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Title: Climate Modeling at LANL

Author(s): Jones, Philip W.

Intended for: HPC division seminar, 04-02-2013

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Climate Modeling at LANL

Phil Jones (T-3)

Project Lead: Climate, Ocean and Sea Ice Modeling (COSIM)

COSIM team: Sham Bhat, Darin Comeau, Xylar Asay-Davis, John Dukowicz, Scott Elliott, Matthew Hecht, Jim Gattiker, Jonathan Graham, Matthew Hoffman, Elizabeth Hunke, Doug Jacobsen, Nicole Jeffery, Gunter LeGuy, Bill Lipscomb, Bob Malone, Mat Maltrud, Sebastian Mernild, Balu Nadiga, Chris Newman, Mark Petersen, Steve Price, Sara Rauscher, Todd Ringler, Joel Rowland, Adrian Turner, Milena Veneziani, Wilbert Weijer, Beth Wingate

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Outline

- Ancient and medieval history
- The real climate change questions
- Climate models
- Current events
- The exascale challenges

History

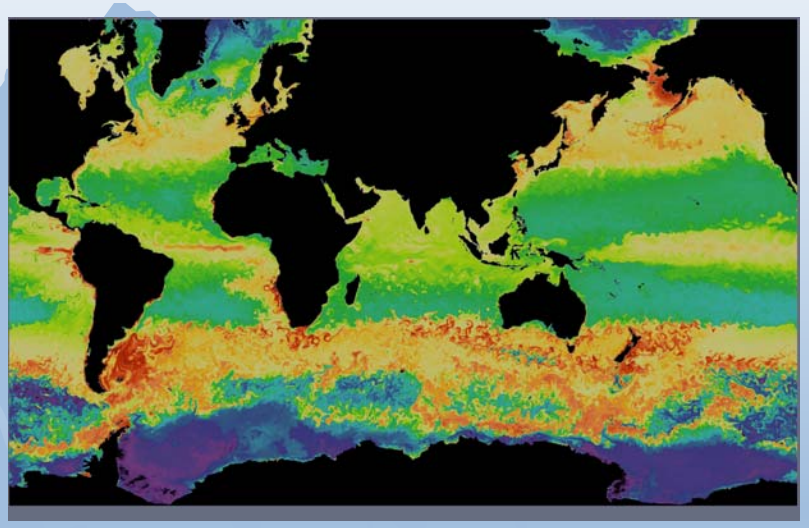
- Late 80s/Early 90s
  - Bob Malone, Rick Smith, John Dukowicz (POP)
  - Andy White and ACL
  - Combined hardware, algorithms
- Sea ice soon after
  - Now community standard
- Now ice sheets too
- Continued, evolving use of LANL open HPC platforms

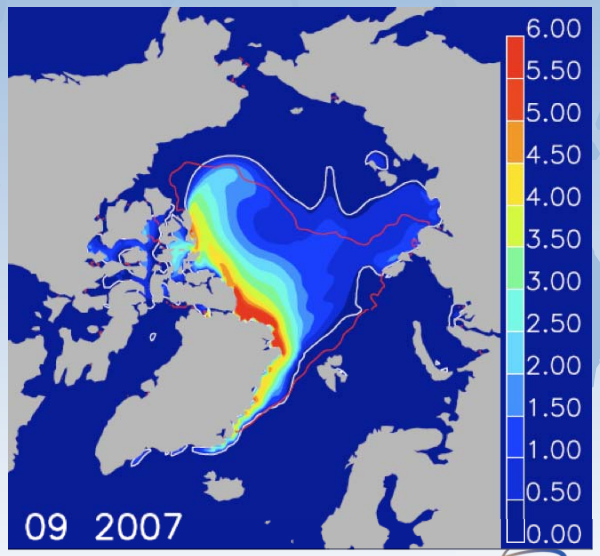
Mission

- Develop and apply high-performance, multi-scale models of the Earth's climate for studying the role of ocean and ice systems in high-latitude climate change and the subsequent impacts on regions throughout the globe.
- Focus on high latitude climate change and its impacts
  - Ice sheets and sea level rise
  - Rapid sea ice changes
  - Ocean circulation and stability
  - High latitude ocean/ice ecosystems, carbon/sulfur cycle
- ~$8M/year, mostly DOE-SC (BER)
  - 15-20 scientists in T-3, CCS-2

COSIM Develops Ocean/Ice Models

- Parallel Ocean Program (POP)
  - State-of-the-art ocean GCM
  - New multi-scale ocean (MPAS-Ocean)
- Los Alamos Sea Ice Model (CICE)
  - Leading sea ice model
- Ice sheet model (Glimmer-CISM)
  - Greenland, W. Antarctic
- Ocean, ice components of Community Climate System Model (NSF/DOE)
  - IPCC, national Assessments
- High performance computing
- Publicly available
  - Large international user base
  - http://climate.lanl.gov





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Climate Change

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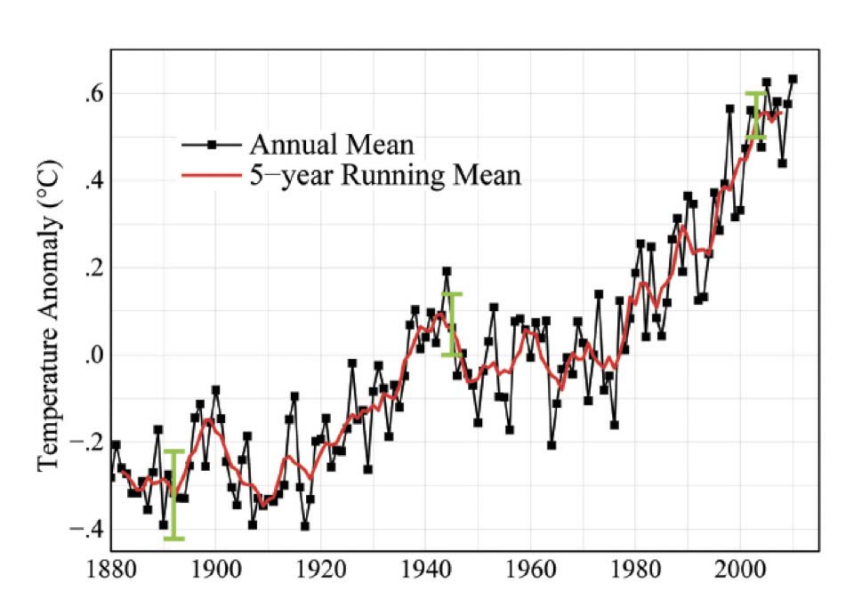
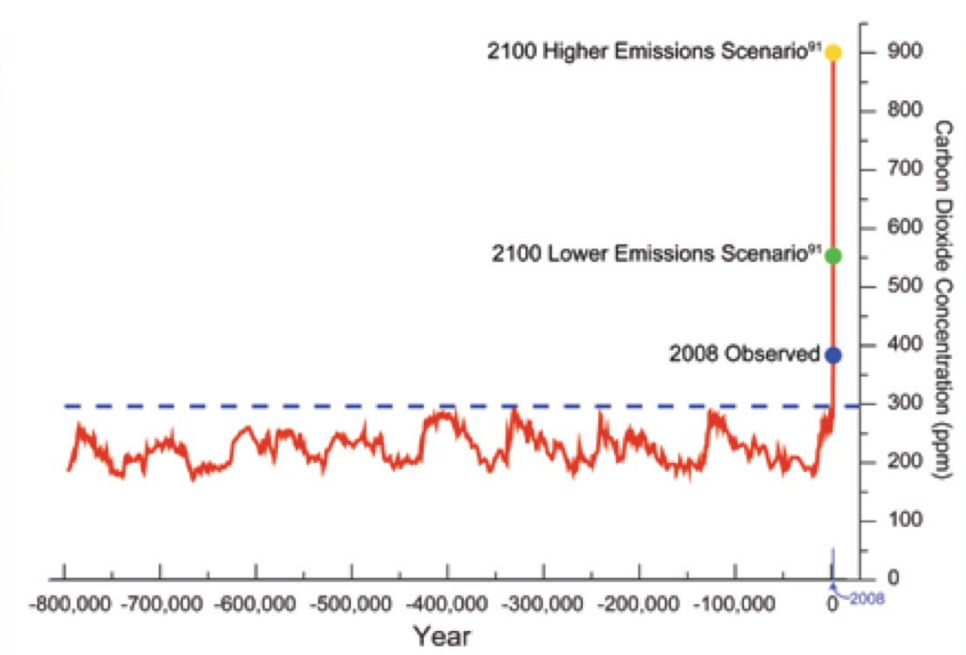
Temperature is Rising due to Anthropogenic Greenhouse Gases





0.8 degrees C

But Tavg is not the only (or even the most important) metric – this ain't QCD

Basic relationship:
Fourier (1824)
Pouillet(1827)
Tyndall (1859)
Arrhenius (1896)

