

Simulations and Models for Teaching Earth System Science

Randy Russell

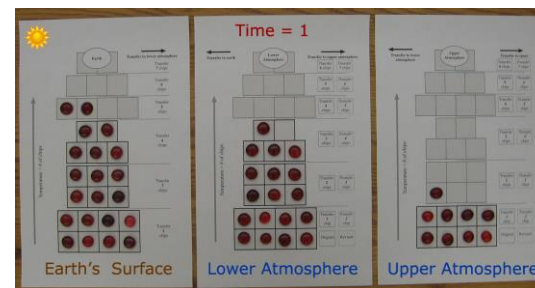
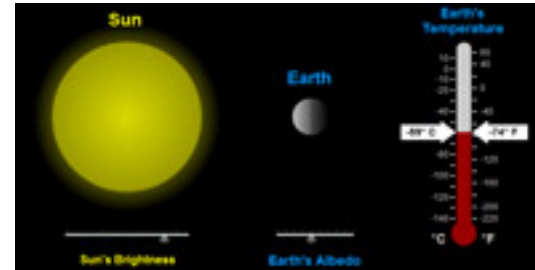
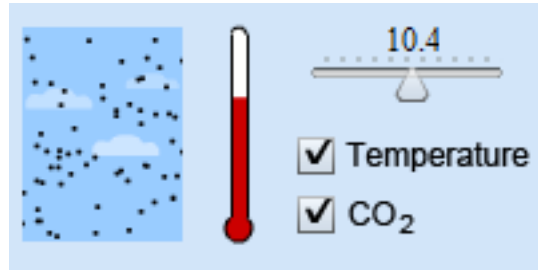
UCAR Center for Science Education

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Presentation Overview

- Mostly: demo simulations
- Quick introductions: myself, NCAR, UCAR Center for Science Education
- NGSS & Modeling
- A bunch of quick demonstrations



About Me



- started in science and engineering (BS astrophysics, MS aerospace engineering)
- switched to STEM education (PhD from Michigan State)
- at NCAR/UCAR in Boulder, Colorado for 15 years and counting
- develop simulations and games, online courses, web pages and activities, teacher PD (online and face-to-face)

National Center for Atmospheric Research

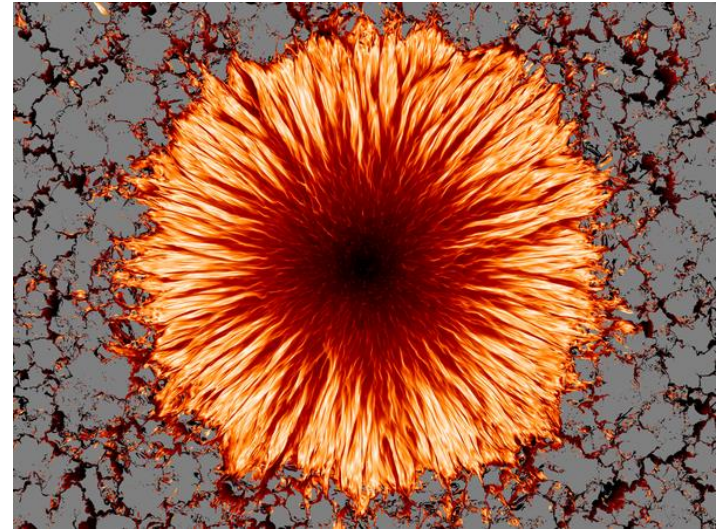
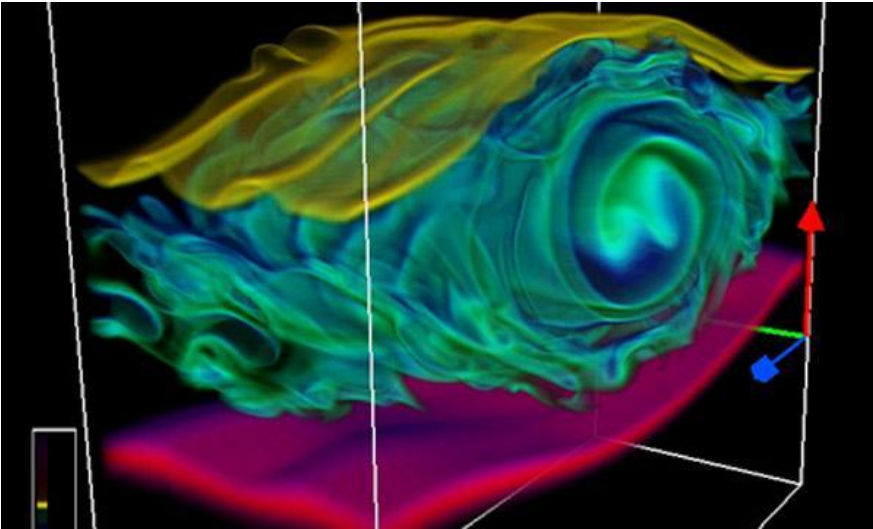
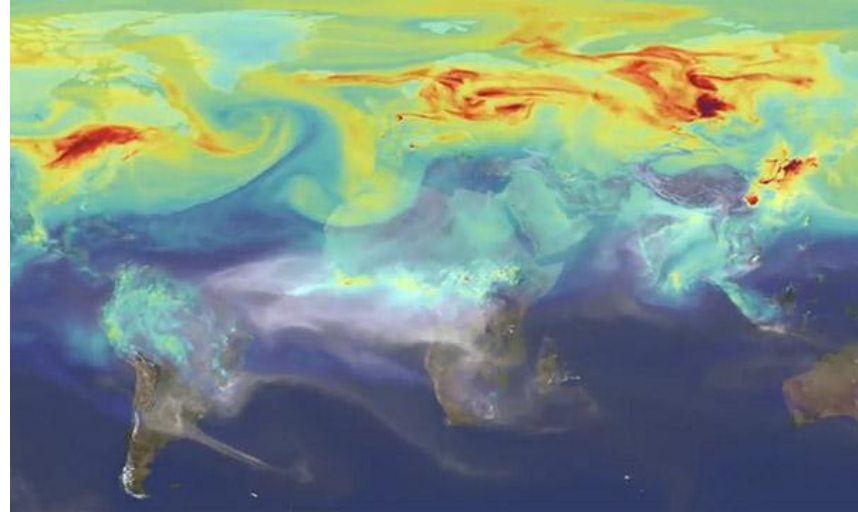
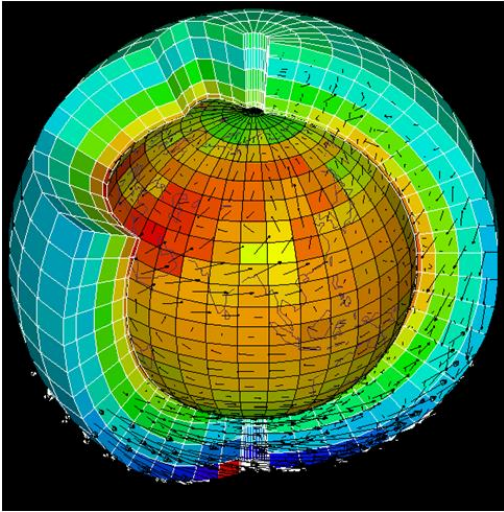
Boulder, CO



Computing & Modeling at NCAR



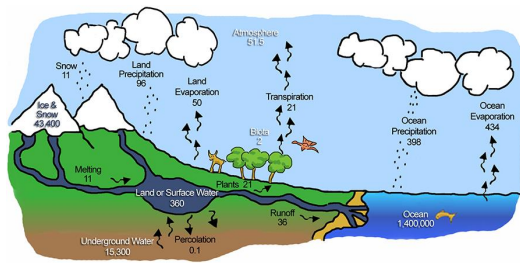
Modeling & Computing at NCAR



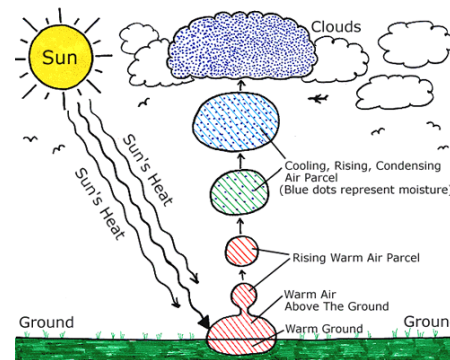
Types of "Models"



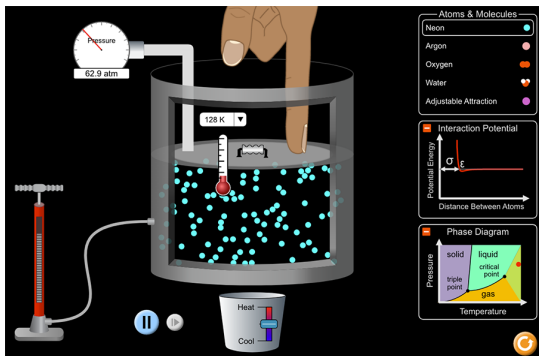
Mental Models



Conceptual Models



Diagrams



Computer Simulations

Δ Rabbits
 Δ Time



Mathematical Representations



Physical Replicas

Mental Models vs. Conceptual Models

NGSS distinguishes between **mental** models and **conceptual** models

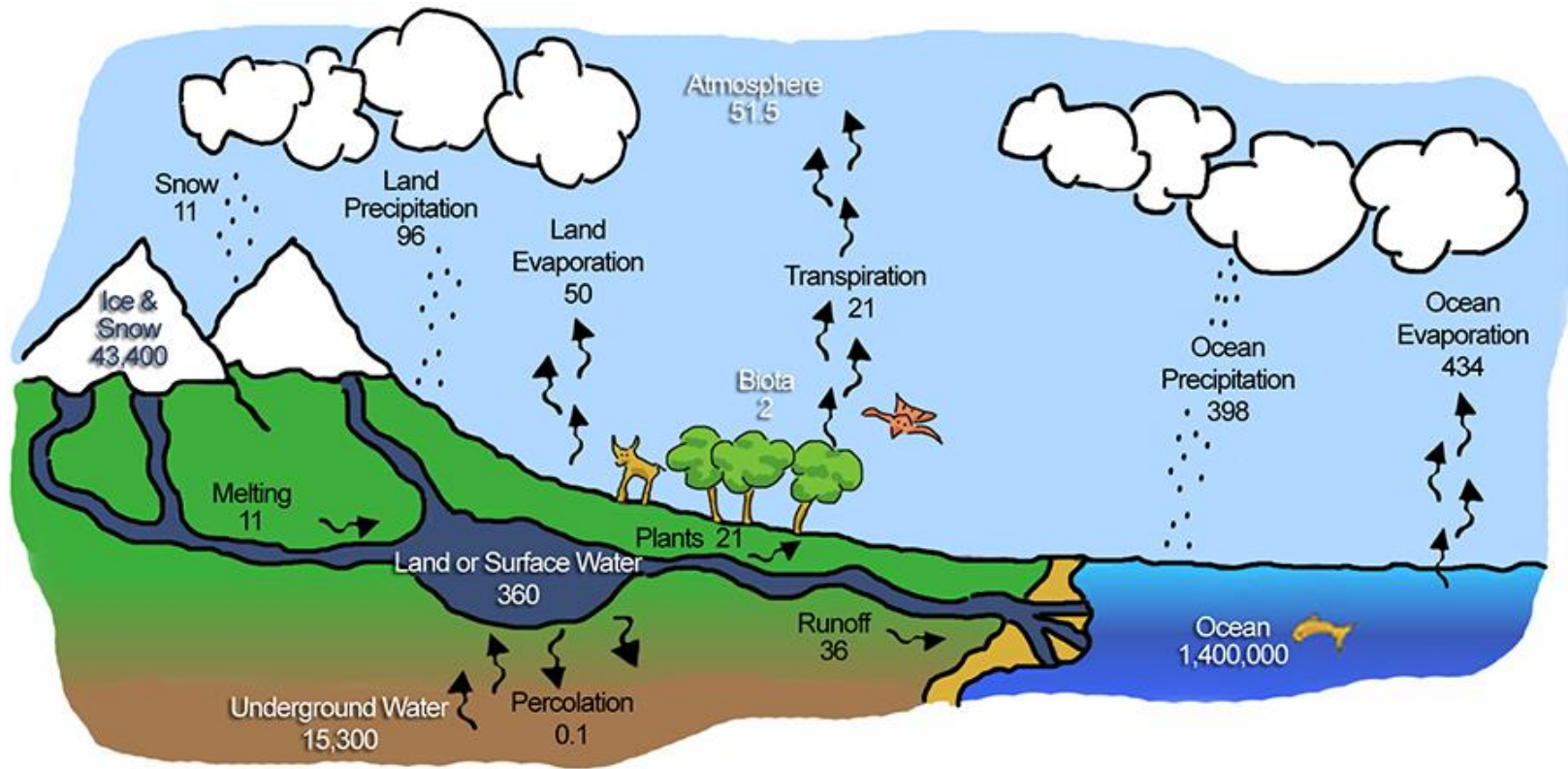
“Scientists construct mental and conceptual models of phenomena. Mental models are internal, personal, idiosyncratic, incomplete, unstable, and essentially functional. They serve the purpose of being a tool for thinking with, making predictions, and making sense of experience.” (NGSS p. 56)

Mental Model: “Bird”



Conceptual Models

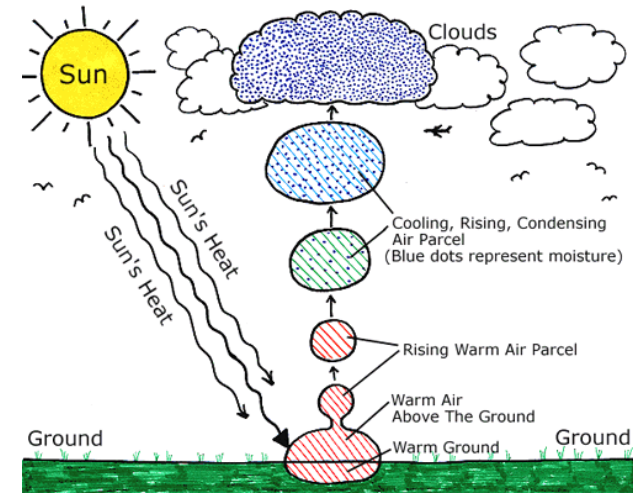
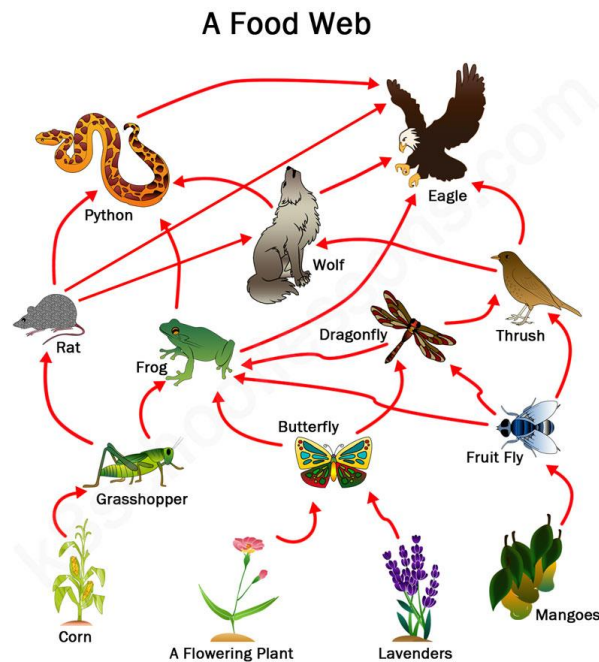
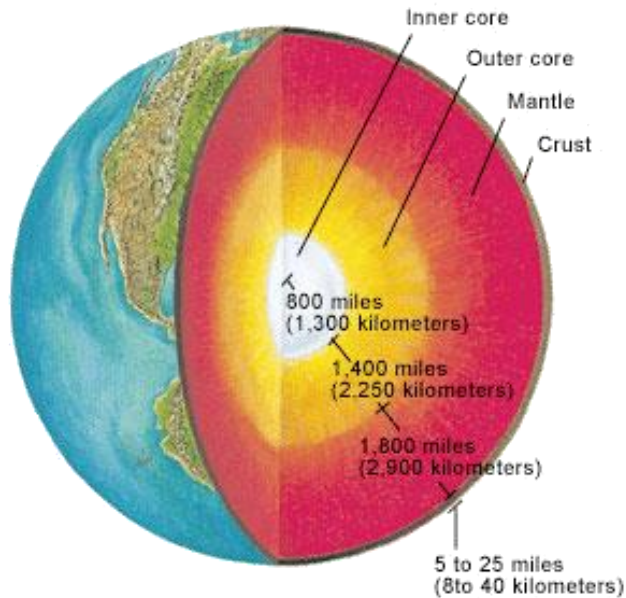
“Conceptual models, are, in contrast, explicit representations that are in some ways analogous to the phenomena they represent. Conceptual models allow scientists and engineers to better visualize and understand a phenomenon under investigation or develop a possible solution to a design problem.” (NGSS p. 56)



Conceptual Models

“... conceptual models include **diagrams, physical replicas, mathematical representations, analogies, and computer simulations.**” (NGSS p. 56)

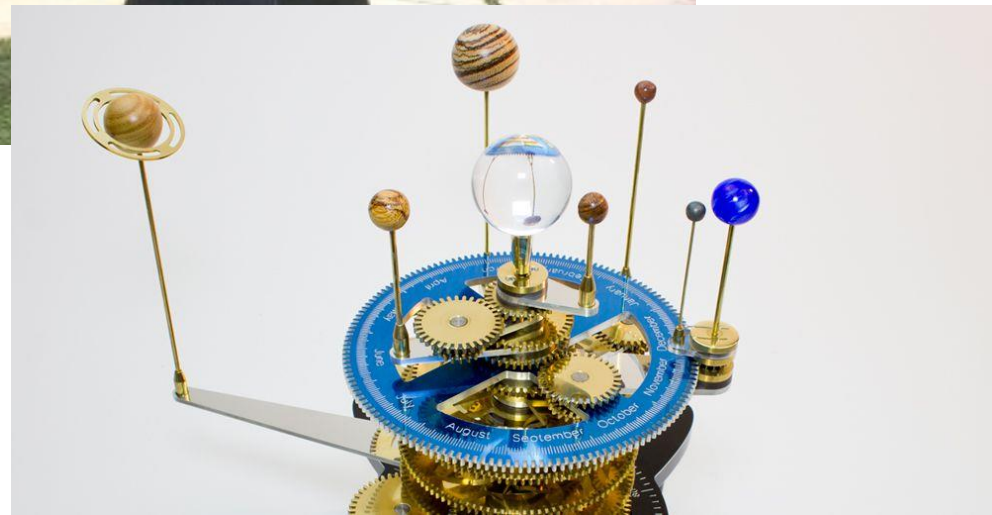
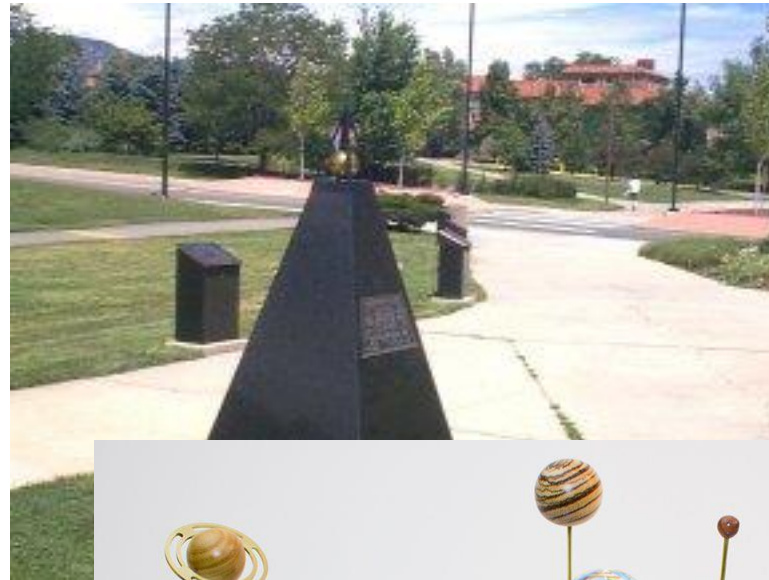
Diagrams



Conceptual Models

“... conceptual models include diagrams, **physical replicas**, mathematical representations, analogies, and computer simulations.” (NGSS p. 56)

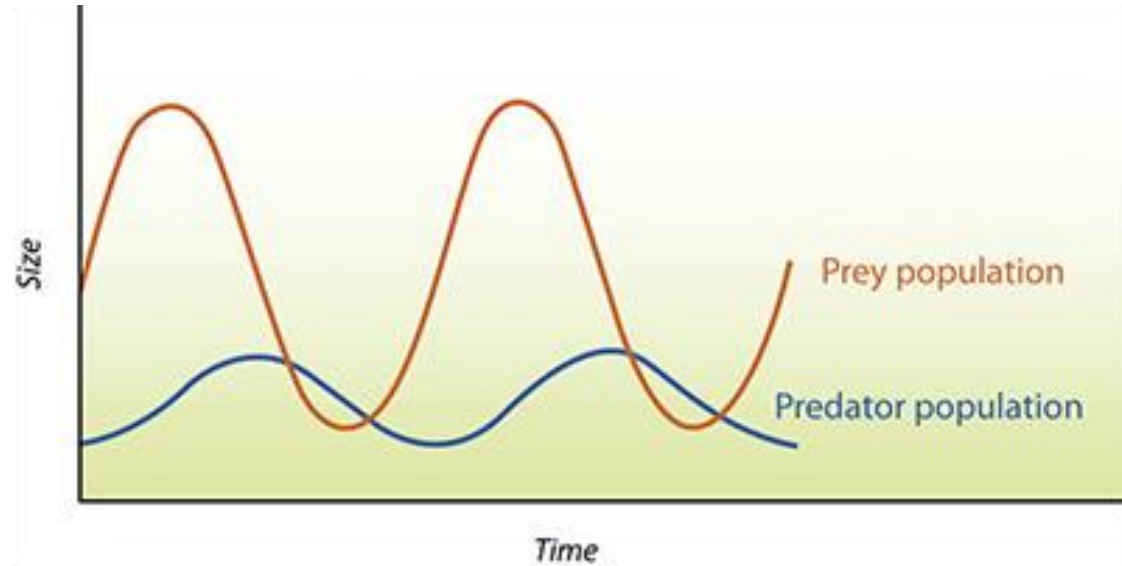
Physical Replicas & Scale Models



Conceptual Models

“... conceptual models include diagrams, physical replicas, **mathematical representations**, analogies, and computer simulations.” (NGSS p. 56)

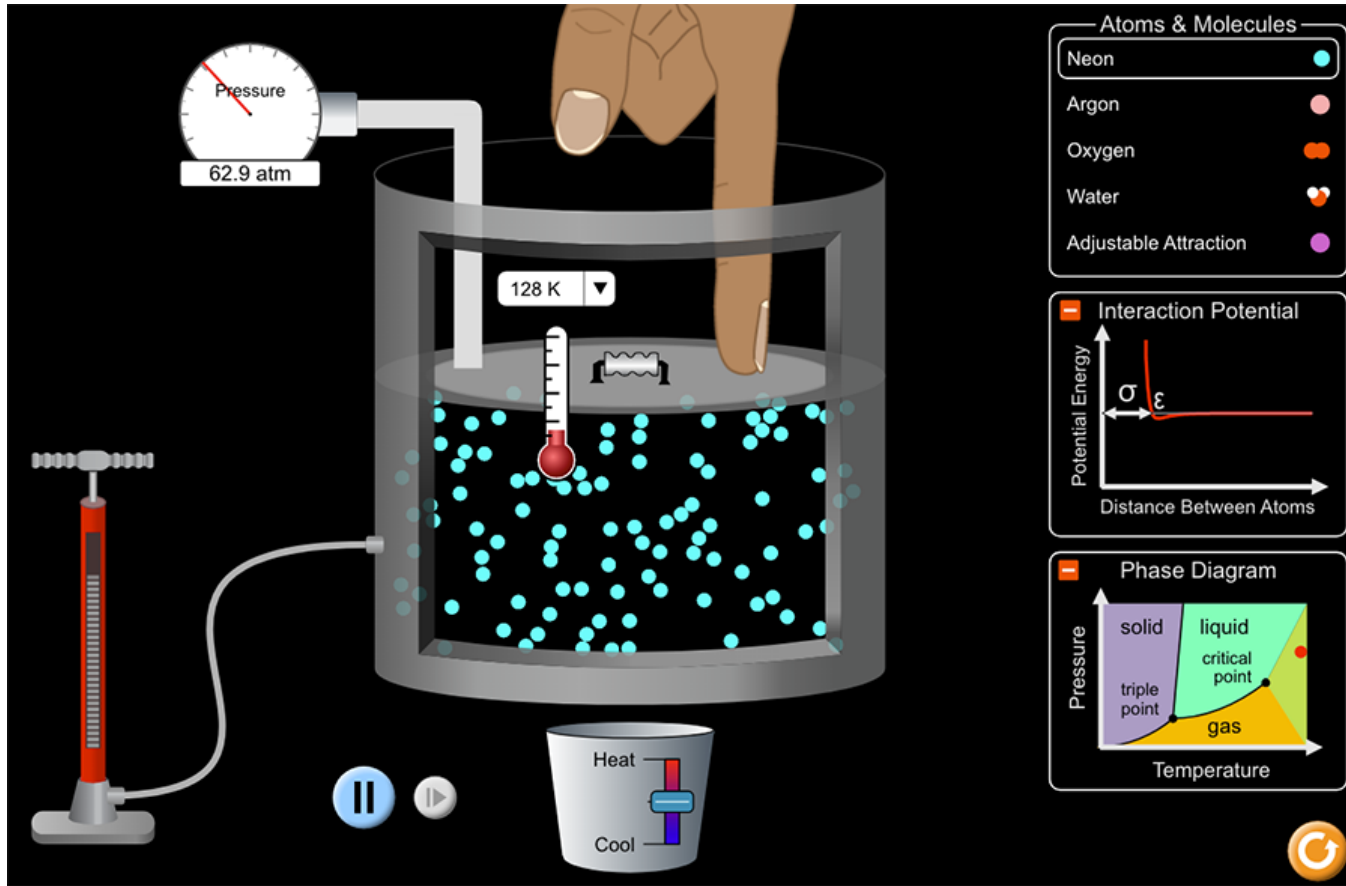
Mathematical Models



$$\frac{\Delta \text{ Rabbits }}{\Delta \text{ Time }} = (\text{birth rate}) \times (\# \text{ rabbits}) - (\text{eat rate}) \times (\# \text{ rabbits}) \times (\# \text{ wolves})$$

Conceptual Models

“... conceptual models include diagrams, physical replicas, mathematical representations, analogies, and **computer simulations.**” (NGSS p. 56)



Most of Webinar on Computer Simulations

- importance of having students behave like scientists – running models – not just being told about them
- other topics important too – students **constructing** depictions of their own models – concept maps as example of this
- models that only show “connections” via arrows are OK as far as they go, but limited... what is the math/behavior behind the arrow (this is often crucial in determining the behavior of the system)... important to also have students run mathematical models expressed as computer simulations to see how systems behave (feedback loops, delays, exponential growth or oscillations)
- visual, interactive, game-like models can allow even very young students to experience “running” models; better prepares them to encounter more advanced simulations and models in MS/HS and beyond, (like math; teach them arithmetic now, knowing they’ll do algebra and trigonometry later)

All models are wrong, but...



