If you can't predict the weather, how can you predict the climate?

A laboratory experiment from the Little Shop of Physics at Colorado State University

Overview

This is a very good question. Here's the one word answer: Chaos.

Necessary materials:

- Calculator

You can also do this exercise with a computer running a spreadsheet.

Theory

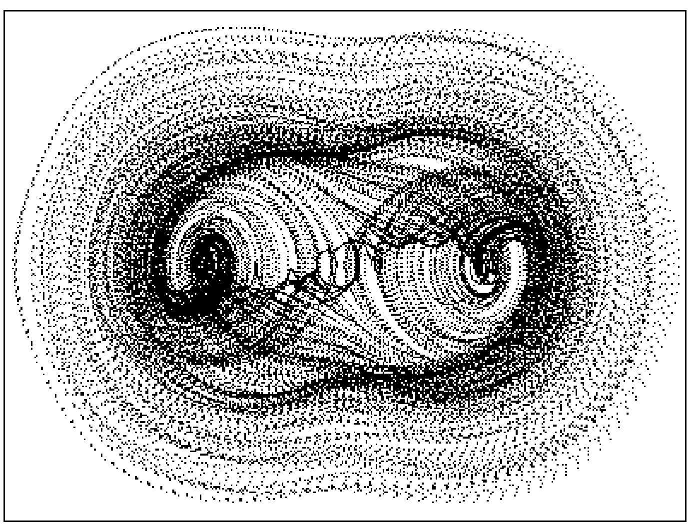
Contrary to popular usage, "chaos" doesn't mean randomness. Systems—like the atmosphere—that are chaotic are unpredictable in some ways but follow certain well-defined patterns. This is the essence of chaos, and rather than trying to explain this seeming contradiction, it's easier to just explore a system that seems like it should be quite regular but is actually chaotic.

Doing the Experiment

We are going to compute successive values of an iterative equation—one in which you use one value to compute the next value. Here's the equation we use:

$$x_{n+1} = (1 - x_n)(x_n)\lambda$$

λ is a parameter that can be varied. We are going to use 3.87 here. We are going to compute successive values with a calculator. To simplify, we have a recipe that tells how to compute these values:



This is a graph of the velocity (vertical axis) vs. the position (horizontal axis) of a pendulum undergoing chaotic motion.

1) Pick a value for the parameter for the equation.

1) Take your starting value. We'll call this x_1. Press STO on the calculator to put it into memory.

2) Now, we need to compute the next value, x_2. Press the following keys:

- 1-RCL= (compute 1-x_n)
- ×RCL= (multiply by x_n)
- ×3.87= (multiply by 3.87)
- STO (put the result in memory for the next round)

3) Record the value and do Step 2 again.

And just keep doing Steps 2 and 3.

The big question is this: What do the results mean? Here are two trends to notice:

- Each value seems random, but there are trends. In particular, notice the “high, low, medium” sets of values. You’ll often—but not always—see this type of trend.
- Small changes in this initial value don’t make much difference in the initial rounds, but make a big difference later. That’s “sensitivity to initial conditions,” one of the hallmarks of chaos.

The values are quite unpredictable on a short scale, but there are some very clear trends that are quite stable. Weather and climate!

Summing Up

This simple experiment does have a lot to tell us about chaos and, ultimately, the difference between weather and climate.

For More Information

CMMAP, the Center for Multi-Scale Modeling of Atmospheric Processes: http://cmmap.colostate.edu

Little Shop of Physics: http://littleshop.physics.colostate.edu

What is a "model"?

A laboratory experiment from the Little Shop of Physics at Colorado State University

Overview

The physics of how the atmosphere works is quite simple, described with some very straightforward equations. The behavior of the atmosphere itself, though, is quite complex, and can't be expressed in a series of simple equations. Building up from the very simple concept of a physical theory to the complicated behavior of a real physical system is the job of a *model*. The best way to learn what a model is is simple to create one, which we will do in this exercise.

Necessary materials:

- Chips or tokens
- 4 copies of the Heat Exchange Model sheet

Students will work in groups of four for this activity, one student representing each "cell" in the model.

Theory

Climate models start with physical theories: How air moves, how water behaves, how radiation transports energy. They then break the earth's atmosphere down into pieces—cells—and then compute what happens in each cell based on these physical theories. Cells exchange energy and matter with each other based on the physics of the transfer of matter and energy. The net result is a simulation of what the actual atmosphere might do. We can illustrate this idea by doing a very, very simple model for a piece of the atmosphere, as described below.

The design of the CMMAP logo tells us something about the model being developed by the center.

Doing the Experiment

Start with a simple simulation:

- Have each element start with 20 tokens—meaning a temperature of 20.
- Now run the model for 10 turns. How do the temperatures change?
- Now, continue the simulation; keep running it, having students keep track of the temperature.

At some point, the model will stabilize; all of the elements will remain at the same temperature for each turn. How long does it take to reach this point? This is the final temperature profile that the model predicts for the atmosphere. Just as for the real atmosphere, the earth is warmer than the lower atmosphere and the temperature drops as you go higher.

The model breaks down at the high end, though: In fact, the stratosphere is hotter than the lower atmosphere. That's because the stratosphere is heated by the sun, something our model doesn't consider. But we can fix this! You should try "tweaking" the model a bit to get a more realistic result. You could add another layer to the atmosphere, and then have space give some energy to the highest level each turn—say 3 tokens to earth and 1 token to the upper atmosphere.

- How does this alter the predicted temperature profile?

You could also do an open-ended discussion of how this model could be made more realistic. What elements would you add?

Summing Up

This is a very simple model, but it captures the key elements of what a model is and does. And it can be made more complex.

For More Information

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Setting up and Running the Model

Setting up the Model

Four people are needed to run the model. Each person represents one segment of the model: One is the earth, one is the lower atmosphere, one is the upper atmosphere and one is space. The four people sit in a row, in order, just as the different segments appear in relation to each other:

Earth Lower Atmosphere Upper Atmosphere Space

Each element can exchange energy to the adjacent element:

- The earth exchanges energy with the lower atmosphere.
- The lower atmosphere exchanges energy with the earth and with the upper atmosphere.
- The upper atmosphere exchanges energy with the lower atmosphere and with space.
- Space exchanges energy with the upper atmosphere.

