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INVESTIGATING THE URBAN HEAT ISLAND EFFECT WITH A COLLABORATIVE INQUIRY PROJECT

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ABSTRACT

Modification of the earth's surface through urbanization can have a dramatic impact on local climate. A phenomenon known as the Urban Heat Island (UHI) effect, which is a measure of the near-surface air temperature contrast between urbanized and adjoining rural areas, can be evaluated with readily available instruments. Students in an undergraduate general education science course study this phenomenon in the Portland, Oregon area through a collaborative research project. This inquiry project includes background content and literature review, preliminary studies, development of research questions, experimental design and implementation, data analysis and report writing. This project successfully enables students to collaboratively generate a data set that is amenable to sophisticated and interesting analysis and provides an opportunity to study a phenomenon in their local environment.

Keywords: undergraduate education, collaborative inquiry.

INTRODUCTION

Urban heat islands are characterized by "islands" of warm surface air centered on urbanized landscapes and surrounded by progressively cooler air over suburban/rural areas. The urban-rural surface air temperature contrast varies diurnally and is one measure of the urban heat island (UHI) effect. Urban heat islands result from factors that differentiate the urban from the non-urbanized landscape, including: anthropogenic energy releases from heating-ventilation-air condition-ing systems, energy emissions from industrial processes and motorized vehicles, the amount of available surface moisture and the differential heat capacities of urban building materials versus natural structures. The magnitude and spatial scale of UHI effects have increased in urban areas around the world and have implications for the transport of air pollutants, modification of bioclimatic conditions, heating and cooling costs and the confounding of long-term temperature records. The investigation of UHI effects provides numerous avenues of exploration that are both topical and relevant to students lives - characteristics that promote successful classroom implementation of science inquiry projects (McNeal and D'Avanzo, 1997).

This paper documents the process used for our Urban Heat Island classroom research project in our undergraduate "Atmospheric Interactions" course and discusses some of the outcomes both in terms of scientific results and achievements in student learning. The course is an upper division undergraduate general education science course that is taken primarily by students not majoring in science to fulfill degree requirements. The objective of the course is to study the physical and chemical properties of the atmosphere through lecture and field studies. We pay particular attention to the impact of human activities on the atmosphere.

This Urban Heat Island project is designed to parallel a scientific research process as it takes the students through literature review, preliminary studies, development of research questions, experimental design and implementation, data analysis and report writing. As an instructional approach it has the following features: it is situated in a meaningful real-world context; it provides students with an opportunity to deepen their understanding of physical principles through application; it requires classroom collaboration combined with significant individual effort; it incorporates an appropriate use of technology and it requires the communication of the analysis in the rhetorical style of a scientific paper. The design and implementation of this project is consistent with science inquiry pedagogy recommended by national organizations to be a part of undergraduate science education (NSF, 1996, Society for College Science Teachers, 1998).

OVERVIEW OF THE URBAN HEAT ISLAND EFFECT

There are numerous on-line and text references that provide good coverage of the basics of boundary layer meteorology and the urban heat island effect (for example - Akbari, 2002, Arnold, 1999, Ahrens, 1994, Turco, 1997, Stull, 1988). The discussion below is based on lecture notes and the references noted above. It is provided as an introduction to the subject in order to understand the general design of the project.

The temperature of air near the surface, or boundary layer, is strongly influenced by the energy flux and physical characteristics of the surface. The natural energy balance between solar radiation input, long-wave emissivity and sensible heat transfer results in a diurnal cycle of heating and cooling of the earth's surface and atmospheric boundary layer. In contrast, significant diurnal variation in air temperature is not observed above the surface-influenced layer of the atmosphere or the free troposphere and above.