“Essentially, all models are wrong,
but some models are useful.”

- George E. P. Box (1951)



NGSS on the Limitations of Models

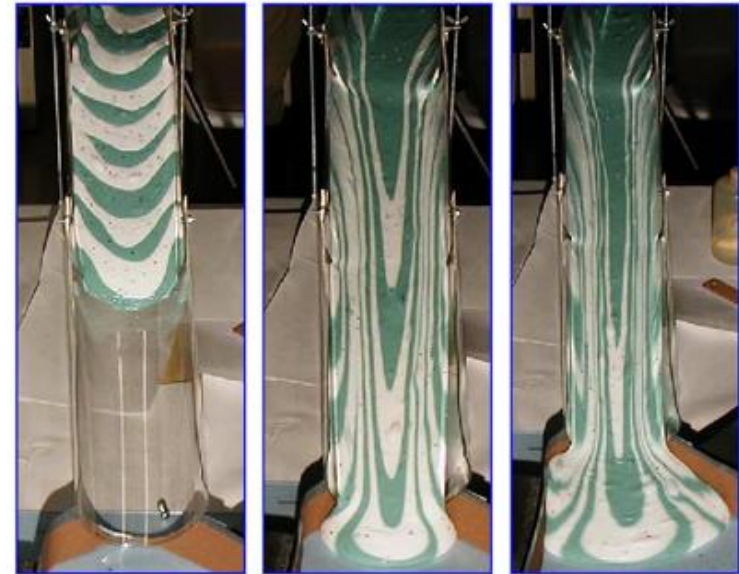


"Although they [conceptual models] **do not correspond exactly** to the more complicated entity being modeled, they do bring certain features into focus while minimizing or obscuring others. Because all models contain approximations and assumptions that limit the range of validity of their application and the precision of their predictive power, **it is important to recognize their limitations.**" (NGSS p. 56)

"But as in science, engineers who use models must be aware of their **intrinsic limitations** and test them against known situations to ensure that they are reliable." (NGSS p. 57-58)

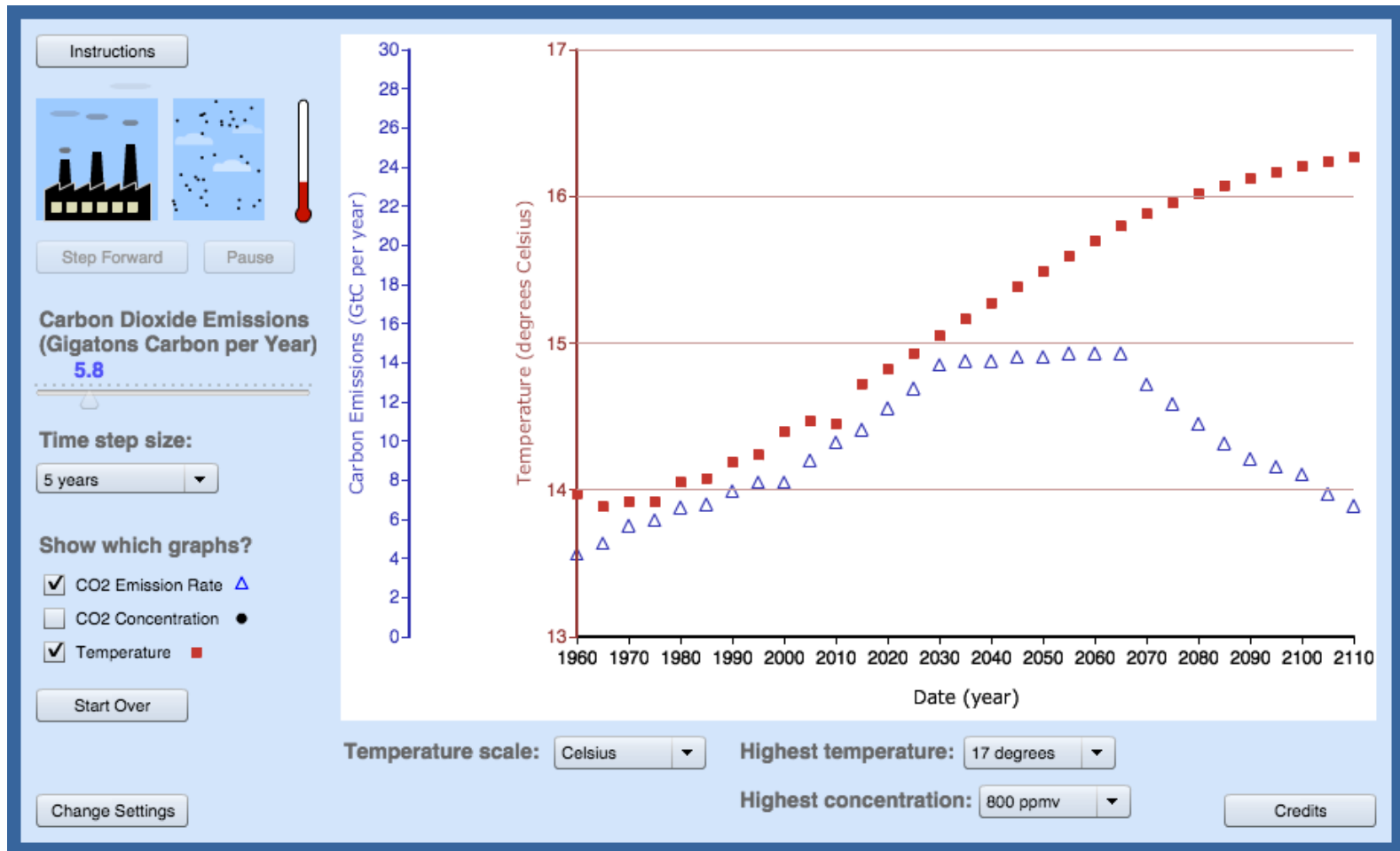
[By grade 12, students should be able to:] "Discuss the **limitations and precision of a model** as the representation of a system, process, or design and suggest ways in which the model might be improved to better fit available evidence or better reflect a design's specifications. Refine a model in light of empirical evidence or criticism to improve its quality and explanatory power." (NGSS p. 58)

Possible Strategy: Pair Concrete Physical Demonstrations with Computer Simulations



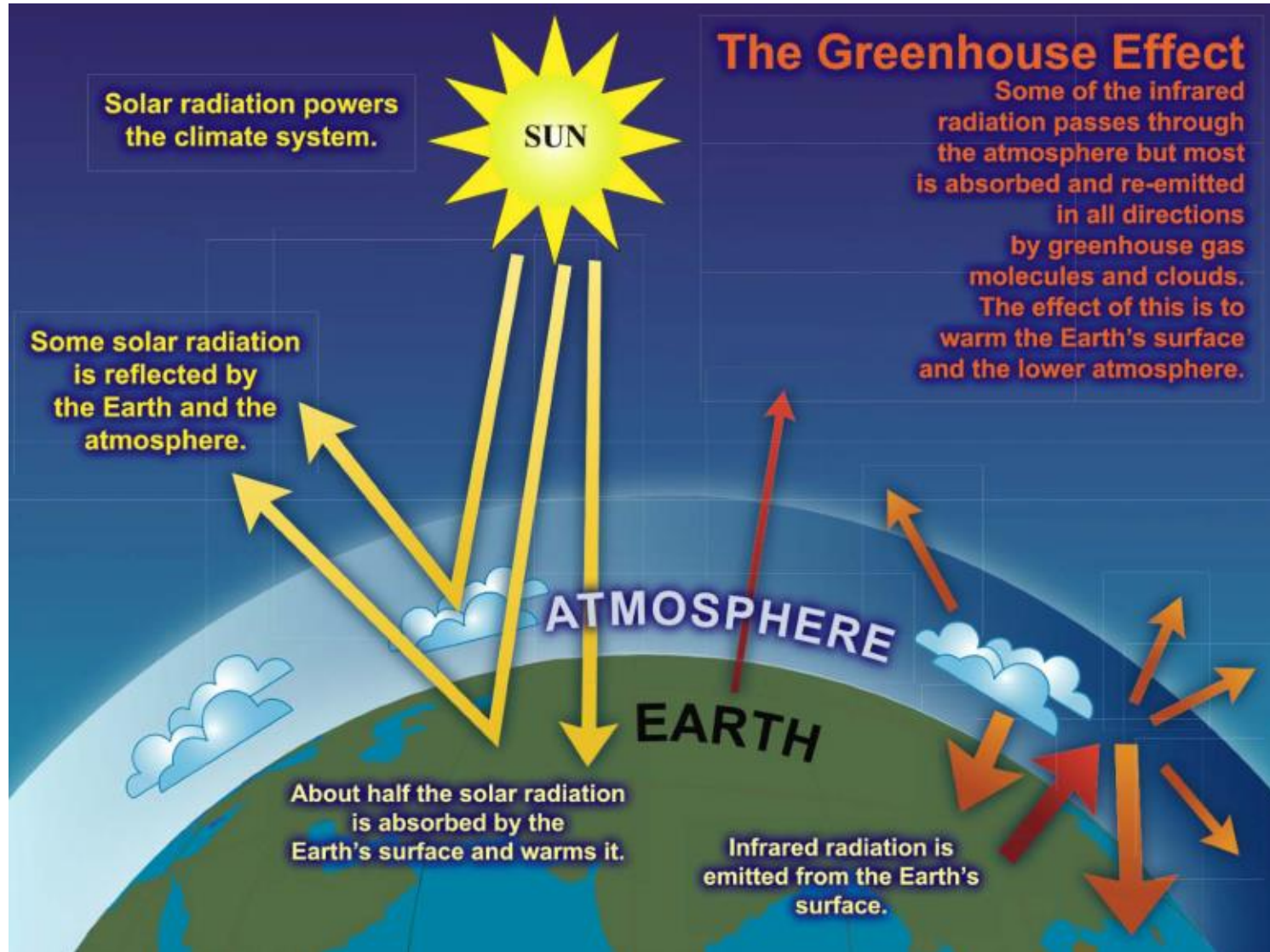
The screenshot shows the 'Glaciers (2.04)' simulation interface. At the top, there are 'File' and 'Help' menus, and tabs for 'Introduction' and 'Advanced'. The main display area shows a 3D cross-section of a glacier system with a brown terrain, a white glacier body, and a blue sky. A small cartoon bear character is visible on the left. Below the main display is a 'Toolbox' with icons for a thermometer, a green flag, a red flag, a saw, a drill, and a mobile phone. The bottom section contains control panels for 'View' (units: English/metric, equilibrium line, snowfall) and 'Climate' (Sea-level air temperature: 55.4 to 68.0 °F, Average snowfall: 0.0 to 4.9 ft). There are also sliders for time (10 years) and speed (slow/fast), and buttons for 'Show real glacier', 'Set glacier to steady state', and 'Reset All'. At the bottom, there are navigation buttons for '?', 'Credits', a home icon, and a refresh icon. A small bar chart at the bottom right shows a 'Year' axis from 1 to 15, with bars for years 1-4 labeled 'Cool' and 'Dry'.

The Very, Very Simple Climate Model

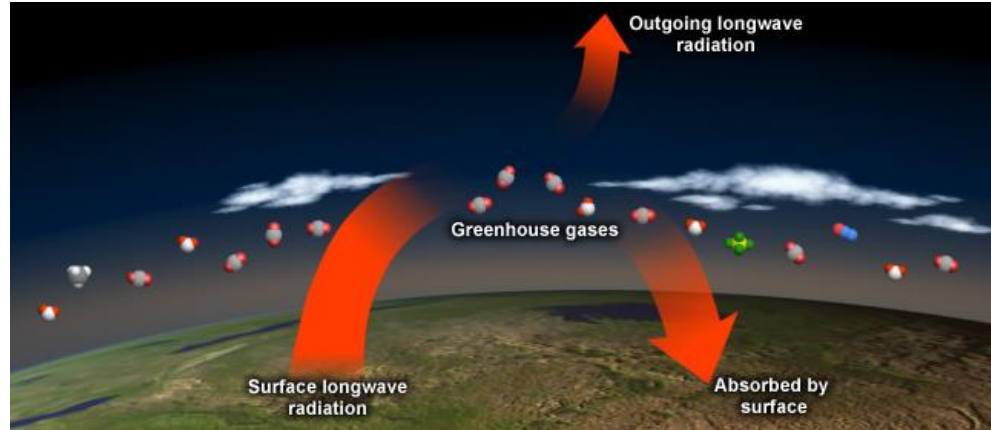
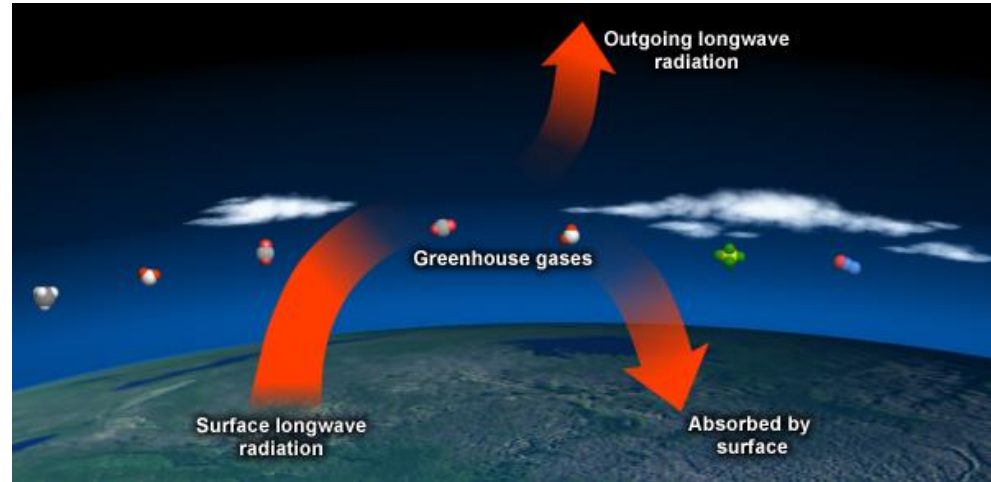
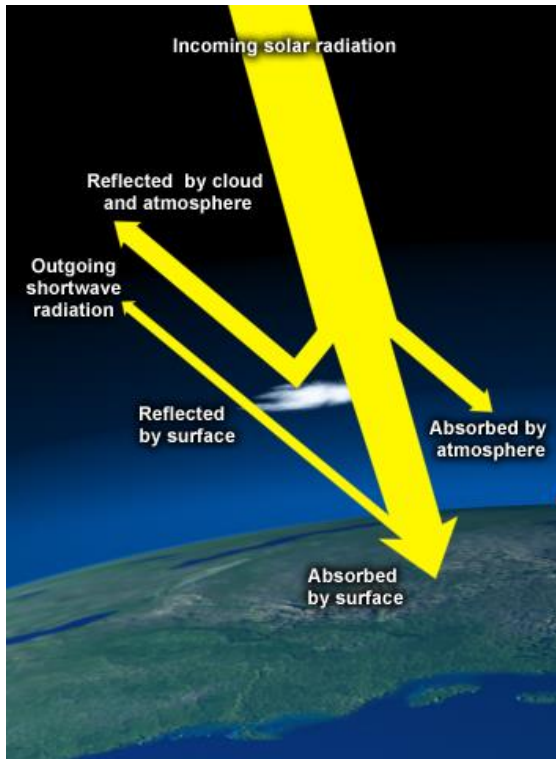


URL: SciEd.ucar.edu/simple-climate-model

The Greenhouse Effect



The Greenhouse Effect



CO₂ Emissions and a Warming Climate

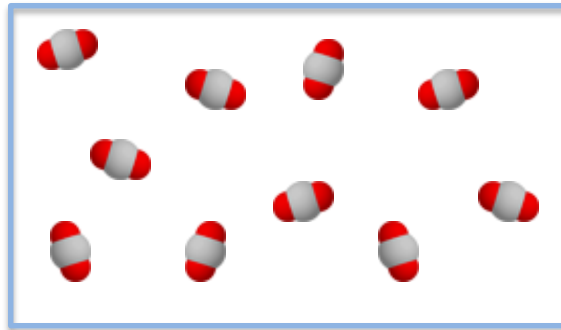
Carbon
Dioxide
Emissions



People
Control This
(input)



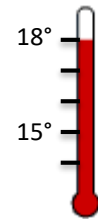
More
Carbon Dioxide
in the
Atmosphere



What
Happens
(output)

