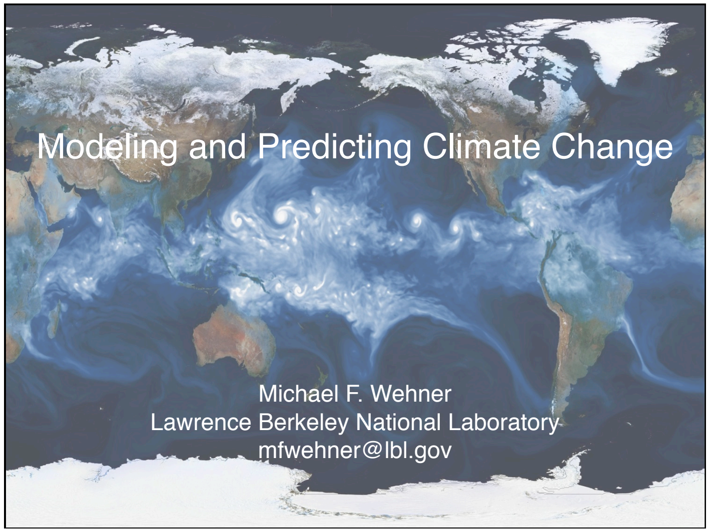


❖ "Climate is what you expect…

❖ …weather is what you get!"

Ed Lorenz

Global Warming: Do you believe?

❖ Intergovernmental Panel on Climate Change 2001

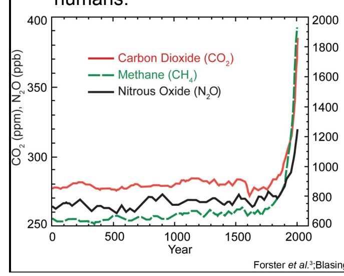
- *"An increasing body of observations gives a collective picture of a warming world and other changes in the climate system"*
- *"There is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities"*

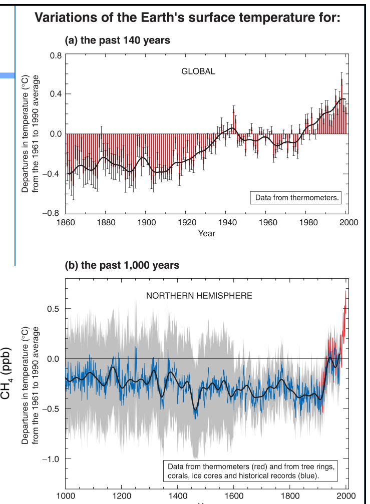
Warming is "unequivocal"

❖ IPCC AR4 2007

❖ Global mean surface air temperature is rapidly increasing.

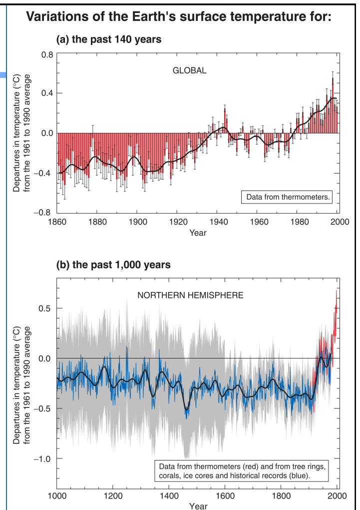
❖ CO_2 is increasing due to humans.





The data

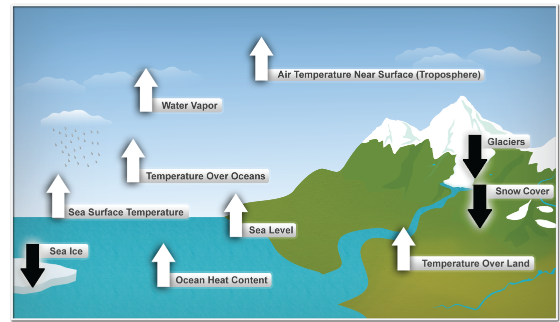
- **Fact**: Global mean surface air temperature is increasing.
- Is this warming due to human factors?
  - Can we quantify natural variability? Signal to noise.
  - Do we understand the causes of this warming?
- What does the future portend?
  - What will happen where I live?
- Modeling helps us address these questions.



The evidence for recent climate change is multivariate.

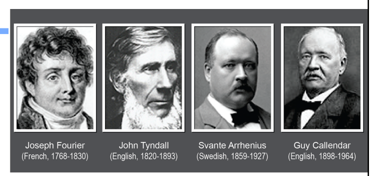
- Consistency across multiple aspects of the climate system.

