Advance Praise for *Being the Change*

A plethora of insights about nature and ourselves, revealed by one man's journey as he comes to terms with human exploitation of our planet.

—Dr. James Hansen, climate scientist and former director of NASA's Goddard Institute for Space Studies

A powerful reminder that it is possible — and joyful — to move away from fossil fuels, even in a society still in the throes of addiction.

— Bill McKibben, author, *Eaarth: Making a Life on a Tough New Planet*

A low-carbon world will not look like *Star Trek*, it will look mostly like it looks today, it's just that we will inhabit it differently. Peter Kalmus's brilliant book is about his deciding to start living that way today. He finds that (a) it's not that hard, and that (b) life improves. He becomes more skilled, connected, fulfilled, nourished. As will we all. Allow him to ease you over the threshold.

— Rob Hopkins, founder of the Transition movement robhopkins.net.

Too many people say that personal action isn't enough to deal with the mess we've made of the global climate, and think that this means personal action isn't necessary. In this timely and provocative book, Peter Kalmus points out that changing the world has to start with changing our own lives. It's a crucial message that needs to be heard.

—John Michael Greer, author of *After Progress* and *The Retro Future*

What does an astrophysicist do if he learns that civilization is on path toward oblivion? If he's Peter Kalmus, he meditates, examines his life, and makes significant changes to reduce his personal carbon output. Then he writes a book. The result is a humane and intelligent exploration of what anyone can do to reduce climate impact — and live a better life in the process.

— Richard Heinberg, Senior Fellow, Post Carbon Institute

A low-emission lifestyle is empowering, happier, and strengthens our connection with community and our environment (plus yes, it saves us thousands of dollars). This is an important and valuable book, and recommended reading for anyone interested in a richer life or a safer climate (doubly so for those interested in both).

—John Cook, research assistant professor at George Mason University and founder of SkepticalScience.com

Too often, books by scientists err toward the ultra-cerebral. Full of facts, figures and charts — but not enough heart. That's what makes *Being the Change* so refreshing. Kalmus is a respected atmospheric scientist and weighs in with authority when it comes to the topic of climate change. But he speaks to us as a person, sharing his experiences, concerns, and aspirations as a fellow human being combatting the existential threat of human-caused climate change. And he shares with us a vital message about how we can indeed be the change we need to see in the world if we are to avert a climate catastrophe.

— Michael E. Mann, Distinguished Professor of Atmospheric Science, Penn State University, and co-author, *The Madhouse Effect: How Climate Change Denial is Threatening the Planet, Destroying our Politics, and Driving Us Crazy*

Cover design by Diane McIntosh.
Interior illustrations by Sam Bower;
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Printed in Canada. First printing June 2017.

Funded by the Government of Canada | Financé par le gouvernement du Canada | Canada

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The author is donating his profits to groups with potential to connect individual agency to collective climate action, such as Citizens' Climate Lobby.

Inquiries regarding requests to reprint all or part of *Being the Change* should be addressed to New Society Publishers at the address below. To order directly from the publishers, please call toll-free (North America)
1-800-567-6772, or order online at www.newsociety.com
Any other inquiries can be directed by mail to:
New Society Publishers
P.O. Box 189, Gabriola Island, BC V0R 1X0, Canada
(250) 247-9737

LIBRARY AND ARCHIVES CANADA CATALOGUING IN PUBLICATION
Kalmus, Peter, 1974-, author
Being the change : live well and spark a climate revolution / by Peter Kalmus.
Includes bibliographical references and index.
Issued in print and electronic formats.
ISBN 978-0-86571-853-1 (softcover). — ISBN 978-1-55092-648-4 (PDF). — ISBN 978-1-77142-243-7 (EPUB)
1. Sustainable living. 2. Climatic changes — Prevention — Citizen participation. I. Title.
GE196.K35 2017 333.72 C2017-902837-5
C2017-902838-3

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Preface

This book explores a lot of territory. It discusses climate science, climate policy, and aquifer depletion—as well as mythology, meditation, and beekeeping. These and other topics herein have been written about in greater detail elsewhere. There are entire volumes devoted to backyard chickens. So why mention them here, in a book with "climate" in its title?

The answer has to do with the nature of our predicament: global warming touches every aspect of our lives. It connects gardening to population growth, bicycling to flying in a plane. Most of all, global warming challenges us to rethink humanity's place in the web of life on this beautiful planet—to reimagine what it means to be human. Global warming is, perhaps first and foremost, a failure of humanity's collective imagination. As such it doesn't fit neatly inside any single box or discipline.

How, then, can we respond as individuals? In searching for answers, I've read books about science, policy, practical action, and spirituality. But none spoke to my being as a whole. And they tended to be too polite, too careful, too narrow; they didn't ask enough of me. Their suggestions were not on a scale commensurate with the scale of the predicament. And far too many were joyless.

As I learned more about climate change, my need to do something intensified. The path was far from clear, but I did my best, gradually and systematically changing my daily life. My response draws on science, practical action, and spiritual examination, and these threads interweave on every level. You hold the unique result in your hands: a book written from the perspective of a meditating climate scientist who has nearly eliminated his own greenhouse gas emissions—and who discovered this to be surprisingly satisfying, empowering, and relevant to collective change. In place of burning fossil fuels, humanity can become smarter, more creative, kinder.

Since beginning down this path, I've covered a lot of ground. I've changed many things about my life and had a lot of fun. At the same time, I've come face-to-face with the seriousness of our climate emergency. To continue business as usual is to tacitly place a blind-faith bet on the emergence of some techno-fix; this amounts to magical thinking. And global warming is happening with a rapidity that leaves me speechless. The longer we take to change direction, the more suffering we'll experience and the longer this suffering will last. And for what? A consumerist lifestyle that doesn't even make us happy. We must do everything we can to change direction. And a big part of this is imagining, living, and telling the stories of *what comes next.*

In addressing something so all-encompassing, you'll ultimately need to forge your own response. My hope is that this book will support and inspire you as you do so.

Writing it has been a long journey, both literally and figuratively, and I'm grateful to the wonderful people who have nourished and sheltered me along the way. These include Audrey, Katie, Christina, my mom and dad, Therese Brummel, Abe de la Houssaye, January Nordman, Lin Griffith, Maya Saran, Baldeep Singh, Paul Livingstone, Mark Rice, John Hopkins, David Sneider, Susan Rudnicki, Paul Taylor, Daniel Suelo, Victoria and Alec Loorz, Russel Greene, Alan Weinstein, Joao Teixeira, Mark Richardson, Ryan Pavlick, Matt Lebsock, Brian Kahn, A. B., Angie Pendergrass, Bryan Allen, Jim Waterhouse, Rob Haw and the rest of the awesome PF-CCL team, Markus Loeffler, Clay Folk, P. J. Parmar, James Bakner, Tera Little, Sarah Baird, Sarah Reber, Ben Denckla, Brent Ranalli, Elizabeth Mathews, Sam Bower, Erik Knutzen, Kelly Coyne and Pancho Ramos-Stierle—many of whom provided detailed comments which greatly improved the manuscript. It was a pleasure working with the artist Sam Bower and the editors Robin Rauzi and Betsy Nuse. I'd like to thank the good folks at New Society Publishers (especially Rob West), and the other good folks at YES! Magazine (especially Tracy Loeffelholz Dunn), for believing in me—and for enabling new voices to take part in this crucial conversation.

Above all I thank my wife, Sharon Kunde, for a lifetime of challenging discussion, insightful comments, unwavering support, and plain old companionship; and for patiently putting up with my many foibles and crazy projects. I couldn't ask for a better Dhamma partner.

— Peter Kalmus

Altadena, California

PART I

PREDICAMENT

Full fathom five thy father lies;
Of his bones are coral made;
Those are pearls that were his eyes:
Nothing of him that doth fade
But doth suffer a sea-change
Into something rich and strange.

— William Shakespeare, *The Tempest*

CHAPTER 1

Waking Up

Trees and people used to be the best of friends.
I saw that tree and decided to buy the house.
— Hayao Miyazaki, *My Neighbor Totoro*

I knew that burning fossil fuels was causing irreversible harm to our planet's life-support systems. And yet I continued to burn.

When I first heard of global warming[1] in sixth grade—the only time it was mentioned during my school years—it seemed like science fiction, not something that would ever concern me. I didn't think about it again for nearly two decades.

I began learning the basic science of global warming in 2006 when my first son, Braird, was born. Fatherhood jolted me out of a selfish careerism. Suddenly my life wasn't just about me, and my perspective shifted to a longer time scale. At the time, I was working on my PhD in physics at Columbia University in New York City. As my eyes were opened, I had a strong emotional response: how could we continue burning fossil fuels at an accelerating pace when this severely damages the biosphere for future generations? It seemed insane. At the same time, I was immersed in our industrial civilization, which dictates that burning fossil fuels is the only *sane* thing to do—that someone who *refuses* to burn fossil fuels is ludicrous, a Luddite.

I became obsessed with finding some way to rectify this deep inconsistency. I longed to know how all of the people around me—family members, colleagues, strangers on the street—were dealing with this glaring disconnect without any apparent difficulty. Did they know about global warming? Had they made peace with it somehow, or did they simply not think about it? I felt afraid of the future, lost. I had so much emotional static that I struggled to connect with people.

Like a splinter in my psyche, this disconnect required me to *do something*. But what?

I first tried converting people with facts. The people around me were acting as though there wasn't a problem: perhaps they simply didn't know. If I could only communicate with greater clarity, people would "get it." I felt like I had the truth, that my job was to wake everyone up.

Like most attempts to convert, though, mine were sanctimonious and alienating. It was impossible for anyone to listen to me, or for me to listen to anyone else. (My wife, Sharon, had to put up with a lot; it's not easy being married to someone who wants to convert you.) This led to even more disconnection. Alone with my angst, at a loss for what to do, I was panicking.

I now realize that few people respond to facts. I also realize that I can't respond meaningfully to our predicament with my intellect alone. I also doubt that even our society's collective intellect, our best scientists and brightest policymakers working within their delineated roles, will be enough. While intellect certainly plays a role, it's a rather small one. Our dire ecological crisis calls us to go deeper.

Going deeper

A few years passed before I began to develop a more coherent response. In 2008, our second child, Zane, was born, and we left New York so I could take an astrophysics job at the California Institute of Technology. But before leaving New York, I was offered a job in atmospheric science at NASA's Goddard Institute for Space Studies (GISS), which at the time was led by James Hansen. Had I accepted it, I'd have worked to improve the representation of clouds in the GISS global climate model. But I didn't feel ready for such a big career change, and my ongoing work of searching for gravitational waves—ripples in the fabric of spacetime—was incredibly exciting. So, after much soul searching, I accepted the Caltech job and continued my work of sifting through LIGO data for scientific gold. Sharon and I moved to Altadena, a suburb northeast of Los Angeles in the foothills of the San Gabriel Mountains where parrots roam the skies and orange trees abound. I felt like I'd landed in paradise.

We chose a house because of the magnificent avocado tree in the backyard. I bonded with this tree. I began to think of it as a friend, and I still do. This relationship with a tree began to change me: I began to understand plants as beings.[2]

After a year of renting, we bought the house. For the first time in my life, I owned a tiny patch of land. I decided to cancel the mow-and-blow landscaping service and tend my own yard. The land seemed alien; I didn't know what any of the plants were called or how to take care of them. But I did know that I love to eat tomatoes, so I planted some tomato plants. I enjoyed their company so much—their smell and their just-perceptible daily growth, their being-ness—that I felt called to plant other little beings. I dismantled a small deck by my back fence that we never used, took a sledgehammer to the underlying concrete (quite a joyous task, it turned out), and turned the scrap lumber into six raised beds. I'd caught the gardening bug. Before long I ripped out the grass of my front lawn to make space for other, more interesting and useful plants.

This, then, is how I started to use my hands: the land drew me in. The land was like a painter's canvas, full of possibility and potential. I could plant things on it. Choosing what to grow, and how, required a new kind of wisdom from me, something essentially human. It asked for more than intellect. It asked for connection and for humility, and it offered simple gifts. I fell in love with the land.

I could see a path stretching far into the distance, and I've come to understand that learning how to tend the land takes a lifetime.

Around this time, in 2010, I began to meditate seriously. Sharon and I had started meditating back in New York, but we simply weren't able to maintain our practice while caring for babies. But one morning, after four years of diapers and inadequate sleep, I remembered how important meditation had been. So I went to a ten-day meditation retreat and started practicing again. This is how I started to know myself more deeply. My eyes opened to what was right in front of them. A few months later, Sharon went on her own retreat, and we began sitting together daily.

I began observing my daily life and changing it to be more aligned with what I knew.

When faced with some daily task—commuting to work, planning a trip, eating, showering, whatever—I began perceiving how it connects to our industrial system's preferred way of doing things, how it affects other beings and too often harms them. I began searching for alternative ways of doing things. This exploration often blossomed into adventure: unpredictable, fun, and satisfying.

