Changing Precipitation, Temperature, and Stream Flow Conditions: Part 2, the long view…

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Editor's Note: The following paper represents a transcription of the speaker's remarks made at the conference. Remarks were edited for publication by the editor. The speaker did not review this version of his presentation and the editor is responsible for any errors.

Thanks for having me back in this beautiful state again. I come from another one of our beautiful states, Montana, and I have to say I was excited to come to the Southwest because I was going to get a bit more summer before eight and a half months of winter sets in. Then sure enough, I come down and it is snow and cold temperatures here, but it is five degrees in Bozeman today, so we are much better off here in New Mexico.

That also brings up another point: Mark Twain summarized best the difference between weather and climate when he said climate is what you expect, but weather is what you get. I think that is a good thing to keep in mind as we start talking about climate change projections. Even in some of our best climate reconstructions, we anchor people with where this region has been hydrologically and where it is going. You will notice a lot of the core tenets of what Sam Fernald talked about. Fellow speakers Lowell Catlett and Dave DuBois will come up in my talk, especially as we start discussing projections into the future.

Figure 1 is a roadmap of what I am going to discuss. I'd like to anchor everybody in the recent changes in climate at a global and then regional scale in temperature, snowpack, and hydrology. It provides very simple lessons that will carry through the entire talk. Then I will summarize much of what has been shown in past research across the western U.S., both warming across the West and its effects on snowpack, glaciers, and our water resources as well as altering our hydrographs. Then, to really anchor everybody in and make their eyes cross, we'll hop into the last thousand years because there are some very important lessons when you look at the past snowpack and stream-flow variability and we start thinking about the future. I was at a meeting in Colorado not long ago talking with water managers and the director of the Southern Nevada Water Authority was there. He summarized it best. He placed himself in a climate agnostic group because he said whether it went backwards or forwards it scares the crap out of him. The way the climate system operates presents big challenges for living in these desirable regions given growing human populations. It is that nexus of climate, humanity, and the human desire to live in these desirable places, like New Mexico, that is one of our problems as water managers. Then, I will talk about projections.

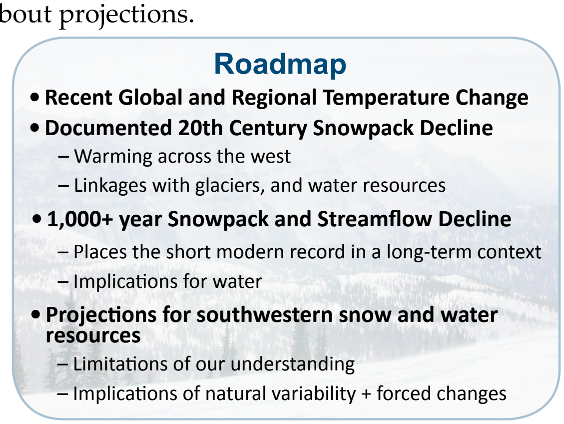

Figure 1. Roadmap of discussion

What everybody needs to keep in mind is that all models are wrong, but some are useful. In the projections category, we get a lot of useful projections out of them, but the climate system and Earth only gives us one. There is only going to be one climate realization, and none of the models will get it right, or only by chance if they do. But, hopefully they will point us down the road at how to plan for what is likely to be next.

Figure 2 provides a recent global update. Dave DuBois talked about this. The year, 2012, wasn't just the hottest year in New Mexico, it was the hottest year in U.S. history, but not globally. It ranked as ninth warmest globally. Our new record of the hottest year globally was 2010. But, if you look at what happened in 2012 in terms of land surface temperatures, they are between two and four degrees Celsius above average for the whole year. We witnessed both record melt in Greenland as well as minimum ice extents over our polar areas, which is a big climate game changer because that actually does have a large impact on our predominant storm tracks and where precipitation and moisture goes across the West. It seems counter intuitive, but as ice comes off the polar regions, we will be operating under a new rule set. But, if we zoom in on the U.S. for 2012 in Figure 3, we see our spring temperatures. I bring up spring temperatures because of their importance, especially minimum springtime temperatures due to their influence on our snowpack. You will see it across much of the West and the Great Lakes region. We are somewhere between two, and up to eight and even fifteen degrees Celsius above the long-term average in the February-March time frame. This is critical because February and March are the months that we rely on for snowpack actually falling on mountains, with temperatures staying cold enough so that snow can still accumulate and stick around. Snow basically represents free storage that accumulates in our mountains and is released slowly through our summer months. We don't have to build dams to hold the stuff up there.

