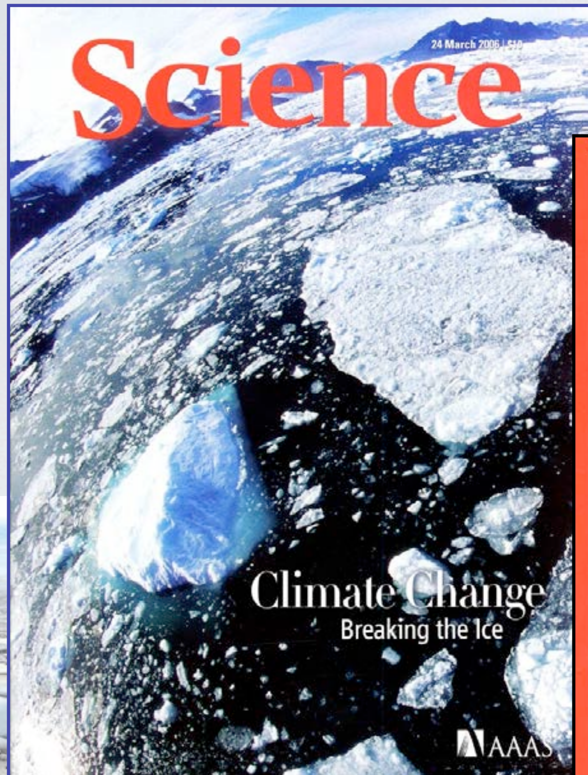
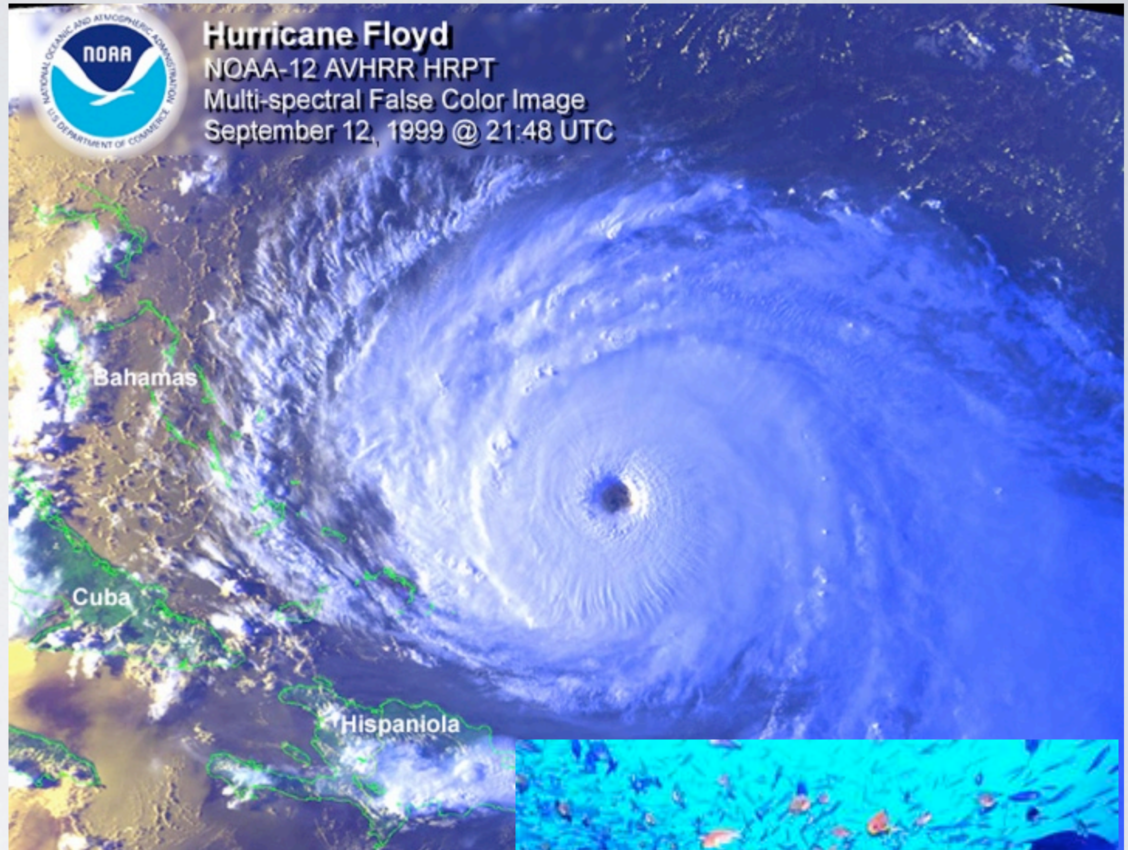
Mathematics, Energy, and Climate Change

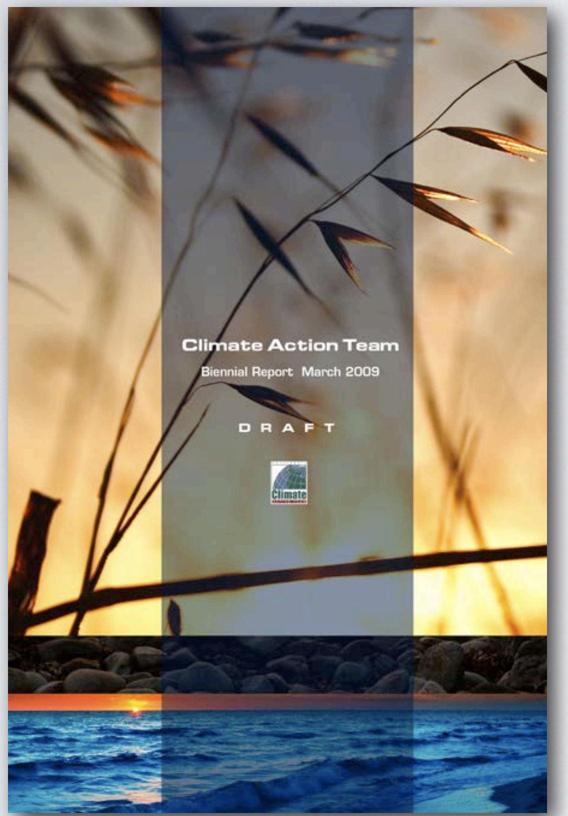
Juan Meza
Department Head, Senior Scientist
Lawrence Berkeley National Laboratory
M*A*T*H Colloquium, Sonoma State University, April 28, 2009

CLIMATE CHANGE IS BIG NEWS

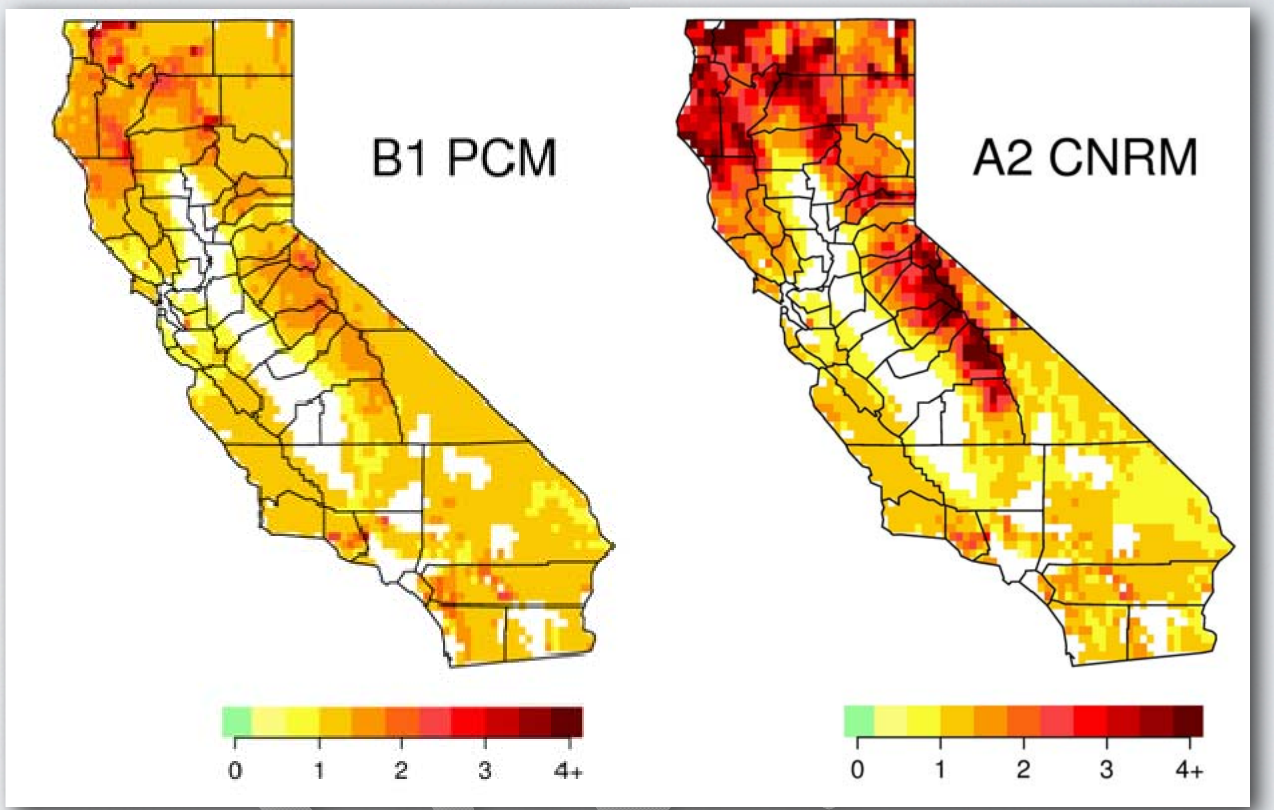



Hurricane Floyd
NOAA-12 AVHRR HRPT
Multi-spectral False Color Image
September 12, 1999 @ 21:48 UTC
Bahamas
Cuba
Hispaniola

