CHAPTER 4

Physical Measurements

Learning Objectives:

- What are physical models and how are they used in geography?
- What are representative types of physical measurements made by geographers and other scientists who study the four earth systems of the lithosphere, atmosphere, hydrosphere, and biosphere?
- What is geodetic measurement and what are some types?
- What are nonreactive measurements in human geographic research?
- What are the three actions of accretion, deletion, and modification that create physical traces of human activity, and what are the four types of functions of physical traces?

This chapter, along with Chapters 5, 6, and part of 7, provides an overview of the specific types of data collection in geography we introduced in Chapter 3. We stress that these chapters provide only *overviews* of the various data collection types. In order to conduct research in a specific area, you will likely want to take additional courses and otherwise get additional training more specifically focused on the types of data to use in your particular topical domain, including how best to collect and interpret them. This suggests an important piece of advice for choosing your measurement tools and techniques and using them properly: *Learn what you can about your domain of interest.* That way, not only will you develop an appropriate knowledge base for choosing and applying types of data, types accepted by a particular research community, but you will be able to evaluate the meaning of data other people use to make their scientific case, and you will be able to develop novel types of data that can help answer new questions and old questions in new ways.

One of the most important ways of collecting data in geography is physical measurement: collecting data by recording physical properties of phenomena at or near the earth surface. It is the major type of data collection in physical geography. Physical properties include size and number, temperature, chemical makeup, moisture content, texture and hardness, the reflectance and transmissivity of electromagnetic energy (including optical light), air speed and pressure, and more. Physical measurement is not exclusive to physical geography, however. Human geographers often observe the **physical traces** or "residues" left behind by human behavior or activity. In this chapter, we discuss some basic tools and techniques for collecting physical measurements in both physical and human geography.

Physical Measurements in Physical Geography

As we learned in Chapter 1, physical geographers investigate a diverse array of topics concerning the physical and biological earth as the home of humanity, including landform formation and change, soils and mineral resources, lakes and rivers, groundwater, climate and atmosphere, glaciers and ice fields, ocean and coastal processes, and plant and animal distribution. These are most of the topics of interest to the earth sciences more broadly, although physical geographers have historically been particularly interested in the earth as the home of humanity, like other geographers. They thus focus their interest on the portion of the earth at or near the surface and the implications of these domains for human activity, experience, society, and culture. Traditionally, they do not focus so much on the interior of the earth or on the upper atmosphere, for example.

There are several aspects of physical measurement that apply generally to subfields of physical geography. One is that geographers who collect physical measurements often do so in field settings where their phenomena of interest occur; we contrast lab and field settings in Chapter 7. In many cases, geographers actually make and record (on paper, in computers, and so on) these measurements in the field and analyze them back in an office. In other cases, they actually take samples of the material to be measured from the field and measure them back in a lab; examples include soil or water samples. However, we prefer to reserve the term "sample" for its technical meaning, discussed in Chapter 8, of a set of cases smaller than the entire population of interest. Materials collected in the field are usually cases in a sample, not the entire sample, and in some situations they could be cases in an entire population. To avoid confusion, therefore, we refer to these field samples as **physical materials**. What is important to note here is that collecting physical materials constitutes only part of the process of measurement. They must still be measured back in the lab by procedures that generate symbols, usually numbers, to represent their values on variables of interest. This is analogous to the "records" created by people, discussed in Chapter 5, that are used as sources of archival data, most often by human geographers. They too must be measured—coded—in order to generate interpretable data.

There are several practical issues common to conducting field research in physical geography that deserve comment; to varying degrees, these can apply to field research in human geography too. Field research often goes on in remote places that are difficult to reach. You must often establish the physical accessibility of your site, of course, but you must also establish its social and legal accessibility. Private property requires permission from landowners for its access, and there are restrictions on what activities are appropriate nearly everywhere (we discuss some ethical implications of field research in Chapter 14). When planning field research trips, make sure to be realistic about all the costs involved, including travel to and from sites and loss of or damage to equipment. Will it be feasible to transport any physical material you collect from the site, as well as the equipment required to measure or collect materials both to *and* from the site? Fieldwork can be very hard on equipment, not to mention people. Make sure your equipment is robust to transport, collisions, weather, and so on; make sure you and your assistants are in suitable condition to survive the trip and that you have contingency plans for medical emergencies and the like.

Geographers do not always collect physical measurements in field settings, however. One alternative is to create simulations of field settings in the lab. For instance, the physical or chemical weathering of rocks and other materials has been studied fairly extensively with the use of **physical models** in the lab that expose materials to such weathering agents as solutions of varying chemical composition. Some labs exert "physical control" (Chapter 7) over variables like temperature, pressure, and humidity that influence the performance of their models; the **environmental cabinet** is a device for exerting this type of control. In Chapter 7, we discuss another way to simulate physical processes in the lab: computational models that apply computer programs designed to simulate structural and/or process aspects of your phenomenon of interest. Finally, we note that geographers very often collect physical measurements from the (near) earth surface with the aid of airplane and satellite remote sensing. This is true of physical measurements in human as well as physical geography. We discuss collecting physical measurements via remote sensing in Chapter 12.

