High Resolution Ocean and Ice Models for Climate

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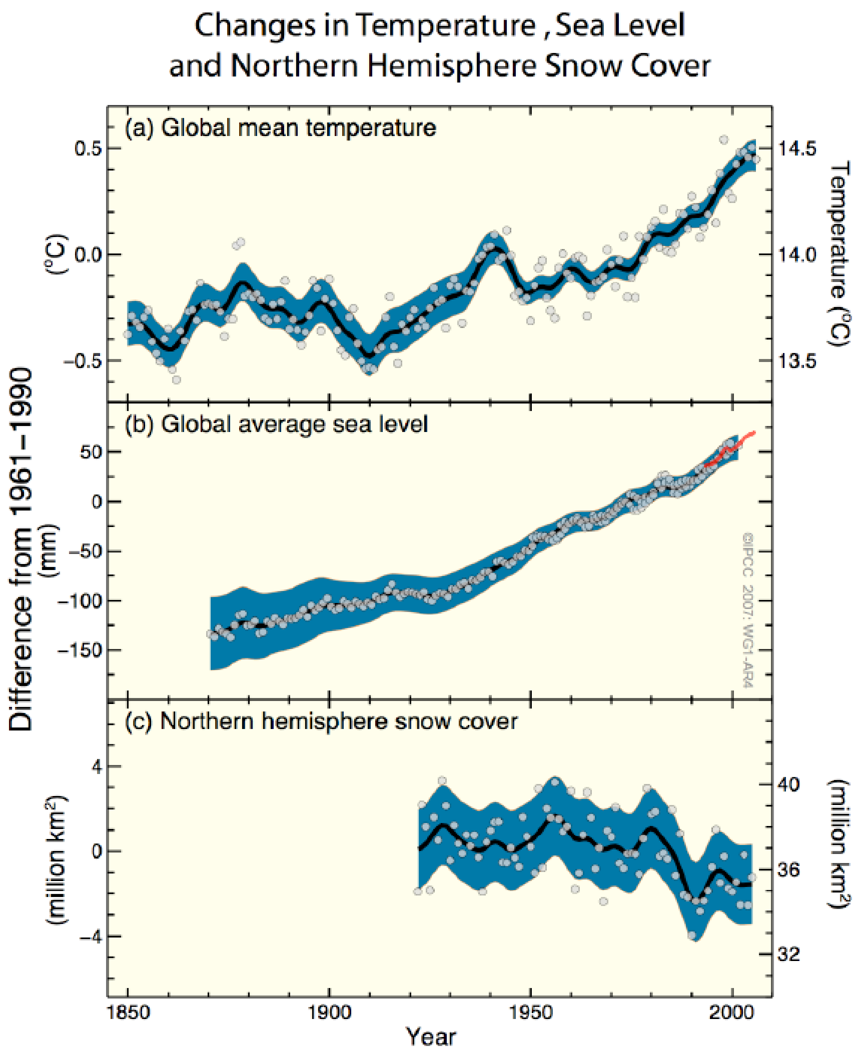
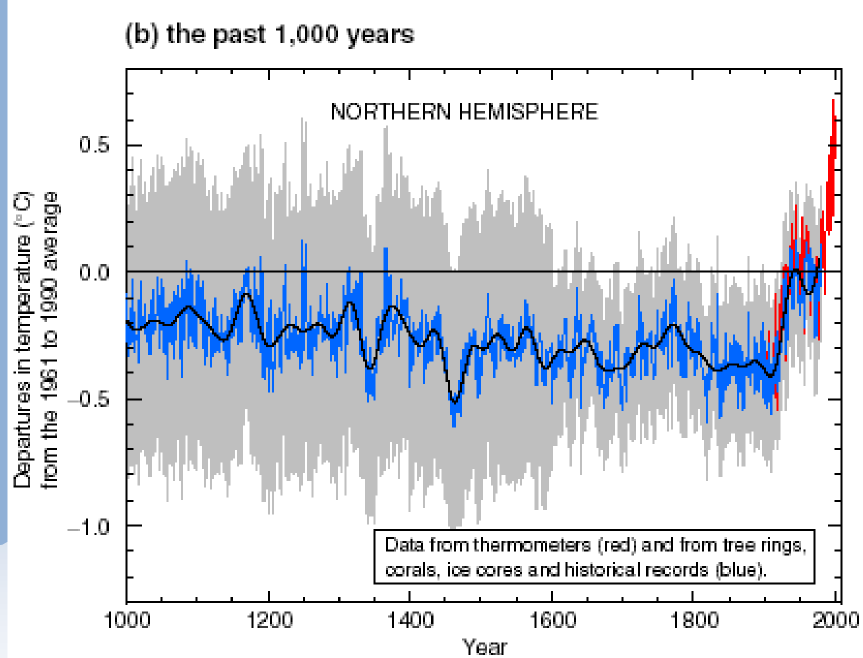
LA-UR 08-02662

Change We Can Believe In



Climate change observed at global scales with increases of surface temperatures, sea level rise and decreasing snow cover



IPCC 2007, 2002
Nobel Peace Prize 2007

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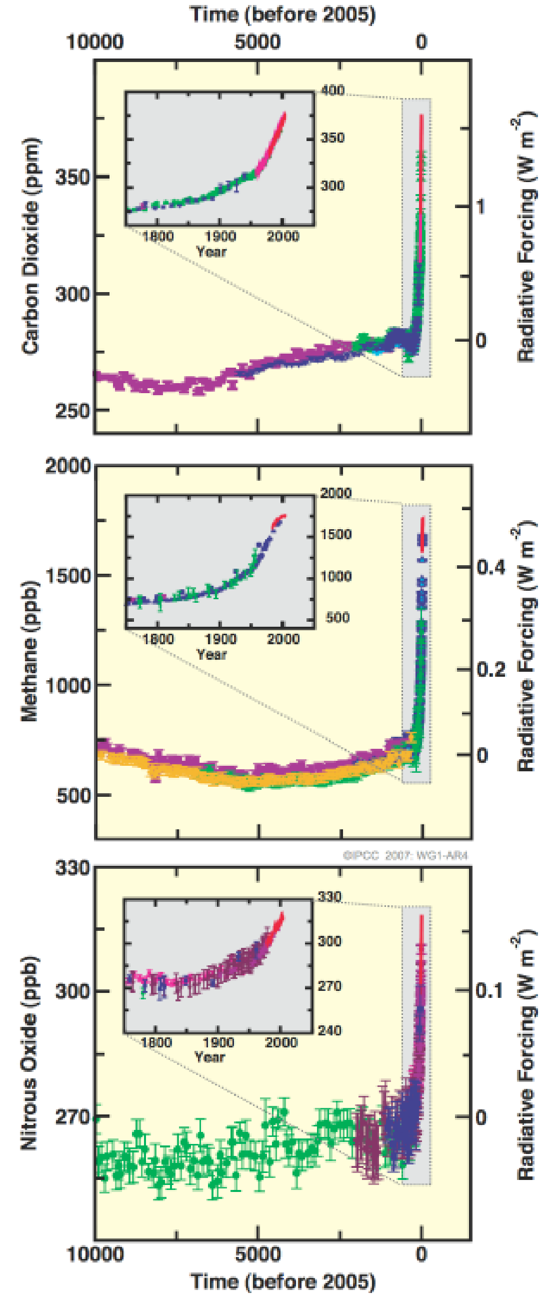
We Are The Change

