

CHAPTER FOUR

CLIMATE AND THE CRYOSPHERE

The Snows of Yesteryear and the Future of the Mountain West

If, dear reader, you've come this far into this book but are still not sure exactly where you stand on the climate issue, I fully understand your position. I have worked for more than a decade on communicating scientific outputs from six climate research networks, and after reading hundreds of scientific papers and reviewing more than 150 books on climate change, there are only three things I am relatively certain of at this moment. Notice, however, that I said I was only *relatively* certain, which suggests that, like the scientists I rely on for my information, I am always open to new perspectives, provided they emerge from credible sources that have had the benefit of being evaluated by others with equally credible reputations for scientific objectivity.

I presently subscribe to three views. First, carbon dioxide concentrations in the atmosphere are increasing rapidly, causing mean annual temperatures to rise. Second, we humans are the principal cause of these temperature increases. And third, the warming atmosphere is becoming more turbulent, resulting in widespread weather pattern disruption, more intense droughts, extreme floods, bigger fires and wilder storms all over the world.

I have not always been this confident on any of these issues. I too have been plagued by doubts. But over time I have had the benefit of examining and testing these doubts in association with some of the world's leading climate scientists. Working among these circles, I can say with confidence that no water or climate scientist I know

wants to see what is happening to the planet's atmosphere continue. We have changed the composition of our atmosphere by way of our collective emissions and now we have to address the consequences of global change. This is not a minor proposition. Our future depends on how we respond now. The full weight of the entire scientific method is being brought to bear on determining the facts so they can be translated into appropriate action.

The scientific method is highly structured. Even when known deniers and cranks challenge any aspect of the growing body of climate science, researchers are bound by the method to test the claim against the entire body of established knowledge to see if it deserves consideration. This is how science spirals gradually forward over time. Science is never "settled." Every critical objection to the hypothesis that our global climate is warming and that the burning of fossil fuels is contributing to this warming has been and will continue to be subjected to analysis and fierce scientific debate. So far, however, what has consistently happened is that after running objections again and again through the entire climate science knowledge system, we keep arriving back at the same conclusions. Yes, of course there are other factors besides carbon dioxide that influence climate. Climate is complex. But when you put all those factors together their influence doesn't even begin to explain current warming.

We now know that the output of the sun has not been a significant influence on global temperatures for the last 50 years. Careful research has concluded that changes in the Earth's orbit will not appreciably affect atmospheric temperatures for probably another 30,000 years. Our fossil fuel burning is presently pumping out CO₂ 50 to 100 times faster than volcanoes do. Yes, modern volcanoes emit only 1 to 2 per cent of human emissions. Yet despite the localized cooling effects of La Niña events and other ocean current influences, average global temperatures continue to rise. Yes, warming will eventually decrease CO₂ concentrations by way of weathering, but that cycle takes half a million years to kick in.

With each passing year and each research outcome we keep arriving at the same conclusion: it's us – we are the cause. Despite this, there are people who continue to insist that the atmosphere is too

large for humans to influence. As mentioned earlier, though, the Earth's atmosphere is only a fraction of the volume of our oceans, and look what we have done to those. It has been estimated that we have dumped perhaps half a trillion tonnes of carbon dioxide into the atmosphere. For purposes of comparison, let's imagine pumping even half that amount – 250 billion tonnes – into our oceans to see if anything will happen. Of *course* something will happen. We may not be exactly sure *what*, but we know *something will happen*.

Nor can you say that the tiny percentage of carbon dioxide in the air makes its presence meaningless. We know that carbon monoxide is fatal at 35 parts per million, which is less than a tenth of the current concentration of CO₂ in our atmosphere. Cyanide gas is fatal at 135 parts per million after just 30 minutes. If there were the same amount of cyanide in our air as there is carbon dioxide, advanced life would cease to exist on land on this planet. If these comparisons don't inspire you, perhaps it would be appropriate to invite you to think of the impact a skunk can have on a campground or in your backyard. A small volume of atmospheric disturbance can go a long way.

