS`[2-5]) can reduce the execution time for higher–resolution mapping. However, make sure to enclose the region where the bulk of the ensemble (used for contouring) falls. That is, if the original ensemble has undergone rotation (see parameter `ANG_ROT`), enclose the region where the bulk of rotated ensemble falls – as this is the ensemble used for contouring, as opposed to the original ensemble.

3. **`DM_CNTR_PERCENT`** (*optional*): List of confidence levels, expressed as percentages, used by MYRIAM to calculate confidence contours of the torque–variation pole. If this parameter is omitted or empty, MYRIAM will calculate the 20% and 68% confidence contours by default. Notice however, that if parameter `DM_CNTR_BINS` is omitted, the calculation of the torque–variation pole distribution is anyways not performed (i.e., the output files `CNTR*_*.txt`, `MAP_ROTATED_CNTR68.png` and `MAP_CNTR20c68_*.png` are not generated).

4. **`ANG_ROT`**: Vector containing three rotation angles, expressed in degrees, used to improve the generation of the torque–variation pole confidence–contours. This parameter is available because in some cases contouring can yield inaccurate results, particularly when the bulk of the torque–variation pole ensemble is close to any of the polar regions. This ultimately owes to the fact that such contouring is performed in equirectangular projection, which carries progressively more stretching (i.e., Tissot's indicatrix) as one gets closer to Earth poles. This input vector allows MYRIAM to perform three elemental rotations that seek to center and horizontally flatten the torque–variation pole ensemble around 0°N–0°E, where the contouring is more accurate due to minimal projection-stretching. The input array of values corresponds to [1] a rotation angle performed along the globe's Z–axis (90°N–0°E), [2] a rotation angle applied along the Y–axis (0°N–90°E), and [3] a rotation angle applied along the X–axis (0°N–0°E). Rotations are performed in that order (i.e., first about Z, then about Y, lastly about X) following the right–hand rotation convention.

   To avoid this option, the user may choose to provide an array of three zeros so that no rotation of the torque-variation ensemble is performed (`ANG_ROT = [0, 0, 0]`). If this parameter is omitted, MYRIAM will use the ensemble's average pole coordinates as rotation angles along the Z- and Y-axes in an attempt to shift the ensemble to the equator (0°N–0°E). If a rotation is performed, the angles employed will be reported in the `INPUT_FILE_REPORT_*.txt` (see Section 6). The user may iteratively refine these values by checking the output image `MAP_ROTATED_CNTR68.png` (this requires a given `PYTHON_PATH` parameter), and assessing how successful was the attempt to shift the bulk of the ensemble to 0°N–0°E. Note that MYRIAM does not provide an estimate for the third rotation (along the X-axis), which may be visually estimated by the user.

5. **`SAVE_ENS`** (*optional*): Boolean value – true or false – that instructs MYRIAM whether or not to save the output torque–variation ensemble to a 3-column plain–text file. If `SAVE_ENS` is set

to `true`, the file `ENSdM_*.txt` will be generated. This output file stores the torque–variation ensemble as Cartesian coordinates (ΔM_x, ΔM_y, ΔM_z), expressed in $\mathrm{N} \cdot \mathrm{m}$. If this parameter is set to `false` or it is empty/omitted, this output file will not be generated. Working with large input Euler–vector ensembles leads to the generation of torque–variation ensembles of a non-negligible storage size ($\sim$30 MB for 10^6 samples).

6. **`PYTHON_PATH`** (*optional*): Path to a Python3 executable in the running machine. To generate figure outputs (see Subsection 6.2), MYRIAM relies on Python3 and the following installed dependencies: *os*, *sys*, *numpy*, *pandas*, *matplotlib*, and *cartopy*. These packages can be readily installed through the terminal using the commands `pip` or `conda` (if Python3 was installed via Anaconda distribution). If this parameter is empty or omitted, no figures are produced.

5 Running the program

5.1 Platform-specific prompts

Once the desired parameters have been set and saved in the input plain–text file, the MYRIAM executable can be run from the terminal. Platform-specific executable files along with sample files and other assets can be found in the MYRIAM repository (see Section 2).

5.1.1 *For Windows:*

Open the Command Prompt by typing `cmd` in the taskbar search box and pressing Enter. Use the command `cd` to navigate to the folder where you have hosted the MYRIAM executable:

```
> cd path\to\MYRIAM_win_x64
```

Call the executable followed by the input file path in double quotation marks. For example:

```
> MYRIAM.exe "C:\path\to\file\INPUT_FILE.txt"
```

5.1.2 *For Linux:*

Open a terminal by typing Ctrl+Alt+T and use the command `cd` to navigate to the folder where you have hosted the MYRIAM executable:

```
$ cd path/to/linux_x64/
```

Next, grant executable permissions to the file `MYRIAM` with the command:

```
$ chmod 755 MYRIAM
```

Finally, call the executable followed by the input file path in double quotation marks. For example:

```
$ ./MYRIAM "/path/to/file/INPUT_FILE.txt"
```

5.1.3 *For macOS:*

Open a new terminal by typing `terminal` in the taskbar search box and pressing Enter. Use the command `cd` to navigate to the folder where you have hosted the MYRIAM executable.

```
% cd path/to/MYRIAM_osx_x64/
```

Next, grant executable permissions to the file `MYRIAM` with the command:

```
% chmod 755 MYRIAM
```

Try to run the program by typing ./MYRIAM. This will likely open a warning, letting you know that the app cannot be opened, as it is from an unidentified developer. This can be circumvented by following these steps:

1. Open the Apple menu, and click on "System Preferences".
2. Click on "Security & Privacy".
3. In the General tab, click on the lock icon in the lower right corner of the window. This will open a new window requesting your username and password.
4. Once unlocked, a message will appear stating that "MYRIAM was blocked from opening because it is not from an identified developer". Click on "Open Anyway".

