TIEE

Teaching Issues and Experiments in Ecology - Volume 10, April 2014

ISSUES : DATA SET

Investigating the footprint of climate change on phenology and ecological interactions in north-central North America

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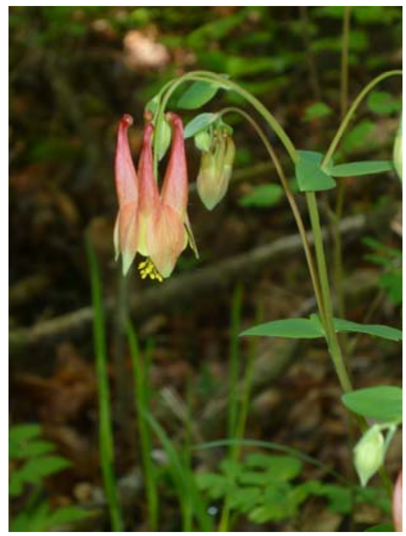

Aquilegia canadensis (red columbine) flowering with open and closed flowers

THE ECOLOGICAL QUESTION:
Have long-term temperatures changed throughout Ohio? How will these temperature changes impact plant and animal phenology, ecological interactions, and, as a result, species diversity?

ECOLOGICAL CONTENT:
Climate change, phenology, pollinators, trophic mismatch, species diversity, arrival time, mutualism

WHAT STUDENTS DO:
- Produce and analyze graphs of temperature change using large, long-term data sets (Synthesis, Analysis)
- Develop methods for calculating species-specific shifts in flowering time with temperature increase (Synthesis)
- Use these methods to calculate flowering shifts in six plant species (Application)
- Describe the ecological consequences of shifting plant and animal phenology (Comprehension)
- Understand how interactions between species as well as with their abiotic environment affect community structure and species diversity (Knowledge, Comprehension)
- Evaluate data “cherry-picking” as a climate change skeptic tactic (Evaluation)

STUDENT-ACTIVE APPROACHES:
Open-ended inquiry, guided inquiry, cooperative learning, critical thinking

SKILLS:
Work with large data sets, create and analyze multiple types of graphs, connect the development of procedures and data analysis to clarifying ecological impacts of climate change

ASSESSABLE OUTCOMES:
Student-made graphs, calculations of temperature and phenology shifts, answers to short questions, brief paragraphs describing student-generated methods

SOURCE:

- Calinger et al., 2013. Herbarium specimens reveal the footprint of climate change on flowering trends across north-central North America. Ecology Letters 16:1037–1044. http://onlinelibrary.wiley.com/doi/10.1111/ele.12135/abstract
- Ledneva et al., 2004. Climate Change as Reflected in a Naturalist's Diary, Middleborough, Massachusetts. Wilson Bulletin 116:224–231. http://people.bu.edu/primack/Ledneva_etal_2004_naturalists.pdf
- U.S. Historical Climatology Network http://cdiac.ornl.gov/epubs/ndp/ushcn/monthly_doc.html

OVERVIEW OF THE ECOLOGICAL BACKGROUND

This exercise was designed to give students experience working with large datasets and to allow them to use real ecological data to evaluate long-term temperature change and its impacts on flowering phenology, pollinator emergence and arrival phenology, and emergent trophic mismatches. The students use several data sets for this activity; long-term temperature records from the U.S. Historical Climatology Network (USHCN, Menne et al. 2010), flowering phenology data from Calinger et al. (2013), and pollinator arrival and emergence time data from Ledneva et al. (2004).

The USHCN has been collecting temperature data at 26 weather stations in Ohio from 1895 to the present (Menne et al. 2010). These data are particularly useful for climate change studies as the weather stations have remained in the same location for the entirety of the collection period and are situated away from urban areas. This eliminates false temperature trends due to altitudinal or latitudinal shifts or due to urban heat island effects. The temperature data presented to the students are the yearly mean spring (February-May) temperatures for each of Ohio's ten National Oceanic and Atmospheric Administration (NOAA) climate divisions. These spring division averages were calculated by determining the mean spring temperature for each of the 26 USHCN weather stations in OH; then, the spring-time temperatures of all USHCN stations in a given division were averaged to create division spring mean temperatures (see Figure 2 in the student handout for a map of USHCN weather stations and NOAA climate divisions in OH and Calinger et al. 2013 for additional details). Using these data, students can evaluate both regional, division-based temperature trends from 1895-2009 and large-scale temperature trends across the entire state.

To determine phenological responsiveness of flowering phenology, we used temperature data from the USHCN and herbarium specimens collected throughout OH from 1895-2009 (Calinger et al. 2013). Only those herbarium specimens with at least 50% of their flower buds in anthesis were included in the study to assess shifts in maximum flowering date. Each individual specimen was paired with a temperature specific to its collection year and location as well as the species' season of flowering. The students are given data from six example species from a total data set of 141 species.

TIEE

Teaching Issues and Experiments in Ecology - Volume 10, April 2014

The data regarding arrival time of the ruby throated hummingbird (*Archilochus colubris*) and emergence time of the Spring Azure butterfly (*Celastrina ladon*) were collected by a naturalist, Kathleen Anderson, from 1970-2002 in Middleborough, MA. Her observations included arrival time of 16 migratory bird species and first appearance of 2 butterfly species among others. A team of scientists lead by A. Ledneva (2004) paired these observations with temperature data from the NOAA weather station in Rochester, MA to calculate shifts in the timing of these phenological events with temperature.

DATA SETS

The temperature data contained in these files originated from the U.S. Historical Climatology Network (Menne et al. 2010) and is freely available to the public. The flowering phenology data are from my own publication and is an Open Access article freely available to the public (Calinger et al. 2013).