Ten Indicators of a Warming World



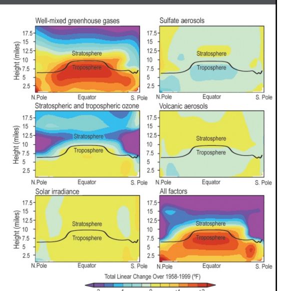
How do we know that recent climate change is due to humans?

- The theoretical basis is solid
  - Not rocket science
  - Steam engine science



Dipolar molecules like CO_2 and H_2O are very effective at trapping heat

- Attribution of climate change to humans relies on climate models.
  - Fingerprinting: Identify the patterns of change due to different "forcing" agents.
  - Greenhouse gases or other human changes to the atmosphere consistently are identified as the largest factor.



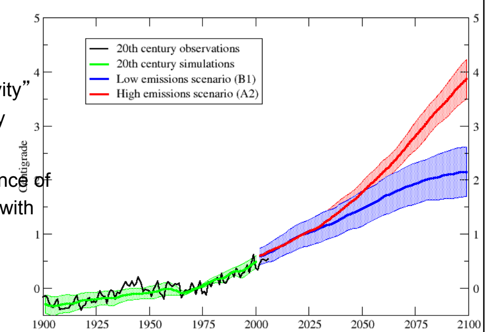
Modified from CCSP SAP 1.1

Projections indicate it will get a lot warmer.

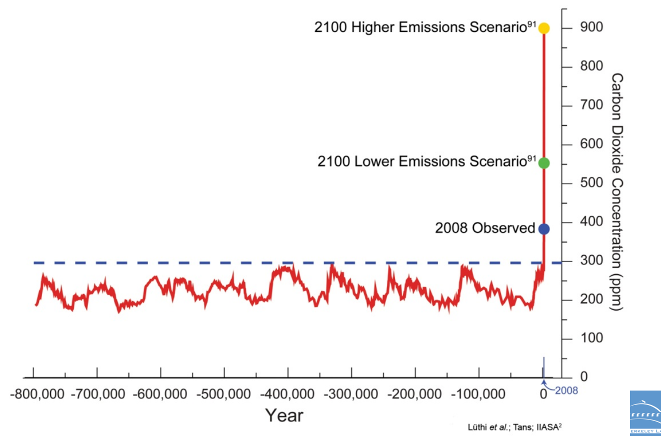
- How much depends on how much greenhouse gas we put in the atmosphere
- Key uncertainties
  - Human activities
  - "Climate sensitivity"
  - Natural variability

The relative importance of these factors varies with projection lead time

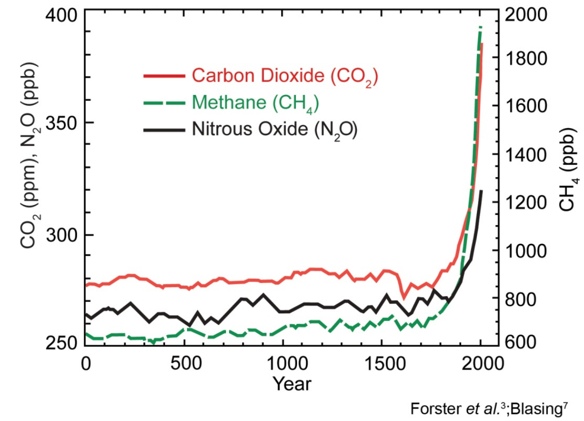
Global mean surface air temperature



Paleo temperature

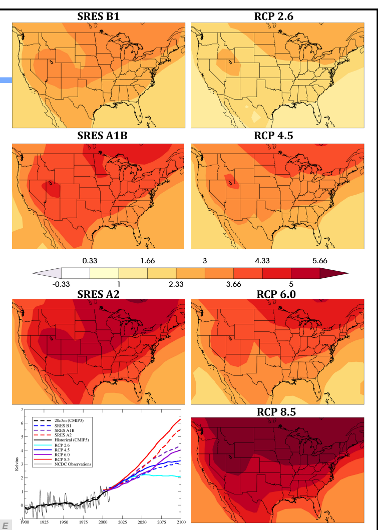


Greenhouse gases



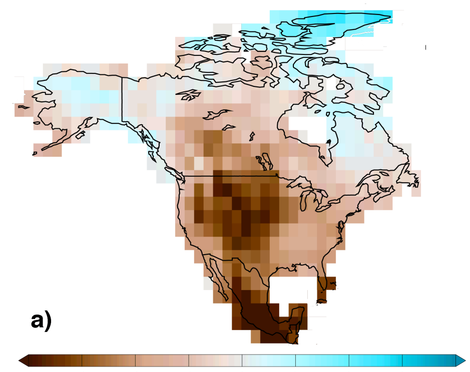
US temperature change

- Projected annual mean change from the end of 21st century relative to now
- Scenarios range from aggressive mitigation to "no policy"
  - 2 to 6+ °C
- Varies by season
  - Winter > summer
  - Any of these futures will come with significant impacts



