Tutorial for plotting netCDF format climate data in Generic Mapping Tool (GMT), and the usage of netCDF operators (NCO and CDO) in Linux environment

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Introduction:
The Generic Mapping Tools (GMT) is a powerful open-source plotting and mapping program that you can easily plot in raster and vector formats. It is especially robust when you have large raster files, such as netCDF file that stores multiple dimensional data. This tutorial will demonstrate how to use GMT to visualize climate data. This chapter will show you 3 basic ways of displaying climate data, including global maps of *climatological mean, multi- year monthly mean and annual sum*, using a free lightning dataset (the WWLLN Global Lightning Climatology and timeseries (WGLC)).

The WGLC lightning dataset (Kaplan and Lau, 2021) is a high-resolution (0.5 degree) monthly global lightning time series covers the years 2010-2021 in the unit of stroke density per km2 per day, stored in netCDF (version 4) format (data can be downloaded from https://zenodo.org/record/4882792#.YY9I7i2w3xQ). NetCDF format can be visualized with a range of open-source software tools, for example ncview, panoply and GMT, and manipulate with netCDF operators such as CDO, NCO and packages for R and Python. To open and use netCDF files, we need at least one of the netCDF visualization tool along with the above netCDF operators. Personally, I preferred ncview for viewing, GMT for plotting and CDO and NCO for manipulation the files.

Program installation and documentations:
Before you get your hands in plotting the data, you will need to install the software. You can install the programs from package manager, such as Fink and Homebrew. The version of GMT in this demonstration is GMT 6.2.0. The GMT documentation and cookbook are useful for looking up GMT examples, commands and modules. (GMT 6.2.0 Documentation : https://docs.generic-mapping-tools.org/latest/modules.html ; GMT Cookbook: https://docs.generic-mapping-tools.org/latest/cookbook.html)

Text editor:
Text editor (e.g. BBedit) is ideal for script writing. In Linux environment, GMT commands can be written in shell scripts with the command line `#!/bin/bash` at the beginning of the script. Save your script in shell script file (.sh). Type `sh filename.sh` in terminal to run the script.

Chapter 1: Netcdf (raster) mapping

1.1 GMT default and specification

1.1.1 Specify map setups

`gmtset` is to change individual GMT default settings (for the detailed list of the parameters see https://docs.generic-mapping-tools.org/latest/gmt.conf.html). Here I set my map frame type as plain, frame pen is 0.5p, page color as white and physical size is A1. The benefit of selecting a larger paper size (A0, A1, A2, A3) is to avoid GMT cropping your plot. `gmtset FONT_` is to set the default of all fonts. Primary annotations, e.g. annotations on xy axis, scale bar and legend; secondary annotations, e.g. time axis. Here the primary annotation is set to font size 12 Helvetica in black color.

```
gmt gmtset GMT_VERBOSE normal
gmt gmtset FORMAT_FLOAT_MAP %lg
gmt gmtset MAP_FRAME_TYPE plain
gmt gmtset MAP_FRAME_PEN 0.5p,0
gmt gmtset PS_PAGE_COLOR white
gmt gmtset PS_MEDIA a1
gmt gmtset FONT_ANNOT_PRIMARY 12p,Helvetica,black
gmt gmtset FONT_LABEL 14p,Helvetica,black
```

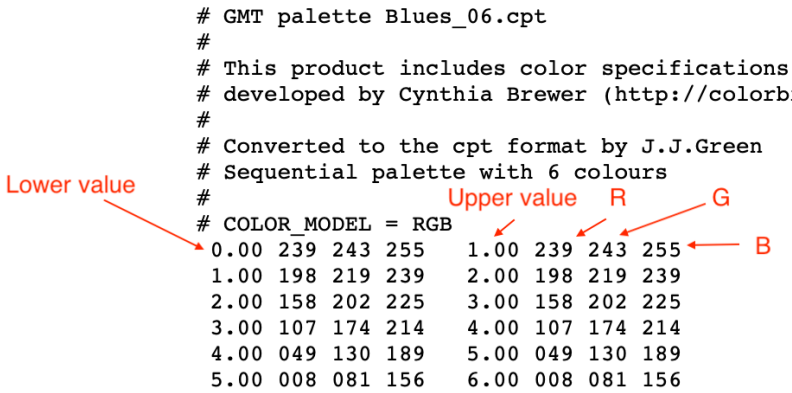
1.1.2 Specify input and output files

Specify input and output file name. Set the desired output format. Here the map will be export as postscript file (.ps).

```
input=input.nc
output=output.ps
```