CLOSER TO HOME



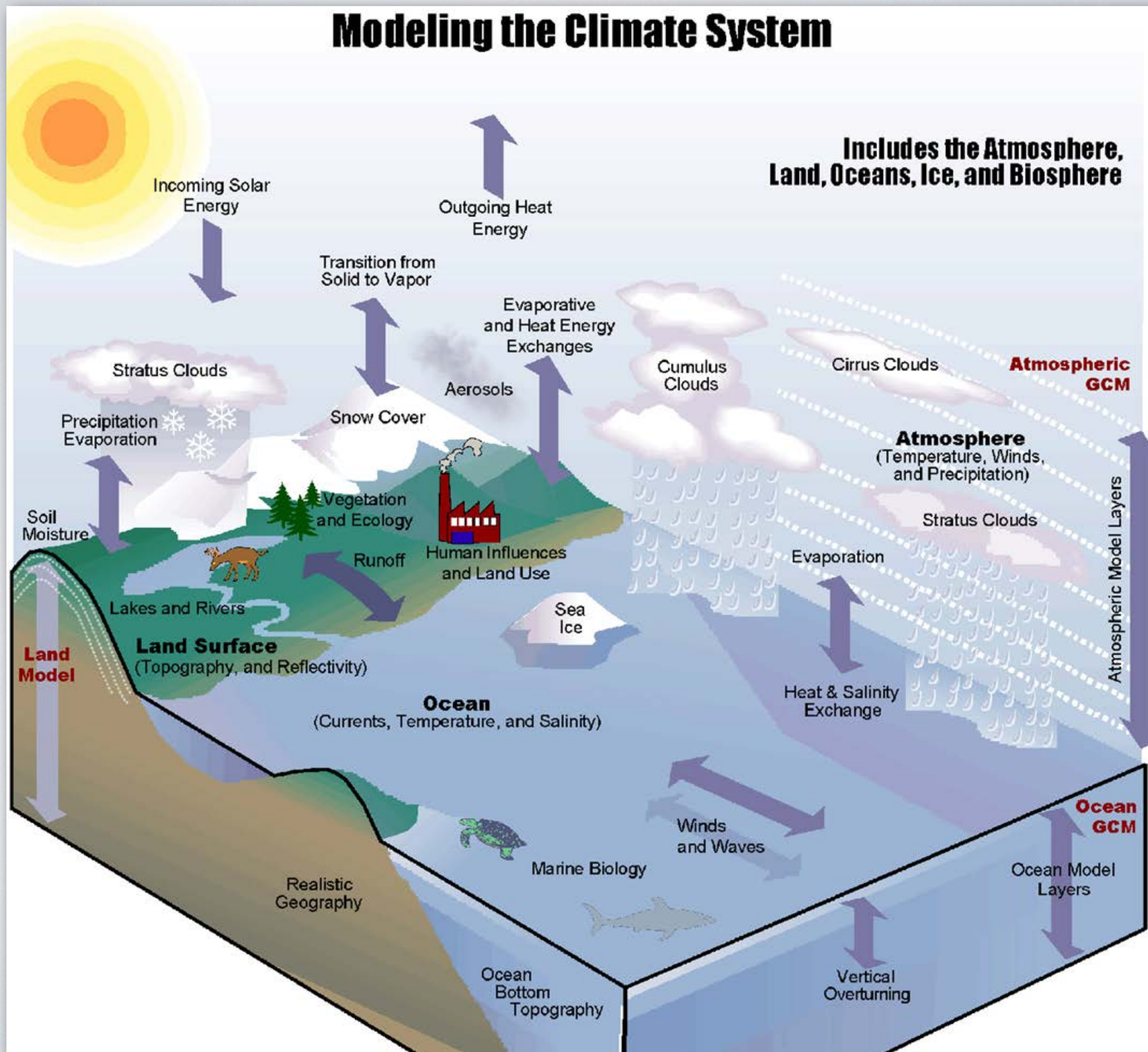
Fire Probabilities in 2085 as a Multiple of the Probability of Fire Occurrence during the Reference Period (1961-1990)



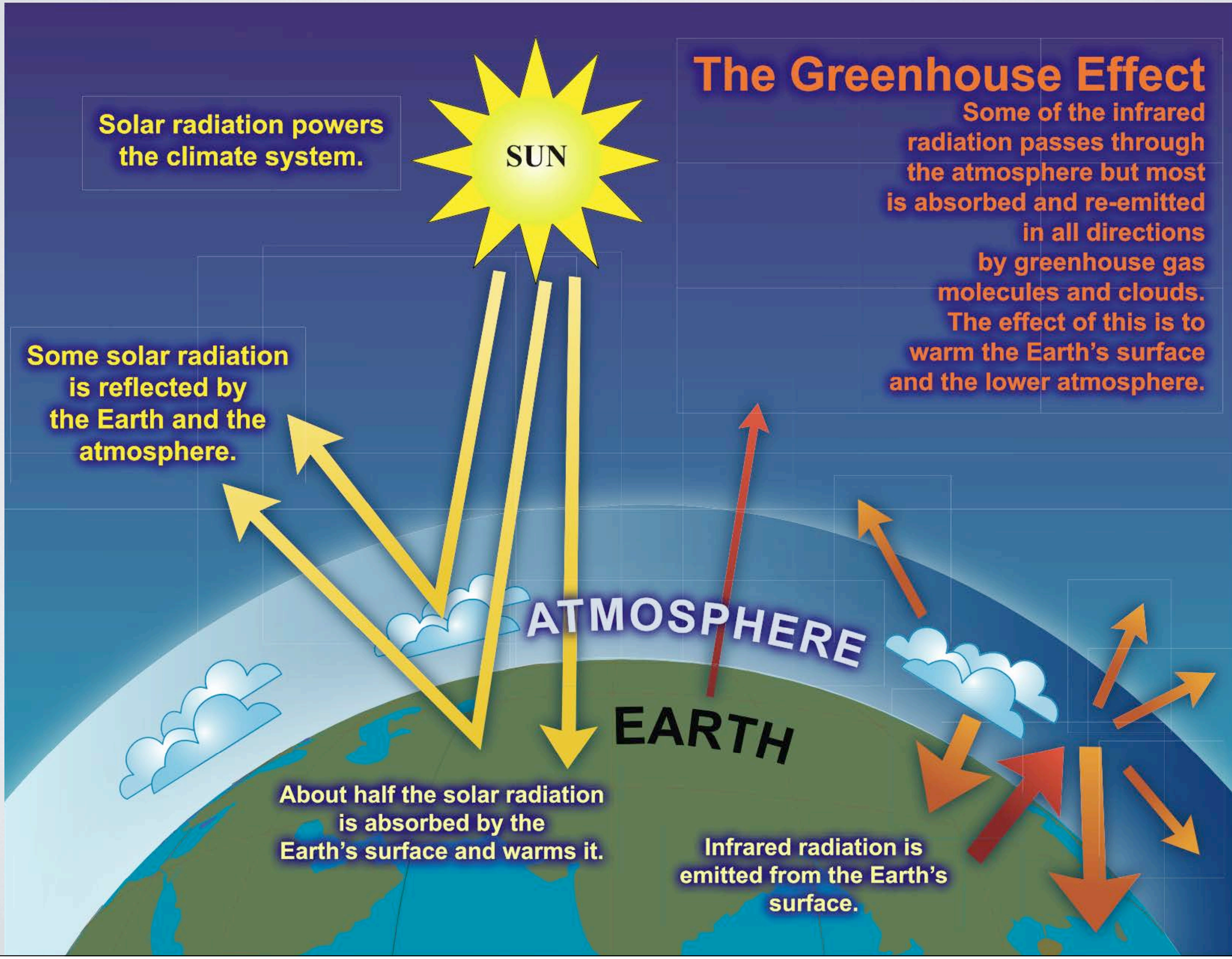
Source: Westerling et al. (2008)

Extreme events from heat waves, floods, droughts, wildfires and bad air quality are likely to become more frequent in the future and pose serious challenges to Californians. *DRAFT 2009 Climate Action Team Biennial Report to the Governor and Legislature*

WHAT IS A CLIMATE MODEL?

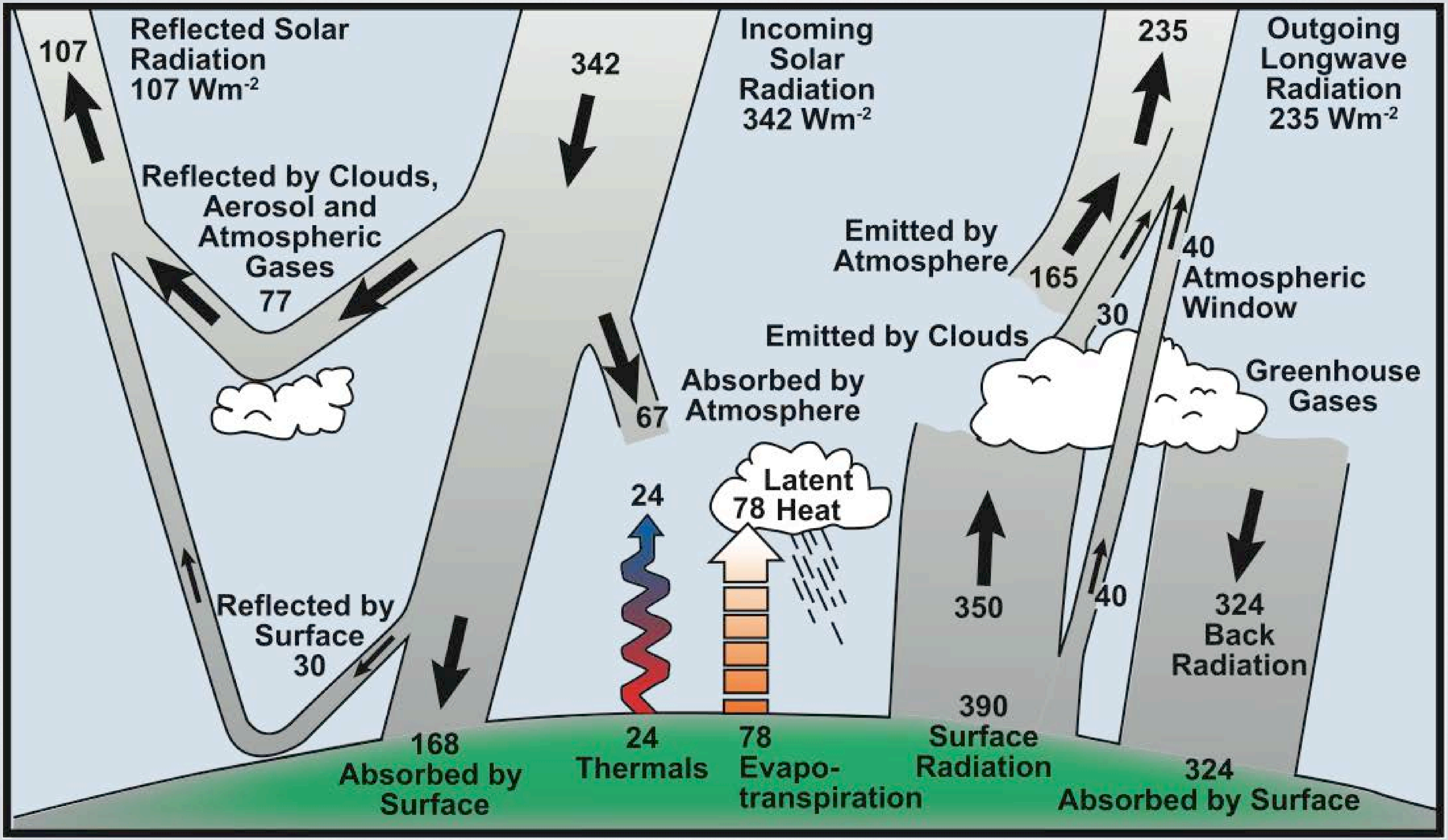

Modeling the Climate System
Includes the Atmosphere, Land, Oceans, Ice, and Biosphere
Incoming Solar Energy
Outgoing Heat Energy
Transition from Solid to Vapor
Evaporative and Heat Energy Exchanges
Stratus Clouds
Aerosols
Cumulus Clouds
Cirrus Clouds
Atmospheric GCM
Snow Cover
Precipitation Evaporation
Atmosphere
(Temperature, Winds, and Precipitation)
Vegetation and Ecology
Soil Moisture
Stratus Clouds
Runoff
Human Influences and Land Use
Evaporation
Atmospheric Model Layers
Lakes and Rivers
Sea Ice
Land Model
Land Surface
(Topography, and Reflectivity)
Ocean
(Currents, Temperature, and Salinity)
Heat & Salinity Exchange
Ocean GCM
Winds and Waves
Marine Biology
Ocean Model Layers
Realistic Geography
Ocean Bottom Topography
Vertical Overturning