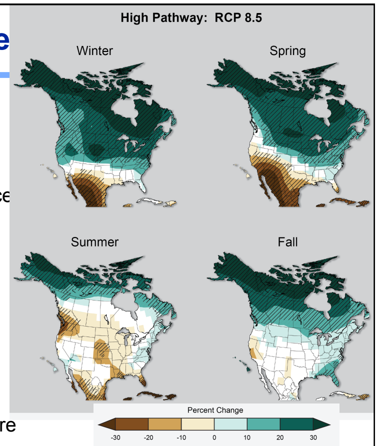
Palmer Drought Severity Index

- End of 21st Century (A1B) relative to 1950-1999 average



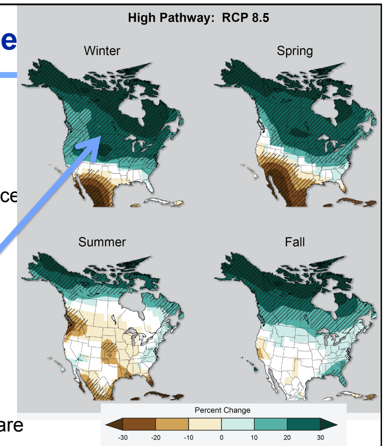
Precipitation change

- Percent change at end of this century relative to now
- Warmest scenario "No policy"
- Green = wetter; brown = drier
- Hatched regions = high confidence that change will be large
- White regions = high confidence that change will be small
- Strong seasonal dependence
    - Will affect impacts
        - — Agriculture
        - — Flooding
- Confidence is enhanced when physical mechanisms of change are understood.



Precipitation change

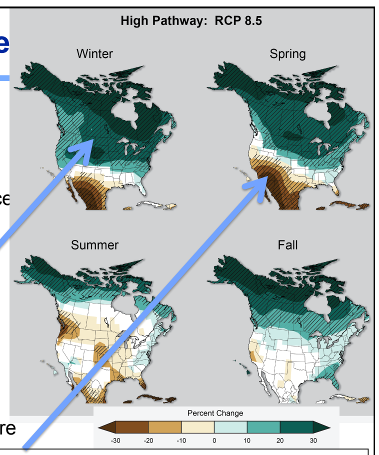
- Percent change at end of this century relative to now
- Warmest scenario "No policy"
- Green = wetter; brown = drier
- Hatched regions = high confidence that change will be large
- White regions = high confidence that change will be small
- Strong seasonal dependence
    - Will affect impacts
        - — Agriculture
        - — Flooding
- Confidence is enhanced when physical mechanisms of change are understood



Warmer air holds more water

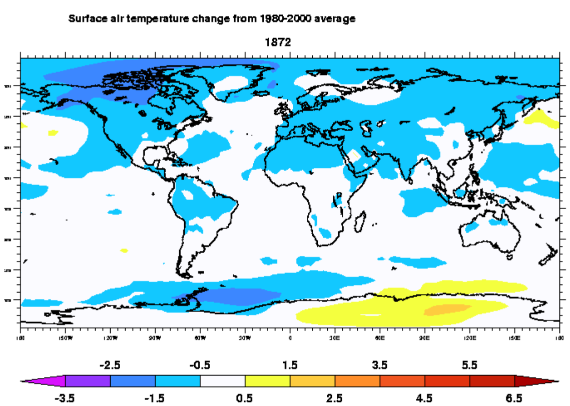
Precipitation change

- Percent change at end of this century relative to now
- Warmest scenario "No policy"
- Green = wetter; brown = drier
- Hatched regions = high confidence that change will be large
- White regions = high confidence that change will be small
- Strong seasonal dependence
    - Will affect impacts
        - — Agriculture
        - — Flooding
- Confidence is enhanced when physical mechanisms of change are understood

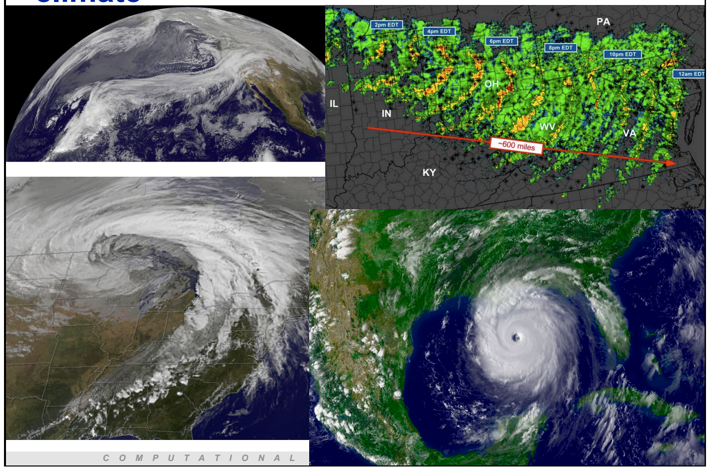


Warmer air holds more water

Expansion of the tropics induces a circulation change



Extreme Weather in a changing climate



What does the IPCC have to say about temperature extremes?