In addition, the earth gets energy directly from space.

How much energy is exchanged depends on the temperature: If an element is hotter, it gives off more energy.

Running the Model

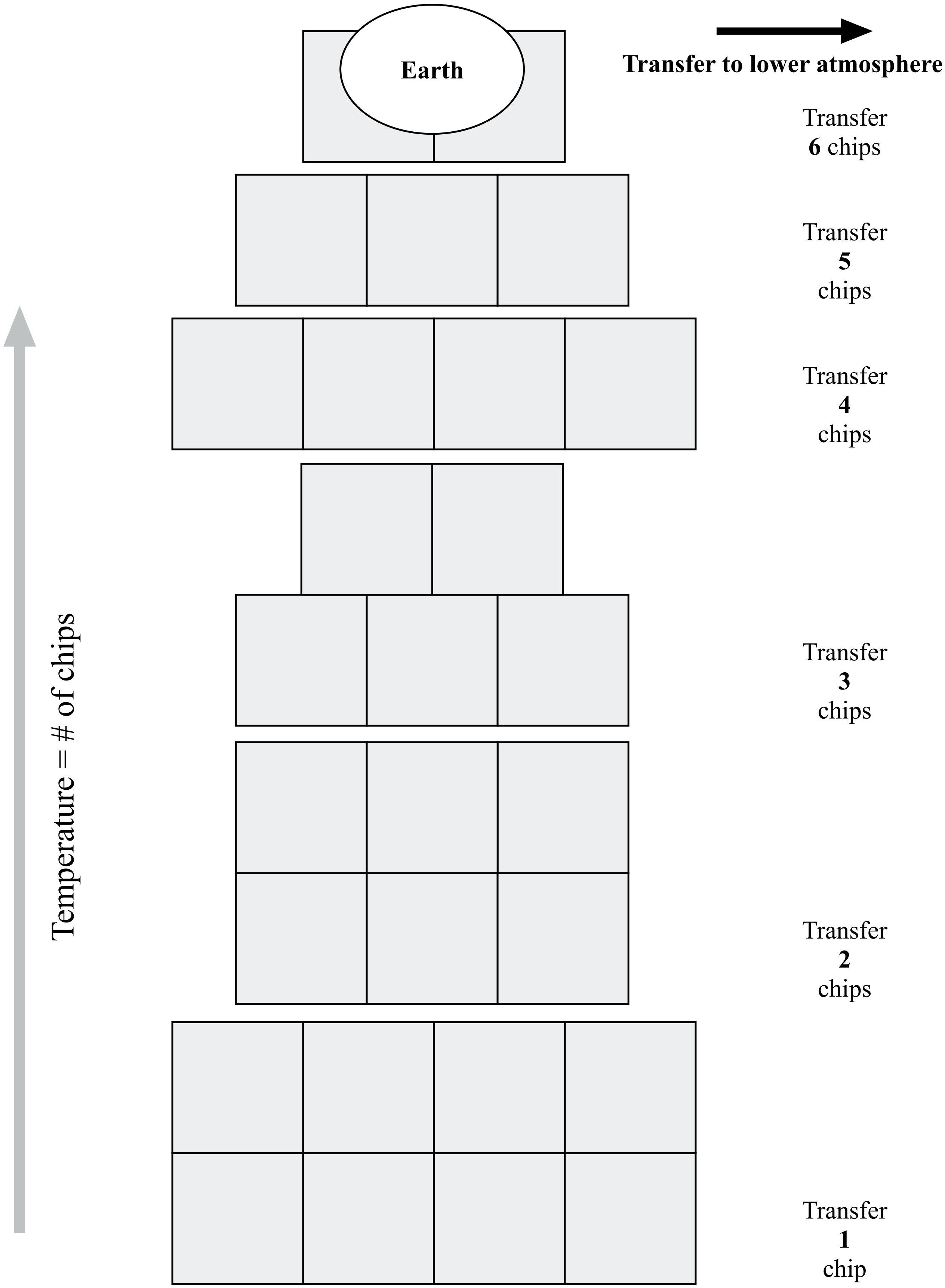
During each "turn" each element exchanges energy with other elements. The energy transfered depends on the temperature of each element.

