Climate Modeling 101:
The role of computer modeling in the climate change challenge

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Note: This is characterized as a "Fundamental Research Communication", according to NOAA guidelines. As such, it will cover scientific research topics, but will not include information on policy or budget matters. For GFDL-specific budget or infrastructure-related questions, please contact NOAA/GFDL's deputy director Brian Gross (**Brian.Gross@noaa.gov**)

For additional information, including copies of the research summaries made available at the briefing, please refer to our

NOAA GFDL Climate Research Highlights:
Summaries, Graphics and Animations

web page at

http://www.gfdl.noaa.gov/research/climate/highlights/

NOAA / OAR / GFDL

Affiliation: US Dept of Commerce, National Oceanic & Atmospheric Administration's Office of Oceanic & Atmospheric Research

Brief History: Formed in 1955 in D.C. Moved to Princeton in late 1960s. The world's first climate model was developed at GFDL.

Size: Approximately 100 scientists and staff producing 120+ peer-reviewed scientific papers per year.

Partnership with: Princeton University

A Mission Goal: ***"Understand climate variability and change to enhance society's ability to plan and respond."***

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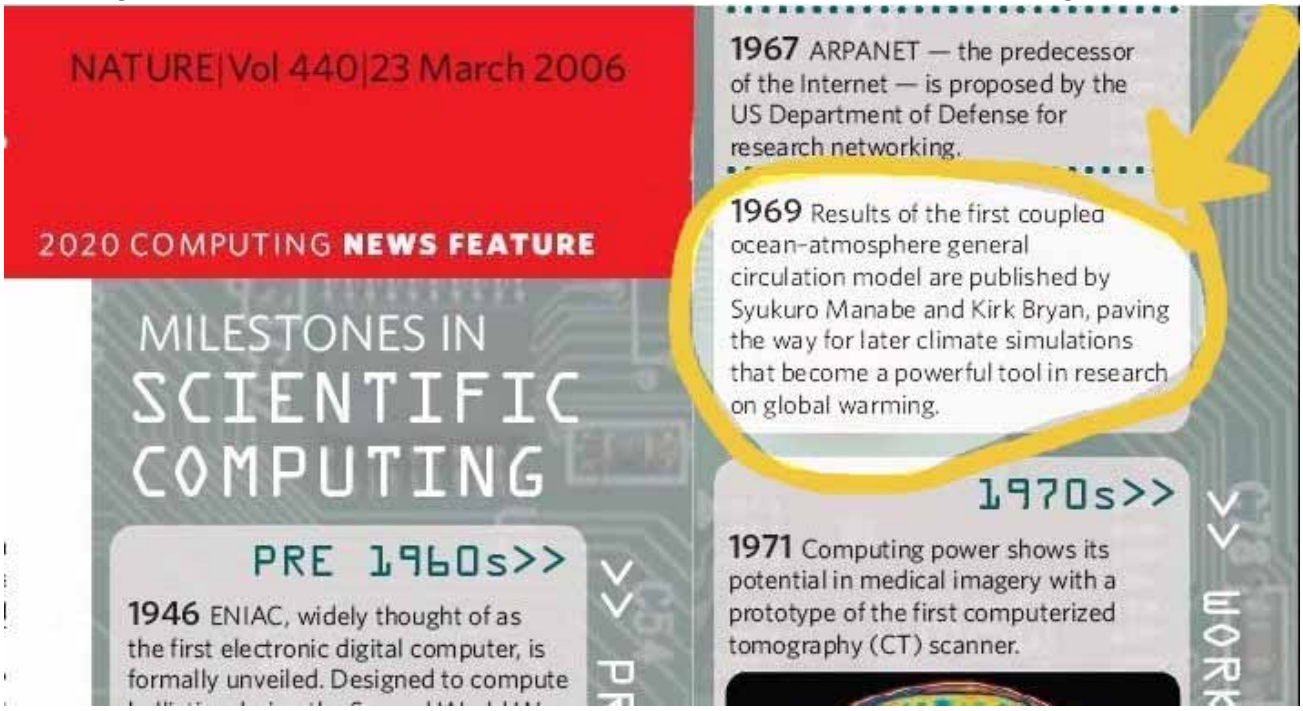
Soon after moving to Princeton, the world's first ever dynamical computer climate model was created by Drs. Manabe & Bryan at NOAA/GFDL. This was a breakthrough in climate science and a milestone in scientific computing. In fact, in 2006 the journal Nature published a list of scientific computing milestones and the first GFDL climate model was on the list, along with things like the invention of the handheld calculator, the internet, and CT scanners (excerpt below) . The point being, GFDL has been, and remains, at the forefront of climate modeling research.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2020 COMPUTING **NEWS FEATURE**

MILESTONES IN SCIENTIFIC COMPUTING

PRE 1960s>>

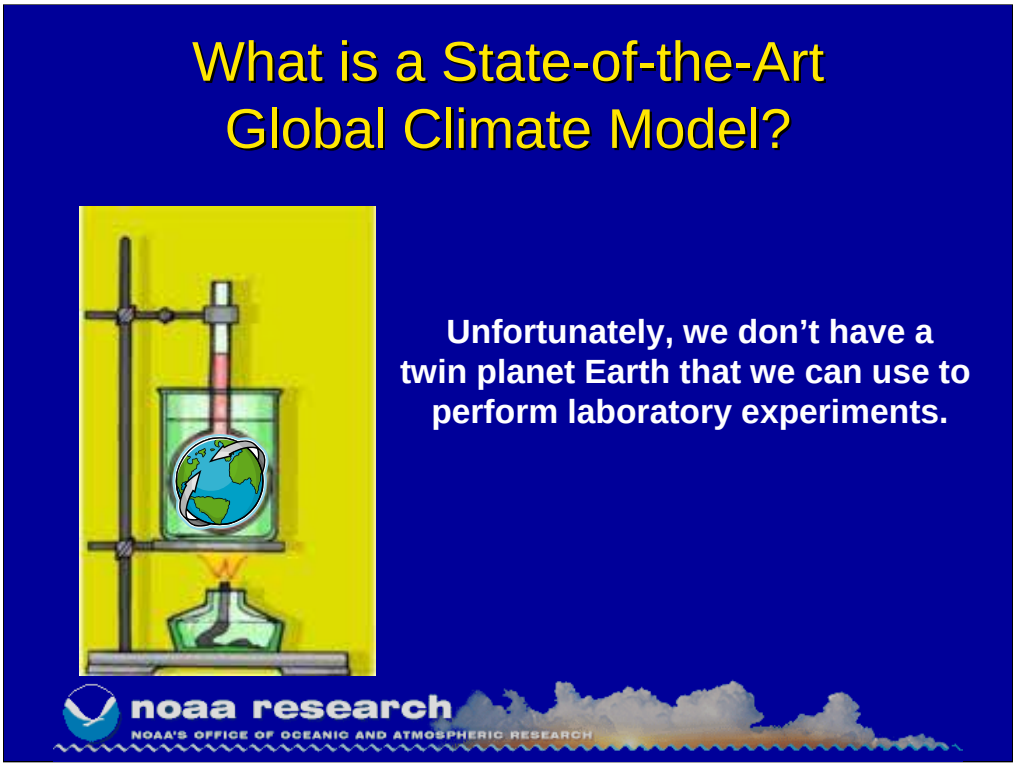
1946 ENIAC, widely thought of as the first electronic digital computer, is formally unveiled. Designed to compute

1967 ARPANET — the predecessor of the Internet — is proposed by the US Department of Defense for research networking.

1969 Results of the first coupled ocean-atmosphere general circulation model are published by Syukuro Manabe and Kirk Bryan, paving the way for later climate simulations that become a powerful tool in research on global warming.

1970s>>

1971 Computing power shows its potential in medical imagery with a prototype of the first computerized tomography (CT) scanner.

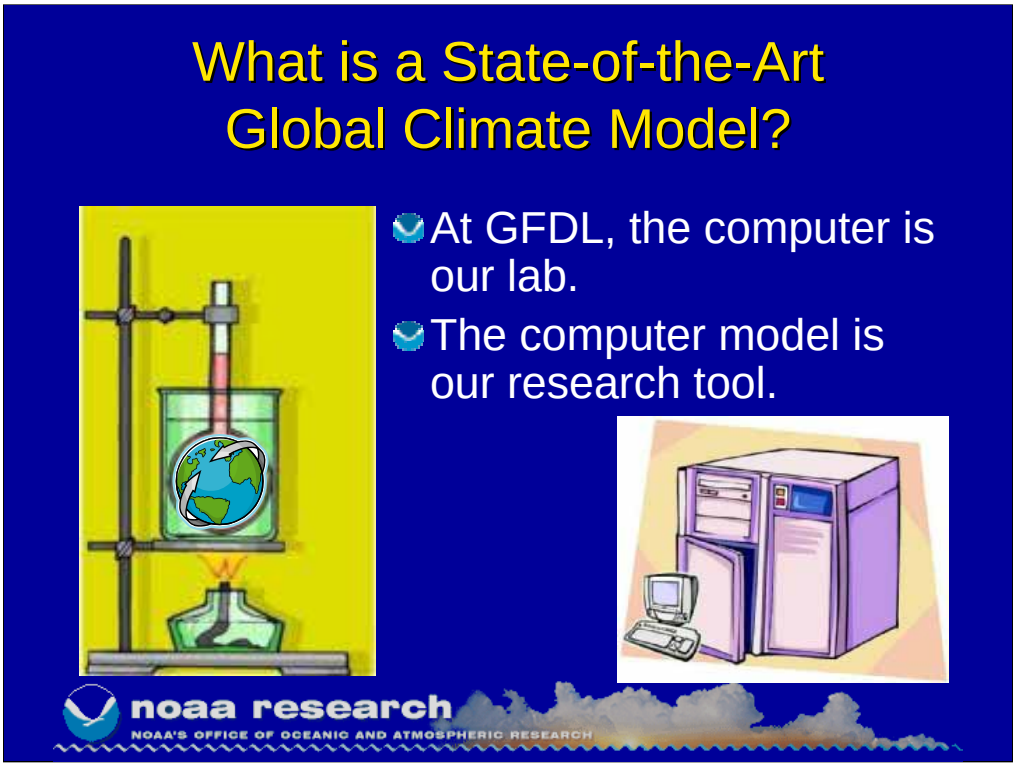


Parsing the strategic goal listed on the previous slide…

The first part… *Understanding climate variability and change* … that's the scientific research part that gets NOAA/GFDL scientists "juices flowing". Learning more about the climate system, advancing our scientific understanding – something that's been at the core of GFDL's work for decades.