Geodetic Measurement

The most fundamental physical measurements in geography are measurements of the spatial structure of the earth itself. In Chapter 1, we defined the theory and technology of measuring the size and shape of the earth and the distribution of features on its surface as the study of geodesy. Geodesy is an ancient field of study; its earliest practice several thousand years ago (by Egyptians, for example) is typically identified with the earliest origins of geography as an intellectual endeavor. Geographic researchers need to have at least a basic understanding of geodesy, insofar as it is usually important that their physical measurements of earth features, such as mountains or rivers, can be accurately located (called "geo-referenced" in Chapter 12). Geographers and others obtain geodetic measurements in one of three ways. First, measurements are made on aerial or satellite imagery; remote sensing is discussed in Chapter 12. Second, measurements are taken from existing geodetic databases. In the past, such data were typically represented in map form; this was an archival function of maps (Chapter 10). In map form, researchers often measured spatial properties off the map as if it were an unmeasured image; for instance, an "opisometer" was a tool like a small wheel on a handle for measuring distances off of straight or curved line segments on maps. Nowadays, these data are frequently stored in numerical database form and accessed via software. Either way, such secondary geodetic data are available from public agencies like the USGS, the British Ordnance Survey, and other national mapping agencies; private companies also have such data for sale. Finally, geographers can measure location and other spatial properties of features directly in the field. This is **ground surveying.**

Geodetic information can tell you about the location of features on the two-dimensional (X-Y) earth surface (**planimetric information**), the third dimension (Z) of **elevation** or **altitude**, or both.[1] Let's consider planimetric information first. Features are typically decomposed into constituent points, as when a rectangle is measured at its four corners, or they are treated directly as points themselves (we further discuss geometric models for features in Chapters 8 and 12). The absolute and relative locations of points on the two-dimensional earth surface can be **fixed** by measuring some combination of distances and/or directions, and subjecting these measurements to geometric and trigonometric calculations. Fixing point locations via directions is called **triangulation**; fixing them via distances is **trilateration.** For example, if I know the location of one point relative to a coordinate system, I can determine the location of another if I know its distance and direction from the first; a line or path segment whose distance *and* direction are known is called a **traverse.** Traditionally, tools such as surveyors' chains or tape measures were used to measure distances over the ground, and various forms of magnetic compasses or more sophisticated **theodolites** were used to measure directions; the theodolite measures angles in horizontal and vertical planes by allowing directions to precisely sighted targets to be measured against internal protractors. Many of these tools are more or less obsolete now, as GPSs (Chapter 12), laser range finders, and other electronic tools have supplanted most of the older mechanical and optical tools. Almost no one uses the opisometer we mentioned above, for example; spatial properties of features can be determined by geographic information systems on digital representations. The supplanting of older technologies by newer ones has always occurred, of course, but it has occurred exceptionally dramatically in the last few decades.

Besides the planimetric properties of distance and direction (and hence area, circumference, and so on), properties of the third spatial dimension are also of interest in many situations. Feature heights can be measured from other features with known heights by using tools like the **clinometer**, a sighting device connected to a gravitational horizontal or vertical index, calibrated by a spirit bubble or plumb bob (the Abney level is another such tool). Theodolites also provide this information, and more precisely. These tools are also useful for measuring slope angles. Conceptually, these traditional approaches are straightforward enough. If I can

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[1]Some people use the terms elevation and altitude as perfectly synonymous. Others make the small distinction between elevation as the height of the ground surface above or below sea level (the "geoid"—see Chapter 12) versus altitude as the height of any object or position in the sky. If you make this distinction, a mountaintop has an elevation, for example, whereas a satellite has an altitude.

establish that my sighting tube is precisely at a right angle to gravity, then anything I see in it will be the same height as the tube. If I attach a protractor to the sighting tube, and I am able to level that protractor, I can read off the direction to any target in my sight that is "uphill" or "downhill." For greater elevations, I can use **barometric heighting**, wherein air pressure differences are measured as a function of altitude above or below sea level. When you have a great number of elevations to determine, such as when collecting data for d**igital elevation models** (DEMs) or sea-surface heights, elevation is determined from **stereoscopic** remotely sensed imagery or satellite range finders.

Physical Measurements of Earth Systems

Since the mid-20th century, physical geographers and other earth scientists have organized their subject matter into major **earth systems,** commonly four of them. Systems are sets of interrelated components; both the components and the system as a whole take on various states as a result of processes operating on them. The four earth systems can be described as follows:

1. ***Lithosphere (geosphere).*** This is the terrestrial earth surface crust, including bedrock, surface rock, and soil. To nongeographers, the lithosphere is sometimes considered to include the entire solid planet, core and all.

2. ***Atmosphere.*** This includes the envelope of gases and other materials surrounding the terrestrial surface. Although the atmosphere rises several hundred kilometers above the earth surface, geographers are mostly interested in the lowest band called the "troposphere," which rises to about 18 kilometers above the surface. Most of the matter of the atmosphere is found in this thin layer, including nitrogen, oxygen, and other normal atmospheric gases; gaseous and particulate pollutants; and water vapor and clouds. The bulk of weather processes and the life forms of the atmosphere occur in the troposphere. Of some special interest is the **boundary layer**, the lower portion of the troposphere whose motion is influenced by the frictional influence of the topography of the land surface (boundary layers also occur in the lower layers of water bodies).