Now try re-running the program, this time by calling MYRIAM followed by the path to the desired input file in double quotation marks. For example:

```
% ./MYRIAM "/path/to/file/INPUT_FILE.txt"
```

This may trigger another warning message, asking if you want to proceed regardless. Click "Open and continue running MYRIAM" to run the program and perform your calculations.

5.2 Performance

Executing a successful run of the software involves, for instance, setting an appropriate model for effective depth-average asthenosphere viscosity estimation. Achieving such model may require some tuning of the parameters and output inspection. To make this process more time-efficient, we recommend starting with some coarse parameters and skipping some procedures within MYRIAM. That is, omitting parameters `DM_MAGHIST_BINS`, `DM_CNTR_BINS`, and `SAVE_ENS`. Once a satisfactory sampling of the asthenosphere channel has been reached, enable parameter `SAVE_ENS` to store the output torque–variation ensemble. If a visualization of the magnitude distribution is desired, enable `DM_MAGHIST_BINS` with a recommended value of 50 (number of bins). If confidence contours are desired, enable `DM_CNTR_BINS` and start with a recommended initial resolution of 5 degrees. Examine the output `MAP_ROTATED_CNTR68.png`, and asses whether a rotation of the ensemble (setting `ANG_ROT`) is necessary to achieve more accurate contouring. Finally, tune the resolution for a smooth contour and set the desired confidence levels as percentages values using `DM_CNTR_PERCENT`.

6 Outputs

MYRIAM generates two[c] output folders, (1) `REPOSITORY_MTX_w2M` for all files related to converting Euler–vector changes into torque variations, and (2) `REPOSITORY_dM_PDD` for all files associated with the probability density distribution of the torque–variation ensemble itself. In the first folder, MYRIAM outputs nine main plain–text files, plus three optional diagnostic figures. In the second folder, MYRIAM outputs one main plain–text file, plus three optional diagnostic figures and a variable number of optional plain–text files. An additional file, `INPUT_FILE_REPORT_*.txt`, reports the parameters used by MYRIAM on its most recent run.

Most file names include labels with details on the particular model–setup used (e.g., plate ID, average asthenosphere viscosity, averaging area, etc). Individual bits of information are separated by using an underscore as in the following example:

$$\texttt{CNTR68\_}\underbrace{\texttt{STGs\_0\_1}}_{1}\texttt{\_}\underbrace{\texttt{SAM}}_{2}\texttt{\_}\underbrace{\texttt{A5}}_{3}\texttt{\_}\underbrace{\texttt{M15}}_{4}\texttt{\_}\underbrace{\texttt{HL180}}_{5}\texttt{\_}\underbrace{\texttt{GLBL}}_{6}\texttt{\_}\underbrace{\texttt{fHA1p0}}_{7}\texttt{\_}\underbrace{\texttt{r3p6}}_{8}\texttt{.txt} \tag{2}$$

- **1**: The two numbers following the label `STGs` indicate the indexes assigned to the old and young temporal stages (see parameter `STG_IDXs`), respectively.
- **2**: The plate ID label (see parameter `PLT_LABEL`).
- **3**: The value following label `A` indicates the value assigned to the average viscosity of the asthenosphere channel (times 10^{20} Pa · s), i.e., parameter `muA`.
- **4**: The value following label `M` indicates the value assigned to the viscosity of the sub-asthenospheric mantle (times 10^{20} Pa · s), i.e., parameter `muM`.
- **5**: The value following label `HL` states the value assigned to the average thickness of the lithosphere (parameter `HL`), in kilometers.
- **6**: This label indicates the extension of the rectangular area used for viscosity averaging (see parameter `REGION_muA_LV`). If a full-globe extension is used, the label is simply set to `GLBL`. Otherwise, the coordinates defined by the `REGION_muA_LV` vector are used.
- **7**: The value following label `fHA` states the fraction of the asthenospheric channel used, i.e., parameter `FRACTION_HA`. Note that `p` replaces the decimal symbol.
- **8**: This label reports the grid resolution used for the torque–variation pole contouring (parameter `DM_CNTR_BINS`[1]), in degrees. Note that `p` replaces the decimal symbol.

In the following, we explain each of the default and optional output files in detail.

6.1 Default outputs

The following outputs are always generated:

[c]A third temporary folder is created to store supplementary files associated with figure-production. However, this folder and all its content is deleted before the software finishes running.

1. INPUT_FILE_REPORT_*.txt: This file contains information on all the editable parameters used by MYRIAM to perform the torque-variation calculation. Empty/omitted parameters may be reported with default values or left omitted (commented with a leading exclamation sign "!"). This file may be re-used as input file in future calculations.

2. VECdM_*.txt: This file contains the torque–variation average vector information, organized as follows: [1-3] Cartesian coordinates of the mean torque–variation vector (ΔM_x, ΔM_y, ΔM_z) expressed in $\mathrm{N \cdot m}$, [4-5] latitude and longitude of the mean torque–variation pole (in degrees), [6] average torque-variation magnitude (in $\mathrm{N \cdot m}$), [7-12] elements of the covariance matrix indicating the associated uncertainties of the torque–variation ensemble (in $\mathrm{N^2 \cdot m^2}$).