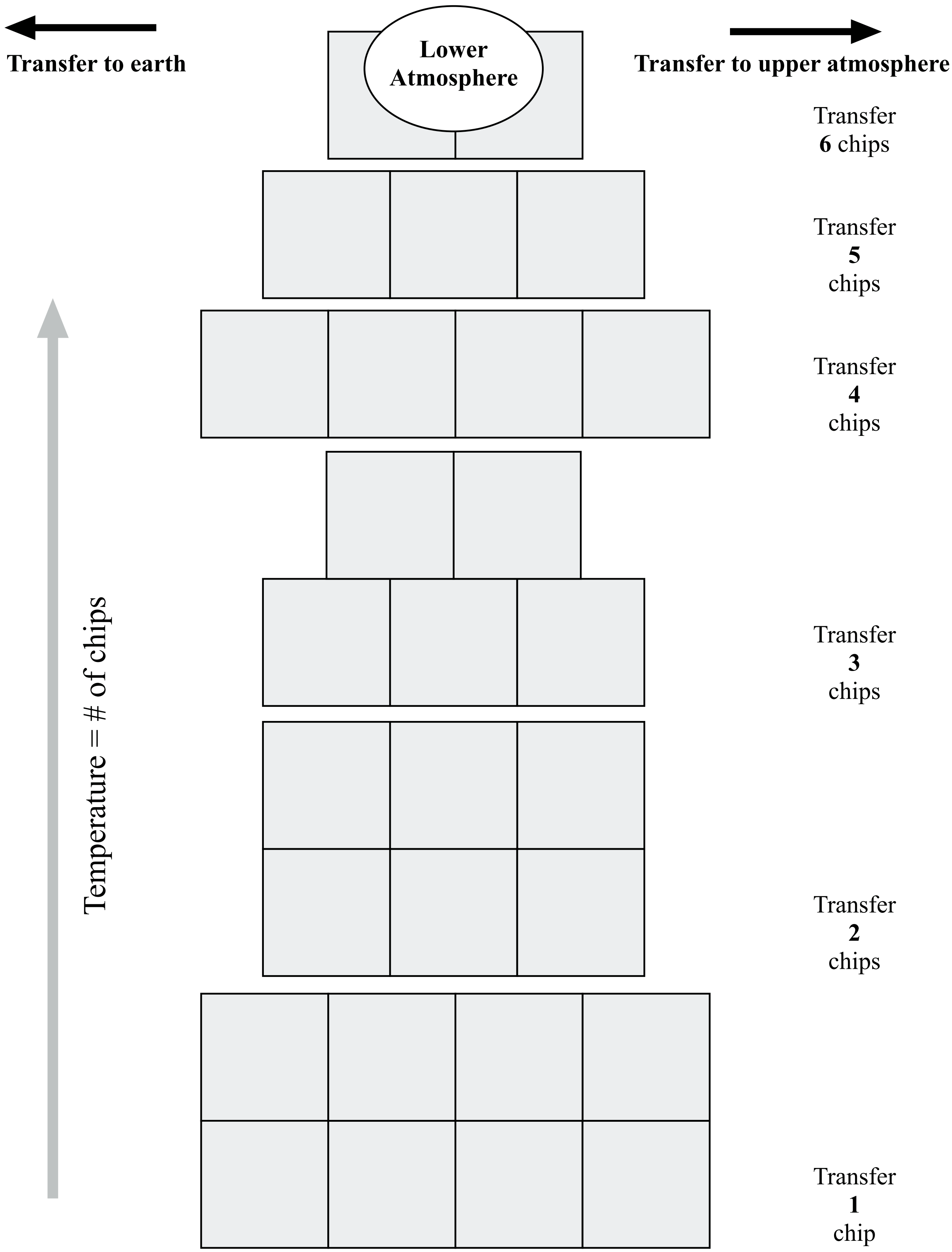
The earth, lower atmosphere and upper atmosphere each get some tokens. Each person puts his or her tokens on the model sheet, a copy of the following page, in order from the bottom. The first uncovered square gives the temperature and the energy to be transferred.

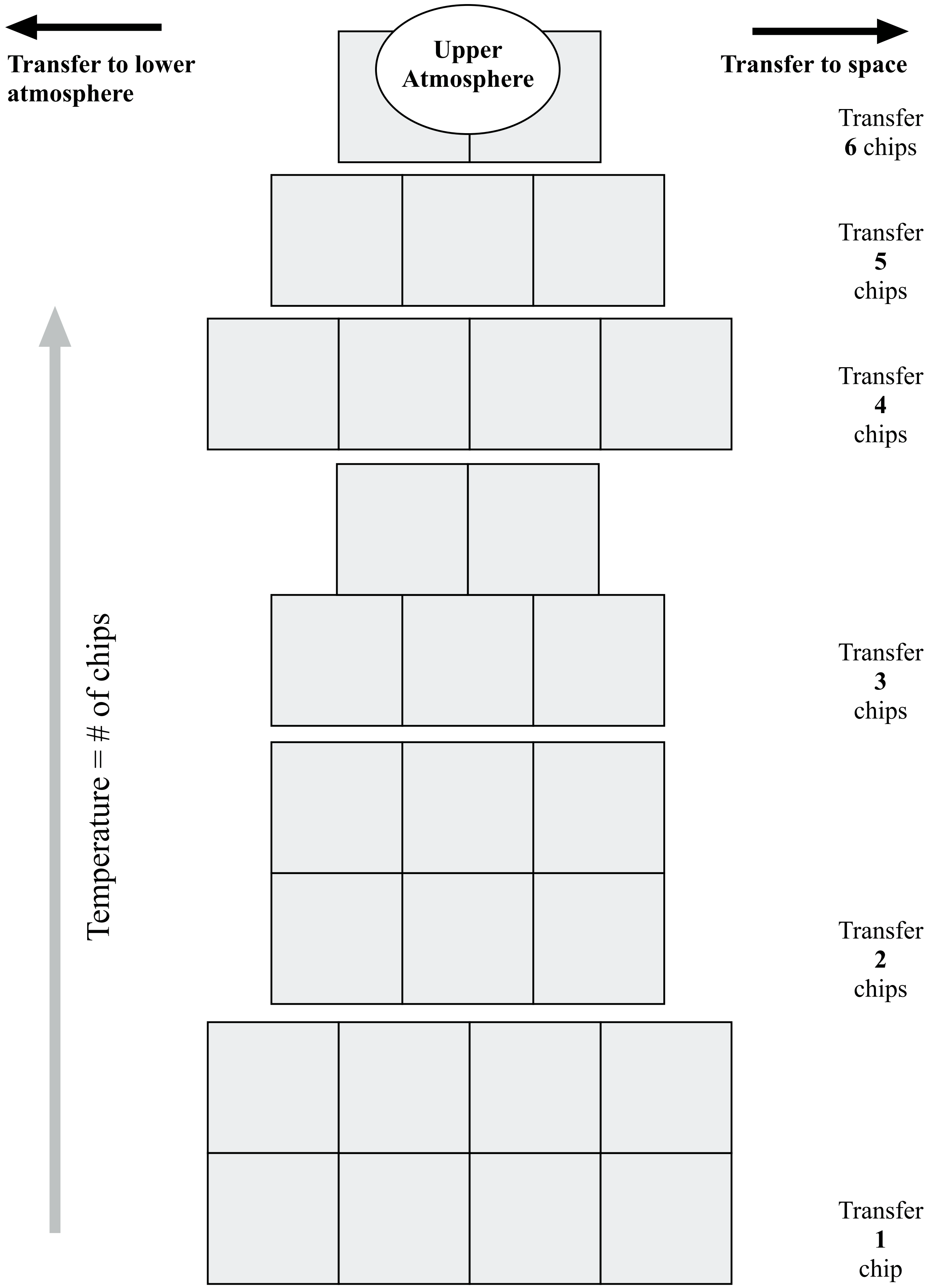
During one "turn", each element exchanges energy with the other elements:

- The earth exchanges energy with the lower atmosphere. The amount transfered is determined by the temperature of the earth. If the temperature is 20, then 3 tokens are transferred to the lower atmosphere.
- The lower atmosphere exchanges energy with the earth and with the upper atmosphere. If the temperature is 20, then 3 tokens are transferred to earth and 3 are transferred to the upper atmosphere.
- The upper atmosphere exchanges energy with the lower atmosphere and with space. If the temperature is 20, then 3 tokens are transferred to the lower atmosphere and 3 are transferred to space.
- Space gives 3 tokens to the earth—because energy from the sun heats the earth directly.

