Welcome to the MPAS tutorial practice guide

This web page is intended to serve as a guide through the practice exercises of this tutorial. Exercises are split into seven main sections, each of which focuses on a particular aspect of using the MPAS-Atmosphere model.

While going through this practice guide, you may find it helpful to have a copy of the MPAS-Atmosphere Users' Guide available in another window. Click here to open the Users' Guide in a new window.

In case you would like to refer to any of the lecture slides from previous days, you can open the Tutorial Agenda in another window.

You can proceed through the sections of this practical guide at your own pace. It is highly recommended to go through the exercises in order, since later exercises may require the output of earlier ones. Clicking the grey headers will expand each section or subsection.

0. Prerequisites and environment setup

The practical exercises in this tutorial have been tailored to work on the Derecho system. Derecho is an HPC cluster that provides most of the libraries needed by MPAS and its pre- and post-processing tools through *modules*. In general, before compiling and running MPAS-Atmosphere on your own system, you will need an MPI-2 implementation as well as the NetCDF-4, PnetCDF, and PIO libraries.

> Beginning with MPAS v8.0, a built-in alternative to the PIO library is available: the Simple MPAS I/O Layer (SMIOL). SMIOL requires just the PnetCDF library, and there is no need for the NetCDF-4 and PIO libraries when compiling MPAS itself. In this tutorial, we will be using MPAS with the SMIOL library.

Before going through any of the exercises in subsequent sections, we will need to run several commands to prepare our environment. Firstly, we will purge all loaded modules to begin from a known starting point (with no modules loaded); then, we will load several modules to give access to the GNU compilers as well as an MPI implementation:

```
$ module --force purge
$ module load ncarenv/23.09
$ module load craype/2.7.23
$ module load gcc/13.2.0
$ module load ncarcompilers/1.0.0
$ module load cray-mpich/8.1.27
```

Next, we will load modules for additional libraries needed by the MPAS-Atmosphere model. Besides the Parallel-NetCDF module (`parallel-netcdf/1.12.3`) needed by MPAS itself, the `netcdf/4.9.2` module is being loaded to support compilation of pre- and post-processing tools and so that we have access to the standard `ncdump` program for showing the contents of NetCDF files.

```
$ module load parallel-netcdf/1.12.3
$ module load netcdf/4.9.2
```

At this point, running `module list` should print the following:

```
$ module list

Currently Loaded Modules:
  1) ncarenv/23.09 (S)    3) gcc/13.2.0            5) cray-mpich/8.1.27        7) hdf5/1.14.3
  2) craype/2.7.23        4) ncarcompilers/1.0.0   6) parallel-netcdf/1.12.3   8) netcdf/4.9.2

  Where:
   S:  Module is Sticky, requires --force to unload or purge
```

Post-processing exercises will need Python along with the NumPy, PyNGL, NetCDF4, and miscellaneous other Python packages. On Derecho, these are available in a Conda environment named 'npl'. The npl environment also provides the NCAR Command Language (NCL). We can load the conda module and activate the npl environment with the following commands:

```
$ module load conda
$ conda activate npl
```

Some Python plotting scripts that will be used in this tutorial rely on additional Python code that is located in a non-standard location. In order for these plotting scripts to work, we'll need to set our `PYTHONPATH` environment variable using the following command:

```
$ export PYTHONPATH=/glade/campaign/mmm/wmr/mpas_tutorial/python_scripts
```

Additionally, we can load a module to provide access to the 'ncview' tool:

```
$ module load ncview
```

When running limited-area simulations, we will need to use Metis to create our own graph partition files. We can add the **gpmetis** command to our **PATH** with the following:

```
$ export PATH=/glade/campaign/mmm/wmr/mpas_tutorial/metis/bin:${PATH}
```

IMPORTANT NOTE: The 'npl' Conda environment on Derecho modifies our **PATH** such that the wrong MPI compiler wrappers appear first. To remedy this, we can simply reload the 'gcc' module as a final step:

```
$ module reload gcc/13.2.0
```

If you've logged out of Derecho and would like a quick list of commands to set up your environment again after logging back in, you can copy and paste the following commands into your terminal:

```
module --force purge
module load ncarenv/23.09
module load craype/2.7.23
module load gcc/13.2.0
module load ncarcompilers/1.0.0
module load cray-mpich/8.1.27
module load parallel-netcdf/1.12.3
module load netcdf/4.9.2
module load conda
conda activate npl
export PYTHONPATH=/glade/campaign/mmm/wmr/mpas_tutorial/python_scripts
module load ncview
export PATH=/glade/campaign/mmm/wmr/mpas_tutorial/metis/bin:${PATH}
module reload gcc/13.2.0
```

We will run all of the practical exercises in this tutorial in our *scratch* directories, i.e., **/glade/derecho/scratch/${USER}/mpas_tutorial**. To keep the MPAS tutorial exercises separate from other work, we'll create a sub-directory named "mpas_tutorial":

```
$ mkdir /glade/derecho/scratch/${USER}/mpas_tutorial
```

Running jobs on Derecho requires the submission of a job script to a batch queueing system, which will allocate requested computing resources to your job when they become available. In general, it's best to avoid running any compute-intensive jobs on the login nodes, and the practical instructions to follow will guide you in the process of submitting jobs when necessary.

As a first introduction to running jobs on Derecho, there are several key commands worth noting:

- **qcmd -A UMMM0006** - This command runs the specified command on a batch node under the UMMM0006 project for this tutorial
- **qsub** - This command submits a job script, which describes a job to be run on one or more batch nodes; it offers increased control over running a simple command with **qcmd**
- **qstat -u $USER** - This command tells you the status of your pending and running jobs. *Note that you may need to wait about 30 seconds for a recently submitted job to show up.*
- **qdel** - This command deletes a queued or running job

At various points in the practical exercises, we'll need to submit jobs to Derecho's queueing system using the **qsub** command, and after doing so, we may often check on the status of the job with the **qstat** command, monitoring the log files produced by the job once we see that the job has begun to run.

With your shell environment set up as described in this section, you're ready to begin with the practical exercises of this tutorial!

1. Compiling MPAS, and creating static files and idealized ICs

In this section, our goal is to obtain a copy of the MPAS source code directly from the MPAS GitHub repository. We'll then compile both the **init_atmosphere_model** and **atmosphere_model** programs before using the former to begin the processing of time-invariant, terrestrial fields for use in a real-data simulation. While this processing is taking place, in another terminal window (*don't forget to set up your environment!*) we can practice preparing idealized initial conditions.

1.1 Obtaining the MPAS-Model source code

Since our default login shell is *bash*, all shell commands throughout this tutorial will be written for bash. However, if you prefer a different shell and don't mind mentally translating, e.g., **export** commands to

`setenv` commands, then feel free to switch shells.

As described in the lectures, the MPAS code is distributed directly from the GitHub repository where it is developed. While it's possible to navigate to https://github.com/MPAS-Dev/MPAS-Model and obtain the code by clicking on the "Releases" tab, it's much faster to *clone* the repository directly on the command-line. After changing to our `/glade/derecho/scratch/${USER}/mpas_tutorial` directory, we can make a clone of the MPAS-Model repository:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial
$ git clone https://github.com/MPAS-Dev/MPAS-Model.git
```

Cloning the MPAS-Model repository may take a few seconds, and at the end of the process, the output to the terminal should look something like the following:

```
Cloning into 'MPAS-Model'...
remote: Enumerating objects: 64819, done.
remote: Counting objects: 100% (29/29), done.
remote: Compressing objects: 100% (13/13), done.
remote: Total 64819 (delta 16), reused 25 (delta 16), pack-reused 64790
Receiving objects: 100% (64819/64819), 35.63 MiB | 20.78 MiB/s, done.
Resolving deltas: 100% (48230/48230), done.
Updating files: 100% (1540/1540), done.
```

We should now have an `MPAS-Model` directory:

```
$ ls -l MPAS-Model
total 72
drwxr-xr-x  3 duda ncar  4096 Apr 12 18:30 docs
-rw-r--r--  1 duda ncar  3131 Apr 12 18:30 INSTALL
-rw-r--r--  1 duda ncar  2311 Apr 12 18:30 LICENSE
-rw-r--r--  1 duda ncar 48657 Apr 12 18:30 Makefile
-rw-r--r--  1 duda ncar  2811 Apr 12 18:30 README.md
drwxr-xr-x 14 duda ncar  4096 Apr 12 18:30 src
drwxr-xr-x  5 duda ncar  4096 Apr 12 18:30 testing_and_setup
```

That's it! We now have a copy of the latest release of the MPAS source code.

1.2 Compiling the MPAS *init_atmosphere* and *atmosphere* cores

As mentioned in the lectures, there are two "cores" that need to be compiled from the same MPAS source code: the *init_atmosphere* core and the *atmosphere* core.

Before beginning the compilation process, it's worth verifying that we have MPI compiler wrappers in our path, and that environment variable pointing to the Parallel-NetCDF library is set:

```
$ which mpif90
/glade/u/apps/derecho/23.09/spack/opt/spack/ncarcompilers/1.0.0/gcc/13.2.0/g5ig/bin/mpi/mpif90

$ which mpicc
/glade/u/apps/derecho/23.09/spack/opt/spack/ncarcompilers/1.0.0/gcc/13.2.0/g5ig/bin/mpi/mpicc

$ echo $PNETCDF
/glade/u/apps/derecho/23.09/spack/opt/spack/parallel-netcdf/1.12.3/cray-mpich/8.1.27/gcc/13.2.0/xqnd
```

If all of the above commands were successful, our shell environment should be sufficient to allow the MPAS cores to be compiled.

We'll begin by compiling the *init_atmosphere* core, producing an executable named `init_atmosphere_model`.

> **IMPORTANT NOTE:** Before compiling on Derecho specifically, there's an important point that needs explanation! In order to avoid saturating the Derecho login nodes with compilation processes and negatively impacting other users, we will run our compilation command on a batch node with the special `qcmd` command. The `qcmd` command launches the specified command on a batch node and returns when the command has finished. So, although you would normally not use "qcmd" when compiling MPAS on other systems, for this tutorial we will prefix the usual compilation command with `qcmd -A UMMM0006 --` (where UMMM0006 is the computing project we're working under).

After changing to the MPAS-Model directory

```
$ cd MPAS-Model
```

we can issue the following command to build the *init_atmosphere* core with the GNU compilers:

```
$ qcmd -A UMMM0006 -- make -j8 gnu CORE=init_atmosphere
```

In the build command, we have also added the `-j8` flag to tell *make* to use eight tasks to build the code; this should reduce the time to compile the `init_atmosphere_model` executable significantly!

After issuing the **make** command, above, compilation should take just a couple of minutes, and if the compilation was successful, the end of the build process should have produced messages like the following:

```
*********************************************************************************
MPAS was built with default single-precision reals.
Debugging is off.
Parallel version is on.
Using the mpi_f08 module.
Papi libraries are off.
TAU Hooks are off.
MPAS was built without OpenMP support.
MPAS was built without OpenMP-offload GPU support.
MPAS was built without OpenACC accelerator support.
Position-dependent code was generated.
MPAS was built with .F files.
The native timer interface is being used
Using the SMIOL library.
*********************************************************************************
```

If compilation of the *init_atmosphere* core was successful, we should also have an executable file named **init_atmosphere_model**:

```
$ ls -l
total 2006
drwxr-xr-x  2 duda ncar    4096 Apr 26 20:32 default_inputs
-rwxr-xr-x  1 duda ncar 2014592 Apr 26 20:32 init_atmosphere_model
-rw-r--r--  1 duda ncar    3131 Apr 26 20:26 INSTALL
-rw-r--r--  1 duda ncar    2311 Apr 26 20:26 LICENSE
-rw-r--r--  1 duda ncar   27864 Apr 26 20:26 Makefile
-rw-r--r--  1 duda ncar    1379 Apr 26 20:32 namelist.init_atmosphere
-rw-r--r--  1 duda ncar    2555 Apr 26 20:26 README.md
drwxr-xr-x 14 duda ncar    4096 Apr 26 20:32 src
-rw-r--r--  1 duda ncar     920 Apr 26 20:32 streams.init_atmosphere
drwxr-xr-x  4 duda ncar    4096 Apr 26 20:26 testing_and_setup
```

Note, also, that default namelist and streams files for the *init_atmosphere* core have also been generated as part of the compilation process: these are the files named **namelist.init_atmosphere** and **streams.init_atmosphere**.

Now, we're ready to compile the *atmosphere* core. If we try this without cleaning any of the common infrastructure code, first, e.g.,

```
$ make gnu CORE=atmosphere
```

we would get an error like the following:

```
*********************************************************************************
 The MPAS infrastructure is currently built for the init_atmosphere_model core.
 Before building the atmosphere core, please do one of the following.


 To remove the init_atmosphere_model_model executable and clean the MPAS infrastructure, run:
      make clean CORE=init_atmosphere_model

 To preserve all executables except atmosphere_model and clean the MPAS infrastructure, run:
      make clean CORE=atmosphere

 Alternatively, AUTOCLEAN=true can be appended to the make command to force a clean,
 build a new atmosphere_model executable, and preserve all other executables.

*********************************************************************************
```

After compiling one MPAS core, we need to clean up the shared infrastructure before compiling a different core. We can clean all parts of the infrastructure that are needed by the *atmosphere* core by running the following command:

```
$ make clean CORE=atmosphere
```

Having cleaned up, we can proceed to compile the *atmosphere* core with:

```
$ qcmd -A UMMM0006 -- make -j8 gnu CORE=atmosphere
```

The compilation of the **atmosphere_model** executable can take several minutes or longer to complete (depending on which compiler is used). Similar to the compilation of the *init_atmosphere* core, a successful compilation of the *atmosphere* core should give the following message:

```
*********************************************************************************
MPAS was built with default single-precision reals.
Debugging is off.
Parallel version is on.
```

```
Using the mpi_f08 module.
Papi libraries are off.
TAU Hooks are off.
MPAS was built without OpenMP support.
MPAS was built without OpenMP-offload GPU support.
MPAS was built without OpenACC accelerator support.
Position-dependent code was generated.
MPAS was built with .F files.
The native timer interface is being used
Using the SMIOL library.
*******************************************************************************
```

Now, our MPAS-Model directory should contain an executable file named **atmosphere_model**, as well as default **namelist.atmosphere** and **streams.atmosphere** files:

```
$ ls -lL
total 33018
-rwxr-xr-x  1 duda ncar  5644864 Apr 26 20:37 atmosphere_model
-rwxr-xr-x  1 duda ncar   209256 Apr 26 20:36 build_tables
-rw-r--r--  1 duda ncar 20580056 Apr 26 20:34 CAM_ABS_DATA.DBL
-rw-r--r--  1 duda ncar    18208 Apr 26 20:34 CAM_AEROPT_DATA.DBL
drwxr-xr-x  2 duda ncar     4096 Apr 26 20:37 default_inputs
-rw-r--r--  1 duda ncar      261 Apr 26 20:34 GENPARM.TBL
-rwxr-xr-x  1 duda ncar  2014592 Apr 26 20:32 init_atmosphere_model
-rw-r--r--  1 duda ncar     3131 Apr 26 20:26 INSTALL
-rw-r--r--  1 duda ncar    29820 Apr 26 20:34 LANDUSE.TBL
-rw-r--r--  1 duda ncar     2311 Apr 26 20:26 LICENSE
-rw-r--r--  1 duda ncar    27864 Apr 26 20:26 Makefile
-rw-r--r--  1 duda ncar     1774 Apr 26 20:37 namelist.atmosphere
-rw-r--r--  1 duda ncar     1379 Apr 26 20:32 namelist.init_atmosphere
-rw-r--r--  1 duda ncar   543744 Apr 26 20:34 OZONE_DAT.TBL
-rw-r--r--  1 duda ncar      536 Apr 26 20:34 OZONE_LAT.TBL
-rw-r--r--  1 duda ncar      708 Apr 26 20:34 OZONE_PLEV.TBL
-rw-r--r--  1 duda ncar     2555 Apr 26 20:26 README.md
-rw-r--r--  1 duda ncar   847552 Apr 26 20:34 RRTMG_LW_DATA
-rw-r--r--  1 duda ncar  1694976 Apr 26 20:34 RRTMG_LW_DATA.DBL
-rw-r--r--  1 duda ncar   680368 Apr 26 20:34 RRTMG_SW_DATA
-rw-r--r--  1 duda ncar  1360572 Apr 26 20:34 RRTMG_SW_DATA.DBL
-rw-r--r--  1 duda ncar     4399 Apr 26 20:34 SOILPARM.TBL
drwxr-xr-x 14 duda ncar     4096 Apr 26 20:37 src
-rw-r--r--  1 duda ncar     1203 Apr 26 20:37 stream_list.atmosphere.diagnostics
-rw-r--r--  1 duda ncar      927 Apr 26 20:37 stream_list.atmosphere.output
-rw-r--r--  1 duda ncar        9 Apr 26 20:37 stream_list.atmosphere.surface
-rw-r--r--  1 duda ncar     1571 Apr 26 20:37 streams.atmosphere
-rw-r--r--  1 duda ncar      920 Apr 26 20:32 streams.init_atmosphere
drwxr-xr-x  4 duda ncar     4096 Apr 26 20:26 testing_and_setup
-rw-r--r--  1 duda ncar    22986 Apr 26 20:34 VEGPARM.TBL
```

Note, also, the presence of files named **stream_list.atmosphere.***. These are lists of output fields that are referenced by the **streams.atmosphere** file.

The new files like **CAM_ABS_DATA.DBL**, **LANDUSE.TBL**, **RRTMG_LW_DATA**, etc. are look-up tables and other data files used by physics schemes in MPAS-Atmosphere. These files should all be symbolic links to files in the **src/core_atmosphere/physics/physics_wrf/files/** directory.

If we have **init_atmosphere_model** and **atmosphere_model** executables, then compilation of both MPAS-Atmosphere cores was successful, and we're ready to proceed to the next sub-section.

1.3 Static, terrestrial field processing

For our first MPAS simulation in this tutorial, we'll use a quasi-uniform 240-km mesh. Since we'll later be working with a variable-resolution mesh, it will be helpful to maintain separate sub-directories for these two simulations.

To begin processing of the static, terrestrial fields for the 240-km quasi-uniform mesh, let's change to our **/glade/derecho/scratch/${USER}/mpas_tutorial** directory and make a new sub-directory named **240km_uniform**:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial
$ mkdir 240km_uniform
$ cd 240km_uniform
```

We can find a copy of the 240-km quasi-uniform mesh at **/glade/campaign/mmm/wmr/mpas_tutorial/meshes/x1.10242.grid.nc**. To save disk space, we'll symbolically link this file into our directory:

```
$ ln -s /glade/campaign/mmm/wmr/mpas_tutorial/meshes/x1.10242.grid.nc .
```

We will also need the **init_atmosphere_model** executable, as well as copies of the **namelist.init_atmosphere** and **streams.init_atmosphere** files. We'll make a symbolic link to the executable, and copies of the other files (since we will be changing them):

```
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/init_atmosphere_model .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/namelist.init_atmosphere .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/streams.init_atmosphere .
```

Finally, so that we can make use of multiple MPI tasks for the static field processing, we will symbolically link a graph partition file with 16 partitions into our working directory:

```
$ ln -s /glade/campaign/mmm/wmr/mpas_tutorial/meshes/x1.10242.graph.info.part.16 .
```

Before running the **init_atmosphere_model** program, we'll need to set up the **namelist.init_atmosphere** file as described in the lectures. With your preferred editor, edit the highlighted options in the default **namelist.init_atmosphere** file so that they match the following:

```
&nhyd_model
    config_init_case = 7
/
&data_sources
    config_geog_data_path = '/glade/campaign/mmm/wmr/mpas_tutorial/mpas_static/'
    config_landuse_data = 'MODIFIED_IGBP_MODIS_NOAH'
    config_topo_data = 'GMTED2010'
    config_vegfrac_data = 'MODIS'
    config_albedo_data = 'MODIS'
    config_maxsnowalbedo_data = 'MODIS'
    config_supersample_factor = 3
/
&preproc_stages
    config_static_interp = true
    config_native_gwd_static = true
    config_vertical_grid = false
    config_met_interp = false
    config_input_sst = false
    config_frac_seaice = false
/
&decomposition
    config_block_decomp_file_prefix = 'x1.10242.graph.info.part.'
/
```

Note, in particular, the setting of the path to the geographical datasets, and the settings to enable only the processing of static data and the gravity wave drag ("gwd") static fields. Note, too, that we only specify the *prefix* of the graph partition file; the number of MPI tasks will be appended to the filename automatically by MPAS.

