

Notes for First half of April

Daisy World, plankton thermoregulator, budgets of geophysical quantities, water cycle, desertification, sulfur budget, carbon budget, future carbon budget

1. James Lovelock, in trying to convey the idea of Gaia in the most fundamental form, invented *Daisy World* to illustrate the idea of planetary homeostatis. Consider a planet with two plant species, a white daisy that reflects sunlight pretty well, and a black daisy that absorbs sunlight pretty well. If we assume that the black daisies grow well at higher temperatures, and assume that it is getting warmer for some reason, then the black daisies will outcompete the white ones, absorb more sunlight, and the planet will quickly get so hot that neither white nor black daisy can survive. We have mistakenly designed a system where components provide positive feedbacks. (In evolutionary terms this system of two plants would fail; they'd become extinct. Later plants with the following properties may arise.) If we assume instead that the white daisies grow well at higher temperatures, then we have a stable system, with each flower type providing a negative feedback to climate change. If it gets hotter, white daisies will outgrow black daisies and reflect sunlight more, cooling the planet off. If it gets too cold, then the black daisies will grow better, absorb more sunlight, and warm things back up, and so on. This simple model illustrates the necessary duality of competition and cooperation inherent in life on earth. The plants compete with each other, but their overall behavior is cooperative, allowing them both to survive by mutual thermoregulation of their planet.

2. Phytoplankton as earth's thermostat. This theory is Gaian in nature, reminiscent of daisy world. It suggests that phytoplankton act as an important governor on planetary temperature changes, with negative feedbacks keeping temperatures from changing very much. Phytoplankton produce dimethyl sulfide (DMS), which evaporates into the air. Scientists believe that some of the air over the ocean is devoid of small particles required to condense raindrops and that DMS can provide the essential cloud condensation nuclei (CCN). If more sunlight reached the ocean, phytoplankton would produce more CCN and more clouds, shutting off the sunlight, thereby limiting phytoplankton growth. With reduced sunlight and less DMS production, few clouds would form and the sunlight would shine through again. Thus, any climate perturbation would be resisted by this mechanism, tending to maintain the status quo.

3. Budgets of geophysical quantities. In order to diagnose a trend and predict future amounts we need to know how much is in each part of the system (reservoirs; kg) and how much is flowing into (source) or out of (sink) each part of the system. Sources or sinks are both fluxes (kg/s). The "net flux" is the sum of sources and sinks. There is equilibrium for a reservoir if the sources = sinks (the net flux is zero). If not there will be a trend. It is sometimes hard to measure either a reservoir amount or a source or a sink, so we usually adopt a strategy of measuring what we can well and trying to infer the remaining quantities. One example is that we know how much fossil fuel we are burning

very accurately. This helps us ask the right questions about what part of the earth system to study for the carbon budget.

4. Sample budget: Eastern U.S. sulfur budget. Atmospheric sulfur loading is measured in $10^9 \text{ kg} = 10^{12} \text{ g} = 1 \text{ Tg} = 10^6 \text{ tons}$ (1 ton is about the mass of a car). Eastern U.S. emissions total $\sim 12 \text{ Tg/yr}$, while $\sim 8 \text{ Tg/yr}$ fall back to the ground as acid rain. This means that $\approx 4 \text{ Tg/yr}$ of acid rain is transported by winds out over the North Atlantic. About 2 Tg/yr then fall on the Atlantic and $\sim 2 \text{ Tg/yr}$ reaches Europe where it contributes to their acid rain problem. In comparison, only $\sim 0.2 \text{ Tg/yr}$ of sulfur are emitted from the ocean surface as a byproduct of phytoplankton metabolism.

5. Water cycle. Averaged over the globe for one year, the hydrologic cycle may be measured in fluxes of 10^3 km^3 water per year. 425 units evaporate from the ocean, while 385 units precipitate back into the ocean. The difference of 40 units must be how much is transported by air currents over the continents. 111 units precipitate onto the land, while 71 units are evaporated or evapotranspired. This difference of 40 units is supplied by these air motions bringing moisture from over the ocean. At the ground, the excess 40 units run off into the ocean, replacing the 40 units that were transported away from the ocean/atmosphere by air currents. Note the primary role that vegetation has in evapotranspiration over the land. If we cut down vegetation then less evapotranspiration would occur, so that less would be available to rain out again. A decreased precipitation would make it harder for plants to grow. This can lead to a positive feedback of increasing dryness and, in extreme cases, desertification. The residence time of water vapor in the atmosphere is roughly 1 week. Typically water falls and evaporates once or twice over North America before it falls on the ocean, while it may cycle 6 or 7 times over Amazonia. The globally averaged precipitation on land is 0.7 m/yr , while it is 1.6 m/yr over South America. This verifies the powerful water trapping power of tropical jungles.

