Astrodynamics

ASD4: Orbital Perturbations

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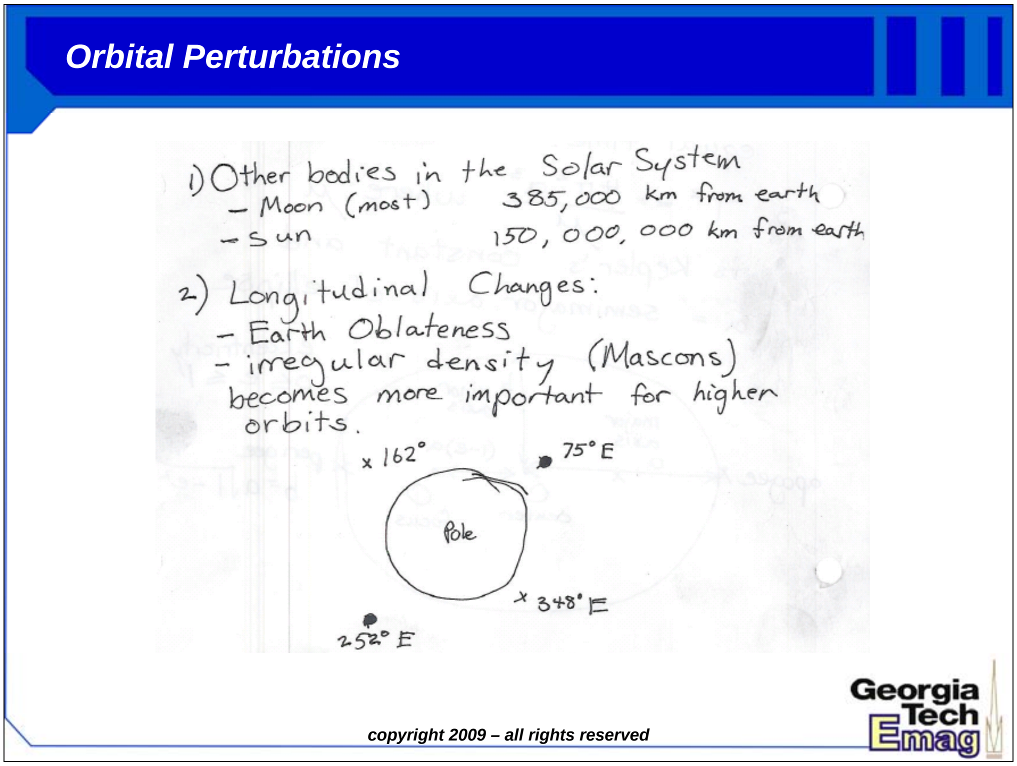
In our studies of Astrodynamics, everything has been an ideal 2-body system that behaves with simple elliptical geometry. In this unit, we cover several non-ideal mechanisms that distort our otherwise ideal analysis.

Note that we will not cover this topic in rigorous quantitative detail – orbital perturbations can require a lifetime of study and falls under the specialty of aerospace engineers and space mission planners. However, as electrical engineers, we need to be aware of these phenomena. While they do not dramatically alter flight paths or distances (and our primary areas of design impacted by these: RF communications links and look angles), orbital perturbations provide some secondary design considerations that may influence mission lifetime and other system attributes.