- Student Data: [xlsx]
- Faculty Data: [xlsx]

STUDENT INSTRUCTIONS

Introduction

Climate change as a result of anthropogenic greenhouse gas (GHG) emissions is clear in both climatological and biological data. Global temperatures have increased by 0.74°C ± 0.18°C over the past 100 years (1906-2005), although some regions experience locally greater warming (IPCC 2007). Along with this average increase in temperature, extreme weather events including extreme heat have become more common. The ten hottest years on record have all occurred since 1998.

Scientists use long-term climate (for example, see Figure 1) and biological datasets to assess past and current rates of warming and the impacts of this warming on key ecosystem functions. These analyses provide crucial information for the prediction of future impacts of warming as we continue to release massive quantities of GHGs into the atmosphere.

TIEE

Teaching Issues and Experiments in Ecology - Volume 10, April 2014

One clear biological indicator of climate change is phenology, or the timing of key life events in plants and animals. Phenological events are diverse and include time of flowering, mating, hibernation, and migration among many others. Generally, phenological events are strongly driven by temperature, with warmer temperatures typically resulting in earlier occurrence of springtime migration, insect emergence from dormancy, and reproductive events. Shifts in phenology in the direction predicted by climate change have been observed worldwide, suggesting that climate change is already having profound, geographically broad impacts on ecology (Parmesan & Yohe 2003, Menzel et al. 2006; Rosenzweig et al. 2008).

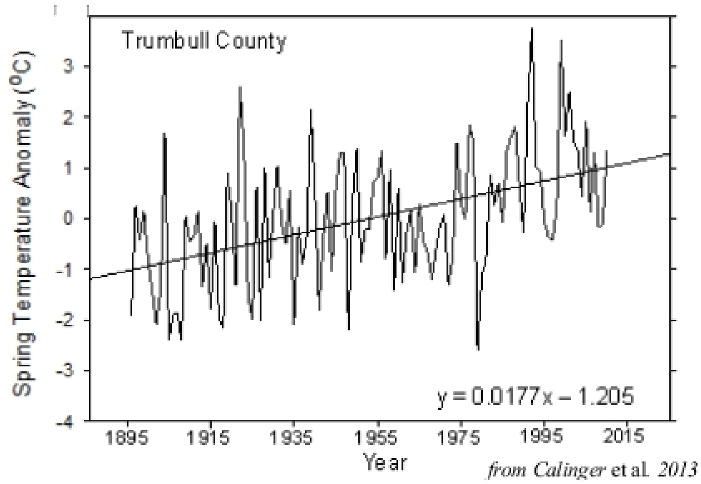

Figure 1. Spring temperature trends in Trumbull County, OH using yearly spring (February through May) temperature anomalies from 1895-2009. A simple linear regression line was used to determine shifts in spring temperatures over the 115-year period. This regression line (see equation in graph) indicates that Trumbull Co. has experienced a 2.0°C average spring temperature increase.

In this lab, you will be analyzing long-term temperature data collected in Ohio by the U.S. Historical Climatology Network (http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html) to establish temperature trends in Ohio over the past 115 years. You will then investigate temperature effects on the flowering of six plant species and the arrival and emergence times of two pollinator species to determine biological signals of climate change in Ohio.

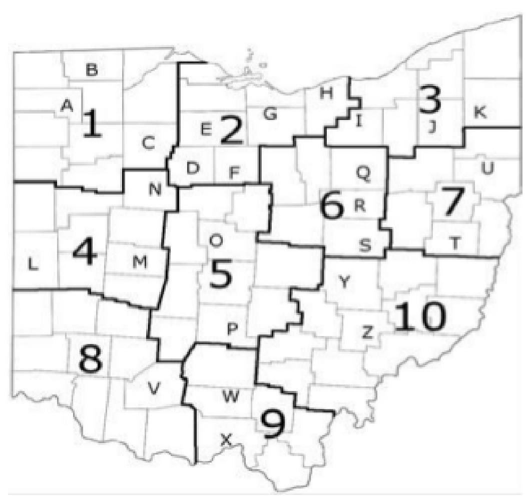

Figure 2. The ten NOAA climate divisions in Ohio and the location of the 26 USHCN weather stations (labeled A-Z).

EXERCISE

i. Regional Long-term Temperature Trends

The data for these exercises are provided for you by your lab instructor. You will work in pairs to analyze the data.

An important component of climate change studies is the analysis of temperature change over long timescales in the region of interest. For our analysis of Ohio, you will assess temperature change across the entire state as well as at smaller, regional scales. The U.S. Historical Climatology Network (USHCN) has collected temperature and precipitation data at 26 weather stations throughout Ohio since 1895 (Figure 2). The number of USHCN weather stations is limited as USHCN stations are required to have a consistent, non-urban location since 1895; this eliminates urban heat island effects (urbanized areas that are hotter than surrounding rural areas, U.S. EPA) and latitudinal/altitudinal effects. Changes in the location of weather stations can cause apparent increases or decreases in temperature as a result of moving to a generally warmer or cooler location. These possible altitudinal or latitudinal effects are eliminated in the USHCN climate record by requiring consistent station locations since the start of data collection. Using the mean of temperatures recorded at all 26 weather stations in Ohio, we can evaluate statewide trends in temperature since 1895.

To assess regional trends in temperature, we can use the ten climate divisions in Ohio established by the National Oceanic and Atmospheric Administration (NOAA, see Figure 1).