3. ***Hydrosphere.*** This refers to the water bodies, both fresh and saline, on the earth surface. It includes oceans and seas, lakes, rivers, wetlands, groundwater, snow, and ice. It includes water in liquid, gaseous, and solid form (the latter is often distinguished as the **cryosphere**). Movement and transformation of water throughout the earth systems is called the **hydrologic cycle**.

4. ***Biosphere.*** This is the living earth of plants, animals, fungi, microorganisms, and so on. It extends from a few meters underground (which may be thousands of feet below sea level at the ocean floor) to near the top of the troposphere. Many earth scientists have recently included humans in this earth system; others set them apart in a separate **anthrosphere**. Although humans are certainly part of the natural earth, the methods of the biophysical sciences alone are inadequate for the study of

human geography and other social sciences, mostly because of the semantic and semiotic nature of humans mentioned in Chapter 3 and discussed further in several other chapters.

Some version of this taxonomy has been widely used as an organizing framework in geography and other earth sciences for several decades. The framework is a bit ambiguous, however. It is based largely on location relative to the earth surface but also involves aspects of the physical states of matter (solids, liquids, gases). In fact, we do not believe there is a single consensus version of this framework; if you ask several geographers about its specifics, we think you will probably get some different answers. Is soil really part of the lithosphere, given that it contains water, gases, and living components? Is water vapor part of the hydrosphere or the atmosphere, or both? Are coastal processes such as beach formation and destruction part of the hydrosphere or the lithosphere? In the end, these ambiguities cannot be definitively clarified; they are largely a matter of semantic preference. The solid, liquid, and gaseous components of our world; phenomena above, below, and at the earth surface; and the living and the nonliving are truly interrelated in the complex system that is our planet.

Let's consider some specific types of physical measurement that geographers use to study the four earth systems. A central research focus for geographers has traditionally been the description and explanation of the shape or form of earth surface landforms—**geomorphology**. This involves knowledge of a variety of earth processes, including orogenesis and denudation. **Orogenesis** refers to mountain formation events, including tectonic plate movement and volcanism. **Denudation** refers to any process that degrades landforms, including physical and chemical weathering, mass movement, and erosion. These processes occur via a great variety of mechanisms, including rainfall, river movement, coastal tides and waves, glaciation, and wind ("eolian" processes). In addition, degraded materials are transported by wind and water to be deposited elsewhere, creating a variety of landforms such as river deltas, sand dunes, cave formations, and loess sediments (windblown silty material probably created by glacial grinding). Coral reefs are formed by biological deposition.

Morphology is the study of forms. In geography it refers specifically to the measurement of landforms, at all measurement levels from nominal to ratio. Morphology is carried out in a variety of ways, with a variety of tools. Maps and drawings are sketched, and many of the geodetic tools discussed above, such as theodolites, are used to measure elevations, slopes, and so on. Landform features both above water and underwater are measured to determine their shape or form. For example, the **cross-sectional** and **longitudinal profile** of a riverbed or streambed can be determined via **hydrographic surveying**. A **ranging pole** can be used to measure depths that are not too great; a **sounding line** (or lead line) or **echo sounder** is used for deeper measurements. Chains, wires, boats, and bridges are used to string measuring instruments across river channels.

Another topic that has traditionally been important to geographers is that of **soils**, the dynamic layer of natural material on the crustal surface composed of fine particles of minerals (not pebbles) and organic matter (humus). The soil layer sits atop the rocky bedrock; it is thin or nonexistent in some places, and as deep as hundreds of meters in other places. Soils are especially interesting to geographers because their character influences wild and domesticated (agricultural) plant patterns so strongly, which in turn influences many human patterns (residential density, economic activities). Soils are created by the chemical and physical weathering of rocks we mentioned above, as well as organic and physical decomposition by macro- and microorganisms.

Geographers measure many different aspects of soils. **Soil texture** is the relative mixture of three particle sizes in a given soil: sand (>0.05 mm), silt (0.05–0.002 mm), and clay (<0.002 mm). Soil texture greatly influences the water- and ion-holding qualities of soil, and thus its potential for natural and domesticated vegetation. **Sieve analysis** is one of several methods used to determine soil texture. Several other properties besides texture are important for characterizing soil, including structure, porosity, and moisture content. The moisture content of soil is typically determined by comparing the weight of some physical material before and after it is oven-dried at a little above the boiling point of water until its weight reduces to a stable value. Geographers also assess the chemical makeup of soils. For example, they measure the concentration of mineral ions and soil **pH** (the acidity or alkalinity of a substance). The chemical composition of soils and other materials that geographers study is determined in a large variety of ways. Some examples include electrical conductivity, colorimetric analysis, spectrophotometric analysis, X-ray diffraction, and scanning electron microscopy.