In order to examine the urban heat island effect, we can consider the energy fluxes through a shallow layer at the surface containing air and surface elements (see Figure 1). The external energy source for this layer is solar radiation. The net radiative energy, Q_{net}, is controlled by the relative magnitude of shortwave and longwave radiation entering and leaving the layer. The radiative energy budget can be accounted for with Equation 1:

$$Q_{net} = K_{dsr} + K_{usr} + L_{dir} + L_{uir} \qquad (1)$$

where, K_{dsr} and K_{usr} refer to upwelling and downwelling solar shortwave radiation flux, and L_{dir} and L_{uir} refer to downwelling and upwelling infrared radiation (Stull, 1988, Oke, 1987). K_{dsr} is a function of solar zenith angle.
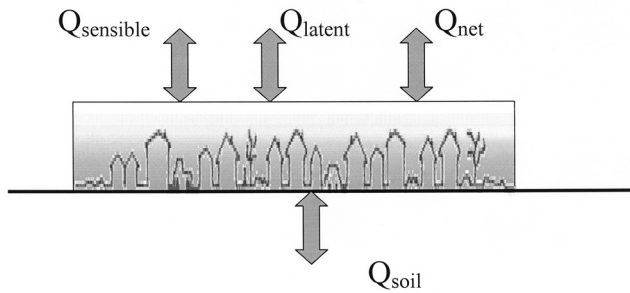
Figure 1. Surface energy balance. The net radiation, Q_{net}, drives repartitioning of energy into sensible heat, $Q_{sensible}$, latent heat, Q_{latent} and soil heat flux Q_{soil}. The direction and magnitude of the energy flows will depend on surface characteristics and time of day (Stull, 1988).
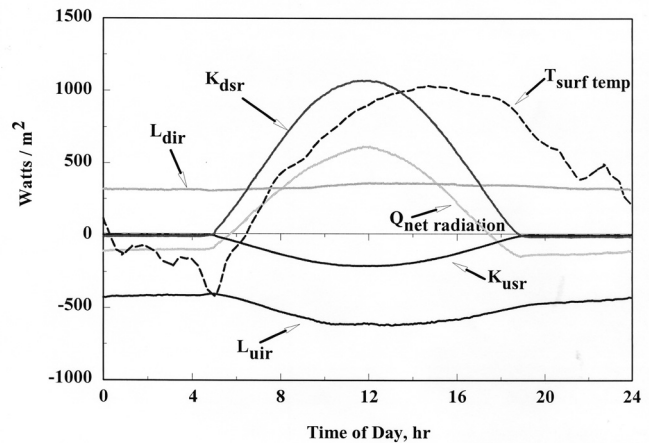

Figure 2. Surface radiation data collected in the Nevada desert on July 12, 2001. Data collected by the NOAA surface radiation monitoring network, SURFRAD, show the diurnal pattern of shortwave and longwave radiation flux.

K_{usr} depends on K_{dsr} and the solar albedo of the surface. The higher the albedo of the surface the less energy is absorbed by the surface and more solar energy is reflected back into the atmosphere. L_{dir} is longwave radiation emitted by the sun and the atmosphere itself towards the surface. L_{uir} is the longwave radation emitted by the surface and is dependent on the temperature of the surface.

Equation 1 can be used to establish the amount of net energy that is potentially available for surface heating. Figure 1 plots surface radiation monitored in the Nevada desert by the NOAA Surface Radiation Monitoring Network (Surfrad) (NOAA, 2001). Downwelling shortwave radiation, K_{dsr}, follows a typical diurnal pattern for cloudless skies. The upwelling shortwave radiation, K_{usr}, mirrors K_{dsr} attenuated by the absorbtivity of the surface (the inverse of albedo). Upwelling longwave radiation is a function of the surface temperature and can be approximated by a Stefan-Boltzmann calculation (Stull, 1988). Figure 2 shows that a surplus of radiative energy is available during most of the day and that a deficit exists during the nighttime. In general, the surface air temperature rises when Q_{net} is increasing and cools when Q_{net} is decreasing. The atmosphere and surface interact within a one hour response time (Stull, 1988).

