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INTRODUCTION TO PHYSICAL OCEANOGRAPHY

UNIVERSITY OF VICTORIA

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Foreword

These are the course notes for Descriptive Physical Oceanography, taught at the University of Victoria, School of Earth and Ocean Sciences, a 13-week undergraduate course.

Unlike many physical oceanography courses, students taking this course are not expected to have studied vector calculus or differential equations, nor are they expected to have learned classical mechanics beyond what is typically offered in a first-year physics course. Many of the students have a deep interest in understanding the ocean and often approach the course with considerable intuition. The challenge of a course like this is to offer more than just a list of facts, but rather to try to give a feeling for the forces that drive the ocean, without becoming too bogged down in mathematical formalism. As such, this course tries to strike a balance between knowing about the various physical phenomena in the ocean and understanding the dynamics that give rise to them, while still giving students some practice in practical calculations.

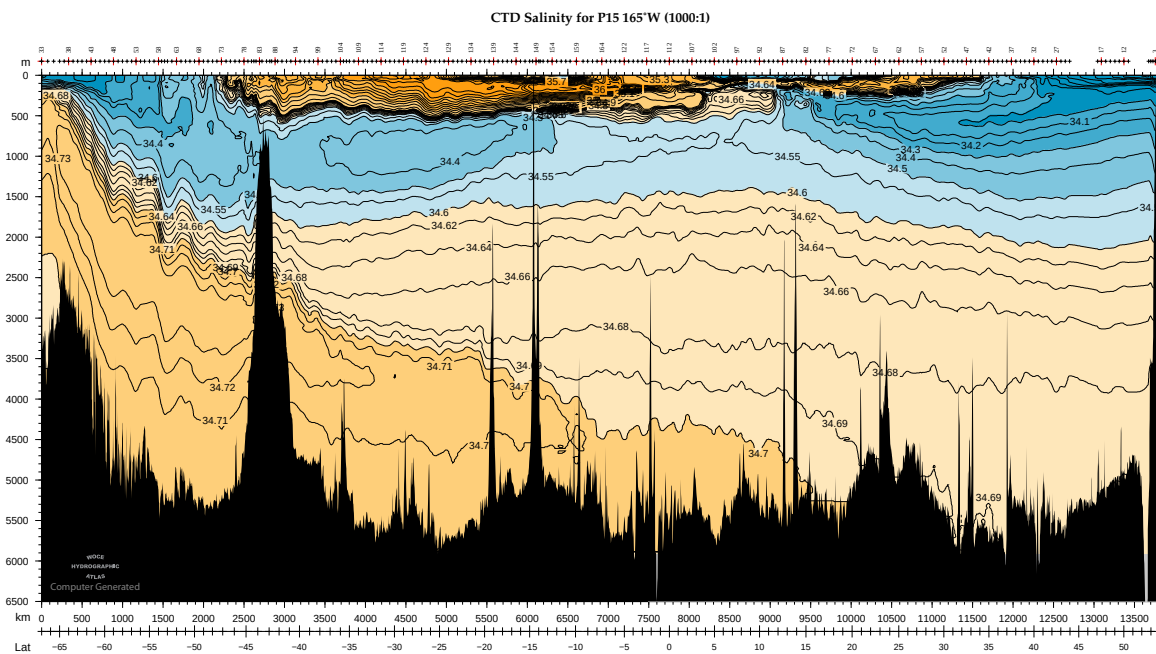
The course is divided into three unequal parts: overturning circulations driven by lateral buoyancy differences and mixing; waves and tides; and wind-driven circulations. We start with estuaries as a nice introduction to overturning circulations, but also because the students do work in Saanich Inlet, and understanding estuaries early is very helpful.

Part I

Overturning circulations

5

Ocean water masses



How does the deep ocean circulate? It moves slowly so it is hard to directly measure the circulation, but a lot can be inferred from the properties of the “water masses”.

Most exchange of ocean heat and freshwater occur at the surface of the ocean, with only minor contributions due to geothermal heatfluxes, and exchange of solutes with the crust. Thus water that is “formed” at the surface tends to retain its signature as it moves through the ocean, leading to the concept of identifiable ocean “water masses”. These water masses are thought of as having “core” values of temperature and salinity set at the ocean surface that are then diluted by mixing with other water masses. Tracking these masses allows us to infer a lot about how the ocean is circulating, particularly

in the deep ocean far from the surface where the water masses are formed.

5.1 Surface distributions of temperature and salinity

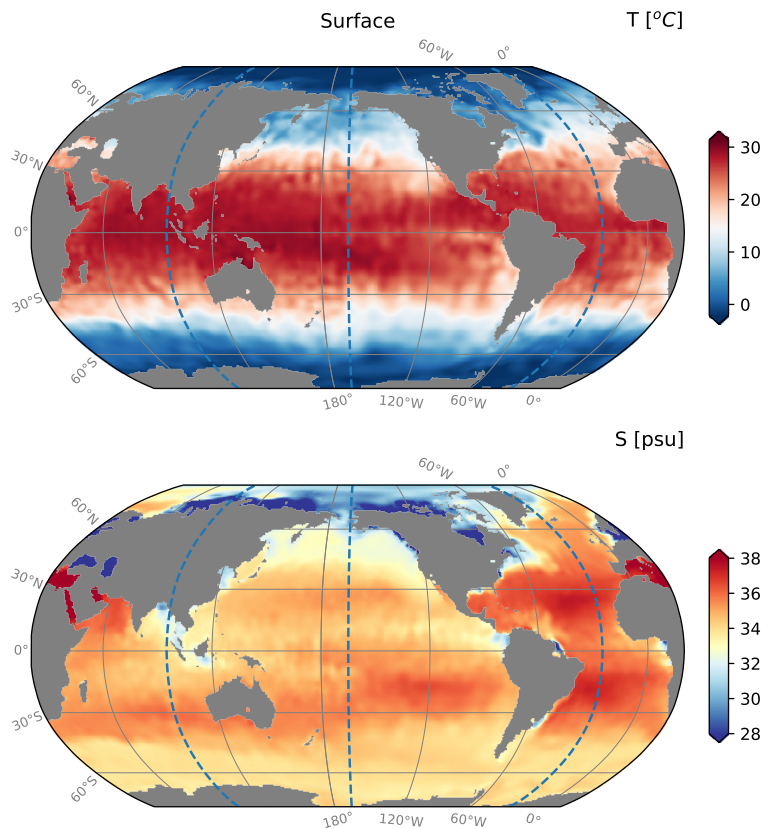


Figure 5.1: Annual average surface temperature and salinity from the [WOCE climatology](#). Dashed lines are sections shown below in the Pacific, Atlantic, and Indian Oceans.

