Calculation of the magnetic perturbation at the ground from TIEGCM

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Contents

1 Purpose of this Description

This documentation should briefly describe how the magnetic perturbation at the ground is calculated. The original code is from Art Richmond. It was modified to fit to the TIEGCM grid, to calculate the magnetic perturbation at the ground for a particular station as well as the global fields written into a NetCDF file. The number of spherical harmonics is now flexible. Also the grid can be defined by the user. In the following the source code is explained and references to the source code can be found.

2 TIEGCM model runs

To calculate the magnetic perturbation from the TIEGCM model a few modification to the source code have to be done. The version which can be used are TGCM15 or TIEGCM1.

Source code: default TGCM15 + modified source code from *maute/Tiegcm.d/modsrc16me*

- Necessary output fields: $SECFMAG$ = *'KQPHI','KQLAM','NSCRRT'*
- Setting flags in the code: *icalkqlam = 1* in *(transf.F)*
- TGCM15 will give four dimensional output fields for $SECFMAG$ = *'KQPHI','KQLAM','NSCRRT'* (time,height,latitude,longitude)

- Example input files and job script can be found in *maute/Work.d/magprt.d/modeloutput.d/-reconsttide.d*
- Only the updated electrodynamo can be used.

Source code: default TIEGCM1

- Necessary output fields: *SECFMAG2D = 'KQPHI','KQLAM','JQR'*
- Setting flags in the code: *icalkqlam==1* in *(dynamo.F)*
- TIEGCM1 will give three dimensional output for *SECFMAG2D = 'KQPHI','KQLAM','JQR'* (time,latitude,longitude)
- Example input files and job script can be found in *maute/Work.d/eej-june95.d/modelout.d*
- Only the updated electrodynamo can be used (*dynamo=2* in the input file).

3 How to run the program?

3.1 Source Code

It is recommended to use the newest version of the postprocessing program since new features were added and more comments were put in the source code. The postprocessing program was tested on the IBM but previous version were also developed on other platform. Basically it should be easy to transfer the code to another platform. Here are a few remarks what has to be taken into account:

- Change the include files: e.g. *#include "netcdf.inc"* on the IBM
- Generate new apex-file on the same platform to avoid problems. A program to do this can be found in */fs/othrorgs/home0/maute/work.d/wtmp.d/apex.d/myglob.f* . The right altitude range has to be used *ALTMN, ALTMX* as well as the path for the apex output file has to be modified. The year *TGRF* has to be the same as for the TIEGCM run.
- Use an f90 compiler. The makefile has to be adjusted.
- For older versions on other platforms (not IBMs) look into */fs/othrorgs/home0/maute/-work.d/wtmp.d*

The postprocessing program for the IBMs can be found in
newest version (takes only three dimensional input fields so far, which means TIEGCM1 has to be used to write secondary history fields): */fs/othrorgs/home0/maute/work.d/maggrd-new-ibm2d.d*
old program (reads four dimensional fields - TGCM15): */fs/othrorgs/home0/maute/work.d/-wtmp-ibm.d*
old program (reads three dimensional fields - TIEGCM1): */fs/othrorgs/home0/maute/work.d/-maggrd-ibm2d.d*

3.2 Running the program

In the following it is described how to run the newest version of the postprocessing program which can be found in */fs/othrorgs/home0/maute/work.d/maggrd-new-ibm2d.d* . The input parameters and different options are discussed.

- To make dependable:*perl mkdep*
  Compile: *gmake*
  Run: *t-ibm.exe*

- **Time** The start time index and end time index have to be specified. File *iface.F* variable:*start-time* , *end-time* (integer). The start and end time index refers to the NetCDF secondary history file on which *'KQPHI', 'KQLAM', 'JQR'* are defined. It is recommended if the output is written to two files to use Ncar Command Operator (NCO) ncrcat to extract the certain fields and put all the time steps into one file. Please note that the variable mtime has to be extracted too.

- **Working directory** File *iface.F* variable:*work* . The secondary history file has to be in this directory. Also the output NetCDF file are written into *maggrd.d/* in this directory. The character length of the variable work has to be exact.

- **Secondary history filename** File *iface.F* variable:*flnm* . This has to be an NetCDF secondary history output file on which the following fields have to be *'mtime', 'KQPHI', 'KQLAM', 'JQR'*. The path of the file is *work//flnm*

- **Apexfile** File *param.F* variable:*fileapex* . Path to the apex-file. Make sure that the year from the TIEGCM run is on the apexfile as well as that the right altitude range. The apex-file can be generated by */fs/othrorgs/home0/maute/work.d/wtmp.d/apex.d/myglob.f* .

