Chapter 7

The Brower-Cousteau Model of the Earth

7.1 How Heavily Do We Weigh upon the Earth?

I once heard the late David Brower[1] end one of his talks with the following: *"Earth's air, water and topsoil are the three things that distinguish our planet from every other dead rock in the universe, and humans are doing their best to obliterate that difference."*

The sentiment of the above quote is clear. If you have read the preceding chapters you have seen plenty of evidence that humans collectively are having significant impacts on the biosphere. Humans supply the world's crops with more nitrogen than the traditional source, bacteria, [81, p. xiv], page 112. Humans have polluted nearly every niche of the biosphere on the planet, cf., Chapter 4. Humans are changing the climate of the entire planet and precipitating a great extinction more rapidly than any of the five great previous extinctions, cf., Chapter 1, [388]. Humans are significantly depleting the seas of life and even altering the chemisty of the world's oceans, cf., Section 5.7. This list, which can be lengthened, might overwhelm with complexity.

In the following I want to do simple, direct calculations, allowing little room for disagreement, which give a picture of the earth not as some vast, unperturbable ball, but rather as a *small world with a thin skin of water and air and a small dot of topsoil* – upon which all of our lives depend.

How Many People are on the Earth? When I first started working on this book there were approximately $5.7 * 10^9$, or 5.7 billion people on earth (December, 1994). That amounts to about 285 million (metric) tons of human biomass, i.e., $2.85 * 10^8$ MT, assuming that the average person has 50 kg of mass. Norman Myers, [475, p. ix], notes that no other species on earth has a cumulative biomass larger than we humans, except perhaps ocean krill –

[1]David Brower was a charismatic conservationist living in Berkeley, California. He was the long time executive director of the Sierra Club, leading the fight to save the Grand Canyon and what is now Dinosaur National Monument from hydroelectric dams. He founded Friends of the Earth, and the Earth Island Institute as well as the League of Conservation Voters. Although he died on November 5, 2000 at his home at the age of 88, his prolific, heroic activist spirit lives on in many who work for the preservation and restoration of the natural world. David Brower voted absentee for Ralph Nader for U.S. president as, presumably, his last political act.

and since we are going after krill with a vengenance that may soon change, cf. Chapter 6, footnote 4.

Exercise 7.1 Global Human Population

(i) As of 2005 the global human population was $6.45(10^9)$, cf., [661, p. 75]. Estimate the increase in the biomass of humans in the approximate decade between December 1994 and 2005.

(ii) Do you think that the impact per person on the biosphere in 2005 was more, less or unchanged from that per person impact in 1994?

(iii) Repeat this exercise for the year you are reading it.

7.2 Mining and Damming: Massive Rearrangements

Human mining activity moves more soil and rock on the earth – an estimated 28 billion tons[2] per year – than is carried to the seas by the world's rivers. This is unarguably a global impact.

In this next exercise I want to examine a tool for figuring out if some claim, like that just made, is remotely true or not. I will say that two statements are *consistent* if they can both be true at the same time. Given the existence of fuzzy/measured logic, the meaning of truth is a bit more complicated than in Aristotelian/sharp logic, and thus deeper more careful analysis is almost always called for. We briefly encountered this concept of consistency before, cf., Exercise 4.1. I wish to call attention to and somewhat formalize what I am talking about by stating an assumption that I will suppose in this book.

Consistency Axiom. *Reality (Nature) is Consistent.*

Exercise 7.2 Consistency and Data

(i) From [283, p. 10], globally 10^{10} m^3 of soil and rock are carried away by river erosion each year. Is this consistent with the figure above, i.e., that 28 billion tons of soil and rock is more than the amount of soil and rock carried by rivers to earth's seas?[3]

(ii) If the numbers in (i) reveal (or do not reveal) a gross inconsistency in the data from our two sources, what do you conclude?

(iii) How do you define the term *consistency*?

(iv) Do you have to take into account the time the statements in (i) were made when determining consistency?

(v) Do you have to take into account the error which always exists in real measurements when determining consistency?

(vi) Can you find sources that are not consistent with the two we have just dealt with in regard to the moving/mining/eroding of soil and rock? Can you find sources of information that you know are independent, e.g., they all didn't just copy a common source?

[2]Note that a ton is 2000 *pounds*. See John E. Young, Aaron Sachs, *The Next Efficiency Revolution: Creating a Sustainable Materials Economy*, WorldWatch Paper 121, p. 11. Do you think that mining activity has increased, decreased or stayed the same since this paper was written?

[3]Hint: How many grams of soil and/or rock on average are in a cubic centimeter of same?

Human imagination made this possible; we invented tools, machines – big ones. The world's largest frontloader is a 1,300-horsepower 994 Caterpillar. It takes 35 to 40 ton bites from the earth. *"The Cat operator sits in a cab twenty feet off the ground, moving his machine's segmented body, on eleven-foot-high tires, in tight radial turns. His machine's radiator block is the size of a garage door. In four rail-car-sized scoops, he fills up a 150-ton mud-splattered yellow haul truck and is ready for the next. This is as big and rudely basic as man's industrial processes get."* See [295, p. 190]. In modern mines 150,000 to 500,000 tons of earth moved per day is not uncommon.

