Chapter 1

Global Climate

1.1 introduction

Informally, we can define climate as the typical weather experienced in a particular region. More rigorously, it is the statistical description, including mean and variability, of relevant variables over a specified period of time. The standard period is 30 years, defined by the World Meteorological Organization. Some commonly used climate variables include temperature, precipitation, humidity, atmospheric pressure and wind velocity.

1.2 the data

In this lab you will work with gridded data sets that represent several global climate variables. Gridding is a procedure in which irregularly spaced data, for example from weather stations, are interpolated to a regular grid, defined in some coordinate system. Here, a geographic coordinate system is used.

1.2.1 surface elevation and the geoid

You will work with three gridded data sets that define Earth's surface: present day surface elevation; a reconstruction of surface elevation, ice sheets and all, at the last glacial maximum (LGM); and the present-day geoid height. The heights are in meters, gridded to a 1° graticule. The LGM reconstruction derives from a numerical inverse model driven by observed isostatic adjustment rates and a notion of the dynamics of Earth's interior. The reference for that work is Peltier, W. R., Ice Age Paleotopography, 1994, *Science*, 265, 195-201.

The geoid is a surface along which the gravitational potential is everywhere equal. The acceleration of an object due to gravity is everywhere perpendicular to this surface. The geoid can be thought of as the surface a globe-covering ocean would form in response to the combined effects of Earth's mass attraction (gravitation) and the centrifugal force due to rotation. Because Earth's mass is not distributed uniformly, the geoidal surface is irregular. The geoid height is the difference between the geoid and an ellipsoid fit to Earth's polar and equatorial radii (this is called the reference ellipsoid or the ellipsoid of revolution). The geoid height can be used to determine if a particular location on Earth's surface is above or below sea level.

The data are stored in a MATLAB-format file, globaltopo.mat. The file contains

```
% globaltopo.mat    Earth surface elevation, meters
%   topoE       present-day 180 x 360 matrix, 1 degree grid
%   geoidE      present-day geoid height
%   IceAge      last glacial maximum as computed by Peltier (ICEG4)
%               Peltier, W. R., Ice Age Paleotopography, 1994,
%               Science, v. 265, pp. 195-201.
%               180 x 360 matrix, 1 degree grid
%   maplat maplon:      latitude and longitude, degrees
```

1.2.2 climatology

Three modern climate variables, mean monthly temperature, precipitation, and atmospheric pressure at sea level are provided for you in this lab. The temperature and precipitation are gridded to a 0.5° graticule and the sea level pressure is gridded to 2.5°. A "climatology" is a data set that expresses mean conditions in a geographic region. Considerable effort is devoted to developing and evaluating the computational methods used to average and interpolate time series data collected at many locations into one representative set of values.

Precipitation is water in any form that falls to the surface. Water condenses from vapor in the atmosphere when the temperature-dependent saturation vapor pressure is exceeded. Condensation may be to either the liquid or solid phase; rain, snow, graupel, and hail are all forms of precipitation. These materials may all have different densities (for example, new snow is typically only 30% water by volume) and so a common reference, such as liquid water equivalent, must be adopted before meaningful comparisons may be made across seasons or regions.

Atmospheric pressure is the force per unit area due to the mass of the atmosphere above a particular height. Pressure decreases with increasing altitude as the mass of molecules above us declines and also varies with geographic location and time. A common reference is needed if we wish to compare values at different locations in a climatological or meteorological context. The atmospheric pressure at sea level, or the pressure reduced to sea level where the land surface is above or below that datum, is often used for pressure near the land surface. The mean sea level pressure on Earth is about 1000 mbar, or 100 kilopascals (kPa), and another common representation is the height of the 1000 mbar surface, which might be above or below sea level.