After editing the **namelist.init_atmosphere** file, it will also be necessary to tell the **init_atmosphere_model** program the name of our input grid file, as well as the name of the "static" output file that we would like to create. We do this by editing the **streams.init_atmosphere** file, where we first set the name of the grid file for the "input" stream:

```
<immutable_stream name="input"
                  type="input"
                  filename_template="x1.10242.grid.nc"
                  input_interval="initial_only"/>
```

and then set the name of the static file to be created for the "output" stream:

```
<immutable_stream name="output"
                  type="output"
                  filename_template="x1.10242.static.nc"
                  packages="initial_conds"
                  output_interval="initial_only" />
```

When interpolating geographical fields to a mesh, the "surface" and "lbc" streams can be ignored (but, you should not delete the "surface" or "lbc" streams, or the **init_atmosphere_model** program will complain).

After editing the **streams.init_atmosphere** file, we can begin the processing of the static, time-invariant fields for the 240-km quasi-uniform mesh. Rather than running the **init_atmosphere_model** program on a batch node with **qcmd**, we will use a job script to run the program, returning a command prompt to us where we can monitor the progress of the job. To begin, we'll copy a prepared job script to our working directory:

```
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/job_scripts/init_real.pbs .
```

If you're interested in doing so, you can take a look at the **init_real.pbs** job script. Once you're ready, you can submit the script to the queueing system with the **qsub** command:

```
$ qsub init_real.pbs
```

Now, we need to wait for our job to start running; we can check on its status every minute or so with the `qstat` command:

```
$ qstat -u $USER
```

Once we see that our job is running — indicated by an "R" in the second-to-last column, e.g,

```
$ qstat -u $USER

                                                            Req'd  Req'd   Elap
Job ID          Username Queue    Jobname    SessID NDS TSK Memory Time  S Time
--------------- -------- -------- ---------- ------ --- --- ------ ----- - -----
4104847.desche* duda     cpu      240km_init    --    1 128  235gb 01:00 R   --
```

we can check on the progress of the `init_atmosphere_model` program by following the messages written to the `log.init_atmosphere.0000.out` file:

```
$ tail -f log.init_atmosphere.0000.out
```

We should expect to see lines of output similar to the following being printed every few seconds:

```
Processing tile: /glade/campaign/mmm/wmr/mpas_tutorial/mpas_static/topo_gmted2010_30s/04801-06000.16801-18
Processing tile: /glade/campaign/mmm/wmr/mpas_tutorial/mpas_static/topo_gmted2010_30s/03601-04800.16801-18
Processing tile: /glade/campaign/mmm/wmr/mpas_tutorial/mpas_static/topo_gmted2010_30s/02401-03600.16801-18
Processing tile: /glade/campaign/mmm/wmr/mpas_tutorial/mpas_static/topo_gmted2010_30s/01201-02400.16801-18
Processing tile: /glade/campaign/mmm/wmr/mpas_tutorial/mpas_static/topo_gmted2010_30s/00001-01200.16801-18
Processing tile: /glade/campaign/mmm/wmr/mpas_tutorial/mpas_static/topo_gmted2010_30s/01201-02400.15601-16
Processing tile: /glade/campaign/mmm/wmr/mpas_tutorial/mpas_static/topo_gmted2010_30s/00001-01200.15601-16
Processing tile: /glade/campaign/mmm/wmr/mpas_tutorial/mpas_static/topo_gmted2010_30s/42001-43200.15601-16
Processing tile: /glade/campaign/mmm/wmr/mpas_tutorial/mpas_static/topo_gmted2010_30s/00001-01200.14401-15
Processing tile: /glade/campaign/mmm/wmr/mpas_tutorial/mpas_static/topo_gmted2010_30s/42001-43200.14401-15
```

The processing of the static, time-invariant fields will take some time — perhaps 10 minutes or so.

If lines similar to the above are being periodically written, we can kill the `tail` process with `CTRL-C` before proceeding to the next sub-section, where we will create idealized initial conditions while the static, terrestrial fields are interpolated.

> **IMPORTANT NOTE:** *If lines of output are not being periodically written to the terminal when running the* `tail` *command as described above, look for a file named* `log.init_atmosphere.0000.err` *and detemine what went wrong before going on to the next sub-section! Exercises in the second section of this tutorial will require the successful processing of static, time-invariant fields!*

1.4 Preparing idealized initial conditions

While the `init_atmosphere_model` program is processing static, time-invariant fields for a real-data simulation in the `240km_uniform` directory, we can try initializing and running an idealized simulation in a separate directory.

The `init_atmosphere_model` program supports the creation of idealized initial conditions for the following cases:

- 3-d baroclinic wave on the sphere
- 3-d supercell thunderstorm on a doubly-periodic Cartesian plane
- 2-d mountain wave in the *xz*-plane

For each of these idealized cases, prepared input files are available on the MPAS-Atmosphere download page. We'll go through the process of creating initial conditions for the idealized supercell case; the general process is similar for the other two cases.

The prepared input files for MPAS-Atmosphere idealized cases may be found by going to the MPAS Homepage and clicking on the "MPAS-Atmosphere download" link at the left. Then, clicking on the "Configurations for idealized test cases" link will take you to the download links for idealized cases.

Although the input files for these idealized cases can be downloaded through the web page, we can also download, e.g., the supercell input files with `wget` once we know the URL. Beginning from our `/glade/derecho/scratch/${USER}/mpas_tutorial` directory, we can download the supercell input file archive and unpack it with:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial
$ wget http://www2.mmm.ucar.edu/projects/mpas/test_cases/v7.0/supercell.tar.gz
$ tar xzvf supercell.tar.gz
```

After changing to the resulting `supercell` directory, the `README` file will give an overview of how to initialize and run the test case. The key points are that we need to symbolically link both the `init_atmosphere_model` and `atmosphere_model` executables into the `supercell` directory:

```
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/init_atmosphere_model .
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/atmosphere_model .
```

Unlike as described in the **README** *file, however, we will not run the* **init_atmosphere_model** *and* **atmosphere_model** *programs directly on the command-line.*

We will run the **init_atmosphere_model** program through **qcmd** with:

```
$ qcmd -A UMMM0006 -- ./init_atmosphere_model
```

Once the initial conditions have been created as described in the **README** file, it's helpful to verify that there were no errors; the end of the **log.init_atmosphere.0000.out** file should look something like the following:

```
------------------------------------------
Total log messages printed:
   Output messages =                  304
   Warning messages =                  13
   Error messages =                     0
   Critical error messages =            0
------------------------------------------
```

Assuming there were no errors, we can run the simulation with 32 processors by first copying a prepared job script to our working directory and submitting the script with **qsub**:

```
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/job_scripts/supercell.pbs .
$ qsub supercell.pbs
```

As with the static field interpolation, we need to wait for our job to start running. We can check on its status every minute or so with the **qstat** command:

```
$ qstat -u $USER
```

Once we see that our job is running, we can move on to the next section. The simulation may take about 10 minutes to run with 32 MPI tasks. During one of the later practical section, if you would like to revisit the simulation to see the results, running the **supercell.ncl** NCL script should produce plots of the time evolution of several model fields:

```
$ ncl supercell.ncl
```

2. Creating real-data ICs and running a simulation

Having compiled both the **init_atmosphere** and **atmosphere** cores, and also having interpolated time-invariant, terrestrial fields to create a "static" file for real-data simulations, we'll interpolate atmospheric and land-surface fields to create complete initial conditions for an MPAS simulation in this section. We'll also process 10 days' worth of SST and sea-ice data to update these fields periodically as the model runs. Then, we'll start a five-day simulation, which will take around an hour to complete. Once the model has started running, we can use any extra time to compile the **convert_mpas** utility program.

If you've reached this point and the static field interpolation from Section 1.3 has not yet finished, you can first go through Section 2.4, before returning to Sections 2.1 - 2.3 after the static field interpolation has completed.

2.1 Interpolating real-data initial conditions

In an earlier section, we started the process of interpolating static geographical fields to the 240-km, quasi-uniform mesh in the **240km_uniform** directory. If this interpolation was successful, this directory should contain two new files: **log.init_atmosphere.0000.out** and **x1.10242.static.nc**.

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial/240km_uniform
$ ls -l log.init_atmosphere.0000.out x1.10242.static.nc
```

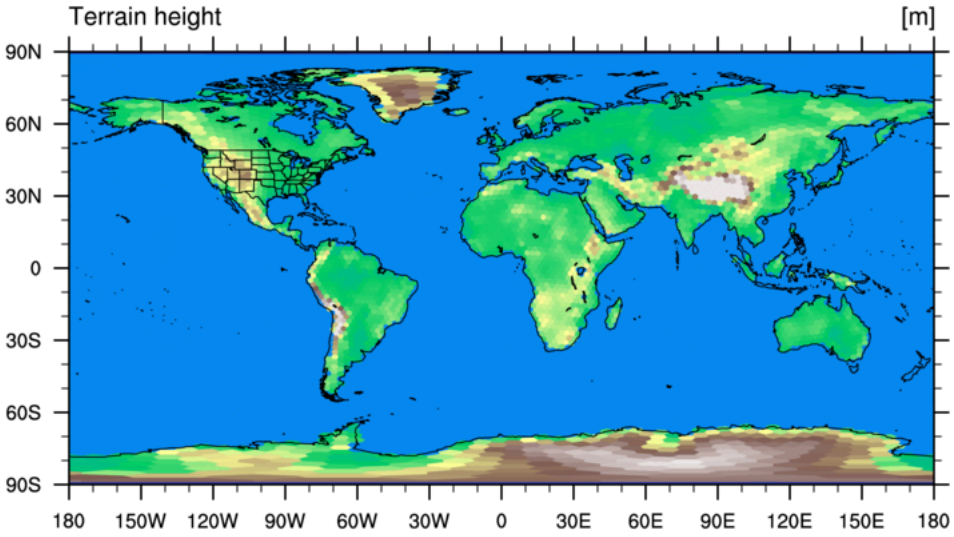
The end of the **log.init_atmosphere.0000.out** file should show that there were no errors:

```
------------------------------------------
Total log messages printed:
   Output messages =                  673
   Warning messages =                   6
   Error messages =                     0
   Critical error messages =            0
------------------------------------------
```

We can also make a plot of the terrain elevation field in the **x1.10242.static.nc** file with a Python script named **plot_terrain.py**. We'll discuss the use of Python and NCL scripts for visualization in a later section, so for now we can simply execute the following commands to plot the terrain field:

```
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/python_scripts/plot_terrain.py .
$ ./plot_terrain.py x1.10242.static.nc
$ display terrain.png
```

Running the script may take 10 or 15 seconds, but the result should be a figure that looks like the following:



Now that we have convinced ourselves that the processing of static, geographical fields was successful, we can proceed to interpolate atmosphere and land-surface initial conditions for our 240-km simulation. Generally, it is necessary to use the *ungrib* component of the WRF Pre-Processing System to prepare atmospheric datasets in the *intermediate format* used by MPAS. For the purposes of this tutorial, we will simply assume that these data have already been processed with the *ungrib* program in **`/glade/campaign/mmm/wmr/mpas_tutorial/met_data/`**.

To interpolate the ERA5 analysis valid at 0000 UTC on 10 September 2014 to our 240-km mesh, we will symbolically link the **`ERA5:2014-09-10_00`** file to our working directory:

```
$ ln -s /glade/campaign/mmm/wmr/mpas_tutorial/met_data/ERA5:2014-09-10_00 .
```

Then, we will need to edit the **`namelist.init_atmosphere`** as described in the lectures to instruct the **`init_atmosphere_model`** program to interpolate the ERA5 data to our mesh. The critical items to set in the **`namelist.init_atmosphere`** file are:

```
&nhyd_model
    config_init_case = 7
    config_start_time = '2014-09-10_00:00:00'
/
&dimensions
    config_nvertlevels = 55
    config_nsoillevels = 4
    config_nfglevels = 38
    config_nfgsoillevels = 4
/
&data_sources
    config_met_prefix = 'ERA5'
    config_use_spechumd = false
/
&vertical_grid
    config_ztop = 30000.0
    config_nsmterrain = 1
    config_smooth_surfaces = true
    config_dzmin = 0.3
    config_nsm = 30
    config_tc_vertical_grid = true
    config_blend_bdy_terrain = false
/
&interpolation_control
    config_extrap_airtemp = 'lapse-rate'
/
&preproc_stages
    config_static_interp = false
    config_native_gwd_static = false
    config_vertical_grid = true
    config_met_interp = true
    config_input_sst = false
    config_frac_seaice = true
/
&decomposition
```

```
    config_block_decomp_file_prefix = 'x1.10242.graph.info.part.'
/
```

You may find it easier to copy the default **namelist.init_atmosphere** file from **/glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/namelist.init_atmosphere** before making the edits highlighted above.

When editing the **namelist.init_atmosphere** file, the key changes are to the starting time for our real-data simulation, the prefix of the *intermediate file* that contains the ERA5 atmospheric and land-surface fields, and the pre-processing stages that will be run.

After editing the **namelist.init_atmosphere** file, we will also need to set the name of the input file in the **streams.init_atmosphere** file to the name of the "static" file that we just produced:

```
<immutable_stream name="input"
                  type="input"
                  filename_template="x1.10242.static.nc"
                  input_interval="initial_only"/>
```

and we will also need to set the name of the output file, which will be the MPAS real-data initial conditions file:

```
<immutable_stream name="output"
                  type="output"
                  filename_template="x1.10242.init.nc"
                  packages="initial_conds"
                  output_interval="initial_only" />
```

Once we've made the above changes to the **namelist.init_atmosphere** and **streams.init_atmosphere** files, we can run the **init_atmosphere_model** program by submitting our **init_real.pbs** script again:

```
$ qsub init_real.pbs
```

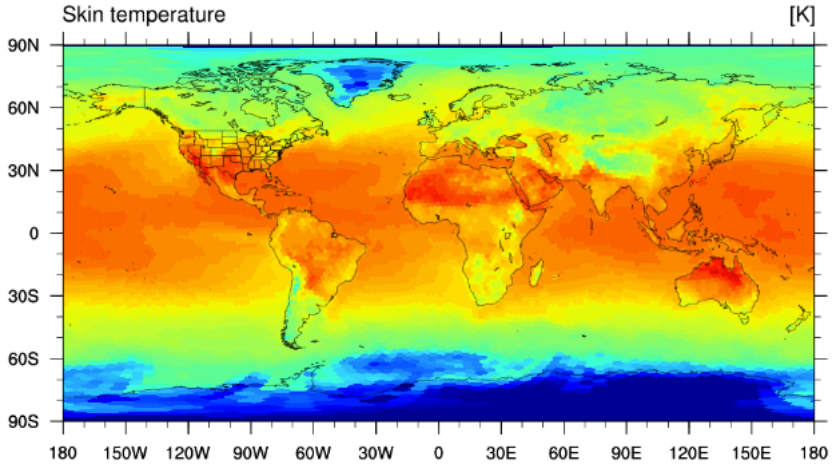
As before, we can check on the status of our job periodically by running

```
$ qstat -u $USER
```

After it begins to run, the program should take just a minute or two to finish running, and the result should be an **x1.10242.init.nc** file and a new **log.init_atmosphere.0000.out** file. Assuming no errors were reported at the end of the **log.init_atmosphere.0000.out** file, we can plot, e.g., the skin temperature field in the **x1.10242.init.nc** file using the **plot_tsk.py** Python script:

```
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/python_scripts/plot_tsk.py .
$ ./plot_tsk.py x1.10242.init.nc
$ display tsk.png
```

Again, we'll examine the use of Python and NCL scripts for visualization later, so for now we only need to verify that a plot like the following is produced:



If a plot like the above is produced, then we have completed the generation of an initial conditions file for our 240-km real-data simulation!

2.2 Generating SST and sea-ice update files

Because MPAS-Atmosphere — at least, when run as a stand-alone model — does not contain prognostic equations for the SST and sea-ice fraction, these fields would remain constant if not updated from an external source; this is, of course, not realistic, and it will generally impact the quality of longer model simulations. Consequently, for MPAS-Atmosphere simulations longer than roughly a week, it is typically

necessary to periodically update the sea-surface temperature (SST) field in the model. For real-time simulations, this is generally not an option, but it is feasible for *retrospective* simulations, where we have observed SST analyses available to us.

In order to create an SST update file, we will make use of a sequence of intermediate files containing SST and sea-ice analyses that are available in **`/glade/campaign/mmm/wmr/mpas_tutorial/met_data`**. Before proceeding, we'll link all of these SST intermediate files into our working directory:

```
$ ln -sf /glade/campaign/mmm/wmr/mpas_tutorial/met_data/SST* .
```

Following Section 8.1 of the MPAS-Atmosphere Users' Guide, we must edit the **`namelist.init_atmosphere`** file to specify the range of dates for which we have SST data, as well as the frequency at which the SST intermediate files are available. The key namelist options that must be set are shown below; other options can be ignored.

```
&nhyd_model
    config_init_case = 8
    config_start_time = '2014-09-10_00:00:00'
    config_stop_time = '2014-09-20_00:00:00'
/

&data_sources
    config_sfc_prefix = 'SST'
    config_fg_interval = 86400
/

&preproc_stages
    config_static_interp = false
    config_native_gwd_static = false
    config_vertical_grid = false
    config_met_interp = false
    config_input_sst = true
    config_frac_seaice = true
/
&decomposition
    config_block_decomp_file_prefix = 'x1.10242.graph.info.part.'
/
```

Note in particular that we have set the *config_init_case* variable to **8**! This is the initialization case used to create surface update files, instead of real-data initial conditions files.