Isotopes and inventories: human emissions and land use change

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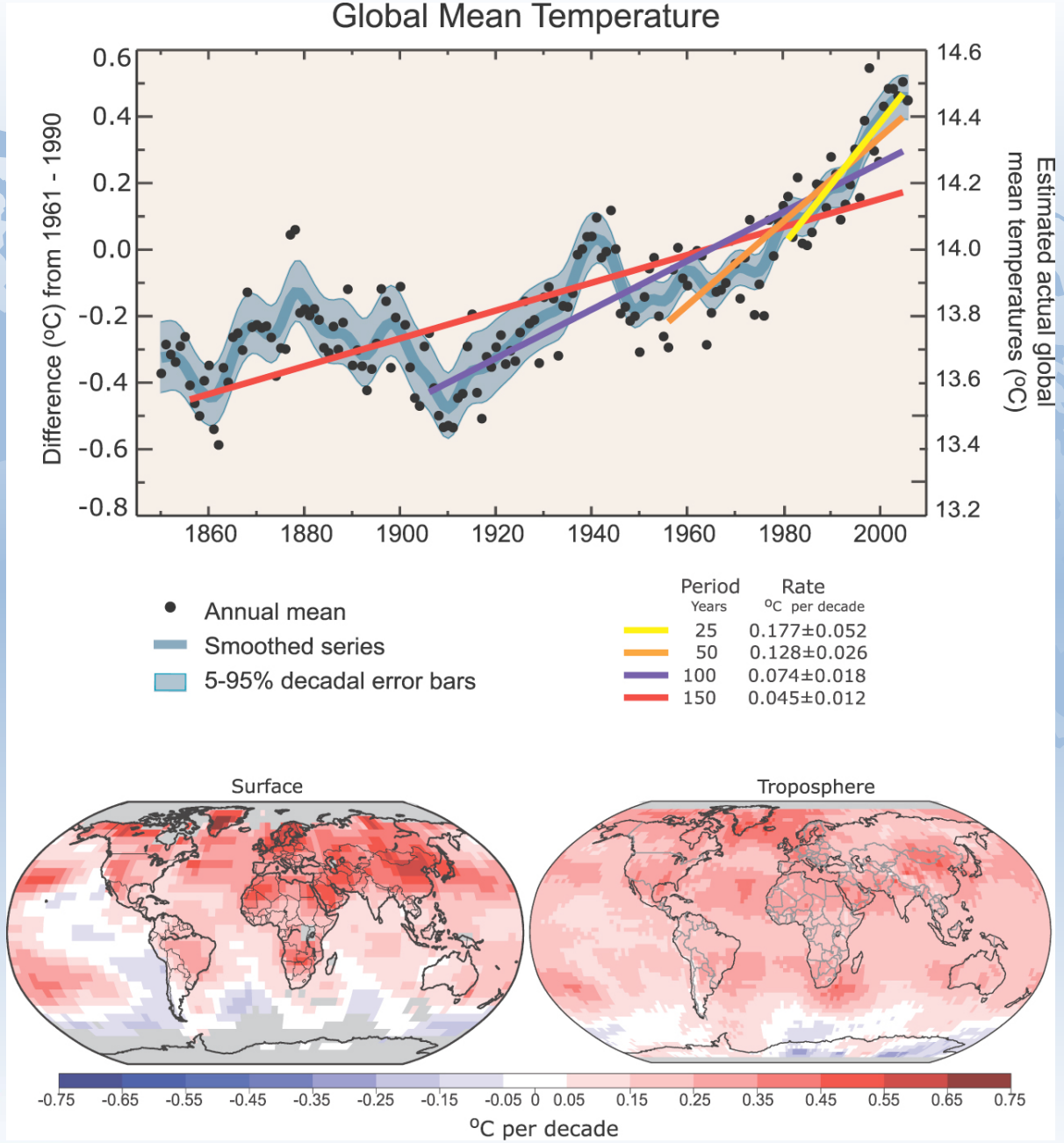

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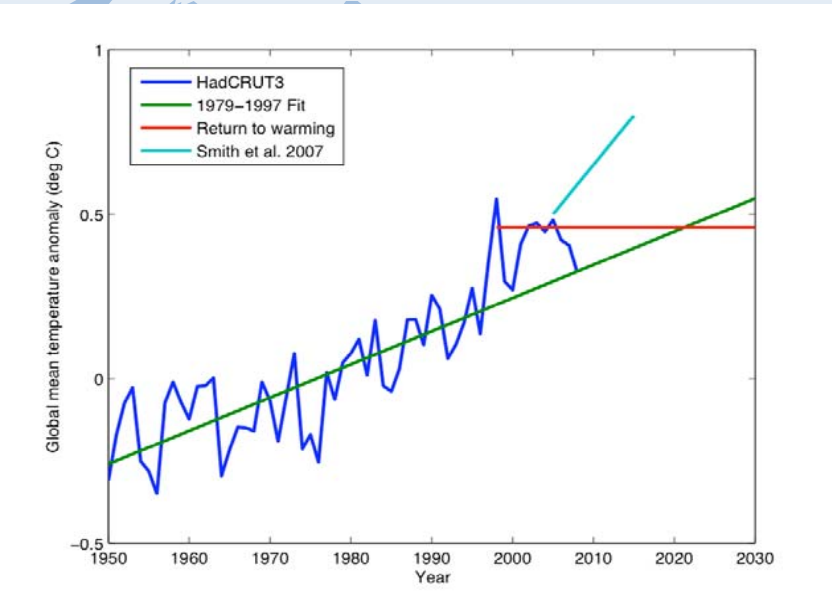
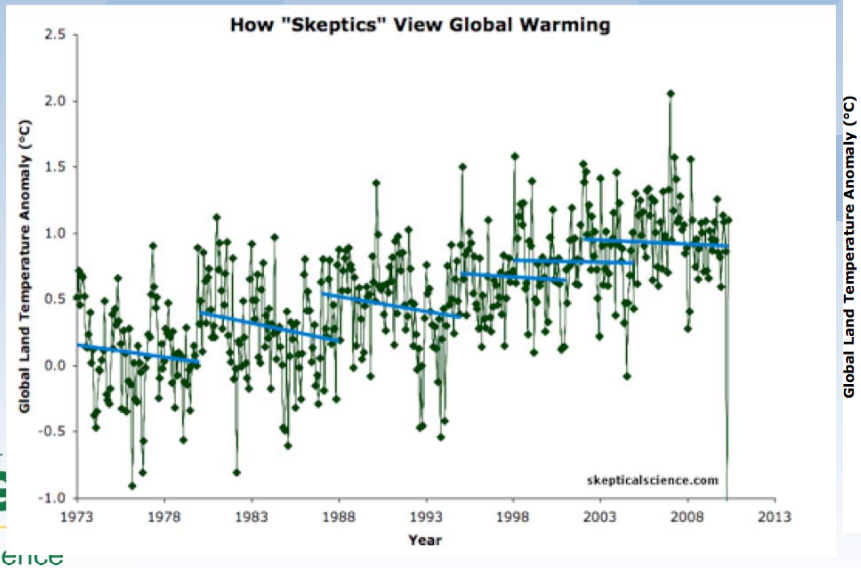
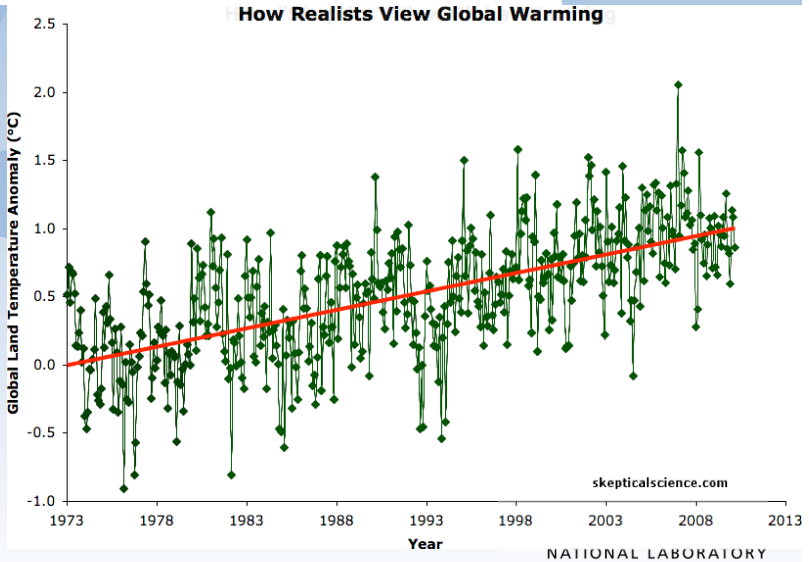
Short Term Records

- Persistent long-term trend
- Decadal variability
- Weather

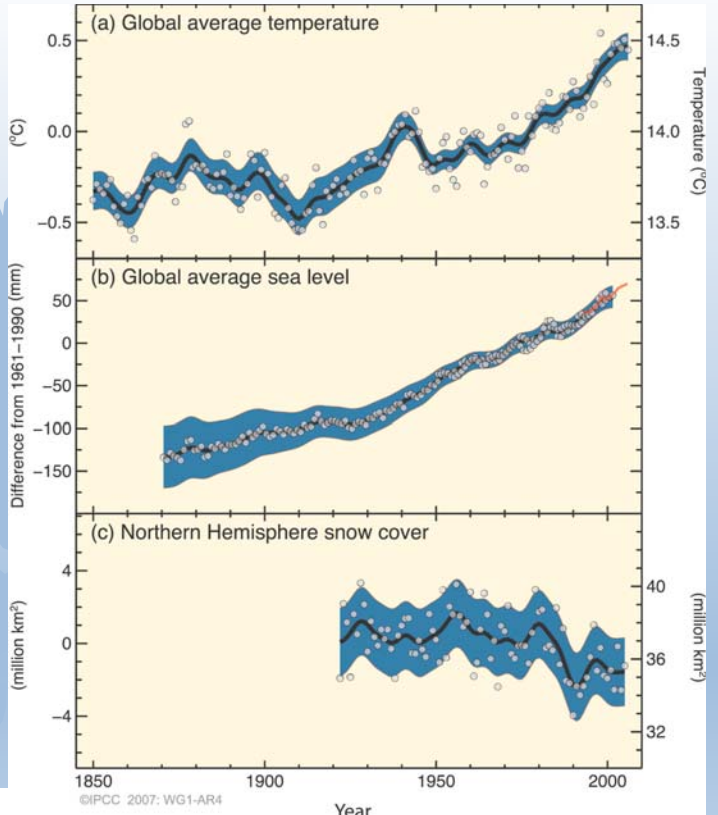


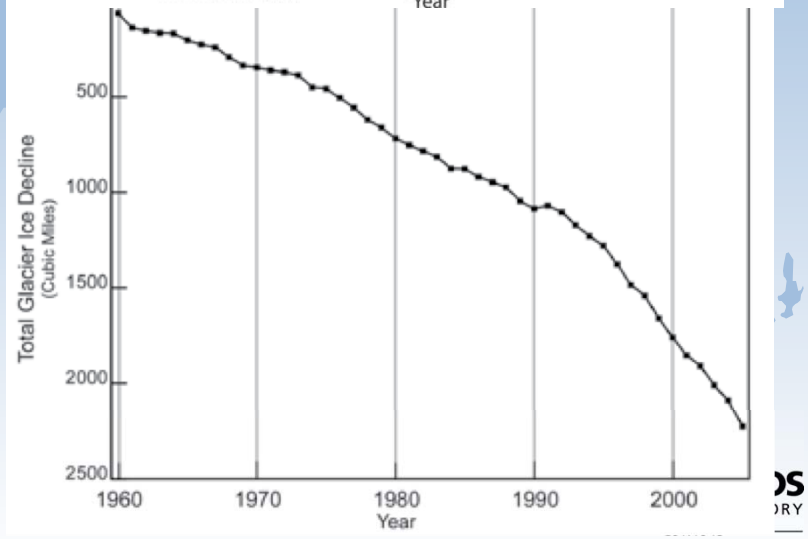




Other observations

- Ocean warming to 3000m depth
- Glaciers, snow cover declined
- Ice sheet losses accelerated
- Sea ice decreased
- Changes in precipitation patterns (poleward and upward, snow pack)
- More intense, longer droughts in tropics, subtropics
- Freq. of heavy precip events increased
- Cold days, nights, frost decreased; hot days increased
- Increased water vapor
- Changes in migrations, plants
- Increases in fire frequency
- 29,000 time series