- **Output** Two different outputs are generated. One is a NetCDF file with the global fields on it. It is in *path = work//"maggrd.d/"//flnm* . All the fields have time as the first dimension. The dimensions for most fields are (time, mag. latitude, mag. local time) otherwise (time, mag. latitude, mag. longitude) or (time, geog. latitude, geog. longitude). The output is written in *subroutine output* in file *nclplot.F* . If there already exists a file with the same name it will be overwritten. To get the global fields the variable *imagprt = 0/2* in *param.F* has to be set.The following fields are written to the NetCDF file *'kqlam-org','kqphi-org','kqlam', 'kqphi','eqcf-tor' , 'eqcf-tor-asym', 'eqcf-tor-sym', 'eqc-tot','eqc-fldalg', 'eqc-tot-sym' , 'eqc-grd', 'magpot-ext', 'magpot-int', 'dB-lam','dB-phi', 'dB-dwn', 'B-abs-mag'*
  To plot the results use IDL or NCL. The output for the magnetic perturbation at a particular station is written in ascii format into a file *'./output.d/'//abr//'.out'* where abr is the station name. Note that for each station a new file is generated. The values will be appended to an existing file. To get this output the variable *imagprt = 1/2* in *param.F* has to be set. The output is linewise with

  - bp,bl,bz : northward, eastward,downward component [nT]
  - bx,by,bz : X,Y Z component [nT]
  - h,d,bz : H,D,Z component [nT]

  To get output in geographic coordinates the variable *igeoplot=1* in *param.F* has to be set as well as *imagprt = 0/2* . The following fields are written to the NetCDF file *'dB-lam-geo', 'dB-phi-geo', 'dB-dwn-geo','B-abs-geo'*

- **Grid dimensions** (optional) The dimensions of the regular magnetic and regular geographic grid can be defined by the user. The secondary history fields are written on an irregular TIEGCM grid which is first mapped onto a regular grid. Note that if an irregular grid is used the higher order spherical harmonics P_n^m are not accurate any more. This was found by calculating the magnetic perturbation at satellite height */fs/othrorgs/home0/maute/work.d/-maggrd.d/ibm-qnmext-2* . The variables for the regular magnetic grid are *rmlon=81,rmlat=97* in *param.F* and *rglon=81,rglat=97* in *param.F* for the geographic grid

- **Height parameters** (optional) defined in *param.F*
  hi = 110. is the height of the ionospheric current shell [km]

hr = 90. is the reference height used in TIEGCM [km].
depth = 600. depth of the conducting layer within the Earth [km].

- **Normalized associated Legendre polynomials** P_n^m:
  maximum degree n: *nm = 80* (defined coeff.F)
  maximum order m: *nm = 24* (defined coeff.F)

- **Functions** Q_n^m:
  maximum degree n: *nqmax = 9* (defined coeff.F)
  maximum order m: *mqmax = 9* (defined coeff.F)
  If symmetric parts of J_{qr} should be included (for high latitude J_{qr} is symmetric) the flag is set to *iodd qnm = 1* (defined in coeff.F). This corresponds to $n - m$ odd which means that Q_n^m is symmetric. Otherwise only the antisymmetric functions of Q_n^m are used. Examining the influence of using higher degree and order we found that increasing the degree n leads to more structure in the high latitudes while increasing the order m will give more longitudinal structure at low latitudes. Therefore we set the default to $n = 9$ and $m = 9$.

- **Induced current**:
  To calculate the induced current two options exist *icm3e* :
  If a superconductor is assumed at a depth of d = 600. km. The internal coefficient are calculated by eq. (21)which corresponds to *icm3e = 0*
  If *icm3e = 1* Nils Olsen [Saba02] has provided us with the code *sphere.f* also used by the CM3E model. The code calculates a transfer matrix between the driving ionospheric signal and the driven induced current for similar frequencies. The model assumes a 1D conductivity. It's a four layer conductivity model derived from S_q and D_{st} data at selected European observatories. Therefore the transfer matrix is diagonal and the elements depend only on the degree n and the frequency.

  $$v_n^{m\ intgrd}(f) = q_{nn}^{mm}(f) v_n^{m\ ext}(f)$$

  with $v_n^{m\ intgrd}(f)$ the internal component depending on the frequency f, $v_n^{m\ ext}$ the external component and q_{nn}^{mm} the complex elements of the transfer matrix. In [Saba02] seasonal and UT dependence of the coefficients are assumed. In our postprocessing program we calculate the spherical harmonics coefficients only by considering each point in time and neglect seasonal and UT variation. (This should be included if we use this code to calculate magnetic perturbations at high latitudes.) Therefore the frequency is assumed to be represented by the longitudinal variation which is expressed by the order m with $f = \frac{m}{24hrs}$. Since q_{nn}^{mm} are calculated only for $f > 0$ i.e. $m > 0$ a few calculations have to be done to relate these complex coefficients to out real coefficients (see the handwritten notes for this). The relation between external and internal coefficient is expressed by eq. (22-24).