1.1.3 Color palette tables (cpt)

To display your data in a specific or customed color scheme, you will need a cpt file (.cpt). Cpt file is a text file contents the data scale and color (either in name or RGB formats). An example from cpt-city shown as below:

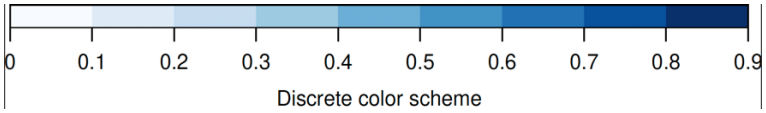



```
# GMT palette Blues_06.cpt
#
# This product includes color specifications and designs
# developed by Cynthia Brewer (http://colorbrewer.org/).
#
# Converted to the cpt format by J.J.Green
# Sequential palette with 6 colours
#                  Upper value    R     G     B
# COLOR_MODEL = RGB
0.00 239 243 255   1.00 239 243 255
1.00 198 219 239   2.00 198 219 239
2.00 158 202 225   3.00 158 202 225
3.00 107 174 214   4.00 107 174 214
4.00 049 130 189   5.00 049 130 189
5.00 008 081 156   6.00 008 081 156
```

Various cpts can be download can be downloaded from cpt-city (http://soliton.vm.bytemark.co.uk/pub/cpt-city/) or you can use built-in cpt by GMT (https://docs.generic-mapping-tools.org/latest/cookbook/cpts.html). You can make your own cpt with `gmt makecpt` and `gmt grd2cpt`. For example (see discrete.cpt and continues.cpt):

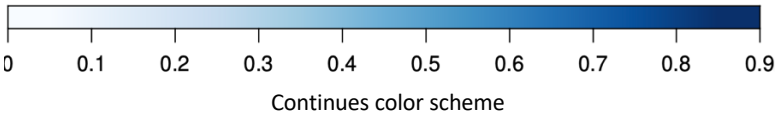
```
gmt makecpt –T0/0.9/0.1 –CBlues_09.cpt  > Mycpt.cpt
```

Where -T[min/max/inc], -C[cpt file with desire color palettes], -Z to make continuous color scheme, and then > to write out into a new file.



Discrete color scheme

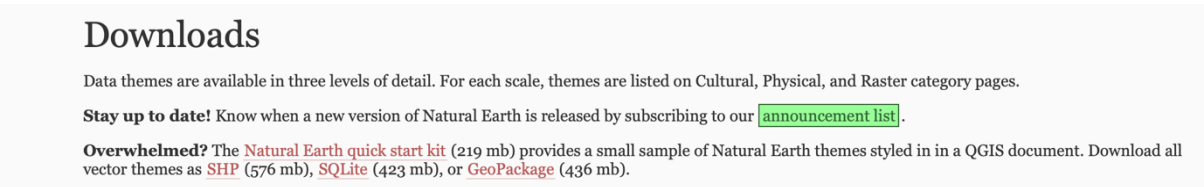
Or use the -Z option to make continues color scale:



Continues color scheme

1.1.4 Vectors

You may need other vectors or shapefiles to plot other geographic features, such as ice sheets, coastline, land, ocean, lakes and rivers, reefs, country boundaries and roads. These files can be downloaded from Natural Earth https://www.naturalearthdata.com in 3 resolutions (1:10m, 1:50m and 1:110m). Download the SQLite pack. You will need a few steps to process the downloaded files to be usable in GMT using GRASS GIS. See the **GMT_tutorial_naturalearth**.