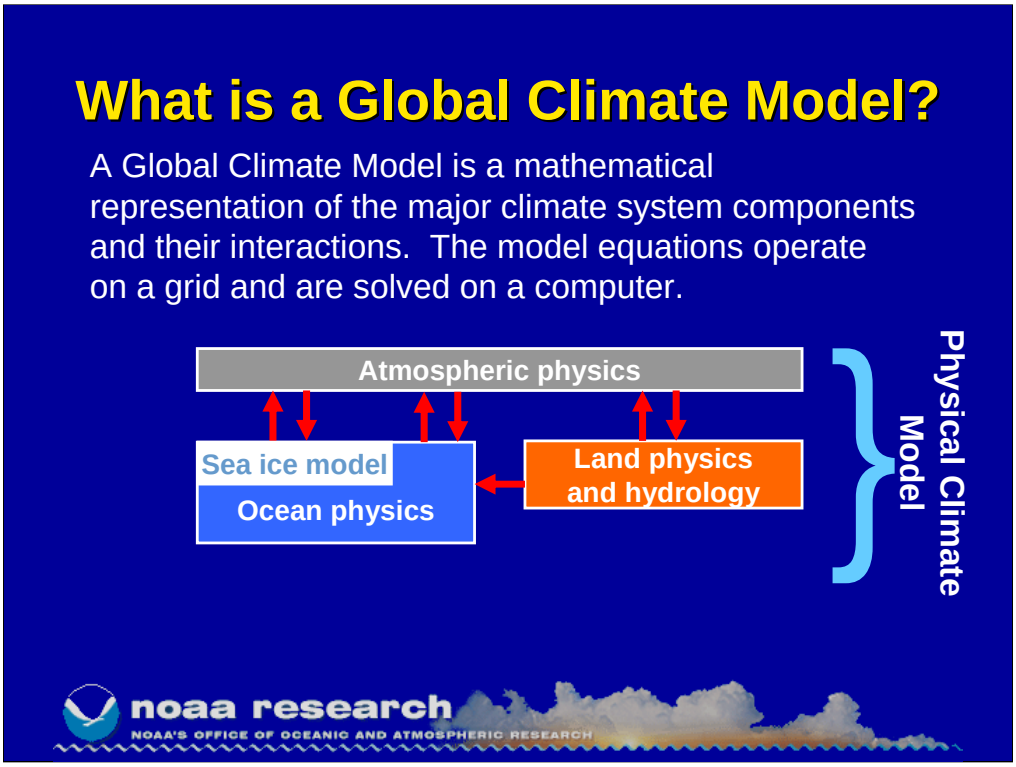
The second part – *enhancing society's ability to plan and respond* – relates to the bridge between the scientific research results and the stakeholders and policy makers for whom these results are relevant. This has become abigger part of the NOAA/GFDL mission over time.

I will discuss both aspects – the research side and the communications of the bits that are relevant to society – as it they related to climate modeling in today's presentation.



Lacking a twin planet, we use our “Virtual Earth” – our global climate model – to perform numerical experiments designed to help us learn more about the way the real climate system “works”.

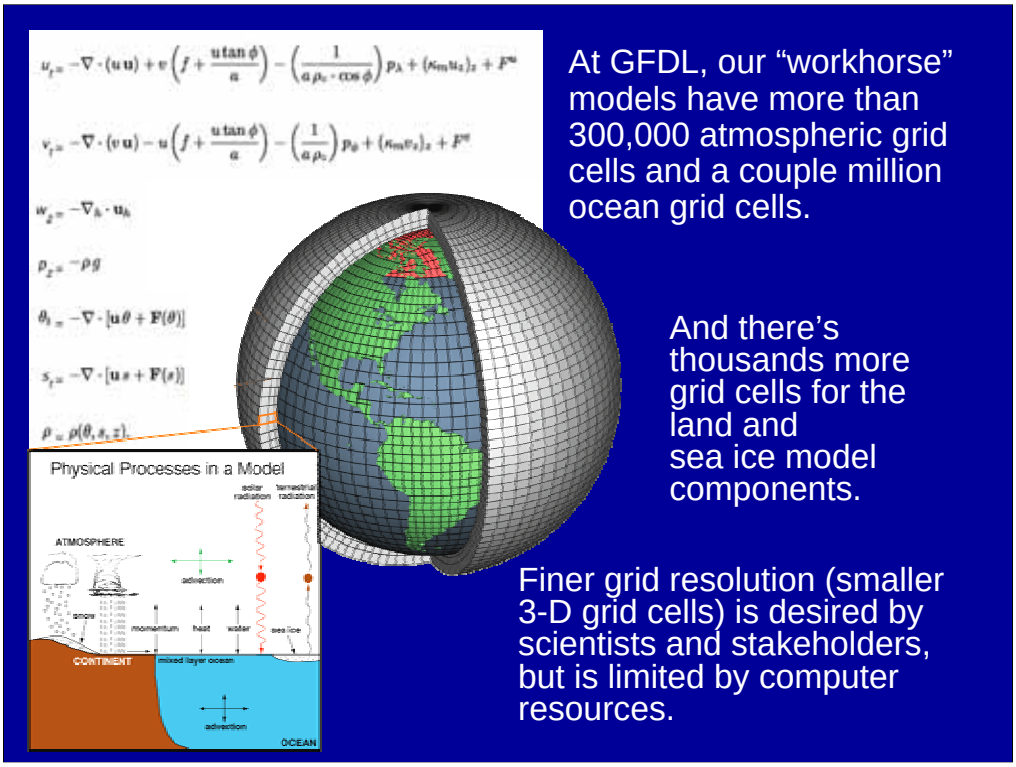
Modeling complex phenomena on big computers is widely accepted in various scientific and engineering fields – it is not unique to climate modeling. Much work in fields such as airplane and automobile design, nuclear weapon testing, etc., employ numerical models run on state-of-the-art supercomputers, as is the case for the global climate models developed, tested, and run at NOAA/GFDL.



Heat, water, momentum, etc. are transported within and between the different climate model components.

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 I show one model each for the atmosphere, the ocean, the land, and sea ice. But 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 others.

And more subcomponents are being added in order to make the models more "complete" or "comprehensive". For example, to simulate the global carbon and nitrogen cycles, GFDL scientists have recently added ocean biogeochemistry, interactive vegetation models, and more atmospheric chemistry modules. This will help us address questions of ocean acidification and vegetation succession as a response to climate changes, etc.

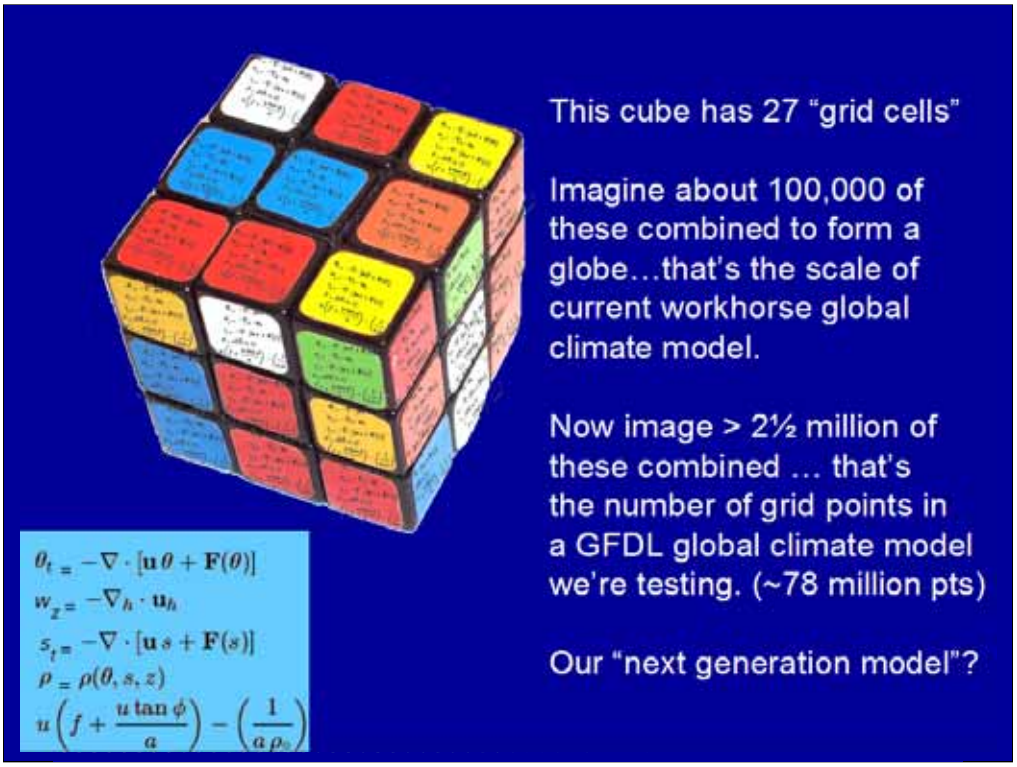


What do I mean when I say the model equations are solved on a grid?

This cartoon is intended to illustrate how we divide the 3-D ocean and 3-D atmosphere into many individual 3-D grid cells, or cubes. Sets of equations that describe the physical processes relevant to the climate are solved at each grid cell repeatedly as the model simulates how the system evolves over time.