- CO2 – 379ppm in 2005
  - Exceeds values for last 650,000 years
  - Fossil fuels primary source
    - 6.4 Gt/year 1990s
    - 7.2 Gt/year 2000s
  - Land use (1.6 GtC/yr)
- Methane
  - 1772 ppb 2005 (700 pre-ind)
  - Agriculture is primary source

ppm – parts/million
Ppb – parts/billion
GtC – billion (giga) tons Carbon

Changes in Greenhouse Gases from ice-Core and Modern Data



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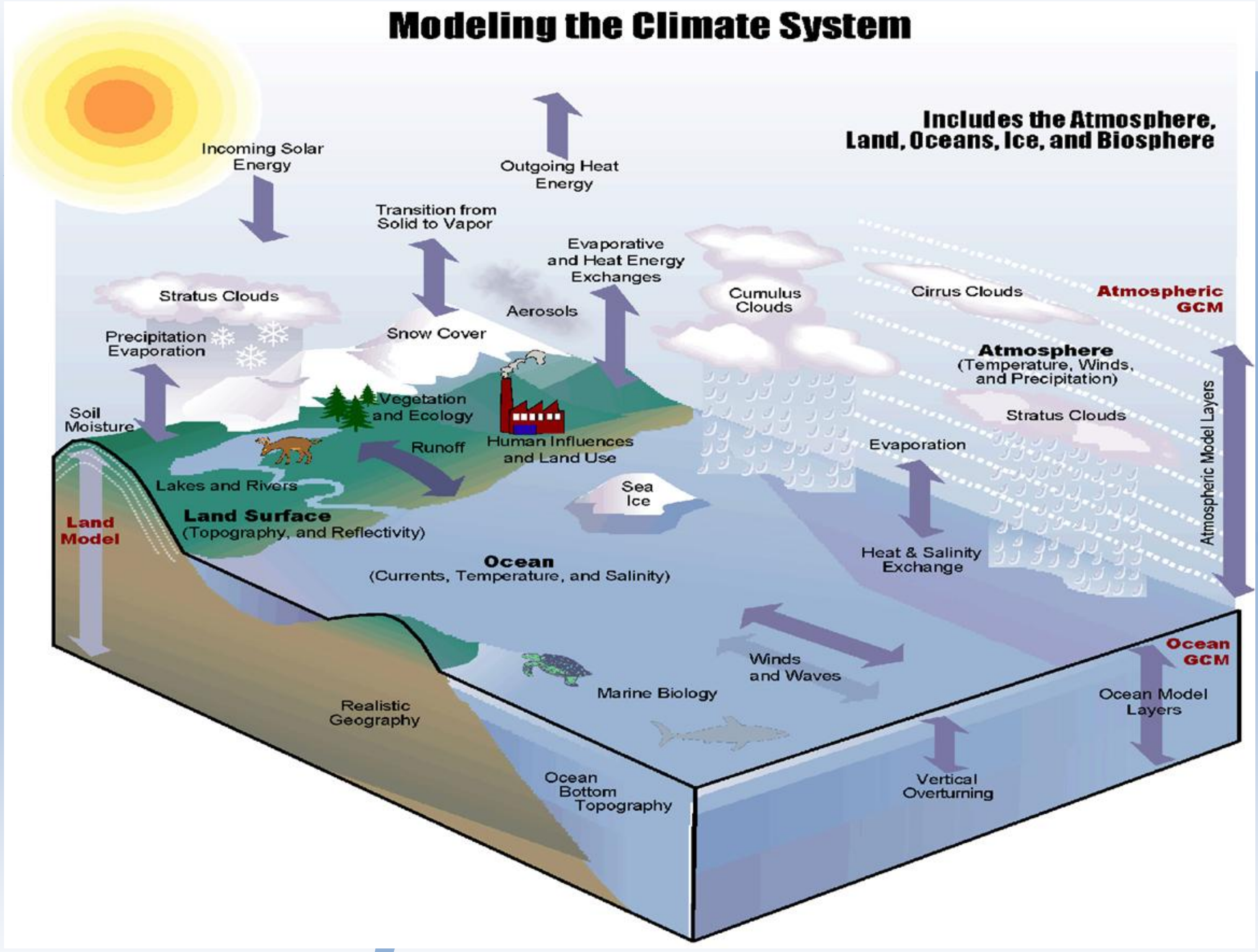
Climate Models as Tools



- Integrate knowledge of climate system
- Used to understand and quantify feedbacks
- Provide information to policy makers on impacts, mitigation

