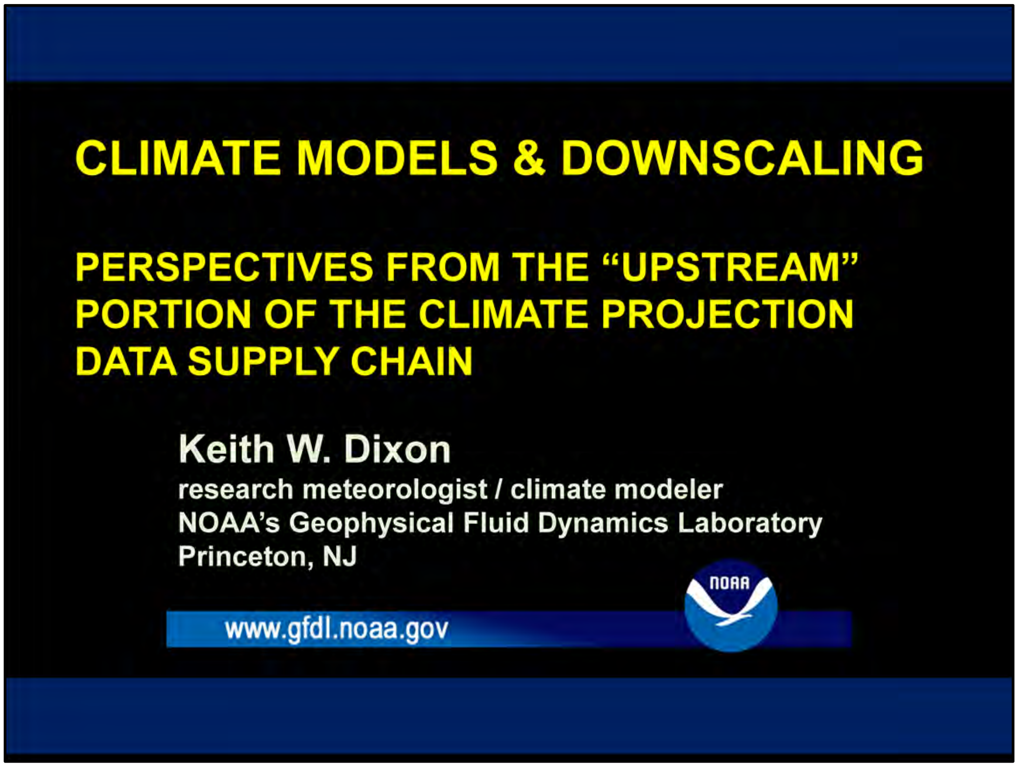
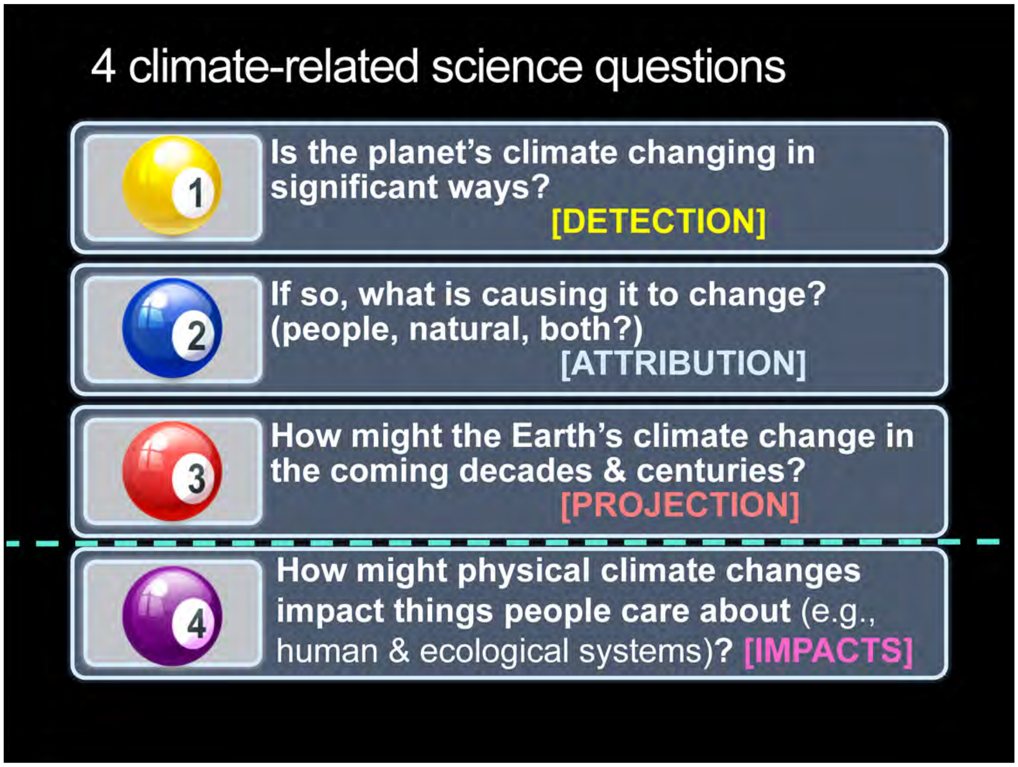


Presented by Keith W. Dixon http://www.gfdl.noaa.gov/kd, a researcher at NOAA's Geophysical Fluid Dynamics Laboratory http://www.gfdl.noaa.gov

My background:
After getting undergrad and graduate degree in meteorology at Rutgers University, I've been a climate researcher at NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) in Princeton, NJ, since the 1980s. At GFDL, I've worked on many different research topics, all of which have somehow involved the big, complex, and continually evolving computer programs we often refer to as global climate models (GCMs). However, back during my undergrad and grad school days, I briefly worked part-time as a radio broadcast meteorologist. So, I've worked on both the short-term weather and long-term climate sides of the fence. I hope that some of the perspectives I have gained over the years will come in handy as I present some info about how climate researchers who study decadal to century time scale climate variations and change use global climate models as one tool in their scientific toolbox… and, how scientifically credible information can be transferred from the realm of the large scale global climate models to that of regional climate impacts applications.

My email: Keith.Dixon@noaa.gov
My team's web page: http://www.gfdl.noaa.gov/esd

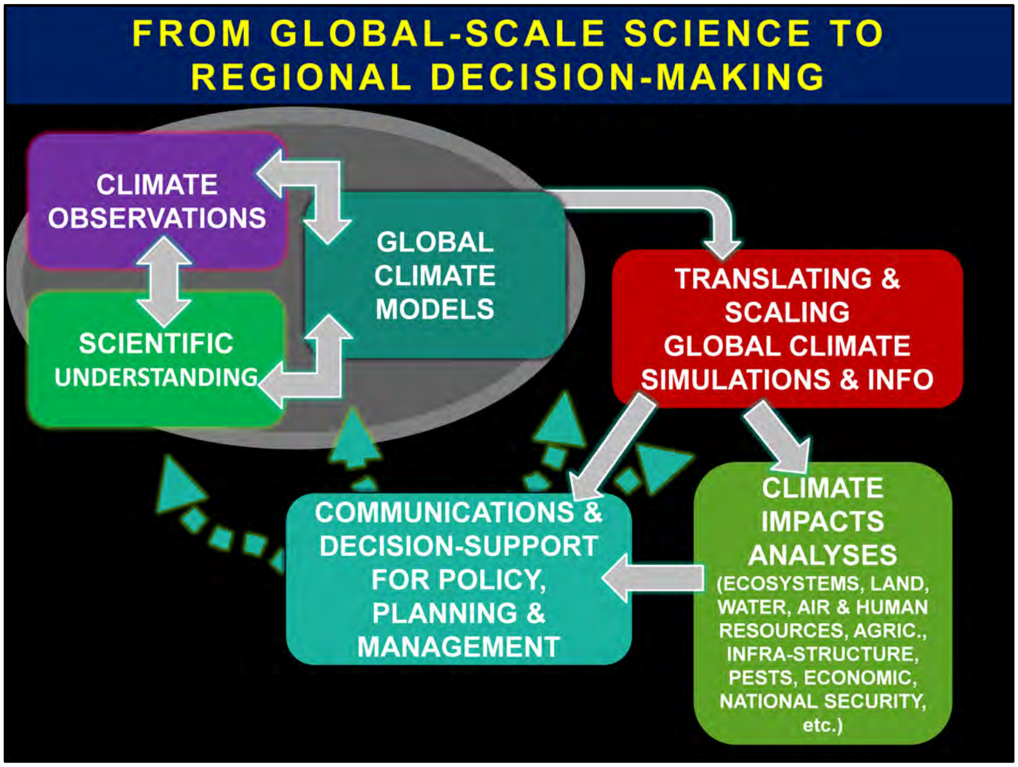


Framing the topic of today's talk:
<1> Questions of Climate Change Detection begin with an analysis of observational records but are also informed by climate model simulations.
<2> Questions of Climate Change Attribution are made via a synthesis of Observations, Theory, and Numerical Climate Models.
<3> Questions of Future Climate Change rely heavily on Numerical Climate Models. Multi-decade to century time scale climate change projections are dependent on "boundary conditions" including assumptions about future greenhouse emissions (and hence, about human choices).

Questions 1, 2 & 3 deal with the physical climate system. Clear statements about the assessment of these questions have been made by many prominent scientific organizations. Historically, one oft cited report linked to the topic's increased visibility is…

•Summary for Policymakers, Climate Change 2007: Working Group I: The Physical Science, the Intergovernmental Panel on Climate Change (IPCC), http://www.ipcc.ch/publications_and_data/ar4/wg1/en/spm.html

<4> Question 4 leaps from the realm of the physical climate to that of a wide variety of systems that are affected by climate. One implication is that climate impacts studies can be more inter-disciplinary and may be led by researchers who are not climate experts themselves. Also, different climate impacts studies will have different data requirements and underlying assumptions. So, the question of what climate science can say about a particular potential future climate impact is very much dependent on the specific system being studied.



The figure illustrates that the process of going from the best available climate science to well-informed planning and decision-making involves a number of steps.

The transfer and translation of information is not just between scientists and the ultimate end users, but it also occurs between scientists with different specialties - such is the interdisciplinary nature of the climate challenge.