Temperature and salinity distributions at the surface of the ocean follow relatively predictable patterns given the fluxes in chapter 3 (figure 5.1). Warm water is found near the equator, and cold at the poles. There is a relatively sharp delineation between warm waters and cold waters just poleward of approximately 45 degrees, particularly in the Northern Hemisphere, a signature of the separation of the western boundary currents from the continents (like the Gulf Stream) at those latitudes. There is often relatively cool water directly adjacent to the western shore of continents due to upwelling.

Salinity is more complicated with relatively salty surface water at the mid latitudes, and fresher water in the subpolar gyres and the equator. The Mediterranean, Red Sea, and Persian Gulf are very salty,

and overall the Atlantic and Indian oceans are much more salty than the Pacific, to no small part because of these marginal seas.

5.2 Meridional sections

Clearly the largest variation at the surface of the ocean in temperature and salinity is in the *meridional* direction (North-south), so we start our exploration of the water masses in the ocean by looking along meridians in the Pacific, Atlantic, and Indian oceans (figure 5.2). There are striking similarities between all three basins, particularly in the Southern hemisphere, with the largest differences in the salinity distribution amongst the oceans.

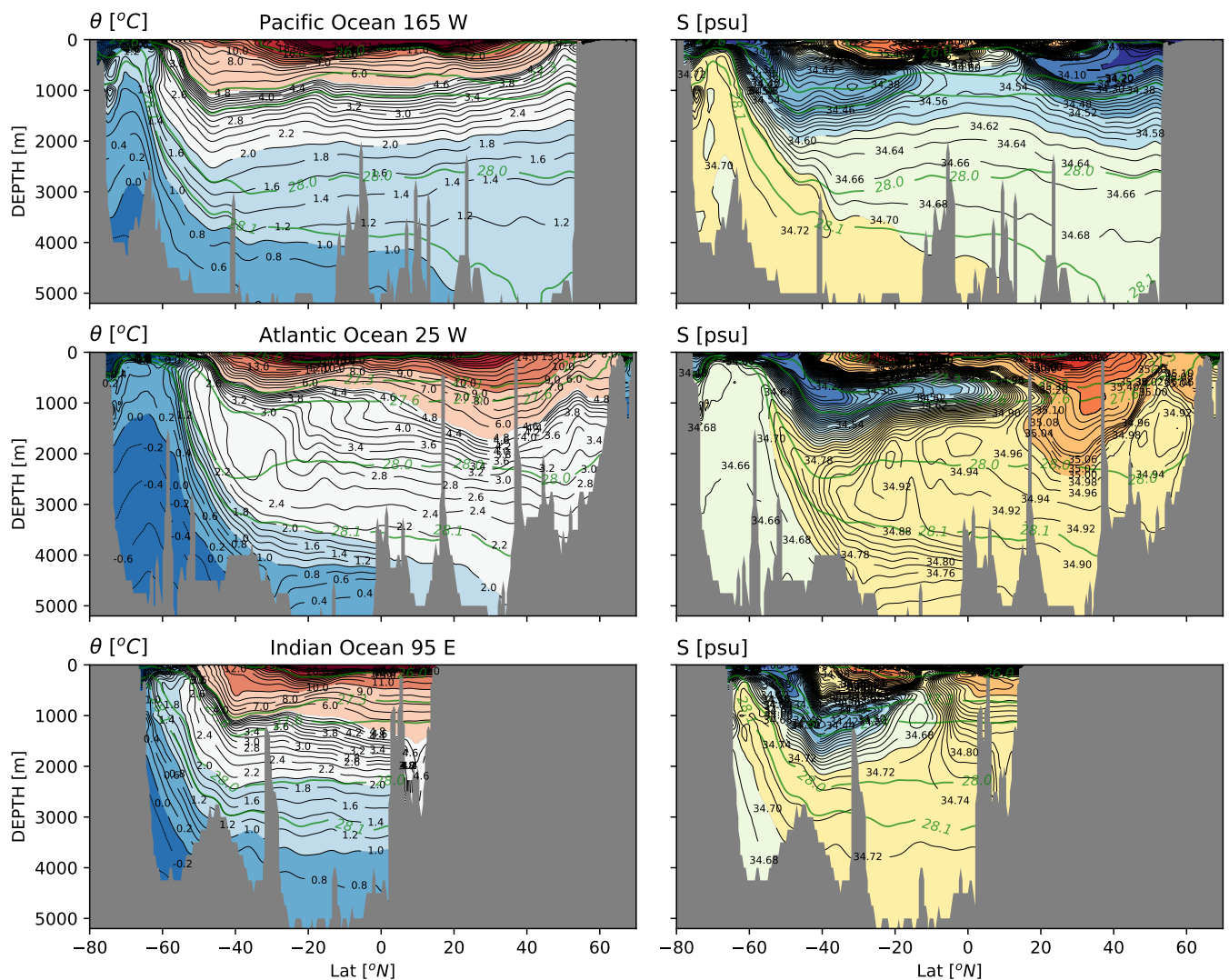


Figure 5.2: North-south cross sections of potential temperature and salinity in the world's oceans. Green contours are levels of constant neutral density. Note the contour levels and colors are non-linear and chosen to highlight ocean water masses. Note the location of these sections is shown in figure 5.1, figure 5.5, and figure 5.4

Surface waters First, in the upper ocean, shallower than 700 m or so, there is a distinct push down of both the isotherms and isohalines centered around 30 degrees. These surfaces rise at the equator, and then again as we move poleward of 30 degrees. This is the signature of the wind-driven *subtropical gyres*, and will be discussed in later chapters. These surface waters are characterized by relatively warm, salty water. Poleward of these bowls are the *subpolar gyres* which tend to be cooler and significantly fresher.

