1. El Nino and La Nina.
   (a) Use the following schematic for the ENSO feedback and describe the feedbacks between the atmosphere and ocean that occur during a La Nina event (opposite of El Nino). In particular, explain why it has a positive feedback. Moving through the feedback diagram, start at any box. I’ll start at the trade wind strength. If trade winds increase, then equatorial upwelling increases, and the thermocline becomes shallower in the east and deeper in the west. With the shallower thermocline and upwelling in the eastern equatorial Pacific, along with upwelling but on thick warm water in the west, the temperature in the east becomes colder and the temperature in the west probably stays about the same. Therefore the zonal SST difference increases. The trade winds in the Walker circulation are driven by this temperature difference, and so they increase. This is a positive feedback. We can assign a sign of +1 to each of the three couplings, multiply and obtain +1, which means positive feedback.

   (b) Assuming that the trade winds are independent of longitude, that is, that they are the same at all longitudes, why is there no cold tongue in the western equatorial Pacific? Because the thermocline is deep in the west (due to the trade winds that push water westward and push the thermocline down), upwelling on the thick warm pool in the west only brings the same warm water to the surface. Therefore there is no cold tongue there.

2. (a) If 20 Sv of NADW is formed in the far northern North Atlantic and adjacent seas, and rises uniformly over the entire ocean, calculate the average vertical velocity of the upwelling. (Assume that the oceans cover 70% of Earth’s surface and, for simplicity, assume the ocean is

\[
\text{Bjerknes tropical feedback (b)}\\
\begin{array}{c}
\text{Trade wind strength} \\
\downarrow \\
\text{Equatorial upwelling. High sea level and deep thermocline in west. Low sea level and shallow thermocline in east.} \\
\downarrow \\
\text{Zonal tropical SST difference} \\
\end{array}
\]
flat bottomed and is all very deep, with no shelves, etc.)
First calculate the area of the ocean, then divide transport by this area, which results in the vertical velocity.
Area of ocean: area of a sphere is $4\pi R^2$. Ocean will be 70% of total area of earth surface. Don’t worry about whether upwelling surface is 2 km down from surface, very small correction to the 6371 km radius. (You can calculate this to see this.)

\[ R = 6371 \text{ km} = 6.371 \times 10^6 \text{ m} \]
\[ A_{\text{earth}} = 4\pi R^2 = 5.10 \times 10^{14} \text{ m}^2 \]
\[ A_{\text{ocean}} = 0.7A_{\text{earth}} = 3.57 \times 10^{14} \text{ m}^2 \]

\[ V_{\text{nadw}} = 20 \times 10^6 \text{ m}^3/\text{sec} \]

Thus
\[ \frac{w}{A_{\text{ocean}}} = \frac{(20 \times 10^6 \text{ m}^3/\text{sec})}{3.57 \times 10^{14} \text{ m}^2} = 5.6 \times 10^{-8} \text{ m/sec} = 5.6 \times 10^{-6} \text{ cm/sec} \]

(b) At a latitude of 20°N, calculate the vertically integrated meridional velocity that results from this upwelling rate, assuming a flat bottom and zero vertical velocity at the bottom. (First write down the form of the potential vorticity equation that was used for Sverdrup balance, including a planetary vorticity term proportional to $\beta$ and a stretching term proportional to the Coriolis parameter $f$. Then evaluate it.) Which direction does this vertically integrated velocity go (north or south)?

\[ \beta v = f \frac{dw}{dz} \]
Vertically integrate: \[ \beta V = f(w - 0) \] where $w$ is the velocity calculated in part (a)
I am looking for $V$.

\[ f = 2\Omega \sin(\text{latitude}) \]
\[ \beta = 2\Omega \cos(\text{latitude})/R \]

\[ V = \left(\frac{f}{\beta}\right)w = \left[\sin(\text{latitude})/\cos(\text{latitude})\right]*R*w = \tan(20^\circ\text{N})*(6.371 \times 10^6 \text{ m})*(5.6 \times 10^{-8} \text{ m/sec}) = (0.36)(6.371 \times 10^6 \text{ m})*(5.6 \times 10^{-8} \text{ m/sec}) = 0.13 \text{ m}^2/\text{sec} \]

This is an upwelling velocity, so the meridional direction is northward at 20°N.