3. MTX_w2M_*.txt: This file contains the 3x3 matrix values that convert Euler vector variations into torque variations (operator $\mathbf{P}$). The elements of this matrix are expressed in $\mathrm{Pa \cdot s \cdot m^3}$, and depend on the viscosity/thickness ratio of the asthenosphere and the geometry of the plate.

4. AREA_*.txt: This file consists of a single value reporting the basal area of the plate of focus, in square meters. Note that this value will vary depending on the set thickness of the lithosphere (see parameter HL_km), as the calculated area corresponds to the base of the plate. Therefore, the larger the thickness of the lithosphere is, the smaller the plate's basal area will be.

5. BDR_*.txt: This file contains the plate boundary coordinates provided by the user or retrieved from the built–in contours (see input CTR_PATH). It consists of two columns, corresponding to the longitude and latitude of the plate contour, expressed in degrees East/North. Beware that this file may contain points not present in the original input plate boundary file, but obtained from an interpolation during MYRIAM's deformation buffer calculation (see details in parameter DEF_DISTANCE_km). Therefore, this file will be either the original plate boundary file or a denser (along the plate contour) version of it.

6. BDRin_*.txt: This file contains the grid point coordinates used to calculate the operator $\mathbf{P}$ (see equations in Espinoza et al. [2023b]). It consists of three columns: [1-2] longitude and latitude of the grid points in degrees East/North, and [3] the rigidity value assigned to each point. This value ranges from 0 to 1, where 1 is assigned to the portions of the plate whose behavior is deemed as perfectly rigid. This value relates to the deformation buffer width optionally implemented along the plate boundary (see parameter DEF_DISTANCE_km).

7. GRID_LON_*.txt: This file contains the longitude values, in degrees East, of the rectangular 2D grid used for estimating the depth–average viscosity of the asthenosphere. The grid encompasses the area set by the parameter REGION_muA_LV, with a spatial spacing set by parameter GRID_RES. This is one of the five plain-text files describing different parameters of the rectangular 2D grid.

8. GRID_LAT_*.txt: Same as output 7, but contains the latitude values of each grid point, in degrees North.

9. GRID_MuA_*.txt: Same as output 7, but contains the depth-averaged viscosity of the asthenosphere for each grid point, expressed in $\mathrm{Pa \cdot s}$.

10. GRID_YM_*.txt: Same as output 7, but contains the Young's modulus values for each grid point, expressed in Pa.

11. GRID_MT_*.txt: Same as output 7, but contains the Maxwell time period for each grid point, expressed in years. This grid is relevant only for calculations of torque-variation required to generate plate-motion changes over geologically-short periods of the order or years/decades (see Martin de Blas et al. [2022]).

6.2 Optional outputs

1. MAGHIST_*.txt: 2–column plain–text file reporting the torque–variation magnitude histogram values as [1] bin count, and [2] bin mid–value. This file will only be created if parameter DM_MAGHIST_BINS is not omitted.

2. ENSdM_*.txt: 3–column plain–text file reporting the Cartesian coordinates (ΔM_x, ΔM_y, ΔM_z) of the calculated torque–variation vector, expressed in $\mathrm{N \cdot m}$. The generation of this file is conditional to a non-omitted parameter SAVE_ENS.

3. CNTR*_*.txt: 2–column plain–text file with the longitude and latitude coordinates (in degrees) for the confidence contours defined in the parameter DM_CNTR_PERCENT. The creation of this file is conditional to a non-omitted parameter DM_CNTR_BINS.

4. MAP_muA_*.png : Map containing (1) the plate's contour, (2) the grid points with their assigned rigidity in gray–scale, and (3) a background color–map with the calculated depth–average viscosity of the asthenosphere.

5. MAP_YM_*.png: Same as optional output 4, but showing values of the depth–average Young's modulus, expressed in Pa.

6. MAP_Mtau_*.png: Same as optional output 4, but showing background values of the depth–average Maxwell time-interval, expressed in years.

7. PLOT_MAGHIST_*.png: Histogram plot displaying the magnitude distribution of the torque–variation ensemble.

8. MAP_CNTR20c68_*.png: Global map showing the location of the 20% and 68% confidence contours for the torque–variation pole.

9. MAP_ROTATED_ CNTR68.png: Global map displaying the original location of the torque–variation ensemble (in blue), and the location after rotation (in red). Also plotted are the ellipses for the 68% confidence contour. For details on the rotation, see parameter ANG_ROT.

7 Example: Anatolia microplate

Here we provide an example run of MYRIAM, using sampled Euler vector rotations of Martin de Blas et al. [2022] for the motion of the Anatolia microplate relative to the geodesic reference system ITRF08 [Altamimi et al., 2011]. The stages used correspond to the following periods of time: (1) between years 1994–1998 (old period), and (2) between years 2013–2015 (young period). Example ensembles and input file can be found inside the folder samples/anatolia_plate. This example has the objective of showing how, in our opinion, users should attempt parameter modifications in MYRIAM in order to achieve refined results in a time-efficient manner. That is, leaving high resolution plotting as last, final step. Most of the suggestions provided in this example concern the outputs of probability density distribution of the torque–variation ensemble, and not the torque–variation calculation itself. It is worth reminding that these are optional features, and the user is free to simply output the ensemble as plain–text file, making use of other statistical tools for its analysis instead.