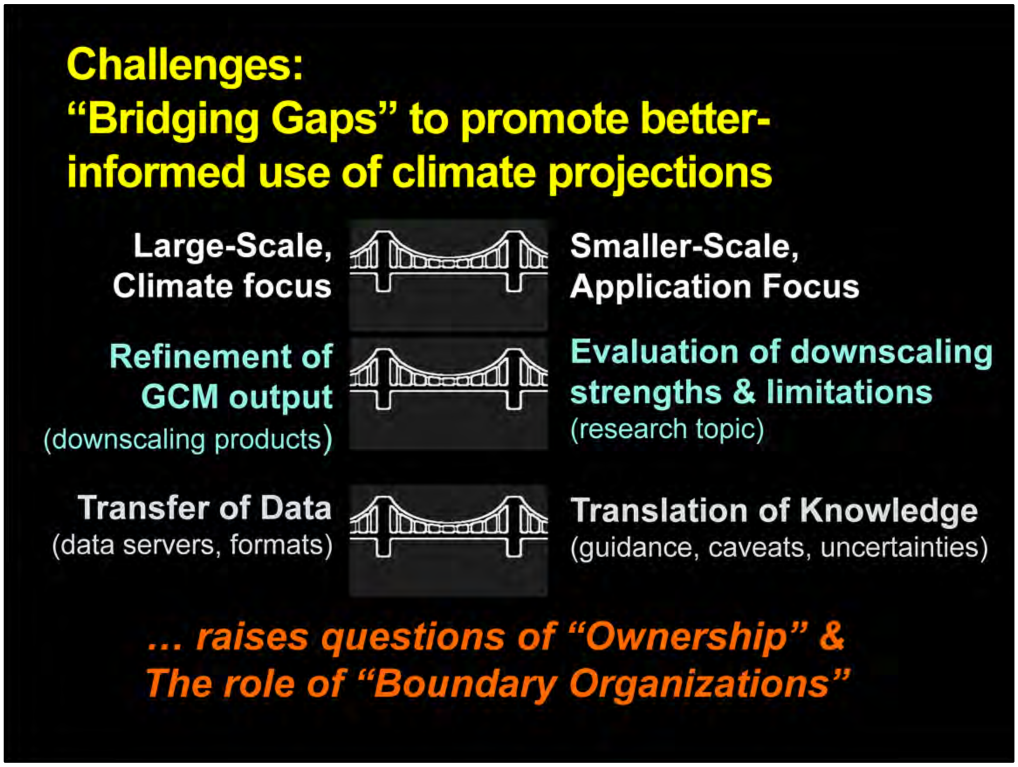
•UPPER LEFT - LARGE-SCALE PHYSICAL CLIMATE SCIENCE: In large part, we're discussing this topic today because of advances climate science has made in the past few decades in understanding the way the global climate system works. That knowledge came about as a synthesis of observations, theory, and numerical modeling came together to tell a consistent, scientifically compelling story about the mechanisms involved in climate variability and change – both natural and human-induced. Yes, the planet is warming; Yes, most of the warming of the past 50 years is associated with human activity; Yes, climate change is a lot more than just temperatures (global hydrology, etc.) ; and Yes, we can expect the changes to continue.

•UPPER RIGHT - DOWNSCALING & TRANSLATING LARGE SCALE CLIMATE MODEL INFO: But the large scale physical climate info itself doesn't meet most decision-making needs. People are interested in smaller spatial scales and climate-related variables that are closely linked to factors other than just the raw output of the global climate models. Translating information about the physical climate into more relevant terms of interest to stakeholders can be done via data processing and by providing guidance.

•BOTTOM RIGHT - CLIMATE IMPACTS ANALYSES: Which leads us towards the many kinds of climate impacts applications that make use of information derived from climate model projections.

•BOTTOM LEFT: This information needs to be communicated effectively – again, transfer and translation (including social science aspects) - so that risk management, adaptation planning, and other concerns of the stakeholders can be met.

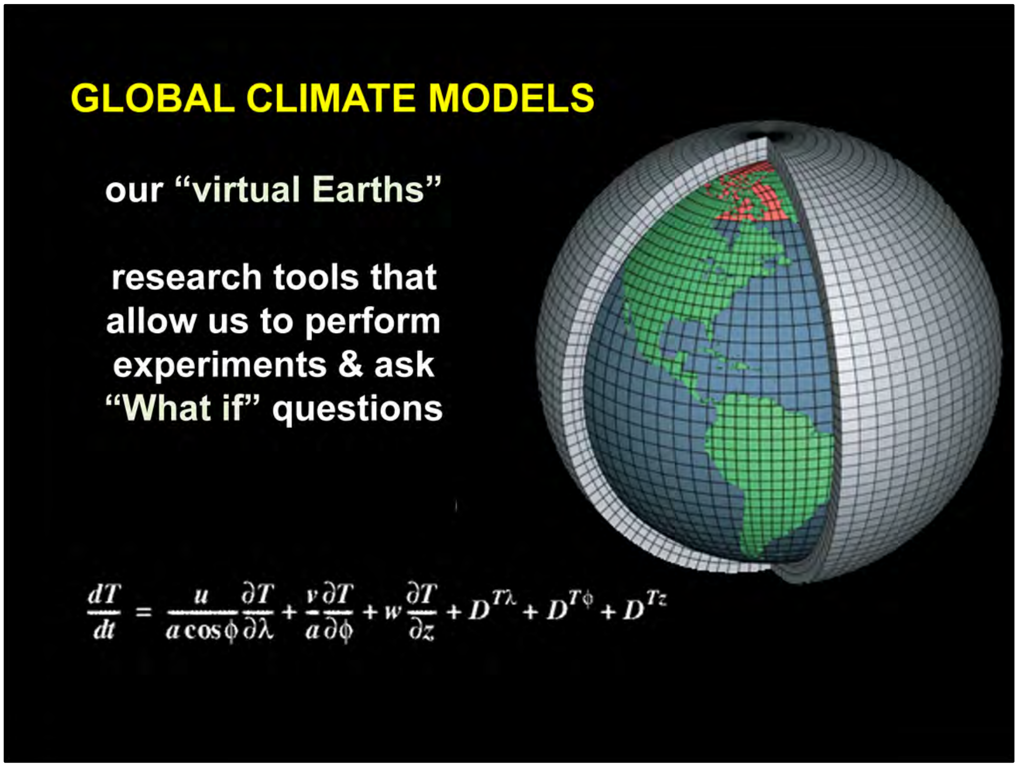
And the dashed arrows are intended to indicate that stakeholder needs in turn influence the topics that garner attention among the researchers in the large-scale climate science community.



Several challenges exist when seeking to make use of future climate model projections as part of a climate impacts study. For one, the global climate models were developed as research tools that simulate the entire 3-dimensional globe (e.g., the global atmosphere, ocean, land surface, and sea ice) and hence focus on large-scale features. They are not calibrated with a particular geographic location in mind. In contrast, many climate impacts studies are interested in smaller spatial scales and non-climate factors.

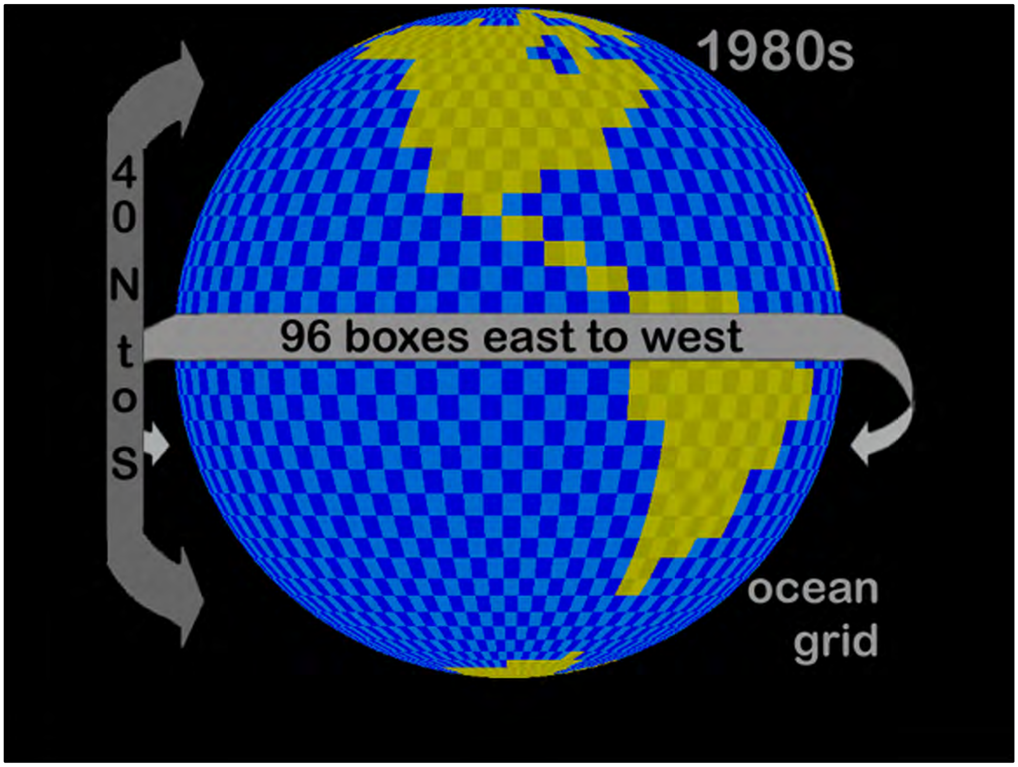
I'll discuss the second bridge – the refinement of GCM output – in more detail later. Here I'll note that GCM output often can be deemed to be unsuitable for direct use in a climate impact study because it may contain biases at the location of interest. For example, compared to observations, a model simulation of the contemporary climate may yield winter temperatures two degrees too warm on average, the number of days per year with precipitation may be overestimated by 20%, the seasonal cycle of precipitation may be shifted by a month, strong gradients along coastlines may not be well represented, etc. While not disqualifying from a global climate perspective, such biases may be unacceptable in a climate impacts application, and so some "refinement" or "downscaling" of the model output may be done.

The third bridge is often underappreciated. It is relatively easy to put climate model projection data sets on servers so that climate impacts researchers can readily download it any continue with their work, without any interaction with a climate scientist. While ready access to data facilitates the ability to do climate impacts studies, it does run a risk of having climate model projections misinterpreted or misused. I use the analogy that we accept that some medicines are over the counter and others are by prescription only. Climate projection data portals, in effect, make a lot of data "over the counter", and so, we shouldn't be surprised if under-informed use of such data products can sometimes lead to sub-optimal results.



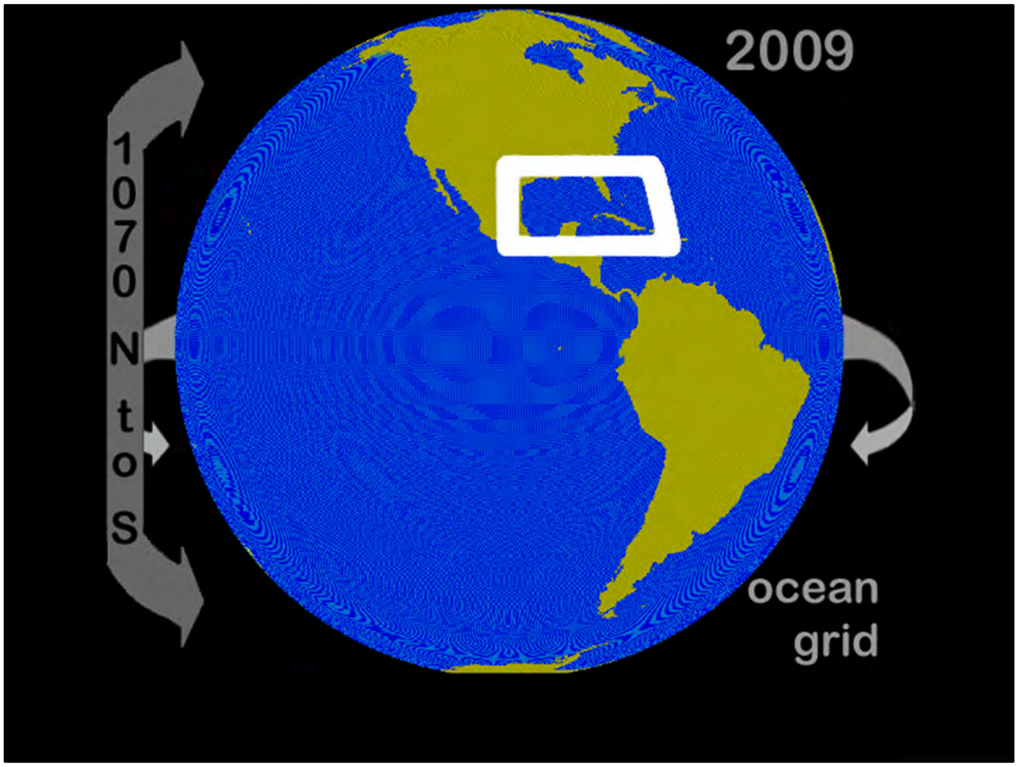
One can view a global climate model as an assemblage of a set of models representing different interacting parts of the Earth's climate system.
In this schematic, one can see the atmosphere, ocean, land, and sea ice components represented. But each of those component models are themselves a collection of subprograms. For example, in the atmospheric model components there are subcomponents that deal with just the simulation of convective clouds, the transfer of electromagnetic radiation (ultraviolet, infra-red, and visible light), the exchange of heat between air that comes into contact with the sea surface, and many other processes. The model equations simulate how heat, water, momentum, etc. are transported within and between the different climate model components.
And, over time, more subcomponents are being added in order to make the models more "comprehensive".
The physics in the model can be divided into 2 or 3 broad categories. There are the well known concepts and basic physics equations that we convert into computer code. And then there's the matter of representing the net effect of processes that occur at spatial scales that are finer than the model resolution – the parameterizations. For example, we need to estimate the rate of evaporation from an ocean grid cell, but we can't represent each water molecule or each white cap. So empirically based equations are used to calculate an estimation of the net evaporation over the entire grid box, based upon the model-simulated state of the ocean and atmosphere.