As before, we also need to edit the **`streams.init_atmosphere`** file, this time setting the name of the SST update file to be created by the "surface" stream, as well as the frequency at which this update file should contain records:

```
<immutable_stream name="surface"
                  type="output"
                  filename_template="x1.10242.sfc_update.nc"
                  filename_interval="none"
                  packages="sfc_update"
                  output_interval="86400"/>
```

Note that we have set both the *filename_template* and *output_interval* attributes of the "surface" stream. The output_interval should match the interval specified in the namelist for the *config_fg_interval* variable. The other streams ("input", "output", and "lbc") can remain unchanged — the input file should still be set to the name of the static file.

After setting up the **`namelist.init_atmosphere`** and **`streams.atmosphere`** files, we're ready to run the **`init_atmosphere_model`** program by submitting our init_real.pbs script again:

```
$ qsub init_real.pbs
```

As before, we can check on the status of our job periodically by running

```
$ qstat -u $USER
```

After the job completes, the **`log.init_atmosphere.0000.out`** file should report that there were no errors. Additionally, the file **`x1.10242.sfc_update.nc`** file should have been created.

We can confirm that the **`x1.10242.sfc_update.nc`** contains the requested valid times for the SST and sea-ice fields by printing the "xtime" variable from the file; in MPAS, the "xtime" variable in a netCDF file is always used to store the times at which records in the file are valid.

```
$ ncdump -v xtime x1.10242.sfc_update.nc
```

This ncdump command should print the following times:

```
 xtime =
  "2014-09-10_00:00:00                                              ",
  "2014-09-11_00:00:00                                              ",
  "2014-09-12_00:00:00                                              ",
```

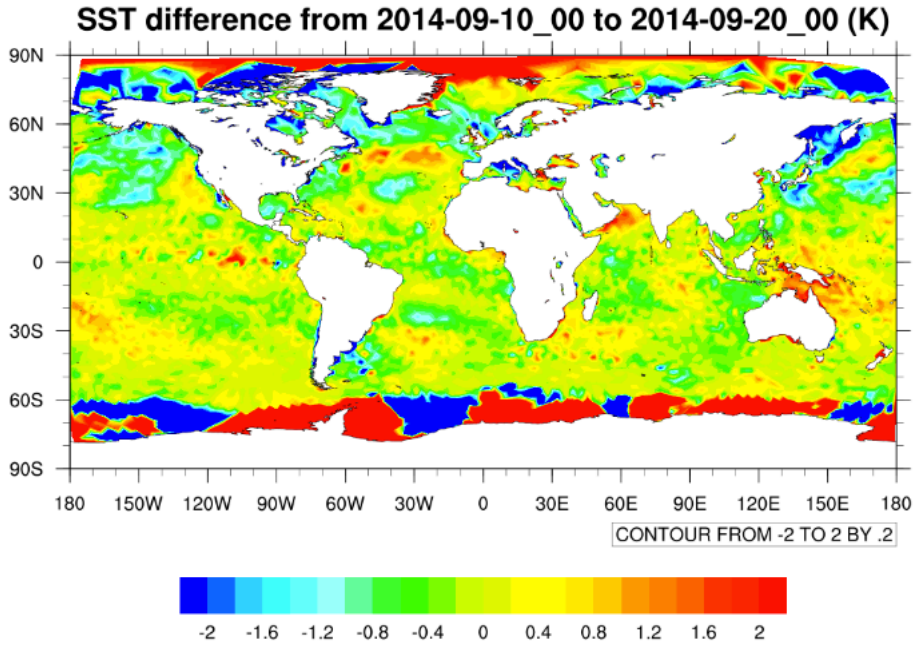
```
    "2014-09-13_00:00:00                                                ",
    "2014-09-14_00:00:00                                                ",
    "2014-09-15_00:00:00                                                ",
    "2014-09-16_00:00:00                                                ",
    "2014-09-17_00:00:00                                                ",
    "2014-09-18_00:00:00                                                ",
    "2014-09-19_00:00:00                                                ",
    "2014-09-20_00:00:00                                                " ;
```

If the times shown above were printed, then we have successfully created an SST and sea-ice update file for MPAS-Atmosphere. As a final check, we can use the Python script from **`/glade/campaign/mmm/wmr/mpas_tutorial/python_scripts/plot_delta_sst.py`** to plot the difference in the SST field between the last time in the surface update file and the first time in the file.

Because the surface update file contains no information about the latitude and longitude of grid cells, we provide two command-line arguments when running this script: one to give the name of the grid file, which contains cell latitude and longitude fields, and the second to specify the surface update file:

```
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/python_scripts/plot_delta_sst.py .
$ ./plot_delta_sst.py x1.10242.static.nc x1.10242.sfc_update.nc
$ display delta_sst.png
```

This script may take a minute or so to run.



In this plot, we have masked out the SST differences over land, since the values of the field over land are not representative of actual SST differences, but may represent differences in, e.g., skin temperature or 2-m air temperature, depending on the source of the SST analyses.

2.3 Model integration

Assuming that an initial condition file and a surface update file have been created, we're ready to run the MPAS-Atmosphere model itself!

Working from our **`240km_uniform`** directory, we'll begin by creating a symbolic link to the **`atmosphere_model`** executable that we compiled in **`/glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model`**. We'll also make copies of the **`namelist.atmosphere`** and **`streams.atmosphere`** files as well. Recall from when we compiled the model that there are **`stream_list.atmosphere.*`** files that accompany the **`streams.atmosphere`** file; we'll copy these, too.

```
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/atmosphere_model .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/namelist.atmosphere .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/streams.atmosphere .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/stream_list.atmosphere.* .
```

You'll also recall that there were many look-up tables and other data files that are needed by various physics parameterizations in the model. Before we can run MPAS-Atmosphere, we'll need to create symbolic links to these files as well in our working directory:

```
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/src/core_atmosphere/physics/physics_wrf/fil
```

Before running the model, we will need to edit the **namelist.atmosphere** file, which is the namelist for the MPAS-Atmosphere model itself. The default **namelist.atmosphere** is set up for a 120-km mesh; in order to run the model on a different mesh, there is one key parameter that depends on the model resolution:

- config_dt — the model integration time step (delta-t), in seconds.

As will be described in the lectures, the model integration step is generally chosen based on the finest horizontal resolution in a simulation domain.

To tell the model the date and time at which integration will begin (important, e.g., for computing solar radiation parameters), and to specify the length of the integration to be run, there are two other parameters that must be set for each simulation:

- config_start_time — the start time of the integration.
- config_run_duration — the length of the integration.

Lastly, when running the MPAS-Atmosphere model in parallel, we must tell the model the prefix of the filenames that contain mesh partitioning information for different MPI task counts:

- config_block_decomp_file_prefix — the file prefix (to be suffixed with processor count) of the file containing mesh partitioning information.

Accordingly, we must edit at least these parameters in the **namelist.atmosphere** file; other parameters are described in Appendix B of the MPAS-Atmosphere Users' Guide, and do not necessarily need to be changed:

```
&nhyd_model
    config_dt = 1200.0
    config_start_time = '2014-09-10_00:00:00'
    config_run_duration = '5_00:00:00'
/

&decomposition
    config_block_decomp_file_prefix = 'x1.10242.graph.info.part.'
/
```

For a relatively coarse mesh like the 240-km mesh, we can also call the radiation schemes less frequently to allow the model to run a little more quickly. Let's set the radiation calling interval to 1 hour:

```
&physics
    config_radtlw_interval = '01:00:00'
    config_radtsw_interval = '01:00:00'
/
```

After changing the parameters shown above in the **namelist.atmosphere** file, we must also set the name of the initial condition file, the name of the surface update file, and the interval at which we would like to read the surface update file in the **streams.atmosphere** file:

```
<immutable_stream name="input"
                  type="input"
                  filename_template="x1.10242.init.nc"
                  input_interval="initial_only"/>

<stream name="surface"
        type="input"
        filename_template="x1.10242.sfc_update.nc"
        filename_interval="none"
        input_interval="86400">

    <file name="stream_list.atmosphere.surface"/>

</stream>
```

Having set up the **namelist.atmosphere** and **streams.atmosphere** files, we're almost ready to run the model in parallel. You'll recall from the lectures that we need to supply a *graph partition file* to tell MPAS how the horizontal domain is partitioned among MPI tasks. Accordingly, we'll create a symbolic link to the partition file for 128 MPI tasks for the 240-km mesh in our working directory:

```
$ ln -s /glade/campaign/mmm/wmr/mpas_tutorial/meshes/x1.10242.graph.info.part.128 .
```

As a general rule, a mesh with *N* grid columns should be run on at most *N*/160 processors in MPAS-Atmosphere to make efficient use of the processors. So, for the mesh in this exercise, which has 10242 grid columns, we could in principle use up to about 64 MPI tasks while still making relatively efficient use of the computing resources. For this exercise, however, we will use a single, full Derecho node with 128 cores.

Now, we should be able to run MPAS using 128 MPI tasks. Before submitting a job with **qsub**, we can copy a prepared job script to our working directory.

```
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/job_scripts/run_model.pbs .
$ qsub run_model.pbs
```

We can check on the status of our job with **qstat -u $USER**. Once the model begins to run, it will write information about its progress to the **log.atmosphere.0000.out** file. We can use **tail -f** to follow the updates to the log file as the model runs:

```
$ tail -f log.atmosphere.0000.out
```

If the model has started up successfully and begun to run, we should see messages like this

```
 Begin timestep 2014-09-10_06:00:00
 --- time to run the LW radiation scheme L_RADLW =T
 --- time to run the SW radiation scheme L_RADSW =T
 --- time to run the convection scheme L_CONV    =T
 --- time to apply limit to accumulated rainc and rainnc L_ACRAIN   =F
 --- time to apply limit to accumulated radiation diags. L_ACRADT   =F
 --- time to calculate additional physics_diagnostics               =F
  split dynamics-transport integration 3

 global min, max w -0.177687 0.512867
 global min, max u -112.127 112.008
  Timing for integration step: 5.78077 s
```

written for each timestep that the model takes. If not, a **log.atmosphere.0000.err** file may have been created, and if so, it may have messages to indicate what might have gone wrong.

The model simulation should take less than about a five minutes to complete. As the model runs, you may notice that several netCDF output files are being created:

- diag.2014.09.*.nc — These files contain mostly 2-d diagnostic fields that were listed in the stream_list.atmosphere.diagnostics file.
- history.2014.09.*.nc — These files contain mostly 3-d prognostic and diagnostic fields from the model.
- restart.2014.09.*.nc — These are model *restart* files that are essentially checkpoints of the model state; a simulation can be re-started from any of these checkpoint/restart files.

If the model has successfully begun running, we can move to the next sub-section to obtain and compile the **convert_mpas** utility for interpolating model output files to a lat-lon grid for quick visualization.

2.4 Obtaining and compiling the *convert_mpas* program

We saw in earlier sections that Python scripts may be used to visualize fields in MPAS netCDF files. Although these scripts can produce publication-quality figures, many times all that is needed is a way to quickly inspect the fields in a file. The **convert_mpas** program is designed to interpolate fields from the unstructured MPAS mesh to a regular lat-lon grid for easy checking, e.g., with **ncview**.

As with the MPAS-Model code, the **convert_mpas** code may be obtained most easily by cloning a GitHub repository. Working from our **/glade/derecho/scratch/${USER}/mpas_tutorial** directory, we'll download the code in this way:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial
$ git clone https://github.com/mgduda/convert_mpas.git
$ cd convert_mpas
```

The **convert_mpas** utility is compiled via a simple *Makefile*. In general, one can edit the **Makefile** in the main **convert_mpas** directory; for this tutorial, however, no changes are needed.

We can build the **convert_mpas** utility by simply running **make** with no command-line arguments:

```
$ make
```

If compilation was successful, there should now be an executable file named **convert_mpas**. So that we can run this program from any of our working directories, we'll add our current directory to our shell **${PATH}** environment variable:

```
$ export PATH=/glade/derecho/scratch/${USER}/mpas_tutorial/convert_mpas:${PATH}
```

You may like to take a few minutes to read through the **README.md** file to familiarize yourself with the usage of the **convert_mpas** program. We'll have a chance to exercise the **convert_mpas** utility in the next section.

3. Running MPAS with variable resolution, and basic visualization

In the previous section, we were able to make a five-day, real-data simulation on a 240-km quasi-uniform mesh. In this section, we'll practice preparing a variable-resolution, 240km – 48km mesh with the **grid_rotate** tool, after which we'll proceed as we did for the quasi-uniform case to process static, terrestrial fields on this variable-resolution mesh.

As we saw in the first section, processing the static fields can take some time, so while this processing is taking place, we'll practice using the **convert_mpas** tool to interpolate output from our 240-km quasi-uniform simulation to a lat-lon grid for quick visualization.

Once the static field processing has completed for the 240km – 48km variable-resolution mesh, we'll interpolate the initial conditions fields and start a simulation on this mesh. This simulation will take about half an hour to complete, so we'll want to get this running so that it will have completed by the next section.

3.1 Obtaining, building, and running the *grid_rotate* program

A common theme with MPAS is the need to obtain source code from *git* repositories hosted on GitHub. The **grid_rotate** utility is no exception in this regard. One difference, however, is that the **grid_rotate** code is contained in a repository that houses many different tools for MPAS cores, including the MPAS-Albany Land Ice core, the MPAS-Ocean core, and the MPAS-Sea Ice core.

The **grid_rotate** utility is found in the MPAS-Tools repository, which we can clone into our **mpas_tutorial** working directory with the following commands:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial
$ git clone https://github.com/MPAS-Dev/MPAS-Tools.git
```

Within the MPAS-Tools repository, the **grid_rotate** code resides in the **mesh_tools/grid_rotate** sub-directory. We can change to this directory and build the **grid_rotate** utility with the **make** command.

```
$ cd MPAS-Tools/mesh_tools/grid_rotate
$ make
```

So that we can more easily run the **grid_rotate** program from any working directory, we'll add our current working directory to our shell **${PATH}**.

```
$ export PATH=/glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Tools/mesh_tools/grid_rotate:${PATH}
```

Now that we have a means of rotating the location of refinement in a variable-resolution MPAS mesh, we can begin the process of preparing such a mesh. For this tutorial, we'll be using a mesh that refines from 240-km grid spacing down to about 48-km grid spacing over an elliptic region.

When creating initial conditions and running the 240-km quasi-uniform simulation, we worked in a sub-directory named **240km_uniform**. For our variable-resolution simulation, we'll work in a sub-directory named **240-48km_variable** to keep our work separated. Let's create the **240-48km_variable** directory and link in the variable-resolution mesh from **/glade/campaign/mmm/wmr/mpas_tutorial/meshes** into that directory:

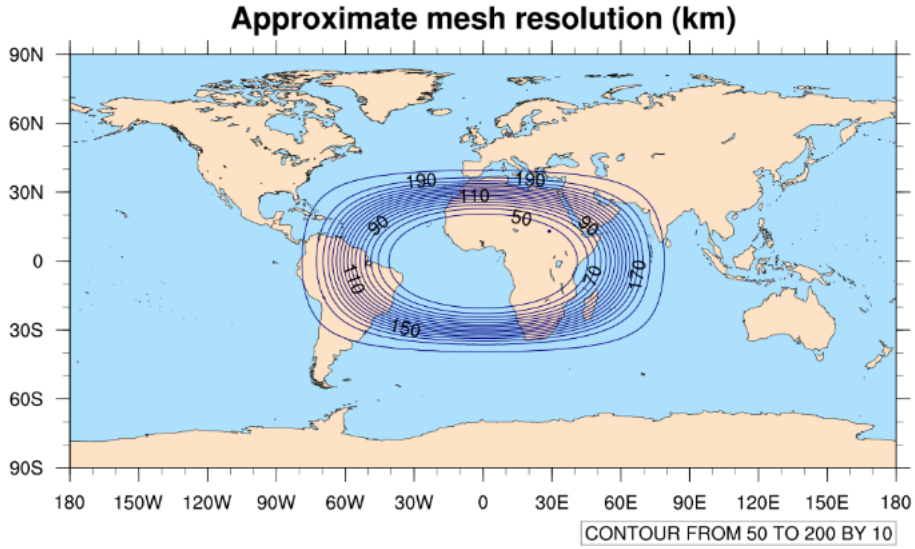
```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial
$ mkdir 240-48km_variable
$ cd 240-48km_variable
$ ln -s /glade/campaign/mmm/wmr/mpas_tutorial/meshes/x5.30210.grid.nc .
```

The **x5.30210.grid.nc** mesh contains 30210 grid cells and refines by a factor of five (from 240-km grid spacing to 48-km grid spacing). The refinened region is centered over (0.0 lat, 0.0 lon), and we can get a quick idea of the size of the refinement by plotting contours of the *approximate* mesh resolution with the **mesh_resolution.ncl** NCL script:

```
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/ncl_scripts/mesh_resolution.ncl .
$ export FNAME=x5.30210.grid.nc
$ ncl mesh_resolution.ncl
```

When running the **mesh_resolution.ncl** script, a plot like the one below should be produced in a file named 'mesh_resolution.png', and which you can view with the **display** command:

```
$ display mesh_resolution.png
```



Using the **grid_rotate** tool, we can change the location and orientation of this refinement to an area of our choosing. Before running the **grid_rotate** program, we need a copy of the input namelist that is read by this program:

```
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Tools/mesh_tools/grid_rotate/namelist.input .
```

As described in the lectures, we'll set the parameters in the **namelist.input** file to relocate the refined region in the mesh. For example, to move the refinement over South America, we might use:

```
&input
   config_original_latitude_degrees = 0
   config_original_longitude_degrees = 0

   config_new_latitude_degrees = -19.5
   config_new_longitude_degrees = -62
   config_birdseye_rotation_counter_clockwise_degrees = 90
/
```

Feel free to place the refinement wherever you would like!

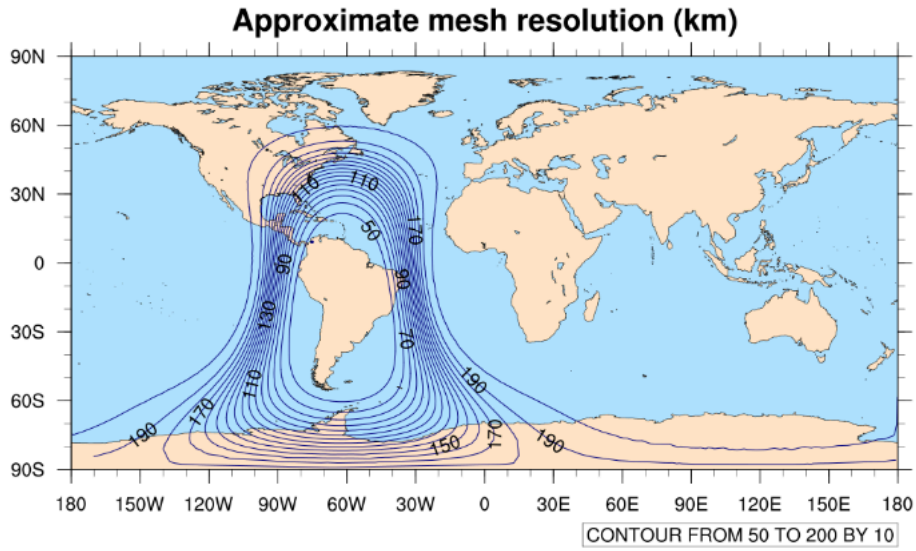
After making changes to the **namelist.input** file, we can rotate the **x5.30210.grid.nc** file to create a new "grid" file with any name we choose. For example:

```
$ grid_rotate x5.30210.grid.nc SouthAmerica.grid.nc
```

As with the original **x5.30210.grid.nc** file, we can plot the approximate resolution of our rotated grid file with commands like the following:

```
$ export FNAME=SouthAmerica.grid.nc
$ ncl mesh_resolution.ncl
```

Of course, the name **SouthAmerica.grid.nc** should be replaced with the name that you have chosen for your rotated grid when setting the **FNAME** environment variable. In our example, the resulting plot looks like the one below.