A **soil horizon** is a recognizable layer within the soil, more or less parallel to the surface, that is differentiated from the materials above and below it because of different soil formation processes, such as alluvial (river) deposition, that operate on the different horizons. A cross-section of soil layers from the surface down to the bedrock is known as a **soil profile** (Figure 4.1). The properties of naturally occurring soils are mostly a product of the climatic and vegetative history of a particular place. Humans influence soils in a variety of ways too, mostly by covering it or disturbing it so that it becomes much more susceptible to weathering and erosion. Geographers and other soil scientists summarize the properties of soils with a classification system; for example, the U.S. system describes 11 (recently, 12) naturally occurring **soil orders**.

Turning to the atmosphere, we find that geographers take measurements at and above the earth's surface, usually up to the "tropopause" between the troposphere and the stratosphere. Of major interest is the study of relatively long-term **climate** and, at smaller temporal scales of variability, **weather**. A central climate construct that must be measured is **insolation**, a word derived from "*in*tercepted *sol*ar radi*a-tion*." Insolation is the amount of solar energy in a given time period, or its intensity at a given moment, incident on the terrestrial surface of the earth or, sometimes, on an elevated surface such as the top of the atmosphere or the tops of tree canopies.[2] Insolation varies across time and place on the earth surface as a

[2]In many cases, researchers conceive of insolation only as energy directly from the sun; in other cases, researchers include indirect solar energy that has reflected from other surfaces.

Figure 4.1 Measurement of depths of soil horizons in a rainforest soil profile on the Island of Hawaii. (Photograph by Oliver Chadwick. Reprinted with permission.)

function of latitude, surface slope and **aspect**, date of the year (seasonality), time of day, and atmospheric clarity. Various surface materials and structures differ greatly in how much insolation they reflect or absorb, an important property of surfaces called **albedo**.

Temperature, pressure, and precipitation are the major components of weather and climate, and of course, their measurement provides central data to geographers and others who study weather and climate. The three components depend on a variety of factors, including insolation, humidity, the movement of air masses from either land or water (continental versus maritime air), the movement of air masses from either north or south (polar versus tropical air), and so on. We measure these various variables with the aid of ground surface and airborne **rain gauges**, **thermometers**, **barometers**, and **hygrometers**, which measure relative humidity. **Doppler radar** detects the direction of water droplets, thereby measuring wind speed and direction. Also important to climate and weather is the material composition of the atmosphere, including especially the presence of clouds, which are three-dimensional regions of liquid or frozen water droplets, often having condensed around tiny particles of matter. These tiny solid or liquid particles dispersed uniformly within the gaseous atmosphere are called **aerosols** (cloud droplets themselves are too large to be considered aerosols). Airflow at a variety of scales is also quite important to patterns of climate and weather, including local winds and breezes and larger-scale Westerlies, trade winds, and high-altitude jet streams. Air and other atmospheric constituents move around the earth in a variety of stable and variable patterns, in response to temperature and pressure gradients, and in response to the rotation of the planet (the "Coriolis force").

Geographers and other earth scientists are interested not only in the climate of the present and the future but of the past, a topical field of study known as **paleoclimatology**. These scientists use a variety of approaches in attempting to "measure" the climate of the past. We put quotes around "measure" because such measurements of course cannot be done directly on past temperature, precipitation, and so on. Instead, various **proxy measures** are taken; these are physical measurements (or even archival documents—see Chapter 5) that are based on a present trace of past climate conditions. For example, trees add a seasonal layer of growth each year, and the layer grows thicker during wet years. **Dendrochronology** (the terms "dendroclimatology" and "dendroecology" are also used) is the taking of cores of materials from trees in order to be able to count and measure the thickness of the layers, which appear as "rings" in the cores (coring does not hurt live trees, a fact with ethical implications to which we return in Chapter 14). **Pollen analysis** is another example of a **biotic proxy**. Cores are also taken from ice sheets and glaciers; trapped gases can be retrieved from these cores at various locations, which indicates age. This provides data on the past gaseous composition of the atmosphere. Measurements from sediments in oceans and lakes can also serve as **geological proxies**.

The age of soils and some other organic materials is often determined by **radiocarbon dating**, a technique in which the beta particle emission rate from radioactive $^{14}CO_2$ (carbon dioxide containing carbon-14 or radiocarbon) is measured. Radiocarbon dating was an important methodological breakthrough for various "paleosciences," including physical geography and geology, paleontology, and archeology. It is based on the fact that the small proportion of atmospheric CO_2 that contains ^{14}C instead of the much more prevalent and nonradioactive ^{12}C becomes incorporated into living creatures at an equilibrium concentration. When an organism dies, its ^{14}C will continue to radioactively decay, emitting beta particles. Because the organism no longer takes in new ^{14}C from the atmosphere, its rate of beta emission continuously decreases over time. The decreasing rate of emission with decreasing ^{14}C, as compared to the concentration of ^{14}C that was at a maximum and equilibrium state upon the death of the organism, provides a basis for measuring the age of a material.