The model equations represent physical processes and laws… among them, F=ma, gravity, conservation of mass and energy, and other physically based relationships that are more specific to climate. Increasingly, equations representing biogeochemical processes are being added. A global climate model is *not* an Excel spreadsheet nor just a set of correlation functions that specify when variable "A" changes "B" responds according to some simple formula.

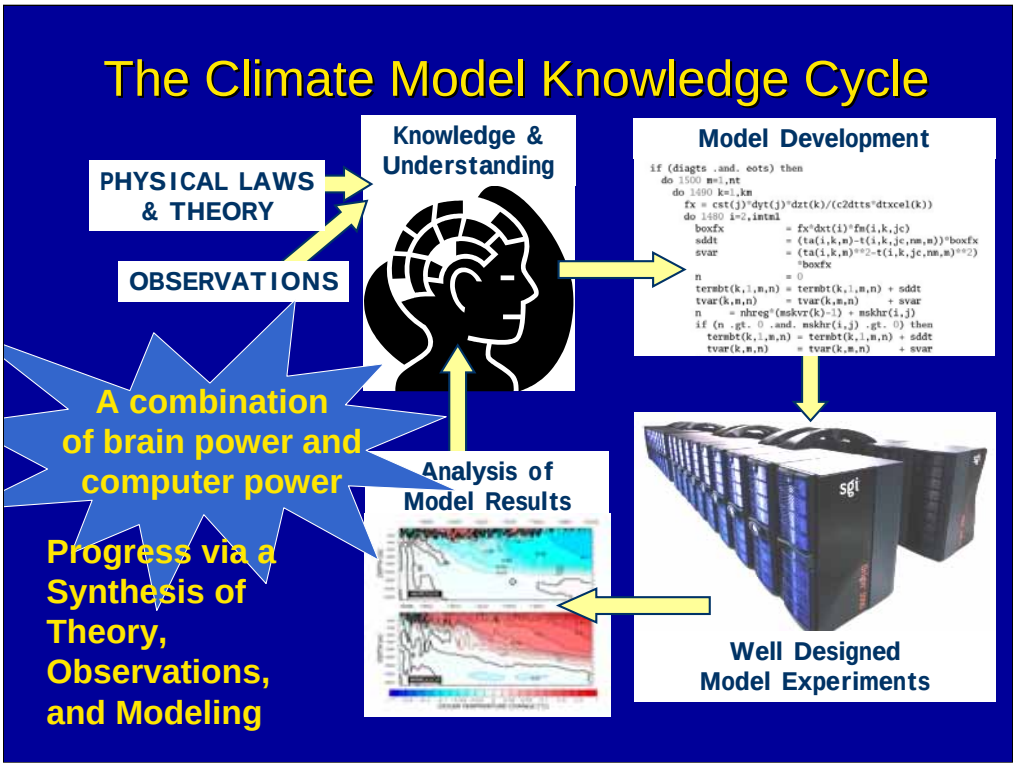
Note: The computer models we use to study climate over decadal to century time scales do not "ingest" observed temperatures… (we don't put observed temperatures into the model as it is running). The model simulates temperatures on its own. In effect, we turn on the Sun in our virtual world, tell it what the "boundary conditions" are – for example, the atmospheric levels of greenhouse gases and aerosols and how they vary in time and space, we specify where there's ocean and land and what the elevations are - and on its own the model then computes internal quantities, like the distribution of temperature, humidity, clouds and precipitation, winds and ocean currents, river runoff, soil moisture, sea ice formation and melt. It does this on its own, according to the physical processes as described by the model equations – and not by using or "assimilating" observations as it runs.



Here's another way to visual the scope or size of climate models. Higher resolution is desirable in modeling 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 YouTube video. The higher resolution provides a more detailed picture. As at other modeling centers, the grid size used in NOAA/GFDL's "workhorse" (aka "production") models is determined by the computer power available.

The higher resolution (78 million grid cell) model has been run as a prototype, simulating a few decades. It is too computationally expensive to run on our current computer system as a "production model" for the thousands of years needed to do IPCC-class science. An analogy is that we've built a better sailboat (the high resolution model) but will have to wait for sufficient wind (computer power) before it can be launched on its scientific voyage.

To get an idea about how a climate model works, let's simplify and consider one grid cell and one variable. Picture one of the grid cells as representing a point a mile above Missouri. Let's say the model has simulated up to noon, July 4, 2076. How does the model move ahead and simulate a temperature there for 12:10PM? The model equations will calculate the time rate of temperature change for that point and time according to the many model equations that describe many different processes. One set of equations will determine the warming due to sunlight being absorbed, which depends on time of day, season, clouds, etc. Another will figure the change due to the absorption and emission of infrared energy according to the grid box's composition (how much water vapor, how much CO2, etc.). The winds going in and out off the box's 6 sides can contribute to warming or cooling, depending on the temperatures at adjacent boxes. If clouds are forming then warming from latent heat release will occur, etc., etc., etc. All these and other process are being simulated for that particular location and time, with each process contributing its own warming or cooling rate. Add them all up, and you get a total time rate of change for that grid cell. Apply that rate of change for the time step length (say 10 minutes) and an updated temperature is calculated for 12:10PM. That same concept applies at all model grid points (ocean, atmosphere, land surface, sea ice) for numerous variables. All those calculations occur at all those grid points in order to move ahead one timestep. Then, after all grid points are updated, it starts all over again. That's a lot of computations representing a lot of physical processes



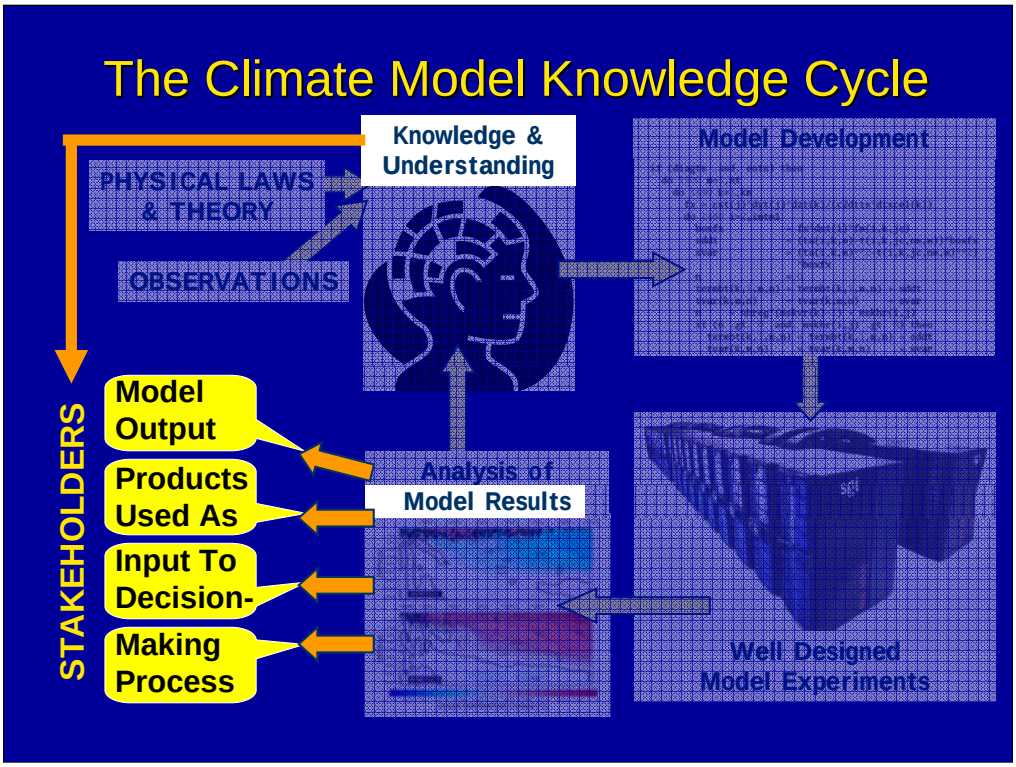
A numerical model of the climate system can be thought of as a very large set of mathematical representations of our understanding of the way the climate system "works". That understanding initially comes from observations of the real world, theories and physical laws. Climate science advances are made as more observations are gathered, theories are refined, and previous model results are analyzed – all of which (hopefully) provide insights and a deeper understanding of how the Earth's climate system works.

Climate science research advances are made via combinations of work done with observations, theory, and numerical modeling. It's like a sturdy three legged stool… and climate modeling is one of those three legs.

A new generation of couple models takes root about once every 5 or 6 years – the time span between successive IPCC reports.

But what's shown on this slide is limited to the science research side of things.