- AR5 ES:
  - It is *virtually certain* that, in most places, there will be more hot and fewer cold temperature extremes as global mean temperatures increase
  - Under RCP8.5 it is *likely* that, in most land regions, a current 20-year high temperature event will occur more frequently by the end of the 21st century (at least doubling its frequency, but in many regions becoming an annual or two-year event) and a current 20-year low temperature event will become exceedingly rare.

What does the IPCC have to say about precipitation extremes?

- AR5 ES:
  - Globally, for short-duration precipitation events, a shift to more intense individual storms and fewer weak storms is *likely* as temperatures increase.
  - Regional to global-scale projected decreases in soil moisture and increased risk of agricultural drought are *likely* in presently dry regions and are projected with *medium confidence* by the end of this century under the RCP8.5 scenario.

Computational demands

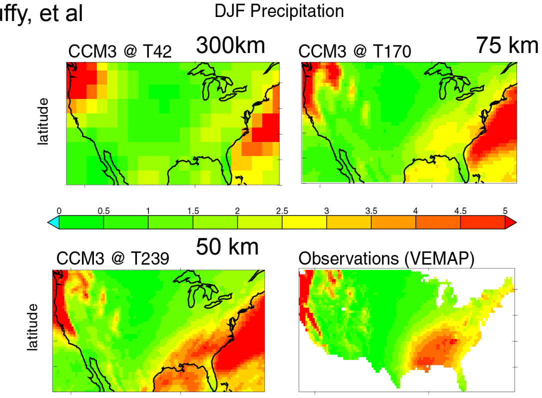
- Historically, climate models have been limited by computer speed.
  - 1990 AMIP1: Many modeling groups required a calendar year to complete a 10 year integration of a stand alone atmospheric general circulation model. Typical grid resolution was T21 (64X32x10)
  - 2011 CCSM5: A fully coupled atmosphere-ocean-sea ice model achieves ~15 simulated years per actual day.
    - Typical global change simulation is 1 or 2 centuries.
    - Control simulations are 10 centuries.
    - Atmosphere is 1^{o} (365x180x26)
    - Ocean is ~1^{o} (384X320x40)

Current resolution is not enough

- Atmosphere
  - Regional climate change prediction will require horizontal grid resolution of 10km (3600X1800) or finer.
  - Cloud physics parameterizations could exploit 100 vertical layers
  - Explicitly resolving cloud systems requires 1km. Estimated 28Pflops sustained.
- Ocean
  - Mesoscale (~50km) eddies are thought to be crucial to ocean heat transport
  - 0.1° grid will resolve these eddies (3600X1800)
  - Short stand-alone integrations are underway now.
- Ensembles of integrations are required to address issues of internal (chaotic) variability.
  - Current practice is to make 4 realizations. 10 is better. 100 is necessary for my work.

Simulated precipitation as a function of resolution

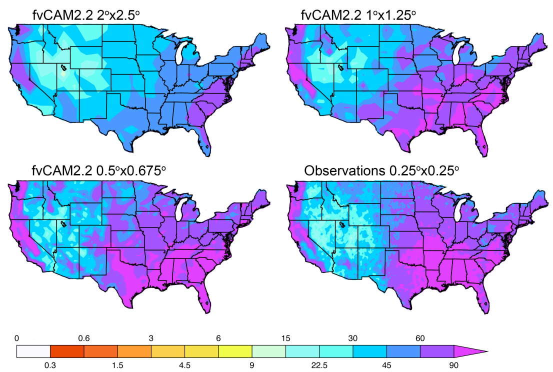
Duffy, et al



COMPUTATIONAL RESEARCH DIVISION

Model resolution and extreme precipitation

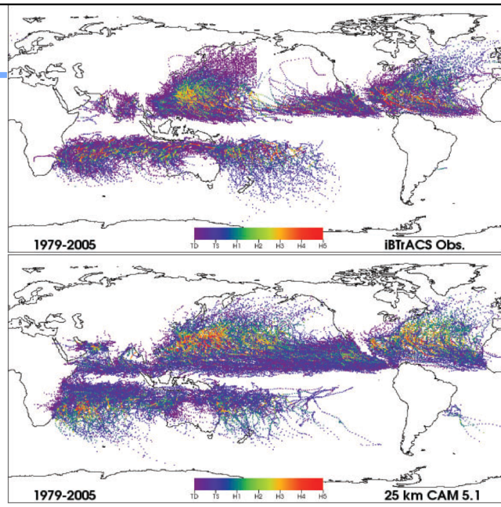
- 20 year return value of annual maximum daily total precipitation (mm/day)