Turning to research on the hydrosphere, we find that geographers are interested in water in its various forms, especially liquid and frozen water; water vapor may be included but is typically seen as being more in the purview of climatologists and atmospheric geographers. Geographers make physical measurements of water temperature, pH, the concentration of various salts and other organic and inorganic compounds, dissolved gasses, the speed and direction of water movement in both the X-Y horizontal dimensions and the Z vertical dimension (**hydrometry** is the measurement of water flow in river and stream channels), and more. For example,

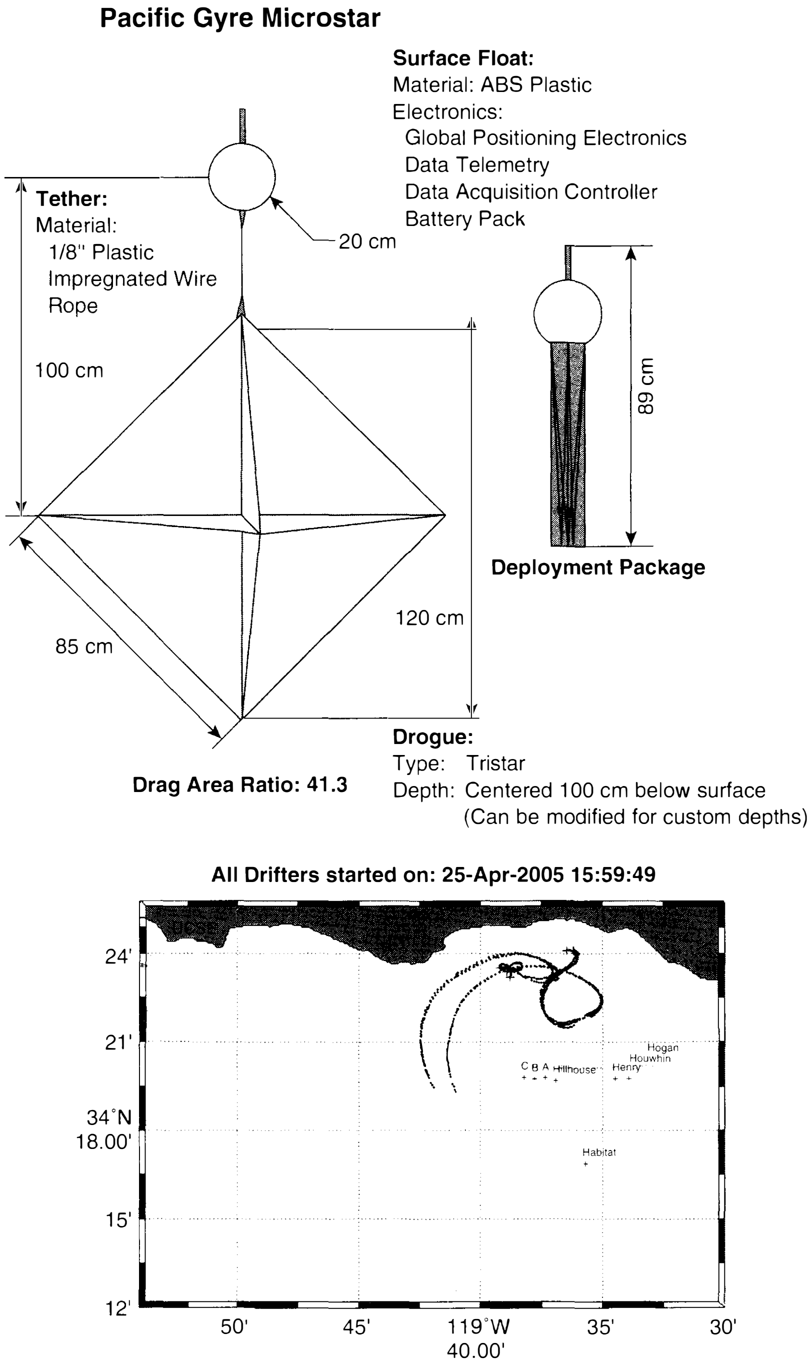

Figure 4.2 Use of drifters to measure near-shore ocean current flow patterns off the coast of Santa Barbara, California. The tracks in the lower image are records of the movements of drifters like that in the Microstar, sent by GPS receivers attached to it. In an attempt to calibrate a new method of measuring currents, the drifter tracks are compared to current measurements from a land-based radar. (Graphic by Carter Ohlmann[3]. Reprinted with permission.)

geographers and oceanographers are interested in the physical properties of ocean currents. Currents are important because they distribute energy, nutrients, and pollutants around the planet. They are driven by atmospheric winds, which pile up surface water into aquatic "ridges"; gravity generates flows in the resulting uneven surface. The Coriolis force deflects these currents clockwise or counterclockwise in the northern and southern hemispheres, respectively. Surface water is fairly warm and well mixed to a depth of a few tens or hundreds of meters; below that, at least in tropical and temperate latitudes, is the **thermocline**. The thermocline is a layer of water within much of the oceans (and some lakes) in which temperature decreases rapidly within distances of something like a few hundred meters. Particularly in the oceans, the thermocline is a relatively stable barrier to interaction between thin surface waters that are warm and well mixed, and the bulk of the deeper, colder ocean.