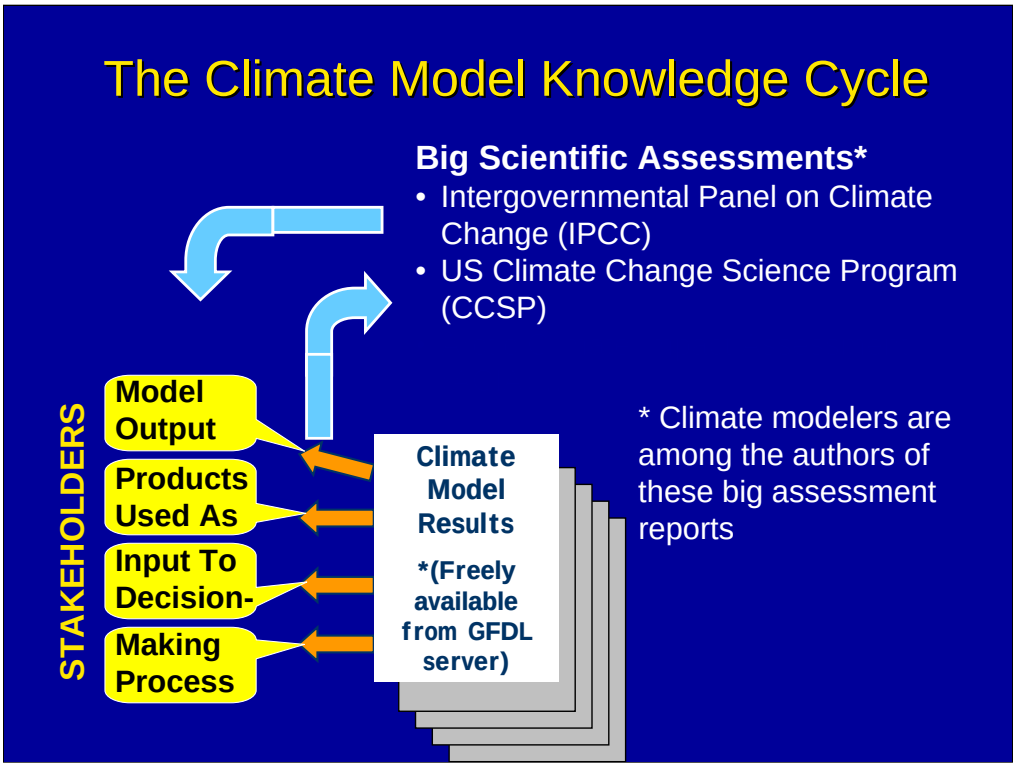
What about the connection of this science to stakeholders? [next slide]



Moving to the connection between the scientific research and stakeholders:

Sometimes stakeholders and policymakers are direct consumers of NOAA/GFDL climate model results. If you've seen graphs, maps, or animations of our model results – or read a report containing excerpts from a GFDL authored scientific paper – or gotten information from our web pages - you've been a direct customer and we can consider that climate related info as having been kind of a "retail product" of NOAA/GFDL.

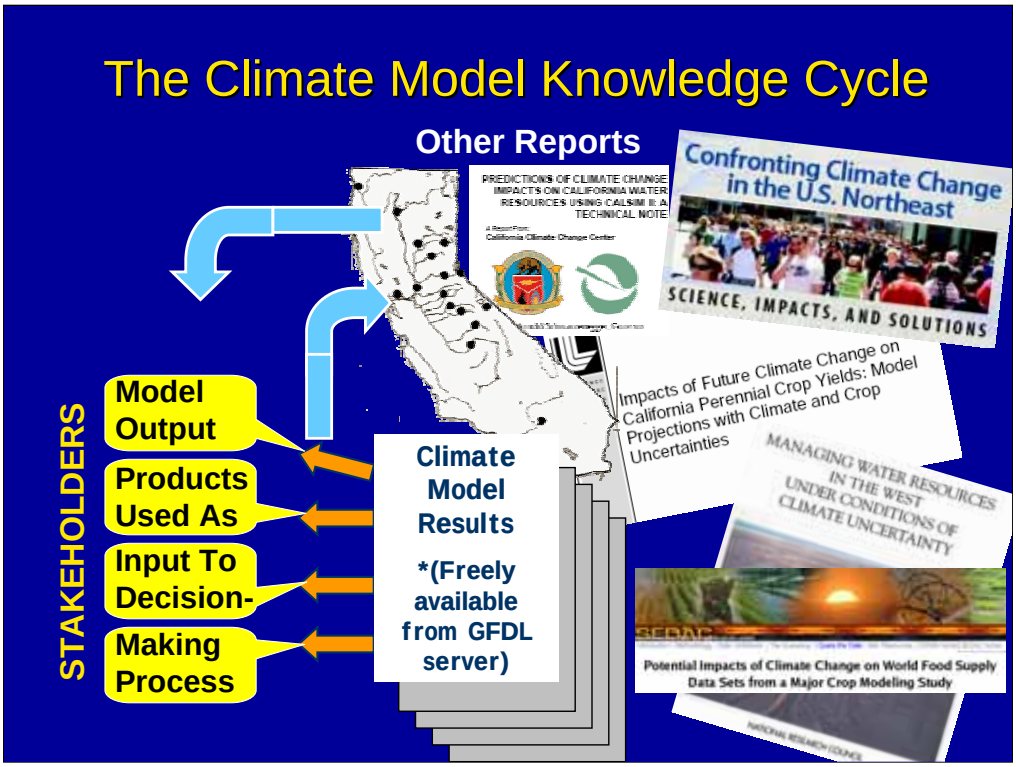
However, more people probably are exposed our work in slightly less direct manner, as our work is incorporated into the collective "knowledge base" of the scientific community and then shared with stakeholders. For example, … [next page]



The Big Scientific Assessment Reports [IPCC = international, CCSP = USA] have relied heavily on research results and scientists from GFDL. One can think of these reports as going through an extra step – an extra distillation process – or as being a review of reviewed work – before being communicated to stakeholders.

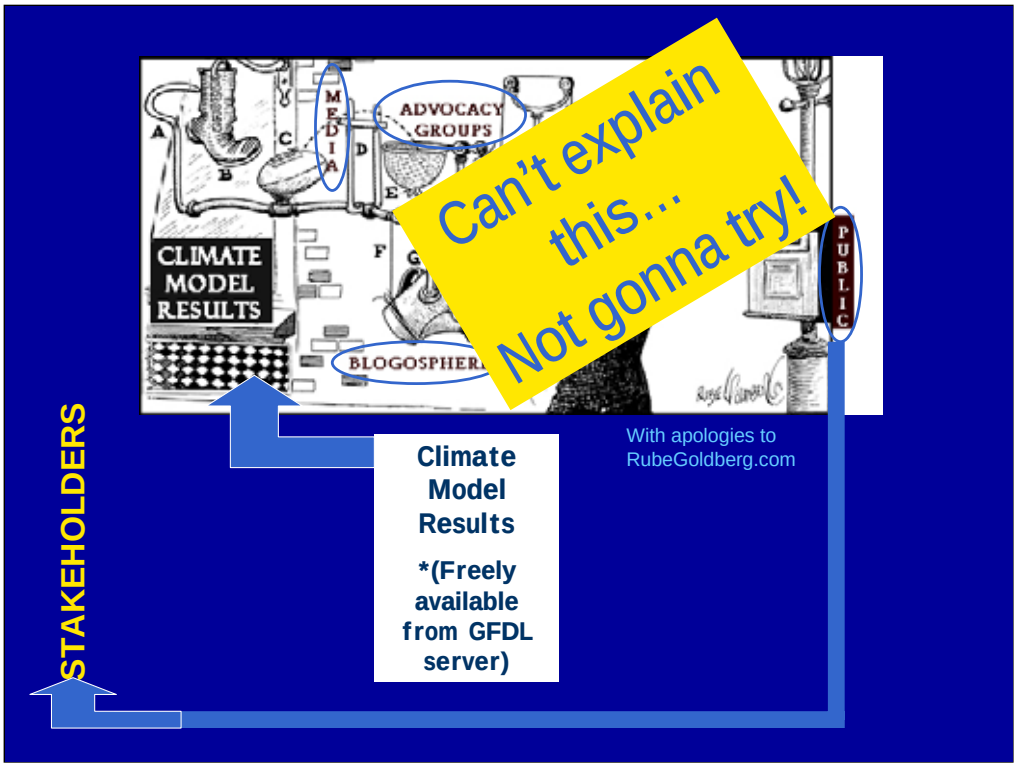
In these big assessments, scientists (including some from GFDL) consider the current state of knowledge and recent work done in the field, determine which parts hold up (are robust), and are relevant to the stakeholders, and then report those scientific findings in a form that is (hopefully) accessible to the policymakers and other stakeholders. With GFDL scientists involved in each step of this process up until the moment the reports are delivered from the scientists to the stakeholders, I consider these to be a “retail product” as well.

NOAA/GFDL climate model output and scientists have been involved in all four high profile IPCC assessments (1990, 1995, 2001, 2007) and in several recent CCSP reports.

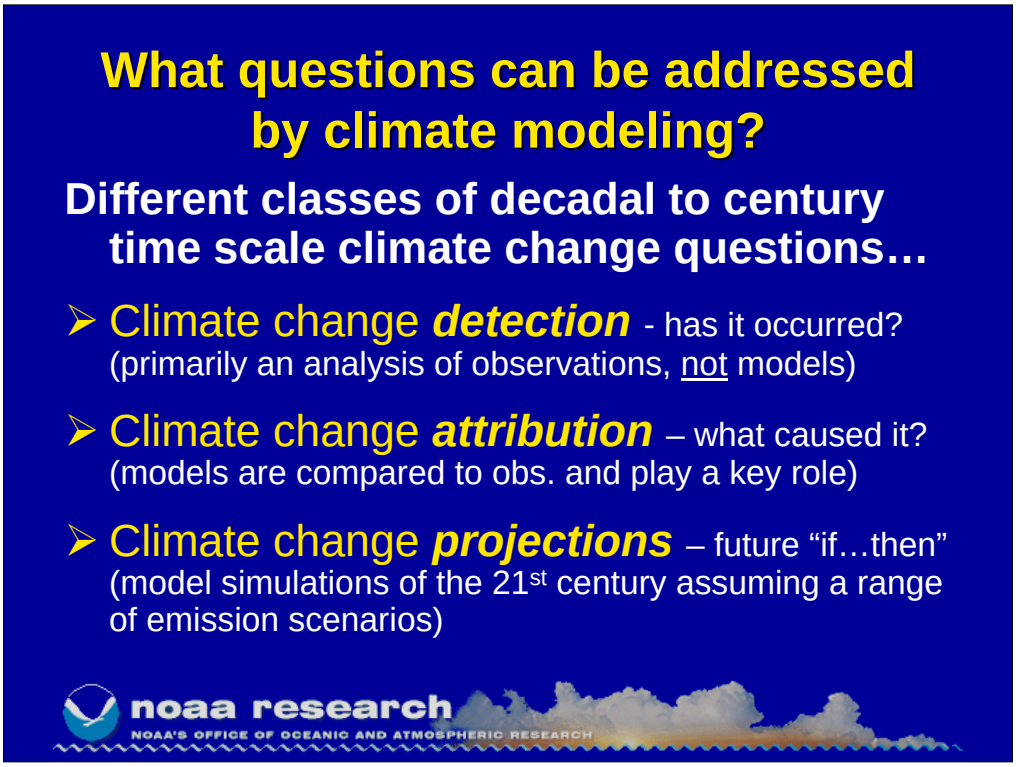


On this slide I show examples of reports in which GFDL climate model results are used more as a “wholesale” climate info product. I’m referring to cases where the output files of our models are downloaded and used as input into other analyses, without any active collaboration with GFDL scientists. This is possible because we place a large amount of our climate model output onto our freely accessible computer server. Anyone can download these model output files – no fees, no registration forms to fill out. Thousands have done so - including researchers at universities, other government agencies in the US and internationally, the private sector.