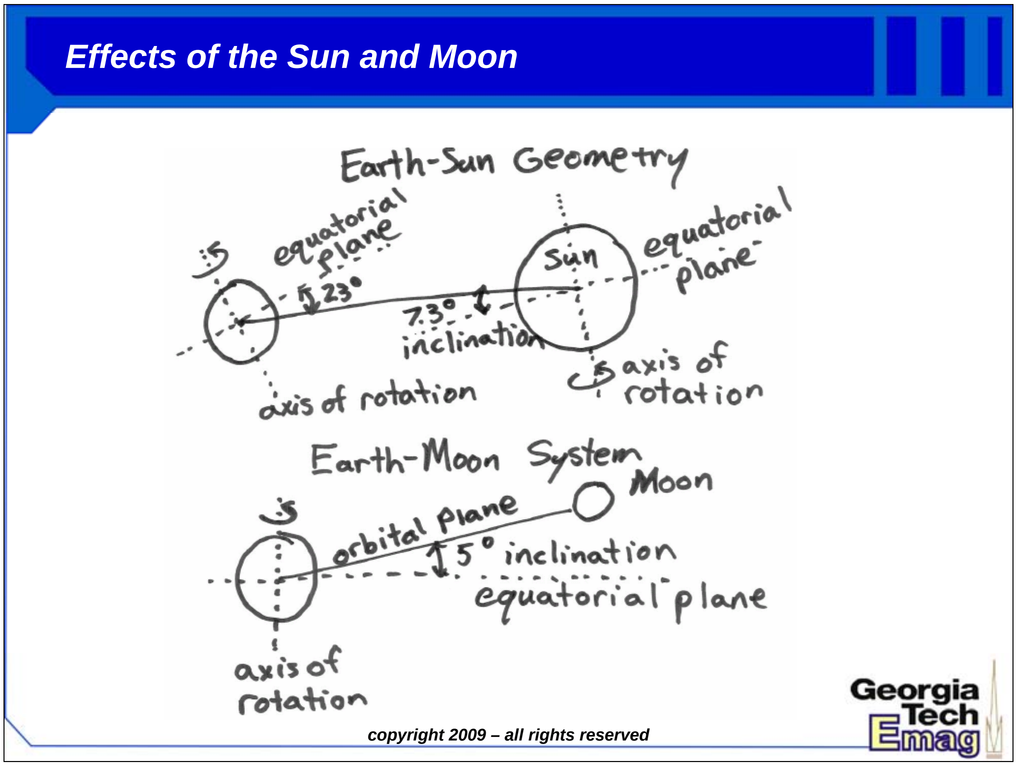


The biggest source of error in our analysis will be introduced by adding a third body to our orbital system. In fact, our entire system of mathematics does extraordinarily well for describing 2-body problems; the introduction of a third body rapidly unravels the nice analytic solutions and ideal ellipses that we have used thus far. Our best recourse is to approximate the system as a 2-body problem and then use numerical analysis to correct the fine details of our plans.

Although every body on the solar system provides a non-zero force acting on our earth-orbit satellites, two bodies dominate when computing earth orbit perturbations. The moon, by virtue of its close proximity, introduces the most irregularities; the sun, by virtue of its extraordinary mass, introduces the second-most irregularities.

Another more subtle disturbance is introduced by the non-ideal shape and density of the earth. Our planet is technically not a sphere – it is an oblate spheroid (i.e. eggplant). There are also regions of higher mass (India) and higher density called mascons that also introduce irregularities. These two attributes breaks the orbital system symmetry; otherwise, we could have treated the earth as if it were a super-massive point source and the gravitational answers we compute would be the same. Instead, this type of calculation is approximate and there will be tiny forces that tug in a variety of directions on the satellite that will, over time, distort the orbit.

These effects are most critical for geostationary satellites, which take relatively little force-over-time to “tug” them out of their fixed-sky position. In fact, there are two unstable points that, if left uncorrected, slowly repel GEO satellites. There are two other stable points that slowly attract GEO satellites. As a result, every GEO satellite is required to save enough fuel so that it may boost itself an extra 200 km into a “graveyard” orbit at the end of its lifetime. Otherwise, over the centuries, a pair of small GEO “trash stars” will develop over time at the two stable points.



The influence of the sun and moon on an earth orbit satellite (now a 4-body problem) is even more complicated by the fact that each orbiting system has an irregular inclination. The earth about the sun is inclined 7.3 degrees with respect to the sun's equator. The moon's orbit is inclined 5 degrees with respect to the earth's equator, which itself is tilted with respect to the plane of the sun-earth orbit by 23 degrees. Thus there are a full complement of 3D perturbations on the elliptical orbits that act over time.