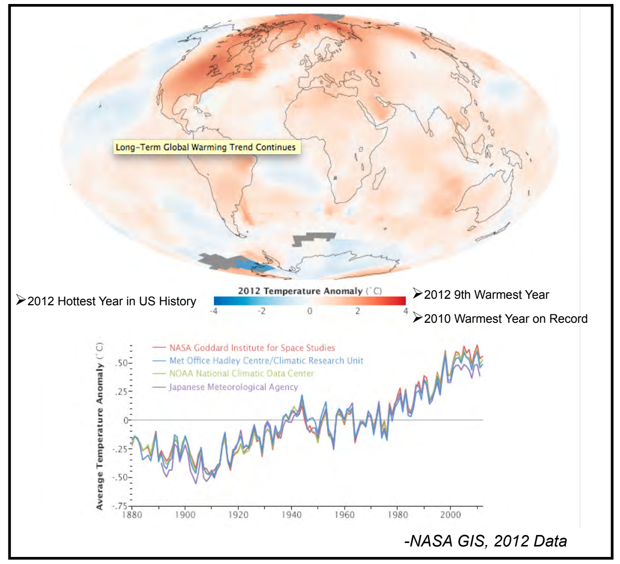

Figure 2. Historic Observed Changes: A Global Context

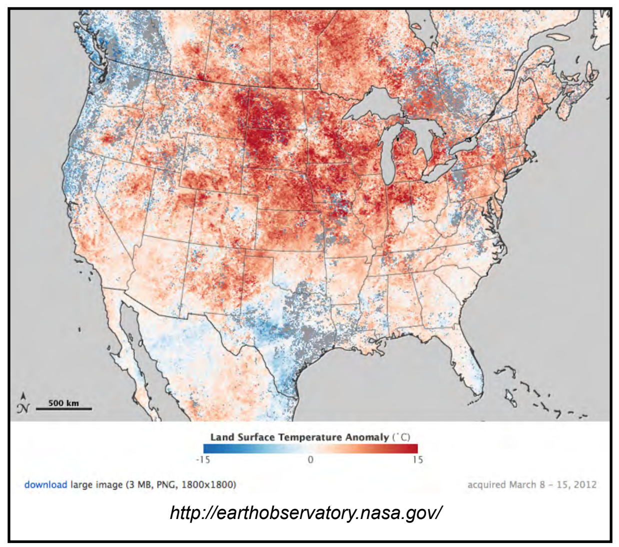

Figure 3. Historic High Temperatures

Between 2011 and 2012, we had the perfect Dr. Jekyll and Mr. Hyde years. In 2011, across most of the country except for New Mexico, we had extremely cool springs and high winter precipitation that gave us some of our record snowpack of the twentieth century into the late spring. That also led to some flooding problems in the Upper Mississippi River Basin when it melted. The white areas on the map in Figure 4 show high snow cover and basically high snow levels. In 2012, we were running temperatures far above normal. The blue areas of the map grew, you could see that temperature influence, plus an overall reduction in precipitation driving that snow out of the mountains, and leading to those big drought setups that Dave DuBois pointed toward. The interplay between temperature and precipitation, much like on our reservoirs as Sam pointed out, shows us that it is the integrating of these two parts of our climate system that generates high or low snowpack and variability from year to year.

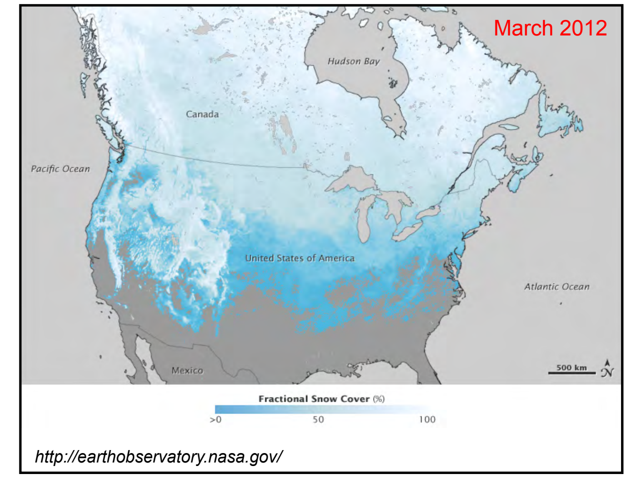

Figure 4. Drive Low Spring Snowpack

Now I will summarize the published literature about where we have been in the past century, especially in the last fifty years, with changes in temperature, precipitation, glaciers, snow, and ice across the West. Since the 1950s, we have seen our minimum temperatures warming faster than our maximums (Fig. 5). We have seen an amplitude of near a few degrees Celsius in most of the West with much of that centered in the Northern Rockies of the Pacific Northwest. The South-Southwest area has been spared somewhat; it hasn't been as rapid, and part of that is due to natural variability of the climate system. We've seen the greatest warming across the North, and in the classic detection and attribution sense of climate and climate modeling studies, you can't generate this amount of warming with natural variability alone. Again, given the warming we would expect from an El Niño event across the West versus a non-El Niño year, you have to consider the role of greenhouse gasses plus those natural influences to generate this magnitude of warming in the past fifty years.

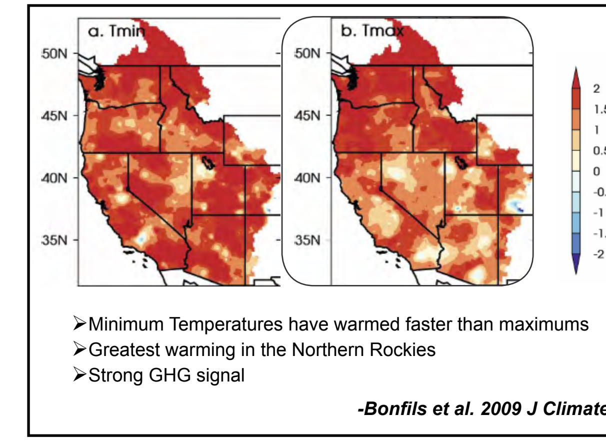

Figure 5. Recent Warming: 1950-2000

Mirroring that warming across the West, you also see general trends in the general time of year that we have peak snowpack, which is around April 1 in most of the mountains of the western U.S. (Fig. 6). At least by April 1 it is a good forecaster for how much snow we are going to have. You can see from the 1950s that snow has declined on the order of 15-60% with the worse declines along the Northern Rockies and the Columbia River Basin. The region in the Upper Colorado has seen a mixed response. The low and middle elevations have shown the same declines, but the higher elevations were showing level to increasing trends of snowpack. One of the reasons we are seeing this response is that a majority of our snow mass in the Northern Rockies fits much closer in the springtime to that zero degrees Celsius melt/freeze threshold than the high mountains of the South and Southwest. It was only about a degree Celsius over the last 30 years away from that freeze/melt threshold, so when you warm things up a little bit or cool them down a little bit, you see a big snow response much more than we are registering down here in the South and Southwest—that is both good and bad.

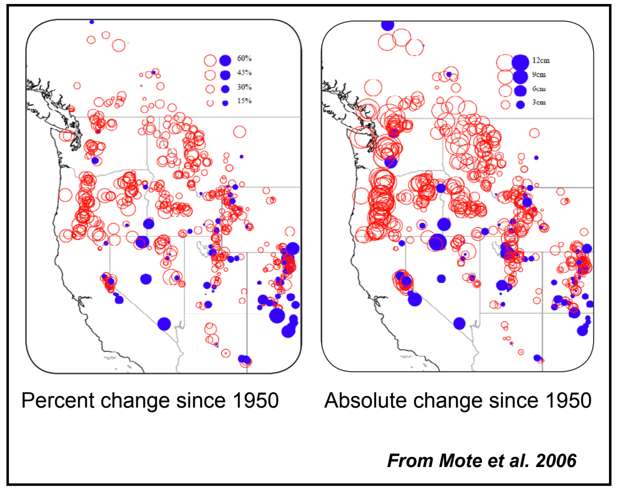

Figure 6. Trends in *APRIL 1* snow pack: 1950-2000

Going back to our snow, which is free storage, and turning to what is happening in our streams, you can see both lower peak flows in most of the West, with that mixed response across the Southwest, and about a one- to four-week advance in that snowmelt driven pulse (Fig. 7). We are seeing earlier and earlier stream flow registered at stream gauges, which leads to the problem of how to manage this resource through hot and dry summers; you have to manage this limited resource through increasingly warm, dry, and long summers. The general story line, and what the data show, is that as temperatures increase, we have seen a decrease in our snowpack with earlier melt-off of snow leading to earlier peak flows in our streams and lower base flows in the summer. It is greatest along the Cascades and Northern Rockies (Fig. 8). You'll notice that one of the more resilient basins, even as bad as this recent drought has been through these long-term trends, has been the Upper Colorado River Basin, at least on the basis of timing based on where this snow sits. The primary driver for this major response is the increasingly warm temperatures, especially the minimum nighttime temperatures in January, February, and March. Everybody who gets involved in the game of detection and attribution of what is causing this change has seen this recent change where about half of the decline of the snowpack has been amplified by natural drivers such as the Pacific decadal variability, and the El Niño Oscillation, and the remaining half seems to be due to the warming of greenhouse gasses. Study after study has parsed it out, but the exact amount is hard to say.

