CLIMATE MODELING 101:
COMPUTER MODELING'S CONTRIBUTION TO THE CLIMATE RESEARCH CHALLENGE

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So we're all on the same page, I'll begin with a discussion of…

- **The kinds of scientific problems & time scales addressed by the global "IPCC-class" climate models.**

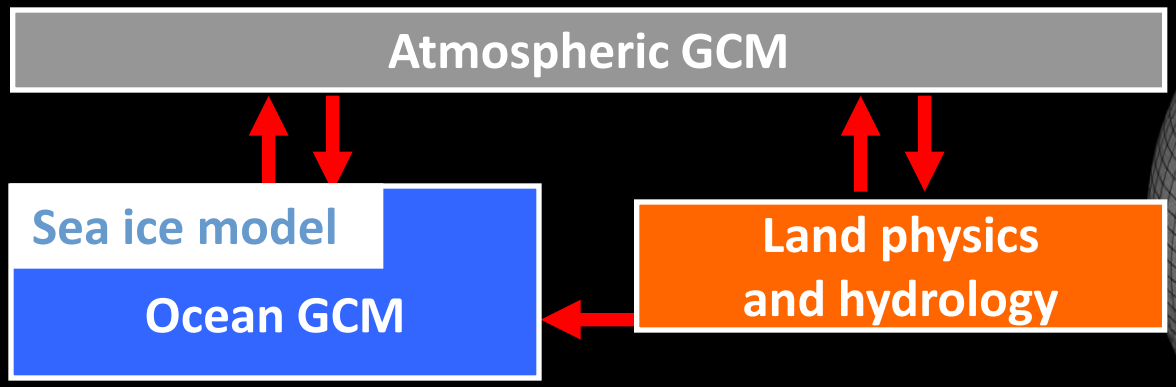
*

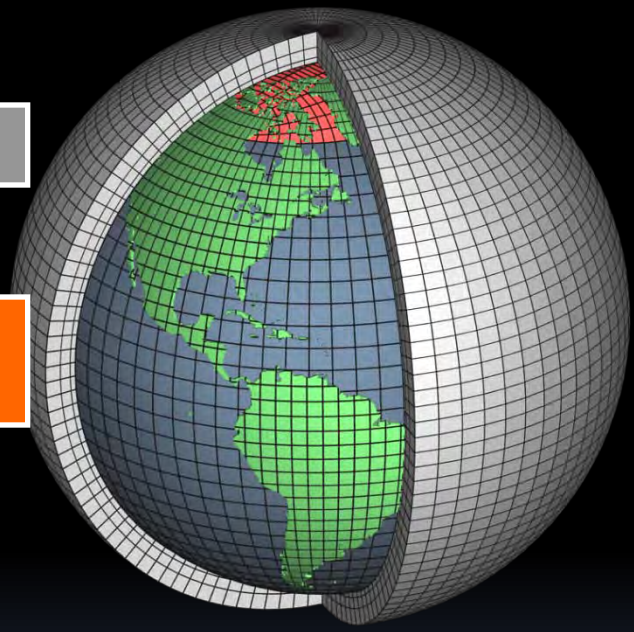
- **What these climate models are, and are not.**

So we're all on the same page, I'll begin with a discussion of…

- **The kinds of scientific problems & time scales addressed by the global "IPCC-class" climate models.**
  ** main focus is multi-decadal to century time scale (today +/-150 years), but daily weather & seasonal climate variations are simulated.*
  ** look at large-scale physical climate features.*
- **What these climate models are, and are not.**

Lacking a Time Machine, Climate Models provide the most credible, science-based means to quantitatively project how the planet's climate will respond to changes in greenhouse gases & other climate "forcing agents".





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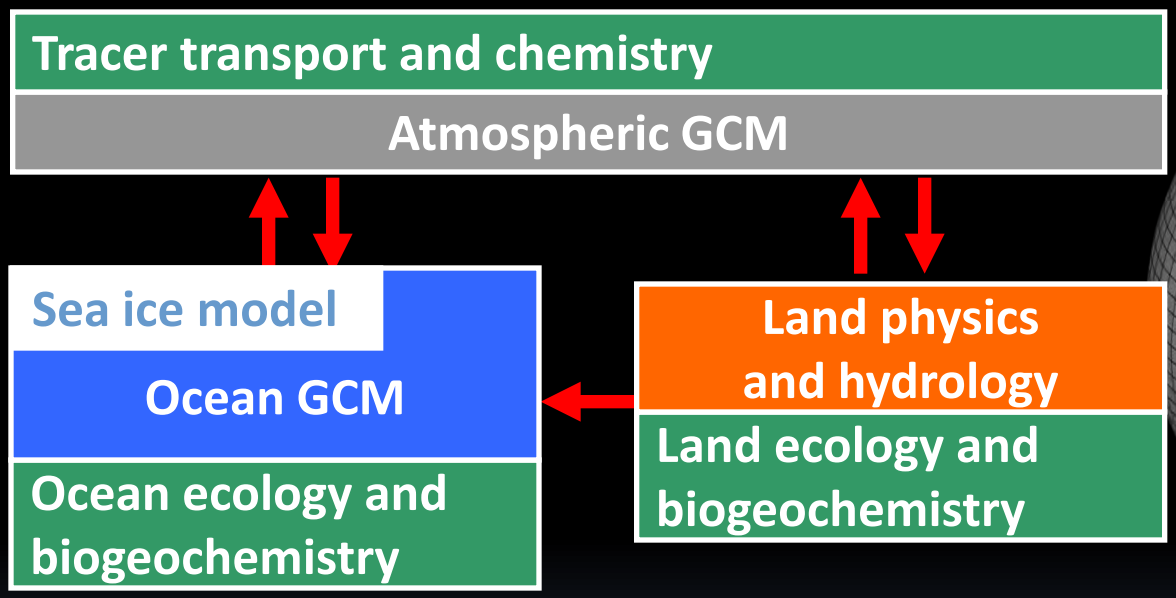
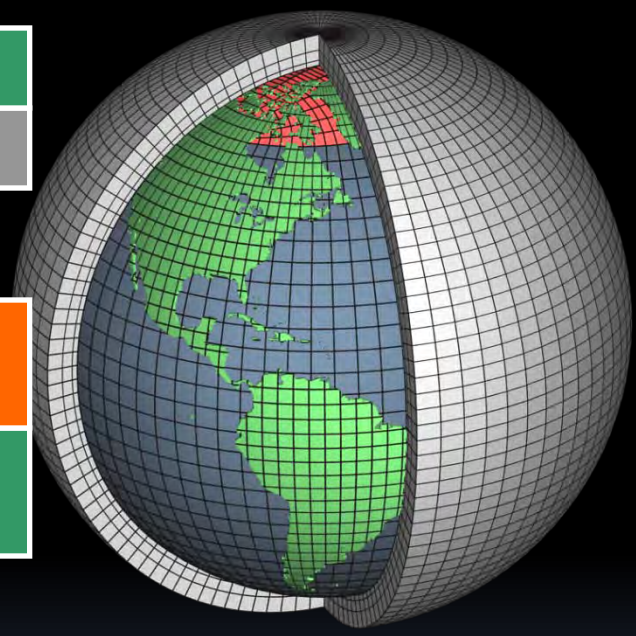




A Global Climate Model is a mathematical representation of the major climate system components and their interactions. The model equations operate on a grid and are solved on a computer.

$$u_t = -\nabla \cdot (u\,\mathbf{u}) + v\left(f + \frac{u \tan\phi}{a}\right) - \left(\frac{1}{a\,\rho_\circ \cdot \cos\phi}\right) p_\lambda + (\kappa_m u_z)_z + F^u$$

$$v_t = -\nabla \cdot (v\,\mathbf{u}) - u\left(f + \frac{u \tan\phi}{a}\right) - \left(\frac{1}{a\,\rho_\circ}\right) p_\phi + (\kappa_m v_z)_z + F^v$$