Orbital Forcing

- Cycles of orbital perturbation on Earth's orbit around the sun
- Largely due to Jupiter, although other planets contribute slightly
- Influences long-term climate (Milankovitch cycles)
- Main results of orbital forcing
  - Eccentricity variations
  - Precession variations
  - Obliquity variations
  - Inclination variations

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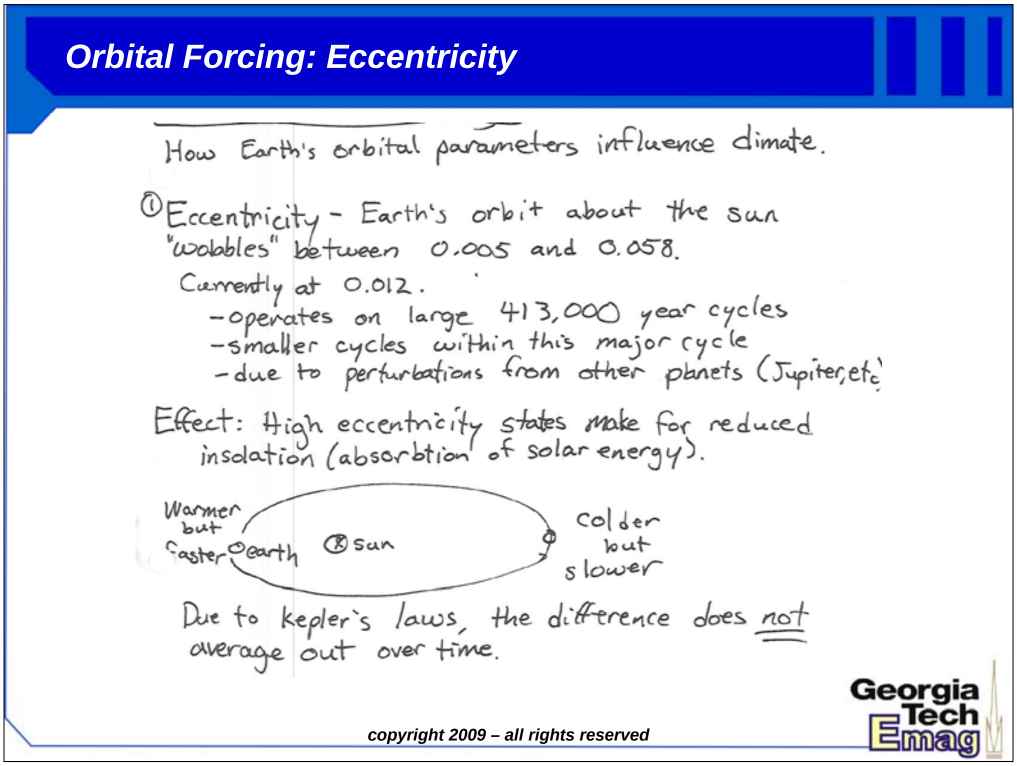
We will summarize and demonstrate some of the orbital perturbations by illustrating different mechanisms and results by which the earth's very own orbit around the sun is influenced by the pull of other solar system planets (most prominently Jupiter). This field of study is called orbital forcing and can have a dramatic effect on earth climate over time, providing predictive models for ice ages and interglacial periods on earth when ice-cover recedes and advances.

So not only does this topic neatly summarize non-ideal effects of multi-body orbital systems, which is applicable to any orbiting system, but the topic is also germane to the discussion of climate change issues which is a hot topic today. In fact, one of the most important areas of research and engineering development is the design of climate-surveying satellites that monitor climate change on earth for making informed decisions on environmental policies. It is important for engineers, who develop a keen sense for the relationship between business and science as well as an understanding of secondary and tertiary consequences of technical policy decisions, to be informed on planetary dynamics and climate change. Engineers are much less likely than pure scientists or lawyers to advocate a solution that is 30 dB more economically destructive to humanity than the actual problem.

Solar system dynamics are very complicated. We will concentrate on just 4 aspects of orbital forcing on earth and its climate: variations on eccentricity, precession, obliquity, and inclination.

