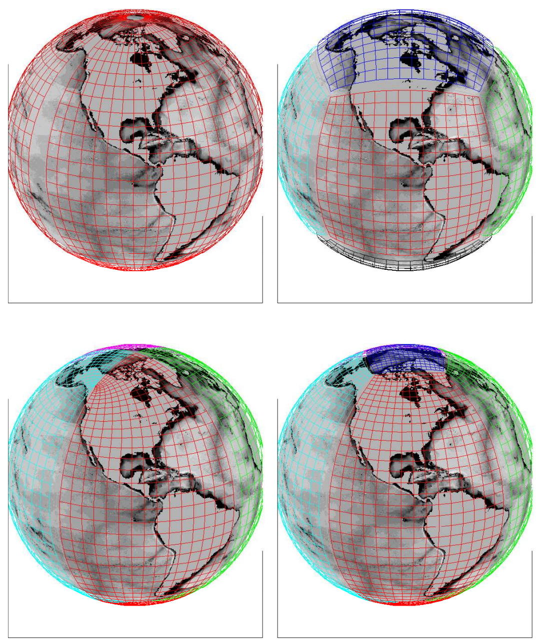
gcmfaces

a Matlab framework for the analysis of gridded earth variables



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Summary

`gcmfaces` is a Matlab toolbox designed to handle gridded earth variables; results of `MITgcm` ocean simulations originally (Forget et al., 2015). It allows users to seamlessly deal with various gridding approaches (e.g. see Fig. 3) using compact and generic codes. It includes many basic and more evolved functionalities such as plotting global maps, computing transports, and budgets. `MITprof` is a complementary toolbox designed to handle in-situ ocean observations (Forget et al., 2015). This document provides guidelines to download, update, and activate the software (section 1), documents basic design and features of `gcmfaces` (sections 2 and 3), and briefly describes higher level `gcmfaces` functionalities (sections 4 and 5).

References

Forget, G., J.-M. Campin, P. Heimbach, C. N. Hill, R. M. Ponte, and C. Wunsch, 2015: ECCO version 4: an integrated framework for non-linear inverse modeling and global ocean state estimation. *Geoscientific Model Development*, **8 (10)**, 3071–3104, doi:10.5194/gmd-8-3071-2015, URL http://www.geosci-model-dev.net/8/3071/2015/.

Forget, G., J.-M. Campin, P. Heimbach, C. N. Hill, R. M. Ponte, and C. Wunsch, 2016: ECCO version 4: Second release. URL http://hdl.handle.net/1721.1/102062.

Disclaimer

Users of the `gcmfaces` *software are kindly asked to include a reference to Forget et al. (2015) when publishing results that rely on* `gcmfaces`*. The free software programs may be freely distributed, provided that no charge is levied, and that the disclaimer below is always attached to it. The programs are provided as is without any guarantees or warranty. Although the authors have attempted to find and correct any bugs in the free software programs, the authors are not responsible for any damage or losses of any kind caused by the use or misuse of the programs. The authors are under no obligation to provide support, service, corrections, or upgrades to the free software programs.*

1 Download And Get Started

There are currently three ways to download `gcmfaces` and `MITprof`:

1. Download the latest frozen versions[1] from `gcmfaces` and `MITprof` @ http://mit.ecco-group.org/opendap/ecco_for_las/version_4/checkpoints/
2. Download using the `MITgcm` CVS server (see section 1.1) which has the major advantage that the codes can later easily be updated.
3. Download from github (https://github.com/gaelforget).

1.1 Download Using CVS

At the command line, login to the `MITgcm` CVS server as explained @ http://mitgcm.org/public/using_cvs.html then download the up to date versions of `gcmfaces` and `MITprof` as follows:

```
cvs co -P -d gcmfaces MITgcm_contrib/gael/matlab_class
cvs co -P -d MITprof MITgcm_contrib/gael/profilesMatlabProcessing
```

All past and future evolutions of the codes can be traced using the `cvs` version control system. To update an existing copy of the codes and take advantage of the latest developments one goes inside a directory and types 'cvs update -P -d' at the command line. If you are new to `cvs` then you may want to read about the update command at http://mitgcm.org/public/using_cvs.html.