Downloads

Data themes are available in three levels of detail. For each scale, themes are listed on Cultural, Physical, and Raster category pages.

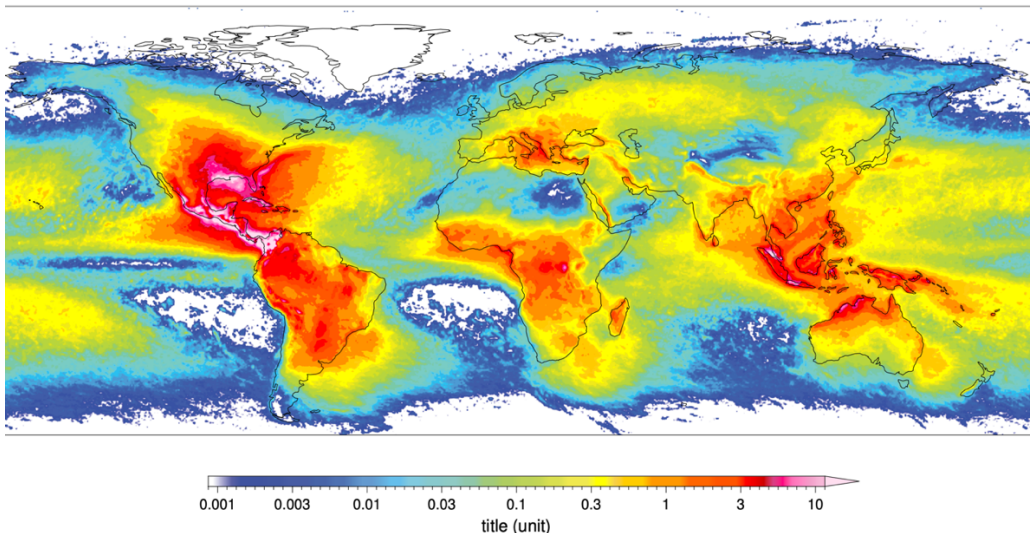
Stay up to date! Know when a new version of Natural Earth is released by subscribing to our announcement list.

Overwhelmed? The Natural Earth quick start kit (219 mb) provides a small sample of Natural Earth themes styled in in a QGIS document. Download all vector themes as SHP (576 mb), SQLite (423 mb), or GeoPackage (436 mb).

1.2 modules in this chapter

- psbasemap
- grdimage
- psxy
- pssscale
- psconvert
- GMT common options: -R, -J, -B, -K, -O, -P

1.3 Map of climatological mean



1.3.1 Data preparation

In this map, we would like to plot the average of world lightning over the 10 years. NetCDF files can be view with `ncview` or print out in text format with `ncdump` (options: -h for headings only; -c for headings and data). As the WGLC data is in stroke density per km2 per day, we will need to convert daily data into monthly by using `cdo –muldmp`, which will multiply the data with days per month. To calculate the time average, `cdo timmean` will computes the mean of all timesteps of the data file.

```
cdo –muldmp dailydata.nc monthlydata.nc
cdo timmean monthlydata.nc monthlymean.nc
```

1.3.2 gmt psbasemap: to make a base map

Set boundary and projection (-R and -J). -R (the region of interest) and -J (projection) are required arguments in many of the plotting, gridding and projection modules, such as psbasemap, grdimage and psxy. It is important to set a suitable boundary and projection, otherwise the map is unable to plot correctly. In this example, I would like to plot the region from 60°S to 90°N and from 169° W to the very east (the maximum longitude is 360°, so the maximum area can be plot is from 169°W to 191°E), therefore I set `–R–169/191/–60/90` (-R*xmin/xmax/ymin/ymax*). You can also set -R by specifying the lower left corner and upper right corner geographic coordinates with the modifier +r at the end (-R*xlleft/ylleft/xuright/yuright*+**r**) (that will be `–R–169/–60/191/90r` in the case).

There is over 30 projections and coordinate transformations available in GMT. Here I use `–JQ30` the Equidistant cylindrical projection for global maps. 30 indicates the map width in plot units.