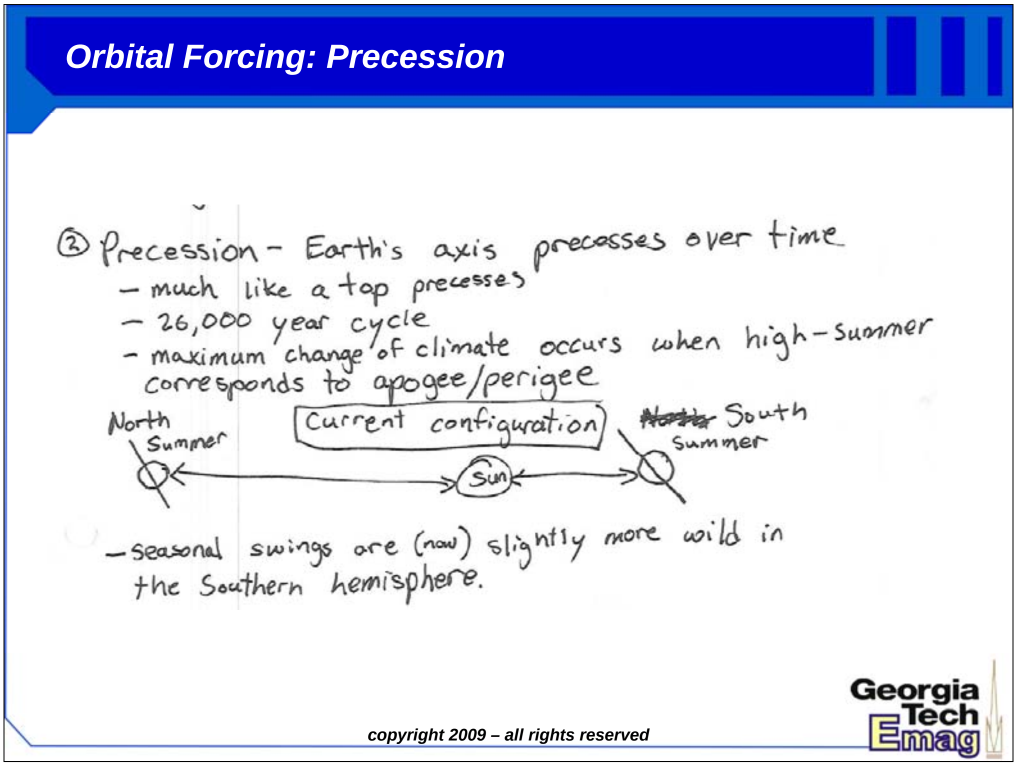


The earth's orbit about the sun is not exactly circular; furthermore, its eccentricity will vary slightly over time due to the influence of other planets. The variation is between e=0.005 and 0.058, which occurs over 413,000 year cycles, which smaller variations within this major cycle.

Clearly, the planet receives more insolation (level of sunlight and energy from the sun) at perihelion than at aphelion. As eccentricity increases, the perihelion portion of the orbit becomes warmer and the aphelion becomes cooler. Now, we might at first expect this to be relatively inconsequential as long as the average radial distance remains the same. After all, if aphelion gets a little farther from the sun, that implies that perihelion gets a little closer; the disparity of insolation on opposite ends of the orbit should cancel.

There is only partial cancellation, however, due to a temporal asymmetry introduced by Kepler's second law. While it's true that the insolation changes at aphelion and perihelion do mostly cancel, the earth will travel through the warmer part of its orbit (on the perihelion side) faster than the colder part of its orbit (on the aphelion side). The net effect is that the planet cools.

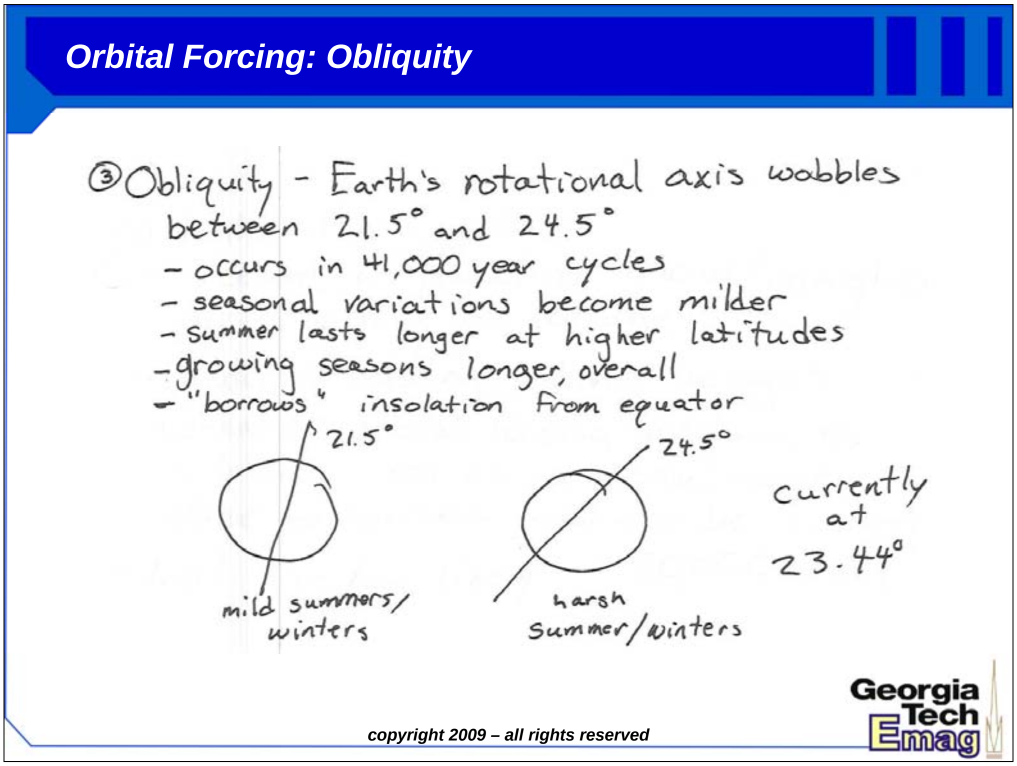
Current eccentricity of the earth about the sun is 0.012 – definitely on the warmer side of eccentricity variations.