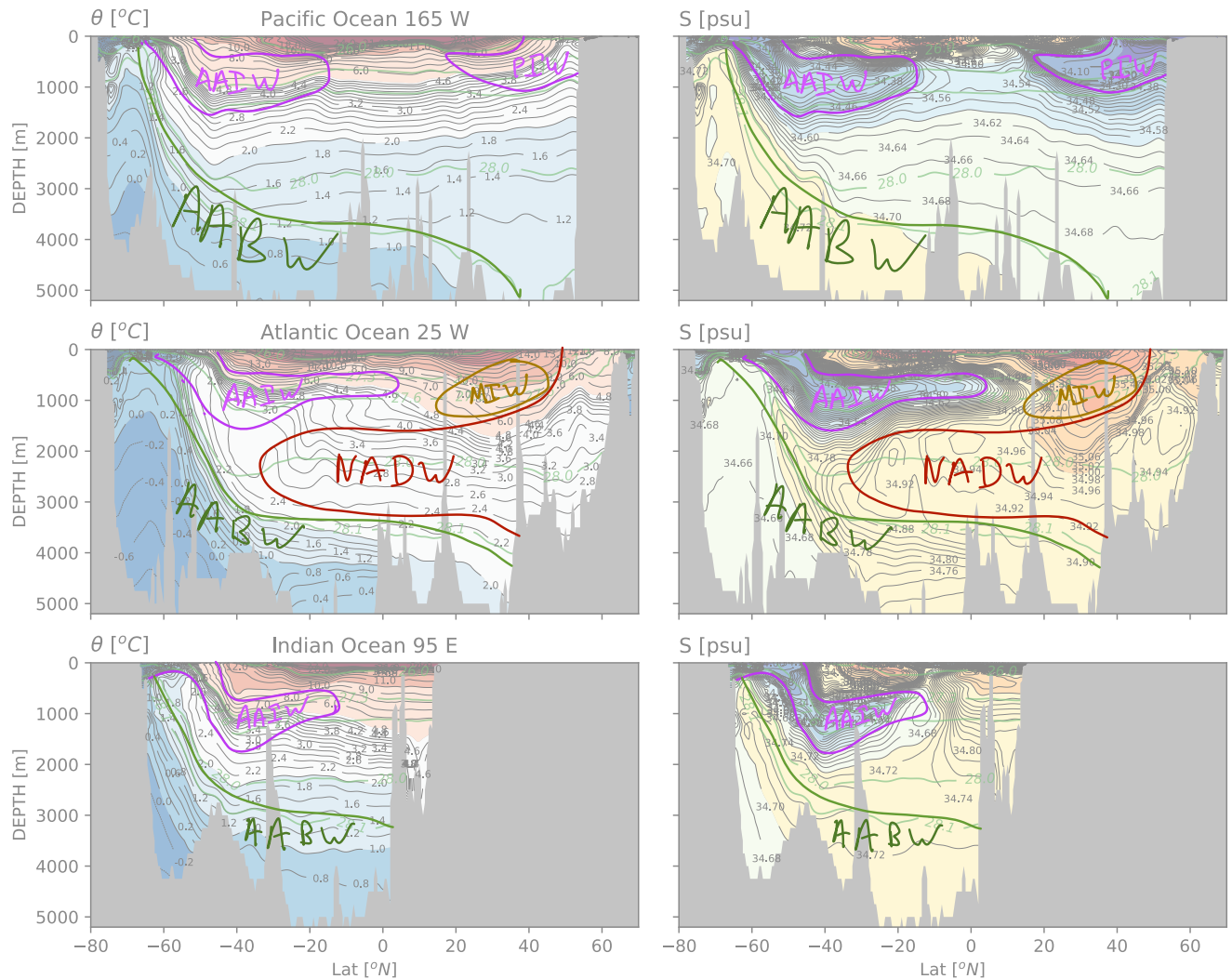


Figure 5.3: As in figure 5.2, with intermediate and deep water masses indicated. AAIW: Antarctic Intermediate Water, PIW: Pacific Intermediate Water, MIW: Mediterranean Intermediate Water, ABW: Antarctic Bottom Water, NADW: North Atlantic Deep Water

Intermediate waters Below the surface water, at depths approximately 1000 m are the Intermediate waters. There is a tongue of fresh cool water found at this depth in all the oceans, clearly connected to the

sub-polar gyre in the Southern Ocean, so this water is called *Antarctic Intermediate Water*. This water is found in all the ocean basins as a northward protruding tongue of water pushed down at around 50 S and then moving up slightly as it moves north (figure 5.3: AAIW). An analogous water mass is found in the North Pacific, and is usually called North-Pacific Intermediate water (figure 5.3: PIW) which originates near 50 N and then is pushed south under the subtropical gyre water.

Finally, there is the very distinct intermediate water mass found in the North Atlantic, called *Mediterranean Intermediate Water* (figure 5.3: MIW). This very salty water is formed in the Mediterranean where salinities exceed 38 psu, which then pours into the North Atlantic as dense water. This water mixes with the ambient water and is diluted, but still has a very robust salinity structure that is found throughout the North Atlantic at the intermediate depths.

Deep and bottom waters Finally, all basins have water along the bottom composed of the densest water in the ocean. It is clear from these cross sections that this water originates in the Southern Ocean (figure 5.3:AABW), where it can be seen *outcropping* south of 60 S, and therefore we call this *Antarctic Bottom Water*. We have the distinct impression that it moves north, as we would expect from the slope of the density surface, and that it becomes diluted with the fresher and warmer above as it moves further north.