Set map boundary frame and axes attributes (-B). Here I don't want any annotation or ticks at the axes so just put -B0.

Tips: -K indicates do not finalize PostScript plot. This essential in each line except for the last line where you are about to finish plotting. -P to select "Portrait" plot orientation also needed to specify in each line. Single arrow "> $output" at the first line and double ">> $output" for the rest.

```
gmt psbasemap –R–169/191/–60/90 –JQ30 –B0 –K –P > $output
```

1.3.3 gmt grdimage: to plot grid files

Set image resolution (-E) to 300 dpi.
Set grid interpolation mode (-n). -nl indicates a bilinear interpolation.
Specify a custom cpt (-C). (see 1.1.3)

Tips: -R and -J is already specified in the previous line. -O is to append to existing PostScript plot which is needed to specify in each line except the first line. If the grid file ($input) has more than one slides, you will need to specify which slide to plot because grdimage can only plot one slide at once. Use the code $input[0] for the first slide, $input[1] the second slide, $input[2] the third slide and so on. If your grid file has more than one variables, specify the desire variable by $input?variable_name, for example, $input?stroke_density in the case.

```
gmt grdimage $input –R –J –E300 –nl –C$cpt –K –P –O >> $output
```

1.3.4 gmt psxy: to plot geographic features downloaded from Natural Earth

psxy reads x and y coordinates (1st and 2nd column by default) from tables and plots dots, lines or polygons. **Specify pen attributes (-W):** pen width 0.5p in black color.

Tips: If you are plotting more than one map in a plot, you can use gmt psbasemap –R –J –B0 –O –P –K >> $output to close the current map before starting a new plot.

```
gmt psxy ne_110m_coastline.gmt –R –J –W0.5p,black –K –P –O >>
$output

gmt psbasemap –R –J –B0 –O –P –K >> $output
```

1.3.5 gmt psscale: to make a scale color bar under the map

Specify reference point for the scale bar on the map (-D): -Dx/y+w(length)/(width). Append +h to get a horizontal scale (default is vertical (+v)). Option +ef1 means to get an arrow at the front (1 is the length of the arrow).

Tips: No **-K** in the last line to let the PostScript plot to finalize.

```
gmt psscale -C$cpt -D6/-1.5+w18/0.3+h+ef1 -L -S -B+l"Title & unit" -O -P >> $output
```

1.3.6 gmt psconvert: converts PostScript files to other formats (JPEG, PDF, PNG, TIFF…) using Ghostscript

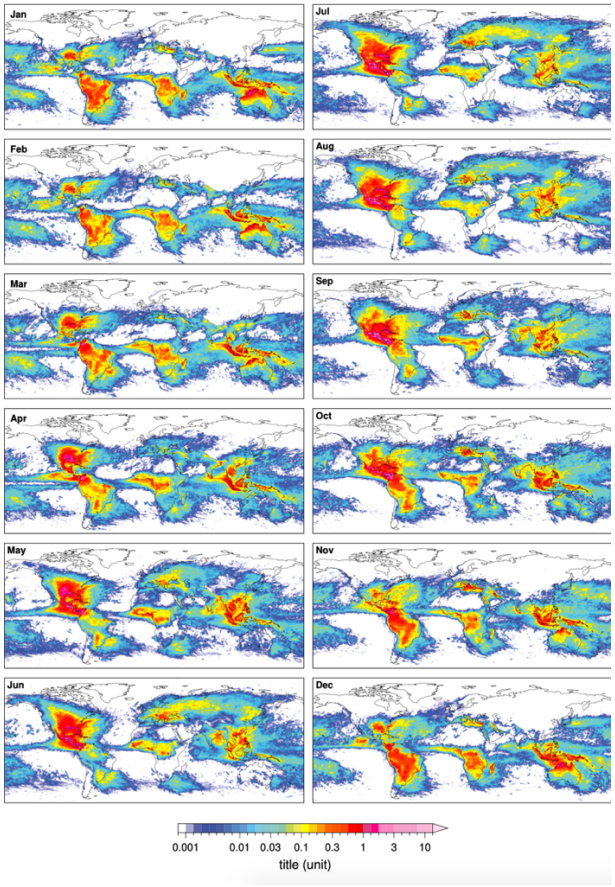
Set the output format (-T): f = PDF. Other options are b = BMP; e = EPS; E = EPS with PageSize command; F = multi-page PDF; j = JPEG (default); g = PMG; G = transparent PNG; m = PPM; s = SVG; t = TIFF.

```
gmt psconvert -A -Tf -Z $output
```