The Earth's precession about its axis of rotation also has an interesting effect when taken into account with its orbital eccentricity. The earth's off-axis tilt of 23 degrees itself spins around slowly over time; it undergoes precession just as the central axis of a top spinning on a table slowly wobbles at a rate much slower than its actual rate of rotation. The earth experiences precession in 26,000 year cycles.

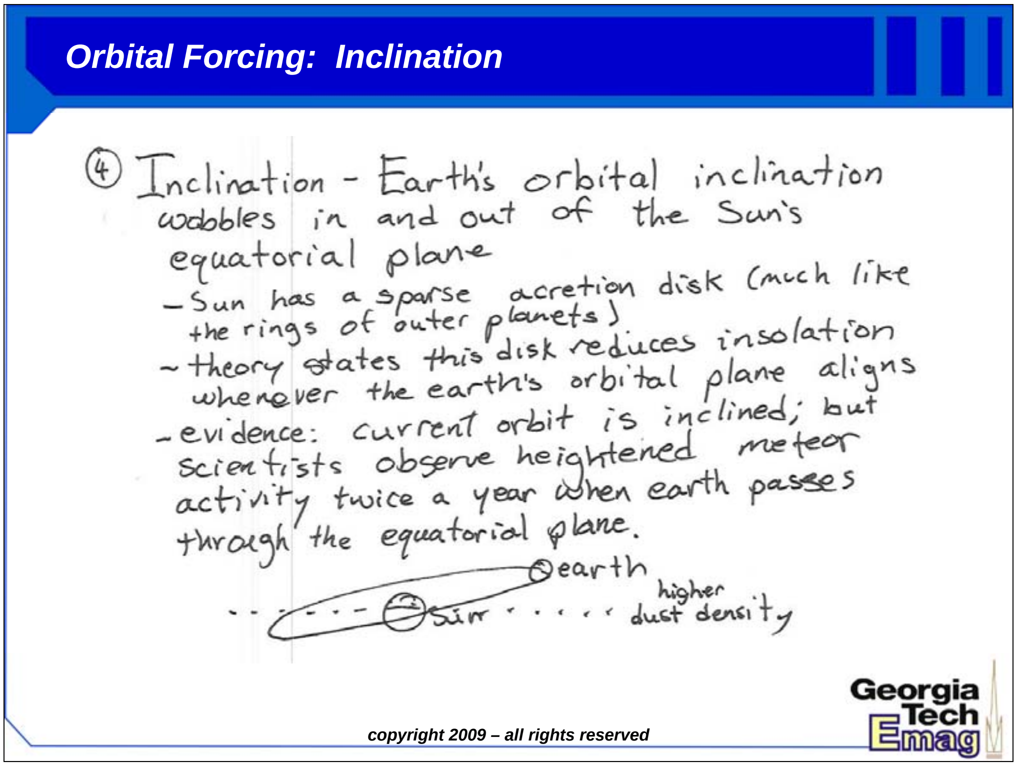
One consequence of precession, when considered alongside eccentricity, is that some phases of precession place a hemisphere's summer at perihelion and its winter at aphelion, which generally exaggerates the extremes of seasons. Currently, this occurs for the southern hemisphere. Under this configuration, the southern hemisphere experiences more wildly varying seasons since its summer is slightly warmer and its winter is slightly cooler. Although "harshness of seasons" is a difficult thing to quantify, it is generally accepted that southern hemispherical climate is more extreme than in the north.