The last major water mass is *North Atlantic Deep Water* (figure 5.3: NADW). This water is produced in the Greenland-Iceland Seas, and to a lesser extent the Labrador Sea, and is not as dense as Antarctic Bottom Water. Its density is centred around $\gamma_N \approx 28$, and flows into the ocean above the AABW from the north to the south.

There are many ways to look at these water masses in addition to meridional sections. Surfaces of constant depth (figure 5.4) and surfaces of constant neutral density (figure 5.5) give a useful reference as to where the water masses come from. For instance the Mediterranean water is very clear at $Z = 2000$ m (figure 5.4) as a tongue of salty water. Its also warmer, as can be seen in the contours of temperature, but it is not as obvious due to the colormap. We can see that the fresh intermediate water clearly at 1000 m in the North Pacific is fresher on the west side of the basin than the east.

The deepest surfaces ($Z = 4000$ m) are interesting in that we can see cold salty water pouring in the Pacific (figure 5.4). We note that it preferentially flows in on the west side of the basin, which is due to the “Coriolis” force turning the flow to the left (see chapter 11). This can be seen, somewhat less dramatically, in the other basins. A similar effect happens with the North Atlantic Deep Water, where it

Recall that γ_N is the neutral density, which like potential density is an approximation to the density a parcel would have if brought adiabatically to the sea surface.

flows south, it hugs the western boundary (because it is turning to the right due to the Coriolis force) though it is less obvious to see in these plots.

Overall these plots reinforce the idea that most of the variation is in the meridional direction, with details showing up in the zonal direction. These east-west differences tend to be most pronounced near the coasts, or adjacent to marginal seas like the Mediterranean.

5.3 Vertical structure and θ - S diagrams

As noted, the water masses tend to have particular characteristics. Another useful tool for tracking water masses is to look at the data as property-property plots, and the most basic of these is a $\theta - S$ plot where potential temperature is plotted on the y axis, and salinity on the x-axis. These are usually useful in *conjunction* with section and profile plots, not only to track water masses, but to identify mixing of water masses.

In figure 5.6, different profiles are coloured by their latitude, with water to the north green, and bronze colour is to the south. Intermediate depths (1000 m) are indicated with triangles. This water is saltier at the equator and fresher towards the poles. The bend a bit shallower than 1000 m in the $\theta - S$ curves is the signature of intermediate waters, and we can see that the north Pacific waters are fresher than the Antarctic Intermediate Water.

Looking deeper, below 2000 m, we can see that the water in the Southern Ocean is substantially different than the water in the rest of the Pacific Ocean, with a large salty bulge at around (34.75 psu, 2 degrees C). This distinct water is the North Atlantic Deep Water that is found in the Southern Ocean, but does not make it into the rest of the Pacific Ocean. The very densest water, at the bottom of the T-S curves, is the saltiest and densest at -50 N, and gets lighter both by warming and freshening in the profiles towards the north.

We can see how the properties vary smoothly with latitude by considering all the T-S curves along P16 (figure 5.7). The cold and very fresh surface waters near the poles show up as large anomalies. The anomalies are quickly eroded but still show up as the intermediate water masses. These intermediate water masses disappear, becoming more salty as the equator is approached.

The power of looking at T-S diagrams is that water should maintain its temperature and salinity properties away from the surface of the ocean, except via mixing between the water masses. Mixing can be inferred from *end members* which tend to mix along straight lines in T/S space. For instance, if we mix equal parts water with salinity and temperature S_1 and θ_1 with a second water mass S_2, θ_2 ,