Scientists traditionally measure surface currents with some sort of physical **drifters** that are dropped into the ocean and tracked. In the past, the drifters would have been tracked visually or by inference when they were retrieved from the water. GPS (Chapter 12) transmitters automatically track the drifters in Figure 4.2 and send near-real-time positional information about themselves to computers on land. The researchers who did this work[3] are using the drifter tracks in Figure 4.2 to calibrate high-frequency radar as a much more efficient technique for measuring ocean currents.

Finally, geographers who study the spatial and temporal distribution of living plants and animals are known as biogeographers.[4] Of course, they measure various physical properties of plants and animals, such as their height, width, color, total mass, and so on, but simple counting is probably the major form of physical measurement that biogeographers employ; human geographers count people too, commonly via the explicit report measure of a census. In some cases, physical measurements of animals, including counts, depend on first netting or trapping the organisms (with ethical implications—see Chapter 14). In other cases, animal populations can be measured by direct observation in the field or by inferences from evidence such as the presence of "scat" (fecal excrement).

Vegetation need not be collected as physical materials to be counted or measured, of course. Geographers often travel into the field to observe, count, and otherwise measure properties of plants. However, the presence of plant species and the hypothetical aggregation complexes of species known as **vegetation assemblages** are very often inferred from local conditions, especially altitude, latitude, slope, and aspect. These factors in turn affect insolation, precipitation, temperature, soil

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[3]Ohlmann, J. C., White, P. F., Sybrandy, A. L., & Niller, P. P. (2005). GPS–cellular drifter technology for coastal ocean observing systems. *Journal of Atmospheric and Oceanic Technology, 22*, 1381–1388.

[4]Ecologists are also interested in the distributions of living organisms, although they tend to focus more on smaller spatial, temporal, and thematic scales—thematic scale in this case referring to the taxonomic level of the organism.

composition, and wind. This inferential approach to the presence of vegetation is significantly fallible, however. The presence of plant species depends not only on these physical factors of energy, water, and nutrients, but on competition and predation from other plants and animals, and the "geographic opportunity" provided by the past activities of animals, winds, currents, and, increasingly over the last few centuries, humans.

Physical Measurements in Human Geography

Physical measurements are the major type of data that physical geographers collect, but human geographers also collect them. Usually such physical measures on humans are observations of the residues of past activities, the effects of past behaviors by people on their physical surroundings. An important characteristic of physical traces is that individuals and groups do not create them with the intention of producing data. They generally don't know that one day, the traces of their acts will be used as data. Physical traces provide sources of data without the measurement process changing a person's feelings, thoughts, or behaviors. Traces do not reflect any intentional or unintentional effort by those who have left them to produce something to cater to a researcher or a research project, or for that matter, to thwart a researcher or research project. An important shortcoming of some other data collection techniques used with humans, particularly the explicit reports discussed in Chapter 6, is that they require people to provide data knowingly and intentionally to researchers. Under these conditions, reactance often results. **Reactance** is when people's behavior (including their expressed opinions, feelings, and so on) changes because they are aware of being measured or observed.[5] As we discuss further in Chapters 6 and 11, such "researcher-case artifacts" are a major threat to the validity of results obtained via techniques such as surveys or interviews. In contrast, physical-trace measurements are an excellent example of **nonreactive measures** in human geography, along with particular versions of behavioral observations and archival data we consider in Chapter 5. Nonreactive approaches to measurement are quite valuable to human geographers, as they are to other social and behavioral scientists.

[5]An analogy is sometimes drawn between behavioral reactance and Heisenberg's "uncertainty principle" from physics. That principle states that both the momentum and the location of a quantum particle cannot be observed simultaneously because observing one requires exposing the particle to energy (such as light photons) that necessarily changes the other. Therefore, by analogy, people speak of something like a "behavioral uncertainty principle": *observing people necessarily changes their behavior because of reactance.* This is a poor analogy, however. Observing or measuring people does not necessarily change their behavior (we return to this in Chapters 5 and 11). Heisenberg's principle only applies to the extremely tiny quantum level in the first place. It does *not* mean we are unable to simultaneously observe the momentum and location of a macroscopic entity like a basketball, at least within the limits of precision that are generally relevant. Otherwise, some people would not be able to catch and shoot the ball so well.

Physical traces are not intentionally created as data, or as artifacts to be measured as a basis for data, but they are often created intentionally. The intentionality with which physical traces are created is an important characteristic that varies across different types. Sometimes people create traces quite intentionally. A family intentionally places certain plants, lawn statues, children's swing sets, unused automobiles, and so on in their front yards. A farmer intentionally plants sorghum and not corn (maize). A transportation planning board puts traffic lights and stop signs at some intersections and not others. In many cases, however, people create traces accidentally or unintentionally. Bare spots in a yard indicate areas of high usage, agricultural chemicals wash into watersheds, and accumulations of paper waste in a recycling bin behind the offices of the transportation planning offices suggest something about the activities of the people who created them.

All physical traces can be understood as a result of one of three actions: accretions, deletions, and modifications. An **accretion** is an intentional or unintentional addition, deposition, or accumulation. Examples of accretions include graffiti painted on city walls or slag piles left by mining operations. A **deletion** is an intentional or unintentional removal, erasure, or obliteration. Examples of deletions include aquifers emptied by intensive agriculture or broken windows in dilapidated buildings. Finally, a **modification** is an intentional or unintentional change, alteration, or conversion. Examples of modifications include a vacant city lot used as a baseball field or a river's course that has been shifted by levee construction.