For more on this general topic, see *The Physics of Climate Modeling*, by Gavin A. Schmidt, printed in the January 2007 edition of the journal 'Physics Today' – available online at http://physicstoday.scitation.org/doi/10.1063/1.2709569



As computers have become more powerful, our climate models have benefited because we have been able to construct them with finer spatial resolution. Higher resolution is desirable in the numerical modeling of weather and climate in much the same way you'd prefer to watch a movie on a high-definition TV screen as opposed to watching a low-resolution video on an old cell phone. The higher resolution provides a more detailed picture. As at other modeling centers, the grid size used in NOAA/GFDL's "workhorse" (aka "production") global climate models is determined largely by the computer power available.

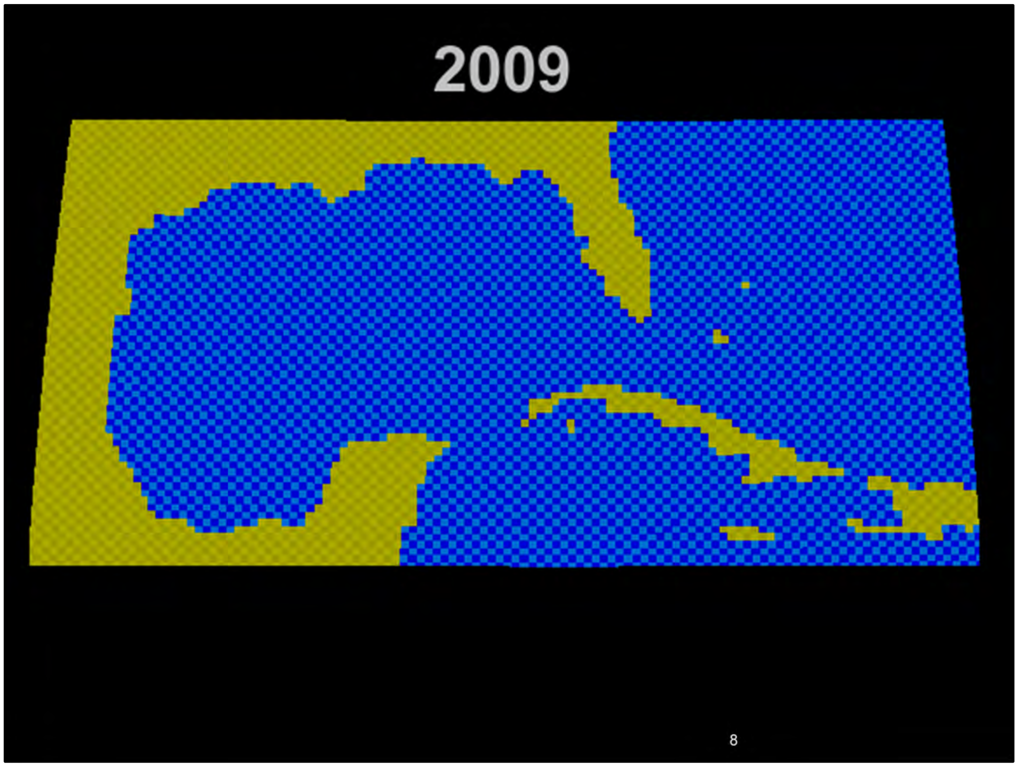
When I arrived at NOAA/GFDL in the 1980s, the horizontal grid spacing of the ocean component of what was then the state-of-the-art global climate model was what is shown above. The grid points were separated by roughly 4.5 degrees of latitude and 3.75 degrees of longitude.



Today one of our newer state-of-the art, “workhorse” models has much higher spatial resolution (~78 million grid cells total if you add together the 3-D atmosphere, 3-D ocean, land surface and sea ice model components).

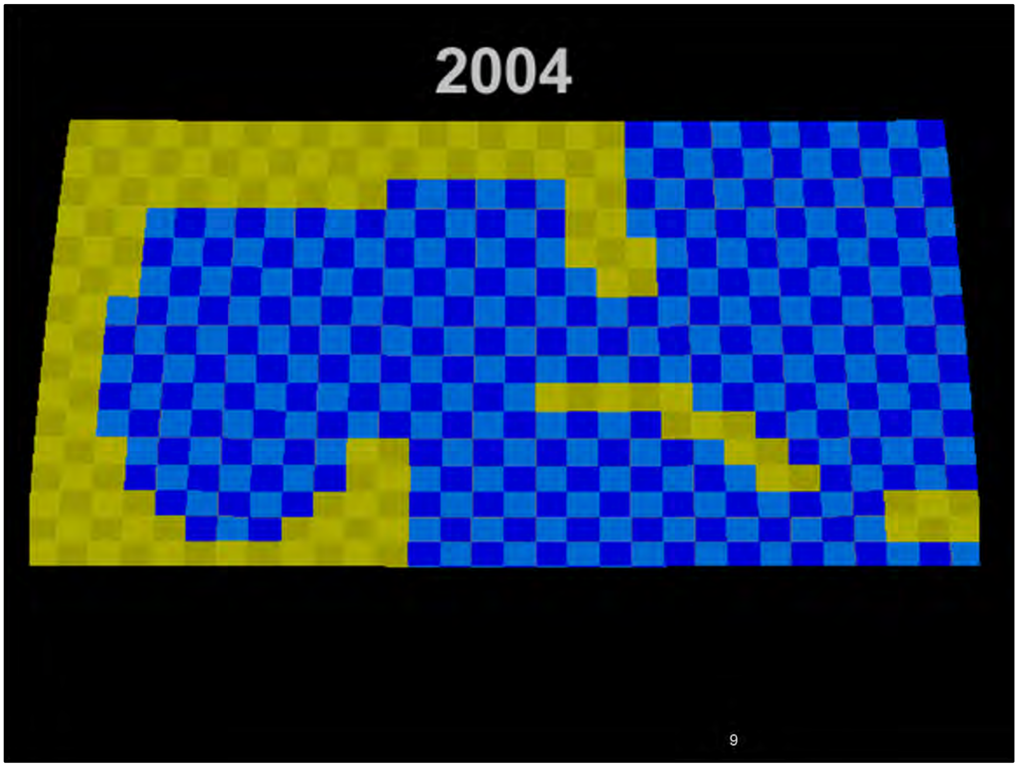
Note that, depending on the scientific questions being addressed, we run different versions of our climate models, having different resolutions and formulations. The one shown here is representative of some of the higher resolution global climate models run today for decadal to century time scale research. However, lower resolution models continue to be run , as well.

This newer model’s ocean grid is too fine to be easy viewed here, so let’s zoom in on the Gulf of Mexico…
[next slide]

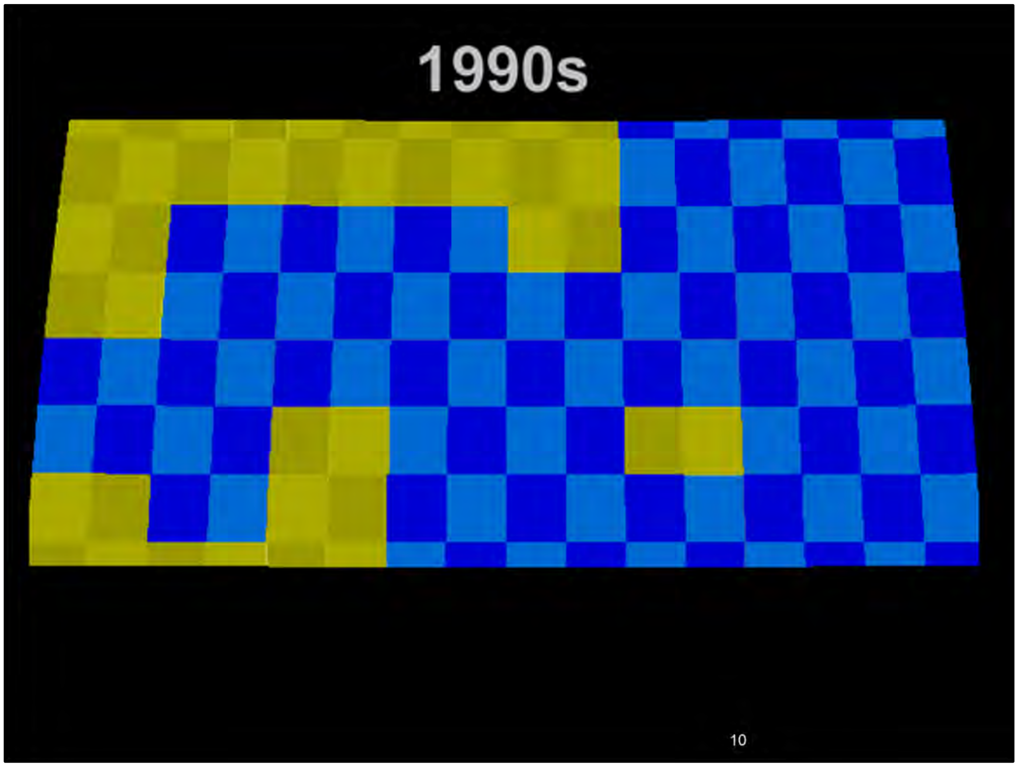


Each of the colored boxes represents the size and location of an ocean model grid cell. Ocean points are shades of blue and land points are shades of green.

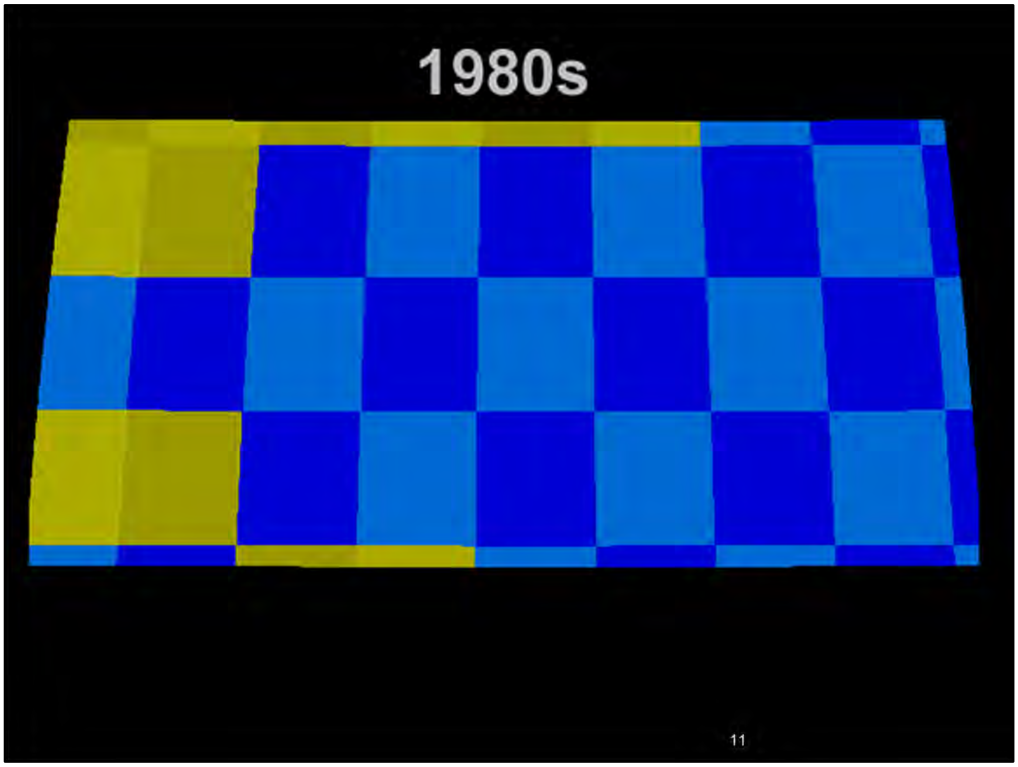
The ocean 's spatial resolution for this newer model is 0.25 degrees of latitude and longitude or smaller across the globe.