(Although not asked for, the average meridional velocity, If this occurs over 2 km depth, would be $0.13 \text{ m}^2/\text{sec})/(2 \times 10^3 \text{ m}) = 6.5 \times 10^{-5} \text{ m/sec} = 6.5 \times 10^{-3} \text{ cm/sec} = 0.01 \text{ cm/sec}. Very small.)

3. Use the vertical sections from the Indian Ocean (I08N and I09S), from the WHP Indian atlas (http://whp-atlas.ucsd.edu/indian/i08i09/sections/printatlas/printatlas.htm), attached, to locate various water masses associated with the wind driven and overturning circulations.
(a) On the salinity section, locate the Antarctic Intermediate Water and the northernmost front of the Antarctic Circumpolar Current (Subantarctic Front).
Label the blue, low salinity water mass, north of about 43°S. The SAF is defined by the southernmost location of this vertical salinity minimum of the AAIW.

(b) On the neutral density section, locate the Subantarctic Mode Water and the main pycnocline that marks the base of the wind driven gyre. Locate the large spread in isopycnals between about 43°S and 24°S, depth range of about 200 to 800 m depth at maximum.

(c) On the salinity section, locate the subducted Subtropical Underwater (salinity maximum water). Shallow salinity maximum is found between 25°S and about 11°S. Band of origin is the high salinity region south of 25°S, extending to the Subantarctic Front. (I’ll accept other answers that are not as far south.)

(d) On the oxygen section, locate the Indian Deep Water. All of the low oxygen water (yellow) below the oxygen maximum which is at about 400 m in the tropics. The low oxygen extends southward as light purple, all the way into the ACC and up across it.

(e) On the salinity section, locate the North Atlantic Deep Water (Lower Circumpolar Deep Water) and the Red Sea Overflow Water. NADW is the high salinity layer south of the ridge at 32°S and extending southward to Antarctica. RSOW is the high salinity layer in the northern Indian Ocean. Technically the upper part of this layer, where salinity is highest, originates at the sea surface in the Arabian Sea or as Persian Gulf outflow, but we did not go over that.

(f) On the salinity section, locate the Indonesian Throughflow Water. The low salinity surface layer at about 15°S to 8°S, and extending down to about 1300 m.

(g) On the potential temperature and oxygen sections, locate the Antarctic Bottom Water. Mark especially the water colder than 0° in the south, and also the layer colder than about 1° all the way up the section.

(h) What is the warmest temperature and coldest potential temperature on the section? Where are they located (circle them)?
Warmest water is the surface layer between 5°S and 5°N, warmer than 28°C. Coldest water is close to the sea surface in the south, <-1.0°C in the temperature minimum layer around 50m deep, and extending down to about 300 m at the southernmost stations.

(i) Why is there no very cold water at the bottom of the Indian Ocean north of the Antarctic Circumpolar Current?
Because the only source of very cold bottom water is the Antarctic continental margin, and there are many deep-sea ridges that the water must cross or flow around to expand north of
the ACC. In addition, the coldest water that does extend northward is subjected to downward diffusion of heat, and so the bottom layer warms to some extent.

(j) Sketch the direction of the meridional overturning circulation on the oxygen section (northward flow, southward flow)
Northward flow would be marked in the AABW layer (colder than 1°C, so oxygen greater than about 180).
Southward flow would be marked in the low oxygen IDW layer.

(k) In the Antarctic Circumpolar Current (ignoring major eddy field), indicate direction and magnitude of the zonal flow using the circle-point/circle-cross annotations (arrow point, arrow tail); make sure to show relative magnitude of near-surface flow and its changes with depth. I would choose to do this on either the neutral density or the potential temperature sections. The ACC is between about 57°S and 42°S, based on the isopycnals that slope downward to the north. I would label this around 50°S, put large circle with arrowhead pointing out of the page towards reader. Circles decrease in size with depth but still showing eastward flow at the bottom.
4. The attached color figures from the WOCE atlas (http://woceatlas.ucsd.edu) show (i) oxygen on the neutral density surface $\gamma^N = 28.10 \text{ kg/m}^3$, (ii) the depth of the neutral density surface $\gamma^N = 28.10 \text{ kg/m}^3$, in the Pacific and Atlantic. NOTE: the color scales are DIFFERENT in the two panels. (Yellow-purple break is 160 $\mu$mol/kg in both Pacific maps but 244 $\mu$mol/kg and 225 $\mu$mol/kg in Atlantic neutral density and 3500 m maps.)