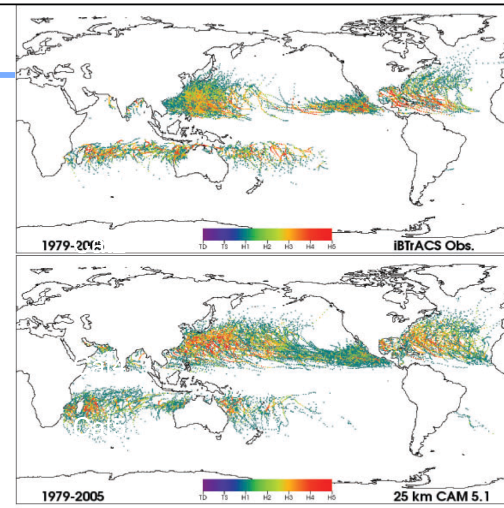
Movie

- Go to CAM5 simulation
- Search fvCAM5 on youtube.

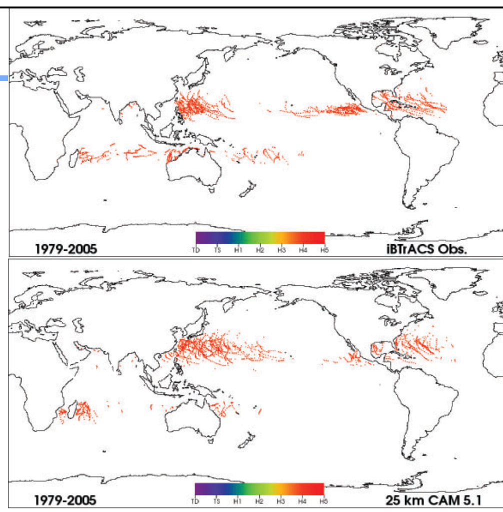
COMPUTATIONAL RESEARCH DIVISION



Figures by Prabhat



Figures by Prabhat



Figures by Prabhat

Global average / year

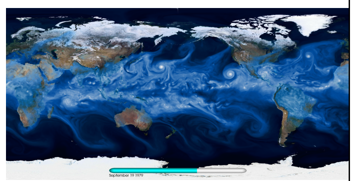
- total TC
  - observations 87±8
  - cam5.1 84±9
- total hurricanes
  - Observations 49±7
  - cam5.1 52
    - cat1 21
    - cat2 5
    - cat3 12
    - cat4 7
    - cat5 1.5

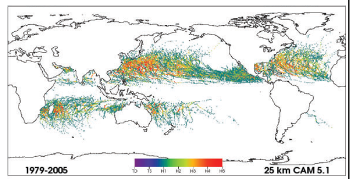
Big Data Analysis at Scale

• Goal: Pattern Detection on modern multi-TB sized climate simulation output

• Accomplishment:
- Developed TECA framework for detecting extreme events in climate output
- Ran TECA tool on 80K-150K cores on NERSC hopper system
- Processed 0.5TB-13TB of state-of-the-art CAM5 model output
- Reduced analysis runtime from several years to 10s of minutes.

• Science Impact:
- Characterization of hurricane formation and evolution
- Verified that higher model resolution results in more accurate storm statistics and is required for confident projection of future changes
- Framework facilitates multi-model comparison and diagnostics for CMIP-5 archive.

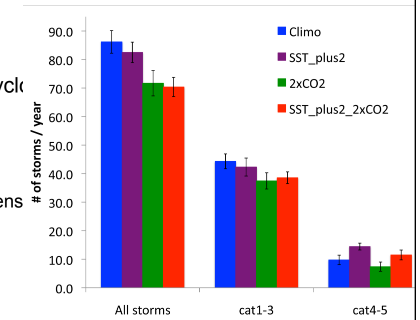




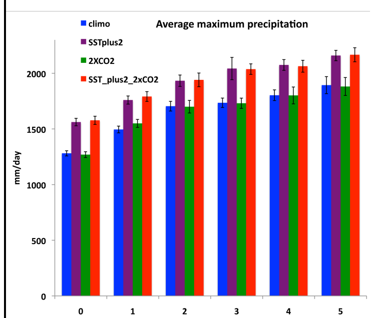
Future global tropical cyclone activity

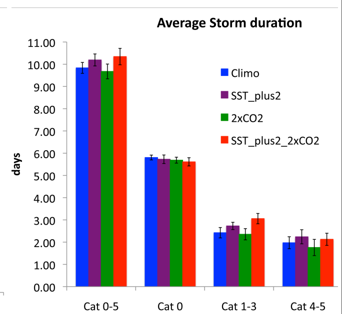
- Blue = idealized now
- Red = idealized 2° warmer future (aggressive mitigation)

- Fewer total # of tropical cycl
  - Fewer weak storms
  - More intense storms
- Impacts
  - More damage from intens
  - Less drought relief
    - — Southeast US
    - — Taiwan
    - — Elsewhere?