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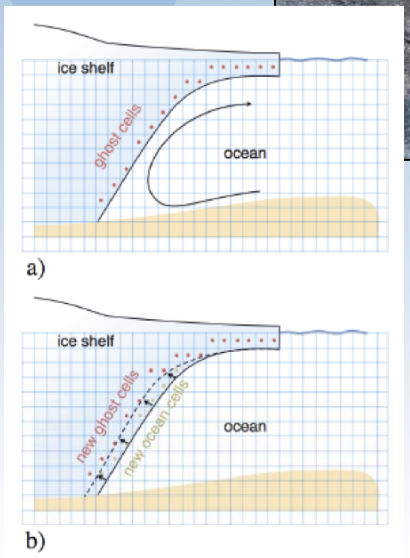
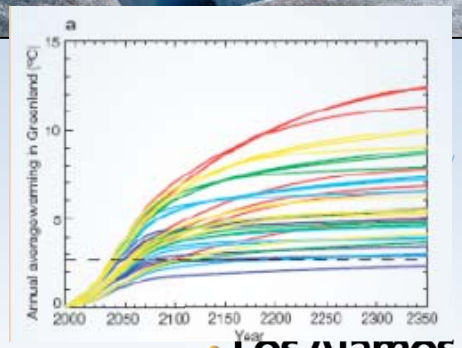
Ice Sheets and Sea Level Rise

- Recent addition to 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
- Gravitation/geodetic

Stephen Leatherman





Gregory et al. 2004

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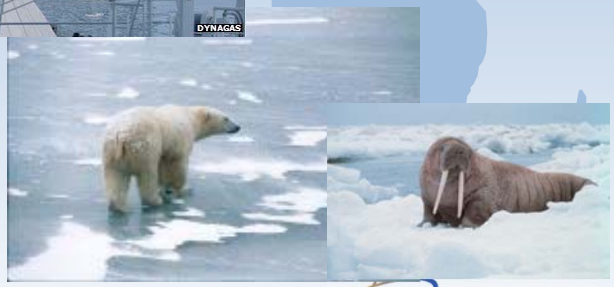
Arctic Prediction

- Polar amplification
  - Rapid ice loss, feedbacks
  - Impacts on global weather
- Human activities/energy
  - Infrastructure, coastal erosion, permafrost melt
  - Resource extraction
  - Shipping
  - Security/safety, staging
- Ecosystem impacts/mgmt
  - Arctic, marine mammals
  - Marine ecosystems
- Regime change
  - Thin ice leads to more variability

Shell Kulluck Arctic oil rig runs aground in Gulf of Alaska (USCG photo)

LNG carrier Ob River in winter crossing (with icebreakers)



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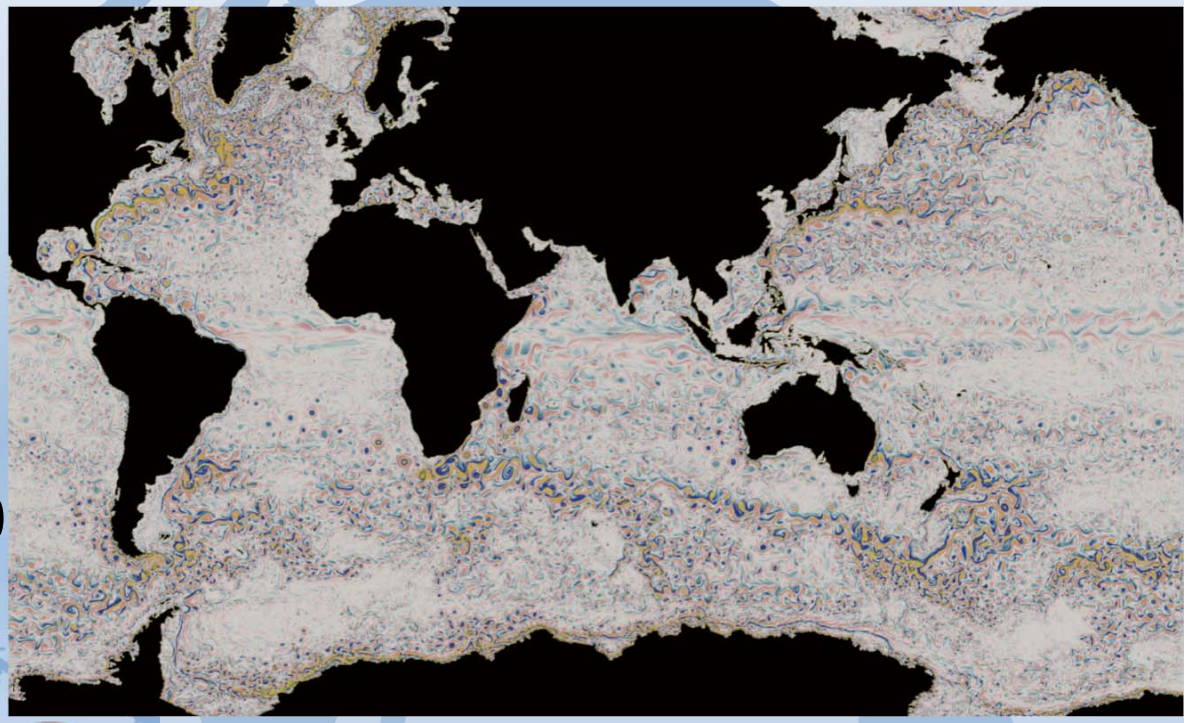
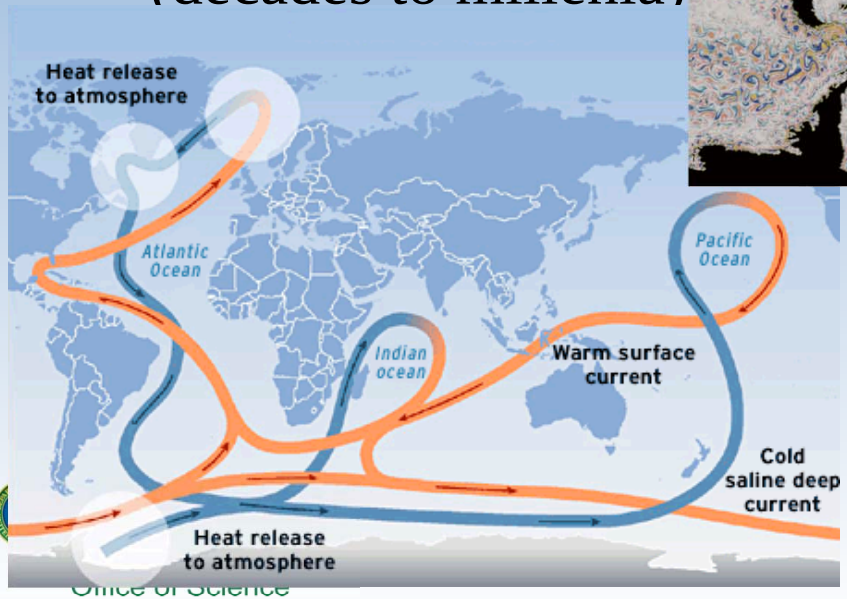
Ocean Circulation

- Ocean Eddies
- Thermohaline circulation
  - Heat, mass transport
  - Long time scales (decades to millenia)





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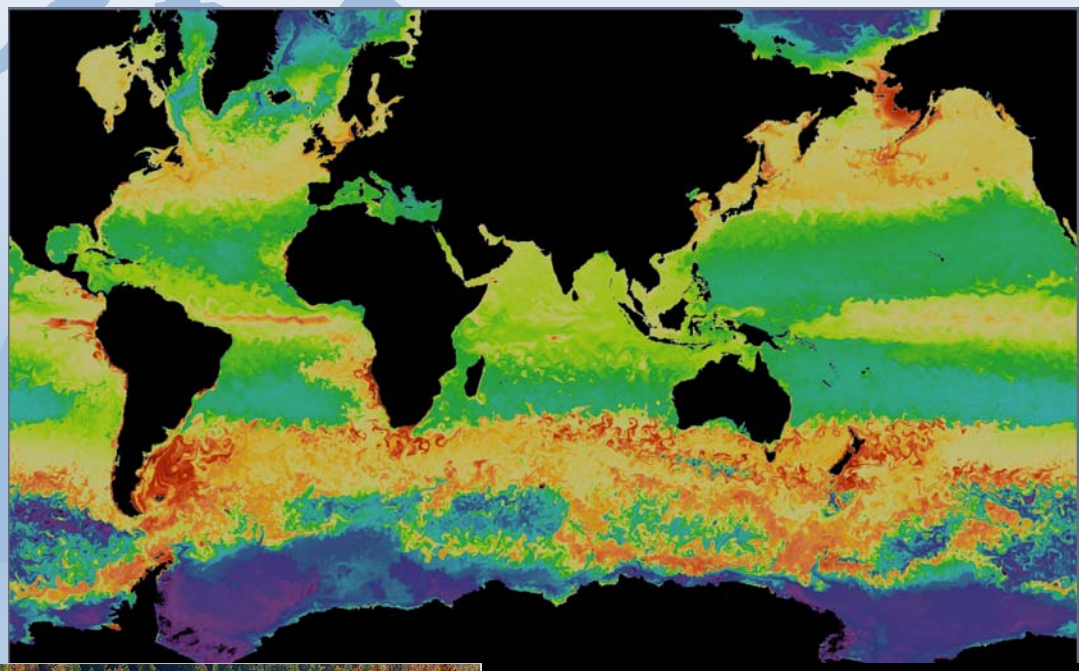
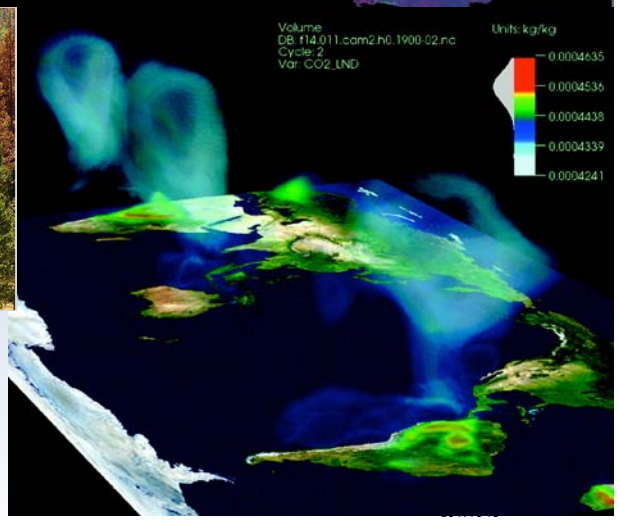
Sequestration

- Biogeochemical feedbacks
  - Carbon/sulfur cycles
  - Methane
  - Nutrient limitation
  - Dynamic vegetation
  - Ocean/ice ecosystems