Physical traces can be grouped according to four types of functions or purposes. The first is **byproduct of use**. This is the only one of the four types that does not in itself reflect function, but results, usually unintentionally, from what people have done in the environment for other reasons. The bare spots left in a yard as a byproduct of activity there is a good example. The second is **adaptation for use**. These are intentional changes to the environment that are meant to make some place more functional to its users. For example, children often make openings in fences in order to create direct routes in the environment. The third type of physical trace is the **display of self**, which is meant to express one's self or group identity. The way families paint their houses and design their front yards provides a good example. The fourth type is the **public message**. These are traces meant to communicate to others, whether officially like a road sign or unofficially like the graffiti we mentioned above that serves to communicate gang territory boundaries at the same time it expresses group identity.

Before we conclude this chapter, we note that there are some other types of physical measurements that human geographers could potentially use besides physical traces of activities. They can measure the physical properties of people themselves, although this is somewhat unusual as of yet in geography. However, we are likely to see a future increase by geographers in the measurement of physiological and neurological states and processes of humans. For example, body weight and height can be measured as indices of malnutrition (including *over*nutrition). Pulse and blood pressure can be measured as reflections of stress or anxiety. Various types of brain scans such as **functional magnetic resonance imaging** (**fMRI**) could tell us about people's brain activities while they think or reason about geographic topics or problems.

Review Questions

Physical Measurements in Physical Geography

- What are physical materials? How is it misleading to call them "samples?"
- What are physical models? Suggest some ways they may not be completely adequate as tools for studying particular research questions?

Geodetic Measurement

- What is geodesy, and what are some basic geodetic properties that are measured?
- What do theodolites measure? What are some other tools for geodetic measurement?

Physical Measurements of Earth Systems

- What are the four earth systems typically said to describe the physical and biological world? What are some problems with conceiving of the earth in terms of separate systems like these?
- For each of the following areas of physical geography, what are some basic variables of interest, and how are some of them measured: geomorphology, soils, climatology, oceanography and hydrology, biogeography?
- What are proxy measures in physical geography, and how does radiocarbon dating in particular work?

Physical Measurements in Human Geography

- What are physical traces of human activity, and how can they be used in the study of human geography? What are examples of physical traces that are accretions, deletions, and modifications?
- What is reactance, and what are nonreactive measures? Why are nonreactive measures valuable to geographers?
- What are the prospects for using physiological measures of humans as data in geography?

Key Terms

accretion: action that creates physical traces via intentional or unintentional addition, deposition, or accumulation

adaptation for use: type of physical trace that results from people's efforts to make some setting more functional

aerosol: tiny solid or liquid particles dispersed uniformly within the gaseous atmosphere

albedo: the reflectance of solar radiation by a surface material and structure; radiation not reflected is absorbed

altitude: geodetic information about the third dimension (Z) of location on or above the earth surface; sometimes restricted to atmospheric height above the earth surface, in contrast to elevation

anthrosphere: portion of the biosphere including human habitation and activity

aspect: the X-Y orientation of a slope face, typically expressed as a heading in cardinal directions

atmosphere: earth system that includes the envelope of gasses and other materials surrounding the terrestrial surface

barometer: tool to measure pressure in the atmosphere

barometric heighting: technique for measuring large feature elevations, based on atmospheric pressure differences at different elevations

biosphere: earth system that includes the living organisms

biotic proxy: any proxy measure based on the analysis of materials that were at one time part of living organisms; in some cases, such as tree coring, they may still be living

boundary layer: the lower portion of a fluid layer over a solid layer whose motion is influenced by the frictional influence of the underlying solid surface; both the bottoms of the atmosphere and of the oceans have boundary layers

byproduct of use: type of physical trace that results, usually unintentionally, from what people have done for other reasons

climate: relatively long-term pattern of atmospheric conditions such as temperature, wind, and precipitation; average weather in an area

clinometer: geodetic tool for measuring feature heights consisting of a sighting device connected to a gravitational horizontal or vertical index and calibrated by a spirit bubble or plumb bob

cross-sectional profile: the shape of a riverbed or streambed going across from one bank to the other, perpendicular to the direction of flow

cryosphere: frozen portion of the hydrosphere, sometimes considered a separate earth system

deletion: action that creates physical traces via intentional or unintentional removal, erasure, or obliteration

dendrochronology: proxy measure in which cores of material are taken from trees in order to count and measure the thickness of the layers, which appear as "rings" in the cores

denudation: any process that degrades landforms, including physical and chemical weathering, mass movement, and erosion

digital elevation model (DEM): digital representation of the elevations, and thus the morphology, of a portion of the earth surface

display of self: type of physical trace that results from people's expressions of their self or group identity