Hurricanes will last longer and rain harder in a warmer world





High resolution is expensive

- This calculation used only 7680 processors on a 120,000 processor machine
  - 5.5 million processor hours.
  - 25 km grid cell
- The coming models will be able to use ~100K processors
- US DOE has several large Intel machines on order.
  - Processor count TBD. In excess of 200K
- Machines in excess of 10M processors are 5-10 years out
  - Co-design of hardware & software
    - Search "green flash berkeley" or
    - Wehner et al (2011) Hardware/Software Co-design of Global Cloud System Resolving Models. *Journal of Advances in Modeling Earth Systems* 3, M10003, DOI:10.1029/2011MS000073.

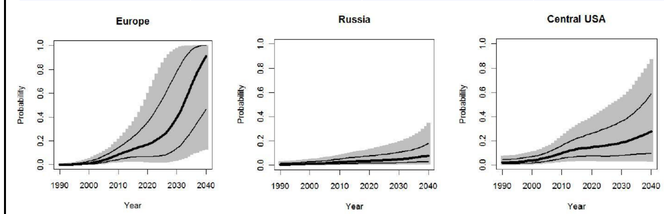
Extreme event attribution: CMIP statistical analysis

- CMIP (Coupled Model Intercomparison Project) is a public database of output from the worlds' leading climate model.
  - Common numerical experiment and data formats, etc.
- Consider three different summer heat wave events
  - Europe 2003 (~70,000 excess deaths)
  - Russia 2010 (~50,000 excess deaths, massive fires)
  - Texas 2011 (lots of dead cows, massive drought)
- These are very rare events. We are interested in how the rarity of these events has changed.
- We calculated the change in risk by comparing the extreme value statistics in these regions from realistic historical simulations to those in the pre-industrial simulations and the observations.
  - (Skipping the statistical mumbo jumbo, including normalization)

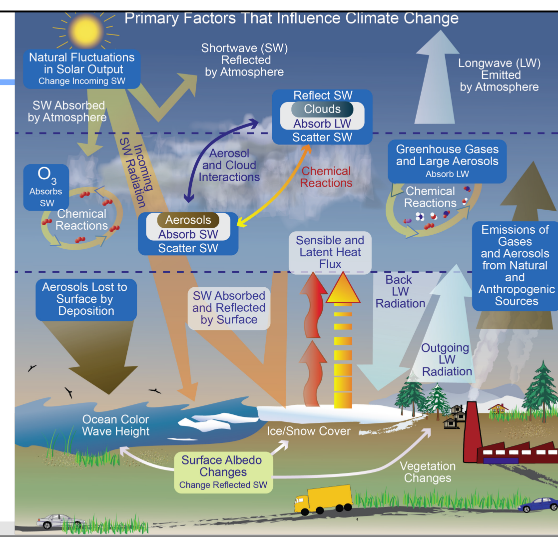
Extreme event attribution: CMIP statistical analysis

The risk of each of these events has least doubled since the preindustrial era

Event	Risk Change at time of event	Change in risk 2023	Change in risk 2040
Europe 2003	~2X	35X	154X
Russia 2010	2-3 X	2.5-4 X	5-8 X
Texas 2011	1.5-4 X	2-5 X	4-10 X
Midwest US 2012	?	?	



Let's talk about how climate change is modeled.



What is in a climate model?

- Atmospheric general circulation model
  - Dynamics
  - Sub-grid scale parameterized physics processes
    - Turbulence, solar/infrared radiation transport, clouds.
- Oceanic general circulation model
  - Dynamics (mostly)
- Sea ice model
  - Viscous elastic plastic dynamics
  - Thermodynamics
- Glaciers
  - Adaptive mesh
- Land Model
  - Energy and moisture budgets
  - Biology
- Chemistry
  - Tracer advection, possibly stiff rate equations.

Technology limits us.

- Models of atmospheric and ocean dynamics are subject to time step stability restrictions determined by the horizontal grid resolution.
  - Adds further computational demands as resolution increases
- Century scale integrations at 1km will require of order 28Pflops (sustained).
  - Current production speed is of order tens to hundreds of Gflops in the US.

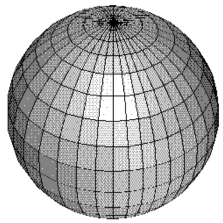
Q.Why are climate models so computationally intensive?