It may take some iteration to get the refinement just where you would like it. You can go back and edit the **`namelist.input`** file, then re-run the **`grid_rotate`** program, and finally, re-run the **`ncl mesh_resolution.ncl`** command until you are satisfied!

3.2 Static, terrestrial field processing

Interpolating static, geographical fields to a variable-resolution MPAS mesh works in essentially the same way as it does for a quasi-uniform mesh. So, the steps taken in this section should seem familiar — they mirror what we did in Section 1.3!

To begin the process, we'll symbolically link the **`init_atmosphere_model`** executable into our **`240-48km_variable`** directory, and we'll copy the default **`namelist.init_atmosphere`** and **`streams.init_atmosphere`** files as well:

```
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/init_atmosphere_model .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/namelist.init_atmosphere .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/streams.init_atmosphere .
```

So that we can make use of multiple MPI tasks for the static field processing, we will symbolically link a graph partition file with 16 partitions for the x5.30210 mesh into our working directory:

```
$ ln -s /glade/campaign/mmm/wmr/mpas_tutorial/meshes/x5.30210.graph.info.part.16 .
```

Note that graph partition files for a mesh are independent of any rotation that may be applied to the mesh. The graph partitioning depends only on the connectivity among cells in the mesh and not on the geographic locations of cells, and rotating a mesh does not alter the local connections among cells.

As before, we'll set the following variables in the **`namelist.init_atmosphere`** file:

```
&nhyd_model
    config_init_case = 7
/
&data_sources
    config_geog_data_path = '/glade/campaign/mmm/wmr/mpas_tutorial/mpas_static/'
    config_landuse_data = 'MODIFIED_IGBP_MODIS_NOAH'
    config_topo_data = 'GMTED2010'
    config_vegfrac_data = 'MODIS'
    config_albedo_data = 'MODIS'
    config_maxsnowalbedo_data = 'MODIS'
    config_supersample_factor = 3
/
&preproc_stages
    config_static_interp = true
    config_native_gwd_static = true
    config_vertical_grid = false
    config_met_interp = false
    config_input_sst = false
    config_frac_seaice = false
/
&decomposition
    config_block_decomp_file_prefix = 'x5.30210.graph.info.part.'
/
```

In editing the **`streams.init_atmosphere`** file, we'll choose the filename for the "input" stream to match whatever name we chose for our rotated grid file:

```
<immutable_stream name="input"
                  type="input"
                  filename_template="SouthAmerica.grid.nc"
                  input_interval="initial_only"/>
```

and we'll set the filename for the "output" stream to follow the same naming convention, but using "static" instead of "grid":

```
<immutable_stream name="output"
                  type="output"
                  filename_template="SouthAmerica.static.nc"
                  packages="initial_conds"
                  output_interval="initial_only" />
```

With these changes, we're ready to run the **init_atmosphere_model** program. In order to submit the job to the queuing system, we can copy the same prepared job script as in Section 1.3 and submit it with **qsub**:

```
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/job_scripts/init_real.pbs .
$ qsub init_real.pbs
```

As before, processing of the static, geographical fields may take roughly 10 minutes to complete.

3.3 Using the *convert_mpas* utility

While the static, geographical fields are being processed for our 240km – 48km variable-resolution mesh, we can experiment with the use of the **convert_mpas** utility to interpolate output from our 240-km, quasi-uniform simulation.

If you didn't have a chance to download and compile the **convert_mpas** program back in Section 2.4, you will need to go back to that section before proceeding with the rest of this section.

We'll change directories to the **240km_uniform** directory, and we may also need to add the directory containing the **convert_mpas** utility to our shell **${PATH}** variable again:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial/240km_uniform
$ export PATH=/glade/derecho/scratch/${USER}/mpas_tutorial/convert_mpas:${PATH}
```

In the **240km_uniform** directory, we should see output files from MPAS that are named **history*nc** and **diag*nc**:

```
$ ls -l history*nc diag*nc
-rw-r--r-- 1 duda ncar  4525528 Apr  8 23:56 diag.2014-09-10_00.00.00.nc
-rw-r--r-- 1 duda ncar  4525528 Apr  8 23:56 diag.2014-09-10_03.00.00.nc
...
-rw-r--r-- 1 duda ncar  4525528 Apr  8 23:59 diag.2014-09-14_21.00.00.nc
-rw-r--r-- 1 duda ncar  4525528 Apr  8 23:59 diag.2014-09-15_00.00.00.nc
-rw-r--r-- 1 duda ncar 94449804 Apr  8 23:56 history.2014-09-10_00.00.00.nc
-rw-r--r-- 1 duda ncar 94449804 Apr  8 23:56 history.2014-09-10_06.00.00.nc
...
-rw-r--r-- 1 duda ncar 94449804 Apr  8 23:59 history.2014-09-14_18.00.00.nc
-rw-r--r-- 1 duda ncar 94449804 Apr  8 23:59 history.2014-09-15_00.00.00.nc
```

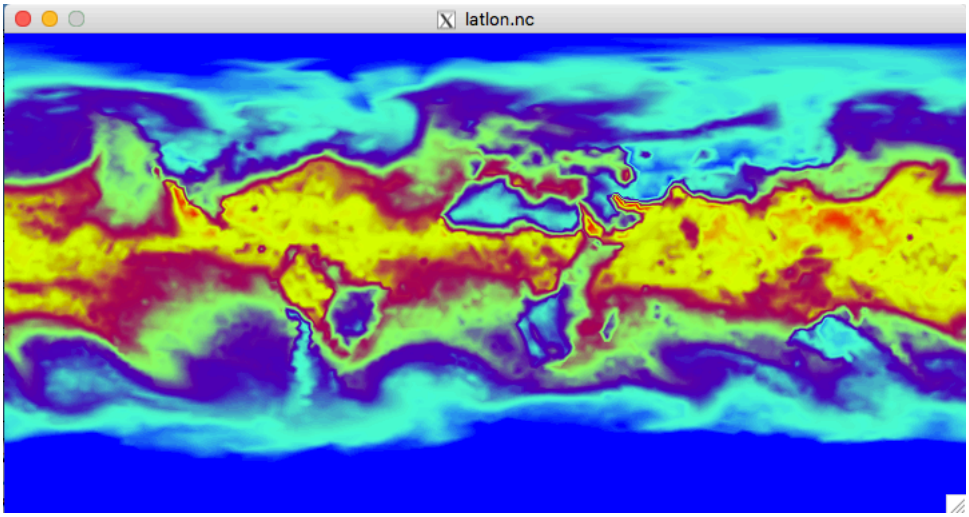
As a first try, we can interpolate the fields from the final model "history" file, **history.2014-09-15_00.00.00.nc**, to a 0.5-degree lat-lon grid with the command:

```
$ convert_mpas history.2014-09-15_00.00.00.nc
```

The interpolation should take less than a minute, and the result should be a file named **latlon.nc**. Let's take a look at this file with the **ncview** utility:

```
$ ncview latlon.nc
```

After launching ncview we can, e.g., view the *qv* field, which may look something like the plot below at the lowest model level.



Feel free to browse some of the other fields in the file by selecting them from the "2d vars" and "3d vars" buttons. All of the fields are described in Appendix D of the User's Guide.

When we're done viewing the **latlon.nc** file, we'll delete it. The **convert_mpas** utility attempts to append to existing **latlon.nc** files when converting a new MPAS netCDF file, and this often doesn't work as expected, so to avoid confusion, it's best to remove the **latlon.nc** file we just created with

```
$ rm latlon.nc
```

before converting another MPAS output file.

As we just saw, it can take upwards of a minute to interpolate a single MPAS "history" file. If we are only interested in a small subset of the fields in an MPAS file, we can restrict the interpolation to just those fields by providing a file named **include_fields** in our working directory.

Using an editor of your choice, create a new text file named **include_fields** with the following contents:

```
u10
v10
precipw
```

After saving the file, we can re-run the **convert_mpas** program as before to produce a **latlon.nc** file with just the 10-meter surface winds and precipitable water:

```
$ convert_mpas history.2014-09-15_00.00.00.nc
$ ncview latlon.nc
```

The **convert_mpas** program should have taken just a few seconds to run; if not, make sure the **latlon.nc** file was deleted before re-running **convert_mpas**. The only fields in the new **latlon.nc** file should be "precipw", "u10", and "v10".

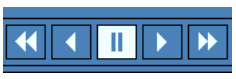
Rather than converting just a single file at a time, we can convert multiple MPAS output files and write the results to the same **latlon.nc** file. The key to doing this is to use the first command-line argument to **convert_mpas** to specify a file that contains horizontal (SCVT) mesh information, and to let subsequent command-line arguments specify MPAS netCDF files that contain fields to be remapped.

To interpolate the "precipw", "u10", and "v10" fields for our entire 5-day simulation, we can use the following commands:

```
$ rm latlon.nc
$ convert_mpas x1.10242.init.nc history.*.nc
$ ncview latlon.nc
```

Note, again, that the first command-line argument to **convert_mpas** is only used to obtain SCVT mesh information by the **convert_mpas** program when multiple command-line arguments are given, and all remaining command-line arguments specify netCDF files with fields to be interpolated!

When viewing a netCDF file with multiple time records, you can step through the time periods in **ncview** with the "forward" and "backward" buttons to the right and left of the "pause" button:



As a final exercise in viewing MPAS output via the **convert_mpas** and **ncview** programs, we'll zoom in on a part of the globe, looking at the 250 hPa vertical vorticity field over East Asia on a 1/10-degree lat-lon grid.

To do this, we will first need to edit the **include_fields** file so that it contains just the following line:

```
vorticity_250hPa
```

Then, we'll create a new file named **target_domain** with the editor of our choice. This file should contain the following lines:

```
startlat=30
endlat=60
startlon=90
endlon=150
nlat=300
nlon=600
```

After editing the **include_fields** file and creating the **target_domain** file, we can remove the old **latlon.nc** file and use the **convert_mpas** program to interpolate the 250 hPa vorticity field from our **diag.*.nc** files:

```
$ rm latlon.nc
$ convert_mpas x1.10242.init.nc diag*nc
$ ncview latlon.nc
```

If the processing of the static, geographical fields for the 240km – 48km variable-resolution mesh has not finished, yet, you can feel free to experiment more with the **convert_mpas** program!

3.4 Interpolating real-data initial conditions

Once the processing of the static, geographical fields has completed in the **240-48km_variable** directory, we should have a new "static" file as well as a **log.init_atmosphere.0000.out** file. In our example, the static file is named **SouthAmerica.static.nc**, but your file should have whatever name was specified in the definition of the "output" stream in the **streams.init_atmosphere** file.

Before proceeding, it's a good idea to verify that there were no errors reported in the **log.init_atmosphere.0000.out** file. We can also make a plot of the terrain height field as we did for the 240-km quasi-uniform simulation:

```
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/python_scripts/plot_terrain.py .
$ ./plot_terrain.py SouthAmerica.static.nc
```

Once we have convinced ourselves that the static, geographical processing was successful, we can proceed as we did for the 240-km quasi-uniform simulation. We'll create a symbolic link to the ERA5 *intermediate file* valid at 0000 UTC on 10 September 2014:

```
$ ln -s /glade/campaign/mmm/wmr/mpas_tutorial/met_data/ERA5:2014-09-10_00 .
```

As before, we'll set up the **namelist.init_atmosphere** file to instruct the **init_atmosphere_model** program to interpolate meteorological and land-surface initial conditions:

```
&nhyd_model
    config_init_case = 7
    config_start_time = '2014-09-10_00:00:00'
/
&dimensions
    config_nvertlevels = 55
    config_nsoillevels = 4
    config_nfglevels = 38
    config_nfgsoillevels = 4
/
&data_sources
    config_met_prefix = 'ERA5'
    config_use_spechumd = false
/
&vertical_grid
    config_ztop = 30000.0
    config_nsmterrain = 1
    config_smooth_surfaces = true
    config_dzmin = 0.3
    config_nsm = 30
    config_tc_vertical_grid = true
    config_blend_bdy_terrain = false
/
&interpolation_control
    config_extrap_airtemp = 'lapse-rate'
/
&preproc_stages
    config_static_interp = false
    config_native_gwd_static = false
    config_vertical_grid = true
    config_met_interp = true
```

```
    config_input_sst = false
    config_frac_seaice = true
/
&decomposition
    config_block_decomp_file_prefix = 'x5.30210.graph.info.part.'
/
```

Besides the **namelist.init_atmosphere** file, we must also edit the XML I/O configuration file, **streams.init_atmosphere**, to specify the name of the static file that will serve as input to the init_atmosphere_model program, as well as the name of the MPAS-Atmosphere initial condition file to be created. Specifically, we must set the filename_template for the "input" stream to the name of our static file:

```
<immutable_stream name="input"
                  type="input"
                  filename_template="SouthAmerica.static.nc"
                  input_interval="initial_only"/>
```

and we must set the name of the initial condition file to be created in the "output" stream:

```
<immutable_stream name="output"
                  type="output"
                  filename_template="SouthAmerica.init.nc"
                  packages="initial_conds"
                  output_interval="initial_only" />
```

After editing the **namelist.init_atmosphere** and **streams.atmosphere** files, and linking the intermediate file to our run directory, we can run the **init_atmosphere_model** program by submitting the **init_real.pbs** script to the queuing system again:

```
$ qsub init_real.pbs
```

The **init_atmosphere_model** program should take just a few minutes to run. Once the **init_atmosphere_model** program finishes, as always, it is best to verify that there were no error messages reported in the **log.init_atmosphere.0000.out** file. We should also have a file whose name matches the filename we specified for the "output" stream in the **streams.init_atmosphere** file. In our example, we should have a file named **SouthAmerica.init.nc**.

If all was successful, we are ready to run a variable-resolution MPAS simulation. For this simulation, we won't prepare an SST and sea-ice surface update file for the model; however, if you would like to try doing so following what was done in Section 2.2, feel free to do so!

3.5 Model integration

Assuming that an initial condition file, and, optionally, a surface update file have been created, we're ready to run a variable-resolution, 240km – 48km simulation with refinement over a part of the globe that interests us.

As a first step, you may recall that we need to create symbolic links to the **atmosphere_model** executable, as well as to the physics look-up tables, into our working directory:

```
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/atmosphere_model .
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/src/core_atmosphere/physics/physics_wrf/fil
```

We will also need *copies* of the **namelist.atmosphere**, **streams.atmosphere**, and **stream_list.atmosphere.*** files:

```
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/namelist.atmosphere .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/streams.atmosphere .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/stream_list.atmosphere.* .
```

Next, we will need to edit the **namelist.atmosphere** file. Recall from before that the default **namelist.atmosphere** is set up for a 120-km mesh; in order to run the model on a different mesh, there is one key key parameter that depends on the model resolution:

- config_dt — the model integration time step (delta-t), in seconds.

The model timestep, **config_dt** must be set to a value that is appropriate for the smallest grid distance in the mesh. In our case, we need to choose a time step that is suitable for a 48-km grid distance; a value of 240 seconds is reasonable. In the lecture on MPAS dynamics we will say more about how to choose the model timestep.

To tell the model the date and time at which integration will begin, and to specify the length of the integration to be run, there are two other parameters that must be set for each simulation:

- config_start_time — the start time of the integration.
- config_run_duration — the length of the integration.

In order to make maximal use of the time between this practical session and the next, we'll try to run a 5-day simulation starting on 2014-09-10_00.

Lastly, when running the MPAS-Atmosphere model in parallel, we must tell the model the prefix of the filenames that contain mesh partitioning information for different MPI task counts:

- config_block_decomp_file_prefix — the file prefix (to be suffixed with processor count) of the file containing mesh partitioning information.

For the 240km – 48km variable-resolution mesh, we can find a mesh partition file with 128 partitions at **`/glade/campaign/mmm/wmr/mpas_tutorial/meshes/x5.30210.graph.info.part.128`**. Let's symbolically link that file to our run directory now before specifying a value of **`'x5.30210.graph.info.part.'`** for the **`config_block_decomp_prefix`** in our **`namelist.atmosphere`** file.

```
$ ln -s /glade/campaign/mmm/wmr/mpas_tutorial/meshes/x5.30210.graph.info.part.128 .
```

Before reading further, you may wish to try making the changes to the **`namelist.atmosphere`** yourself. Once you've done so, you can verify that the options highlighted below match the changes you have made.

```
&nhyd_model
    config_dt = 240.0
    config_start_time = '2014-09-10_00:00:00'
    config_run_duration = '5_00:00:00'
/
&decomposition
    config_block_decomp_file_prefix = 'x5.30210.graph.info.part.'
/
```

After changing the parameters shown above in the **`namelist.atmosphere`** file, we must also set the name of the initial condition file in the **`streams.atmosphere`** file:

```
<immutable_stream name="input"
                  type="input"
                  filename_template="SouthAmerica.init.nc"
                  input_interval="initial_only"/>
```

Optionally, if you decided to create an SST update file for this variable-resolution simulation in the previous section, you can also edit the "surface" stream in the **`streams.atmosphere`** *file to specify the name of that surface update file, as well as the interval at which the model should read updates from it:*

```
<stream name="surface"
        type="input"
        filename_template="SouthAmerica.sfc_update.nc"
        filename_interval="none"
        input_interval="86400">

    <file name="stream_list.atmosphere.surface"/>

</stream>
```

Having set up the **`namelist.atmosphere`** and **`streams.atmosphere`** files, we're ready to run the model in parallel. We can copy the same job script as we used for the quasi-uniform 240-km simulation and submit it as usual with **`qsub`**.