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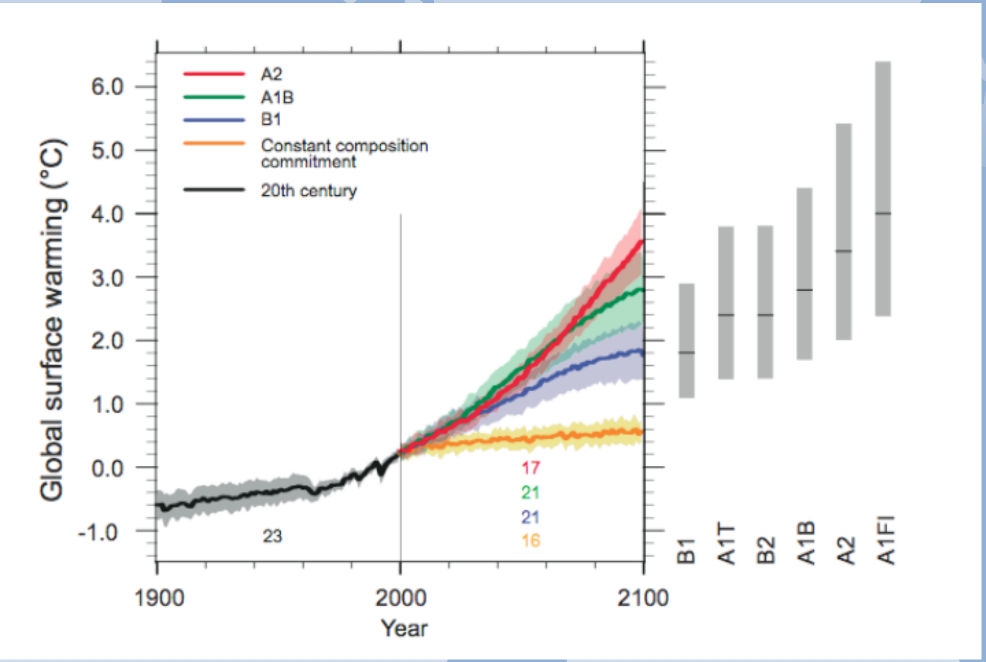
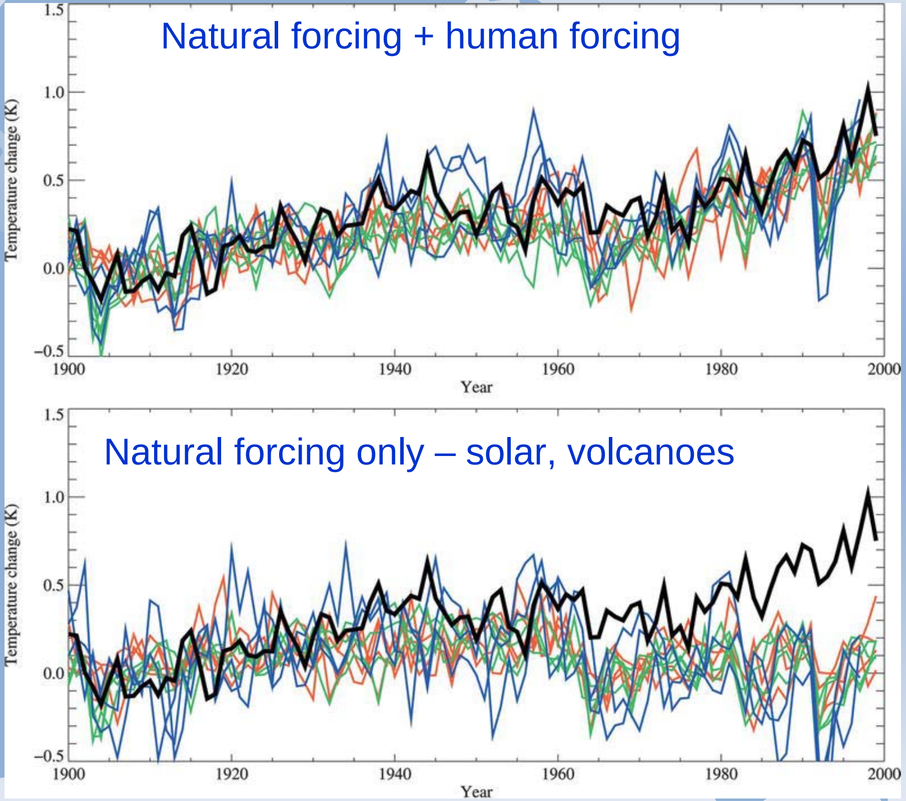
Use of Climate Models

Projection of Future Change



Intergovernmental Panel on Climate Change: Fourth Assessment (www.ipcc.ch)

Determine Causes, Attribution



Solid black line is observational record
Other lines are ensemble of model results
Observations can only be explained by increased human influence.