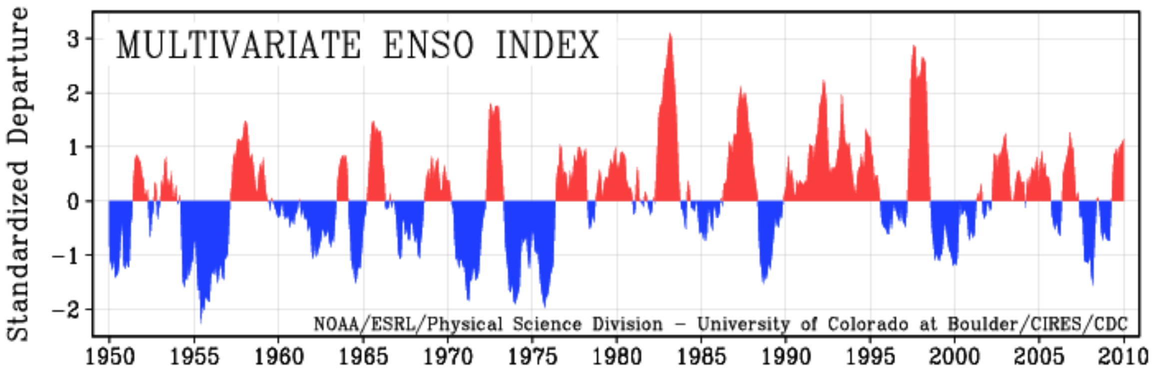
Each element places the newly received tokens and then determines the new temperature. This temperature is used for determining the energy transferred during the next "turn."


Earth
Transfer to lower atmosphere
Transfer 6 chips
Transfer 5 chips
Transfer 4 chips
Transfer 3 chips
Transfer 2 chips
Transfer 1 chip
Temperature = # of chips

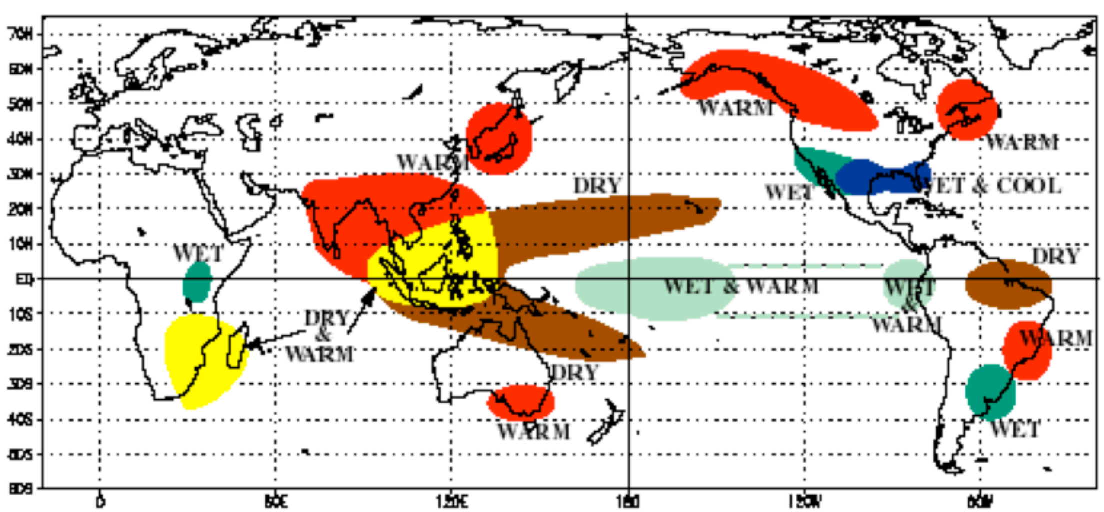

Transfer to earth
Lower Atmosphere
Transfer to upper atmosphere
Transfer 6 chips
Transfer 5 chips
Transfer 4 chips
Temperature = # of chips
Transfer 3 chips
Transfer 2 chips
Transfer 1 chip


Transfer to lower atmosphere
Upper Atmosphere
Transfer to space
Transfer 6 chips
Transfer 5 chips
Transfer 4 chips
Transfer 3 chips
Transfer 2 chips
Transfer 1 chip
Temperature = # of chips

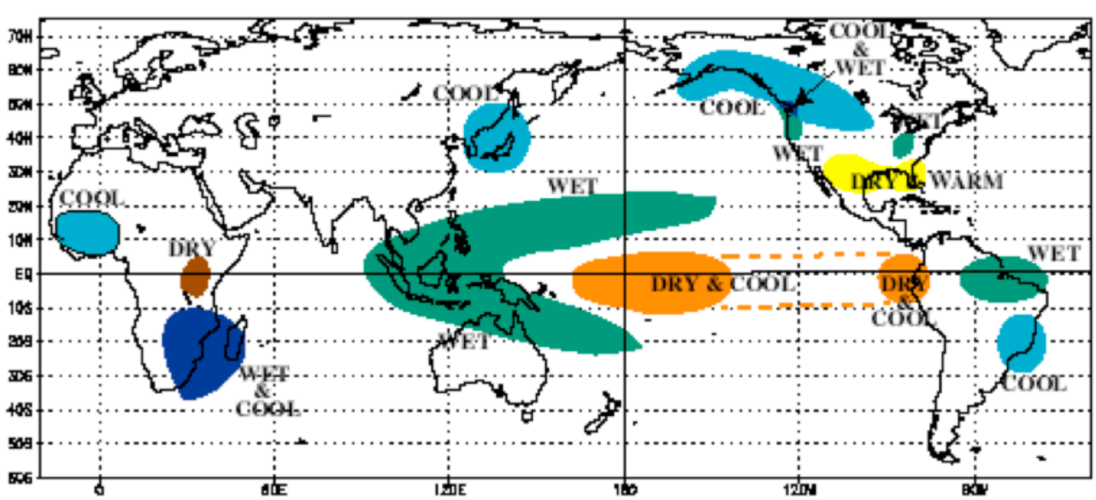
The **El Niño Sothern Oscillation (ENSO)**, is a phenomena in the ocean and atmosphere of the Pacific that has global climatic impact. ENSO is described as having a cool or negative phase (La Niña), when warm water gathers in the West Pacific Warm Pool, and a warm or positive phase (El Niño), when that water moves East, “sloshes back” over the Pacific.