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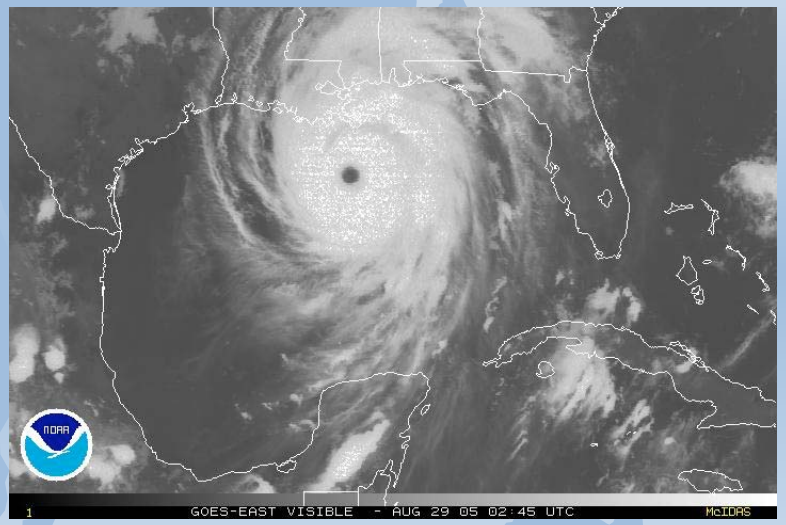
Others

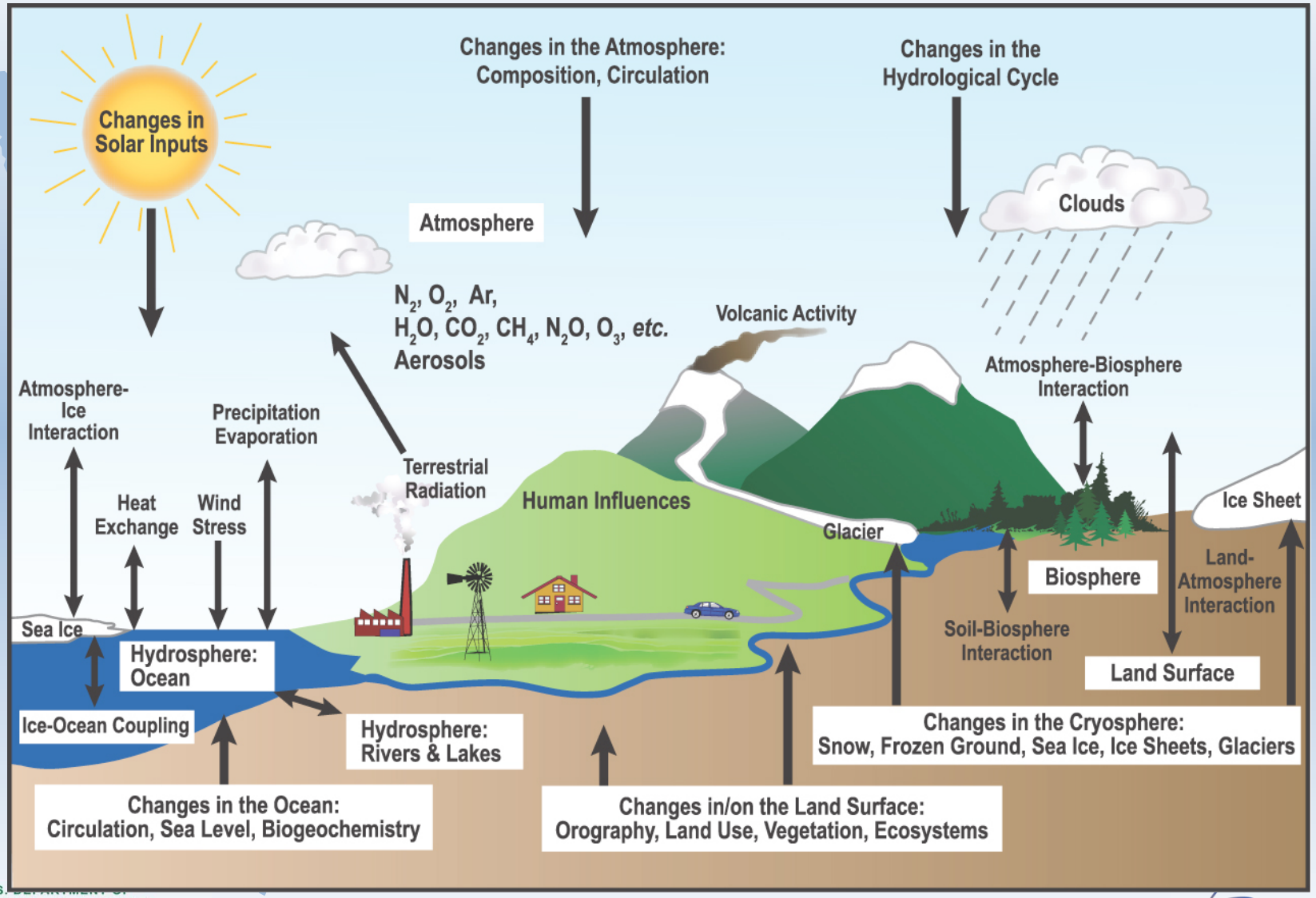
- Cloud/aerosol/radiation feebacks
  - Enhance or counter GHGs
- Extreme events
  - Droughts
  - Heat waves
  - Severe storms
- Interactions with economy, human behavior



Dynamics
Physics

Climate is Complex

Biogeochemistry
Human Interactions



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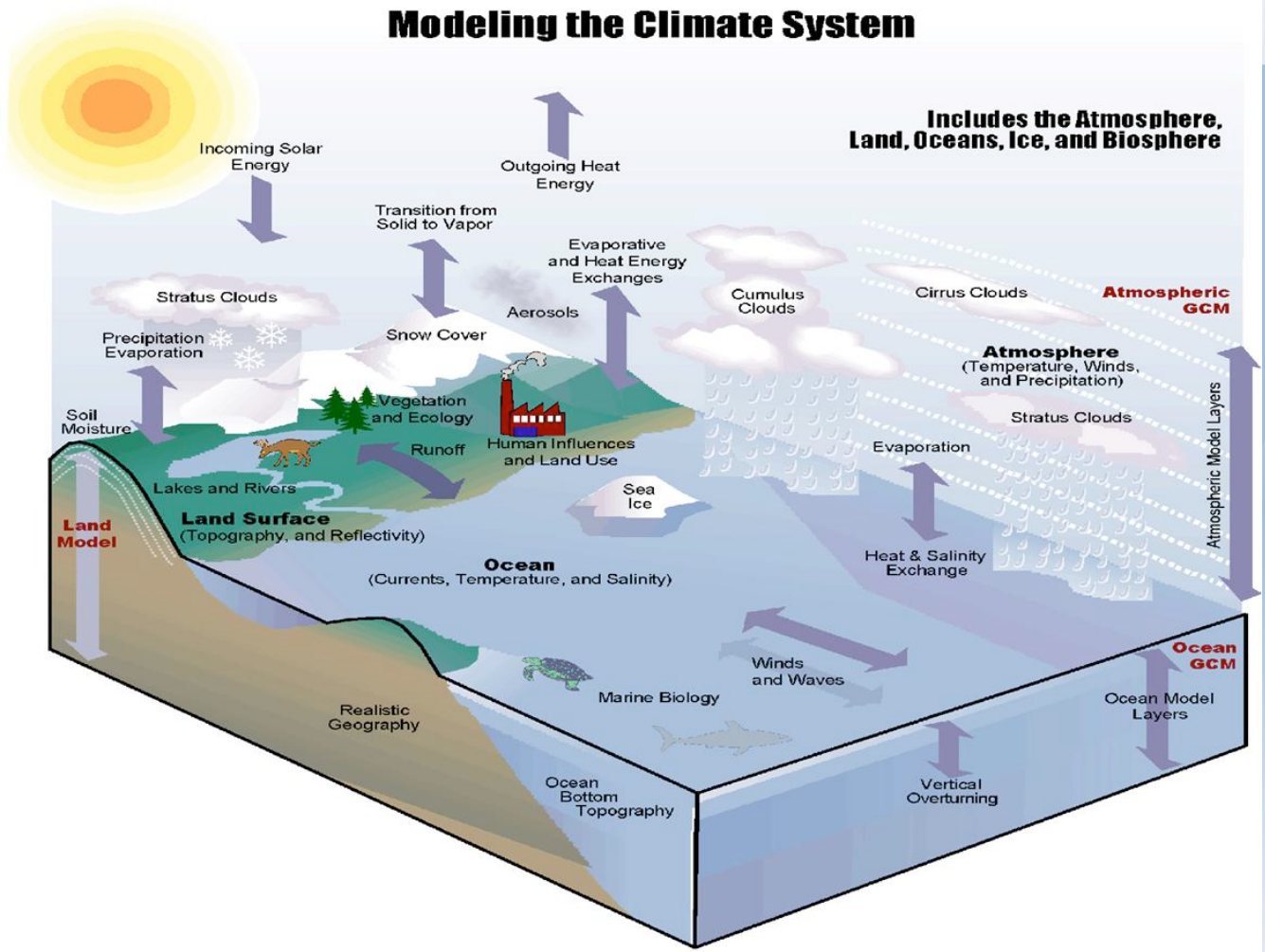
Climate Models are Tools for:



- Integrating knowledge of climate system
- Understanding and quantifying feedbacks
- Attributing causes
- Projecting future change
- Mitigation and adaptation