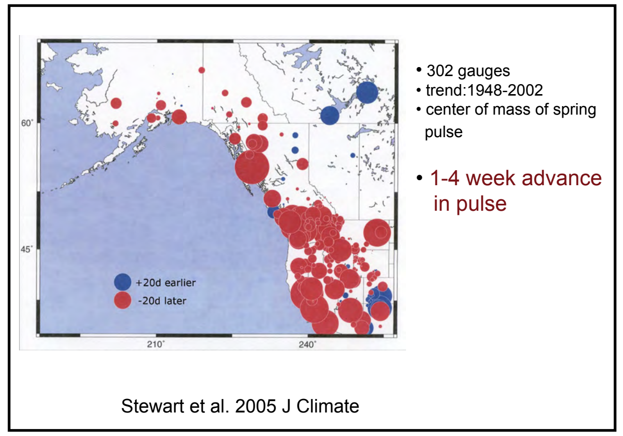

Figure 7. Trends in Snowmelt Timing

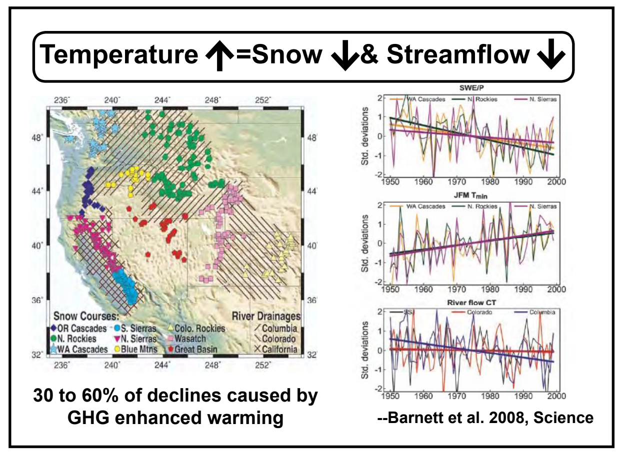

Figure 8. Increasing Temperatures Result in Less Snow and Streamflow

Figure 9 shows this hydrographically; this is middle 21st century and already similar to what we have seen in warming across most of the West. What we expect, for example, is a three-degree Fahrenheit increase. The blue line shows an historic plot where spring flows from snowpack peaking around June and early July run off into your base flows by September. What is more or less expected, and what is being detected at our stream gauges, is this shift toward diminished winter flows with more spiky winter flows due to increased mid-winter melt events of our high elevation snowpack. This shifts your hydrograph in runoff starting earlier and moving toward a lower peak that also occurs earlier. You then slide into this in early August where you are already seeing low-base flows that you used to see in September. That is a good visualization of what is happening and what is projected to keep happening. And similar to reservoirs, which are good integrators of the effects of temperature and precipitation on water balances, glaciers serve the same purpose but for the frozen part of our hydrologic system, the cryosphere so-to-speak. You can use old geologic and historical maps (everything that the USGS has been doing for the greater part of a century) and see the changes in glaciers and ice masses across the West. They tell this story better than any of the graphics I have can show you (Fig. 10) Looking at the decline in terms of a fraction of glacier area lost since 1900, you see that basically every place across the West is registering losses (Fig. 11). Some of our largest glacial losses are in areas like Glacier National Park in northern Montana where we have gone from a high of around 150 glaciers at the height of the last Ice Age to around 25 remaining today. The story is quite similar for the Yellowstone ecosystem where the 66% loss in area equates to about an 80% loss in mass.