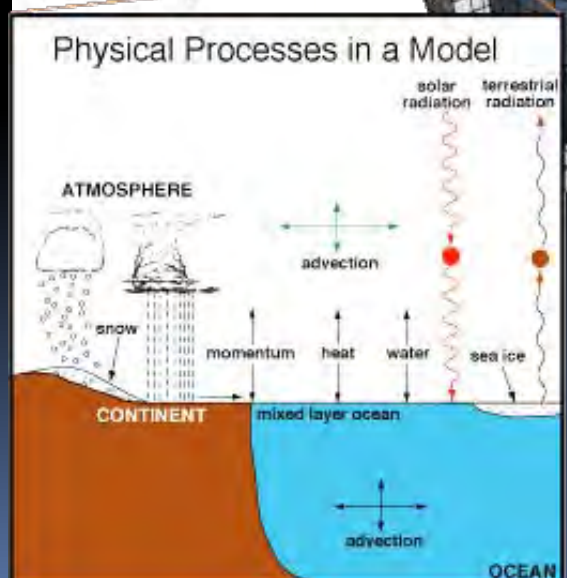
$$w_z = -\nabla_h \cdot \mathbf{u}_h$$

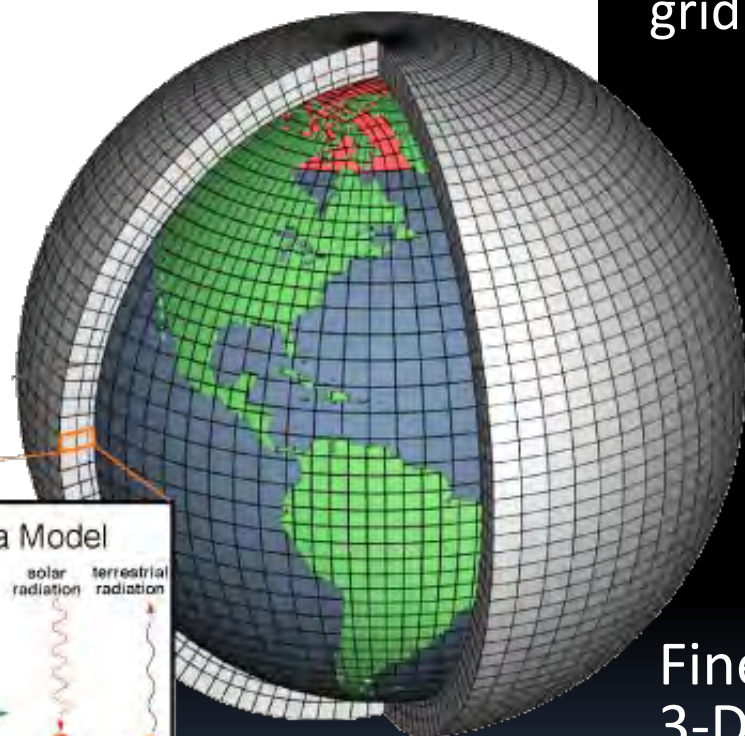
$$p_z = -\rho\, g$$

$$\theta_t = -\nabla \cdot [\mathbf{u}\,\theta + \mathbf{F}(\theta)]$$

$$s_t = -\nabla \cdot [\mathbf{u}\,s + \mathbf{F}(s)]$$

$$\rho = \rho(\theta, s, z).$$





At NOAA/GFDL, our recent "workhorse" models have more than 300,000 atmospheric grid cells and a couple million ocean grid cells.

And there's thousands more grid cells for the land and sea ice model components.

Finer grid resolution (smaller 3-D grid cells) is desired by scientists and stakeholders, but is limited by computer resources.

Model grids

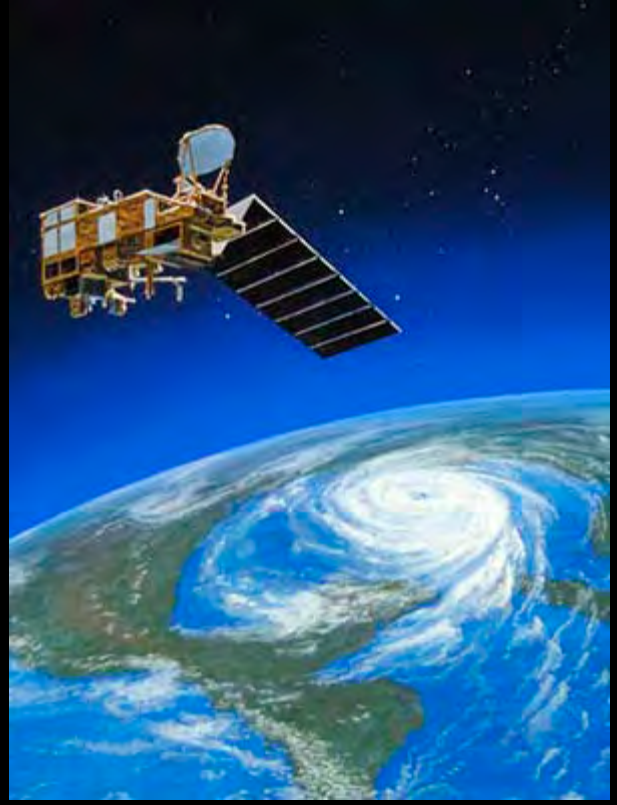
$$\theta_t = -\nabla \cdot [\mathbf{u}\,\theta + \mathbf{F}(\theta)]$$
$$w_z = -\nabla_h \cdot \mathbf{u}_h$$
$$s_t = -\nabla \cdot [\mathbf{u}\,s + \mathbf{F}(s)]$$
$$\rho = \rho(\theta, s, z)$$
$$u\left(f + \frac{u \tan\phi}{a}\right) - \left(\frac{1}{a\,\rho_\circ}\right)$$

This cube has 27 “grid cells”

Imagine about 100,000 of these combined to form a globe…that’s the scale of GFDL’s workhorse global climate model circa 2004.

Now image > 2½ million of these combined … that’s the number of grid points in a GFDL global climate model we’re testing. (~78 million pts)

