OCES 2003 sort of finals, Spring 2021

Inusuke Shibemoto

Set on: Thurs 14th$^{\text{th}}$ May; due: Thurs 14$^{\text{th}}$ May

Model solutions and mark scheme

Problems

1. The only yes case is part (c). For Rossby waves we need the planetary β. There is no β in (a) becasue there is no mismatch of the rotation axis with the local vertical axis. There is no f let alone β in (b). For (c) there is a β around the equator beacause while f_0 itself is zero, β does not have to be: since $f < 0$ just South of equator and $f > 0$ just North of equator, $\partial f / \partial y = \beta \neq 0$ (you get equatorial Rossby waves).

   (1 mark for each correct justification; the yes/no by itself gets no marks)

2. (a) The linear EOS is

   $$\rho = \rho_0 \left[1 - \alpha(T - T_0) + \beta(S - S_0)\right]$$

   With the relevant numbers, I make it

   $$\rho_{\mathrm{Med}} = 1026.40\ \mathrm{kg\ m^{-3}}, \qquad \rho_{\mathrm{Wedell}} = 1025.78\ \mathrm{kg\ m^{-3}}.$$

   (0.5 marks for each numerical answer, 0.5 marks for units, 0.5 marks for accuracy)

   (b) Overflows are underwater waterfalls, with denser water flowing down the bathymetric slopes, and the depth of penetration of the overflow depends on the density of the arriving water. Overflows contribute to the downward transport of water within the MOC, thus to supply of deep and abyssal waters.

   (1 mark for describing overflow, 1 mark for the MOC stuff; use 0.5 marks as necessary)

   (c) $\rho_{\mathrm{Med}} > \rho_{\mathrm{Wedell}}$ so it might imply Med sea water should be under the Weddell sea water, when we know it should be the other way round. The question is trying to force you to conclude that the characteristics of the overflow matters: if the dense water in the Med sea gets diluted by mixing then it might not be dense enough to reach depths below the Weddell sea water. If the Atlantic side of bathymetry is rough then this presumably leads to enhanced bottom boundary turbulence and enhanced mixing, enabling the aforementioned dilution.

   In reality it depends also on volume of water associated with a particular overflow, the roughness of bathymetry, the slope of the bathymetry, and other things that affect the dynamics.

   (1 mark for the dilution due to mixing, 1 mark for enhanced mixing because of bottom boundary layer turbulence or similar; use 0.5 marks as necessary, and take marks off in increments of 0.5 marks for a narrative that is too long and/or not to the point)

3. (a) Interfacial form stress first of all comes from pressure gradients enabled by flow 'pressing' into bumps in the isopycnals. Baroclinic mesoscale eddies, satisfying low Rossby number dynamics and geostrophic dynamics, and together with hydrostatic balance leads to the thermal wind shear relation tells you the geostrophic flow and the density are directly linked to each other. Since baroclinic mesoscale eddies lead to geostrophic velocity perturbations, this in turn has to lead to density perturbations, and therefore generically give rise to interfacial form stress.

   (1 mark for some definition of interfacial form stress, 1 mark for velocity and density perturbations are related because of thermal wind, 1 mark for applicability of geostrophic balance and therefore thermal wind because

mesoscale eddies satisfy low Rossby number dynamics; use 0.5 marks as necessary, and take marks off in increments of 0.5 marks for a narrative that is too long and/or not to the point)

(b) ACC transport and global pycnocline depth increases. You kill the vertical transfer of momentum by killing the eddies, but since the momentum input by the wind is kept the same, that implies that same amount of momentum is being moved at a lower rate to the bottom for it to be removed from the ocean system by bottom form stress. So there is overall more momentum in the system, with an associated increase in the ACC transport.

This is kind of like the queue size before a toll booth (for tunnels, highways or the Suez canal, whatever). If the rate incoming vehicles is kept exactly the same, and the number of tool booths and competency of the people/equipment there are fixed, but you artificially block off a few lanes (e.g. accident, repairs, the Evergreen ship getting stranded), then the queue will increase in size.

<u>Note</u>: A similar picture could be used for global warming by greenhouse gas emissions, but there you are decreasing the amount of toll booths and/or replacing the competent people with n00bs who don't know what they are doing. The rate of input is still the same, but you are reducing the rate of removal, so there are more things in the system.

(cf. Marshall *et al.*, 2016, GRL; the traffic analogy is mine)

(1 mark for ACC transport increasing, and 1 mark for the reasoning; use 0.5 marks for the reasoning as necessary)

(c) By thermal wind shear relation and global pycnocline connectivity, the pycnocline increases in depth over long century to millennial time-scales, because there is a lot of stratification to change. The transport due to AMOC will probably increase, because you deepen the stratification, so there is substantially more volume for a similar amount of flow.