As my scientific interest in global warming increased, it eventually occurred to me that I'd be happier studying it full-time. So I finally left the beautiful, giddy world of astrophysics. This was a sacrifice, and it meant sitting on the sidelines during humanity's first detection of gravitational waves—an endeavor to which I've given nearly a decade of my life. But I simply could no longer concentrate on astrophysics; it felt like fiddling while Rome burned. I'm now an Earth scientist studying the role of clouds in a warming world. I've also reduced my personal CO_2 emissions from about twenty tonnes per year (near the US average) to under two tonnes per year. Overall, this hasn't been a sacrifice. It has made me happier.

Head, hands, and heart

The path I'm on has three parts. One is intellectual understanding: the head. The head allows me to prioritize. It helps me navigate to my goals, although I find it's not always good at *choosing* those goals. One of the lessons I've learned is that I'm limited, in time, energy, and ability; if I'm to make any progress, I need to choose my path wisely. This means asking the right questions, gathering information about reality as it is (which is often different than how it appears to be, or how I want it to be), and drawing conclusions objectively. The head is a scientist.

Another part of my path is practical action: the hands. As we'll see, society's business-as-usual trajectory is carrying us toward disaster. If we wish to avoid disaster, we must take action. Since I can't change the entire global trajectory single-handedly, I perform practical and local actions, changing myself and how I live right here and right now. Direct practical action is empowering; it brings measurable, tangible change. It's fun, and therefore I can sustain it easily. It also provides its own guidance. Time and again I've found that only by taking a step—making some actual change—is the next step revealed. I find that all the planning and intellectualizing in the world can't substitute for just doing something. There's wisdom in doing.

A third part of my path is seeing from the heart. This third part is what connects me to myself, to other people, and to nature. Without it, action can become compulsive, joyless. Connection brings purpose and meaning to thought and action.

I have a specific and concrete practice for this third part: I meditate by observing my body and mind in a particular way. Meditation allows me to be joyful (most of the time) even while studying global warming every day at work. Meditation helps me connect to the sea of everyday miracles around me—the plants growing, the sun shining, my older son lovingly putting his arm around his brother's shoulders. I find great strength in this awareness.

These three parts support and balance one another. In shaping a response to our predicament, each part is important.

Aligning with the biosphere

The changes I've been making to my own life are simple, but they go far beyond recycling or green consumerism. I came to see that the business-as-usual ways of industrial society are bankrupt. So I actively replace those parts of my everyday life that feel unsatisfying with new ways of living that I do find satisfying.

Such changes don't require sacrifice so much as exchange, swapping daily actions that aren't satisfying for ones that are. In this way, my everyday life has gradually come into harmony with my beliefs. My experience has been that congruence between outer and inner life is the key to happiness. I'm no good at fooling myself.

I also came to see how deeply I'd been influenced by the subconscious whisper of culture, how little I questioned my everyday actions, and how completely I accepted the illusion that the way things are is the only way they could be. My old mindset was separation; my emerging mindset is connection. I'm learning that acceptance and detached observation of my own mind is the basis of compassion. I'm learning how to become sustainable, internally.

We could coin a word for this path of inner and outer change: *becycling*, beyond recycling. Becycling entails restoring cyclical natural processes at the local scale. It requires getting busy instead of passively hoping that "they will think of something." It means accepting responsibility for your own everyday actions and changing those that harm other beings in our planet's biosphere. It means actually being the change.

Straightforwardness

My path is straightforward: if fossil fuels cause global warming, and I don't want global warming, then I should reduce my fossil fuel use.

Similarly, if I don't like conflict, killing, and wars, then I should reduce my own addiction to anger and negativity. This seems obvious to me now, but it didn't always. My need to be right used to be blindingly strong, and fear and defensiveness led me to react to anger with more anger, to negativity with more negativity. If we say we want a world without wars, then we shouldn't add hostility to the world ourselves! Yet wherever I go I see people arguing, fighting, and spreading negativity.

In our society, this kind of straightforwardness is often dismissed as idealistic, impractical, and out of reach. But *my own direct experience* says that it is possible to drastically reduce my fossil fuel use, and that it is possible to come out of conflict and negativity. What's more, the personal rewards for doing both are tremendous: a less stressful, more satisfying life.

These two seemingly disparate things—reducing my own fossil fuel use and increasing my ability to love—are actually intimately interconnected. As I learn how to love more, it becomes increasingly clear that I am connected to everything. How, then, can I voluntarily harm the rest of the life on this planet? How can I harm the children who will be born 100 years from now? When someone else suffers, I also suffer. There is no separation between me and the rest of the life on this planet.

To be clear: I'm not saying that selfless love is the near-term answer to global warming. Unfortunately, there are many who, for whatever reason, will never strive to love selflessly; there's no time to wait for them. And even for those who do so strive, it's a long path. This is why we also need sensible policies and technologies that result in cheaper alternatives to fossil fuels.

But for those who are ready to walk on the straightforward path, the path of love, it's certainly worth doing. It may even help to hasten the sensible collective action we desperately need.

Why walk on this path?

I'm aware that the changes I'm making to my daily life will not solve global warming or stave off global economic collapse. How could they? We're rapidly approaching eight billion people on the planet,[3] and I am only one of them.

However, my actions do make me happier, and that's reason enough to do them. I also suspect that, for most of us, individual and local-scale actions are the most skillful means to effect global-scale change. This is a paradox of scale. Our individual actions don't make much of an immediate difference in the global response to our predicament, but they are pieces in a vast puzzle. As more pieces get added, more people will get excited by the emerging picture and begin to add their own pieces.

The prevailing mindset in our industrial society is to search for a silver bullet solution, some brilliant techno-fix that allows us to avoid personal change (which is assumed to be undesirable). After decades of searching by the world's brightest minds, however, it seems likely that there is no such silver bullet. Personal change will therefore likely be necessary. Here are the reasons I'm an early adopter of personal change:

It's enjoyable

In my experience, cutting back on burning fossil fuels became possible—easy, even—when I began to realize that I enjoy my life more when I live mindfully and burn less. I realized that I don't want to burn so much, and I don't need to burn so much. And I genuinely enjoy the changes I've made, such as biking and gardening.

It's empowering

Back when I was concerned about global warming but still burning lots of fossil fuels, I was suffering from cognitive dissonance, living inconsistently. This made me feel depressed and confused. Now I live in a more consistent way, which is empowering. It's the key to connecting with others: my life is my calling card.

I want to help others, not harm them

Burning fossil fuels warms the planet, which harms others. It's that simple. Although the processes involved are distributed globally, accrue over decades, and are statistical in nature—and therefore difficult for our brains to connect directly back to our individual actions—the harm is nonetheless real.

Burning fossil fuels should be unacceptable socially, the way physical assault is unacceptable. The harm it does is less immediate, but just as real.[4] We need to start speaking this truth—burning fossil fuels harms others—so that society can begin realizing it.

It leads to connection and gratitude

Living with less fossil fuels leads to more connection with the land and with my community. It leads to increased awareness that food, water, fuel, and friends are precious. This connection and gratitude makes me happy.

Small actions lead to larger actions

We need to use our unique talents and interests to make a difference, and changing ourselves can reveal how to do this. Small actions gradually led me to two major actions that might have some impact beyond my local community: becoming an Earth scientist and writing this book. These efforts of mine may have larger impact, or they may not. Either way I'll keep making simple changes to my life, while simultaneously looking for opportunities to catalyze collective change.

I've known passionate environmentalists who dreamt of "saving the planet" but who weren't willing to begin changing themselves. But how can we reasonably expect to contribute meaningfully in the larger arena if we can't be bothered to make small changes to our daily lives? If I want to contribute to a change in the narrative, I must begin with myself.

It demonstrates a new story

Few people in the US realize that it's possible to live without fossil fuels. This is a huge failure of imagination. By changing ourselves, we demonstrate what's possible. We explore the new story, and we tell it.

Cynicism and inaction at the national level is nothing more than the collective expression of cynicism and inaction of individuals. When enough of us change ourselves, large-scale change is bound to happen. And when it comes to global warming, our actions speak louder than our words.

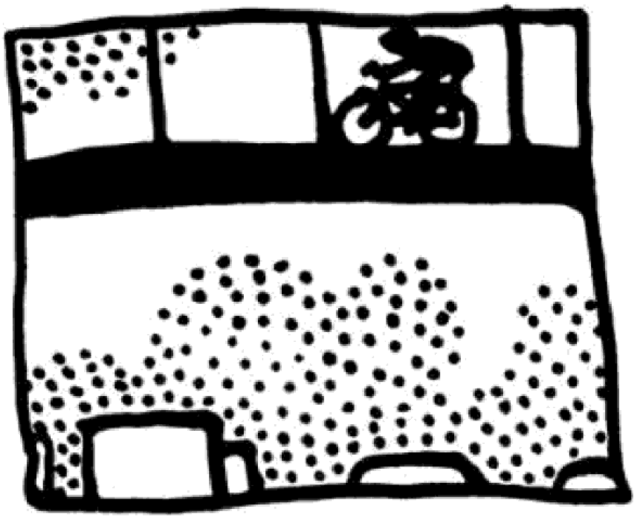
It's meaningful

Meaningful work is a great joy. And what could be more meaningful than exploring a new way for humanity to live, in harmony with the biosphere?
As Gandhi wrote: “We but mirror the world. All the tendencies present in the outer world are to be found in the world of our body. If we could change ourselves, the tendencies in the world would also change. As a man changes his own nature, so does the attitude of the world change toward him. This is the divine mystery supreme. A wonderful thing it is and the source of our happiness. *We need not wait to see what others do.*”[5]

Limits, patience, and grief

When I say that I can’t save the world, and that I’m aware I have limits, climate activists often misunderstand. They say that I need to stay optimistic, and that I won’t inspire anyone by talking about my limits. When they tell me this, I realize that they’re operating from one story, and I’m operating from another.
I know that I can change the world; indeed, I am changing the world. What I can’t do is save it.
That I have limits is a fact, and I accept it. I don’t expect my changes to have a big impact. (I don’t expect anything, actually.) If what I do has impact, I know this impact arises only from an existing resonance, a resonance that grows through interacting with many other people in turn. We are like water molecules in a wave: we simultaneously transmit the wave and are moved by it. No one water molecule causes the wave, but together an enormous number of water molecules carry the wave. It’s all of us together, carried by a resonance, that will effect great change.
In other words, I operate from the story of the wave, not the story of the hero.

I operate from the story of the wave,
not the story of the hero.



As I ride my bicycle on the overpass over the freeway,
the traffic below looks impermanent.
The way our society lives now feels ephemeral to me.

Sometimes, when I say we need to be patient, activists tell me that the situation is urgent and we have no time for patience. When they say this, I realize they don't know what to do, and that they're panicking. I know because I used to feel that way myself. But in my daily life, patience helps me get tasks done more quickly, not less quickly. Why would responding to global warming be any different? Patience is usually the fastest way to get somewhere worth going to.

I'm aware of how serious our predicament is. I've gone through a process of grief. My grief was deep and intense. It felt like I was part of the ocean, like I was connected to everything. Every now and then this grief comes back to remind me why I do what I do. It purifies and clarifies. I doubt that anyone who understands the seriousness of global warming can avoid this grief.

However, this grief is very far from despair. Grief comes from love, while despair comes from fear. I don't despair; instead I feel joy. It's true that we've lost a lot—a lot of wondrous species, a lot of beautiful places, a lot of opportunities—and that we'll lose even more. But even through this loss, we can experience how much there is to love, how much there is left to save. Our grief and love can lead us to move forward with more creativity and more joy than we ever thought possible.

I have no blind hope that "they will think of something," and yet I still feel optimistic in my own way. My particular optimism comes from the direct experience of connection.

Lifting the illusion

It used to be difficult for me to imagine living in another way, to imagine this land around me in Southern California without freeways, parking lots, or gas stations; to imagine the world without the constant noise of cars, helicopters, planes, and leaf blowers. These seemed like permanent fixtures. I took the conveniences of modern industrial life for granted—the frozen foods aisle, the cheap airplane flights, the internet, the constant distractions. I was attached to them; I wanted more of them. I kept hoping that more would make me happy. More stuff, more money, more clickbait, more convenience. After all, that's what our culture of industrial civilization —*petroculture*—constantly whispers to our subconscious: more of this and you will finally be happy.

Now, as I ride my bicycle on the overpass over the freeway, the traffic below looks impermanent. The way our society lives now feels ephemeral to me.

While I used to see the future as more, I now see it as less. Far from feeling scary to me, less feels right. I've learned that wanting more actually gets in the way of happiness. The feeling of "more and then I'll finally be happy" is an illusion.

I now see the imminent transformation of all that's around me not as an end but as a beginning. This shift in my way of thinking has grown over time out of many moments of simple connection to nature and to other people. Even on a warmer planet, even after today's global industrial civilization is no more than legend, there will still be mountains and sunsets, forests to walk in and oceans to sail, and good people to enjoy it all with.

But there's lots of work to do to prepare for the coming storms. Happily, the work is fun.

