

Chapter 2

The World Ocean

2.1 Levitus Ocean Atlas

The National Oceanographic Data Center maintains a large archive of quality-controlled oceanographic databases for use by the scientific community. The work is supported by NOAA's Climate and Global Change program.

We will use ocean temperature and salinity data sets compiled to make the Levitus 1994 Ocean Climatology Atlas. More recent data sets are also available, for example the World Ocean Atlas 1998 and WOA 2001. The data are gridded with a 1° graticule. The complete data set includes temperature, salinity, oxygen, phosphate, silicate, and nitrate. You can read more about the data at http://ingrid.ldgo.columbia.edu/SOURCES/.LEVITUS94/.dataset_documentation.html.

In-situ temperature is reported as Kelvin above the triple point for water (273.15 K), that is, degrees Celsius.

Salinity is reported in practical salinity units (p.s.u.).

2.2 Ocean water characteristics

The temperature and salinity of water in the ocean's near-surface mixed layer is determined according to heat exchange with the atmosphere, evaporation, rainfall, terrestrial runoff, and freezing and melting of sea ice. The temperature and salinity "signal" in a parcel of water is set by processes acting at the ocean surface. Changes in temperature and salinity can increase or decrease the density of water at the surface, which in turn leads to convection.

While circulation of surface waters is driven by wind, circulation of the deep ocean is driven by density gradients. As a water parcel moves below the surface mixed layer, its salinity and temperature can change only by mixing with other water parcels. Measurements of these *conserved* quantities (temperature and salinity) can be used to trace the path of a water mass that originated

at a particular location at the ocean surface. If past water salinity and temperature can be determined, past ocean circulation patterns can be inferred.

2.2.1 Salinity

At the simplest level, salinity is the total amount of dissolved material in grams in one kilogram of sea water, a dimensionless quantity. The variability of dissolved salt is very small, the range of salinity for most of the ocean's water is from 34.60 to 34.80 parts per thousand, 200 parts per million. As you might imagine, "total dissolved solids" is not a very practical definition as this is a difficult quantity to measure. Instead, oceanographers have defined standards based on proxies for the total dissolved material, such as Chlorinity or conductivity.

The modern standard for salinity measurements uses conductivity. The practical salinity scale defines salinity in terms of the conductivity ratio of a sample to that of a solution of 32.4356 g of KCl at 15° C in a 1 kg solution. A sample of seawater at 15° C with a conductivity equal to this KCl solution has a salinity of exactly 35 p.s.u. At 15° C, 35 p.s.u. is 35,000 ppm, 35 ppt, or the solution is 3.5% salt.

This standard works well because the ratios of the various ions in sea water are nearly independent of salinity and location in the ocean. Only very fresh waters have ratios that differ significantly from the global oceanic ratios.

2.2.2 Temperature

As water sinks below the ocean surface, pressure increases, the water is compressed, and the compression does work on the water, causing it to warm. The heating is small, but measurable. As a result, *in situ* temperature is not a conserved quantity *sensu stricto*. To remove the influence of compressibility from measurements of temperature, oceanographers use a quantity called the potential temperature, the equivalent temperature of a parcel of water raised adiabatically to the sea surface. For the purposes of this lab, the *in situ* temperature is fine. However, if you are interested in calculating the potential temperature, a function for that purpose is included in the suite of programs for this lab.

2.2.3 Density

The density of water depends on its salinity and temperature, and on hydrostatic pressure (the weight of the overlying water column). Temperature has a greater effect on ocean water density than does salinity. Water of higher salinity will float atop water of lower salinity if the higher-salinity water is warm enough. The *equation of state* for sea water, the empirical relationship between pressure, temperature, salinity, and density has a complicated, non-linear form. This yields some interesting effects in the ocean. For our purposes, a relatively simple formulation is adequate. As an optional exercise, you are provided with a set of computationally efficient equation-of-state routines developed by Phil Morgan, in the Marine Research division of Australia's Commonwealth Scientific and Industrial Research Organization. You can find information about

the complete suite of routines at <http://www.marine.csiro.au/datacentre/processing.htm>. The routines provided allow you to calculate both density and potential density, a quantity similar to potential temperature. Obviously, density is not a conserved thermodynamic property of ocean water but potential density is.