Exercise 7.3 Digging the Earth

(i) How many pounds (or kg) per year would each person on earth today have to dig with a pick and shovel, say, to move 28 billion tons of earth?

(ii) What is the answer to (i) in pounds per day?

(iii) How much of your day would be spent digging? Remember that much of this "earth" is solid rock that is loosened up with explosives. Assume you have no explosives, fossil fuel or machines, except the pick and shovel.

(vi) The quote just before this exercise is from 1994. Consider the following quote from June 25, 2010 (by Clayton Thomas-Müller on www.democracynow.org) concerning Canadian tar sands, one of America's main sources of oil: *"... they're using the biggest trucks on the planet to move this stuff twenty-four hours a day, seven days a week, 300 tons per truck carrying capacity. The biggest earth movers on the planet, ten stories high, 300 tons per scoop, are operating twenty-four/seven in Canada's tar sands. They have a workforce of 77,000 workers to drive this massive, massive development. And so, you know, to provide a scale for the viewers, they move enough earth every single day in Canada's tar sands to fill up the Toronto SkyDome. ..."* Comparing these two quotes do you see a quantitative increase in the largest earth moving operations? What impacts does this extraction of oil from Canadia tar sands have on: the boreal forests, water resources, production of global warming gases, and the health of indigenous people living nearby?

People have Changed the Length of the Day on Planet Earth. Perhaps it is not easy to believe the following, but human activities have even measurably altered the earth's rate of spin.[4] Eighty-eight of the reservoirs built since the early 1950s have impounded more water than is contained in all of the moisture in the earth's atmosphere. So massive is the amount of water that has been moved that the earth's axis has been tilted slightly and the planet's rate of spin has changed by about .2 millionths of a second per day. According to Goddard Space Flight Center's geophysicist, Dr. Benjamin Fong Chao, who made the measurements and did the calculations, our oceans would have risen 1.2 inches more than they did had it not been for these reservoirs. Chao also found that the earth's gravitational field has been altered.[5]

[4]Malcolm W. Browne, "Earth affected by dams," *The New York Times*, as reported in the *Denver Post*, 3 March 1996.

[5]The IPCC estimates sea level rose on average 1.8 mm (1.3 mm to 2.3 mm) per year from 1961 to 2003. From 1993 to 2003 estimated average rise was 3.1 mm (2.4 mm to 3.8 mm) per year. Melting ice, thermal expansion, and anomalies in the earth's rotation all play a role in these numbers. The recent long term rise in sea level: sea levels rose 2 cm in the 18th century, 6 cm in the 19th century, 19 cm in the 20th century, and for the 21st century 30 cm is the projected, cf., UNFPA State of World Population 2009, p. 14.

Of course, we would not know these things were it not for the incredible technology I discussed on page 58. It is not comforting to note, however, that we did not anticipate and seemingly cannot control these global consequences of our human activities. On the other hand I derive some small comfort to read that Nature has created even more massive freshwater storage in the past. In the November 5, 2002 edition of *Science News* there is an article about Lake Agassiz, which was a fresh water lake about 10,000 years ago located north of the current Great Lakes of North America. This lake contained more fresh water than all of our current bodies of fresh water combined. When the lake finally burst through the barrier that separated it from the Atlantic, the massive influx of fresh water altered the climate by altering what we call today the Gulf Stream, which brings warm tropical water as far north as Norway. The melting of the Greenland icecap, i.e., a massive influx of fresh water into the Atlantic, raises similar concerns.

7.3 Fish, Forests, Deserts, and Soil: Revisited

Fish Feel our Machines. "After decades of buying bigger boats and more advanced hunting technologies, fishers have nearly fished the oceans to the limits. Of the world's 15 major marine fishing regions, the catch in all but 2 has fallen; in 4, the catch has shrunk by more than 30 percent." [6] Indications from scientists and fishers alike are that humans are having a global impact on life in the world's oceans. Overfishing, pollution, habitat destruction and modification are all adding up and the sum is a loss in the world fish catch.[7]

The work of [735] and [94] indicate that human pressures on global fish populations are increasing – with increasing effect. In [94] we read of a scientific paper which calculated a global "fish peak" in the year 1989. Seventy-five percent of the world's fishing stocks are (in 2006) fully exploited or overfished.[8] Climate change/global warming and fisheries overexploitation are perhaps the clearest and most urgent examples of the "Tragedy of the Commons," cf., VII.