7.1 Run 1: Default values

We start by modifying the input file `INPUT_FILE_AT.txt` inside the folder `samples/anatolia_plate`. The full path to the old and young stage ensembles must be written next to input parameters `EVo_PATH` and `EVy_PATH`, respectively. These plate-motion sampled ensembles can be found as plain–text files in the same folder under the names `ENS_EV_AT_OLD.txt` and `ENS_EV_AT_YOUNG.txt`. For parameter `STG_IDXs`, which serves to identify each stage with an integer, we will arbitrarily use `0` and `1` to identify the used time stages. Since the plate at hand is the Anatolia microplate, the plate's label parameter `PLT_LABEL` may well be set to `AT`. This label does not point to any built-in plate contour [Matthews et al., 2016, see Table 1], therefore we will need to provide the path to a file containing a digitized version of Anatolia's plate boundaries. A contour by Bird [2003] can be found in the same folder, under the name `BDR_AT_Bird2003.txt`. We use the path to this file as parameter `CTR_PATH`. The last mandatory parameter we shall supply is the path to an existing directory where the outputs will be stored, `OUTPUTS_DIR`.

We omit all other parameters, save the modifications to `INPUT_FILE_AT.txt`, and run MYRIAM as explained in Section 5. Once the run has been completed, an output similar to that in Figure 2 will be prompted in the terminal.

```
====================================================================
|                              MYRIAM                              |
|                                                                  |
|  MYRIAM is an open-source software that implements tomography-   |
|  based lateral variations on the viscous shear-resistance to     |
|  calculate the torque variation required to produce a given      |
|  change in plate motion.                                         |
|                                                                  |
|  Valentina Espinoza                                              |
|  Juan Martin de Blas                                             |
|  Giampiero Iaffaldano                                            |
|                                                                  |
|  Copenhagen, 2023                                                |
====================================================================

Input Summary

                           Plate : AT
                             muA : 5E+19 Pa s
                             muM : 1.5E+21 Pa s
                     LAB's Depth : 180 km
     Asthenosphere fraction used : 1.00


Output Torque Variation (dM) Summary

                    Average Pole : 17.35 °E, -50.04 °N
               Average Magnitude : 2.93E+22 N m
        Average Cartesian Vector : 1.79E+22, 5.6E+21, -2.24E+22


Done!
[████████████████████████████████████████████████████████████] 100%
```

Figure 2: Terminal screenshot of a successful run of MYRIAM (Example Run 1).

In there, the main parameter values used in the model, as well as the resulting torque variation vector are reported. The latter one can be also found in output file `VECdM_*.txt`, while parameter values are reported in the file `INPUT_FILE_REPORT_AT.txt`.

7.2 Run 2: Python asthenosphere rheology outputs

From here on, we can make use of parameter `OUTPUT_LABEL` to generate new output folders for each meaningful run. Our next step is to visualize the grid points and 2D distribution of depth–average asthenosphere viscosity used to estimate the torque–variation vector. Outputs `BRDin_AT.txt` and `GRID_*.txt` files inside the `REPOSITORY_MTX_w2M` folder allow doing so. Conveniently, MYRIAM offers the option to supply a Python3 path (through parameter `PYTHON_PATH`), in order to generate maps showing the calculated depth–average asthenosphere (1) viscosity, (2) Young's modulus, and (3) Maxwell time-interval (see Subsection 6.2). Default values for all optional parameters are used in generating maps in Figure 3.

7.3 Run 3: Python-made images of torque–variation distributions

In the next iteration, we make use of a slightly–denser grid by decreasing the value controlling the grid spacing `GRID_RES` from 1 (default value) to 0.5 degrees. It is worth noting that making the grid denser will not sample the asthenosphere rheology better, as the tomography results from Priestley & McKenzie [2013] have a fixed resolution of 2 degrees. Instead, a denser grid aims at improving the sampling of plate–motion change.

It is generally convenient to visualize the distribution of the torque–variation ensemble using spherical coordinates. This can be achieved by plotting the torque–variation magnitude and pole distributions separately. To do so, we declare parameter `DM_MAGHIST_BINS = 50` to generate a magnitude–distribution histogram with 50 bins (see Figure 4). For the pole contouring, we declare (i) `DM_CNTR_BINS = [5]` to start with a very coarse contour resolution, and (ii) `ANG_ROT = [0, 0, 0]` to perform no rotation of the ensemble before contouring (see Figure 5).

Figure 4 shows a histogram with reasonable magnitudes for a motion change of a microplate. Figure 5 shows instead the torque–variation pole position and its 68% confidence contour, both of which look similar to results in Martin de Blas et al. [2022]), though it is hard to assess how accurate the contouring is due to the distortion inherent to the equirectangular projection.

7.4 Run 4: Rotation of torque–variation ensemble

We let MYRIAM do its own attempt at centering the torque–variation ensemble on 0°N–0°E, for a more faithful representation of the pole distribution (see Figure 6). To do this, we omit parameter `ANG_ROT` from the input file. As a result, the 2D–binning and contouring is done in the equatorial region, though for this case the output is fairly similar. We advise users to actively take this option, as though an un-rotated contour may look fine, equirectangular projections can visually distort distributions, and hence the user's perception of the output's fairness.