The density of ocean water increases continuously with decreasing temperature, until the water freezes. This is not the case for fresh water, a property that causes freshwater lakes in cold regions to “overturn” twice a year. Ocean water, with an average salinity of 35 psu, freezes at -1.94°C . Upon freezing, salt is “rejected” from the ice crystal lattice and the salinity of the underlying water increases.

2.3 Ocean circulation in brief

Ocean circulation is due to wind stress acting on the sea surface and to buoyancy. Wind-driven circulation is relatively energetic but is limited to the upper few hundred meters of the ocean, the “mixed layer.” Mixed layer depth is not easy to observe directly and is usually calculated using potential temperature and potential density according to some defined combination of changes in those two quantities relative to the ocean surface. The relatively sluggish buoyancy-driven circulation overturns the ocean, connecting deep waters with the atmosphere and correcting thermohaline imbalances created by processes acting at the surface.

Wind drives the general circulation associated with the subtropical and subpolar gyres, and the Antarctic Circumpolar Current. Steady winds blowing on the sea surface produce a horizontal boundary layer, the Ekman layer, that at most extends a few hundred meters below the ocean surface. Similar boundary layers exist at the ocean bottom and in the atmosphere just above Earth’s surface (the planetary boundary layer). The Coriolis force due to Earth’s rotation results in a net transport in the surface Ekman layer that is normal to the wind direction, to the right of the wind in the northern hemisphere and to the left of the wind in the southern hemisphere. The circulation in oceanic gyres is asymmetric because the Coriolis force varies with latitude.

Ekman transport produces relatively high sea levels in regions of convergence and relatively low sea levels in regions of divergent regions (for example, western and eastern boundaries of ocean basins). Divergence and convergence lead to upwelling and downwelling of ocean water, respectively, which in turn move relatively less dense water upward and relatively more dense water downward. This results in horizontal pressure gradients within the ocean. Away from the Ekman layers, over distances of 10’s of kilometers or more, horizontal pressure gradients in the ocean almost exactly balance the Coriolis force resulting from horizontal currents. This balance is known as the geostrophic balance.

Surface waters store and release heat from solar radiation in a process that works to balance the spatial variation in insolation. As warm tropical surface waters flow poleward, interaction with the atmosphere and with water from terrestrial sources modifies both their temperature and salinity. In locations where surface waters become sufficiently dense, the water sinks and becomes part of the buoyancy-driven circulation commonly called the “thermohaline conveyor.” The Atlantic and Pacific oceans have very different roles in the thermohaline circulation.

2.4 data interpretation

2.4.1 plan-view maps of ocean salinity and temperature

2.4.1.1 mean annual data

The data files are named `levitus94_sal.mat` and `levitus94_temp.mat`. They each contain two arrays, `Z` containing the depths of the map layers, and a three dimensional array containing gridded data for each depth layer.

The function `f_map_levitus.m` can be used to plot the map data. Different seasons or seasonal differences may be mapped by passing the correct array name to the function. The variables passed to the function are listed in the function description as follows:

```
%* map levitus seasonal data f_map_levitus(FN, mdat, mlat, mlon, ttl, xlb, ylb)
% FN      figure number
% mdat    map data to be rendered
% mlat    latitudes for mdat
% mlon    longitudes for mdat
% ttl     figure title, expects character string
% xlb     x-axis label, character string
% ylb     y-axis label, character string
```

The variables must be passed to `f_map_levitus.m` in exactly the same order as they appear in the function declaration. The procedure is the same as in the atmosphere climatology lab. For example, the mean annual temperature of the surface layer could be rendered

```
>> load levitus94_sal
>> load levitus94_temp
>> load coast
>> maplat=[-90:1:89];
>> maplon=[-180:1:179];
>> Ctmin=min(min(min(temp)));
>> Ctmax=max(max(max(temp)));
>> ttl='temperature in surface layer';
>> xl='longitude';
>> yl='latitude';
>> f_map_levitus(10, temp(:,:,1), maplat, maplon,[Ctmin Ctmax], ttl, xl, yl)
```

