Climate Science

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This is the first in a series of articles on climate change. My purpose is to review the evidence that climate change is damaging ecosystems and disrupting the economy. Its costs are rising rapidly, and we have a very short time in which to prevent catastrophic effects on water systems, food supply, and infrastructure.

I propose a four part series. First I will describe the science behind our understanding of the climate. How do we know the planet is warming? How do we know that the rise in global temperatures is caused by human activity? How do we know that climate change threatens our way of life? Next, I will explain how we can predict future climate. How do we know that, unless we reverse current trends in greenhouse gases, changes in earth's climate system very likely will have catastrophic consequences within the next ten to twelve years? What are climate models, on which scientists base their predictions, and how do they work? Then I will present evidence for climate change in our region, including changes documented locally in the White River basin. Finally, I will propose measures we can take to limit the change and to adapt to changes that are already inevitable.

It's not a happy picture. It requires attention and action.

First the science.

Science is a rigorous process of investigation that demands careful measurement, analysis, replication, and review.

Scientists are curious. They ask questions about how the world works then follow rigorous protocols to try to answer those questions.

Suppose we want to understand the climate history of the American Southwest. That requires many years of work, by lots of scientists. One university research group counts pollen grains in successive layers of a dry lake bed. Tedious. Time consuming. Another group measures distance between successive tree rings backward in time a hundred years, five hundred years, a thousand years. Another measures successive depositional layers in stalactites and stalagmites in a limestone cave.

That's just the beginning. Scientists are skeptical. That's the nature of the work. Nobody accepts your results unless they have been verified beyond reasonable doubt. So you double check the data, review all the graphs and tables. Run statistical analysis. Are the gaps in tree rings really thinner since 1850? Or is that just some chance variation? Only then, after lying awake nights trying to imagine what you might have missed, you write it all up and send in a report for peer review.

Peers. Other scientists who have done the same sort of work, addressed the same kinds of questions. Tree experts. Pollen experts. Sediment experts. You learn to dread them. They'll return your report covered with red ink. They'll think of all the things you didn't think of. Did the drainage systems change, bringing different sediments into that lake? Was other, competing vegetation introduced into that forest? So you go back to work. More core samples. More pollen analysis. Experiments to see whether competition from aspen trees narrows the rings on your study trees. Re-analyze the data. Re-write the report.

Finally finished! Right? Not yet. If it passes peer muster, your report is published in the appropriate, vetted science journal and the general scientific community gets a chance to comment. You get emails, requests for access to your data. Other scientists comment on your work. Didn't you read the report last year in *Nature* showing that it was acid rain that inhibited forest growth in the Northeast? You respond that forests in the Southwest did not experience that degree of acidification. Another researcher claims you should have used a different statistical analysis. And so on.

You respond. You collect more data. You publish further results. And it's still not finished. Your work isn't fully accepted until somebody else independently confirms your findings. If it's an especially important piece of science, it's not fully accepted until it's been confirmed by many different studies in many different labs.

Climate science fully meets the high standards of scientific research.

That's the nature of science. Including climate science. It's thorough. It's thoroughly vetted. Work by trained professionals using protocols and logic established over millennia, reviewed by expert peers, published in reputable journals, replicated by other scientists. It's as close to truth as nature allows.

Here is a small sample of recent research in climate science, all published in the past couple months. These represent just a handful of the hundreds of similar reports published in the past year, thousands over the past fifty years. Check the references. See how the studies were done. It's only by reading the primary research reports that you can fully appreciate the science.

Item: Entomologists compared insect surveys in the Puerto Rican rainforest in 2016 with surveys forty years ago. (Lister, 2018) They find that insect numbers in some regions of a protected rainforest reserve have dropped ten- to sixty-fold. Numbers of frogs and lizards, who feed on insects, have dropped similarly. Food webs are collapsing. It's not insecticides. It's not birds eating the insects. Evidence from this study and others point to higher temperatures as the cause: rainforest organisms are adapted to stable temperatures, and they cannot tolerate the increasing temperatures of recent years, on the order 2℃ (about 4°F) in those forests.

Item: Farther south, in the Andean cloud forest above the Amazon basin, ornithologists have documented an "elevator to extinction." Like the Puerto Rican insects, Andean birds tolerate only a narrow range of temperatures. They move up the mountainside, to cooler elevation, as temperatures rise in the basin. Several species that were documented in the records fifty years ago have disappeared, and populations of other species on the mountain slopes are in decline. Their temperature range has risen above the mountaintops. (Freeman et al, 2018)

Item: Mass extinctions at the end of the Permian Age, 252 million years ago, wiped out over 90% of marine animals and 70% of terrestrial life. Sediments dating back to that Great Dying provide evidence that extinctions were particularly severe in oceans at high latitudes and were caused by anoxia aggravated by higher ocean temperatures due to greenhouse gases from massive volcanic eruptions. (Penn et al, 2018) We're starting to see similar conditions in the oceans today, including extensive "dead zones" in the Gulf of Mexico. Harbingers of things to come?

Item: The Greenland ice sheet is melting faster than at any time in recorded history, and the rate of melting exceeds any natural variation. (Trusel et al, 2018) Greenland ice stores enough water to raise global sea levels by about six meters (about 20 feet). (For comparison, the Florida Keys have an average elevation about four feet above sea level. Highest elevation in Sarasota, the highest coastal city in south Florida, is sixteen feet above sea level. And, oh yes, Antarctica, also melting, stores enough water to raise global sea levels by about 200 feet.)

These are not isolated findings. They are part of the general pattern.

