SpringerBriefs in Earth System Sciences

John A. Whitehead

Energy Flow and Earth

How Earth Works

Springer

SpringerBriefs in Earth System Sciences

SpringerBriefs in Earth System Sciences present concise summaries of cutting-edge research and practical applications. The series focuses on interdisciplinary research linking the lithosphere, atmosphere, biosphere, cryosphere, and hydrosphere building the system earth. It publishes peer-reviewed monographs under the editorial supervision of an international advisory board with the aim to publish 8 to 12 weeks after acceptance. Featuring compact volumes of 50 to 125 pages (approx. 20,000—70,000 words), the series covers a range of content from professional to academic such as:

- A timely reports of state-of-the art analytical techniques
- bridges between new research results
- snapshots of hot and/or emerging topics
- literature reviews
- in-depth case studies

Briefs are published as part of Springer's eBook collection, with millions of users worldwide. In addition, Briefs are available for individual print and electronic purchase. Briefs are characterized by fast, global electronic dissemination, standard publishing contracts, easy-to-use manuscript preparation and formatting guidelines, and expedited production schedules.

Both solicited and unsolicited manuscripts are considered for publication in this series.

John A. Whitehead

Energy Flow and Earth

How Earth Works

Springer

John A. Whitehead
Department of Physical Oceanography
Woods Hole Oceanographic Institution
Woods Hole, MA, USA

ISSN 2191-589X ISSN 2191-5903 (electronic)
SpringerBriefs in Earth System Sciences
ISBN 978-3-031-62693-7 ISBN 978-3-031-62694-4 (eBook)
https://doi.org/10.1007/978-3-031-62694-4

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Dedicated to the Geophysical Fluid Dynamics Summer School

Preface

This relates to my personal experience as I watched mankind's discovery of the basic understanding of how the flow of energy acts as a giant architect for many large things on Earth. These "things" include the giant plates, volcanos, continents, ocean basins, Earth's magnetic field, our atmosphere, and ocean circulation. My journey as a scientist taught me how energy flow produces overall support while mechanics and chemistry provide invisible skeletons that hold them together. Energy flow is invisible, and it takes many forms. Two examples are an electric current that brings energy into the house and sunlight that provides a flow of heat to warm us when we are cold. My specialty led to studies of the effect of energy flow on our planet that involved work both in a laboratory and in the Earth. I am excited to write about this, because much of this invisible skeleton was uncovered in my lifetime.

My trip started when I became a graduate student in Engineering and Applied Science at Yale in 1963 after being trained as a mechanical engineer at Tufts University. After completing my thesis in fluid mechanics and receiving a PhD in 1968, I went to UCLA to learn about geophysics and planetary science and then to the Woods Hole Oceanographic Institution to learn about the ocean and marine geology, where I have been ever since. I have been extremely fortunate to have experienced personal contact and to have known a large percentage of the people involved in the discoveries in this book. I worked with at least two hundred of them! I attended countless seminars and read hundreds of research papers. Many of the people who developed these ideas have now died and quite frankly, I want to write this view down before all of us are gone. This book expresses my sense of obligation to all of them.

This book is my own view from my own experience rather than a fastidious history. I don't include large lists of names, biographical snippets, and citations of all the contributors. Numerous talented contributors are generally cited in many books, and there are countless review papers about topics discussed in this book. As a first start at describing my experience, I have found that many people are left out of any list of the famous. Some examples are technicians left out of the list of authors; volunteers; people who simply were in a laboratory or classroom at a moment when they made a remark that made all the difference; students who were simply obscured by efforts by more senior people who swiftly followed them; students who did a great job but then went into another field so that their names are not commonly recognized anymore; scientists who made the first discovery but were not well-known because of missing citations in later papers; people who had political or financial constraints that made their results obscure; and people who unfortunately had a second person following their work who was more eloquent and quick to claim the credit. I can name examples of each of these. Each chapter has citations about significant contributions and key books. Although they are a good guide for the historian, I'd like to paraphrase ("with tongue in cheek") a wonderful friend, Ed Spiegel who said something like "I kept leaping up because the giants' shoulders were blocking the view". We all did this together!

