Coupling & Feedback in Climate (BBB – 10/3/13)

I. Time Dependence

   Constant behavior: \( \frac{dT}{dt} = 0 \)
   \( T(t) = a. \)

   Linear behavior: \( \frac{dT}{dt} = a, \)
   \( T(t) = T_0 + at. \)

   Nonlinear behaviors and responses:

   Exponential: \( \frac{dT}{dt} = kT, \)
   \( T(t) = T_0 \exp(kt). \)

   SHM (Sinusoidal): \( \frac{d^2T}{dt^2} = -\omega_0^2T, \)
   \( T(t) = T_0 \cos(\omega_0 t + \phi). \)

   Damped harmonic motion, \( \frac{d^2T}{dt^2} + a \frac{dT}{dt} + \omega_0^2T = 0, \)
   \( T(t) = T_0 \exp(-bt/2) \cos(\omega_0 t + \phi). \)

   Forced damped motion, \( \frac{d^2T}{dt^2} + a \frac{dT}{dt} + \omega_0^2T = F_{\text{external}}, \)
   \( T(t) = T_0 \cos(\omega_{\text{forced}} t + \phi). \)

II. Coupling: Coupling implies that a change in one part of a system produces a change in another part of that same system. In a system with a network of couplings, a change in a variable can produce a change in that same variable. For example, an increase in Earth’s surface temperature increases evaporation from the ocean. This in turn increases the amount of cloud cover that, in turn, reflects more of the incident visible radiation from the sun. That loss of radiation decreases the temperature of the surface of the earth. That is, a change in temperature, for whatever reason, produces a further change in the same variable, here temperature. This effect is called feedback. Thus, a series of couplings can produce feedback.

   An Example: Atmosphere-Ocean coupling. The ocean and atmosphere are tightly coupled through a number of mechanisms. Uneven heating of the atmosphere produces wind that couples to the ocean driving large scale ocean circulation. Also, ocean evaporation puts more latent heat into the atmosphere. The ocean also redistributes heat and fresh water from one part of the Earth’s surface to another, greatly influencing the corresponding temperature behavior of the atmosphere. Moreover, oceans store heat on several time scales, delivering it back to surface. Deep ocean circulation has time scale of ~750 years. In addition, CO\(_2\) is absorbed by the ocean marine biology provides a number of feedback loops that we discuss below under "Biology."

III. Feedback and Stability: Feedback mechanisms allow the change in a quantity to produce a corresponding change in the same quantity. Positive feedback means that a change in a quantity produces an additional change in that quantity in the same direction. Negative feedback means that a change in a quantity produces a change in the opposite direction. Whereas negative feedback often leads to stability (e.g. - when the temperature in a home rises, the thermostat mechanism provides negative feedback by reducing the temperature, turning off the furnace.), positive feedback can lead to instability (an increase in the number of contagious flu cases leads to additional exposures and hence to additional cases of flu). Exponential growth of a population can be viewed as a form of positive feedback. Babies born leads to the eventual increase in number of parents and to additional babies born...

IV. Feedback examples involving global temperature:

   Positive Feedback: \{can lead to instability\}
   1.) \( +\Delta T \rightarrow \) more evaporation of sea water \( \rightarrow \) more greenhouse gas \( \rightarrow +\Delta T. \)
   2.) \( +\Delta T \rightarrow \) more organic decay \( \rightarrow \) more CO\(_2\) \( \rightarrow +\Delta T. \)
   3.) \( +\Delta T \rightarrow \) melts snow on glaciers and ice caps \( \rightarrow \) darker surface with smaller albedo \( \rightarrow +\Delta T. \)
   4.) \( +\Delta T \rightarrow \) ocean holds less gaseous CO\(_2\) \( \rightarrow \) release of more CO\(_2\) into the atmosphere \( \rightarrow +\Delta T. \)
**Negative Feedback:** {can help to maintain stability}
1.) $\Delta T \rightarrow$ more evaporation of sea water $\rightarrow$ more clouds $\rightarrow$ reflected sunlight $\rightarrow$ larger albedo $\rightarrow$ - $\Delta T$.
2.) More atmospheric CO$_2$ $\rightarrow$ more crop growth $\rightarrow$ carbon sink or storage $\rightarrow$ less atmospheric CO$_2$.
3.) More CO$_2$ from burning coal $\rightarrow$ $+\Delta T$ $\rightarrow$ more SO$_2$ from sulfur in coal $\rightarrow$ SO$_2$ reflects visible light $\rightarrow$ greater albedo $\rightarrow$ - $\Delta T$.
4.) $+\Delta T$ $\rightarrow$ increase in Stefan Boltzmann Radiation $(P=\varepsilon\sigma AT^4) \rightarrow - \Delta T$.
5.) - $\Delta T$ $\rightarrow$ build-up of glaciers $\rightarrow$ drop in ocean level $\rightarrow$ reduced pressure on methane hydrates $\rightarrow$ released greenhouse gas CH$_4$ $\rightarrow$ $+\Delta T$.
6.) $+\Delta T$ $\rightarrow$ glacial melt $\rightarrow$ fresh water in N. Atlantic $\rightarrow$ slowed thermohaline circulation (Gulf Stream) $\rightarrow$ - $\Delta T$.