Look at the Excel file with data we have provided. The temperature record for each climate division is given in separate worksheets. Each climate division worksheet includes two columns; “Year” provides the year in which the temperature data were collected, and “Temp (deg C)” provides the spring time temperature for that year in degrees Celsius. These division temperatures were calculated by averaging the temperature records for every USHCN weather station in that division for the year of interest from February to May (spring temperatures). For example, Division 1 temperatures are the mean Feb.-May temperatures of USHCN weather stations A, B, and C (Figure 2).

With your partner, pick two climate divisions you will analyze. If you’re from Ohio, take a look at your home town division as one of your two climate divisions.

1. Looking at the data for the two climate divisions you have chosen to analyze, how would you determine temperature change from 1895-2009? In your answer,

TIEE

Teaching Issues and Experiments in Ecology - Volume 10, April 2014

address the following questions: What are your independent and dependent variables? What type of graph would be useful and why? What statistics would you use to extract the rate of temperature change from that graph? How would you calculate total temperature change over the 115 year period?

Based on your answer to the question above, produce a plot of temperature change for each of your climate divisions of interest (two graphs total). Using these graphs, record the rate of change (^{o}C/year) and total temperature change (^{o}C) from 1895-2009 in the table below.

Division	Rate of Temperature Change (^{o}C/year)	Total Temperature Change (^{o}C)
2a.		
2b.		

3. Is temperature increasing, decreasing, or remaining stable in your climate divisions? Do your divisions show similar trends or are they different?

TIEE

Teaching Issues and Experiments in Ecology - Volume 10, April 2014

Another tool commonly used by climate change scientists is a temperature anomaly plot. Yearly temperature anomalies indicate how much warmer or colder a given year is compared with the long-term average temperature. These plots are useful because they clearly indicate anomalously warm and cold years while still providing information on long-term temperature trends.

To calculate yearly temperature anomalies for your division, you first need to calculate the average spring-time temperature (^oC) for your division. Simply calculate the mean of all 115 temperatures in your division. Next, subtract the mean temperature from each of the yearly temperature values to produce yearly temperature anomaly values.

4. If the temperature anomaly for a given year is negative, what does this mean?

5. If the temperature anomaly for a given year is positive, what does this mean?

6. What type of graph should you use to analyze temperature anomaly data?

Based on your answer to question 6, produce a temperature anomaly graph for each of your climate divisions of interest (two graphs total). Using these graphs, answer the following questions:

Division	Rate of Temperature Change (^oC/year)	Total Temperature Change (^oC)
7a.		
7b.		

8. Are the temperature change rates and total temperature change values the same as in your original graphs? Why?

ii. Statewide Long-term Temperature Trends

Click on the worksheet labeled "State T Trends." We have provided both the temperature and temperature anomaly data for you. Plot these data to calculate the statewide rate of temperature change and total temperature change over the past 115 years.

9. What is the statewide rate of temperature change (^{o}C/year)? -

____

10. How much has spring time temperature (^{o}C) in Ohio changed over the past 115 years?

____

Your instructor will show you spring temperature change values for each of the 10 divisions.

11. Is temperature change even across the state or do some divisions show greater change than others? Use specific examples of division temperature trends in your answer.

12. Why is it important to assess temperature change across large areas rather than simply at small, regional scales (such as climate divisions)? How might climate change skeptics use long-term temperature data collected in small regions to present misleading temperature trends? Provide specific divisions as examples of this tactic in your answer.

iii. Biological Indicators of Climate Change: Flowering Time

Flowering time is a crucial phenological event for plants as it can strongly impact reproductive success (Calinger *et al.* 2013). Previous research has shown significant advancement of flowering with temperature increase (called phenological responsiveness, days flowering shifted/^{o}C), although species vary in the degree to which they shift flowering with temperature change. Since flowering time can have substantial fitness effects, climate change may alter species performance as climate warms, causing some species to decrease in abundance. You will analyze data on Ohio flowering times and assess impacts of temperature increase on species diversity.

Click on the worksheet labeled “Flowering data.” This worksheet provides data on the dates of flowering for six plant species collected throughout Ohio as well as temperature data and additional descriptive data (Calinger *et al*. 2013).

Look at the column headings: Species, Common Name, County, Year, Division, Temperature, and DOY. Species and Common Name specify the plant species of interest. Each row represents an individual observation for a given species. County and Division provide information on the county of observation and the NOAA Climate Division in which that county is found. Year simply indicates the year in which the observation was made.

Flowering dates are given in the “DOY” column. DOY stands for “day of year” and is the numeric day of year (day 1=Jan.1, Dec. 31=365, and so on) that the plant was flowering. Each flowering date is paired with a temperature specific to the individual plant’s location, year, and season of observation. This temperature (^{o}C) is given in the Temperature column.

13. Given these data, how will you assess phenological responsiveness (days/°C) for each species? Consider the following questions in your answer: What are your independent and dependent variables? What type of graph would be appropriate for your data? What statistical technique will you use to determine your phenological responsiveness value for each species?

14. Based on your answer above, create a graph showing the relationship between flowering date (DOY) and temperature for each of the six species. Use these graphs and the appropriate statistics to determine phenological responsiveness values for each species and fill in the chart below.

Species	**Flowering Shift (days/°C)**
Carduus nutans	
Castilleja coccinea	
Cornus florida	
Clematis virginiana	
Aquilegia canadensis	
Cypripedium acaule	
Average Flowering Shift	

15. Do all species exhibit identical shifts in flowering time with an increase in temperature, or do some species advance/delay flowering more than others as temperature increases? Use specific species as examples in your answer.