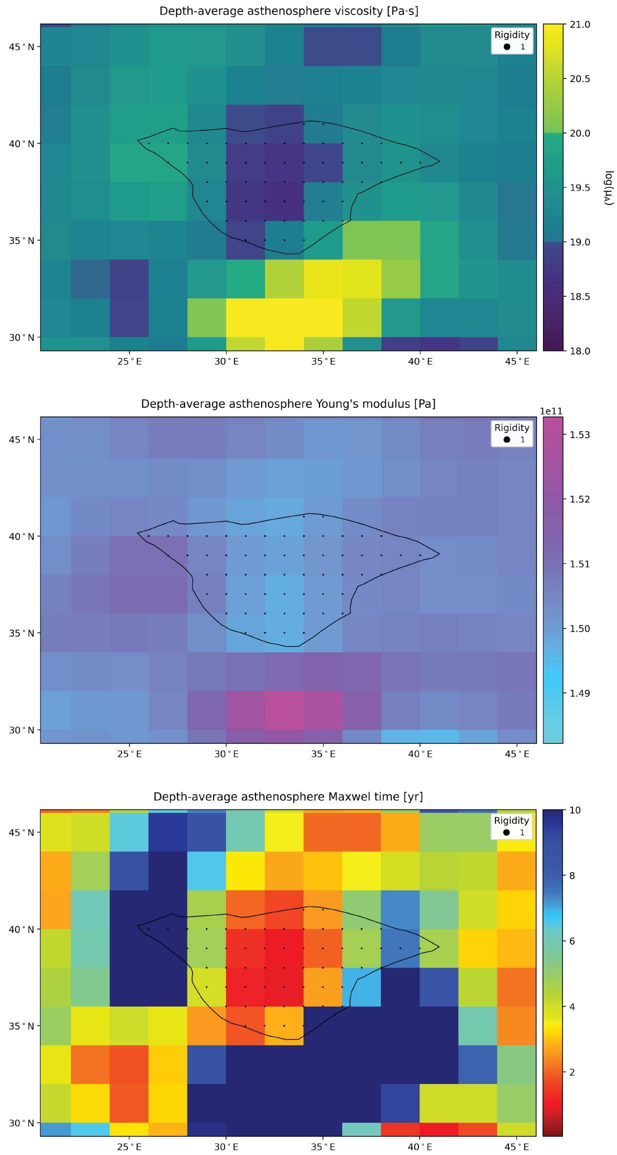

Figure 3: Output figures generated by MYRIAM with Python3 for the Anatolia microplate, using default input parameters (Example Run 2).

7.5 Run 5: Flattening the distribution of torque–variation poles

While MYRIAM's default centering of the torque-variation pole distribution appears adequate, the final flattening along the equator is left to the user. The reported angles in the output file `INPUT_FILE_REPORT_*.txt` are `ANG_ROT = [-16.7, -50.2, 0.0]`. From visual inspection of Figure 6, we propose a rotation angle along the X–axis (0°N–0°E) of 9 degrees. Be reminded that rotations are performed by MYRIAM following the right–hand rule, meaning anti–clockwise rotations are associated with angle positive values. We also use the report on `DM_CNTR_BINS` to improve the contouring by: (i) decreasing the 2D-histogram grid size from 5 to 1 degrees, and (2) narrowing down the longitudinal extension of the grid from [-180, 180] to [-85, 85].

The resulting contour in Figure 7 is not smooth, which may be due to (i) excessive resolution used for building the 2D histogram on this particular case, and/or (ii) an torque–variation ensemble

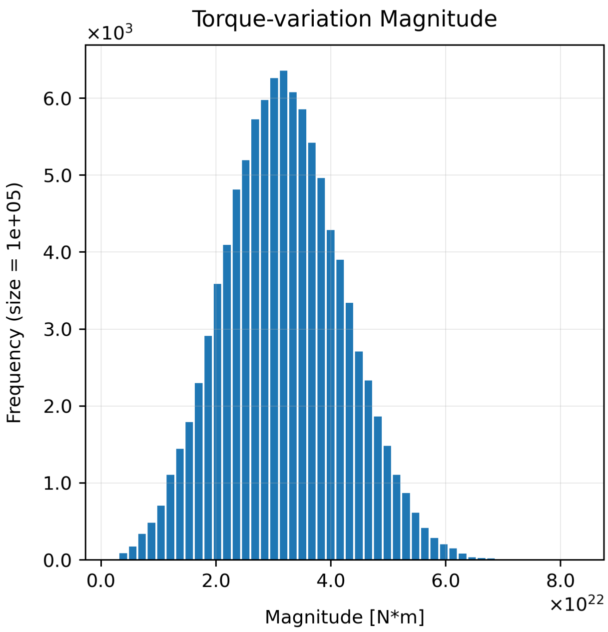

Figure 4: PLOT_MAGHIST_*.png output example for the Anatolia microplate motion–change, showing a 50–bin histogram of the torque–variation magnitude distribution (Example Run 3).