Other studies reported in the past year have documented the obvious. Wildfires are larger and more intense. Smoke from wildland fires presents an increasing health hazard. Prolonged episodes of smoke damage the tourism economy; nobody wants to visit a tourist lodge when the skies are black and ash covers the parking lot. Dust blowing off the Great Basin, exacerbated by extended drought, darkens snowpack in the Rockies and causes earlier runoff, which in turn extends the wildfire season, reduces irrigation, damages fisheries, and decreases municipal water supplies. Extreme weather events are becoming more common; hurricanes are more powerful and intense precipitation events are more frequent. (Remember hurricane Maria? Harvey? Florence?) And, even on top of the economic impact of prolonged drought in the Southwest, those extreme weather events have already caused hundreds of billions of dollars damage to infrastructure in the U.S.

It's not conjecture that these are consequences of global warming. They are confirmed by the climate models. (That's the discussion next week.) Study after study shows the climate is changing. Faster than we thought. And with consequences beyond our anticipation.

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Climate models and global warming

In this article, I summarize scientific consensus on the state of the global climate and explain the basis for climate predictions. Climate projections are based on computer models, and few people in the general population understand how the models work. If there's been a failure in climate science, perhaps it is this: climate science understands the trends in the global climate, but we haven't done a very good job explaining the models by which we came to that understanding.

Two major reports published in the last few months summarize scientific consensus on climate: the updated Intergovernmental Panel (IPCC) report analyzes the effects of a 1.5℃ (about 2.7°F) rise in average global temperature, and the Fourth National Climate Assessment from the U.S. Global Change Research Program analyzes effects on ecosystems, agriculture, infrastructure, and the economy.

Who writes these reports? What is their purpose? Why can we believe them?

Last week I described the process of science by which we study climate and the effects of climate change. Many thousands of independent scientists, working in different places all over the world, study questions of particular interest to them. Some study ant colonies in the rainforest. Others study cichlid fishes in the great lakes of Africa. Others study ice volume on Greenland. The climate research community comprises thousands of scientists asking questions about how the planet works. Their findings are published only after rigorous review by experts in the field, and their findings are accepted only after they have been confirmed by other scientists.

Every four years a panel of climate scientists and policy experts in the United States, mandated by Act of Congress, review the latest reports from scientists in the field and update their recommendations for policy makers in Congress and the executive branch. Their findings are published as the *National Climate Assessment*. Also every four to five years the Intergovernmental Panel on Climate Change (IPCC) convenes for the same purpose but with a wider audience. The IPCC includes over four hundred climate scientists and policy experts from all over the world. They review the most recent research and updated climate models, and their reports provide guidance for governments all around the world.

The latest reports from IPCC and the National Climate Assessment warn of impending severe disruption to ecosystems, to agriculture, and to infrastructure.

The most recent IPCC summary, released in October 2018, is based on review of more than 6,000 published research studies by many hundreds of climate scientists all over the globe. It finds that the climate is changing more rapidly than anticipated and that even a rise of 1.5 ℃

above pre-industrial average global temperature will very likely result in catastrophic disruption to ecosystems, water supply, and agricultural productivity. A change of that magnitude also very likely will result in more extreme weather events (stronger hurricanes, more intense rainfall, etc.), increasing extreme heat events and heat deaths, larger and more intense wildfires, and emerging infectious diseases, among other potential catastrophes. Previous assessments have used 2 ℃ as the benchmark for projections. 1.5 ℃ warming is our near future. We have about twelve years, given current trends, to re-align the world economy to net zero carbon emissions.

The Fourth National Climate Assessment, published in November 2018, presents the same picture with specific reference to the United States. Following are quotations with summary findings from the Assessment. The particulars, with links to the primary research, are available online (U.S. Global Climate Research Program, 2018).

> Climate change creates new risks and exacerbates existing vulnerabilities in communities across the United States, presenting growing challenges to human health and safety, quality of life, and the rate of economic growth.
>
> Without substantial and sustained global mitigation and regional adaptation efforts, climate change is expected to cause growing losses to American infrastructure and property and impede the rate of economic growth over this century.
>
> Communities, governments, and businesses are working to reduce risks from and costs associated with climate change by taking action to lower greenhouse gas emissions and implement adaptation strategies. While mitigation and adaptation efforts have expanded substantially in the last four years, they do not yet approach the scale considered necessary to avoid substantial damages to the economy, environment, and human health over the coming decades.
>
> The quality and quantity of water available for use by people and ecosystems across the country are being affected by climate change, increasing risks and costs to agriculture, energy production, industry, recreation, and the environment.
>
> Impacts from climate change on extreme weather and climate-related events, air quality, and the transmission of disease through insects and pests, food, and water increasingly threaten the health and well-being of the American people, particularly populations that are already vulnerable.
>
> Ecosystems and the benefits they provide to society are being altered by climate change, and these impacts are projected to continue. Without substantial and sustained reductions in global greenhouse gas emissions, transformative impacts on

> some ecosystems will occur; some coral reef and sea ice ecosystems are already experiencing such transformational changes.
>
> Rising temperatures, extreme heat, drought, wildfire on rangelands, and heavy downpours are expected to increasingly disrupt agricultural productivity in the United States. Expected increases in challenges to livestock health, declines in crop yields and quality, and changes in extreme events in the United States and abroad threaten rural livelihoods, sustainable food security, and price stability.
>
> Our Nation's aging and deteriorating infrastructure is further stressed by increases in heavy precipitation events, coastal flooding, heat, wildfires, and other extreme events, as well as changes to average precipitation and temperature. Without adaptation, climate change will continue to degrade infrastructure performance over the rest of the century, with the potential for cascading impacts that threaten our economy, national security, essential services, and health and well-being.
>
> Coastal communities and the ecosystems that support them are increasingly threatened by the impacts of climate change. Without significant reductions in global greenhouse gas emissions and regional adaptation measures, many coastal regions will be transformed by the latter part of this century, with impacts affecting other regions and sectors. Even in a future with lower greenhouse gas emissions, many communities are expected to suffer financial impacts as chronic high-tide flooding leads to higher costs and lower property values.
>
> Outdoor recreation, tourist economies, and quality of life are reliant on benefits provided by our natural environment that will be degraded by the impacts of climate change in many ways.