(0.5 marks for deepened pycnocline, 0.5 marks for increase in AMOC transport, 1 mark in total for the justifications)

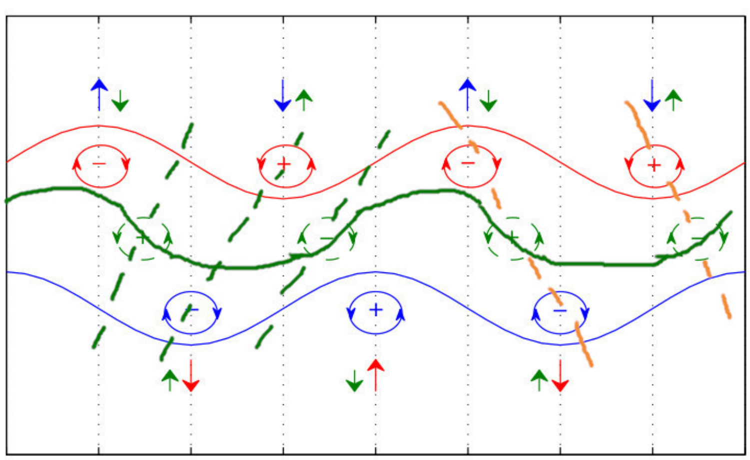
(d) Nothing except the direction of the ocean and atmospheric wind is going to change, because none of the above argument really cares about the sign of f.

(1 mark for reasoning relating to no change; use 0.5 marks as necessary, and the yes/no by itself gets no marks)

4. (a) The blue wave propagates to the right (because of the vorticity anomaly configuration).

(0.5 marks for answer, and 0.5 marks for some sort of justification)

(b) Something like the following:



The phase difference between the red and blue is $\theta_0 = \pi/2$, 90° or quarter of a wavelength. The green wave should have wavenumber 2 and should essentially be shifted halfway between the red and the blue, and the lines connecting the peaks/troughs/nodes should tilt as the green dashed lines drawn in the diagram. The vorticity anomalies at the nodes should be as drawn on in the diagram and tilted in a sandwich position as in the orange dashed line, which ends up damping the red and blue waves.

(cf. Heifetz *et al.*, 2015, JFM; Mak *et al.*, 2016, JFM)

(0.5 marks for $\theta_0 = \pi/2$ or analogous answer, 0.5 marks for the green wave to have wavenumber 2, 0.5 marks for it having the right shifts between the red and blue waves, 0.5 marks for drawing some vorticity anomalies onto the nodes, 0.5 marks for drawing on the desired configuration of vorticity anomalies, and 0.5 marks for some sort of justification for that configuration)

5. (a) Internal waves propagating into the shallow regions can bring in deeper colder water since there is associated vertical motion to the waves, as a way to help coral reef ecosystems acclimatise to heat.

   (1 mark for something like above; use 0.5 marks as necessary, justification optional)

   (b) M2 refers to the lunar semi-diurnal (twice daily) tidal forcing, so the frequency is about 12 hours; the spectral peak refers to the tides being forced that has the semi-diurnal signal (which is perhaps obvious if you read the horizontal log axis, since this is one along from $10^0 = 1$, so it should be two cycles daily). From that, a change of units gives

$$\gamma = 2\ \mathrm{day}^{-1} = \frac{2}{3600 \times 24}\ \mathrm{s}^{-1} = 0.00002\ \mathrm{Hz}.$$

   (1 mark for the lunar semi-diurnal and/or twice daily forcing for M2, 1 mark for the calculation; use half marks as necessary [e.g. wrong answer right working], no penalty for using 12.whatever *as the M2 frequency, but do not accept anything that is not* 0.00002*, since a period of 12 and 13 should still give that answer at the requested degree of accuracy)*

   (c) There is a transfer of power from the lower modes (at the lower frequency) to higher modes, by instability, turbulence, triad interactions and others. The scale of motion is going from large to small.

   (1 mark for noticing higher frequency correspond here to lower modes, either by heuristic argument, via the dispersion relation, or otherwise, 1 mark for instabilities some sort of excitation of lower modes; use 0.5 marks as necessary)

   (d) Internal waves have vertical motion as well as temperature anomalies associated with them, so something like (moored) ADCPs and/or CTD type equipment will do it. Moorings with ADCPs and CTDs would be ideal, but then you need to put a mooring in; just mounted ADCPs to get the vertical velocities would be probably be ok but might be more subject to noise. You probably want quite high frequency (below 5 minutes) to resolve the waves at higher frequencies, and long enough to get sensible statistics for the lower frequency waves (over a week at least to get enough M2 tides).

   (0.5 marks for a naming some instruments and 1 mark for arguing why you want to measure the quantity that could be measured by the instruments, and 0.5 marks for something on frequency and duration of observation)

   (e) You want something that depresses the thermocline, so something that is a converging zone at the surface and diverging zone at depth, which has to be an anti-cyclonic geostrophic eddy. Since we are in the Southern Hemisphere, these have to be anti-clockwise flowing geostrophic eddies.

   (0.5 marks for anti-clockwise, 1.5 marks for the justification; 0.5 marks as necessary for the various bits of justification, and allow some credit if there is a mention of anti-cyclonic eddies but the flow direction is wrong)