Net radiation, Q_{net}, is a forcing term that results in partitioning of energy into sensible heat leaving the box through conduction (Q_H), latent heat of evaporation removing energy from the surface (Q_E), conduction to the subsurface (Q_{soil}), and storage of energy within the box (Q_s) (see Figure 1) (Stull, 1988).

$$Q_{net} = Q_{sensible\ heat} + Q_{soil} + Q_{latent\ heat} + Q_s \qquad (2)$$

The amount of energy stored is a function of the mass and heat capacity of the layer and the rate at which energy is lost and absorbed. The ambient temperature within the shallow layer will be a function of the amount of energy stored there. The exact partitioning of the net radiative energy is a complex function with feedback to the radiative budget (Oke, 1988), and is beyond the scope of the science content discussed for this project. The nature of the surface, its albedo, water content, heat capacity and thermal conductivity all play a role in partitioning the net radiative energy. The ambient temperature is an element of the microclimate modified by such surface properties (Oke, 1987). The urban heat island project allows students to investigate the impact of surface features on the microclimate.

In an urbanized environment, there are significant modifiers of the natural cycle of heating and cooling. These include:

1. Human-made structures such as streets and buildings generally have a lower albedo than natural surfaces and therefore absorb more visible radiation (Oke, 1987, pp 280-281). A study recently conducted by Taha showed that decreased vegetation and increased urban surfaces enhance the urban heat islands effect (Taha, 1997). Artificial structures also add mass to the earth's surface and therefore can store (and release) more energy than an undeveloped surface (reduces K_{usr}, increases L_{uir}, increase Q_s).

2. Urban surfaces tend to heat up faster than natural surfaces that retain water (increases Q_s). Evaporation of water removes energy from surfaces and leads to cooler surfaces temperatures. Urban surfaces are designed to quickly eliminate standing water, in contrast to natural surfaces, such as vegetation, that retain water.

3. Introduction of anthropogenic heat sources from heating and ventilation systems, industrial processes and internal combustion engines. In general, energy consumption will generate heat as a by-product (directly warms the atmosphere, increases Q_s and also increases L_{dir}).

Since more energy is stored in the urban environment, these modifiers result in relatively slower nocturnal cooling rates in urbanized environments. This results in warmer average temperatures in urban areas relative to non-urbanized areas. However, this "average" effect is complicated by the presence of parks, forested areas, rivers and streams, and other "non-urban" features that exist in the landscape. Thus,

detailed spatial investigations of the UHI can reveal micro-climatic details that explain how various surface features enhance or mitigate the UHI effect.

General meteorological conditions also affect the magnitude of the UHI effect. The UHI is maximized under conditions of minimal cloud cover (increased solar input), low wind speeds (reduced mixing of air) and high vertical stability (thermal inversions) (Oke, 1987). The horizontal and vertical motions of air reduce the rural-urban microclimate contrast. Cloud-cover at night absorbs and re-radiates long-wave radiation emanating from the surface back to the ground so that surface cooling everywhere is diminished and tends to reduce the UHI effect (Oke, 1987, Stull, 1988).

Ground-based studies of UHI effect have typically been investigated with at least two or more continuously running fixed meteorological stations, at least one rural and one urban station (Klyzik and Fortuniak, 1999, Jagurei, 1997, Djen, 1992). The data from these stations are examined across time of day and season. The project described here is typically run on one day and during a specific time of day. The data collected is more conducive to understanding the spatial nuances of the UHI effect and can examine multiple surface factors sim-ultaneously. Many temperature records are gathered within a short period of time creating a high resolution "snapshot" of the temperature in a region. Thus, this investigation is complementary to studies involving limited sites analyzed over long periods.

DESCRIPTION OF PROJECT

Although we pre-determine the overall research area (UHI effect) we attempt as much as possible to leave the design of the experiment and the specific research questions up to the students. Our role is to provide the students with enough background material and experiences that will enable them to generate a well-designed project.

Each class session is roughly 2 hours in duration. Several of the activities are homework assignments that students are expected to complete outside of class.

The project is organized into five phases:

1. Introduction of science content background relevant to the study (1 session).

Students are given lecture-based background information about forms of energy, energy transformations in the environment, temperature and fundamental physical properties of the environment. Supplemental reading in an atmospheric science text is also assigned. We use *Earth Under Siege* by Richard Turco since the rest of the course deals with air quality but treatment of these topics in a general meteorology text would suffice.