In general, air masses flow away from areas of relatively high pressure toward areas of relatively low pressure with trajectories that appear deflected due to the Coriolis effect. That deflection is to the right of the direction of motion in the northern hemisphere and to the left of the direction of motion in the southern hemisphere. Maps of mean monthly sea level pressure show the locations of seasonal highs and lows, and with that information we can infer some general attributes of low-level (near the surface and thus steered by pressure gradients there) winds. For example, the strong summertime high in the north pacific drives an *anticyclonic* circulation (clockwise in the northern hemisphere) and keeps Pacific moisture away from Oregon. The strength and extent of the high changes from hour to hour and day to day but over time tends to form in a particular region with a particular strength (the mean about which variation is defined). Meteorologists often call a persistent high pressure area a "blocking high" because it forces other weather systems to move around it. The *cyclonic* circulation around a low is counter-clockwise in the northern hemisphere.

The data are stored in the file globalclimatology.mat:

```
% Ta             monthly mean temperature in degrees C,
%                0.5 degree gridded data  360x720x12
%                layer 1: January; layer 2: February; etc.
% Ta_ann          mean annual surface air temperature, from Ta
% Tlat           grid latitudes
% Tlon           grid longitudes
% precip         30-year mean monthly precip. over land surface
%                360x720x12
%                layer 1: January; layer 2: February; etc.
% precip_ann     mean annual total precipitation
% plat           grid latitudes
% plon           grid longitudes
% slp            monthly mean sea level pressure, millibars
%                2.5 degree gridded data, 73x144x12
%  slplat        grid latitudes
%  slplon        grid longitudes
%  wdays         monthly mean number of days with precipitation
%                0.5 degree gridded data  360x720x12
%  wlat          grid latitudes
%  wlon          grid longitudes
```

- Ta and Ta_ann
  Ta contains mean monthly surface temperature from terrestrial observations of shelter-height air temperature and shipboard measurements in degrees Celsius. Mean monthly data are stored in a multi-dimensional array with a layer for each of the 12 months (Ta (:,:,1) stores January data, Ta (:,:,2) stores February data, and so on). Annual means are stored in Ta_ann.

  The land station records are for the years between 1920 and 1980. Median air temperatures over the oceans are taken from the Comprehensive Ocean-Atmosphere Data Set (COADS) for the years 1950-79. The reference for these data is Legates, D. R. and C. J. Willmott, 1990, Mean Seasonal and Spatial Variability Global Surface Air Temperature, *Theoretical and Applied Climatology*, 41, 11-21.

- precip and precip_ann
  Mean monthly precipitation in mm day^{-1} for the time period 1960 to 1990. The data were interpolated to a regular grid from records collected at 26,858 stations. Mean monthly data are stored in a multi-dimensional array with a layer for each of the 12 months (precip (:,:,1)

stores January data, precip (:,:,2) stores February data, and so on). Annual means are stored in precip_ann.

The reference for this data is:
Legates, D. R. and C. J. Willmott, 1990, Mean seasonal and spatial variability in gauge-corrected, global precipitation, *International Journal of Climatology*, 10, 111-127.

The data set is archived at the University of Delaware Center for Climatic Research `http://climate.geog.udel.edu/~climate/`

- wdays
  Mean monthly total days with precipitation (defined as 0.1 mm or more) for the time period 1960 to 1990. The data are stored in a multi-dimensional array with a layer for each of the 12 months.

  The references for this data are:
  New, M., Hulme, M. and Jones, P.D., 1999, Representing twentieth century space-time climate variability. Part 1: development of a 1961-90 mean monthly terrestrial climatology, *Journal of Climate*, 12, 829-856.

  New, M. G., M. Hulme and P. D. Jones, 2000, Representing 20th century space-time climate variability. II: Development of 1901-1996 monthly terrestrial climate fields, *Journal of Climate*, 13, 2217-2238.

  The data sets are archived at the Intergovernmental Panel on Climate Change Data Distribution Center, `http://ipcc-ddc.cru.uea.ac.uk/obs`

- slp
  Mean monthly sea level pressure in millibars (mbar) for the period 1968 to 1996. The data are stored in a multi-dimensional array with a layer for each of the 12 months. January is 1, February is 2, and so on. The grid spacing, 2.5°, is coarser than for the other climatology fields. The data set was created as part of a cooperative "reanalysis" project between the U.S. National Centers for Environmental Prediction (NCEP) and National Center for Atmospheric Research (NCAR). All available historical data from 1948 forward, measured at weather stations on the land surface, on board ships, from weather balloons, aircraft, satellites, and more are collected, quality controlled, and assimilated into a global grid.