CHAPTER 2

Beyond *Green*

If we feel helpless or overwhelmed,
if we have anger, fear, or despair,
then no matter what we do to heal ourselves or the planet,
it will not succeed.
— THICH NHAT HANH, *Love Letter to the Earth*

Language both reflects and shapes how we see the world. The words we use to talk about our predicament reveal fundamental assumptions in how we perceive and relate to nature. Taking words for granted leads to confusion, and worse.

In this chapter, I discuss a few words and concepts we may be better off abandoning, and suggest some alternatives. In doing so, I hope to provide insights into some limitations of current environmental thinking, and to develop a new mindset that will better serve us as we revise humanity's relationship with the biosphere.

Nature and environmentalism

The word *environment* (as typically used by environmentalists) implies a dualism, a competition between the needs of humans and the needs of a nonhuman environment. It has become interchangeable with the word *nature*, which no longer signifies the totality of the physical universe, but instead signifies the domain of nonhumans. This dualism contributes to human exceptionalism, the idea that humans are outside of nature, unbound by natural laws, special among all species.

The reality, though, is that we're one among millions of species supporting each other (while simultaneously competing with each other) in the diverse web of relationships that is the biosphere. The human species depends on this biosphere just like every other species on Earth. The biosphere gives us food, water, oxygen, and a climate in which we can survive. At this level of understanding, there is no dualism. We are nature, and nature is us.

The dualism in the word *environment* manifests on the left as the idea that the environment needs to be saved, and on the right as the idea that the environment is humanity's to extract and exploit. These worldviews are actually two sides of the same coin, stemming as they do from a false sense of separation and human exceptionalism.

Biospherism

When we talk about the environment, we're usually talking about the biosphere or some part of the biosphere. Why not just say "biosphere"?

Whereas environmentalism seeks to protect the environment from humans, *biospherism* seeks to transition to a way of life that respects the limits of the biosphere and all life.

Whereas environmentalism implies duality, biospherism implies unity. Whereas environmentalism is reactive, chasing after the latest disaster, biospherism is proactive, seeking to transform the way we think and live. Whereas environmentalism treats the symptoms, biospherism treats the underlying cause.

What's at issue in fact is not an environment; it's a living world.

— David Quammen

Humans will always have an impact on the biosphere, and biospherism doesn't seek to eliminate our impact. Biospherism accepts that the biosphere just is the sum of the impacts of individuals (human and nonhuman, from any of the kingdoms of life) comprising it. It seeks to reduce human impact to sustainable levels by changing our priorities.

Biospherism seeks balance. It's the word I'll use in place of *environmentalism*. Someday I hope we can drop such terms altogether and simply say that we're human, and it will mean we live aligned with the biosphere, with each other, and with ourselves.

Beyond fear-and-guilt environmentalism

Environmentalism has had a strong tendency to use shame, guilt, and fear in an attempt to motivate action. But guilt and fear don't motivate me—they discourage me.

It's common for mainstream environmental speakers and writers to put a long and fearsome litany of climate change consequences front and center.[1] These presenters assume their audiences aren't aware of how scary global warming is (because if they were, the assumption goes, they'd certainly act). They therefore communicate fear with visions of hellfire and brimstone. At the end they tack on a few superficial suggestions, "ten things you can do" such as changing light bulbs or shopping at farmers' markets. Finally, they add a thin veneer of hope: "there's still time, but we must act now."

Hellfire and brimstone don't inspire us to change; they lead to guilt. Guilt is a coping mechanism that allows us to merely limp along with our anxiety. It's what we feel when we engage in some action that goes against our deeper principles, but that we don't actually intend to change. Guilt is an insincere self-apology for a painful internal fracture. It leads us to symbolic actions that allow us to function with this fracture. Why not just heal the fracture?

Interestingly, some of the most prominent leaders in the environmental movement reveal this inconsistency between their actions and their edicts. They tell us to stop burning fossil fuels, and yet they themselves have outsized carbon footprints. This hypocrisy might help to explain why the movement itself swirls with guilt. It may also help to explain why it has been ineffective. I suspect that most people notice hypocrisy at some level, and that it has a paralyzing effect. People think, "If even prominent environmental leaders can't reduce their carbon footprints, then it must be impossible."

What an incredible thing, a miraculous thing —
and now we know, a harmful thing —
to fly in an airplane.

While we do need to change ourselves, we also need to forgive ourselves. Those of us who were born into industrial society entered a powerful system that determines our beliefs and daily actions. Socialization colors how we see the world and makes it difficult, maybe even impossible, to see objectively. For example, until recently I drove cars and flew in airplanes without realizing their harmful consequences. Isn't it remarkable that as a society we take flying in airplanes for granted? What an incredible thing, a miraculous thing—and now we know, a harmful thing—to fly in an airplane.

It's time to move on to a more mature advocacy focused on developing a vastly deeper response to the predicament we face, beyond recycling and shopping for "green" cars and carbon offsets. Let's instead learn how to live in alignment with the biosphere, both as individuals and as a collective. This practice demands that we change our everyday lives, how we think about ourselves and our place on this planet.

Earth is a wondrously beautiful place, and will remain so even as we pass through this ecological crisis and ultimately come out the other side. Let's not fear our mother when she's sick. Instead, let's learn to feel compassion for her, and remind ourselves how precious her gifts are. Let's cultivate fierce and fearless love. And for goodness sake, let's stop performing the daily actions that are sickening her! We can stop burning fossil fuels out of a sense of compassionate love. *This* is the action we must perform. The second part of this book is about *how* to do this.

Let's not go green

The word *green* has been thoroughly co-opted by corporate marketing. Maybe it was useful once, maybe not, but now it zombie-walks through environmental discourse.

The word has no precise meaning in an environmental context, yet it strongly signifies vague environmental virtue. This makes it the perfect word for corporations seeking to profit from environmental guilt: "Go green! Buy our product (and feel better about yourself)." The corporations even get to decide what counts as green; in the US there's no regulation of green advertising. Corporations that do great damage to the biosphere regularly brand themselves as green, including car makers, airlines, and fossil fuel producers. It sometimes seems as if the more damaging a corporation is, the greener it claims to be.

Buying green stuff promotes the *status quo* consumer mindset. Green allows us to feel like we're responding to our predicament without needing to change. Green precludes meaningful action, and in this way does more harm than good. Our predicament is deep, and it demands a deeper response from us than shopping.

Low-energy

I propose *low-energy* as a replacement for *green.*

Using less energy at the global scale would reduce greenhouse gas emissions and serve as a bridge to a future without fossil fuels. Using less energy in our individual lives would equip us with the mindset, the skills, and the systems we'll each need in this post-fossil-fuel world.

If the adjective *low-energy* replaced *green*, its specificity would encourage meaningful collective action, such as using less energy. Furthermore, it could not be co-opted. Low-energy could not be used to sell airplane flights, air conditioners, or other fixtures of a high-energy lifestyle.

Many of the changes I've made to my daily life originated from realizing how precious energy really is. I think most people are afraid of a low-energy lifestyle because we equate quality of life with quantity of energy use. My experience has been the opposite: low-energy living is more fun and satisfying.

Sustainable and regenerative

The word *sustainable* is everywhere, but what does it actually mean? The literal meaning is "able to endure." Sustainability therefore involves both a time scale and an object: something is sustained, for some length of time. Thinking about sustainability, then, means thinking about change. This makes it clear that nothing sustains forever.

When we talk about sustainability, we're usually talking about a way of living, a relationship between humans and the biosphere. What time scale should we choose? We need a time scale that reflects the changing biosphere. One hundred years is too short, only a couple of human generations. Fifty thousand years is too long: there's already evolutionary change on this time scale. Indeed, we evolved to become cognitively human only 50,000 years ago. I suggest we aim for a way of living that we can sustain for 1,000–10,000 years. We can use this working definition to evaluate specific human behaviors.

Exponential population growth at a rate of 1.7% (the long-term historical rate; see Chapter 4) is no longer sustainable. After 1,000 years, at this rate we'd have 176 million billion people—which works out to 1,200 people on every square meter. We humans wouldn't even fit on the planet. So our growth will necessarily change—and, in fact, it is changing. Roughly speaking, having more than two children is not currently sustainable for our planet.

Our path to long-term sustainability is to stop growing and to find balance: to pull back to a global consumption and population that the biosphere can sustain. This will require a deep cultural shift, especially within affluent societies and minds. And if we don't make this change, the biosphere will do it for us, for example through global warming-induced disease or famine.

We can go a step further and think in terms of *regeneration* rather than sustainability. Doing so neatly sidesteps the need for a time scale, and it embraces the concept of change. Regeneration means bringing some part of the Earth, or some part of the human way of life, back into alignment with the biosphere. Regeneration calls us to do more than merely sustain: it calls us to heal, and to make our lives expressions of love for all beings.

What would a regenerative society look like in practice? For starters, it would respect the regeneration rate of every resource. Its food system would not depend on fossil fuels, and regions using groundwater would do so at a rate less than the aquifer's regeneration rate. Energy use would be essentially limited to what we could glean from the sun and wind. Metals would be entirely recycled. The population size would remain steady at a biospherically appropriate level, and economies wouldn't depend on growth. Huge swaths of land and ocean would be allowed to rewild. Science and technology would continue to thrive, but their focus would shift: science might be more interested in understanding the relationship between fungi and plants and might no longer concentrate capital for ever-larger atom smashers; technology might focus on doing more with less. A regenerative society would necessarily be more just and equitable. Accumulating wealth would no longer be the main goal of life.

Whether humans are capable of this transformation or not remains an open question. But changing yourself is one way to vote for it.

Recycling

Somewhere within our industrial mindset, there's a place called Away. When something breaks, or bores us, we throw it in the garbage and trash collectors take it Away. We flush a toilet and invisible pipes take it all Away. However, we are slowly learning that Away was always really just Somewhere Else, because everything is connected. But despite our increasing awareness, most of us still haul our bins to the curb and flush our toilets. It feels like we have no other choice. (There are other choices. See Chapters 12 and 13.)

This explains why industrial society fetishizes recycling. Recycling seems like a good thing on the surface, but it contributes to the broken *status quo*. Doesn't recycling help to keep the concept of Away alive in some sense? I know it does for me. I throw a plastic bottle into the recycling and I like knowing it goes Away—but to some better Away. Recycling helps me feel good about Away and allows me to go on consuming as before.

I'm not saying we shouldn't recycle. I'm saying that we shouldn't let recycling stunt our awareness of the impacts of our consumption. Recycling is Garbage 2.0. Let's reduce what goes in the recycling bin, as well as what goes in the garbage bin.

Independence, self-reliance, community-reliance

Independence is an illusion. If you truly depended on nothing, it would mean that you could float out in deep space by yourself, alive and happy. We certainly depend on our biosphere. We also depend on each other. If you depend on some tool for survival, a parka or a knife perhaps, doesn't this mean you depend on the people who made that tool, and the people who made it possible for those people to make the tool? And would life be meaningful if it were lived in isolation, apart from any other person?

Self-reliance differs from independence. I'm self-reliant when I rely on myself first. Ironically perhaps, self-reliance can make an individual a more valuable member of the community. A self-reliant person can solve problems and find new ways of doing things; has a wide array of skills; is confident and optimistic; is strong and able to help others.

In my experience, *community-reliance* grows out of self-reliance. Community-reliance means contributing to community, so that the community is strong and there for you when you need it.

I reject selfish survivalism, heading to the hills with guns and a supply of food. While I do think we need to first look to ourselves for our security (self-reliance), we need to do this within the context of community. Selfish survivalism is ultimately a losing strategy.[2]

A civilization that tried to turn all its predicaments into problems has been confronted with problems that, ignored too long, have turned into predicaments.

— John Michael Greer

Problem, predicament, challenge

I used to think that climate change, overpopulation, and biospheric degradation were *problems*. In identifying them as problems, I assumed there were solutions, which kept me from seeing that my way of life had to change. I really believed that the future would look like *Star Trek*, a comforting belief. Perhaps there were solutions a few decades ago. For example, we could have avoided climate change if we'd started seriously addressing it in 1986, the year Ronald Reagan ordered the solar panels on the White House roof be taken down.[3]

At this point, though, we can't avoid climate change for the simple reason that it's already here. Global surface temperatures have already increased by more than one degree Celsius, and additional warming is guaranteed no matter how quickly we reduce our fossil fuel use. What was a problem with a solution in 1986 has become a *predicament*. We probably can't solve it, but we can choose how we respond to it and how bad we let it get.

A predicament is an existential challenge. We cannot make it go away. Death, the archetypal predicament, challenges us to respond by finding meaning in our brief lives. Likewise, I think our collective socio-ecologic predicament challenges us to find out who we really are and what it means to be children of this Earth, in harmony with ourselves, each other, and the rest of the biosphere.

Re-minding

I doubt we'll come through our predicament without a deep change of mindset, a kind of rebirth of our shared existential world-view. Maybe this change will originate within us, or maybe the change will originate externally, catalyzed by the disasters we are bound to experience as our predicament deepens. Either way, we will be re-minded of what is important.

The energy that changes mindset from within is *mindfulness*. Mindfulness means every moment awareness—being aware of reality as it is, as manifest in the mind and the body, from moment to moment. When mindful, I'm present for the reality of this moment, not rolling in thoughts of the past or the future, or wishing for something other than what is. I'm aware of the action I'm engaged in and its consequences, not acting on autopilot; and this awareness of the present moment and its consequences is what drives self-change.