Since we at GFDL did not participate in writing the reports depicted on this side, we can’t speak to the quality of these particular reports. But it is becoming increasing common for our model output to be used as a valuable “wholesale climate product” - downloaded by people with expertise in climate change impacts and adaptations, who use it as input and aim to add value according to their own expertise. Supporting this kind of effort, though not participating or consulting on the individual projects, is partly why we devote resources to making these files freely available on the web.



For completeness, I should mention a third, more convoluted route by which the public hears about our climate model results. I'm referring to pathways that go through the media, advocacy groups, or the blogosphere. Sometimes the scientific content passes though pretty well and reaches a substantial audience. Other times the information is mischaracterized or misunderstood, and … well, I can't explain the process and certainly won't try to do so here today.

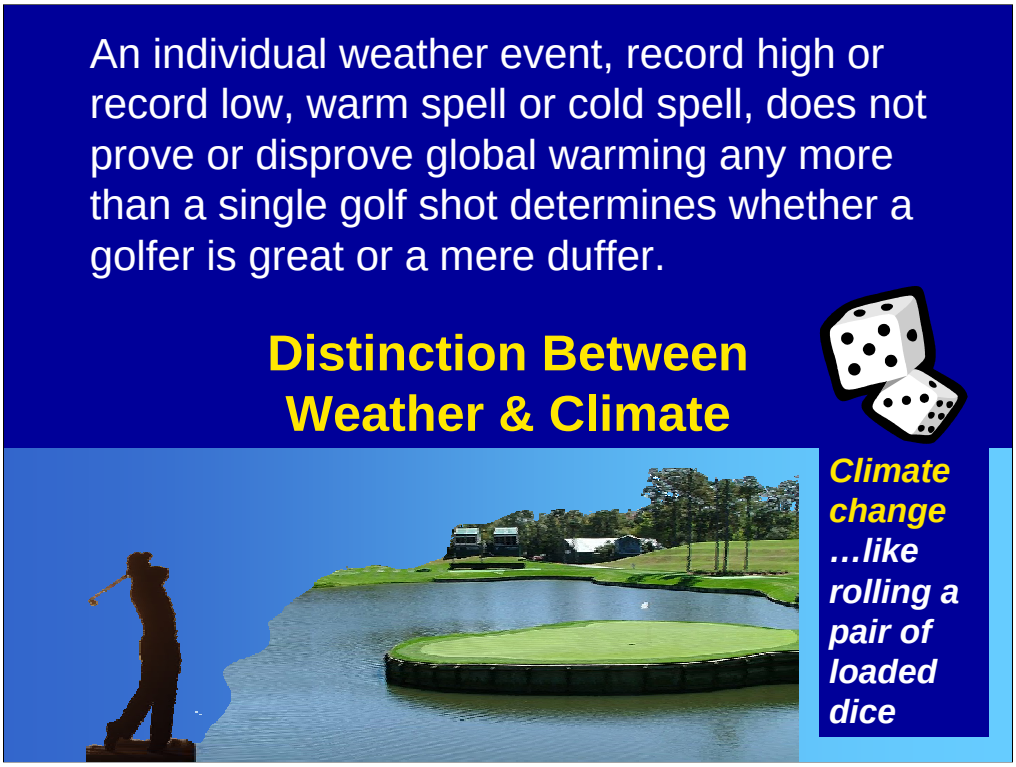


Many policy- relevant climate change questions can be binned into 3 categories:

First are questions about the DETECTION of climate change. Has a clear signal of climate change emerged from the noise of the natural, random fluctuations that are always occurring? Science is conservative… the null hypothesis is that nothing unusual has taken place and it takes a lot to reject that default assumption. Yet compelling evidence has accumulated that large scale warming of the planet (oceans and atmosphere) indeed has taken place during the 20th century. The IPCC 2007 report used the word "unequivocal" to describe the large scale warming… not a word scientists throw around casually. But DETECTION is primary based on observations – not models.

Once detected, the next question is one of ATTRIBUTION. You may ask, "How in the world can you say what caused the warming just by looking at the observed warming data?" The answer is that you can't easily do so using observations alone, and that where climate models – experiments done with our virtual worlds - fit in together with the observations.

And thirdly there are questions about how climate might change during the rest of the 21st century. Climate change PROJECTIONS rely heavily on climate models. There simply aren't any observation of the future.



Before discussing Climate Change Attribution in more detail, I first want to go over the answer to a frequently asked question… one that deals with the difference between "weather" and "climate". Sometimes analogies help.

I'm a lousy golfer. If I shoot a round in the 90s it's a good day. If I shoot in the 80s it's a great year! But there have been a few times when I've stepped up to a 140 yard par 3, hit my tee shot to within a few feet of the hole, made the putt, and walked off with a birdie. The only way even Tiger Woods could beat that would be to get a hole in one. But does that one shot make me a great golfer? Am I ready to win on the PGA tour? Obviously not. My birdie was like a rare "weather" event. It's in my golf "climatology"- it's happened before, it will hopefully happen again – but the probability for me making a birdie is still much less than Tiger Woods'. One shot doesn't change that.

That one birdie of mine was like a weather event. And one cold winter in one region, or one regional heat wave doesn't make a global climate change trend. You can think of climate as the sum total of weather events… not just the average, but the extremes and the variability as well. Climate is more about the probabilities of events over longer periods of time, while weather is more about individual, short-lived, discrete events.

So one year of very little summer Arctic sea ice doesn't "prove" global warming any more than people throwing snowballs in Baghdad one day this winter "disproves" it.

Another analogy: What we are doing by adding more greenhouse gases to the atmosphere decade after decade is making some weather events more likely than they had been previously, and other events are becoming less likely. It's like rolling a pair of loaded dice.

Climate change ***attribution***

That global scale climate has warmed is *"unequivocal"*

But can we determine what caused it?

(models are compared to obs. and play a key role)

"Most of the observed increase in globally averaged temperatures since the mid-20th century is very likely* due to the observed increase in anthropogenic greenhouse gas concentrations."

*(*very likely = 90-95% certainty)*

- IPCC AR4 WG1 SPM, Feb 07

This is the oft-quoted attribution statement from the 2007 IPCC Working Group I Summary for Policymakers. (http://www.ipcc.ch)