  The reference for this work is Kalnay et al., 1996, The NCEP/NCAR 40-year reanalysis project, *Bull. Amer. Meteor. Soc.*, 77, 437-470. The reanalysis process is not without its problems and these are discussed at the NCEP/NCAR Reanalysis website. The data were retrieved from the NOAA/OAR/ESRL PSD, Boulder, Colorado, USA, web site `http://www.esrl.noaa.gov/psd/`.

1.3 working with the gridded data using Matlab

A set of MATLAB scripts have been written for your use in exploring the data provided in this lab. These scripts should do everything you need in order to answer the questions at the end of this chapter but please, do create others if you are interested.

1.3.1 topgraphy

The simplest way to produce a map of a single gridded variable is to use the map rendering function available at the class website. The function, called f_map.m (listed in section 1.3.6) renders a specified gridded data set in a simple plate carrée projection (see section 1.3.5 for more on projections). Starting with loading the globaltopo.mat data file into the MATLAB workspace, the Earth surface elevation map would be created at the command line in the MATLAB command window as follows:

```
>>load globaltopo.mat

>>Cv=[-9000 7000];
>>xls='longitude';
>>yls='latitude';
>>f_map(1,topoE, maplat, maplon, Cv, 'surface elevation (m)', xls,yls)
```

The variable Cv defines minimum and maximum values of the variable to be used in making a color map. xls and yls define labels for the horizontal ("x") and vertical ("y") axes, respectively. The function call sends a set of information to the function, in a specific order, to the function f_map. The first item in the list is a figure number, the second item is the data set to be rendered, the third and fourth are values along the rows and columns of the gridded data set, the fourth is the range Cv, the fifth is a title for the figure, and the last two items are as described.

Alternatively, you may wish to use the customizable script map_earthsurf.m, also available at the class website. Running the script as provided generates several colormaps using a simple plate carrée projection: Earth's surface elevation for the present and as reconstructed for the last glacial maximum; the difference between those two surface elevations; and the geoid height. The script requires the globaltopo.mat datafile. The listing and an explanation are provided in section 1.3.7.

1.3.2 temperature

The simplest way to generate maps of the gridded data is to use the generic map rendering function f_map.m Here is an example for a map of mean January temperature with a defined color range Cv going from the minimum to maximum January mean temperature:

```
>>load globalclimatology

>>Cv=[min(min(Ta(:,:,1))) max(max(Ta(:,:,1)))];
>>xls='longitude';
>>yls='latitude';
>>f_map(15,Ta(:,:,1), Tlat, Tlon, Cv, 'mean January T (C)', xls,yls)
```

Rendering a map of mean annual temperature would be a little bit simpler because the array storing the data is only 360 x 720 (that is, no additional dimension for the monthly values). Using the map rendering function f_map.m,

```
>>load globalclimatology

>>Cv=[min(min(Ta_ann)) max(max(Ta_ann))];
>>xls='longitude';
>>yls='latitude';
>>f_map(15,Ta_ann, Tlat, Tlon, Cv, 'mean annual T (C)', xls,yls)
```

An alternative is to write a script explicitly for a particular data set. The script map_surfacetemp.m, available at the class website, renders the global temperature data in a simple plate carrée projection. A script listing and description are provided in section 1.3.8.

1.3.3 precipitation

As before, you have two options for producing flat maps of precipitation rate over the land surface, the function f_map.m or the script map_precip.m.