2. Reading and analysis of a study published in the scientific literature (1 session)

A published research paper about urban heat islands is read and discussed in detail. We have used several different ones (Jagueri, 1997, Djen, 1992). Students are assigned the reading for homework and work in groups to prepare oral summaries of assigned sections. Through an in-depth analysis and discussion of these papers, we have an opportunity to examine how the physical principles of energy and energy transformations in various materials under many environments are key to interpreting data relevant to UHI effects. This literature analysis also introduces students to the rhetorical style and format of a scientific paper.

3. Preliminary temperature studies (1 session) "T vs. The X Factor"

Preliminary studies are an important component of scientific research. (In fact, most experimental work can be categorized as such until we figure out how to carry out the most fruitful experiment.) During this phase of the project, students are asked to carry out simple temperature studies in the outdoor environment that would help the class to elucidate the effects of different environmental features (the "X - Factor") on measured air temperature. All hand-held temperature measure-ments are made with an electronic temperature device (Check 1, Hanna Instruments ~ $25) that has been calibrated in water baths with National Institute of Standards and Technology (NIST) - traceable mercury thermometers. Each student checks out a thermometer for the duration of the project.

The goal is to carry out a study in which temperature varies with respect to one known variable. The assignment is titled "T vs. The X Factor". Examples of such studies are: measuring temperature as a function of: distance away from a river, elevation (by climbing a hill or a parking structure), distance away from a building or ground surfaces of varying kinds.

We usually ask for one volunteer to study the effect of air speed on temperatures by measuring temperature out of a car window at various speeds. A second "volunteer" would be asked to conduct a similar study but with a thin layer of wet tissue around the probe. Without exception, students have come into the class believing that increased air speed alone will reduce the temperature sensed by the instrument and are surprised a second time by the effect of the wet tissue.

This assignment is designed to allow the students to gain experience in scientific claimsmaking. Students present their experiments to the class and propose explanations for the data. Obviously, in "X factor" studies, students are never completely able to isolate the temperature variation to one variable. Unlike canonical, well-controlled teaching laboratories, these temperature measurements are a function of numerous variables. In their presentations students are forced to account for and/or rationalize the effects of "unintended" X factors on their temperature measurements.

4. Preliminary research questions, design of measure-ment protocols and transects (1 session)

Based on their reading and research, we attempt to develop researchable questions constrained by the limitations of resources (temperature probes) and time - limitations that are well-known to experimentalists. Examples of such questions are: " Are there spatial differences in air temperature that are related to level of urbanization? ", " How does the presence of rivers effect urban climatology?", "What is the influence of vegetative cover on the ambient temperature?" During this session we also discuss some of the strengths and weaknesses of previous class studies in order to improve on experimental design. For instance, during our earliest studies we found that data collection was too sparse along each transect. Subsequent groups have designed their studies to collect 15-20 data points along a transect traversed within an hour.

Once preliminary questions are agreed upon, students determine what data is necessary to address the question. This process leads to the determination of

ID	X	Y	Time (hr)	Temp (C)	UHI Index	Land-use	Sur-face	Cloud cover	Wind	Field Notes
117	7,666,804	695,203	5	13.1	0.45	com	asp	clr	c	Near large grass field
118	7,656,498	699,791	5.12	13.4	0.00	urb	asp	clr	c	Grass parkways along street
142	7,623,018	707,953	5.75	14.3	-1.10	com	asp	pc	c	Under bridge
153	7,614,071	671,974	5	13.6	-0.1	com	asp	pc	c	Hwy 217 & Beav/Hillsdale Hwy
154	7,612,548	671,918	5.17	13.1	0.2	com	con	pc	c	Lombard and Farmington
155	7,609,276	672,031	5.33	12.5	0.7	os	con	pc	c	Cedar Hills Blvd & Farmington
156	7,605,609	671,861	5.42	12.9	0.3	com	asp	pc	c	Murray & Farmington
157	7,597,997	670,113	5.53	12.5	0.6	mix	asp	pc	c	Farmington & Kinnaman
215	7,594,892	668,308	5.6	12.6	0.5	mix	asp	pc	c	Farmington & 185th
216	7,588,292	665,318	5.72	12.1	1	rur	asp	pc	c	Farmington & 209th
217	7,578,139	658,380	5.97	12.1	0.9	os	asp	pc	c	Farmington & Tile Flat Rd.