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[6]Peter Weber, "Net Loss: Fish, Jobs, and the Marine Environment," *Worldwatch Paper* 120, Worldwatch Institute, Washington D.C., 1994, pp.5–6. Have things improved or worsened by the time you read this? See Section 5.7

[7]See also the article Carl Safina, "The World's Imperiled Fish," *Scientific American*, November 1995, pp 46–53. Are the world's fish more or less imperiled now, cf. [661, pp. 26–7]? Recent (2006) work of Boris Worm, [735], professor of Marine Conservation Biology at Dalhousie University, Nova Scotia, Canada, predicts that if global fishing practices/rates do not change, global collapse of all species currently fished is possible as soon as 2048. Collapse is defined as decline to 10% of previous historic populations, i.e., decimation.

[8]Acidification of the world's oceans due to carbon emissions is emerging simulataneously as a threat to fish populations, cf., Section 5.7.

Exercise 7.4 50 Plus Ways to Save the Seas

(i) David Helvarg's Blue Frontier Campaign, cf., www.bluefront.org, suggests 50 ways to save the ocean. What are they? See also [295, 296, 297].

(ii) Captain Paul Watson suggests a couple other ways. What are they? What is seaacide? See [707, 708] and www.seashepherd.org.

Forests Fall. French writer, François-René de Chateaubriand, of the late 18^{th} century, summarized the relationship between civilizations and forests thusly: *"Forests precede civilizations and deserts follow them."* Such books as [546, 137, 531, 145, 574, 328] among many document Chateaubriand's sentiment. (The book, *Deforesting the Earth: From Prehistory to Global Crisis*, [725], gives a history from which a clear pattern can be deduced, while [145] provides graphic pictures, at least for the U.S. and Canada, of what it means on the ground.) What is new is the global scale of forest destruction. The global appetite for forest products leaves not a single tree on the planet safe from saws. If the pattern oft observed locally of tree/forest collapse, followed by soil depletion followed by civilization collapse, is repeated today, the collapse will likely be more global in nature.[9] If anyone anywhere tries to stand in the way of civilization's consumption of a particular resource, such as a local forest, that person must prepare to meet an iron fist.[10]

"The current pace of tropical deforestation is frightening. The World Resources Institute estimates that almost half of the original 3.7 to 3.9 billion acres of tropical mature forests have been cleared to accommodate other uses. Satellite observations suggest that the rate of tropical deforestation worldwide is 40.5 to 50.4 million acres a year."[11]

"Although efforts to save the world's tropical rain forests have rightly received widespread attention, another type of rain forest is perhaps even more threatened. Now estimated to cover less than half their original area, coastal temperate rain forests are an exceptionally productive and biologically diverse ecosystem. They include some of the oldest and most massive tree species in the world, and constitute some of the largest remaining pristine landscapes in the temperate zone."[12]

If you ever get a chance to visit some of the world's remaining pristine forests do so (and, of course, tread lightly). I would like to devote a chapter

[9] From [546, 137, 677] and similar studies we see that the collapse of earlier civilizations followed a pattern: trees/forests collapse first, then the soil and/or food supply goes, followed by the collapse of the civilization itself. This pattern is quite familiar to archeologists.

[10] Those who dispute this claim almost invariably have never tried to save any part of the biosphere in its natural state. A group I helped found in 1989 in Colorado, Ancient Forest Rescue, AFR, successfully prevented the logging of Bowen Gulch old growth forest, on the western boundary of Rocky Mountain National Park. Many of the group's members gave up conservation work, however, when they found themselves under surveillance by private police, forest police, local police, state police and the FBI. Not much is written about AFR; however, the book *Powder Burn: Arson, Money, and Mystery on Vail Mountain*, Pubic Affairs, New York (2001) will have to do until I write my version.

[11] See [339, p. 16]. What is the state of tropical forests when you read this?

[12] Derek Denniston, "Conserving the Other Rain Forest" from *Vital Signs: 1994*, edited by Lester R. Brown, et al., Worldwatch Institute, W.W. Norton & Company, Inc., Publishers, New York, NY.

or two telling you what an indescribably fantastic experience this is, but I cannot for two reasons. First, you're not supposed to do that in a math book; and second, words cannot come close to doing justice to the feeling – it really is indescribable!

In the United States (lower 48) we have cut over 96% of our original forests, some of them have not grown back, some of them have been turned into tree farms and some have grown back but do not have the diversity and complexity[13] they once had since that takes time – often longer than the current age of our nation. The point is clear, humans have had global, devastating impacts on the world's forests. Hosts of statistics corroborate this point.[14]

Exercise 7.5 What is the Current State of the World's Forests?

(i) Russel Monson and Jia Hu, researchers at the University of Colorado, Boulder, published a paper in *Global Change Biology*, Jan. 8, 2010, with the conclusion: as the climate warms and the growing seasons lengthen, subalpine forests are likely to soak up less carbon. Jia Hu said, "Our findings contradict studies of other ecosystems that conclude longer growing seasons actually increase carbon uptake."

Quiver trees (aloe dichotoma), which can live longer than 300 years, have begun dying in parts of South Africa and Namibia in their native habitat. A Namibian government report in 2008 stated that temperatures during the last century have risen about 2 degrees Fahrenheit in that country. It is believed that climate change is affecting the quiver trees.