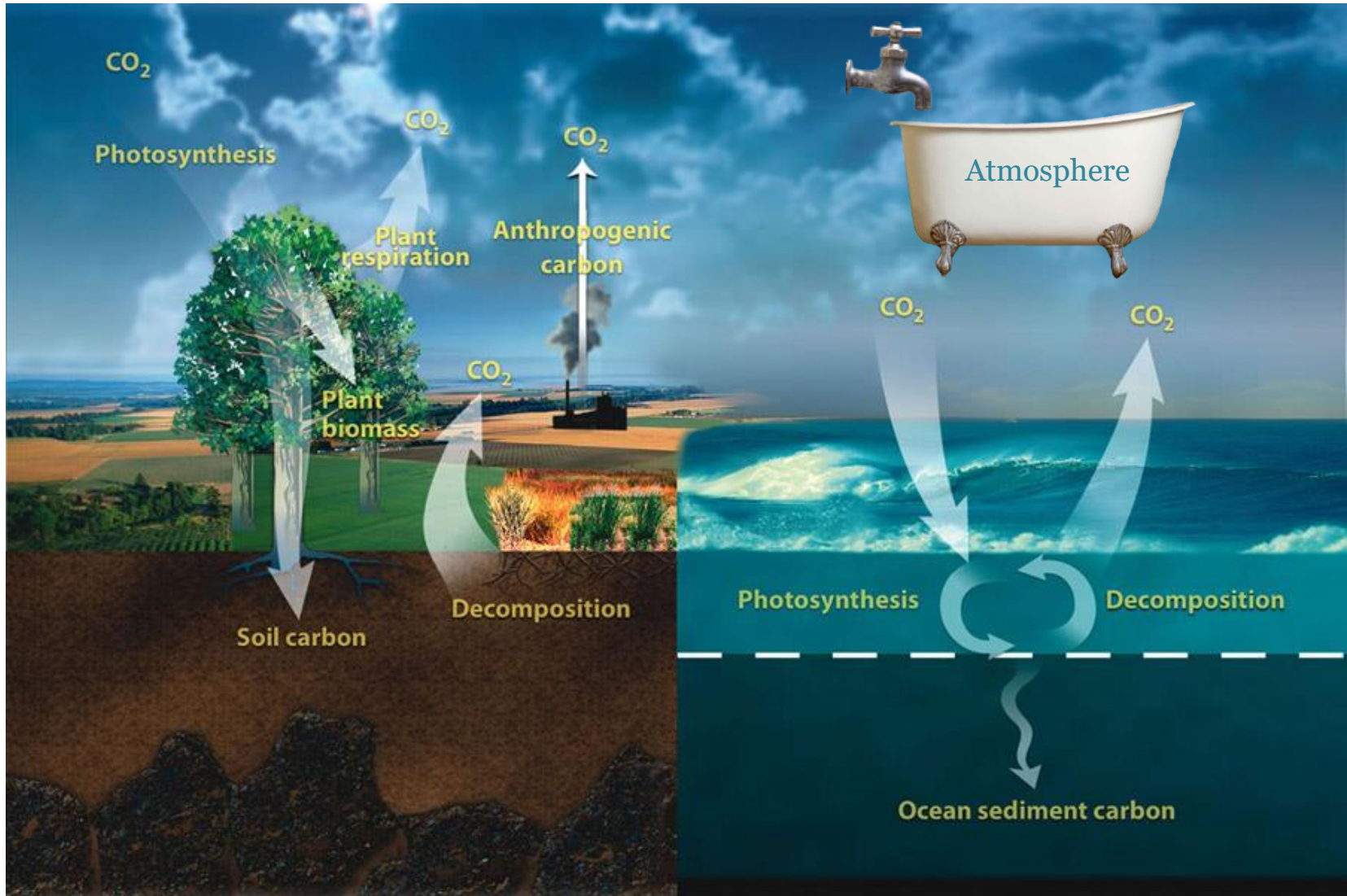


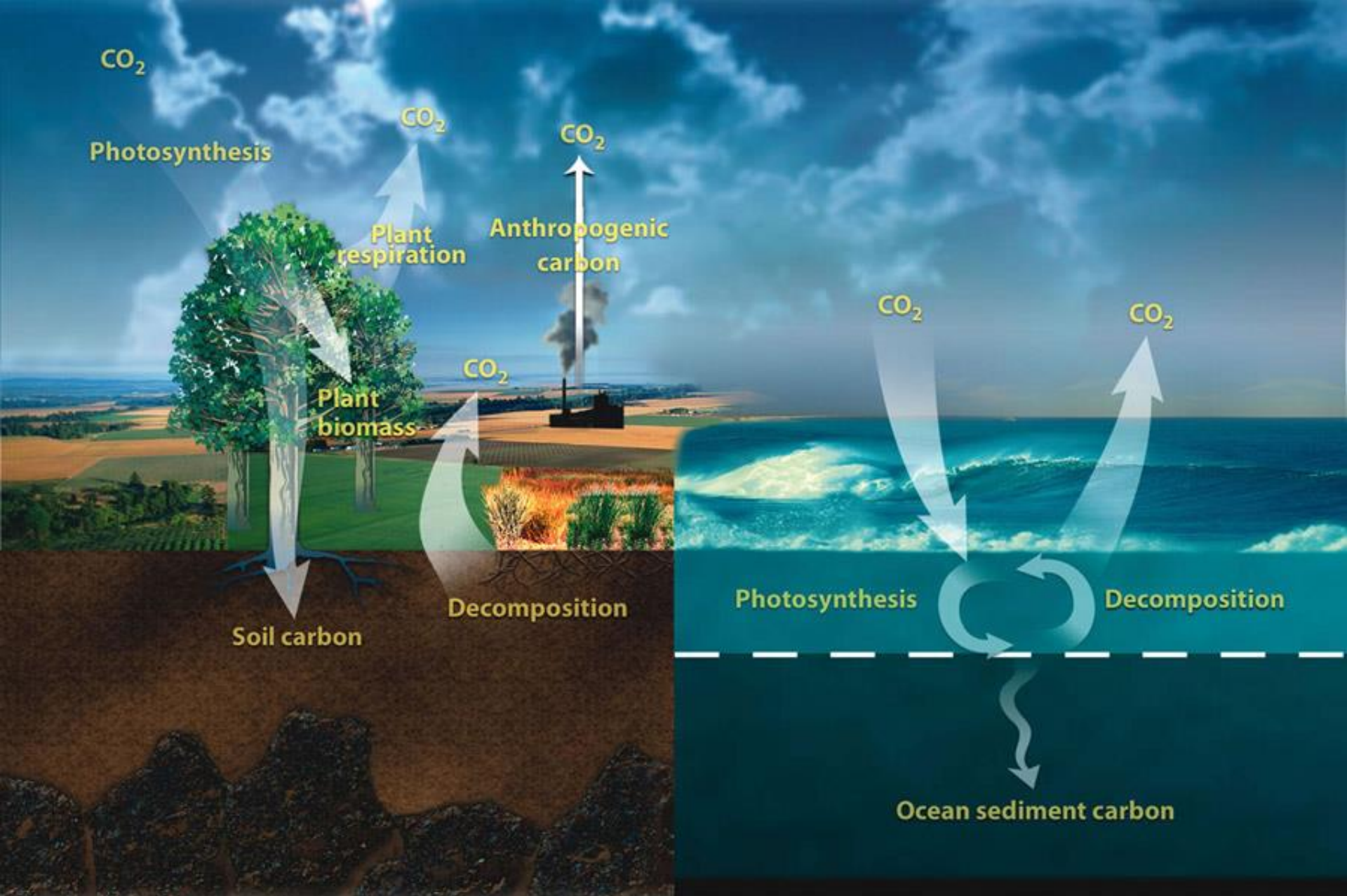
Higher
Temperatures

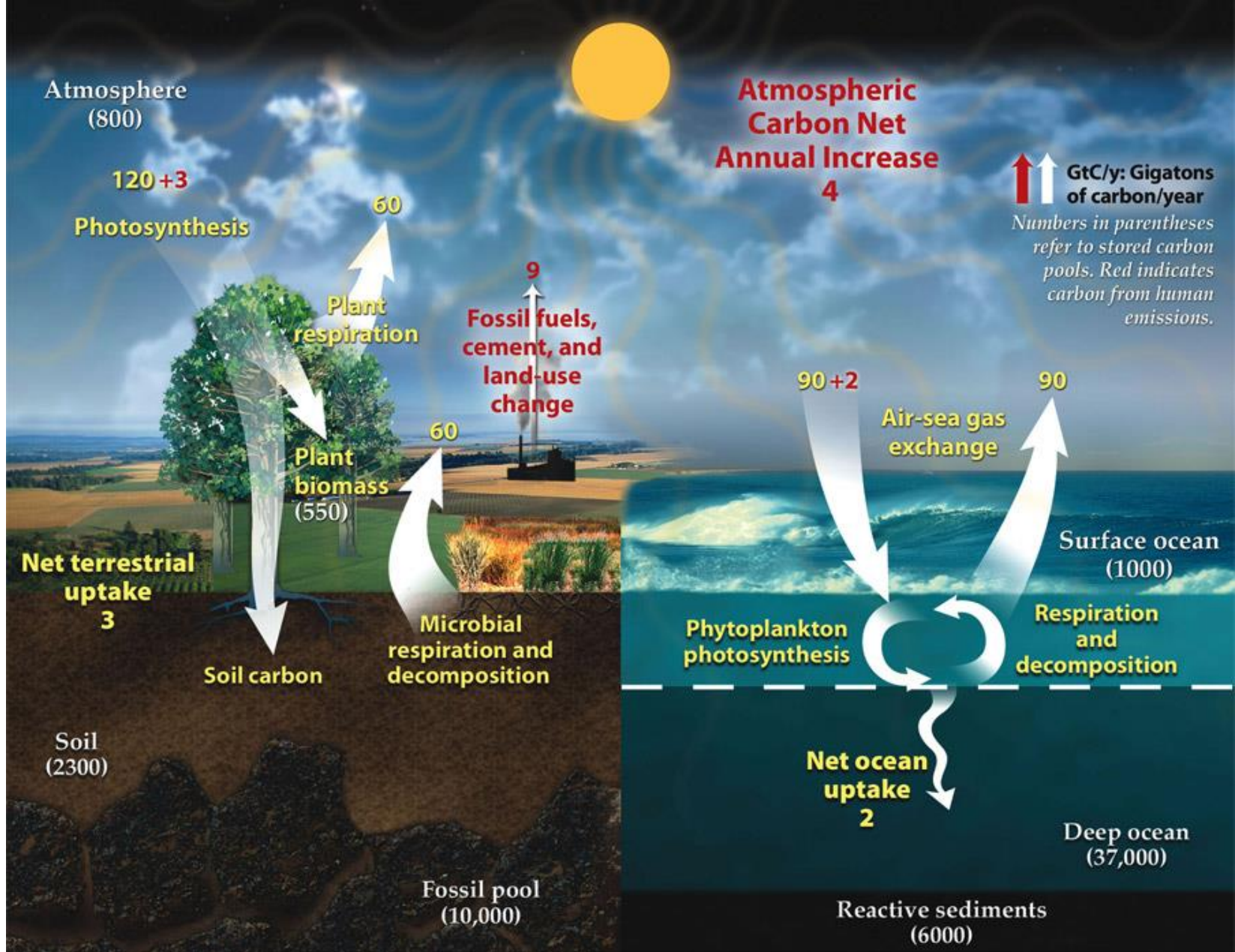


What
Happens
(output)

The Carbon Cycle

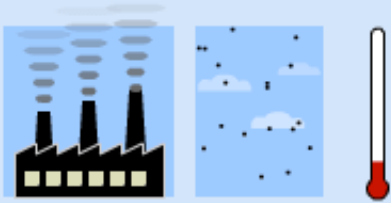






The Very, Very Simple Climate Model

Instructions



Step Forward

Play


Carbon Dioxide Emissions
(Gigatons Carbon per Year)


10.5


Time step size:

5 years

Show which graphs?

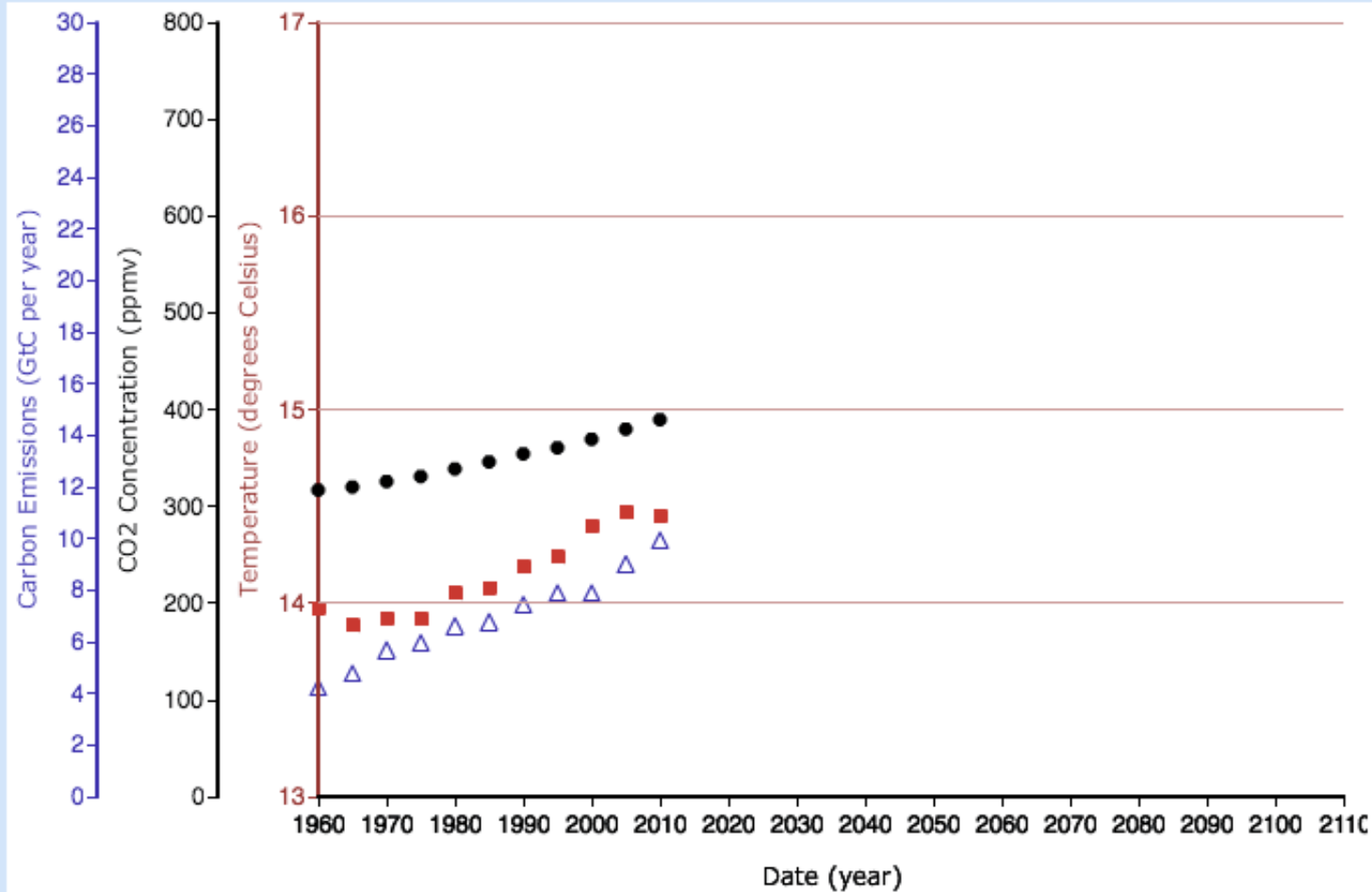
CO2 Emission Rate 

CO2 Concentration 

Temperature 

Start Over

Change Settings



Temperature scale: Celsius

Highest temperature: 17 degrees

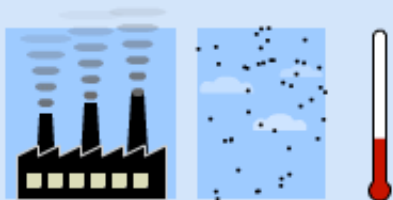
Show Warming Limit Targets

Highest concentration: 800 ppmv

Credits

The Very, Very Simple Climate Model

Instructions



Step Forward

Play


Carbon Dioxide Emissions
(Gigatons Carbon per Year)


20.6


Time step size:

5 years

Show which graphs?

CO2 Emission Rate 

CO2 Concentration 

Temperature 

Start Over

Change Settings

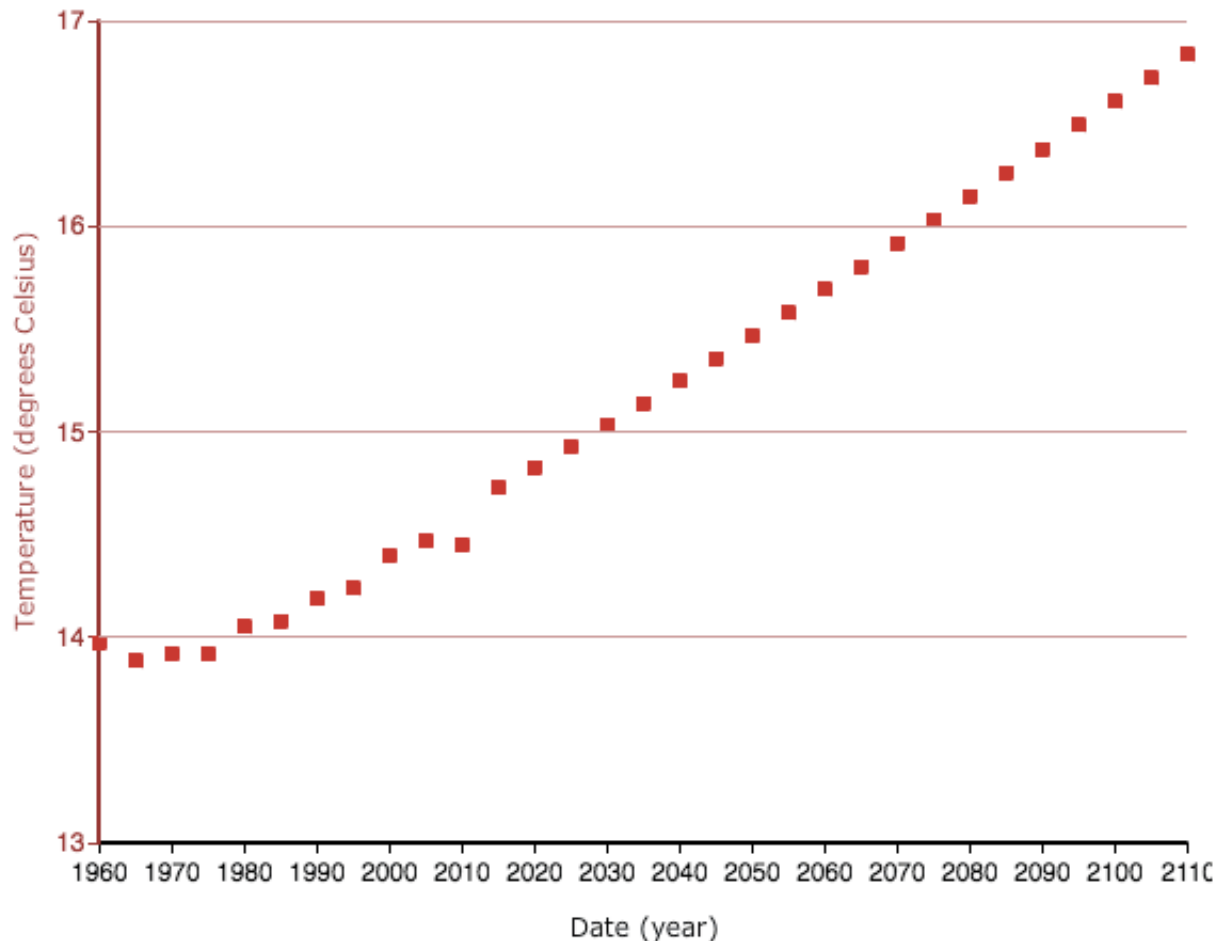
Temperature scale: Celsius

Highest temperature: 17 degrees

Show Warming Limit Targets

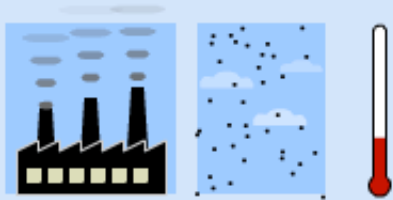
Highest concentration: 800 ppmv

Credits



The Very, Very Simple Climate Model

Instructions



Step Forward

Play


Carbon Dioxide Emissions
(Gigatons Carbon per Year)


13


Time step size:

5 years

Show which graphs?

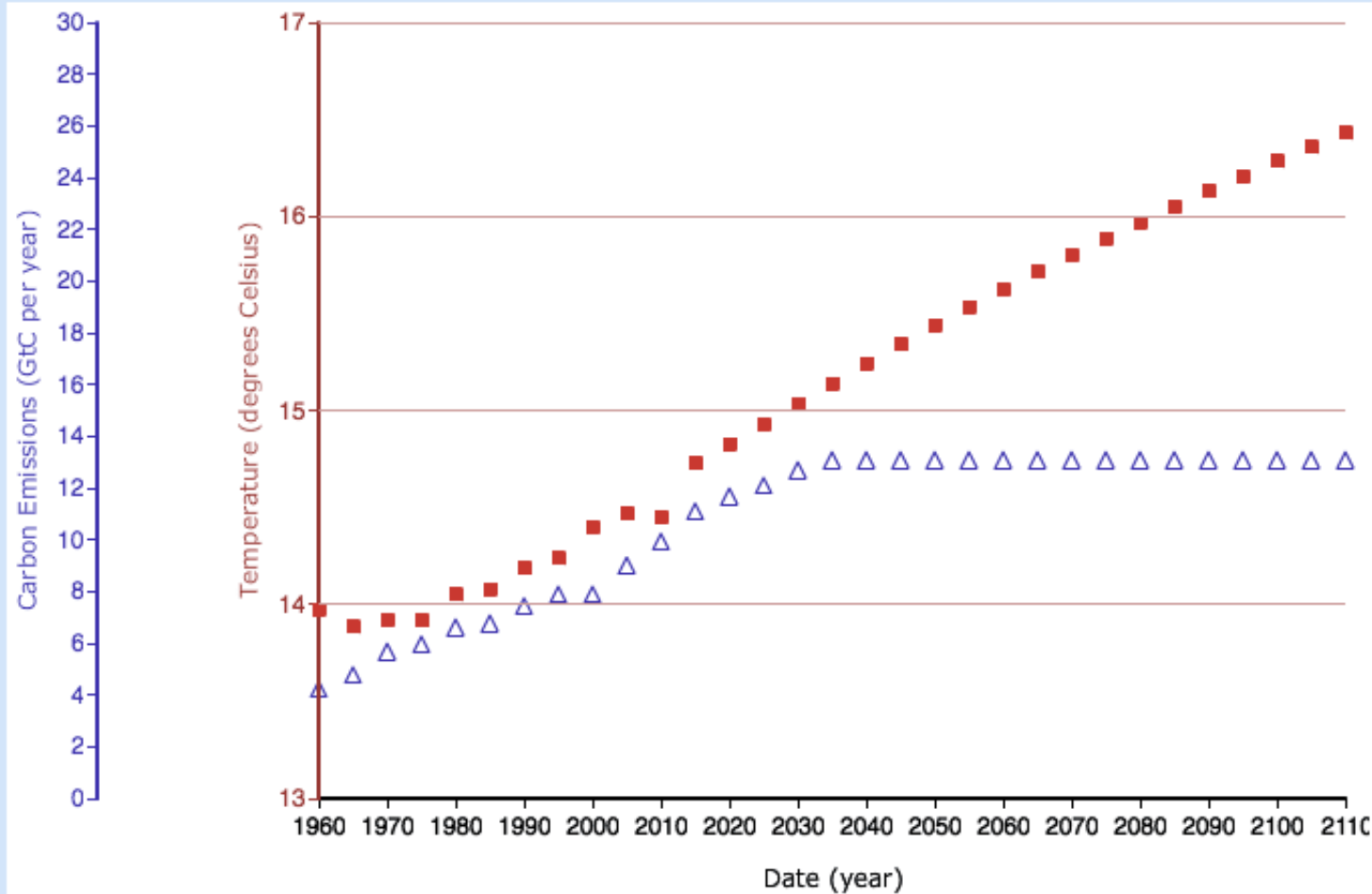
CO2 Emission Rate 

CO2 Concentration 

Temperature 

Start Over

Change Settings



Temperature scale: Celsius

Highest temperature: 17 degrees

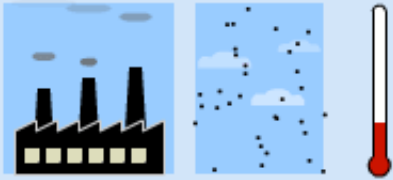
Show Warming Limit Targets

Highest concentration: 800 ppmv

Credits

The Very, Very Simple Climate Model

Instructions



Step Forward

Play


Carbon Dioxide Emissions
(Gigatons Carbon per Year)


5.6


Time step size:

5 years

Show which graphs?