**Ambiguous Feedback:**
1.) $+\Delta T$ $\rightarrow$ melting ice $\rightarrow$ darker surface with lower albedo $\rightarrow$ $+\Delta T$, but more open water $\rightarrow$ more water vapor $\rightarrow$ cloud + fog $\rightarrow$ - $\Delta T$.
2.) $+\Delta T$ $\rightarrow$ change in biology of system $\rightarrow$ new surface albedo $\rightarrow$ new evapotranspiration $\rightarrow$ new roughness $\rightarrow$ new wind $\rightarrow$ new ocean current driver $\rightarrow$ +/- $\Delta T$.

**Feedback examples with biological component:**
1.) **Biopump Feedback:** (positive feedback plankton multiplier). In winter/spring the surface ocean water cools $\rightarrow$ thermal instability with cold above warm $\rightarrow$ convection, cycling of nutrient rich water to surface $\rightarrow$ spring bloom in sunlight. During an ice age $\rightarrow$ greater biological plant activity in oceans because of colder surface and more convection $\rightarrow$ more CO$_2$ absorbed from atmosphere $\rightarrow$ lower CO$_2$ level in atmosphere $\rightarrow$ cool atmosphere $\rightarrow$ greater ocean surface cooling $\rightarrow$ further drop in temperature $\rightarrow$ further increase in bio activity $\rightarrow$ more ocean plankton.
2.) **CO2 Fertilization** (negative feedback): More CO$_2$ in atmosphere $\rightarrow$ faster plant growth $\rightarrow$ removal of CO$_2$ from atmosphere.
3.) **Soil Effects** (positive feedback): $+\Delta T$ $\rightarrow$ more microbial activity in soil $\rightarrow$ more CO$_2$ $\rightarrow$ $+\Delta T$
4.) **Forest Dieback** (positive feedback): $+\Delta T$ $\rightarrow$ rapid change in forest environment $\rightarrow$ forest dieback $\rightarrow$ release of sequestered CO$_2$ $\rightarrow$ $+\Delta T$
5.) **Wetlands Effects** (positive feedback): $+\Delta T$ $\rightarrow$ increase in methane in wetlands $\rightarrow$ added greenhouse gas $\rightarrow$ $+\Delta T$

**Feedback from Methane Hydrates** (possible Ice Age switching mechanism)
- $\Delta T$ $\rightarrow$ additional ice formed $\rightarrow$ ocean level drops $\rightarrow$ methane hydrate melt as pressure rises $\rightarrow$ methane released (suddenly?) $\rightarrow$ GHG increase $\rightarrow$ $+\Delta T$. If rapid enough, this release could account for switching from one glacial mode to another, ice age to interglacial for example.

**Feedback and Ocean Circulation:** (possible Ice Age switching mechanism)
**Thermal drive:** heavy cold water sinks at poles $\rightarrow$ bottom flow, heated at equator $\rightarrow$ lighter water rises at equator $\rightarrow$ a conveyor belt for transport of heat energy to poles that drives the Gulf Stream. This is an example of negative feedback because $+\Delta T$ global warming $\rightarrow$ larger polar warming $\rightarrow$ polar ice melt $\rightarrow$ warm (light) fresh water introduced at poles $\rightarrow$ surface flow to equator weakens Gulf Stream $\rightarrow$ potential reduction of Gulf Stream flow $\rightarrow$ snow & ice buildup in polar regions $\rightarrow$ albedo change $\rightarrow$ - $\Delta T$. 
Saline drive: Warm water on surface evaporates as it travels pole-ward becoming saltier (heavier) water → it sinks near poles → helps drive the Gulf Stream.

V. Natural External Climate Driving Forcings

The Milankovitch Cycles: Milankovitch has 3 major time periods:

* Precession of the Earth's axis about its orbital normal (~21,000 years). At present, the axis tilts toward the sun on about January 1.
* Obliquity angle oscillation (~41,000 years). The angle is presently 23.5° with a range of 22.1 to 24.5 degrees to vertical.
* Eccentricity: The Earth's orbit varies from an eccentricity e of 0.005 to 0.060 (~105,000 years). Its present value is close to the minimum value of 0.005.