1.2 Get Started

Download the LLC90 grid (see Forget et al., 2015) from the ECCO server: ftp://mit.ecco-group.org/ecco_for_las/version_4/release2/nctiles_grid/

[1] c66a_gcmfaces.tar and c66a_MITprof.tar at the time of writing.

Assuming that 'gcmfaces/', 'MITprof/', and 'nctiles_grid/' have been downloaded to a common directory, start Matlab from there and type:

```
%add gcmfaces and MITprof directories to Matlab path:
p = genpath('gcmfaces/'); addpath(p);
p = genpath('MITprof/'); addpath(p);

%load nctiles_grid in memory:
grid_load;

%displays list of grid variables:
gcmfaces_global; disp(mygrid);
```

The applications in sections 4 and 5 further require downloading model output from the ECCO version 4, release 2 ocean state estimate (Forget et al., 2016) from ftp://mit.ecco-group.org/ecco_for_las/version_4/release2/ (e.g., using commands reported in Fig. 1) that should be organized as shown in Fig. 2. The 'nctiles_monthly/' directory (170G) contains the 1992-2011 monthly time series that, along with the 'nctiles_remotesensing/' and 'profiles/' (model-data misfits), allows users to reproduce the 'standard analysis' in Forget et al. (2016). The 'nctiles_climatology/' directory (10G) provides a light-weight alternative (Sect. 5). Finally the `m_map` plotting toolbox is available at https://www.eoas.ubc.ca/~rich/map.html.

```
wget --recursive ftp://mit.ecco-group.org/\
ecco_for_las/version_4/release2/nctiles_grid
wget --recursive ftp://mit.ecco-group.org/\
ecco_for_las/version_4/release2/nctiles_climatology
wget --recursive ftp://mit.ecco-group.org/\
ecco_for_las/version_4/release2/nctiles_monthly
wget --recursive ftp://mit.ecco-group.org/\
ecco_for_las/version_4/release2/nctiles_remotesensing
wget --recursive ftp://mit.ecco-group.org/\
ecco_for_las/version_4/release2/profiles
```

Figure 1: One method to download model output from the ECCO version 4, release 2 ocean state estimate (Forget et al., 2016) at the command line.

Figure 2: Directory structure that allows users to execute Matlab code snippets provided in this document. The most basic gcmfaces installation only requires the 'gcmfaces/', 'MITprof/', and 'nctiles_grid/' directories (see section 1 for details). The 'm_map' toolbox is frequently used for geographic depictions. The 'release2_climatology/', and 'release2/' directories serve to demonstrate higher-level functions in sections 4 and 5.

```
./
|__gcmfaces/ (Matlab toolbox)
|__MITprof/ (Matlab toolbox)
|__m_map/ (Matlab toolbox)
|__nctiles_grid/ (netcdf files)
|__release2_climatology/
|  |__nctiles_climatology/
|  |__mat/ (see section 5)
|  |__tex/ (see section 5)
|__release2/
   |__nctiles_monthly/
   |__nctiles_remotesensing/)
   |__profiles/
   |__mat/ (see section 5)
   |__tex/ (see section 5)
```