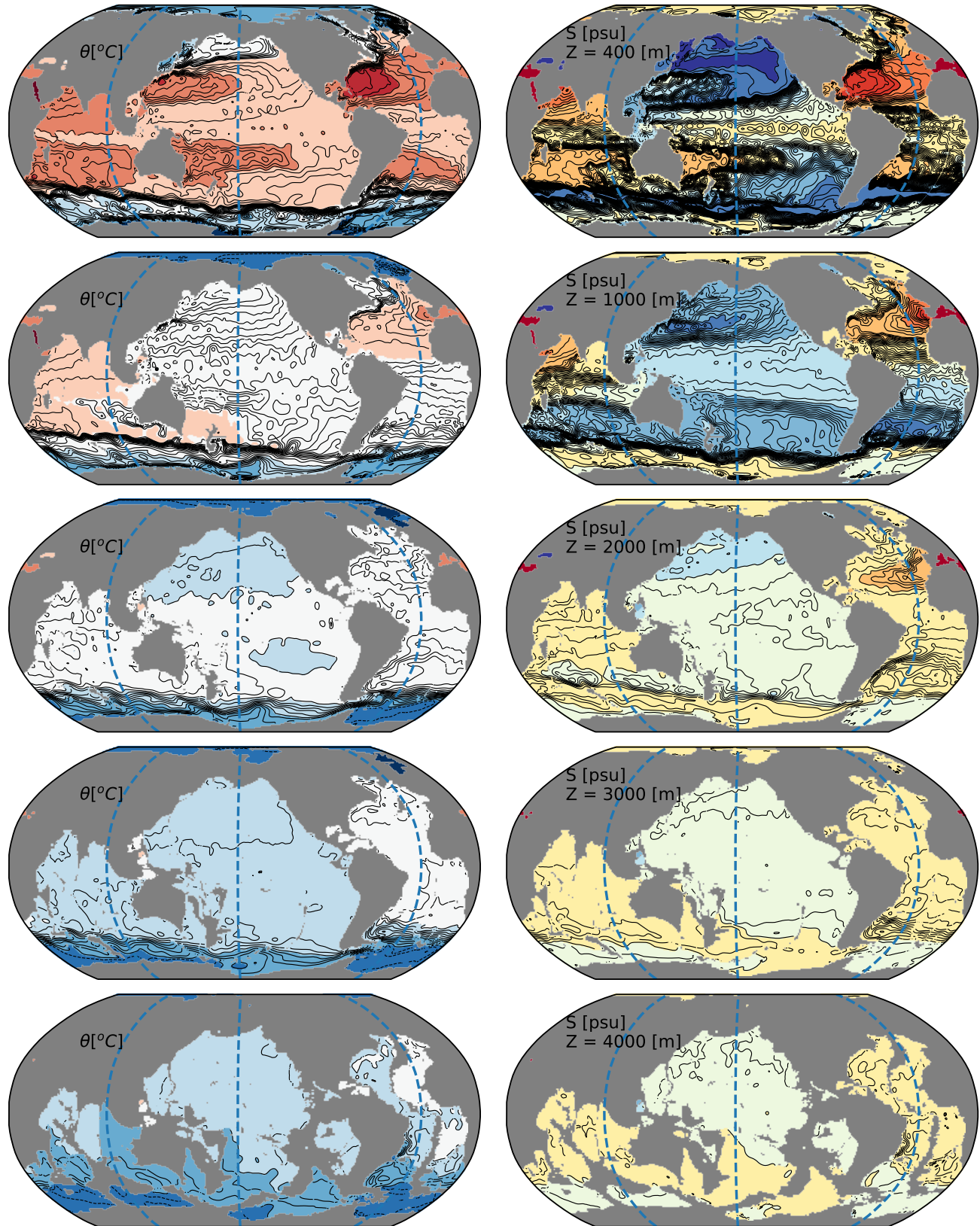


Figure 5.4: Global views of potential temperature and salinity on surfaces of constant depth. Dashed blue lines are sections shown in figure 5.2

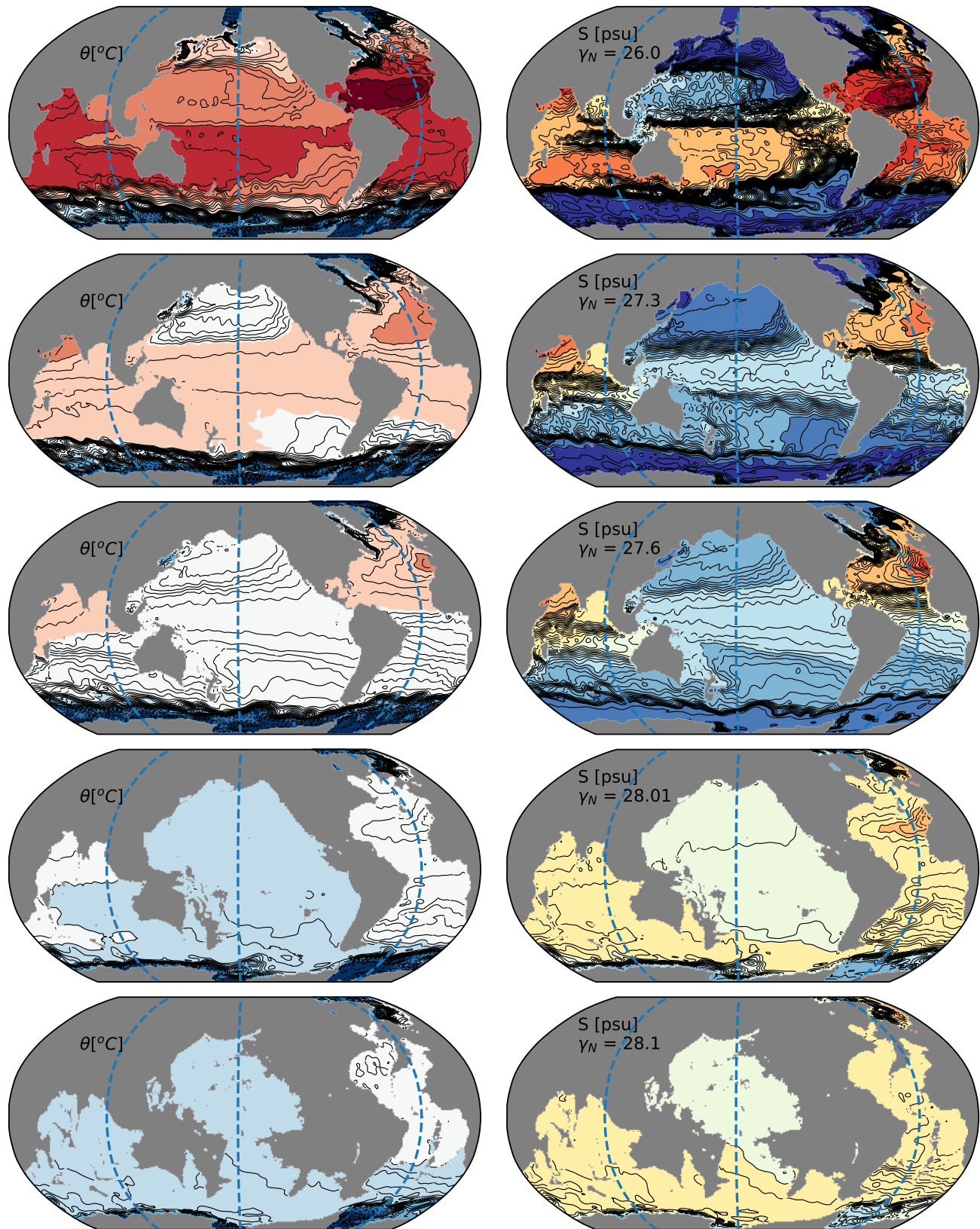


Figure 5.5: Global views of potential temperature and salinity on neutral density surfaces. The surfaces chosen are the same ones contoured in figure 5.2 in green. Dashed blue lines are sections shown in figure 5.2