The model we at GFDL developed in 2004 had ocean grid cells that were nominally 1 degree latitude and longitude on a side. In other words, about 16 of the newer, higher resolution model's grid cells fit within each grid cell of our previous generation model.



And as we go back in time, computers were less powerful, and thus the model resolutions were coarser…



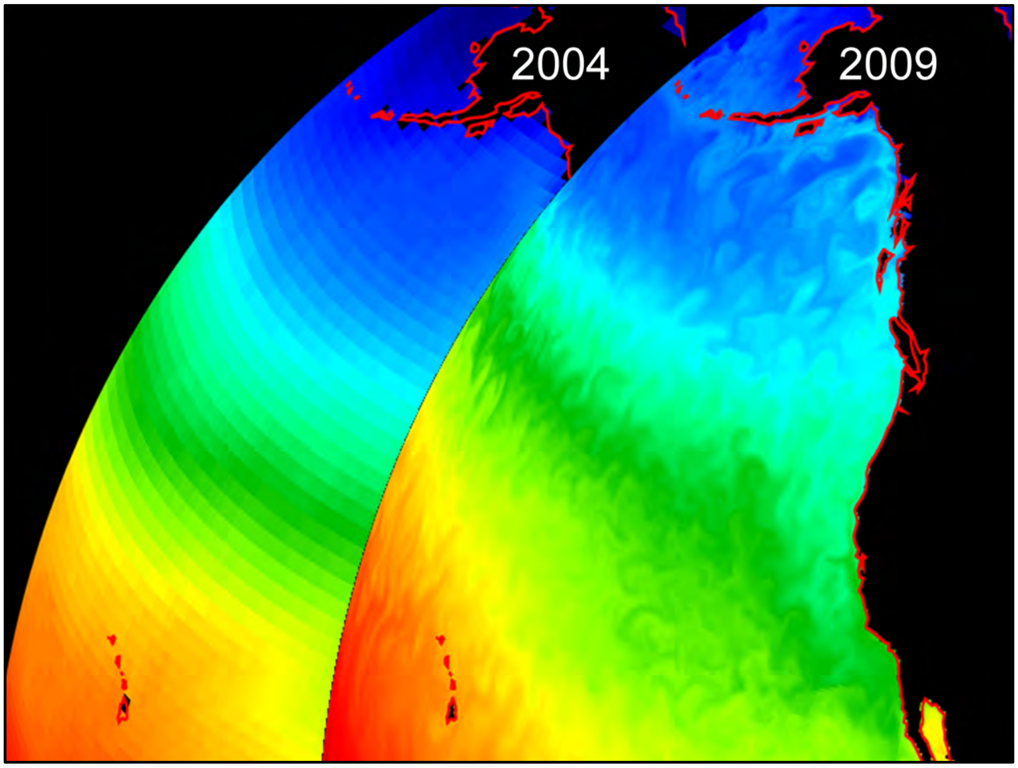
…to the point where in the 1980s it was hard to tell that the Gulf of Mexico was the Gulf of Mexico without Florida or Cuba being resolved.

Access to increasingly powerful computers are responsible for the finer spatial resolution.

Q: How does the spatial resolution of the atmospheric component of global climate models used in Decadal to Century time scale research compare with that of the models use for weather forecasting back when I was a student in the early 1980s?

A: For many years, global climate models have had finer vertical resolution (more layers) than did NOAA's main weather forecast models of the early and mid-1980s. And in recent years, GFDL has been routinely running some global climate models having horizontal resolution (50km) that is finer than those older weather forecast models.
So, if you hear someone dismiss climate models out of hand because of their coarse spatial resolution, realize that the new generation of models being developed at a few international research centers will have finer resolution than the weather forecast models used (successfully) 30 years ago and earlier.

Two main reasons that state-of-the-art global climate models will always tend to run a lower spatial resolution than state-of-the-art weather forecasts models are..
[a] global climate models used to study decadal to century time scale topics have to run for much longer than weather models, which requires more computer time, and
[b] global climate models spend about half of their computer resources on simulating the global ocean – including the deep ocean (more than a kilometer deep), which is important for longer term climate but can be largely neglected for short-term weather forecasts.

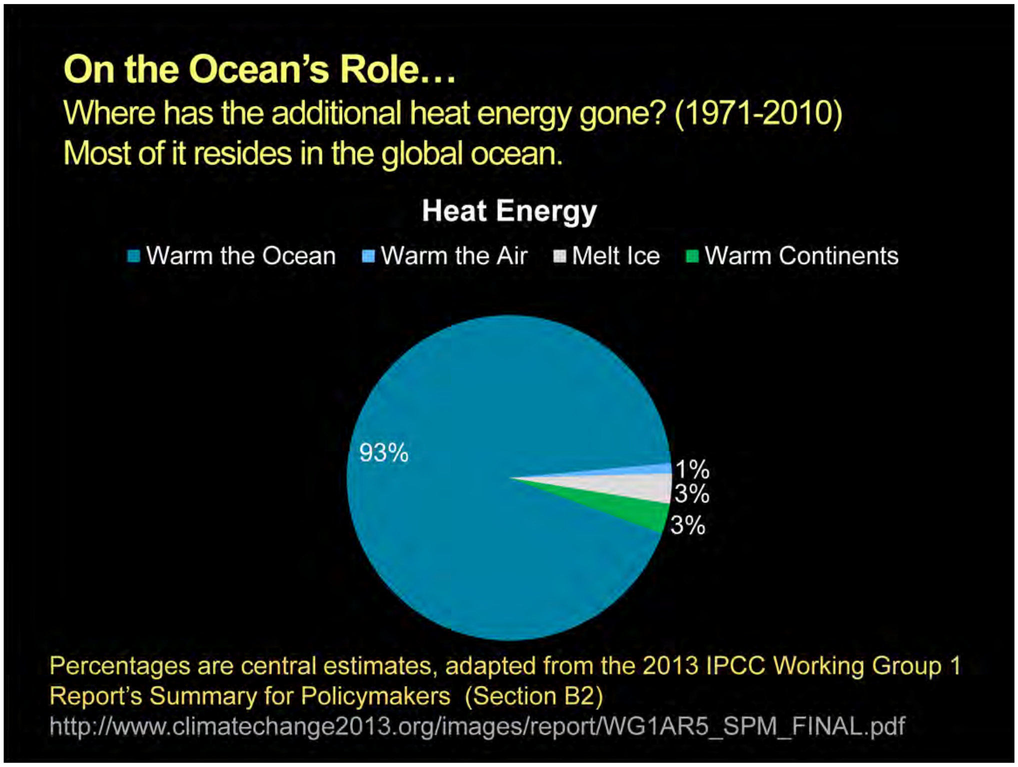


Here you can see side-by-side the difference in spatial resolution in two successive generations of NOAA GFDL's global climate models.

LEFT: segment of the CM2.1 ocean model (nominal grid resolution ~1 degree latitude & longitude) This was the model that was developed in 2004 and reported on in the 2007 IPCC report.

RIGHT: segment of the NOAA/GFDL CM2.5 climate model (nominal grid resolution ~0.25 degree latitude & longitude)

Variable shown: model simulated sea surface temperature for a day in December.
Note that at the higher resolution the model begins to resolve ocean eddies – you can think of them and somewhat analogous to the synoptic weather systems of the ocean.

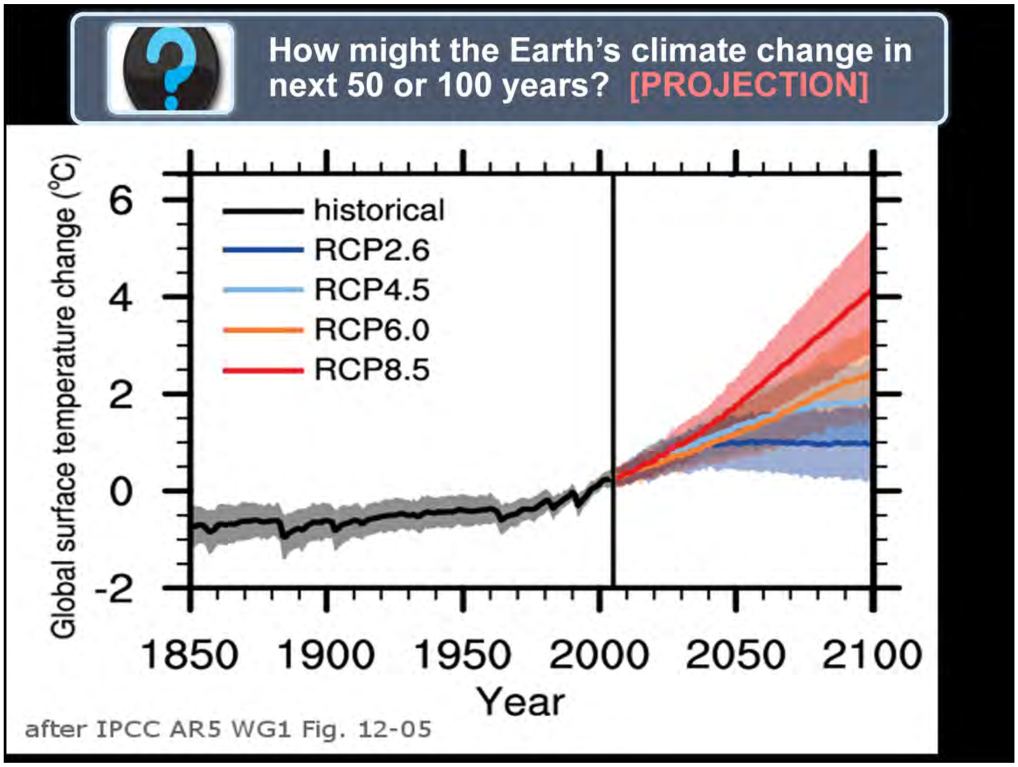


When we take an inventory of how and where the Earth has been gaining heat over the past several decades, we find that by far most of the heat energy that has been gained by the planet has gone to warm the oceans… about 90% or more of it.
The smaller slivers in this pie chart represent the smaller amounts of heat energy that have gone to warm the air and the land, and to melt ice on land and in the sea. (As the atmosphere warms the ocean absorbs, or "takes up" some of that additional atmospheric heat. The heat gained by the ocean has flowed through the atmosphere.)
The ocean has a much greater heat capacity than the atmosphere and provides "thermal inertia" to the climate system.
So while much of the public's attention to climate change focuses on surface air temperatures, climate scientists need to consider the complete climate system, and thus they devote significant time and resources to the analysis of the oceans, including in the form of detection/attribution studies.