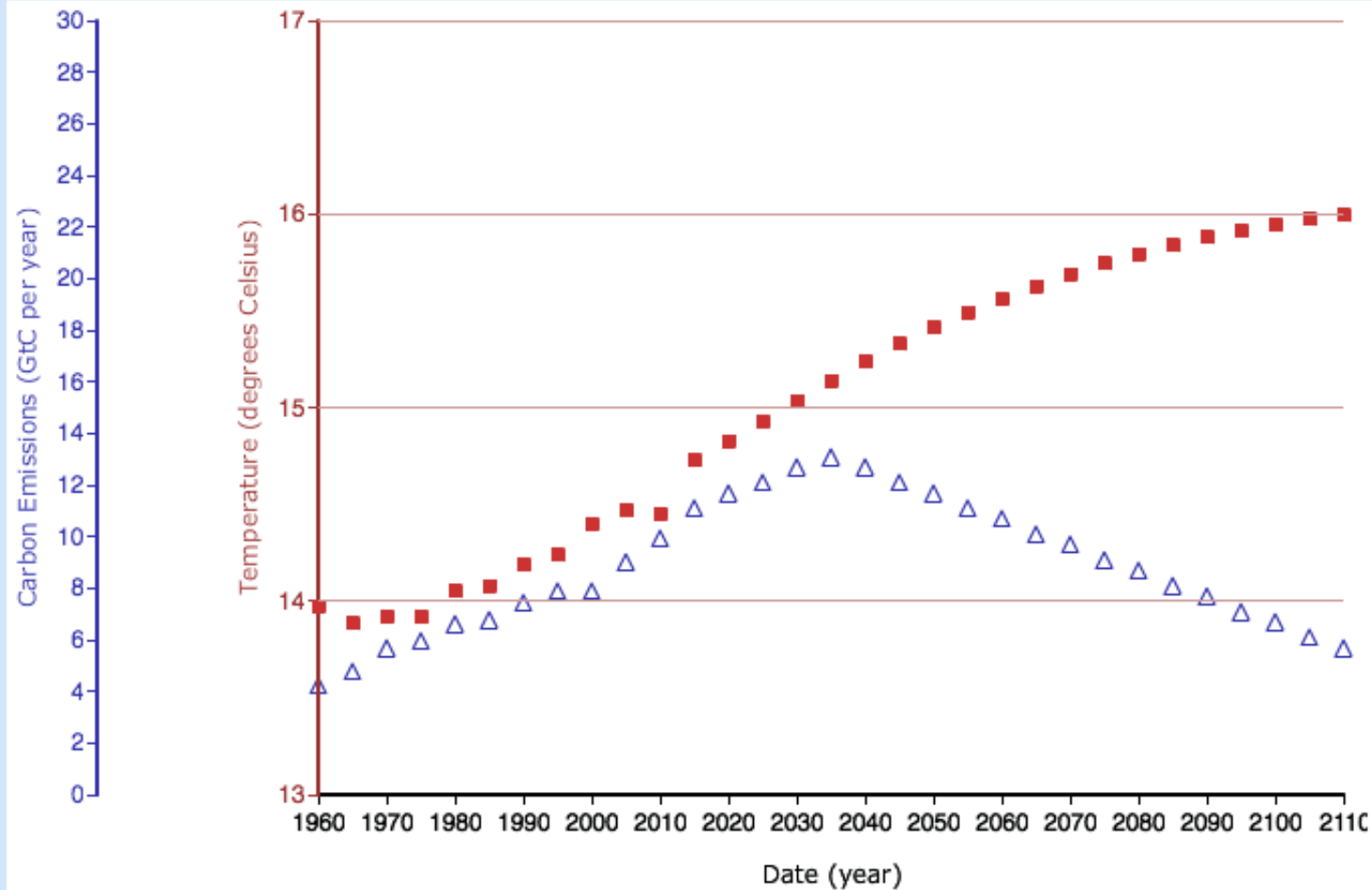
CO2 Emission Rate 

CO2 Concentration 

Temperature 

Start Over

Change Settings



Temperature scale: Celsius

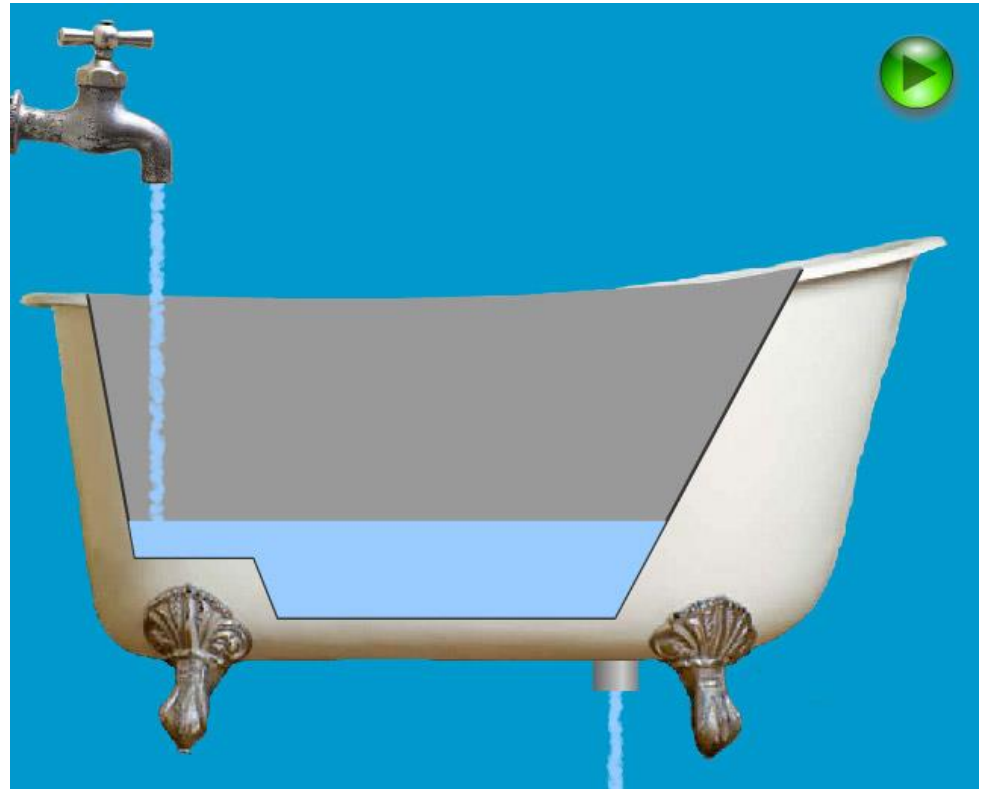
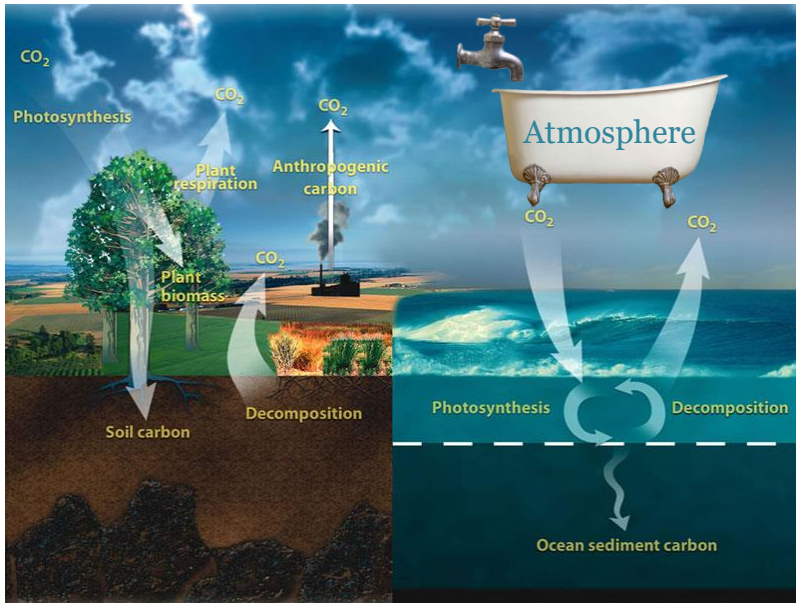
Highest temperature: 17 degrees

Show Warming Limit Targets

Highest concentration: 800 ppmv

Credits


Carbon Bathtub Animations



URL: SciEd.ucar.edu/climate-bathtub-model-animations

Constantly Rising Emissions

Instructions



Step Forward Play

Carbon Dioxide Emissions
(Gigatons Carbon per Year)

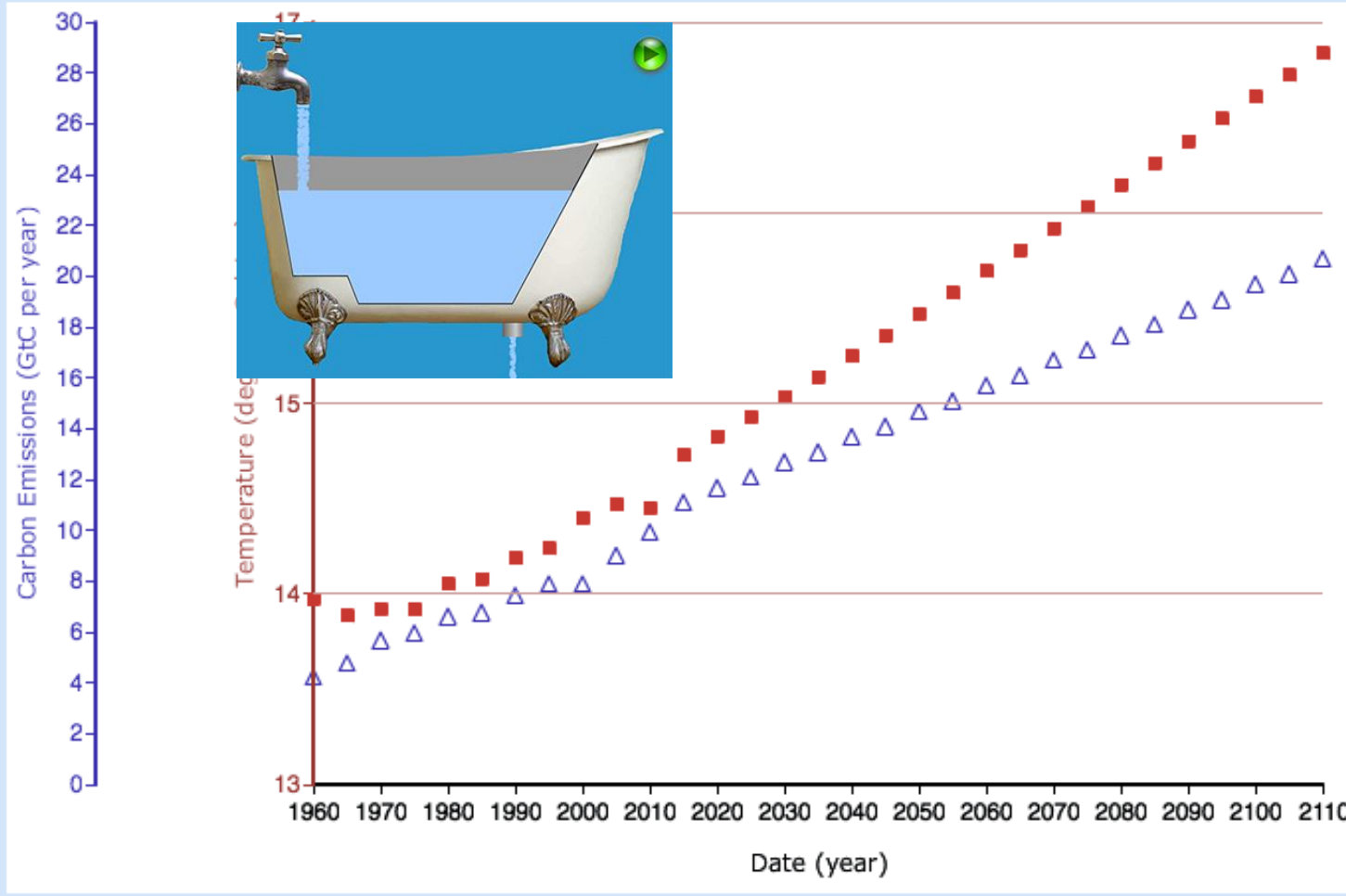
20.6

Time step size:
5 years

- Show which graphs?
- CO2 Emission Rate ▲
 - CO2 Concentration ●
 - Temperature ■

Start Over

Change Settings



Temperature scale: Celsius

Highest temperature: 17 degrees


Show Warming Limit Targets

Highest concentration: 800 ppmv

Credits

Emissions Rise, Then Level Off

Instructions






Step Forward Play

Carbon Dioxide Emissions
(Gigatons Carbon per Year)

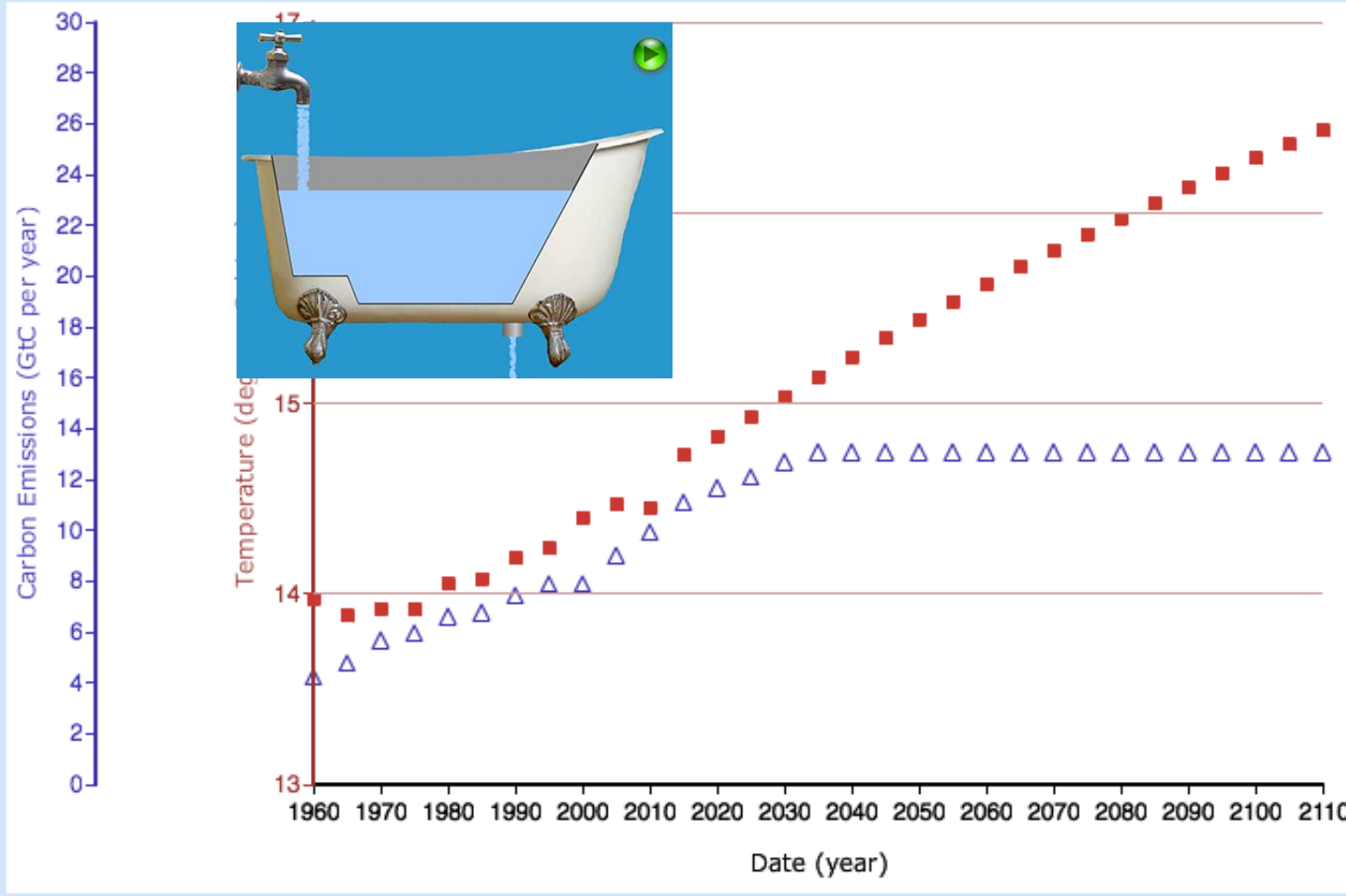
13

Time step size:
5 years

- Show which graphs?
- CO2 Emission Rate 
 - CO2 Concentration 
 - Temperature 

Start Over

Change Settings






Temperature scale: Celsius Highest temperature: 17 degrees

Show Warming Limit Targets Highest concentration: 800 ppmv

Change Settings Credits

Emissions Rise, Then Fall (to 1970s level)

Instructions






Step Forward Play

Carbon Dioxide Emissions
(Gigatons Carbon per Year)

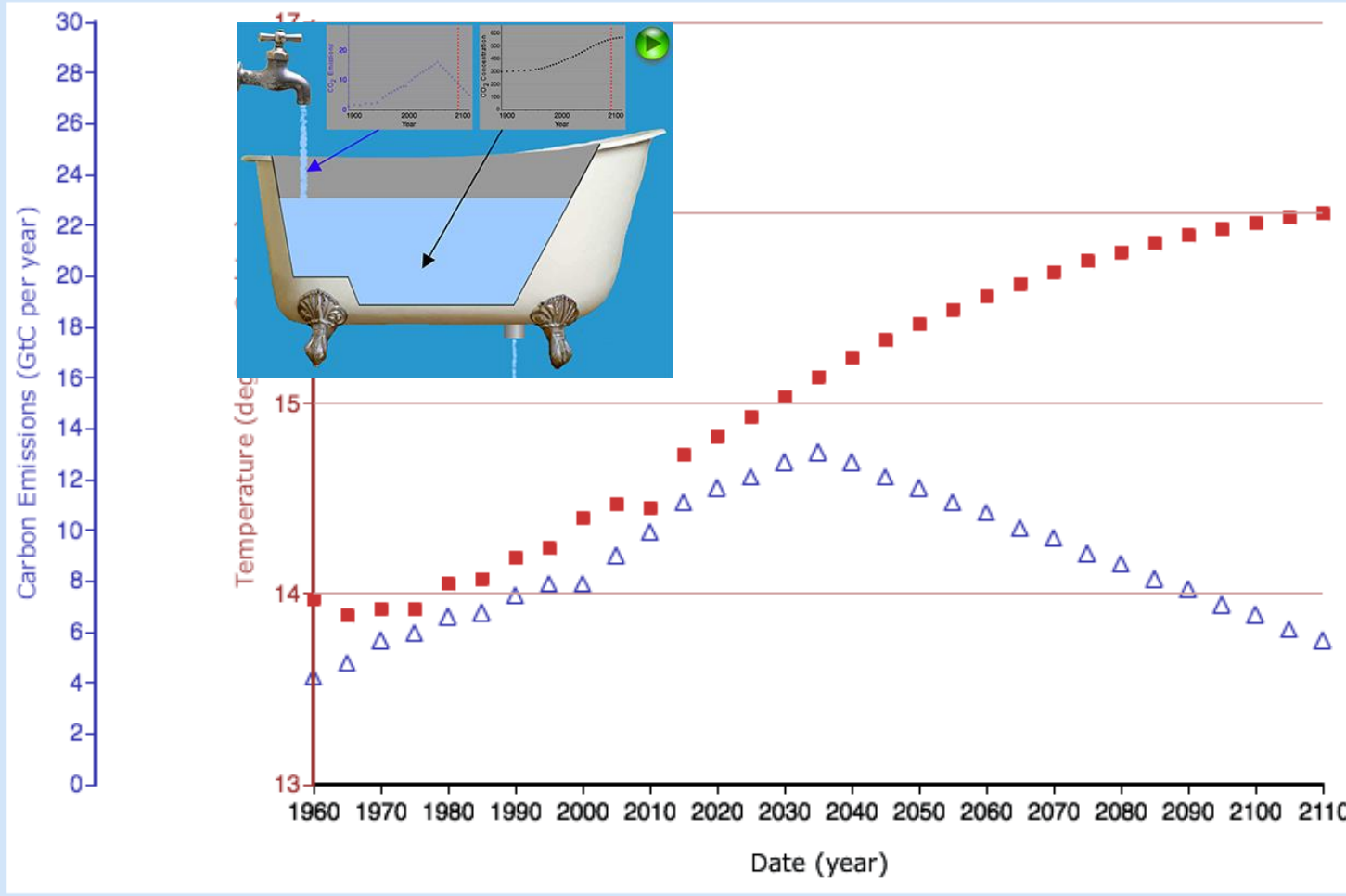
5.6

Time step size:
5 years

- Show which graphs?
- CO2 Emission Rate 
 - CO2 Concentration 
 - Temperature 

Start Over

Change Settings




Temperature scale: Celsius Highest temperature: 17 degrees

Show Warming Limit Targets Highest concentration: 800 ppmv

Credits

2 degree temperature rise

Instructions



Step Forward Play

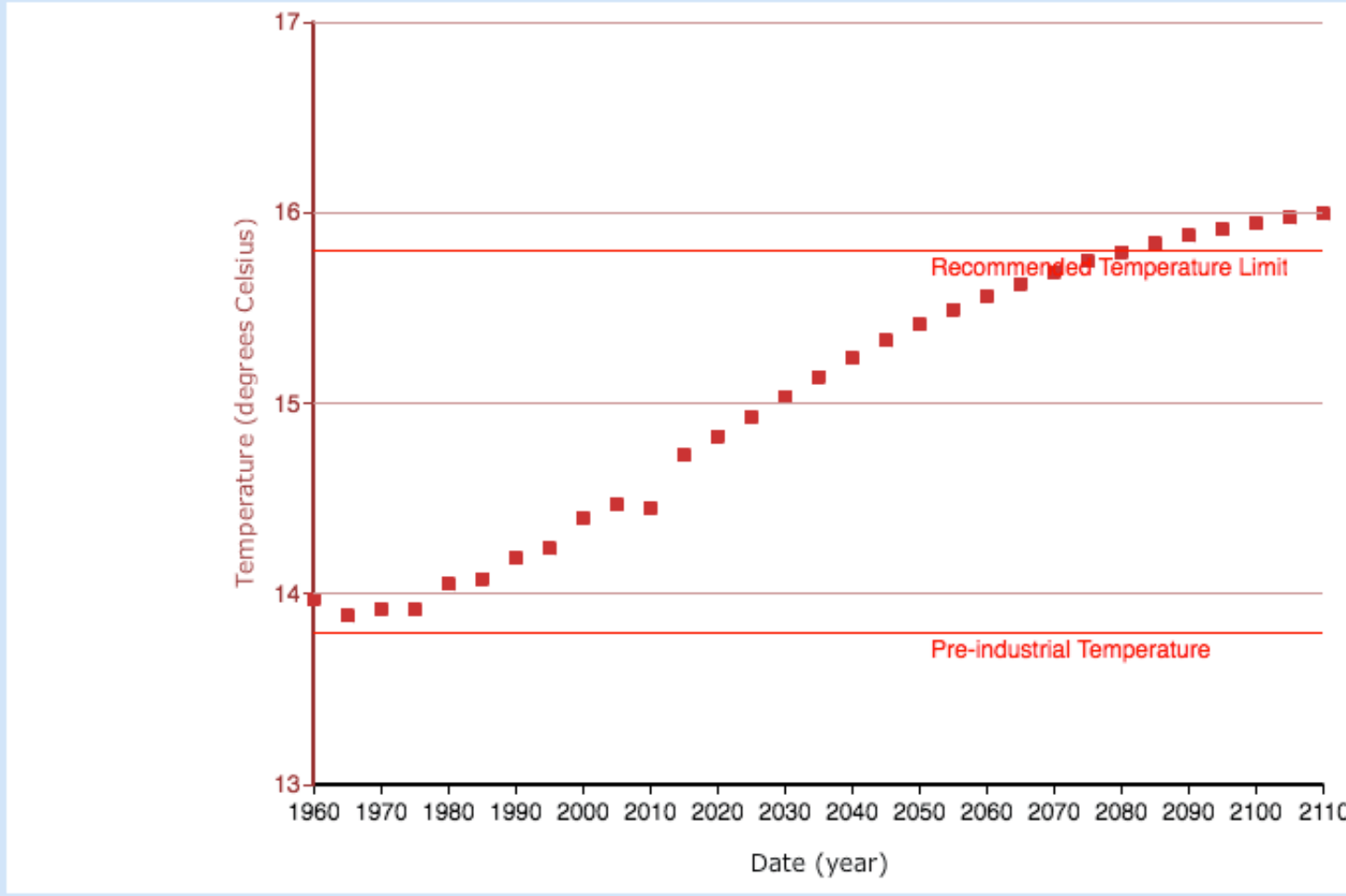
Carbon Dioxide Emissions
(Gigatons Carbon per Year)
5.6

Time step size:
5 years

Show which graphs?
 CO2 Emission Rate Δ
 CO2 Concentration \bullet
 Temperature \blacksquare

Start Over

Change Settings



Temperature scale: Celsius Highest temperature: 17 degrees

Show Warming Limit Targets Highest concentration: 800 ppmv

Credits

Tree Rings – Dendrochronology - Paleoclimate



- Have students work with actual tree cookies (counting annual growth rings) BEFORE using the tree ring simulation
- Help students make connections between concrete, physical object and the abstract computer simulation

Choose a Tree to Match:

Always Normal

+ 31
Grow New Ring

~~31~~
Remove Last Ring

Moisture

Dry

Normal

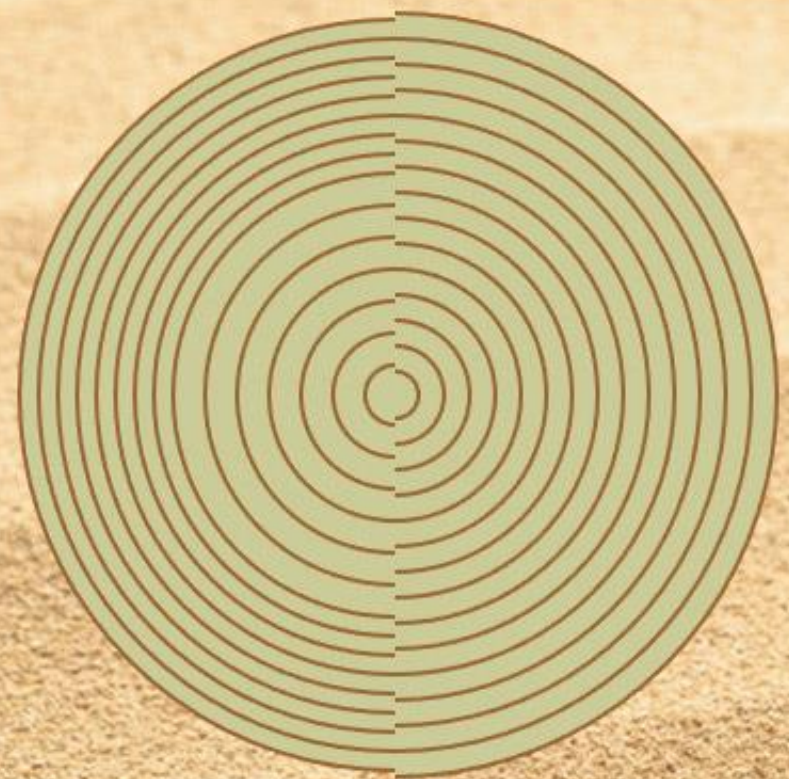
Wet

Temperature

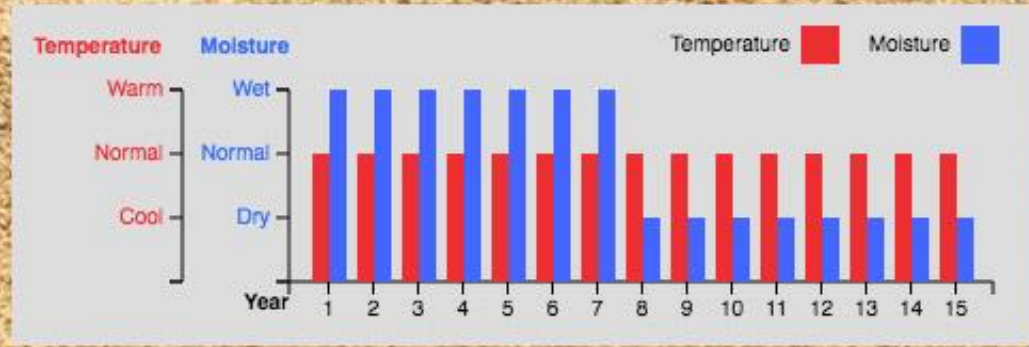
Cool

Normal

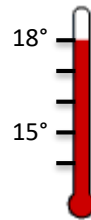
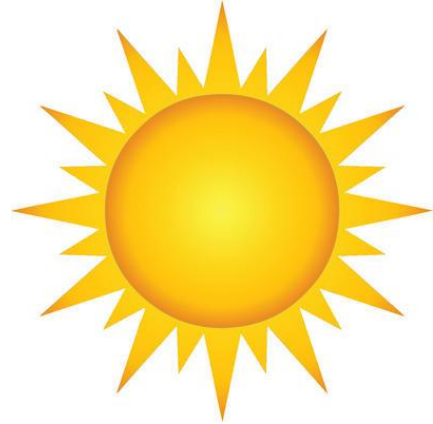
Warm



? Credits Home Refresh

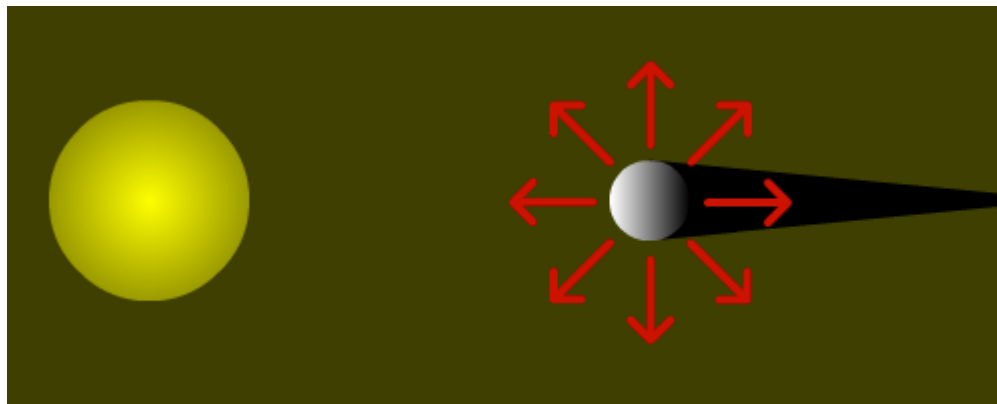
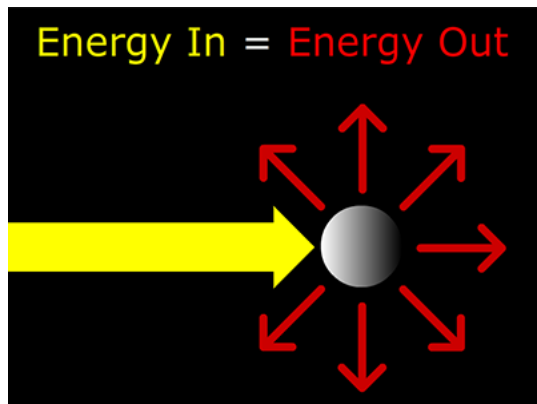


Which is hotter on a sunny day?

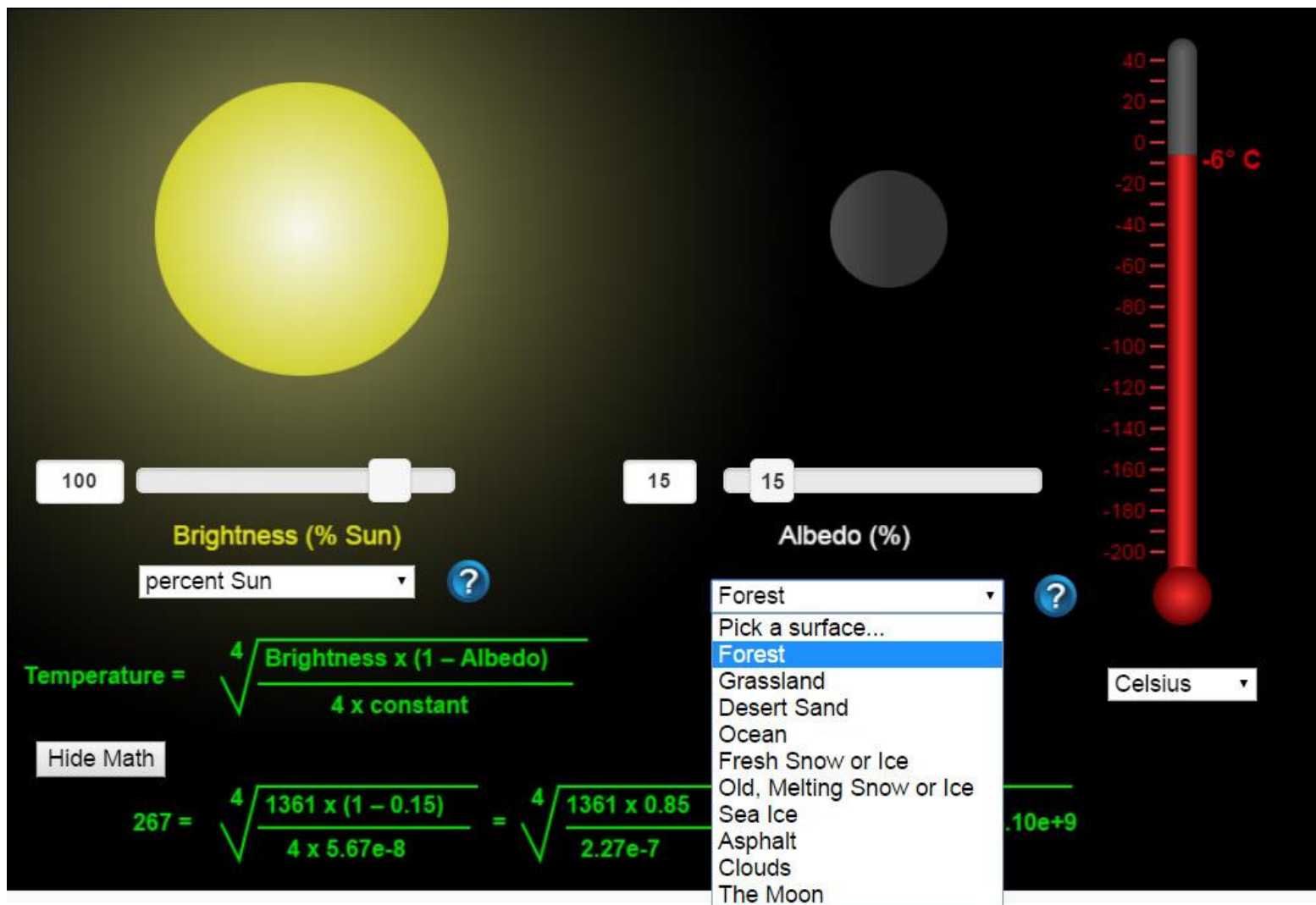


Draws on personal experience – concrete experience paired with abstract simulation

Earth's Energy Balance



Earth's Energy Balance



LASP Kelvin Climb

The screenshot shows the 'Planet Designer Kelvin Climb' interface. At the top, the title 'Planet Designer Kelvin Climb KC' is displayed. Below the title is a 'PROGRESS' menu with options: DISTANCE, ALBEDO, ATMOSPHERE, SUMMARY, EM RADIATION, and DEBRIEFING. A toolbar on the left contains icons for a paint palette, a pencil, an eraser, a selection tool, a sphere, and a undo button. A row of color swatches (red, orange, yellow, green, cyan, blue, magenta, white) is positioned above the main workspace. The workspace features a black and white checkerboard background with a 3D planet model in the center. The planet has a white polar ice cap, a blue ocean, and a green landmass. To the right of the planet, a 'Blackbody Temperature' panel shows a value of 179 K and a thermometer graphic. Below this, an 'Albedo' panel shows a value of 0.1672 and a 'What's this?' button. At the bottom right, there are 'BACK' and 'NEXT' navigation buttons. A disclaimer at the bottom left states: '*Sizes and distances not to scale.' Below the disclaimer, instructions read: 'Paint the planet to see how coloring affects albedo, and note how the albedo affects the planet's blackbody temperature. Click 'Next' when finished.'

Add an Atmosphere with Greenhouse Gases

The screenshot shows the 'Planet Designer Kelvin Climb KC' interface. On the left is a navigation menu with options: PROGRESS, DISTANCE, ALBEDO, ATMOSPHERE (highlighted), SUMMARY, EM RADIATION, and DEBRIEFING. The main area features an artistic rendering of a planet's surface with a lake and mountains. To the right of the rendering are two sliders: 'Atmosphere thickness: Moderate' (positioned between Mars and Earth) and 'Greenhouse strength: Moderate' (positioned between Mars and Earth). Below these sliders is a tip: 'Tip: increase atmosphere thickness to enable a stronger greenhouse.' To the right of the sliders are three gauges: a pressure gauge showing 0.50 bars, a temperature gauge showing 276 K, and a thermometer showing the same temperature. At the bottom right are 'BACK' and 'NEXT' buttons. At the bottom left, there is a disclaimer: '*Sizes and distances not to scale.' and a paragraph: 'Change the atmosphere thickness and greenhouse strength and see what your planet might look like from the surface. What sort of atmosphere is required in order to have liquid water on your planet? Click 'next' when finished.'

Planet Designer Kelvin Climb KC

PROGRESS

DISTANCE

ALBEDO

ATMOSPHERE

SUMMARY

EM RADIATION

DEBRIEFING

ARTISTIC RENDERING

Atmosphere thickness: Moderate

Mars Earth

Greenhouse strength: Moderate

Mars Earth

Tip: increase atmosphere thickness to enable a stronger greenhouse.

This planet could have lakes of liquid water. Its atmosphere could contain nitrogen or oxygen, and may contain greenhouse gases such as carbon dioxide or methane.

0.50

Atm. pressure (bars)

276 K

Avg. Surface Temperature

800

600

400

200

0

BACK NEXT

*Sizes and distances not to scale.

Change the atmosphere thickness and greenhouse strength and see what your planet might look like from the surface. What sort of atmosphere is required in order to have liquid water on your planet? Click 'next' when finished.

Change distance from Sun

Planet Designer Kelvin Climb KC

PROGRESS

- DISTANCE
- ALBEDO
- ATMOSPHERE
- SUMMARY
- EM RADIATION
- DEBRIEFING

Mass

Avg. density

Planet mass (Earth masses) 1.00

Planet radius (Earth radii) 1.00

Avg. density (kg / m³) 5490

Avg. distance from Sun (AU) 3.00

161 K

Blackbody Temperature

800

600

400

200

0

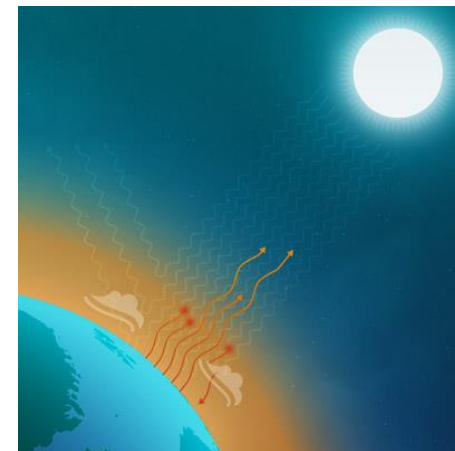
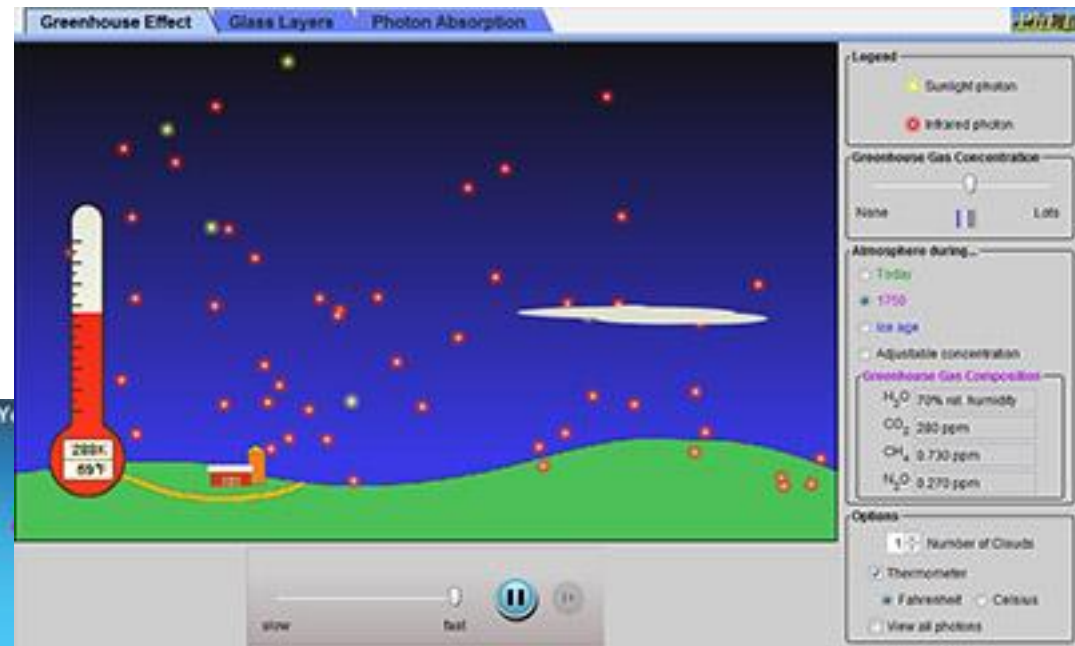
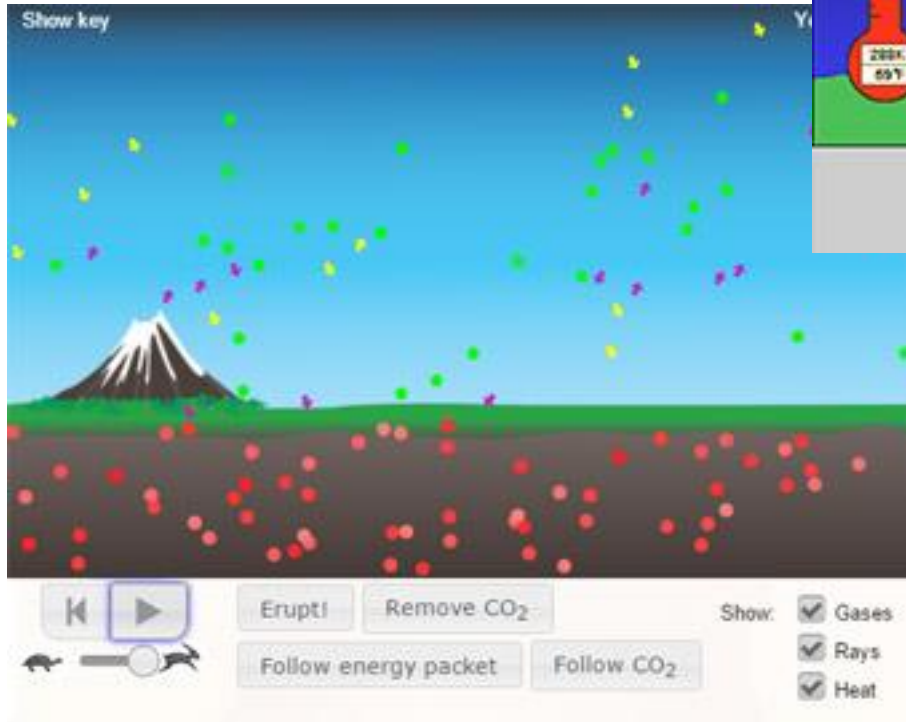
← BACK

NEXT →

*Sizes and distances not to scale.

This is a completely black planet with no atmosphere. Drag the planet to change its distance from the Sun, and adjust its mass and density to see how temperature is affected. Click 'Next' when done.

Greenhouse Effect Teaching Box



URL: SciEd.ucar.edu/teaching-box/greenhouse-effect

PhET (U. Colorado) – Greenhouse Effect

The Greenhouse Effect (3.04)

File Help

Greenhouse Effect Glass Layers Photon Absorption

Legend

- Sunlight photon
- Infrared photon

Greenhouse Gas Concentration

None | | Lots

Atmosphere during...

- Today
- 1750
- Ice age
- Adjustable concentration

Greenhouse Gas Composition

H ₂ O	70% rel. humidity
CO ₂	388 ppm
CH ₄	1.843 ppm
N ₂ O	0.317 ppm

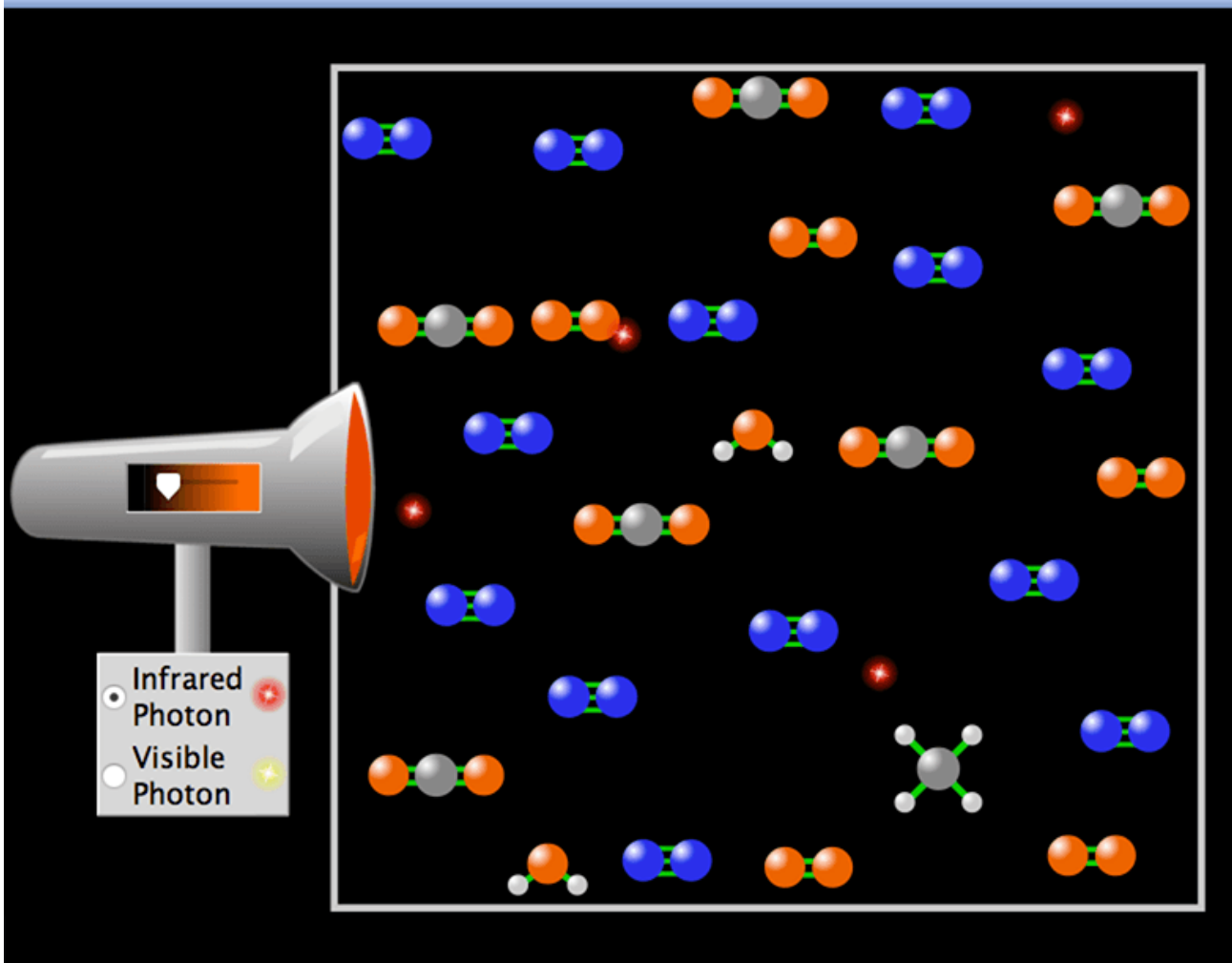
Options

- 0 Number of Clouds
- Thermometer
- Fahrenheit Celsius
- View all photons

Reset All

slow | fast

289K
60°F



Atmospheric Gases

- CH₄
- CO₂
- H₂O
- N₂
- O₂
- Build Atmosphere

CH₄ Molecules

CO₂ Molecules

H₂O Molecules

N₂ Molecules

O₂ Molecules



Concord Consortium – Greenhouse Effect

Show key

Year: 2032

slow fast

Show: Gases Rays Heat

Erupt!