2.4.1.2 seasonal means

The NOAA ocean atlases include seasonal as well as monthly data sets. The volume of data in the monthly ocean climatology is quite large so we won't use it in this lab but we can work with the seasonal climatology. The data are organized into mean values for four, three-month periods: January/February/March, April/May/June, July/August/September, and October/November/December. An easy method by which to compare the seasonal data is to compute differences or normalized differences between seasons. For example, subtracting the July/August/September surface salinity from the January/February/March salinity and dividing that number by the

annual mean surface salinity would allow us to examine summer-winter changes in the northern hemisphere and winter-summer changes in the southern hemisphere.

The data files are named **levitus94_salseas.mat** and **levitus94_tempseas.mat**. They each contain five arrays, **Z** containing the depths of the map layers, and one array for each season, using the first letters of the three-month groups as identification. For example, **salJFM** is the array containing mean January/February/March salinity map layers.

Seasonal data or seasonal differences may be mapped by passing the correct array name to the function `f_map_levitus.m`, as above and in the first lab.

The appropriate data sets must be loaded into the workspace and appropriate variables created before `f_map_levitus.m` can be used to render a map. For example, if we wish to make a map of salinity difference between JanFebMar and JulAugSept normalized to the annual mean, we could do the following in the command window:

```
>> clear
>> load levitus94_salseas
>> maplat=[-90:1:89];
>> maplon=[-180:1:179];
>> salmean=(salJFM+salAMJ+salJAS+salOND)/4;
>> mapZ=1;
>> diff=(salJFM(:,:,mapZ)-salJAS(:,:,mapZ))./salmean(:,:,mapZ);
>> Cax=[min(min(diff)) max(max(diff))];
>> ts='surface salinity difference JanFebMar-JulAugSept normalized to mean';
>> xls='longitude';
>> yls='latitude';
>> FN=50;
```

To run the function:

```
>> f_map_levitus(FN, diff, maplat, maplon, Cax, ts, xls, yls)
```

It is also possible to compute all the values and define the character arrays within the function call but that would be a bit messy for our intended use here.

2.4.1.3 `f_map_levitus.m`

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

```
%* map levitus seasonal data f_map_levitus(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 coastlines
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, 'r-')     % plot world coastlines

```

2.4.2 meridional slices of ocean salinity and temperature

2.4.2.1 overview

This program loads the Levitus and MATLAB-native coast data sets and plots contour maps of the depth-variation in mean annual salinity and temperature along a user-specified longitude. A reference map showing the location of the line of longitude (a *meridion*) is also drawn. There are several things you may want (or are asked) to change when running this program:

select meridian Change the value of SL to change the meridian, negative indicates west longitude. *Note that the longitude is written in the figure window, at the upper right of the plot.*

```
SL=-30;                % SET slice longitude
```

select figure numbers for plotting In order to preserve one set of figures, change the starting number to a value that has not been used before.

```
FN=101;                % SET starting figure numbers
```

suppress contour lines You may wish to use MATLAB's `shding` function to suppress the (black) contour lines on plots where the contour spacing is so close that the fill colors are obscured.

```

shading flat           % suppresses contour lines
shading faceted       % re-draws contour lines