It is important to choose a color range that allows you to see all the features you wish to study in the rendered color map. If one location experiences very large precipitation rates compared to global means, selecting a color range that includes both very large and very small rates will obscure subtle features. Another option would be to set the upper limit of the color range below the global maximum. A few locations on the map would "saturate" at the maximum color but the rest of the map would be easier to interpret. In this example, minimum and maximum values of 0 and 20, respectively, are specified.

```
>>load globalclimatology

>>Cv=[0 20];         % set color range for map
>>ttl='1961 to 1990 mean June precipitation (mm/day)';
>>xls='longitude';       %set x-axis label
>>yls='latitude';        %set y-axis label
>>f_map(200,precip(:,:,6), plat, plon, Cv, ttl, xls,yls)
```

Total annual precipitation has been calculated for you using the monthly precipitation rate data. It is stored in the variable precip_ann. A flat map of total annual precipitation can be made in the same way as the monthly maps.

1.3.4 sea level pressure

As before, you have two options for producing flat maps of sea level pressure, the function f_map.m or the script map_slp.m.

You will be asked later to examine changes in mean sea level pressure between seasons. The simplest way to do this is to compute the difference between two months and map those values. A December to June difference would be created by subtracting the values in the sixth layer of slp from the values in the twelfth layer of the data set. Difference maps with both positive and negative values, as will be created here, are usually easiest to read when centered around zero.

```
data=slp(:,:,12)-slp(:,:,6);
Cdmin=floor(min(min(data)));
Cdmax=abs(Cdmin);

Cv=[Cdmin Cdmax];
ttl='December - June mean sea level pressure (mbar)';
xls='longitude';
yls='latitude';
f_map(50,data, slplat, slplon, Cv, ttl, xls,yls)
```

1.3.5 map projections

A simple plate carrée ("flat square") projection is used in the scripts provided for you with this lab chapter but the Matlab Mapping Toolbox provides many built-in map projections. Please explore these if you are interested. The projection you choose can make a big difference when it comes to data visualization.

The plate carrée projection is equirectangular cylindrical projection. A cylindrical projection is one in which points from the sphere are projected onto a cylinder wrapped around the sphere. Equirectangular means that the parallels and meridians are rendered as equally-spaced horizontal and vertical lines. Neither area nor angles are preserved. This is a standard projection in thematic mapping and is very easy to produce.

Stereographic projections are common in polar studies. Stereographic simply means a projection of points from the sphere onto a plane tangent to the sphere. The *center point* of the projection, the point held in common by the sphere and plane, can be anywhere on the sphere but for polar studies, either the north or south geographic pole would be chosen. Stereographic projections are conformal, meaning that angles are preserved, but do not preserve area.

Another projection you might encounter in thematic maps is the "psuedocylindrical" Mollweid projection. The psuedo prefix tells you that this is not a true conic section. The projection is desirable because it represents areas correctly (an equal-area projection). It is not, however equidistant.

The Matlab Mapping Toolbox command axesm is used to define the map projection, set axes, and other properties. surfm and plotm are plotting functions for use with map axes. A simple example to create a polar stereographic projection is as follows:

```
figure(FN)
clf
axesm('MapProjection','stereo', 'Origin',[-90 0 0])
```

```
gridm off
framem on
surfm(slplat*ones(1,144), ones(73,1)*slplon, data)
plotm(lat, long, 'k-')
```

In this example, axesm is used to set two properties, the projection and its center point and orientation [latitude, longitude, orientation]. You can see that the projection above is to a plane tangent at the south pole. When rendering a map, surfm requires gridded latitudes and longitudes, which are created here using the vector products slplat *ones(1,144) and ones(73,1)* slplon . The arrays containing coastline locations, lat and long, are from the MATLAB native coasts.mat data set. If you wish to change the projection or another axes property, use the setm function:

```
setm(gca,'MapProjection','mollweid', 'Origin',[0 0 0])
```

gca is used to get the current axes. You can read about more properties in the MATLAB Help Navigator.