However, in my experience it's not possible to simply decide to "be mindful." Developing mindfulness takes dedicated practice, as I'll discuss in Chapter 11.

Happiness

When I experience some success, my mind is excited and full of a pleasant sensation. I feel larger, like there's more of "me." I've learned that this feeling isn't happiness. Rather, it's the ego being inflated.

I think that we often mistake this sort of ego-excitation for happiness. This is a mistake: it causes us to chase after things that ultimately increase our suffering. Real happiness doesn't depend on external situations. Instead, it's a sense of peace and wellness, of satisfaction and wholeness, a sense that it's wonderful to be alive, a joy in the happiness of others. Real happiness has no anxiety or craving. It vibrates with gratitude, and translates into an eagerness to help others, to spread happiness. Unlike ego-excitation, which is directed toward the self ("I win!"), real happiness is directed toward others, and all of life ("It's a miracle to walk on this Earth!").

As I become happier, the roller-coaster ride of my ego becomes less wild. The lows become less severe: when I fail I find myself smiling with kind laughter, as with a child who is learning to walk. The highs become opportunities to serve. I ask myself "how can this success help others?"

Saving the planet, saving the world

"Saving the planet" is a fantasy for society's collective ego. It allows us to continue in our false belief that we're separate from the biosphere, that what's happening to "the planet," while sad for polar bears, somehow won't affect us.

If you feel discouraged, maybe you're trying to save the world. It's discouraging to have an impossible goal. I think there are a lot of people who subconsciously want to save the world. But saving or not saving is a false binary, and arises from the same instant gratification mindset that got us into this predicament in the first place. Saving the world is a fantasy for our egos.

The opposite of wanting to save the world is having sincere patience. With patience comes humility, openness, and a more skillful capacity for positive change.

We each have the power to make the world better, or worse. Each of us can choose to push the world toward a warmer temperature, or pull back. I used to want to save the world. I've finally accepted that I can't, and this has brought me peace. Instead, I try to live a good life so that I can *change* the world.

How dare you talk of helping the world? God alone can do that. First you must be made free from all sense of self; then the Divine Mother will give you a task to do.

— Ramakrishna

CHAPTER 3

Global Warming: The Science

These are the kinds of disciplines in the field of science
that you have to learn—to know when you know
and when you don't know, and what it is you know
and what it is you don't know. You've got to be
very careful not to confuse yourself.
— RICHARD FEYNMAN

Human influence on the climate is now crystal clear. But the general public has so far failed to understand how rapidly humans are warming the planet and how irreversible the changes will be.

The rapid progression of global warming continues to amaze me. Our CO_2 emissions, which drive modern-day global warming, are following an exponential trajectory. Many changes in the Earth system are accelerating. It's fair to say that scientists, as a group, are surprised by the rapidity.

In this chapter and the next, I hope to clarify two basic time scales of our predicament: speed of onset and duration. I also hope that this brief tour of Earth science will enrich you with a deeper understanding of your relationship with this beautiful planet.

I haven't attempted to write a mini-textbook or to be complete. (An attempt at completeness, the Intergovernmental Panel on Climate Change's Fifth Assessment Report[1] weighed in at 4,852 pages.) Neither have I attempted to describe past climate changes. I've attempted to give the context necessary for a basic understanding of the global warming that's happening at this moment, but not to overwhelm you with more than that.[2]

At the topmost level, climate science has one thing to teach in regards to the well-being of our species and the rest of the biosphere: *to curtail global warming, stop burning fossil fuels*. Of course, there's no guarantee that humans will stop burning fossil fuels in time to avoid truly catastrophic warming. Indeed, part of the scientific work is in understanding how the Earth is likely to change at different emission levels. This is an important discussion for us to have, calmly and with vigilant attention to the evidence, as we boldly continue up the exponential curve into this unprecedented age of planetary change.[3]

The weight of this knowledge

Before diving in, it's worth acknowledging that learning about global warming can be stressful. I once had a friend tell me that she didn't want to know about global warming because she was afraid of becoming too anxious or depressed to function effectively. This is a precarious and short-term stance to take, however; the evidence of global warming will continue to mount in our daily experience, and therefore the psychological stress of holding its reality at bay will also mount. I personally find it less stressful to face the reality of global warming and to begin responding appropriately.

As I described in Chapter 1, though, I had to go through a grieving process to get to this point. And nine out of ten of my colleagues in Earth science have also grieved to some extent—though you'd never know this unless you performed an anonymous survey (as I did).[4] I think the scientific community's response to global warming has been objective to a fault. We're scientists, yes, but we're also humans. If we'd let our humanity shine out more, perhaps it would help our message get through.

The year of climate departure

The first thing to know about global warming is simply that it's already here. The global mean surface temperature rose by 1.0°C between 1880 and 2012,[5] and many impacts of this warming are already clear. The second thing to know, perhaps, is how fast it's progressing.

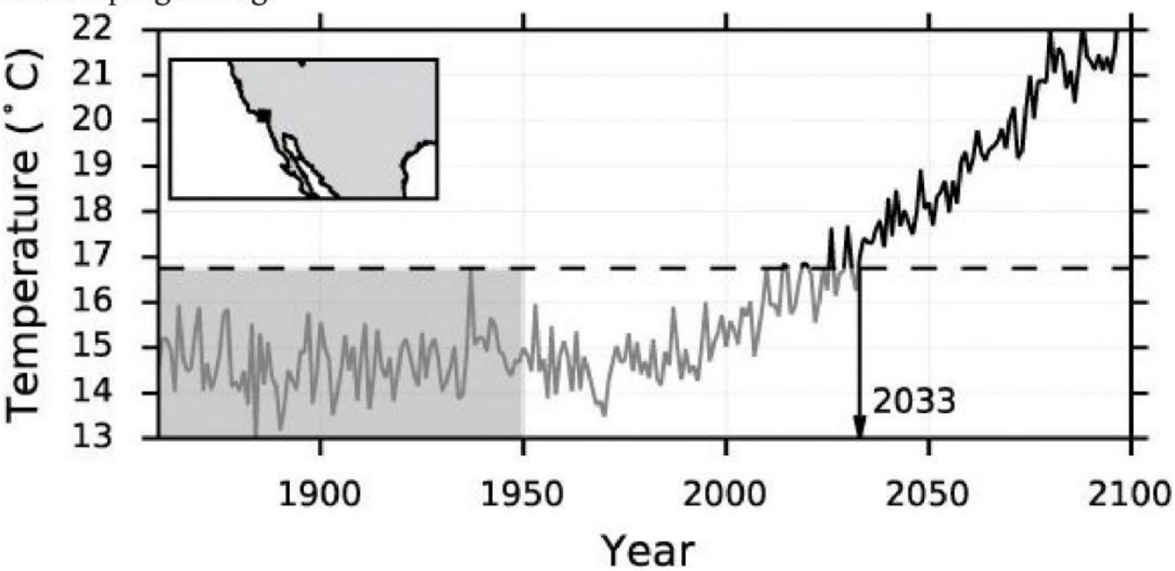


FIGURE 3.1. The predicted climate departure of the grid point containing Altadena, California (the small square on the map) under the business-as-usual scenario (RCP 8.5), for a single climate model (called HadGEM2-ES). The historical baseline variability is shown in grey shading. The arrow indicates the year of climate departure. Different models give different estimates of departure.

We can ask a simple question: at a given location, when will the annual mean temperature exceed the hottest year from a historical baseline, never to return? After this year of no return, the climate at that location will be in a new regime; the climate will have "departed." Figure 3.1 illustrates this.

Camilo Mora and his colleagues at the University of Hawaii explored this question,[6] using estimates of surface temperature from 17 separate global climate models simulating the planet from 1860 until 2100, for over five million 100 km by 100 km grid cells on the planet.[7] They analyzed model runs simulating two global emission scenarios. In one scenario, humanity makes only a modest effort to reduce emissions, which continue to grow until 2100 and beyond (business-as-usual, i.e., what we're doing now). In the other scenario, humanity makes a stronger mitigation effort such that emissions peak near the year 2040 and then decline.[8]

Each region on the planet has its own predicted year of annual climate departure for a given scenario. After departure, a region will still occasionally experience cool days or even cool months, relative to its historic climate; but there will be no cool years there until after the age of global warming. Under the business-as-usual scenario, Mora et al. estimate that global average climate departure (the average over regional departures) will occur in 2036, less than 20 years from now. Under the mitigation scenario, global departure is delayed by an estimated 15 years, to 2051.[9]

Departure will occur first in the tropics, since there is less year-to-year variation there. This is unfortunate both for people in developing nations, who have contributed the least to global warming, and to species in biodiversity hot spots like the Amazon rain forest, where plants and animals are adapted for survival in a narrow range of temperatures.

Global climate departure is no longer avoidable, and it's coming very soon.[10] It will likely be here while my children are still in their twenties. Whether this rapidity of the onset of global warming is bad or not is a separate question, and depends on one's values.

Generally speaking, a given plant, animal, or human civilization is evolutionarily adapted to a specific range of temperature, precipitation, and other climate conditions. If the climate moves out of this range, the plant, animal, or civilization must move, adapt, or die. These migrations, adaptations, and deaths are already causing disruption for both humans and nonhumans. My opinion is that this disruption clearly outweighs any benefits from warming. We'll take a brief look at impacts in Chapter 4.

Peak temperature: Why mitigation is crucial

The proximity of climate departure is disturbing, but in my opinion it's worth working toward mitigation no matter how late it gets or how warm it becomes.

This is because peak temperature is still up to us. No matter the date of climate departure, global warming likely will trace a trajectory in which the climate warms, reaches a peak temperature, and then gradually cools down over many millennia. But *how much* it warms will make a difference, largely determining the long-term (e.g., after 2100) depth of impacts such as crop loss, sea level rise, precipitation changes, ice loss, heat waves, and loss of species.[11]

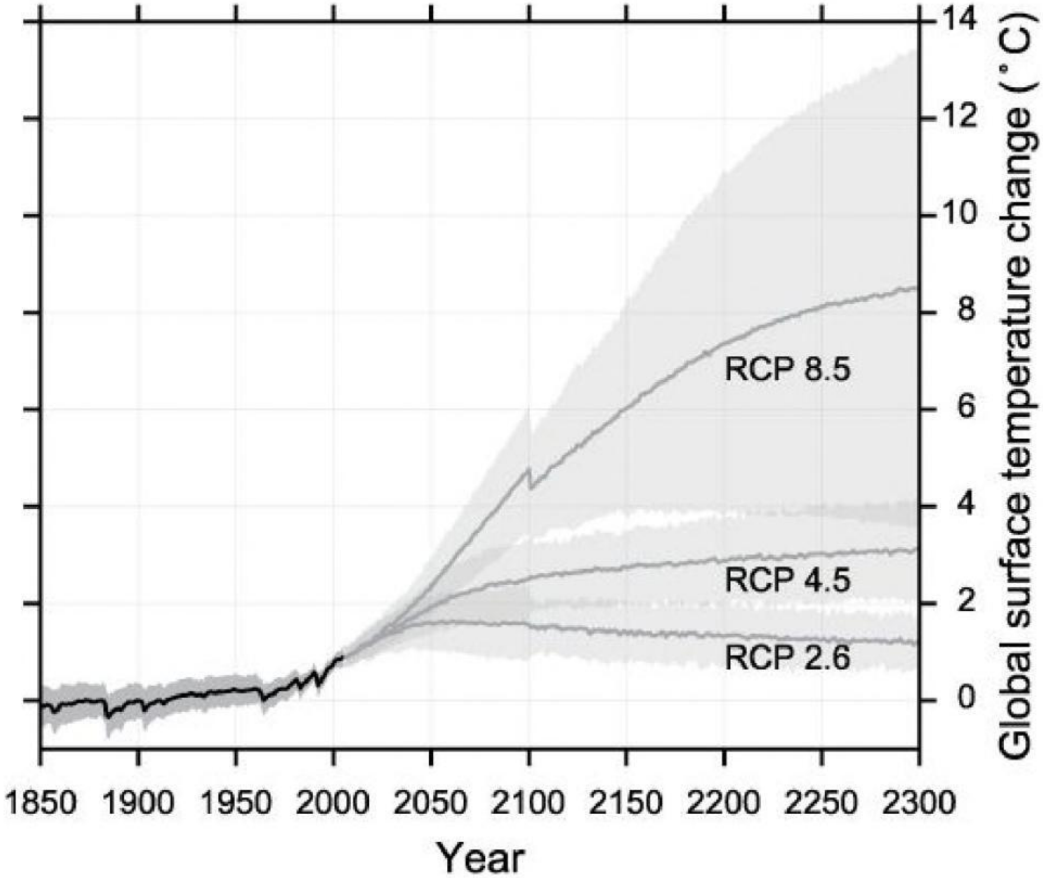


FIGURE 3.2. Temperature trajectories relative to the 1850 to 1900 mean, for three CMIP5 RCP experiments. Solid lines give the multi-model mean of the global mean surface air temperature; shading gives the 5 to 95% uncertainty range across the model ensemble (that is, 90% of model predictions lie in the shading). The black line gives the multi-model mean for the historical experiment (with results from 1850 to 2005). The discontinuity at 2100 has no physical meaning; it's due to the fact that not all models ran to 2300.

