1. Complete the two-component system diagram of the fundamental negative feedback that prevents Earth’s climate from a runaway due to its positive feedbacks. Also describe how this negative feedback works in one sentence. (5 points)

![Two-component system diagram](image)

If the surface temperature increases, the outgoing longwave flux will increase too, and the imbalance in the net radiation ultimately cools the planet back towards the starting temperature.

2. Name three greenhouse gases and indicate whether they are natural, anthropogenic, or both (check both). (3 points)

<table>
<thead>
<tr>
<th>greenhouse gas</th>
<th>natural</th>
<th>anthropogenic</th>
</tr>
</thead>
<tbody>
<tr>
<td>carbon dioxide</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>water vapor</td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>CFC’s</td>
<td></td>
<td>X</td>
</tr>
</tbody>
</table>

3. Explain why an increase in low cloud cover surrounding the earth would increase the planetary albedo somewhat, yet not necessarily lower the surface temperature. (6 points)

Low clouds typically have a higher albedo than the surface, so they increase the planetary albedo. However, they also have a greenhouse effect — that is they absorb longwave and reemit longwave in all directions. Clouds warm the surface by emitting longwave radiation towards the surface. They also are colder than the surface, so they tend to lower the outgoing longwave radiation compared to cloud-free days.

4. Crudely sketch net radiation at the top of the atmosphere as a function of latitude on the axes provided. Give two examples of circulations that act to redistribute the heat among latitudes. (6 points)

![Net Radiative Flux graph](image)

**Hadley** and **Thermohaline**
5. What must the global net radiation at the top of the atmosphere be for the climate to be in equilibrium? (2 points) $0 \text{ Wm}^{-2}$

6. (a) What two forces are in balance for geostrophic flow (either wind or ocean current)? (2 points) Pressure gradient and Coriolis

(b) How is the geostrophic wind oriented relative to isobars (lines of constant pressure) on a weather map? (2 points) Circle one: parallel, from high to low pressure, OR from low to high pressure

7. Where in North America might one expect to find the greatest annual temperature range (i.e., summer high minus winter low)? (2 points) Circle one: Pacific Northwest, Midwest, Mississippi, OR California

8. Why are the surface winds in the midlatitudes of the Southern Hemisphere more zonal than in the Northern Hemisphere? (5 points)

   There is much less land in the SH to disrupt winds in three ways (you were required to give one to receive full credit) causing pressure gradients due to land-sea heating contrast in winter and summer, increasing friction, and mountains blocking.

9. Crudely sketch the average density profile of the ocean on the axes provided. In one sentence, explain how deep water can be formed at the surface and give one location where it happens. (6 points)

   Deep water is formed at the surface when density is increased to the point where the surface density is higher than the water below it down to depths of several km. This happens when water either cools and/or becomes more saline. Substantial cooling occurs when warm Atlantic waters from the gulf stream make their way into the northern North Atlantic. The Atlantic surface is already fairly high in salinity due to the salinity balance from evaporation, precipitation, runoff, and sea ice formation and transport. The high northern North Atlantic water is further made more dense by salt refection from sea ice formation in fall and winter. Deep water formation also occurs near the Antarctic continent where strong offshore winds blow sea ice away from the continent, causing unusually high ice production.
10. Draw and label arrows showing the direction of Ekman transport and the associated upwelling OR downwelling in the coastal setting below for the Northern Hemisphere. Explain the consequences on sea surface temperature and nutrients near the shore for this example. (in one sentence) (5 points)

![Ekman Transport Diagram](image)

Ekman transport to the right of the wind draws water away from the shore, which causes coastal upwelling of cool and nutrient rich deep water.

11. Sketch and briefly describe the sea surface temperature and the atmospheric circulation for a vertical cross section on the equator in the Pacific Ocean for (6 points)

(a) normal conditions

![Equatorial Circulation Diagram](image)

Persistent easterly trades blow equatorial surface waters westward creating a pool of warm water in the west. Coastal upwelling results along South America which maintains cooler sea surface temperature in the east. This sea surface temperature gradient creates a pressure gradient above that gives rise to the Walker circulation as shown.
(b) El Nino condition

El Nino is associated with a breakdown in the strength of the trade winds (may even change direction). This causes the warm pool to move towards the central Pacific. The Walker circulation shift eastward, and another convective cell occupies the western Pacific. The changes in pressure are known as the Southern Oscillation.