CHASING LAKES

Love, Science, and the Secrets of the Arctic

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Polar map view of locations in my story

Notes

Chapter 1: An American Girl in Cherskii

1. S. A. Zimov et al., "North Siberian Lakes: A Methane Source Fueled by Pleistocene Carbon," *Science* 277, no. 5327 (1997): 800–2.

2. Greenhouse gases in the atmosphere warm the planet by acting like a blanket, trapping the sun's heat. While methane is far less abundant in the atmosphere than carbon dioxide, it is a more potent greenhouse gas and accounts for roughly 25 percent of the radiative force driving climate change. The century-scale global warming potential of methane—GWP_{100}—is approximately 28 times greater than that of carbon dioxide; over twenty years, methane's GWP is 84.

   A. L. Ganesan et al., "Advancing Scientific Understanding of the Global Methane Budget in Support of the Paris Agreement," *Global Biogeochemical Cycles* 33 (2019): 1475–512; and G. Myhre et al., "Anthropogenic and Natural Radiative Forcing," in IPCC, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. T. F. Stocker et al. (Cambridge, UK, and New York: Cambridge Univ. Press, 2013), 659–740, https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter08_FINAL.pdf.

3. For a description of the formation of thermokarst lakes in general, see L. J. Plug and J. J. West, "Thaw Lake Expansion in a Two-Dimensional Coupled Model of Heat Transfer, Thaw Subsidence, and Mass Movement," *Journal of Geophysical Research* 114, no. F1 (2009): F01002, 18, https://agupubs.onlinelibrary.wiley.com/doi/epdf/10.1029/2006JF000740.

4. Polar ice core records indicate that during ice ages, carbon dioxide concentration in the atmosphere was around 200 parts per million, and during the warmer interglacial periods, the levels were around 280 parts per million. Methane concentrations were lower, around 375 parts per billion during ice ages and 680 parts per billion during interglacials. Since the start of the Industrial Revolution, the concentration of carbon dioxide in the atmosphere has increased annually, and the

pace of increase is accelerating, leading to global warming. Methane has also mostly increased, although stabilization of concentrations between 2000 and 2007 followed by a continuation in its rise have scientists scratching their heads. In 2020, global atmospheric carbon dioxide measured at the National Oceanic and Atmospheric Administration (NOAA) remote sampling stations was 412.5 parts per million; global average methane concentration in December 2020 was 1,892.3 parts per billion, which is the highest so far on record.

IPCC, *Climate Change 2001: The Scientific Basis. Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change*, ed. J. T. Houghton et al. (Cambridge, UK, and New York: Cambridge Univ. Press, 2001), 881, https://www.ipcc.ch/site/assets/uploads/2018/03/WGI_TAR_full_report.pdf; K. Kawamura et al., "Northern Hemisphere Forcing of Climatic Cycles in Antarctica over the Past 360,000 Years," *Nature* 448 (2007): 912–16; P. O. Hopcroft et al., "Understanding the Glacial Methane Cycle," *Nature Communications* 8, no. 14383 (2017), https://www.nature.com/articles/ncomms14383/; and NOAA, "Despite Pandemic Shutdowns, Carbon Dioxide and Methane Surged in 2020," *NOAA Research News*, April 7, 2021, https://research.noaa.gov/article/ArtMID/587/ArticleID/2742/Despite-pandemic-shutdowns-carbon-dioxide-and-methane-surged-in-2020.

5. M. C. Serreze et al., "Observational Evidence of Recent Change in the Northern High-Latitude Environment," *Climatic Change* 46 (2000): 159–207; and M. Sturm, D. K. Perovich, and M. C. Serreze, "Meltdown in the North," *Scientific American* 289, no. 4 (2003): 60–67.

6. During the last Ice Age, when the tilt, wobble, and orbital pathway of Earth around the sun aligned to minimize the amount of solar radiation reaching the planet, wintertime snowfall did not entirely melt in summer. This caused much of North America and Europe to become covered by ice sheets and glaciers. In areas where precipitation was too low for glaciers to form, extreme cold winters and warm summers supported vast grasslands. These grasslands extended across great swaths of Alaska and much of North Siberia and Eurasia, covering almost fifteen million square miles of the unglaciated parts of the Northern Hemisphere—an area equal to the size of the North American continent.