The entire script (https://github.com/hkLAU/GMT_tutorial_1/blob/main/climatological_mean_GMTscript.sh):

```
#!/bin/bash

gmt gmtset GMT_VERBOSE normal
gmt gmtset FORMAT_FLOAT_MAP %lg
gmt gmtset MAP_FRAME_TYPE plain
gmt gmtset MAP_FRAME_PEN 0.5p,0
gmt gmtset PS_PAGE_COLOR white
gmt gmtset PS_MEDIA a1
gmt gmtset FONT_ANNOT_PRIMARY 12p,Helvetica,black
gmt gmtset FONT_LABEL 14p,Helvetica,black

input=input.nc
output=output.ps
coast=ne_110m_coastline.gmt
cpt=cpt.cpt

gmt psbasemap -R-169/191/-60/90 -JQ30 -B0 -K -P > $output

gmt grdimage $input -E300 -nl -R -J -C$cpt -O -K -P >> $output

gmt psxy $coast -R -J -W0.5p,black -O -P -K >> $output

gmt psbasemap -R -J -B0 -O -P -K >> $output

gmt psscale -C$cpt -D6/-1.5+w18/0.3+h+ef1 -L -S -B+l"Title & unit" -O -P >> $output

psconvert -A -Tf -Z $output
```

1.4 **Map of multi-year monthly mean of world lightning**



1.4.1 Data preparation

In this map, we would like to display the mean of lightning stroke density of each month of the entire period in one panel. A gridded map of multi-year monthly mean (mean of each monthly of year) can be calculated with the command `cdo ymonmean`. The output file (ymonmean.nc) contents 12 slides (from Jan to Dec) of gridded maps.

```
cdo –muldmp dailydata.nc monthlydata.nc
cdo ymonmean monthlydata.nc ymonmean.nc
```

1.4.2 plotting and the setting of -X, -Y

The settings of boundary and projection (-R & -J), and the flow of mapping are the same as the climatological mean map.

```
Bounds=–169/191/–60/90
projection=–JQ10
imageres=300
```

Here is an example of plotting the first year of data:

```
# plot 1

gmt psbasemap -R$bounds $projection -B0 -K -P -X2 -Y50 > $output

gmt grdimage $input?var[0] -E$imageres -nl -R -J -C$cpt -K -P -O >>
$output

gmt psxy $coast -R -J -Wthinnest,black -O -P -K >> $output

gmt psbasemap -R -J -B0 -O -P -K >> $output

echo "Jan" | gmt pstext -R -J -F+cTL+f9p,Helvetica-Bold -Dj0.2 -
Gwhite -O -P -K >> $output
```

When reading input data in `gmt grdimage`, GMT recognize the first slide as "0". Therefore, the first slide of data in the input files is **`$input?`*`variable_name`*`[0]`**. In `gmt psbasemap`, it is important to set a suitable -X & -Y, otherwise the maps will overlap with each other. Given that the size of each map is 10 (-JQ10) and we have 12 maps to plot in one panel, I am splitting them into 2 columns. The order of the map of each month shown as below:

1	7
2	8
3	9
4	10
5	11
6	12

Therefore, plot 2 will be like:

```
# plot 2

gmt psbasemap -R$bounds $projection -B0 -K -P -X0 -Y-4.5 -O >> $output

gmt grdimage $input?var[1] -E$imageres -nl -R -J -C$cpt -K -P -O >> $output

gmt psxy $coast -R -J -Wthinnest,black -O -P -K >> $output

gmt psbasemap -R -J -B0 -O -P -K >> $output

echo "Feb" | gmt pstext -R -J -F+cTL+f9p,Helvetica-Bold -Dj0.2 -Gwhite -O -P -K >>
$output
```

Where –Y–4.5 indicates moving the second plot downward with a gap 4.5 from the first plot. –X0 indicates the plot stays in the same column with the previous plots. The following 3-6 plots can be done with the same approach.