Our “next generation model”?



```
if (diagts .and. eots) then
  do 1500 m=1,nt
    do 1490 k=1,km
      fx = cst(j)*dyt(j)*dzt(k)/(c2dtts*dtxce
      do 1480 i=2,imtm1
        boxfx            = fx*dxt(i)*fm(i,k,jc
        sddt             = (ta(i,k,m)-t(i,k,jc
        svar             = (ta(i,k,m)**2-t(i,k,jc,nm,m)**2)
                           *boxfx
        n                = 0
        termbt(k,1,m,n) = termbt(k,1,m,n) + sddt
        tvar(k,m,n)      = tvar(k,m,n)      + svar
        n     = nhreg*(mskvr(k)-1) + mskhr(i,j)
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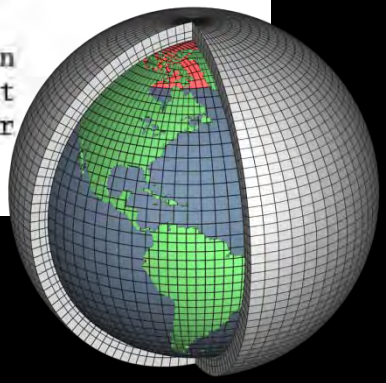


Observational records can tell us about the past and the present…

…state-of-the-art climate models can provide info by simulating the past, present, & future.

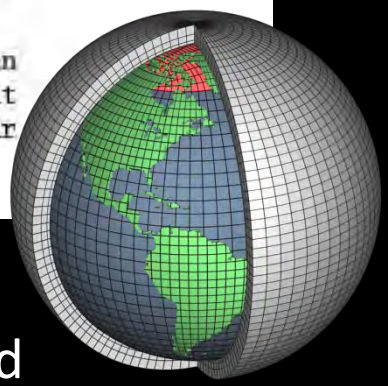
We learn & gain confidence from their ability to simulate observed large-scale, decade to decade variations.

Some of what climate models offer:

- Can simulate potential future conditions and the past quantitatively.

- Can simulate linkages between the different Global Climate System components (air, ocean, land, sea ice, biogeochemistry)

Climate models are powerful yet imperfect tools that allow us to ask *"What if…"* science questions.



- Can isolate individual factors (role of natural vs. human-induced climate forcing factors).

- Can provide insight into whether short term "wiggles" or trends are climate signals or just random noise.

The Climate Model Knowledge Cycle

PHYSICAL LAWS & THEORY

OBSERVATIONS

Knowledge & Understanding

Model Development

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```
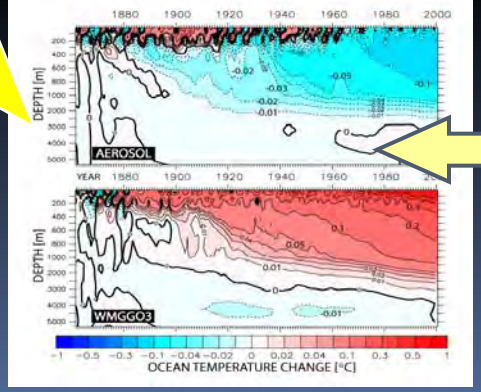

A combination of brain power and computer power

Analysis of Model Results



Well Designed Model Experiments

The Climate Model Knowledge Cycle

PHYSICAL LAWS & THEORY

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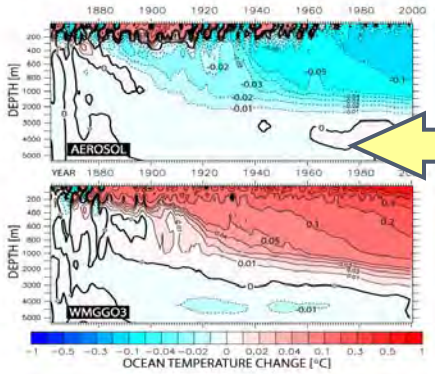
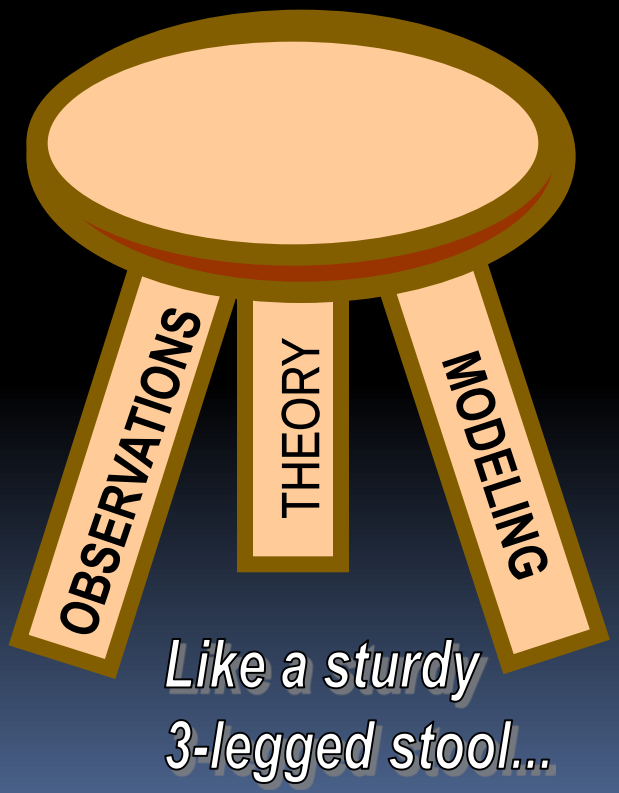