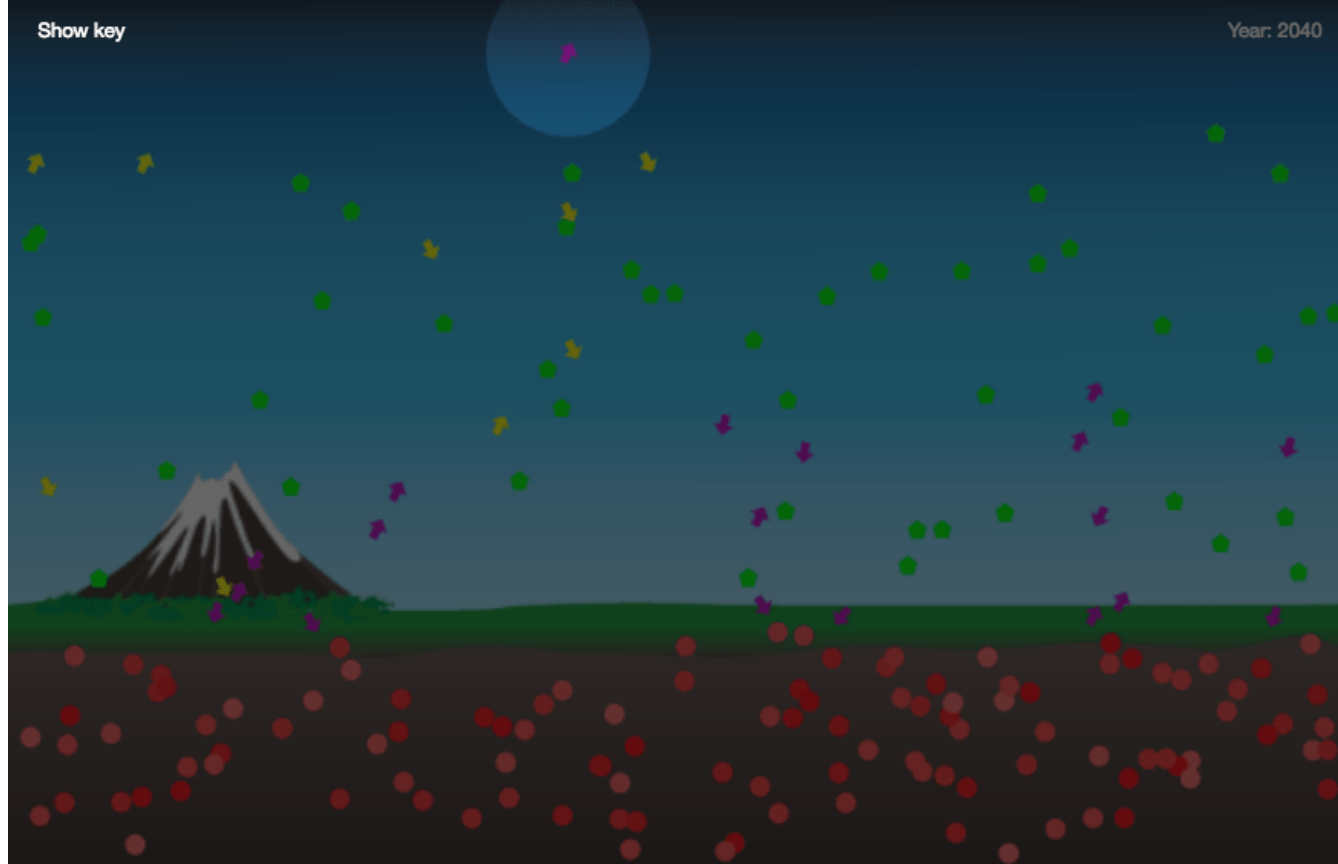
Remove CO₂

Follow energy packet

Follow CO₂

Show key

Year: 2040



Navigation controls including a play/pause button, a slider, and labels 'slow' and 'fast'.

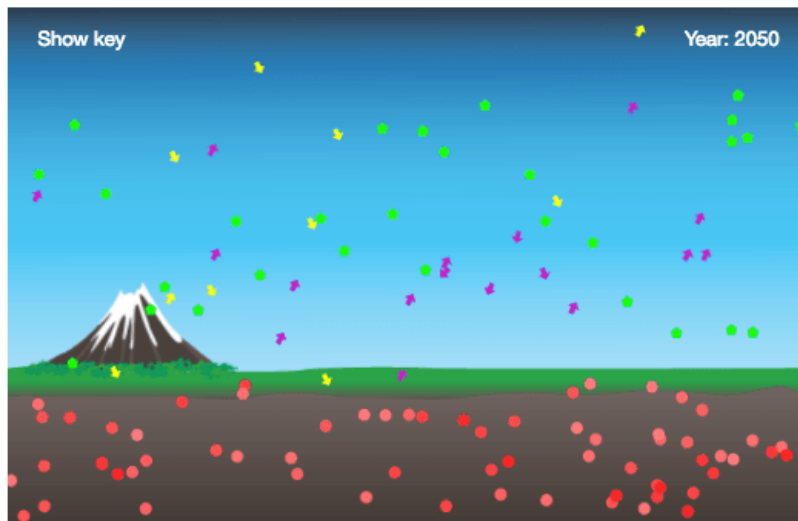
Show: Gases Rays Heat

Erupt!

Remove CO₂

Stop following

Follow CO₂



Show: Gases Rays Heat

Erupt!

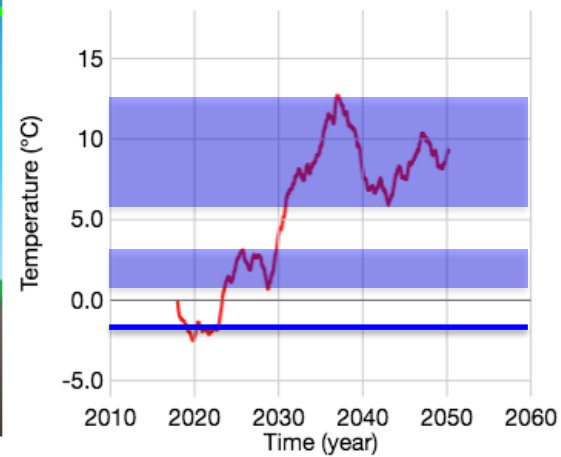
Remove CO₂

Follow energy packet

Follow CO₂

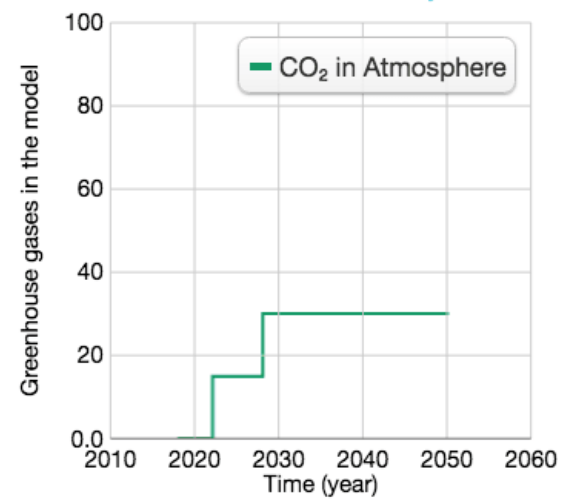
Temperature Change

Key Zoom

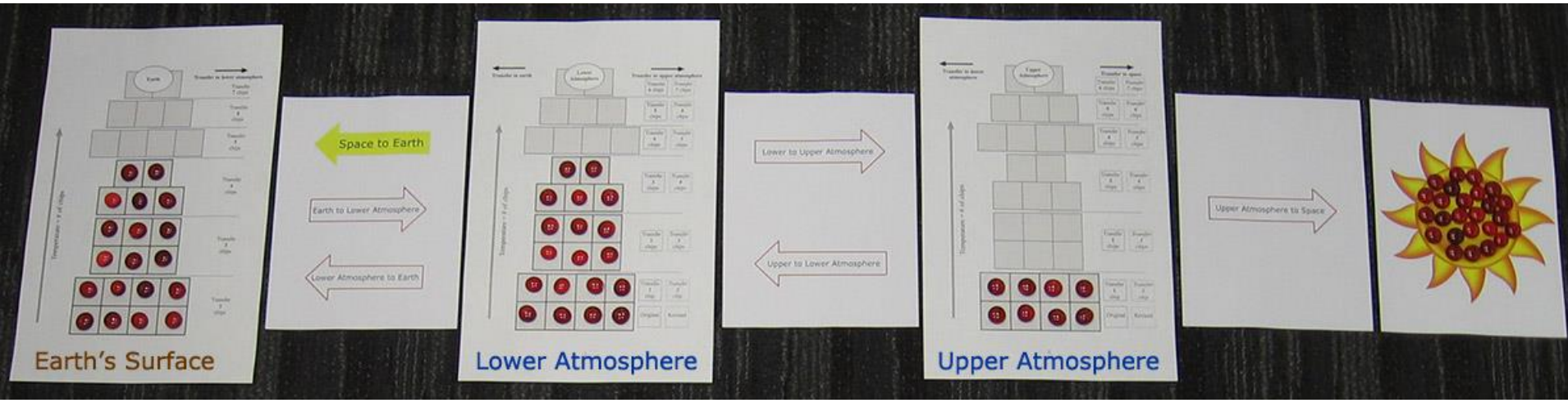


CO₂ Concentration

Key Zoom



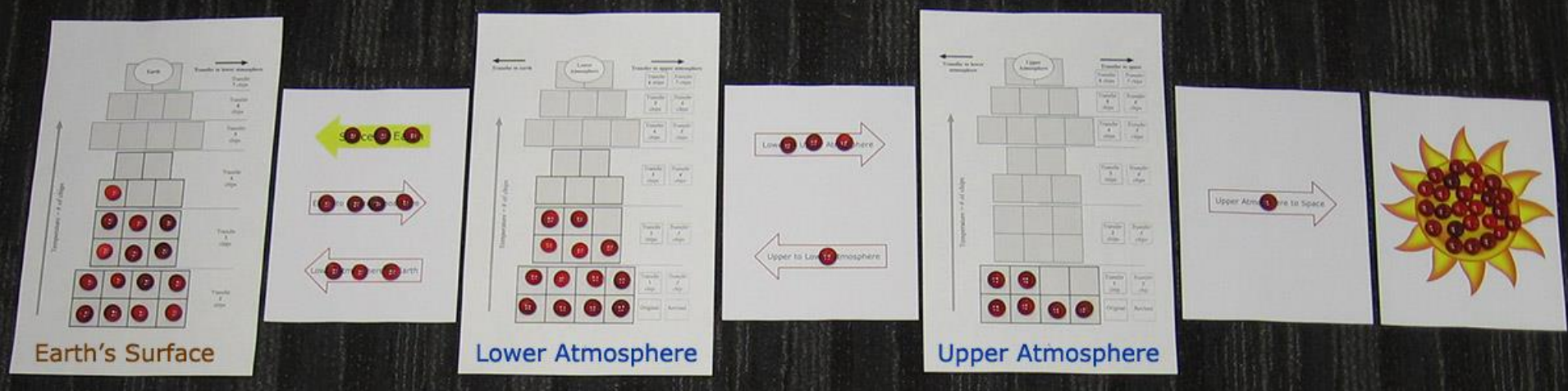
Atmosphere Model – Hands-on Activity



Earth's Surface

Lower Atmosphere

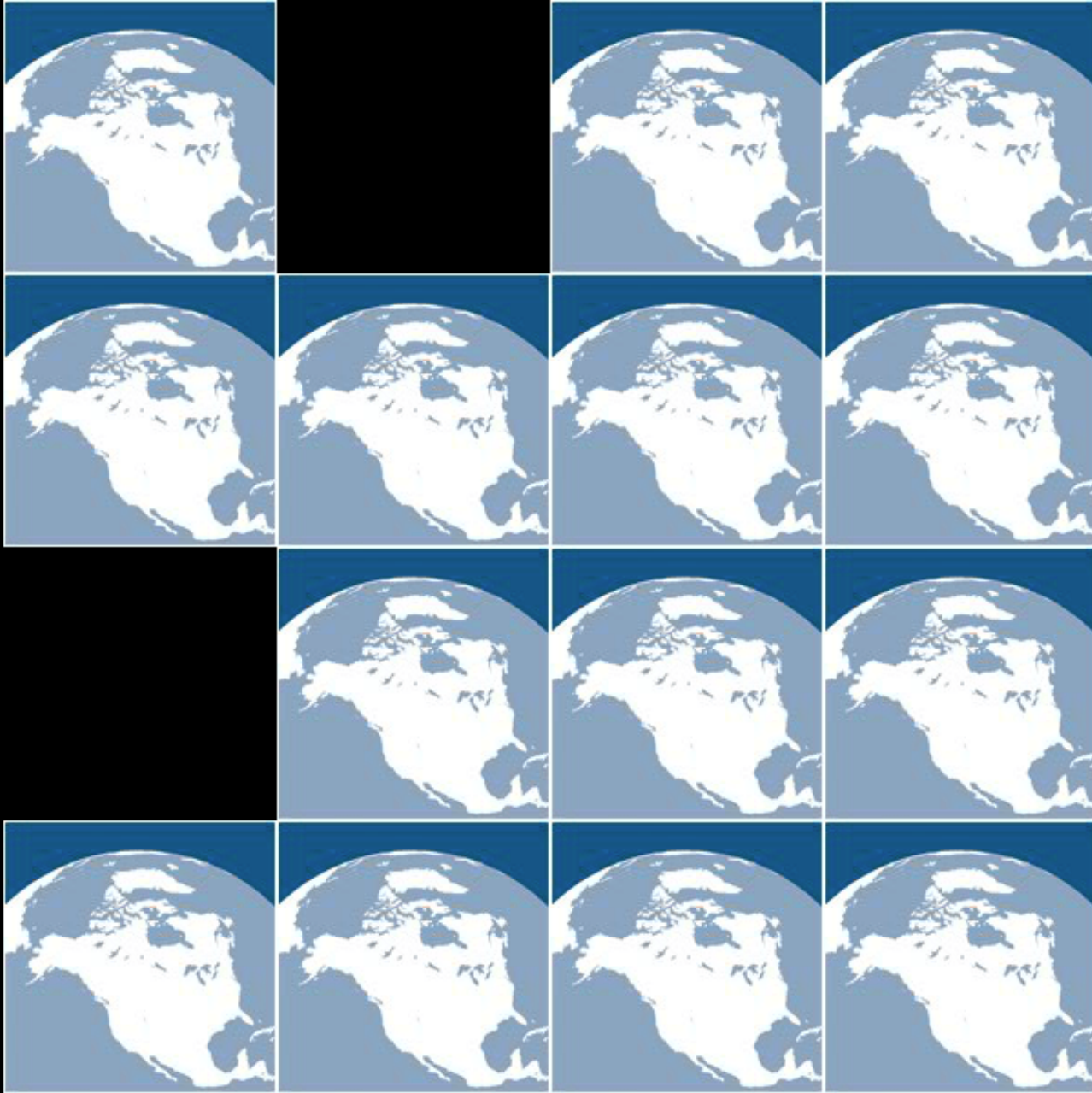
Upper Atmosphere

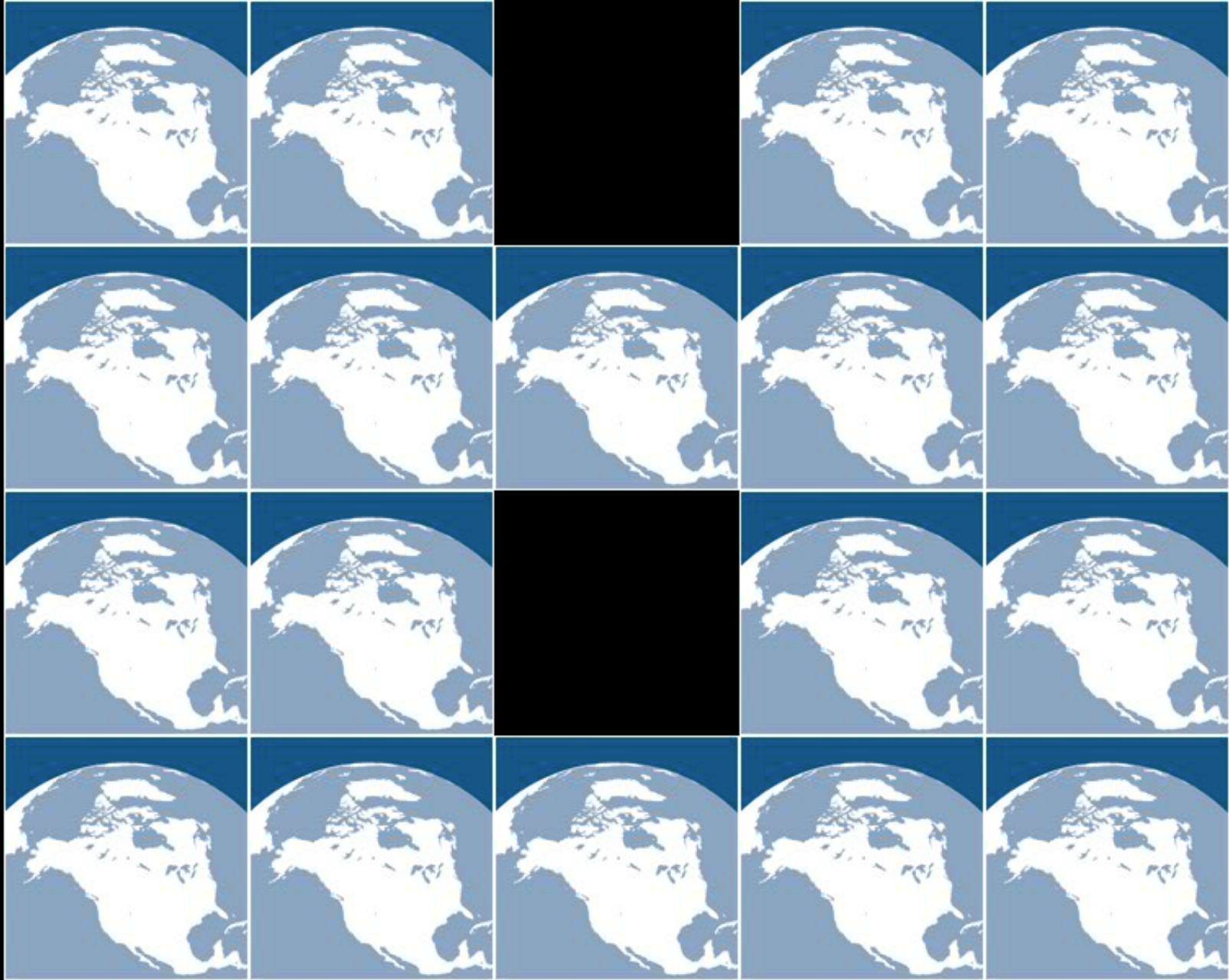


Earth's Surface

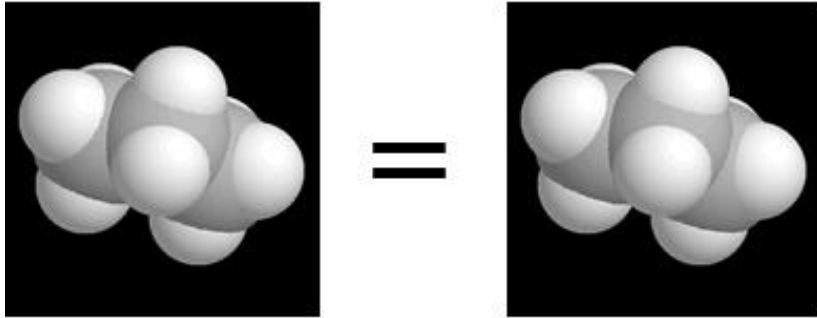
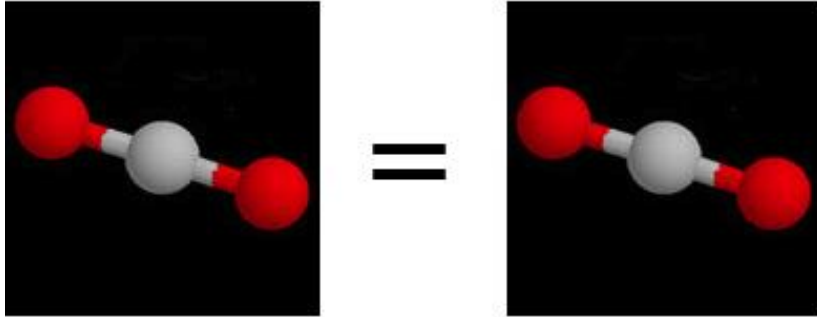
Lower Atmosphere

Upper Atmosphere

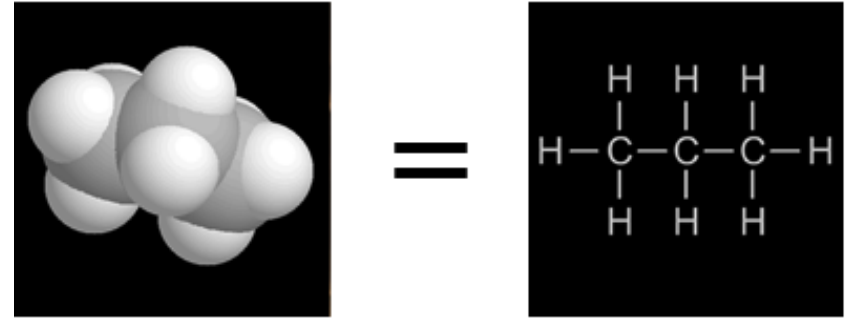
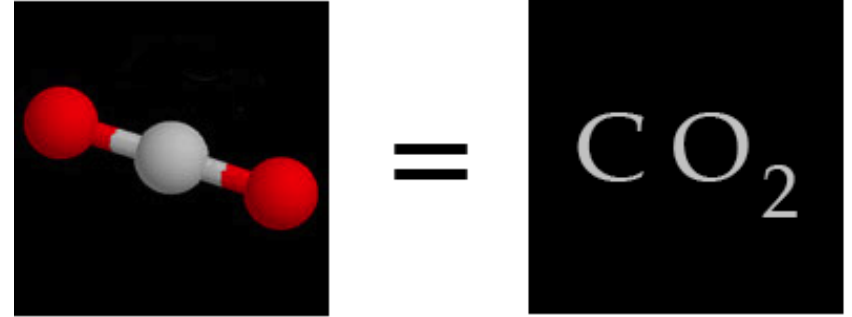




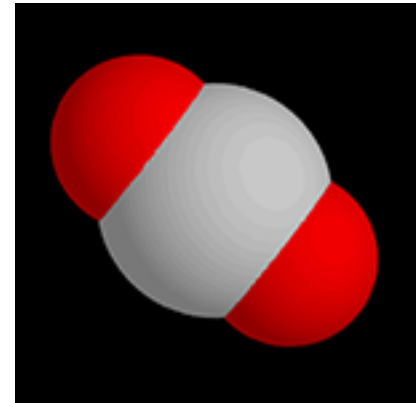
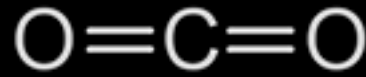
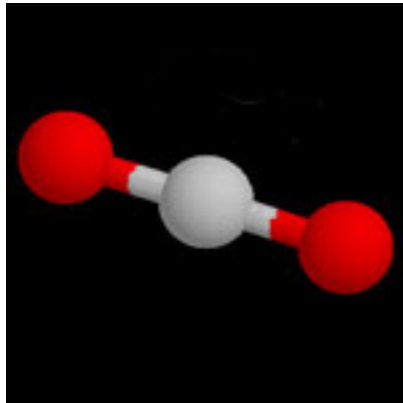
Identical Models



Equivalent Models

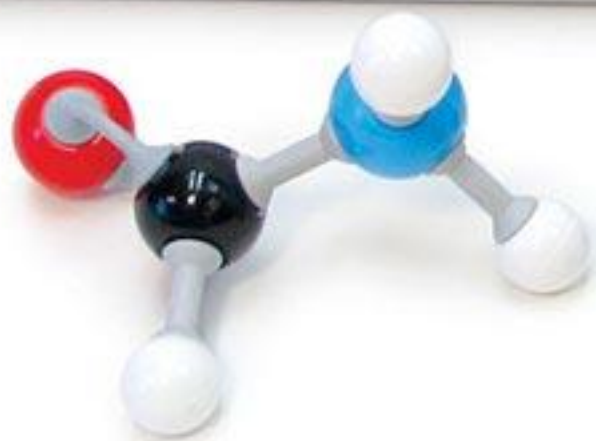
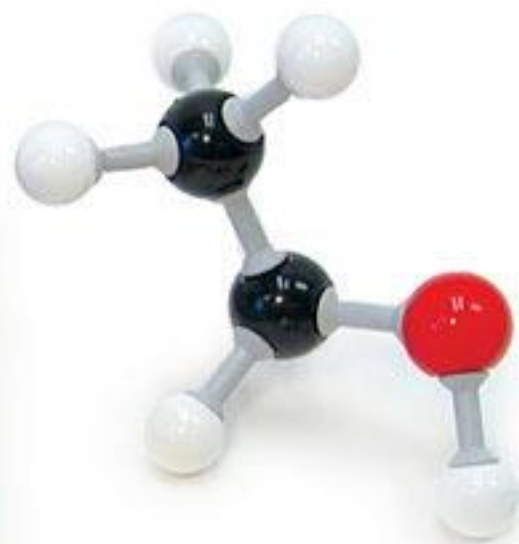