The Assessment notes that people living in poverty and, especially, native peoples are disproportionately affected by climate change because they live in more vulnerable areas, rely more heavily on ecosystem services, and lack the resources to adapt.

As summarized by the IPCC and the National Climate Assessment, there is no doubt among scientists that climate change is real. It is human-caused. And it threatens human existence as well as the planet's web of life.

Projections of future climate are based on climate models that analyze and extrapolate measurements from field research all over the globe.

How is it possible to predict future climate? Why do IPCC and NCA say we've got about twelve years to re-engineer the world economy?

Measuring global temperature and precipitation is straightforward; put thermometers and rain gauges all over the planet and record those measurements year to year over decades and centuries. Comparing present climate to the distant past requires more sophisticated tools. Tree rings take us back hundreds or thousands of years. Ice cores, which record year to year accumulation of snowpack and the gases trapped in the snow, can take us back hundreds of thousands of years. Lake and ocean sediments with layers of foraminifera push the record back hundreds of thousands to millions of years. And other proxies can take us back even further. Such studies have been replicated all over the planet, and they show that the present climate is changing faster than at any time in the historic or geologic record (Royal Society, 2018).

OK, but how do we know that warming isn't just part of a natural cycle? And how can you predict the climate into the future? We still aren't very good at knowing whether or not it will snow next week. Here's where you have to understand the climate models.

Climate models are computer programs that replicate temperature and precipitation (and other climate data) in mathematical equations. Climate models, like other scientific models, are then tested by real world experiment and observation.

First a word on the word, "model." Scientists often borrow terms from the general vocabulary but assign them specific meaning. And often times that scientific meaning may not correspond to the general usage of the term. "Model," in science, refers to a set of mathematical equations that capture the behavior of a natural system. A good model accurately reproduces how nature behaves and allows scientists to predict the outcome of experiments. That's the test of the model: do the results of actual experiments agree with the model's predictions? A good model passes all the experimental tests thrown at it. Newton's model of gravity, for example,

$$F_g = \frac{-Gm_1m_2}{r^2}$$

accurately reproduces the measured gravitational forces in our solar system and enables us to calculate the rocket forces needed to send spacecraft to the moon and to the distant planets. Another example, the logistic equation accurately models the growth of populations, be it a population of E.coli bacteria in a test tube or a population of caribou on an island in the Bering Sea.

$$\frac{dN}{dt} = \frac{rN(K-N)}{K}$$

The rate of growth of a population of size N depends on the unrestricted growth rate r and the carrying capacity of the environment K.

Modern science builds models from data then tests those models by experiment and observation. Climate models are scientific models under the definition above. The equations are more complicated because earth's climate system includes many more variables than just the handful of variables in Newton's laws or the logistic model. Climate models include contributions from incident solar radiation, earth's rotation, heat transport by convection, the heat capacity of ocean water, reflectivity of ice and snow, atmospheric CO_2 concentration, cloud cover, and more. Climate models require many hours of computation on supercomputers. We have the computers. We have the models. And they work. Like other scientific models, climate models have been tested rigorously against observation and experiment.

How on earth do you do that? Test the predictions of a climate model against the actual results of an experiment? You can't experiment with planet earth.

Well, it turns out you can. Here's the trick. Reset the clock in your computer. Tell the computer it's the year 1900. Give the computer all the climate data it needs from the records for that year. Solar radiation, snow cover, jet stream track, concentration of greenhouse gases in the atmosphere, etc. Then let the model run, updating from year to year 1901, 1902, '03, '04 . . . Output the model's calculated temperature and precipitation for those years. Compare with the actual weather-station records. See if they agree.

The best available models are pretty much spot on. They successfully retrodict known climate. Temperature and precipitation graphs generated by the models for the twentieth century track the actual records. The models also have successfully reproduced the effects of unanticipated events such as the eruption of Mt. Pinatubo. And they have successfully predicted otherwise unanticipated patterns of global warming such as the dramatic increase in Arctic temperatures. (See Skeptical Science, 2018). So we have considerable confidence that they can predict future climate. And it's those models that provide compelling evidence it is human activity, particularly our use of fossil fuels, that drives current global warming. Run the models without oil and gas and coal combustion and you get steady global temperatures. Run the models with the addition of fossil fuel combustion and the models reproduce the rising temperature trend that we actually see.

The climate is warming rapidly. That is absolutely clear in the records. And it's warming because of human activity, particularly the addition of greenhouse gases to the atmosphere. That is absolutely clear in the models and in the observations testing those models.

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Evidence for climate change in the White River Basin

The two previous articles in this series examined the science behind our understanding of Earth's climate and presented evidence that climate change threatens to destabilize ecosystems, disrupt food and water supplies, and destroy infrastructure. In this article, I present evidence for effects of climate change closer to home. We see consequences of global warming right here in Rio Blanco County.