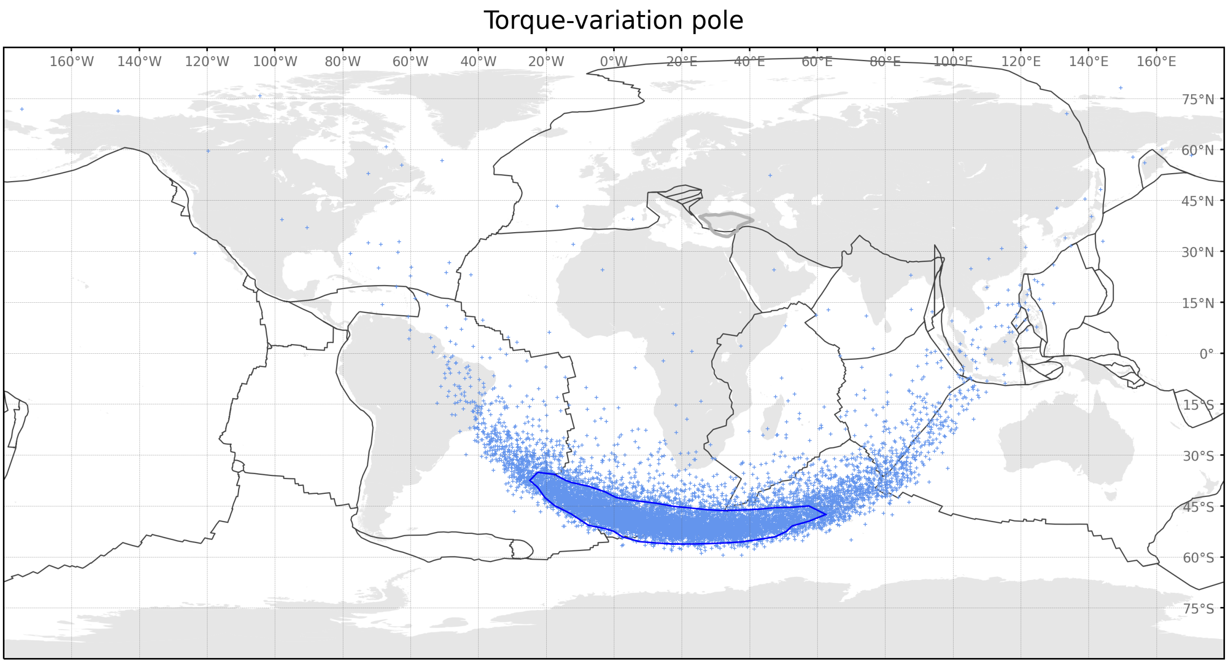

Figure 5: MAP_ROTATED_CNTR68_*.png output example for the Anatolia microplate motion–change, without ensemble rotation (Example Run 3). Global map shows a sub-sample of the torque–variation pole location and the ensemble's 68% confidence contour. Given 2D histogram resolution is 5 degrees (DM_CNTR_BINS = [5]). No rotation has been performed (ANG_ROT = [0, 0, 0]).

that is under–sampled in the first place leading to patches in the contour.

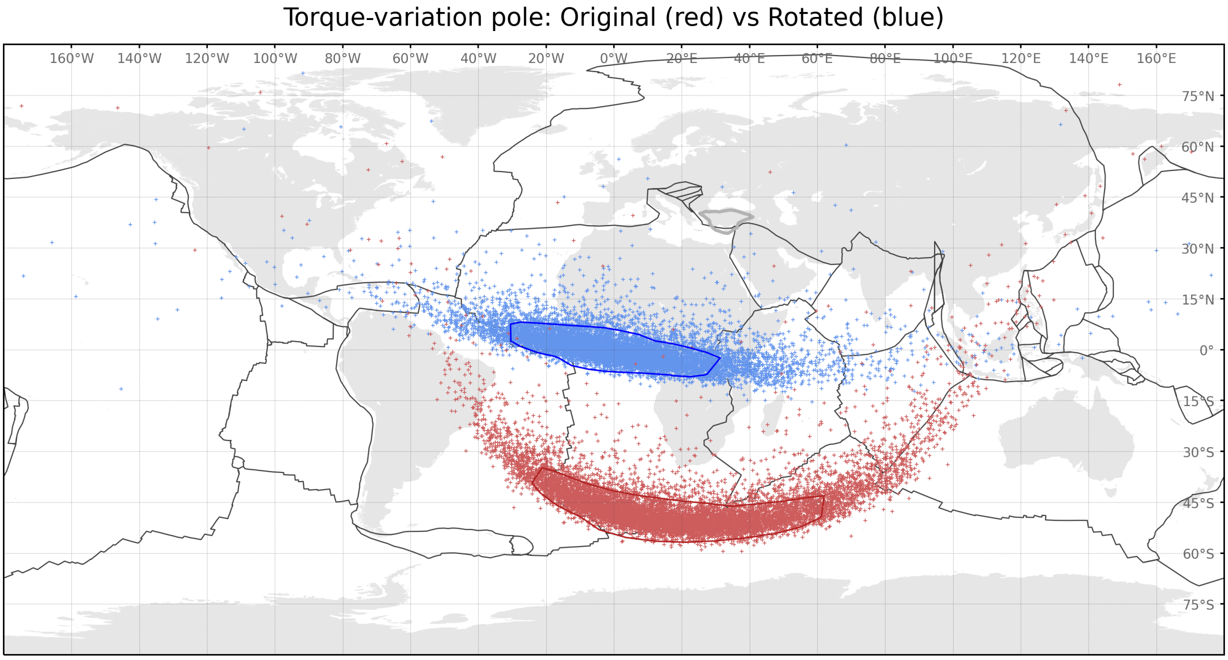

Figure 6: Same as in Figure 5, but with an ensemble rotation calculated by MYRIAM (Example Run 4). Original ensemble is shown in blue, rotated ensemble is shown in red. The rotation angles (`ANG_ROT = [-16.7, -50.2, 0.0]`) are set by MYRIAM and only aim at centering the ensemble at 0°N–0°E.