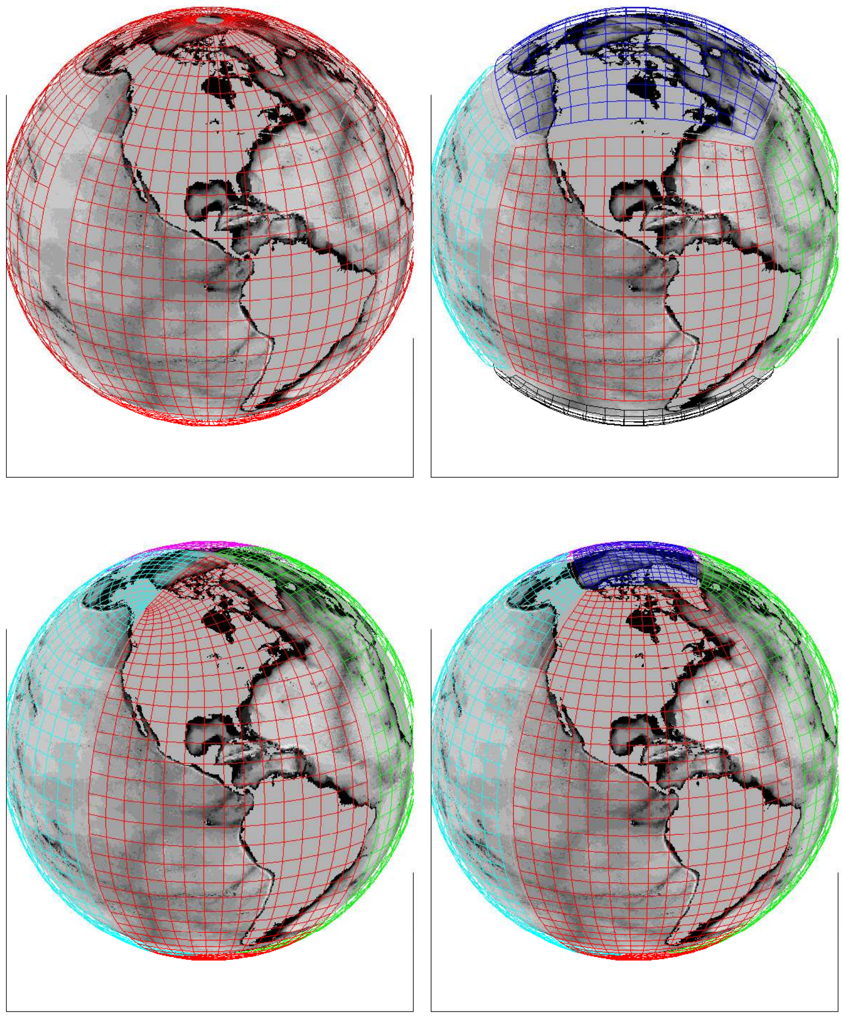


Figure 3: Four different ways of gridding the earth. Top left: lat-lon grid, mapping the earth to a single rectangular array ('face'). Top right: cube-sphere grid, mapping the earth to the six faces of a cube. Bottom right: lat-lon-cap 'LLC' grid (five faces). Bottom left: quadripolar grid (four faces). Faces are color-coded, and the ocean topography underlaid. Only a subset of the grid lines are shown in this depiction, which furthermore artificially shows gaps between faces to magnify face edges.

2 The gcmfaces class

The basic motivation for developing `gcmfaces` was to provide a unified framework that allows for analysis of earth variables on various grids. Fig. 3 shows four types of grids that are commonly used in ocean general circulation models (GCMs). Despite evident differences in GCM grid designs, such grids can all be represented as sets of connected arrays ('faces'). This fact is illustrated in Fig. 4 for the LLC90 grid (bottom right panel in Fig. 3) that is used in ECCO v4 (Forget et al., 2015).

The core of `gcmfaces` lies in its definition (in the '@gcmfaces/' subdirectory) of an additional Matlab data type ('class') that represents gridded earth variables as sets of connected arrays. An object of the `gcmfaces` class is stored in memory as shown in Table 1. The `gcmfaces` class inherits many of its basic operations (e.g., '+') from the 'double' class as illustrated by `@gcmfaces/plus.m` in Table 2. Objects of the `gcmfaces` class can thus be manipulated simply through compact and generic expressions such as 'a+b' that are robust to changes in grid design (see section 3.3 for details).

Table 1: Gridded variable represented using the gcmfaces class. In this case the LLC90 grid (Fig. 3, bottom right) is used that has five faces (f1 to f5).