In *Science News*, 2/14/09, p. 8, researchers reported that small background rates of customary tree death have doubled in old-growth, western U.S. forests since 1955, possibly because of climate change.

What are the explanations for the above findings? At the time you read this what is the net effect of climate change on forests globally and their role in sequestering carbon?

(ii) What is the Rainforest Action Network, cf., www.ran.org, doing about the world's forests?

Deserts Follow. "According to the United Nations Environment Program, 11 billion acres – 35 pecent of the earth's land surface – are threatened by desertification and, with them, fully one-fifth of humanity. Three-quarters of this area has already been at least moderately degraded and an astonishing one-third has lost more than 25 percent of its productive potential. ... The four principal causes of land degradation – overgrazing on

[13]Complexity is a concept that is amenable to being defined and studied by mathematicians. It is a worthy project for the interested student.

[14]On July 27, 1995, President Clinton signed Public Law 104-19. One of the effects of this law was the lawless logging of much of the last 4% of America's roadless, ancient forests. I say lawless, because the law expressly ordered unsustainable levels of logging *"notwithstanding any other provision of law."* At the end of Clinton's second term, after nationwide public hearings in support, he promulgated the "Roadless Rule" in an attempt to protect the last roadless forests in the U.S. Constant efforts to overturn this rule have followed. In 2002 the "Healthy Forests Initiative" (note the spin) of the Bush II administration delivered treatment of our national forests that conservationists found heartbreaking, not to mention the species trying to live therein. Thus environmental legislation, extensively debated and carefully crafted over decades, does not apply in some of the most critical places for which it was designed.

rangelands,[15] *overcultivation of croplands, waterlogging and salting of irrigated lands, and deforestation – all stem from human pressures or poor management of the land."* [16]

In this next exercise I want you the check up on some of the numerical claims about the earth that were just made.

Exercise 7.6 The Area of the Earth, its Lands and Oceans

(i) The area of the earth is $5.10 * 10^{14}$ m^2. One *hectare* = 10^4 m^2. One hectare is abbreviated as 1 *ha*, and 1 *ha* = 2.47 *acres* (an English system of area measurement, where there are 640 acres in one square mile). What is the area of the earth in acres?

(ii) Using the information in the paragraphs immediately above, viz., 11 *billion acres* equals 35 percent of the earth's land surface, calculate the total area of land on the surface of the earth in acres. In square meters. Compare this answer with the information in part (i).

(iii) What is the area of the world's oceans?[17]

(iv) What fraction of the earth's surface is ocean? Land? Compare these estimates with answers you look up in another source, like the Web, or an encyclopedia. How close are they? Explain any discrepancies.

Soils at Risk. In a speech at the University of Colorado, Jeff DeBonis[18] said that in the United States, during the life of the nation, we have gone from an average topsoil depth of 28 inches to a current average topsoil depth of 8 inches. Of course, to know exactly what this means one must ask questions about the lithosphere, the solid part of the earth – are we dealing with the O horizon, A horizon or B horizon of the soil and such, cf., [339, pp. 324–348], Exercise 5.4. Without getting into a deep study of the state of the world's topsoil, the evidence is clear.[19] Humans are impacting the soil on a global scale.[20]

Exercise 7.7 Topsoil Formation/Loss Calculations: Are They Consistent?

(i) Topsoil is a complex association of living beings without which you and I do not eat. Thus it should be of supreme importance to know the state of topsoil, especially any topsoil that you depend on for food. One book estimates say that it takes 10,000 years for the formation of 30 centimeters (about 1 foot) of topsoil. Another reference, [173], says that it takes 100 to 400 years for 1 centimeter of soil to form. Still another reference, *Vital Signs, 1995*, says that it takes between 200 and 1,000 years to form 1 inch, or 2.5 centimeters

[15]See [325, 736], two remarkable texts that document situations, some tragic, on the public lands of the American west.

[16]Sandra Postel, "Restoring Degraded Land," in *The Worldwatch Reader*, Lester R. Brown, editor, W.W. Norton & Company, New York, NY, 1991, p.27. Are things improved when you read this?

[17]The polar ice cap at the north pole, is not land – besides it is disappearing. Antarctica is a continent covered with ice, do you think it is being considered as land by Postel?

[18]The founder of AFSEEE, the Association of Forest Service Employees for Environmental Ethics, (now FSEEE) and the founder of PEER, Public Employees for Environmental Responsibility, www.peer.org and www.fseee.org.

[19]If you feel like reading a little more about soil, see [173, 308, 37, 537, 226, 536].

[20]There is a two page update on soil erosion in *Vital Signs 1995*, Worldwatch Institute, W.W. Norton & Company, 1995, p. 118. *Vital Signs* is a yearly publication and a valuable reference along with *State of the World*, also by the Worldwatch Institute.

of topsoil. Are all of these estimates consistent? Do you think the rate of soil formation depends on many variable factors?