Memories fade quickly, but think back just a few months. Remember the extensive fires and smoke so thick you could hardly breathe? For days on end? Remember how dry it was? And the river at record low flow? Barely a trickle, relatively, by August and September.

That by itself doesn't mean much. Maybe just a really dry year. But it's more than that. It's part of a long-term trend. It's a signal of climate change.

We have a readily available record of climate trends for the White River basin.

We know that other rivers in the American West are changing. Published reports document earlier runoff and lower flow in several river systems in the western U.S. (Regonda et al, 2005; Stewart et al, 2005). Records for the White River show the same general trend.

The White River drainage has been well monitored. Temperature and precipitation at the headwaters are recorded by the snotel weather stations at Trappers Lake established in 1986 (Trappers Snotel) and at Ripple Creek. River flow data are collected by the U.S. Geologic Survey (USGS) continuous real time gauging station near Meeker (station 09304500) and other gauging stations along the river. The USGS database includes essentially continuous record from 1950 to the present.

The White River Basin is experiencing a long-term trend toward higher temperatures and lower precipitation.

The data speaks for itself. Temperatures at the headwaters of the White River in the period 2011-2015 were significantly warmer than 1986-1990 (Figure 1), and both January and August mean daily temperatures are trending significantly upward in the snotel data (Figure 2). These data are consistent with other climate stations in the Rockies.

Figure 1: Mean daily temperatures at Trappers Lake, average of water years 1986-1990 vs. 2011-2015. Temperature difference is significant; $P < 0.001$, paired t-test, $n = 365$. Mean daily temperatures in recent years are significantly higher than when data collection began thirty years ago. The greatest increases in temperature occur in mid-winter and late summer.