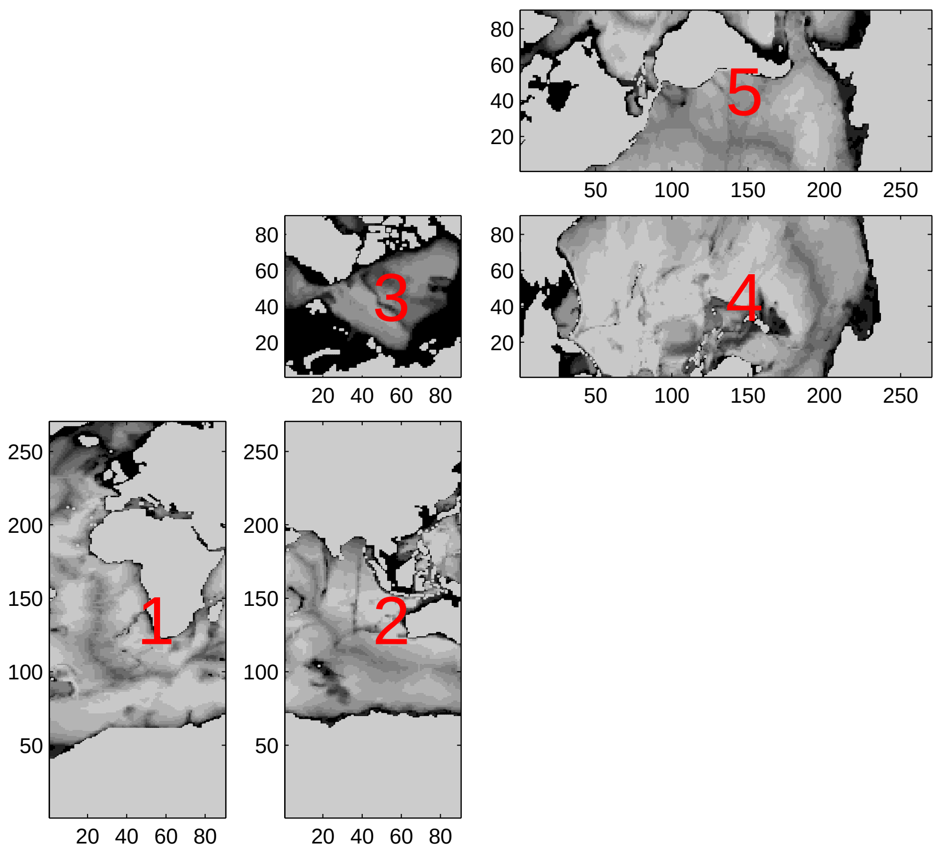
```
fld =
      nFaces:  5
          f1:  [90x270 double]
          f2:  [90x270 double]
          f3:  [90x90 double]
          f4:  [270x90 double]
          f5:  [270x90 double]
```

Table 2: The '+' operation for gcmfaces objects (@gcmfaces/plus.m).

```
function r = plus(p,q)
%overloaded gcmfaces `+' function :
%  simply calls double `+' function for each face data
%  if any of the two arguments is a gcmfaces object

if isa(p,'gcmfaces'); r=p; else; r=q; end;
for iFace=1:r.nFaces;
   iF=num2str(iFace);
   if isa(p,'gcmfaces')&isa(q,'gcmfaces');
       eval(['r.f' iF '=p.f' iF '+q.f' iF ';']);
   elseif isa(p,'gcmfaces')&isa(q,'double');
       eval(['r.f' iF '=p.f' iF '+q;']);
   elseif isa(p,'double')&isa(q,'gcmfaces');
       eval(['r.f' iF '=p+q.f' iF ';']);
   else;
      error('gcmfaces plus: types are incompatible')
   end;
end;
```

Figure 4: Ocean topography displayed face by face for the LLC90 grid (Fig. 3, bottom right). The face indices (from 1 to 5) are overlaid in red. Within each face, grid point indices increase from left to right and bottom to top in this view that reflects the data organization in memory (Tab. 1). This plot is generated by calling 'example_display(1)'.