Assessment Reports, Climate Impacts Analyses, Downscaling…

Progress in Climate Science Occurs via a Synthesis of Observations, Theory, & Numerical Modeling



Since the 1970s, many of the major advancements in climate science have come about as improved observations, refinements to theory, and the results of computer modeling have revealed a consistent story.

Uncertainties In Climate Change Projections

Two broad types of uncertainties:

1) What will be the future emissions of greenhouse gases, etc. in the atmosphere?

2) How will the climate system respond to the changes in greenhouse gases, etc.?

)

Uncertainties In Climate Change Projections

Two broad types of uncertainties:

1) What will be the future emissions of greenhouse gases, etc. 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, etc.?

(these are climate model outputs – they're valuable, but computer models are incomplete & are not perfect)

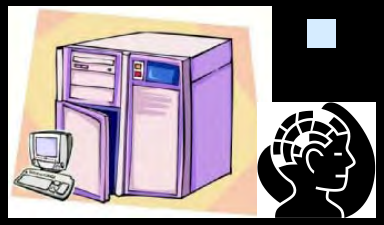
Uncertainties In Climate Change Projections

The smaller the spatial scale, the greater the uncertainty.

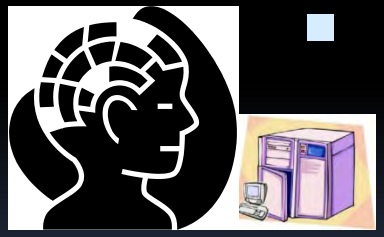
In other words, we have more confidence in projections about how the climate may change over large areas (for example, the Arctic vs. the tropics… temperatures over mid-latitude oceans vs. mid-latitude land) than we do for individual states or congressional districts.

PROBABILISTICALLY SPEAKING…

How do we improve global climate models?



- **Higher Spatial Resolution:** Increased computer power makes smaller grid cells possible, allowing for more accurate representation of small scale features.

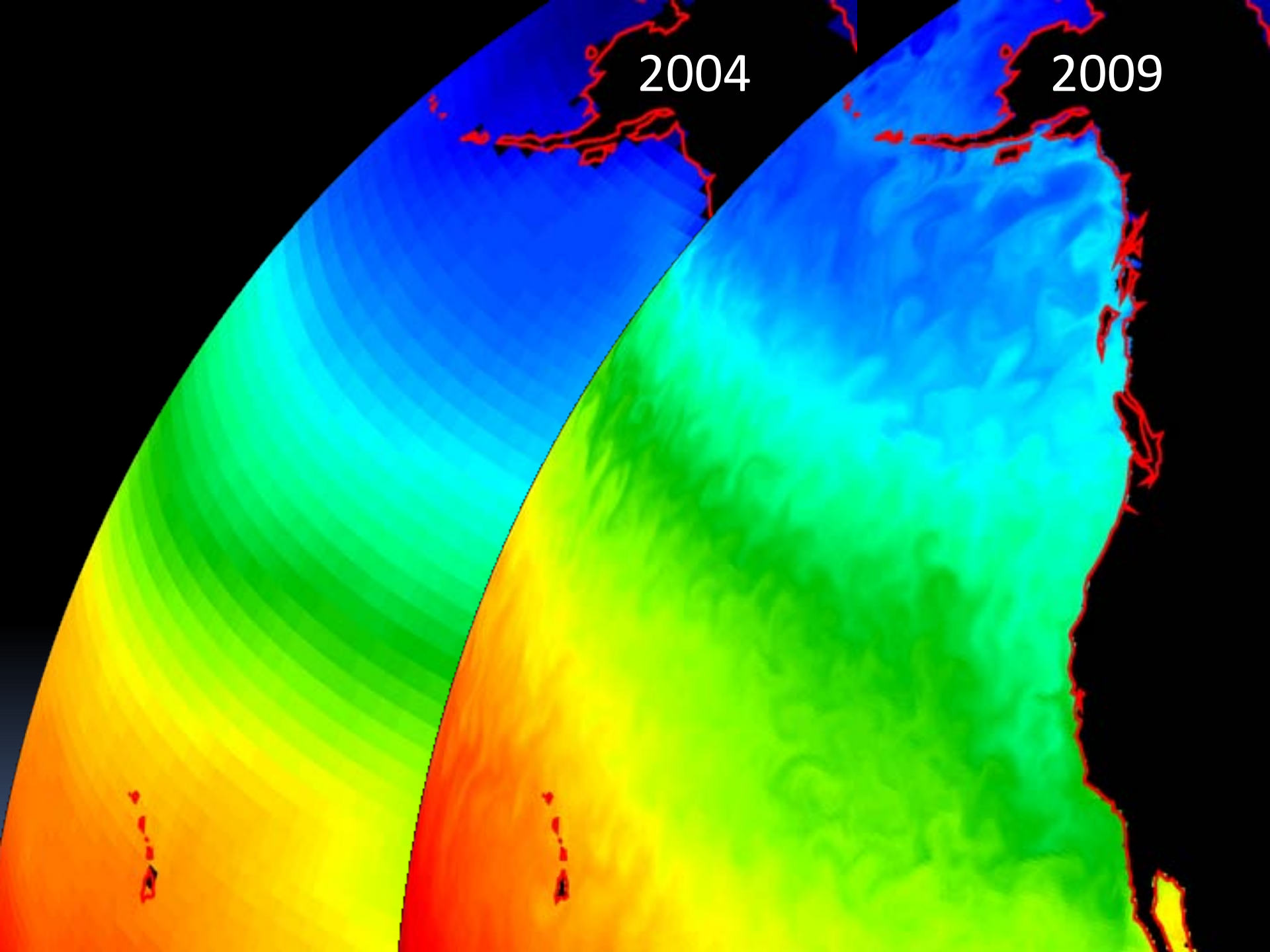


- **Add New Parts & Upgrade Existing Parts:** new processes, more comprehensive forcing, compare to observations, refine theory, reformulate.

Uncertainties In Climate Change Projections

Higher resolution climate models can provide finer scale details that are beneficial both for regional analyses and because they contribute to a potentially better representation of the larger scale climate.