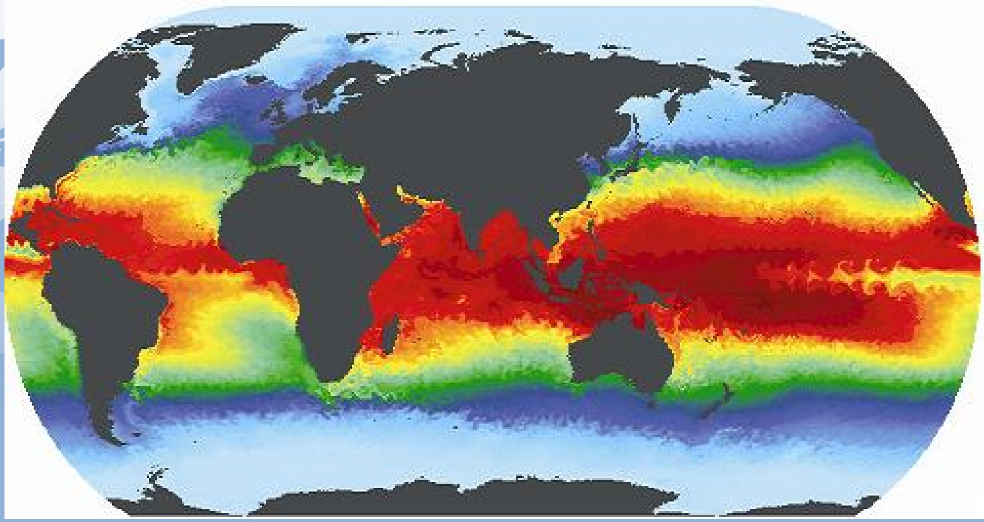
From Stott et al. 2006

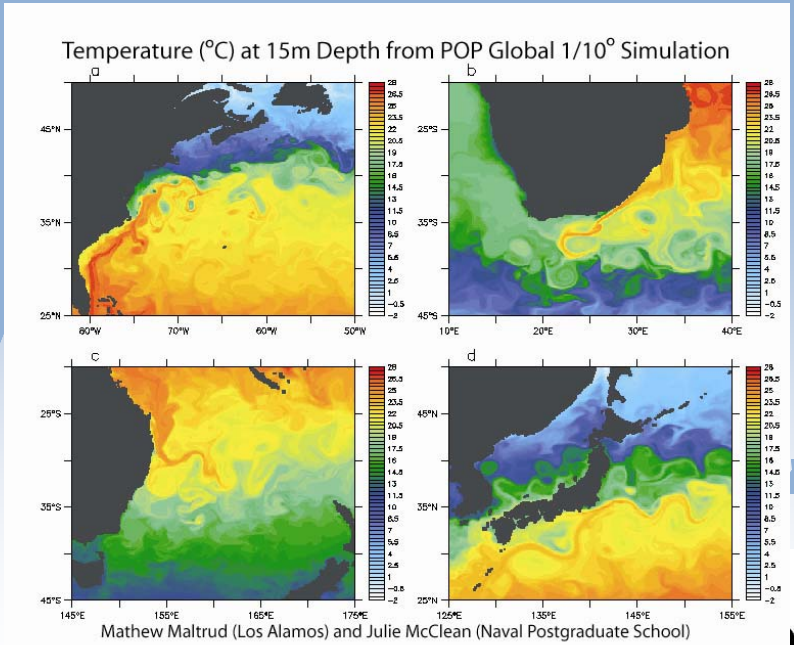
The Question(s)

- If you had access to a petascale computing system, what would you do with it?
- When you get access to your petascale computing system, what will you do with it?
- When you get access to your [exa,zetta]scale computing system, will you be able to use it?
- And will you be happy?

Ready on Day One

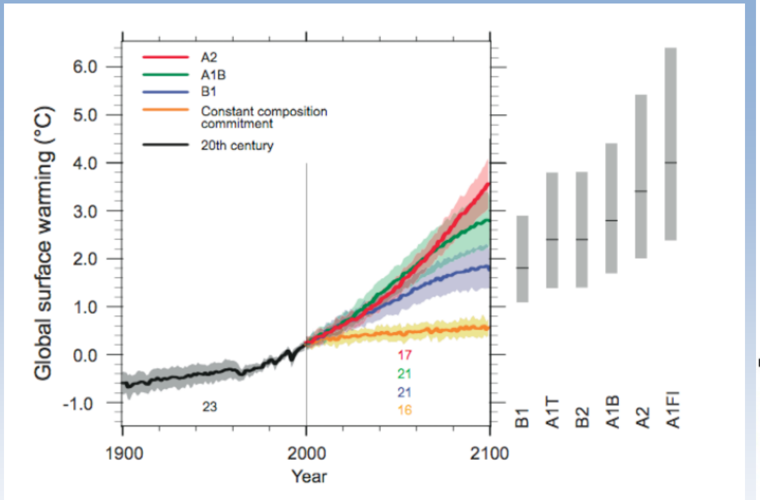
- Ocean dynamics
  - Small spatial scales
  - Long (millenial) time scales
- Resolving eddies
  - accurate simulation of currents
  - sea ice edge and deep water formation.
- Current/near future
  - Resolving mesoscale eddies at century timescales
  - Fully coupled w/ eddying ocean
- Exascales
  - Higher vertical resolution for mixing, overflows, topo
  - Higher horizontal resolution
  - Non-hydrostatic

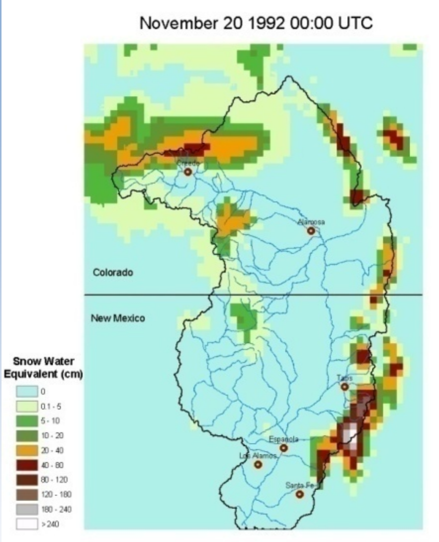




Fierce Urgency of Now – Decadal/Regional Prediction

- Impacts at regional scales
- High Resolution
  - 10 km (10x)
  - Nested regional models
  - Better regional info
  - Better precip
  - Better extremes
- Model improvements
  - Dynamic vegetation
  - Improved hydrology/ water cycle
  - Ocean assimilation





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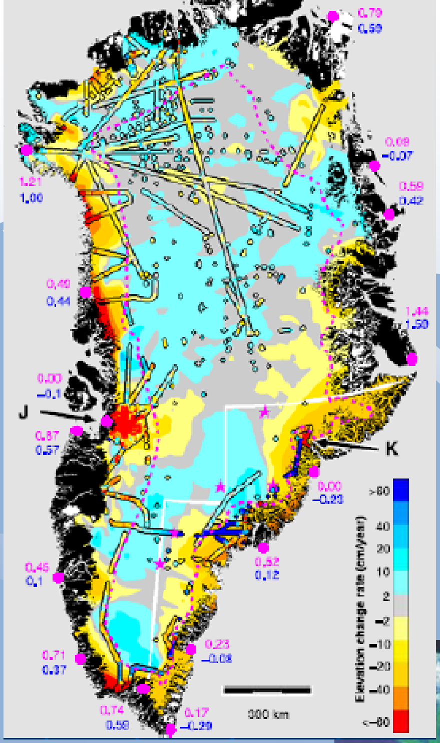
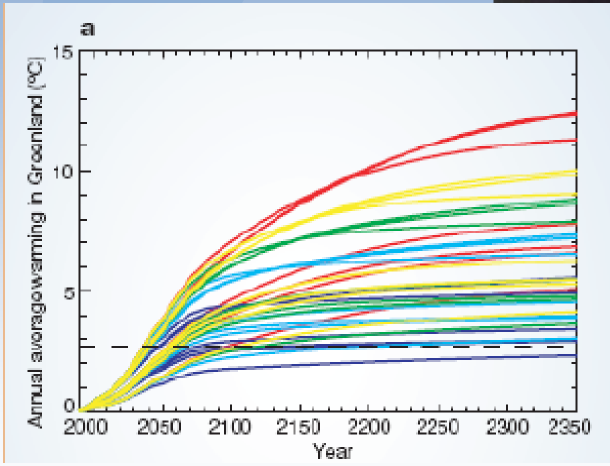
Ice Sheets and Sea Level Rise

- Largest missing piece of physical climate in current models
- Needed for sea level rise prediction
- 6m of sea level rise if Greenland melts, 6m if W. Antarctic ice sheet melts
- Slow melt over 1000 years or more rapid?
- Threshold of no return?
- Small-scale ice sheet dynamics, ocean/ice interaction, disparate timescales
- Variable coastlines, topography