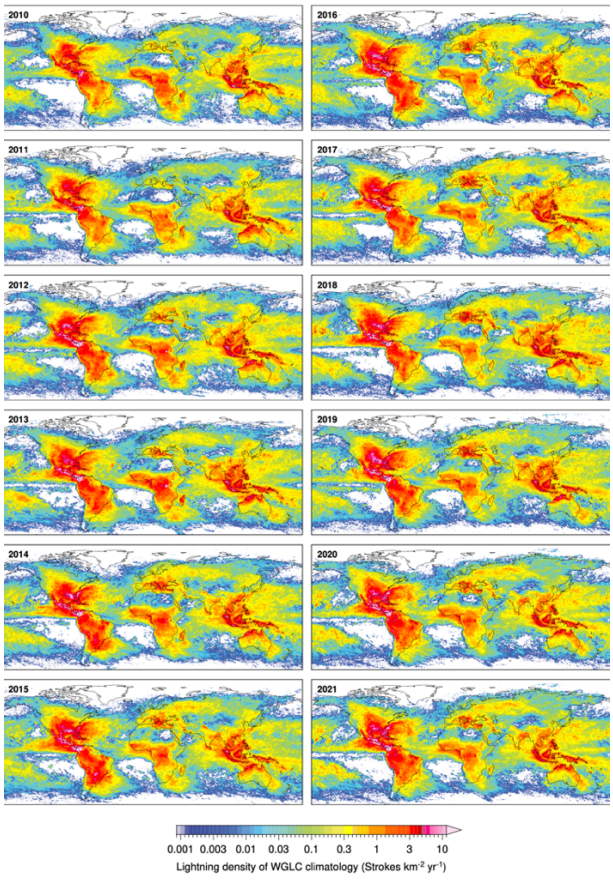
In plot 7, as we wanted to start a new column for the rest plots, we can do:

```
# plot 7

gmt psbasemap -R$bounds $projection -B0 -K -P -X10.3 -Y22.5 -O >> $output

gmt grdimage $input?var[6] -E$imageres -nl -R -J -C$cpt -K -P -O >> $output

gmt psxy $coast -R -J -Wthinnest,black -O -P -K >> $output

gmt psbasemap -R -J -B0 -O -P -K >> $output

echo "Jul" | gmt pstext -R -J -F+cTL+f9p,Helvetica-Bold -Dj0.2 -Gwhite -O -P -K >>
$output
```

Where –X10.3 indicates shifting the new plot rightward with a gap 10.3 (the width of one plot is 10, here I make 0.3 gap between two columns) and upward 22.5 (4.5 * 5) from the last plot (plot 6).

The entire script (https://github.com/hkLAU/GMT_tutorial_1/blob/main/multiyear_mon_mean_GMT_script.sh).

1.5 **Map of annual sum of world lightning**



1.5.1 Data preparation

In this map, we would like to display the sum of lightning stroke density of each year. Gridded maps of annual sum can be calculated with the command `cdo yearsum`. The output file (yearsum.nc) contents 12 slides (2010-2021) of gridded maps.

```
cdo yearsum monthlydata.nc yearsum.nc
```

1.5.2 Plotting

The approach is same as the multi-year monthly mean map that we split 12 small plots into 2 columns, set boundary and projection with psbasemap, plot data of each year with grdimage, plot coastline with psxy, add label on the top right corner with pstext, add scale bar with psscale and export pdf with psconvert.

The entire script see
https://github.com/hkLAU/GMT_tutorial_1/blob/main/Annualsum_GMTscript.sh.

-End of Chapter 1-