From the 2013 IPCC Working Group 1 Report's Summary for Policymakers (Section B2)
http://www.climatechange2013.org/images/report/WG1AR5_SPM_FINAL.pdf

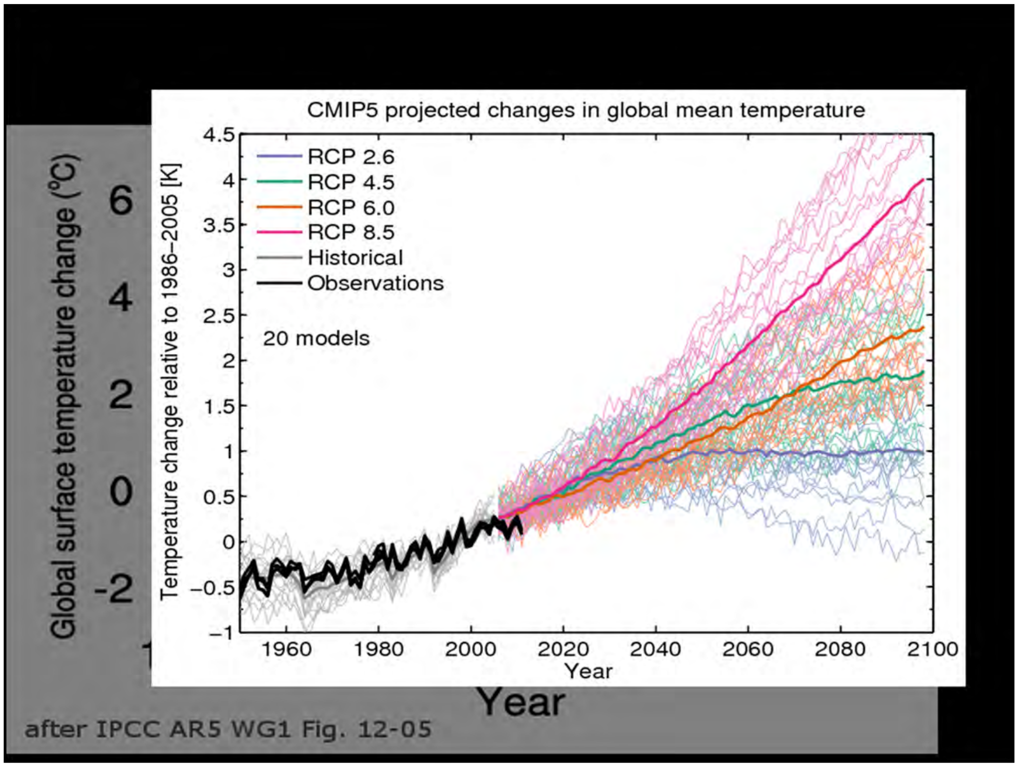
> Ocean warming dominates the increase in energy stored in the climate system, accounting for more than 90% of the energy accumulated between 1971 and 2010 (*high confidence*). … More than 60% of the net energy increase in the climate system is stored in the upper ocean (0–700 m) during the relatively well-sampled 40-year period from 1971 to 2010, and about 30% is stored in the ocean below 700 m.
> It is *virtually certain* that the upper ocean (0−700 m) warmed from 1971 to 2010 (see Figure SPM.3), and it *likely* warmed between the 1870s and 1971. It is *virtually certain* that the upper ocean (0−700 m) warmed from 1971 to 2010, and it *likely* warmed between the 1870s and 1971.
>
> IPCC, 2013: Summary for Policymakers. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 1–30, doi:10.1017/CBO9781107415324.004.

Data used to produce the pie chart was taken from central estimates found in Box 3.1 of the IPCC 2013 WG1-AR5 report, pages 264-265 of Chapter 3 – "Observations: Ocean".
http://www.climatechange2013.org/images/report/WG1AR5_Chapter03_FINAL.pdf



Absent observations of the future, we can use climate models to generate "What if…" projections of how the climate might change for different potential scenarios of how atmospheric greenhouse gases and aerosol concentrations may change over the 21st century. Note the different colors for years 2000-2100. These are referred to as different "emissions scenarios". So, the four different colors can be thought of as linked to "uncertainties" associated with different possible human choices, with the four being just a sample of a larger set of possibilities.
The darker lines represent the average computed over several (~30+) climate models run at different international research centers. About two-thirds of the models' results lie within the lighter, shaded region surrounding each of the darker lines. So, the width of each shaded band can be thought of as linked to the uncertainties associated with the global climate models' responses to a given emissions scenario.

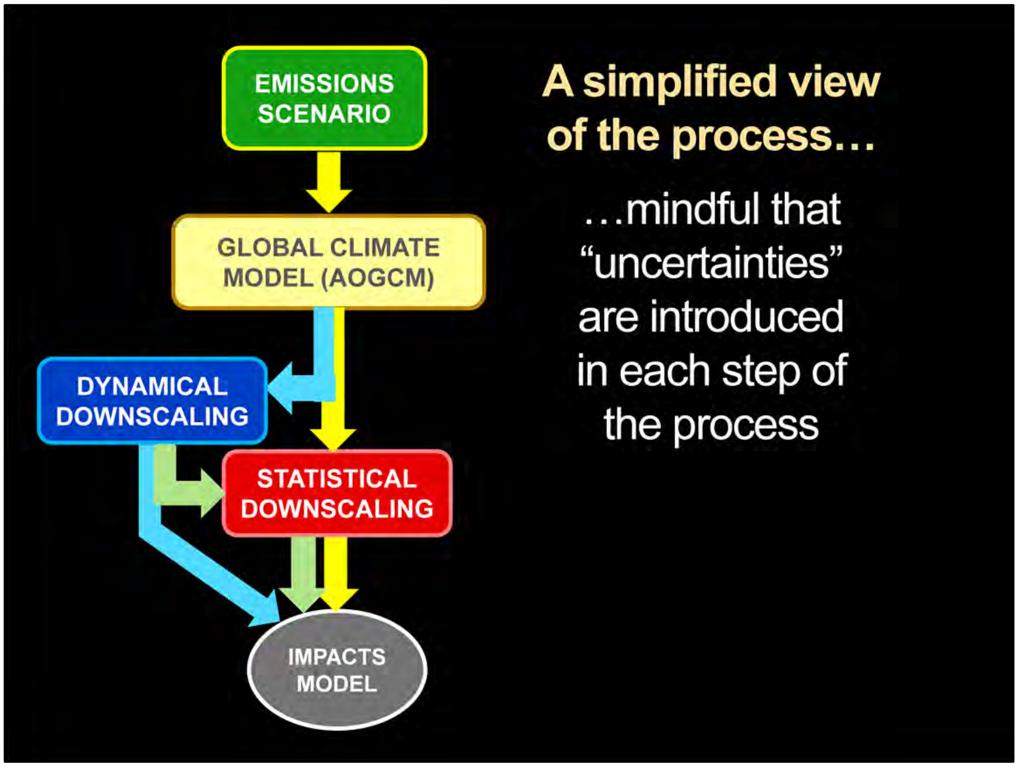
Image source:
Graph of model results is an edited version of IPCC 2007 WG1-AR4 Fig 12-5 (Chapter 12)
Caption excerpts: Time series of global annual mean surface air temperature anomalies (relative to 1986–2005) from CMIP5 concentration-driven experiments. Projections are shown for each RCP for the multi-model mean (solid lines) and the 5 to 95% range (±1.64 standard deviation) across the distribution of individual models (shading).



Here's what the graph would look like if we plotted each of 20 different climate model results individually (a multi-model ensemble) rather than only showing the shaded +/-1 standard deviation shaded regions.

I show it here to remind us that, just like the real world, climate model simulations contain significant amount of year-to-year variations. The smoothed, averaged curves shown on the previous slide should not be interpreted as indicating that climate models suggest that each and every year will be warmer than the one that preceded it.

Image source:
Ed Hawkins
https://twitter.com/ed_hawkins/status/299161479268139009



Many steps are involved in the process by which multi-decadal global climate change projections are generated and processed so that they may be used as input to regional or local-scale adaptation planning and climate change impacts studies contains. And each of the steps has its own set of assumptions, imperfections, and hence uncertainties.

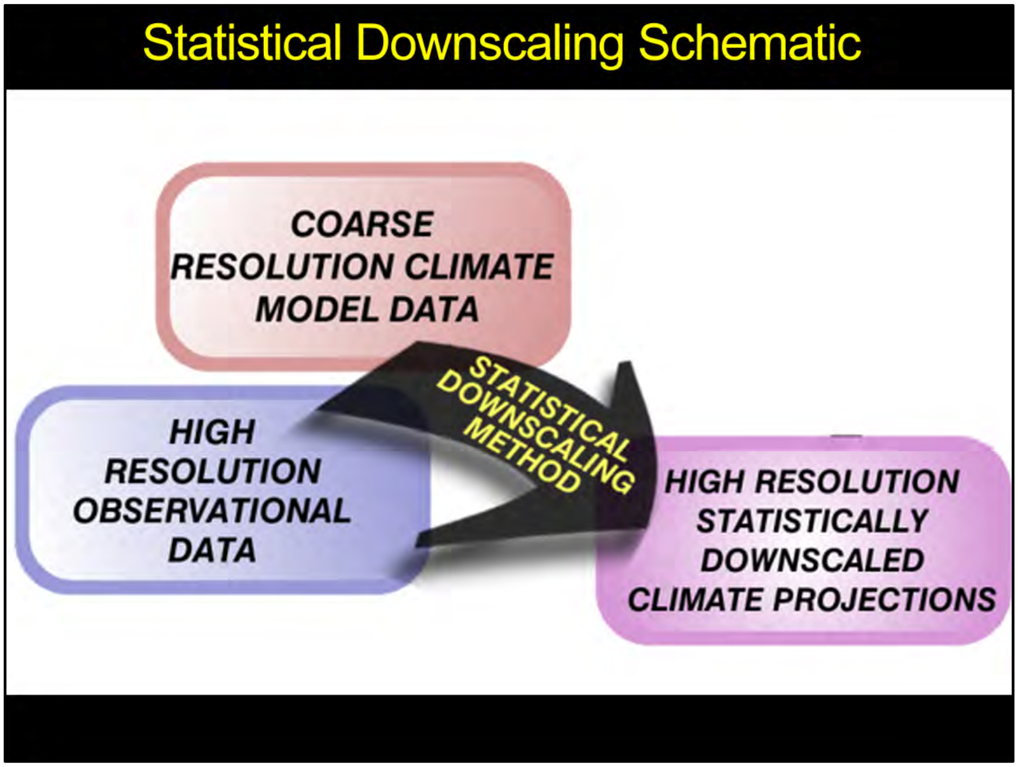
Uncertainties exist regarding the amounts and types of greenhouse gases and radiatively active aerosols that will be emitted in the future. This uncertainty is often acknowledged by examining climate model-based projections forced by different emissions scenarios.

Uncertainties in how the global climate system will respond to a given emission scenario is evident in that different global climate models (GCMs) exhibit somewhat different climate sensitivities and patterns of response. Users often explore this type of uncertainty by examining output derived from GCMs developed at different research institutions.

Yet, a GCM's results can fall short of the expectations of end users if the GCM's grid is too deemed too coarse. For example, a GCM with 100km grid spacing can have a single grid cell that overlies ocean waters, beaches, mountains, and everything in between, though the user may be interested in a single location within that area. Additionally, GCM simulations of the contemporary climate may exhibit significant biases at the location of interest (*e.g.,* too hot, too cold, too wet, too dry).

