Why is it tropical in the tropics?

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

Overview

We have all seen the proverbial "wish you were here..." postcard featuring white sand beaches and palm trees bordering sapphire blue water that stretches as far as the eye can see. Why is it that there are certain regions of the world that never seem to experience winter? Why do some areas of the world have dramatic seasonal variations in temperature and others tend to stay within a smaller range?

This activity will allow students to explore the relationship between angle of incidence, intensity of solar radiation, and how it relates to seasons as well as the general climate of different regions of our planet.

Necessary materials:

Per group of 3 or 4:

- One large inflatable Earth
- A solar grasshopper with leads
- Multimeter
- Alligator clip leads

We purchased the solar grasshoppers from Deal Extreme but you can use any device that acts similarly.

Theory

Our planet is warmed by the sun, but not every part of the planet is warmed equally. The amount of energy transferred depends on the angle that the sun's rays make with the surface. If you hold a flashlight above a table top and shine it straight down you see a circle of light. If you tilt the flashlight, however, the light will stretch out to form an oval, covering a larger area of the table. The amount of light is the same, but it's spread out over a larger area; we say that the **intensity** is less.

The Earth's spin axis is tipped 23.5° from the plane of its orbit around the sun. For folks in southern Florida, during the middle of the northern hemisphere summer, the noonday sun is nearly overhead, so the sunlight is quite intense. But 6 months later, the sun is never higher than a bit more than 40° above the horizon, so even at noon the intensity of sunlight never reaches the peak it does in the summer.

For locations on or near the equator, the intensity of sunlight experiences a much smaller seasonal variation. Equatorial locations are always warm, but they are also always about the same temperature. There's no winter in Mombasa, only a wet season and a dry season, both quite toasty.

Doing the Experiment

Your students will use the large inflatable Earth and the solar grasshopper to determine the intensity of the sun's radiation at a given point on the surface. Most students are familiar with the fact that solar cells use the sun's light to create electricity, but this is a good point to reiterate. The current that the cell produces is, more or less, directly proportional to the captured energy. Have your students do the following:

- Align the Earth so the sun shines directly on the equator, by the Galapagos Islands.

- Attach the clip leads to the solar grasshopper and to the multimeter.
- Set the meter to measure current and adjust the range so that the maximum current stays on scale.
- Place the solar grasshopper in the direct sunlight and measure the current
- Place the solar grasshopper where they live and measure the current. (Note: Fort Collins is about 40° N)

The amount of current you see will be proportional to the intensity of the sunlight. Have your student explore taking readings from different areas on the Earth at different latitudes. The current position of Earth, with the sun on the Galapagos Islands represents how it would be on either of the equinoxes. Think about how to tip the ball to represent northern hemisphere winter and summer; this takes some thought.

Look at the variation in current (and thus received power) over the course of one rotation (representing a day) for the northern hemisphere winter and summer. The key is to measure the seasonal variation. How much do things change between winter and summer. For latitudes of 40° N, a good deal. For the equator... Not so much.

Summing Up

When the solar grasshopper is at the equator, the angle between it and the sun isn't greatly affected by the precession of the planet and so students should see values that vary over a small range compared to the data from the higher latitude position. For the latter, students should be getting higher values when the solar grasshopper is tilted towards the sun and lower values when it is tilted away. This is not due to the fact that the grasshopper is closer or further from the sun, as per the common misconception, but due to the changing angle and therefore changing intensity of the solar radiation. This yields the vast seasonal variation experienced at the higher latitudes. The solar intensity at the equator stays high and relatively stable throughout the year making it a rather postcard-worthy region of the world.

For More Information

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

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

What is the "greenhouse effect"?

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

Overview

You know that putting on another layer of clothing helps keep you warm on a chilly day. The same thing is true for the earth—the layers of the atmosphere keep the earth from losing so much energy to space, keeping us nice and toasty.

Necessary materials:

- Infrared thermometer
- Cold day
- Students with layers of jackets, sweaters and other warm clothes

The crucial piece is the infrared thermometer. You need one that can measure very cold temperatures, and one with a reasonably narrow field of view.

IR thermometers can be found at www.harborfreight.com under "non-contact pocket thermometer".

Theory

If the earth was bare rock, with no atmosphere, like the moon, the average surface temperature would be about -18°C, about 0°F.

We know that the earth is warmer than this—quite a bit warmer, as it turns out. The average surface temperature on the earth is about 15°C, or about 60°F. The earth is kept warmer by the insulation of the atmosphere; this is known as the **greenhouse effect**. It's easy to do a simple experiment that gives clues as to how the atmosphere works this magic. The key, just like the key to keeping warm in the winter, is layers.

If you take your warm hand and place it in a cup of cold water, heat will flow from your hand to the water. If you put your hand in a cup of hot water, heat will flow from the water to your hand. That's thermodynamics, specifically the second law of thermodynamics: heat flows from hot to cold. The amount of heat that flows depends on the temperature difference; more heat flows if the temperature difference is large, less if it is small. If you swim in a cool river, you'll get chilly after a while; if you swim in the ocean in the Arctic, you will quickly get hypothermia.

Layers keep you warm. As you "step down" from body temperature to outside temperature, the more steps there are, the smaller the steps.

This dependence on temperature difference is true for all mechanisms of heat exchange, including **conduction** (direct transfer by two objects in physical contact), **convection** (transport of fluids, like water or air), or **radiation** (transfer of energy by emission of electromagnetic waves.) The earth sits in the vacuum of space, so the only way it can gain or lose energy is by radiation. Understanding energy gain and loss by radiation helps us explain why the earth is warmer than it "should" be.

The atmosphere above us has many layers, and there is a variation in temperature as well. The earth gets radiant energy from the sun, and it gives off radiant energy to space. But there's a difference in these two types of radiation. The wavelength of the electromagnetic waves that an object emits depends on its temperature. Higher temperature means shorter wavelength. (That's how the thermometers you will use in this experiment work—they measure the radiation that objects emit. Shorter wavelength means a higher temperature.) The incoming radiation, from the sun, with its 6000°C surface temperature, is mostly visible light. The visible light comes right through the atmosphere. The outgoing radiation, from the surface of the earth, at an average temperature of 15°C, is mostly longer wavelength infrared. Infrared doesn't go through the atmosphere so easily; much is absorbed, largely by water vapor and carbon dioxide. There are layers of the atmosphere between the earth and space that absorb most of this radiation. They are warmer than space, and so their presence keeps us warmer. Above us is a warm layer of atmosphere, not the cold of space.