Table 1. Example of UHI data spreadsheet. The categories and appreviations contained in the spreadsheets are designed by the students. The students collectively agree how each designation is to be assigned in the field. The spreadsheet above is just an example and is not intended to be prescriptive. ID # is a unique point identity; X and Y refer to coodinates in the mapping system; Time is data collection time; Temperature is ambient temperature measured at the site; UHI index is reference temperature (city center) - the site temperature; Landuse designations - com - commercial, urb -urban, os - open space, rur -rural , mix - mixed use; Surface designations - asp - asphalt, con- concrete, grass -grs; Cloud cover - clr - clear, pc - partly cloudy, c - cloudy; Wind speed designation - c -calm, b- breezy, g- gusty; Wind direction - n - north, s - south, e - east, w- west, na - not available.

measurement protocols and ancillary data collection. This ancillary data collection protocol probably requires the most professional intervention, as inexperienced researchers it is difficult for students to anticipate what data might be useful in subsequent analysis (for instance cloud cover, surface characteristics, wind speed etc.). However, once these factors are considered, it is useful for students to struggle with the "calibration" of ancillary data. For instance, how will each student determine level of cloud cover? Decisions are also made about when to make the measurements, which day(s) and at what time(s). Discussion can often become quite animated as students come to a consensus about how to conduct the study. Measurement protocols are based on their previous work and experience with the preliminary studies. The students grapple with the question, "How can we make meaningful temperature measurements in a complex environment in order to investigate the research question at hand?"

Typical protocols for temperature measurement:

1. Hold calibrated probe one approximately 1m above ground and arm's length away from body.
2. Do not make measurements within 3 feet of a building.
2. Shade probe with an umbrella or other suitable device.

3. Wait at least 30 seconds and for thermometer display to stabilize.
4. Record temperature reading and other data.

Most groups determine that the optimal time of day for a maximum UHI effect is right before sunrise. At the end of the session, each student leaves with data sheets and knows when the data collection is to be made. In addition to the temperature measurements made along transects, there are two important measurements necessary for making sense of the field data in later analysis: 1) an assessment of the stability of the air and 2) a continuous temperature record at a fixed location. Both of these measurement tasks are the responsibilities of a student or a student group.