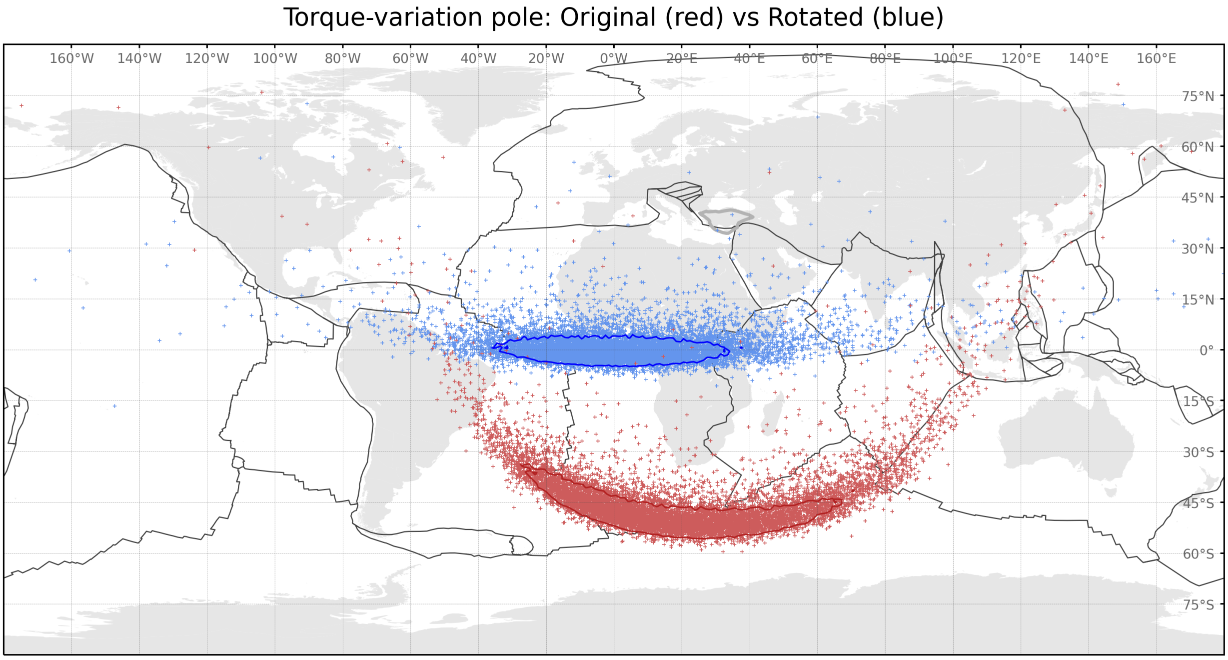

Figure 7: Same as in Figure 6, but with rotation angles and 2D binning parameters set by the user (Example Run 5). The given rotation angles are `ANG_ROT = [-16.7, -50.2, 9.0]`, and the 2D binning parameters are `DM_CNTR_BINS = [1.0, -85.0, 85.0, -25.0, 85.0]` (see Section 4 for details).

7.6 Run 6: Increasing the Euler–vector ensemble size

To improve the contouring obtained in Run 5, in the next run we address both issues. We increase the grid spacing from 1 to 2.5 degrees through parameter `DM_CNTR_BINS`, and let MYRIAM perform the sampling by providing single Euler vectors as inputs, instead of utilizing files `ENS_EV_AT_*.txt`, which contain only 10^5 samples. By supplying the average Euler vector and its covariance, we can request MYRIAM to sample e.g., 10^6 realizations of the Cartesian Euler vectors. These single–vector files can also be found inside the `samples/anatolia_plate` folder, under the names `STG_EV_AT_OLD.txt` and `STG_EV_AT_YOUNG.txt`. Before running MYRIAM, make sure to change parameters `EVo_PATH` and `EVy_PATH` accordingly.