Temperature trajectories (with large uncertainties) for various *representative concentration pathways* (RCPs) from now to 2300 are shown in Figure 3.2.[12] RCPs define future greenhouse gas concentrations under hypothetical emission scenarios. Scientists can then run global climate models with these predefined concentrations, facilitating comparison and collaboration. RCP 8.5 is the business-as-usual scenario, while the other two RCPs in Figure 3.2 represent varying levels of mitigation. The lower the RCP number, the more mitigation it presumes.[13]

In RCP 2.6, greenhouse gas emissions peak before 2020 and then decline rapidly, and warming stays below 2°C. However, this pathway is no longer achievable due to our collective procrastination.[14]

RCP 4.5 is a less aggressive pathway that's still open to us. In it, models predict global mean surface warming of 2.4 ± 0.5°C by 2100 over preindustrial levels (and 3.1 ± 0.6°C by 2300).[15]

Our current trajectory is best approximated by RCP 8.5. If we choose this pathway, models predict mean surface warming of 4.3 ± 0.7°C by 2100 (and 8.4 ± 2.9°C by 2300). Note also that in RCP 8.5, warming accelerates rapidly in the 21st century: global temperature rises more during the second half of the century than during the first half.

To put these numbers in one context, the last glacial maximum, in which ice sheets covered not only Greenland but most of North America and much of northern Europe and Asia about 20,000 years ago, was 4.0 ± 0.8°C cooler than in modern preindustrial times.[16] To put them in another context, the last time the planet was about 2°C warmer was 125,000 years ago (the Eemian Maximum, long before humans evolved),[17] and it has been tens of millions of years since the planet was 4°C to 8°C warmer.[18]

The distinction between social and scientific uncertainty is well-illustrated by Figure 3.2. The large spread covered by all the different RCPs indicates social uncertainty; physical science cannot predict what humans will do. On the other hand, the width of the shaded swath for each RCP gives a particular estimate of the scientific uncertainty: the spread between different models.[19] This estimate, however, doesn't capture uncertainty due to physical processes that aren't modeled in the first place—the "unknown unknowns." These could include various carbon cycle feedbacks, discussed below, which might augment warming.

Under all of the RCP scenarios, significant warming persists for many centuries, far beyond 2300, but the peak temperatures are very different. It's unclear exactly what those peak temperatures will be or when they'll occur because far-future model predictions become increasingly uncertain. But I think for our purposes here, and for the purposes of policymakers, Figure 3.2 provides a clear enough picture: to prevent warming far beyond levels humanity has ever experienced, we need to mitigate immediately and rapidly.

The physical basis for warming

Let's now examine the causes of warming and how warming interacts with the Earth system. Along the way we'll continue developing our understanding of what we know and what we don't know.

The Earth system

The Earth system is tremendously complex. Its main parts, viewed in the big picture and from the perspective of climate, are the atmosphere, the ocean, the land, the ice, and the biosphere. They interact with one another via physical, chemical, and biological processes, over space scales ranging from microscopic to planetary, and time scales ranging from nearly instantaneous to billions of years.

Before I switched into atmospheric science, I studied neutron stars and black holes. Everything knowable about a stable isolated black hole is (we think) encoded in just three numbers: mass, electric charge, and spin. But the state of the Earth depends on every cloud, tree, drop of moisture, mountain peak, ocean eddy, patch of snow, bacterium, and internal combustion engine. Instead of just three numbers, the state of the Earth system is described by an essentially infinite number of numbers. And to understand the system, we need to understand how they interact.

Despite this internal complexity, the Earth's climate system interacts energetically with the universe in only three significant ways: by absorbing sunlight, by reflecting sunlight, and by emitting infrared light. Infrared light is invisible to humans, but we feel it as radiant heat when we sit near a fire. The key fact about infrared emission is that *hotter objects emit more infrared energy than cooler objects*. This fact allows the Earth system to balance the sunlight energy coming in with infrared energy going out to cold space. For example, if the sun became dimmer, the Earth would cool. A cooler Earth would emit less infrared light, eventually arriving at a new balance at a cooler temperature.

The greenhouse effect

Greenhouse gases like CO_2 act like a blanket warming the planet. We need this blanket. Without it the Earth's average surface temperature would be −18°C (0°F) and there could be no life as we know it.[20] So the greenhouse effect per se is not a bad thing. The problem is that by burning fossil fuels into the atmosphere we're causing the blanket to become warmer. By 2014 we'd already increased the atmospheric CO_2 fraction by 43% over preindustrial levels, and this increase is accelerating exponentially.[21]

Have you ever thought about how a blanket works? Imagine being naked without a blanket on a cool, windless night. Like any warm object, your body emits infrared radiation which carries away energy, cooling you off. Now imagine that you have a blanket. The underside of the blanket absorbs your emitted infrared energy, heats up, and then re-emits infrared radiation back to you. Some heat, however, is conducted through the blanket, causing the relatively cool top side to emit more infrared energy out into the air. *But the top side of the blanket is cooler than your body*, so it radiates less energy. This system reaches equilibrium when the top of the blanket loses infrared energy at the same rate that heat is conducted from its underside. The thicker the blanket, the less heat it conducts, and the hotter it gets underneath before reaching equilibrium.[22]

In place of body heat, the Earth's main source of energy is incoming sunlight. About 70% is absorbed, and the rest is reflected back into space by clouds, ice, snow, and other bright surfaces. Like your body on a cold night, the warm Earth loses heat by emitting infrared radiation into space. Greenhouse gases in the atmosphere act like the blanket, with a warm underside facing Earth (the lower atmosphere) and a colder top side facing space (the upper atmosphere). Greenhouse gases in the atmosphere absorb some of the infrared energy emitted by the Earth's surface.[23] The warmer lower atmosphere then radiates some of this infrared energy back down to the Earth's surface. It radiates in the upward direction, as well; this radiation is trapped by the higher atmospheric layers, in turn (think of the atmosphere as many thin layers). The upward-directed infrared radiation from the cold upper layer streams into space, but since that highest layer is colder, it emits less energy than the planet's surface.

What if we suddenly increase infrared-absorbing greenhouse gases? This makes the atmosphere act like a better blanket, and a smaller fraction of the upwelling surface infrared escapes into space. Because the absorbed solar energy hasn't decreased,[24] there is now an energy imbalance, and Earth warms. Warmer objects emit more infrared radiation, and eventually the escaping infrared energy will once again balance the incoming solar energy, despite the warmer blanket. Eventually the Earth will regain energy balance *but at a warmer temperature.*

Greenhouse gases

The main two human-emitted greenhouse gases are carbon dioxide (CO_2) and methane (CH_4). Human emissions of halocarbons and nitrous oxide (N_2O) also contribute, but to a lesser degree. Each gas is made from atoms electromagnetically connected in a particular geometric configuration. These geometries have specific resonant frequencies that determine how the gas interacts with infrared radiation.

The Earth system exchanges energy primarily by absorbing shortwave solar radiation and emitting longwave infrared radiation. We call factors that change one or the other of these two quantities *radiative forcings*. The Earth is in energy balance when the net radiative forcing is zero. Increasing the atmospheric concentration of a greenhouse gas decreases the outgoing longwave radiation, and this change (in units of power per area, W/m^2) is an example of a radiative forcing.

Water vapor (H_2O) is the largest contributor to the greenhouse effect, but we humans have no direct control over it. It remains in dynamic equilibrium, evaporating into the atmosphere and condensing out as rain. A hotter atmosphere, though, holds more water than a cooler atmosphere. As we warm the atmosphere with the other greenhouse gases, water vapor acts as an amplifier. Ozone (O_3) is another greenhouse gas which humans influence indirectly (via atmospheric chemistry).

Today human emissions do directly influence the atmospheric amounts of the other greenhouse gases. The global warming impact from emitting a tonne of some greenhouse gas depends on how efficiently that gas absorbs infrared light, as well as how long it stays in the atmosphere—its *residence time*.[25]

To allow for apples-to-apples comparisons of different greenhouse gases, we can integrate atmospheric absorption over the residence time of a gas species to calculate its *global warming potential* (GWP). GWPs are estimated relative to CO_2, and given in units of "CO_2-equivalents" (CO_2e). For example, after 100 years, a tonne of methane causes a total of about 34 times more warming than a tonne of CO_2; we say it has a GWP of 34 on a 100-year horizon, or GWP_{100} of 34. However, methane is reactive and has a residence time of only about 12 years, so on a 20-year horizon, its total warming potential relative to CO_2 is even higher: the GWP_{20} of methane is about 105.[26]

The choice of time horizon is subjective, but important—especially for methane. Some methane inevitably escapes during natural gas extraction, processing, and distribution. Most analysts choose GWP_{100} over GWP_{20}, downplaying the contribution of this leakage to global warming and making natural gas appear more attractive as a "bridge fuel."

Nitrous oxide, N_2O

Anthropogenic nitrous oxide in the atmosphere is produced mainly by the agricultural use of nitrogen fertilizers. It's also produced by internal combustion engines and the breakdown of livestock manure and urine. It resides in the atmosphere for 120 years, and has GWP_{20} of 260 (with a GWP_{100} that's essentially the same due to a residence time of over 100 years).[27] Human emissions of nitrous oxide accounted for about 5% of the current greenhouse radiative forcing (measured in 2011; see Figure 3.7, page 50, which we will discuss below).[28]

Halocarbons

Halocarbons are chemicals containing at least one carbon atom and halogen atom (usually chlorine or fluorine), useful as refrigerants, solvents, pesticides, and electrical insulators. They were regulated in the 1990s because they deplete Earth's protective stratospheric ozone layer (and also create dramatic "ozone holes" over the poles). Out of this family of compounds, the CFC-12 (CCl_3F, brand name Freon-12, formerly common in refrigerators, Silly String, air horns, gas dusters, and other applications requiring an easily compressible gas) still has the most impact on the climate, with a residence time of about 100 years and a GWP_{20} of about 10,800.[29] While emissions of CFC-12 have stopped, its global warming impact will continue for many decades. Meanwhile, emissions of other halocarbon compounds are increasing. Human emissions of halocarbons account for another 5% of the greenhouse radiative forcing (see Figure 3.7, page 50).[30]

Methane, CH_4

Methane is a powerful greenhouse gas (GWP_{20} of about 105,[31] with an uncertainty of about 30%) with a short residence time of about 12 years. These two facts mean that mitigating methane emissions would have an immediate and significant impact on our warming trajectory.

Human emissions of methane account for about 30% of the current (instantaneous) greenhouse radiative forcing (see Figure 3.7, page 50).[32] In terms of GWP (integrated

over time), in 2010 it accounted for 16%[33] or 37%[34] of anthropogenic greenhouse gas emissions on a GWP_{100} basis or a GWP_{20} basis, respectively.
Over the last 200 years, atmospheric methane concentration has almost tripled, from 650 ppb (parts per billion) to 1,800 ppb.[35] From 2000 to 2009, 50–65% of global methane emissions came from human activities; the remaining 35–50% came from natural sources, mainly from anaerobically decomposing matter in wetlands. This source of methane may increase in the near future due to melting permafrost in northern regions, but the size of the increase is still highly uncertain.[36]

TABLE 3.1. Sources of anthropogenic global methane emissions, in megatonnes (Mt) of CH_4 per year (2000 to 2009 annual means from IPCC AR5 WG1 Chapter 6, p. 507). Ranges of estimates assimilated by the IPCC are given in brackets. "% anthro. CH_4" is the percentage relative to total anthropogenic emissions.

Source	MT CH_4 per yr	% anthro. CH_4
Fossil fuel production	96 [85–105]	29
Livestock	89 [87–94]	27
Landfills and waste	75 [67–90]	23
Rice cultivation	36 [33–40]	11
Biomass burning	35 [32–39]	11

Table 3.1 gives methane emission estimates from human activities (annual means from 2000 to 2009). The largest anthropogenic sources of methane are fossil fuel production[37] (leakage) and livestock (75% of which is from cattle, who burp methane generated by fermentation in their digestive tracts). Each of these two sources accounts for between 4% and 10% of total anthropogenic greenhouse gas emissions, depending on choice of GWP time horizon.