(ii) The U.S. does one of the most extensive estimates of topsoil loss (condition) of any country. If DeBonis is right and we have lost an national average of 20 inches of topsoil in approximately 225 years, out of a total initial estimated average of 28 inches, how much longer will the 8 remaining inches remain if we do not change the way we do agriculture? What agricultural practices might slow or reverse the loss of topsoil? Do you think this soil loss should be of concern equal to, greater than, or less than, say, the threat of attack from a foreign nation or terrorist group? When do you think we should start doing something to halt topsoil loss?

(iii) Ellis and Mellor, [173], assume a bulk density of topsoil of 1.33 grams per cubic centimeter. Another source says that 1 inch of topsoil weighs about 140 tons per acre (here a ton is 2,000 pounds). Are these figures consistent?[21]

(iv) Hillel, [308], says the in the 1960s the U.S. Soil Conservation Service's guidelines for soil loss tolerance set a maximum of 5 tons per acre (12.6 tons per hectare) per year. In actual practice, soil losses 10 times as great are common throughout the U.S. How many inches (or centimeters) of soil loss is equivalent to a 5 ton per acre loss? To a 50 ton per acre loss? Do you think such soil loss is noticeable from year to year?

(v) Ellis and Mellor, [173], state that background soil loss is less than 1 tonne per hectare per year. (Here a tonne is 1,000 kilograms.) Is this less than or greater than or equal to the rate of formation of topsoil given in part (i)? Recall that 1 hectare = $10^4\ m^2 = 2.47\ acres$.

(vi) Ellis and Mellor, [173], state that soil erosion accelerated by humans commonly exceeds 10 tonnes per hectare per year and sometimes exceeds 100 tonnes per hectare per year. In India and Nepal erosion of over 200 tonnes per hectare per year has been measured. Are these figures consistent with the figures of Hillel, [308], in part (iv)?

7.4 The Cousteau-Brower Earth Model

It is hard for one person to grasp intuitively what it means for the human population to be of global scale and impact. There are various ways to tackle this difficulty. One way – one model, most beautiful in its simplicity, is what I call the Cousteau-Brower earth.[22] I first heard this model described in a speech by the late David Brower. Brower said he first heard of the model from Jacques-Yves Cousteau.[23]

The basic idea of Cousteau and Brower is to use *scale*: If we scale the earth down to something one human can intuitively grasp, such as an egg or an apple, what would the water, air and topsoil look like? Once vast, unperturbable oceans, limitless skies and soil are all brought down to the scale of one human.

[21] Hint: Recall that 1 pound = 453.6 grams, 1 acre = 43,560 square feet, and 1 inch = 2.54 centimeters.

[22] If the you get stuck on some of the math in this last section of Chapter 7 you might want to read II first, then come back and try this section again.

[23] Jacques-Yves Cousteau, who passed away 25 June 1997, founded the Cousteau Society (www.cousteau.org), spent most of his life in a heroic effort to prevent destruction of life on earth – especially life in the world's oceans.

I just ate the apple on my desk, but a similarly sized, smaller, more spherical orange which remains is 4 cm in diameter. I want to mentally scale the earth down to the size of this orange and see what happens to the water, air and topsoil. The radius of the earth varies from $6.38 * 10^6\ m$ at the equator to $6.36 * 10^6\ m$ at at the poles. Let's just say that the radius of the earth is $6.37 * 10^6\ m$.

Exercise 7.8 Mathematics of the Area of a Sphere, Which the Earth Almost Is

(i) The area of a sphere of radius R is $4\pi R^2$. Using the value of $R = 6.37 * 10^6\ m$, how close do you come to the value of $5.10 * 10^{14}\ m^2$, used in Exercise 7.6, for the area of the earth? Note the following interesting geometric fact. The area of a sphere is 4 times the area of a "great circle" on the sphere. In the case of the earth an example of a great circle is the equator. In so far as the earth is spherical, the area of the earth is 4 times the area of the disk abstractly visualized by chopping the earth through the equator into two hemispheres.

(ii) Let A_{orange} be the area of our orange with a diameter of 4 cm. Calculate A_{orange}.

(iii) Calculate the fraction $\frac{A_{orange}}{A_{earth}}$ where A_{earth} is the area of the earth. Now calculate $[\frac{R_{orange}}{R_{earth}}]^2$ and compare it with $\frac{A_{orange}}{A_{earth}}$, where R_{orange} is the radius of our orange, i.e., .02 m, and R_{earth} is the radius of the earth, i.e., $\approx 6.37 * 10^6\ m$.

How Much Water – Salty and Fresh – is on the Earth? The waters of the earth, called the hydrosphere, comes in salty and fresh liquid and frozen forms. There are various sources of information on water, including: [230, 115, 339]. From [339, pp. 289–290], we read that 97% of the earth's water is saline (salty) and less than 3% is fresh. Of the fresh water $\frac{3}{4}$ was found in polar ice caps and glaciers (1999),[24] i.e., it was (is?) solid ice. Almost $\frac{1}{4}$ of the fresh water is found underground in water-bearing porous rock or sand or gravel formations. This water is called groundwater. Only a small fraction, $\frac{1}{2}$%, of all water in the world is found in lakes, rivers, streams and the atmosphere. This water is called surface water.