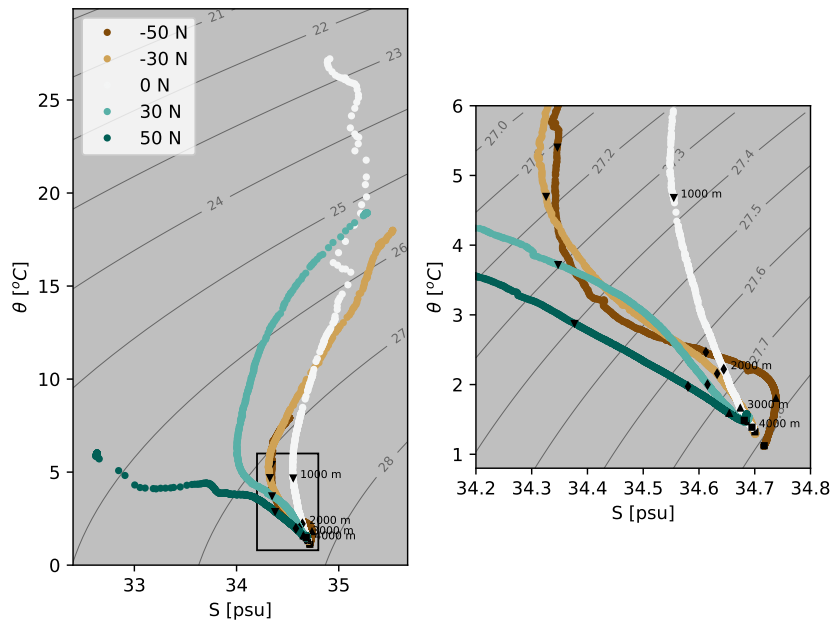


Figure 5.6: Example T-S plots from along P16 in the Pacific, from the profiles shown in figure 4.1. The depth of the data are shown with symbols on each curve, and the right hand side is meant to emphasize the properties in the deepest 1000 m. The white line has the depths labeled. Grey contours are potential density relative to the sea surface.

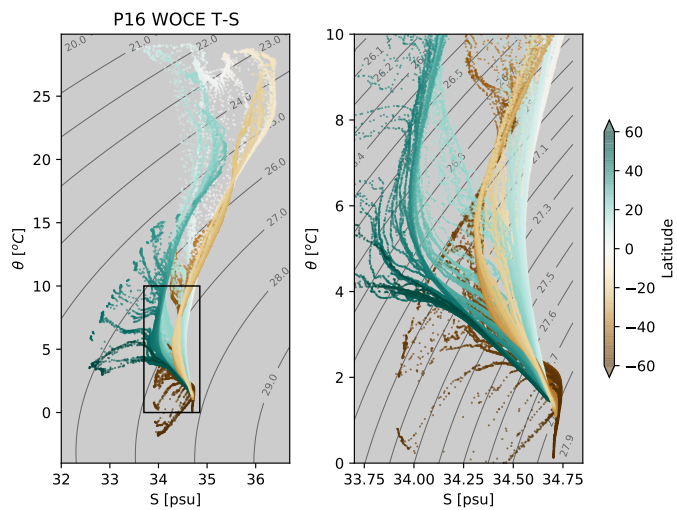


Figure 5.7: WOCE $\theta - S$ properties along P16. Data is color-coded by latitude.

then the mixture will have a new salinity $(S_1 + S_2)/2$, and potential temperature $(\theta_1 + \theta_2)/2$ (figure 5.8). This new water mass lies on the line connecting the two water masses in space. If there is more of one water mass in the mixture, the point will still be along the line connecting the two water masses in T/S space, but it will be closer to the dominant water mass.

Box 5.3.1: Quick proof that mixture is along line between endpoints

The line connecting S_1, θ_1 and S_2, θ_2 is given by

$$\theta = \frac{\theta_2 - \theta_1}{S_2 - S_1} (S - S_1) + \theta_1 \quad (5.1)$$

If we then substitute $S = \frac{aS_1 + bS_2}{a+b}$ we get

$$\begin{aligned} \theta &= \frac{\theta_2 - \theta_1}{S_2 - S_1} \left(\frac{aS_1 + bS_2}{a+b} - S_1 \right) + \theta_1 \\ &= \frac{\theta_2 - \theta_1}{S_2 - S_1} \left(\frac{-bS_1 + bS_2}{a+b} \right) + \theta_1 \\ &= \frac{b\theta_2 - b\theta_1 + a\theta_1 + b\theta_1}{a+b} \\ &= \frac{a\theta_1 + b\theta_2}{a+b} \end{aligned}$$

so $\frac{aS_1 + bS_2}{a+b}, \frac{a\theta_1 + b\theta_2}{a+b}$ lies along the line between the two water masses for any values of $a > 0$ and $b > 0$. If either a or b are less than zero, the point lies beyond the two end point, which is not a possible situation for mixing.

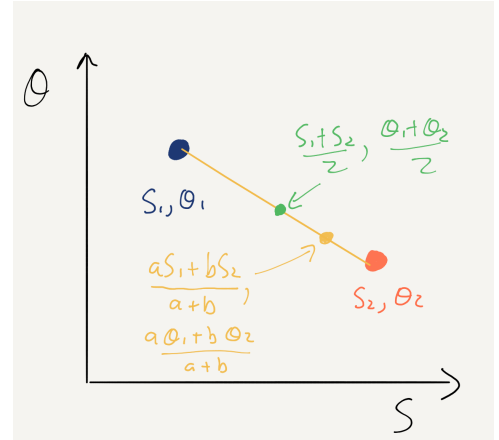


Figure 5.8: Result of mixing two water masses in T/S space. An equal mixture will lie midway on the line between the two water masses. An unequal mixture will also be along the line.