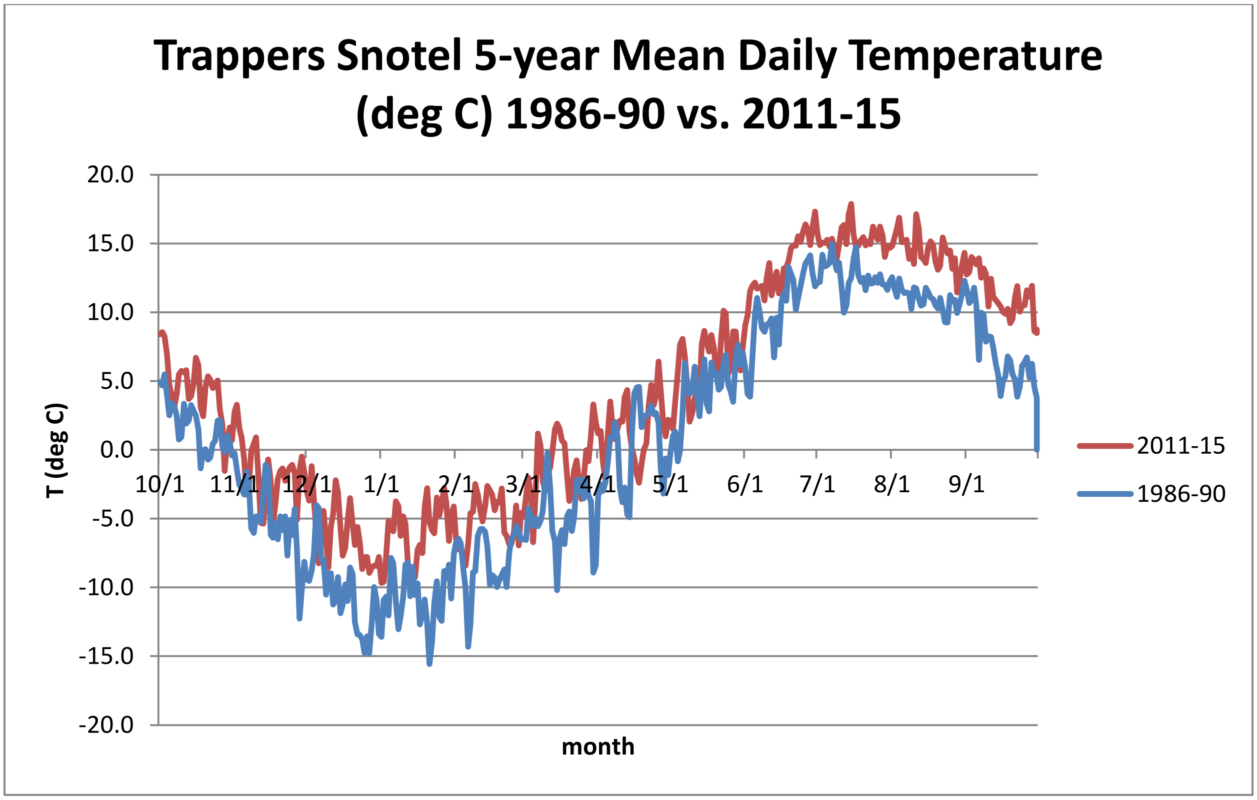
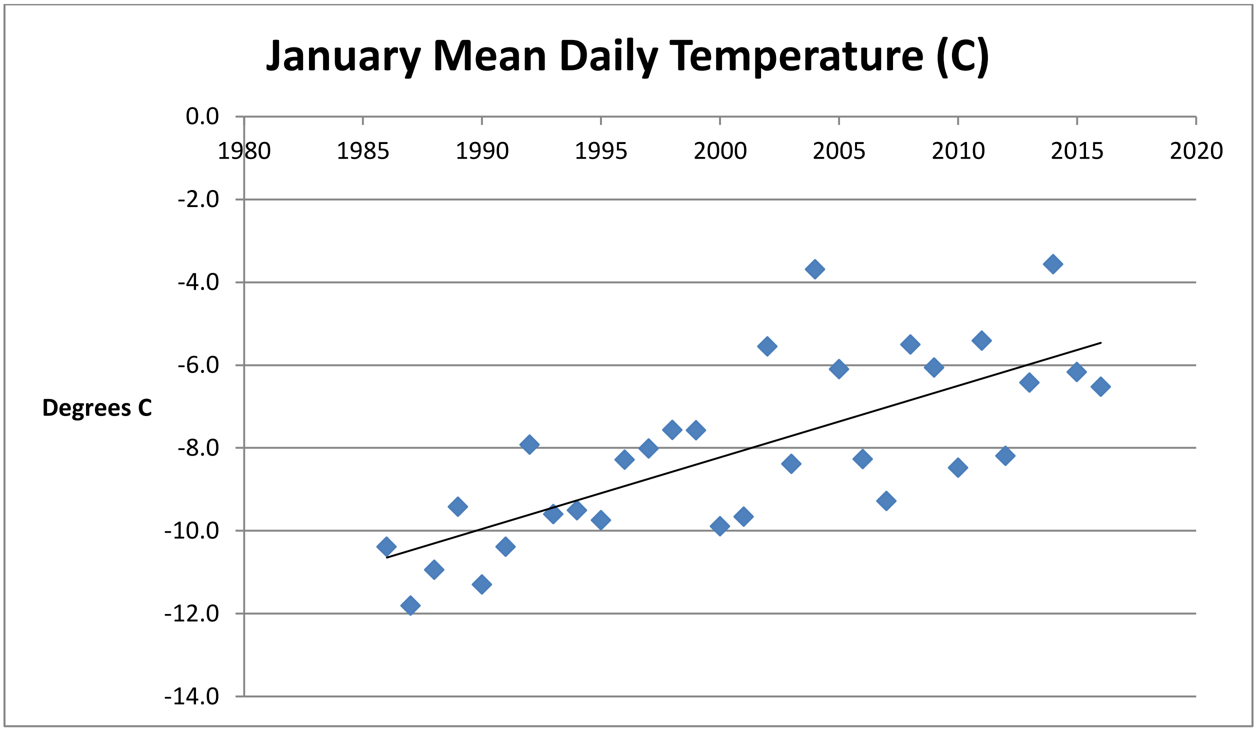
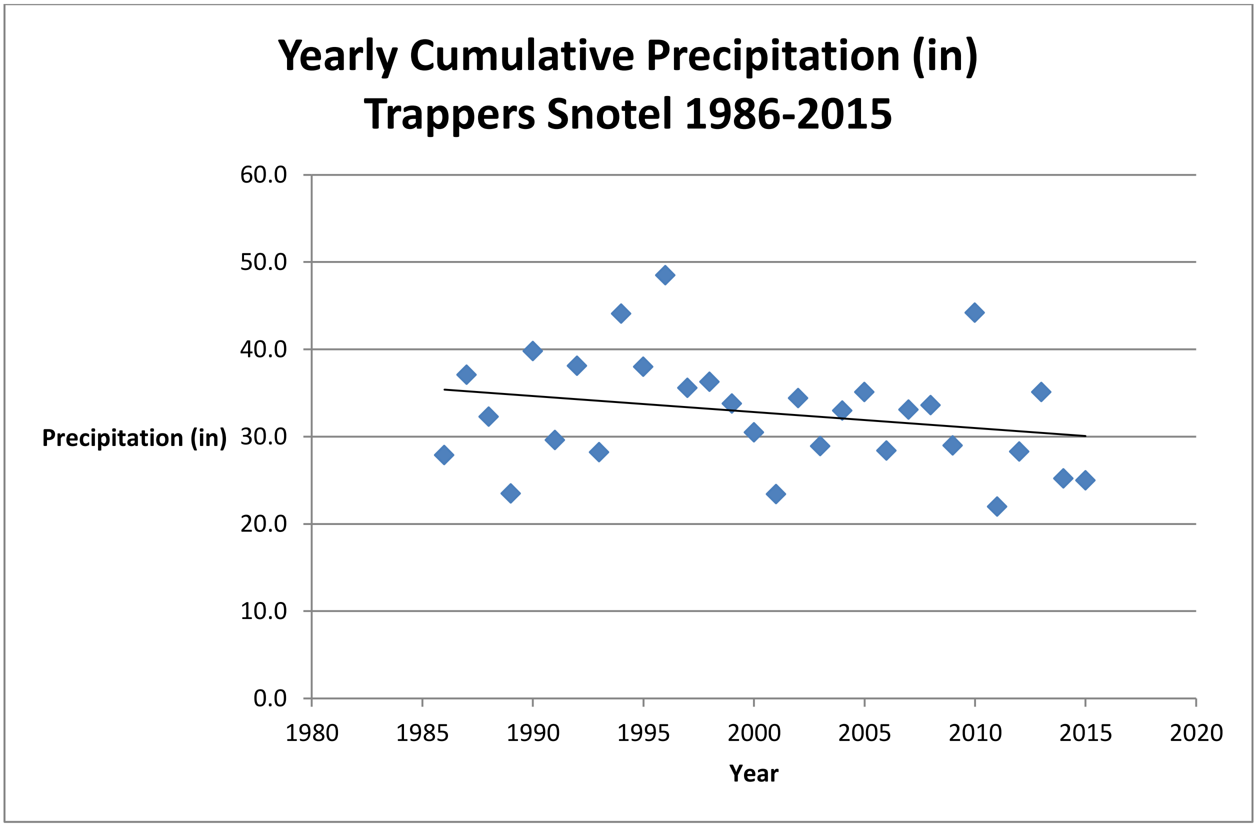