WARM EPISODE RELATIONSHIPS DECEMBER - FEBRUARY



COLD EPISODE RELATIONSHIPS DECEMBER - FEBRUARY



Q. Focusing on the West Pacific Warm pool, what happens in the atmosphere during an El Niño? During a La Niña?

Estimates of **global temperature** depend on surface measurements as well as satellite observations. These data are combined in models, a process called "reanalysis", to estimate the state of the atmosphere.

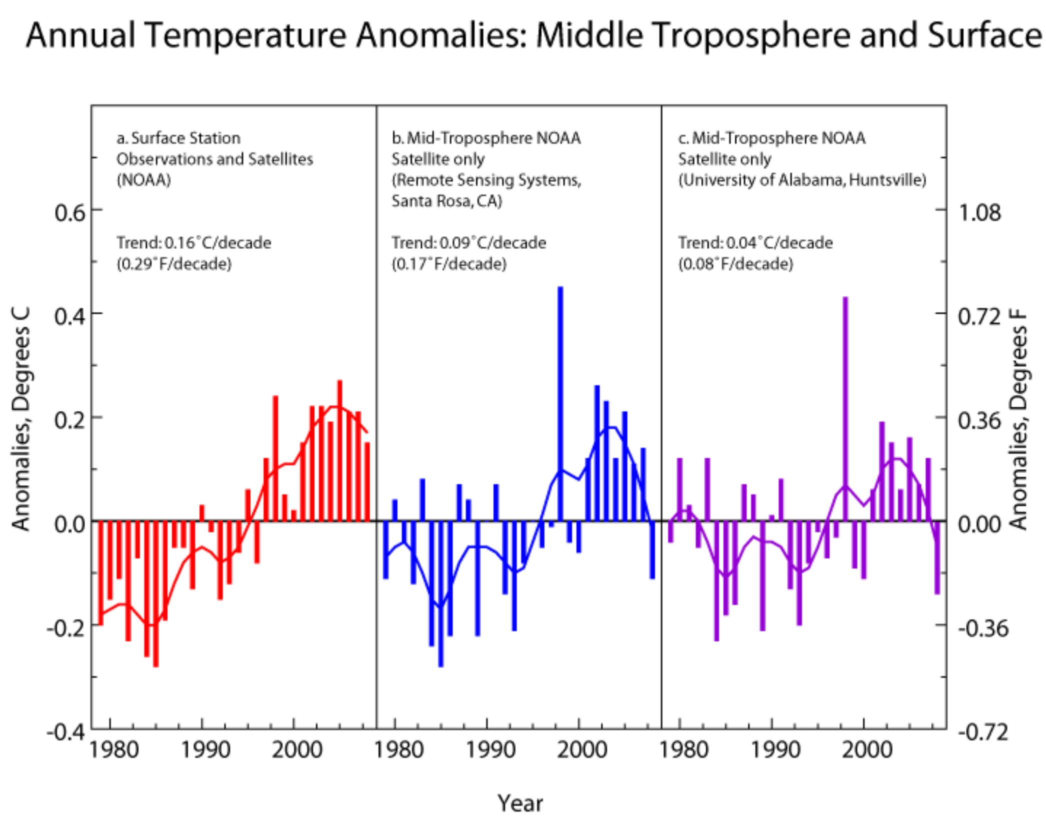
Both types of measurement have their advantages and limitations.

Satellites often measure temperature at the tops of clouds, which can be quite high and cold; this also means that their measurements are not always made at the same height. Satellites also cannot see the entire world at once, so their measurements are not simultaneous.

Surface measurements use many different instruments, which may not all be calibrated identically. Surface measurements are also be subject to highly localized processes.