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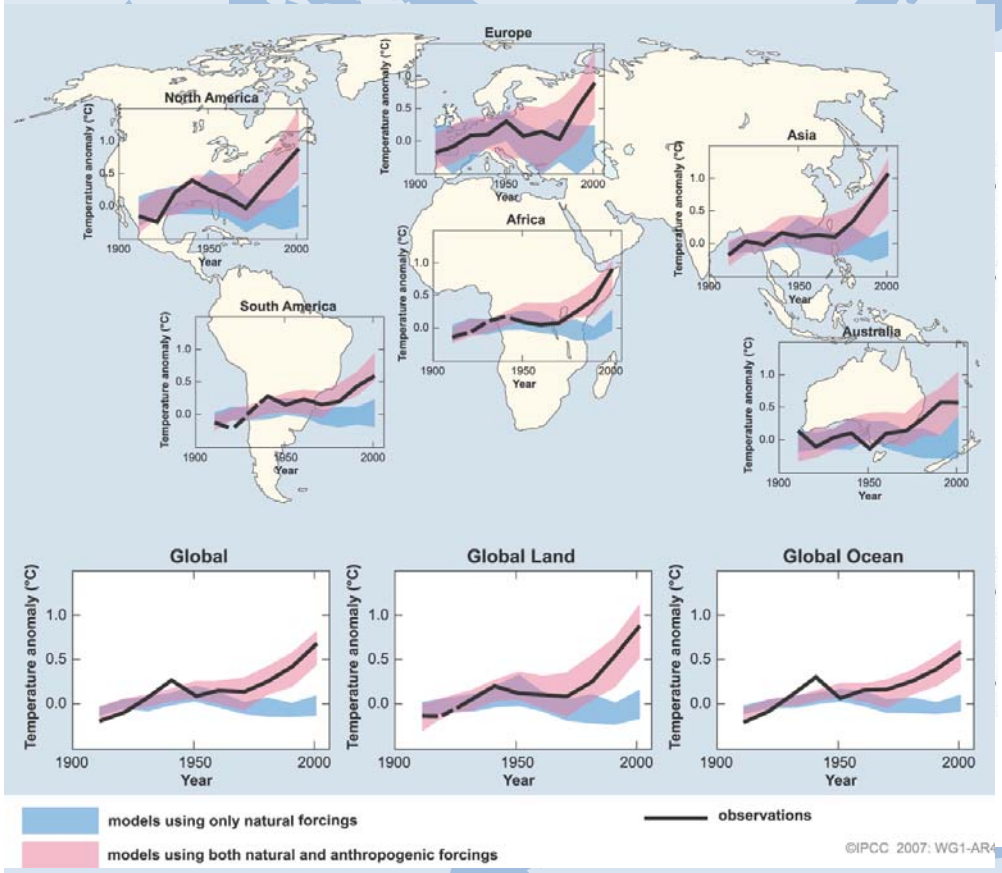
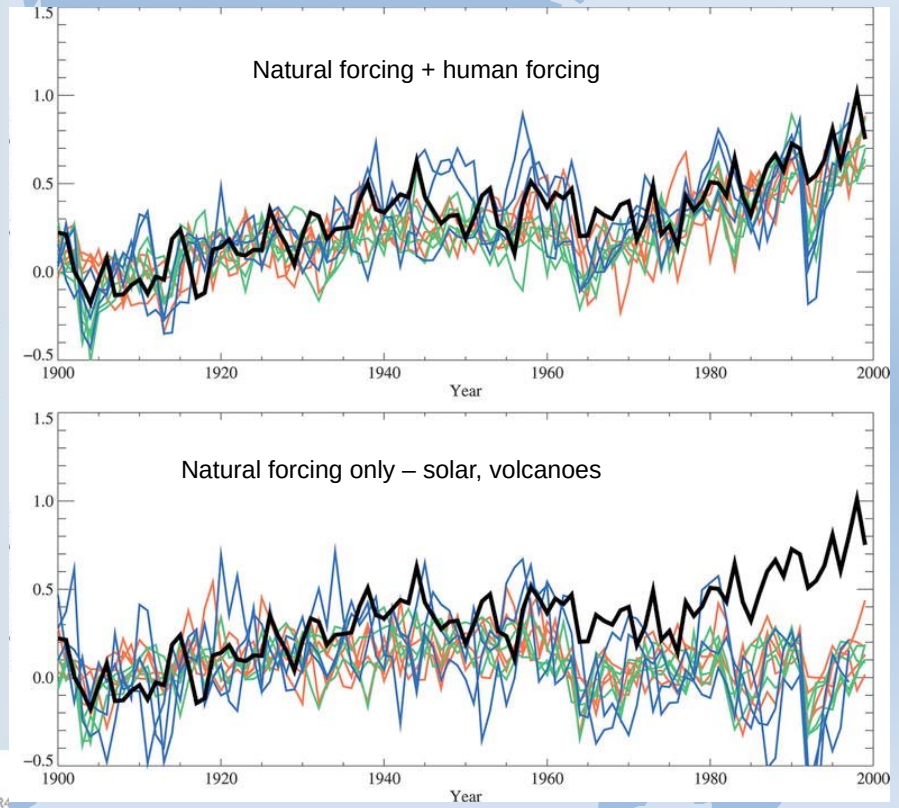
Attribution

Controlled Experiments





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

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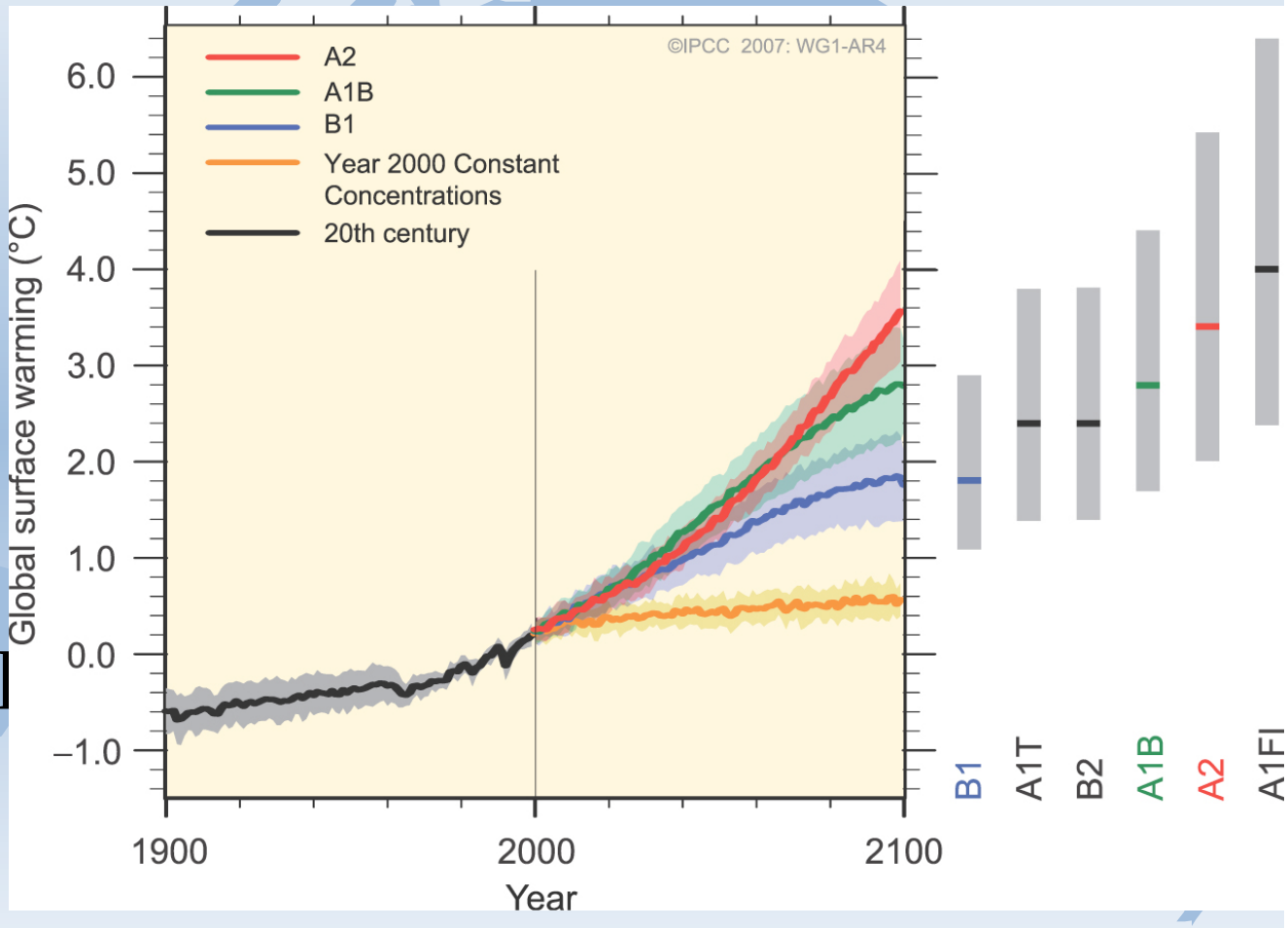
Projections

- Multiple modeling groups
- Ensembles
- Emissions scenarios
- Forced signal
- “UQ”



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Community Earth System Model

Atmosphere
CAM

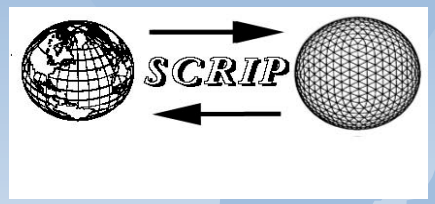
NSF/DOE
300+ Participants
Million lines code

Land
CLM

Once per hour

hour per Once

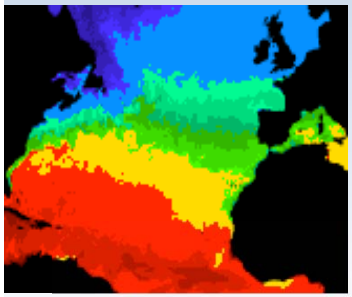
Flux Coupler



day per Once

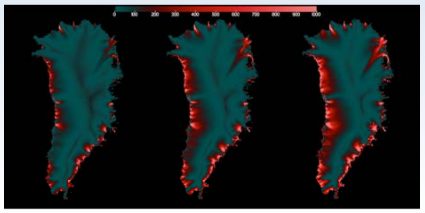
Once per Year?

Once per hour



Ocean
POP

Ice Sheet
CISM



Sea Ice
CICE

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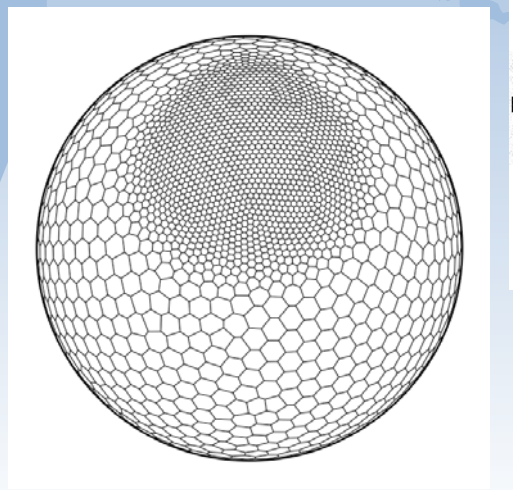
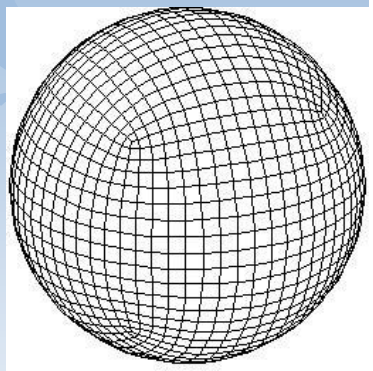
Global Climate Models

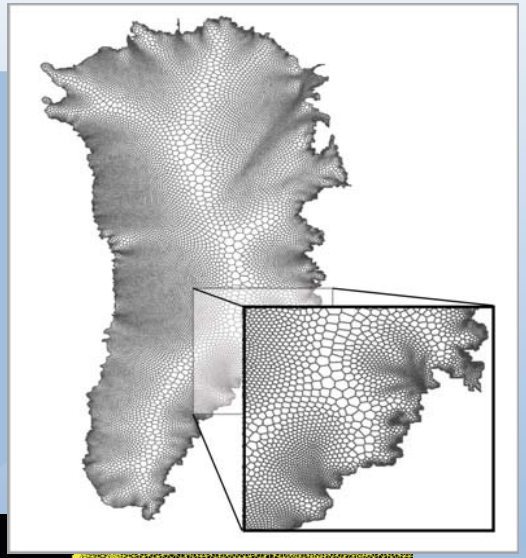
- Atmosphere (CAM)
  - 3-d Fluid equations (N-S, hydro)
  - Spectral-element, finite-volume, spectral
  - Column physics (radiation, clouds, convection)
  - Mixed time
- Ocean (POP is dead, long live POP; MPAS)
  - 3-d Fluid equations (N-S, hydro, incomp)
  - Finite diff., EOS, mixing
  - Explicit, semi-implicit or subcycled barotropic
- Sea Ice (CICE)
  - Viscous-plastic (EVP), subcycled E
  - Thermodynamics
- Land Surface (CLM)
  - Plant functional types
  - Surface water, energy
- Ice sheets (CISM)
  - Stokes (or approximations), JFNK/elliptic
  - Surf mass balance, hydrology
- BGC: coupled ODEs, many tracers
- All Components: MPI + OpenMP + ?

