1. The California Current is driven by a southward alongshore wind. The wind causes an offshore Ekman transport. Assume that the total Ekman transport is 1 Sv. (1 Sv = 1x10^6 m^3/sec.)

(a) Explain how the California Current itself arises from this forcing. (short answer)

Wind blows alongshore, causing offshore Ekman transport and upwelling along the coast. This causes the isopycnals to slope upward towards the coast. The geostrophic response to the offshore Ekman transport and the upward-sloping isopycnals is a southward alongshore current, which is the California Current.

(b) Along the coast, there is upwelling in a strip that is about 10 km wide. Assume that it occurs over a 1000 km length of the coast. Make a reasonable assumption for the thickness of the upwelling layer based on what is causing the upwelling. ___100 to 200m. I will use 100 m for the rest of the answer.

Assuming that the Ekman transport of 1 Sv occurs out of this box, calculate the offshore Ekman velocity (using the transport and dimensions of the box).

Transport through offshore side of box is

(1000 km) x (100 m) x v = 1 Sv = 1x10^6 m^3/sec

so the velocity v = 0.01 m/sec = 1 cm/sec

(c) Calculate the upwelling velocity into the box (using the transport and dimensions of the box).

(1000 km) x (10 km) x w = 1 Sv = 1x10^6 m^3/sec

so the vertical velocity w = 10^-4 m/sec = 0.01 cm/sec

(d) The upwelled water temperature is around 8°C. This water must become 13°C to join with the offshore waters. The expression for heat in terms of temperature is

\[ Q = \rho c_p T \]

Assume that the seawater density is 1020 kg/m^3 and the specific heat is 4000 J kg^-1 K^-1

What is the heat transport into the box from the upwelling?

\[ (1020 \text{ kg/m}^3)(4000 \text{ J kg}^{-1} \text{ K}^{-1}) \times 8^\circ \text{C} \times 10^6 \text{ m}^3/\text{sec} = 3.3 \times 10^{13} \text{J/sec} \]

which is actually a “temperature” transport and not a heat transport. If you added 273.16K to the 13C, then you would get a heat transport. But since all that really matters is the difference between heat transport into and heat transport out of the box, the 273.16 is not important (see next 2 parts of question).

If you computed full Kelvin temperature:

\[ (1020 \text{ kg/m}^3)(4000 \text{ J kg}^{-1} \text{ K}^{-1})(281 \text{K}) \times 10^6 \text{ m}^3/\text{sec} = 1.15 \times 10^{15} \text{J/sec} \]
(e) What is the heat transport out of the box at the higher temperature?
\[(1020 \text{ kg/m}^3)(4000 \text{ J kg}^{-1} \text{K}^{-1})(13^\circ \text{C} \times 10^6 \text{ m}^3/\text{sec} = 5.3 \times 10^{13} \text{J/sec}
\]
or if you computed full Kelvin temperature:
\[(1020 \text{ kg/m}^3)(4000 \text{ J kg}^{-1} \text{K}^{-1})(286 \text{K}) \times 10^6 \text{ m}^3/\text{sec} = 1.17 \times 10^{15} \text{J/sec}
\]

(f) What is the net air-sea heat flux that must occur within the box to create this heating?
\[Q = 1.17 \times 10^{15} \text{J/sec} - 1.15 \times 10^{15} \text{J/sec} = 0.02 \times 10^{15} \text{J/sec} = 0.02 \text{ PW}
\]

2. Along the equator in the Pacific Ocean, the prevailing winds are easterlies (trades).

(a) Is the sea surface in the western equatorial Pacific HIGH or LOW compared with the sea surface in the eastern Pacific? Explain. Why does this differ from the sea surface height beneath the trades/westerlies in the subtropical North Pacific?
HIGH, because the easterly trade winds pile water up towards the west along the equator, since \( f = 0 \) so the viscous flow driven by the wind stress is directly downwind.

Beneath the trades/westerlies in the subtropical North Pacific, the viscous transport is to the right of the wind, so the water cannot be piled up downwind.

(b) Is the sea surface in the western Pacific WARM or COLD compared with the sea surface in the eastern Pacific? Explain briefly why the SST in one region is warm and cold in the other.
WARM. Water piled up in the west is warm surface water. Upwelling in the east through both westward flow at surface, and through off-equatorial Ekman transport, causes the surface water to be colder in the east. Upwelling through Ekman transport in the west draws up similarly warm water as the surface water since the thermocline is deeper in the west.

(c) How does this distribution of sea surface temperature from west to east in the Pacific help to sustain the equatorial trade winds?
With warm SST in the west and cool SST in the east, there is rising air in the west and sinking air in the east, which results in easterly trade winds at the surface.

[What is the name of the equatorial atmospheric circulation – winds - associated with this equatorial SST distribution?]
Walker circulation

(e) During an El Nino event, the atmospheric circulation of part (c) weakens. What does this do to the ocean circulation at the sea surface along the equator?
This slows the downwind transport, and eastward transport can dominate. It also reduces the equatorial upwelling. [More specifically, although not carefully described in the lecture, when the winds change, the adjustment of the sea surface height creates a Kelvin wave that propagates eastward and adjusts the sea surface height to balance the new winds.]
(f) What would (e) do to the SST distribution along the equator? What in turn does this do to the atmospheric circulation?
Through reduction in the equatorial upwelling, the cold tongue becomes warmer. The west-east contrast in SST weakens, and this further weakens the winds.