Doppler radar: radar (*ra*dio *d*etecting *a*nd *r*anging) that measures the velocity of water droplets in the atmosphere by analyzing reflected high-frequency electromagnetic radiation, thereby measuring the velocity of atmospheric movement

drifters: floating objects dropped into the ocean and tracked in order to measure currents

earth systems: sets of interrelated components of the natural earth in which both the components and the system as a whole take on various states as a result of processes operating on them; they are commonly organized into the four systems of the lithosphere, atmosphere, hydrosphere, and biosphere

echo sounder: tool used to measure water depths that are very deep, even too great for a sounding line

environmental cabinet: device for exerting physical control over variables like temperature, pressure, and humidity in a physical model

elevation: geodetic information about the third dimension (Z) of location on or above the earth surface; sometimes restricted to land surface height above sea level, in contrast to altitude

fixed: geodetic determination of the absolute and relative locations of points on the two-dimensional (X-Y) earth surface

functional magnetic resonance imaging (fMRI): type of brain scan used to measure human brain activity during mental processing; increasingly popular in cognitive and neurosciences, and likely to be increasingly applied to mental processing involving spatial, geographic, and environmental information

geodetic measurement: measuring spatial properties of the earth and features on it

geological proxy: any proxy measure based on the analysis of materials that were not at one time part of living organisms

geomorphology: the description and explanation of the shape or form of earth surface landforms

ground surveying: geodetic measurement of feature location and other spatial properties directly in the field

hydrographic surveying: techniques for measuring cross-sectional or longitudinal profiles in streams and rivers

hydrologic cycle: movement and transformation of water throughout the earth systems

hydrometry: the measurement of water flow in river and stream channels

hydrosphere: earth system that includes water bodies, both fresh and saline; sometimes it is considered to include only liquid water, whereas at other times it is considered to include water in all three forms of liquid, gas, and solid

hygrometer: tool to measure relative humidity in the atmosphere

insolation: amount of solar energy in a given time period, or its intensity at a given moment, incident on the terrestrial surface of the earth or, sometimes, on an elevated surface such as the top of the atmosphere or the tops of tree canopies; from "*in*tercepted *sol*ar radi*ation*"

lithosphere (geosphere): earth system that includes the terrestrial earth surface crust, including bedrock, and surface rock and soil

longitudinal profile: the shape of a riverbed or streambed going parallel to the direction of flow

modification: action that creates physical traces via intentional or unintentional change, alteration, or conversion

morphology: the study of forms; in geography it refers specifically to the measurement of landforms at all measurement levels from nominal to ratio

nonreactive measures: measures of people's behavior or activity that do not induce reactance, typically because they do not make people aware they are being measured or studied

orogenesis: mountain formation events, including tectonic plate movement and volcanism

paleoclimatology: study of past climates

pH: the acidity or alkalinity of a substance

physical materials: samples collected by physical geographers in the field that must be measured, typically in a lab, in order to produce scientific data; examples include soil, rock, water, gases, and plants

physical model: model (see Chapter 2) expressed in physical form; essentially a physical or material simulation of a portion of reality

physical trace: type of physical measurement in which "residues" left behind by human behavior or activity (or that of other animals) are recorded

planimetric information: geodetic information about two-dimensional (X-Y) location on the earth surface

pollen analysis: proxy measure in which microscopic pollen grains in sediments are analyzed

proxy measure: measurement, usually physical, that is based on a present trace of past conditions, particularly climate conditions

public message: type of physical trace that results from people's efforts to communicate to others, either officially or unofficially

radiocarbon dating: technique for dating organic materials based on their emission of beta particles from radioactive ^{14}C (carbon-14); important to various paleosciences

rain gauge: tool to measure the amount of rainfall at some location

ranging pole: tool used to measure water depths that are not too great (up to a few meters)

reactance: when people's behavior, including their expressed opinions, feelings, and so on, changes because they are aware of being measured or observed; although it does not necessarily occur in all situations, it is an important reason to use nonreactive measures

sieve analysis: one of several methods used to determine soil texture

soil: the dynamic layer of natural material on the earth's crustal surface composed of fine particles of minerals and organic matter (humus)

soil horizon: recognizable layer within the soil, more or less parallel to the surface, that is differentiated from the materials above and below it because of different soil formation processes

soil orders: categories of soil types

soil profile: cross-section of soil layers from the surface down to the bedrock

soil texture: the relative mixture in a given soil of the three particle sizes of sand, silt, and clay

sounding line: tool used to measure water depths that are more than a few meters, too great for a ranging pole; also called a lead line

stereoscopic: imagery that reveals information about depth or elevation by representing a surface from two perspectives, one offset a little from the other

theodolite: geodetic tool for measuring angles in horizontal and vertical planes by allowing directions to precisely sighted targets to be measured against internal protractors

thermocline: layer of water within much of the oceans (and some lakes) in which temperature decreases rapidly within distances of something like a few hundred meters

thermometer: tool to measure temperature in a solid, liquid, or gas

traverse: line or path segment whose distance and direction is known; used to fix locations

triangulation: fixing location by means of measuring directions

trilateration: fixing location by means of measuring distances

vegetation assemblage: hypothetical aggregation complex of plant species, often inferred from local physical conditions such as soil, slope, and precipitation

weather: relatively short-term pattern of atmospheric conditions such as temperature, wind, and precipitation

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