The fact is that we have eliminated all other ways to explain the warming and are reduced to matters of basic atmospheric chemistry and physics. You can create your own physics – or dismiss physics outright or even deny science altogether as is happening in parts of this country and in the US – but you can't avoid the basic fact. We are changing the composition of our atmosphere, and the effects of that are becoming hard to ignore. If you wish to test the validity of this argument, visit your nearest glacier.

INVESTIGATING THREE COLD CASES

Under the aegis of the Canadian Foundation for Climate and Atmospheric Science, the Western Canadian Cryospheric Network, or WC²N as it was known, orchestrated research at six Canadian universities and an American one into what is happening to our cryosphere – that part of the world characterized by ice and frozen ground. The objective of the undertaking was to clarify the fate of the glaciers in Western Canada. These scientists' work revealed

dynamics that will enable further research to build on WC²N's findings so as to more accurately characterize exactly how much water might reside in the glacier ice of the mountain West.

PEYTO GLACIER

The area of Peyto Glacier in Banff National Park was about 14.2 square kilometres in 1949. By 2010 that extent had diminished to about 11.6 square kilometres, an areal loss of 19 per cent over the intervening 60 years. This is different from linear loss but directly linked to it. The volumetric loss of the Peyto over the same period is estimated at between 10 and 20 million cubic metres of water a year. Today the rates of melt are faster, the glacier itself smaller. Obviously, if these trends continue it will not be long before the volume of the Peyto will be so small that such melt rates will not be sustainable, a point that may have been reached in 2015.

It appears now, however, that some of the areal loss attributed to recession of the Peyto Glacier was in fact not loss at all. Though the lost ice disappeared from sight, some of it did not melt. Instead it became entrained in moraines, where it continues to sustain high annual discharge. The exact area of the Peyto entrained in ice-cored moraines is not known. It is exactly this kind of information that is missing from the outcomes generated by the Western Canadian Cryospheric Network. The same information is also missing from the evaluations of the current state of glaciers around the world presently being undertaken by the World Glacier Monitoring Service.

What is happening to Peyto Glacier is not unique. Periglacial areas are increasing exponentially while exposed glacial surfaces are being reduced linearly all around the world. The downwasting of the ice on the Peyto, however, is quite substantial. On average, the ice has been shrinking by some 4 metres a year, which explains why glaciologist Mike Demuth was able to toss a pebble onto the glacier surface from Peyto Hut in 1966 but would need a bionic arm to throw that far now. According to researcher Chris Hopkinson, both downwasting and periglacial entrainment are occurring simultaneously. This presents a number of problems. For example, when Geomatics Canada recreates maps, they may get the area of a given glacier right but they often use the same topographic data used in earlier maps to

establish elevation. In most cases, however, the surface elevation of a given glacier will have changed because of downwasting – in some cases quite dramatically. If you are a researcher or maybe work for the Geological Survey, you might know that. But if you are a non-specialist just reading a topographical map, you might not.

Because of the long record of research into its dynamics, Peyto Glacier is used as a surrogate for other, similar glacier headwater situations. The dynamics of the Peyto, Hopkinson has noted, are different from those of surrounding glaciers. The nearby Bow Glacier, for example, at one time flowed over two big subsurface rock steps. It has recently experienced two periods of accelerated recession, one in the 1920s and '30s and another in the 1970s. Though the Peyto doesn't have the same underlying geology, it is anticipated that it too will experience episodes of step-like recession in the next 20 years. As the unglaciated area surrounding it becomes larger, the heat trapped by the greater area of bare rock and talus will overwhelm the glacier. This, researchers note, could happen quickly as change suddenly goes from linear to exponential in terms of the amount of area that becomes bare of ice and late-lying snow.