4 Source code to calculate of the magnetic perturbation at the ground

4.1 Overview

- **apex-mod.F**: apex routines default code (Roy Barnes).
- **coeff.F**: calculate the spherical harmonics coefficients c_n^m, v_n^m.
- **eqvcur-mod.F**: define global fields and grid arrays.

- **iface.F**: interface between TIEGCM output file and postprocessing program.
- **magfld.F**: apex routine default code (Roy Barnes).
- **maggrd.F**: controls calculation of c_n^m and output.
- **magloctm.f**: computes magnetic local time from magnetic longitude, subsolar coordinates, and geomagnetic pole coordinates.
- **map.F**: prepare for mapping fields from irregular TIEGCM grid to regular magnetic grid.
- **mapirr2reg.F**: mapping of the fields.
- **nclplot.F**: set up NetCDF output file and write output.
- **param.F**: set up all parameters used in this program.
- **subsol.F**: find subsolar geographic latitude and longitude given the date and time (Universal Time).
- **subsol-mlon.F**: get magnetic longitude (xmlon) for subsolar point.
- **xyz-magprt.F**: calculate magnetic perturbation.

4.2 Structure of code

The basic structure of the program can be summarized as follows:

- Create output file (IFACE)
- Define coordinates and dimensions (IFACE)
- CALPARAM: set up parameters
- NCDEFPDIM: set up regular grids (magnetic and geographic)
- Loop over all time-steps
  - Read from NetCDF file: KQLAM, KQPHI on TIEGCM magnetic grid (*mlon, mlat*) (IFACE)
  - MAPIRR2REG: convert KQLAM, KQPHI from irregular TIEGCM grid to regular magnetic grid (*rmlon, rmlat*)
  - SUBSOLLON: calculate subsolar point (*common/ssolar/ xmlon*)
  - MAGGRD: calculate magnetic perturbation at the ground (s. next paragraph)

The magnetic perturbation is calculated in *subroutine maggrd* which is briefly described in the following

- PREP-MAG2GEO: set up arrays for mapping fields to the geographic grid (*igeoplot = 1*)
- COEFFICIENT: calculate the spherical harmonics coefficients $c_n^{m(1)}$ and $c_n^{m(2)}$ for $\mathbf{K}^{equiv}$ by using $K_{q\phi_q}$ and $K_{q\lambda_q}$ (total c_{tot}, field-aligned c_{fld} and toroidal part c_{tor})
- COEF-EQCGRD: calculating the influence from external field mapped from the ionospheric layer to the ground (c_{grd})

- COEF-MAGPOT-EX: coefficient for magnetic potential v_n^m for the external magnetic potential (c_{mptext})
- COEF-MAGPOT-TOT: coefficient for total magnetic potential (external and induced) ($c_{mpttotgrd}$, $c_{mptextgrd}$, $c_{mptintgrd}$)
- XYZ-GLB: calculate magnetic perturbation due to equivalent current $K_{q\phi_q}^{equiv}$ and $K_{q\lambda_q}^{equiv}$ globally in magnetic and geographic coordinate system
- XYZ-STAT: calculate the magnetic perturbation at a particular station at the ground.
- CAL-BMAGNITUDE: calculate magnitude of magnetic perturbation in magnetic and geographic directions
- OUTPUT: write all the calculated fields to the output NetCDF file

5 Magnetic perturbation at the ground

The total current system $\mathbf{K}$ can be described by

$$\mathbf{K} = \mathbf{k} \times \nabla\Psi^{(1)} + \nabla_h \xi = K_{q\phi}\mathbf{f}_1 + K_{q\lambda}\mathbf{f}_2 \tag{1}$$

with $\mathbf{f}_1$ and $\mathbf{f}_2$ as basis vectors. The $\Psi^{(1)} = \eta$ from eq.(22) in [Rich74]. The first part in (1) $\mathbf{k}\times\nabla\Psi^{(1)}$ is divergence-free. The second part $\nabla_h\xi$ closes the field aligned current in the current sheet such that $\nabla_h\xi + \mathbf{J}_{qr}$ is also divergence-free. For representing the ground-level magnetic perturbation the concept of "equivalent current" is introduced. The equivalent current $\mathbf{K}^{equiv}$ is a fictitious divergence-free current which produce the same magnetic perturbation at the ground as does the three dimensional current system.