Doing the Experiment

This lesson gives you a good excuse to teach outside—in the winter! You want your (warmly attired) students to be outside long enough that the temperatures of the layers of their clothes have equilibrated. This will take some time, at least 10-15 minutes. After this time, their garments will be warm on the inside, cool on the outside. You'll get the most interesting results from students wearing layers—a shirt, a sweater and a thin jacket would be ideal. We'll assume this set of layers for the following description. We will mea

- Have one student with a good set of layered clothing serve as the test subject. Pick a spot in the middle of her back and use the infrared thermometer to measure the surface temperature of his jacket.
- Now, have him quickly remove his jacket, and measure the surface temperature of his sweater at the same spot.
- Next, have him quickly remove her sweater, and measure the surface temperature of his shirt at this spot.
- Finally, use the thermometer to measure his skin temperature—ideally, in the same spot, but use your judgement here. The inside of the forearm could work as well.

Look at the range of temperatures, from the warm skin to the cool outside of the jacket. There is a big difference in temperature between the inside and the outside, but each layer sits next to another layer which is only slightly different in temperature. Ask your students to explain how this layering, this "stepped" temperature profile, will help them stay warm.

Now, do this:

- Aim the infrared thermometer at the sky. Space is quite cold—deep space is about -270°C, or -455°F. But the thermometer measures a temperature that is much less frosty; it will probably read about 0°C, or perhaps as cool as -10°C or even -20°C. Cold, yes, but not -270°C!

What the thermometer is measuring is the temperature of a layer of the atmosphere that absorbs the earth's emitted radiation. Because the earth is covered by a layer of atmosphere that is cooler than the earth but warmer than space, it keeps the earth warmer. After making both sets of measurements, you can help your students make this connection.

Summing Up

Now, for the obvious question: If the earth is kept warm by the atmosphere, and if carbon dioxide in the atmosphere is responsible for this warming, and if we are increasing the level of carbon dioxide in the atmosphere, won't that cause the earth to warm up? The answer is: Almost certainly. It's like putting on another layer of clothing on a cold winter day, a simple matter of thermodynamics.

Of course, the atmosphere is more complicated than this; there might be other effects. But the fact is that *we are adding carbon dioxide to the air, and that the climate is changing*. There is clear data to show both effects.

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

How does the earth cool itself off?

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

Overview

The earth gets energy from the sun. The sun shines on the earth's surface, warming it.

If the earth had no way of cooling off, it would simply keep getting hotter and hotter. So the earth must have some way of cooling off, some way of losing energy to space...

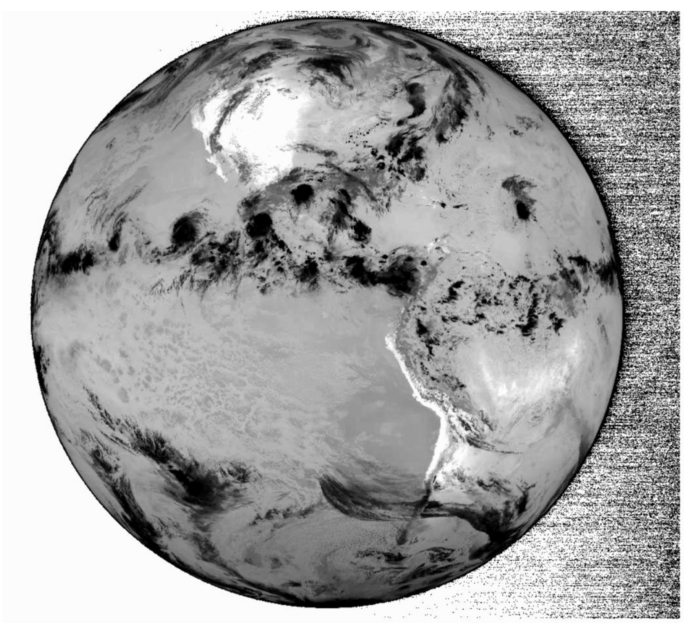
Theory

When light shines on the earth, different places heat up by different amounts. Snow reflects most of the incoming light, so snowy areas tend to stay cool. Dark areas, like black parking lots, absorb incoming light, and so will warm up.

Necessary materials:

- World map placemat
- Desk lamp
- IR thermometer
- 3 squares of standard transparency

The infrared thermometer is the key item; it measures temperature by measuring an object's emitted thermal radiation. They can be found at www.harborfreight.com under "non-contact pocket thermometer". The desk lamp is used to heat up the surface; any lamp will do, though an incandescent or halogen lamp is best.



GOES-9 11 July 1995, 1800 UTC 12 micron IR GOES Project, NASA-GSFC

An infrared view of the earth, at 12 microns. The atmosphere is transparent to infrared of this wavelength. White is bright, black is dim. Look for hot spots and cold spots. Deserts are hot, and emit a lot; clouds are cool, and emit very little.

In order to keep at a relatively constant temperature, the earth must get rid of energy too. And it does: As emitted thermal energy, infrared, that is transmitted to space.

The hotter something is, the more infrared emitted. So a picture of the infrared that the earth emits shows us the hot spots and the cold spots. Look at the satellite photo at left; the American west is clearly pretty hot, as is appears quite bright. Cloudy patches appear dark; clouds absorb or reflect the infrared from the surface, so we only see the infrared they emit. Clouds are cool, so clouds appear as dark spots. Deserts are hot during the day, because they absorb a lot of incoming radiation, but at night they radiate energy back to space, so they get quite cool.

The same principles work on a smaller scale as well, of course. And this lets us do a simulation of these principles on a tabletop scale.

Doing the Experiment

In this experiment, students will simulate the energy transfer between the earth and space by using the light from a desk lamp to warm up a placemat. The placemat will warm up, so it will emit infrared, which they can detect with an infrared thermometer. The hotter the surface, the more energy emitted, which the thermometer will show. Adding an "atmosphere" can reduce the transmission of infrared, holding heat in, another thing that the experiment can show.