Chris Hopkinson has observed that while the exposed ice of the Peyto Glacier was downwasting at up to 4 metres a year, moraines were downwasting at a rate of 1.5 metres per year and then collapsing out onto the bare ice at a rate of as much as 6 metres a year, making it difficult to measure the full extent of glacial ice remaining beneath the rock and scree that covers its margins. Refining his earlier estimates, Hopkinson observed that mean wastage of the Peyto between 1949 and 2010 was likely to be in the order of 14 million cubic metres of water a year. Hopkinson's key point, however, was that moraine wastage and associated melt are now increasing exponentially as was feared. His main scientific concern was that none of these dynamics were presently being captured in the mass-balance record for the Peyto or for that matter any other glacier in the Rocky Mountains. The public policy implications of this are significant. It means we still have some way to go before we can accurately predict how much water will be released from the remaining glaciers in the western cordillera under a variety of climate change scenarios.

Hopkinson thinks he has a solution, however. Further thermal

sensing aimed at located ice buried under moraines would be conducted, along with LiDAR measurements of the entire glacier and surroundings. LiDAR is short for “light detection and radar,” and its operating principles are similar to those of its much earlier sister technology, RADAR, for “radio detection and ranging.” With LiDAR, however, the radio microwaves typical of radar are replaced by near-infrared pulses emitted by a laser. This laser energy interacts with surface features and, upon scattering, returns to a detector. The calculation of surface area is a simple “time of flight” measurement, with the position of the survey aircraft accurately known using the Global Positioning System. As a result of these observations it should be easier to include the dynamics of ice-cored moraines more accurately into future mass-balance calculations.

THE COLUMBIA ICEFIELD

Between 1975 and 1998, glacier cover as measured by area decreased by approximately 36 per cent in the South Saskatchewan basin and 22 per cent in the North Saskatchewan basin. The loss of the glaciers at the headwaters of these two rivers is no small matter to the three million people who live in the two basins and rely on that water. In the South Saskatchewan, where much of Alberta’s irrigation agriculture is located, water is already scarce and in some instances already fully allocated. The North Saskatchewan basin is less water-stressed, but nevertheless is affected by annual average ice volume wastage equivalent to the amount of water used by approximately one and a half million people. Obviously, when there is no ice left to become water, the growing needs of water-reliant populations, industries and agricultural sectors will exert ever-increasing pressure on water availability.

The biggest challenge to properly assessing how much water is stored in the glaciers in the western and northern cordillera regions is the difficulty in accurately determining the exact volume of existing glacial masses. It is relatively easy to measure surface area, but as noted earlier it is far harder to know how much ice is entrained in moraines and rock falls. It is also very difficult to measure volume, because it is hard to know the nature and character of the landforms beneath the ice that define the volume of ice that can exist in any

given place. Because there is no simple and inexpensive way to do this, many of the early projections regarding the state and fate of Canada's remaining glaciers are only rough estimates based on the best information available as to the general topography of Canada's mountain regions.

In association with Parks Canada, the Geological Survey has funded preliminary research to precisely determine the volume of ice contained in the largest glacier system in the Canadian Rockies – the Columbia Icefield. Once popularly thought to cover 325 square kilometres, the icefield has recently been estimated at 223 square kilometres and shrinking. Now, however, the volume of the glacier system will no longer be merely approximated by estimating it as a function of area only. Instead the volume of ice will be calculated directly and exactly, through the use of ground penetrating radar surveys conducted on the surface of the icefield and by remote sensing using LiDAR. The aircraft carrying the LiDAR system will fly over the area, capturing information in swaths. Careful analysis of the data will yield an illuminated footprint of the landscape over which the detection of features and their exact relative distance from one another has been put into relief. The combination of LiDAR and ground-penetrating radar should yield the first truly accurate measurement of the form and thickness of the Columbia Icefield. By multiplying the amount of ice by its water equivalent it will be possible to estimate with a fair degree of predictive accuracy how long individual glaciers and even the Columbia Icefield itself may last under a number of projected climate change scenarios.