$$\mathbf{K}^{equiv} = \mathbf{k} \times \nabla\Psi^{(1)} + \mathbf{k} \times \nabla\Psi^{(2)} \tag{2}$$

with $\mathbf{k}$ the unit upward vector. The equivalent current function $\Psi(\theta_q, \phi_q)^{(k)}$ can be expressed with the spherical harmonics Υ_n^m by using the correspondent coefficients $c_n^{m\ (k)}$.

$$\Psi(\theta_q, \phi_q)^{(k)} = \sum_{m=-M}^{M} \sum_{n=|m|}^{N} c_n^{m\ (k)} \Upsilon_n^m(\theta_q, \phi_q) \tag{3}$$

There is no contribution to the equivalent current from the $\nabla_h\xi$ since this part is diverging and is multiplied by a rotational part. By definition multiplying divergent and rotational spherical harmonics will give zero (see eq.(24) in [Rich74]). To express the sheet current orthogonal spherical harmonics functions Υ_n^m are used as described in [Rich74].

$$\Upsilon_n^m(\theta_q, \phi_q) = \frac{1}{\sqrt{4\Pi}} P_n^m(cos\theta_q) e^{im\phi_q} \tag{4}$$

where P_n^m are normalized associated Legendre polynomials and ϕ_q the quasi-dipole longitude and θ_q the quasi-dipole colatitude with $\theta_q = \frac{\Pi}{2} - \lambda_q$. The normalized associated Legendre polynomials are given by

$$
\begin{aligned}
P_0^0(cos(\theta) &= 1 && && (5)\\
P_m^m(cos\theta) &= \sqrt{\frac{2m+1}{2m}} sin(\theta)P_{m-1}^{m-1}(cos(\theta)) && \text{for} \quad m>0 && (6)\\
P_n^m(cos\theta) &= [cos(\theta)P_{n-1}^m(cos(\theta) - R_{n-1}^m P_{n-2}^m(cos\theta)]/R_n^m && \text{for} \quad n>m\geq 0 && (7)\\
\frac{dP_n^m(cos\theta)}{d\theta} &= ncos\theta\frac{P_n^m(cos\theta)}{sin\ theta} - (2n+1)R_n^m\frac{P_{n-1}^m(cos\theta)}{d\theta} && \text{for} \quad n>m\geq 0 && (8)\\
P_n^{-m}(cos\theta) &= P_n^m(cos\theta) && && (9)\\
R_n^m &= \sqrt{\frac{n^2-m^2}{4n^2-1}} && && (10)
\end{aligned}
$$

$$
\begin{aligned}
f_m(\phi_q) &= \sqrt{2}sin(m\phi_q) && \text{for} \quad m>0 && (11)\\
f_m(\phi_q) &= 1 && \text{for} \quad m=0 && (12)\\
f_m(\phi_q) &= \sqrt{2}cos(m\phi_q) && \text{for} \quad m<0 && (13)
\end{aligned}
$$

and

$$
\begin{aligned}
e^{-im\phi_q} &\rightarrow f_m(\phi_q) && (14)\\
ie^{-im\phi_q} &\rightarrow f_{-m}(\phi_q) && (15)
\end{aligned}
$$

The calculation of the coefficients is done in *subroutine coefficient*. The input height is thereby h_i, the altitude of the ionospheric layer.

$$c_n^{m\ (1)} = \frac{r_i}{\sqrt{4\Pi}n(n+1)}\int_0^{2\Pi} e^{-im\phi_q}d\phi_q\int_0^{\Pi}\left(\frac{dP_n^m(\theta_q)}{d\theta_q}K_{q\phi_q} - m\frac{P_n^m}{sin\theta_q}(\theta_q)ie^{-im\phi_q}K_{q\lambda_q}\right)d\theta_q \quad (16)$$

$$
\begin{aligned}
c_n^{m\ (2)} = \frac{r_i}{\sqrt{4\Pi}n(n+1)}\int_0^{2\Pi} e^{-im\phi_q}d\phi_q\int_0^{\Pi}\frac{1}{sin\theta_q}\Big(&mQ_n^m(\theta_q)K_{q\phi_q}+ \\
&[-mP_n^m(\theta_q)+2ncos\theta_q Q_n^m(\theta_q)]iK_{q\lambda_q}\Big)d\theta_q
\end{aligned} \quad (17)
$$