1.3.6 function listing: render flat maps

```
function f_map(FN, mdat, mlat, mlon, Cr, ttl, xlb, ylb)

%* render flat map data  f_map(FN, mdat, mlat, mlon, Cr, ttl, xlb, ylb)
%  FN      figure number
%  mdat    map data to be rendered
%  mlat    latitudes for mdat
%  mlon    longitudes for mdat
%  Cr      color axis [min max] array
%  ttl     figure title, expects character string
%  xlb     x-axis label, character string
%  ylb     y-axis label, character string

%* load a MATLAB native data set containing lat & lon of world coaslines
load coast

%* map plot window
wind=[min(mlon) max(mlon) min(mlat) max(mlat)];

%********
% flat map using data passed to the function
%********

figure(FN)                      %open figure window
clf
axis equal
axis(wind)                      % define axes for this plot
hold on
caxis(Cr)                       % define color range for this plot
pcolor(mlon, mlat, mdat)        % simple Plate Carree projection
```

```
shading flat
xlabel(xlb)
ylabel(ylb)
title(ttl)
colorbar('horiz')
hold on
plot(long, lat, 'k-')                 % plot world coastlines
```

You need to define all of the variables to be passed to f_map. This can be done at the command line in the command window or you can collect all the commands together in a script that "drives" f_map. Examples using this function are provided in earlier sections.

1.3.7 script listing: geographic maps

As provided, the script generates the following colormaps in a plate carrée projection: Earth's surface elevation for the present and as reconstructed for the last glacial maximum; the difference between those two surface elevations; and the geoid height. One example from map_earthsurf.m is provided here. All of the flat maps are produced in the same way.

```
load globaltopo.mat
load coast               % Matlab native file

wind=[min(maplon) max(maplon) min(maplat) max(maplat)];     % plot window
Cmint=-9000;             % minimum surface elevation for color
Cmaxt=7000;              % maximum surface elevation

%******
%  Earth surace elevation
%******

figure(1)
clf
pcolor(maplon, maplat, topoE)
shading flat
axis equal
axis(wind)
hold on
caxis([Cmint Cmaxt])
plot(long, lat, 'k-')
colorbar('horiz')
title('Earth surface elevation (m) on a 1x1 grid')
xlabel('longitude')
ylabel('latitude')
```

The first line instructs Matlab to open a figure window numbered 1. The next statement clears the figure window in case anything was already drawn there. The Matlab function **pcolor** is used to render a colormap of the data stored in topoE with axis values as specified in maplon and maplat. The option flat is passed to the Matlab function **shading** to supress drawing boundaries between map grid cells. The grid tick mark spacing is set to be equal for the latitudes and longitudes and the maximum and minimum longitudes and latitudes stored in the variable wind, are used instead of whatever MATLAB produced as a default. The MATLAB function **caxis** is used to define a color range for the rendering. The function plot is used to draw present-day coastlines on the map with long and lat from the MATLAB data file coast.mat. A figure title and axis labels are added as well.

Additional sections of the script repeat this procedure for IceAge and IceAge−topoE.

1.3.8 script listing: surface temperature maps

The script map_surfacetemp.m renders the global temperature data in a plate carrée projection. You must specify the month you wish to plot, using the variable mapT, and a figure number, FN. In the example below, the January temperature is mapped by setting mapT to 1. The script is designed to write the month number at the upper right of the map but you may also wish to change the plot title using MATLAB's built-in **title** function.

```
load globalclimatology
load coast

%* SET map month and figure numbers
mapT=1;          % select index number of month to plot
FN=15;           % starting figure number

%* ranges for color scales
Ctmin=min(min(min(Ta)));
Ctmax=max(max(max(Ta)));


%* map plot window
wind=[min(Tlon) max(Tlon) min(Tlat) max(Tlat)];

%********
% surface air temperature flat map for specified month
%********

figure(FN)                              % open figure window
clf
caxis([Ctmin Ctmax])                    % set color range for this plot
axis equal
axis(wind)                              % define axes for this plot
hold on
pcolor(Tlon, Tlat, Ta(:,:,mapT))        % simple Plate Carree projection
shading flat
xlabel('longitude')
ylabel('latitude')
title('mean monthly surface air temperature (degrees C)')
text(190, 90, int2str(mapT))
colorbar('horiz')
hold on
plot(long, lat, 'k-')
```

1.4 Questions

Please use the MATLAB *programs at the course website to answer the following questions. Short paragraphs are sufficient. You may wish to print a coastline map to use as a reference but please do not print all the colormaps. You may email electronic documents or hand in paper copies.*

everybody

1. Where have ice sheets changed the most from the Last Glacial Maximum to the present? Where has the change been the smallest?