```
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/job_scripts/run_model.pbs .
$ qsub run_model.pbs
```

Once the model begins to run, you may like to "tail" the **`log.atmosphere.0000.out`** file with the "-f" option to follow the progress of the MPAS simulation:

```
$ tail -f log.atmosphere.0000.out
```

If the model has started up successfully and begun to run, we should see messages like this:

```
 Begin timestep 2014-09-10_00:12:00
 --- time to run the LW radiation scheme L_RADLW =F
 --- time to run the SW radiation scheme L_RADSW =F
 --- time to run the convection scheme L_CONV    =T
 --- time to apply limit to accumulated rainc and rainnc L_ACRAIN   =F
 --- time to apply limit to accumulated radiation diags. L_ACRADT   =F
 --- time to calculate additional physics_diagnostics               =F
  split dynamics-transport integration 3

 global min, max w -1.06611 0.722390
 global min, max u -117.781 118.251
  Timing for integration step: 4.18681 s
```

This simulation will take about half an hour to run. Now may be a convenient time to ask any questions that you may have!

4. Running limited-area simulations

Having gained experience in running global simulations, we are now well positioned to run a limited-area (i.e., a regional) simulation with MPAS-Atmosphere. We will begin by defining the simulation domain using the MPAS-Limited-Area tool to cover any part of the globe that interests us. Then, we will subset the "static" fields from an existing 60-km quasi-uniform static file.

Once we are satisfied with the geographic coverage of our regional static fields, we will interpolate initial and lateral boundary conditions from the 0.5-degree CFSv2 datset. Given ICs and LBCs for our regional domain, we can begin running a 3-day regional simulation from 2019-09-01 0000 UTC through 2019-09-04 0000 UTC.

After our simulation has run (or, even after the first few model output files are available), we will practice using NCL and the **`convert_mpas`** tool to visualize the regional output.

4.1 Defining a regional domain and subsetting static fields

To begin the work of defining a regional simulation domain for MPAS-Atmosphere, we will first obtain a copy of the MPAS-Limited-Area tool. As with the MPAS model code and MPAS-Tools code, we will clone the MPAS-Limited-Area repository from GitHub. From within our **`/glade/derecho/scratch/${USER}/mpas_tutorial`** directory, we can do this with the following commands:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial
$ git clone https://github.com/MPAS-Dev/MPAS-Limited-Area.git
```

After changing to the **`MPAS-Limited-Area`** directory that should have been created by the **`git clone`** command, we can prepare a file describing our desired regional domain. Depending on the type of region that we intend to define (circular, elliptical, channel, or polygon), we can use any of the example region definition files in the **`docs/points-examples/`** sub-directory as a starting point.

For the purpose of illustration, we'll use the **`japan.ellipse.pts`** file from **`docs/points-examples/`** as a starting point to set up an elliptical domain over the Mediterranean Sea; however, *you may set up your regional domain over any other part of the globe using any of the available region types*. After copying this file to a file named **`mediterranean.pts`** in our current working directory with

```
$ cp docs/points-examples/japan.ellipse.pts mediterranean.pts
```

we can edit the file so that its contents look like the following:

```
Name: Mediterranean
Type: ellipse
Point: 37.9, 18.0
Semi-major-axis: 3200000
Semi-minor-axis: 1700000
Orientation-angle: 100
```

Again, you can set up any alternative regional domain as you prefer — the Mediterranean domain is only used here as an example!

To aid in locating your regional domain, it may be helpful to use OpenStreetMap, where you can right-click anywhere on a map and choose "Show address" to find the latitude and longitude of a point.

Having prepared a region definition file, we can use the **`create_region`** tool to create a subset of an existing global "static" file for our specified region. We can symbolically link a global, quasi-uniform, 60-km static file to our working directory with:

```
$ ln -s /glade/campaign/mmm/wmr/mpas_tutorial/meshes/x1.163842.static.nc .
```

Then, we can create a regional static file with a command like:

```
$ ./create_region mediterranean.pts x1.163842.static.nc
```

The **`create_region`** tool should take just a few seconds to run, and the result should be a new static file and a new **`graph.info`** file, named according to the "Name" we specified in our region defintion file, e.g,:

```
Mediterranean.static.nc
Mediterranean.graph.info
```

At this point, we may like to plot one of the time-invariant, terrestrial fields from our new regional static file. We can plot the terrain height field using an NCL script, **`regional_terrain.ncl`**, which we will first copy to our working directory:

```
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/ncl_scripts/regional_terrain.ncl .
```

This NCL script uses a custom color map. In order for NCL to find this color map, we'll need to set the **`NCARG_COLORMAPS`** environment variable as follows:

```
$ export NCARG_COLORMAPS=/glade/campaign/mmm/wmr/mpas_tutorial/ncl_colormaps/:$NCARG_ROOT/lib/ncarg/colorma
```

Before running the script, we will also need to set the latitude and longitude view point for the orthographic projection used by the script. In the **regional_terrain.ncl** script, locate the section that looks like the following, and modify the **cenlat** and **cenlon** values so that they coincide roughly with the center of your regional domain.

```
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
;
; Main script
;
;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;;
begin

  ;
  ; Center latitude and longitude
  ;
  cenlat = 37.9
  cenlon = 18.0
```

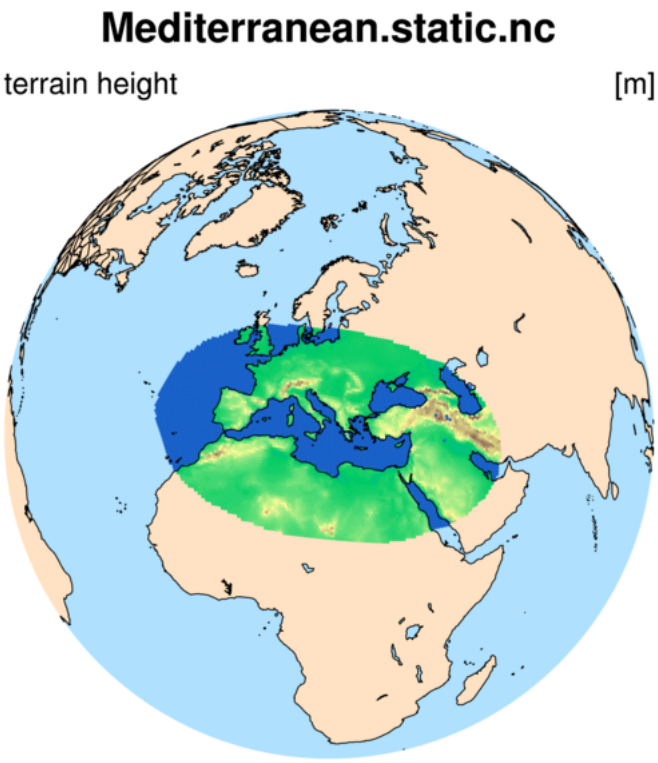
Additionally, we will need to set the **GNAME** environment variable to the name of our regional static file; e.g., for our Mediterranean example:

```
$ export GNAME=Mediterranean.static.nc
```

We can then run the script with

```
$ ncl regional_terrain.ncl
```

to produce a PNG image that should look something like the following:



Before proceeding to the next section, you may need to iterate between (1) modifying your region definition file, (2) running the **create_region** tool to create a new netCDF file, and (3) plotting the new regional terrain field with the **regional_terrain.ncl** script.

4.2 Interpolating regional initial conditions (ICs)

Now that we have a regional static file for our domain of interest, we can prepare initial conditions for this domain in essentially the same way as we prepared initial conditions for global simulations. *The key difference is that we will blend the terrain field along the regional domain boundaries with the terrain from our initial conditions data.*

Let's create a new directory in **/glade/derecho/scratch/${USER}/mpas_tutorial** to run our regional simulation:

```
$ mkdir /glade/derecho/scratch/${USER}/mpas_tutorial/regional
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial/regional
```

We can then move the regional static file and **graph.info** files that we created in Section 4.1 to this directory:

```
$ mv /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Limited-Area/Mediterranean.static.nc .
$ mv /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Limited-Area/Mediterranean.graph.info .
```

As with the global simulations from earlier sections, we will need to link the **init_atmosphere_model** executable to our run directory, and we will also need to *copy* the **namelist.init_atmosphere** and **streams.atmosphere** files, which we will modify for our regional domain.

```
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/init_atmosphere_model .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/namelist.init_atmosphere .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/streams.init_atmosphere .
```

For our regional simulation, we will use 0.5-degree CFSv2 data valid on 2019-09-01 0000 UTC for initial conditions. We can symbolically link the CFSV2 intermediate file to our run directory as follows:

```
$ ln -s /glade/campaign/mmm/wmr/mpas_tutorial/met_data/CFSV2:2019-09-01_00 .
```

Recall that we use the Metis tool to create mesh partition files for a specified number of MPI tasks. Using Metis's **gpmetis** tool, we can create a partition file for 128 MPI tasks from the **Mediterranean.graph.info** file that was generated by MPAS-Limited-Area. The following command should be work:

```
$ gpmetis -minconn -contig -niter=200 Mediterranean.graph.info 128
```

Even if we choose not to interpolate the initial conditions in parallel, we will ultimately need the mesh partition file to run the model in parallel.

Now, we are ready to edit our **namelist.init_atmosphere** and **streams.init_atmosphere** files. *To test your understanding, you may like to first try preparing these files yourself for the creation of initial conditions for your regional domain.* Once you've finished editing these files, you can compare against the changes highlighted below (click on the light blue header bars). *Remember that your static file and* **graph.info** *file may have different names, depending on where your regional domain is located.*

The edited namelist.init_atmosphere file

```
&nhyd_model
    config_init_case = 7
    config_start_time = '2019-09-01_00:00:00'
    config_stop_time = '2010-10-23_00:00:00'
    config_theta_adv_order = 3
    config_coef_3rd_order = 0.25
/
&dimensions
    config_nvertlevels = 55
    config_nsoillevels = 4
    config_nfglevels = 38
    config_nfgsoillevels = 4
/
&data_sources
    config_geog_data_path = '/glade/campaign/mmm/wmr/mpas_tutorial/mpas_static/'
    config_met_prefix = 'CFSV2'
    config_sfc_prefix = 'SST'
    config_fg_interval = 86400
    config_landuse_data = 'MODIFIED_IGBP_MODIS_NOAH'
    config_topo_data = 'GMTED2010'
    config_vegfrac_data = 'MODIS'
    config_albedo_data = 'MODIS'
    config_maxsnowalbedo_data = 'MODIS'
    config_supersample_factor = 3
    config_use_spechumd = false
/
&vertical_grid
    config_ztop = 30000.0
    config_nsmterrain = 1
    config_smooth_surfaces = true
    config_dzmin = 0.3
    config_nsm = 30
    config_tc_vertical_grid = true
    config_blend_bdy_terrain = true
/
&interpolation_control
    config_extrap_airtemp = 'lapse-rate'
/
&preproc_stages
    config_static_interp = false
    config_native_gwd_static = false
    config_vertical_grid = true
```

```
    config_met_interp = true
    config_input_sst = false
    config_frac_seaice = true
/
&io
    config_pio_num_iotasks = 0
    config_pio_stride = 1
/
&decomposition
    config_block_decomp_file_prefix = 'Mediterranean.graph.info.part.'
/
```

The edited streams.init_atmosphere file

For namelist and streams settings that were not modified, either the default value of the setting is acceptable, or the setting is not used when interpolating time-varying initial conditions. Now is also a good time to check that you understand why we needed to modify the settings that we did in the **namelist.init_atmosphere** and **streams.init_atmosphere** files.

After checking your modifications to the **namelist.init_atmosphere** and **streams.init_atmosphere** files, above, we can run the **init_atmosphere_model** program with 128 MPI tasks to create regional initial conditions. To do this, we can copy a prepared job script to run the **init_atmosphere_model** program and submit it with **qsub**.

```
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/job_scripts/init_parallel.pbs .
$ qsub init_parallel.pbs
```

Once the job completes, as always, it's important to verify that there were no errors during the execution of the **init_atmosphere_model** program; the end of the **log.init_atmosphere.0000.out** file should report zero errors:

```
------------------------------------------
 Total log messages printed:
    Output messages =                 464
    Warning messages =                  6
    Error messages =                    0
    Critical error messages =           0
 ------------------------------------------
```

If there were no errors, we should now have a regional initial conditions file; for our example regional domain the file should be named **Mediterranean.init.nc**. We're now ready to generate lateral boundary conditions for our domain in the next section!

4.3 Interpolating regional lateral boundary conditions (LBCs)

The interpolation of lateral boundary conditions for a regional simulation domain is conceptually similar to the interpolation of initial conditions: the key differences are: (1) fields are interpolated at several time periods, and (2) the set of fields to be interpolated are a subset of those required for initial conditions (they include: theta, rho, u, w, and moisture species).

We will use the CFSv2 reanalyses for lateral boundary conditions. Three days' worth of six-hourly CFSv2 fields are available in the **/glade/campaign/mmm/wmr/mpas_tutorial/met_data** directory, and we can symbolically link all of these CFSv2 files to our run directory with the following command:

```
$ ln -sf /glade/campaign/mmm/wmr/mpas_tutorial/met_data/CFSV2* .
```

All that is needed now is to once again edit the **namelist.init_atmosphere** and **streams.init_atmosphere** files to set up the interpolation of LBCs using "init case" 9. The relevant settings are highlighted in the sections, below (click the light blue headers to expand each edited file).

The edited namelist.init_atmosphere file

The edited streams.init_atmosphere file

There are a few points worth making about the changes in the **streams.init_atmosphere** file.

- Because the interpolation of LBCs is not only a horizontal interpolation to the regional mesh, but also a vertical interpolation to the vertical coordinate surfaces, the "input" stream must read from a file that contains a valid "zgrid" field. The initial conditions file contains horizontal and vertical mesh information, and so we use it as the file from which the "input" stream reads.
- The MPAS *stream manager* infrastructure will complain if an input stream and an output stream share the same **filename_template**, so the **filename_template** for the "output" stream must be set to some other filename; since "init case" 9 only writes the "lbc" stream, we can make up any filename we like for the "output" stream.

- The **output_interval** for the "lbc" stream must match the value of the **config_fg_interval** namelist option. In this regional example, using "21600" or "6:00:00" are equivalent (we could even specify "360:00" if we would like!).

After having edited our **namelist.init_atmosphere** and **streams.init_atmosphere** files, we are ready to run the **init_atmosphere_model** program again using 128 MPI tasks. We can submit the **init_parallel.pbs** script again with **qsub**:

```
$ qsub init_parallel.pbs
```

After the **init_atmosphere_model** program completes, it is a good idea (as always!) to verify that there were no errors reported at the end of the **log.init_atmosphere.0000.out** file:

```
 ------------------------------------------
 Total log messages printed:
    Output messages =                 2742
    Warning messages =                   0
    Error messages =                     0
    Critical error messages =            0
 ------------------------------------------
```

If there were no errors, we should now have "lbc" files in our run directory:

```
$ ls -l lbc*nc
-rw-r--r-- 1 class112 cbet 15469296 Sep  5 16:37 lbc.2019-09-01_00.00.00.nc
-rw-r--r-- 1 class112 cbet 15469296 Sep  5 16:37 lbc.2019-09-01_06.00.00.nc
-rw-r--r-- 1 class112 cbet 15469296 Sep  5 16:37 lbc.2019-09-01_12.00.00.nc
-rw-r--r-- 1 class112 cbet 15469296 Sep  5 16:37 lbc.2019-09-01_18.00.00.nc
-rw-r--r-- 1 class112 cbet 15469296 Sep  5 16:37 lbc.2019-09-02_00.00.00.nc
-rw-r--r-- 1 class112 cbet 15469296 Sep  5 16:37 lbc.2019-09-02_06.00.00.nc
-rw-r--r-- 1 class112 cbet 15469296 Sep  5 16:37 lbc.2019-09-02_12.00.00.nc
-rw-r--r-- 1 class112 cbet 15469296 Sep  5 16:37 lbc.2019-09-02_18.00.00.nc
-rw-r--r-- 1 class112 cbet 15469296 Sep  5 16:37 lbc.2019-09-03_00.00.00.nc
-rw-r--r-- 1 class112 cbet 15469296 Sep  5 16:37 lbc.2019-09-03_06.00.00.nc
-rw-r--r-- 1 class112 cbet 15469296 Sep  5 16:37 lbc.2019-09-03_12.00.00.nc
-rw-r--r-- 1 class112 cbet 15469296 Sep  5 16:37 lbc.2019-09-03_18.00.00.nc
-rw-r--r-- 1 class112 cbet 15469296 Sep  5 16:37 lbc.2019-09-04_00.00.00.nc
```

We're now ready to run a regional simulation in the next section!

4.4 Running a regional simulation

Given regional initial conditions and lateral boundary conditions, we are almost ready to run a regional simulation. The only differences from running a global simulation are: (1) we need to set a namelist option to enable the application of LBCs in each model timestep, and (2) we need to set up an LBC input stream for the model.

As in previous exercises, we will need to symbolically link the **atmosphere_model** executable, as well as the look-up tables used by physics schemes, into our run directory. We can do this with the following commands:

```
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/atmosphere_model .
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/src/core_atmosphere/physics/physics_wrf/fil
```

We also need copies of the default **namelist.atmosphere**, **streams.atmosphere**, and **stream_list.atmosphere.*** files, which we will edit for our simulation.

```
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/namelist.atmosphere .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/streams.atmosphere .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/stream_list.atmosphere.* .
```

As with global simulations, the key namelist parameters that must be modified are:

- **config_dt** - the model integration timestep; roughly six times the minimum grid distance in km is a reasonable first guess
- **config_start_time** - the starting time for the simulation
- **config_run_duration** - the duration of the simulation
- **config_block_decomp_file_prefix** - the prefix (excluding the final number) of the file providing mesh partition information

Different from global simulations, we must also set the namelist option **config_apply_lbcs = true**!

You may like to try editing the **namelist.atmosphere** file yourself before checking your changes against those highlighted, below (click on the light blue header).

The edited namelist.atmosphere file

In the **streams.atmosphere** file, we will need to set the **filename_template** for the "input" stream to the name of our regional initial conditions file. We will also need to set the **input_interval** for the "lbc_in" stream to the interval at which we have prepared lateral boundary conditions files.

After editing the **streams.atmosphere** file, you can compare your changes against those highlighted, below (click on the light blue header).

The edited streams.atmosphere file

Once we have finished editing the **namelist.atmosphere** and **streams.atmosphere** files, we're ready to run a simulation. We can copy the same job script as we used for the quasi-uniform 240-km simulation and submit it as usual with **qsub**.

```
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/job_scripts/run_model.pbs .
$ qsub run_model.pbs
```

This simulation will take a while to run. Once the first few netCDF output files have been produced, even before the full simulation has completed, we can proceed to the next section to practice visualizing the initial regional model output.

4.5 Visualizing regional output

If the regional simulation ran successfully — or even if it has just begun running and has produced several time periods of output — we can visualize the output using two different methods.

In order to take a quick first look at the output, we can use the **convert_mpas** tool to interpolate our output to a regular latitude-longitude grid, after which we can view the interpolated fields using **ncview**.