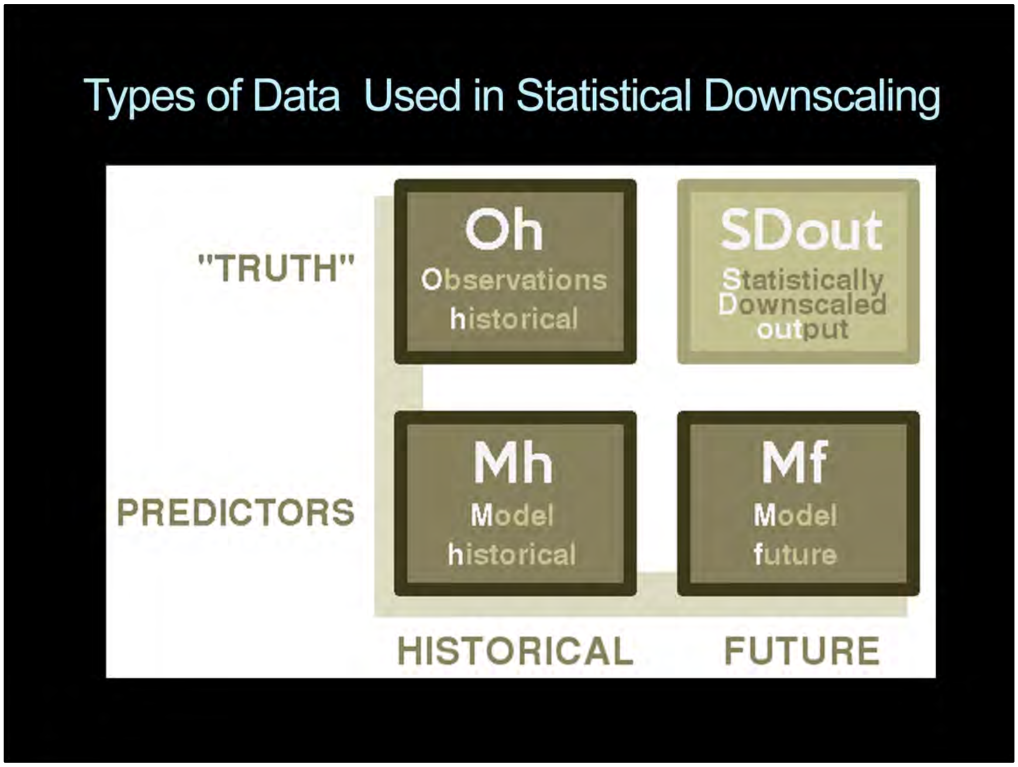
Statistical downscaling is often used in an attempt to account for model biases and to provide additional spatial detail. (For those familiar with operational weather forecasting, you can think of statistical downscaling of climate model output as being a refinement step analogous to the MOS - Model Output Statistics.) Statistical downscaling does however, introduce its own uncertainties.

I will also note that statistical downscaling is not the only approach one can take when seeking to generate climate model projections at finer spatial resolution than a GCM. Dynamical Downscaling – the use of finer scale three-dimensional regional climate models driven by GCM output – is another approach, but is not covered in this talk. For some applications, the output of regional climate models is refined further by statistical downscaling or bias corrections.



There are several "classes" of statistical downscaling + bias correction techniques, and within each class there are many different methods. This simple schematic of statistical downscaling aims to represent the basics of these methods.

Presented with coarse resolution climate model simulations of both a historical period and the future, the GCM results are statistically compared with observation-based data from the same historical period. Information from the model vs. observations comparison is gleaned according to the specific mathematical processing steps employed by whatever particular downscaling method is being used. That information, in turn, is used to refine the model's future projections, yielding what is assumed to be a "value-added data product" – a refined climate projection, informed by observations, intended to have some of the underlying GCM's biases addressed and the refined output made more representative of the specific locations of interest.



This is another way to visualize the data sets associated with statistical downscaling of climate model projections.

We begin with three data set types.

Oh = the historical observations of the variable(s) of interest at the location(s) of interest. It can be station data or a gridded observation-based data product.

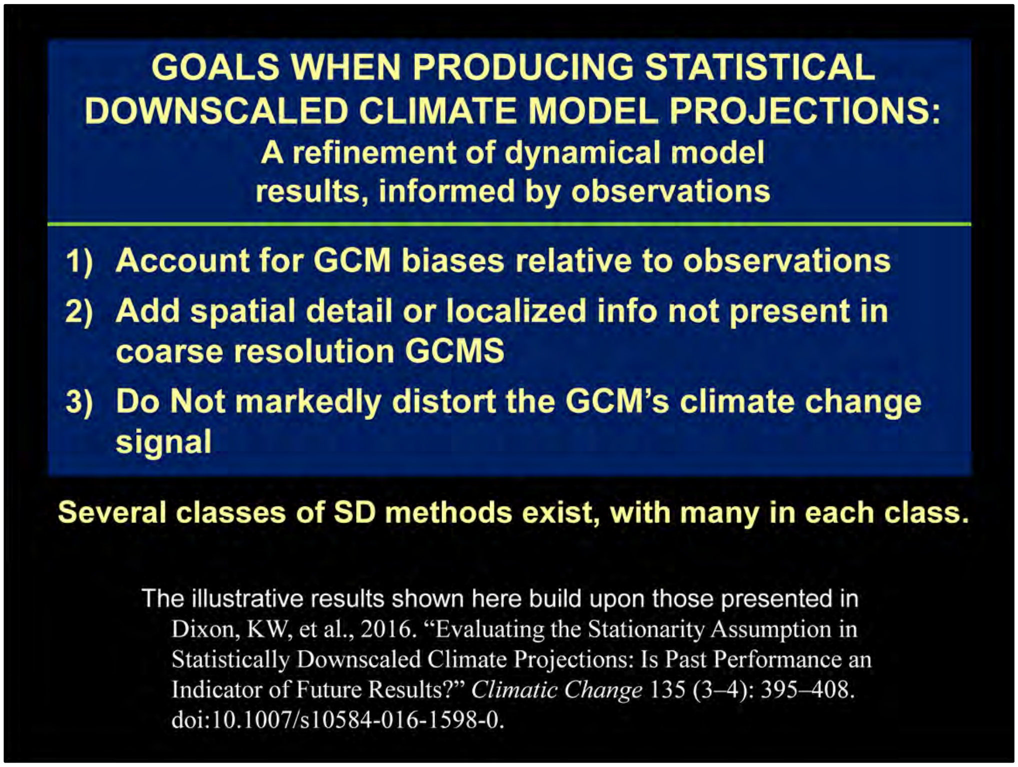
Mh = climate model output for the same historical period for which one has observations.

Mf = climate model output for a future time period.

Statistical comparisons of Oh and Mh yield information about GCM biases and how to relate the large scale climate model output to observations of the variables of interest.

Statistical comparisons of Mh and Mf yield information about model-simulated climate variability and change signals.

Statistical downscaling processing makes use of information gleaned from the previously mentioned types of comparisons to generate what is labeled here as "SDout" (Statistical Downscaling output) to produce a statistically downscaled future projection – one that can be thought of as a being a refined climate projection that has been informed by observations.



Some statistical downscaling references, for those who may be interested:

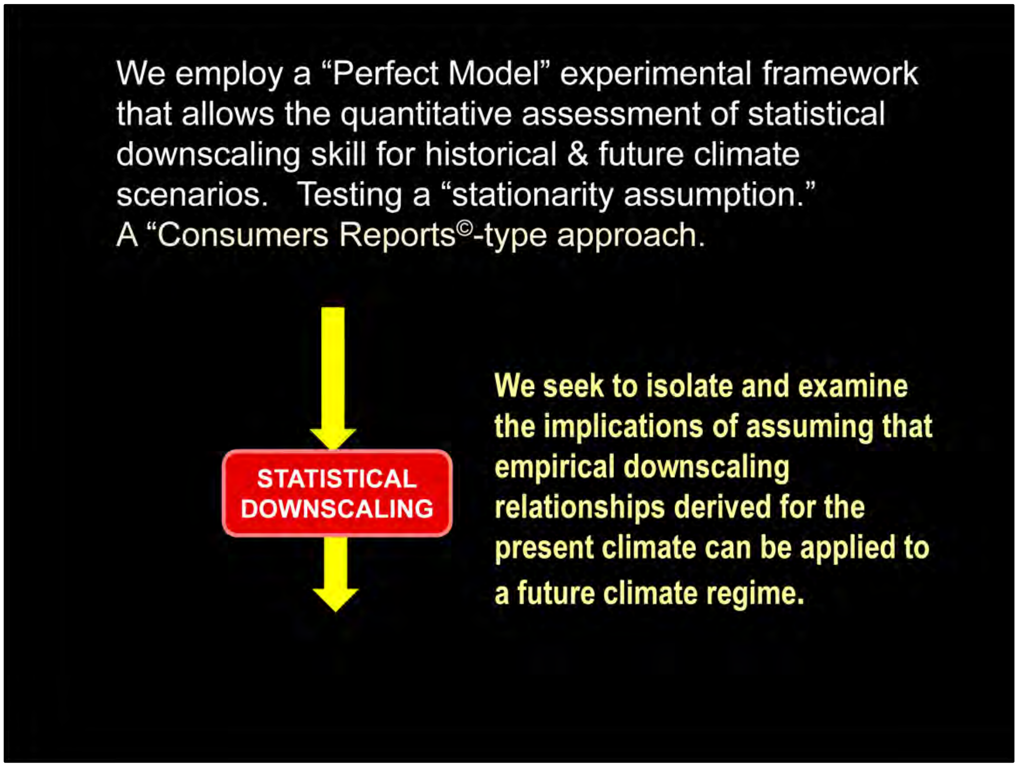
Barsugli, J. J., and Coauthors, 2013: The Practitioner's Dilemma: How to Assess the Credibility of Downscaled Climate Projections. *Eos, Trans. Amer. Geophys. Union*, **94**, 424–425, doi:10.1002/2013EO460005.

Dixon, K. W., J. R. Lanzante, M. J. Nath, K. Hayhoe, A. Stoner, A. Radhakrishnan, V. Balaji, and C. F. Gaitán, 2016: Evaluating the stationarity assumption in statistically downscaled climate projections: is past performance an indicator of future results? *Climatic Change*, **135**, 395–408, doi:10.1007/s10584-016-1598-0.

Hewitson, B. C., J. Daron, R. G. Crane, M. F. Zermoglio, and C. Jack, 2014: Interrogating empirical-statistical downscaling. *Climatic Change*, **122**, 539–554, doi:10.1007/s10584-013-1021-z.

Maraun, D., 2016: Bias Correcting Climate Change Simulations - a Critical Review. *Current Climate Change Reports*, doi:10.1007/s40641-016-0050-x. http://link.springer.com/10.1007/s40641-016-0050-x (Accessed November 1, 2016).

Mearns, L. O., M. S. Bukovsky, S. C. Pryor, and V. Magaña, 2014: Downscaling of Climate Information. *Climate Change in North America*, G. Ohring, Ed., Springer International Publishing, Cham, 201–250 http://dx.doi.org/10.1007/978-3-319-03768-4_5.