The UHI effect is maximized under conditions of low wind speed and high atmospheric stability (temperature inversion) since this minimizes mixing through vertical or horizontal motion. It is useful to document these conditions during the period of data collection to help explain and interpret the data. Although the National Weather Service provides twice-daily vertical profiles of temperature and wind speed, the National Weather service stations tend to be away from urban areas (http://www.rap.ucar.edu/weather/upper/). Another source for data is a relatively new product derived from GOES satellite soundings but cloud cover limits availability of useful data (http://orbit-net.nesdis. noaa.gov/goes/soundings/skewt/html/skewtus.html)
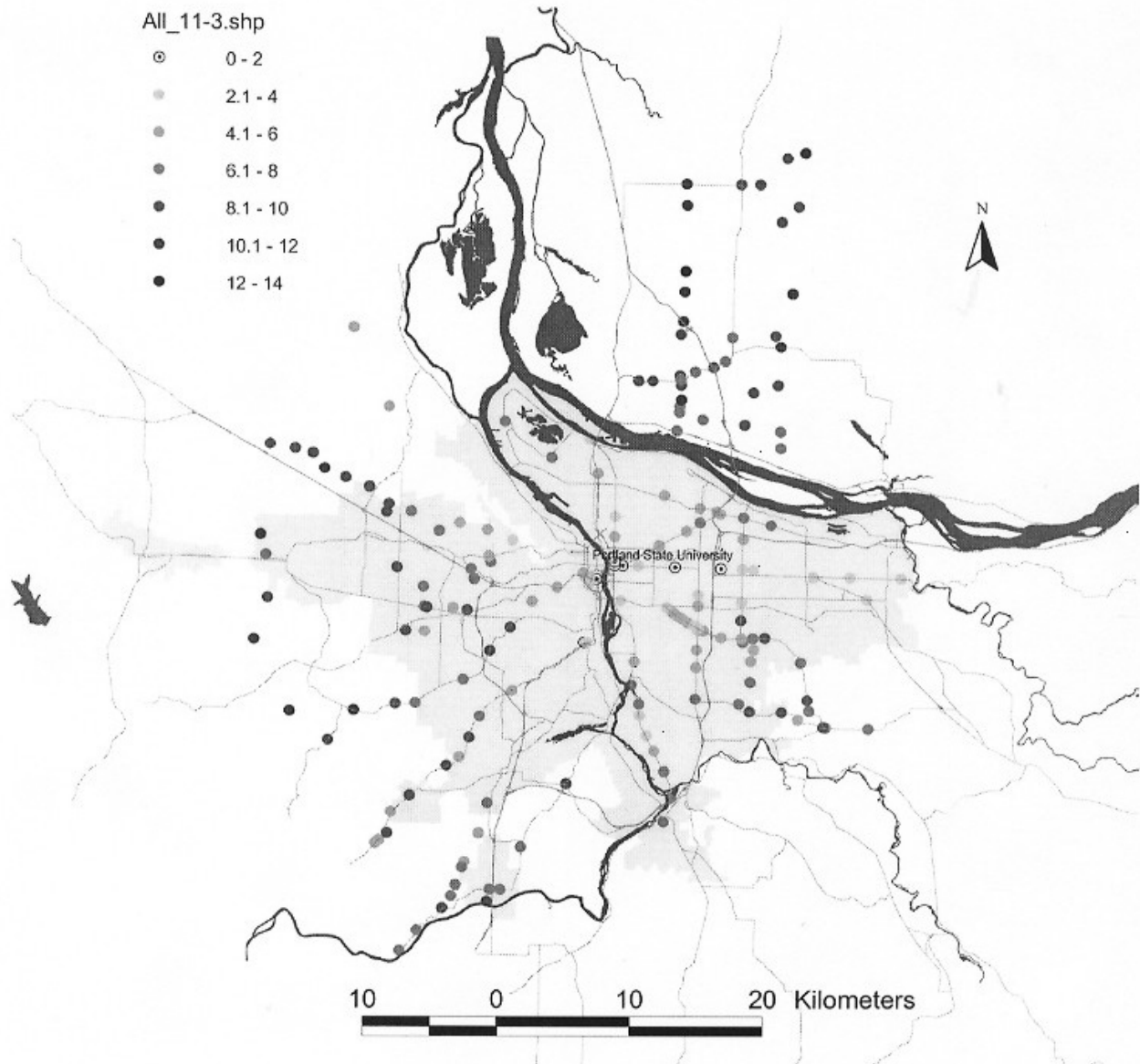
UHI Effect - Delta T, C

Figure 3. Map of UHI effect in Portland Oregon at 8AM. The points represent data collection locations and the grayscale indicated the magnitude of the UHI effect. Darker points are larger temperature differences between the downtown reference location (Portland State University) and the collection site.

. Stability conditions can be also be successfully assessed using, for example, a small rocket launched with temperature and pressure logger payload (we used HOBO, Inc. sensors and dataloggers), generating smoke and taking pictures of its movements, or taking temperature measurements along elevation features (such as hills, towers or tall buildings). Relative stability can be determined by comparing temperature profiles with adiabatic lapse rates (Turco, 1997, pp 119-125, Seinfeld and Pandis, 1998).