*16. Based on the average shift in flowering (*days/^{o}C*) over all species, is flowering time in Ohio changing with warming temperatures? On average, how much would flowering shift with a 1^{o}C or 2^{o}C temperature increase?*

17. Based on your flowering shift calculations for each species, will all species be equally well adapted to our warming Ohio climate? What impacts might this have on Ohio species diversity (we will consider species richness, or the total number of species in a given area, as our measure of species diversity)? Explain.

iv. Biological Indicators of Climate Change: Butterfly Emergence and Hummingbird Arrival Times

Along with shifts in the timing of plant phenological events, scientists have observed significant shifts in the timing of animal phenological events such as migration, insect emergence, and mating associated with temperature increase (Cotton 2003). Like flowering time in plants, the timing of these phenological events has direct impacts on reproductive success in animals.

Further, changes in the timing of phenological events in plants and animals may disrupt important plant-animal interactions such as pollination. These disruptions of interactions as a result of shifting phenology are called trophic mismatches. For example, in pollination mutualisms, the pollinator benefits from pollen and nectar food resources and the plant benefits by being pollinated and increasing its reproductive success. Under average climate conditions, without climate change associated warming, flowering time in the plant and arrival time of the pollinator (based on migration or insect emergence date) are cued to coincide. However, if the plant or pollinator responds more strongly to climate warming and shifts their phenology more than their mutualistic partner, this relationship will be disrupted. This trophic mismatch results in decreased pollination and reproduction for the plant and a loss of important floral food resources for the pollinator.

Using data provided below, you will be assessing the effects of warming on shifts in arrival time of the migratory ruby throated hummingbird, *Archilochus colubris* and emergence from overwintering of the Spring Azure butterfly, *Celastrina ladon* (data from Ledneva *et al.* 2004). Both of these species occur in Ohio although this data was collected in Massachusetts. For this study, we will assume that the responses of both the ruby throated hummingbird and the Spring Azure butterfly are uniform throughout their ranges. You will also discuss whether we have evidence for trophic mismatches based on your findings.

Species	Arrival Time Change (days/^oC)
Celastrina ladon (adults)	0.55
Archilochus colubris	-1.40

18. Based on the data given above for arrival time change, describe the pattern of shifting arrival/emergence time phenology for each pollinator species.

19. Archilochus colubris *uses* Aquilegia canadensis (*columbine*) *flowers as a nectar food resource, and, in turn, is an important pollinator of this plant (Bertin 1982).* Celastrina ladon *caterpillars feed on* Cornus florida (*flowering dogwood) flowers (University of Florida IFAS Extension), although this interaction is not mutualistic as the dogwood receives no benefit. Given your knowledge of flowering shifts with temperature in* A. canadensis *and* C. florida *as well as arrival time shifts with temperature in* A. colubris *and* C. ladon*, speculate on what effects climate warming might have on survival and reproduction in these species. How would species interactions change with a 1^oC temperature increase? With a 3^oC temperature increase?*

TIEE

Teaching Issues and Experiments in Ecology - Volume 10, April 2014

v. Debunking a climate change skeptic tactic

Climate change skeptics often try to argue that temperatures have not been increasing and present misleading data to support their point. Frequently, they use a tactic called "cherry picking" data. Cherry-picking data involves including only the data that supports whatever point you are trying to make while disregarding the rest of the data that would discredit that point.

Look at your plot of spring temperature change across Ohio. The data indicate a significant temperature increase of about 0.9^{o}C since 1895. In fact, 3 of the 5 warmest years in the temperature record are in the 1990's and 2000's.

Now plot statewide temperature including ONLY yearly spring temperatures from 1990-2009.

20. Does your plot indicate temperature increase or decrease from 1990-2009? What is the rate of temperature change?

21. Based on the long-term, 115-year assessment of temperature change versus the shorter, 20-year assessment, can we accurately assess temperature change using a small subset of the data? Refer to the data in your answer.

22. Why is it inappropriate to use only a subset of the total years to establish a climatic pattern?

Your instructor will tell you how to turn in this assignment.

TIEE

Teaching Issues and Experiments in Ecology - Volume 10, April 2014

LITERATURE CITED

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NOTES TO FACULTY

Description of Excel Files:

Ohio Climate Change Lab Student Copy: The student file contains yearly spring temperature data (°C) for Ohio's ten NOAA climate divisions as well as statewide yearly spring temperature averages. This file also contains data regarding flowering time of six plant species including flowering date of individual specimens paired with temperatures specific to their year and locations of collections as well as each species' average month of flowering.

Ohio Climate Change Instructor Copy: The faculty file contains the same data as the student file, but also includes all completed plots of temperature with time and provides regression equations and R^2 values. This file also provides compiled temperature change rate values and calculated temperature change over 115 years for each of the ten climate divisions and across the state (under "State T Trends" tab). Plots of flowering shift with temperature as well as phenological responsiveness values (slope, d/°C) and R^2 values for each of the six plant species have also been provided.

Running the Class:

i. *General Overview*

This lab was designed to complement materials presented during in-class lectures on climate change and includes all six components of Bloom's taxonomy of learning (see parentheses in "What Students Do" above). Students will benefit greatly from some basic knowledge of climate change principles and biological impacts of climate change. Particularly, students should understand that increased temperatures associated with climate change are the result of anthropogenic greenhouse gas emissions (with additional complex feedback loops) and that climate change varies regionally across the globe. Further, students should have some introduction into biological impacts of climate change such as species range shifts, shifting phenology, increased productivity in terrestrial and marine environments, etc.