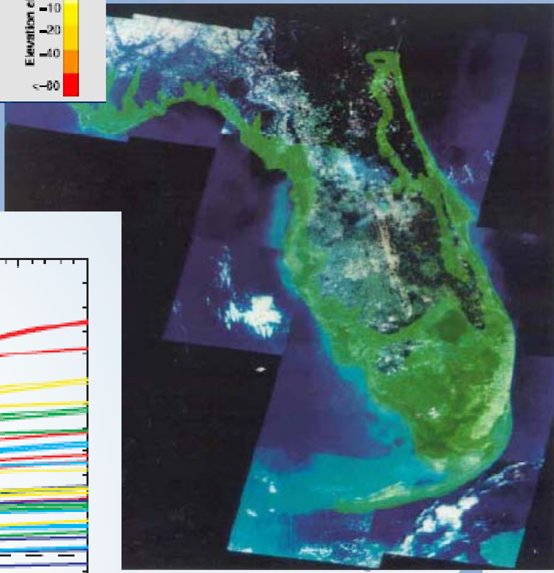


Greenland ice sheet melting observations from Krabill et al. 2004

Red indicates rapid melting
2007 rate highest observed



Gregory et al. 2004

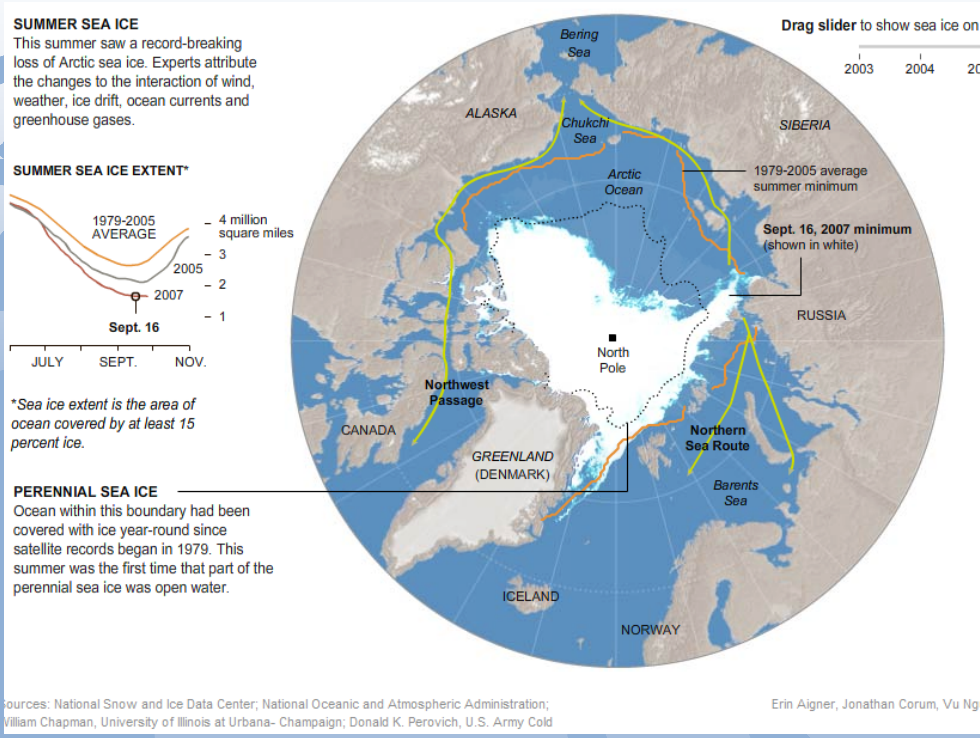


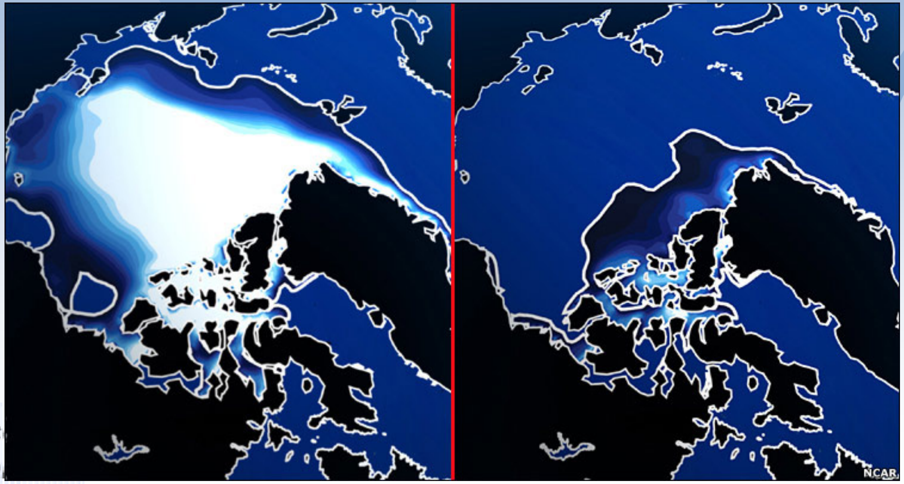
Stephen Leatherman

Sea Ice

NY Times, 10/1/07

- Poles warm at least 2x faster
- Large ice feedbacks
- Ice free summer by 2050
- Record low arctic ice in 2007
- Impacts
  - Ecosystems (polar bears, walrus)
  - Oil, resource extraction
  - Ocean thermohaline circulation
- Need mechanisms for faster ice melt (algae, cracks, etc.)





Nearly ice-free summertime arctic predicted by CCSM between 2000-2040, much of it within a decade due to ice thinning combined with pulse of warm water input (M. Holland et al.)