From [230], we see that volume of the water in the oceans is $1.338 * 10^9\ km^3$, and this is 96.5% of the total water on the planet, $1.386 * 10^9\ km^3$. Does this contradict the above figures from [339]? No. There are other sources of saline water besides the oceans, and [230] also tells us that there is an unknown uncertainty in all of these figures.

Exercise 7.9 Mass and Mass Density and Water

(i) Recall that the mass density of pure water (at 3.98 degrees Celsius and normal atmospheric pressure) is $\frac{1\ g}{cm^3}$. What is the volume of 1 kg of pure water (at this temperature)? One thousand kilograms?

(ii) The appendix in [283] gives the mass of the water in the world's oceans as $1.4*10^{21}\ kg$. Assuming all our figures are correct, what is the average mass density of the oceans? Explain any differences with the mass density of pure water.

(iii) Check the numbers for water given here against the numbers you find in some of the references in your library or on the Web. Explain any differences. How confident are you in these numbers?

[24] How much of this has changed by the time you read this?

(iv) Consider the statement: "97% of all water on the earth is salty." Does it make a difference if the percentage is in terms of volume or weight? Do changes in temperature and pressure effect this percentage? Are we doing calculations in this book to such a degree of accuracy that any of these considerations make a difference to us?

Exercise 7.10 Some Politics and Water.

(i) Comment on the following quote, taken out of context, from [295, p. 220]:

"Nothing disappears. People talk about 1 percent of the world's water is fresh water. All the water in the world is potential freshwater. It's a natural system of recycling. There's no scientific basis for what they're doing, so the only rationale must be to take us to utter socialism."

(ii) An open-ended project is to investigate the political future of water. In the year 2002, for example, in the United States over 85% of domestic water supplies to homes is provided by municipal water companies, i.e., the citizens via their city governments own their own water supply and delivery systems. There is a global effort on the part of some corporations to privatize these water supplies, i.e., transfer ownership of water systems to certain private corporations. Would such a change be in your self-interest? For an argument that privatization of water is not in the public interest see: [33, 631], [337, pp. 135-6, 237, 334-6].[25] What are the arguments for privatization of city water supplies?[26]

Lest it be forgotten that species other than humans also need water, see Don Hinrichsen, "Appropriating the Water: What's left for wildlife?" in the January/February 2003 issue of *World Watch*.

Related to the public versus private ownership paradigms see also VII in this book.

Rounding off the figures in Gleick, [230], we again see that 97% of all the water on the earth is salt water, and it cannot be used for drinking or growing crops. The bulk of the remaining 3% is fresh, amounting to about $35 * 10^6\, km^3$. Gleick says that most of this fresh water is locked up in ice caps and deep underground aquifers which are at the moment technically and/or economically beyond our ability to exploit. Gleick concludes that $10^5\, km^3$, or just .3% of the total fresh water reserves on earth constitutes most of the fresh water available for our use. From the references we have mentioned so far, we see that between .3% and .5% are available for our use – where the .5% includes atmospheric water.

Exercise 7.11 Some Interesting Calculations for Fresh Water on Earth and a Rope Around the Equator

(i) If the 3% of the earth's water that is fresh were all liquid (it is not), and if it were spread out evenly over the earth's surface, how deep would the layer be?[27]

(ii) Assuming Gleick's figures are correct, what percentage of the earth's total water supply is useable fresh water?

(iii) What percentage of the earth's water is in the atmosphere?

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[25] See also two articles on water privatization by Jon R. Luoma, Jon Jeter, respectively, in the December 2002 issue of *Mother Jones*, a magazine.

[26] See, for example, http://www.esrresearch.com/Theprivatewaterindustry.htm, http://www.mackinac.org/article.aspx?ID=3157.

[27] Hint: If you take into account the fact that we have the radius of the earth to no more than three significant figures you will eventually be forced to use a fact like $x^3 - y^3 = (x-y)(x^2+xy+y^2)$. See the next exercise if you have forgotten the formula for the volume of a sphere.

(iv) This is a classic mathematics problem. Assume the earth is a sphere. Suppose you have a rope snugly wrapped around the earth at the equator. Suppose you wanted to lengthen the rope enough so that anyone could easily walk under it anywhere on earth. For the sake of completeness assume that you wanted your newly lengthened rope to be exactly 7 feet above the equator all around the earth. How much would you have to lengthen the rope? (Before solving the problem carefully using mathematics, guess the answer and write it down so you can compare it with the actual answer.)

(v) In part (iv) do you really need to know the radius of the earth to do the problem? Is your answer the same if you replaced the earth with the moon? Would your answer be the same if you replaced the earth by a sphere of any radius?