3 Basic Features

The representation of grid variables in memory is documented in section 3.1. Other key features of `gcmfaces` are 'exchange' functions that implement connections between faces (section 3.2) and 'overloaded' operations (section 3.3). I/O functions are discussed in section 3.4.

3.1 Grid Variables

In practice the `gcmfaces` framework gets activated by adding its directories to the Matlab path and loading a grid in memory using the `grid_load.m` function as done in sections 1.2. The default grid (LLC90) can be loaded in memory through a call to `grid_load.m` without any argument. For other grids, `grid_load.m` arguments need to be specified as explained by 'help grid_load.m'. `grid_load.m` stores all grid variables in memory within a global structure named `mygrid` (Tab.3).

`mygrid` can be accessed within Matlab at any point by declaring it as 'global mygrid;' or using `gcmfaces_global.m` . The latter method additionally: (1) issues a warning when 'mygrid has not yet been loaded to memory'; provides a few environment variables via `myenv`; adds `gcmfaces` directories to the path if needed. It should be stressed that `gcmfaces` functions often rely on `mygrid` and `myenv`. If they get deleted from memory (e.g., by a 'clear all') then a call to `grid_load.m` will re-activate `gcmfaces` properly.

The C-grid variable names listed in Tab.3 follow the MITgcm naming convention (see sections 2.11 and 6.2.4 in the MITgcm documentation[2]). In brief, XC, YC and RC denote longitude, latitude and vertical position of tracer variables. DXC, DYC, DRC and RAC are the corresponding grid spacings (in m) and grid cell areas (in m^2). Another set of such fields (XG,

[2]http://mitgcm.org/public/r2_manual/latest/online_documents/manual.pdf

Table 3: List of grid variables contained in the mygrid global structure. The naming convention are directly inherited from the MITgcm. For details, see: http://mitgcm.org/public/r2_manual/latest/online_documents/manual.pdf

XC	:	[1x1 gcmfaces]	longitude (tracer)
YC	:	[1x1 gcmfaces]	latitude (tracer)
RC	:	[50x1 double]	depth (tracer)
XG	:	[1x1 gcmfaces]	longitude (vorticity)
YG	:	[1x1 gcmfaces]	latitude (vorticity)
RF	:	[51x1 double]	depth (velocity along 3rd dim)
DXC	:	[1x1 gcmfaces]	grid spacing (tracer, 1st dim)
DYC	:	[1x1 gcmfaces]	grid spacing (tracer, 2nd dim)
DRC	:	[50x1 double]	grid spacing (tracer, 3nd dim)
RAC	:	[1x1 gcmfaces]	grid cell area (tracer)
DXG	:	[1x1 gcmfaces]	grid spacing (vorticity, 1st dim)
DYG	:	[1x1 gcmfaces]	grid spacing (vorticity, 2nd dim)
DRF	:	[50x1 double]	grid spacing (velocity, 3nd dim)
RAZ	:	[1x1 gcmfaces]	grid cell area (vorticity)
AngleCS	:	[1x1 gcmfaces]	grid orientation (tracer, cosine)
AngleSN	:	[1x1 gcmfaces]	grid orientation (tracer, cosine)
Depth	:	[1x1 gcmfaces]	ocean bottom depth (tracer)
hFacC	:	[1x1 gcmfaces]	partial cell factor (tracer)
hFacS	:	[1x1 gcmfaces]	partial cell factor (velocity, 2nd dim)
hFacW	:	[1x1 gcmfaces]	partial cell factor (velocity, 1rst dim)

YG, RF, DXG, DYG, DRF, RAZ) is necessary to complete the C-grid specification where velocity variables are shifted compared with tracer variables.