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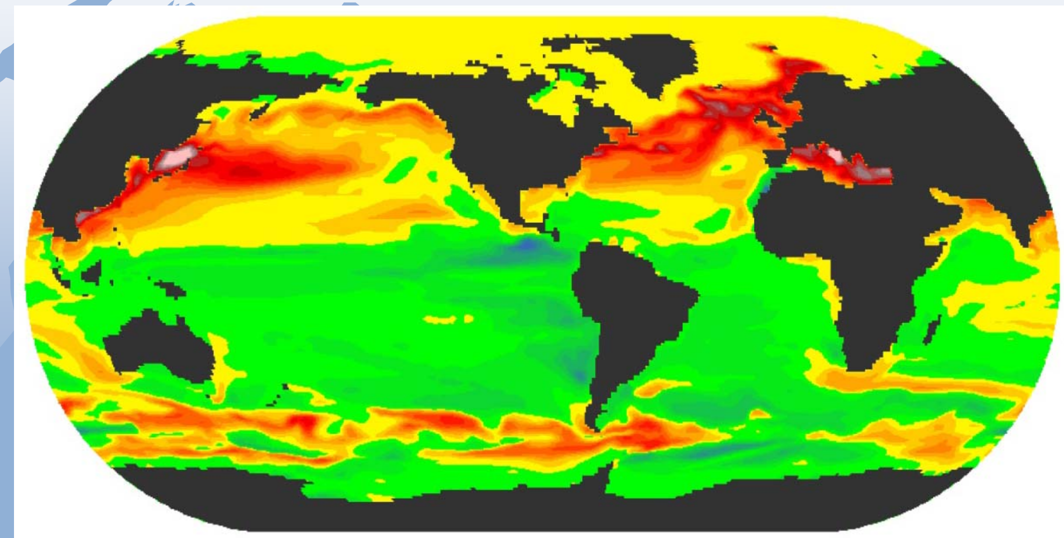
Chemical/Biogeochemical Models

- Coupling ocean biogeochemistry with extensive atmospheric chemistry and land biogeochemistry
  - Carbon and sulfur cycles
  - Needed to assess ability of oceans and land to sequester carbon
  - Aerosol direct/indirect (reduced precipitation?)
  - Projections with specified emissions
  - Methane hydrates/clathrates
  - Ocean acidification
  - Engineered climate
- Many tracers
  - 100x atm, 20x ocean
  - Many reactions
  - Metagenomics



Flux of CO_2 at ocean surface
Red/yellow – CO_2 leaving ocean
Green/blue – ocean uptake of CO_2

Coral bleaching

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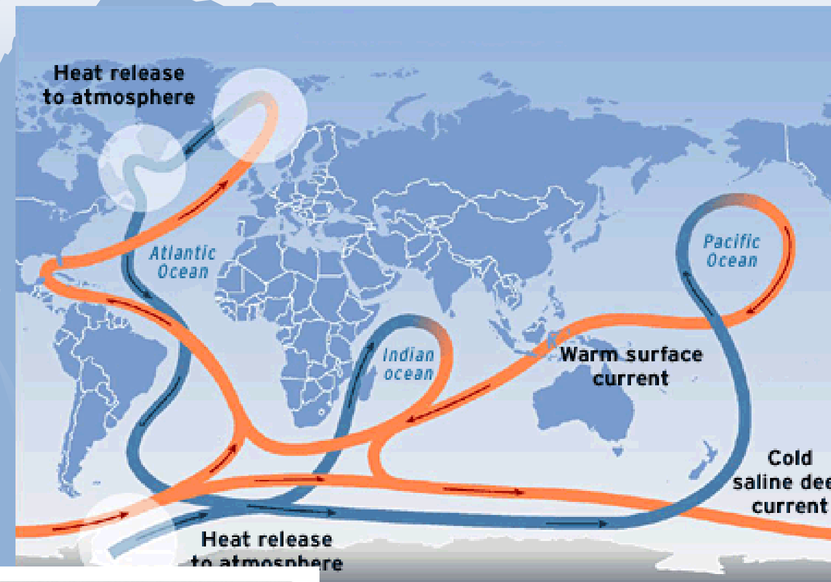
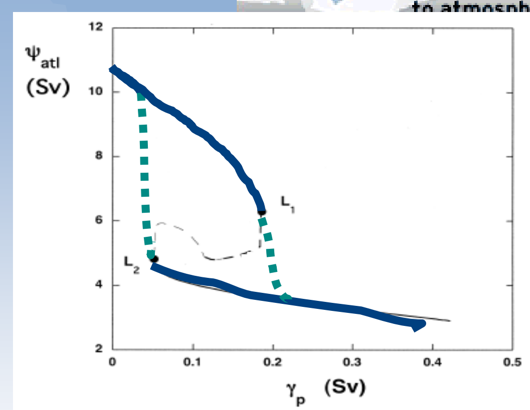
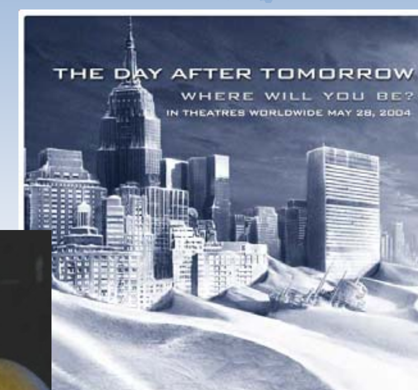
Abrupt change:
Ocean Thermohaline Circulation

- Carries large fraction of heat from equator to poles
- Driven by formation of cold, salty water in N. Atlantic and Antarctica
- Abrupt scenario:
  - Large influx of fresh water due to ice melt, increased precipitation
  - Prevents formation of dense water
  - THC slows/shuts down in response
  - Impacts on Europe, NE US and overall atmospheric circulation
- Implicated in past abrupt climate shifts
- Current models predict weakening, then recovery
- Implicit models/parameter continuation







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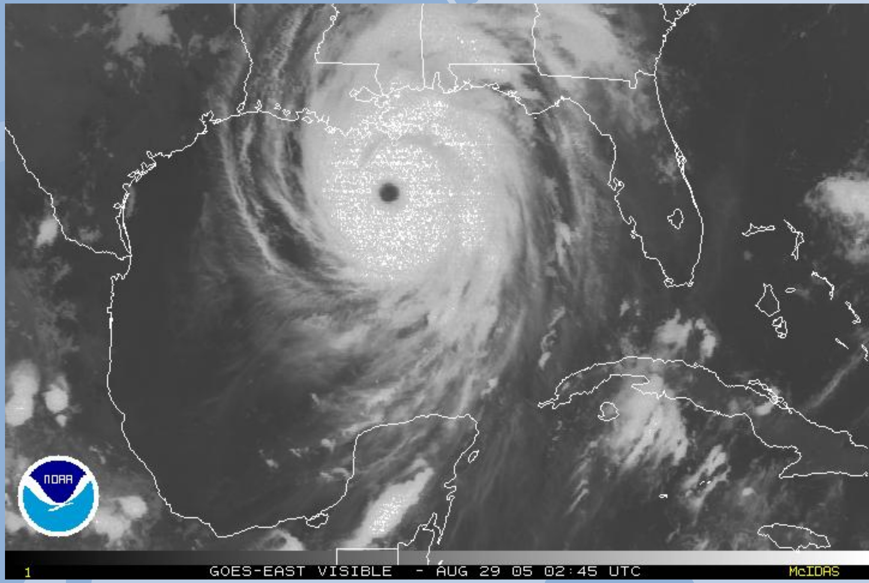
Extreme Events and Impacts