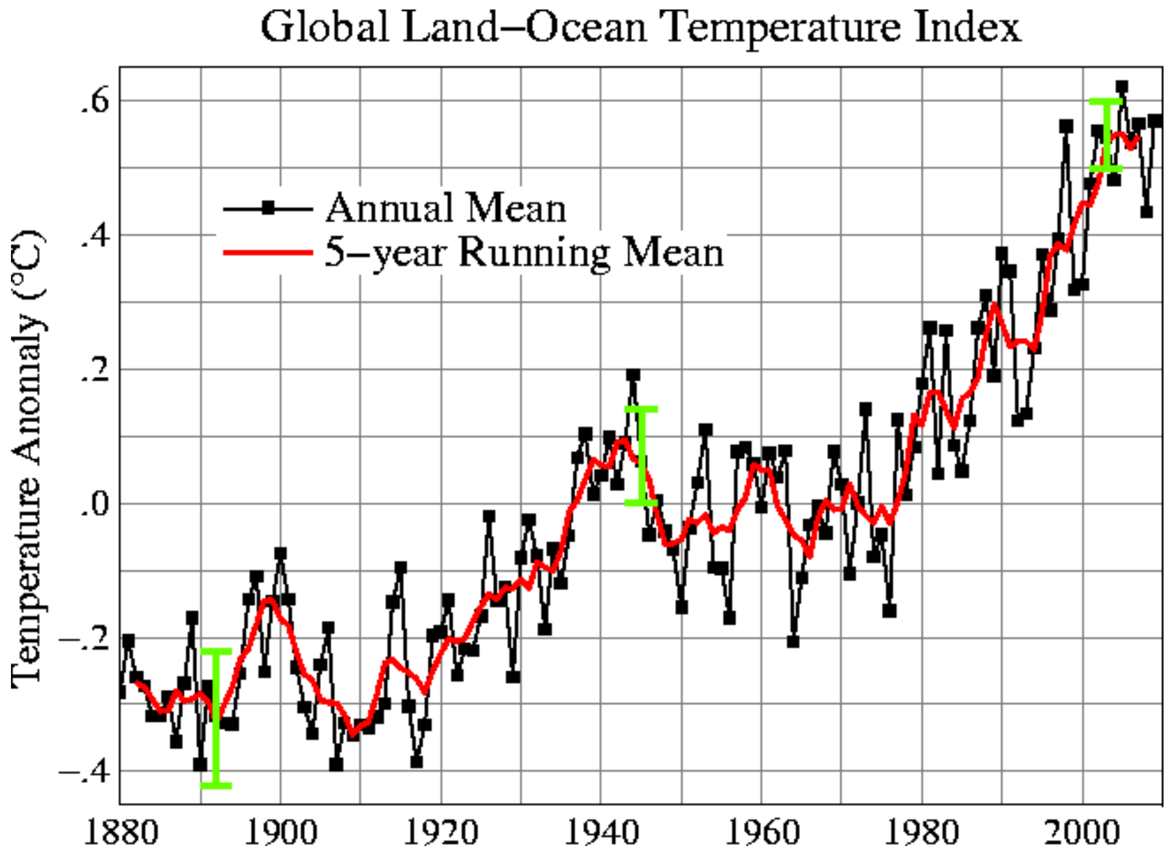
People work hard to account for and correct these problems, but the biases of each are one reason they are generally used as model drivers in the reanalysis process rather than considered directly.

Q. What advantages might the surface record have over satellites? What are satellites better at?



Q. Can what we know about ENSO be used to explain some of the differences between the satellite and surface observations? Look at 1998, a strong El Niño year; and 2008 (the last year of temperature anomalies shown) a significant La Niña year. Why might ENSO have a stronger impact on satellite observations than surface measurements?

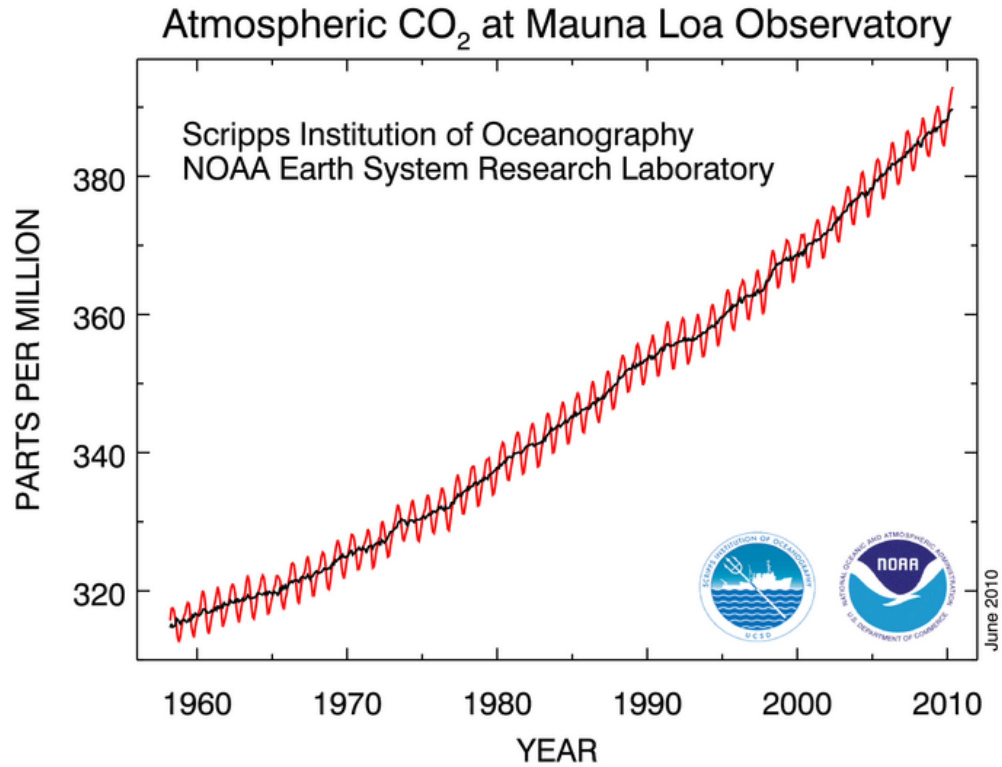
Once estimates of global temperature have been made, analyzed and reanalyzed; **global warming** may be considered.