The same principle applies if there are more water masses, though this becomes more complicated. Usually, to start, the mixing is just between two water masses, and the newly mixed water falls along a T-S line; in figure 5.9 the second row of plots shows what happens after a moderate amount of mixing between three water masses. There are two T-S lines, and the data will follow a "V" shape. As more mixing occurs, the original water masses start to be mixed way, until the final steady state of complete mixing is reached (figure 5.9, last row, step=9999). Note that during this whole time the mixed product stays within the triangle defined by the three water masses we started with. Indeed, unless there are surface processes, the T-S properties of any water parcel made up of these water masses *must* fall within this envelope.

We can then look at the WOCE data again, considering the origin of the water masses in the southern hemisphere (figure 5.10). If there

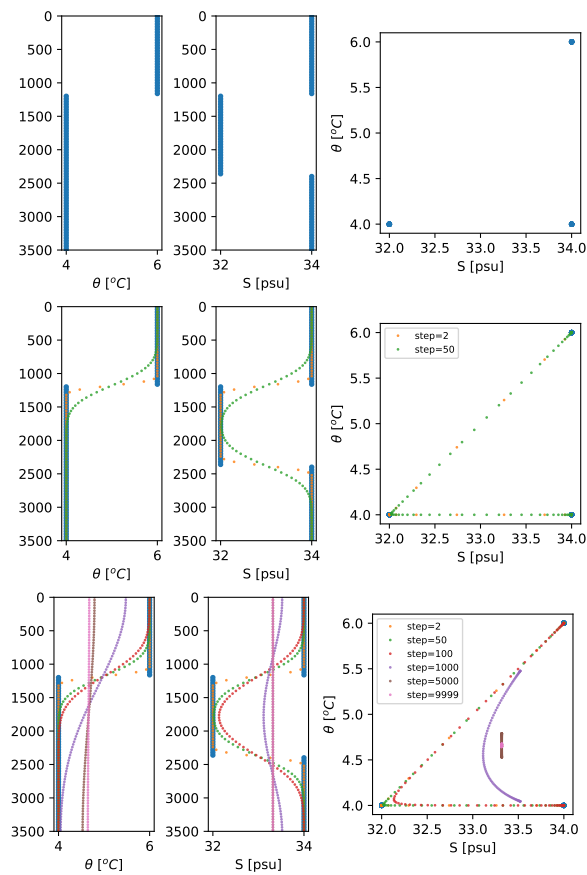


Figure 5.9: Result of mixing three water masses that are originally well mixed. The first row is the initial state. The second row is after some mixing has occurred, but all three water masses still exist. The last row is what happens after a long time. Eventually the temperature and salinity are well-mixed and all the points coalesce to a dot in T-S space.

were no North Atlantic Deep Water, there would be no kink in the T-S curves between $\gamma_N = 27.7$ and $\gamma_N = 27.8$. By the time we get to the equator (white line), the T/S curve looks a lot like the schematic shown in figure 5.9, where it curves between the bottom water and the surface towards the AAIW.

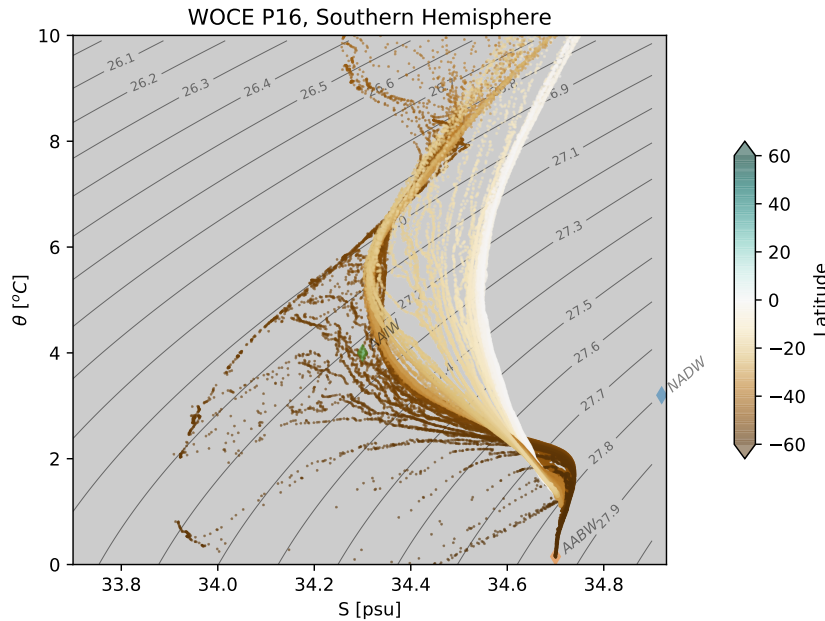


Figure 5.10: T/S diagram of the southern hemisphere Pacific, with core water masses indicated

5.4 Summary

- The water properties in the ocean are largely set at the surface by heat and freshwater fluxes.
- Away from the surface, water retains its temperature and salinity signature, changing only through mixing. This allows us to identify distinct *water masses* by their core T-S properties and trace them across ocean basins.
- There are few locations where water is able to sink away from the surface, namely:
 1. the subpolar gyres: Intermediate waters (AAIW, PIW)
 2. marginal seas: i.e. Mediterranean and Red Seas (MIW)
 3. high latitudes (also often marginal seas): Antarctic Bottom Water, and North Atlantic Deep Water.
- θ -S diagrams are a powerful tool for identifying water masses and inferring mixing: because mixing between two water masses

produces water that falls along the line connecting them in T-S space, the shape of a T-S curve tells us which water masses are present and where mixing is occurring.

- The large-scale distribution of these water masses — intermediate waters spreading from the subpolar gyres, deep and bottom waters filling the basins from high latitudes — gives us a picture of the deep ocean circulation that is difficult to measure directly.