- A. Lots of stuff to calculate!
  - This is why successful climate modeling efforts are collaborations among a diverse set of scientists.
    - — Big science.
- But this computational burden has other causes.
  - Fundamental cause is that interesting climate change simulations are century scale. Time steps are limited by stability criterion to minute scale.
    - A lot of minutes in a century.

An example of a source of computational burden

- Task: Simulate the dynamics of the atmosphere
- The earth is a sphere (well, almost).
- Discretize the planet.
- Apply the equations of motion
  - Two dimensional Navier-Stokes equations + parameterization to represent subgrid scale phenomena

Spherical Coordinates (θ,φ)



- Latitude-Longitude grid.
- Uniform in θ,φ
- Non-uniform cell size.
- Convergent near the poles
  - Singular
- Simple discretization of the equations of motion.
  - Finite difference.
  - Finite volume.

Spherical Coordinates (θ,φ)

- Two issues.
- Courant stability criterion on time step
  - $\Delta t < \Delta x / v$
  - Δx = grid spacing, v = maximum wind speed
  - Convergence of meridians causes the time step to be overly restrictive.
- Accurate simulation of fluids through a singular point is difficult.
  - Cross-polar flows will have an imprint of the mesh.

Spherical Coordinates (θ,φ)

- Solutions to time step restrictions.
  - Recognize that the high resolution in the polar regions is false.
  - Violate the polar Courant condition and damp out computational instabilities by filters.
    - Works great, but…
    - Maps poorly onto distributed memory parallel computers due to non-local communication.

$$F` = \Sigma a_{ij} F_i$$

- Commonly used, most notably by the Community Atmospheric Model (CAM4,CAM5)

Spectral Transform Method

- Previously, the most common solution to the “polar problem”
- Map the equations of motions onto spherical harmonics.

$$\psi(\lambda,\mu) = \sum_{m=-M}^{M} \sum_{n=|m|}^{\mathcal{N}(m)} \psi_n^m P_n^m(\mu) e^{im\lambda},$$

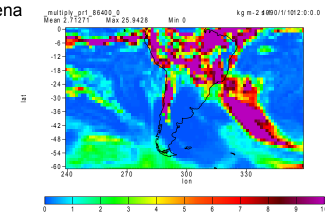
- *M* = highest Fourier wavenumber
- *N(m)* = highest associated Legendre polynomial, *P*
- Resolution is expressed by the truncation of the two series. I.e.
  - T42 means triangular truncation with 42 wavenumbers
  - R15 means rhomboidal truncation with 15 wavenumbers.

Spectral Transform Method

- Replace difference equations with Fourier and Legendre transforms.
- Advantages
  - No singular points.
  - Uniform time step stability criteria in spectral space.
  - Very accurate for two-dimensional flow
  - Fast Fourier Transforms (FFT)
    - scales as $m\log(m)$ rather than m^2
    - Very fast if m is a power of 2
    - Very fast vector routines supplied by vendors.

Spectral Transform Method

- Disadvantages
  - No parallel FFT algorithms for m in the range of interest.
  - mlog(m) is still superlinear. Scaling with higher resolution is poor.
  - Works poorly near regions of steep topography like the Andes or Greenland.
    - Gibb's phenomena causes 'spectral rain' and other nonphysical phenomena

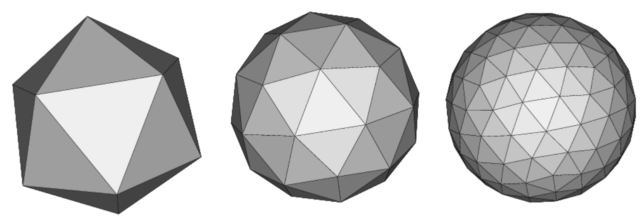


Spectral Transform Method

- Use of FFT limits parallel implementation strategies
  - CCSM3 used a one dimensional domain decomposition.
    - Restricts number of useful processors.
  - ECMWF uses three separate decompositions.
    - One each for Fourier transforms, Legendre transforms and local physics.
    - Requires frequent global redecompositions of every prognostic variable.
    - No further communication required within each step.
    - Hence, code is simpler as communications are isolated.
- ECMWF performs operational weather prediction at T1000+
  - Proved the naysayer wrong!
  - But most codes do not scale well.