In this book, I want to tell a central part of this story that describes giant flows of rock, water, air, ice liquid metal, and magma. We learned that the global flow patterns of these flows are constructed or at least strongly influenced by natural processes with an invisible underpinning of energy flow. We can visualize the flows as being components of large engines, and the story includes the flow of energy propelling them. Therefore, this book includes the principal concepts of energy flow. The invisible flow of energy not only runs these giant engines, but it also takes an active part in producing and maintaining the flows and structure of the engines. Many other things around us are produced and driven by a flow of energy, too. For example, all of nature is driven by the flow of energy. Every living thing needs energy flow to produce and reproduce itself and keep itself going. This is true of bumblebees, birds, sunspots, tornados, mountains, oceans, rainstorms, and hurricanes. It is also true in many other aspects of our existence such as city traffic, politics, economics, and kings. They concern ideas I learned as a scientist. Some of them were discovered as I watched.

We describe natural flows and think about how they were started and about the power that propels them. Like the gasoline driving a running engine, heat flow provides the power to drive many flows on Earth and provides a ghostlike figure behind a skeleton of mechanics and chemistry holding the flows together. Both some material substances and the flow of energy are needed to explain Earth's giant engines. Usually, the latter has been ignored. My own ghost is my food and metabolism, and my skeleton includes all the structures and functions of my own body. When my ghostlike internal energy flow stops, I will die and decay away. But the ideas in this book won't. Hence, time to write!!

Anyway, here is how it all works.

Woods Hole, USA John A. Whitehead

Contents

About the Author

John A. Whitehead studied mechanical engineering and intended to enter human engineering and make machines easy for people to use. Instead, he became enchanted by the challenges of fluid dynamics and went to graduate school. A student project on the fluid mechanics of thermal convection led to a life's work in studying natural fluid flows, starting at the Institute of Geophysics and Planetary Physics at UCLA, followed by about 50 years in the Geophysical Fluid Dynamics Laboratory at Woods Hole Oceanographic Institution. His experimental work on convection helped us to understand the nonlinear character of stability theory for thermal convection. He has also done fundamental experimental work on the dynamics of flows in volcanic conduits in the Earth's mantle, in deep, hydraulically controlled oceanic flows in straits connecting ocean basics, the fluid mechanics of coastal currents, and on multiple equilibria in fluid dynamics concerning oceanic thermohaline circulation. Work was also spiced up with theory, field trips, ocean cruises and, of course, countless seminars including the Institution's Geophysical Fluid Dynamics Summer Study program. He is a Guggenheim Fellow, a Fellow of the American Physical Society, the American Meteorological Society (Henry M. Stommel Research Award, 2007), and the American Geophysical Union (Ewing Medal, 2014) and a member of the American Academy of Arts and Sciences.

Chapter 1
An Introduction to Energy Flow and the Discovery of the Great Plates

Abstract This chapter begins with a discussion about the flow of energy. The story begins with a short history of the discovery of mantle convection. In the early part of the twentieth century, the ideas that continents slowly move around on the surface of the Earth was put forth, but after a couple of decades the idea remained stagnant. Then it was found that these continents were on great rigid moving plates that are formed at ocean ridges. The plate material in the seafloor moves away from the ridges and ultimately plunges back into the Earth at ocean trenches. This chapter tells of how the primary features of the great plates were discovered and how sinking slabs of cold ocean floor within the mantle of the Earth were detected. These were shown to drive the plates in the 1960s and early 1970s.

1.1 Energy Flow

In this book, we describe the energy flow that drives numerous things in our natural world. Energy flow occurs everywhere. We put gasoline in an automobile and the motor takes us on a trip by burning the fuel. The gasoline flows into the engine to propel us. We burn fossil fuels to produce heat. We use fuel to propel machines that provide food, heating, transportation, and almost everything else that runs our modern civilization. Unlike many books and essays that are coming out now, this book is not about humanity's energy crisis. It is instead a primer about how the flow of energy, generally in the form of heat, naturally moves and forms things on Earth. Unlike an automobile, these "giant flows" are not made by people but are even constructed or at least strongly modified by the flow of the energy. They are truly natural engines. Some examples of these giant engines are the continents, ocean basins, storms, tornados, volcanos, mountains, rivers, ocean waves, and even our magnetic field.