The next slide shows the kind of change in detail that can be realized between successive generations of NOAA GFDL climate models.


2004
2009

Sea Level Rise In a Warming World

One can read about the implications of sea level rise on US infrastructure in the popular press…
Some of which may not sufficiently distinguish between persistent inundation due to long-term sea level rise vs. flooding during storm surges and high tides on top of sea level rise.
A once in 100 year flooding event may become a once in 50 yr or 20 yr or 5 yr event…

Illustrating some Climate Modeling 101 points with sea level as the variable of interest…

- ? What physical processes lead to changes in sea level? (globally & locally)
- ? How well are those processes understood? *(well enough to represent mathematically in a model?)*
- ? How well have the contributions of the different processes to sea level change been observed? What about the global sum?
  When comparing obs to model results, one must consider issues of data coverage, error bars, data coverage, consistencies between observational data sets, etc.

What physical processes lead to changes in sea level?

- **Thermal expansion (thermosteric or steric)**

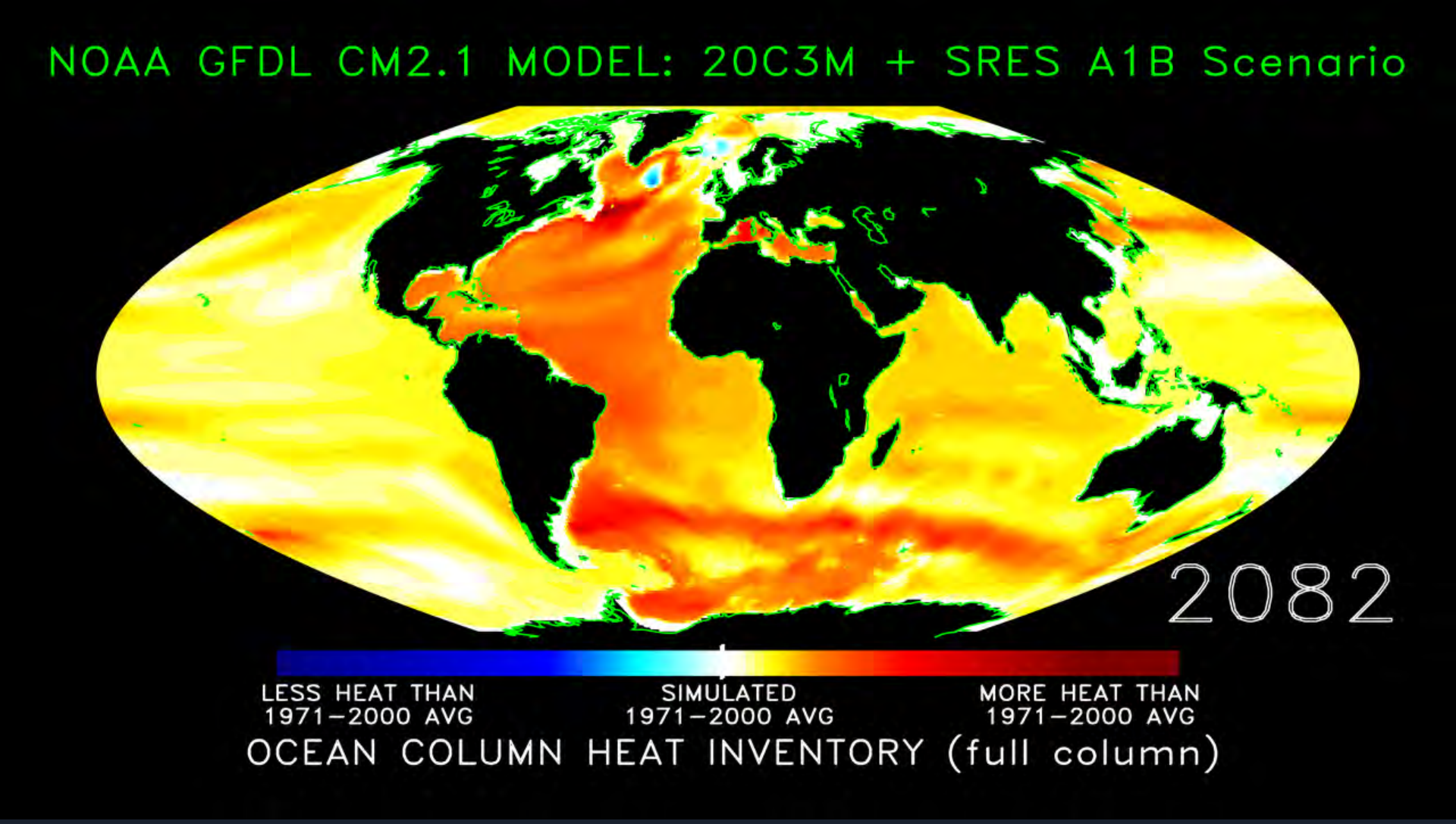
Not only are the processes associated with air-sea heat exchange fairly well quantified and incorporated in climate models, but comparisons with global ocean heat content observations show our models can do a good job of reproducing the past 50 years.

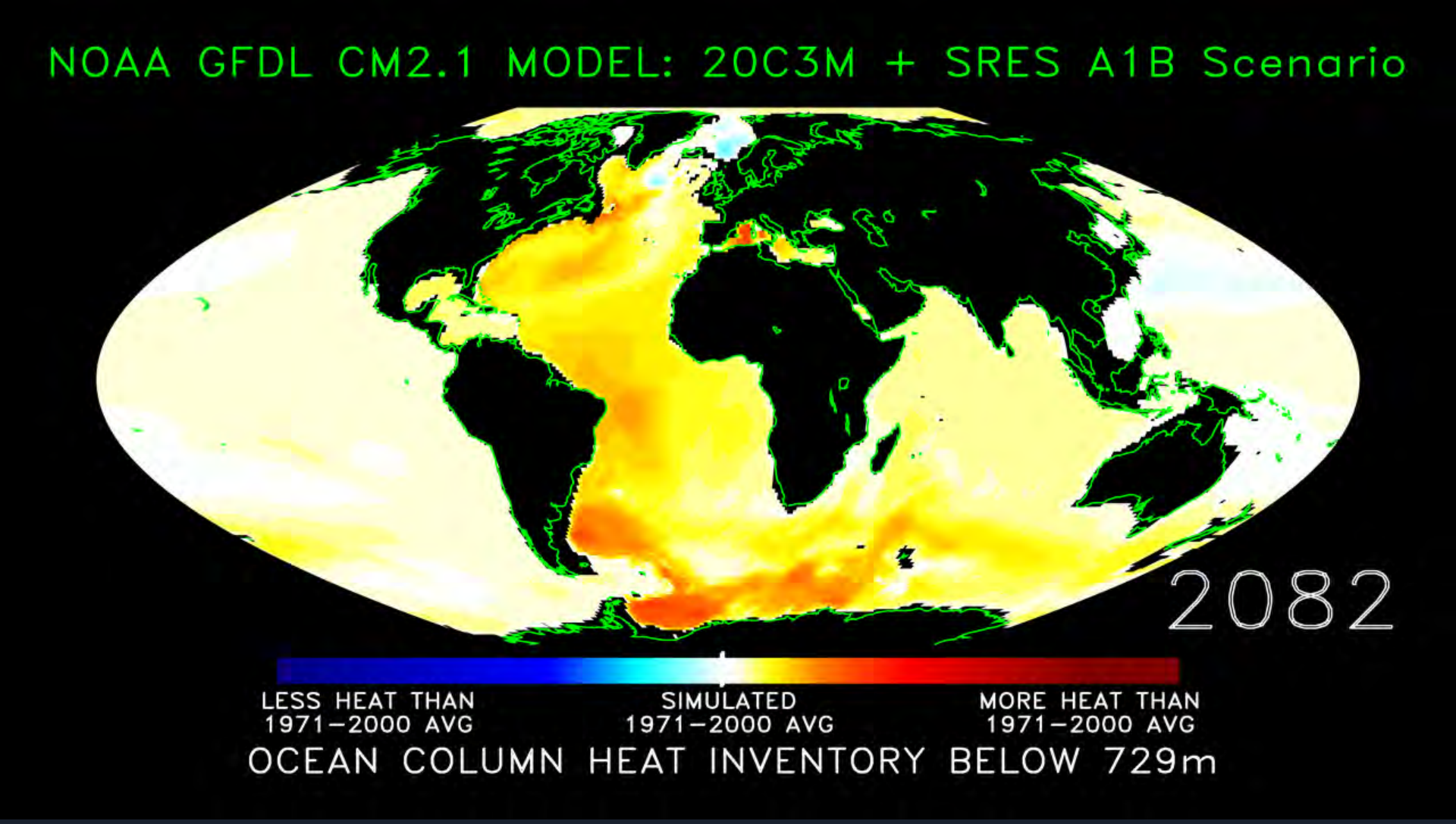
* *Key for attribution & model credibility. (2001+)*

Understanding and Attributing Climate Change

- Warming of the climate system has been detected in changes of surface and atmospheric temperatures in the upper several hundred metres of the ocean, and in contributions to sea level rise. Attribution studies have established anthropogenic contributions to all of these changes.