Given the central position of this icefield at the headwaters of three of the country's most important river systems, the Columbia Icefield Research Initiative, had it continued to be adequately funded, would have generated research outcomes of great value in estimating how much water will be available to future residents of the West. The Initiative could have been the most important scientific project undertaken in a Canadian national park since the parks system was created 130 years ago. A great deal of ice in the West is becoming water. By refining our understanding of the glacier ice that forms the hydrologic apex of Western Canada, this research could very well have defined the state and fate of the entire

region. Out of this research we might have learned the hydrological limits of the dry West. We may have been able to better understand what the Western landscape can support, for it is water and not just natural resources that ultimately constrains sustainability on the Great Plains. It is water that makes the mountain and prairie West habitable. Financial support for the Columbia Icefield Research Initiative, however, was largely eliminated by the Harper government in 2014. Fortunately this did not mark the complete end of research on the rate of decline of glaciers in Canada's mountain West. But it did mean that the status of ongoing government monitoring and research is at the time of this writing uncertain and the work done at research institutions and universities has become more important than ever.

THE DEGLACIATION OF THE WEST

Garry Clarke of the Earth, Ocean and Atmospheric Sciences department at the University of British Columbia is one of Canada's most renowned scientists and one of the world's most respected glaciologists. In April of 2015, Clarke and his colleagues Alexander Jarosch, Faron Anslow, Valentina Radić and Brian Menounos published a paper in one of the most prestigious scientific journals in the world, on projected deglaciation of Western Canada in the 21st century. The paper, which appeared in *Nature*, confirmed earlier research conducted by many of the same scientists under the aegis of WC²N concerning the rate and extent of deglaciation in the coastal and interior ranges of British Columbia and in the Rocky Mountains of Alberta. What was different about Clarke's and his co-authors' research was that it was founded on much improved and far more accurate models of glacial dynamics. Simulations of projected changes in the extent and volume of glacial ice in the region were also vetted against a broader ensemble of climate models.

The results of this research indicate that on average we can expect to lose, by the end of the current century, about 70 per cent of the glacial ice that existed in Canada's western mountains in 2005. The effects of this loss will be greatest in the interior ranges of BC and the Rockies and slightly less in the tidewater and coastal glaciers of central to northern BC. We can expect coastal glaciers to be

diminished by 65 to 85 per cent, while losses in the interior ranges and the Rockies will be 90 per cent or more. Peak meltwater discharge into streams and rivers from shrinking glaciers will likely occur between 2020 and 2040. The projections of this research are that the main results of deglaciation will be changes in the hydrologic cycle in the region that will have consequent effects on water availability and the structure and health of existing aquatic habitat; on the timing and amount of hydropower generation possible; and on the diminishment of aesthetic elements that are at the heart of the region's recreation and tourism reputation. The loss of glacier ice will also affect water availability for cities, agriculture and natural ecosystem function.

The authors of the paper made specific reference to impacts that can be expected in the Columbia River basin, where the loss of glacial ice is expected to have effects on hydropower generation and flood control significant enough to have implications for the Columbia River Treaty reconsideration discussions that were initiated between Canada and the United States in 2014.

The takeaway from this research is that by the middle of the current century we can expect the Canadian West to be a different place. The people who live there should prepare to get along in that new reality. But there is a larger warning in this work that goes beyond the impacts associated with the loss of glacier ice. The same warming that is melting the region's glaciers will ultimately diminish snowpack and affect the timing and duration of snowcover, which will in turn impinge on water security in ways that will cascade through the social, economic and political fabric of the entire West. Snow matters.