Let's first check whether the path to the **convert_mpas** program is in our **$PATH** environment variable with:

```
$ which convert_mpas
```

If the "which" command prints something like

```
/usr/bin/which: no convert_mpas ...
```

we can set our **$PATH** environment variable by typing:

```
$ export PATH=/glade/derecho/scratch/${USER}/mpas_tutorial/convert_mpas:$PATH
```

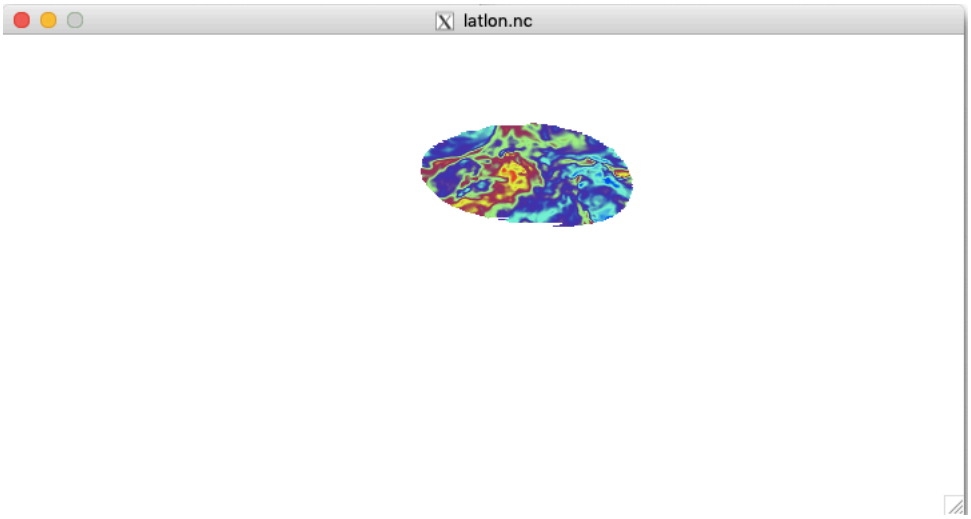
To start, we can simply interpolate the full set of fields from all diagnostics output files to a global 0.5-degree lat-lon grid with the following command:

```
$ convert_mpas Mediterranean.static.nc diag*nc
```

We can then view the resulting **latlon.nc** file with **ncview**:

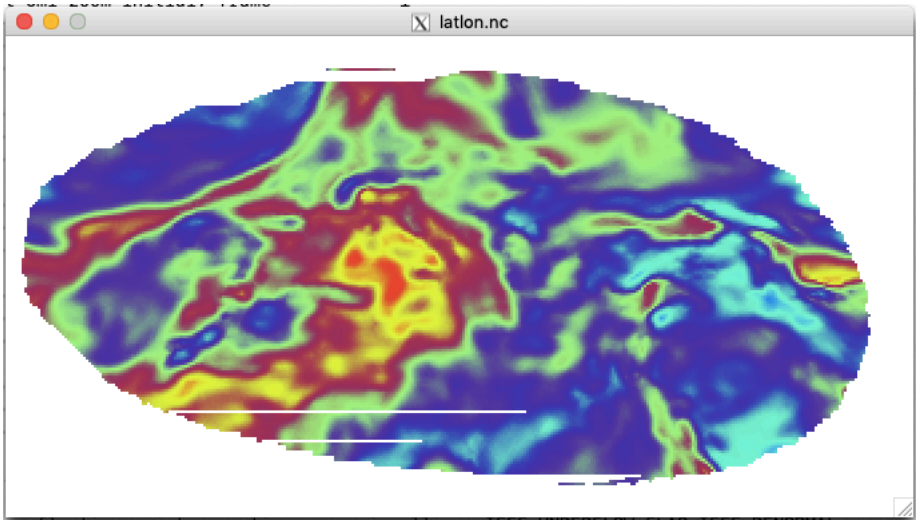
```
$ ncview latlon.nc
```

Because the default target grid for the **convert_mpas** program is a global, 0.5-degree grid, viewing, e.g., the "precipw" field might look like the image below.



As we did in Section 3.3, we can try to interpolate to a lat-lon grid that is windowed around our regional domain. Following Section 3.3 to prepare a **target_domain** file, can you produce a **latlon.nc** file that looks something like the following?

Remember: it's generally best to remove any existing latlon.nc file before re-running the convert_mpas program!



As mentioned in the lectures, the **convert_mpas** program may produce some interpolation artifacts as of the time of this tutorial. We expect to have this fixed in the near future, but for now, we can ignore any interpolation artifacts and animate through all time slices of several model diagnostic fields in **ncview** to gain confidence that our regional simulation is producing plausible results.

After we've taken some time to browse the interpolated diagnostic fields with **ncview**, we can make use of NCL to produce figures more suitable for use in publications or presentations.

In **/glade/campaign/mmm/wmr/mpas_tutorial/ncl_scripts** is a template script, **regional_cells.ncl**, for plotting the individual cell values from a regional MPAS netCDF file. We can copy this script to our run directory with the following command:

```
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/ncl_scripts/regional_cells.ncl .
```

By default, this script plots the vegetation type field, *ivgtyp*, with the view-point set to 20.0 N latitude, 80.0 E longitude. With the editor of your choice, open the **regional_cells.ncl** file and locate the section of the script with the following (it should be around line 68):

```
;
; Center latitude and longitude
;
cenlat = 20.0
cenlon = 80.0
```

Let's change the center latitude and longitude values for the view-point to the approximate center of our regional domain. For our example Mediterranean domain, the following settings might be reasonable, *but if your regional domain is located over a different part of the globe, you should modify these values as necessary*.

```
;
; Center latitude and longitude
;
cenlat = 38.0
cenlon = 20.0
```

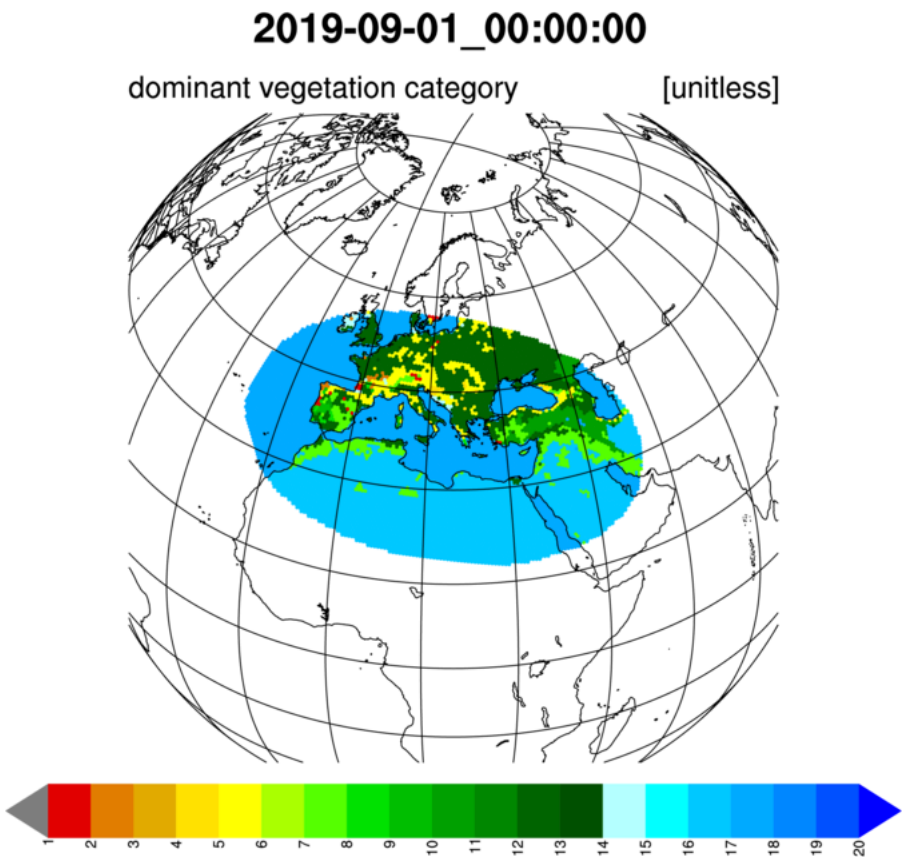
In general, the **regional_cells.ncl** script reads three environment variables:

- **FNAME** - the name of the file containing the field to be plotted
- **GNAME** - the name of the file containing the mesh information
- **T** - for time-varying fields, the time period to plot (0 is the first time in a file)

In order to plot the vegetation type field from our initial conditions files, the following settings of these variables will work:

- **FNAME=Mediterranean.init.nc**
- **GNAME=Mediterranean.init.nc**
- **T=0**

After setting these environment variables and running the NCL script, we should have a plot equivalent to the one below in a file named "cells.png".



The part of the **regional_cells.ncl** script that handles the actual plotting is general enough to handle any field — we just need to set an appropriate plotting range and color table in the script when changing fields. Next, we can try to modify the script to plot the precipitable water ("precipw") field using a different color map.

Before proceeding, you may like to open the NCL Color Table Gallery in a new tab to see the available NCL color tables.

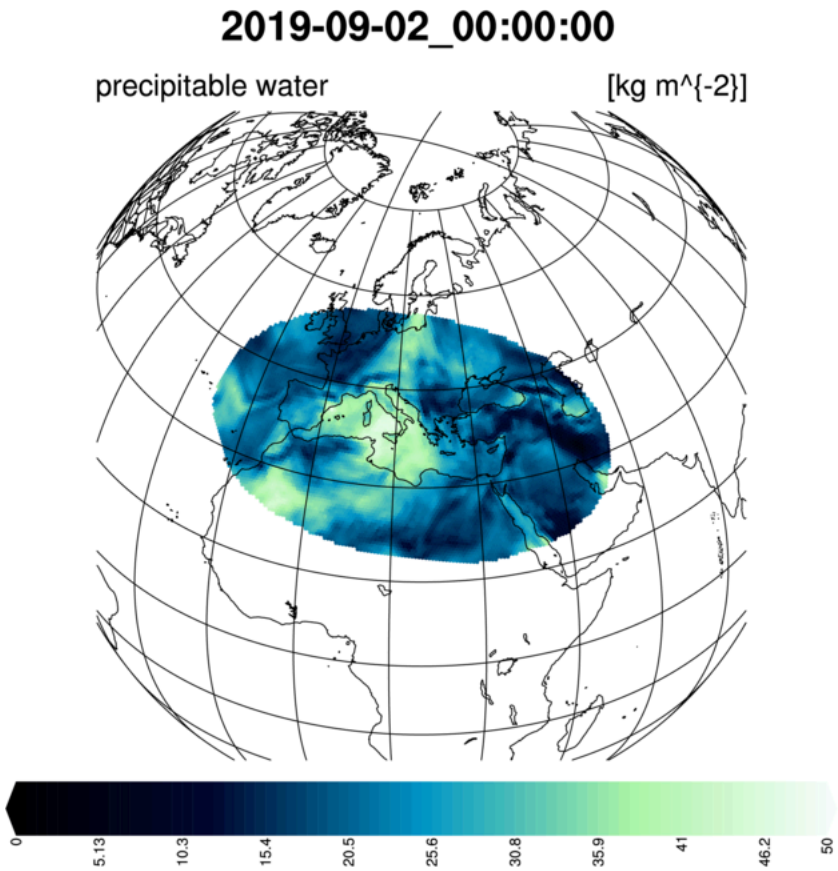
With the editor of your choice, open the **regional_cells.ncl** file and locate the section of the script (beginning around line 84) where the field to be plotted, the color map, and the contour levels are set. Let's modify this section of the script so that it looks like the following:

```
;
; The field to be plotted
;
h = f->precipw(iTime,:)


;
; The color map to use
; (see https://www.ncl.ucar.edu/Document/Graphics/color_table_gallery.shtml)
;
colormap = "GMT_ocean"

;
; The number of colors in the color map
;
nColors = 80

;
; The contour intervals
; E.g., fspan(1, 10, 10) yields (/1, 2, 3, 4, 5, 6, 7, 9, 10/)
; Typically, we have nColors-1 levels
;
cnLevels = fspan(0.0, 50.0, nColors-1)
```

We located the "GMT_ocean" color table from the NCL Color Table Gallery link, above. Before re-running the script, we will need to set the **FNAME** environment variable to the name of one of our diagnostics model output files. If our regional simulation has progressed through at least forecast hour 24, we could use the following:

```
$ export FNAME=diag.2019-09-02_00.00.00.nc
```

We can then re-run the script to produce a plot like the one below.



With the remaining time in this session, feel free to experiment with plotting other fields from any of the netCDF output files. Browsing the model output that has been converted to a latitude-longitude grid with the **`convert_mpas`** before deciding on the field to plot and the range of values to set in the **`regional_cells.ncl`** script may be helpful.

5. Defining new output streams, and visualization

In this section, we'll restart a simulation from the end of the five-day, global 240-km simulation that we started in the second section. Before restarting the simulation, though, we'll define new output streams.

Optionally, before restarting the simulation, we can also try adding a list of sounding locations for the simulation.

After launching the restart simulation with new output streams (and perhaps some sounding output), we'll practice using some NCL scripts to visualize the first five days of output from the variable-resolution 240-km – 48-km simulation

5.1 Setting up the restart simulation

As we saw in the lectures, setting up a simulation to restart from a previously run simulation is relatively simple. We'll begin by making sure that we're in the directory where we ran the original, 5-day 240-km global simulation:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial/240km_uniform
```

Before making any changes to the **`namelist.atmosphere`** file, we will first check to see which restart files are available; if our original simulation completed successfully, we should have one restart file per day, valid at the end of each of the five days of the simulation:

```
$ ls -l restart*nc
-rw-r--r-- 1 duda ncar 197382136 Apr  8 23:57 restart.2014-09-11_00.00.00.nc
-rw-r--r-- 1 duda ncar 197382136 Apr  8 23:57 restart.2014-09-12_00.00.00.nc
-rw-r--r-- 1 duda ncar 197382136 Apr  8 23:58 restart.2014-09-13_00.00.00.nc
-rw-r--r-- 1 duda ncar 197382136 Apr  8 23:59 restart.2014-09-14_00.00.00.nc
-rw-r--r-- 1 duda ncar 197382136 Apr  8 23:59 restart.2014-09-15_00.00.00.nc
```

In principle, we could restart our simulation from any of these files, but we'll begin from the last available file, valid at 0000 UTC on 15 September.

There are just two changes that need to be made to the **`namelist.atmosphere`** file: we need to set the starting time of the simulation to **`2014-09-15_00:00:00`** and we need to set the **`config_do_restart`**

option to **true**:

```
&nhyd_model
    config_start_time = '2014-09-15_00:00:00'
/
&restart
    config_do_restart = true
/
```

We can keep all of the other namelist options as they were, including the **config_run_duration** option — restarting the simulation and running for another five days should be fine, since we had a total of 10 days of SST and sea-ice information in our surface update file.

Before running the model, we'll make a few other changes as described in the next sections!

5.2 Defining new output streams

We may also like to write out some additional fields from our restart simulation at a higher temporal frequency. You may recall from the lectures that we can define new output streams in the **streams.atmosphere** file.

We will provide an example here of writing out the 10-meter AGL horizontal winds every 60 minutes, but you can feel free to look through Appendix D of the MPAS-Atmosphere Users' Guide to see if there are any other fields that you may like to write out.

Let's define a new output stream named "sfc_winds" in the **streams.atmosphere** file:

```
<stream name="sfc_winds"
        type="output"
        filename_template="surface_winds.$Y-$M-$D_$h.nc"
        filename_interval="output_interval"
        output_interval="60:00" >

        <var name="u10"/>
        <var name="v10"/>
</stream>
```

This new stream must be defined somewhere between the opening **<streams>** and closing **</streams>** tags in the **streams.atmosphere** file.

Note in the stream definition above that the files that will be written will have names like **surface_winds.2014-09-15_00.nc**, **surface_winds.2014-09-15_01.nc**, etc. by our choice of the "filename_template". Also, MPAS will create new files at each output time, rather than packing many time records into the same file; this is controlled by the "filename_interval" option. Finally, note that the stream will be written every 60 minutes. Since our simulation starts at 00:00:00 UTC, the minutes and seconds part of the output files is unnecessary. Of course, we may want to add **$m** and **$s** to our filename template if we were writing this stream more frequently than once per hour.

In the next section, we'll describe the steps to write out vertical profiles at specific (lat,lon) locations before we run our restart simulation.

5.3 Adding soundings to the simulation

It may at times also be helpful to write out vertical profiles of basic model fields at specified (lat,lon) locations from a model simulation. In MPAS terminology, this is described as writing "soundings" from the simulation.

In principle, we can write out soundings for as many locations as we would like. Here, we'll describe how to write out soundings from three locations: Boulder, Colorado; McMurdo Station, Antarctica; and New Delhi, India.

We will need to specify the locations for the soundings in a text file named **sounding_locations.txt** in our model run directory:

```
40.0   -105.25  Boulder
28.7     77.2   NewDelhi
-77.85  166.67  McMurdo
```

The three columns of the file contain the latitude, longitude, and name of the sounding. The latitude and longitude are given as decimal degrees, and the name cannot contain whitespace (since it will be used to name output files).

For this exercise, if you would prefer to write out soundings for different locations, feel free to change the list of locations as you would like!

Lastly, we need to specify how frequently these soundings will be written during the model simulation. This is done through the **config_sounding_interval** option in the **namelist.atmosphere** file. By

default, this option can be found near the bottom of the file. Let's choose to write soundings every three hours:

```
&soundings
    config_sounding_interval = '3:00:00'
/
```

Having set the output interval for soundings, we're ready to make a restart simulation.

5.4 Running the restart simulation

Now that we've edited our **namelist.atmosphere** file for our restart run, we've added a new output stream with surface winds to the **streams.atmosphere** file, and we've specified a list of locations for which profiles will be written every three hours, we can restart the model and simulate an additional five days by submitting our existing **run_model.pbs** script with **qsub**:

```
$ qsub run_model.pbs
```

Once the job has started to run, it's a good idea to check several points:

- Does running **tail -f log.atmosphere.0000.out** show timesteps being taken by the model?
- Do you see new output files named **surface_winds.2014-09-15_00.nc**, etc.?
- Do you see sounding files for Boulder, New Delhi, and McMurdo Station as files with the **.snd** suffix?

If all of the above check out, our restart simulation is successfully running! In the next section, we'll look at a couple of new NCL scripts for plotting model output.

5.5 Using NCL to visualize output

Now that our restart simulation is running, we can examine in more detail an example NCL script for plotting horizontal fields as individual cells. To try out this script, we can work with output from our 240km – 48km variable-resolution simulation.

In order to plot horizontal fields, we can begin by ensuring that we are in the **240-48km_variable** directory before copying over the **latlon_cells.ncl** script:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial/240-48km_variable
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/ncl_scripts/latlon_cells.ncl .
```

This script reads the name of the MPAS NetCDF file with SCVT mesh information from an environment variable named **GNAME** (roughly, "G" means "grid"). The MPAS NetCDF file that contains the actual field to be plotted is identified by the environment variable **FNAME** (roughly, "F" means "field").

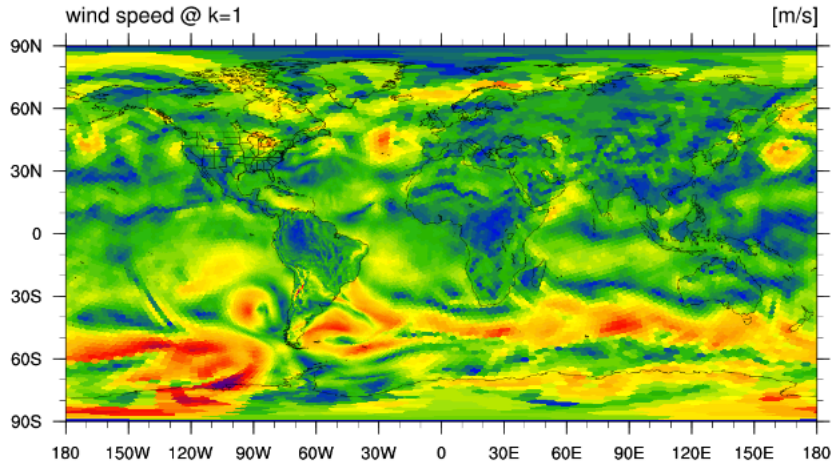
We'll plot a field from the **diag.2014-09-11_00.00.00.nc** file. The mesh information can be found in the MPAS initial conditions file, which may be named **SouthAmerica.init.nc**, though you may have chosen a different name corresponding to a different location of refinement. We'll set the **GNAME** and **FNAME** environment variables before proceeding:

```
$ export GNAME=SouthAmerica.init.nc
$ export FNAME=diag.2014-09-11_00.00.00.nc
```

Remember, your initial conditions file may have a different name!

