I Multiple Choice

1. Which of the following is NOT a site which contributes to production of North Atlantic Deep Water (NADW)?

   (a) Caribbean Sea

2. The strongest signal of inter-annual variability (e.g. time-scales longer then one year) in the 20th century was ...

   (a) El Niño / Southern Oscillation

3. The Southwest Monsoon in the Indian Ocean is typically associated with ...

   (a) Strong upwelling off the Arabian Peninsula

4. The water property which provides the clearest evidence for the location of bottom water formation sites in the southern ocean is ...

   (a) Chlorofluorocarbons

5. Which of the following statements is NOT true?

   (a) There is a seasonal reversal of the direction of the California Current off the coast of San Diego.

6. The rate of meridional overturning circulation of the North Atlantic plays an important role in the global climate system. Which of the following is NOT associated with this phenomena:

   (a) Generally warmer climate conditions in Europe should the overturning markedly decrease.

7. If you wanted to determine if a strong El Niño is currently happening, which of the following would be LEAST useful to consult.

   (a) Magnitude of the wind-driven Ekman divergence in the eastern Tropical Pacific

8. On average, which is the dominant term for cooling the ocean?

   (a) Turbulent transfer of latent heat

9. Which of the following statements is FALSE?

   (a) Water formed through deep convection in the Labrador Sea makes up the coldest component of the NADW.

10. Heat transport in the North Pacific ocean ....

    (a) is poleward due to the action of the wind-driven gyres.

11. Internal waves in the ocean...

    (a) have a vertical displacement amplitude greater then surface gravity waves.

12. Which of the following is NOT true?

    (a) Accurate prediction of tides is based on the observation that tides are nearly always in equilibrium with the tidal potential.

13. The primary westward flowing current(s) in the tropical Pacific is/are:

    (a) The South Equatorial Current and North Equatorial Current

14. The above map shows

    (a) Amplitude and phase of semi-diurnal lunar tide.

15. Comparing the formation rates of North Atlantic Deep Water (NADW) and Antarctic Bottom Water (AABW)

    (a) Formation rates of both water masses is about the same

16. Of the following, which is NOT commonly observed from satellites

    (a) Mixed Layer Depth (microwave sensors)

II Short Answer

17. Discuss the importance of the Mediterranean Sea on global ocean circulation. Include a description of the main characteristics of the exchange of waters between the Mediterranean Sea and the Atlantic Ocean.

    The Mediterranean Sea is a marginal sea of the North Atlantic Ocean with a high rate of evaporation. The sea exchanges water with the North Atlantic through the narrow Straits of Gibraltar. Roughly 1 Sv of water flows into the Mediterranean at the surface balanced by an underlying outflow over the shallow sill. Because of the high rate of evaporation the outflowing water is very salty (inflow water is about 36.1 psu while outflow is 38.4 psu). This influences the global ocean circulation by contributing to the meridional overturning circulation of the North Atlantic. Though the volume transport is small, the high saltiness of the outflow water helps to create the very salty signature of the NADW which is distinguishable throughout the Atlantic basin and into the southern Indian and Pacific basins.

18. GOTH (Group for Ocean Transport of Heat) has assigned you the task of determining the seasonal variations of heat transport in the subtropical North Atlantic. Discuss what types of observations or measurements you would need to complete this task? How often would you need to make observations?

    There are numerous ways one could approach this problem. The necessary components of a heat transport estimate are concurrent observations of water temperature and velocity. The net transport of heat is given by $Q = \int \rho c_p v T dA$. A traditional way to calculate that this is with a zonal hydrographic transect across the basin. One needs profiles of temperature and salinity spanning the basin. Density can thus be calculated and the meridional velocity determined using the geostrophic balance. To resolve a seasonal cycle one would hope to have at least 4 occupations in a year, though you could argue that a minimum number of 2 would reveal something about seasonal differences.

    Other observations which one might use for this calculation include XBTs (to measure upper ocean temperature) and current meters, floats, ADCP, or satellite altimetry to aid in the determination of the velocity field.

19. Discuss the primary features of the Pacific Decadal Oscillation. Describe how changes in the PDO may be related to temporal variation in the strength of El Niño.

    The PDO is a large-scale, low frequency variation of the climate of the Pacific basin. It has signatures in both the atmosphere (sea level pressure, winds) and ocean (sea surface temperature). The pattern of the PDO in the ocean is much like ENSO - a warming of the eastern tropical pacific in opposition to cooling in the higher latitude western subtropic and subpolar regions. Unlike ENSO, which has its largest manifestation in the tropics, the PDO has more pronounced effects at higher latitudes. The timescale of variations is not well described by the observational record but appears to be at least 10-20 years.

    Since the PDO partially overlays the ENSO pattern in the tropics, changes in the PDO modulate the strength of El Niño. Although the mechanism of this modulation is not certain, one possibility is that heat anomalies in the subtropics are subducted and subsequently advected toward the equator. When these anomalies arrive at the equator (a trip which takes about 10 years) they may enhance either the warm or cold phase of ENSO, thus leading to interdecadal variations.

20. Suppose the earth had no moon. How would ocean tides compare to those observed today? Include in your discussion aspects of amplitude, frequency and phase.