GREENHOUSE EFFECT



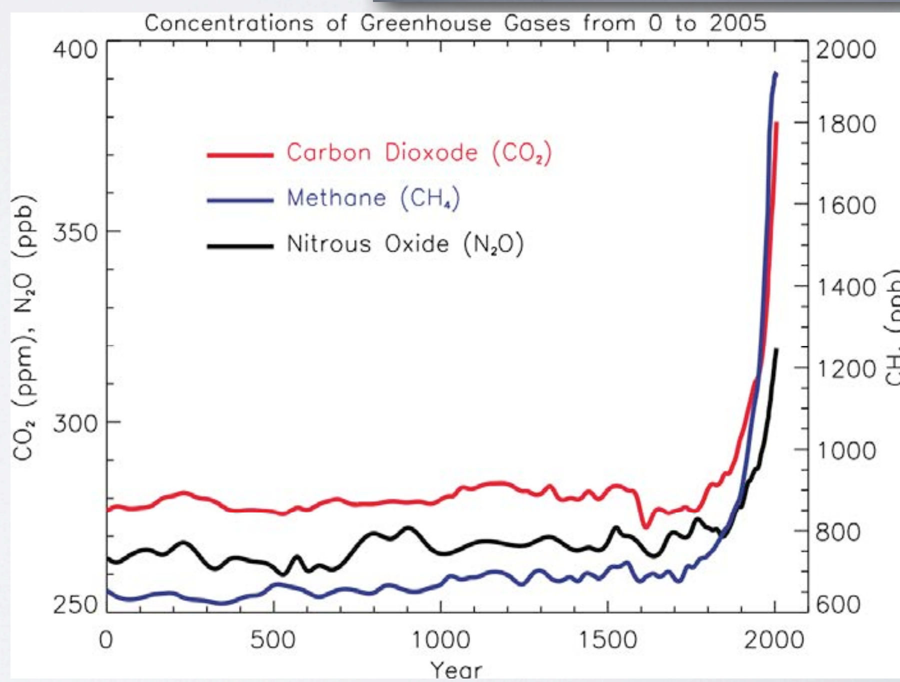
ATMOSPHERE ENERGY BALANCE

$342 = 107 + 235$



ANNUAL GLOBAL RELEASE OF CO_2 IS 27 BILLION TONS

- In US, combustion
  - Transportation
  - Power generation
- 40% coal, 40% oil, 20% natural gas
- US consumes (per day):
  - 20 million barrels of oil
  - 60 billion cubic feet natural gas
  - 3 million tons of coal



Climate Change 2007, The Physical Science Basis, Working Group 1, Solomoon, Qin, Manning ed.

MATHEMATICAL CONTEXT

FIRST MENTION OF GREENHOUSE EFFECT

- Developed mathematical theory for the temperature of the terrestrial globe

- "*The temperature [of the Earth] can be augmented by the interposition of the atmosphere, because heat in the state of light finds less resistance in penetrating the air, than in repassing into the air when converted into non-luminous heat*" (1824)

JEAN BAPTISTE JOSEPH FOURIER

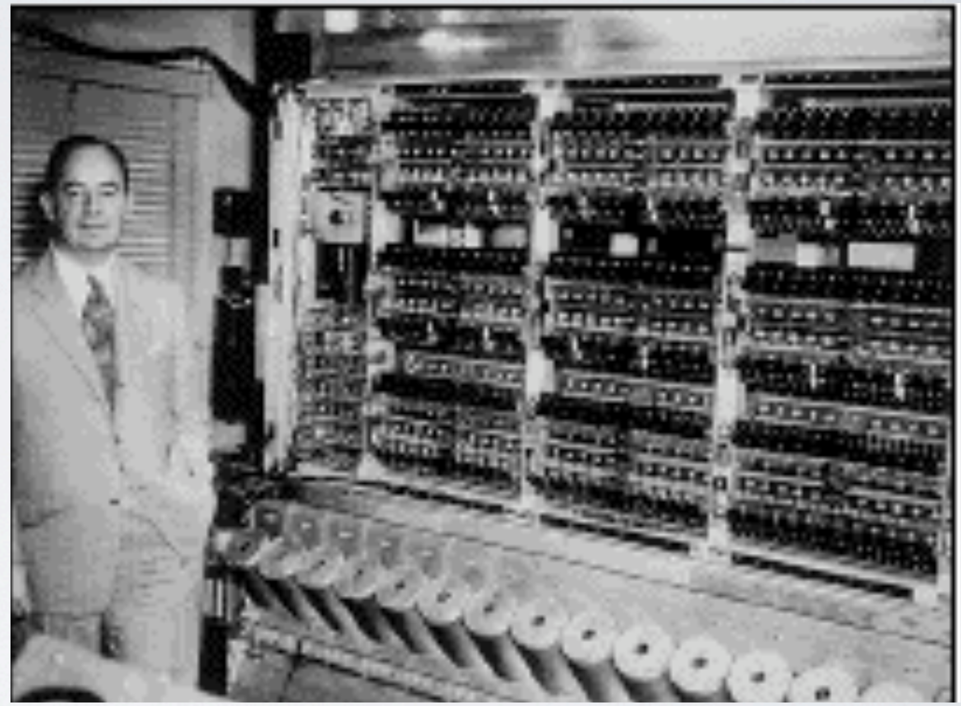
LEWIS FRY RICHARDSON

- British mathematician Lewis Fry Richardson proposed numerical weather forecasting using partial differential equations in 1922
- Computed 1 day weather forecast over a period of 6 weeks, while working as the driver of a Quaker ambulance unit in northern France.
- Sadly, first calculations were unsuccessful, due to numerical problems and time steps that were too large.

Fascinating talk by Peter Lynch (University College Dublin) can be found at:
http://www.ncep.noaa.gov/nwp50/Presentations/Tue_06_15_04/Session_1/Lynch_NWP50.pdf

JOHN VON NEUMANN'S METEOROLOGY PROJECT

- Recognized numerical weather forecasting as a problem of great importance
- In collaboration with Charney and Fjortoft, they completed the first numerical computer forecast in 1950
- Used ENIAC, first multipurpose electronic digital computer
- Each 24 hour forecast took 24 hours to compute

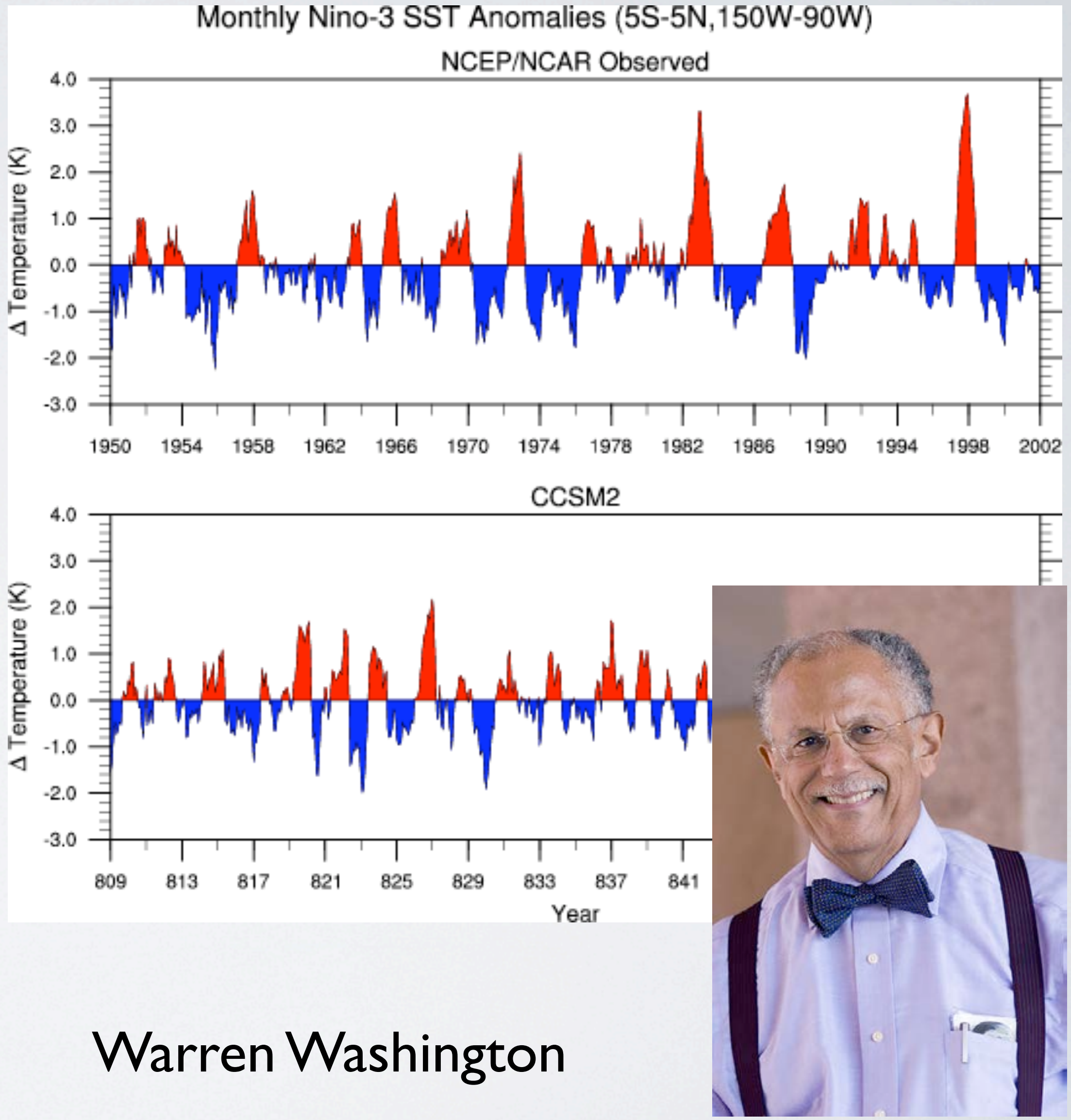


"If people do not believe that mathematics is simple, it is only because they do not realize how complicated life is."