This lab emphasizes data analysis as a tool to investigate temperature change and phenology shifts associated with climate change. Most students have likely been exposed to misleading or skewed data and figures regarding climate change. However, if we provide them with the tools to assess these figures and data, students will be better able to evaluate the accuracy of these figures and identify "tricks" used to manipulate data. Here, we use a combination of open-ended and guided inquiry to teach students basic principles of graph making, data and figure analysis, and how to draw conclusions using their data.

ii. Pre-lab Information and Student Activity

The data analysis in this lab requires not only basic graph making skills, but also simple linear regression, which many students likely will not have encountered. Thus, in the introduction to the lab, it would be helpful for instructors to present some basic graphing essentials. Particularly emphasize the following terms/concepts: independent and dependent variables (which is plotted on the x- or y-axis, which is controlled), axis labels, appropriate axis scale, line graphs vs. scatter plots (why we use different graphs for different data types, line graphs: continuous variables over time, scatterplots: two continuous variables), lines of best fit (aka regression lines), the formula of a line (the basics of $y = mx + b$), and slopes as indicators of rates.

Discussing examples of both line graphs and scatterplots before the activity should help students select the appropriate graph types in the lab activities. The graph of Trumbull Co. spring temperature change provided in the background section of the lab handout is a useful example of a line graph. Particularly, point out the use of line graphs for continuous data throughout time, which students will need to understand during the temperature investigation activities. An example scatterplot can be found at the following link http://iopscience.iop.org/1748-9326/3/3/034003/fulltext/ in Figure 2. Each of the panels shows the relationship between crop yield of corn or soybean in relation to trends in temperature or precipitation over time. Point out that scatterplots are useful when plotting two continuous variables. Also, have students interpret the trend lines based on the equations provided in each panel.

Discussion of graphs can be done as pre-lab activity and can be completed either as an entire class discussion, using think-pair-share, or "turn to your neighbor" techniques (see http://tiee.esa.org/teach/teach_glossary.html#studentactive for more information on think-pair-share and turn to your neighbor teaching techniques). It might be useful to have students define some of the above terms and concepts using the example graphs (or other example graphs) to ensure they all have a proper understanding of graph analysis. Remind students to use what they've learned about graph making as they prepare their own figures in this lab.

iii. General Tips

Students will work in pairs for the duration of the lab (please see the TIEE link above for additional information on cooperative learning). The amount of time required to complete this activity will vary based on the Excel experience level of each pair. It might be helpful to ask which students are confident in their Excel skills and pair them with a less experienced partner. Alternatively, the instructor could do a brief introduction to graphing in Excel.

The order of activities in this lab can also be adjusted based on which activities the instructor would like to emphasize. Currently, the activities are arranged such that the investigation of temperature change flows immediately into the examination of its biological impacts on flowering time and pollinator phenology. With this arrangement, the lab ends with an investigation of the effects of data cherry picking. This could be followed by a group discussion on data manipulation and its use by climate change skeptics. Alternatively, the data cherry picking activity could be placed immediately after the "Statewide Long-term Temperature Trends" section as a continuation of student's analysis of temperature trends.

There are also several options for student submission of their work for this activity. Since this is a computer based lab, the student worksheet could be distributed electronically rather than as hardcopies. In this case, students could fill in answers in Word and copy and paste their completed graphs into the Word document from Excel. Students could submit these files electronically for grading. Alternatively, if the instructor prefers hardcopies for answering lab questions, students could electronically submit their completed Excel files including both students' names in the file name.

iv. Answer Guide for Student Evaluation (Assessable Outcomes: student made graphs, calculations of temperature change and phenological responsiveness, short answer responses to methods questions and critical thinking questions)

The Answer Guide below provides a sample rubric based on a 50 point exercise along with answers to each question. These points can be easily adapted to fit different grading schemes and are meant to weight the relative importance of each section with an emphasis on critical thinking questions.

i. Regional Long-term Temperature Trends

The data for these exercises are provided for you by your lab instructor. You will work in pairs to analyze the data.

TIEE

Teaching Issues and Experiments in Ecology - Volume 10, April 2014

An important component of climate change studies is the analysis of temperature change over long timescales in the region of interest. For our analysis of Ohio, you will assess temperature change across the entire state as well as at a regional scale. The U.S. Historical Climatology Network (USHCN) has collected temperature and precipitation data at 26 weather stations throughout Ohio since 1895 (Figure 2). The number of USHCN weather stations is limited as USHCN stations are required to have a consistent, non-urban location since 1895; this eliminates urban heat island (urbanized areas that are hotter than surrounding rural areas, U.S. EPA) and latitudinal/altitudinal effects. Changes in the location of weather stations can cause apparent increases or decreases in temperature as a result of moving to a generally warmer or cooler location. These possible altitudinal or latitudinal effects are eliminated in the USHCN climate record by requiring consistent station locations since the start of data collection. Using the mean of temperatures recorded at all 26 weather stations in Ohio, we can evaluate statewide trends in temperature since 1895.

To assess regional trends in temperature, we can use the ten climate divisions in Ohio established by the National Oceanic and Atmospheric Administration (NOAA, see Figure 1).

Look at the Excel file we have provided with data. The temperature record for each climate division is given in separate worksheets. Each climate division worksheet includes two columns; "Year" provides the year in which the temperature data were collected, and "Temp (deg C)" provides the spring time temperature for that year in degrees Celsius. These division temperatures were calculated by averaging the temperature records for every USHCN weather station in that division for the year of interest from February to May (spring temperatures). For example, Division 1 temperatures are the mean Feb.-May temperatures of USHCN weather stations A, B, and C (Figure 2).

With your partner, pick two climate divisions you will analyze. If you're from Ohio, take a look at your home town division as one of your two climate divisions.