Solar Activity: The insolation from the sun, presently ($I_0 = \sim 1365 \text{W/m}^2$) varies with a 9 to 13 year solar cycle and at present has a longer increasing component of some 0.36%/century.

Volcanic Activity: Adding particulate matter (aerosols) to the atmosphere changes the albedo (whiteness or reflectivity of the earth's atmosphere). Volcanic activity leads to a reduced solar intensity at surface level for a period of several months after a volcano eruption.

VI. Anthropogenic (Human) Climate Driving Forces

Greenhouse gases (GHG): GHGs added to the atmosphere from human activity includes CO$_2$, CH$_4$, O$_3$, CFC's, N$_2$O, etc.

Particulate matter: The amount of sunlight reaching the surface of the Earth is influenced by both black (absorbing) soot and white (reflecting) cloudlike soot, and by particulates that serve as nucleation sites for water droplets.

SO$_2$: Sulfur dioxide molecules are hygroscopic. They attract water molecules increasing their effective size. The water droplets formed increase the albedo (reflectivity) of the atmosphere with a consequent reduction in visible energy reaching the Earth's surface.

VII. Time Lags and Hysteresis: The highly coupled world system has substantial physical memory. For example, the specific heat of water gives the ocean a long temperature memory. That is, the response of the system is often delayed. It lags behind the forcing mechanism. In the case of recent increases in global surface temperature, the fact that the ocean has large reservoirs of water with cycle times of order 1000 years gives the system this temperature memory. For example, the ocean cooling resulting from the eruption of a large volcano with its increase in particulates and SO$_2$ is delayed by the thermal memory of the ocean. Hysteresis (from the same route word as history) refers to the influence of the recent history of a system on its response to a forcing event. The ocean-atmosphere system, as a whole, exhibits hysteresis.

Examples of Hysteresis:

Polar ice: The ice volume of polar ice over Greenland and Antarctica is sufficient to delay temperature change on time scales comparable to the Milankovitch cycles (21,000 yr precession, 40,000 yr tilt, 105,000 yr orbit eccentricity). The time for ice to build up (accretion time ~40,000 years) is greater than melt time (~10,000 years). It is this difference that helps to explain why Milankovitch periods of small seasonal temperature variability are also favorable for the buildup of continental ice and the maintenance of an ice age. Periods of large seasonal temperature variation tend to result in the net melting of continental ice.
**Isostatic uplift:** The Earth’s crust of bedrock subsides under the weight of continental ice during an ice age. During an interglacial period, after the ice melts, the crust rises slowly. Continental rise continues for ~10,000 years after ice melt. The British Isles continue to rise as a result of ice removed more than 10,000 years ago.

**Reduction of CO\textsubscript{2} from weathering:** The weathering of calcium carbonates and calcium silicates from isostatic uplift consumes CO\textsubscript{2}, reducing the GHG level, and providing a negative feedback mechanism to the melting of ice at the end of an ice age. This tends to decrease the effects of the 20,000 year variation created by the Milankovitch precession cycle.

**CO\textsubscript{2} buildup:** Ice volume decreases lag behind CO\textsubscript{2} buildup by 3000 years. Meanwhile, CO\textsubscript{2} buildup lags behind Milankovitch increases in I\textsubscript{0} by about 5000 years. Adding hysteresis of polar ice sheets, isostatic uplift, and CO\textsubscript{2} to Milankovitch models really helps in explaining past temperature behaviors.

**VIII. One of many interesting puzzles:** For the last 800,000 years the 100,000 year cycle seems to have dominated the temperature profile. (See $\delta^{18}$ from foraminifera). **Why?** Is there some phenomenon that enhances the impact of these longer cycles in I\textsubscript{0}? Is there a phase locking among the three Milankovitch cycles? From about 2.8M to 0.8M years ago temperatures varied with a 40,000 year period. Did the switch from 40,000 year cycles to 100,000 year cycles, starting some 800,000 years ago, have to do with the dropping of CO\textsubscript{2} levels below a critical threshold?

**IX. Why we need GCMs:** The CO\textsubscript{2} and global warming relationship is tricky and sometimes counterintuitive. Here are two logical arguments that tend to cancel. Adding more CO\textsubscript{2} to the atmosphere may produce less new absorption of infrared than you expect because most of the infrared radiation from the earth is already absorbed. This would lead to less global warming than expected as you increase atmospheric CO\textsubscript{2}. However, as the ocean absorbs CO\textsubscript{2} it begins to saturate, absorbing less atmospheric CO\textsubscript{2} than before. This leaves more CO\textsubscript{2} in the atmosphere increasing global warming more than expected.

****** End of Oct. 3, 2013 version ******