> **SAFETY NOTE: The desk lamps get hot, and if they are too close to the placemat, they can melt it. Please be careful!**

The experiment goes like this:

- Have students shine the light on the placemat for a few minutes, allowing it to warm. (Note: You can also do this experiment outside, letting the placemat warm up in the sun. That's actually a better way to do it, if you can get your class outside!)
- Now have them use the infrared thermometer to probe the temperature of different places on the placemat. Different colors will absorb different fractions of incoming radiation, and so will be at different energies. Reds will be cool, blues will be warm. (That's because reds tend to reflect infrared too; blues tend to absorb it, and so heat up more.)
- Now, add an atmosphere to a warm spot. While monitoring the temperature with the infrared thermometer, slip three taped-together sheets of transparency onto the placemat. This "atmosphere" will block the outgoing infrared, so the observed temperature will quickly drop. But as the "atmosphere" heats up the emitted infrared (from the transparencies) will come back.

We chose three sheets of transparency for this reason: Three sheets of standard transparency are about the same thickness, relative to the scale of the placemat, as the thickness of the earth's atmosphere. This is another good point to make—just how thin the earth's atmosphere is! (Three sheets of transparency corresponds to about 30 km on the scale of the placemat; 99% of the earth's atmosphere is below this height.)

Summing Up

This is a good way to illustrate in a qualitative manner the radiational warming and cooling of the earth's surface.

You could actually make this quantitative. If you measure the temperature vs. time, you can see that hot spots cool more quickly than cool spots—because they emit more infrared.

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

Why does it get colder on clear nights than on cloudy nights?

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

Overview

You know it's true: If there isn't a cloud in the sky, the air temperature will drop much more over night.

Why? It's all about radiation...

Necessary materials:

- Infrared thermometer
- Sheets of plastic, glass, etc.

The crucial piece is the infrared thermometer. You need one that can measure very cold temperatures, and one with a reasonably narrow field of view. IR thermometers can be found at www.harborfreight.com under "non-contact pocket thermometer".

Theory

All objects radiate electromagnetic waves. And increasing an objects temperature increases the total amount of energy radiated; hot objects "glow" more brightly.

Increasing the temperature also decreases the peak wavelength of the emitted radiation. The sun gives off visible light. You are cooler than the sun, so you emit energy, and you emit it at a longer wavelength, in the far infrared region of the spectrum.

The sun does glow more brightly than you. But you are still pretty bright! The amount of energy you emit might come as a bit of a surprise.

Here's a remarkable fact: An unclothed human will *emit* a significant amount of electromagnetic energy—about 850 W. Your body's basal metabolic rate is only about 150 W, so something else must be going on. If this was all there was to the story, you'd be losing 700 W more than you generate, so you'd cool off and die.

Taking the temperature of the sky. On this clear Colorado afternoon, it was a frosty -30°C.

But there is a piece we left out: The radiated energy that your body absorbs from the environment. An unclothed human in a room at about 20°C will your *absorb* about 750 W of thermal energy that is emitted by the walls, floor and ceiling of the room. The net loss of energy is only 100 W—enough that you will feel chilly, but not so much that you will develop hypothermia.

If the walls of the room you are in are cold, you will radiate just as much, but you will get less back. If the walls are warm, you will get more back. The temperature of the walls, ceiling and floor in a room are every bit as important to your comfort as the temperature of the air.

Now, let's look at the earth. The only way the earth can gain or lose energy is by radiation. During the day, sunlight warms the earth. At night, the earth radiates—a lot—and it cools. Think about this: The earth, as a whole, stays at about the same temperature from day to day. This means it must be radiating as much energy to space as it receives from the sun. If you were to look at the earth with infrared eyes, it would be really bright.

This emitted infrared carries away energy. But the atmosphere isn't particularly transparent to infrared, so the earth doesn't cool off so much. It ends up being a bit warmer than it would be with no atmosphere. If the earth had no atmosphere, the earth would radiate enough energy to cool off to an average temperature of -18°C. But we do have an atmosphere, and one that blocks infrared. This keeps the earth's temperature at a much more pleasant 15°C. This warming is called The Greenhouse Effect, and it is, undoubtedly, A Good Thing. But as the atmosphere changes, the earth might warm up further... Perhaps catastrophically. This isn't good.

Doing the Experiment

If you point an infrared thermometer at something, it measures the emitted infrared and translates this into a temperature. Some things are transparent to infrared, and some things aren't.

> **SAFETY NOTE: The thermometers we use have lasers on them. The usual precautions regarding lasers in the eyes should be followed.**
>
> **EQUIPMENT SAFETY NOTE: The instruments should not be pointed at the sun! This will destroy them.**

Here are some things you can try:

- Point the thermometer at your hand, and pull the trigger. You will measure you hand's temperature by the infrared it emits. Try measuring the temperatures of other things.
- Now, put a piece of glass between your hand and the thermometer. Can it measure your hand's infrared through the glass? Nope. Glass is opaque to infrared.
- Try other things between your hand and the thermometer. What things absorb? what things transmit?
- Can you find surfaces from which infrared reflects? How would you measure this?
- Now, go outside and point the thermometer at the sky. If it "saw" all the way to space, it would measure a really, really low temperature. But it doesn't. It "sees" upper levels of the atmosphere, which absorb (and emit) infrared. These upper levels are cold, quite cold, so, at night, the earth will radiate a good deal of energy while getting little back.
- Now, point the thermometer at a cloud. You will see a much higher temperature—the cloud is warmer, but it also reflects infrared from the surface. If you are underneath a cloud at night, you will get more radiation back, and cool down less.

After some experimenting, you students should be ready to answer the central question of this exercise:

> **How do the observations show us that the earth will cool down more on clear nights than on cloudy nights?**

Summing Up

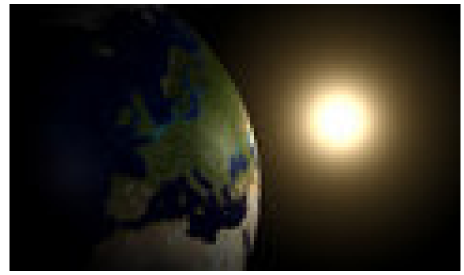
What happens when the atmosphere as a whole transmits less infrared? Think about it!