By default, the **latlon_cells.ncl** script plots the lowest-model-level wind speed, and the output is saved to a PNG image in a file named **cell_plot.png**. Running the script should produce this plot, which you can view with the **display** command.

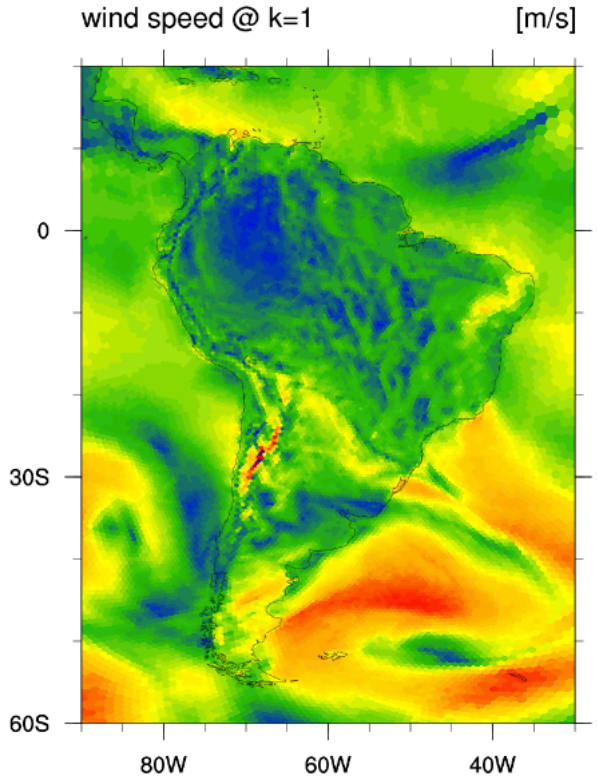
```
$ ncl latlon_cells.ncl
$ display cell_plot.png
```



Since we are working with a variable-resolution mesh, we may like to set a plotting window to cover only part of the refined region in our simulation. We can set a plotting window in the **`latlon_cells.ncl`** script by editing the section of the script that looks like this:

```
; The bounding box for the plot
mapLeft   = -180.0
mapRight  = 180.0
mapBottom = -90.0
mapTop    =  90.0
```

Feel free to set the plotting window however you would like for your variable-resolution simulation. For example, if we were to set the plotting window to cover South America before re-running the script, the result might look like the following:



Finally, we may like to plot other fields. We can see which fields were written to the **`diag.*.nc`** files using **`ncdump`**:

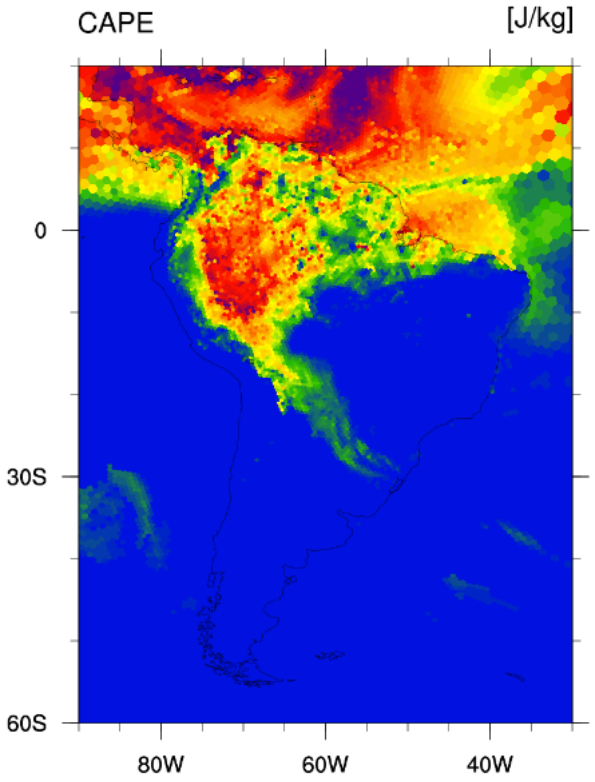
```
$ ncdump -h diag.2014-09-11_00.00.00.nc
```

If, for example, we would like to plot Convective Available Potential Energy (CAPE), we could edit the **`latlon_cells.ncl`** script near the comment "The field to be plotted" so that it looked like the following:

```
; The field to be plotted
h   = f->cape(0,:)
```

```
; The field name
field_name = "CAPE"
field_units = "[J/kg]"

; The range of field values to plot (start, stop, number)
cnLevels = fspan(0,3000,50)
```

Generally, we will need to assign the variable to be plotted, specify the plotting name and units for the field, and specify a range of value for the field. Making these changes and re-running the NCL script might produce a plot like the following:



Now that you have a feel for how to edit the **`latlon_cells.ncl`** script, feel free to try plotting other fields!

6. Adding new passive tracers

In this section, we'll get some experience in making source-code changes to add a passive tracer to the model. Although the exercises in this section are independent of those in other section, it may be best to finish the exercises from the previous section first, since we will be changing the model source code and re-compiling the model executable.

6.1 Creating initial conditions for the tracer

We'll begin by defining our new passive tracer in the **`Registry.xml`** file for the **`init_atmosphere`** core. Let's change directories to the copy of the MPAS-Model source code in our **`/glade/derecho/scratch/${USER}/mpas_tutorial`** directory:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model
```

Opening up the **`src/core_init_atmosphere/Registry.xml`** file with our editor of choice, we will look for the **`var_array`** section named **`"scalars"`**; it should look something like this:

```
                <var_array name="scalars" type="real" dimensions="nVertLevels nCells Time">
                        <var name="qv" array_group="moist" units="kg kg^{-1}"
                             description="Water vapor mixing ratio"/>

                        <var name="qc" array_group="moist" units="kg kg^{-1}"
                             description="Cloud water mixing ratio"/>

                        <var name="qr" array_group="moist" units="kg kg^{-1}"
                             description="Rain water mixing ratio"/>
                </var_array>
```

As we saw in the lectures, we will need to add our new passive tracers here. Let's add a new passive tracer named "mytracer1". The `array_group` that we assign to this tracer can be anything other than `"moist"`. By convention, we'll call the array group for this new tracer `"passive"`. After adding our new tracer, the `"scalars"` `var_array` should look like this:

```
                <var_array name="scalars" type="real" dimensions="nVertLevels nCells Time">
                        <var name="qv" array_group="moist" units="kg kg^{-1}"
                             description="Water vapor mixing ratio"/>

                        <var name="qc" array_group="moist" units="kg kg^{-1}"
                             description="Cloud water mixing ratio"/>

                        <var name="qr" array_group="moist" units="kg kg^{-1}"
                             description="Rain water mixing ratio"/>

                        <var name="mytracer1" array_group="passive" units="kg kg^{-1}"
                             description="A simple passive tracer"/>
                </var_array>
```

After making this change to the Registry.xml file, we'll clean and re-compile the init_atmosphere core. Recall that, after we make changes to the Registry.xml file, we need to "clean" the build first so that the changes take effect. Later, when we modify only Fortran source code, there will be no need to "clean" before re-compiling. The following two commands should suffice:

```
$ make clean CORE=init_atmosphere
$ qcmd -A UMMM0006 -- make -j8 gnu CORE=init_atmosphere
```

If compilation was successful, we should now have a new `init_atmosphere_model` executable. At this point, if we were to create new initial conditions, the "mytracer1" field would be present in the initial conditions, but it would be zero everywhere. We next need to add code to define the initial conditions for "mytracer1".

To define the initial value of our new tracer, use your preferred editor to open the `src/core_init_atmosphere/mpas_init_atm_cases.F` file. Search for these two lines of code that call the routine to initialize real-data test cases:

```
                call init_atm_case_gfs(block_ptr, mesh, nCells, nEdges, nVertLevels, fg, state, &
                                       diag, diag_physics, config_init_case, block_ptr % dimensions, block_ptr
```

An appropriate place to add a call to our tracer initialization routine would be directly after the call to `init_atm_case_gfs`. Let's add a new line of code below this to call a new subroutine, which we'll name `init_tracers`.

```
                call init_atm_case_gfs(block_ptr, mesh, nCells, nEdges, nVertLevels, fg, state, &
                                       diag, diag_physics, config_init_case, block_ptr % dimensions, block_ptr
                call init_tracers(mesh, state)
```

Notice that this new routine (which we have yet to define!) takes as input two arguments; as we will see, these two arguments are MPAS "pools", which we discussed in the lectures.

As a start, we will define the `init_tracers` function so that it simply writes a message to the log file. At the bottom of the `src/core_init_atmosphere/mpas_init_atm_cases.F`, but before the line `"end module init_atm_cases"`, let's add the following Fortran code:

```
    subroutine init_tracers(mesh, state)

        implicit none

        type (mpas_pool_type), intent(in) :: mesh
        type (mpas_pool_type), intent(inout) :: state

        call mpas_log_write('====== Handling tracer initialization ======')

    end subroutine init_tracers
```

After saving our code changes, we can re-compile the `init_atmosphere` core with:

```
$ qcmd -A UMMM0006 -- make -j8 gnu CORE=init_atmosphere
```

Again, because we have not changed the `Registry.xml` file since we last re-compiled, there's no need to "make clean".

Compilation should take just a minute, and if it completes successfully, we're ready to try out our modified code, even though it won't actually create initial conditions for our passive tracer, yet. So that we don't overwrite files from any of our previous sessions, we'll work in a new directory, `passive_tracer`:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial
$ mkdir passive_tracer
$ cd passive_tracer
```

We'll test out our passive tracer on the 240-km uniform mesh, for which we have already created a "static" file. Now that we have experience in creating initial conditions, the following procedure should seem familiar:

```
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/240km_uniform/x1.10242.static.nc .
$ ln -s /glade/campaign/mmm/wmr/mpas_tutorial/met_data/ERA5:2014-09-10_00 .
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/init_atmosphere_model .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/namelist.init_atmosphere .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/streams.init_atmosphere .
```

As in Section 2.1, we'll edit the **namelist.init_atmosphere** so that it looks like the following:

```
&nhyd_model
    config_init_case = 7
    config_start_time = '2014-09-10_00:00:00'
/
&dimensions
    config_nvertlevels = 55
    config_nsoillevels = 4
    config_nfglevels = 38
    config_nfgsoillevels = 4
/
&data_sources
    config_met_prefix = 'ERA5'
    config_use_spechumd = false
/
&vertical_grid
    config_ztop = 30000.0
    config_nsmterrain = 1
    config_smooth_surfaces = true
    config_dzmin = 0.3
    config_nsm = 30
    config_tc_vertical_grid = true
    config_blend_bdy_terrain = false
/
&interpolation_control
    config_extrap_airtemp = 'lapse-rate'
/
&preproc_stages
    config_static_interp = false
    config_native_gwd_static = false
    config_vertical_grid = true
    config_met_interp = true
    config_input_sst = false
    config_frac_seaice = true
/
```

We'll then edit the filename that will be read by the "input" stream in the **streams.init_atmosphere** file so that it matches the name of our "static" file:

```
<immutable_stream name="input"
                  type="input"
                  filename_template="x1.10242.static.nc"
                  input_interval="initial_only"/>
```

Also as in Section 2.1, we'll change the name of the initial conditions file to be created:

```
<immutable_stream name="output"
                  type="output"
                  filename_template="x1.10242.init.nc"
                  packages="initial_conds"
                  output_interval="initial_only" />
```

We should now be able to run the **init_atmosphere_model** executable to produce an **x1.10242.init.nc** file:

```
$ qcmd -A UMMM0006 -- ./init_atmosphere_model
```

If there were no errors in the **log.init_atmosphere.0000.out** file, we can check for the presence of our passive tracer in the **x1.10242.init.nc** file:

```
$ ncdump -h x1.10242.init.nc | grep mytracer1
```

Besides the creation of the **x1.10242.init.nc** file, we should also look for this message in the **log.init_atmosphere.0000.out** file:

```
 ====== Handling tracer initialization ======
```

If all was successful, we can go back to the **MPAS-Model** directory and add code to provide initial conditions for our passive tracer. Let's change back to the MPAS source code directory:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model
```

Using our favorite editor, let's open the **src/core_init_atmosphere/mpas_init_atm_cases.F** file and change the code for our **init_tracers** subroutine so that it looks like the following:

```
    subroutine init_tracers(mesh, state)

        implicit none

        type (mpas_pool_type), intent(in) :: mesh
        type (mpas_pool_type), intent(inout) :: state

        integer, pointer :: index_mytracer1
        integer, pointer :: nCells
        integer, pointer :: nVertLevels

        integer :: k, iCell

        real (kind=RKIND), dimension(:), pointer :: latCell
        real (kind=RKIND), dimension(:), pointer :: lonCell
        real (kind=RKIND), dimension(:,:,:), pointer :: scalars

        call mpas_log_write('====== Handling tracer initialization ======')

        call mpas_pool_get_dimension(mesh, 'nCells', nCells)
        call mpas_pool_get_dimension(mesh, 'nVertLevels', nVertLevels)

        call mpas_pool_get_dimension(state, 'index_mytracer1', index_mytracer1)

        call mpas_pool_get_array(state, 'scalars', scalars)
        call mpas_pool_get_array(mesh, 'latCell', latCell)
        call mpas_pool_get_array(mesh, 'lonCell', lonCell)

        do iCell = 1, nCells
            do k = 1, nVertLevels
                scalars(index_mytracer1,k,iCell) = &
                          0.0001 * 0.5 * (sin(latCell(iCell)*4.0) * &
                                          sin(lonCell(iCell)*8.0) + 1.0)
            end do
        end do

    end subroutine init_tracers
```

Based on what was discussed in the MPAS software lecture about Registry, pools, and logging, you have the necessary information at your disposal to make sense of the code for the **init_tracers** routine!

After saving our changes, we can re-compile the **init_atmosphere** core once again:

```
$ qcmd -A UMMM0006 -- make -j8 gnu CORE=init_atmosphere
```

We can now try creating new initial conditions with our updated **init_tracers** routine. Let's change back to the **passive_tracer** directory, remove the old **x1.10242.init.nc** file, and create a new initial conditions file:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial/passive_tracer
$ rm x1.10242.init.nc
$ qcmd -A UMMM0006 -- ./init_atmosphere_model
```

If the creation of the new **x1.10242.init.nc** file was successful, you may like to try using the **convert_mpas** utility to see what our new "mytracer1" field looks like. For a quick reminder of how the **convert_mpas** tool works, you may find it helpful to refer back to Section 3.3.

6.2 Adding the tracer to the model

Now that we have a new passive tracer in our initial conditions, we'll need to edit the **Registry.xml** file for the **atmosphere** core so that the model itself will know about the new tracer.

Let's begin by changing back to the model source code directory:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model
```

We can edit the **src/core_atmosphere/Registry.xml** file, recalling from the lectures that we not only need to define the tracer, but we also need to define an array that will hold the tendencies for the tracer. Even if we don't supply any sources or sinks, the model needs memory to be allocated for the tracer tendency, e.g., for use in the scalar transport routines.

In the **src/core_atmosphere/Registry.xml** file, search for the word "var_array" several times until you come to the definition of the **scalars var_array** tag, which should begin with lines that look like this:

```
<var_array name="scalars" type="real" dimensions="nVertLevels nCells Time">
        <var name="qv" array_group="moist" units="kg kg^{-1}"
             description="Water vapor mixing ratio"/>
```

Let's add a new XML **var** tag inside the **var_array** tag to define our new "mytracer1" tracer; this new tag may look something like the following:

```
        <var name="mytracer1" array_group="passive" units="kg kg^{-1}"
             description="Our first passive tracer"/>
```

Remember: it's important that the passive tracer belongs to an **array_group** *other than "moist"; here, we've just used the string "passive", though in principle you could choose another name.*

Similarly, we need to define a tendency array for our new passive tracer. Searching for the word "scalars_tend", we should find a section of XML for the **scalars_tend var_array** that begins with the following lines:

```
<!-- scalar tendencies -->
<var_array name="scalars_tend" type="real" dimensions="nVertLevels nCells Time">
        <var name="tend_qv" name_in_code="qv" array_group="moist" units="kg m^{-3} s^{-1}"
             description="Tendency of water vapor mass per unit volume divided by d(zeta)/dz"/>
```

We'll define a new **var** entry in this **var_array** for our passive tracer tendency; this new entry might look something like the following:

```
        <var name="tend_mytracer1" name_in_code="mytracer1" array_group="passive" units="kg m^{-3} s^{-1}"
             description="Tendency of our first tracer mass per unit volume divided by d(zeta)/dz"/>
```

Don't forget to set the value for **array_group** *to* **"passive"***!*

With these changes to the **Registry.xml** file, we can re-compile the **atmosphere** core. But, we'll first need to "clean" the code, since the last core that we compiled was the **init_atmosphere** core.

```
$ make clean CORE=atmosphere
$ qcmd -A UMMM0006 -- make -j8 gnu CORE=atmosphere
```

If compilation was successful, we can change directories to our **passive_tracer** directory and prepare to run MPAS:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial/passive_tracer
```

You may recall from Section 2.3 that we need the MPAS executable, **atmosphere_model**, as well as a number other files in order to run a simulation. Let's link or copy these files as we did in Section 2.3:

```
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/atmosphere_model .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/namelist.atmosphere .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/streams.atmosphere .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/stream_list.atmosphere.* .
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/src/core_atmosphere/physics/physics_wrf/fil
```

In order to run the model in parallel with 128 MPI tasks, we'll need to link the **/glade/campaign/mmm/wmr/mpas_tutorial/meshes/x1.10242.graph.info.part.128** mesh partition file into our working directory:

```
$ ln -s /glade/campaign/mmm/wmr/mpas_tutorial/meshes/x1.10242.graph.info.part.128 .
```

Now, we can proceed to set up the **namelist.atmosphere** and **streams.atmosphere** files as we did in Section 2.3 before running the model simulation.

Hints:

(1) When editing the **namelist.atmosphere** *file, there are three key changes to make:*

- *The model time step,* **config_dt***, must be set based on the minimum grid distance in the mesh*
- *The starting time of the simulation must be specified with the* **config_start_time** *variable*
- *If running with multiple MPI tasks,* **config_block_decomp_file_prefix** *must be set to the prefix of the graph partition file*

(2) In the **streams.atmosphere** *file, there is only one change that needs to be made:*

- *The* **filename_template** *for the "input" stream must be set to the name of the netCDF file with initial conditions*

When running the model, we can copy the **run_model.pbs** batch script before submitting the job with **qsub**:

```
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/job_scripts/run_model.pbs .
$ qsub run_model.pbs
```

The entire set of scalars is written to the default "history" files, so as soon as the first several output files are available, we can try making plots of our new "mytracer1" passive tracer. Then, we can stop the model simulation and proceed to the next sub-section, where we will add sources and sinks for our new tracer before running a longer simulation.