- Observations since 1961 show that the average temperature of the global ocean has increased to depths of at least 3000 m and that the ocean has been absorbing more than 80% of the heat added to the climate system. Such warming causes seawater to expand, contributing to sea level rise (see Table SPM.1). {5.2, 5.5}


NOAA GFDL CM2.1 MODEL: 20C3M + SRES A1B Scenario
2082
LESS HEAT THAN
1971–2000 AVG
SIMULATED
1971–2000 AVG
MORE HEAT THAN
1971–2000 AVG
OCEAN COLUMN HEAT INVENTORY (full column)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SIMULATED
1971–2000 AVG
MORE HEAT THAN
1971–2000 AVG
OCEAN COLUMN HEAT INVENTORY BELOW 729m

What physical processes lead to changes in sea level?

- **Mass exchange between ocean and glaciers & ice caps, and ice sheets.**

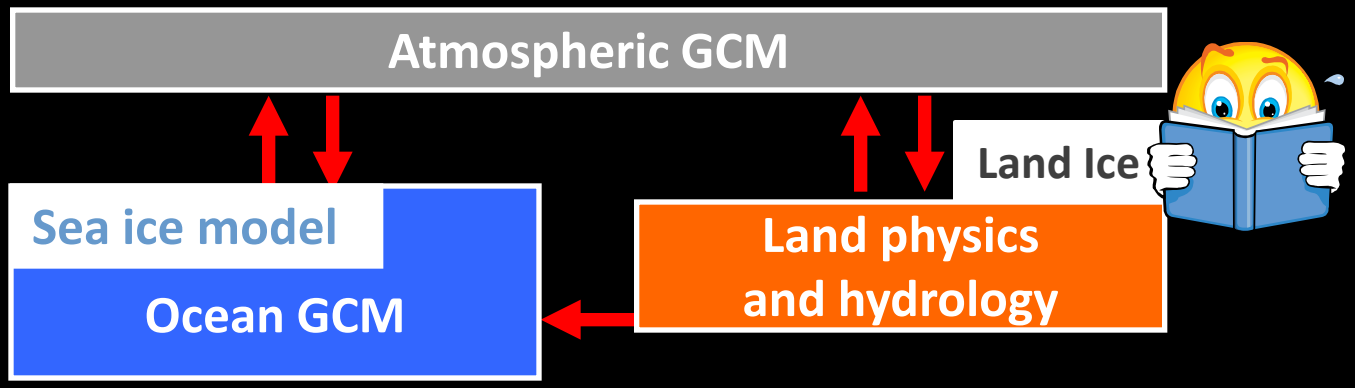
Work is going on, but our global climate models haven't included interactive ice sheet models, because...

"current scientific understanding leaves poorly known uncertainties in the methods used to make *[offline]* projections for land ice".

-IPCC AR4 CH. 10.6.5

Surface mass balance & dynamics

Dynamical ice sheet models have not yet been added to the NOAA/GFDL global climate models, but it is one of our new model development research efforts…



What physical processes lead to changes in sea level?

- Other sources of sea level change – often poorly constrained by observations – complicates comparing modeled sea level to observations.
- Other land reservoirs (-1.1 to +0.4 mm yr^{-1} 1910-1990 total; dams -.6 mm yr^{-1}; groundwater mining + [IPCC AR4])
- Land movements (Glacial Isostatic Adjustment +/- 0.15mm yr^{-1}, other natural movements, human induced movements, effect on satellite calibration +/- 0.4mm yr^{-1})
- Changing ocean shape due to GIA (0.3 +/- 0.15mm yr^{-1})

Table SPM.1. *Observed rate of sea level rise and estimated contributions from different sources.*

Source of sea level rise	Rate of sea level rise (mm per year) 1961–2003	1993–2003
Thermal expansion	0.42 ± 0.12	1.6 ± 0.5
Glaciers and ice caps	0.50 ± 0.18	0.77 ± 0.22
Greenland Ice Sheet	0.05 ± 0.12	0.21 ± 0.07