The indexing and vector conventions also derive from the `MITgcm`. The indexing convention is illustrated for the LLC90 grid in Fig. 4. For a vector field the first component (U) points straight to the right of the page in Fig. 4, whereas the second component (V) points strait to the top of the page. The location of U components are shifted by half a grid point towards the left of the page, while the location of V components are shifted by half a grid point towards the bottom of the page (reflecting the C-grid approach).

3.2 Exchange Functions

Many quantities of interest (e.g., gradients and flow convergences) involve values from neighboring grid points that often need to be 'exchanged' between faces. This is achieved in practice by appending rows and columns at the sides of each face that are obtained from the neighboring faces – appending rows and columns from faces #2, #3, and #5 at the sides of face #1 in the Fig. 4 example. These exchanges are operated by `exch_T_N.m` for tracer fields and by `exch_UV_N.m` for velocity fields. These functions are needed for example to compute gradients (with `calc_T_grad.m`) and flow convergences (with `calc_UV_conv.m`) in sections 4 and 5.

3.3 Overloaded Functions

Table 2 depicts the overloading of the '+' operation by `@gcmfaces/plus.m` . In executing commands such as 'fld+1', Matlab will select `@gcmfaces/plus.m` if one of the arguments of '+' is of the `gcmfaces` class. Many common operations and functions are similarly overloaded in the '@gcmfaces/' directory that defines the `gcmfaces` class and its operations:

1. Logical operators: and, eq, ge, gt, isnan, le, lt, ne, not, or

2. Numerical operators: abs, angle, cat, cos, cumsum, diff, exp, imag, log2, max, mean, median, min, minus, mrdivide, mtimes, nanmax, nanmean, nanmedian, nanmin, nanstd, nansum, plus, power, rdivide, real, sin, sqrt, std, sum, tan, times, uminus, uplus.

3. Indexing operators: subsasgn, subsref, find, get, set, squeeze, repmat.

It is worth mentioning the case of `@gcmfaces/subsasgn.m` (subscripted assignment) and `@gcmfaces/subsref.m` (subscripted reference) since they are some of the most commonly used Matlab functions. For example, if fld is of the 'double' class then 'tmp2=fld(1);' and 'fld(1)=1;' respectively call subsref.m and subsasgn.m. If fld instead is of the `gcmfaces` class then `@gcmfaces/subsref.m` behaves as follows:

```
fld{n}      returns the n^{th} face data (i.e. an array).
fld(:,:,n) returns the n^{th} vertical level (i.e. a gcmfaces).
```

And `@gcmfaces/subsasgn.m` behaves similarly but for assignments. The variables in Table 1 can also be accessed 'manually'. For example:

```
fld.nFaces  returns the nFaces attribute (double).
fld.f1      returns the face #1 array (double).
```

3.4 I/O Functions

Objects of the `gcmfaces` class can simply be saved to or read from file in Matlab's own I/O format ('.mat' files). An alternative is to use `convert2array.m` or `convert2gcmfaces.m` to re-organize the faces data into one array (or vice versa) that can readily be written to or read from binary files. The other file formats that are currently supported in the `gcmfaces` framework are: (1) the MITgcm 'mds' binary format documented here[3]; (2) the 'nctiles' format used to distribute ECCO v4 fields (Forget et al., 2015). When reading

[3]http://mitgcm.org/public/r2_manual/latest/online_documents/manual.pdf

such files, the provided I/O functions (rdmds2gcmfaces.m, read_bin.m, and read_nctiles.m) reformat the data into `gcmfaces` objects on the fly.

4 Tutorial

Here it is assumed that the user has completed the installation procedure in section 1.2 (including the installation of 'nctiles_climatology/' and 'm_map/'). `gcmfaces_demo.m` can then be executed by starting Matlab and typing

```
p = genpath('gcmfaces/'); addpath(p);
p = genpath('m_map/'); addpath(p);
gcmfaces_demo;
```

to illustrate several `gcmfaces`' capabilities. As prompted by `gcmfaces_demo.m` the user specifies a desired amount of explanatory text output. `gcmfaces_demo.m` then proceeds through the examples while displaying explanations in the Matlab command window. Before each example the user is prompted to type the return key to proceed further. The Matlab GUI and debugger can also be used to run the examples line by line.