(vi) **A Global Warming Exercise:** In an article, Nov. 2009, for the Associated Press by Seth Borenstein: "Warming's impacts have sped up, worsened since Kyoto," we read: "Measurements show that since 2000, Greenland has lost more than 1.5 trillion tons of ice, while Antarctica has lost about 1 trillion tons since 2002, according to two scientific studies published this fall." "...in the dozen years leading up to next month's climate summit in Copenhagen: The world's oceans have risen about an inch and a half." How much of this inch and a half rise is accounted for by the 2.5 trillion tons of melted ice? Hint: The area of the world's oceans is roughly $3.61(10^{14})\ m^2$. If you were curious, the volume of the earth's oceans is roughly $1.35(10^{18})\ m^3$, cf., [283, p. 236].

Recall that from Gleick's book all the water on the earth has a volume of $1.386 * 10^9\ \ km^3$.

Exercise 7.12 Some Mathematics of Volume

(i) The volume of a sphere of radius R is $\frac{4}{3}\pi R^3$. What is the volume of a sphere with a radius of $6.37 * 10^6\, m$? Is this the volume of the earth, V_{earth}?

(ii) What is the volume of our orange, V_{orange}? How does $\frac{V_{orange}}{V_{earth}}$ compare with $[\frac{R_{orange}}{R_{earth}}]^3$?

(iii) What is the ratio of the volume of all the water on the earth to the volume of the earth?

(iv) What is the ratio of the volume of all useable freshwater on the earth to the volume of the earth?

We are now going to pretend that all of the water on the earth is in the form of a gigantic sphere of water. This sphere of water, as we see above, has a volume of $1.386 * 10^{18}\, m^3$. (You have to convert from km^3 to m^3, can you do it?) What is the radius of this sphere? Let this unknown (for now) radius be R_{water}. Then we have the following equation:

$$\frac{4}{3}\pi R^3 = 1.386 * 10^{18} m^3.$$

Solving this equation for R^3 we get:

$$R^3 = \frac{3}{4\pi} * 1.386 * 10^{18}\, m^3 = .331 * 10^{18}\, m^3.$$

We will systematically review how to solve equations, like the one above, for R in Chapter 2. For now just observe that to solve this equation for R, all you have to do is raise both sides of the equation (feel free to use your calculator) to the power $\frac{1}{3}$ and get:

$$R = [R^3]^{\frac{1}{3}} = [.331 * 10^{18}\, m^3]^{\frac{1}{3}}$$
$$= [.331]^{\frac{1}{3}} * [10^{18}]^{\frac{1}{3}}]\, m$$
$$= .692 * 10^6\, m.$$

Exercise 7.13 The Relative Volume of Water on Earth

(i) The ratio of the radius of our "water ball" to the radius of the earth is $\frac{.692*10^6\, m}{6.37*10^6\, m} = .109$. Compare the cube of this ratio to the ratio from Exercise 7.12 (iii).

(ii) Are all of the results of your calculations consistent so far?

We are now going to scale everything down to the size of our orange. In order to scale the radius of the earth, $6.37 * 10^6\, m$, down to the radius of our orange, $2\, cm$, we must divide by $6.37 * 10^6\, m$ and multiply by $2\, cm$. If we take $.692 * 10^6\, m$ and do the same we get:

$$[.692 * 10^6\, m] * [6.37 * 10^6\, m]^{-1} * 2\, cm = .217\, cm.$$

Thus if the earth were the size of an orange (with a radius of 2 cm), and if all the water on the earth were in the shape of a sphere, that sphere would have a radius of $.217\, cm$.

All the liquid fresh surface water on the earth is about $35 * 10^6\, km^3$. This is $35 * 10^{15}\, m^3$. *Thus on an earth shrunk to the size of our 2 cm radius orange, all the fresh liquid water on the earth would be a droplet with a radius of .06 cm.*

Exercise 7.14 The Relative Volume of Fresh Water (Useable Water) on Earth.

(i) Verify that the radius of our droplet of fresh liquid water on earth-orange would be .06 *cm*. How big is that?

(ii) What would be the radius of the droplet of useable fresh water, scaled down to the size of our orange?

The point of this exercise, thus far, is not to give you the impression that there is no fresh water on the earth; in fact there is quite a bit. The point is to leave you with the impression that the human population is of global scale and is big enough to impact the planet's water. Also the next time you are thinking of dumping some toxic nuclear waste in the ocean where no one will notice, think of that drop of water .217 *cm*, i.e., a little over 2 *mm*, in radius.

A quick way to see that the water calculation is believable is as follows. The mean depth of the oceans[28] is 3,730 *m*, or $3.73*10^3\, m$. The radius of the earth is $6.37 *10^6\, m$. Thus the "fractional thickness" of the ocean on our orange would be $\frac{3.73*10^3}{6.37*10^6} = .000586$. If our orange has a radius of 2 *cm* then the ocean on our orange would be $.000586 * 2\, cm \approx .001\, cm = .01\, mm$ deep. That is a pretty shallow sea! The next time someone tells you that the oceans are so

[28]Don't take my word for this, look it up somewhere and see if you get the same number.

vast that humans could never hurt them, tell them about this earth-orange with an ocean only one hundredth of a millimeter deep.