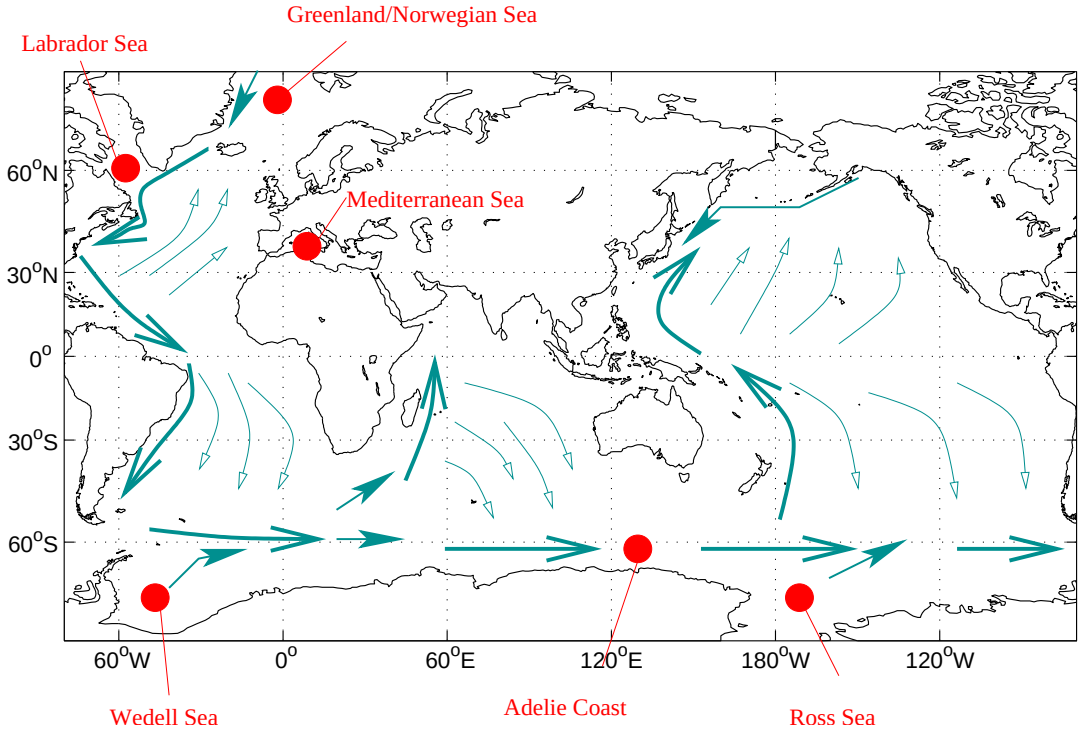
    If the earth had no moon, the sun would provide the only significant tidal forcing. Since the tidal potential of the sun is weaker then the moon (46%, to be exact), the tides (as measured by tidal currents an tidal variations in sea level) would be smaller. The frequency of tides would be based on a solar day with both a diurnal and semi-diurnal component. The semi-diurnal component would be in response to the twice daily tidal potential which would be high at solar noon and midnight. The diurnal component would arise due to the tilt of the earth's axis. The relative strength of the diurnal and semi-diurnal component would depend on the local geography. The phase of the tides would be locked to the solar day (24 hours) thus the time of high and low tides at any location would always occur at the same time every day. Because of the ellipticity of the earth's orbit, the strength of the tidal potential would change slightly over the course of the year. Thus the spring/neap modulation of tides would have a period of one year rather then about a month.

III Problems

21. On December 10th, a powerful earthquake near the island of Kiribati causes a subsurface sediment slump and initiates a large tsunami. Tsunami watchers at Hawaii are immediately notified and begin to evacuate low-lying areas. The tsunami has a wavelength of 500 km and the distance separating Kiribati from Hawaii is 2,800 km. Approximately how much time do the Hawaiians have before the tsunami wave arrives?

    The speed of tsunami is given by the group velocity of a shallow water wave: $c_g = \sqrt{gH}$. All shallow water waves travel the same regardless of wavelength, though the wavelength here reminds one that shallow water dynamics are appropriate since $\lambda >> H$. A typical water depth is 4000m, giving a group velocity of 198 m/s. Since time = distance/velocity, the elapsed time is about 14100 seconds or **3.9 hours.**

22. Indicate and label on the following map the major sites of deep water formation. Sketch the main features of the deep circulation expected based on Stommel-Arons theories of abyssal circulation. (e.g. indicate locations and directions of deep boundary currents and direction of interior flow in each basin)



23. (a) A steady westward wind blows across an ocean basin which is 3000 km wide. The surface wind stress measured at 5°north and 5°south is 0.08 N/m^2. Calculate the net Ekman mass transport at these two latitudes. What is the average rate of upwelling (in m/s) between 5°north and 5°south?

The expression for Ekman mass transport per unit length is: $M_e = |\frac{\tau}{f}|$. To get the net transport across the whole section we multiply this by the length of the section, 3000 km. Thus at 5°north the mass transport is $1.89x10^{10}kg/s$ northward while at 5°south it is the same magnitude but southward. To calculate upwelling we need to express this as a volume transport. We can convert this to a volume transport by dividing by an average density: $V_e = |\frac{\tau}{\rho f}|$. The volume transport at 5°north is 18.4 Sv and the net divergence driven by the winds is twice this: 36.8 Sv. Upwelling is total volume transport divided by area: $w = \frac{V_e}{A}$ which turns out to be $1.1x10^{-5}m/s$.

(b) Suppose the water upwelling between 5°north and 5°south has a temperature of 24°. Furthermore, the mean temperature of the water flowing across 5°latitude in the Ekman layer is 28°. Calculate the mean ocean heating over this region (express your answer in W/m^2).

The heat budget is for a box with net throughflow of $3.78x10^{10}kg/s$. The water enters with a temperature of 24°and leaves with temperature 28°so the $\Delta T = 4°$. The total heat input (per unit second) is thus: $\frac{\Delta Q}{second} = \frac{m}{second}\ c_p\ \Delta T$ which is $6.03x10^{14}$ J/s. To express this is W/m^2, divide by the total area of the box: 181 W/m^2.