The first section of `gcmfaces_demo.m` illustrates I/O (`grid_load.m`) and plotting (`example_display.m`) capabilities. `gcmfaces` relies on `m_map` (https://www.eoas.ubc.ca/ rich/map.html) for geographical projections through the `m_map_gcmfaces` front-end that typically produces Fig. 5. The `convert2pcol` function provides an alternative way to display results directly via 'pcolor' (Fig. 6). The second section of `gcmfaces_demo.m` focuses on data processing capabilities such as interpolation (`example_interp.m`) and smoothing (`example_smooth.m`). `example_interp.m` illustrates the interpolation of `gcmfaces` fields to a lat-lon grid, and vice versa. `example_smooth.m` integrates a diffusion equation, which illustrates computations of tracer gradients and flux convergences. Finally `gcmfaces_demo.m` illustrates computations of oceanic transports (`example_transports.m`).

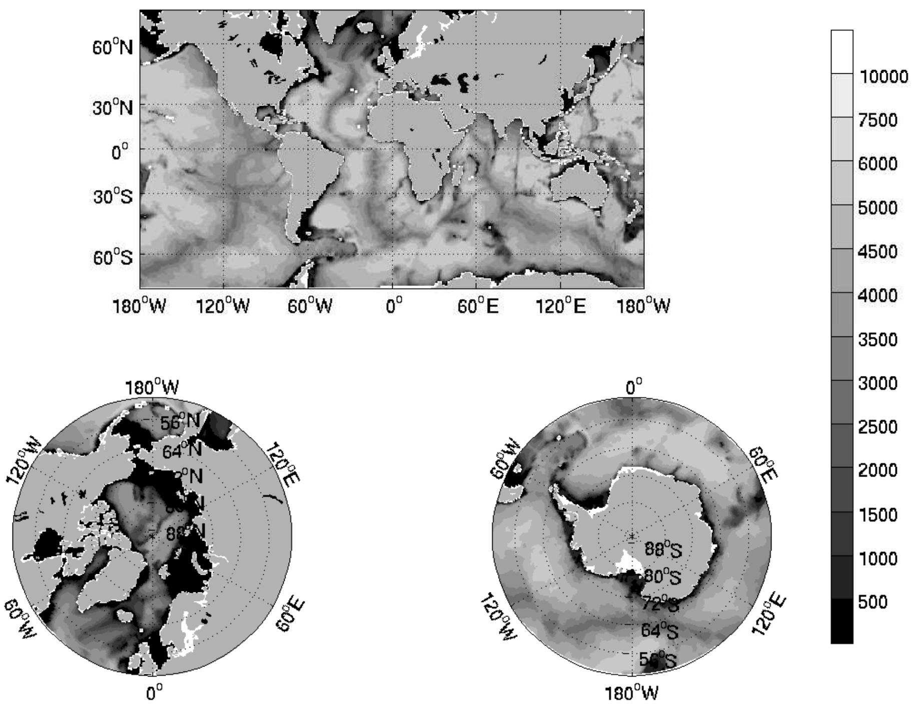


Figure 5: Same as Fig. 4 but plotted in geographical coordinates using m_map_gcmfaces.m. This plot is generated by calling 'example_display(4)'.