Antarctic Ice Sheet	0.14 ± 0.41	0.21 ± 0.35
Sum of individual climate contributions to sea level rise	1.1 ± 0.5	2.8 ± 0.7
Observed total sea level rise	1.8 ± 0.5[a]	3.1 ± 0.7[a]
Difference (Observed minus sum of estimated climate contributions)	0.7 ± 0.7	0.3 ± 1.0

Table note:
[a] Data prior to 1993 are from tide gauges and after 1993 are from satellite altimetry.

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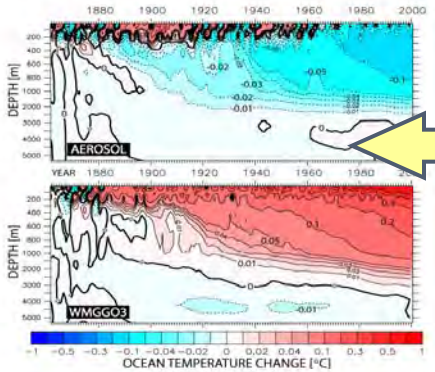
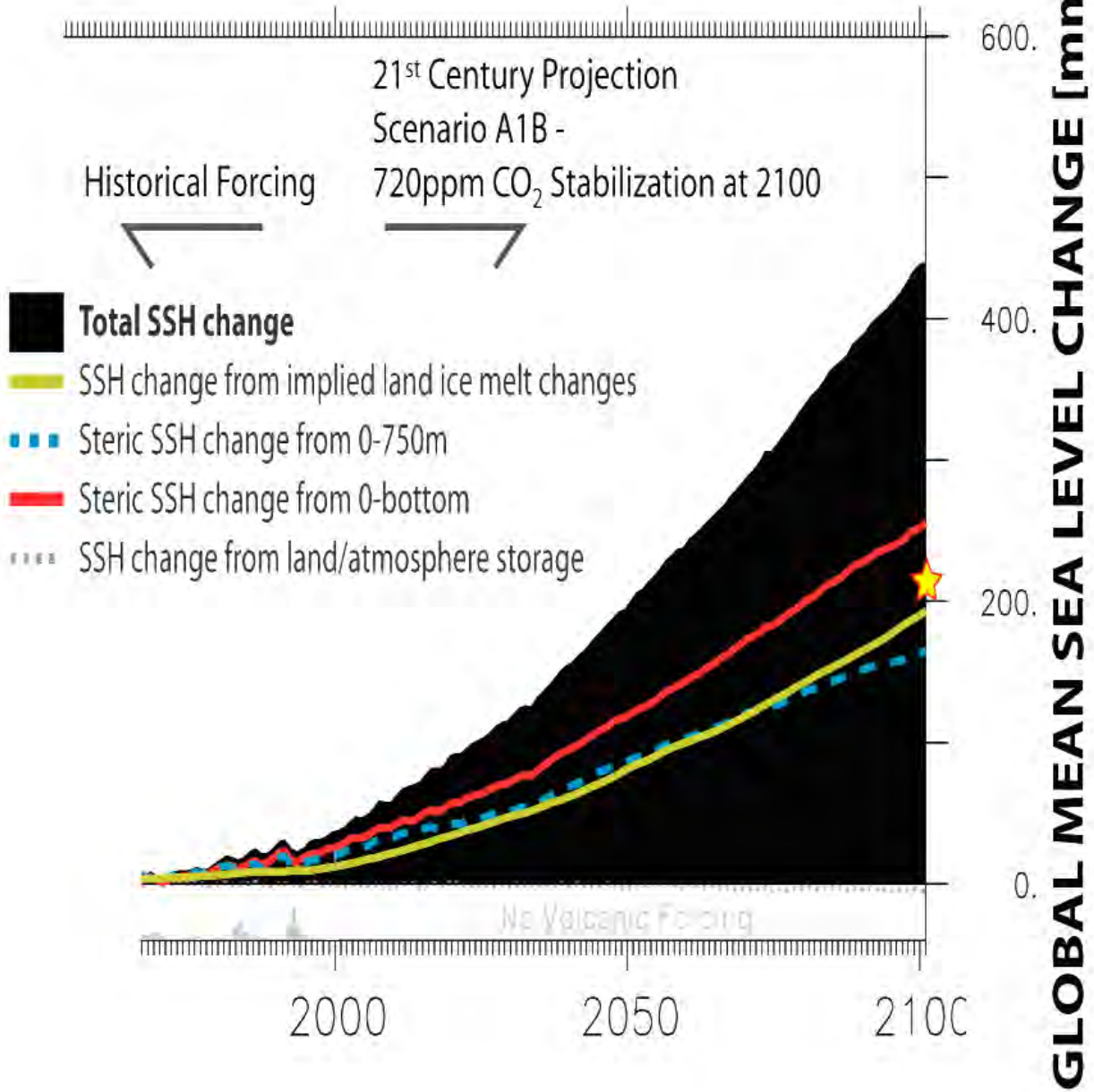
Analysis of Model Results



Well Designed Model Experiments


21st Century Projection
Scenario A1B -
720ppm CO_2 Stabilization at 2100
Historical Forcing
Total SSH change
SSH change from implied land ice melt changes
Steric SSH change from 0-750m
Steric SSH change from 0-bottom
SSH change from land/atmosphere storage
No Volcanic Forcing
600.
400.
200.
0.
2000
2050
2100
GLOBAL MEAN SEA LEVEL CHANGE [mm]

CLIMATE MODELING 101:
COMPUTER MODELING'S CONTRIBUTION TO THE CLIMATE RESEARCH CHALLENGE

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INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

WMO

UNEP

"IPCC AR4": 2007

A report of Working Group I of the Intergovernmental Panel on Climate Change

Summary for Policymakers

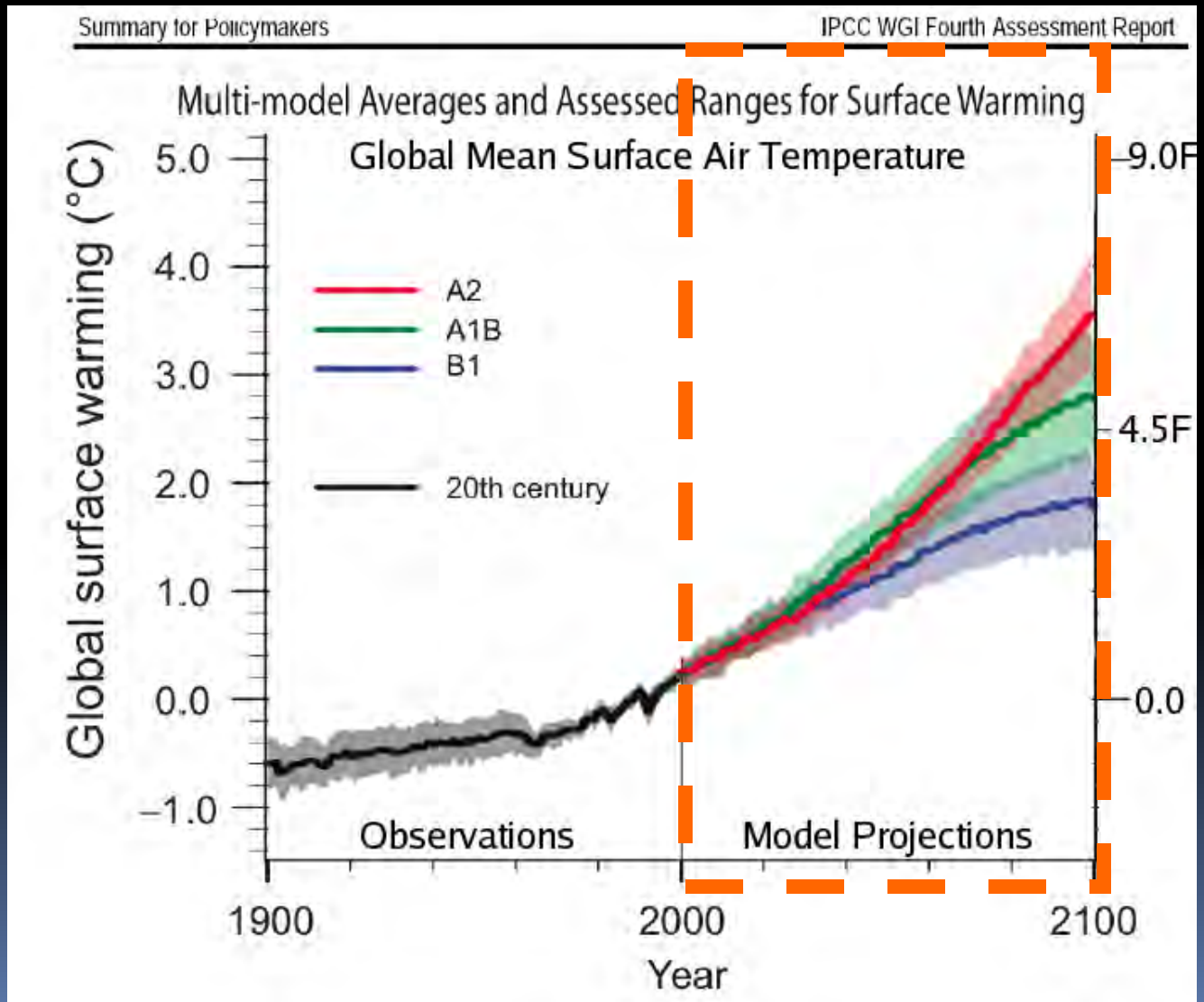
This Summary for Policymakers should be cited as:

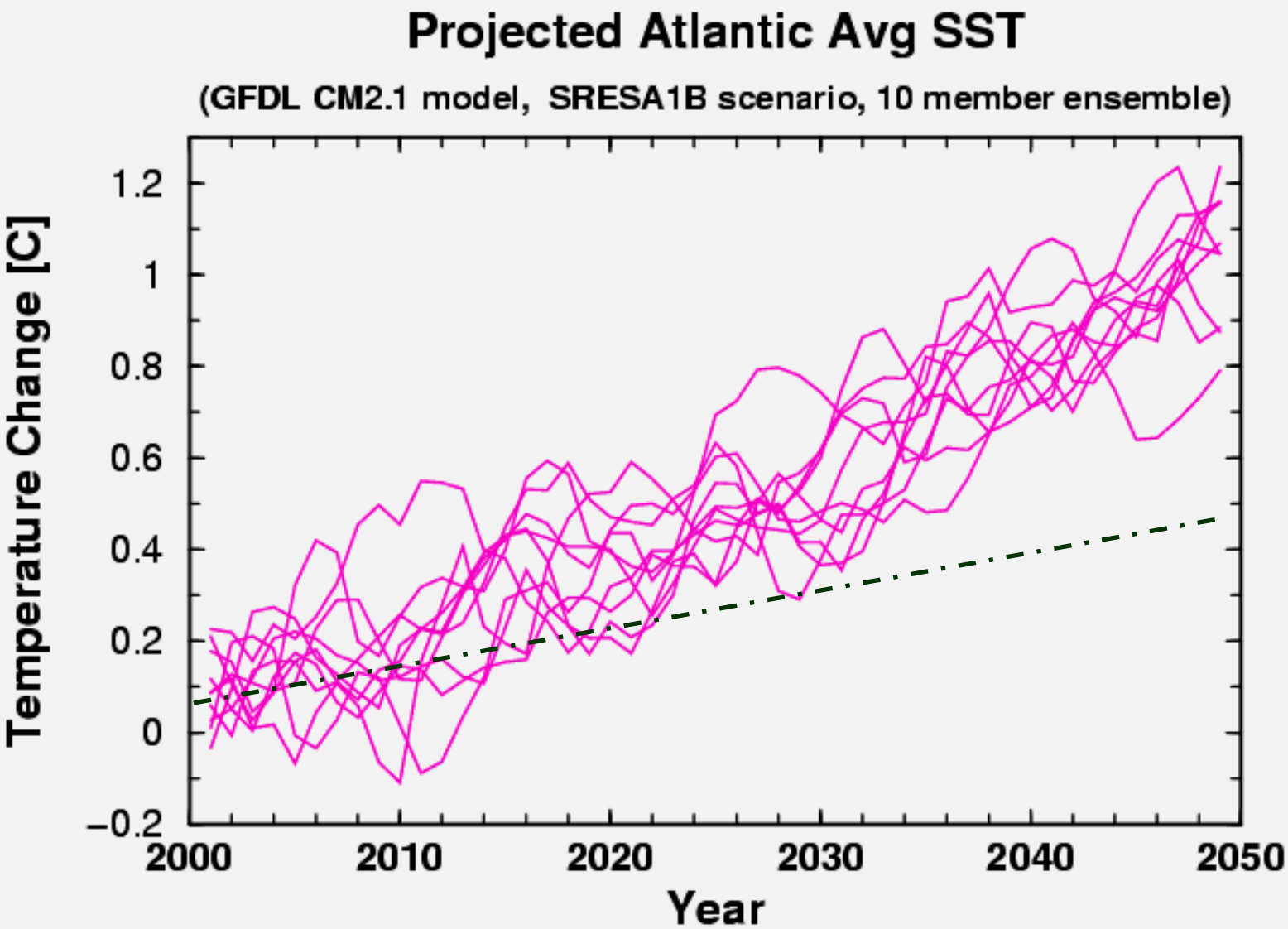
IPCC, 2007: Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M.Tignor and H.L. Miller (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

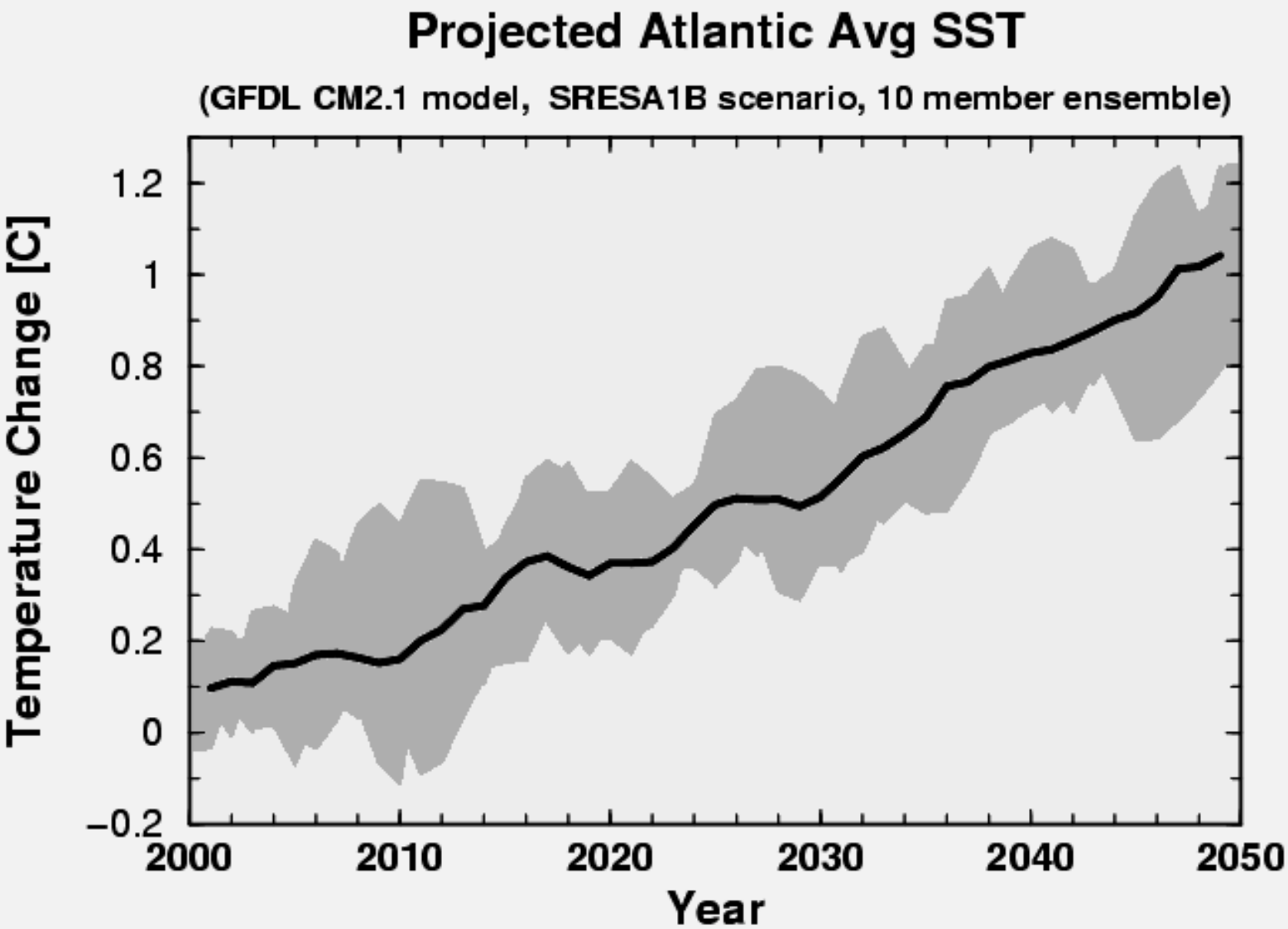
Table SPM.3. *Projected global average sea level rise at the end of the 21st century.*

Case	Sea Level Rise (m at 2090-2099 relative to 1980-1999) Model-based range excluding future rapid dynamical changes in ice flow
B1 scenario	0.18 – 0.38
A1B scenario	0.21 – 0.48
A2 scenario	0.23 – 0.51
A1FI scenario	0.26 – 0.59

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




Projected Atlantic Avg SST
(GFDL CM2.1 model, SRESA1B scenario, 10 member ensemble)