```

2.4.2.2 script : slice_levitus .m

```

%* slice levitus data
% draw filled contour transects through the world ocean

% levitus94_sal.mat      mean annual salinity , 1 deg graticule , Z depths
% levitus94_temp.mat    mean annual temperature (K above triple point),
%                        1 deg graticule , Z depths

%
% Z (-ve): 0 10 20 30 50 75 100 125 150 200 250 300 400 500 600 700 800 900
%           1000 1100 1200 1300 1400 1500 1750 2000 2500 3000 3500 4000 4500
%           5000 5500

%* load the data
load levitus94_sal
load levitus94_temp
load coast

%* make some plotting variables
% -ve is W lon , S lat
% +ve is E lon , N lat

maplat=[-90:1:89];
maplon=[-180:1:179];

%* SET slice longitude
SL=-20;
slicelon=find(maplon==SL); % get index number for selected longitude

%* SET starting figure numbers
FN=101;           % first of two figures , change to preserve oldies
Fnref=100;       % reference map, don't change or overwrite this

%* ranges for color scales
Csmn=min(min(min(sal)));
Csmx=max(max(max(sal)));
Ctmin=min(min(min(temp)));
Ctmax=max(max(max(temp)));

%* define contour values for filled contours
cvT=[-2:2:30];   % temperature
cvS=[30:0.5:42]; % salinity

%* map plot windows
wind=[min(maplon) max(maplon) min(maplat) max(maplat)];

```

```

windslice=[min(maplat) max(maplat) min(Z) max(Z)];

%*****
% reference map to show location of meridional slice
%*****

figure(FNref)
clf
axis(wind), axis image, hold on
plot(long, lat, 'k-')
plot(SL*ones(180,1), maplat, 'b-')

%*****
% meridional slices through the world ocean
%*****

%* salinity
salslice=sal(:, slicelon,:); % extract values
salslice=squeeze(salslice); % get rid of singleton column
salslice=salslice'; % transpose for ease of plotting

%* temperature
tempslice=temp(:, slicelon,:); % extract values
tempslice=squeeze(tempslice); % get rid of singleton column
tempslice=tempslice'; % rotate for ease of plotting

figure(FN)
clf
caxis([min(cvS) Csmax])
axis(windslice), hold on
[csS, hS]=contourf(maplat,Z, salslice, cvS);
clabel(csS, hS, 'manual') % use return values to label contours
xlabel('latitude (deg)')
ylabel('depth (m)')
title('mean annual salinity in a meridional slice (ci = 0.5 p.s.u.)')
text(100, 0, int2str(SL))
colorbar('horiz')

figure(FN+1)
clf
caxis([Ctmin Ctmax])
axis(windslice), hold on
[csT, hT]=contourf(maplat,Z, tempslice, cvT);
clabel(csT, hT, 'manual') % use return values to label contours
xlabel('latitude (deg)')
ylabel('depth (m)')
title('mean annual temperature in a meridional slice (ci = 2 deg C)')
text(100, 0, int2str(SL))
colorbar('horiz')

```


2.4.3 density along a meridional slices

The script, `slice_lev_density .m`, computes and plots water density and potential density along a meridian using the variables `salslice` and `tempslice` created by `slice_levitus` for the meridian you last selected when running that program. `slice_lev_density` uses ocean-water equation-of-state routines introduced in section 2.2.3. The functions, listed in the comments to this program, must all be present in the working directory in order for `slice_lev_density` to run.