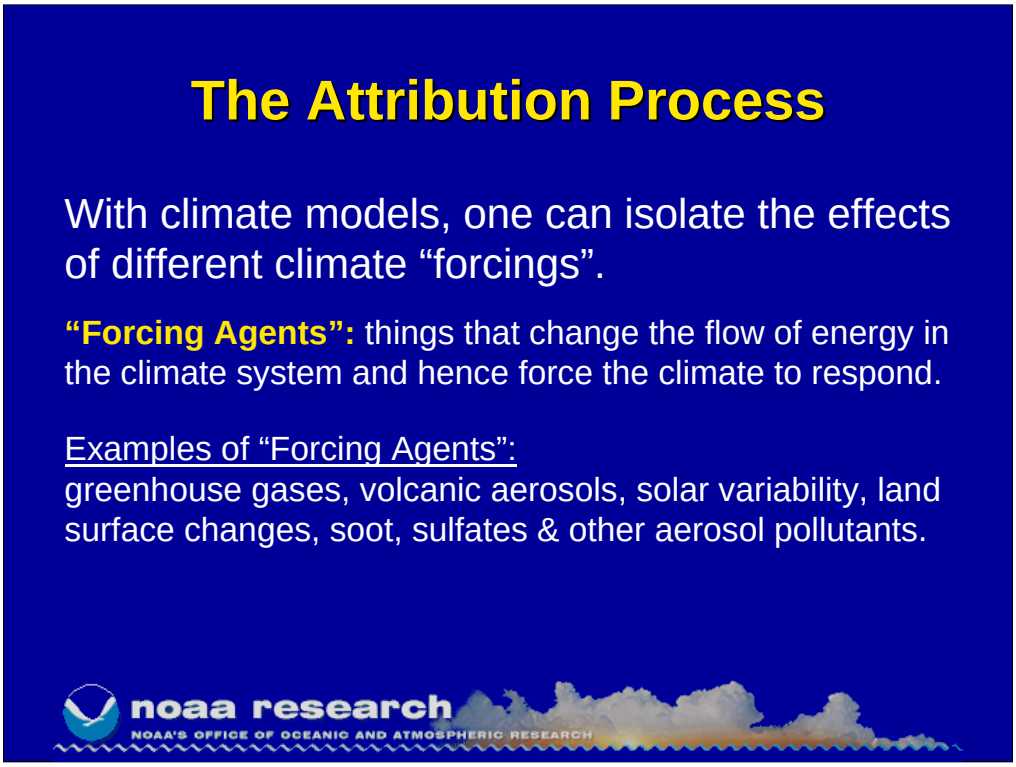
Parsing it…

•Most of the **global** warming

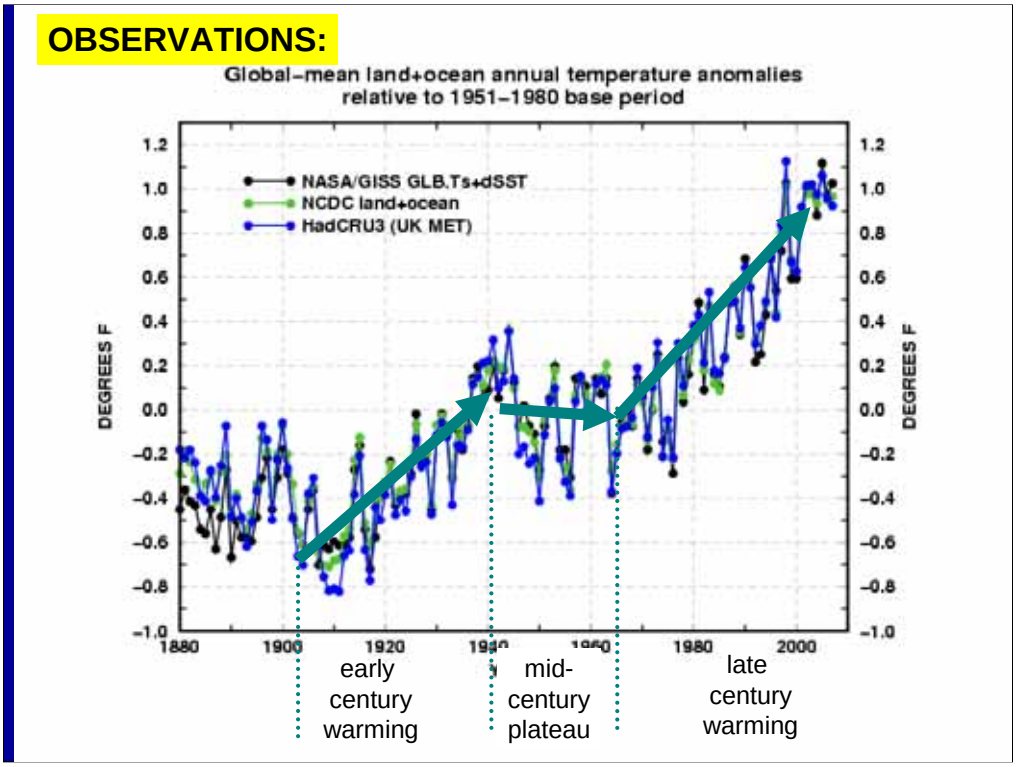
•Over the last **50 years**

•Is due to **man-made greenhouse gases** (>90% certainty)

Again, the null hypothesis – our default assumption – is that we can't say what factor or combination of factors was responsible for the observed global scale warming. But, as evident in the IPCC's expert judgment, that null hypothesis can be rejected because of evidence garnered largely from studies that compare observations with results from climate model experiments – model experiments set up specifically to simulate and isolate the potential contribution from a number of different factors (not just greenhouse gases)…



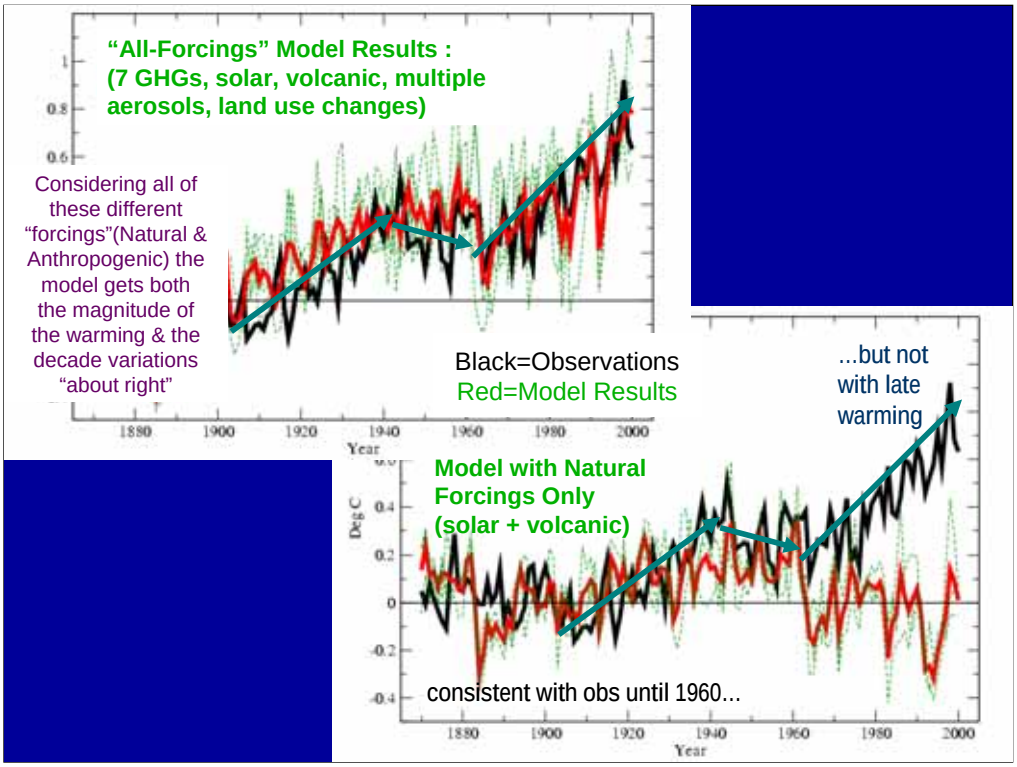
Here's the list of the different kinds of "forcing agents" we can simulate in our current model. These agents (a) affect the flow of electromagnetic energy (e.g., sunlight and infrared energy) in the climate system in ways that can be described by equations in the model and (a) have varied over the past century or so in ways that have been estimated from observations.



This graph shows observations of global average surface temperatures as reported by 3 groups – one from NOAA/NCDC, one from NASA, and one from the UK. It has nothing to do with models – it's just observational estimates.

I show it to point out the decade to decade variations. There was an early century warming in the 20th century… a plateau period near the middle of the century … and several decades of warming in the late 20th century. (The late century warming is what is referred to in the previously listed IPCC's attribution statement.)

The question is, can our climate models reproduce these observed changes, and if so, what then is the role of the different forcing agents? We can use the models to do something one can't do with observations… we can ask what the simulated response of the climate system would have been if only some forcing agents had changed over time, while the others were held constant at 1860 levels during the duration of the experiments. And we can ask this question using different combinations and permutations of forcing agents. This way, we can isolate the effects of the different forcing agents in our virtual world.



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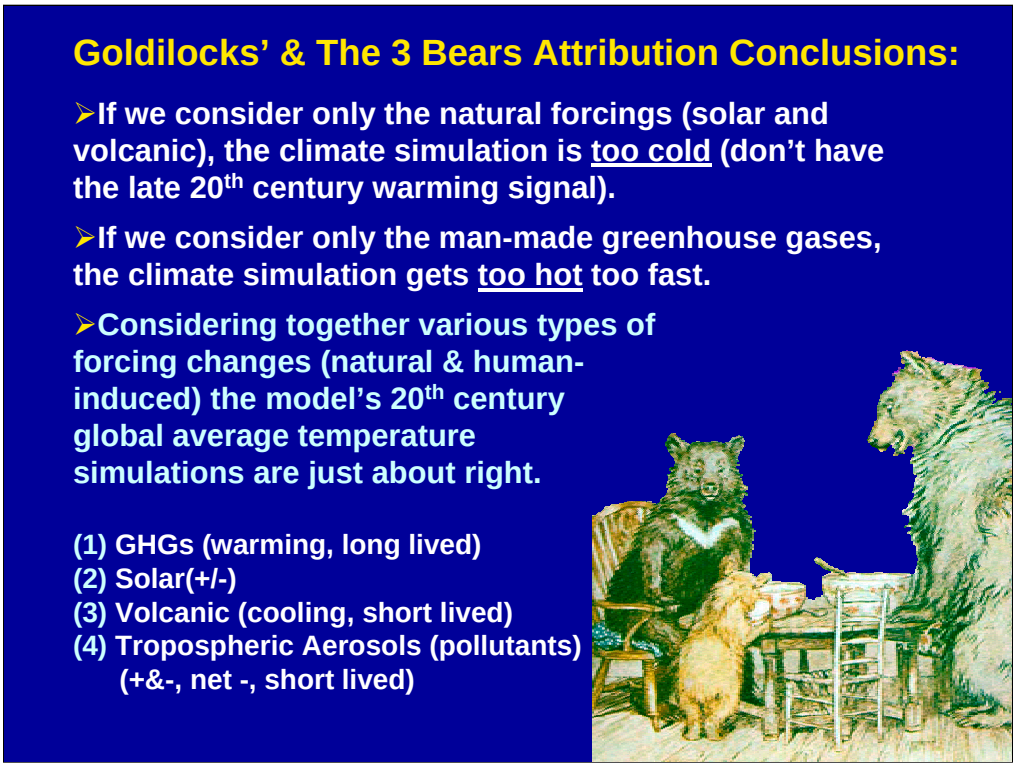
First consider the figure at the **bottom right**. The black line show the same observations depicted on the previous slide, just re-plotted. The red line shows the NOAA/GFDL model results when we only consider the "natural" forcing agents – namely, volcanic aerosols and changes in solar irradiance. Up until about 1960, the model with natural forcing agents only (no human influences) agrees pretty well with observations. However, during the last several decades, the model and observations diverge. Punctuated by some major volcanoes – Agung (1960s), El Chicon (1980s), and Pinatubo (1990s) - the model with only natural forcing cools a bit while the observations show significant warming. Similar simulations preformed at other modeling centers show the same thing – we can not reproduce the observed warming of the late 20th century by using these natural forcings alone.

Turning to the plot at the **upper left** we see a case where the model simulation (red) matched the observed global average temperature variations very well on decadal and longer time scales. This is achieved by including all the forcing agents we have (all that we have model equations and observation for) – both man-made and natural. And analyses show that the model's late century warming is mostly due to the increased concentrations of man-made greenhouse gases.