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

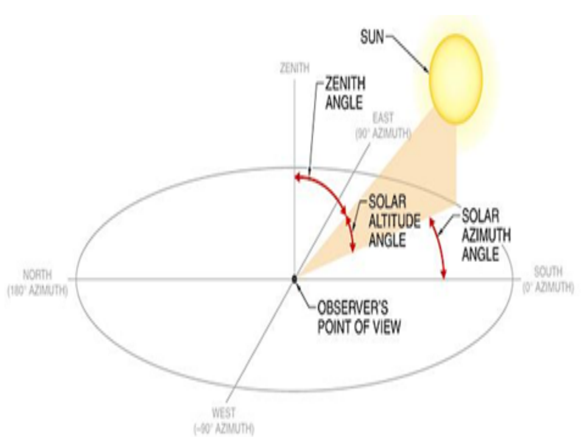
Radiation, Temperature, and Seasons



Part 1:
How does the angle of the sun affect the amount of radiation the Earth receives?

To explore the concept of sun angle and seasons, you are given an “Earth” with a solar cell attached. The solar cell is connected to a multimeter that measures the current in the solar cell. The higher the current, the more higher the energy output of the cell, so the more energy it is capturing. Angle matters!

- Take your Earth outside and point the solar cell directly at the sun. What current do you read? Now try this again in the shade. What do you measure now?
    - Do you see a difference in the amount of current?
    - Why do you still measure current in the shade?
- The sun angle is measured in degrees from true south, as pictured in the diagram below. You are given the approximate sun angle over Fort Collins for the equinox and the summer and winter solstices. Estimating as best you can, point the Earth so that the solar angle best matches the given angles.
    - Note the current that you read at each angle.
    - How does the amount of radiation that the Earth receives change depending on the sun angle?
    - Is this what you expected?



Part 2:
How does the sun's radiation affect the surface temperature?

Now that you have seen how radiation changes from month to month, it is time for you to plot it, and see how it affects the temperature. You are given monthly maximum solar radiation and average temperature. All of the data have been collected from the Fort Collins weather station on campus and averaged over a 10 year period (2000-2009).

1. Plot both fields and answer the following questions:

    - In what month is solar radiation a maximum in Fort Collins?
    - In what month is temperature a maximum in Fort Collins?
    - Why do you think they are different?

Month	Solar Radiation (Wm^{-2})	Temperature (^{o}F)
January	527	28
February	682	31
March	814	38
April	884	47
May	961	56
June	982	65
July	967	71
August	867	69
September	807	60
October	691	49
November	554	37
December	475	29

2. Now plot the temperature data for one of the following cities: Anchorage, Quito, Seattle, and Sydney.

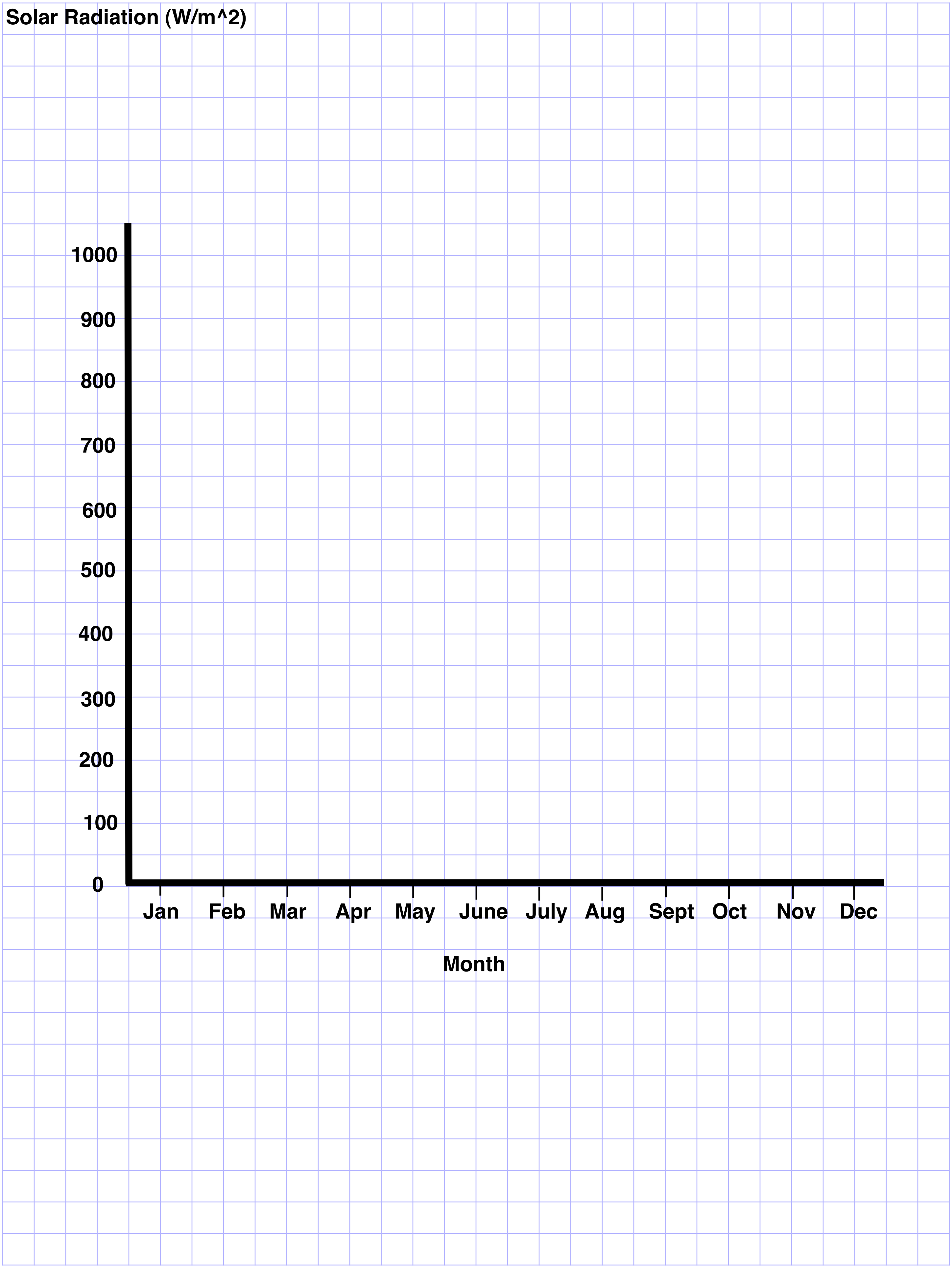
    - How are the temperature graphs different between Ft. Collins and your city?