- Extremes
  - Hurricanse, droughts, high/low temps, frost dates, etc.
- Global forcing at large scale
- High resolution for dynamics
- Coastal models for impacts
- Connections to economic, infrastructure models
  - Falwell effect? – social models
- Statistics at the tails of distribution – model distributions



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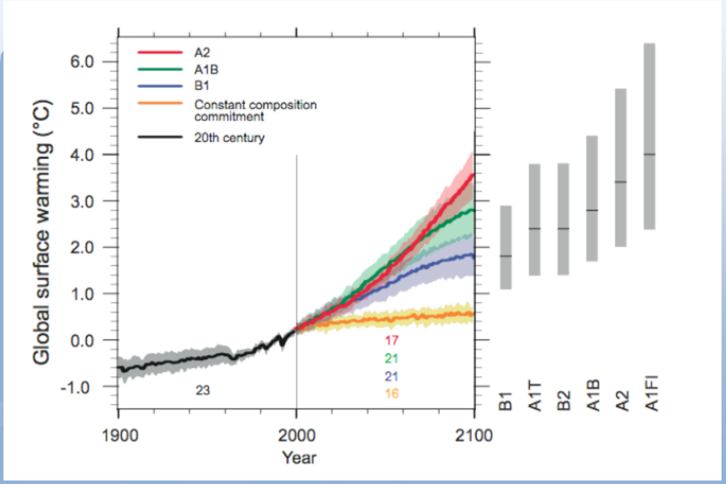
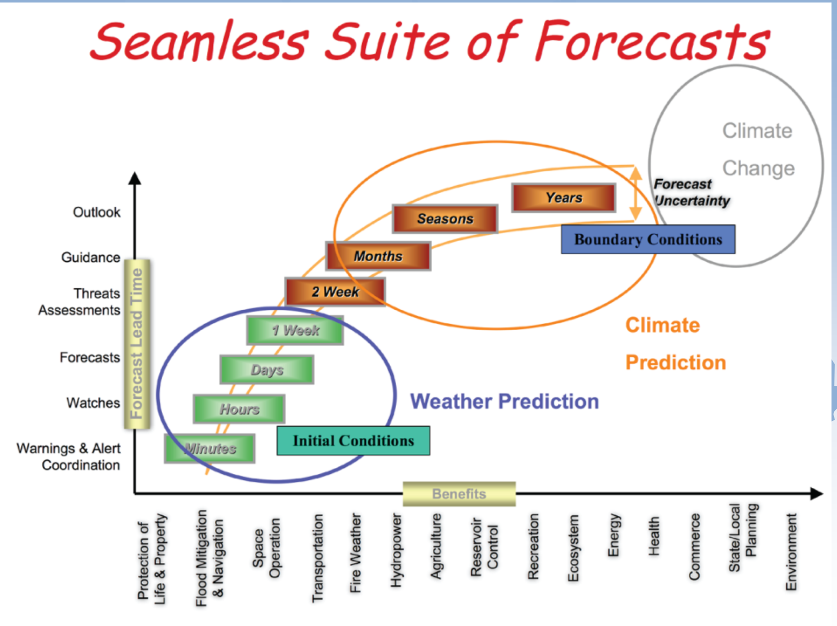
Assessments

- More ensembles
  - Integrated ensembles
  - 2-10x
- Decadal prediction
  - Data assimilation
  - 3-10x?
  - Massive data stream
- Error propagation/estimation
- Rapid turnaround to respond to policy-maker queries
  - Low-order surrogate models





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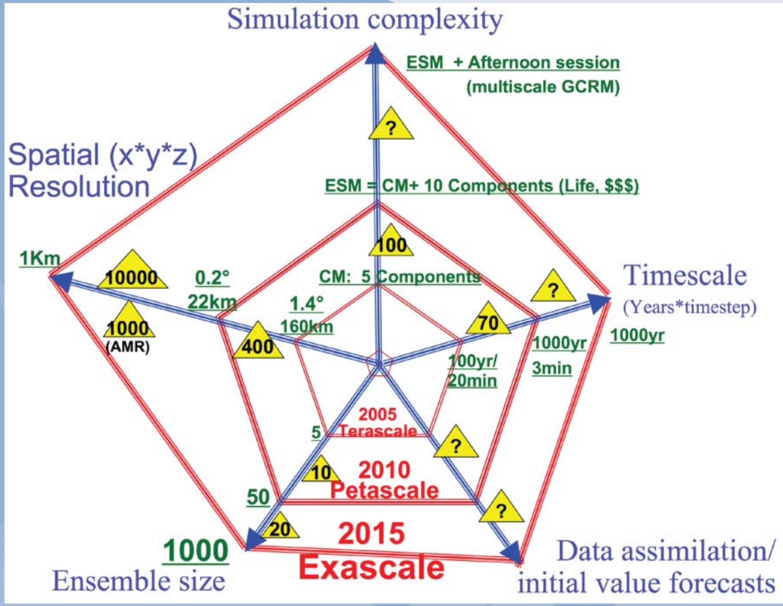
Computing needs (10^{10}-10^{12})

- Resolution (10^3-10^5)
  - x100 horiz, x10 timestep, x5-10 vert
  - Regional prediction (10km)
  - Eddy resolving ocean (< 10km)
- Completeness (10^2)
  - Biogeochem (30-100 tracers, interactions)
  - Ice sheets
- Fidelity (10^2)
  - Better cloud processes, dynamic land, etc.
- Increase length/number of ensembles (10^3)
  - Run length (x100)
  - Number of scenarios/ensembles (x10)
  - Data assimilation (3-10x)
- Data requirements have similar factors
  - 35 TB currently, distributed
  - More for assimilation