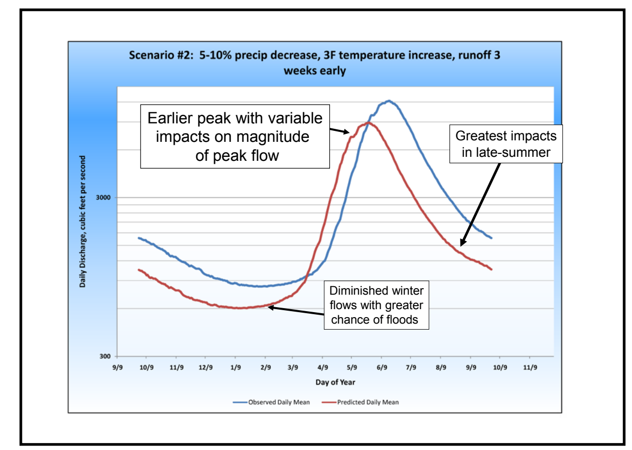

Figure 9. Projected Impacts of Increasing Evaporation & Earlier Snowmelt

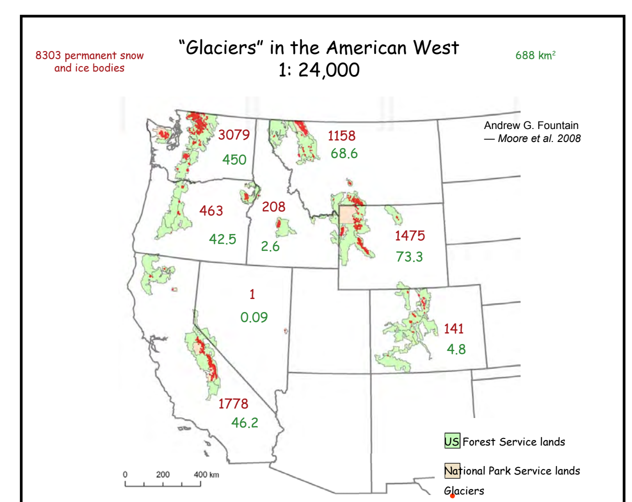

Figure 10. Glaciers in the American West

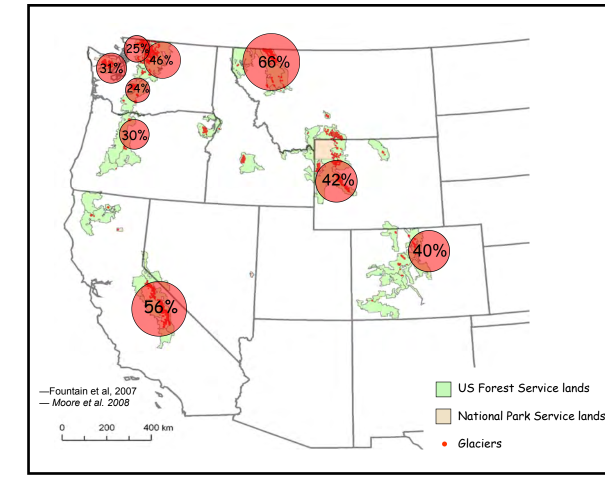

Figure 11. Fraction of Glacier Area Lost since 1900

Pictures tell the story best. Figure 12 shows these rapid and massive high elevation changes. The photos show Boulder Glacier in Glacier National Park, Montana in 1910 and in 2007. You can even see where its maximum extent once was from the entire Holocene. Sperry Glacier in 1913 and 2005 shows similar dramatic changes (Fig. 13). Massive changes have happened, and this represents our storage coefficient in the western United States. Ice masses and snowpack really sustain summertime base flows.

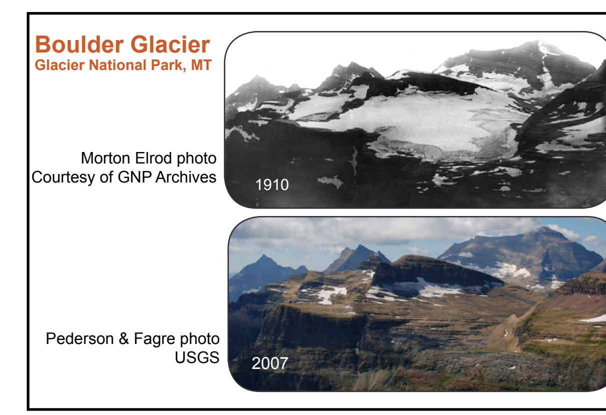

Figure 12. 20th Century Retreat, Boulder Glacier, Glacier National Park, MT

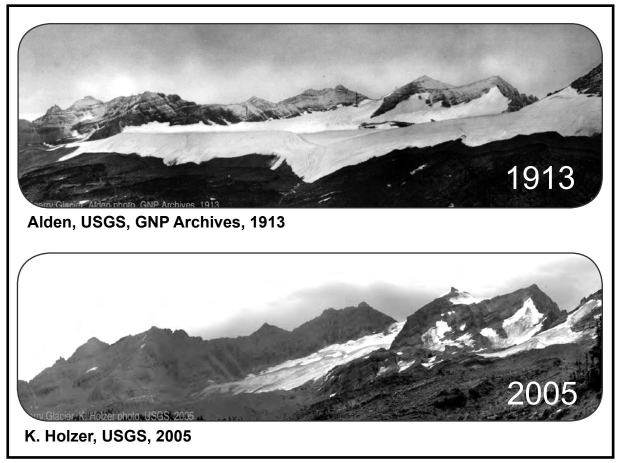

Figure 13. Sperry Glacier

We'll move on to the regionally focused part of this talk and look at the long-term history of changes of both the Upper Colorado and Rio Grande. They are both important water sources, of course, for New Mexico. We can look at this through both the recent lens of modeling studies that we have just done that run on temperature and precipitation across the basin, but also with our tree-ring study reconstructions of both snowpack and stream flow. One of the core papers that I will feature was published in 2011 and to which Sam referred (i.e., The unusual nature of recent snowpack declines in the North American Cordillera, Science, 9 June 2011, by G.T. Pederson, S.T. Gray, C.A. Woodhouse, J.L. Betancourt, D.B. Fagre, J. Littell, B. Luckman, E. Watson, and L.J. Graumlich). I was fortunate enough to work with this large group of people because we could compile all of our records from western North America where we had trees responding ecologically to changes in growth in our snowpack. I will explain briefly how they do that how that provides a reference point and a long-term history of snow change in the West.

We reconstructed snowpack in all of the basins shown in Figure 14. There is everything from level six hydrologic minutes to the entire Upper Colorado and the headwaters to the Rio Grande. We calibrated and screened all tree-ring records with long-term Natural Resources Conservation Service (NRCS) snow course records. The colored dots represent our network of tree-ring chronologies that span the West. Basically, they can tell us something about snow. There are two basic responses to how a tree tells us how much snow falls in a region. Here is the standard which everyone would probably expect; it is the "watering can" effect. The snow we get in the wintertime translates into soil moisture, trees grow on that soil moisture, and you have larger rings when the trees grow on larger amounts of snowpack. The other ecological response to snow that we captured across these basins was from many of our high-alpine trees and subalpine trees. Figure 15 is a photo from British Columbia showing Subalpine Larch at Hazeldene Lake. This is a deciduous conifer that sits at such high elevations near the upper limit of the tree line that when you get high snowpack winters, it shortens their growing seasons and they put on smaller rings. So both the timing and amount of snowpack, when it runs off, and how much is there gives you the inverse relationship at high elevations. Figure 16 is a great picture of the change in the northern Cascades just before the trees drop needles –you can pick those out from other tree species. They tell us a lot about the timing and how much snow there is along with Mountain Hemlock.