2. Where are the largest continental shelves found? Why are they located in these regions? How and why are the *neritic* (or *sublittoral*) zone biomes found on continental shelves different from other ocean biomes?

3. At the Last Glacial Maximum, sea level was approximately 120 meters lower than it is today. Where was that water? How might the change in sea level have affected terrestrial organisms?

4. Which geographic regions experience relatively large and relatively small temperature ranges over the course of the year? Why do those regions experience such different annual cycles?

5. Use the data provided in this lab to predict present-day permafrost occurrence. Explain how you used the climatology data sets to answer this question. Use the maps in *Global Outlook for Ice and Snow* to evaluate your prediction. *You may wish to print a coastline map and draw the boundary on it.*

6. Are seasonal changes in sea level pressure in the Arctic the same or different from the seasonal cycle over the Antarctic? Why is this so?

graduate students

7. A typical climatologic definition for "the Arctic region" is the 10 °C summer isotherm, which corresponds reasonably well to the northern treeline. The geographic definition is usually everywhere north of the Arctic Circle, 66° 33' N. Using the mean annual temperature data set, draw the temperature-defined boundary on a coastline map. Describe its deviation from the Arctic Circle. Develop an hypothesis to explain the deviation you observe.

8. Use the sea level pressure data set to investigate seasonal change at high latitudes in the northern hemisphere.

    (a) Compare the winter/summer contrast over the Arctic basin with the same seasonal contrast over the north Atlantic and north Pacific. Describe the patterns and develop an hypothesis to explain the result of your comparison. That is, what physical processes underlie what you have observed?

    (b) Describe, in general, the pressure gradient from the interior of Antarctica to surrounding ocean surface. How does the pattern change over the course of the year? Sketch a map of Antarctica and draw the pattern of low-level winds that would be established by the pressure pattern you have identified.

(c) Use your answer to part 8b to speculate about how the pressure field and low-level winds over north America would have been different at the last glacial maximum.

You can use the regular flat maps here but a polar stereographic projection with its origin at 90 N or 90 S is better. The northern hemisphere map for March, slp (:,:,3) , could be made by typing and entering the following lines at the prompt in the Command Window:

```
figure(90)
clf
axesm('MapProjection','stereo', 'Origin',[90 0 0])
surfm(slplat*ones(1,144), ones(73,1)*slplon, slp(:,:,3))
plotm(lat, long, 'k-')
gridm on
axis off, framem on
title('March slp (mbar)')
caxis([975 1065 ])
```

A difference map between December and June could be made

```
figure(90)
clf
axesm('MapProjection','stereo', 'Origin',[90 0 0])
surfm(slplat*ones(1,144), ones(73,1)*slplon, slp(:,:,12)-slp(:,:,6))
plotm(lat, long, 'k-')
gridm on
axis off, framem on
title('December - June slp (mbar)')
caxis([-65 65 ])
```

The Matlab function **caxis** sets values for the minimum and maximum colors. It will be easiest to compare maps if they all have the same color scale. If you use a color map like Matlab's default **jet**, which runs from blue at small values to red at large values, difference maps may be easier to read if the color scale is centered around zero.

The Matlab function gridm renders parallels and meridians on the map, toggling between on and off. The default spacing is 15° for parallels (lines of latitude) and 30° for meridians (lines of longitude). You may label these if you wish by setting the property mlabel and setting the location of the labels to the edge of the map setm(**gca**,*'MLabelParallel'*,0). There is a gap where Matlab fails to interpolate between the bounding latitudes. We can fix it in lab if there is interest.