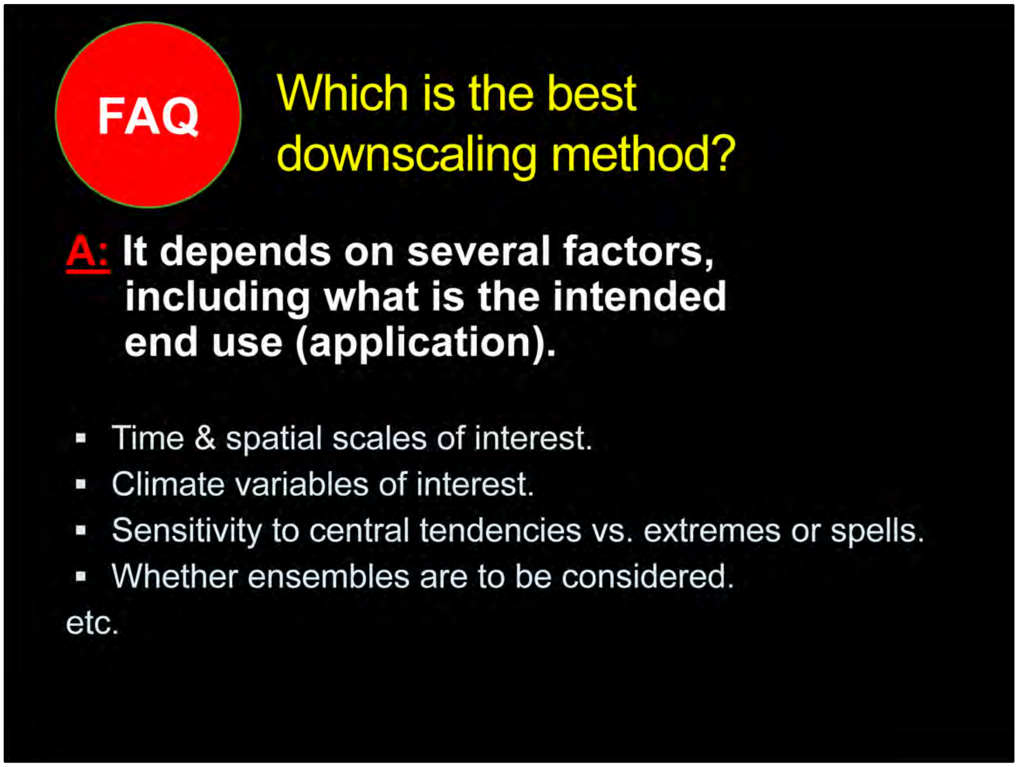


In the past couple of years, my team at NOAA GFDL has collaborated with others to develop an experimental design that isolates and quantifies one particular source (but not the only source) of uncertainty arising from statistical downscaling of climate projections – the stationarity assumption.

The stationarity assumption is inherent to statistical downscaling of multi-decadal climate change projections, with the assumption being that statistical relationship between global climate model simulation outputs and real, observed climate data remain constant over time.

In other words, we seek to test the assumption that the statistical relationships (aka transfer functions) 'learned' during the statistical downscaling training step, are valid when used to generate downscaled estimates of future climate projections. We evaluate the extent to which the stationarity assumption holds by using a 'perfect model' (or 'big brother') framework, as described on the following paper and follow-on work.

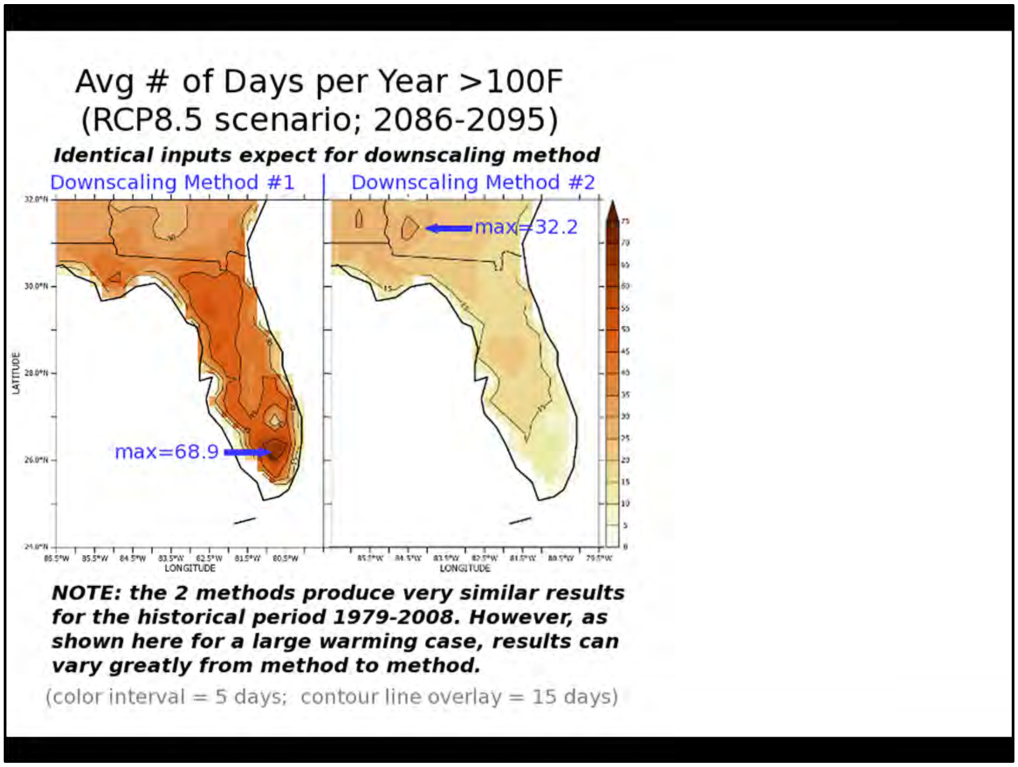
Dixon, K. W., J. R. Lanzante, M. J. Nath, K. Hayhoe, A. Stoner, A. Radhakrishnan, V. Balaji, and C. F. Gaitán, 2016: Evaluating the stationarity assumption in statistically downscaled climate projections: is past performance an indicator of future results? *Climatic Change*, **135**, 395–408, doi:10.1007/s10584-016-1598-0.



Among researchers seeking to conduct climate impact studies that will make use of future climate projections, a very frequently asked question centers on what downscaling method is "the best". Unfortunately, there is no easy answer. Different downscaling methods have their own strengths and weaknesses. And different applications that use downscaled climate projections have different requirements and sensitivities. So, the answer to the FAQ is going to be very much application dependent.

Additionally, our research has demonstrated that a given downscaling method's performance may vary by geographic location, time of year, amount of projected climate change being considered, and by various pre-processing and post-processing steps that may be used when generating the downscaled projections.

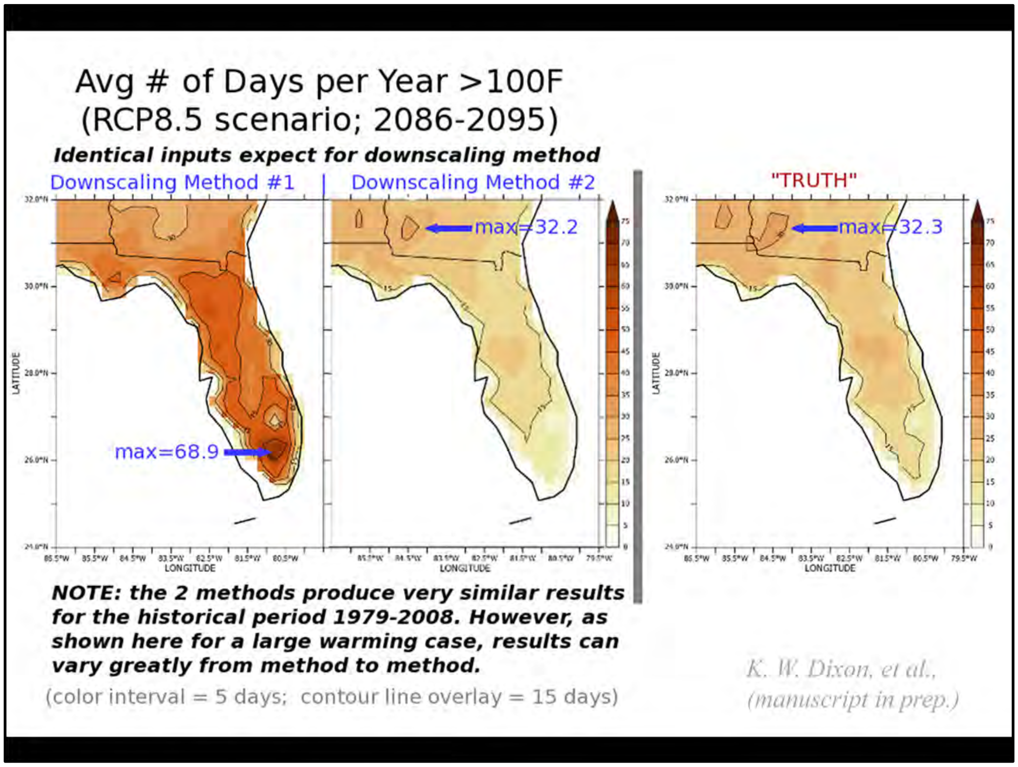
For these reasons, there can be benefits to having persons with some expertise in climate model projections and downscaling involved in the design and analysis of climate impacts studies that make use of climate projections. Referring back to the 4th slide (bridges), one could envision boundary organizations as perhaps filling the role of providing guidance regarding the use of "over the counter" climate projections. (Examples of climate boundary organizations include, but are not limited to: the DoI USGS Climate Science Centers, NOAA's RISAs, USDA Climate Hubs, various university, state government-sponsored, and private sector organizations and consultants.)



How sensitive can downscaled results be to the specific formulation of a downscaling method? Here I show an extreme case, for illustration purposes.

The two figures depict the number of days per year that maximum temperatures above 100F are projected for an end of 21st century, high greenhouse gas emissions scenario. The input files used to produce the two maps are identical (i.e., referring to slide 18, they used the same Oh, Mh, and Mf data sets). However, the statistical downscaling method used to produce each of the two maps are different. The one on the left yields output with more than 65 days per year above 100F west of Miami, FL… a location for which the method on the right produces downscaled output with fewer than 15 days per year above 100F.

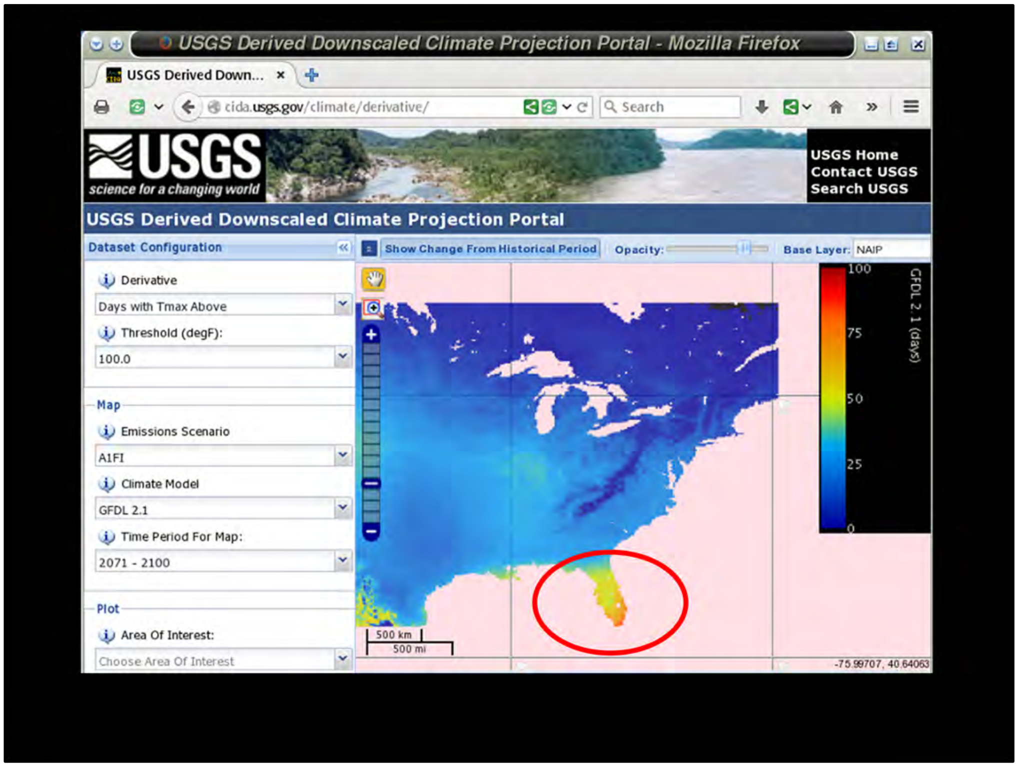
Which is the more realistic result?
Normally, because we lack observations of the future, one could not readily determine which is more correct. However, these results were generated using a Perfect Model framework in which high resolution GCM results serve as a proxy for observations, allowing for a comparison with a future "truth" (next page)



…and we see that the downscaling method on the left is the one that is most in error.