Alternative formulations

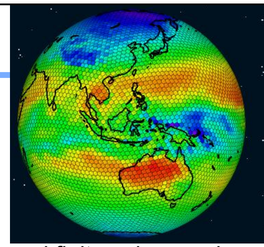
- An icosahedral mesh approximation to a sphere



n=1 n=2 n=4

- No polar singularities
  - But 6 points in each hemisphere have a different connectivity

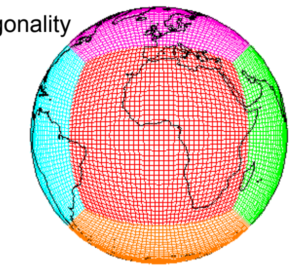
Icosahedral mesh



- Spatially uniform
  - Ideal for finite differences
  - Would also be ideal for advanced finite volume schemes.
- Easily decomposed into two dimensional subdomains for parallel computers.
- Connectivity is complicated. Not logically rectangular.
- Used in the Colorado State University climate model and by Deutsche Wetterdienst, a weather prediction service.
- Japanese group has run at 400mglobally on the K machine!
  - 0.9 Pflops sustained. A world record for an AGCM.
  - But still not faster than real time.

Cubed Sphere

- Similar to the icosahedral grid
- 8 special connectivity points instead of 10
- Grid is logically rectangular
- Not as spatially uniform
  - Unless you relax orthogonality
- Used by
  - Spectral element CAM
  - DOE ACME
  - GFDL



Variable resolution

- Two major DOE efforts
  - MPAS: Based on the Icosohedral mesh
  - ACME: Based on the Cubed Sphere mesh
  - Pros and Cons.

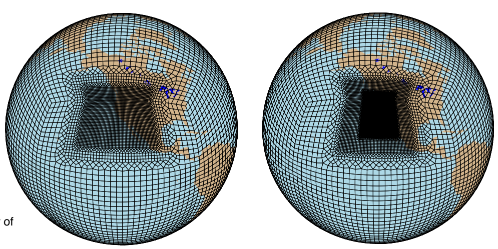
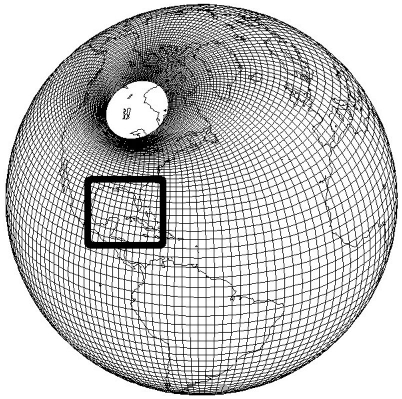


Figure courtesy of Paul Ullrich

A final creative mesh

- In ocean circulation modeling, the continental land masses must be accounted for.
- If the poles were covered by land, no active singular points in a rectangular mesh.
- A clever orthogonal transformation of spherical coordinates can put the North Pole over Canada or Siberia.
- Careful construction of the transformation can result in a remarkably uniform mesh.
- Used today in the Los Alamos ocean model, POP.

POP mesh



POP mesh

A general modeling lesson from this example.

- Modeling is always a set of compromises.
  - It is not exact. Remember this when interpreting results!
- Many different factors must be taken into account in the construction of a model.
  - Fundamental equations are dictated by the physics of the problem.
  - Algorithms should be developed with consideration of several factors.
    - Scale of interest. High resolution, long time scales, etc.
    - Accuracy
    - Available machine cycles.
      - Cache
      - Vectors
      - Communications
      - Processor configuration (# of PEs, # of nodes, etc.)

Computational Science Opportunities

- Petaflop to exaflop computing
  - Millions of processors
    - multi-core chips
  - Higher efficiencies
    - 5% of peak performance is considered good
  - Hardware/software co-design
- Large databases
  - Petabytes to exabytes
  - Database management
    - Efficient distribution to analysts
  - Parallel diagnostic routines

Conclusions

- Climate change prediction is still a "Grand Challenge" modeling problem.
  - Large scale multidisciplinary research requiring a mix of physical and computational scientists.
- The path for the modeling future is relatively clear.
  - Higher resolution → Regional climate change prediction
  - Larger ensembles, longer control runs, more parameter studies → quantify uncertainty in predictions
  - More sophisticated physical parameterizations → better simulation of the real system
- All of this requires substantial increases in US investments in hardware and software.

Editorial comment

- My generation has only identified that there is a problem.
  - The general public seems to finally accept that. (Or at least they did for a while.)
  - The politics of climate change is ugly.
- We leave it to your generation to do something about it.
  - And computer simulation will continue to play a major role!

Additional climate model resources

- Intergovernmental Panel on Climate Change
  - http://www.ipcc.ch/
- Community Climate System Model
  - http://www.cgd.ucar.edu/csm
- IPCC model data distribution
  - http://www-pcmdi.llnl.gov
- Climate data tools (PYTHON)
  - http://esg.llnl.gov/cdat
- SciDAC Earth System Grid project
  - CCSM and PCM data distribution
  - http://www.earthsystemgrid.org

- Michael Wehner, mfwehner@lbl.gov