"PURE AS THE DRIVEN SNOW"

As Martyn Tranter and Gerald Jones make clear in their chapter in the anthology *Snow Ecology: An Interdisciplinary Examination of Snow-Covered Ecosystems*, there is good reason to study snow, beginning with its chemistry. The chemistry of snow meltwaters can have a significant, if not definitive, influence on the nature and quality of surface waters. It has been found, for example, that

snow generated in air masses originating in industrial and urban areas scavenges pollutants such as sulphur dioxide and nitrous oxides from the atmosphere. This produces acid snow. It has also been found that airborne pollution from operations like oil sands upgraders can result in highly toxic contaminants falling on and becoming part of regional snowcover. These pollutants can be flushed out of the snowpack early in the melt season, creating periods of relatively acidic conditions in soils and streams. As snowmelt continues, these contaminants circulate in higher concentrations throughout aquatic ecosystems, sometimes causing fish kills during the spring freshet.

Although pervasive, human activities are not the only influences on snow chemistry, however. Important processes also occur within the snowpack naturally. Researchers have demonstrated that snow is not a passive reservoir of chemicals. As snow ages and metamorphoses, its composition is altered as a result of chemical reactions within it. "Pure as the driven snow" may be a familiar cliché, but the sarcasm it's usually voiced with nowadays isn't too far off the mark.

When snow falls it brings down with it all the substances that become trapped within individual flakes during the descent, which means just about every kind of particulate that happens to be in the atmosphere at the time. Snow formation and snowfall absorb chemicals from the atmosphere in three ways: through imprisonment of substances in the initial stages of ice crystal formation; through capture of gases, aerosols and floating particulate matter that snowflakes pick up while falling through clouds; and through the scavenging of airborne contaminants as the flakes fall through the air below the cloud layer. Water droplets in clouds contain a broad range of solutes that come into suspension as a result of particulate capture and through the diffusion of atmospheric gases into the resulting liquid solution. These solutes normally include sea-salt aerosols, sulphur dioxide, calcium, potassium and magnesium.

The range of solids that come down in any given snowfall can also be astounding. If you have ever put freshly fallen snow in your mouth and tasted dust, you will have some idea of just how much freight returns to earth in the nearly silent wafting of snowflakes. Tranter

and Jones report that any given snowfall will contain elements that once formed the Earth's crust, such as the calcium and magnesium mentioned earlier, as well as terrigenous dust. There may also be weak organic acids, trace metals and whatever else was in the air at the time, including particulate matter from the incomplete combustion of fossil fuels and the out-gassing of volcanoes.

Tranter and Jones also recount that during the winter the chemistry of cold snow is influenced as well by the biological debris that falls on the snow from above or that comes into existence within the snowpack as a result of biological activity there. In our northern forests Canadians are familiar with the leaf and needle litter that covers the surface of aging snowpacks, particularly in the spring. The excrement of mammals such as moose, elk and deer that have crossed the snow also finds its way deep into the snowpack. Wind-borne arthropods and winged insects also fall to the snow surface, creating additional chemical sources that become nutrients for organisms already living in the snow.

Such organisms can be surprisingly numerous. Bill Streever's remarkable book *Cold: Adventures in the World's Frozen Places* cites a Canadian study that revealed nineteen species of spiders, fifteen of mites, sixty-two of beetles, sixteen of springtails, thirty-two of ants and wasps and two species of centipedes, all living together in a complex ecology in and under the winter snow.

Neither does falling snow always look the same, as any Canadian winter driver could tell you. Streever cites a report of snowflakes four inches across falling in Berlin and a case from Montana in 1887 when flakes were fifteen inches across and eight inches thick. Snow isn't always white, either: in 1815, when Mount Tambora in Indonesia exploded, it launched so much particulate matter into the atmosphere that snow later falling in Hungary was brown, in Italy red and in the eastern US blue.

It is well known that snow is one of the lightest substances on Earth and one of the best natural insulators. The insulation provided by snow often allows soils beneath to remain unfrozen. It has been observed that microbial activity does not cease in most soils until the temperature of the frozen soil drops below -8°C . Above this temperature, microorganisms produce trace gases by way of their

respiration. While colder temperatures reduce the overall rate of this microbiological activity, the volume of trace greenhouse gases trapped beneath snowcover can still be substantial relative to annual natural emissions from the soil: up to 20 per cent of the carbon dioxide and up to 50 per cent of the nitrous oxide. Because snow is porous, these gases can concentrate in gas-rich air pockets within the snowpack. This is especially the case in alpine regions where the snowpack is particularly thick, providing excellent insulation for the soils underneath. Microbiological processes are sustained all year round in snow-covered alpine soils. In such situations, the snowpack also serves as a sink for carbon dioxide and methane. Changes in the depth and area of seasonal snowcover resulting from global warming have an effect on the trapping of these greenhouse gases, though just what the effect might be remains unclear.