   As the glaciers ground and pulverized rock, winds blew the resulting flour of the glacial mill, transporting it around the Northern

Hemisphere. This aeolian silt settled on the unglaciated, arid grasslands of North Siberia and Alaska. Nutrients in the silt fertilized growth of grasses that supported the great grazing animals of the Ice Age: mammoths, lions, bison, horses, and musk oxen. By trampling, grazing, and depositing excrement, this mammalian megafauna in turn controlled the vegetation and soil moisture, giving advantage to grass-dominated steppe over a steppe dominated by mosses or shrubs.

The dust fell at such a rate, and for so long, that grasses themselves became buried in silt. Animals were buried in silt where they died, as evidenced from the plethora of bones and occasional intact carcasses found in excavations of these icy, permafrost soils known today by scientists as yedoma. Ice Age winters much colder than those we have today caused the ground to freeze and remain frozen below the surface, even in summer. In winter, the ground cracked. Snow meltwater ran into the cracks in spring and refroze in the ground, leading to the formation of massive, dark ice wedges in the ground. The dust piled on, year after year, freezing in place each winter and building the ice-supersaturated yedoma to depths of 30, 100, or even 200 feet. Formation of these perennial frozen yedoma permafrost soils locked away billions of tons of Ice Age carbon and precipitation in an icy, underground freezer.

S. A. Zimov et al., "Steppe-Tundra Transition: A Herbivore-Driven Biome Shift at the End of the Pleistocene," *American Naturalist* 146, no. 5 (1995): 765–94; R. D. Guthrie, "Origin and Causes of the Mammoth Steppe: A Story of Cloud Cover, Woolly Mammal Tooth Pits, Buckles, and Inside-Out Beringia," *Quaternary Science Reviews* 20 (2001): 549–74; and J. B. Murton et al., "Paleoenvironmental Interpretation of Yedoma Silt (Ice Complex) Deposition as Cold-Climate Loess, Duvanny Yar, Northeast Siberia," *Permafrost and Periglacial Processes* 26, no. 3 (2015): 208–88.

7. S. A. Zimov et al., "Contribution of Disturbance to Increasing Seasonal Amplitude of Atmospheric CO_2," *Science* 284, no. 5422 (1999): 1973–76.

8. S. A. Zimov et al., "North Siberian Lakes: A Methane Source Fueled by Pleistocene Carbon," *Science* 277, no. 5327 (1997): 800–2.

9. The atmosphere currently contains more than 830 gigatons of carbon (GtC). Sergey's calculations suggested that 450 GtC were stored in Pleistocene-aged yedoma permafrost soils. Analysis of more extensive

data later revealed a smaller soil carbon pool size for the yedoma region (211 +160/−153 GtC); however, when the refrozen yedoma deposits beneath drained thermokarst lakes were factored in, the more extensive data yielded a yedoma region soil carbon pool size of 456 ± 45 GtC, very similar to Sergey's original regional estimate.

P. Ciais et al., "Carbon and Other Biogeochemical Cycles," in IPCC, *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*, ed. T. F. Stocker et al. (Cambridge, UK, and New York: Cambridge Univ. Press, 2013), 465–570, https://www.ipcc.ch/site/assets/uploads/2018/02/WG1AR5_Chapter06_FINAL.pdf; S. A. Zimov et al., "Permafrost Carbon: Stock and Decomposability of a Globally Significant Carbon Pool," *Geophysical Research Letters* 33, no. 20 (2006): L20502, https://agupubs.onlinelibrary.wiley.com/doi/full/10.1029/2006GL027484; J. Strauss et al., "The Deep Permafrost Carbon Pool of the Yedoma Region in Siberia and Alaska," *Geophysical Research Letters* 40, no. 23 (2013): 6165–70; and K. M. Walter Anthony et al., "A Shift of Thermokarst Lakes from Carbon Sources to Sinks During the Holocene Epoch," *Nature* 511, no. 7510 (2014): 452–69.