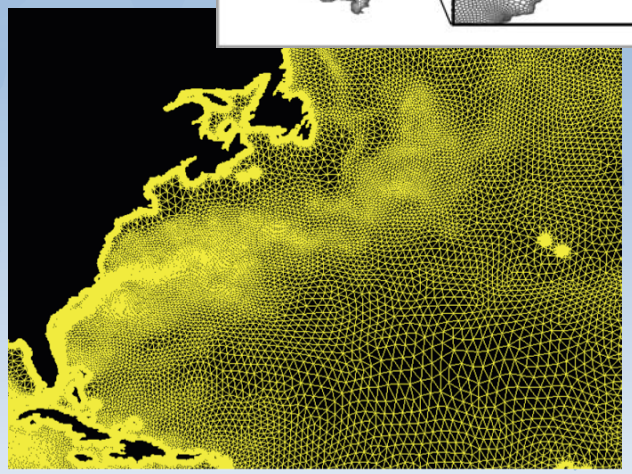




Climate Model Characteristics

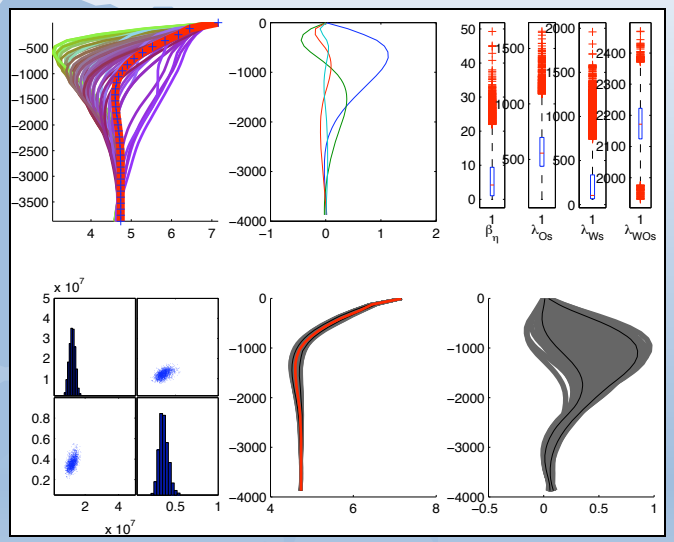
- Multiscale in space
  - Must resolve some scales (ideal < 1km)
  - Parameterize unresolved scales
  - Mix of two in same model
- Multiscale in time
  - Seconds to centuries/millenia
  - Scale space, but not time
  - Implicitness and performance
- Multiphysics? Multiscience
  - Physics, chemistry, biology, ecology, astronomy
  - Disparate components
  - Model coupling (conserve, data motion)
- Large algorithm diversity
  - Domain specific = not specific

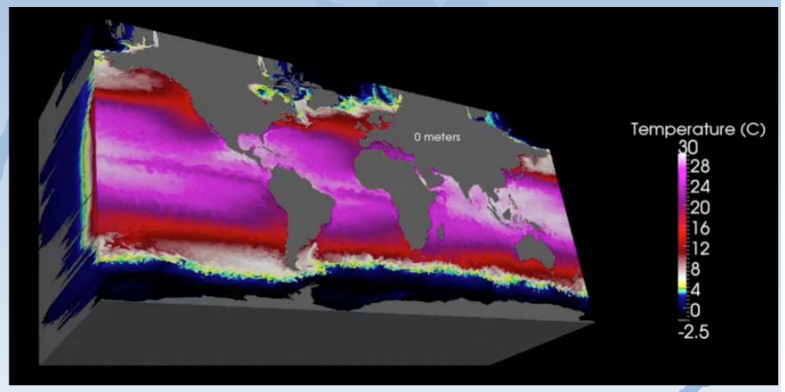




Policy-relevant

- Testing and Validation
  - Emphasize validation
  - Testing needs work, missing data
- Conservative
  - Stuffy old white guys, do no harm
- Uncertainty Quantification
- Ensembles
  - UQ
  - Decadal prediction, data assimilation
- Diverse stakeholders
  - Implications for in situ analysis
  - Data distribution, provenance
  - High-perf analysis tools





Validation of Ocean Models using Integrated Testbed (VOMIT)

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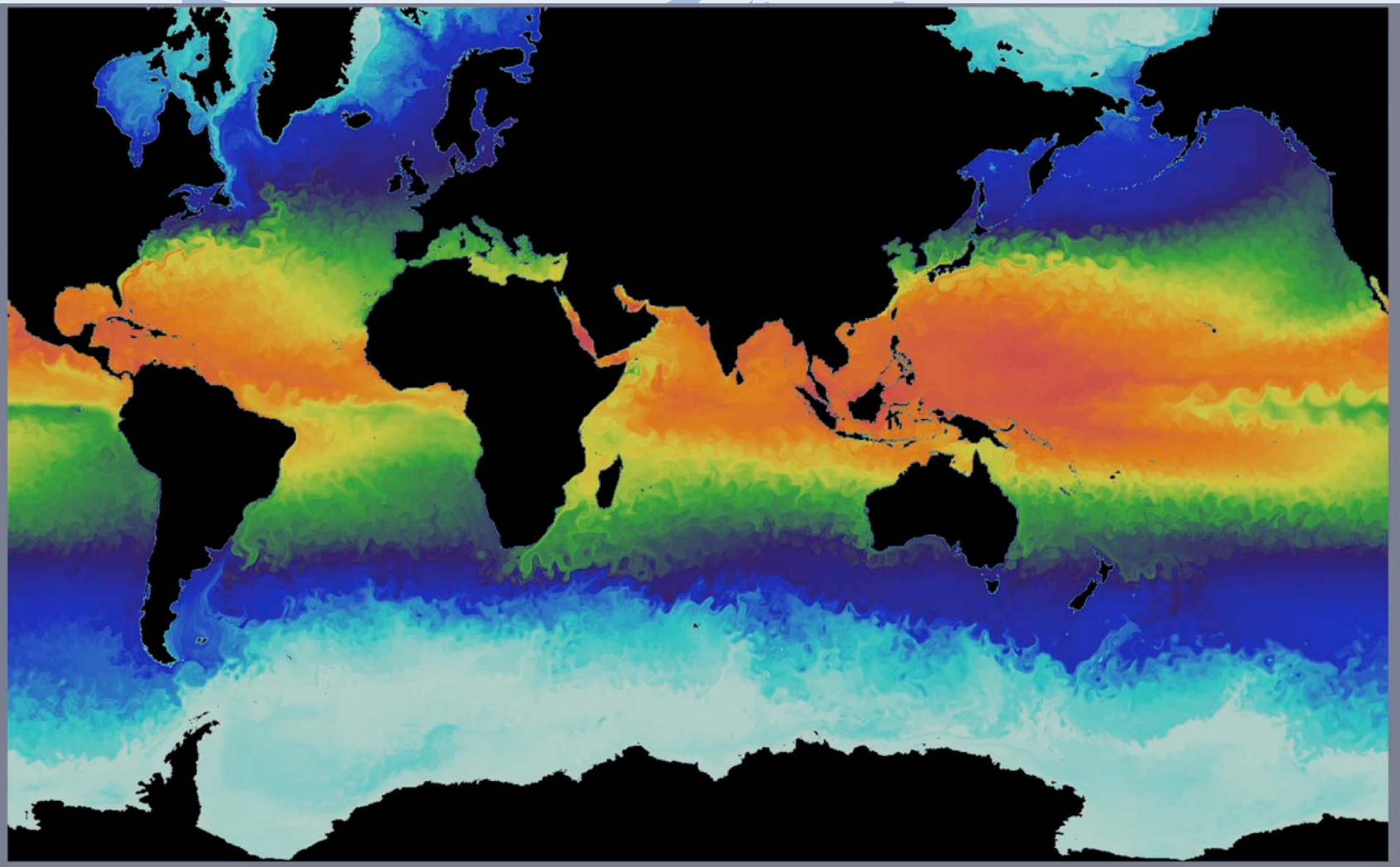
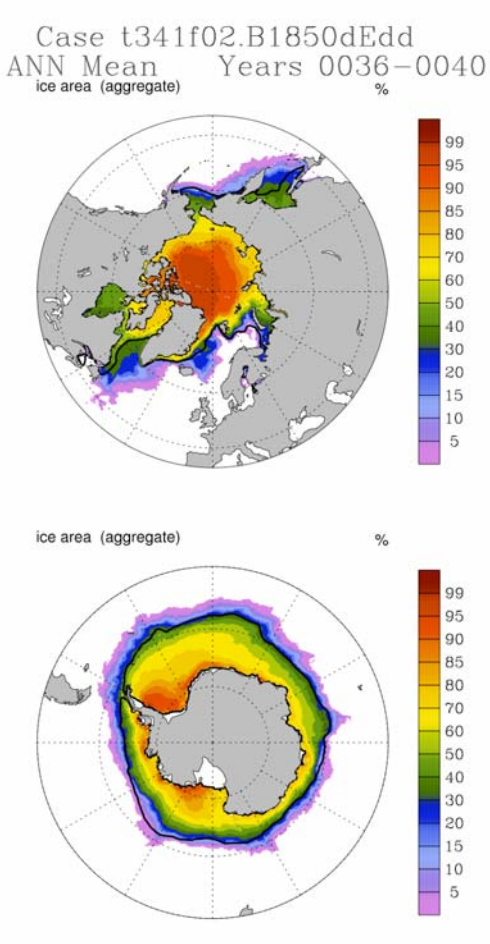
Current Applications and New Development