(g) If an El Nino event lasted for a while, would you expect a response in the Equatorial Undercurrent? Why?
With less water piling up in the west, the eastward pressure gradient force that drives the EUC would weaken and we would expect to see a weaker EUC.

(h) The equatorial thermocline in the eastern Pacific, as marked by the 20°C isotherm, is centered at 70 meters depth. The vertical temperature gradient through the thermocline is 0.1°C/meter. How far up or down must the 20°C isotherm move in order to produce a positive (warm) 5°C temperature anomaly at 70 meters depth?
To produce a 5°C temperature anomaly, the isotherms must move down:
$$\frac{5°C}{(0.1°C/m)} = 50 \text{ m}.$$ 

3. The figure shows steric height (dynamic height) at 4000 dbar (from Reid).

(a) Mark the Deep Western Boundary Currents in BOTH the South Atlantic and North Atlantic.
I’ve done this crudely using powerpoint (dragged figure into it, and then added blue ellipses, etc.)
(b) Indicate where high and low pressure are relative to these currents and the direction of the pressure gradient forces that drives these currents.
High inshore of DWBC, Low offshore, both hemispheres, pgf arrows should point from high to low

(c) Which water masses are these two DWBCs carrying? What are their sources?
N. Atlantic DWBC is carrying North Atlantic Deep Water. Source of this very deep flow is Nordic Seas Overflow Water (source in the Greenland Sea). (Labrador Sea Water is also carried by the DWBC but at a much shallower depth, around 2500 m.)
S. Atlantic DWBC is carrying Antarctic Bottom Water. Sources are polynyas along the continental margin of Antarctica.

(d) The potential vorticity balance in the abyssal layer provides the reasoning for this abyssal circulation. Write down the potential vorticity conservation statement (including planetary and relative vorticity, and vertical column height – stretching).

\[ Q = \left( f + \zeta \right)/H \] is conserved.

What two terms in the potential vorticity are balanced for the interior (non-DWBC) part of the abyssal circulation?
The planetary vorticity \( f \) and the stretching \( (1/H) \).

(e) This abyssal vorticity balance results in INTERIOR flow, which is balanced by the flow in the DWBCs. What direction is the interior flow for a flat-bottomed abyssal layer? For stretching, \( H \) increases so \( f \) must increase. In the Southern Hemisphere, \( f \) is negative, and increase means even more negative. So motion is poleward in both hemispheres.

(f) Which part of the upper ocean, wind-driven circulation has the same type of potential vorticity balance, and same direction of INTERIOR flow as this abyssal flow?
Cyclonic circulations.
Which locations in the North Atlantic and South Atlantic have this type of wind-driven flow, with the same direction of interior circulation as the abyssal circulation?
N. Atlantic subpolar gyre, and the Weddell Sea gyre.
Mark them on the map (based on surface steric height, which you have seen in class and in the textbook).

(a) If there is a net heat transport of 0.5 PW northward at 24°N in the Atlantic due to the global overturning circulation (meridional overturning circulation), what is the average air-sea heat flux north of 24°N that is part of this MOC?
Very simple answer: 0.5 PW total.
But, I really wanted them to estimate the area of the ocean north of 24°N, and then estimate the air-sea flux. Area is approximately 50°latitude by 40° longitude (see figure in problem 3). At 111 km/deg latitude, and choosing a central latitude of, say 50°N, for calculating distance for longitude, I would estimate an area of 50° (111 km/°) x 40° (111 km/°) \( \cos(40°) = (111 \text{ km})^2 \times 50 \times 40 \times 0.766 = 1.89 \times 10^7 \)
km² = 1.89 x 10¹³ m²
The average air-sea heat flux is therefore 0.5 x 10¹⁵ W/(1.9 x 10¹³ m²) = 26 W/m²

(b) What simplified circulation, in terms of coast-to-coast isopycnal layers, is responsible for this northward heat transport? (Ignore the wind driven gyre.)
Northward flow in the upper ocean isopycnal layers (warm layers; thermocline) and southward flow in the deep water layers (cold layers; NADW). There is also northward flow in the bottommost layer (Antarctic Bottom Water), but it is much smaller transport than the NADW and thermocline transports.

(c) The net heat transport from all parts of the circulation across 30°S in the South Pacific is southward. However, the opposite is true at 30°S in the South Atlantic. Explain how this can be – what is different between these two oceans?
The South Pacific meridional heat transport is dominated by the anticyclonic gyre circulation that brings warm water south in the East Australian Current and cooler water northward in the interior and eastern parts of the circulation. Therefore there is southward heat transport.
The South Atlantic has a similar gyre circulation, with southward heat transport. However, there is a superimposed large northward heat transport due to warm waters moving northward to be returned at depth as cooler NADW; this heat transport is larger and therefore the total is northward.