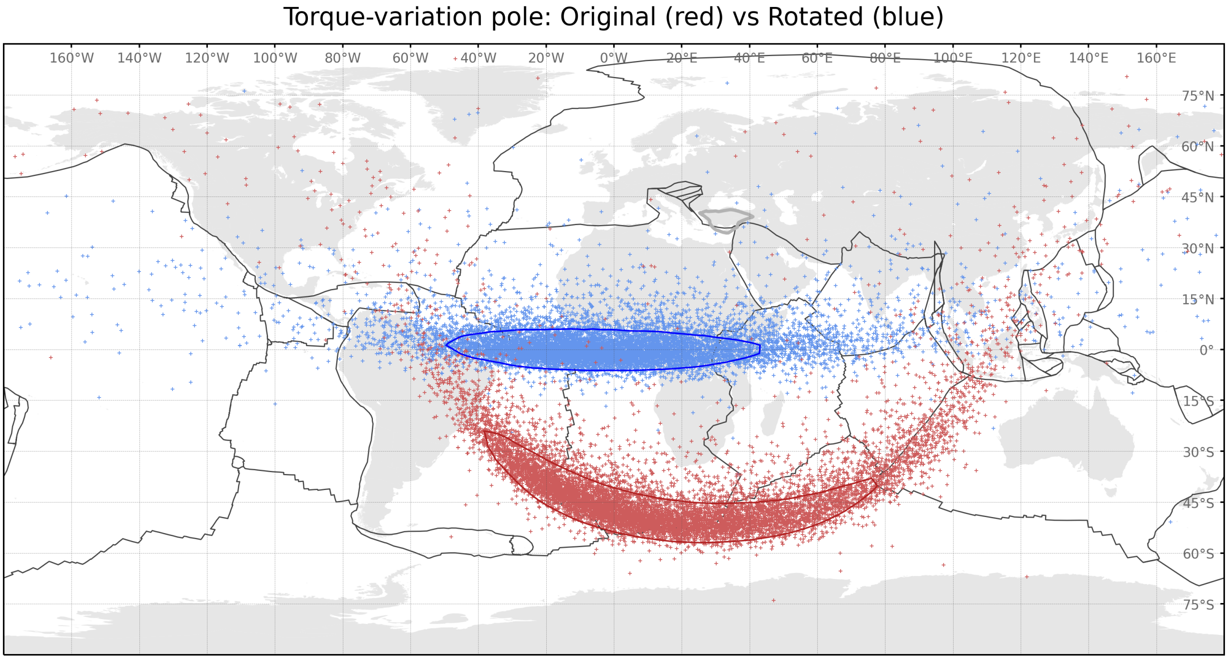

Figure 8: Same as in Figure 7, but with lower resolution binning and larger input Euler–vector ensembles (Example Run 6). The 2D binning resolution is set to 2.5 and the input Euler–vectors are sampled to a 10^6 ensemble size.

The improved contouring associated with using a larger resolution and ensemble size is evident in Figure 8.

Figure 9, which is not a direct output of MYRIAM, illustrates the impact onto the contouring of some of the variables utilized in the example above. Panel a) shows the effect of performing or not a rotation of the ensemble – towards a more equatorial zone – prior to contouring. In this particular example, this happens to be the least influential variable – i.e., MYRIAM performs adequately without the need for rotation. Panel b) in Figure 9 shows the influence of the 2D–histogram resolution utilized for contouring. This parameters impacts more onto the smoothness of the contour than onto its coordinates. Panel c) shows a comparison between the contouring performed with a torque ensemble of size 10^5 versus 10^6. This is arguably the most important factor to obtain more–faithful contours. An ensemble size of 10^6 generally offers a good trade–off between computing time and contour accuracy.

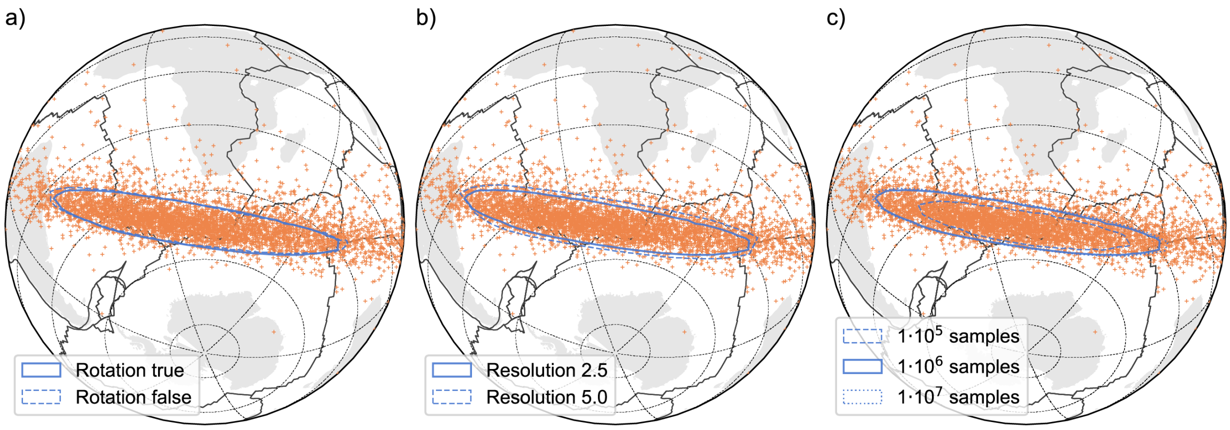

Figure 9: Comparison maps for the impact of a) rotation, b) resolution, and c) ensemble size on the ensembles contouring. Orange markers show a sub–sample of torque–variation poles. Blue lines show the resulting 68% confidence contours. The solid contour in all three plots is the same as the one in Figure 8 (parameters from Example Run 6). Dashed lines show the 68% confidence contour when a) Disabling the ensemble rotation (`ANG_ROT = [0.0, 0.0, 0.0]`). b) The resolution for the 2D histogram is set to 5 degrees (`DM_CNTR_BINS = [5.0]`). c) The ensemble size is equal to 10^5.

Table 1: Plate IDs for the plate contours built in the program, following Matthews et al. [2016].

Plate ID	Plate Name	Plate ID	Plate Name
ANT	Antarctica	NCA	Caroline
ARB	Arabia	NHF	New Hebrides–Fiji
AUS	Australia	NNB	North New Britain
BSS	Barisan/South Sumatra	NSU	North and Central Sulawesi
CAP	Capricorn	NUB	Nubia
CAR	Caribbean	NWB	North Woodlark Basin
CEL	Celebes Basin	PAC	Pacific
COC	Cocos	PAL	Palawan
EAW	Eastern Dinarides	PES	Pelso
EPH	East Philippines	RIV	Rivera
ESB	East Shikoku Basin	SAM	South America
EUR	Northern European Craton	SAN	Sandwich
GAL	Galapagos	SBA	South Banda Arc
IND	Southern India Craton	SCO	Scotia
JDF	Juan de Fuca	SNB	South New Britain
JFD	Juan Fernandez	SOL	South Solomon Basin
KAM	Kamchatka Peninsula	SOM	Somalia
MAR	Mariana Ridge	SPN	Southern Panonian
MAW	Mawgyi	SPS	South Philippine Sea
MOL	Molucca Sea	SSU	Southeast Sulawesi
NAM	North America	SUL	South Sulu Sea
NAZ	Nazca	TIS	Tisza
NBS	North Banda Sea	TON	Tonga Ridge

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