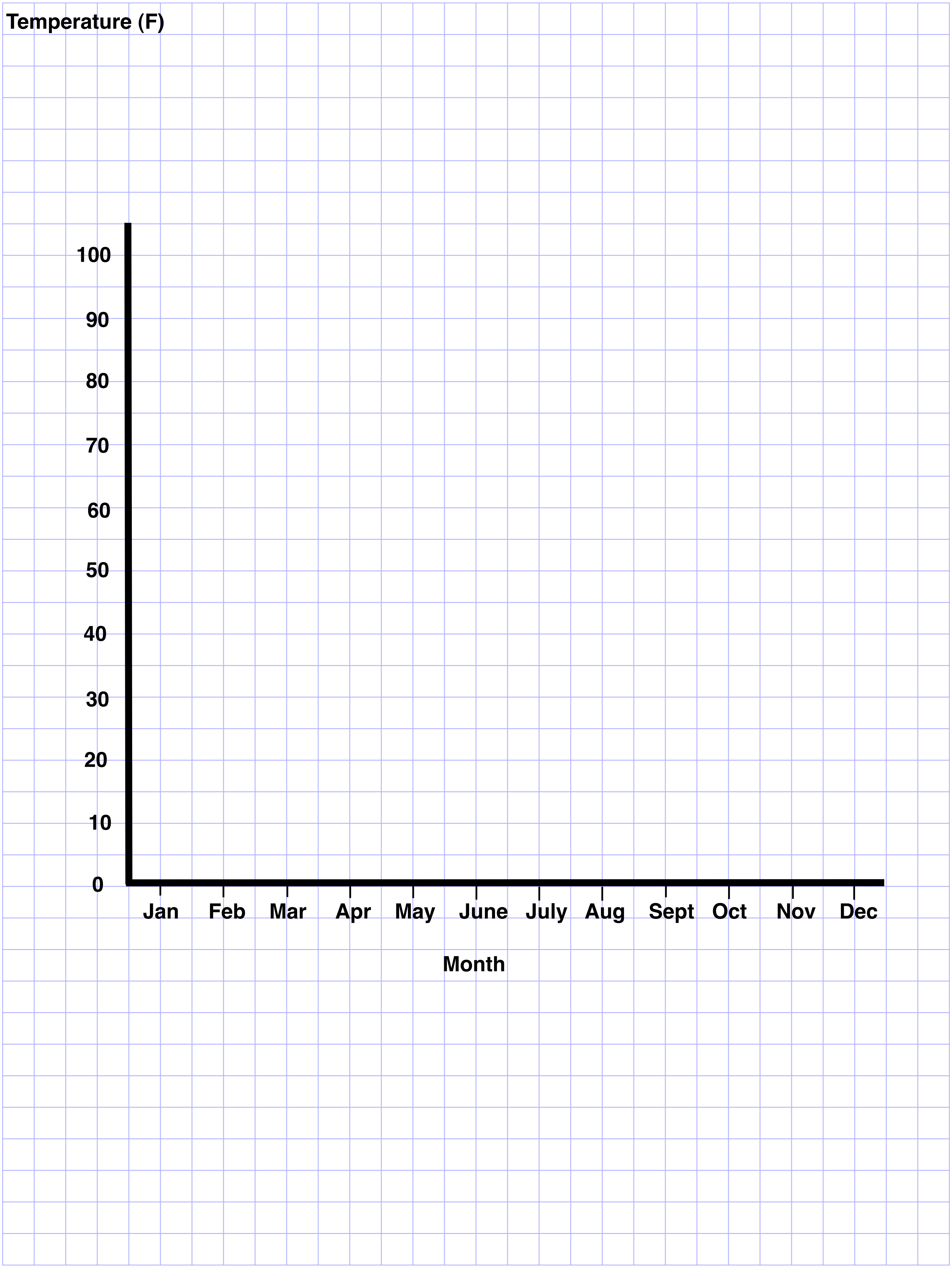
    - How are the temperature graphs different between your city and your other group members?

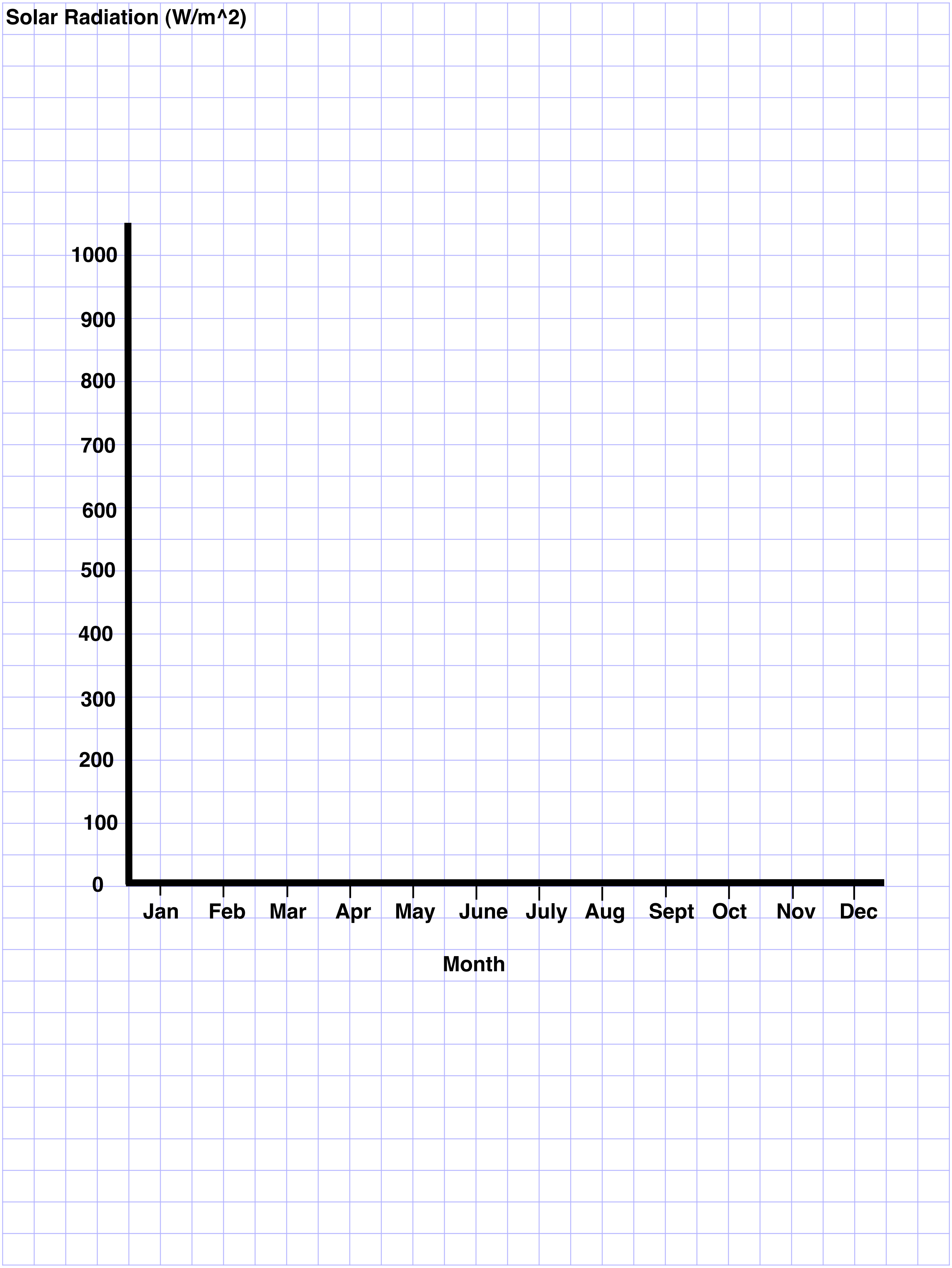
    - What reason(s) can you think of to explain this? Discuss this in your group.