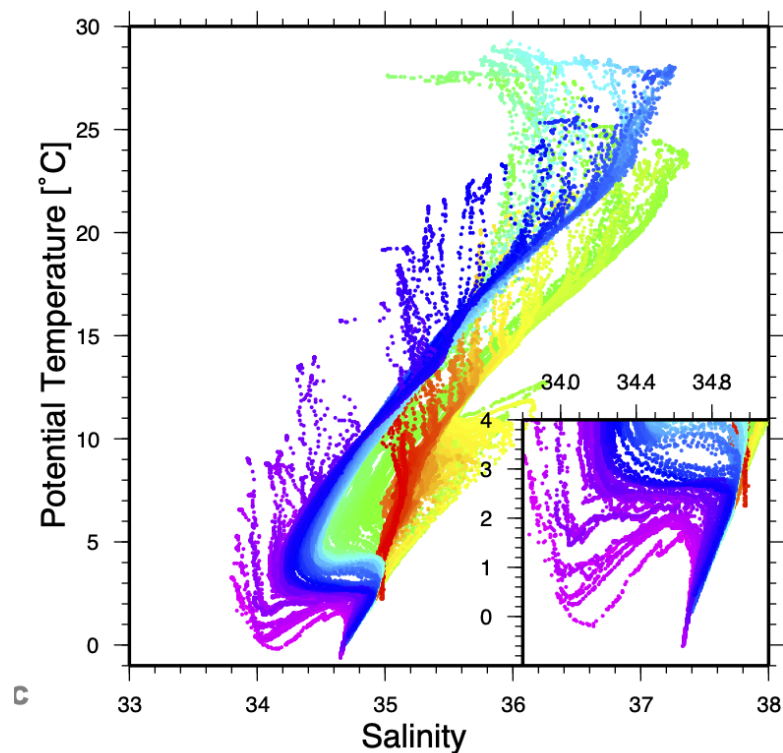
We will discuss in the next chapter where the deep waters arise and why they circulate as they do due to mixing creating lateral density gradients.

5.5 Exercises

Construct a T/S diagram Suppose we have a water column that initially is divided into three water masses:

z [m]	T [deg C]	S [psu]
0-10	20	30
10-20	10	31
20-30	5	30

- Sketch (or plot) the temperature and salinity vertical profiles ($T(z)$, $S(z)$) i) initially, ii) after they have undergone some mixing in the vertical, but there is still some 31-psu water that is unmixed; iii) after the 31 psu water has started to be mixed; iv) when the water is in steady state. NOTE: assume that the water column is not heated or cooled externally, and that there are no external salt sources or sinks.
- Draw the T/S diagram associated with each of your profile sketches.



Interpret a T/S diagram

Consider the T-S diagram above.

- What do the colours represent? Explain why the different colours have different T/S properties

- Identify, if possible, the major deep water masses.
- Compare and contrast to the T/S diagram in figure 5.7. What different water masses can you see and which water masses are more prominent in the "mystery T/S plot"?

5.6 Example problems

Three-layer mixing Consider a three-layer fluid, with equal 1-m thick layers:

depths [m]	T [°C]	S [psu]
0–1	12	0
1–2	14	20
2–3	11	30

Assume that at the top and bottom of the fluid (0 m depth and 3 m depth), the temperature and salinity are *not* allowed to change (not the whole 1-m block, just the top and bottom interface).

Sketch these profiles, and sketch the T/S diagram. Also sketch the direction of the initial heat and salt flux due to diffusion at each of the interfaces.

Sketch the profile and T/S diagram after *some* mixing has happened, but not enough to completely erase any of the individual water masses.

Sketch the profiles and T/S diagram after steady state has been achieved under mixing.

Indicate the direction and relative magnitude (with depth) of the heat and salinity fluxes at steady state.

This is similar to the exercise above and to figure 5.9, but with the added constraint of fixed boundary conditions at the top and bottom — so think about what steady state means when the endpoints are pinned.

Sketch a meridional section of tracers Make approximate sketches in a N/S cross-section of the distribution of *four* tracers in the *Pacific* Ocean:

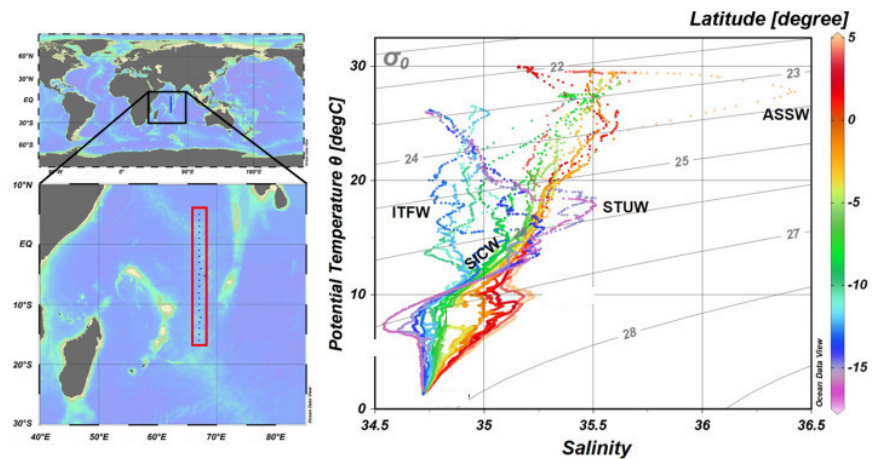
Salinity; label the deep and intermediate water masses (acronyms OK) and indicate relative salinity (i.e. low/high).

One biologically active gas and where low/high.

One nutrient and where low/high.

One man-made tracer and where low/high.

Identify the tracers, and indicate very briefly what the distributions mean. Do not worry about what these look like in the shallower waters, where they can be complicated.



Interpret an Indian Ocean T/S diagram

Consider the T/S plot from the Indian Ocean above.

There are two global water masses and one regional water mass deeper than $\sigma_\theta = 27.0 \text{ kg m}^{-3}$. Identify the global ones, and give an educated guess as to the regional one.

As you move north in considering the T/S curves, why does the water at $\sigma_\theta = 27.7 \text{ kg m}^{-3}$ get saltier?

Sketch what you think the depth-latitude cross sections of the temperature and salinity data look like.

Part II

Waves and Tides

Part III

Wind-driven circulations