Carbon dioxide, CO_2

CO_2 is the principal driver of global warming. Human emissions of CO_2 accounted for about half of the 2011 greenhouse gas radiative forcing (see Figure 3.7, page 50). When considered on the extended GWP_{100} basis instead of the instantaneous radiative forcing basis, however, CO_2 accounts for three-quarters of warming, because it remains in the atmosphere for a very long time.
Humans cause CO_2 emission by burning fossil fuels and removing forests. Approximately 90% of anthropogenic CO_2 currently[38] comes from burning fossil fuels, while approximately 10% comes from deforestation.[39] The amount of CO_2 released from removing forests is still uncertain, though, and current net CO_2 emissions from deforestation could range from 1% to 20% (with fossil fuel burning taking up the remainder). In the past, deforestation played a larger role. One-third of net *cumulative* emissions from 1750 to today are due to land-use change (mainly deforestation), which releases the carbon stored in wood and soils into the atmosphere via decomposition or fire.[40]

The residence of CO_2 in the atmosphere is complex, mediated by multiple processes transferring carbon between the reservoirs—the atmosphere, the ocean, the biosphere, and the rocks—on different time scales. (We'll discuss this "carbon cycle" in more detail below.) Because of this, the residence time of CO_2 isn't captured well by a single number. If humans stopped emitting CO_2 today, in a few hundred years, one-quarter or so of what we'd emitted would remain in the atmosphere, and in a few tens of thousands of years, one-tenth or so would remain.

Atmospheric CO_2 fraction has been precisely measured, to a small fraction of a part per million by volume (ppmv) high on Mauna Loa in Hawaii since 1958.[41] Today, the CO_2 fraction is measured at many different locations; as you'd expect, it tends to be a bit higher over areas of intense human activity. The annual highpoints in the Mauna Loa record are about two ppmv above the global average, Mauna Loa being in the northern hemisphere where 90% of humanity lives.

Atmospheric CO_2 fraction from Mauna Loa and from the global average are shown in Figure 3.3.[42] Notice the annual variation. The CO_2 fraction increases during the northern hemisphere winter months (from October to May) and decreases during the summer months (from May to October). Most of the world's plants are also in the northern hemisphere, and during the northern summer months, plants are actively growing and incorporating CO_2 into their bodies. In the winter months, there is less growth but decomposition continues, releasing carbon back into the atmosphere via the tiny oxidative "fires" of biological respiration. Many have pointed out that this cyclical variation is like the biosphere breathing.

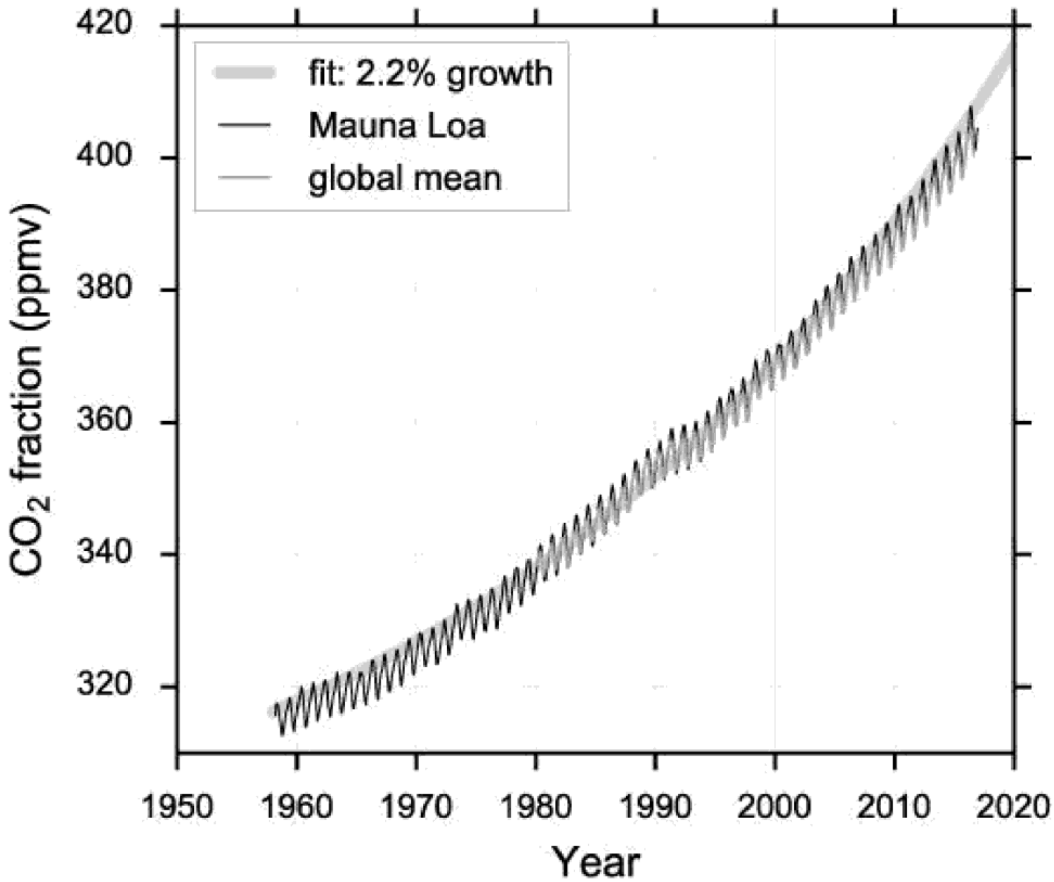


FIGURE 3.3. Atmospheric CO_2 fraction on Mauna Loa in Hawaii (black) and the global average CO_2 fraction (gray, traced over, and closely matching, the black curve), in the monthly average. The thick gray curve is the best exponential fit to the Mauna Loa data, with growth rate and start year allowed to vary. Best-fit growth rate is 2.2% per year, with best-fit starting year 1790.

CO_2 fraction in our atmosphere has risen exponentially; the best exponential fit (thick gray curve in Figure 3.3) has growth starting in 1790, increasing annually at a rate of 2.2%.[43] In 1790, of course, James Watt had just succeeded in commercializing the steam engine. It's remarkable that an atmospheric CO_2 fraction record beginning in 1958 points back so precisely to humanity's fossil fuel revolution.

What about further back in time? Figure 3.4 shows the CO_2 fraction going back to 800,000 years ago from three ice cores in Antarctica, including a zoomed-in view of the last 12,000 years. Ancient air bubbles trapped in the ice are analyzed for their CO_2 fraction, and time is inferred from the depth in the ice core.[44]

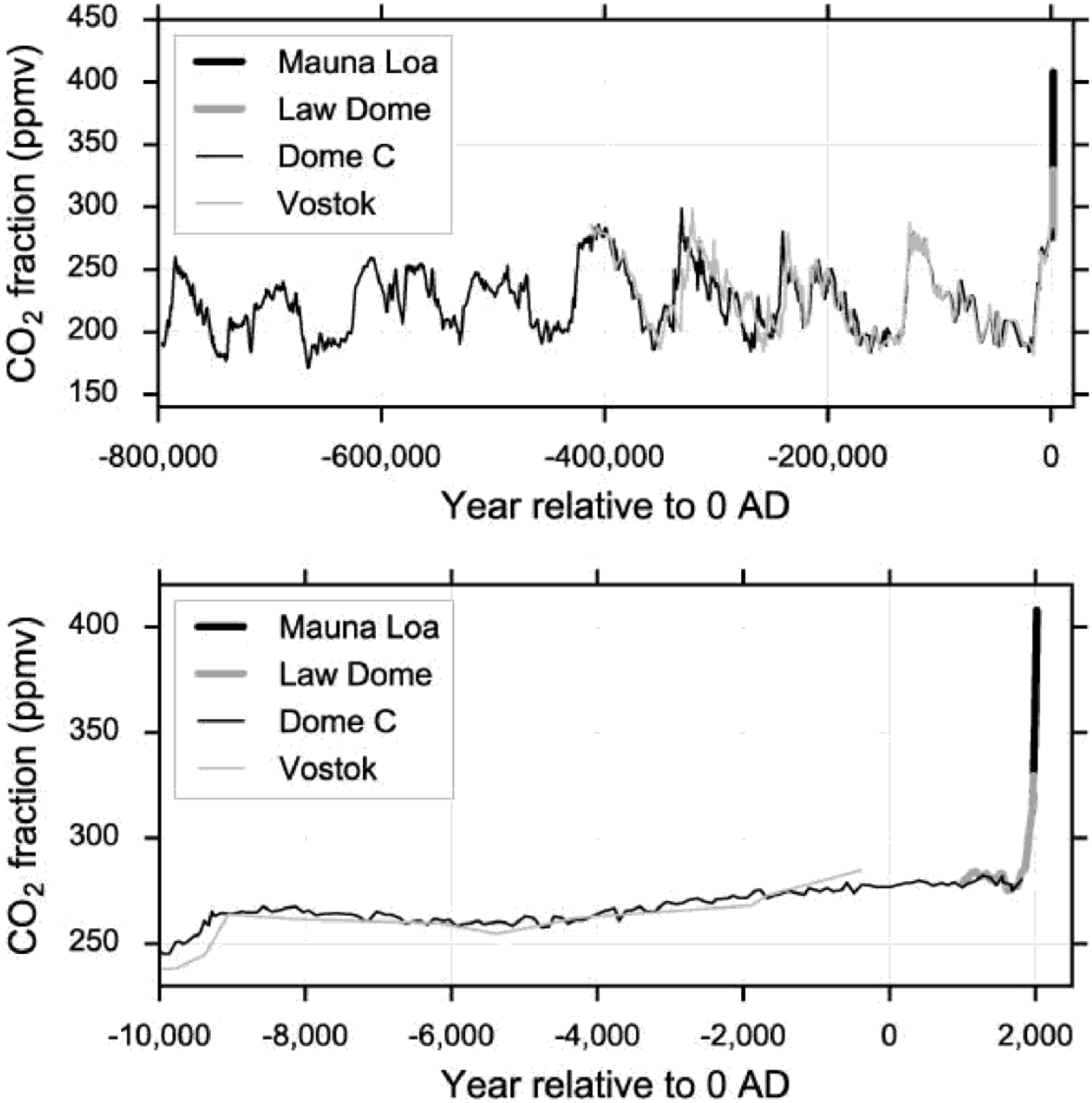


FIGURE 3.4. Ice core records combined with the Mauna Loa record; the bottom plot is a zoom of the right-hand edge of the top plot. The Mauna Loa record is shown in thick black, and only appears at the far right edge of the plots. The three ice core records are shown in black, gray, and thick gray (representing the Dome C core, the Vostok core, and the Law Dome core, respectively). Discrepancies between the black and gray curves give a sense of the uncertainty.

A few interesting things leap out of this record of nearly a million years of CO_2 fraction. First, CO_2 fraction is obviously much higher today than it has been at any time in the last 800,000 years. Second, the CO_2 fraction was remarkably constant over the last 11,000 years, allowing for the stable climate which supported the rise of agriculture and complex civilizations. Third, during this epoch, there were a dozen or so relatively rapid and significant rises in CO_2 fraction, although these were all far slower than the rise happening today, and stopped below 300 ppmv (whereas ours will clearly go far beyond 400 ppmv). For example, the rise beginning about 140,000 years ago took 10,000 years[45] from beginning to end, and maxed out at about 290 ppmv. These rises correspond to transitions from glacial periods to interglacial periods. Fourth, the CO_2 increases happened much more quickly than the CO_2 decreases, giving a sawtooth pattern to the record. Although reuptake of CO_2 is complicated and controlled by multiple processes, this suggests that our current warming might last tens of thousands of years. We'll see below that this is likely about right.

What humans do: Sources of global warming

What human activities cause the most greenhouse gas emissions, worldwide? Estimates for 2010 are shown in Table 3.2.[46] It's striking how human emissions come from a multitude of sources; no single line item dominates the list. This reflects the deep penetration of fossil fuels into today's predominantly industrial way of life.

The estimate for the agriculture, forestry, and other land-use (AFOLU) sector has relatively high uncertainty, as it is difficult to separate natural from human-made emissions. Livestock production (which includes clearing of land, manure decomposition, feed production, and enteric fermentation) accounts for 10–20% of humanity's global emissions.[47] The transportation sector is growing faster than any other, more than doubling between 1970 and 2010.[48]

Increasing global temperature

Figure 3.5 shows the average surface temperature of our planet since 1850, relative to the mean value of 1850–1900.[49] These data originate from land weather stations and ocean surface temperature estimates from ships and buoys, which are statistically combined to produce a global average estimate.[50] Care is taken to avoid biases from a variety of causes, such as imperfect sampling (you can't put a thermometer on every meter of the Earth's surface). However, despite this care they have been shown to be biased about 10% too low, if we interpret them as estimates of surface *air* temperature, as they use surface *water* temperature over the oceans.[51] Therefore, although this data set estimates that 2015 was 1.1°C to 1.2°C warmer than the historical mean, the truth was likely between 1.2°C and 1.3°C. Similarly, 2016 was likely 1.4°C to 1.5°C warmer than the historical mean.

TABLE 3.2. Mean anthropogenic global emissions by source, in 2010, as percentage of total. In 2010, we emitted a total of 49 gigatonnes (Gt) of CO_2e.