Figure 2. Mean daily temperatures in month of January at Trappers Lake, 1986 – 2016. Upward trend is significant; Mann-Kendall $Z = 4.266$, $Z_{critical} = 1.96$, $n = 31$. Trendline is best linear fit by least squares analysis in Excel. August trend (not shown) is similar, with Mann-Kendall $Z = 4.103$, $n = 31$. January mean daily temperatures at Trappers Lake are significantly higher today than thirty years ago. Mean daily temperatures also show greater variability in recent years. These observations are consistent with larger scale climate studies. Global temperatures are increasing, and as the climate drifts into a new regime, as in any chaotic system we can expect greater year-to-year variability (see e.g. Scheffer et al, 2009).



As temperatures rise, cumulative yearly precipitation at Trappers Lake is trending downward. (Figure 3). There's less snow accumulating in Flat Tops winters.

Figure 3. Cumulative yearly precipitation at Trappers Lake, water years 1986-2016. Trendline is best linear fit by least squares analysis in Excel. Mann-Kendall Z = -1.534, $Z_{critical}$ = -1.96, n = 31. Cumulative precipitation at Trappers Lake is trending downward. Ripple Creek Snotel data (not shown) exhibits a similar trend. There is less water-equivalent accumulation in the snowpack and summer rain today than there was thirty years ago. Snowpack disappears earlier in the summer (as documented in other studies), and there is less runoff into the river system.



Peak flows in the White River historically occurred in early June and typically ran 2000 to 4000 cubic feet per second (cfs), with considerable year-to-year variation. Given decreased snowpack in a warming climate, it is not surprising that peak runoff in the White River occurs earlier in the Spring and is trending toward lower volume. (Figures 4 and 5.) With decreased snowpack and earlier Spring warming there's less water running down the river at peak flow, and low flow volume extends from late June into the Fall. Among other consequences, these conditions enhance algae growth, stress fish, and limit availability of water for irrigation and municipal water supplies.

Figure 4. Date of peak flow in White River near the Town of Meeker (USGS gauging station 09304500) 1950-2016 plotted as interval number of days after the Spring equinox. Trendline is best linear fit by least squares analysis in Excel. Mann-Kendall $Z = -1.865$, $Z_{critical} = -1.96$, $n = 67$. Spring runoff these days occurs about ten days earlier, on average, than it did in 1950.