- Using both LANL IC resources and DOE LCFs

High-resolution modeling



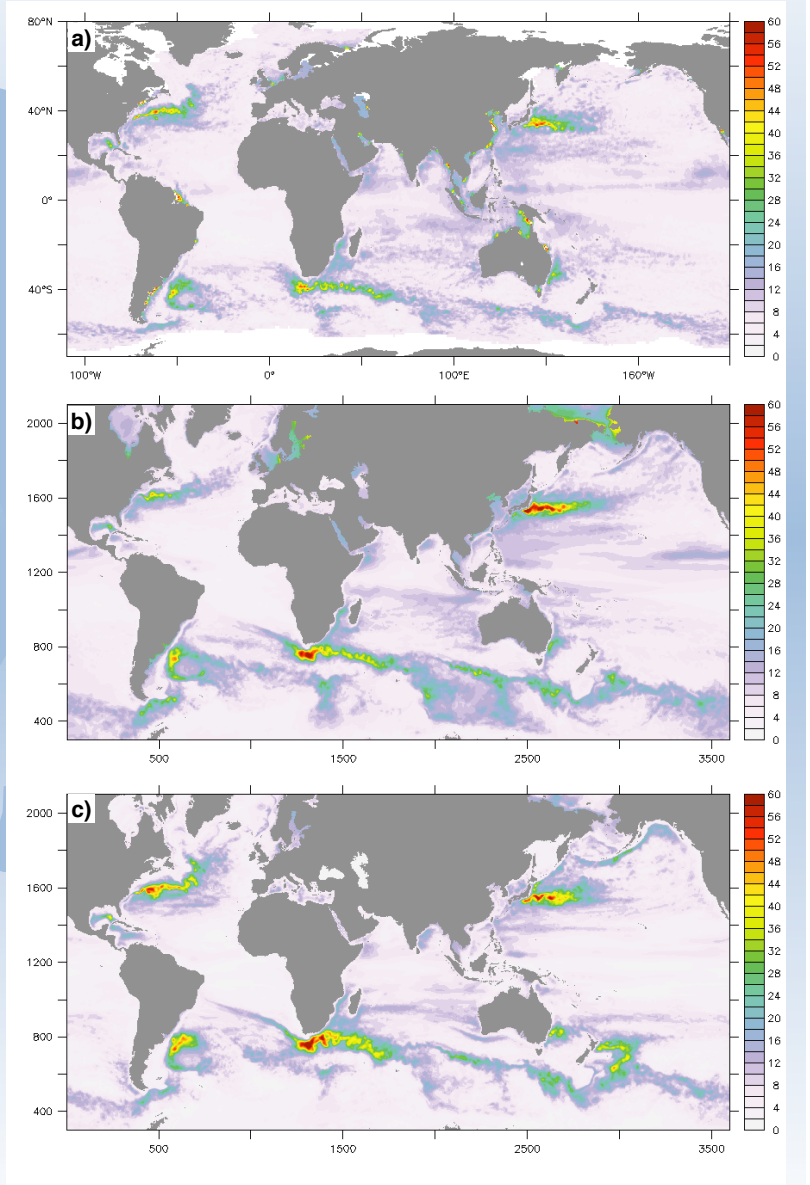
High-resolution coupled simulation



Ice area from last 4 years of 40-year integration

First CESM simulation with 10km resolution in ocean and 25km resolution atmosphere

Regional detail for better impacts, extremes



Sea surface height variability from (a) altimetry, (b) coupled simulation, (c) standalone ocean

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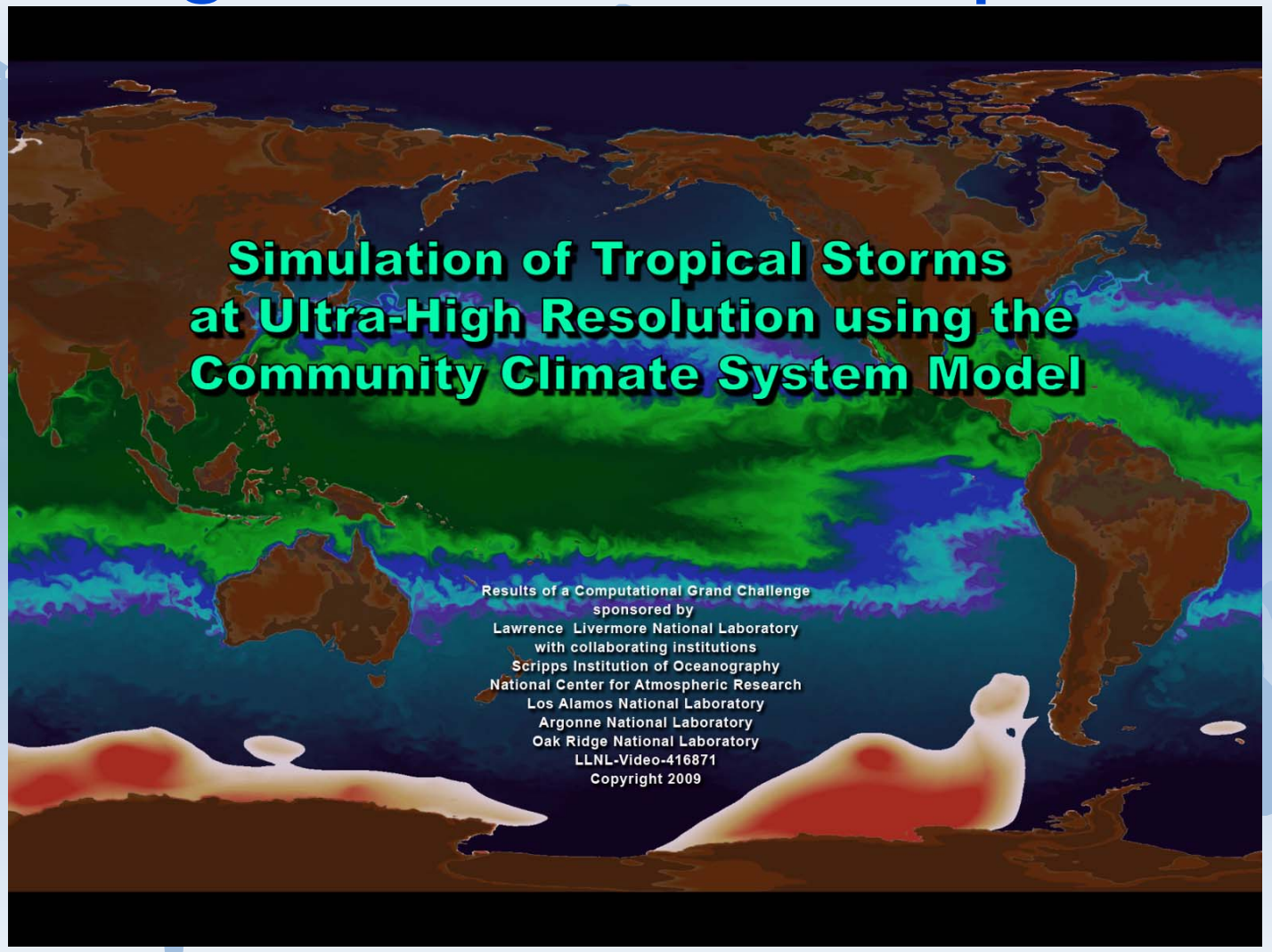
High resolution coupled



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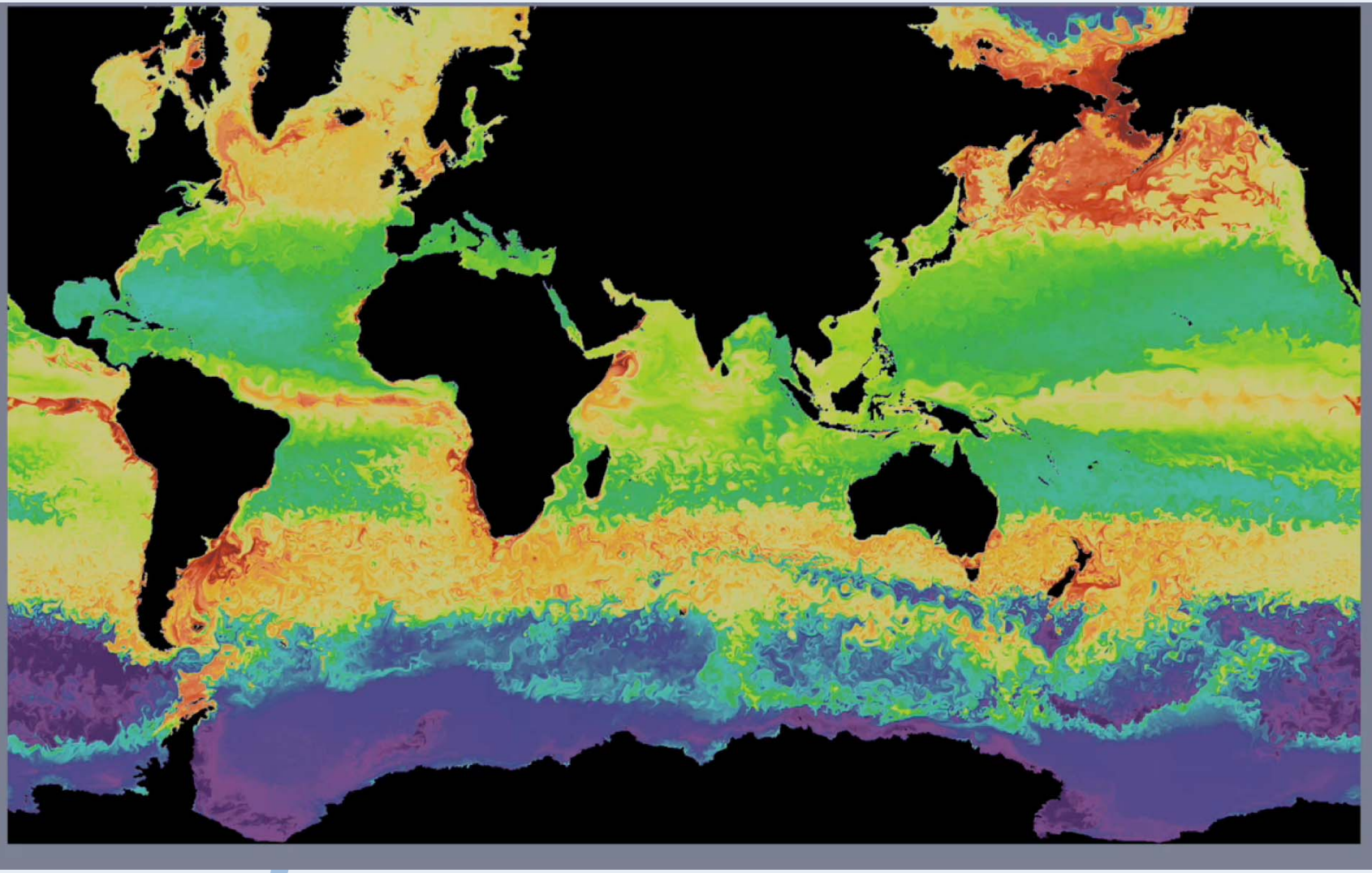
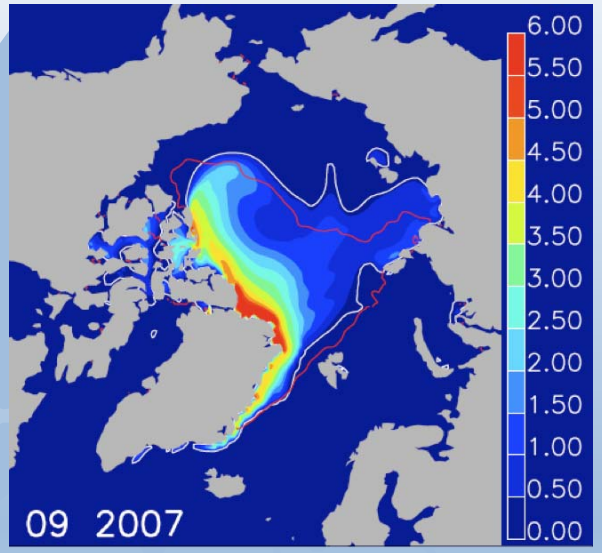
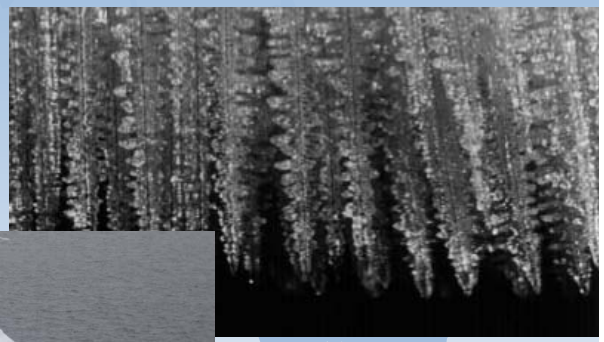
Now…with biology