1000 YEAR CLIMATE SIMULATION

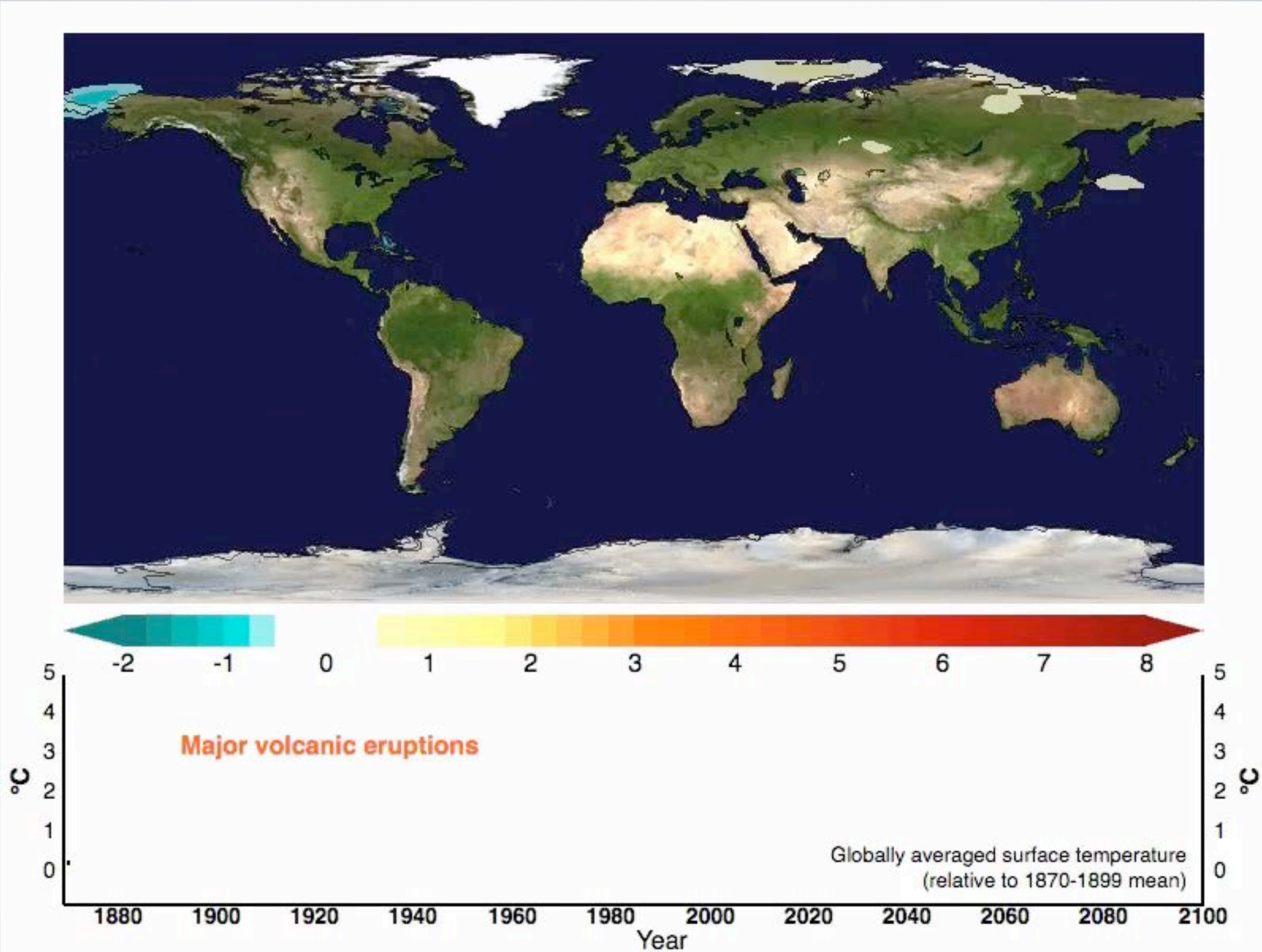
- A 1000-year simulation demonstrates the ability of models to produce a long-term, stable representation of the earth's climate

- Used more than 1 million processor hours over several months



Warren Washington

Warren Washington and Jerry Meehl, National Center for Atmospheric Research; Bert Semtner, Naval Postgraduate School; John Weatherly, U.S. Army Cold Regions Research and Engineering Lab Laboratory.


-2
-1
0
1
2
3
4
5
6
7
8
Major volcanic eruptions
°C
Globally averaged surface temperature
(relative to 1870-1899 mean)
1880
1900
1920
1940
1960
1980
2000
2020
2040
2060
2080
2100
Year

MATH BEHIND THE MODELS

PRIMITIVE EQUATIONS FOR ATMOSPHERE

$$\frac{du}{dt} - \left(f + u\frac{\tan\phi}{a}\right)v = -\frac{1}{a\cos\phi}\frac{1}{\rho}\frac{\partial p}{\partial \lambda} + F_\lambda$$

$$\frac{dv}{dt} + \left(f + u\frac{\tan\phi}{a}\right)u = -\frac{1}{\rho a}\frac{\partial p}{\partial \phi} + F_\phi$$

$$g = -\frac{1}{\rho}\frac{\partial p}{\partial z}$$

momentum

$$\frac{\partial \rho}{\partial t} = -\frac{1}{a\cos\phi}\left[\frac{\partial}{\partial \lambda}(\rho u) + \frac{\partial}{\partial \phi}(\rho v \cos\phi)\right] - \frac{\partial}{\partial z}(\rho w)$$

mass

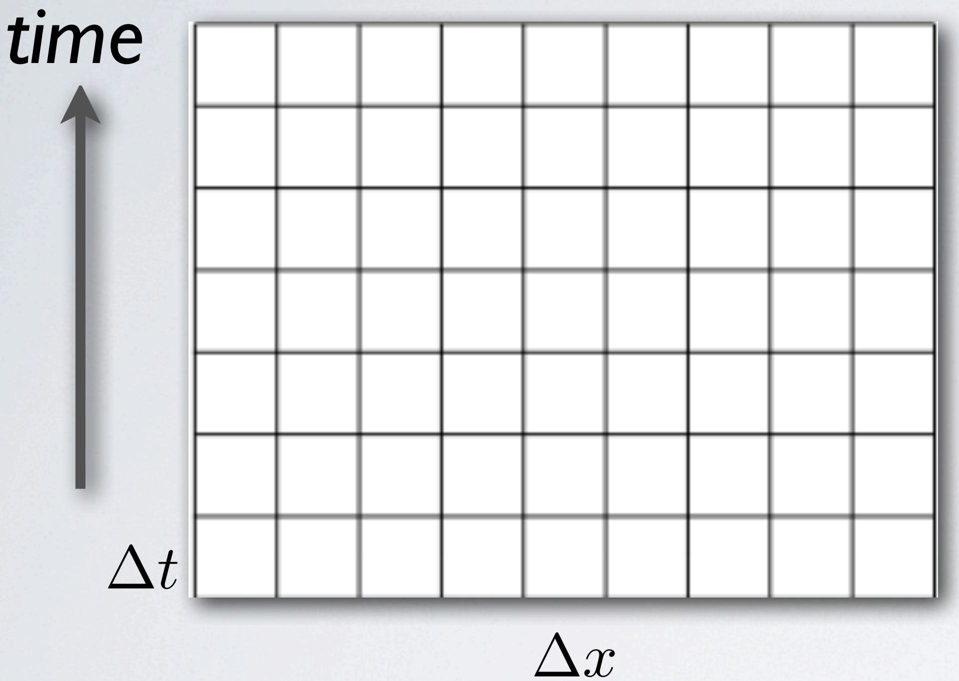
$$C_p\frac{dT}{dt} - \frac{1}{\rho}\frac{dp}{dt} = Q$$

energy

$$p = \rho R T$$

equation of state

FINITE DIFFERENCE PRIMER



Derivatives approximated through finite differences:

$$\frac{dp}{dx} = \frac{p(x + \Delta x) - p(x)}{\Delta x}$$

$$\frac{du}{dt} = \frac{u(t + \Delta t) - u(t)}{\Delta t} = F$$

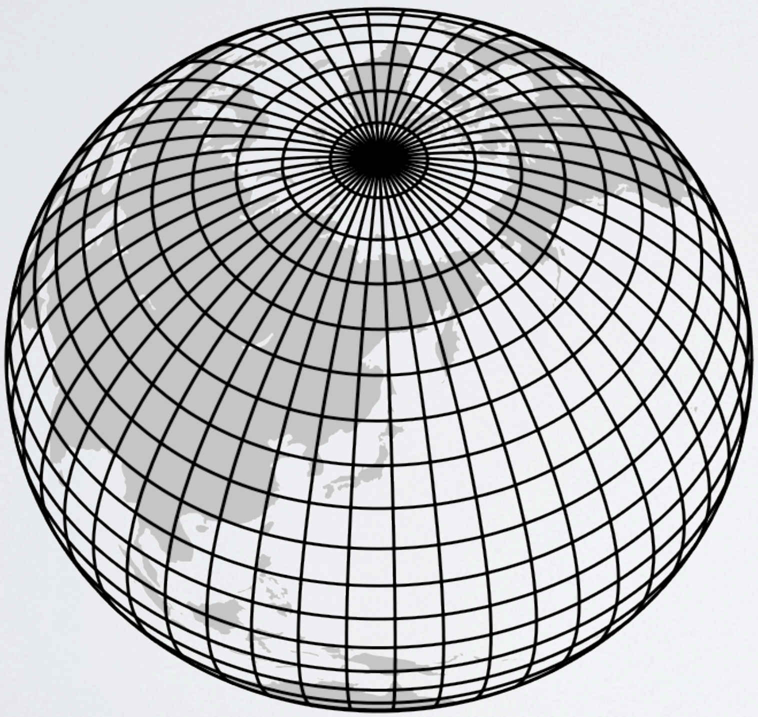
Solution at next time step is then computed by:

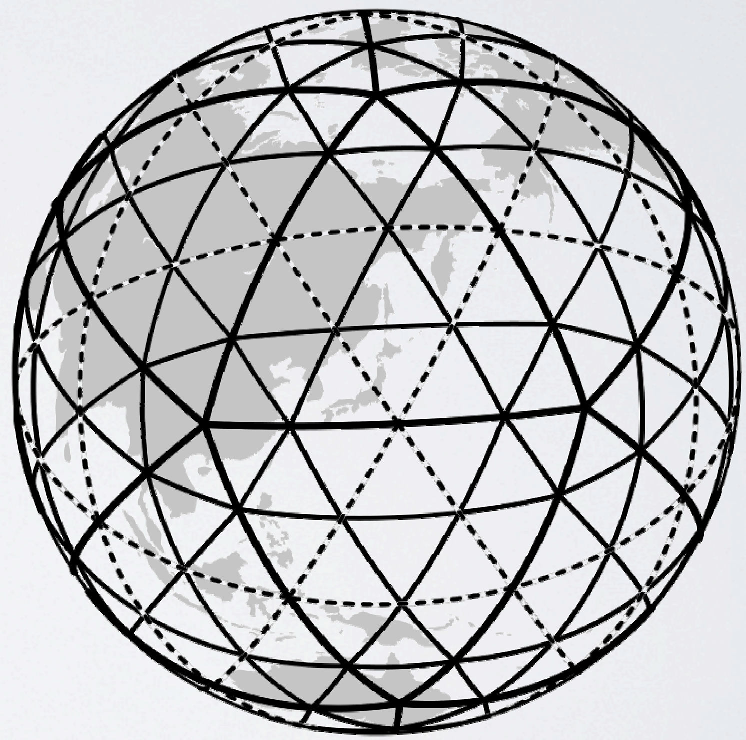
$$u(t + \Delta t) = u(t) + \Delta t F$$

ATMOSPHERIC GRID STRUCTURES

Latitude-Longitude Grid: Problem near the poles where longitudes converge

Spherical Geodesic or Icosahedral Grid: Still being investigated



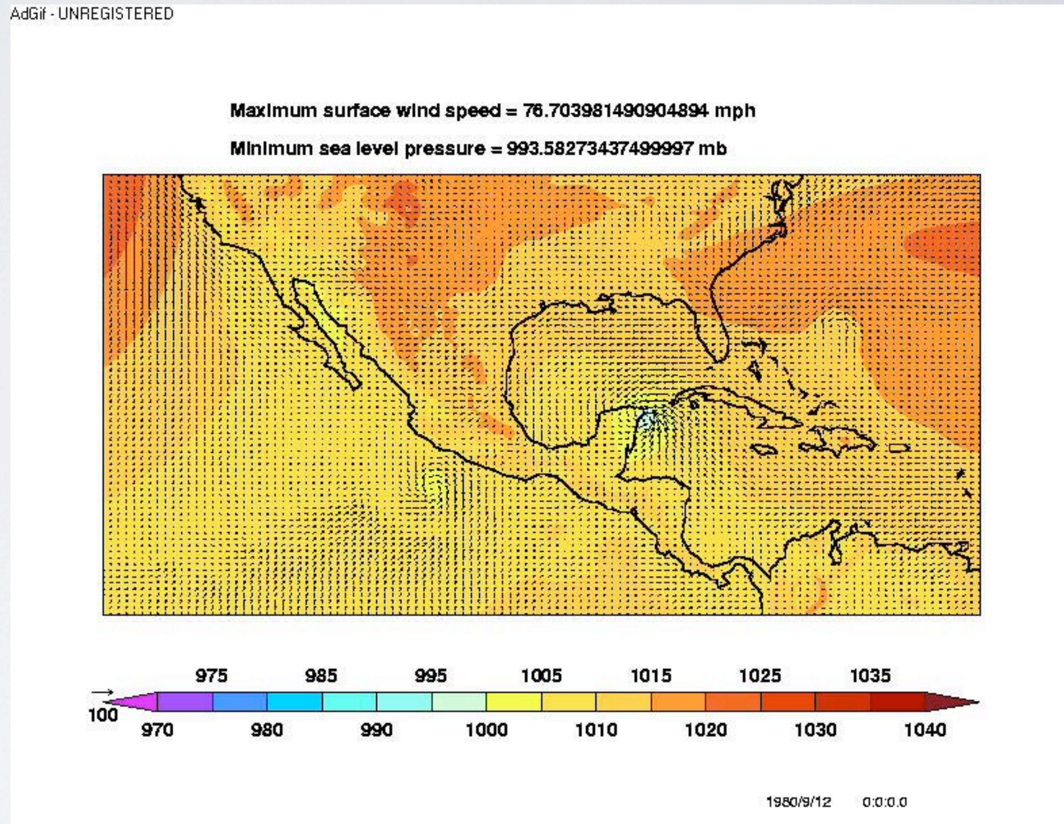


PROBLEM IN GEOMETRY!

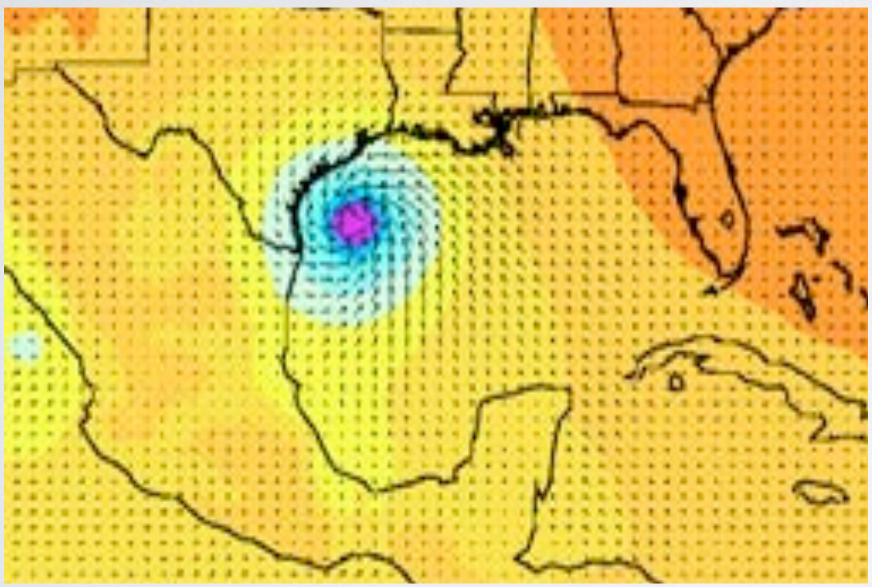
CLIMATE MODELING AND PREDICTING HURRICANE PATTERNS

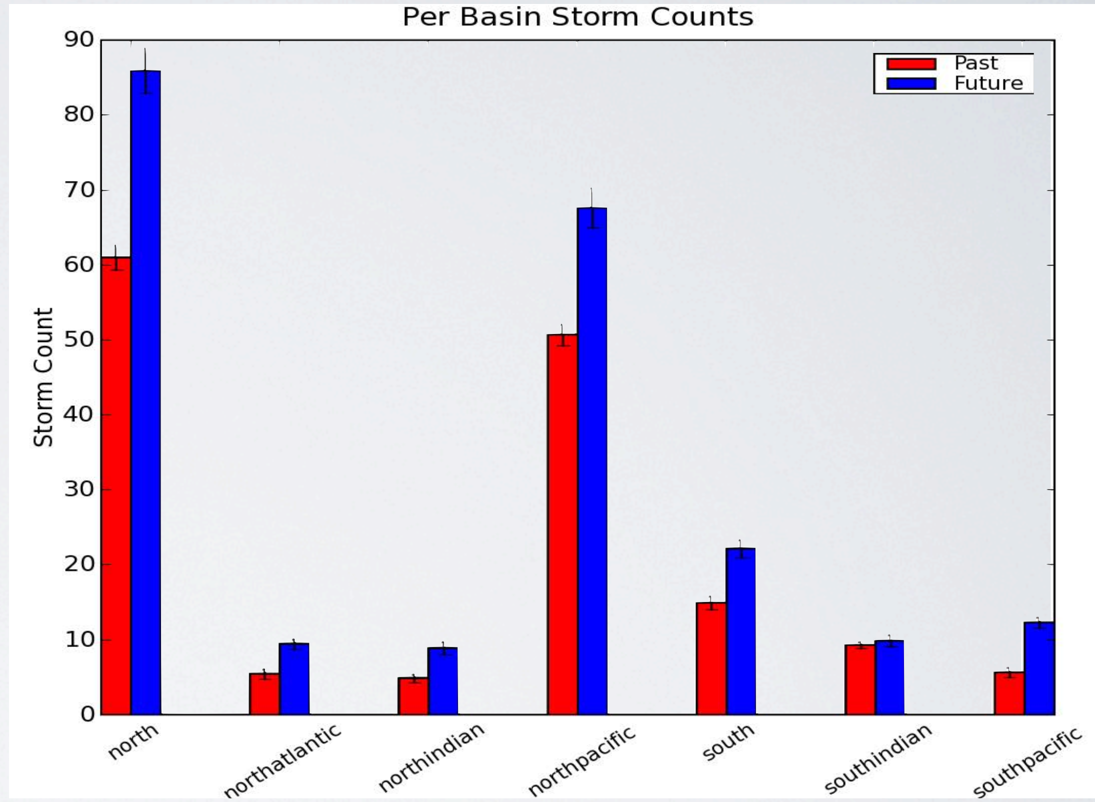
- Tropical cyclones are not generally seen global atmospheric general circulation models at climate model resolutions T42 (~300km)

- In high resolution simulations of the finite volume dynamics version of CAM2, strong tropical cyclones are common



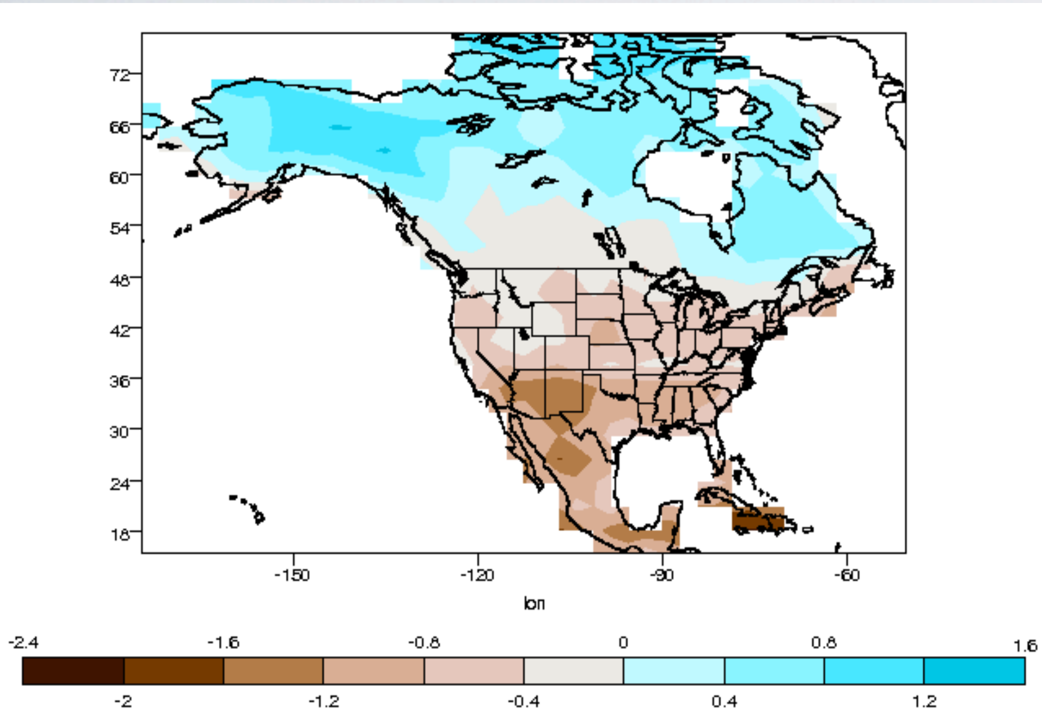
SIMULATED PRESENT DAY AND END OF CENTURY HURRICANE COUNT





50km captures realistic tropical cyclone characteristics

DROUGHT CONDITIONS INCREASE IN SW US AND MEXICO



Drought ——— Flood

The predicted average value of PDSI in 2090 using the 1950-1999 period as a reference. Analysis of 22 models contributed to IPCC AR4 database