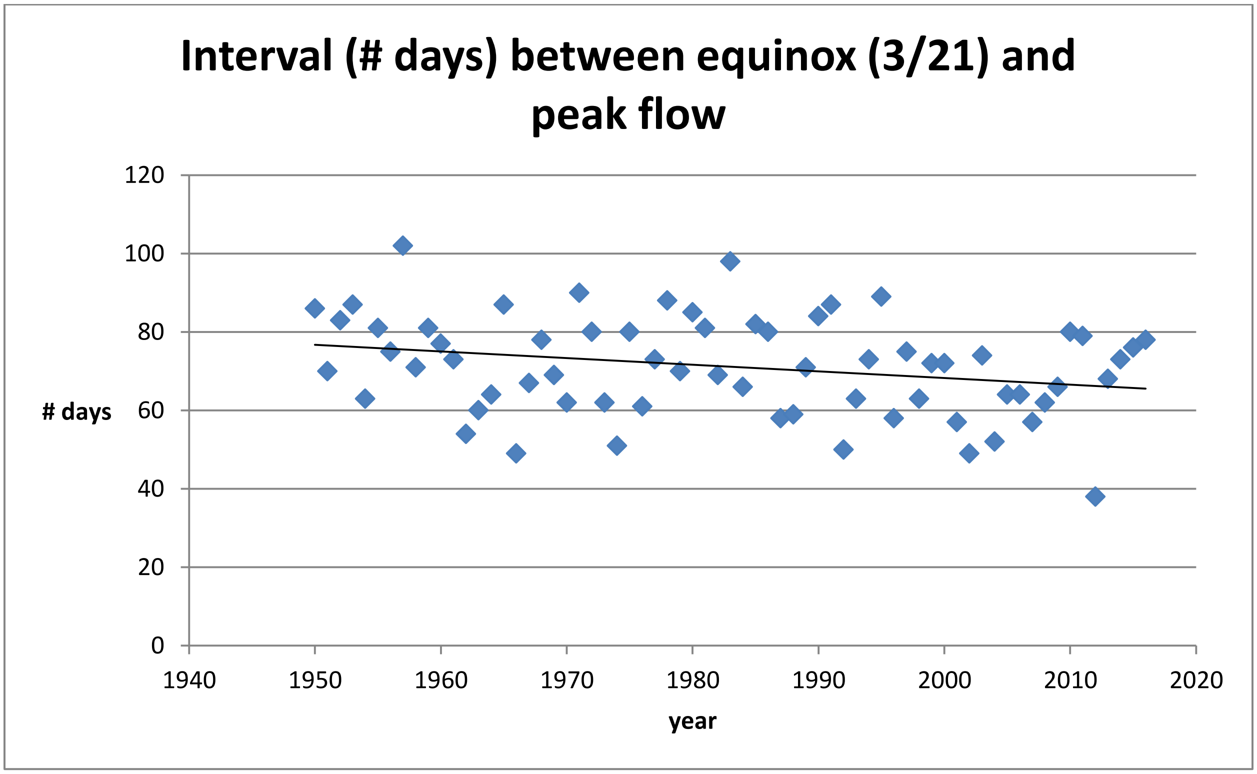
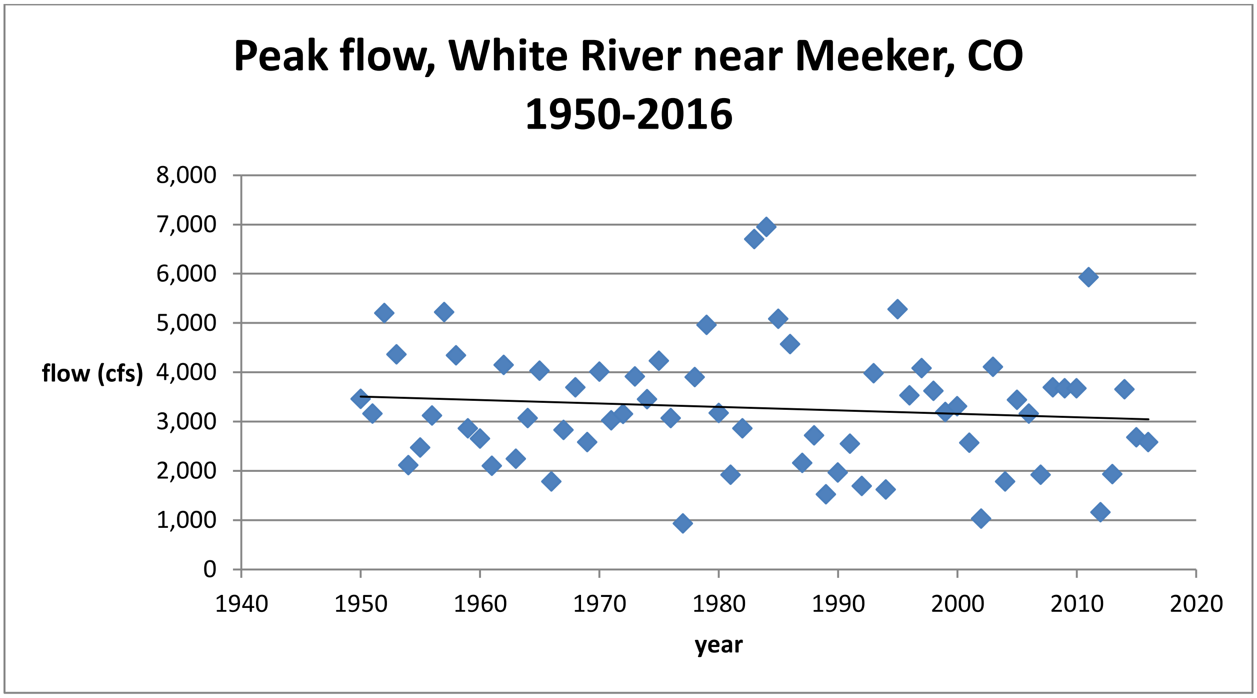


Figure 5. Peak flow (cubic feet per second) in White River near Meeker (USGS gauging station 09304500) water years 1950-2016. Mean flow for the period is 3276 cfs. Trendline is best linear fit by least squares analysis in Excel. Mann-Kendall $Z = -1.393$, $Z_{critical} = -1.96$, $n = 67$. Peak flow is decreasing and now averages roughly 500 cfs lower than it was thirty years ago. Among other consequences, decreased peak flow is not as effective at scouring algae off the stream bed, so more algae remains on the substrate from one year to the next. Decreased flow has other effects on the river ecosystem, as well, including changes in sediment transport and fish habitat.



These data are part of the general pattern of aridification of the American West.

These results show significant trends toward a warmer and drier climate regime at the headwaters of the White River in northwestern Colorado with higher temperatures at the headwaters, decreasing precipitation, decreasing stream flows, and earlier Spring runoff. While there is considerable year-to-year variability, it is likely that river flow in the summer will continue to diminish, causing further change in the river ecosystem. These findings confirm data from regional studies (National Climate Assessment: Southwest Region, 2014). Climate models forecast decrease in snowpack water to 75% of historical average by mid-century, with concomitant drops in runoff and reservoir storage (NCA:SW, 2014). Decreasing flows and warming climate will affect ranchers, municipal water systems, recreational activities, and everyone who depends on the river.

Next question, then: what can be done?

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Prospects for a future energy economy

In previous articles I summarized the facts of global climate change and evidence for its effects in the White River drainage. The trend is toward higher temperatures and increasingly drier conditions. We are at significant risk for ecosystem collapse, severe disruption of the food supply, adverse health consequences from extreme heat events and emerging infectious diseases, and increased damage to infrastructure from severe weather events. What can we do?

The short answer is: transition to a sustainable carbon neutral economy. The good news is that we are already in the midst of economic transition. Renewable technologies now offer economic alternatives to fossil fuel energy sources, and employment in solar energy has surpassed employment in both natural gas and coal (DOE, 2017). The bad news is that the global economic transition is far larger than the energy sector alone, and many traditional jobs are at risk – not just in the energy sector and not just because of the advent of renewables, but because of economic dislocations comparable to the industrial revolution two centuries ago.

We are living in times of unprecedented economic change.