Carbon Dioxide – Various Models of Molecules

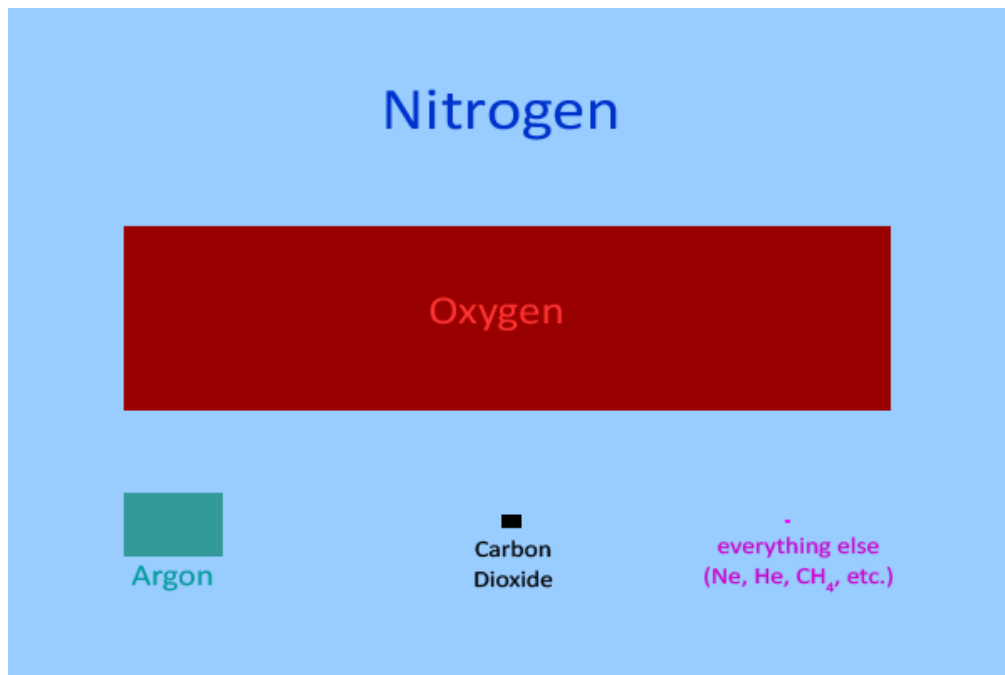


Marshmallow Models of Molecules

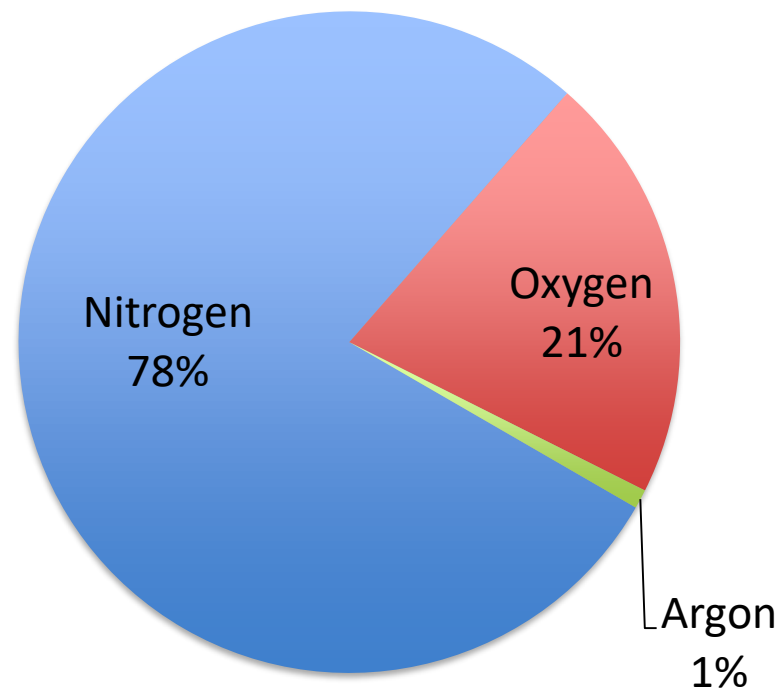




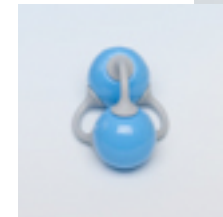
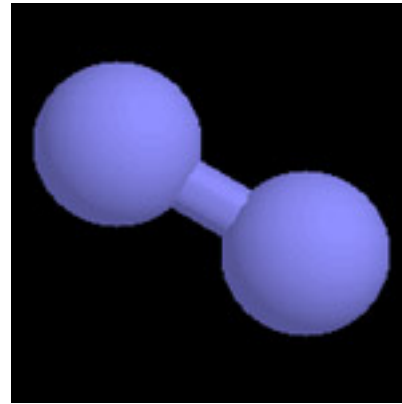
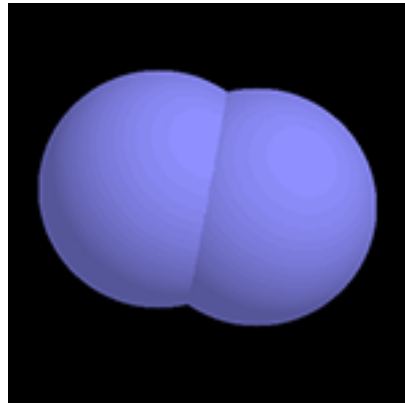
Molecules in Earth Science



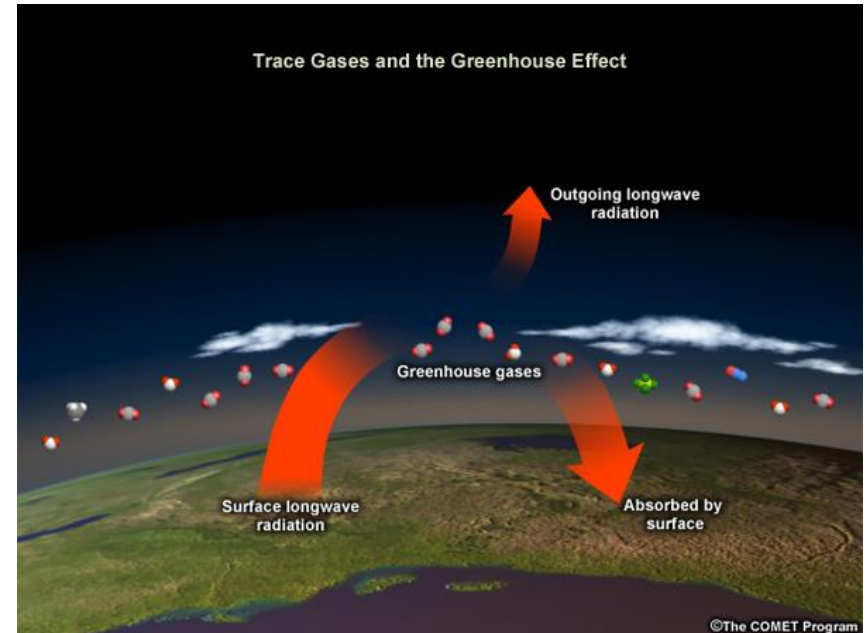
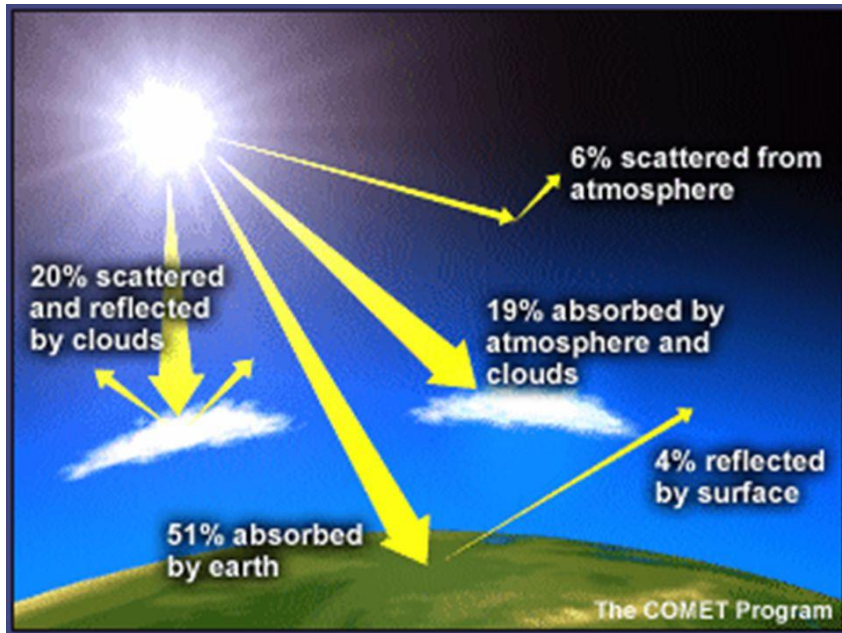
Gases in Earth's Atmosphere



Why so much nitrogen? Triple bond!

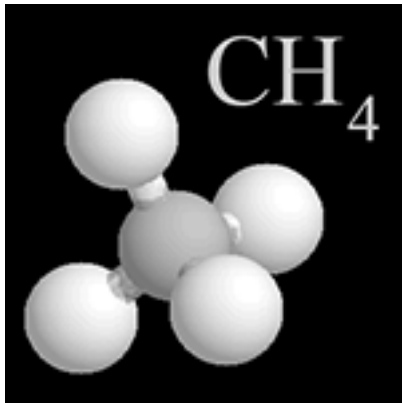
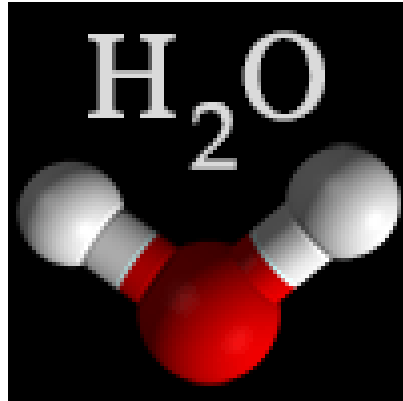
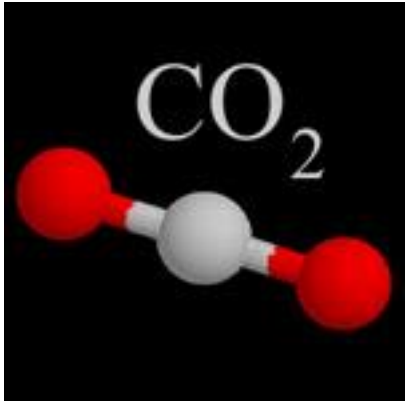


Molecules in Earth Science – Greenhouse Gases

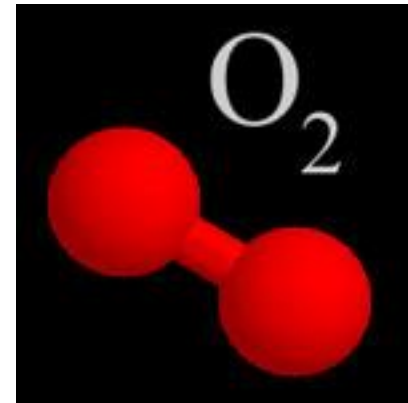
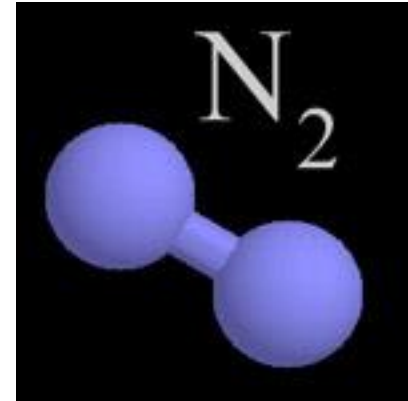


- most sunlight passes right through the atmosphere
- some infrared "light"

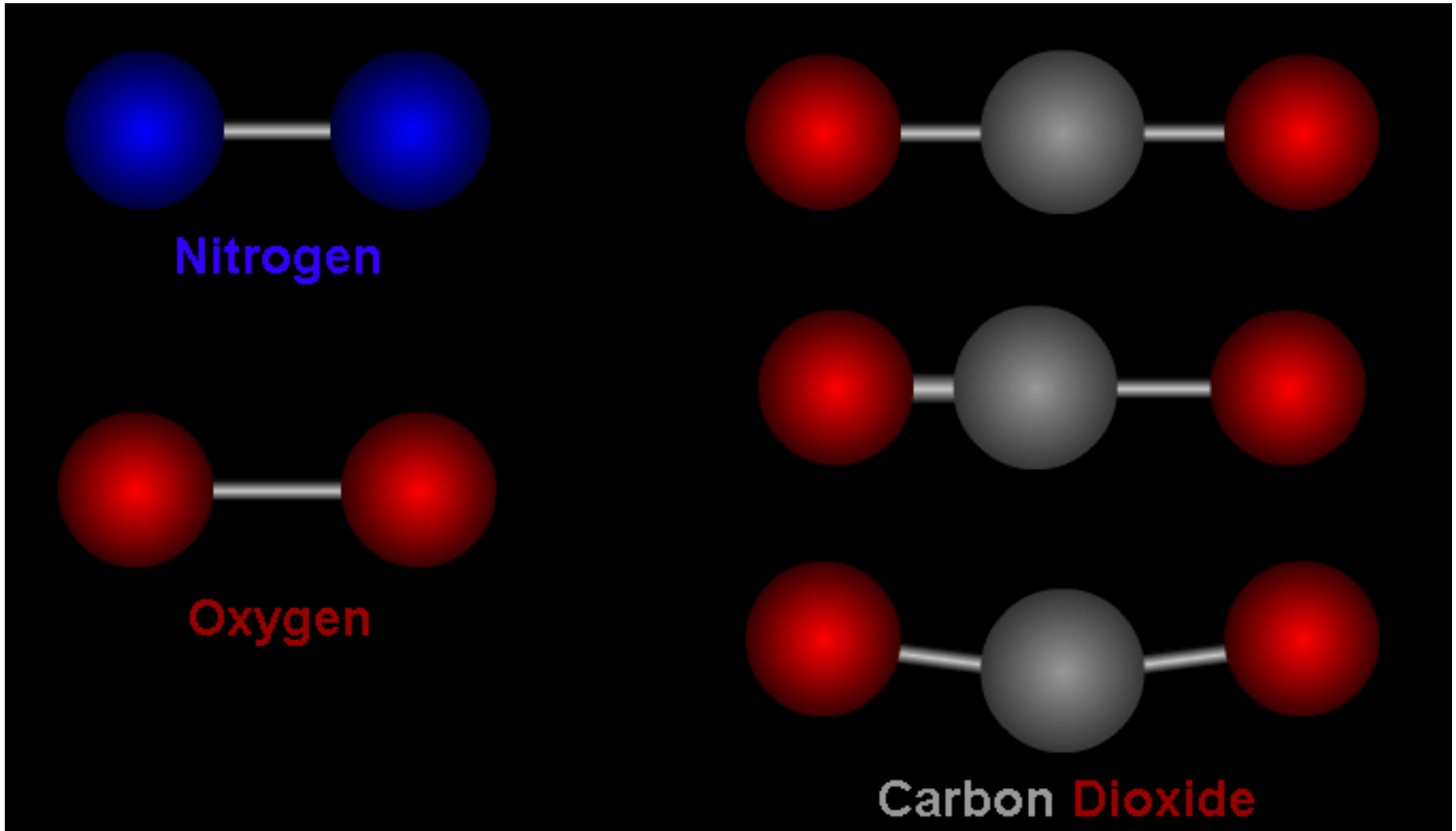
Greenhouse Gas Molecules



Not Greenhouse Gases



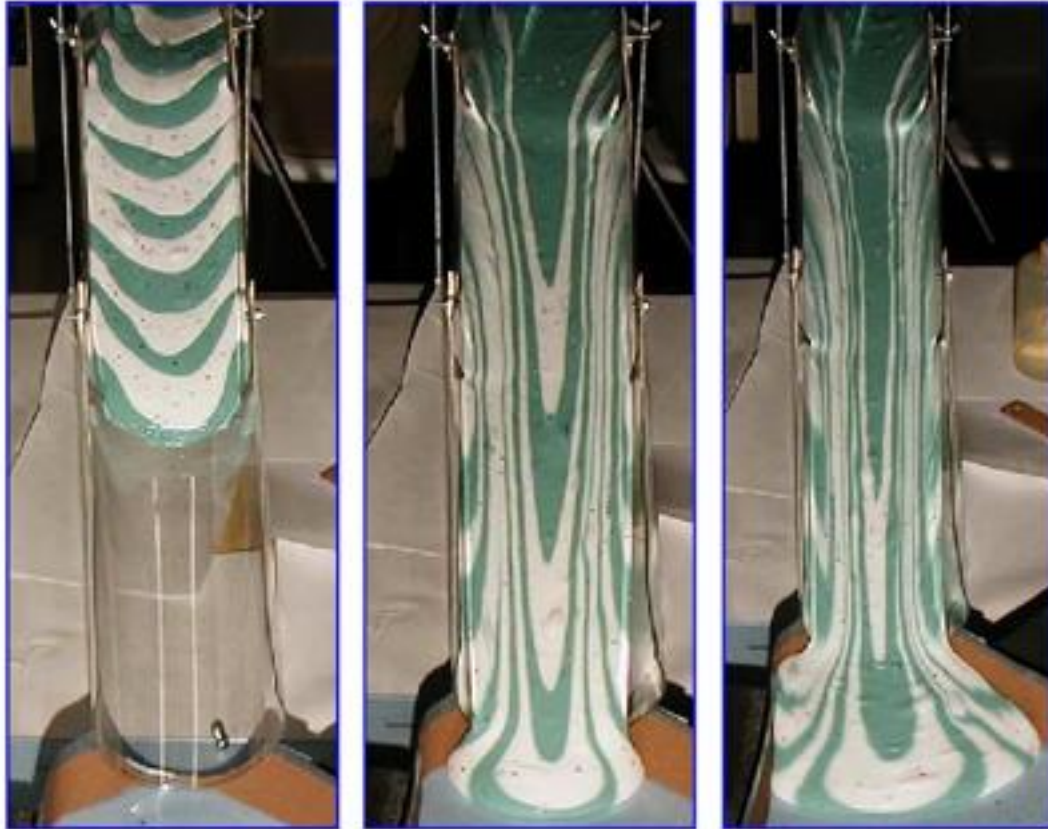
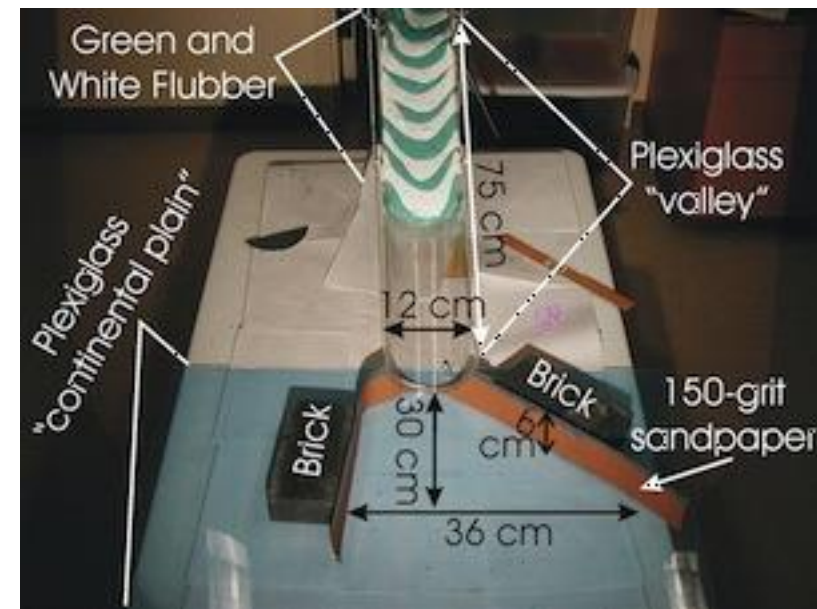
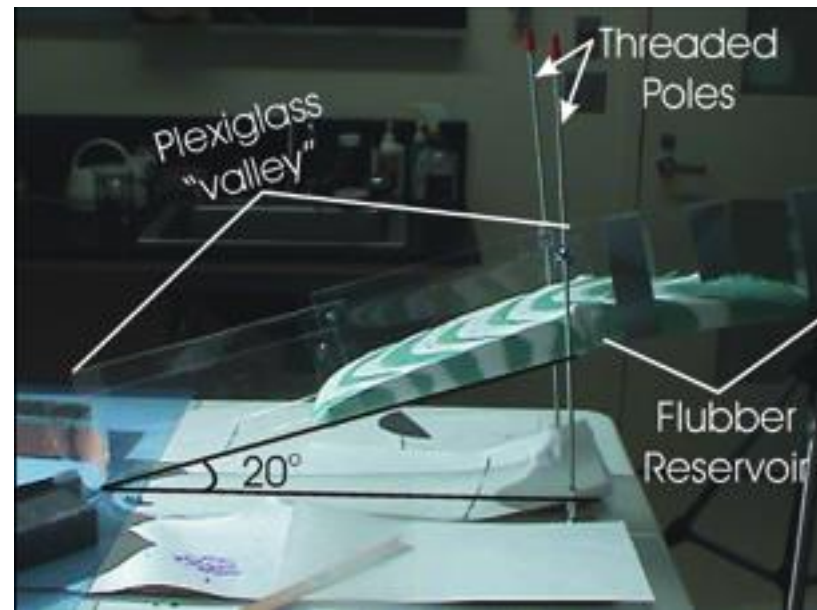
Shape -> Vibration Energy -> GHG (or not!)



Glaciers Then and Now Activity



Model a Moving Glacier Activity ("Glacier Goo")

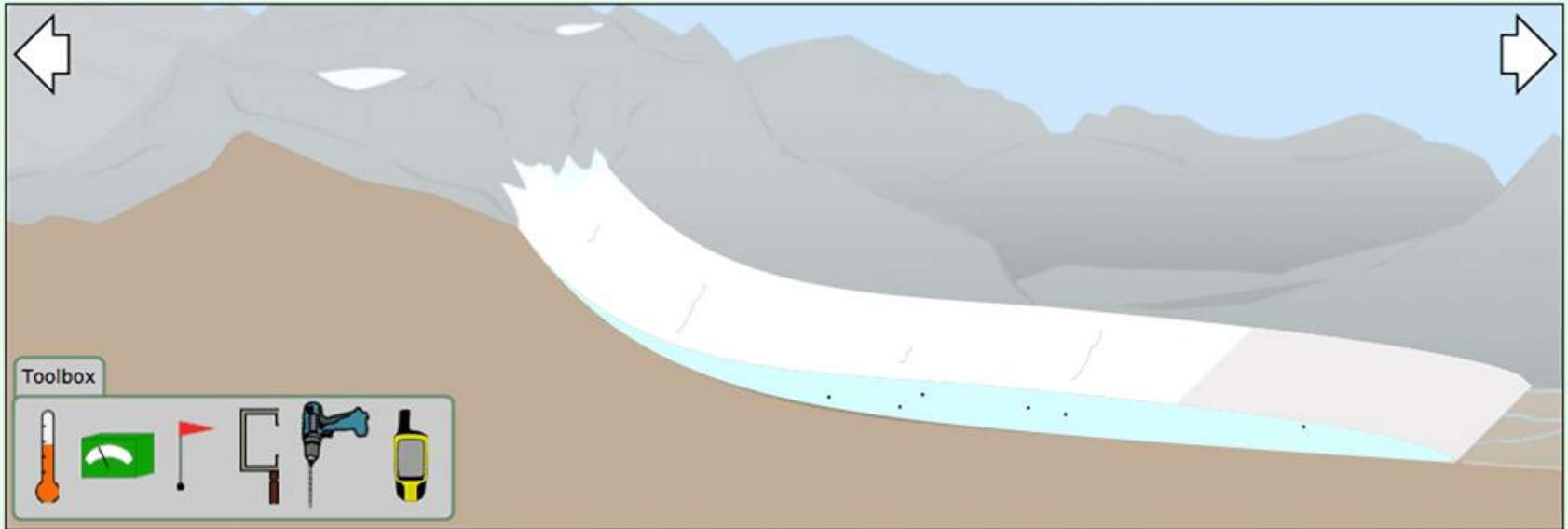
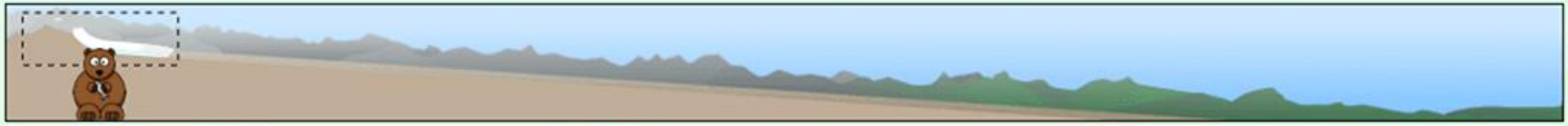


PhET (U. Colorado) – Glaciers

The screenshot shows the PhET Glaciers simulation interface. At the top, the title bar reads "Glaciers (2.04)" with "File" and "Help" menus. Below the title bar are tabs for "Introduction" and "Advanced", with the "Advanced" tab selected. A small cartoon bear character is visible in the top left corner of the simulation area. The main simulation area displays a cross-section of a glacier system, showing a snowfield on a mountain slope, a glacier flowing down, and a subglacial lake. Navigation arrows are present on the left and right sides of the simulation area. A "Toolbox" is located in the bottom left of the simulation area, containing icons for a thermometer, a green flag, a red flag, a clipboard, a blue drill, and a yellow handheld device. Below the simulation area are two control panels: "View" and "Climate". The "View" panel includes options for units (English selected, metric unselected), a checkbox for "equilibrium line" (unchecked), and a checked checkbox for "snowfall" with a snowflake icon. The "Climate" panel features two sliders: "Sea-level air temperature" with values 55.4, 68.0, and 66.2 °F; and "Average snowfall" with values 0.0, 4.9, and 3.1 ft. At the bottom of the interface, there is a time slider set to "10 years" with "slow" and "fast" markers, a play button, and a pause button. To the right of these are three buttons: "Show real glacier", "Set glacier to steady state", and "Reset All".