Courtesy L. Buja

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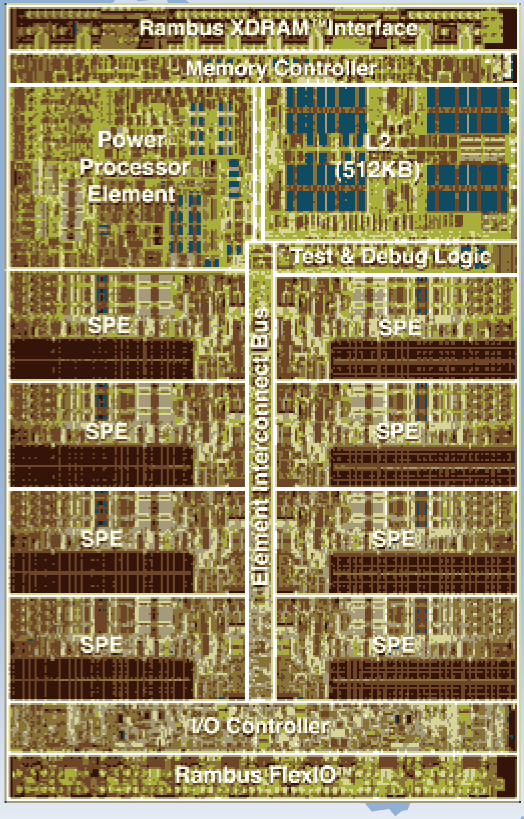
Terror Cells and other Future Architectures

- Large processor counts
- Hybrids, power envelope
  - Difficulties due to low memory/bandwidth
  - No kernel
  - Increased work per grid point, time integration
- Unknown future
  - Machines
  - Algorithms (50/50 rule)
  - Abstractions (adaptation strategies)
  - Programming models, non-traditional approaches



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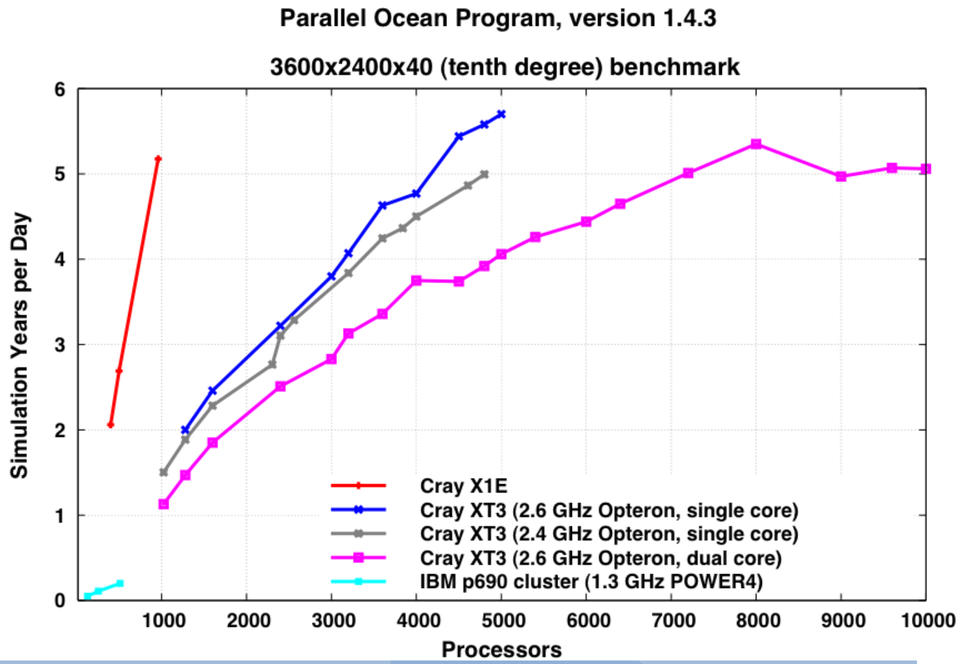
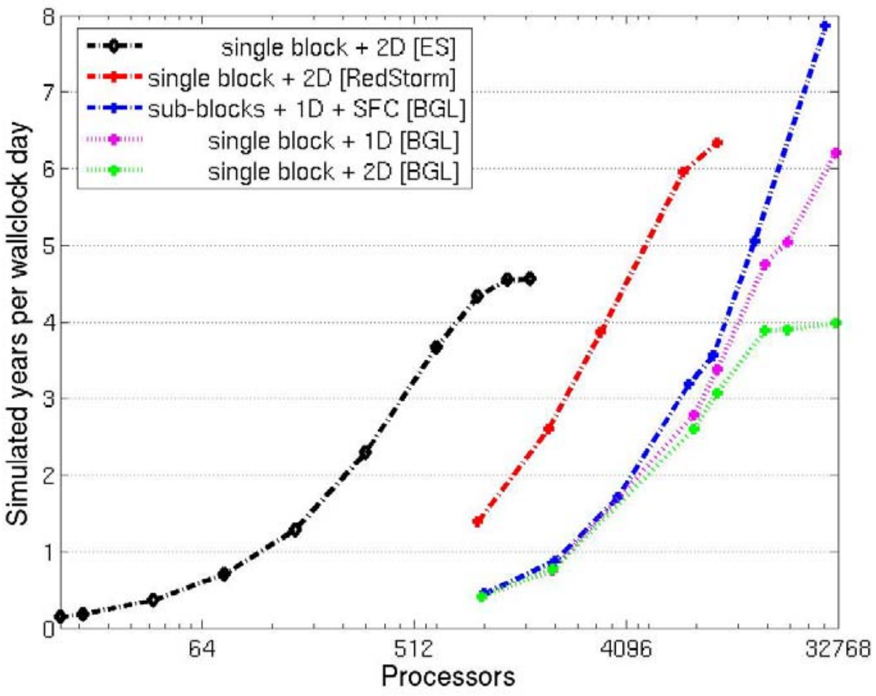
Scaling to Large Processor Counts



Effective for high resolution, multiple scenarios…but can't scale time (1hr to 7 min)



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Algorithm Changes

- Time integration
  - Can’t scale your way out
  - Implicit/alternative time stepping
- Smarter resolution
  - Existing models
  - Regional downscaling

Decision Tools

Global Climate Models
- Future climate driven by emissions scenarios and assumptions of technology insertion, human behavior and policy implementation.

Regional-scale impacts
- Regional models with temporal and spatial resolution appropriate for coupling to infrastructure systems of interest.

Infrastructure impacts
- Driven by regional climate data of temperature, water availability, etc. to identify diverse set of vulnerabilities and test mitigation strategies.

Uncertainty quantification

Example Application: Climate Impacts on Western US Energy and Water Infrastructure