To terminate a running job on Derecho, we first need to find its job ID from **qstat**:

```
$ qstat -u $USER
                                                                  Req'd  Req'd   Elap
Job ID          Username Queue    Jobname    SessID NDS TSK Memory Time  S Time
--------------- -------- -------- ---------- ------ --- --- ------ ----- - -----
4153631.desche* duda     cpu      run_240km  186105   1 128  235gb 00:30 R 00:00
```

We just need the numeric part of the job ID in order to cancel the job with **qdel**:

```
$ qdel 4153631
```

You can verify that the job has been terminated by waiting a minute or so before running **qstat** again.

6.3 Adding sources and sinks

Having added a passive tracer to our initial conditions and defined the tracer in the model so that it will be transported during a simulation, it's not much additional work to define sources and sinks for the tracer. Here, we will define time-invariant sources and sinks that are set up when the model begins running, but we could in principle define time-varying sources and sinks that are periodically updated from an input file, for example.

To add time-invariant sources and sinks, we can change to our MPAS-Model source directory and edit the **src/core_atmosphere/Registry.xml** file with the editor of our choice. Searching for the section of the file that begins the definition of the "tend" **var_struct** around line 1751 we should see the following:

```
        <var_struct name="tend" time_levs="1">


                <!-- tendencies for prognostic variables -->
```

Just below the **tendencies for prognostic variables** comment line, let's add a definition for our passive tracer's sources/sinks:

```
                <var name="mytracer1_sources" type="real"
                     dimensions="nVertLevels nCells Time"
                     units="kg m^{-2} s^{-1}"
                     description="Our first passive tracer areal production rate" />
```

As in the lecture on adding passive tracers, our example tracer will be produced and destroyed at the surface of the model.

Next, we can add code to set the "mytracer1_sources" field when the model starts up. In the **src/core_atmosphere/mpas_atm_core.F** source file in the **atm_mpas_init_block** subroutine (around line 368), we will add declarations of two new array pointers at the end of the variable declarations (around line 418) as in the highlighted code, below:

```
      integer, pointer :: nThreads
      integer, dimension(:), pointer :: cellThreadStart, cellThreadEnd
      integer, dimension(:), pointer :: cellSolveThreadStart, cellSolveThreadEnd
      integer, dimension(:), pointer :: edgeThreadStart, edgeThreadEnd
      integer, dimension(:), pointer :: edgeSolveThreadStart, edgeSolveThreadEnd
      integer, dimension(:), pointer :: vertexThreadStart, vertexThreadEnd
      integer, dimension(:), pointer :: vertexSolveThreadStart, vertexSolveThreadEnd


      logical, pointer :: config_do_restart, config_do_DAcycling

      real (kind=RKIND), dimension(:,:), pointer :: mytracer1_sources
      integer, dimension(:), pointer :: ivgtyp

      call atm_compute_signs(mesh)
```

Then, near the end of the **atm_mpas_init_block** subroutine, around line 585, we can add code to set the production/destruction of our tracer based on whether a model cell is land or water:

```
      call mpas_pool_get_array(tend, 'mytracer1_sources', mytracer1_sources)
      call mpas_pool_get_array(sfc_input, 'ivgtyp', ivgtyp)

      mytracer1_sources(:,:) = 0.0_RKIND
      do iCell=1,nCells
         ! Assume that vegetation category 17 is water
         ! (true for MODIS land use, not true for USGS)
         if (ivgtyp(iCell) == 17) then
            ! 2 g/m^2/day destruction over water
```

```
            mytracer1_sources(1,iCell) = -0.002 / 86400.0
         else
            ! 4 g/m^2/day production over land
            mytracer1_sources(1,iCell) = 0.004 / 86400.0
         end if
      end do

   end subroutine atm_mpas_init_block
```

Finally, we can add our source terms to the tendency array for our new tracer. In **src/core_atmosphere/physics/mpas_atmphys_todynamics.F** at the bottom of the variable declarations in the **physics_get_tend** subroutine, we can add the following variable declarations around line 124:

```
real(kind=RKIND),dimension(:,:),allocatable:: theta,tend_th

integer, pointer :: index_mytracer1
real(kind=RKIND),dimension(:,:),pointer:: mytracer1_sources
real(kind=RKIND),dimension(:,:),pointer:: zz
real(kind=RKIND),dimension(:,:),pointer:: zgrid

!=================================================================================================================
 call mpas_pool_get_dimension(mesh, 'nCells', nCells)
```

Then, near the bottom of the subroutine before several arrays are deallocated, we can add code to include our source terms in the tendency for our passive tracer:

```
call mpas_pool_get_dimension(state, 'index_mytracer1', index_mytracer1)
call mpas_pool_get_array(tend, 'mytracer1_sources', mytracer1_sources)
call mpas_pool_get_array(mesh, 'zz', zz)
call mpas_pool_get_array(mesh, 'zgrid', zgrid)

do i = 1, nCellsSolve
   do k = 1, nVertLevels
      tend_scalars(index_mytracer1,k,i) = tend_scalars(index_mytracer1,k,i) &
          + mytracer1_sources(k,i) / (zgrid(k+1,i) - zgrid(k,i)) / zz(k,i)
   end do
end do

!
! Clean up any pointers that were allocated with zero size before the call to
! physics_get_tend_work
!
```

Since we have modified the **Registry.xml** file, we will need to clean the code before re-compiling the model:

```
$ make clean CORE=atmosphere
$ qcmd -A UMMM0006 -- make -j8 gnu CORE=atmosphere
```

After the model has been successfully re-compiled, we can change directories to our run directory, remove any existing model output files, and re-run the model:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial/passive_tracer
$ rm -f diag*nc history*nc restart*nc
$ qsub run_model.pbs
```

Once the model has started to run and has produced several history files — which should now contain our new "mytracer1" field — we can use, e.g., **convert_mpas** to interpolate the model history files to a lat-lon grid for quick visualization of our new tracer with sources and sinks in the lowest model layer!

7. Computing new diagnostic fields

In this final section, we will add a new diagnostic field to the model: an approximation to the radiative energy balance computed as the integrated difference between the outgoing and incoming radiation fluxes (both long-wave and short-wave) at the top of the model. The integration will occur between output times of the new diagnostic field.

Disclaimer: this exercise was developed by a software engineer; if the diagnostic described here makes no physical sense or otherwise contains errors, please don't let this negatively affect your views of MPAS-Atmosphere as a scientifically credible model!

7.1 Defining the diagnostic field and adding place-holder code

The MPAS-Atmosphere model contains a framework for organizing new diagnostic computations into their own modules, which contain routines to perform different stages of the computation of the diagnostic (e.g., accumulation, averaging, and resetting). To separate the complications of computing the diagnostic from those of implementing the diagnostic in the MPAS-Atmosphere code, we can begin by simply defining a variable for our new energy balance diagnostic along with some placeholder code with print

statements. We can then verify that the model compiles correctly and prints the expected lines to the `log.atmosphere.0000.out` file, demonstrating that at a technical level we have successfully connected our new diagnostic module with the MPAS-Atmosphere diagnostic framework. In the next section, then, we will be free to focus on the correct computation of the diagnostic itself.

Let's begin by changing to the directory containing our MPAS-Model source code:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model
```

All of the changes for our energy balance diagnostic will be confined to the `src/core_atmosphere/diagnostics` subdirectory; we can change to that sub-directory now:

```
$ cd src/core_atmosphere/diagnostics
```

There are just three files in this directory that serve as the interface between the rest of the MPAS-Atmosphere model and our new diagnostic:

- `Makefile` — changes here will ensure that our new Fortran code will be used when we recompile MPAS
- `Registry_diagnostics.xml` — changes here will allow any new variables defined by our diagnostic code to be available to the rest of the MPAS code (in particular, to the stream manager, which allows our diagnostic field to be written to output files)
- `mpas_atm_diagnostics_manager.F` — changes here will ensure that the different stages of computation required by our new diagnostic are called at the correct points in each model timestep

Before modifying the three files listed above, we can first define a new variable in an XML file for our diagnostic. With the editor of your choice, create a new file named `Registry_energy_balance.xml` with the following contents (click the light blue header):

Registry_energy_balance.xml

We can also create a new Fortran module with place-holder code, in which each subroutine simply prints a message to the log file. With the editor of your choice, create a new file named `mpas_energy_balance_diagnostics.F` with the following contents (click the light blue header):

mpas_energy_balance_diagnostics.F

Having defined a variable to store our diagnostic as well as placeholder code in a new Fortran module, we can edit the `Makefile`, `Registry_diagnostics.xml`, and `mpas_atm_diagnostics_manager.F` files to connect our diagnostic. The required changes to each of these files are highlighted in the code, below.

Makefile

Registry_diagnostics.xml

mpas_atm_diagnostics_manager.F

Now, we can try re-compiling MPAS-Atmosphere. When making changes to diagnostic Registry files, it's generally necessary to clean the code before recompiling. Let's change to the top-level MPAS-Model directory, and clean and re-compile with the following commands:

```
$ cd ../../..
$ make clean CORE=atmosphere
$ qcmd -A UMMM0006 -- make -j8 gnu CORE=atmosphere
```

After the model has been successfully compiled, we can create a new directory to run a short test simulation, through which we can verify that our diagnostic is being invoked by the model by looking for our print statements in the log file. Let's first make a new sub-directory in `/glade/derecho/scratch/${USER}/mpas_tutorial` for our new diagnostic simulations:

```
$ mkdir -p /glade/derecho/scratch/${USER}/mpas_tutorial/energy_balance
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial/energy_balance
```

Rather than create new initial conditions, we can simply re-run the 240-km quasi-uniform simulation, this time with our new diagnostic. We can therefore symbolically link the initial conditions, surface update, and mesh partition file from that simulation into our new run directory, and copy the `namelist.atmosphere`, `streams.atmosphere`, and `stream_list.atmosphere.*` files, too:

```
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/240km_uniform/x1.10242.init.nc .
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/240km_uniform/x1.10242.sfc_update.nc .
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/240km_uniform/x1.10242.graph.info.part.128 .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/240km_uniform/namelist.atmosphere .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/240km_uniform/streams.atmosphere .
$ cp /glade/derecho/scratch/${USER}/mpas_tutorial/240km_uniform/stream_list.atmosphere.* .
```

Additionally, we will need to symbolically link to our newly recompiled **atmosphere_model** executable as well as the physics look-up tables with the following commands:

```
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/atmosphere_model
$ ln -s /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model/src/core_atmosphere/physics/physics_wrf/fil
```

Lastly, we will edit the **namelist.atmosphere** file to run a non-restart (i.e., a "cold-start") simulation from 2019-09-10 0000 UTC for just one hour. Our only goal with this initial simulation is to verify that our place-holder diagnostic code is being called!

```
config_start_time = '2014-09-10_00:00:00'
config_run_duration = '1:00:00'

config_do_restart = false
```

After verifying that the variables above are set correctly in the **namelist.atmosphere** file, we can copy the **run_model.pbs** batch script before submitting the job with **qsub**:

```
$ cp /glade/campaign/mmm/wmr/mpas_tutorial/job_scripts/run_model.pbs .
$ qsub run_model.pbs
```

This simulation should take just a minute or so to run. After the model completes, you can check the **log.atmosphere.0000.out** file for the print statements from our dignostic routines. Do you see lines like the following?

```
min/max of meshScalingDel2 = 1.00000 1.00000
min/max of meshScalingDel4 = 1.00000 1.00000
Sounding location file 'sounding_locations.txt' not found.
TESTING: energy_balance_setup
TESTING: energy_balance_reset
TESTING: energy_balance_update
TESTING: energy_balance_compute
Timing for diagnostic computation: 6.03111 s
Timing for stream output: 1.10848 s
TESTING: energy_balance_reset
```

If our diagnostic prints appear in the log file, we can proceed to the next section, where we will focus on the computation of the diagnostic without having to worry about the software details that were dealt with in this section.

7.2 Adding code to compute the diagnostic

In order to compute the accumulated net radiative energy between output times for our 'accradflux' field, we will need to implement three functions in our new **mpas_energy_balance_diagnostics.F** module. Let's begin by changing directories to our MPAS-Model source directory, and then to the diagnostics subdirectory:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial/MPAS-Model
$ cd src/core_atmosphere/diagnostics
```

Conceptually, we will need to implement changes to the following routines:

- **energy_balance_setup** — here we need to set the initial *accradflux* field to zero
- **energy_balance_update** — here we need to add in the net energy flux for the current model time step
- **energy_balance_reset** — here we need to reset the *accradflux* field after it has been written to an output stream

The expandable headers, below, highlight the changes that we need to make in each of these three subroutines.

subroutine energy_balance_setup

subroutine energy_balance_update

subroutine energy_balance_reset

After editing the file, we can change back to the top-level MPAS-Model directory and recompile the model. Because we did not change any Registry XML files, there is no need to "make clean", first.

```
$ cd ../../..
$ qcmd -A UMMM0006 -- make -j8 gnu CORE=atmosphere
```

If the model compilation was successful, we are ready to try a model simulation with our new *accradflux* diagnostic in the next section!

7.3 Testing the diagnostic with a short simulation

To test our our diagnostic field, we can use a short, 12-hour simulation in which we write our "accradflux" field every six hours to its own output stream. All code changes have been completed, so we can change directories to **`/glade/derecho/scratch/${USER}/mpas_tutorial/energy_balance`**:

```
$ cd /glade/derecho/scratch/${USER}/mpas_tutorial/energy_balance
```

Let's begin by adding a new stream like the following to our **`streams.atmosphere`** file:

```
<stream name="toa_energy_balance"
        type="output"
        clobber_mode="overwrite"
        filename_template="accradflux.$Y-$M-$D_$h.$m.$s.nc"
        filename_interval="output_interval"
        output_interval="6:00:00" >

        <var name="accradflux"/>
</stream>
```

Remember: the new stream must be defined between the opening <streams> and closing </streams> tags!

Next, we can set the duration of our model simulation to just 12 hours by setting **`config_run_duration`** to '12:00:00' in our **`namelist.atmosphere`** file:

```
    config_run_duration = '12:00:00'
```

Finally, we can remove any existing output files from our earlier test run with

```
$ rm diag*nc history*nc surface_winds*nc
```

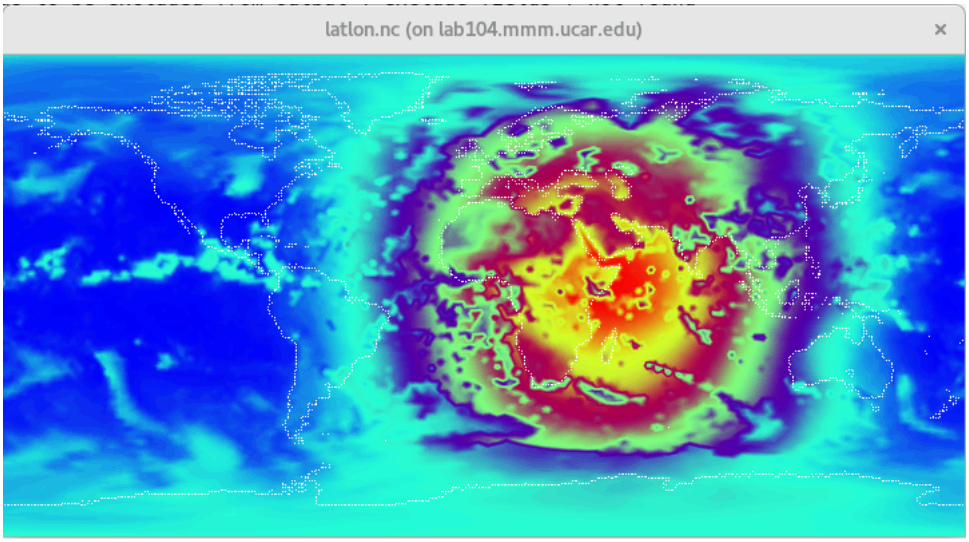
before running our short simulation with 128 MPI tasks:

```
$ qsub run_model.pbs
```

This simulation should take just a couple of minutes to complete, and when it has finished, we should have "accradflux" files in our run directory:

```
$ ls -l accradflux*
-rw-r--r-- 1 class104 cbet 46088 Sep 10 17:56 accradflux.2014-09-10_00.00.00.nc
-rw-r--r-- 1 class104 cbet 46088 Sep 10 17:57 accradflux.2014-09-10_06.00.00.nc
-rw-r--r-- 1 class104 cbet 46088 Sep 10 17:58 accradflux.2014-09-10_12.00.00.nc
```

If you interpolate the "accradflux" files to a 0.5-degree latitude-longitude grid with the **`convert_mpas`** tool, does the last time period for the field (valid 12 hours after our initial time) look like the following?



Now that we have the top-of-the-atmosphere accumulated net radiative energy flux integrated over two six-hour periods from our 12-hour simulation, we can compute a radiation budget (in W / m^2) for these time periods with a Python script. Using an editor of your choice, create a file named **`compute_budget.py`** with the following contents:

```
import numpy as np
from netCDF4 import Dataset

f = Dataset('accradflux.2014-09-10_12.00.00.nc')
accradflux = f.variables['accradflux'][:]
```

```
g = Dataset('x1.10242.init.nc')
areaCell = g.variables['areaCell'][:]

print(np.sum(accradflux * areaCell) / np.sum(areaCell) / 21600.0)
```

We can run this script with:

```
$ python compute_budget.py
```

You can try changing the time perdiod for which this radiation budget is computed by changing 'accradflux.2014-09-10_12.00.00.nc' to 'accradflux.2014-09-10_06.00.00.nc' in the script.

Positive values indicate more incoming radiation at the top of the atmosphere than outgoing radiation.

With the remaining time in this session, you may like to try one of the following:

- Run a multi-day simulation, writing the "toa_energy_balance" stream only once per day; then, compute the radiation budget for 24-hour periods using a modified version of the Python script described above
- Run a two-day simulation, writing the "toa_energy_balance" stream every three hours; then, compute the radiation budget for these three-hour periods and note how the resulting values change during the simulation.

IMPORTANT NOTE: By default the MPAS stream manager will refuse to overwrite any existing output files. Before re-running simulations, you will generally need to remove previous model output files with:

```
$ rm diag*nc history*nc surface_winds*nc accradflux*nc restart*nc
```

However, as described in Section 5.2 of the MPAS-Atmosphere User's Guide, you can set the **clobber_mode** attribute for output streams so that any existing files will be overwritten.

As an example of processing multiple NetCDF files in a loop in Python, you can use the following script:

```
import numpy as np
from netCDF4 import Dataset

g = Dataset('x1.10242.init.nc')
areaCell = g.variables['areaCell'][:]
g.close()

for filename in ['accradflux.2014-09-10_00.00.00.nc',
                 'accradflux.2014-09-11_00.00.00.nc',
                 'accradflux.2014-09-12_00.00.00.nc']:

        f = Dataset(filename)
        accradflux = f.variables['accradflux'][:]
        f.close()

        print(np.sum(accradflux * areaCell) / np.sum(areaCell) / 86400.0)
```