Energy flows everywhere, and we experience aspects of the flow all the time. We feel warmth from a heater in cold weather, and a cool breeze removes heat from our face on a hot day. Beyond our personal reach, we marvel at the giant energy expended by a large steamship, the awesome power of a train locomotive, and the immense

J. A. Whitehead, *Energy Flow and Earth*, SpringerBriefs in Earth System Sciences,
https://doi.org/10.1007/978-3-031-62694-4_1

cascade and turbulence of a waterfall. Very high winds show us great forces from the invisible drag of air. We marvel at a giant crashing wave or a bolt of lightning. Projectiles from the wind can scare us. We hop into a car, bus, train, or airplane to travel at speeds that were not even imagined by Benjamin Franklin. Electric motors operate everywhere driven by an invisible flow of electrons. Energy flows invisibly all around us, and the flow of energy is vital to all we do.

Despite its continual presence, the flow of energy is not generally appreciated, probably because it is not easy to visualize and understand. We only know about energy and its flow as a concept or a feeling. Energy flow is invisible even though it is present! Nobody holds flowing energy in their hand or pokes it or paints a picture of it or photographs it. For example, with electricity we don't see all those electrons flowing through wires, but we see the video screen or hear the radio. We don't see the heat flowing into our frying pan, but we certainly know if it gets hot.

Energy is contained in all matter, and it can be stored and transferred in many forms. When energy flows into a region, it can change the energy within the region in various ways. It can make the temperature increase, it can produce a compositional change such as solidification, by melting it, it can start a chemical reaction, or it can simply increase kinetic energy. If gravity (or another body force) is present, energy flow can change potential energy. Energy flow can involve an electric current or create a change in a magnetic field. Energy often changes its form in complex ways.

A simple example of changing forms of energy starts with cold firewood inside a fireplace. After igniting the wood, the chemical energy stored in the carbon of the wood links up with the oxygen in air to release heat and form carbon dioxide. The air leaving through the chimney is much warmer than the ambient air, so the fire exports this heat along with the carbon dioxide. The fire also exports heat by radiation. Therefore, the chemical energy of wood and air has changed to heat. The remaining materials, mostly carbon dioxide and ash, have lower chemical energy. In this book, we will look at power budgets that are in a fixed region just like this fireplace, but our regions will be laboratory fluids or portions of Earth, such as our atmosphere, ocean, mantle, and core. Some of these concepts are being applied to other planets, too.

This book concerns energy-flow structures. The fireplace itself is not strictly an energy-flow structure, because people constructed the fireplace, prepared the wood, and ignited it. Most mechanical machines that we deal with, and many of our activities (such as cooking) are made by people. In contrast, I think of the fire itself and the circulation of heat associated with it as an energy-flow structure. The energy flow within the flame converts chemical energy to three forms. The first is kinetic energy production of the air flow. The second is heat flow away from the flame by both thermal conduction and convection. The third is radiation of the heat energy. The flame only exists after being started. For a flame, an elevation of temperature above a certain value is needed to start it. After ignition, the flame produces the conditions to keep itself going. Chemists can give us a formula that expresses the required temperature for a fire to be self-sustaining. This formula is a criterion for the existence of this energy-flow structure. Some energy-flow structures start spontaneously after the ambient conditions slowly change to be moved into a situation that fits the criterion. If we made the bricks or rocks of the fireplace hot enough, the fire would start without a match.

Energy flow is more than a servant. Did you know that not only do these giant flows that we see on Earth come from a flow of energy but also that most of them will retain their shape only with continual energy flow? One might call the structures associated with these giant flows “Earth’s engines”, even though no factory made them. Energy flow is involved in the construction of many of the gigantic things that we consider part of Earth: our land; the sea; our air; the wind; ocean waves; ocean currents; and even our mysterious magnetic field. All of nature is driven by the flow of energy, too, although smaller engines in biology are not included in this book. Every living thing needs energy flow to make itself grow from a tiny seed or egg and to keep itself alive. When energy flow stops in every living thing, it dies and decays away.