That's a simplified view of the attribution process. In reality much more sophisticated analyses of variables in addition to surface temperature tell the same, consistent, lareg scale story in models developed at a number of international modeling centers.

Again, a synthesis of theory, observations, and modeling is how advances are made.



Perhaps this is a simple way to remember these climate change attribution findings.

(Graphs for the 2nd bullet – the greenhouse gas only experiments) were not shown here due to time constraints)

Note that the major man-made greenhouse gases (CO2, CH4, N2O, CFCs) all warm the lower atmosphere and have long atmospheric lifetimes. Put an extra molecule of these gases in the atmosphere and an extra molecule remains for a decade to more than a century, depending on which gas it is.

In contrast, volcanic aerosols, that warm the stratosphere but cool the surface, remain in the stratosphere (up above where commercial jets fly) for only a few years before settling out via gravity.

And other aerosol pollutants like soot (which warms the surface) and sulfates (which cool) tend to get removed from the air by gravity or rain or chemical processes in less than a week. The net effect of the tropospheric (the lower part of the atmosphere where weather occurs) aerosols is to cool the surface, though it's precise magnitude is still an open research question.

Solar irradiance goes through 11 year cycles and subtle trends, but no trend has been detected over recent decades, according to observational estimates.

Climate change ***projections***

future "if…then"

(based on model simulations of the 21st century assuming a range of emission scenarios)

"Continued greenhouse gas emissions at or above current rates would cause further warming and induce many changes in the global climate system during the 21st century that would very likely be larger than those observed during the 20th century."

*(*very likely = 90-95% certainty)*

- IPCC AR4 WG1 SPM, Feb 07

This is the oft-quote IPCC 2007 statement on climate change projections.

Note it contains assumptions about future greenhouse gas emissions… something that is an input into climate models, but is not dependent on the climate or climate science.

Emissions levels are basically a result of human choices (population size, per capita economic output, energy efficiency per unit economic production, and greenhouse gas emissions per unit energy), not climate processes. However, the climate does respond to them.

Uncertainties In Climate Change Projections

Two broad types of uncertainties:

1) What will be the future concentrations of greenhouse gases in the atmosphere?
(these are climate model inputs – they depend on population size, economic growth, energy use efficiency & development of alternative energy sources)

2) How will the climate system respond to the changes in greenhouse gases?
(these are climate model outputs - the computer models are incomplete & are not perfect)

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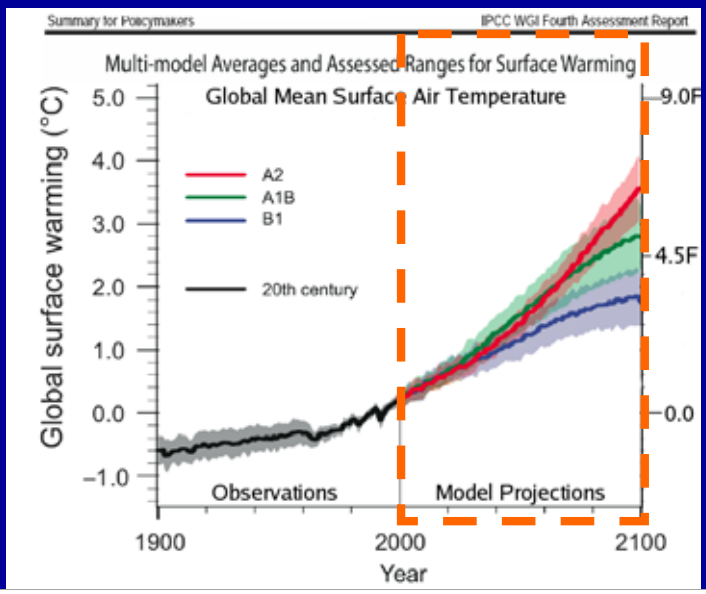
These two broad categories of uncertainties are evident in the next slide's graph.

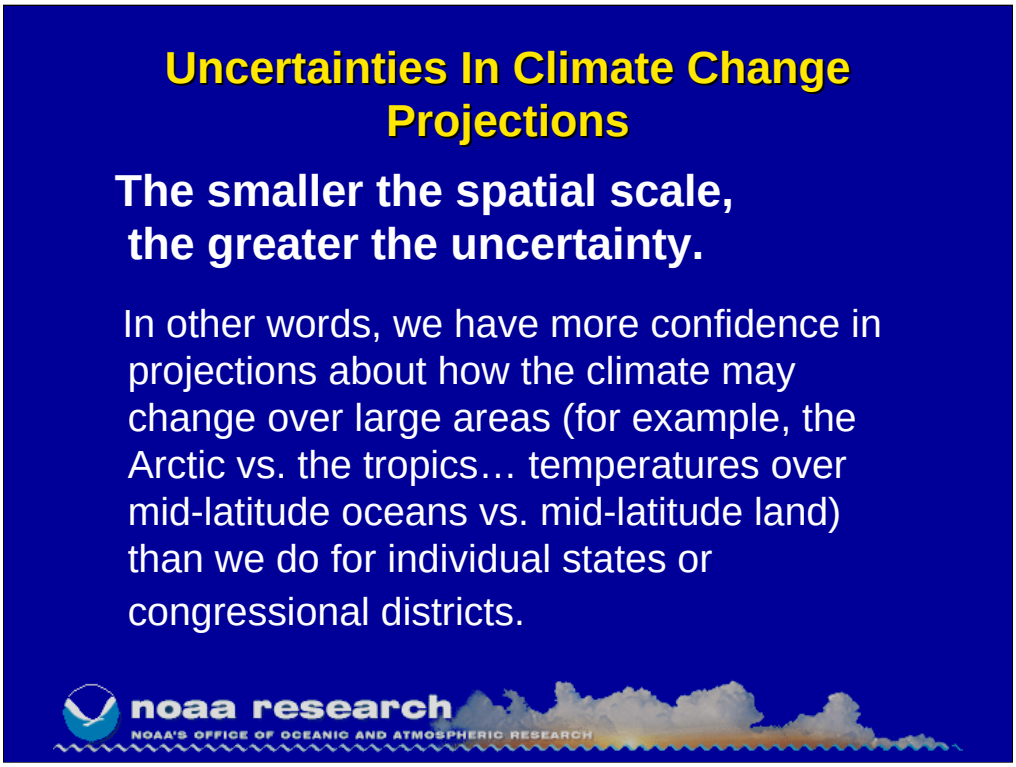
Projections: Climate modeling is the only way to obtain a reasonably complete and quantitative outlook for climate change over the coming century.



From the IPCC 2007: The 3 different colors for 2000-2100 denote model simulated global temperature changes associated with three different future emissions scenarios.

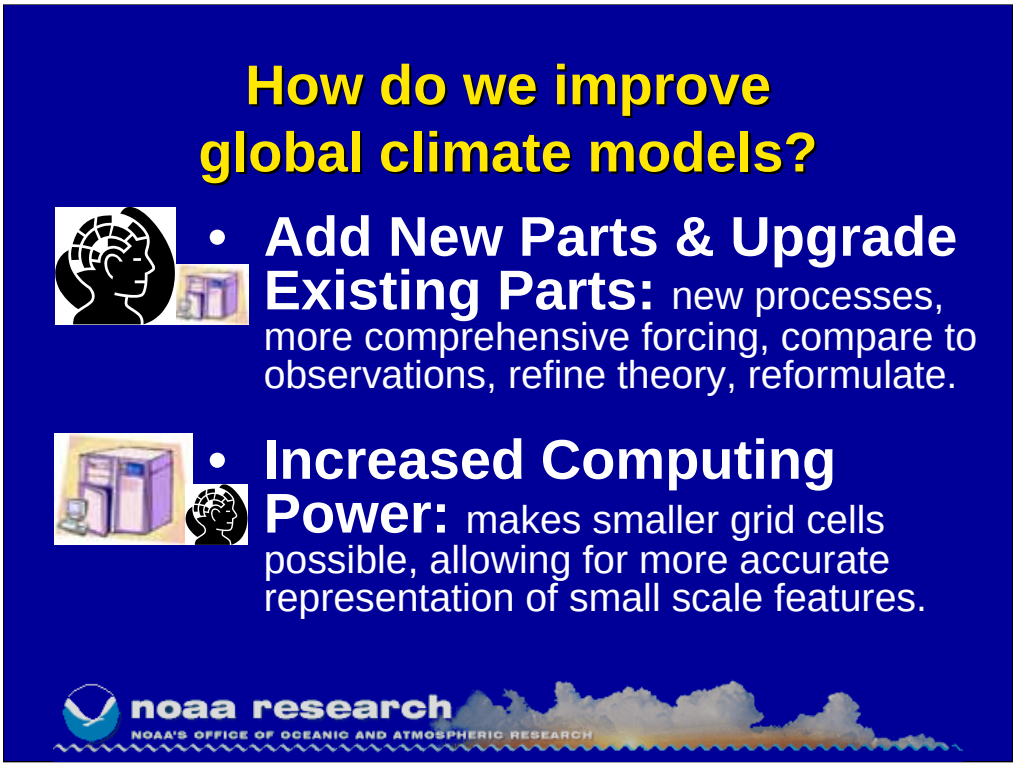
The 3 dark lines show the average simulated climate response computed over about 20 climate models from a dozen or so international modeling centers (including 2 models from NOAA/GFDL). So the 3 dark lines can be taken as consensus projections assuming 3 different pathways for future concentrations of greenhouse gases in the atmosphere.

The light shading around each of the darker lines shows an envelope that encompasses the range of results produced by about two-thirds of the models. This can be viewed as a measure of the extent to which models agree or disagree when they all follow the same greenhouse gas emissions assumptions.



People tend to put climate change on their personal radar screens as a result of the convincing evidence presented on the global or very large spatial scales. (These are the spatial scales referred to in the IPCC statements I showed on earlier slides).