M.F.Wehner (LBNL) et al. work in progress

- Most of SW US and Mexico would be in drought, while most of Canada would be in flood conditions
- Precipitation decreases in the Southwest and increases substantially in the Northern latitudes
- This assumes that the CO_2 content of the atmosphere stabilizes to 720ppm in the middle of the 22nd century

THE GENERALIZED EXTREME VALUE (GEV) DISTRIBUTION CAN BE USED TO STUDY CLIMATE

$$F(x) = \begin{cases} e^{-[1+\xi(x-\mu)/\sigma]^{-1/\xi}} & , \quad \xi \neq 0 \\ e^{-e^{-(x-\mu)/\sigma}} & , \quad \xi = 0 \end{cases}$$

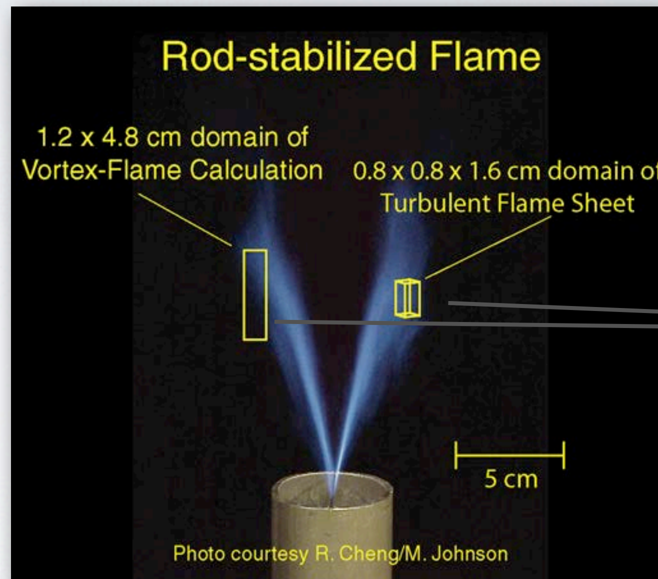
$$\text{where} \quad \mu = \text{location}, \sigma = \text{scale}, \xi = \text{shape}$$

The return value of a random variable, X_T is that value that is exceeded, on average, once in a period of time, T

$$X_T = \begin{cases} \mu + \sigma[1 - \{-ln(1-1/T)\}^{-\xi}/\xi & , \quad \xi \neq 0 \\ \mu - \sigma[ln(-ln(1-1/T)) & , \quad \xi = 0 \end{cases}$$

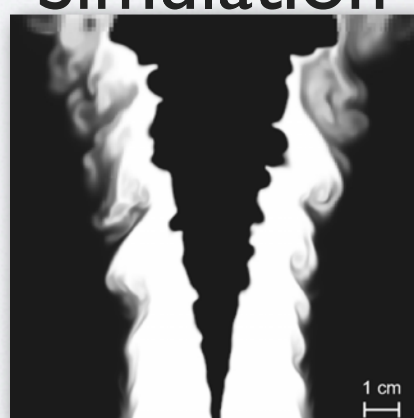
INCREASING COMBUSTION EFFICIENCY IS IMPORTANT IN REDUCING GREENHOUSE GASES

- Most new systems are based on lean premixed turbulent combustion because they have potentially high-efficiency and low emissions
- Challenges to system design
  - Natural flame instabilities
  - Sensitivity to fuel
- Advances in applied mathematics have dramatically increased our simulation capability

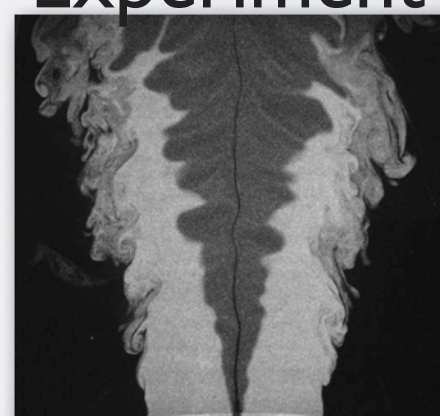


Before

Simulation



Experiment



LOW MACH NUMBER EQUATIONS

$$\rho \frac{DU}{Dt} = -\nabla\pi + \nabla\cdot\tau$$ *momentum*

$$\frac{\partial \rho Y_m}{\partial t} + \nabla\cdot(\rho U Y_m) = \nabla\cdot(\rho D_m \nabla Y_m) + \dot{\omega}_m$$ *species*

$$\frac{\partial \rho}{\partial t} + \nabla\cdot(\rho U) = 0$$ *mass*

$$\frac{\partial \rho h}{\partial t} + \nabla\cdot(\rho h U) = \nabla\cdot(\lambda\nabla T) + \sum_m \nabla\cdot(\rho h_m D_m \nabla Y_m)$$ *energy*

Y_m mass fraction

$\dot{\omega}_m$ species production, $\sum \dot{\omega}_m = 0$

h enthalpy, $h = \sum Y_m h_m(T)$

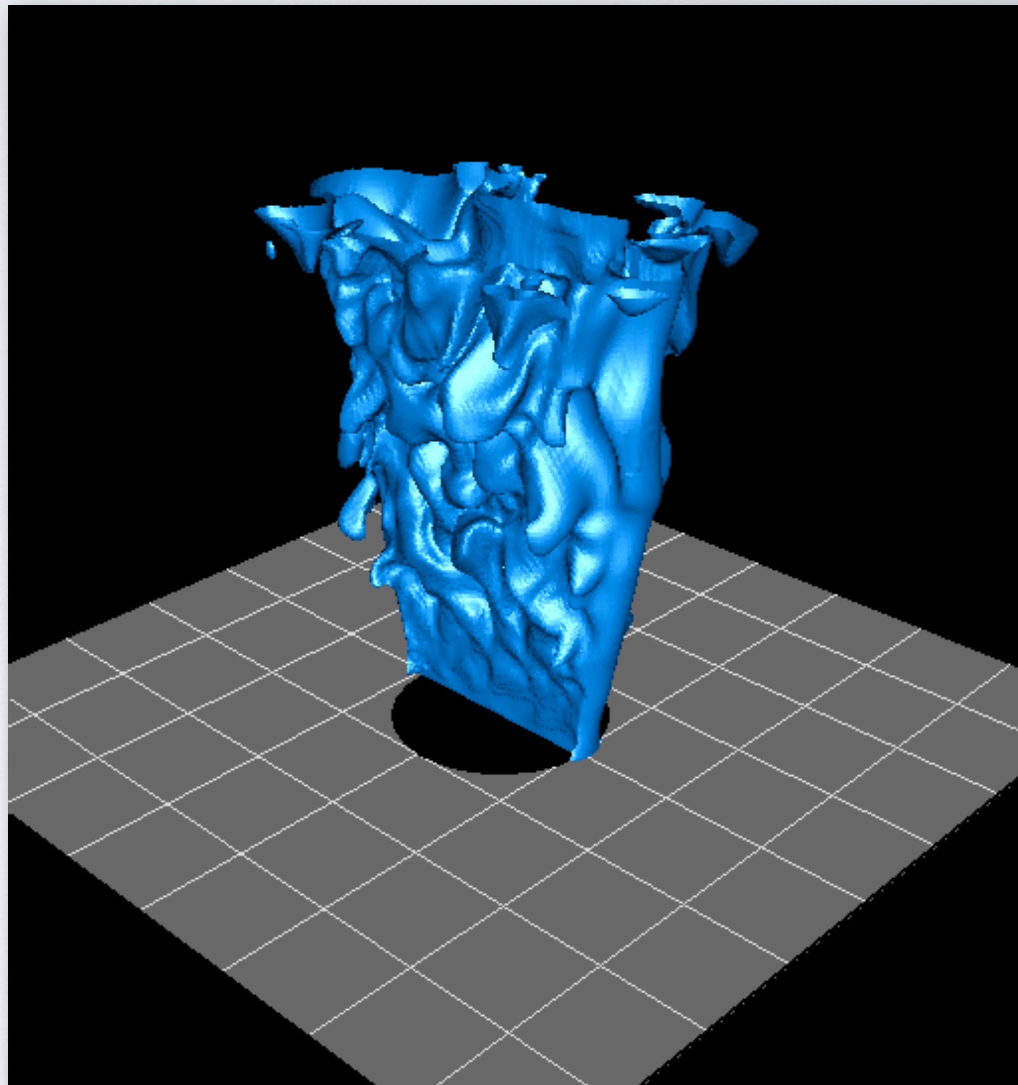
Equation of State $p_0 = \rho R T \sum Y_m / W_m$ *equation of state*

MATHEMATICS GROUP INCREASED SIMULATION CAPABILITY BY A FACTOR OF 10,000

Experimental Turbulent V-Flame

(photo courtesy R. K. Cheng, LBNL)

Calculations

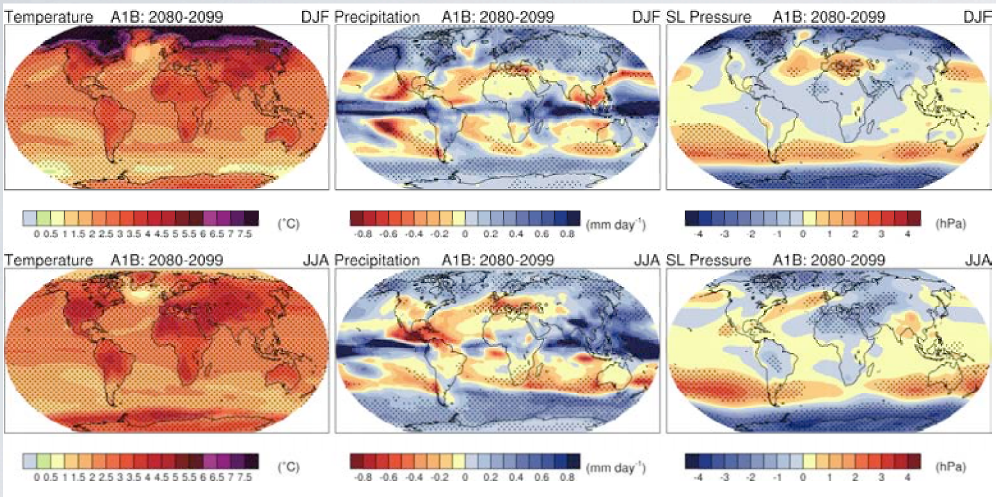


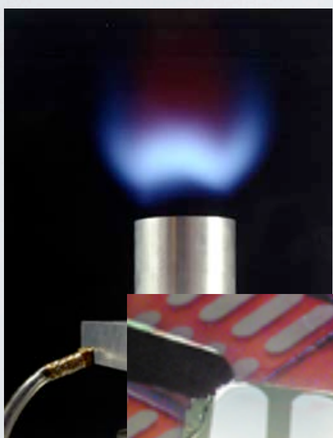
SUMMARY

- Climate change and energy will become increasingly important areas for study
- Modeling and simulation can be used to understand and predict climate change and energy alternatives
- Mathematics is the foundation for climate and energy models, including *calculus*, *linear algebra*, *geometry*, *statistics*, etc.
- New mathematical advances needed everyday to solve real-world problems