Since the field measurements will be made along a transect during a window of time, it is necessary to have a continuous record of temperature made at one fixed station, preferably in either the coolest or warmest region of the study domain. With this continuous record the temperature value collected in the field, which should be timestamped, can be subtracted from the fixed station temperature at that time. The temperature difference or

UHI effect can be calculated for each data point at any time. For example, if a measurement was made in the field at 6:05AM, the UHI effect would be calculated by subtracting the temperature at the fixed site at 6:05AM from the field measurement. Continuous temperature records can be obtained with temperature sensors and data loggers (such the ones used for rocket launches) or from airport records. This approach will generate a UHI "snapshot" with an "exposure time" of the monitoring window.

5. Data analysis and report writing (3 sessions)

Students generate a common spreadsheet that contains the data from all participants. This spreadsheet is used to calculate the UHI by subtracting each of the temperature values from a downtown meteorological
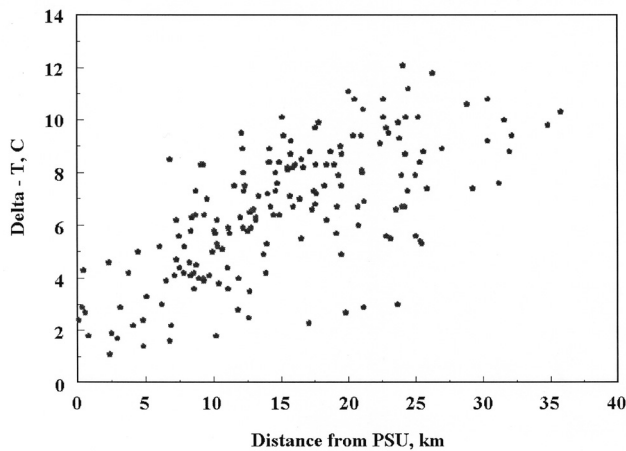
Figure 4. Graph of data collected using GIS analytical tools on maps. This graph examines the UHI effects as a function of distance from the reference location, Portland State University, located in the city center.

station. An example of the spreadsheet contents is given in Table 1.

The UHI value is calculated by subtracting the temperature measurement made along a transect from the fixed station measurement at that time. In the experiment shown in Table I, "Benson" is the temperature at the fixed "Benson" site, where a temperature logger was located. Note that ancillary data, such as observed land use and cloud cover, that the students had agreed to collect are also part of the data record. The X and Y coordinates in Table I were determined using mapping software (discussed below) but could also be determined using mobile GPS units carried by students. Once the collected data are merged into a common dataset, students are charged individually to analyze the data and write up their analysis. This has been our practice but small group analysis of the dataset is also possible.

Data analysis can be accomplished with or without sophisticated software tools. If spatial analysis software is unavailable, data can be analyzed by students mapping the data by hand onto thematic maps of urban regions. Thematic maps based on land use, vegetative cover, topography etc. are generally available at city planning agencies or local USGS offices.

We have found that Geographical Information Systems (GIS) software is well-suited for the analysis of the data generated in this project. One popular publisher of GIS software, ESRI Inc., provides a freely available and powerful GIS viewer and analytical tool on their website called ArcExplorer. Use of GIS software for spatial analysis allows students to assess, quickly and visually, the relationship of the data to various spatially varying parameters. This software program has additional analytical tools, such as the ability to query the data with Boolean-like operators, which allows the analyst to screen the data for various conditions. For instance, one could examine only data for which cloud cover was less than 10% and measure their distance from the city center.

There are two barriers to simple implementation of the ArcExplorer for this project. First, this package does not allow the creation of new spatial datasets. In order to convert the data from spreadsheet format to a format that is GIS compatible, it is necessary to utilize the commercial package ArcView. ArcView is widely available on university campuses (and some middle and high schools) and the conversion process only takes a few minutes. A friendly colleague or graduate student in the Geography department is likely to do it for a cup of coffee. The second barrier is the availability of suitable spatial databases to overlay with temperature data. Increasingly, the federal government, municipal agencies, and others are providing their spatial data in GIS compatible form (for landuse data, see http://www.webmet.com/lulc_data.htm).

Students have three in-class work sessions in which to analyze the data with respect to their research question. We have found that allowing work time during "class time" is essential as it provides an opportunity for collaboration among students, technology access and assistance, and quick feedback from instructors. Each student is responsible for writing his/her own paper based on the collective data. The paper is written in the form of a scientific paper and the students use our reference UHI paper, analyzed in step 2, as a guide.