How different are the two downscaling methods? Actually, the core of the two methods is the same – the main difference lies in pre-processing steps that make different choices with respect to detrending the input data before performing some of the statistical processing steps.

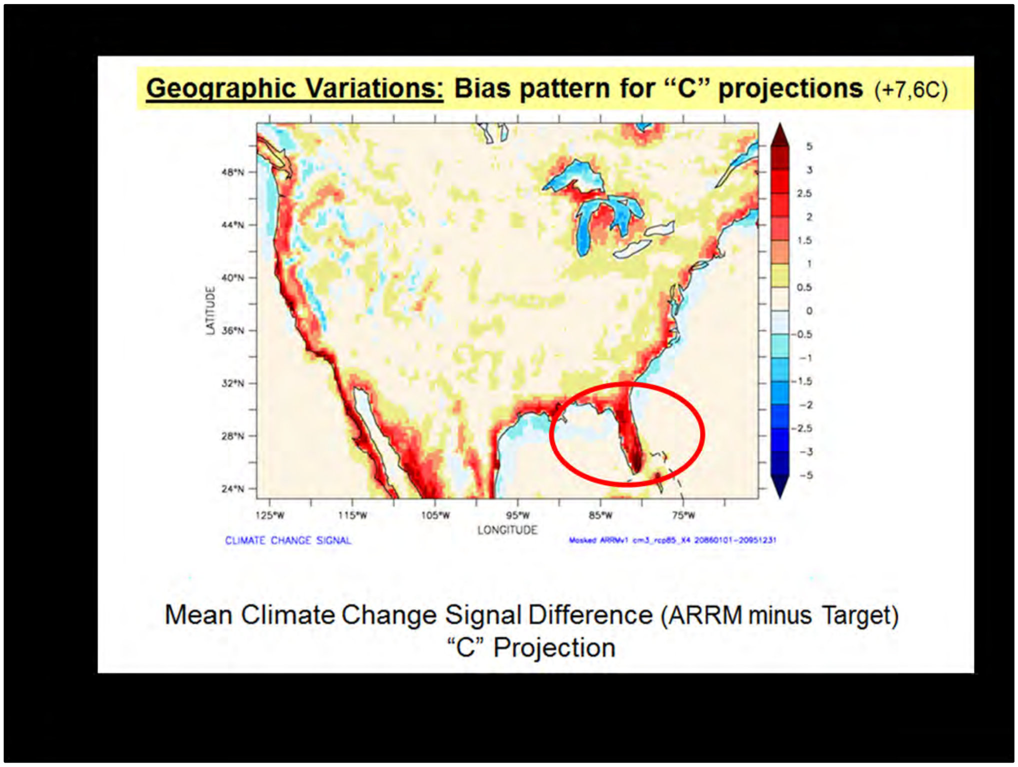
So, while an extreme case, one could download downscaled data sets that could have behaviors like that shown above present in the data. For example… (next page)



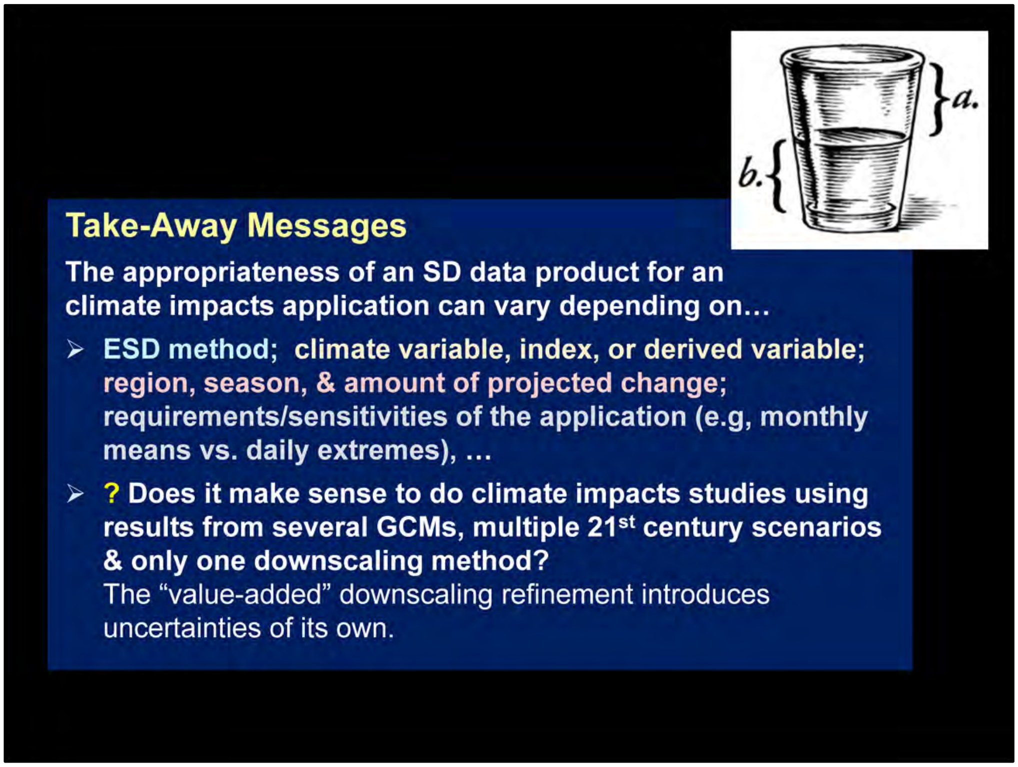
This example shows the potential relevance of the previous 2 slides to "over the counter" downscaled data products being available for use in climate impacts work.

A figure similar to the one shown above was presented as a USGCRP workshop in Feb 2015… it shows the increase in the number of days with max temps >100F as revealed in a statistically downscaled product based on an end of 21st century, high emission scenario. Attention was drawn to the results that Florida was projected to see the largest increase in day >100F (and increase of more than 50 days/yr) … an increase that dwarfed those seen across the rest of the CONUS domain. Some found this surprising, given that Miami, with its largely maritime climate, doesn't see days >100F now.

Having, by chance, examined in our Perfect Model framework a variant of the statistical downscaling method used to generate the data shown in this figure, we offered a possible explanation that suggested the Florida bullseye may have been more an artifact of the statistical downscaling process rather than a product of the GCM's simulation. (I have also learned subsequently that the USGS downscaled data product may have been influenced by a bad observational data point in Southern Florida)



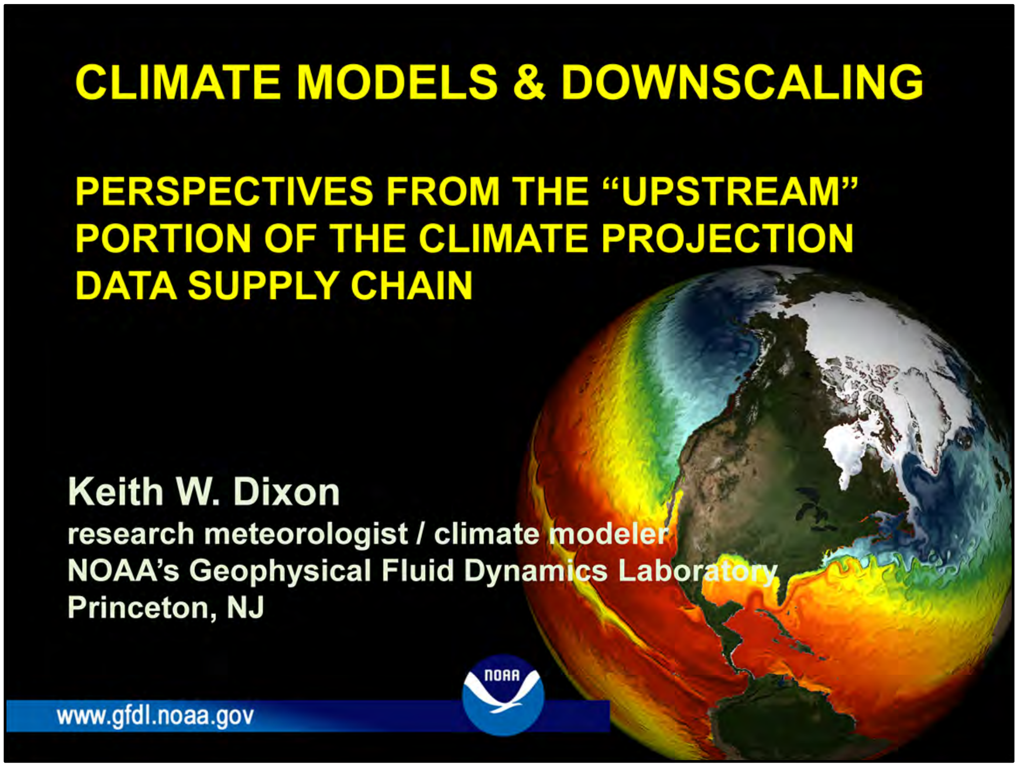
This figure, from our team's perfect model work, shows that the variant of the downscaling method we studied produced a bias of ~5C (or 9F) over southern Florida when applied to late 21st century projections in the Perfect Model framework. Because different GCM data sets and slightly different variants of the downscaling method were used, the comparison is not 100% apples-to-apples. However, it is reasonable to assume that a similar bias exists in the downscaled data product – a bias that could very well explain a substantial part of the Florida >100F bullseye seen in the previous figure (e.g., a 93F day could become a 102F day because of the downscaling method's bias under late 21st century, high emissions scenario conditions)



Summary slide with "Take-Away" messages:

Overall, climate models are research tools that are being used to provide information about plausible future climate conditions. Today's global climate models, some operating at spatial resolutions that are finer than weather forecast models of the 1980s, have been shown to produce credible simulations of the large scale climate system (ocean, atmosphere, land surface, and sea ice). While there is reasonably high confidence in many of the large scale, model-simulated climate responses to increasing levels of greenhouse gases, some uncertainties remain. Key multi-decadal uncertainties stem from questions about how humans will change the composition of the atmosphere in coming decades as well as from the details of how the physical climate system will respond (different GCMs have somewhat different sensitivities).

Additionally, as one's interests move to smaller spatial scales, as is the case for many climate impacts studies and applications, the GCMs' relatively coarse spatial resolution and local-scale biases often make the GCM's raw output inappropriate for direct use in climate impacts studies. In these cases, bias correction and downscaling (dynamical and/or statistical) can be employed as a kind of post-processing step to generate refined, presumably value-added data products more suitable for use in applications. However, users should be aware that not all downscaled products have the same strengths and weaknesses. Matching appropriate "over the counter" climate projection data sets to applications can be challenging, and may benefit from guidance (prescriptions) from those with expertise in the climate modeling and downscaling community.


CLIMATE MODELS & DOWNSCALING
PERSPECTIVES FROM THE "UPSTREAM" PORTION OF THE CLIMATE PROJECTION DATA SUPPLY CHAIN
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