(a) Explain the oxygen pattern on the isoneutral surface in the Atlantic in terms of water mass formation and circulation that affect this isoneutral surface:

(i) What water masses dominate the Atlantic map? (All the way from Greenland to Antarctica). This surface is at about 3500 m depth. The high oxygen in the north is the Nordic Seas Overflow Water (it is too deep and dense to be Labrador Sea Water). This high oxygen extends southward as NADW along the western boundary down to about 30°S. The low oxygen water in the east is Lower Circumpolar Deep Water, which comes from the ACC, and is modified NADW that includes low oxygen water from the Pacific and Indian. The very low oxygen between 50°S and 60°S is the Pacific Deep Water signature of great age. The isopycnal rises steeply upwards south of 60°S, and the high oxygen in the Weddell Sea indicates formation of dense brine-rejected waters. We probably wouldn’t call this AABW. We call it Weddell Sea Deep Water.

(ii) What circulation of those water masses is suggested by the oxygen pattern? Southward flow along the western side in the DWBC, with circulation/recirculation that moves this water out to fill the basin west of the Mid-Atlantic Ridge. Sluggish northward flow from the south in the eastern Atlantic. Eastward flow in the ACC. Confined circulation in the Weddell Sea.

(iii) Locate the Deep Western Boundary Current (DWBC) from the simple Stommel abyssal circulation schematic shown in class (DPO Fig. 7.16) and sketch on THIS Atlantic map. Is there a signature in the oxygen pattern? What major differences do you see between the inferred circulation from oxygen and the Stommel schematic? Described partly in (ii): the narrow DWBC would be along the western boundary. The eastward spread of the high oxygen could be accounted for by Stommel-Arons abyssal flow outside the DWBC. The Mid-Atlantic Ridge interrupts this pattern. It is difficult to infer northward flow in the interior from this oxygen pattern.

(b) Explain the oxygen pattern on the isoneutral surface in the Pacific in terms of water mass formation and circulation that affect this isoneutral surface:

(i) What water masses dominate the Pacific map? In the south this is Lower Circumpolar Deep Water, with relatively higher oxygen than the North Pacific waters. Low oxygen in the north is part of the Pacific Deep Water.

(ii) What circulation of those water masses is suggested by the oxygen pattern? The structure of high oxygen suggests northward flow along the western side just east of New Zealand, and up across the equator. The lowest oxygen is in the northeast (< 150) suggesting that the horizontal inflow ends here, and there is outflow of the low oxygen southward east of Hawaii. Hard to guess anything in the tropics other than mostly zonal flow.

(iii) Locate the Deep Western Boundary Current (DWBC) from the simple Stommel abyssal
circulation schematic shown in class (DPO Fig. 7.16) and sketch on THIS Pacific map. Is there a signature in the oxygen pattern? What major differences do you see between the inferred circulation from oxygen and the Stommel schematic? The DWBC in S-A is a narrow northward current along the western boundary, northward across the equator and then along western N. Pacific. The feature in the S-A model that is not easy to see in this oxygen is the southward DWBC in the northwestern Pacific.

(c) Where is this isoneutral surface the shallowest on these maps? Why is it shallowest there? (Explain in terms of the large-scale external forcing in the region where it is shallowest.) The surface is shallowest south of the ACC, within 200 m of the sea surface in the Weddell Sea in the far southwestern Ross Sea. These are regions of Ekman divergence and upwelling, that domes this isoneutral towards the sea surface. There is also likely formation of dense waters in these regions, although interestingly, on the Pacific map, the broad region of highest oxygen is within the ACC (> 200). This implies very little formation of this water in the Pacific sector, but a lot of formation in the Weddell Sea where the isoneutral is close to the sea surface over a wide region and oxygen is very high.