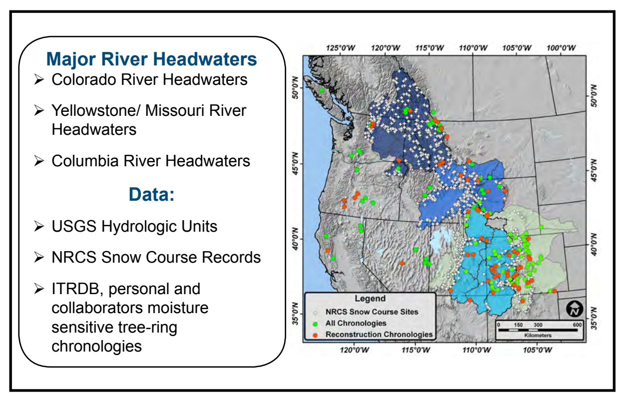

Figure 14. Primary Data for Major River Headwaters

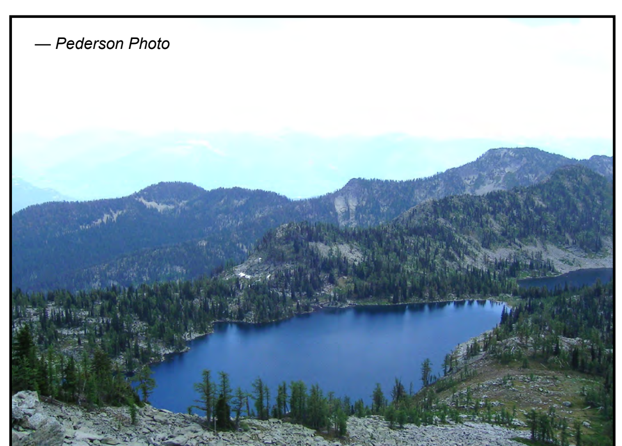

Figure 15. Subalpine Larch

Figure 16. Northern Cascades

From those two responses, you can do a pretty darn good job at reconstructing snow. Figures 17 and 18 are classic slides where we can show how well or how poorly we actually did. We looked at our observational studies for our snow courses from 1920 to 2006. We compiled all of these records, and here are the Upper Colorado River Basin snow records. The black line is the observational record. You don't see as much of the low frequency or decadal variability in a large magnitude change like you have seen in the Northern Rockies. You do see the high snowpack events of the 1940s and early 1950s before the 1950s drought. Then you can see the latter part of the century with the 1980s high snowpack when we were stilling our dams and reservoirs. What you are seeing in the background with the light grey are these individual watershed reconstructions for basins within the larger basin. The orange is the entire basin's reconstructions. What you can pull away from this is that the trees do a pretty good job at both tracking yearly events and this low frequency change that we call the decadal variability, as well as long-term trends. They match the records well.

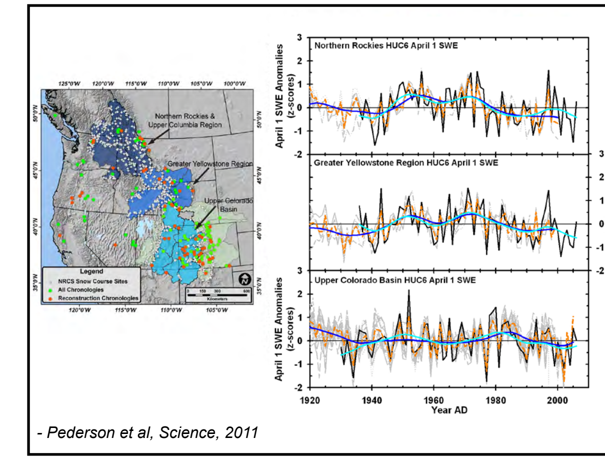

Figure 17. Results: Calibration 1

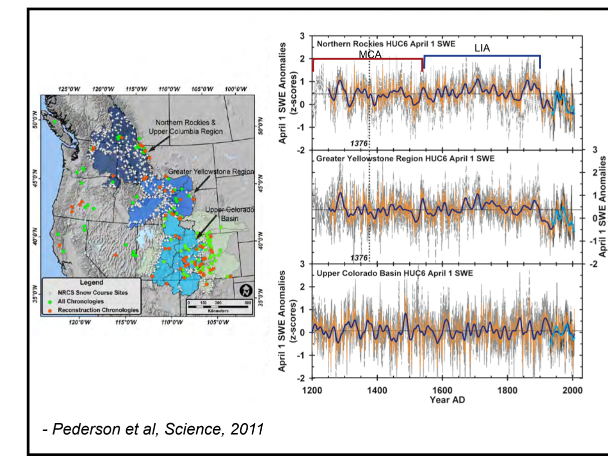

Figure 18. Results: Calibration 2

We have the backing and confidence to take this relationship and hind cast it as long as these trees have been growing at a population level, and that is what the graph shows. There are lots of squiggly lines but some summary points here. Looking at snowpack in places like the Upper Colorado River Basin, when we allocated all of our waters to the down river basins like New Mexico, Arizona, and California, it was again like our stream-flow reconstructions. It was a high snowpack and high-flow event. On a linear scale it was one of the highest. So, we started right off the bat looking at early water legislation that over-allocated water. The other thing that you see in all of these records is that bumpy ride where you can be in a wet sustained period for ten or twenty years at a time, or a sustained dry period for ten or twenty years at a time. As you will see in upcoming slides, the Upper Colorado River Basin seems to do that inversely to our northern basins. That is due to steering of our storm tracks from events like the

El Niño Southern Oscillation and Pacific Decadal Variability. When you have an El Niño event down south, you get high precipitation whereas across the upper areas of the country you get low precipitation.

I want to point out that even the paleo-records show the northern regions have seen both the cooling effect of temperatures generating higher snowpack in the last Ice Age where all the glaciers reached their maximums, and our lower snowpack at the end of the twentieth century during the 1940s to 1970s when snow was good. This gives you some perspective – at best, it was average for the period from the 1400s to the 1890s. But, years like 2011 certainly spike up into this range that gives you some idea of what little different ice conditions and snowpack conditions were for extended periods of time.

Now we turn to what has changed in a lot of these dynamics. What gave us confidence that we had succeeded in recreating winter snowpack was this tendency as we look across the record depicted in Figure 19: the Upper Colorado River Basin is in red, the northern regions are in blue. You can see that as you have high snowpack in the Upper Colorado River Basin, you typically have low snowpack in the northern regions. This represents where the jet stream is delivering moisture more or less. For the majority of these records, at least where we have continuous records for the past 800 years, that is what these records show. Very seldom do you see a breakdown in that behavior. Figure 20 shows graphically where little ice age glaciers expanded to their maximums in the North. You can see our upper basins of the northern Columbia and Missouri. We are registering extremely high snowpack. This even extends into the upper headwaters of the Colorado, but the lower part of the basin was actually dry. Going back further in time, from 1511 to 1530, you have a period of extremely low snowpack across the northern Rockies, but really good conditions in the Upper Colorado (Fig 21). But, when you look at records now, you see this synchronicity in decline. There isn't much of a dipole left (Fig 22). You have the recent decline in Colorado coupled with one up north. When you look back through the record, you only see these intervals in brief spots in the 1350s and 1400s where you see a synchronicity in declines as well. When you look at historic reconstructions of temperature, they coincide with temperatures that are nearly as warm as what we are seeing today.