So, precisely what is energy flow? It is connected to a concept in mechanics that is literally called “work”. This concept has a precise scientific definition. A tutorial example is given in Chap. 9. The mechanical definition is unlike our common usage of the word. If I say to a small child, “How Earth works!” he or she might imagine a cartoon with an animated planet and a cartoon of Earth that is hard at work doing something. To someone in the working community, the concept of labor comes to mind. On the other hand, if I say this to an engineer, physicist, or person interested in how nature works, that individual might imagine that I will explain exactly how something mechanically works. Likewise, a chemist might think I am going to explain how work and energy are involved in chemical reactions that produce all the materials we use (including for example gasoline). A geochemist might think I write about Earth’s past and how the oceans and land as we know them were formed (including, for example, rocks, water, and air). Energy flow is readily measured, and, in this book, it will be expressed in Watts (with the abbreviation W). More aspects of the units are discussed in a tutorial in Chap. 9.

This book involves all these roles involving work and energy, but we go further. I will show how energy flow and the rate of work (using the scientific definition of work) PRODUCES and SHAPES things. In fact, it helps to produce and shape almost everything in our natural world. Energy flow can act like the skeleton sketched in Fig. 1.1a lurking behind the heat ghost.

Energetics associated with classical physics is so well studied that many physicists find it rather dull. However, in this book we will go one step beyond this simple energy flow and dissipation. We don’t impose a prescribed machine. Instead, a specific mechanical machine is formed in the process.

What???

Yes, we show how over the past 150 years it slowly was discovered that by using only simple classical physics, we can understand how many new things are formed as energy flows. The “new things” are not atoms, molecules, or any sort of particles alone, nor are they locomotives or steamboats or airplanes or cars or roller coasters. Instead, they are energy-flow structures that form only when there is a flow of energy in and out of a region, like the flame we already mentioned. It’s like an automobile being manufactured that includes the inventor, the factory workers, and the mechanic.

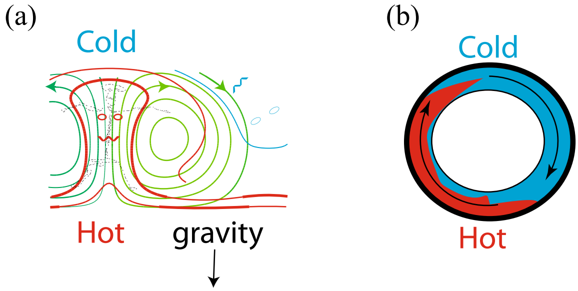

Fig. 1.1 **a** The heat ghost and an underlying skeleton. A hot thermal (red isotherms) rises from a hot bottom next to a cold sinking downdraft from a cold top. The ghost represents energy flow, and the skeleton-like framework is some sort of mechanical law governing a response (green streamlines). **b** Buoyancy-driven heat flow in a tube of water driven by heating from below

There are various technical terms to refer to energy-flow structures depending on the community interested in them. Some examples of other terms are dissipative structures (chemical physics); finite-amplitude flow (applied math); nonequilibrium structures (physics); or self-organized structures (physics and the media).

There is a hint about how energy-flow structures operate the overturning flow in the tube of water heated from below that is sketched in Fig. 1.1b. It reveals why I am continually hypnotized at how physics and mathematics build upon each other. Mathematically, there are four aspects of even the very simple flow in Fig. 1.1b. First, there is the possibility of either zero flow at all, just hot water along the bottom and cold at the top. Second, the fluid mechanics and heat transfer principles dictate that here is a minimum criterion for the existence of the flow to grow from zero. The criterion depends on several factors such as the temperature, the shape and size of the passageways, the expansion of the liquid with temperature, the strength of gravity, the thermal conductivity of tube walls liquid, and the viscosity of the fluid. We will show how these are grouped together to make a formula to express a criterion that must be exceeded for flow to exist. Third, there might be a need for a large push to switch from zero flow to the full flow shown there. If the flow were intelligent (which it is not), we could anticipate that the fluid has flow options, but here I want simply to think of these options as mathematical branch points between no flow and flow. The location of the branch points depends on the value of the criterion we mention above, or even on other criteria. Fourth, the rate of heat transfer (and therefore the rate of release of potential energy) for the situation with no flow has a different value than the one with flow present. I like this example because it shows the relation between physics and math. Numbers 2 and 4 are physical criteria, and 1 and 3 are mathematical aspects of branch points.

It is easy to imagine more complex examples than Fig. 1.1b that have even more branches. Warning: Numerous branch points can produce confusion! Branch points are responsible for the complexity and uncertainty about many commonplace aspects of our world: weather is variable, turbulence exists, geology is complex, nature is full of surprises, and the future is hard to predict.