Earth’s Climate System:
A 21st Century Grand Challenge

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There are many ways to view the Earth.....

With different stories to tell....
What global surface temperature change has occurred so far?

Data from thermometers

Departures in temperature (deg C)
From the 1961 to 1990 average

Year

Data from thermometers

IPCC 2001
Human Influence on Climate

Carbon Dioxide Trends: 100yr lifetime

Methane Trends

Sulfate Trends

Global Temperature Trends

From M. Prather University of California at Irvine
Radiative Forcing from 1750 to 2000

Anthropogenic Forcings

- Halocarbons
- N₂O
- CH₄
- CO₂
- Tropospheric ozone
- Aerosols
  - Black carbon from fossil fuel burning
- Mineral Dust
- Aviation-induced
  - Contrails Cirrus
- Stratospheric ozone
- Sulphate
- Organic carbon from fossil fuel burning
- Biomass burning
- Aerosol indirect effect
- Land-use (albedo) only

IPCC, 2001
Of the total forcing of the climate system, 40% is due to the direct effect of greenhouse gases and aerosols, and 60% is from feedback effects, such as increasing concentrations of water vapor as temperature rises.
Global Temperature Predictions

Model: natural forcing

IPCC, 2001
Global Temperature Predictions

Model: natural + anthropogenic forcing

IPCC, 2001
Global Temperature Predictions

Uncertainty in climate sensitivity

Uncertainty in future emissions

Temperature change (°C)

Year

Bars show the range in 2100 produced by several models

IPCC, 2001
Predicted Sea Level rise from 1990 to 2100

Uncertainty in climate sensitivity

Uncertainty in future emissions

IPCC, 2001
Sea level rise continues for centuries:
Long after atmospheric temperature stabilizes

IPCC, 2001
Example 2100 Climate Model Prediction: Baseline Scenario (Anomaly in Deg C)

Courtesy Warren Washington, NCAR
U.S. summer soil moisture predictions:

A tale of two climate models...

...and of large regional uncertainties.
What is Climate?

- Climate is the long term average of weather.
  - 14-day weather prediction limit: but no known limit to climate prediction.
  - Weather data accuracy is 1 degree, but climate accuracy is 0.1 degree: a factor of 10 tougher measurement.
What is a computer model of the climate system?
Major Climate System Elements

- Carbon Cycle
- Water & Energy Cycle
- Atmospheric Chemistry
- Coupled Chaotic Nonlinear
- Atmosphere and Ocean Dynamics
How can we use observations to test and improve climate models?
NASA Has Engaged in Earth Science
From the Very Beginning

TIROS IX mosaic, February 13, 1965
Earth View From MODIS on the Terra Spacecraft 2001
Vegetation from MODIS on Terra
Summer, 2001
Carbon Monoxide

MOPPITT
On Terra

April & October 2000
Unprecedented Accuracy of new EOS Radiation Data

Emitted Thermal Flux Measured By CERES
Terra    March 2000

Watts per square meter

160  200  240  280  320
Early NASA EOS Satellite Results
On the Role of Clouds in Climate

• **Focus on the Tropics**

• **What about the recent Iris hypothesis?**

• **Was the 1997/98 El Nino really different?**

• **Is there evidence for decadal change?**
Global Atmospheric Circulation
The Iris Cloud Feedback Concept

Normal Sea Surface Temperature

Warmer Sea Surface Temperature

Solar Absorption ~ Unchanged

Thermal Emission Increase (Cooling)

More efficient precipitation decreases upper cloud anvil area

Thermal
The Iris: New Observations Reject

Normal Sea Surface Temperature

- Solar
- Cloud Reflection $\sim 0.5$ (Iris assumed $\sim 0.35$)

Warmer Sea Surface Temperature

- Thermal Emission Increase (Cooling)
- Solar Increase (Warming)

- More efficient precipitation decreases upper cloud anvil area
- Re-analysis did not confirm anvil area temperature relation
The dramatic 1997/98 El Nino

- Rivaled only by the 1983 El Nino during the last century.
- First useful climate prediction using ocean and atmosphere observing systems
- Can we use it as a test of short term climate as well as the effects of clouds on long-term climate change?
Jan/Feb 98 El Nino Thermal Flux Anomalies

NASA CERES Radiation Observations

NOAA GFDL Standard Climate Model

NOAA GFDL Experimental Prediction Model
1998 El Nino Tropical Mean (20S - 20N) Longwave Flux Anomalies
(Anomalies Referenced to 1985 through 1989 Baseline)

*5 Climate Models and NCEP Re-analysis; All used observed SSTs; Climate Models: NCAR-CSM (Kiehl)
UKMO (Allan, Slingo), GFDL and GFDL-EP (Soden, Gordon), CSU (Randall)
An overlapping Earth radiation climate record: 22 years from Nimbus 7 to Terra.
Comparison of Observed Decadal Tropical Radiation Variation with Current Climate Models

LW: Emitted Thermal Fluxes
SW: Reflected Solar Fluxes
Net: Net Radiative Fluxes

Models less variable than the observations:
- missing feedbacks?
- missing forcings?
- clouds physics?
Why are clouds so tough?

- Aerosols <0.1 micron, cloud systems >1000 km
- Cloud particles grow in seconds: climate is centuries
- Cloud growth can be explosive: 1 thunderstorm packs the energy of an H-bomb.
- Cloud properties can vary a factor of 1000 in hours.
- Few percent cloud changes drive climate sensitivity
- Best current climate models are 250km scale
- Cloud updrafts are a 100m to a few km.
- A climate model resolving all cloud physics down to aerosol scale would require $10^{38}$ supercomputers: 190 years of current Moore’s Law rate of advance.
How can we improve in the future?
“A-Train” Formation for Aerosol and Cloud Vertical Profiles
Atmospheric State => Aerosol/Cloud => Radiative Heating
But isn’t this the tip of the iceberg?

• Yes. Oceans, ice sheets, carbon cycle, aerosols all remain critical issues as well.
• There currently is no rigorous climate observing system in place or yet planned.
  - we use well sampled weather data (but often lacks accuracy for climate, and misses many variables)
  - we use poorly sampled research data (often good accuracy but gaps or poor overlap)
• There is no single U.S. climate agency. Key contributors: NASA, NOAA, NSF, DOE, EPA.
• Cost of a climate system would be well beyond current US programs (factor of 5? $10B/yr?)
• Major change would require a “climate epiphany”…
A possible future

• An international climate mission: analogous to Apollo or the Manhattan Project.
  – Implement rigorous and robust climate observations.
  – Comprehensive climate modeling efforts.
  – But no a-priori guarantees of success.

• What would we do with climate prediction certainty if we had it and climate change is predicted to be large?
  – Renewable energy development.
  – Energy conservation/efficiency.
  – Decadal plans for energy system transitions, land use change patterns, sea-level rise mitigation.
  – Vary response with regional changes.

• Is human society capable of coordinated and planned action on global & decade time scales?
“Nature is a mutable cloud which is always and never the same”.
- Ralph Waldo Emerson (1803-1882)

“Man masters nature not by force, but by understanding.”
- Jacob Bronowski, 1956
Altitudes above sea level
Chesapeake Bay area

A large portion of Chesapeake & Delaware Bay wetlands would be inundated by 0.8-m rise in sea level

Beaches would be lost & new bridges would be required for newly formed islands

More areas would be exposed to storm surges