6. Human influences on the water cycle. Worldwide water consumption has increased from $10^3 \text{ km}^3/\text{yr}$ in 1950 to about $6 \times 10^3 \text{ km}^3/\text{yr}$ in 2000. Per capita water consumption varies greatly among countries: $100 \text{ m}^3/\text{yr}$ in Ghana, $200 \text{ m}^3/\text{yr}$ in Jordan, $500 \text{ m}^3/\text{yr}$ in Switzerland, and $2,200 \text{ m}^3/\text{yr}$ in the U.S. The water used by people in Madison per year is about as much as the volume of Lake Mendota. This mainly includes diversion of water for cooling power plants, irrigation of crops to eat, and irrigation of crops to feed to animals that we eat. Wherever we divert rivers the local hydrologic cycle will change. Las Vegas is warmer at night because of extra evaporated surface water from manmade lakes, pools, fountains, and lawns. Due to diversion of the Amu Darya and Syr Darya rivers, the Aral Sea is shrinking, partly because it rains less there now, due to the decreased surface water. Nevada and Arizona may exercise their rights to obtain more of the Colorado river water. What will growers in California do? What will the whole Southwest region do if there is a prolonged drought? A leading theory for the rapid disappearance of the Mesa Verde culture is a prolonged drought, so that noone could grow food. The climate record indicates that droughts exceeding 3 years in a row occur there at least every century.

7. The Sahel desertification issue. Climate/vegetation zones are oriented east west in subtropic North Africa, including the Sahara desert north of about 20°N, grasslands beginning near 15°N, and the Sahel region of scattered bushes and grass in between. The sparse vegetation is maintained by summertime rains. The amount of evapotranspiration by plants contributes a great deal to atmospheric moisture. The band of thunderstorms across tropical Africa varies with the seasons, composing an east-west band of thunderstorms known as the Intertropical Convergence Zone (ITCZ). The latitude of the ITCZ tends to follow the sun, with rain most likely in the Sahel during northern summer. The problem is that a growing number of people are grazing their animals on sparse vegetation and using firewood, diminishing the evapotranspiration capability of the region. A positive feedback occurs starting with fewer plants, reduced evapotranspiration, less moisture available to help supply the “fuel” for thunderstorms at the farthest northern edge of the thunderstorms, so they don’t get as far north, it becomes drier, stressing the plants further. During the Hypsithermal 4-8 kybp, intense northern summer sunlight tended to coincide with much more vegetation in what is now the Sahara desert. This configuration favored monsoon rains penetrating farther into Africa. It would be tempting to extrapolate from that situation and try to apply it to a doubled CO₂ scenario. However, it is not at all clear that a 200-400% increase in atmospheric carbon dioxide would have a similar effect. Numerical simulations of future climate give a broad range in changes for soil moisture. Most models suggest global drying of soil moisture with an increase in greenhouse gases.

8. Global carbon budget and (*The Missing Carbon Sink Problem*).

Studying the global carbon budget may seem like a dry exercise. Yet the element carbon is central to our studies of the greenhouse effect and climate change, is a measure of the health of our land and ocean biosphere, and measures our energy supply from fossil fuels. We measure carbon in a reservoir in terms of 10^{12} kg = 10^{15} g = 1 Pg (petagram) = 10^9 tons = 1 Gt (gigaton).

We know the atmospheric reservoir quite well: 365 ppmv CO₂. Since there are 12 kg C in 44 kg of CO₂, the atomic weight of air is 29.5 kg/kmole, and there are 5×10^{18} kg of air in the atmosphere, there are thus 740 Gt of carbon in the atmosphere. We further know the trend in the atmospheric reservoir: 1.5 ppmv/yr = 0.4%/yr = 3 Gt C/yr. But when we attempt to carefully account for the fluxes between the atmosphere and other reservoirs we estimate that the atmospheric reservoir ought to be increasing by 6 Gt C/yr. This means that our understanding of the global carbon budget, and all that it implies, is rather poor: we are off by a factor of two, undermining confidence in forecasting future CO₂ trends.