The world economy is transitioning from human labor to robotics and artificial intelligence systems. (See e.g. Anthes, 2017, and Rotman, 2013.) Robots replace line workers in automobile assembly lines. Automated loaders, automated drilling machines, self-driving trucks and other equipment replace mine workers. Digital recognition software now out-performs trained dermatologists in recognizing skin cancer. And on and on, economic sector after sector, one job after another. For the first time since the industrial revolution, productivity is increasing faster than wages, which have been essentially flat for the past twenty years in the U.S., and economic inequality is widening. Corporations reap the profits of more efficient technologies, leaving workers with lower-paying jobs – or no jobs at all.

We’ve seen it before, in the historical record. For example, among other disruptions the Industrial Revolution in Britain displaced thousands of home spinners. Steam-driven spinning machines were far more efficient, and cheaper, than the cottage industry. That sent thousands of home spinners, especially women, into poverty. Market driven capitalism does that. Is it right? Is it fair? Society has to figure out how cushion such economic dislocation, if that’s our choice of economy. (And, we should point out, centrally planned economies in communist Russia and Eastern Europe did a whole lot worse, by all measures, than the West.)

Point is, it’s not all tree-huggers and wild-hair environmentalists closing down coal mines. If gas-fired power plants are more efficient and cost less than coal, natural gas takes a greater share of the market. And if land-based wind farms generate electricity more cheaply than gas-fired power plants, wind-generated power takes more of the market from gas. (For cost comparison on all of these, gas vs. coal vs. wind vs. solar, see U.S. EIA, 2018.) Then the problem becomes: how to care for and provide meaningful employment for displaced workers? Same problem as two hundred years ago, but on a much bigger scale. It's not clear we're any smarter how to solve it, but there certainly are more opportunities today than there were then.

Now pile on the economic impacts of climate change. Costs to the U.S. economy attributable to damage from events related to climate change, especially extreme weather and wildfires, exceeded $300 billion last year, and the overall figure doesn't measure individual suffering of the many thousands of people who have lost homes and livelihood (Gramling, 2018). The Fourth National Climate Assessment projects that if we continue business as usual, costs of climate change to the U.S. economy will exceed 10% of GDP by the end of the century (USGCRP, 2018). That would be $2 trillion, roughly, today – a little over half the present federal budget.

Driving climate change and economic disruption is human population growth. It is simply not sustainable. There were one billion people on the planet in 1800. 1.5 billion in 1900. 3 billion in 1950, a doubling time of 150 years. 6 billion in 2000, a doubling time of fifty years. 7.7 billion now, and on track to reach 10 billion by 2050 (UNDP, 2017). We use about 1.7 times more renewable resources, e.g. fish and forestry products, than nature can replenish (Global Footprint Network, 2018).

Things have to change. We can, as a society, decide to build a sustainable system. Or we can anticipate economic and social collapse.

Mitigation requires a new energy economy.

We are making progress toward sustainable energy sources, primarily wind and solar electricity production, but we have a long way to go. The long-term cost (LCOE) of wind-generated electric power and utility-scale photovoltaic solar now are both lower than the LCOE of coal generation (U.S. EIA, 2018). Energy economists forecast considerable further reductions in the costs of wind and photovoltaic solar electricity generation through this century (Bloomberg, 2018). On the other hand, fossil fuel consumption reached a new record last year (Forbes, 2018).

Converting to sustainable energy sources is not cheap or easy, and it will demand societal adaptations comparable to those experienced in the industrial revolution. Along with change in technologies and infrastructure, a new energy economy requires a change in human behavior. That's the hard part. It's a change in lifestyle and familiar habits. We're going to have to figure out, each of us, how to get along with new technologies and on a lower energy footprint. (See, e.g., Berkeley Carbon Calculator, 2018.)

Rio Blanco County can be a leader.

I don't pretend to have answers, but the evidence is clear. We're in trouble. How can we survive on a planet with finite resources and too many people? It's reassuring that we have developed sustainable energy technologies, and it is mind-boggling that machine learning and artificial intelligence put us on the cusp of a robot-driven economy and who-knows-what else. But that's a huge lurch in the lives of lots of people. At minimum, it is important to discuss these issues in the community and start to plan, at all levels of government, for an unfamiliar future. Rio Blanco County can be a leader in figuring out how to move forward.

Among other things, preparing for a new economy includes re-training for clean energy jobs. Other communities such as Paonia and Carbondale now host industry-leading solar training programs (SEI, 2018). With support from the County, the community college and schools we could invest in sustainable energy training programs here, too.

Fundamentally, the options are to adapt or scrape by in survival mode. Learn new skills for the new economy. Learn to program those robots, learn to install photovoltaics and wind turbines. Or re-train for the service sector: nursing, restaurants, outdoor recreation, etc. Otherwise, and not unreasonable, follow Voltaire's advice and "cultivate our own garden." Hunt and fish and grow vegetables and live off the grid. Then there's no worries what happens when the robots take over.

It's hard to be optimistic, given the current state of affairs. People tend to postpone change until it's too late. We are comfortable right now, so why worry? Pricing carbon to mitigate climate change, as has become the norm among most other industrialized nations, seems unlikely in our present political climate. A $40 per ton carbon tax, as has been proposed (get this) by ExxonMobil, GM, and other fossil fuel industries (Washington Post, 2018), would raise the price of a gallon of gasoline by about 36 cents. (For comparison, Europeans spend between $6 and $8 per gallon.)

36 cents on the gallon would cover about one-fifth the costs incurred in last year's hurricane season. But it's not likely Americans will agree to pay that price any time soon. And it's unlikely anybody is going to change their energy habits without other incentives.

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