How Much Air is in the Atmosphere? How Much Soil is on the Earth? Let's take another, cf., Section 4.5, look at the earth's atmosphere. The mass of the atmosphere, cf., [283, p. 235], is $5.14 * 10^{18}\,kg$. The bulk of the earth's atmosphere that is closest to earth is called the *troposphere*. Atmospheric scientists define the troposphere as that part of the atmosphere closest to the earth in which the temperature drops with increasing elevation. Over 90% of the air in the atmosphere is in the troposphere. The average elevation of the top of the troposphere is 12,000 m. The next layer of the atmosphere is called the *stratosphere*. This is where the ozone layer that we examined briefly in Section 4.5 is located. In the stratosphere the temperature increases with increasing elevation (up to about 50 km).

If we look at the ratio of the thickness of the troposphere to the radius of the earth we get $\frac{1.2*10^4}{6.37*10^6} = .0019 \approx .002$. Thus on our 2 cm radius orange, the troposphere (over 90% of the air) would be in a layer $.002 * 2\,cm = .004\,cm$ thick. That is four times thicker than our shallow sea, but still not very thick. And, of course, air is far less dense than water.

Now if we "liquefied" all the earth's atmosphere, i.e., assumed that the mass of the air was replaced by an equivalent mass of pure water, we would have $5.14 * 10^{15}\ m^3$ of liquid. If this were in a spherical droplet, it would have a radius of 107,059 m. Scaling this down to our orange, we get that all the air on the earth if liquefied would form a droplet .034 cm in radius.

The next time you hear an argument about the cost of pollution controls on smoke stacks or automobile exhaust, think about how thin the earth's blanket of air actually is.

David Brower includes in his recitation of numbers on the Cousteau-Brower earth the statement: *"...and if all the topsoil on earth were put in one pile on our (orange), it would be a speck barely visible to the naked eye."*

Exercise 7.15 The Relative Amounts of Air and Topsoil on Earth

(i) Verify our calculation of the radius of the droplet of liquefied air on earth-orange.

(ii) If all the topsoil on earth were rolled into one spherical ball, estimate as best you can the radius of this ball on earth-orange. You can use the references already mentioned in this book, or others.

(iii) If the atmosphere were 78% nitrogen and 22% oxygen how many grams of mass would there be in 1 mole of air?[29]

(iv) The air is actually 78.08% nitrogen and 20.95% oxygen. The rest of the air is a mixture of argon, carbon dioxide, and many other gases, including water vapor, cf., [283]. Using the information in II, show that 1 mole of air has a mass of 28.96 grams.

(v) Verify our calculation alluded to above that if the mass of the air were replaced by an equal mass of water, that water would occupy $5.14 * 10^{15}\ m^3$.

So the comments of David Brower at the beginning of this section are quite apt. If the earth were reduced to the size of a sphere you could hold in your

[29]For the definition of a *mole* and examples of calculating with it see II.

hand, the seas and atmosphere would be very thin indeed; and the soil nearly invisible.

Some folks will say that the above exercise is quite meaningless and "not scientific." whatever that may mean in this context. One could point out that if we scale all the humans down we will have a hard time seeing them on our orange. My immediate reply is that the effects humans are having on the planet far transcend their physical size. I contend that given the present documented impacts of humans on the planet it is important to have the notion of limited air, water and soil in each of our minds to compete with our natural tendency to think of these three things as limitless.

Calculating Your Ecological Footprint. My enthusiasm for the following exercise is not shared by all. Professor Rees, coauthor of [695], once gave a lecture which I attended on the concept of *ecological footprint*[30] that he and Mathis Wackernagel introduced. An economics professor in the audience announced at the end of the talk that he would give Professor Rees an F for his analysis.

Exercise 7.16 Calculate Your Ecological Footprint

(i) Calculate your personal and/or family ecological footprint, or that of a "typical" American. Note that http://www.rprogress.org/ and http://wwwfootprintnetwork.org are Web sites (as I write) that will help you calculate your ecological footprint on earth, i.e., "how much of the earth is required to support your lifestyle." You should do an internet search for "calculate ecological footprint" and compare results from a variety of footprint calculators. Of course, you could do the calculation all by yourself as well. This requires that you put together an analysis of all impacts your life has on the planet and estimate the area of the planet you impact (directly or indirectly).

(ii) Repeat part (i) replacing the American by a person from a very poor country, then by a person who has an income in excess of $1,000/day, then by a "middle class" person who earns between $750 and $7,000 per year, measured in 1992 dollars just to be precise. See VII.

[30]Roughly, a person's ecological footprint is an estimate of the area of the earth needed to supply all of the consumption of that person.