Month	Anchorage, Alaska	Quito, Ecuador	Seattle, Washington	Sydney, Australia
January	16	58	40	72
February	19	58	43	73
March	26	58	45	71
April	37	59	49	66
May	47	59	55	61
June	55	58	60	56
July	58	58	65	55
August	56	58	65	56
September	48	59	60	60
October	34	58	53	65
November	22	58	45	67
December	18	58	40	71

The data used in this activity were collected from http://ccc.atmos.colostate.edu/ and http://www.ncdc.noaa.gov/oa/ncdc.html.


Solar Radiation (W/m^2)
1000
900
800
700
600
500
400
300
200
100
0
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec
Month


Temperature (F)
100
90
80
70
60
50
40
30
20
10
0
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec
Month


Solar Radiation (W/m^2)
1000
900
800
700
600
500
400
300
200
100
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Jan
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June
July
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Nov
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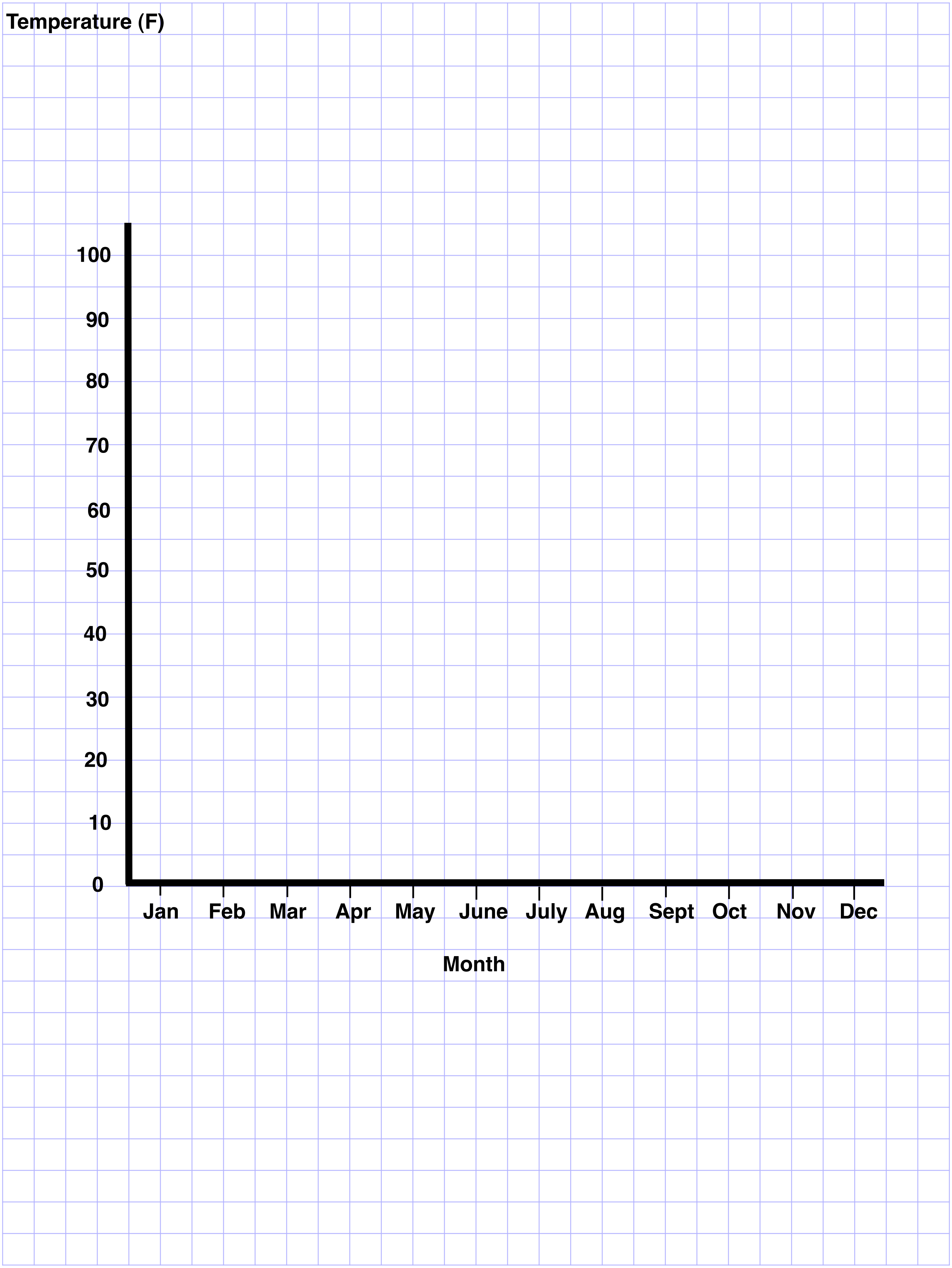
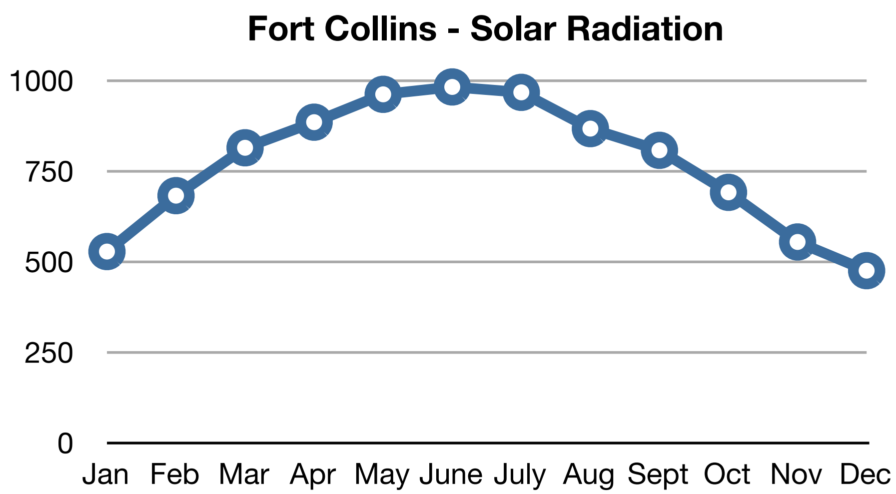
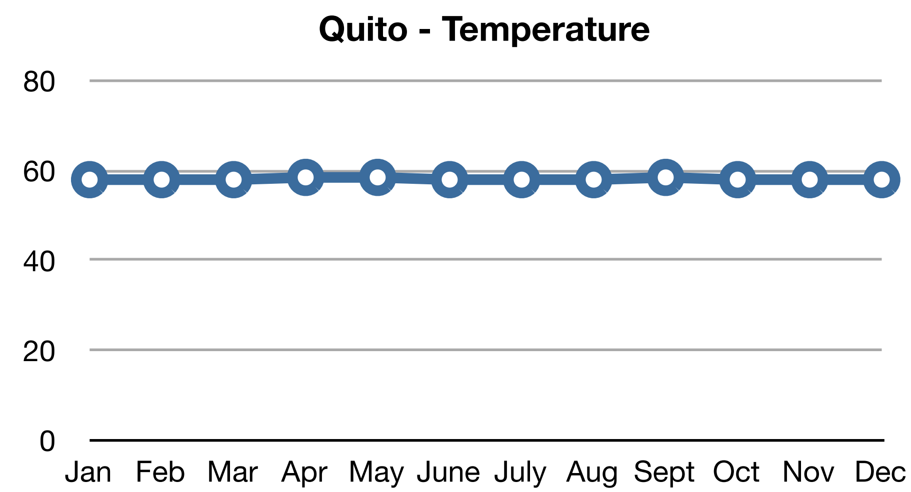
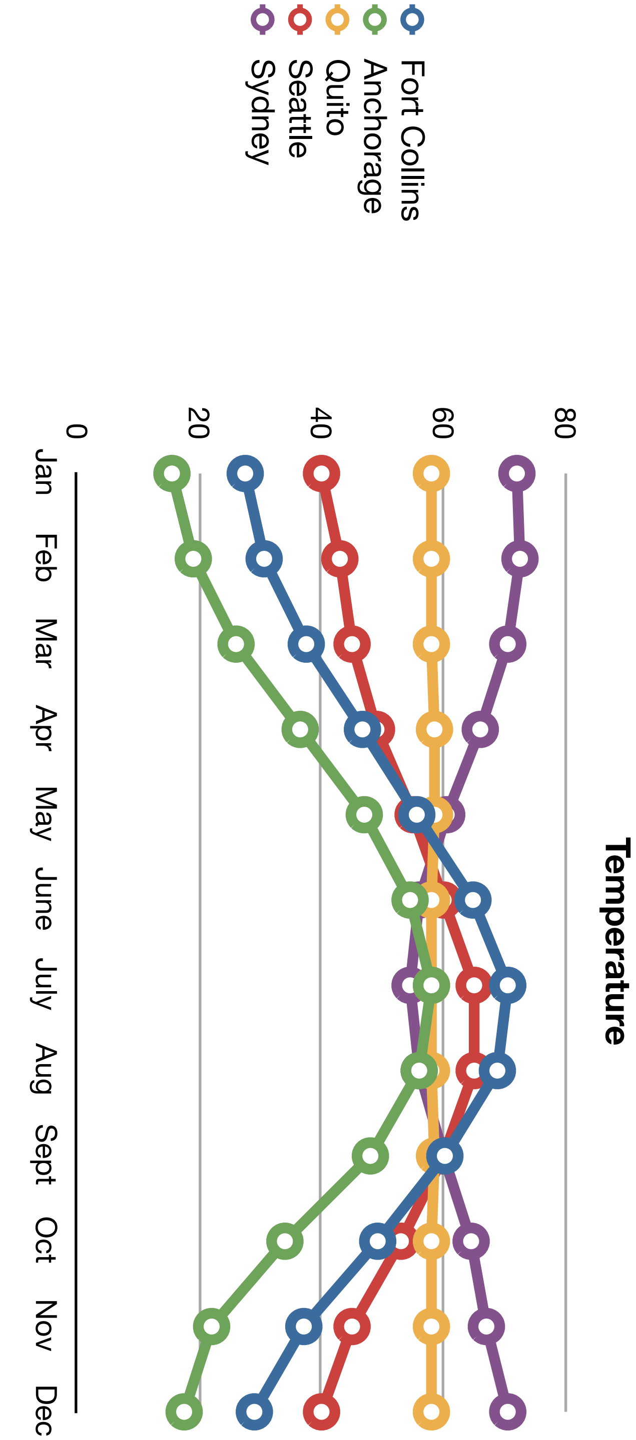
Month