Chapter 9: A Scientific Author

1. K. M. Walter et al., "Methane Bubbling from Siberian Thaw Lakes as a Positive Feedback to Climate Warming," *Nature* 443, no. 7107 (2006): 71–75.
2. K. M. Walter et al., "Thermokarst Lakes as a Source of Atmospheric CH_4 During the Last Deglaciation," *Science* 318, no. 5850 (2007): 633–36.
3. J. D. McDowell, More Than a Carpenter (Carol Stream, IL: Tyndale House, 1977); and L. Strobel, The Case for Faith: A Journalist Investigates the Toughest Objections to Christianity (Grand Rapids, MI: Zondervan, 1998) Pp. 416.
4. C. S. Lewis, *Mere Christianity* (New York: Macmillan, 1960), 52.

Chapter 10: Truth Pursuit

1. K. M. Walter, L. C. Smith, and F. S. Chapin III, "Methane Bubbling from Northern Lakes: Present and Future Contributions to the Global

Methane Budget," *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* 365, no. 1856 (2007): 1657–76.

2. Many publications on the topic of permafrost carbon have largely been archived through the Permafrost Carbon Network: http://www.permafrostcarbon.org/publications.html.

Chapter 11: Peat Cakes and Wedding Cakes

1. After combining measurements of methane emissions from present-day thermokarst lakes with paleo records of thermokarst-lake initiation events since the Last Glacial Maximum, my research concluded that thermokarst lakes contributed substantially to new sources of Northern Hemisphere methane during the last deglaciation. Additional data, synthesized by L. S. Brosius et al., demonstrate that widespread lake formation in the early Holocene was a response to climate warming at that time. Projected twenty-first-century global warming is two orders of magnitude faster (decadal warming) than deglacial warming (millennial warming), and the associated permafrost carbon emissions are anticipated to be up to 900 times greater.

   K. M. Walter et al., "Thermokarst Lakes as a Source of Atmospheric CH_4 During the Last Deglaciation," *Science* 318, no. 5850 (2007): 633–36; L. S. Brosius et al., "Using the Deuterium Isotope Composition of Permafrost Melt Water to Constrain Thermokarst Lake Contributions to Atmospheric CH_4 During the Last Deglaciation," *Journal of Geophysical Research: Biogeosciences* 117, no. G1 (2012): G01022; L. Brosius et al., "Spatiotemporal Patterns of Northern Lake Formation Since the Last Glacial Maximum," *Quaternary Science Reviews* 253 (2021): 106773, 12; and K. M. Walter Anthony et al., "Methane Emissions Proportional to Permafrost Carbon Thawed in Arctic Lakes Since the 1950s," *Nature Geoscience* 9, no. 9 (2016): 679–82.

2. Sergey and Nikita Zimov had combed beaches along headwalls where permafrost was actively thawing to collect bones and fossilized teeth remains of mammoths, musk oxen, lions, rhinos, and other large mammals that lived in North Siberia during the last Ice Age. The bones would tell them the density of animals this region could support if it were a grassland, as it had been during the last Ice Age. This information would be used to resurrect an Ice Age biome in a nature

preserve south of Cherskii, which they called Pleistocene Park. Their aim was to repopulate Siberia with large herbivores to restore a highly productive grazing ecosystem, similar to that which dominated the region thousands of years ago before the animals were either hunted out by humans or suffered extinction due to a rapidly changing climate. The Zimovs were confident that restoration of these animals was a promising means to help fight climate change today. The animals would do their part to help keep the Siberian permafrost frozen: grazers would maintain a grassland ecosystem that (1) reflects incoming solar radiation, (2) stores carbon belowground, and (3) gets trampled in winter, allowing cold air temperatures to penetrate into the ground to keep permafrost cold. For more information about Pleistocene Park, see S. A. Zimov, "Pleistocene Park: Return of the Mammoth's Ecosystem," *Science* 308, no. 5723 (2005): 796–98; R. Anderson, "Welcome to Pleistocene Park," *The Atlantic*, April 2017, https://www.theatlantic.com/magazine/archive/2017/04/pleistocene-park/517779/; and the Pleistocene Park website, https://pleistocenepark.ru/.