Source	Percentage of Total
Industry	**33%**
Electricity and heat	11%
Metals	5%
Chemicals	3%
Industrial waste	3%

Cement production	3%
Other industries	8%
AFOLU	**25%**
Land-use change and forestry	10%
Enteric fermentation	5%
Drained peat and peat fires	3%
Buildings	**18%**
Electricity and heat	12%
Transport	**14%**
Road	10%
Aviation	2%
Shipping	1%
Other	**10%**
Fuel production	6%
Petroleum refining	3%

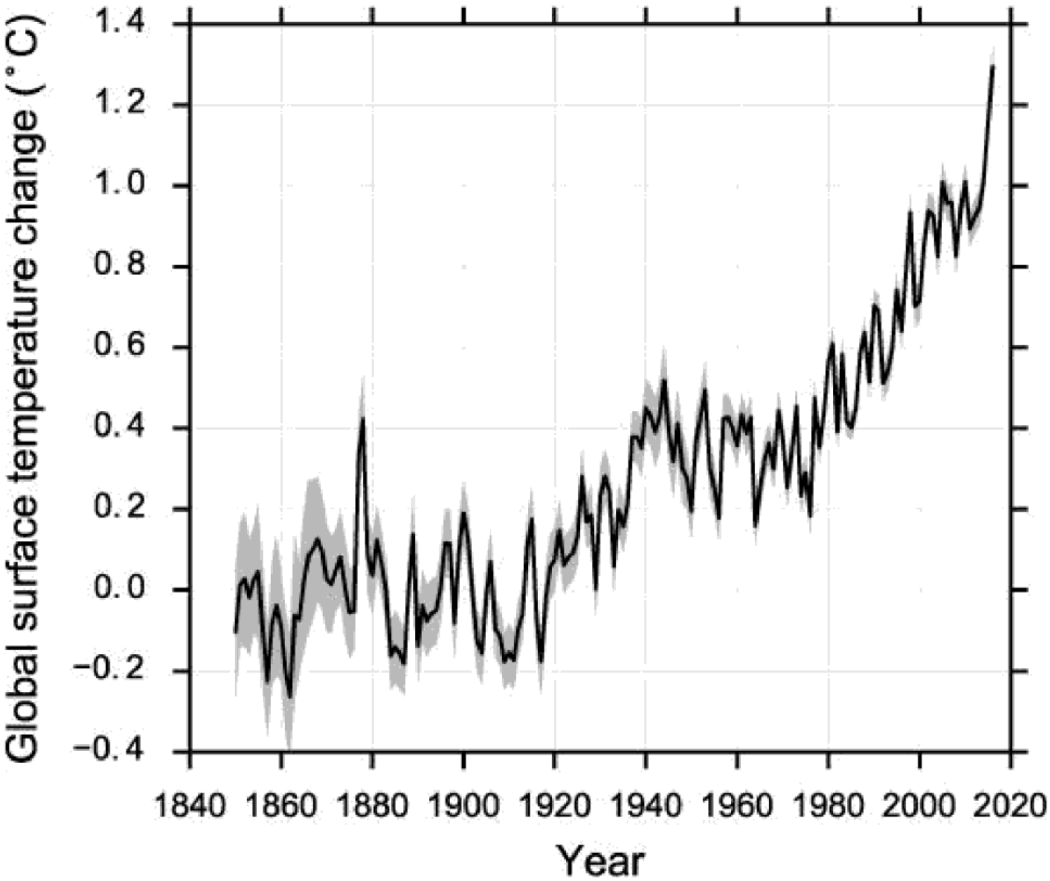


FIGURE 3.5. Global average surface temperature, relative to the 1850–1900 mean, through 2016. The shading gives a 90% confidence interval.

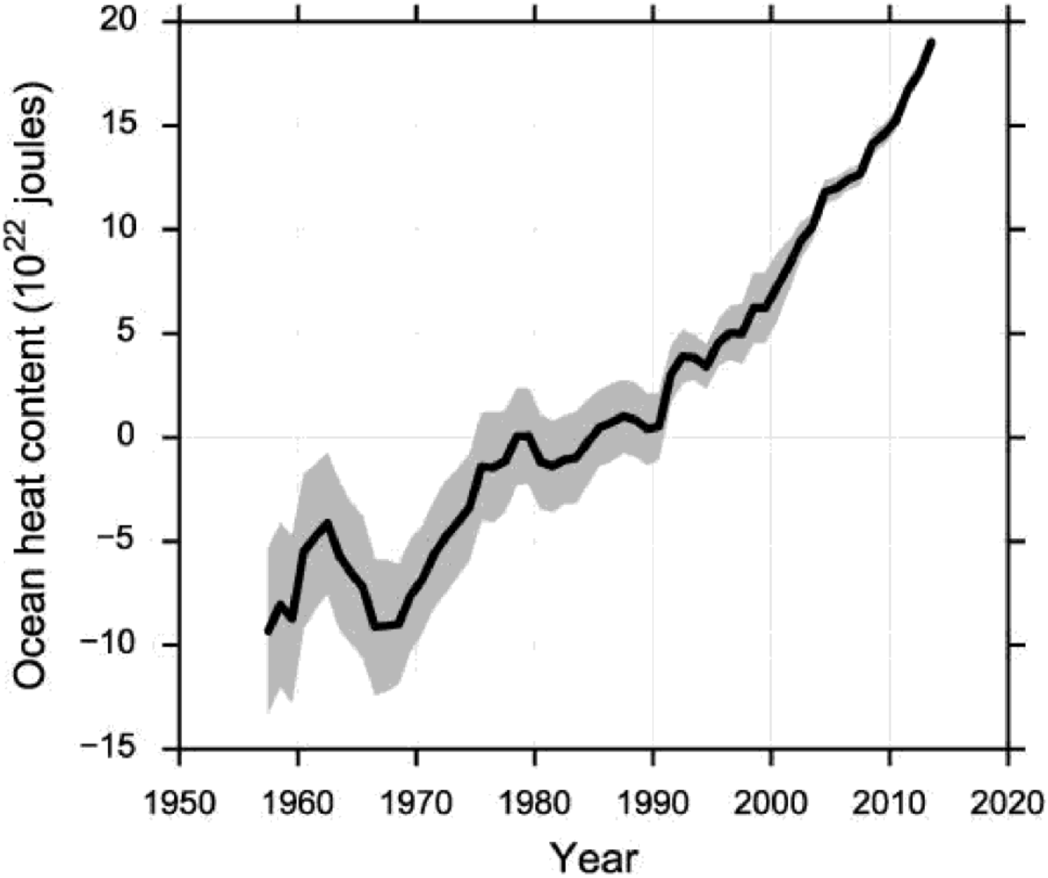


FIGURE 3.6. Global average ocean heat content, relative to the 1955–2006 mean. The shading gives a 90% confidence interval.

According to this data set, the 17 hottest years on record occurred between 1998 and 2016—a period of just 19 years.[52] This is remarkable given how noisy the data is. And there's no end in sight to this warming trend.[53] Today, people who simply point out this obvious trend in the data are often labeled "alarmist." In my opinion, it would be foolish *not* to be alarmed. So let me be perfectly clear: I'm a scientist, and I'm sounding an alarm.

Ocean heat content provides an even better measure of global warming, albeit less immediate to the human experience. The oceans absorb 93% of the heat pouring into the planet due to the energy imbalance from human greenhouse gas emissions, and ocean heat content has less variability than surface air temperature.[54] The global increase in ocean heat content since 1955, in the ocean layer from the surface down to a depth of 2,000 meters, is shown in Figure 3.6.[55]

Today's global warming is occurring more rapidly than any known warming in Earth's geologic history by more than a factor of ten.[56] Unsurprisingly, our planet is changing radically as a result. The rate of Greenland ice sheet loss has increased from 34 gigatonnes (Gt) per year from 1992–2001 to 215 Gt per year from 2002–2011, a staggering six-fold increase in just a decade;[57] the ice sheet is lowering by 1.5 m per year around its edges.[58] Sea level has risen by about 20 cm and is rising at about ⅓ of a centimeter per year,[59] and accelerating.[60] The Arctic sea ice is roughly half gone (as of

2014, measured by summer minimum ice extent) and vanishing rapidly: summer ice extent is decreasing at a rate of between 9% and 14% per decade.[61] And, of course, hot days and heat waves are increasing in frequency and severity.[62] All of these changes are further evidence of warming, independent "thermometers." The Earth's warming is unequivocal, and the impacts are accelerating.[63]

But the climate system, of course, interacts complexly with the rest of the Earth system and is highly variable. Even as the global surface temperature increases, regional and temporal variations can create local or temporary colder weather. Indeed, changes in air and ocean circulation patterns caused by global warming could conceivably lead to regional cold anomalies. It's also quite possible for heat to be transferred from one part of the climate system to another, for example from the surface to ocean sublayers. It's important to remember that our ability to monitor the climate system is limited, and that particular variables (such as surface air temperature) impose their own idiosyncrasies and limitations on our view of the system.

The drivers of global warming

Radiative forcing estimates allow us to rank different drivers of global warming such as atmospheric CO_2, or changes in the sun's radiance. Figure 3.7 summarizes the state of our knowledge.[64]

It's worth carefully unpacking this figure, which gives radiative forcings in 2011 relative to 1750. First, note that 98% of the total change in forcing is human-caused. Most of this is due to human-emitted gases. The forcing from solar changes since 1750 are miniscule compared to human-caused changes; and over the last few decades, the sun has, in fact, been getting cooler.[65] In other words, relative to a few decades ago (as opposed to 1750), *more than* 100% of the forcing is attributable to humans.

Albedo changes due to land use (albedo means reflectivity) are from human-caused changes to the land surface, such as cutting down dark forests and replacing them with brighter crops and cities, which reflect more sunlight. These changes have a net cooling effect, and so are a negative radiative forcing. However, land-use change also causes CO_2 emissions, a positive forcing.

For each emitted compound, the figure includes indirect contributions from processes caused by the emission. For example, consider methane, CH_4. In addition to its direct greenhouse gas forcing, methane induces the creation of ozone (O_3) and stratospheric (high-altitude) water (H_2O^{str}), then eventually oxidizes to become CO_2. (As in the figure, I've listed these effects from strongest to weakest. Note that the shading in the figure's bars correspond to the "resulting drivers" as listed.) Ozone, water, and CO_2 are also greenhouse gases. If we tallied these indirect effects somewhere else, we would underestimate the climate impact of human methane emissions. Halocarbons, on the other hand, destroy ozone, creating an ozone hole and producing a negative (cooling) forcing. Tallying this elsewhere would lead us to overestimate the effect of halocarbons.[66]

Note that human emissions of CO and NO_x don't contribute *directly* to the greenhouse gas forcing—they aren't greenhouse gases—but they do contribute *indirectly* via atmospheric chemistry (the creation and destruction of gases like CH_4, O_3, and CO_2).

Next, note that some aerosol pollution—especially sulfates and organic carbon from burning biomass—counteracts warming. These aerosol particles in the air reflect sunlight like tiny mirrors. I've referred to this group of aerosols as "bright aerosols" in the figure. They also act as cloud condensation nuclei, brightening clouds by inducing smaller but more numerous water droplets and increasing the cloud cover. These effects are "cloud changes due to aerosols."

You may have noticed the prominent plateau in warming between 1940 and 1978 in Figure 3.5; this is likely due to an increase in bright aerosol pollution.[67] Ironically, if we somehow suddenly eliminated these pollutants, the global warming forcing could conceivably jump up by almost 40%, although the uncertainty here is still quite large.

Black carbon, on the other hand, contributes significantly to warming. Black carbon is an aerosol produced in the agricultural burning of forests and savannas, residential biomass burning, and diesel engines. Instead of reflecting sunlight, black carbon absorbs it, giving a positive forcing of similar magnitude to methane's direct greenhouse gas effect.[68]

Finally, the figure gives the trend in total anthropogenic radiative forcing, from 1950 to 2011. We humans have nearly doubled our global warming impact since 1980. Radiative forcing is accelerating rapidly, driven mainly by exponentially increasing CO_2 emissions.