Temperature Change [C]
1.2
1
0.8
0.6
0.4
0.2
0
−0.2
2000
2010
2020
2030
2040
2050
Year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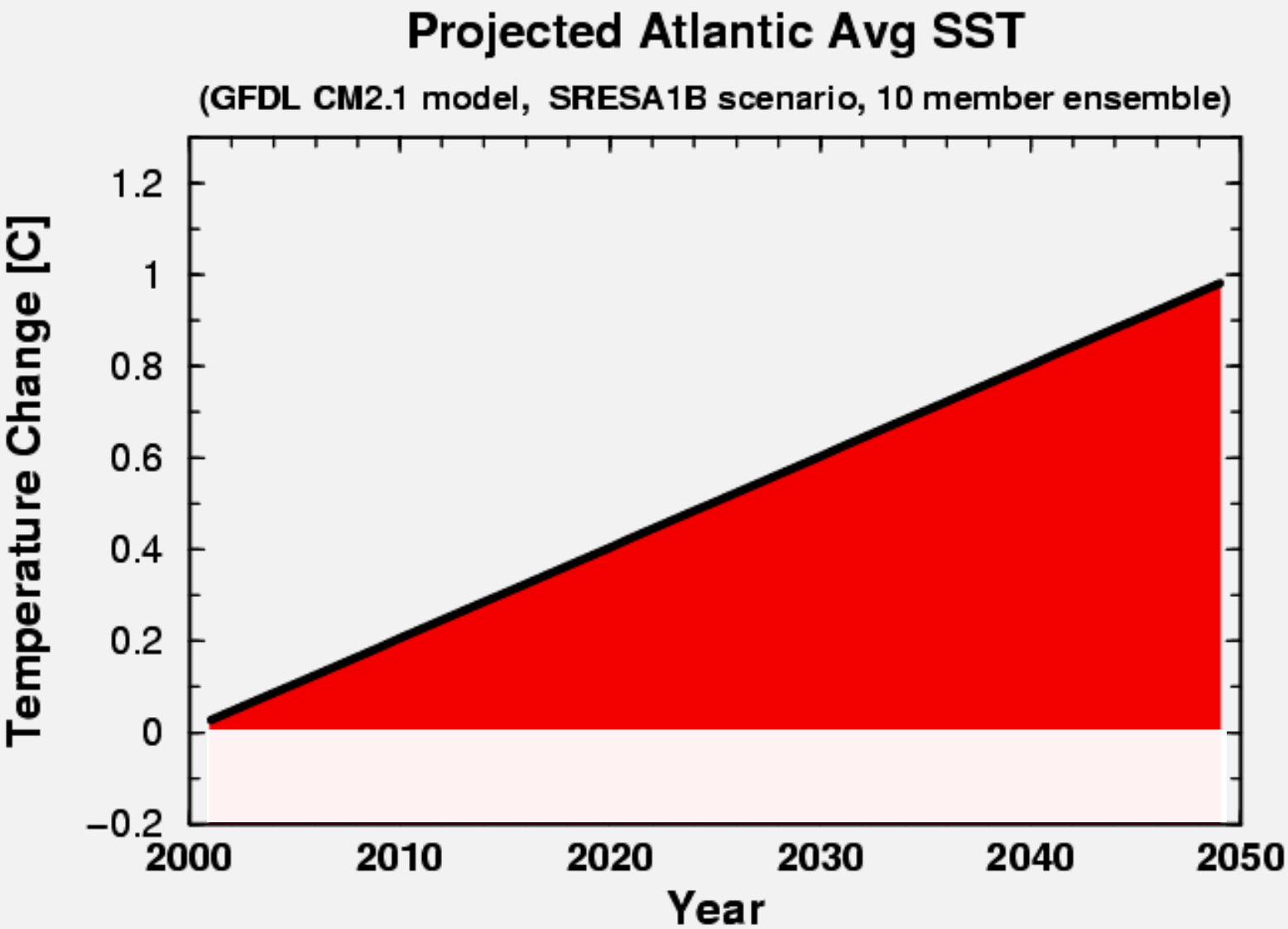
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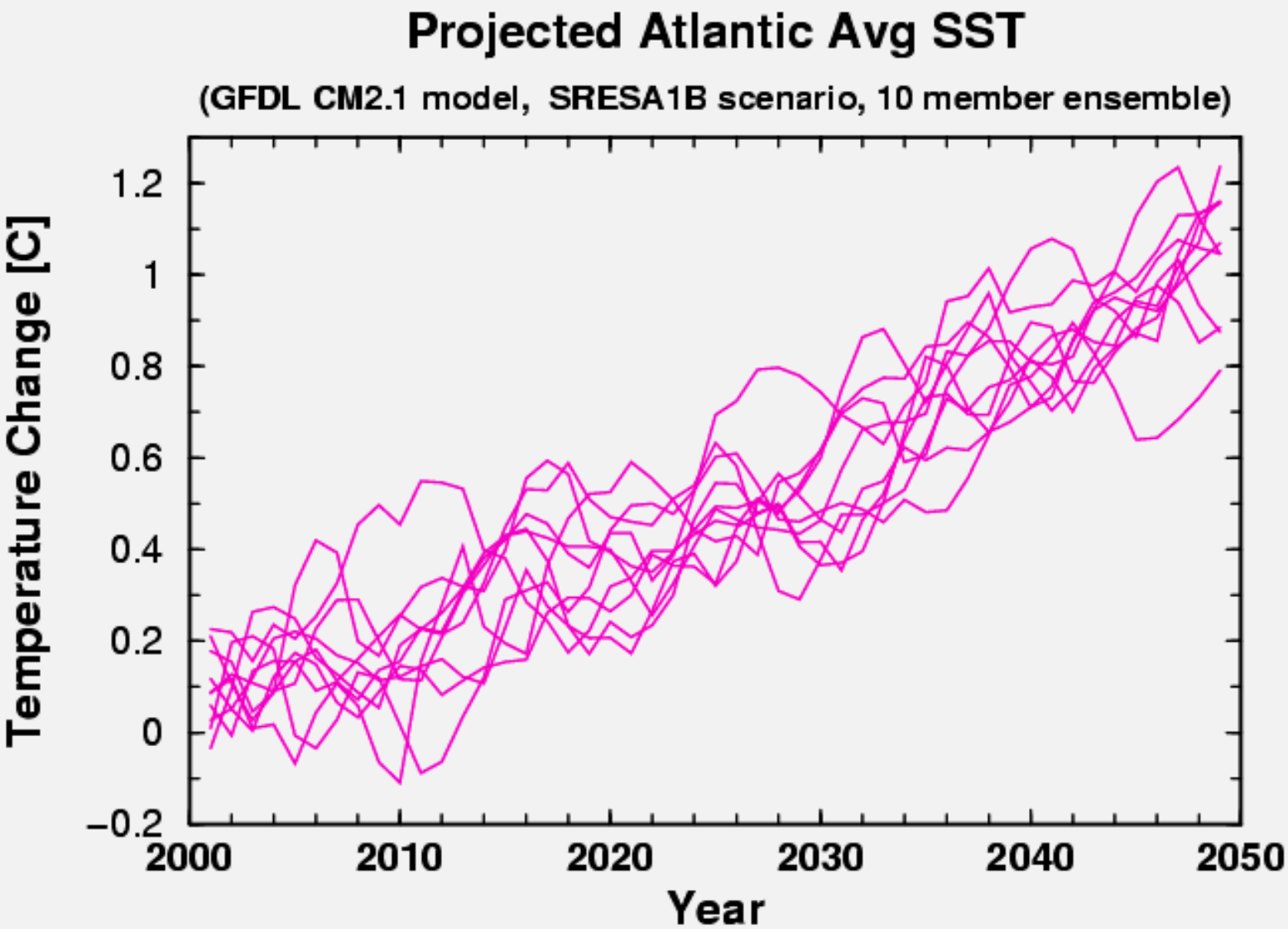
2020
2030
2040
2050
Year


Projected Atlantic Avg SST
(GFDL CM2.1 model, SRESA1B scenario, 10 member ensemble)
Temperature Change [C]
1.2
1
0.8
0.6
0.4
0.2
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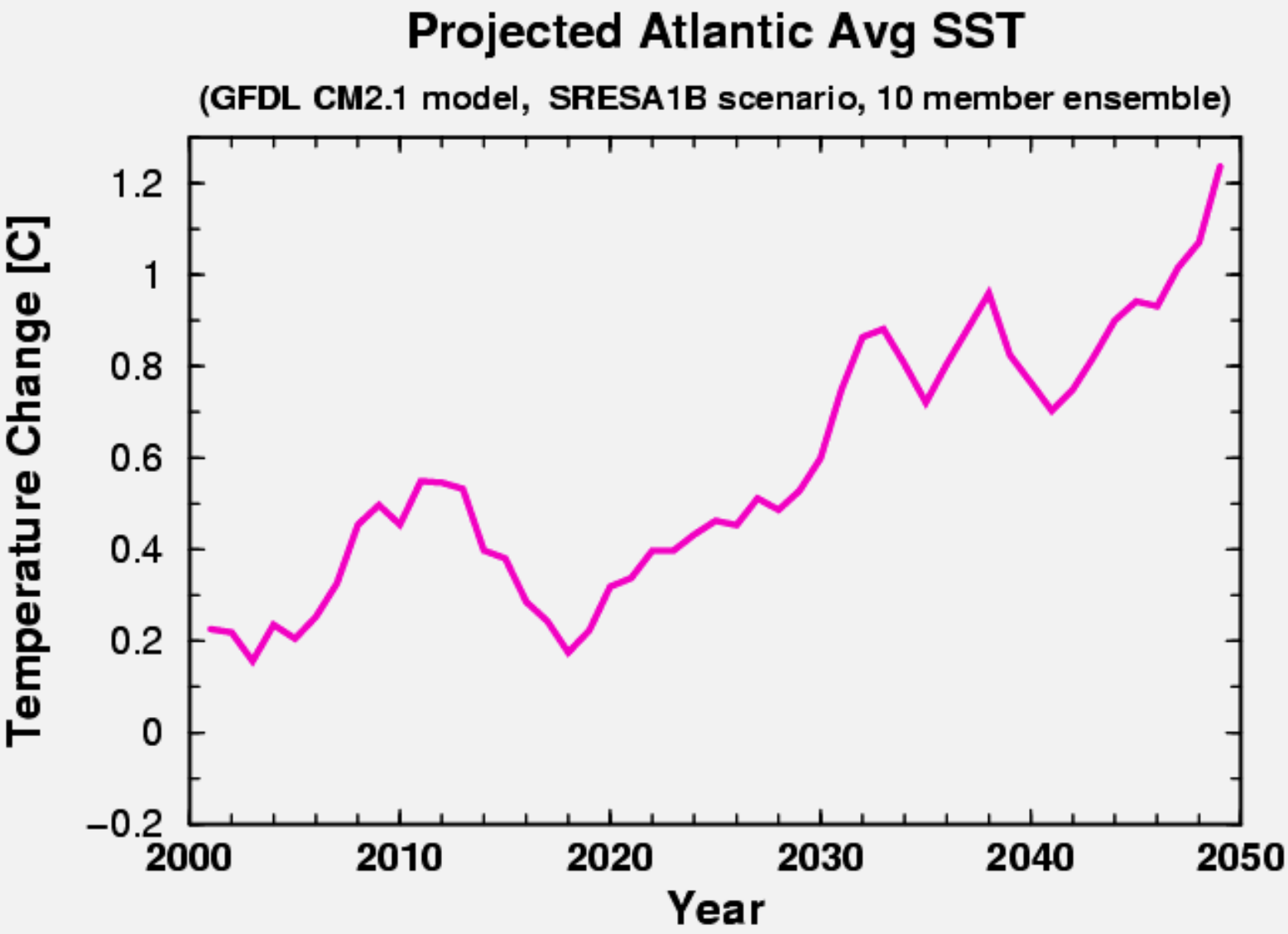
−0.2
2000
2010
2020
2030
2040
2050
Year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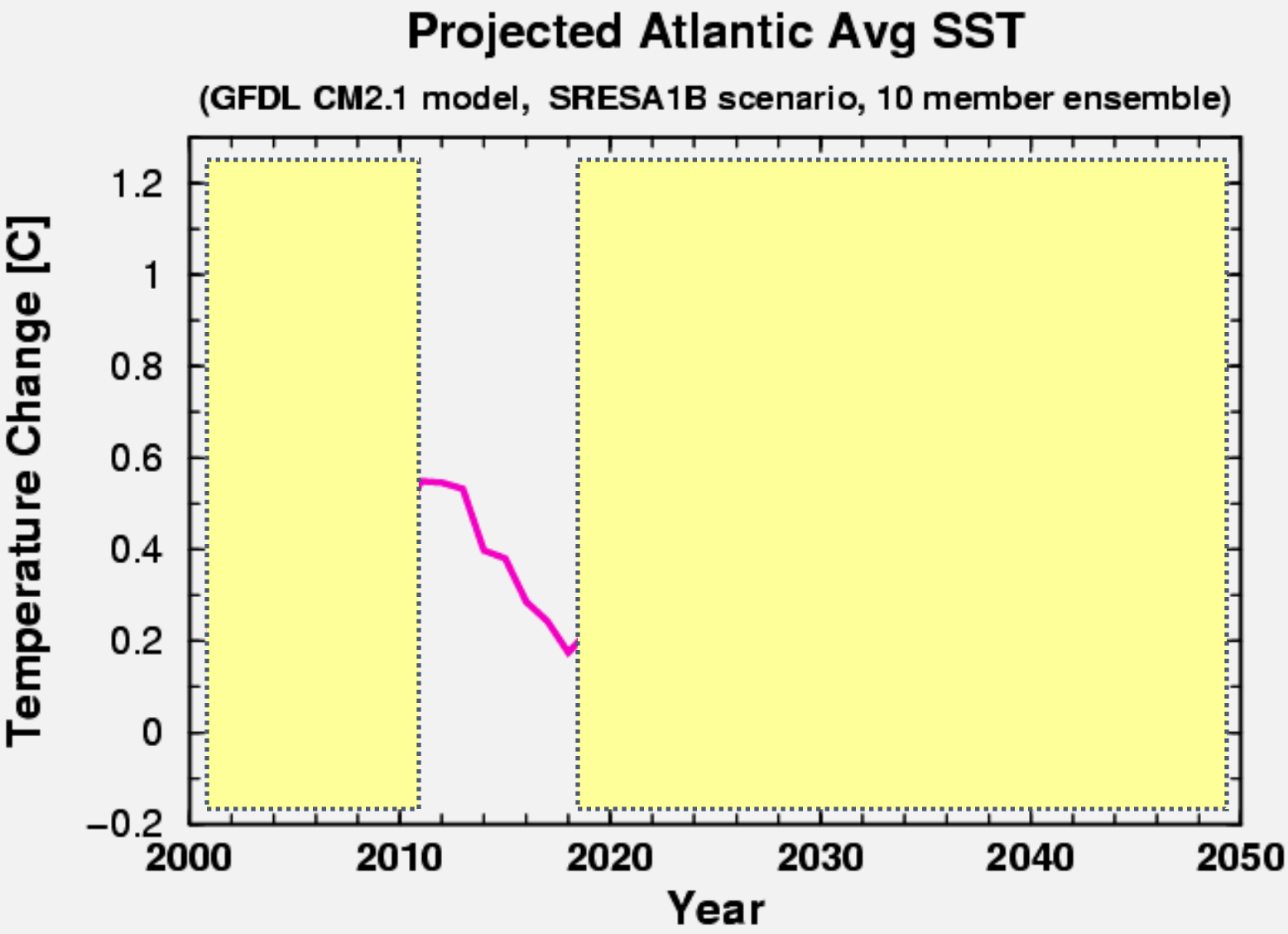
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Global Surface Air Temperatures

Goldilocks' & The 3 Bears Attribution Conclusions:

- If we consider only the natural forcings (solar and volcanic), the climate simulation is too cold (don't have the late 20th century warming signal).
- If we consider only the GHGs, the climate simulation gets too hot too fast.
- Considering together 4 types of changes (natural & human-induced) the model's 20th century global average temperature simulations are just about right.

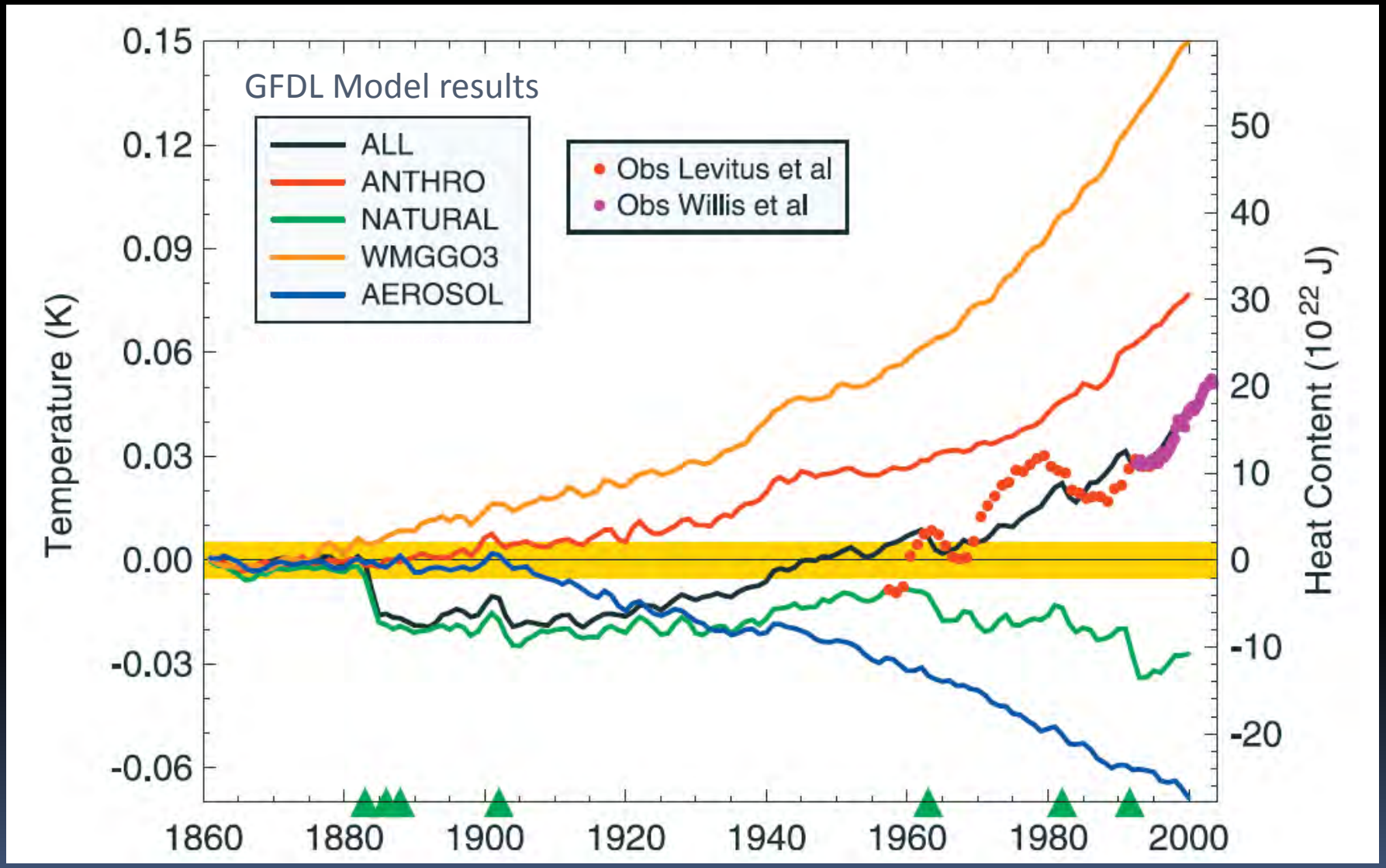
(1) GHGs (warming) (2) Solar(+/-)
(3) Volcanic (cooling)
(4) Tropospheric Aerosols (pollutants) (+&-, net -, short lived) *[stay tuned]*

Global Surface Air Temperatures

Goldilocks' & The 3 Bears Attribution Conclusions:

- The simplified explanation presented here is meant to illustrate the Detection/Attribution process. In reality, much more detailed analysis (with some sophisticated statistical methodologies) have been performed using…
- Results from several modeling research centers
- Looking at 4-D atmospheric temperatures (regional, vertical)
- Similar studies have also looked multiple climate variables, including ocean heat content (80-90% of the heat gained in the past century resides in the ocean)

Ocean Heat Content



[stay tuned: ocean heat content … observations, volcanoes, regionality]