1. Looking at the data for the two climate divisions you have chosen to analyze, how would you determine temperature change from 1895-2009? In your answer, address the following questions: What are your independent and dependent variables? What type of graph would be useful and why? What statistics would you use to extract the rate of temperature change from that graph? How would you calculate total temperature change over the 115 year period?

Independent variable: Time/years (0.5 points)
Dependent variable: Temperature (0.5 points)

TIEE

Teaching Issues and Experiments in Ecology - Volume 10, April 2014

Type of Graph: Students may use either a line graph or a scatter plot for this exercise. Line graphs are preferable as temperature trends are more obvious based on a simple visual examination of the data in this format. Students should be guided to line graphs for this question through presentation of introductory material by the teacher as well as the temperature graph presented in the student handout background section. (1.5 points)

Statistics: Regression, line of best fit. Use the slope of this line to determine the rate of temperature change. (1.25 points)

Calculating total temperature change: Use the slope from the regression line to determine yearly temperature change. Multiply this slope by 115 (total number of years) to determine cumulative temperature change from 1895-2009. (1.25 points)

Based on your answer to the question above, produce a plot of temperature change for each of your climate divisions of interest (two graphs total). Using these graphs, record the rate of change (^{o}C/year) and total temperature change (^{o}C) from 1895-2009 in the table below.

See the Instructor Copy of the data set for temperature change rates and total temperature change for all ten divisions.

Division	Rate of Temperature Change (^{o}C/year)	Total Temperature Change (^{o}C)
2a.	(0.5 points)	(0.5 points)
2b.	(0.5 points)	(0.5 points)

3. Is temperature increasing, decreasing, or remaining stable in your climate divisions? Do your divisions show similar trends or are they different?

Student answers will vary based on their choice of divisions. Eight of the ten divisions experienced temperature increase while one division remained essentially stable and one division showed temperature decrease.

A good answer would comment not only on the direction of temperature change, but also on the magnitude of change. (complete answer = 2 points. If students do not include the direction of change or some description of the magnitude of change, <1.5 points)

Another tool commonly used by climate change scientists is a temperature anomaly plot. Yearly temperature anomalies indicate how much warmer or colder a given year is compared with the long-term average temperature. These plots are useful because they clearly indicate anomalously warm and cold years while still providing information on long-term temperature trends.

To calculate yearly temperature anomalies for your division, you first need to calculate the average spring time temperature (^{o}C) for your division. Simply calculate the mean of all 115 temperatures in your division. Next, subtract the mean temperature from each of the yearly temperature values to produce yearly temperature anomaly values.

4. If the temperature anomaly for a given year is negative, what does this mean?

A year with a negative temperature anomaly value is colder than the long term average. (0.5 points)

5. If the temperature anomaly for a given year is positive, what does this mean?

A year with a positive temperature anomaly value is warmer than the long term average. (0.5 points)

6. What type of graph should you use to analyze temperature anomaly data?

As in the question above:
Type of Graph: Students may use either a line graph or a scatter plot for this exercise. Line graphs are preferable as temperature trends are more obvious with a simple visual examination of the data. Students should be guided to line graphs for this question through presentation of introductory material by the teacher as well as the temperature graph presented in the student handout Background section. (1 point)

Based on your answer to question 6, produce a temperature anomaly graph for each of your climate divisions of interest (two graphs total). Using these graphs, answer the following questions:

Student answers for this table should be identical to the previous table.

Division	Rate of Temperature Change (^{o}C/year)	Total Temperature Change (^{o}C)
7a.	(0.5 points)	(0.5 points)

7b.	(0.5 points)	(0.5 points)

8. Are the temperature change rates and total temperature change values the same as in your original graphs? Why?

Yes. Because temperature anomaly plots are simply a different presentation of the same data set. (1 point)

ii. Statewide Long-term Temperature Trends

Click on the worksheet labeled "State T Trends." We have provided both the temperature and temperature anomaly data for you. Plot these data to calculate the statewide rate of temperature change and total temperature change over the past 115 years.

9. What is the statewide rate of temperature change (^oC/year)? ___0.007_ *(1 point)*

10. How much has spring time temperature (^oC) in Ohio changed over the past 115 years?

_______0.92___________(1 point)

Your instructor will show you spring temperature change values for each of the 10 divisions.

11. Is temperature change even across the state or do some divisions show greater change than others? Use specific examples of division temperature trends in your answer.

Temperature change is not uniform across the state. While most divisions (8 of 10) show temperature increase, Division 9 has shown almost no change, and Division 8 has experienced temperature decrease. Among those with increasing temperature, the increase ranges from over 1.5 degrees to only 0.5 degrees.

3 points: contains complete description of variation in temperature change among divisions and cites specific examples from the data
2 points: description of temperature variation incomplete, makes some reference to the data
1 point or less: incomplete descriptions of variation, no reference to the data

12. Why is it important to assess temperature change across large areas rather than simply at small, regional scales (such as climate divisions)? How might climate change skeptics use long-term temperature data collected in small regions to present misleading temperature trends? Provide specific divisions as examples of this tactic in your answer.

Assessing only a small area may present misleading information on the climatic trends of a region as a whole. If we had only assessed divisions 8 and 9, we would think Ohio climate is unchanging or cooling slightly. Alternatively, if we had examined only divisions 3 and 7, we would think Ohio was warming more rapidly than the state wide mean would suggest. Climate change skeptics could use only a small subset of large-scale regional temperature data to mask or minimize warming trends.