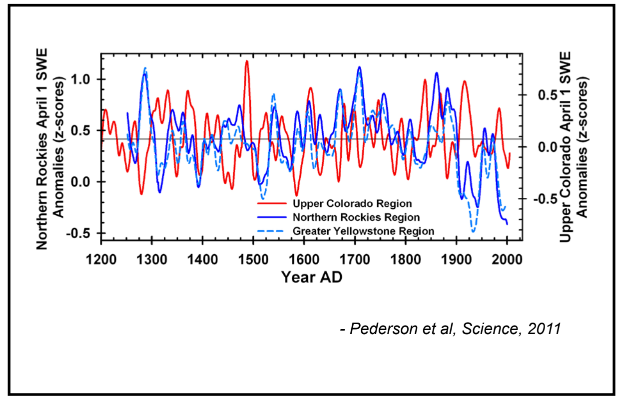

Figure 19. Stationary N-S Dipole

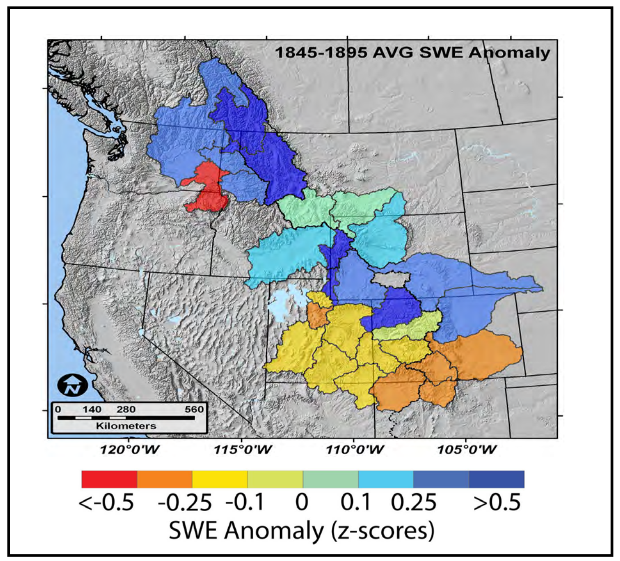

Figure 20. Little Ice Age Glacier Expansion

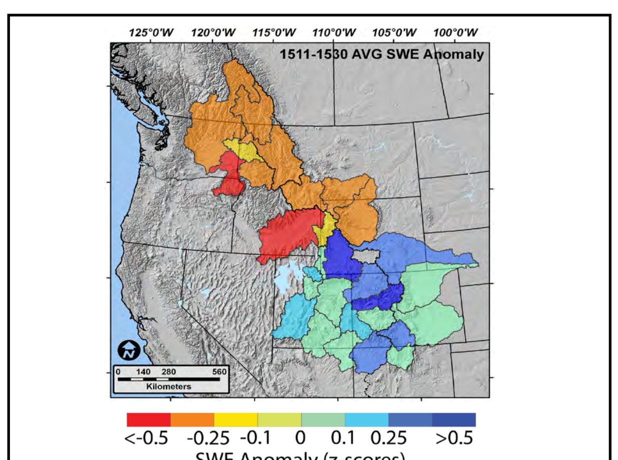

Figure 21. Little Ice Age Glacier 2

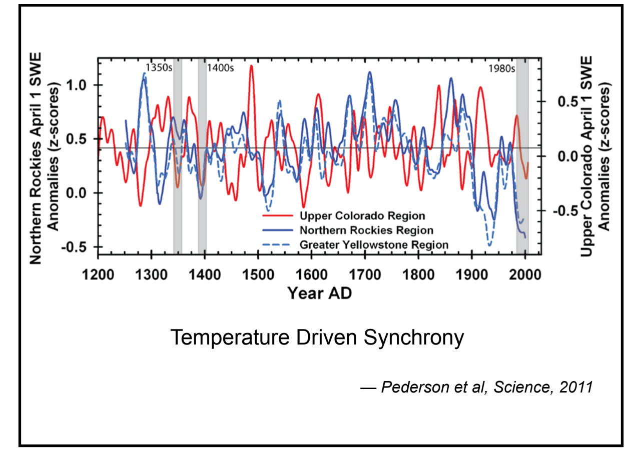

Figure 22. Stationary N-S Dipole, Temperature Driven Synchrony

Figure 23 shows what we currently look like compared to the long-term average, even when we hit 100% of snowpack that is now based on the 1980 to 2010 mean. Again, our greatest declines are being witnessed across the northern regions due to that temperature sensitivity and degree of recent warming and the start of those temperature driven declines in snowpack across the Upper Colorado. This is not good and is part of what is talked about when you hear things like a non-stationarity climate being driven by temperature. This is one of those changing rules that would be on a hydrologic rule curve. It is fair to ask how we know that it is a temperature driven phenomenon. We looked at our paleo-record work and we modeled snowpack across the West using only temperature and precipitation. We wanted to look specifically at what portion of the snowpack changes with temperature versus precipitation change. This model yielded some pretty interesting insights into the 2010 snow and temperature relationship.

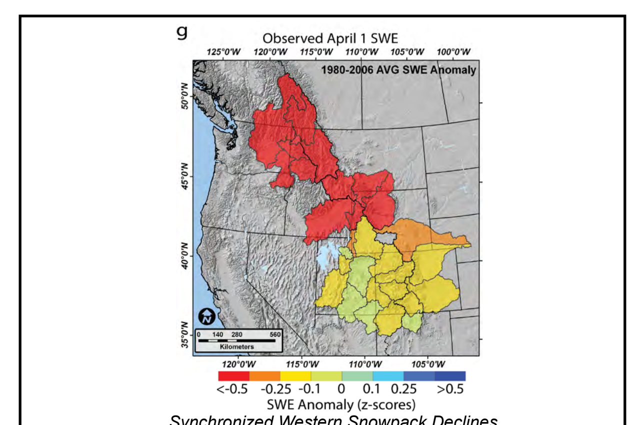

Figure 23. Recent Non-Stationarity

Figure 24 shows our tree ring reconstructions using our snow course records for both the Upper and Lower Colorado. The black lines show you how well the model did at reconstructing twentieth century snowpack. The reason we employed the model was to back out whether it was temperature or precipitation driven. Figure 23 has a lot of lines to look at, but the simple summary for these basins is: blue shows winter and spring precipitation effect on snowpack, and red and yellow show the winter and spring temperature influence on snowpack. For both basins, there has been a huge growth in the influence of temperature undercutting the accumulation of snowpack. This again is temperature driven synchronicity. High precipitation events spilling over dams in the 1980s were primarily driven by a huge influx of precipitation across the Southwest. When we allocated southwestern water resources, everything was pointing in the right direction for high snowpack and high stream flow. We had cold temperatures, shown in red above the mean line, with high precipitation leading to high snowpack and high flows that were unique in the last thousand years (Fig 25).