Los Alamos Sea Ice Model (CICE)

- Reproduces ice conditions very well
  - Reproduces past climate
  - Used in both climate, forecast models
- Improvements ongoing
  - New dynamics for cracks, fine scale features
  - Ice hydrology for better melt ponds, physical ice structure (eg mushy layers), transport in brine channels
  - Ice algae and other biogeochemical tracers and reactions
  - Ice bergs
  - Merge for release
- New release this summer





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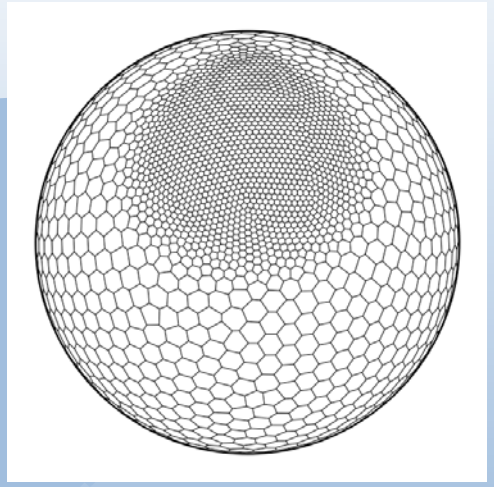
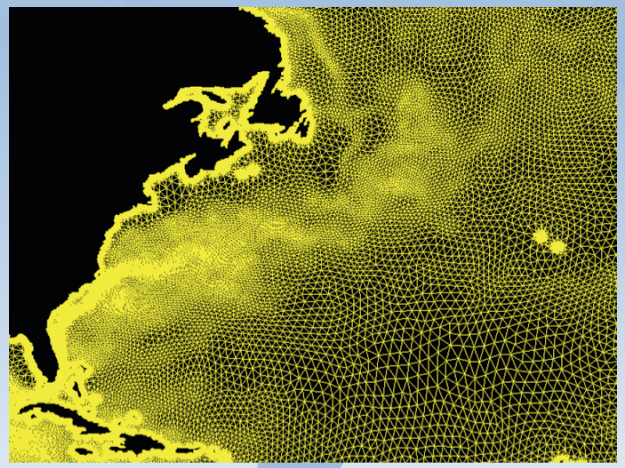
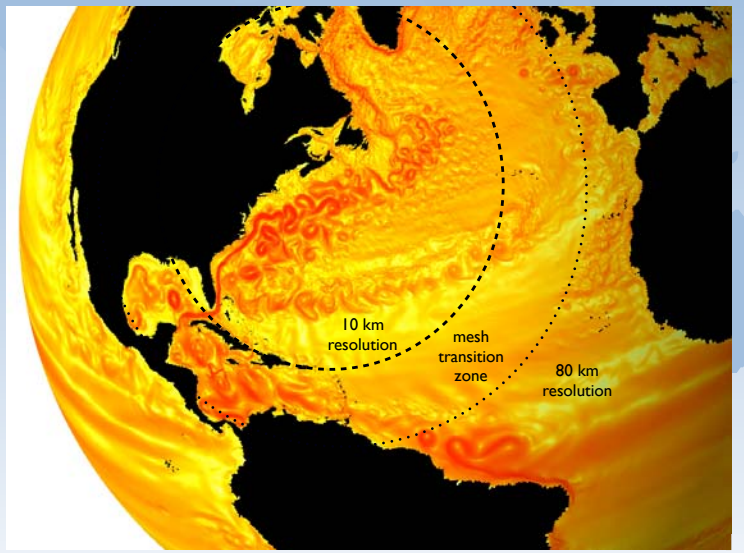
Model Development - Ocean

- New variable resolution ocean
  - Allows resolution where important
  - Cost-effective for eddying simulations
  - Regional models, polar focused







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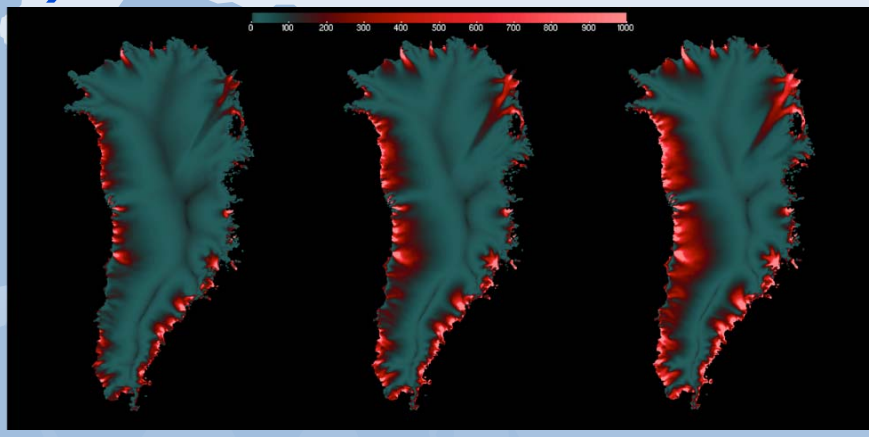
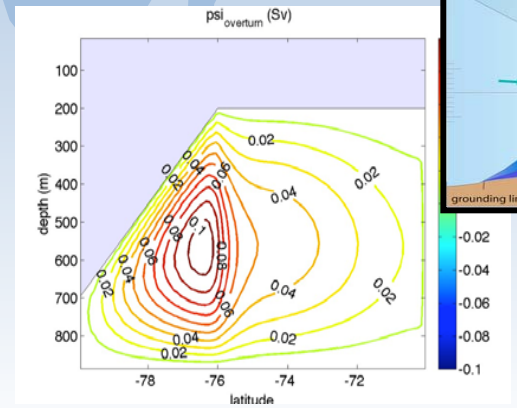
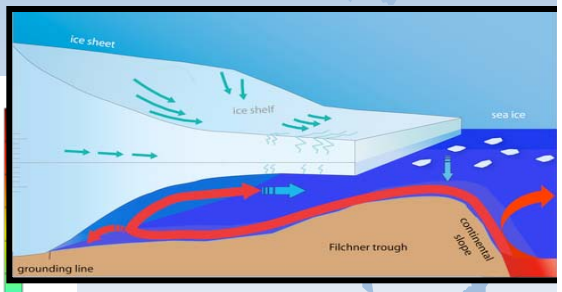
New Community Ice Sheet Model (CISM)

- Ice sheet component of CESM
  - Full coupling with other components
- New dynamics
  - Most mass loss from ice streams, outlet glaciers
- Physical processes
  - Basal lubrication
- Ocean-ice shelf interactions
  - Likely dominant mechanism for melt
  - Requires interaction between ocean model and ice model



CISM simulations of Greenland exploring different rates of basal lubrication (SEARISE)





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Exascale Challenges

- Exposing more parallelism
  - May not be enough in domain decomp
  - Tasks?, stochastic parameterizations, ensembles
- Acceleration
  - Enough work to amortize data motion, esp. quasi-2d models, submodels
  - Algorithm diversity, no kernels
  - Unstructured grids, irregular access
- Optimize Data motion
  - Low flop/memory ratio, though vectorizable
  - Transfer to accelerators
  - Solvers
- I/O
  - In-situ can't be only solution
  - Diverse stakeholders require lots of output

Community Model

- Large number of users/developers (100s), million LOC
- Large inertia
- Project management, change management
- Configuration management
  - Common and/or distributed repositories
  - Different build, config, language approaches: dev friendly vs user
  - Input datasets, config files, support infrastructure for creating
- Coding, data standards
  - Clean interfaces, encapsulation, naming/namespace conflicts
  - Can degrade over time, educate new developers
- Performance portability
  - Support high-end and desktop/departmental
- Need broad buy-in, training, clear programming models or abstractions

POP for GPUs/Titan, Moonlight

- GPU needs
  - Expose parallelism at lower levels
  - Provide enough work for vectors
  - Data transfer expensive
- Refactoring
  - Focus on momentum
  - Push k-loops down
  - OpenACC not up to task
  - CUDA Fortran (esp. data txfr)
- Results
- Next up (before INCITE)
  - Tracers
  - Index/loop reordering
  - Tavg
  - abstractions
  - Titan

Routine	2 cores, no GPU	2 cores, GPU	16 cores, no GPU
vmix_exp_mom	1.99	0.00	0.32
hmix_mom_del2	2.73	0.01	0.44
advect_momentum	4.73	0.02	0.70
device_copy	0.00	4.68	0.00

Path Forward

- Quick porting
  - Already: Performance evaluation
  - Create compact apps for rapid prototyping of ideas
- Identify bottlenecks, needed development
- Develop programming models, abstractions
- New algorithms
  - Like 90s transition
- Other issues
  - resilience