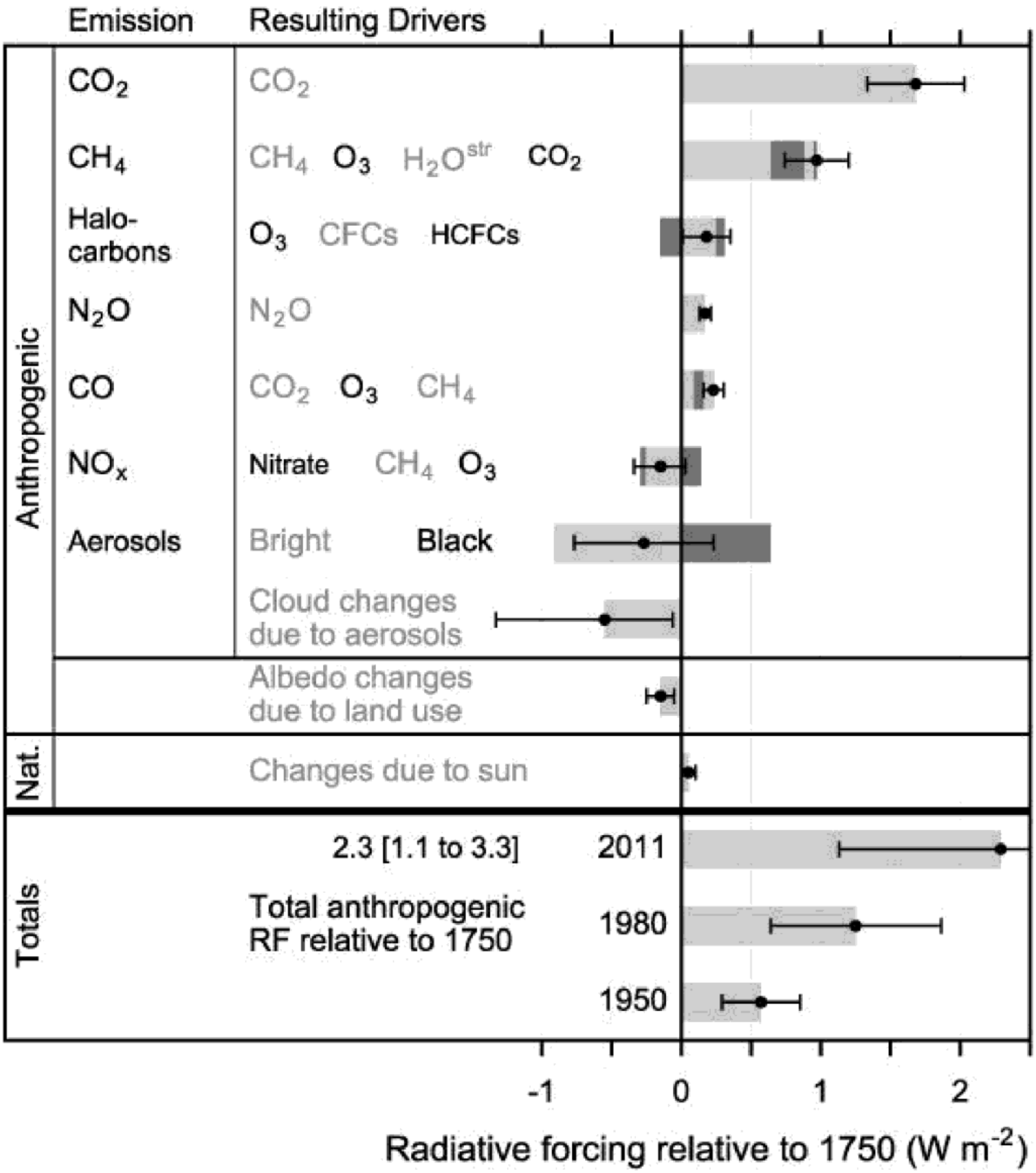


FIGURE 3.7. Radiative forcing estimates for the main drivers of global warming, in 2011 relative to 1750. The black dots indicate best estimates and the horizontal lines emanating from them indicate 90% confidence uncertainties.

Radiative forcings are half of the story. We're now ready to discuss the other half: how the Earth system changes as a result of these forcings.

Earth system feedbacks

Increasing greenhouse gas concentrations in the atmosphere force the Earth to a warmer state. Meanwhile, the Earth system changes in response to this forcing. The total amount of warming for a given greenhouse gas concentration—the climate sensitivity—depends on how the Earth responds to the forcing.

Processes that further enhance warming are called *positive feedbacks* (positive as in they go in the same direction as warming, not as in good), while processes that slow warming are called *negative feedbacks*. Together, forcings and feedbacks determine the temperature.

I've already mentioned a fundamental positive feedback: a warmer atmosphere holds more water vapor, which is a strong greenhouse gas. I've also mentioned a fundamental negative feedback: hotter objects lose more heat through infrared emission. Here are two other important feedbacks:

- **Surface albedo:** I've already mentioned albedo in the context of land-use change: when forests are destroyed and replaced with agriculture or human development, more sunlight is reflected to space (albedo increases). On the other hand, ice and snow reflect more sunlight than the ocean or soil exposed after it melts. This is a positive feedback: as ice and snow melt, the surface absorbs more sunlight, warming further. Albedo feedback due to sea ice loss is an important driver for changes occurring in the Arctic, which is warming more rapidly than the rest of the planet—and more rapidly than scientists expected.[69] Snow and ice albedo is also lowered by algae growth and buildup of anthropogenic soot.
- **Clouds:** Small changes in the global cloud cover can have large repercussions on climate. Clouds can block incoming sunlight (playing a huge role in global albedo) as well as outgoing infrared light; different kinds of clouds have different effects. Low-altitude clouds like cumulus (puffballs) and stratocumulus (overcast clouds) are warm and thick. They reflect sunlight, but because they're nearly as warm as the surface, they don't have a strong effect on the net upwelling infrared radiation; their net effect is cooling. Cold, wispy high-altitude clouds let sunlight through, but they absorb upwelling infrared light. Since these high cloud tops are cold, they don't emit much infrared. So their net effect is warming. The overall cloud feedback is likely positive: cloud changes are amplifying global warming.[70]

Surface albedo and clouds both contribute to Earth's global planetary albedo, which has a value of 0.29; Earth reflects a bit less than a third of the total incoming sunlight back into space. Global planetary albedo represents an average of all the ice, clouds, water, forests, cities, and deserts. Globally, clouds seem to act as a stabilizing buffer to the planetary albedo system in ways that we don't yet fully understand.[71]

There are additional climate feedbacks associated with the carbon cycle.

The Earth's carbon cycle

Carbon gets cycled through the atmosphere, the ocean, geological formations, and the bodies of all living things. Over the last four billion years of Earth's history, the processes of the carbon cycle have acted like a thermostat, tending to maintain a climate with liquid oceans, even when the sun was fainter in its youth. This stability has allowed Earth's biodiversity to flourish.

People ask me if they should be especially worried about methane. I tell them there's plenty to worry about from human-released CO_2.

— David Archer, climate scientist

On shorter time scales, however, the carbon cycle amplifies abrupt climate changes; these climate changes played an important role in the biosphere's previous mass extinctions.[72] These past examples of carbon cycle amplification inform our current global warming event.

There are several major reservoirs of carbon on Earth that vary widely in size and interact with each other and with the climate system on vastly different time scales; see Table 3.3.[73] Before the industrial era, carbon flows between these reservoirs were roughly in balance—no net flows. Now, because of human emissions, there are imbalances and net flows. The CO_2 we emit accumulates in the atmosphere, but also spills into other reservoirs on various time scales. Currently about 57% of the CO_2 we emit does not end up in the atmosphere;[74] instead, it's absorbed by the ocean, biomass, and soils, all of which are acting as "carbon sinks." In general, these carbon sinks are poorly understood; but it seems likely that over the next few decades or centuries they'll decrease in effectiveness, as the ocean becomes increasingly saturated and the land reservoirs respond to a warmer world.[75]

TABLE 3.3. Carbon reservoirs.

Reservoir	**Size (GtC)**	**Note**
Atmosphere (1750)	589	
Atmosphere (2011)	830	increasing at 4 GtC/yr in 2011
Ocean waters	38,000	
Ocean sediments	2000	calcium carbonate
Ocean methane	1500–7000	frozen in deep sediments
Biomass	450–650	mostly trees
Soils	1500–2400	
Fossil fuels	~13,000	resources plus reserves
Coal reserves	450–540	
Gas reserves	380—1100	
Oil reserves	170—260	
Permafrost	2000	frozen but thawing peat
Limestones	>60,000,000	
Kerogens	15,000,000	fossil fuel precursors

Here's a brief picture of the carbon cycle in terms of its reservoirs:

- **The atmosphere:** While small in size, this key reservoir interconnects many parts of the carbon system, a Grand Central Station of the carbon cycle. Carbon flows in from the ocean, the respiring biosphere, and from burning fossil fuels and forests; and carbon flows out into the ocean and into the growing biosphere (mainly trees). Because of additional emissions from humans, in the 2000s carbon was accumulating in the atmosphere at an average rate of 4.0 ± 0.2 GtC (gigatonnes of carbon) per year.[76] This accumulation rate is likely to increase due to our accelerating emissions, and also due to a slowdown in uptake from the ocean and land reservoirs.
- **The ocean:** About 28% of the total CO_2 we've emitted so far has been absorbed by the

ocean and converted into carbonic acid.[77] As the ocean warms and becomes increasingly saturated with CO_2 it will become a less efficient sink. This means more of our emitted CO_2 will remain in the atmosphere, accelerating warming. There is some evidence that the ocean carbon sink is already becoming saturated,[78] but our understanding of how the ocean sink works and how it will work in the future remains uncertain.

Indeed, we know (from isotopic analysis) that the ice age cycle was driven by a positive feedback loop involving ocean uptake of CO_2. During glacial times, the colder ocean somehow pulled more CO_2 out of the atmosphere than can be explained by the temperature dependence described above. However, we don't know what additional process (or processes) were operating. We can't eliminate the possibility that this additional unknown feedback might also operate in reverse, contributing to warming.[79]

• **The land:** Soil and plants (which are intimately interconnected), together with permafrost, make up the land carbon reservoir. Increased atmospheric CO_2 augments plant growth and therefore plant carbon uptake, up to a point.[80] We don't know how to directly measure the size of this land carbon sink, but we infer that, on average, about 29% of the total CO_2 we've emitted has been absorbed by the land sink (that is, the total sink, 57%, minus the ocean sink, 28%). Annual variability of land carbon uptake is high. During some El Nino years, the land "sink" ends up being a net source; in other years, it absorbs more than 29%. It's still unknown where and how this absorbed carbon is apportioned between tropical forests and boreal forests. Unfortunately, however, there's strong empirical evidence that future warming will drive a net loss of soil carbon to the atmosphere,[81] and that global forest mortality and wildfires will increase in the future—and that these sources of atmospheric carbon have been underrepresented in projections to date.[82] We might see the catastrophic loss of the Amazon rain forest and release of its carbon into the atmosphere within decades, as drought makes the forest increasingly susceptible to fire,[83] and projected severe drying in the 21st century pushes it toward a tipping point.[84]

About a quarter of the northern hemisphere is covered in permafrost. As the permafrost thaws, microbes convert the biomass (mostly peat) into CO_2 if oxygen is present, and CH_4 if oxygen isn't present. It's estimated that there are about 1,700 GtC in the permafrost, more than four times what we've emitted from burning fossil fuels. The rates of permafrost CO_2 and methane release as the planet warms are unknown.

It's likely that the global land carbon sink will switch from being a net carbon sink to a net carbon source, accelerating climate change. However, as with our understanding of the ocean sink's future, uncertainty about the details is high.[85]

• **Frozen ocean methane:** Methane is frozen in ocean sediments on continental shelves. There's a lot of it, thousands of GtC worth, many times the carbon that humanity has so far emitted. If the Earth warmed enough to begin releasing this methane, it would be a positive feedback. Everything about ocean methane release is uncertain—mechanism, magnitude, and timing—but we might be wise to plan for at least 0.5°C additional warming from ocean methane release after 3°C of global warming, and this warming boost could last for thousands of years.[86]

Most climate models don't yet include the carbon-thawing feedbacks (permafrost and frozen ocean methane), biasing their predictions of future warming toward being too conservative. Slow release from these reservoirs could ultimately end up contributing about the same amount of CO_2 to the atmosphere as humans end up emitting, effectively doubling our emissions; exactly how this plays out, though, is anyone's guess.[87]

• **Limestones:** Carbonate rock (limestone) is the largest carbon reservoir, and it interacts with the climate system on tectonic time scales, as we'll discuss below.

• **Fossil fuels:** Humanity had burned a total of 375 ± 30 GtC of fossil fuels as of 2011, and in one year (2011), we burned 9.2 GtC.[88] Between 2000 and 2010, our global greenhouse gas emissions accelerated exponentially at 2.2% per year;[89] this increase was driven by an increase in our burn rate. (Recall that the measured atmospheric CO_2 fraction has this same growth rate over the long term; see Figure 3.3, page 42.)

• **Kerogens:** When organisms die on land or in the ocean, their carbon can become trapped in kerogens—fossil fuel precursors—which can eventually transform into coal, oil, and natural gas. As with the rock sink processes, these processes operate on long time scales. Both the rock and the kerogen sinks will be irrelevant on human time scales, but over millions of years, they will be significant. Perhaps in ten or 100 million years, Earth's "battery" will once again be charged, with much of the fossil carbon that humans dug up and burned again buried underground in the form of coal, oil, and gas.

Carbon flows

How does carbon flow between these reservoirs? Table 3.4 lists the flows of carbon in and out of just one of the reservoirs: the atmosphere.[90] This table separates these flows into estimates of human-caused and natural (i.e., preindustrial) portions. The much larger human-caused flows dramatically demonstrate the dominance of modern human emissions over the carbon cycle.

The amount of atmospheric carbon is a direct driver of climate change. Over time scales of thousands of years and more, atmospheric exchange of carbon with the other reservoirs determines this amount, as the carbon cycle recovers a dynamic equilibrium.

One such slow flow is the weathering of rocks on land. Rain is weakly acidic (it contains dissolved CO_2); it slowly dissolves exposed carbonate and silicate rocks, creating calcium ions and bicarbonate ions which eventually wash into the oceans. Marine organisms use these materials to build their shells, which then accumulate on the ocean floor, forming limestones. On geologic time scales, the limestones are subducted under the Earth's crust. Subjected to heat and pressure, they morph back into silicates,

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