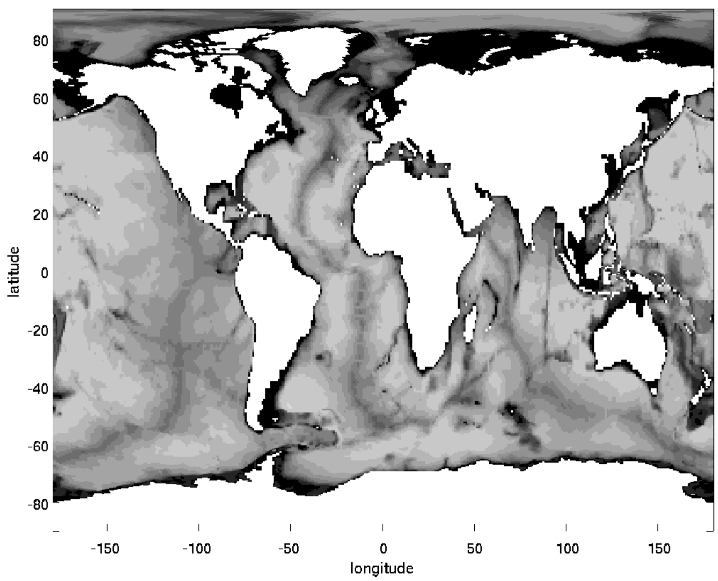


Figure 6: Same as Fig. 4 but plotted in geographical coordinates using convert2pcol.m. This plot is generated by calling 'example_display(3)'.

5 Standard Analysis

The `gcmfaces` ‘standard analysis’ consists of an extensive set of physical diagnostics that are routinely monitored in MITgcm simulations and ECCO v4 estimates (e.g., Forget et al., 2015, 2016). The computational loop is operated by `diags_driver.m` that expects the data organization shown in Fig. 2. The results of `diags_driver.m` are stored in a dedicated directory (‘mat/’ in Fig. 2). The display phase is done afterwards by calling `diags_display.m` (simple display to screen) or `diags_driver_tex.m` (to generate a tex file).

Here it is assumed that the user has completed the installation procedure in section 1.2 (including the installation of ‘nctiles_climatology/’ and ‘m_map/’). The code below then generates and displays mean and variance maps (setDiags=’B’ encoded in `diags_set_B.m`) from the ECCO v4 monthly mean climatology (12 monthly fields), which takes ≈ 5 minutes:

```
%add paths:
p = genpath('gcmfaces/'); addpath(p);
p = genpath('MITprof/'); addpath(p);
p = genpath('m_map/'); addpath(p);

%compute diagnostics:
help diags_driver;
dirModel='release2_climatology/';
dirMat=[dirModel 'mat/'];
setDiags='B';
diags_driver(dirModel,dirMat,'climatology',setDiags);

%display results:
diags_display(dirMat,setDiags);
```

Each generated plot has a caption that indicates the quantity being displayed. Other sets of diagnostic can be displayed similarly with different specifications of setDiags. Each one requires a specific set of model output. Sets of diagnostics that can be generated using 'nctiles_climatology/' or 'nctiles_monthly/' include oceanic transports ('A'), mean and variance maps ('B'), sections and time series ('C'), and mixed layer depths ('MLD').

If the 'setDiags' argument to `diags_driver.m` is omitted then these four diagnostic sets are generated at once, which takes ≈1/2 hour. Each set of diagnostics (computation and display) is encoded in one routine with a name such as 'diags_set_XX.m' (where 'XX' stands for e.g., 'A', 'B', 'C', or 'MLD'). These routines can be found in the 'gcmfaces_diags/' subdirectory and are expected to be operated via diags_driver.m.

The results generated via diags_driver.m can then be displayed via diags_driver_tex.m which saves plots to disk and creates a compilable tex file including all of the plots. This can take an additional 10 minutes:

```
dirModel='release2_climatology/'; dirMat=[dirModel 'mat/'];
dirTex=[dirModel 'tex/']; nameTex='standardAnalysis';
diags_driver_tex(dirMat,{},dirTex,nameTex);
```

These same diagnostics can be generated for the monthly ECCO v4 time series (see Sect. 1.2 and Fig. 2) by setting 'dirModel' to 'release2/' in the above code snippet and changing the 'diags_driver.m' call to:

```
 diags_driver(dirModel,dirMat,[1992:2011]);
```

Since the 20 year time series consists of 240 monthly records, computational times reported above are then multiplied by 20. The full computation therefore typically runs overnight. To speed up the process it can be distributed over multiple processors by splitting [1992:2011] into subsets.