At first blush, this effect may appear to be a wash. Would we expect there to be no net effect on planetary climate? Actually, no, because there is much more land mass (and ability to collect and retain winter ice) in the northern hemisphere and much more ocean mass in the southern hemisphere. If winters are more severe in the northern hemisphere, there is a greater risk (all other factors kept the same) of pushing the earth into a semistable "white earth" state. Under this condition, large portions of the earth that collect ice and snow also increase the reflectivity of the earth and minimize net insolation; the amount of reflectance is called albedo. Under many climate computer models, the earth slips into a reinforcing cooling state where snow and ice reduce insolation, which in turn leads to less melting of ice and snow, which reduces insolation and so forth. An unusually bad Northern hemisphere winter can be the prelude to a glacial period that could even turn into an ice age.



Related to precession is the change in the physical earth axis of rotation itself (the obliquity of rotation). Historically, scientists estimate that the earth's axis changes obliquity between 21.5 and 24.5 degrees over a cycle that lasts about 41,000 years. Our current geological epoch places us in the middle of these extremes at 23.44 degrees.

As obliquity increases, seasonal variations become more severe across the planet as higher latitudes receive more insolation in the summer and less in the winter. The seasons are overdriven, resulting in harsher winters (potential for more albedo) as well as longer growing seasons for plants.



Another consequence of orbital forcing is the oscillation of the earth's angle of inclination about the sun. The period of this phenomenon is not well understood, but scientists do know that the inclination will wobble above and below the mean plane of our solar system.

This may also influence climate as well. Why? Scientists speculate that the sun, like all of the gas giants in our solar system, contains an accretion disk of dust particles in its rotational plane. This is a natural consequence of having left over dust and particles after star or planetary formation. The most dramatic example of an accretion disk is responsible for the rings of Saturn, although all gas giants in our solar system have this disk and even faint rings of their own. The earth currently has 7 degrees of inclination and, twice a year, passes through the plane of the solar system. During this phase, observed meteor activity always increases. Thus, there is anecdotal evidence of this accretion disk.

The implication is that, when the inclination of the earth approaches zero, it spends all of its time in the accretion disk. Although the particle density around the sun is quite low, all sunlight travels through 150 million miles of this particulate matter, possibly reducing the net insolation on earth. The planet's climate would cool during this period.

Milankovitch Cycles

Milankovitch cycles - predicts climate changes (ice ages, glacial, inter-glacial periods) based on these orbital forcing mechanisms.

Milankovitch Cycles
- excellent at predicting glacial/interglacial periods within an ice age
- predicts entering/leaving ice ages whenever orbital forcing mechanisms re-inforce; not as successful - some other mechanisms must also be involved.
- Next Ice Age likely in 50,000 years.

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These many different orbital forcing mechanisms can add constructively or destructively cancel to result in a net warming or cooling trend on earth. The synthesis of these collective effects results in a set of Milankovitch cycles, which does well (but not perfectly) at predicting interglacials and the start and end of ice ages.

We should note that the current geological epoch appears to be naturally warmer than most in recent earth history. The next ice age should not appear for at least 50,000 years. While I do not advocate indiscriminate belching of pollutants into the atmosphere, it is interesting to ponder how a future civilization of humans 50,000 years might regards us. They might refer to us as "those self-absorbed people in the 21st century that were always trying to minimize or even sequester their greenhouse gases."

Note, while none of this discussion is meant to provide ammunition to either side of the climate change debate, one thing should be abundantly clear: there is no such thing as a "planetary balance" in climate. Earth climate has been chaotically varying between some rough bounds ever since the beginning of time. The orbital forcing mechanisms discussed here operate over centuries and millennia and could not be responsible for trends observed over decades. (There are extra-planetary factors, such as solar radiation cycles, that do contribute over this scale of time.) If anything, I hope the student appreciates how extraordinarily complicated planetary climate dynamics truly are … and that a healthy respect be afforded to the degree which man can and should try to "change" climate.