The equation-of-state routines use decibars, a common unit of pressure in oceanographic applications. This is convenient, as a pressure change of 1 dbar is approximately equal to a depth change of 1 meter. Here, the default **reference pressure** used to compute potential density is 0 decibars. Standard atmospheric pressure at sea level is about 10 dbar. At depth, the surface reference is not very useful for comparing adjacent water masses. If you wish to reset the reference pressure, the variable you would change is `RP`. This would in turn require a change in the contour scale. An interesting change would be:

```
%* select reference pressure and contour values
RP=3000;
cvPR=[1038:0.25:1042];

%* compute density of ocean water a longitudinal slice created
% by slice_levitus.m
% draw filled contour transects through the world ocean
%
%* functions

% potential density calculation uses routines created by Phil
% Morgan, Marine Research division of Australia's Commonwealth
% Scientific and Industrial Research Organization.

% sw_adtg.m sw_pres.m
% sw_dens.m sw_ptmp.m
% sw_dens0.m sw_seck.m
% sw_pden.m sw_smow.m
%
%* variables
% Z: vertical layer depths in Levitus data set
% maplat: latitudes of Levitus grid points, defined elsewhere
% salslice: salinity in p.s.u. in a slice of the Levitus ocean
% tempslice: temperature in deg C in a slice of the Levitus ocean
% SL: slice longitude, -ve is west of the prime meridian
%
% rhoslice: potential density, kg m^-3
%*****
% compute potential density
%*****

RP=0;                                % select reference pressure, dbar

pslice=sw_pres(-Z'*ones(size(maplat)), ones(size(Z'))*maplat);
```

```

rhoslice=sw_dens(salslice , tempslice , pslice);
prhoslice=sw_pden(salslice , tempslice , pslice ,RP);

%*****
% plot density in meridional slice through the world ocean
%*****

%* define contour values for filled contours

% ocean surface density ranges from about 1000 to 1030
cvR=[1023:1:1060];
cvPR=[1020:0.25:1028];

%* map plot window
windslice=[min(maplat) max(maplat) min(Z) max(Z)];

figure(200)
clf
caxis([min(cvR) max(cvR)])
axis(windslice), hold on
[csR, hR]=contourf(maplat,Z, rhoslice , cvR);
clabel(csR, hR, 'manual') % use return values to lable contours
xlabel('latitude (deg)')
ylabel('depth (m)')
title('density (ci = 1 kg m-1)')
text(100, 0, int2str(SL))
colorbar('horiz')

figure(201)
clf
caxis([min(cvPR) max(cvPR)])
axis(windslice), hold on
[csPR, hPR]=contourf(maplat,Z, prhoslice , cvPR);
clabel(csPR, hPR, 'manual') % use return values to lable contours
xlabel('latitude (deg)')
ylabel('depth (m)')
title('potential density, sea level pressure reference (ci = 0.25 kg m2-1)')
text(100, 0, int2str(SL))
colorbar('horiz')

```

2.5 Questions

Short paragraph answers 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.

1. map_levitus .m

- (a) Where are the freshest (mean annual) surface waters in the world ocean? Why does the surface water in these areas have such low salinity? Does that signal persist with depth in those locations?
- (b) Compare the spatial pattern of sea surface temperature with that of sea surface salinity. What relationship do you expect to see between sea surface temperature and salinity? Are there locations where that relationship does not hold? Discuss your observations in a short paragraph.
- (c) Describe the contrast in salinity between tropical Pacific and tropical Atlantic surface waters. What do you think is the cause of that contrast? The large range in salinity makes details hard to see in the original plot. You may wish to shift the color scale of the sea surface salinity plot as follows:

```
>>figure(FNZ)
>>caxis([25 Csmax])
>>colorbar('horiz')
```

Does the difference you observe in the tropics persist to higher latitudes in these two ocean basins? Why is that (or why is that not) the case?

2. slice_levitus .m

- (a) Make salinity and temperature slices at 20 West longitude (as in the code above). Two deep water masses emerge in these plots, one of which is notable for its cold temperature and the other of which is notable for its high salinity. Trace the two deep water masses apparent in these plots back to their sites of (surface water) origin. Where does the coldest water, which fills the deep ocean, form?

Next, make salinity and temperature slices at 160 West longitude and compare them with the slices at 20 West. In a few sentences, compare the deep water masses found in the Atlantic and Pacific Oceans.

- (b) Salinity and temperature both have a distinct vertical distribution across latitudes in the tropical ocean. Draw that geometry and in a short paragraph, discuss how it originates.

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3. synthesis

- (a) The data set we are looking at represents mean annual properties of the world ocean. Where would you expect seasonal temperature and salinity to be significantly different from the annual mean conditions and why? Think about both horizontal and vertical

variations. Use the function `f_map_levitus.m` to evaluate your predictions. Were you correct? If not, why not?

- (b) Where are the largest seasonal ranges in sea surface temperature and in salinity? What do you think are the causes for those variations?
- (c) Where are the smallest seasonal ranges in sea surface temperature and salinity? What do you think are the causes for those variations?