Note that the signs can be changed according to the usage of $\lambda_q = \frac{\Pi}{2} - \theta_q$. In the code θ_q is used. Also $K_{q\lambda_q}$ is replaced by $K_{q\theta_q}$ which points southward.
The coefficients are added together to form $c_n^{m\ equiv} = c_n^{m(1)} + c_n^{m(2)}$ in *subroutine coefficient* (c_{tot}). The field-aligned contribution is calculated from $c_n^{m\ (2)} = c_{fld}$. The toroidal part is represented by $c_n^{m\ (1)}$.
To calculate the equivalent current function at the ground the coefficients are mapped from the ionospheric layer at $r_i = r_e + h_i$ down to the earth surface r_e.

$$c_n^{m\ grd} = \left(\frac{r_e}{r_i}\right)^n c_n^{m\ equiv} \quad (18)$$

The coefficients $c_n^{m\ grd}$ are used to calculate the coefficients of the magnetic potential v_n^m (eq. (14) [Rich74]). Note that in the source code these are still called c_n^m. The external component is derived from

$$v_n^{m\ ext} = \mu_0\frac{n+1}{2n+1}c_n^{m\ grd} \quad (19)$$

with μ_0 the permiability of free space. The contribution from the earth magnetic field with an assumed conducting layer at 600km depth is calculated in *subroutine cal-magpot-tot*. The external $v_n^{m\ extgrd}$ and internal $v_n^{m\ intgrd}$ and total $v_n^{m\ totgrd}$ part at the ground is

$$v_n^{m\ extgrd} = \frac{v_n^{m\ ext}}{r_e} \tag{20}$$

For a pertfectly conducting layer at depth d the following relation is applied ($icm3e = 0$)

$$v_n^{m\ intgrd} = \frac{v_n^{m\ ext}}{r_e} \frac{n}{n+1} \left(\frac{r_e - d}{r_e} \right)^{2n+1} \tag{21}$$

If a 1D conductivity model used by CM3E is used with assumed longitudinal dependence the internal coefficient will be calculated by

$$v_n^{m\ intgrd} = Re(q_{nn}^{mm}) \frac{v_n^{m\ ext}}{r_e} + Im(q_{nn}^{mm}) \frac{v_n^{-m\ ext}}{r_e} \quad \text{for} \quad m \neq 0 \tag{22}$$

with

$$Re\ (q_{nn}^{-mm}) = Re\ (q_{nn}^{mm}) \quad \text{and} \quad Im\ (q_{nn}^{-mm}) = -Im\ (q_{nn}^{mm}) \tag{23}$$

and

$$v_n^{m\ intgrd} = \frac{v_n^{m\ ext}}{r_e} \frac{n}{n+1} \left(\frac{r_e - d^*}{r_e} \right)^{2n+1} \quad \text{for} \quad m = 0 \tag{24}$$

with $d^* = 1000.$ km which corresponds to very long periods. The relation (23) can be derived from the comparision with CM3E and our code (see handwritten notes).

$$v_n^{m\ totgrd} = v_n^{m\ extgrd} + v_n^{m\ intgrd} = \frac{v_n^{m\ ext}}{r_e} \left(\frac{n}{n+1} \left(\frac{r_e - d}{r_e} \right)^{2n+1} + 1 \right) \tag{25}$$

Knowing the coefficients of the magnetic potential V the magnetic perturbation can be evaluated by using

$$\Delta \mathbf{B} = -\nabla(\Delta V) \tag{26}$$

$$\Delta B_{q\ \theta_q}^{equiv} = \sum_{m=-M}^{M} \sum_{n=|m|}^{N} v_n^{m\ totgrd} \frac{dP_n^m(\theta_q)}{d\theta_q} e^{-im\phi_q} \tag{27}$$

$$\Delta B_{q\ \phi_q}^{equiv} = -\sum_{m=-M}^{M} \sum_{n=|m|}^{N} v_n^{m\ totgrd} \frac{P_n^m(\theta_q)}{sin\theta_q} ime^{-im\phi_q} \tag{28}$$

$$\Delta B_{q\ down}^{equiv} = \sum_{m=-M}^{M} \sum_{n=|m|}^{N} \left(nv_n^{m\ extgrd} - (n+1) v_n^{m\ intgrd} \right) P_n^m(\theta_q) e^{-im\phi_q} \tag{29}$$

References

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