Mathematics accelerates the discovery of science
AND
will continue to do so

FUTURE WORK





- Predict future climate scenarios
- Develop more efficient, environmentally friendly combustion processes
- Investigate other sources of renewable energy

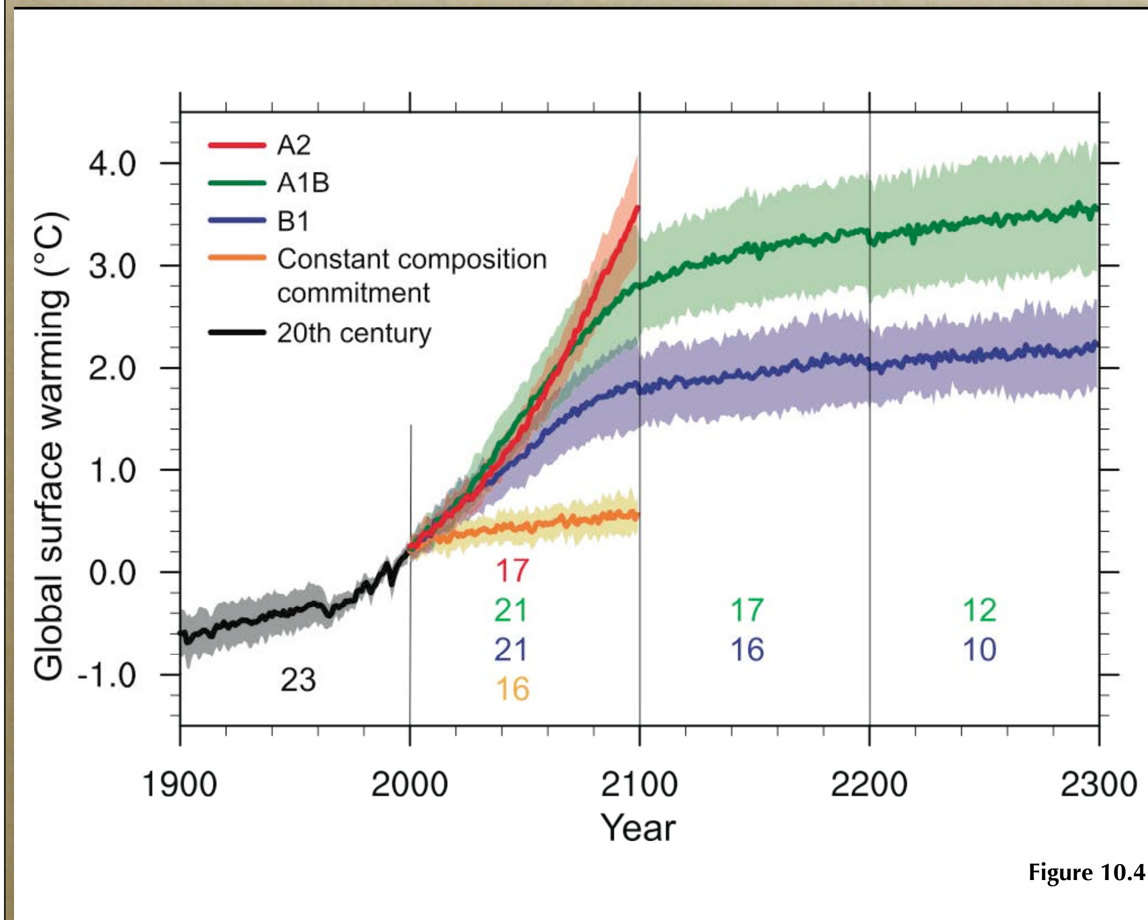
SO IF SOMEONE ASKS YOU WHY YOU'RE STUDYING MATH?

I'm Going To Help Save The World!

THANK YOU !

EXTRA SLIDES

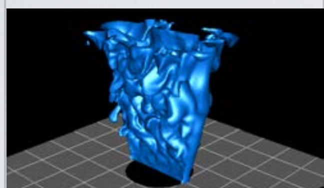
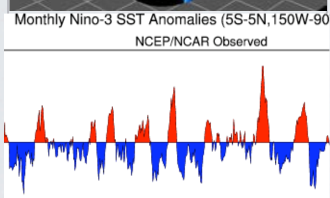
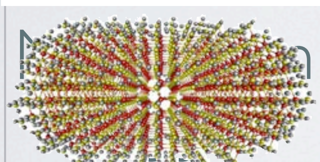
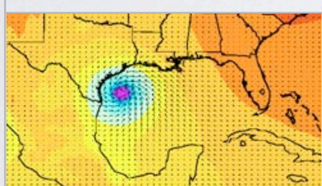
We'll consider three areas where math is being used to study effects of climate change



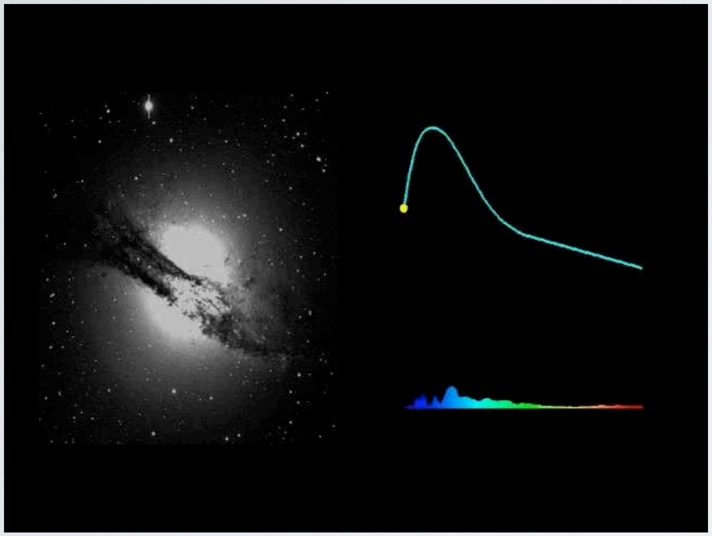
- ***What are we doing today to improve our use of energy?***
- ***What can we do to change how we use energy in the future?***
- ***What can we say about our future climate and its effects on us?***

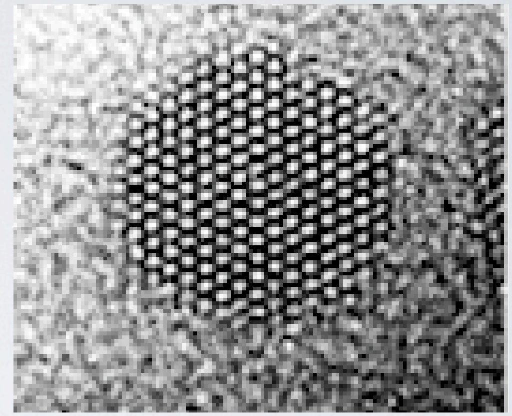
http://ipcc-wg1.ucar.edu/wg1/wg1_home.html

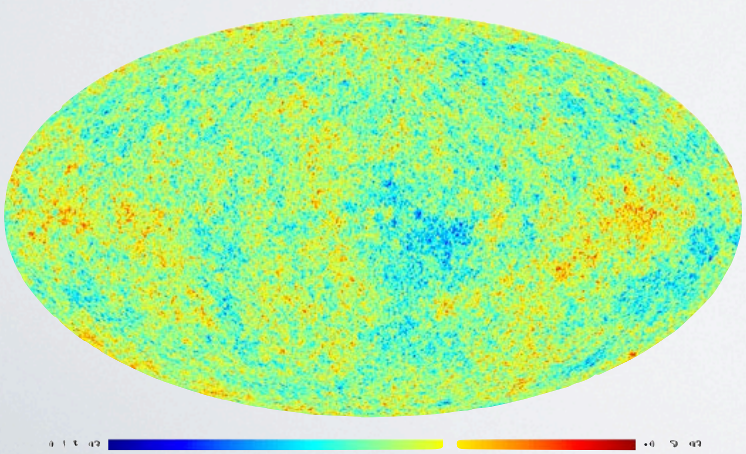
WHERE DID WE USE MATHEMATICS IN THESE PROBLEMS?

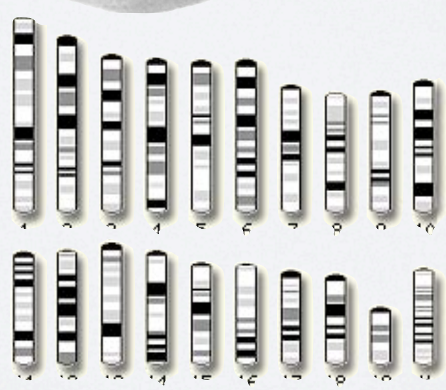
	Calculus	Linear Algebra	Numerical Methods	Statistics
	✓	✓	✓	✓
	✓	✓	✓	
	✓	✓	✓	
	✓	✓	✓	✓

BROADER USE OF COMPUTATIONAL MATH AND SCIENCES FOR SCIENTIFIC DISCOVERY









THE TIMES

Nation & World

MONDAY, MARCH 24, 2008 For more reports: ContraCostaTimes.com SVE PAGE

Forecasters warn of historic floods in Arkansas

By Jon Gambrell

Robinson wrote in an e-mail to reporters Sunday.

A tributary of the White River, the Black River, ruptured a levee in two places Saturday near Pocahontas, said Renee Preslar, a spokeswoman for the Ar[illegible] Department of Emergenc[illegible] agement.

That stream has been [illegible] by water pouring down[illegible] from hard-hit southeaster[illegible] souri.

Preslar said the levee allowed flooding in outl[illegible] eas but she did not have on what might have bee[illegible] aged.

The Army Corps of En[illegible]

worked through the night to plug the breaks with sandbags, and that work appeared to be holding as of Sunday afternoon, Preslar said.

"Right now, it's kind of a wait-

time, they had closure gates on them, but they couldn't be closed" Saturday, Spaul said. "Everything was rusted out on them."

Arkansas emergency man-

Last week's torrential rainstorms also caused flooding in parts of Ohio and southern Illinois and in wide areas of Missouri.

At least 17 deaths have been

ANTARCTIC ICE SHELF COLLAPSES

NASA

THIS SATELLITE PHOTO shows the Wilkins Ice Shelf beginning to break apart March 6. Part of the ice shelf suddenly collapsed, scientists said Tuesday. Experts blame global warming for the disintegration.