3. Guido Grosse was involved with fieldwork and remote sensing studies of North Siberian permafrost characteristics that yielded articles in numerous publications dating as early as 2000. A few examples of his work include: G. Grosse et al., "Geological and Geomorphological Evolution of a Sedimentary Periglacial Landscape in Northeast Siberia During the Late Quaternary," *Geomorphology* 86 (2007): 25–51, https://permafrost.gi.alaska.edu/sites/default/files/Grosse%20et%20al%202007%20Geomorphology.pdf; L. Schirrmeister et al., "Periglacial Landscape Evolution and Environmental Changes of Arctic Lowland Areas for the Last 60,000 Years (Western Laptev Sea Coast, Cape Mamontov Klyk)," *Polar Research* 27, no. 2 (2008): 249–72, https://polarresearch.net/index.php/polar/article/view/2886/6513; and A. A. Andreev et al., "Weichselian and Holocene Palaeoenvironmental History of the Bol'shoy Lyakhovsky Island, New Siberian Archipelago, Arctic Siberia," *Boreas* 38, no. 1 (2009): 72–110.

Chapter 16: A Sleeping Giant

1. I. S. A. Isaksen et al., "Strong Atmospheric Chemistry Feedback to Climate Warming from Arctic Methane Emissions," *Global Biogeochemical Cycles* 25, no. 2 (2011): GB2002, https://atmos.uw.edu/academics/classes/2011Q2/558/IsaksenGB2011.pdf.

2. K. M. Walter Anthony et al., "Geologic Methane Seeps Along Boundaries of Arctic Permafrost Thaw and Melting Glaciers," *Nature Geoscience* 5 (2012): 419–26.

Chapter 17: Farm Wife

1. K. M. Walter Anthony et al., "A Shift of Thermokarst Lakes from Carbon Sources to Sinks During the Holocene Epoch," *Nature* 511 (2014): 452–56.
2. K. M. Walter Anthony et al., "Methane Emissions Proportional to Permafrost Carbon Thawed in Arctic Lakes Since the 1950s," *Nature Geoscience* 9, no. 9 (2016): 679–82; and K. M. Walter Anthony et al., "21st-Century Modeled Permafrost Carbon Emissions Accelerated by Abrupt Thaw Beneath Lakes," *Nature Communications* 9, no. 3262 (2018), https://www.nature.com/articles/s41467–018–05738–9#citeas.
3. K. Schaefer et al., "The Impact of the Permafrost Carbon Feedback on Global Climate," *Environmental Research Letters* 9 (2014): 085003; C. D. Koven, D. M. Lawrence, and W. J. Riley, "Permafrost Carbon—Climate Feedback Is Sensitive to Deep Soil Carbon Decomposability but Not Deep Soil Nitrogen Dynamics," *PNAS* 112, no. 12 (2015): 3752–57; C. D. Koven et al., "A Simplified, Data-Constrained Approach to Estimate the Permafrost Carbon–Climate Feedback," *Philosophical Transactions of the Royal Society A* 373, no. 2054 (2015): 20140423, https://royalsocietypublishing.org/doi/pdf/10.1098/rsta.2014.0423; E. J. Burke et al., "Quantifying Uncertainties of Permafrost Carbon-Climate Feedbacks," *Biogeosciences* 14, no. 12 (2017): 3051–66; and A. D. McGuire et al., "Dependence of the Evolution of Carbon Dynamics in the Northern Permafrost Region on the Trajectory of Climate Change," *PNAS* 115, no. 15 (2018): 3882–87, https://www.pnas.org/content/pnas/115/15/3882.full.pdf.
4. C. D. Arp et al., "Threshold Sensitivity of Shallow Arctic Lakes and Sublake Permafrost to Changing Winter Climate," *Geophysical Research Letters* 43, no. 12 (2016): 6358–65; M. Langer et al., "Rapid Degradation of Permafrost Underneath Waterbodies in Tundra Landscapes—Toward a Representation of Thermokarst in Land Surface Models," *Journal of Geophysical Research: Earth Surface* 121, no. 12 (2016): 2446–70; and P. Roy-Leveillee and C. R. Burn, "Near-Shore Talik Development Beneath Shallow Water in Expanding