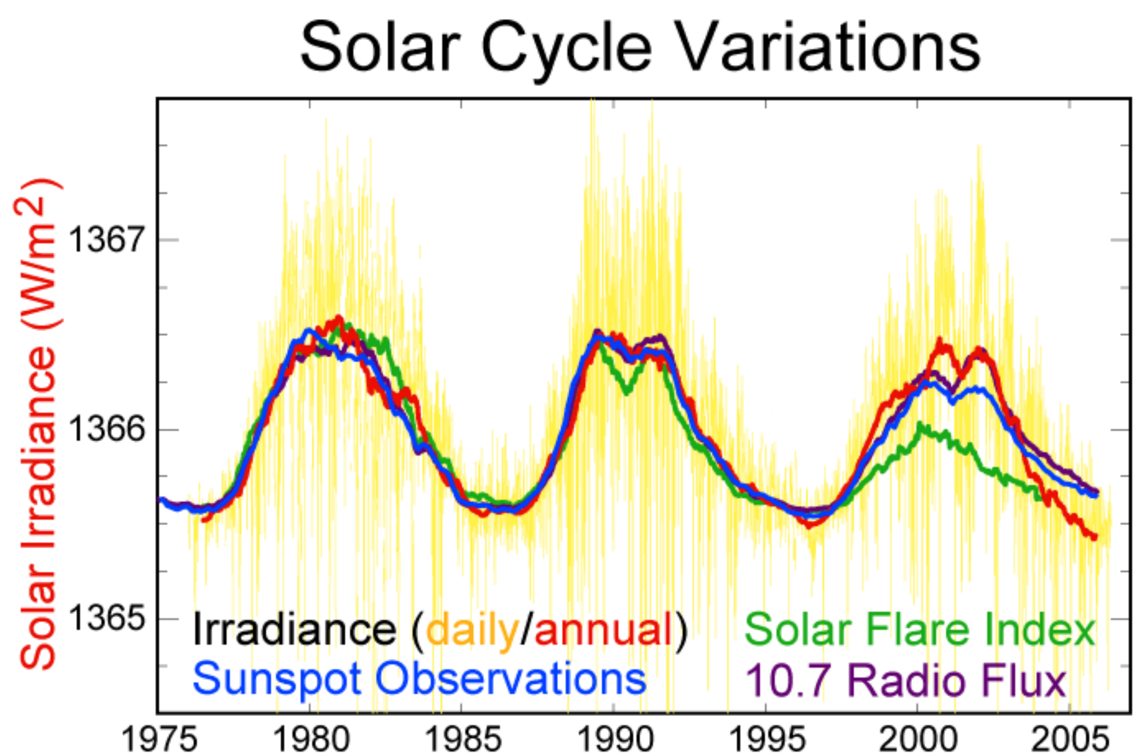


Q. In the previous temperature graph 1980 had a negative anomaly, in this graph its anomaly is positive, why?

Q. Is the temperature trend linear, or are their "kinks"? What might be responsible for the decreased rate of warming from about 1950-1975?

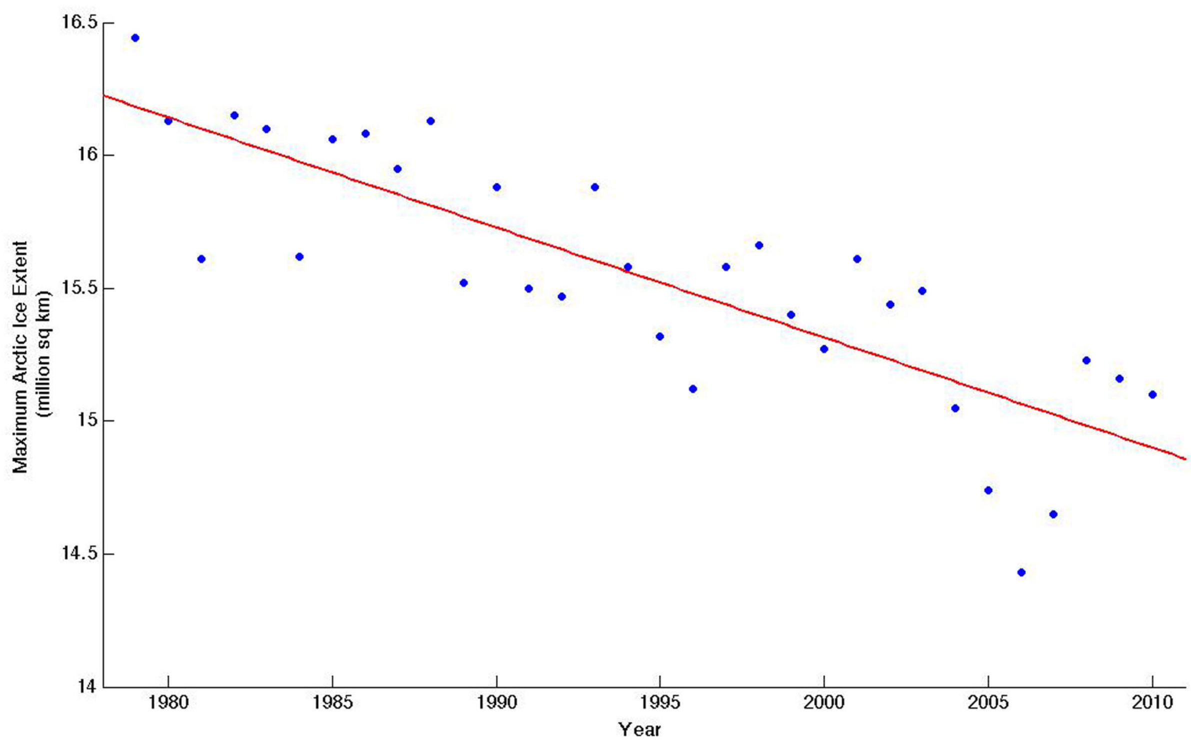
There are many **forcings** of global temperatures. Some change over very long timescales like the arrangement of the continents or the Earth's orbital characteristics. Most of these forcings are beyond our control, like aerosols from volcanic eruptions or solar variability. A few factors, like carbon dioxide emissions and land use change, are the direct result of human activities.