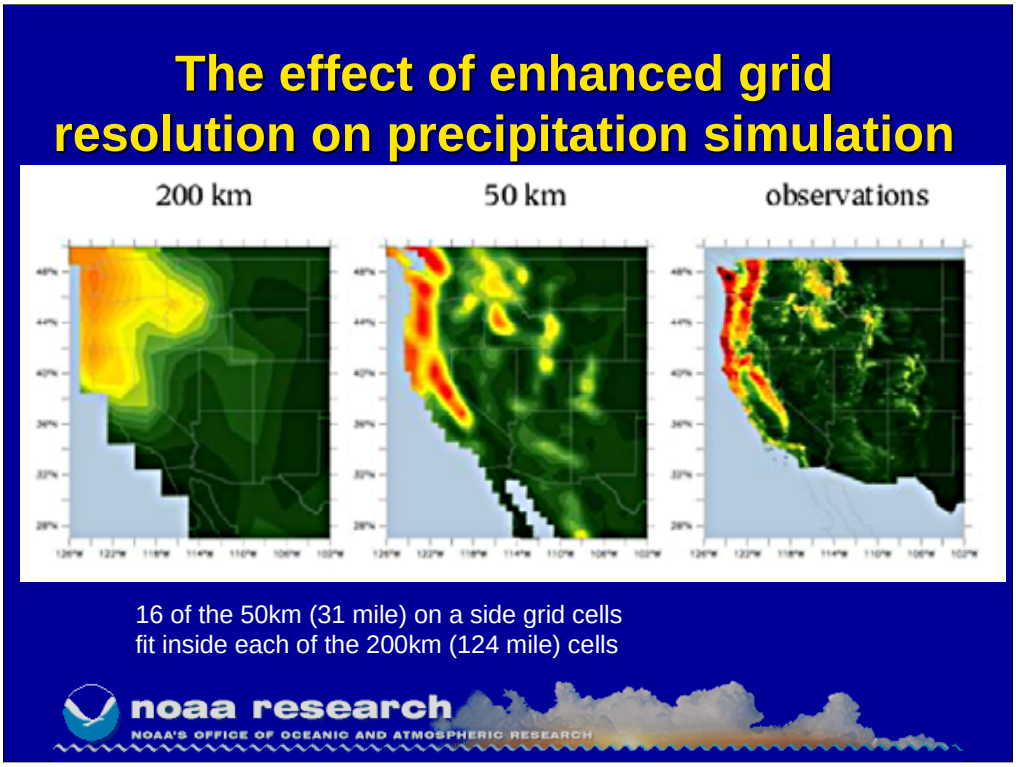
However, it is quite understandable that once climate change has someone's attention, they then ask what it means for their particular location. Unfortunately, the state of the science is such that we tend to have more confidence in the larger scale climate responses and less confidence in the details at the smaller spatial scales.



I've said that climate science advances via a synthesis of observations, theory, and modeling. And advances in climate modeling itself advances by a combination of these three elements, too.

Increasing computer power is a necessary brute force method that enables higher spatial resolution and several other kinds of climate modeling improvements to be realized – improvements that benefit both the scientific research side *and* the stakeholder support side.

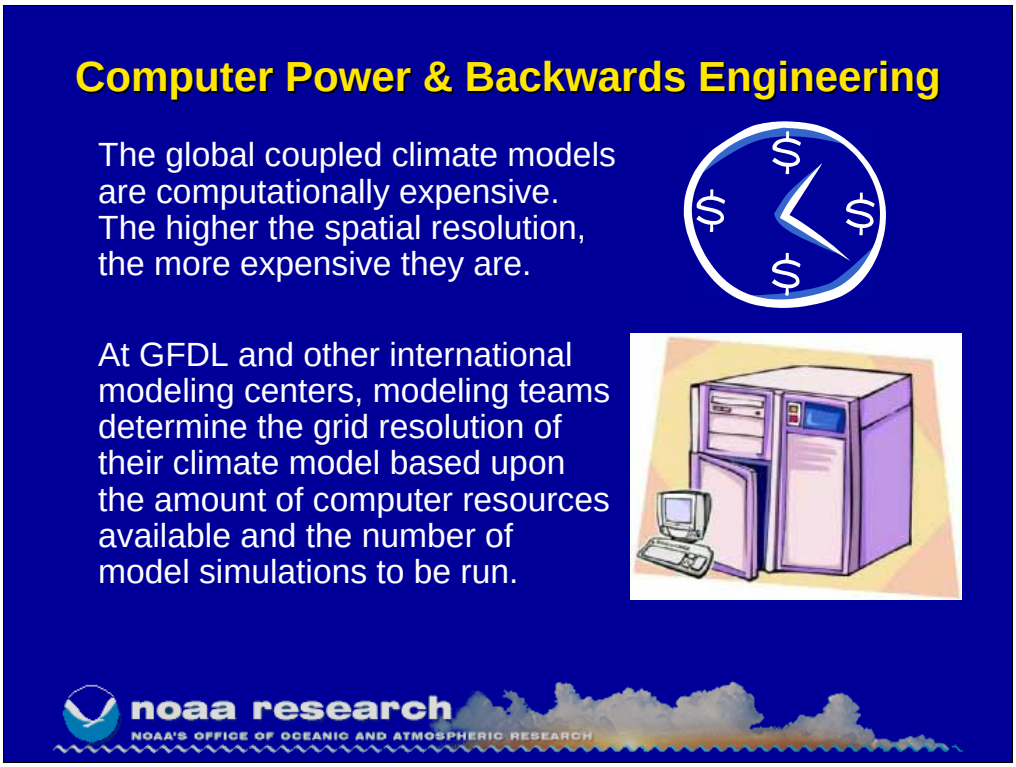
And a continued application of brain power is what's needed to learn more about how the climate system works and to find ways to translate that knowledge into computer programs.



I've spoken in the abstract about how higher spatial resolution can improve a model. Here's a more concrete example.

The atmospheric model component's horizontal grid for the model results pictured on the left is coarser than for the model shown in the center. Notice how with the higher resolution the precipitation simulation becomes sharper, more detailed, and more similar to the observations shown on the right.

That's the kind of improvement higher spatial resolution (smaller model grid cells) can produce.

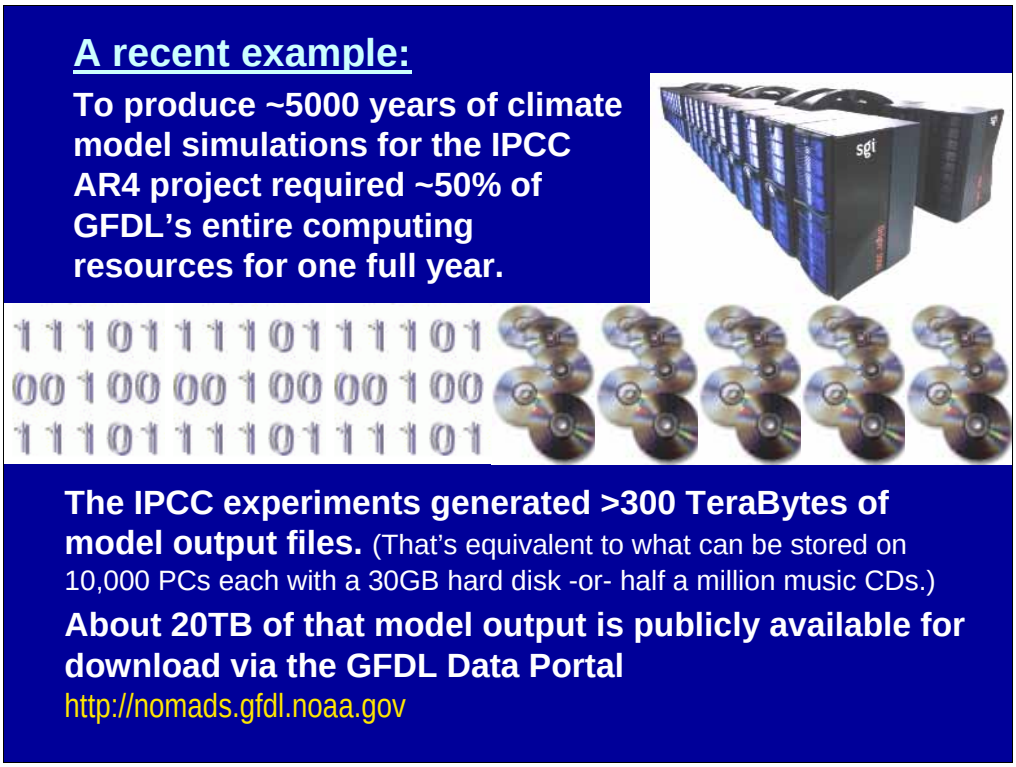


How much computer can climate modelers use? In practice we turn the question around. We take stock of how much computer is available and figure out how to fully utilize it. But in short order we could utilize 10, 100 times or more computer power by…

•Increasing model resolution (figure roughly 10x more compute power is needed if we double the resolution in 3 dimensions … 8 times more grid points and a shorter time step.)

•Run more model years of experiments: a) Running longer experiments (to better characterize internal variability and extreme event probabilities) b) Run larger ensembles of experiments, and c) Run more different experiment types (explore the responses to a wider range of future emissions scenarios)

•Develop more comprehensive and complex models. e.g., Going from a purely physical climate model (ocean, atmos, sea ice & land) to one with interactive biology and chemistry to model carbon and nitrogren cycles and air pollution transports requires more computations, as would adding an dynamical and fully interactive ice sheet model.



Data storage demands are increasing rapidly for both our traditional model analysis purposes and for stakeholders. There's increasing demand for high resolution and high frequency output for more model variables.

(driven in part by desire for regional climate change impacts and extreme event analyses)

SUMMARY

Increased scientific understanding & stakeholder support come from a synthesis of ***observations, theory****, &* ***modeling****.*

Advancements in climate modeling, such as that done at NOAA/GFDL, involve a combination of ***Brain Power*** *&* ***Computer Power***

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