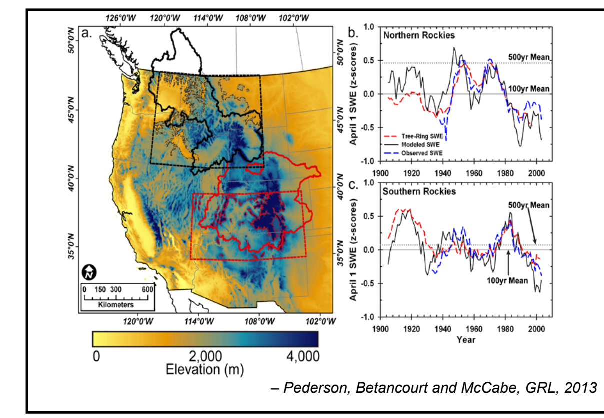

Figure 24. Snow Model: Temperature Relationship

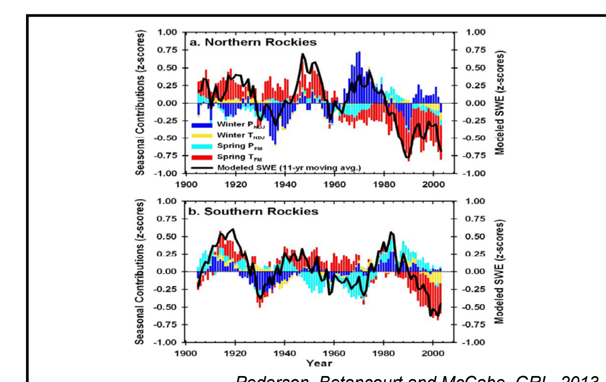

Figure 25. Post - 1980s Synchronous Snowpack Declines

We can also use this model to look at snow cover changes over the twentieth century In both the northern and southern Rockies, the middle elevations were where the majority of the snow mass sits. It has shown about a 20% decline, with the Upper Colorado Rockies in the 1980s showing a minor 5-6% decline. There wasn't that much change in high elevation snowpack of the southern part of the Rockies, which are headwaters to the Rio Grande. This synchronous snowpack decline my imply a new point of non-stationarity of western water resources. The last few decades may in fact represent a fundamental shift from precipitation to temperature as the predominant factor in snowpack in the North America area. We continue to see across a lot of these regions increasing spring and winter precipitation, mostly a phenomenon north of here, but decreases in overall snowpack. That is an important factor to parse out, and that changes our hydrographs. Increased warming will continue to modify annual hydrograph and stream temperatures altering our aquatic habitat and challenging water resources.

There are just a few points to be made when we compare our snowpack reconstructions to stream flow reconstructions. For the most, part they are a mirror image. When we have high snowpack, historically we have high stream flows. There are very little differences. All of the major droughts, like the medieval mega-droughts of the 1450s, the 1550s, even our 1950s drought, pair out in our records. They show the predominant nature of this system to shift very rapidly from a period of low sustained flows to high flows and high snowpack.

As Dave DuBois mentioned, it's a bumpy ride and it tends to get stuck for ten to twenty years in a row, which presents interesting management challenges. We can similarly compare our reconstructions to the Upper Rio Grande, which looks a lot like the Colorado plot. Figure 26 shows the individual snowpack reconstruction for the headwaters of the Rio Grande versus another tree ring reconstruction of flows at the Del Norte Gauge. You can see the same thing where there was high 1980s flows with high snowpack, and same thing when you have drought. With the low snowpack you get low flows in the stream flow records. They all point to the large influence that snow has on stream flow in this region, at least in terms of how it modulates your total annual and water year flows that are coming out of these basins.

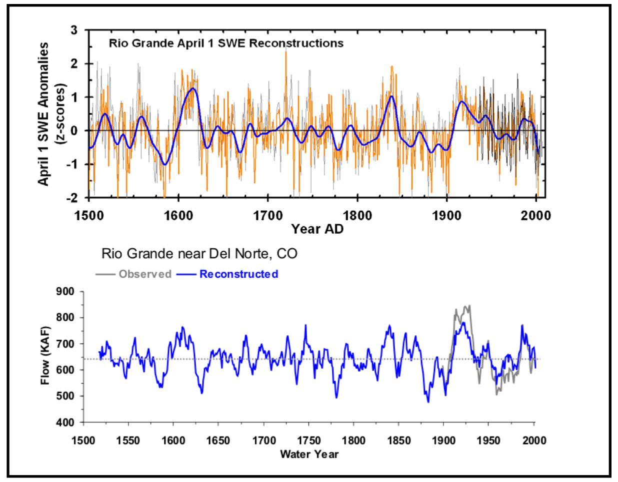

Figure 26. Snowpack & Stream Flow Reconstruction: Upper Rio Grande

Moving away from the paleo analysis, we move into the world of using big expensive models to produce really hazy and oftentimes poor forecasts. That isn't to say that they don't have some valuable information. We need to keep that in mind. Remember, all models are wrong, but some are useful. I find these models to be very useful, but they also challenge us as we work with data that have such high uncertainty when we plan for the future.

Figure 27 shows the new IPCC C55 model runs on twenty-first century precipitation projections. The vast majority of them show dry areas getting drier and wet areas getting wetter in terms of general precipitation. It is important to keep in mind that about two-thirds of these models are producing this enhanced loss of precipitation across the Southwest. It is a dynamic response that is expected from the models in which we get an intensification of Hadley cell circulation and increased subsidence across the south and southwestern parts of the U.S. This increases bridging and increases evapotranspiration; all of those processes that block storms from entering the region and also increased evapotranspiration out of the region.