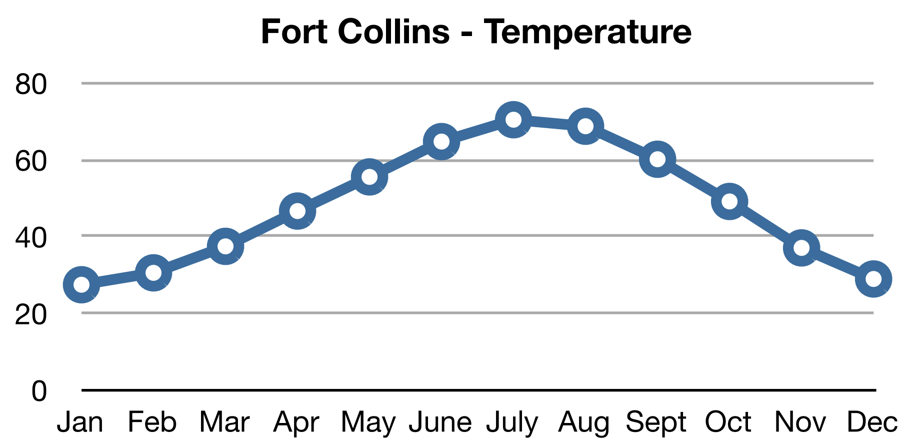

Temperature (F)
100
90
80
70
60
50
40
30
20
10
0
Jan
Feb
Mar
Apr
May
June
July
Aug
Sept
Oct
Nov
Dec
Month

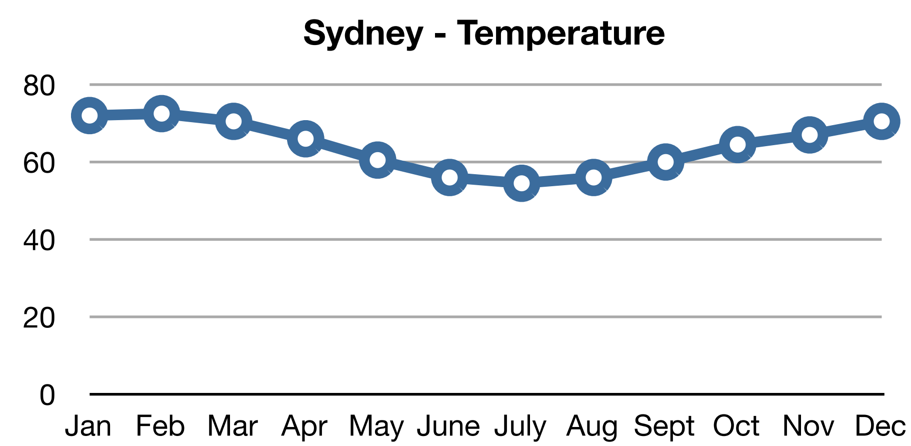
Answer Key
Solar Radiation and Temperature Plots


Fort Collins - Solar Radiation
1000
750
500
250
0
Jan Feb Mar Apr May June July Aug Sept Oct Nov Dec


Quito - Temperature
80
60
40
20
0
Jan Feb Mar Apr May June July Aug Sept Oct Nov Dec


Fort Collins
Anchorage
Quito
Seattle
Sydney
Temperature
0
20
40
60
80
Jan Feb Mar Apr May June July Aug Sept Oct Nov Dec


Fort Collins - Temperature
80
60
40
20
0
Jan Feb Mar Apr May June July Aug Sept Oct Nov Dec


Sydney - Temperature
80
60
40
20
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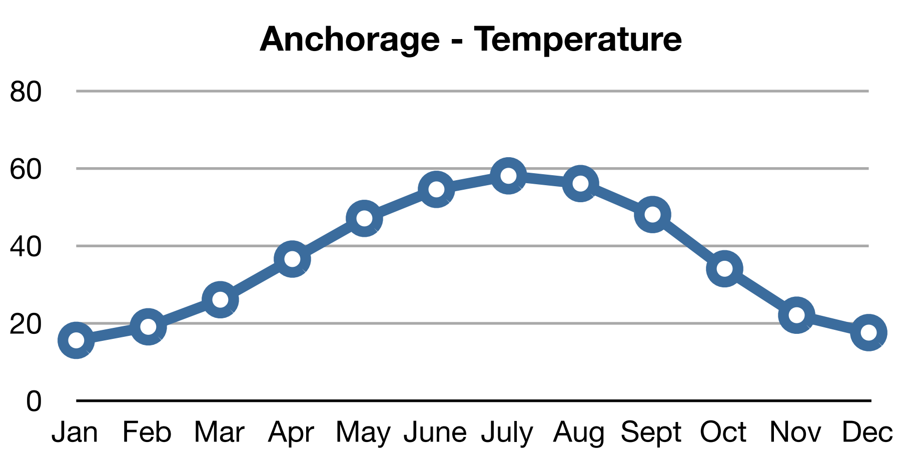
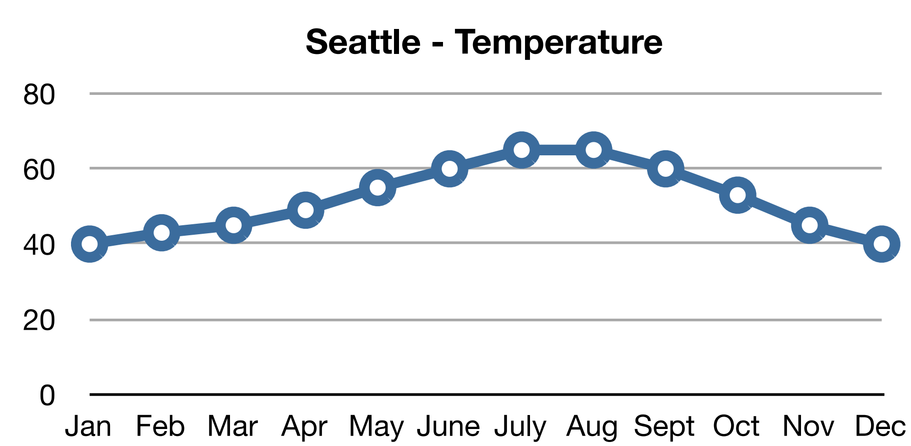
Jan Feb Mar Apr May June July Aug Sept Oct Nov Dec


Anchorage - Temperature
80
60
40
20
0
Jan Feb Mar Apr May June July Aug Sept Oct Nov Dec


Seattle - Temperature
80
60
40
20
0
Jan Feb Mar Apr May June July Aug Sept Oct Nov Dec