The fluxes between various carbon reservoirs are as follows. Let a flux into the atmospheric reservoir be defined as a positive flux. The reservoir amounts are: land biosphere = 2,100 Gt; fossil fuels = 7,500 Gt; ocean = 38,000 Gt; sediments = 20,000,000 Gt. The land biosphere is estimated to cause -120 Gt/yr from photosynthesis sucking up CO₂, +120 Gt/yr in carrying out respiration, and +2 Gt/yr from deforestation, yielding a net flux of +2 Gt/yr from the land biosphere. The ocean biosphere is estimated to cause

-107 Gt/yr from photosynthesis, +105 Gt/yr from respiration, for a net flux of -2 Gt/yr. Phytoplankton fix carbon into their cells. When they die they settle to the bottom of the ocean, where they are buried in sediment. This “biological pump” sequesters carbon in ocean sediments, leaving the upper ocean depleted in dissolved CO₂, so the ocean takes up 2 Gt/yr of carbon from the atmosphere. Note that the biosphere is essential for uptake of carbon from the atmosphere. We burn +5 Gt/yr of fossil fuels and produce +1 Gt/yr by making cement worldwide! The net flux into the atmosphere is +6 Gt/yr, twice what the observed rate of increase is for the atmospheric reservoir.

Since we probably can't measure uptake into the boreal forest or global ocean with more than about 20% accuracy, this is probably where the uncertainties lie. Factors affecting the local flux of carbon into the ocean include temperature, mixing with fresh river inflow, history of primary productivity, and upwelling. In warmer waters the carbon dioxide flux is into the air! Other factors such as ENSO or a volcanic eruption will influence the global carbon budget. When tropical temperatures are warmer during El Nino, atmospheric carbon increases. After an eruption the rate of increase of atmospheric carbon slows. This may reflect the strong control of temperature on the respiration rate of soil organisms: reduced after a cooling eruption, increased when it's warm.

9. Future carbon budgets. Do we understand the carbon budget well enough to conscientiously interfere in countries undergoing significant tropical deforestation? Do we understand how changes in the earth system in a greenhouse warming scenario might affect the carbon budget? For example, will warmer sea surface temperatures make it harder for the ocean to take up CO₂?

It is worth noting what we know about the ocean regarding delaying the onset of global warming and prolonging its effects once it begins. This problem can be easily understood in terms of the *residence time* = reservoir amount / flux out of that reservoir. The atmosphere has 740 Gt C and the total flux out is 227 Gt/yr, giving a mean residence time for carbon in the atmosphere of 3 years. For the living land biosphere it is 9 yr, for the dead part (soil litter) it is 25 yr. The surface layer of the ocean has a carbon residence time of 6 yr, but the deep ocean has a carbon residence time of ~350 yr. Let's assume that CO₂ doubles by the year 2100, whereupon we stop burning fossil fuels. Until that time there will be a net flux of CO₂ into the oceans out of the overburdened atmosphere. So the oceans will “buffer” atmospheric loading for a while, delaying the maximum concentration of CO₂. But it will possibly take centuries for the elevated, huge amounts of oceanic carbon to come out of the oceans back into the atmosphere. Thus, a substantial

10. Greenhouse warming issues. Robust changes expected from increased anthropogenic greenhouse gas loading include: 1) colder stratosphere and mesosphere (already occurring), 2) global temperature should go up by 3 K in this century, poles up by 10 K (0.7 K so far), 3) warmer nights (already occurring), 4) sea level rise by 0.5-1.0 m (already up 0.1 m), 5) changes in rainfall patterns, 6) more and more powerful hurricanes, 6) challenges to plant migration, 7) increased incidence of global change related diseases. Overall, more high

clouds would help warm the planet (IR trapping is large, solar reflection is small), while more low clouds would cool the planet (weak IR trapping, but a lot of reflected solar). It is the uncertainty with respect to future cloud distributions that is at the root of current political debate. Most atmospheric scientists believe that there will be more high clouds, exacerbating the problem, but our lack of certainty makes it hard to establish firm public policy.

11. Land, water, energy. Here is a summary for you personally. You use 2500 m³ of water per year, mostly for cooling power plants and irrigation for crops or for crops to feed animals that you eat. Your fair share of existing agricultural land is about 1/2 a football field, which is just capable of growing enough food to keep you alive, as you glow in the infrared with as much power as a 100 W lightbulb. Vegetarianism is a globally conscientious choice regarding land use, water use, and energy use, since 7 times more land and water are used to produce 2000 kcal of meat compared to 2000 kcal of plant food. You use 10,000 W of energy all of the time, which is 100 times the energy content of your food. You are part of the USA which has only 5% of the world's population, but uses 25% of the world's energy. Altogether on this planet, people directly use or appropriate 40% of the land's net primary productivity, (NPP being defined as the amount of energy captured from the sun by photosynthetic organisms, minus the amount those organisms use themselves). It would be hard for this planet to support twice as many people.