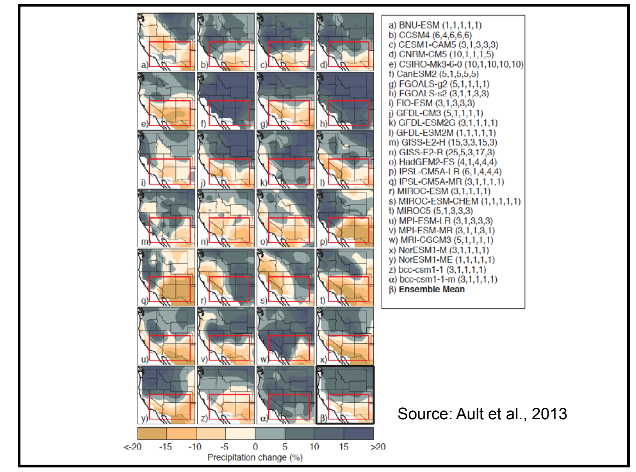

Figure 27. Near-Term Uncertainty—CAUTION: Models Disagree

You will notice that some models produce an entire wet West and Southwest. What do you do with those models? Who is to say which model is right? I will say one thing: about a third of the models that show this wet or neutral Southwest are normally coupled with models having a tendency toward future ENSO cycles to be more El Niño like. In the climate sciences, it is hotly debated whether the future of our southern tropic sea surface temperatures variability will be more El Niño or more La Niña. So, these models are operating on a mechanism that we are not even sure will be operating in the future. Thus you have model uncertainty, and you have between model uncertainty as well as within model uncertainty. In the Figure 28 model, they parameterized a single model, the CCSM, with different sea surface start temperature conditions or boundary conditions. It was run 46 times to see how it would change twenty-first century forecasts of precipitation and temperature. Basically for temperature, it doesn't show much difference. It shows you a mean difference of two degrees Celsius globally. But, you can look at the influence of that natural variability on the mean, and the end members say the warming across the U.S. You have one end member showing extreme rapid warming and one showing very little warming, but the central tendency being two degrees Celsius. Regions like Phoenix or Seattle show the same thing. That influence of natural variability or what is happening in our basins and overlying circulation can change the end members but they are more or less predicting this mean mid-century two degree rise. Warming is expected and especially so across the South and Southwest over the next twenty to thirty years.

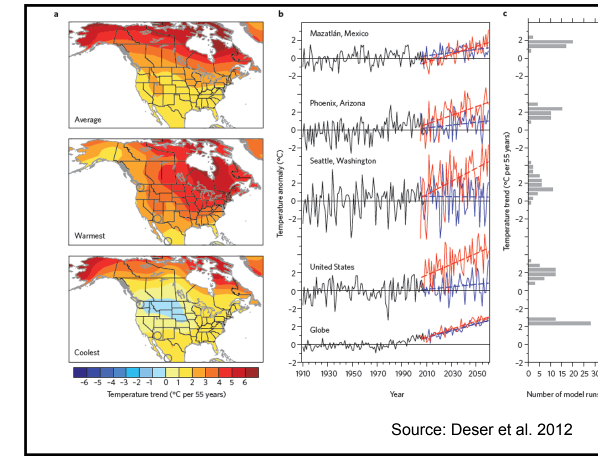

Figure 28. Near-Term Uncertainty—CAUTION: Natural Variability Still Applies

Figure 29 considers precipitation. The model shows that globally, it doesn't make much difference. You have around a 10% increase in global precipitation. But, if you look at our region where we are at right now, in southern North America, most areas are showing between a 10-20% decline with the most optimistic end member keeping precipitation similar to what it is today and the worst case scenario being really bad—around a 40% decline. In our northern regions, models are showing an increase in the range of 10-20%. Plus, given our natural variability and our uncertainty with precipitation, future projections of drying come from this temperature response. As you warm everything up, you melt snowpack and increase evapotranspiration.

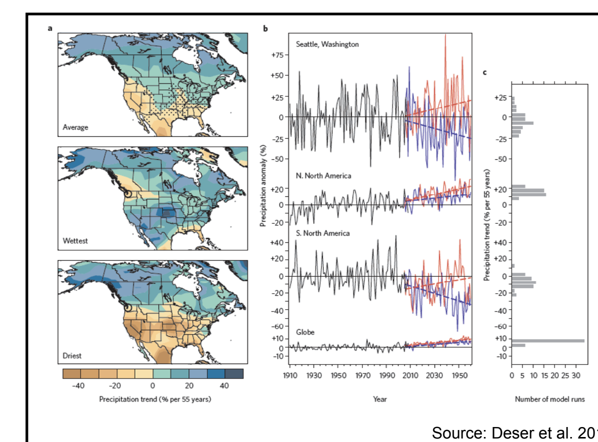

Figure 29. Near-Term Uncertainty—CAUTION: Natural Variability Still Applies

Regardless of what precipitation does, the magnitude and ubiquity of warming is expected to drive the Southwest and the West as a whole. But we can't say exactly where or how fast the West is going to dry because of errors associated with problems that Lowell Catlett pointed out earlier this morning. When you look at future model projections of increased aridity, I think we tend to think of it as some nice, linear, slow transition from today's more moist environments to tomorrow's more dry environments. What we have learned from both the paleo records and the global climate models is that our future climate is going to be a realization of natural variability in the system plus warming. We may ultimately end up with a more arid environment via a wavy path like in Figure 30 or any one of these realizations. The climate models can't tell you which one of these it is going to be. This upper threshold is a management target for when things get really bad in terms of aridity and stream flow and you have to change allocation rules. You may end up on one of these luckier paths where you approach but always avoid the worst case scenarios. Or, you might have a large amplitude swing in the future climate system where it gets really bad.

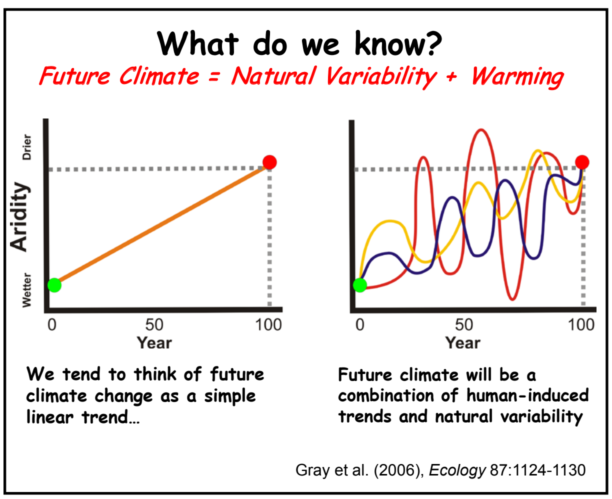

Figure 30. Climate Model Projections

What do you do when the system behaves this way? How do we think about setting up management portfolios that allow for this type of variability superimposed over long-term trends? This is the question with which I would like to leave to everyone.