3.5 points: addresses both questions and includes specific examples from the data
2.5 points: incomplete answer to one of the questions, makes some reference to the data
1 point: answers are vague, data not referenced

iii. Biological Indicators of Climate Change: Flowering Time

Flowering time is a crucial phenological event for plants as it can strongly impact reproductive success (Calinger *et al.* 2013). Previous research has shown significant advancement of flowering with temperature increase (called phenological responsiveness, days flowering shifted/^{o}C), although species vary in the degree to which they shift flowering with temperature change. Since flowering time can have substantial fitness effects, climate change may alter species performance as climate warms, causing some species to decrease in abundance. You will analyze data on Ohio flowering times and assess impacts of temperature increase on species diversity.

Click on the worksheet labeled “Flowering data.” This worksheet provides data on the dates of flowering for six plant species collected throughout Ohio as well as temperature data and additional descriptive data (Calinger *et al*. 2013).

Look at the column headings: Species, Common Name, County, Year, Division, Temperature, and DOY. Species and Common Name specify the plant species of interest. Each row represents an individual observation for a given species. County and Division provide information on the county of observation and the NOAA Climate Division in which that county is found. Year simply indicates the year in which the observation was made.

Flowering dates are given in the "DOY" column. DOY stands for "day of year" and is the numeric day of year (day 1=Jan.1, Dec. 31=365, and so on) that the plant was flowering. Each flowering date is paired with a temperature specific to the individual plant's location, year, and season of observation. This temperature (^oC) is given in the Temperature column.

13. Given these data, how will you assess phenological responsiveness (days/^oC) for each species? Consider the following questions in your answer: What are your independent and dependent variables? What type of graph would be appropriate for your data? What statistical technique will you use to determine your phenological responsiveness value for each species?

Independent variable: Temperature (0.5 points)
Dependent variable: flowering date (DOY) (0.5 points)

Type of Graph: Students will need to use scatterplots to plot paired temperature and flowering date data. Introducing some examples of scatterplots in the class introduction would be helpful in guiding students to this point. (1.5 points)

Statistics: Regression using the slope of the line (days/^oC) as phenological responsiveness (1.5 points)

14. Based on your answer above, create a graph showing the relationship between flowering date (DOY) and temperature for each of the six species. Use these graphs and the appropriate statistics to determine phenological responsiveness values for each species and fill in the chart below.

Species	**Flowering Shift (days/^oC)**
Carduus nutans	-12.5 (0.5 points)
Castilleja coccinea	-7.3 (0.5 points)
Cornus florida	-2.3 (0.5 points)
Clematis virginiana	4.9 (0.5 points)
Aquilegia canadensis	-3.1 (0.5 points)
Cypripedium acaule	-3.4 (0.5 points)
Average Flowering Shift	-4.0 (0.5 points)

15. Do all species exhibit identical shifts in flowering time with an increase in temperature, or do some species advance/delay flowering more than others as temperature increases? Use specific species as examples in your answer.

Flowering shifts with temperature show considerable variation between species. *C. nutans* shows the strongest response, advancing flowering 12.5 days for every ^{o}C temperature increase while *C. florida* advances flowering by only 2.3 days. *C. wisteriana* delays flowering by roughly 2 days for every ^{o}C temperature increase and thus show a flowering shift trend opposite the other species.

2.5 points: describes variation in flowering shift between species and provides specific examples
1.25 point: Describes either variation or provides examples, but is lacking one of these components
>1.25 points: does not provide sufficient detail for either aspect of the question

*16. Based on the average shift in flowering (*days/^{o}C*) over all species, is flowering time in Ohio changing with warming temperatures? On average, how much would flowering shift with a 1^{o}C or 2^{o}C temperature increase?*
Total points for question 16: 2 points

Yes, on average flowering time in Ohio will be earlier with warming temperatures. With a 1^{o}C increase, flowering will be 4 days early and with 2^{o}C, flowering will advance by 8 days.

0.5 points: student correctly states that flowering time is shifting with warming
1.5 points: student correctly calculates flowering shift for both temperatures (0.75 points each)

17. Based on your flowering shift calculations for each species, will all species be equally well adapted to our warming Ohio climate? What impacts might this have on Ohio species diversity (we will consider species richness, or the total number of species in a given area, as our measure of species diversity)? Explain.

No. Given the highly variable flowering shifts, it is extremely unlikely that all responses will be equally adaptive to warming climate. If some species are predisposed to perform worse with increasing temperatures as a function of their phenological responsiveness, we would expect a decline in abundance of these species. If this decline is severe, we may even experience extirpation of the species in parts of its range thus decreasing the total number of species. Thus, we predict a decline in Ohio species diversity with warming.

Points for part 1 of question 17 (*Based on your flowering shift… climate? Explain)*:
2 points: Student states that all species will not be equally well adapted to warning and provides some explanation

1 point: Student correctly answers the questions but does not provide an explanation
<1 point: answer incorrect and lacking explanation

Points for part 2 of question 17 (*What impacts… species diversity? Explain.)*:
2 points: Provides a reasonable discussion of species diversity impacts and includes explanation
1 point: Describes a potential species diversity effect but lacks explanation
<1 point: No clear species diversity effect described and no explanation

iv. Biological Indicators of Climate Change: Butterfly Emergence and Hummingbird Arrival Times

Along with shifts in the timing of plant phenological events, scientists have observed significant shifts in the timing of animal phenological events such as migration, insect emergence, and mating associated with temperature increase (Cotton 2003). Like flowering time in plants, the timing of these phenological events has direct impacts on reproductive success in animals.