Thermokarst Lakes, Old Crow Flats, Yukon," *Journal of Geophysical Research: Earth Surface* 122, no. 5 (2017): 1070–89.

5. T. Schneider von Deimling et al., "Observation-Based Modelling of Permafrost Carbon Fluxes with Accounting for Deep Carbon Deposits and Thermokarst Activity," *Biogeosciences* 12, no. 11 (2015): 3469–88; and Koven, Lawrence, and Riley, "Permafrost Carbon—Climate Feedback Is Sensitive," 3752–57.
6. Walter Anthony et al., "21st-Century Modeled Permafrost Carbon Emissions Accelerated by Abrupt Thaw Beneath Lakes," *Nature Communications* 9, no. 3262 (2018), https://www.nature.com/articles/s41467-018-05738-9#citeas.
7. S. Fuss et al., "Betting on Negative Emissions," *Nature Climate Change* 4, (2014): 850–53; M. Meredith et al., "Polar Regions," in *IPCC Special Report on the Ocean and Cryosphere in a Changing Climate,* ed. H.-O. Pörtner et al. (prepared 2019; in press), 203–320, https://www.ipcc.ch/site/assets/uploads/sites/3/2019/11/07_SROCC_Ch03_FINAL.pdf.
8. Fuss et al., "Betting on Negative Emissions," 850–53.

Chapter 18: Spying on Methane

1. K. M. Walter et al., "The Potential Use of Synthetic Aperture Radar for Estimating Methane Ebullition from Arctic Lakes," *Journal of the American Water Research Association* 44, no. 2 (2008): 305–15; M. Engram et al., "Synthetic Aperture Radar (SAR) Backscatter Response from Methane Ebullition Bubbles Trapped by Thermokarst Lake Ice," *Canadian Journal of Remote Sensing* 38, no. 6 (2013): 667–82; and M. Engram et al., "Remote Sensing Northern Lake Methane Ebullition," *Nature Climate Change* 10 (2020): 511–17.

Chapter 19: Love at Last

1. K. Martin, "Gentleness," in *In God's Orchard* (Milwaukee, WI: Northwestern Publishing , 2019), 70.
2. Martin, "Gentleness," in *In God's Orchard*, 71.

Epilogue

1. The terrestrial Arctic is projected to warm 4 to 6 degrees Celsius under RCP4.5 and more than 7 degrees Celsius following RCP8.5 this century.

A. D. McGuire et al., "Dependence of the Evolution of Carbon Dynamics in the Northern Permafrost Region on the Trajectory of Climate Change," *PNAS* 115, no. 15 (2018): 3882–87; IPCC, 2013: Summary for Policymakers. In: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. (Fig. SPM.8,Page 22)

2. E. G. Nisbet et al., "Methane Mitigation: Methods to Reduce Emissions, on the Path to the Paris Agreement," *Reviews of Geophysics* 58, no. 1 (2020): e2019RG000675.
3. K. M. Walter Anthony et al., "Decadal-Scale Hotspot Methane Ebullition Within Lakes Following Abrupt Permafrost Thaw," *Environmental Research Letters* 16 (2021): 035010, https://iopscience.iop.org/article/10.1088/1748-9326/abc848/pdf.
4. K. M. Walter Anthony et al., "A Shift of Thermokarst Lakes from Carbon Sources to Sinks During the Holocene Epoch," *Nature* 511, no. 7510 (2014): 452–69.