Glacial melt worries scientists

By Seth Borenstein
ASSOCIATED PRESS

WASHINGTON — A chunk of Antarctic ice about seven times the size of Manhattan suddenly

ONLINE
■ The National Snow and Ice Data Center: http:/nsidc.org
■ The British Antarctic Survey:

There's still a chance the rest of the ice shelf will survive until next year because this is the end of the Antarctic summer and colder weather is setting in,

PLEASANTON • LIVERMORE • DUBLIN

THE VALLEY TIMES

Edition of the Contra Costa Times

Tuesday, March 25, 2008 ContraCostaTimes.com Volume 96, Number 299 50 cents plus tax

Future of Lake Tahoe looks murky, study says

■ UC Davis researchers predict climate change will cause permanent damage

By Julie Sevrens Lyons
MEDIANEWS STAFF

The jewel of the Sierra could be worse off than previously thought.

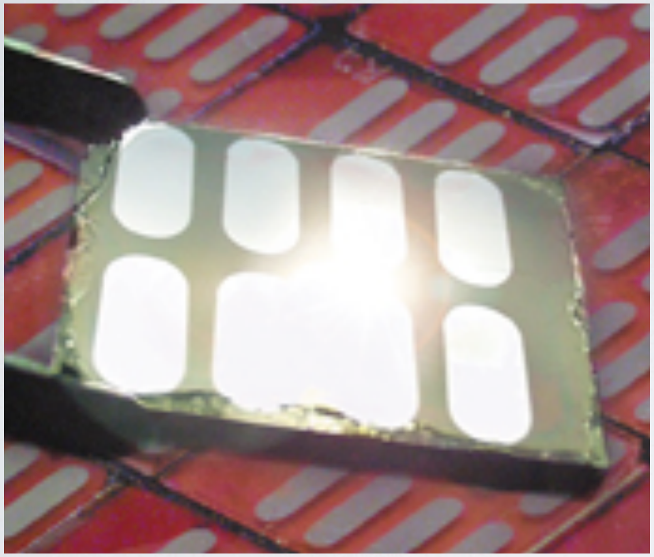
Global warming already is causing warmer lake temperatures along the shoreline, and it is likely to continue to cloud up the cobalt waters that attract tourists from all over the world. However, the most recent news came as a shock to even the researchers.

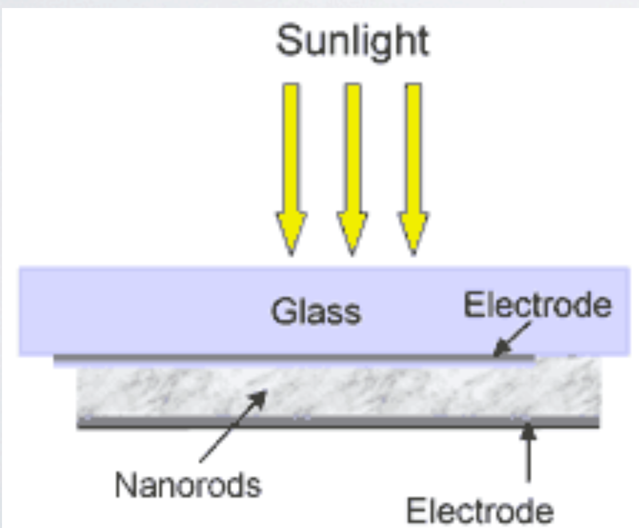
"This is one of the early indi-

RICHARDSON FORECAST FACTORY

- Proposed parallel computer for weather forecasting
- 64,000 computers working in parallel
- Here a computer referred to a human!

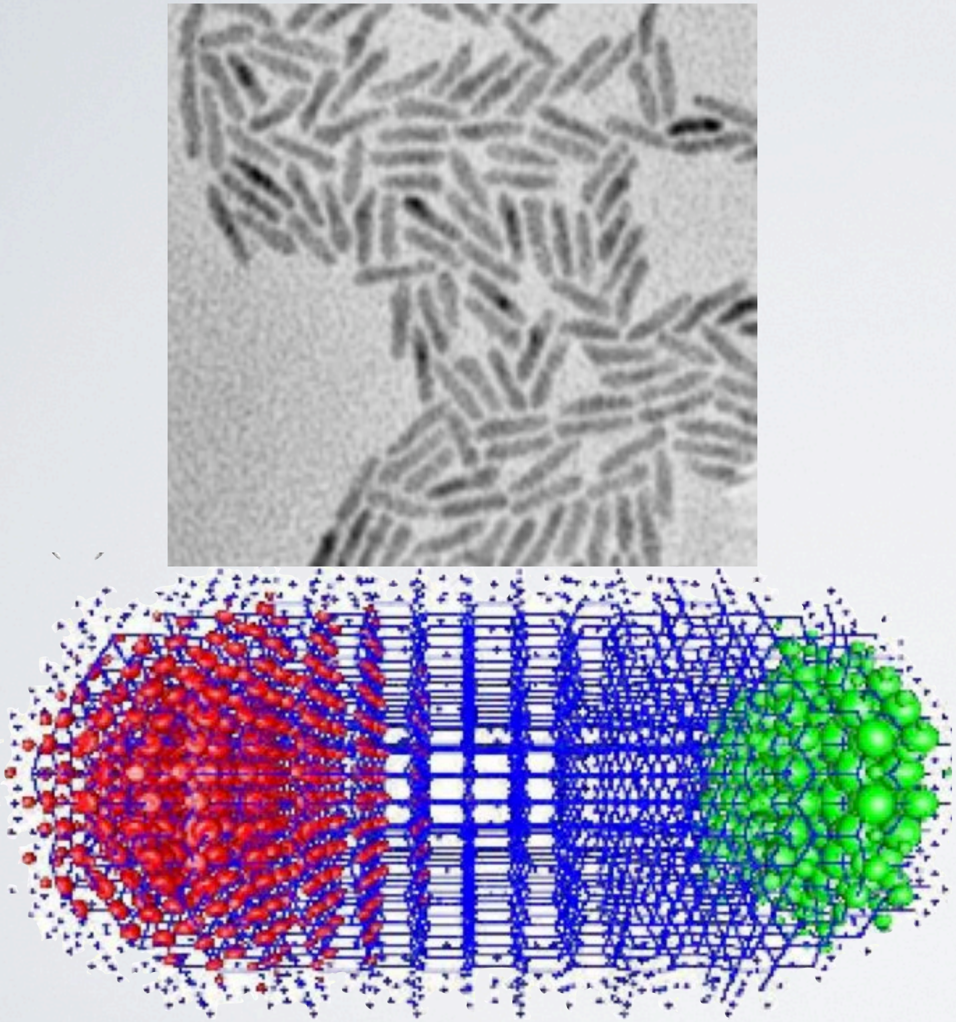
PHOTOVOLTAIC SOLAR CELLS





- Solar cells based on inorganic nanorods and semiconducting polymers
- Nanorods can be made of CdSe, a semiconducting material
- Nanorods act like wires, absorbing light and generating hole-electron pairs
- Biggest challenge is cost, ~30 cents/kWh

DIPOLE MOMENT CALCULATIONS HELP TO EXPLAIN EXPERIMENTS



Linear-scaling three-dimensional fragment method for large-scale electronic structure calculations, Wang, Zhao, Meza, doi:10.1103/PhysRevB.77.165113, April 2008.

- Experiments show that these structures have a dipole moment
- The calculated dipole moment of a 2633 atom CdSe quantum rod, $Cd_{961}Se_{724}H_{948}$
- Using 2560 processors at NERSC, the calculation took about 30 hours.

DENSITY FUNCTIONAL THEORY AND THE KOHN-SHAM EQUATIONS

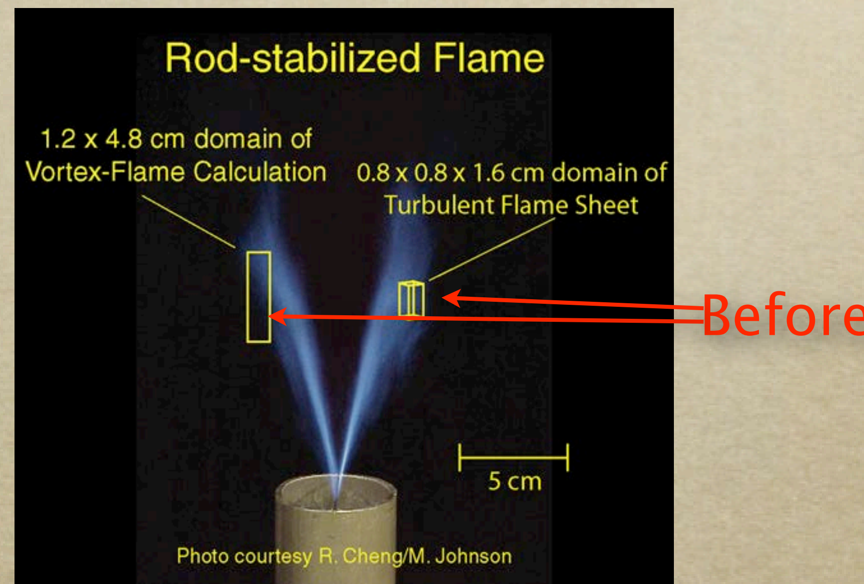
$$
\begin{aligned}
E_{total}[\{\psi_i\}] &= \frac{1}{2}\sum_{i=1}^{n_e}\int_\Omega |\nabla\psi_i|^2 + \int_\Omega V_{ext}\rho \\
&+ \frac{1}{2}\int_\Omega \frac{\rho(r)\rho(r^{'})}{|r-r'|}drdr^{'} + E_{xc}(\rho),
\end{aligned}
$$

$$\rho = \sum_{i=1}^{n_e} |\psi_i(r)|^2,\ \int_\Omega \psi_i\psi_j = \delta_{i,j}$$

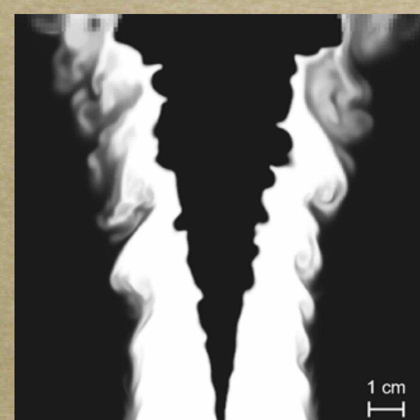
$$\left[-\frac{1}{2}\nabla^2 + V_{ext}(r) + \int \frac{\rho}{|r-r'|} + V_{xc}(\rho)\right]\psi_i = \epsilon_i\psi_i$$

Mathematics group increased simulation capability by a factor of 10,000

- *Advances in applied mathematics have dramatically increased our simulation capability*
- *Mathematical formulation to exploit separation of scales*
- *Specialized discretization methods*
- *Adaptive mesh refinement*
- *Parallel numerical algorithms*



Simulation



Experiment