Further, changes in the timing of phenological events in plants and animals may disrupt important plant-animal interactions such as pollination. These disruptions of interactions as a result of shifting phenology are called trophic mismatches. For example, in pollination mutualisms, the pollinator benefits from pollen and nectar food resources and the plant benefits by being pollinated and increasing its reproductive success. Under average climate conditions, without climate change associated warming, flowering time in the plant and arrival time of the pollinator (based on migration or insect emergence date) are cued to coincide. However, if the plant or pollinator responds more strongly to climate warming and shifts their phenology more than their mutualistic partner, this relationship will be disrupted. This trophic mismatch results in decreased pollination and reproduction for the plant and a loss of important floral food resources for the pollinator.

Using data provided below, you will be assessing the effects of warming on shifts in arrival time of the migratory ruby throated hummingbird, *Archilochus colubris* and emergence from overwintering of the Spring Azure butterfly, *Celastrina ladon* (data from Ledneva *et al.* 2004). Both of these species occur in Ohio although this data was collected in Massachusetts. For this study, we will assume that the responses of both the ruby throated hummingbird and the Spring Azure butterfly are uniform throughout their ranges. You will also discuss whether we have evidence for trophic mismatches based on your findings.

Species	Arrival Time Change (days/°C)
Celastrina ladon	0.55
Archilochus colubris	-1.40

18. Based on the data given above for arrival time change, describe the pattern of shifting arrival/emergence time phenology for each pollinator species.

The spring azure butterfly is emerging later by half a day per °C temperature increase. In contrast, the ruby throated hummingbird is arriving 1.4 days early per °C temperature increase. (1 point)

19. Archilochus colubris *uses* Aquilegia canadensis (*columbine*) *flowers as a nectar food resource, and, in turn, is an important pollinator of this plant (Bertin 1982).* Celastrina ladon *caterpillars feed on* Cornus florida (*flowering dogwood) flowers (University of Florida IFAS Extension), although this interaction is not mutualistic as the dogwood receives no benefit. Given your knowledge of flowering shifts with temperature in* A. canadensis *and* C. florida *as well as arrival time shifts with temperature in* A. colubris *and* C. ladon*, speculate on what effects climate warming might have on survival and reproduction in these species. How would species interactions change with a 1°C temperature increase? With a 3°C temperature increase?*
(5 points total)

Archilochus colubris and *Aquilegia canadensis*: While both species show earlier phenology (of arrival and flowering, respectively), columbine is twice as responsive advancing flowering by 3.1 days versus earlier arrival of hummingbirds of 1.4 days/°C. The mismatch between the phenological events of these mutualists increases with greater warming. With 3°C temperature increase, columbine will bloom 9.3 days earlier while the hummingbirds will arrive only 4.2 days earlier. Thus, with warming, the columbine may have decreased pollination benefit from hummingbirds and hummingbirds may lose access to an important nectar food resource.

2.5 points: Describes mismatch effects on both the plant and its pollinator. Correctly states phenological shifts for both temperature increase scenarios.
1.5 points: Describes mismatch effects for only the plant or its pollinator, includes at least most phenology shift values for different temperature increase scenarios.
<1.25 points: Effects on plant and pollinator are unclear. Phenology shift calculations either incomplete or incorrect.

Celastrina ladon caterpillars and *Cornus florida*: The dogwood species advances flowering by 2.3 days/^{o}C while *C. ladon* delays emergence by 0.5 days/^{o}C. With 3^{o}C temperature increase, the dogwood will flower almost a week earlier while *C. ladon* will emerge a day and a half later. This suggests a potential mismatch between these species in which *C. ladon* caterpillars may lose an important food source.

2.5 points: Describes mismatch effects on both the plant and the butterfly. Correctly states phenological shifts for both temperature increase scenarios.
1.5 points: Describes mismatch effects for only the plant or the butterfly, includes at least most phenology shift values for different temperature increase scenarios.
<1.25 points: Effects on the plant and the butterfly are unclear. Phenology shift calculations either incomplete or incorrect.

v. Debunking a climate change skeptic tactic

Climate change skeptics often try to argue that temperatures have not been increasing and present misleading data to support their point. Frequently, they use a tactic called "cherry picking" data. Cherry-picking data involves including only the data that supports whatever point you are trying to make while disregarding the rest of the data that would discredit that point.

Look at your plot of spring temperature change across Ohio. The data indicate a significant temperature increase of about 0.9^{o}C since 1895. In fact, 3 of the 5 warmest years in the temperature record are in the 1990's and 2000's.

Now plot statewide temperature including ONLY yearly spring temperatures from 1990-2009.

20. Does your plot indicate temperature increase or decrease from 1990-2009? What is the rate of temperature change?

The temperature anomaly plot shows temperature decrease of -0.0217^{o}C/year. (1 point)

21. Based on the long-term, 115-year assessment of temperature change versus the shorter, 20-year assessment, can we accurately assess temperature change using a small subset of the data? Refer to the data in your answer.

No, using smaller subsets of data will not reflect actual long-term temperature patterns. Our 20-year temperature trend was opposite that of the entire 115 year dataset.

2 points: Correct response with reference to the data.
1 point: Correct response but no reference to the data.
<1 point: Response incorrect/incomplete with no reference to data.

22. Why is it inappropriate to use only a subset of the total years to establish a climatic pattern?

By cherry picking a small subset of the total dataset, you could find any number of temperature trends ranging from decrease, no change, and rapid increase, and thus these short term trends are not representative of any long-term patterns. When assessing climatic patterns, it is necessary to assess long-term data sets to determine actual temperature trends.

2.5 points: Describes problems with cherry picking relative to use of the complete record.
1.5 points: Answer is vague, provides limited rationale for avoiding data cherry picking.
>1.5: Response doesn't answer question or is extremely vague.

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