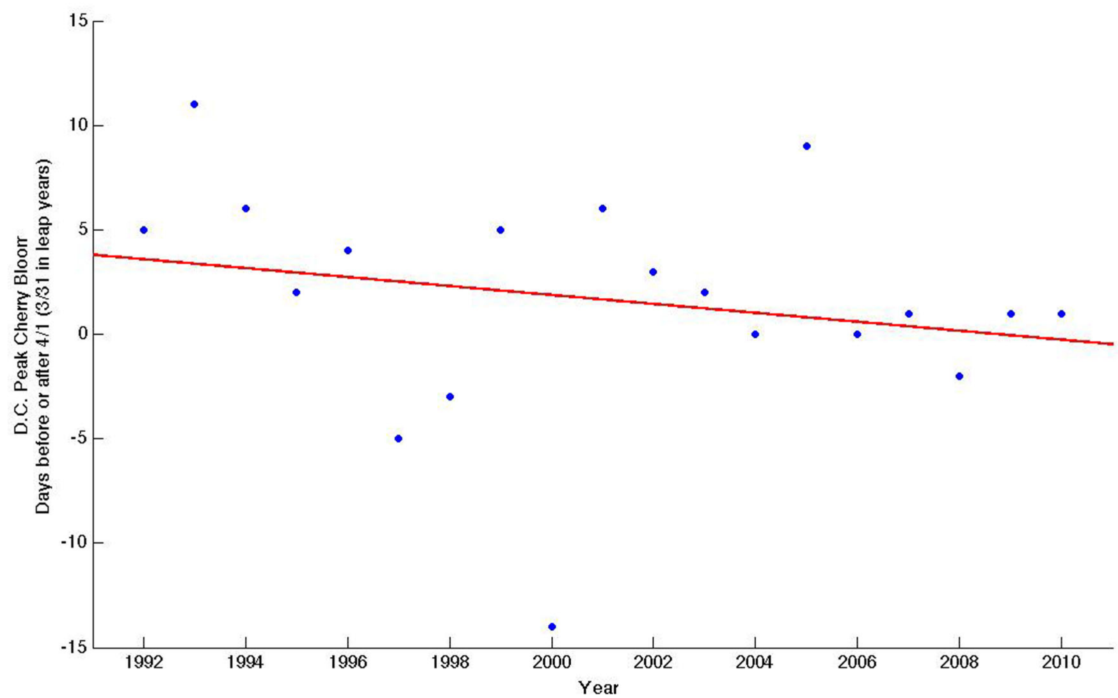
Q. Are these trends is consistent with the temperature record?

Year	Max Ice Extent (million sq km)
1979	16.44
1980	16.13
1981	15.61
1982	16.15
1983	16.1
1984	15.62
1985	16.06
1986	16.08
1987	15.95
1988	16.13
1989	15.52
1990	15.88
1991	15.5
1992	15.47
1993	15.88
1994	15.58
1995	15.32
1996	15.12
1997	15.58
1998	15.66
1999	15.4
2000	15.27
2001	15.61
2002	15.44
2003	15.49
2004	15.05
2005	14.74
2006	14.43
2007	14.65
2008	15.23
2009	15.16
2010	15.1



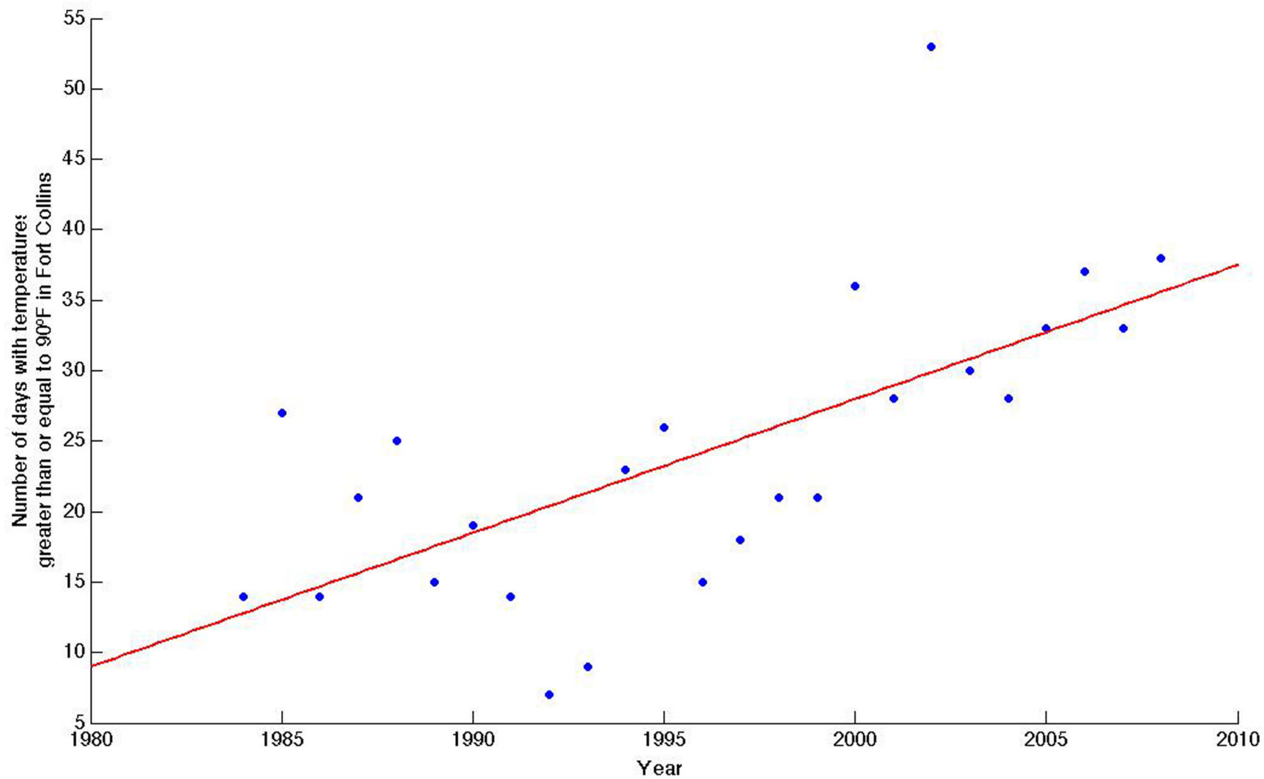
National Snow and Ice Data Center
http://nsidc.org/data/seaice_index/

Year	D.C. Peak Cherry Anomaly from 4/1
1992	5
1993	11
1994	6
1995	2
1996	4
1997	-5
1998	-3
1999	5
2000	-14
2001	6
2002	3
2003	2
2004	0
2005	9
2006	0
2007	1
2008	-2
2009	1
2010	1



National Cherry Blossom Festival
http://www.nationalcherryblossomfestival.org/cms/index.php?id=404

Year	Days ≥ 90ºF Fort Collins
1984	14
1985	27
1986	14
1987	21
1988	25
1989	15
1990	19
1991	14
1992	7
1993	9
1994	23
1995	26
1996	15
1997	18
1998	21
1999	21
2000	36
2001	28
2002	53
2003	30
2004	28
2005	33
2006	37
2007	33
2008	38



National Climatic Data Center
http://www.ncdc.noaa.gov