Levels of Interaction with Simulations/Models

- Run the Model, observe the results
- Adjust inputs/parameters, run the model more than once, see what is different
- Modify the model – can be as simple as changing some constants or the relationships between variables (exponential growth versus linear trend), or may involve adding whole new sections to the existing model
- Construct a model from scratch – Spreadsheets an easy way, but also block programming languages like Scratch



Toolbox

View

units: English metric

equilibrium line -----

snowfall *

Climate

Sea-level air temperature: 55.4 68.0 **66.2** °F

Average snowfall: 0.0 4.9 **3.2** ft

204 years

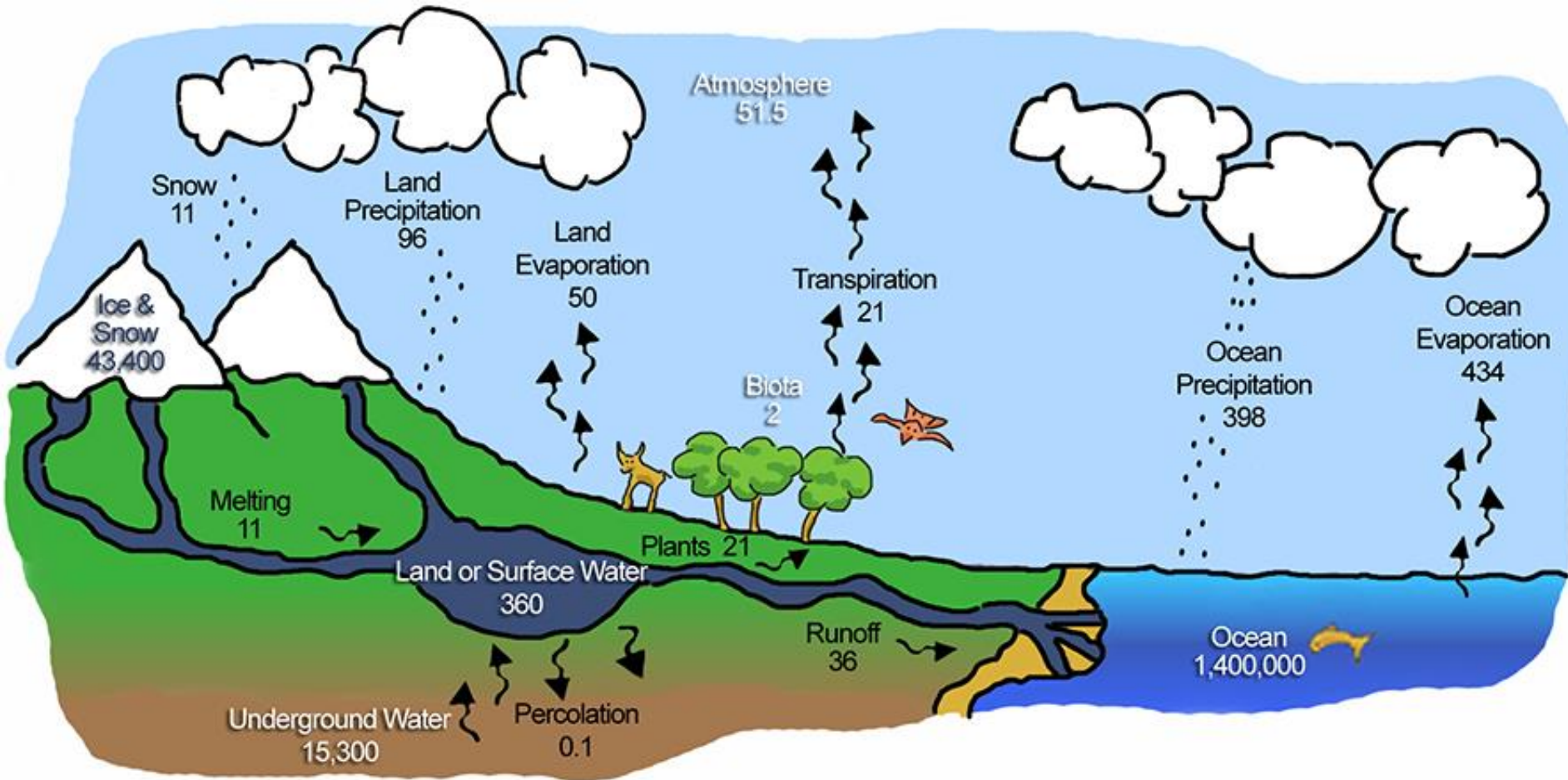
slow fast

Show real glacier

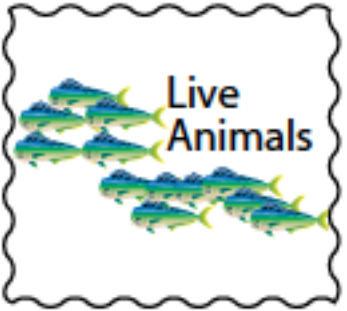
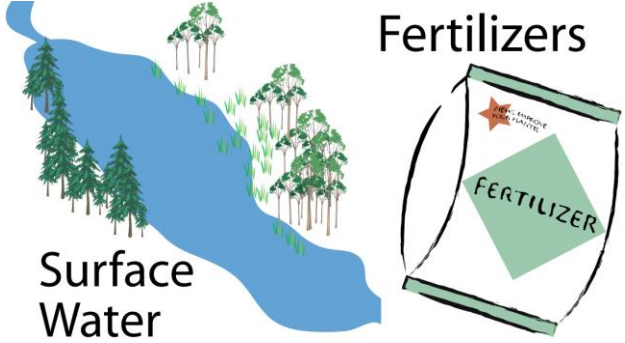
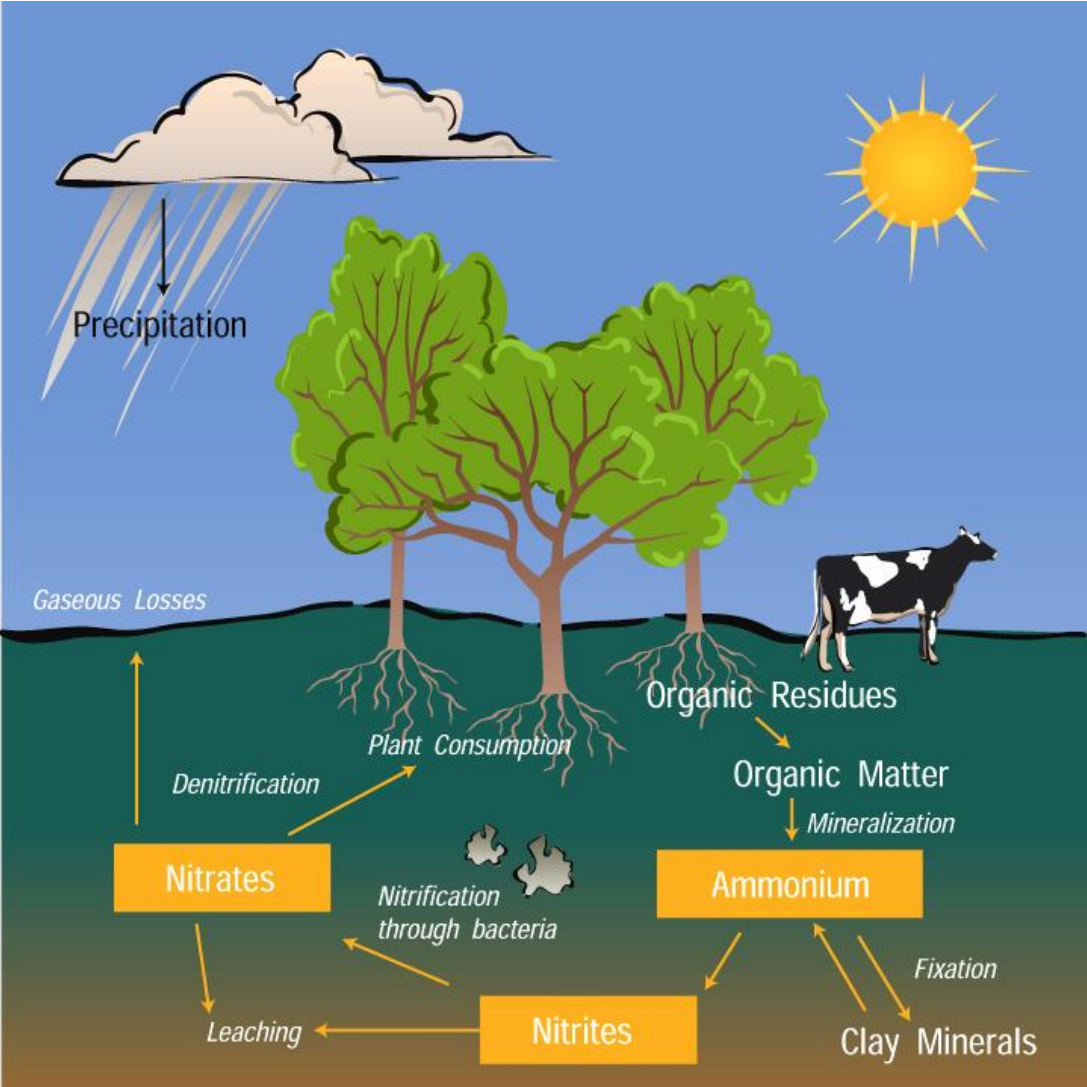
Set glacier to steady state

Reset All

Cycles in the Earth Sciences



Nitrogen Cycle Game



Nitrogen Cycle Game



Atmosphere

Put a stamp on your passport and then roll the die to see where you will travel next!

If your die reads: 1 or 2
Lightning strikes! Nitrogen gas is made into a solid and travels to the soil!

If your die reads: 3
Blue-green algae and bacteria change you into a solid, bringing you to the soil!

If your die reads: 4
Bean plants extract you from the air and bring you to the soil!

If your die reads: 5 and 6
Some nitrogen can get into the water in clouds and then fall as rain!



Rain Water


Put a stamp on your passport and then roll the die to see where you will travel next!

If your die reads: 1
You fall into a lake or stream so now you are part of surface water.

If your die reads: 2 or 3
You fall on the land and become part of the soil!

If your die reads: 4
You percolate deep underground in the groundwater!

If your die reads: 5 or 6
You run into the ocean!



Surface Water

Put a stamp on your passport and then roll the die to see where you will travel next!

If your die reads: 1 or 2
You are just the sort of nitrogen that plants need to live. You are now within a live plant!

If your die reads: 3 or 4
You travel through the rivers and streams to the ocean!

If your die reads: 5 or 6
You percolate deep underground in the groundwater!




Live Plants

Put a stamp on your passport and then roll the die to see where you will travel next!

If your die reads: Odd numbers (1, 3, or 5)
The plant that you are within has died. Go to dead plants and animals.

If your die reads: Even numbers (2, 4, or 6)
An animal has eaten the plant that you are within! Go to live animals!

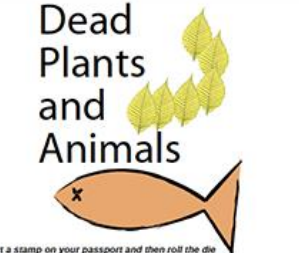


Live Animals

Put a stamp on your passport and then roll the die to see where you will travel next!

If your die reads: Odd numbers (1, 3, or 5)
The animal that you are within has died. Go to dead plants and animals.

If your die reads: Even numbers (2, 4, or 6)
Congratulations! The animal that you were within has excreted and you are in its waste. Go to animal waste!



Dead Plants and Animals

Put a stamp on your passport and then roll the die to see where you will travel next!

If your die reads: 1 or 2
You are decomposed and become part of the soil!

If your die reads: 3
You are decomposed and become dissolved in surface water!

If your die reads: 4
You are decomposed and become dissolved in the ocean!

If your die reads: 5 or 6
Forest Fire! The wood you were within is burnt and you have been released into the atmosphere.



Soils

Put a stamp on your passport and then roll the die to see where you will travel next!

If your die reads: 1
You dissolve and wash into the groundwater!

If your die reads: 2
You dissolve and wash into the surface water!

If your die reads: 3 or 4
You are just the sort of nitrogen that plants need to live. You are now within a live plant!

If your die reads: 5 or 6
Bacteria have transformed you into nitrogen gas and you are now part of the atmosphere!



Animal Waste

Put a stamp on your passport and then roll the die to see where you will travel next!

If your die reads: 1 or 2
Look out before someone steps in you! Now you are decomposing in the soil!

If your die reads: 3 or 4
A farm supply company has picked you up and made you into fertilizer!

If your die reads: 5 or 6
What's that in the water? You have dissolved into surface water!

Nitrogen Cycle Game - Stations



Put a stamp on your passport and then roll the die to see where you will travel next!

If your die reads: 1

You fall into a lake or stream so now you are part of **surface water**.

If your die reads: 2 or 3

You fall on the land and become part of the **soil!**

If your die reads: 4

You percolate deep underground in the **groundwater!**

If your die reads: 5 or 6

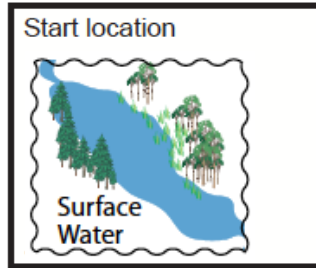
You rain into the **ocean!**

The Nitrogen Cycle Game Passport Worksheet

Name: _____

Directions:

- Stamp your start location in the space below.



- Roll the die to find out where to go next.
- Write **How I traveled** in the Trip #1 (see example at right).
- Go to that station and stamp the Trip#1 **Where I went** box.
- Then, roll the die to find out where to go for Trip #2.

Guess what! In this game you are a nitrogen atom. You are going to travel the nitrogen cycle stopping in many exciting locations - some of which you probably never have been to before.

For each stop along your journey, remember to record where you went and how you got there.

Here's an example of how to fill out each stop along the way:

Trip#1:How I traveled:	Where I went:
Fertilizer washed into stream	

Trip #1:How I traveled:	Where I went:

Trip #5:How I traveled:	Where I went:
	<i>Stamp above</i>

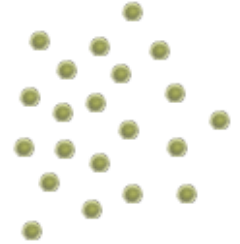
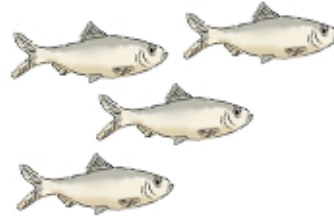
Trip #2:How I traveled:	Where I went:

Trip #6:How I traveled:	Where I went:
	<i>Stamp above</i>





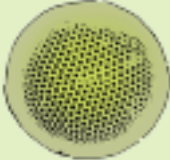










Trip #3:How I traveled:	Where I went:

Trip #7:How I traveled:	Where I went:













Food Chain Checkers



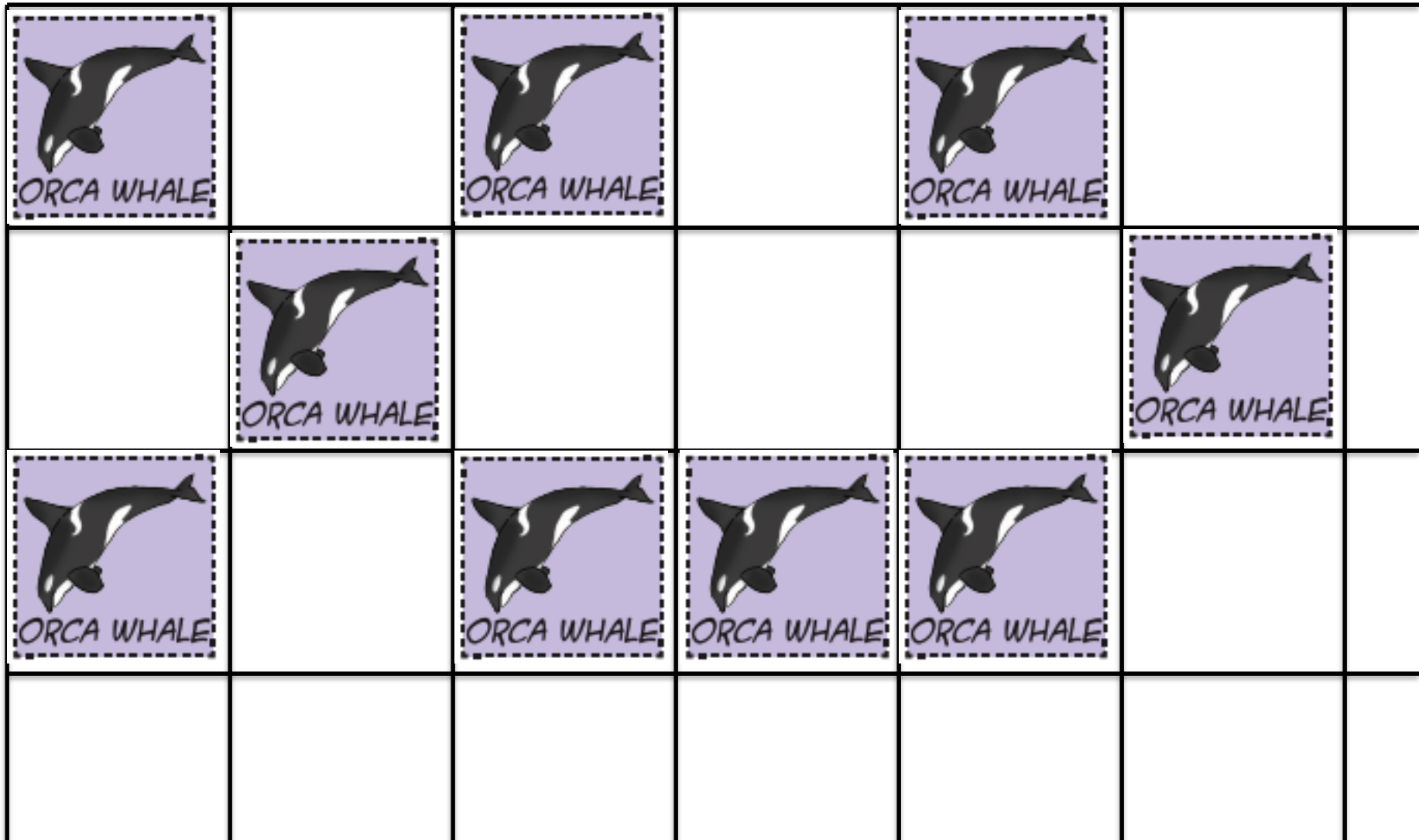
Food Chain Checkers

 COPEPOD	 ORCA WHALE	 ORCA WHALE	 ORCA WHALE	 DIATOM		
 HERRING	 HERRING	 HERRING			 ORCA WHALE	
 ORCA WHALE	 COPEPOD	 COPEPOD	 COPEPOD	 HERRING	 DIATOM	

Food Chain Checkers

 <p>COPEPOD</p>		 <p>ORCA WHALE</p>		 <p>ORCA WHALE</p>		
 <p>HERRING</p>	 <p>ORCA WHALE</p>	 <p>HERRING</p>			 <p>ORCA WHALE</p>	
 <p>ORCA WHALE</p>		 <p>COPEPOD</p>	 <p>ORCA WHALE</p>	 <p>HERRING</p>	 <p>DIATOM</p>	

Food Chain Checkers





“Essentially, all models are wrong,
but some models are useful.”

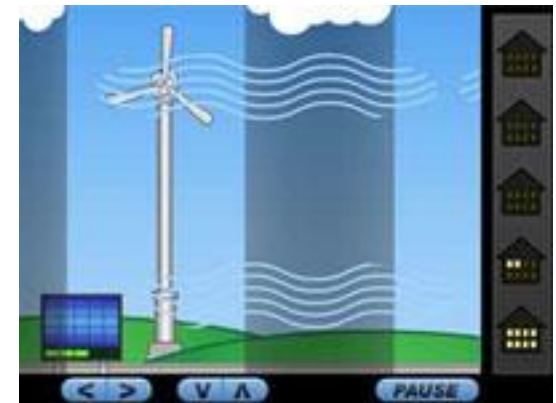
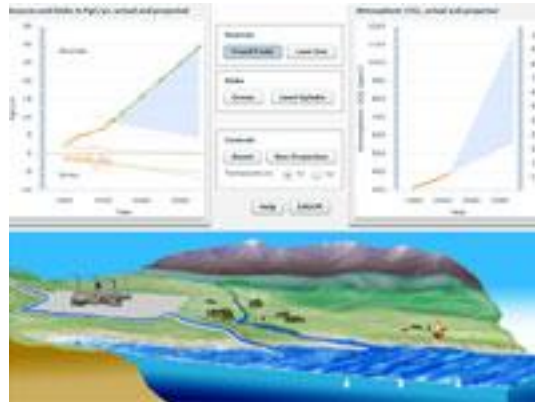
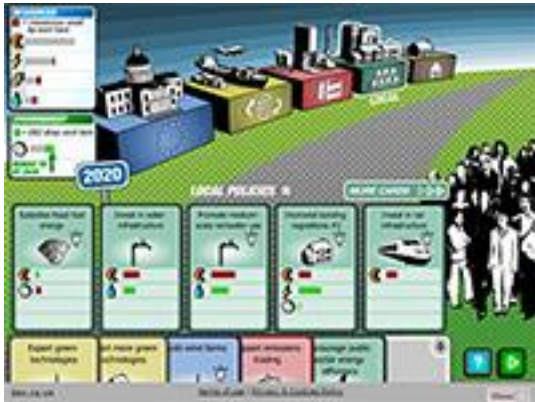
- George E. P. Box (1951)

NGSS:

“Because all models contain approximations
and assumptions that limit the range of validity
of their application and the precision of their
predictive power, **it is important to
recognize their limitations.**”

“... and suggest ways in which the model might
be **improved** to better fit available evidence...”

Collection of Sims/Games on Climate



URL: SciEd.ucar.edu/games-sims-weather-climate-atmosphere