RESULTS

We have conducted this study with several classes over the last three years. Figure 2 is an example of a map created with a GIS program (ESRI ArcGIS/ArcExplorer) that students generate as part of their analysis. This particular data set of over 200 points was collected with a class of 22 students. The data were gathered between 6:15-8:15AM on November 10, 1999 using protocols discussed above. Each student was responsible for gathering data along an assigned transect, which was determined by the class.

This particular dataset was acquired in the second attempt. For the first scheduled data campaign, cloud cover appeared overnight and did not generate a "good" dataset for analysis. The students, with a little prompting, decided to repeat the experiment under better conditions.

The overarching analytical objective for the students is to explain the pattern of temperature variation present on the map. Students are provided with access to several spatial databases for the region that could help their interpretation. These spatial databases can be imported into ArcExplorer include: land use, zoning, elevation, vegetative cover, soil type, population, etc. Although these databases have been organized by our regional government for research purposes, many of these databases are available on-line at federal and local government GIS sites.

Once these maps are generated, students must devise methods of quantifying the data for comparison. Figure 3 is an example of an attempt to analyze the UHI data by determining the distance of each point from the city center. Students who first generated this graph were disappointed that all the data "did not lie on a straight line". The challenge in working with this kind of data with students is to get them to see through the "messiness" of the data with statistical or graphical tools and to persevere in examining the reasons for the underlying variations. Although UHI is plotted against distance many other variables are at play and students struggle with the multi-variable nature of environmental research. Students submit a draft version of their report for review. The draft-revision process is critical in engaging the students in the desired learning outcomes. Most student papers improve dramatically in this process.

UHI PROJECT LEARNING OUTCOMES

Content

♦ understands the factors controlling the energy balance at the earth's surface
♦ understands how the vertical temperature profile of the atmosphere relates to atmospheric stability
♦ can interpret indicators of atmospheric stability
♦ understands how atmospheric stability effects UHI
♦ can explain the diurnal temperature cycle
♦ can explain how human-made structures and water effect the diurnal cycle

Science Process

♦ recognizes the importance of controlling variables and accounting for variables that cannot be controlled
♦ able to frame addressable research questions
♦ understands the role of preliminary studies in research
♦ understands the relevance of precision and accuracy
♦ able to construct a supportable knowledge claim

Skills

♦ able to gather and record data using a scientific instrument using data collection protocols
♦ able to graph data using Excel
♦ able to utilize ArcExplorer to map data and thematic overlays

In addition to the learning outcomes outlined above, we have also observed two important attitudinal shifts in our classes: 1) Recognizing the importance of collaboration in science and 2) Becoming aware that they *can* "do" science. The design of the project makes every student's data collection activity critical to the research. In fact, the spatial analysis is nearly impossible without high-resolution data. Students go to great lengths to insure that their transect is completed at the correct time. During the data analysis and report writing phase of the projects, many students experience frustration with "inconclusive data" as they search for the "right" answer. As students persevere through this period they come to recognize that doing science is usually not about finding a clear answer but about discerning meaningful and supportable patterns in otherwise "noisy" information. Follow-up projects have included the economics of heating and cooling with an UHI-affected area, assessing the UHI with remote temperature data and analyzing the conditions for optimal UHI effects.

CONCLUSION

Science education reform efforts underscore the need to engage students at all levels in "doing science as science is done" (Flower et al, 1997). The science inquiry project described here presents a transferable opportunity to engage students in an authentic investigation that incorporates real world scientific processes. The project goals are consistent with the goals of science education reform efforts for undergraduate science courses (NSF, 1996). Students enrolled in a general education science course undertake the evaluation of the urban heat island effect in the Portland metropolitan area. We have implemented this project with classes of between 20-35 students and with over 150 students altogether. This project successfully utilizes the collective abilities of the students to design and implement a scientific experiment and engages the individual student's ability to analyze the data and communicate the results.

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