It is not surprising, given how much chemical activity can go on within snow itself, that changes in snowpack and snowcover in the cold parts of Canada affect the very composition of the runoff that is produced in any particular region. Where snowpack and snowcover have diminished, the water available to streams and rivers will be chemically different from that produced by melt where the nature and extent of the snowcover have not changed. Cold, evidently, does not just matter to the amount and extent of seasonal snowcover; it also defines the very composition of the water generated in those regions where hydrological regimes are dominated by snow.

Chemical evolution in snowpacks begins as soon as snow falls, and continues right up until it melts. Certain chemicals are both created and lost as a result of physical changes that take place during the buildup and later dissolution of seasonal snowcover. Throughout the time snow remains on the ground, the fundamental chemical nature of the snowpack is transformed by meteorological conditions and in many cases by microbiological activity. Chemicals within the snowpack will migrate and may concentrate within the snowcover depending upon temperature and changes in the mass of the snowpack that occur as a result of sublimation or melting. The physical properties of individual chemicals play a role in determining the chemical loading of snowcover. As the snowpack melts, properties such as solubility and vapour pressure of chemicals scavenged from

the atmosphere during snowfalls become important factors in determining the chemical composition of meltwater. It is important to note, however, that chemical transformations such as oxidization also occur within the snowpack, and the substances that fall with the snow are not always exactly what finally gets into the meltwater. As mentioned earlier, chemical transformations also take place as a result of microbial activity in the snowpack. Snow algae, for example, of which there are many species, assimilate nitrogen from within the snowpack. Other organisms in the snow also metabolize nutrients they find suspended in the snow column.

From all this complexity we begin to understand just how many parameters must be taken into account in order to predict how much water might be generated as streamflow in any given spring. We also get a sense of how many more parameters must be understood if a researcher wants to be able to predict what might happen in a snow-dominated system as the climate of that system changes over time. Modellers who wish to understand what changes in snowpack may mean in terms of the future security of supply cannot separate water quantity from quality. Changes in the volume or extent of snowcover will have clear effects on physical and biogeochemical characteristics of the entire environment influenced by seasonal snowcover. These effects will be significant far in advance of concerns over water availability for purposes such as dilution of treated wastewater or agricultural runoff.

The modelling of changes in the hydrological cycle also demands that processes related to such transport be parameterized. This is not a simple task. Though they may appear separate, the atmosphere and the surface of the biosphere form a single biogeochemical continuum in which interactions and exchanges between the two regulate and maintain the composition of the Earth's atmospheric envelope. To accurately model what happens over time to the snowdrift in your backyard – and what will happen to the contents of that snowdrift – one must understand the thousands of physical and chemical interactions that occur at the larger ocean–air–water–land–life interface and then be able to apply that knowledge on a local scale. Though techniques are improving, this continues to be a supreme challenge to the accuracy of existing predictive

models. Such modelling will become even more difficult in the future in the face of rapid changes to many established parameters that are occurring as a result of the loss of relative hydro-climatic stability as a consequence of atmospheric warming.

Because we have changed the composition of the Earth's atmosphere, and energized the global hydrological cycle in doing so, we have inadvertently created a hydro-climatic time bomb in Canada that threatens to undermine our established sensibilities with respect to the reliable availability and quality of water we presently take for granted. As the next chapter will demonstrate, the hydro-climatic genie is out of the bottle and we don't yet know enough about the genie or the bottle to restore conditions to the relative stability we once enjoyed.