Hot Topics in Climate 2: Climate Models & The Cryosphere

Warren Wiscombe
NASA Goddard
The missing temperature plots 1: Global-average anomaly, 1880-2012

- NASA Goddard Institute for Space Studies
- Met Office Hadley Centre/Climatic Research Unit
- NOAA National Climatic Data Center
- Japanese Meteorological Agency

Average Temperature Anomaly (°C)

1880 1900 1920 1940 1960 1980 2000

Summer 2013 Wiscombe: Climate for
The missing temperature plots 2: 2012 anomaly relative to 30-yr mean
Climate Modeling
Movie: Intro to climate modeling (4 min)
Variables in a climate model

Solve “primitive equations”

PDEs for conservation of mass, momentum, energy, + gas law

Cloud liquid water added recently
THEMES in climate modeling

Bad models?

Models vs. theories

Models have emergent behavior.

Problem: it takes > 10 yr to verify a 10-yr forecast

Trenberth bet in 2010 that current IPCC models would have larger uncertainties due to adding more complexity (like aerosol effect on clouds, permafrost and CO2 fertilization).
THEMES in climate modeling

Climate modeling is counter-intuitive: as knowledge increases, so does uncertainty.

‘Idealized emissions scenarios’: lead to projections, not predictions or forecasts

Rather than rely on these scenarios, modest predictions are possible because “the amount of warming that will take place up to 2030 is largely dependent on greenhouse gases that have already been released into the air”
Climate modeling pyramid in 1987

Fig. 2. The climate modeling pyramid. Adapted from Henderson-Sellers and McGuffie (1987)
Fig. 1. Pictorial definition of EMICs. Adapted from Claussen (2000)
Types of models

Model Domain Size (km)

- DNS = Direct Numerical Simulation
- LES = Large Eddy Simulation
- CRM = Cloud-Resolving Model
- WRF = Weather Research and Forecast Model
- GCM = Global Climate Model
- RCM = Regional Climate Model
- GCRM = Global CRM
- NWP = Numerical Weather Forecasting
- SCM = Single Column Model

Model Grid Size

- Parcel Model
- Microphysics
- LES
- MMF
- GCRM
- GCM
- NWP
- RCM
- WRF
- SCM
The imprints of our efforts (toward a widening abyss)
There are ways to find robust behavior and make progress despite the difficulty of the problem.

- **Perturb Physics**
- **GCM**
- **Multiple GCMs**

Check with fancy model

Find a simple story/physics

Dorian Abbott
Climate modeling is NOT like weather forecasting

Unlike a weather prediction, climate models are not initialized with the current or past state of the climate system, as derived from observations.

Instead, they begin with arbitrary climatic conditions and examine only the change in projected climate.

The actual initial states of climate models differ quite a lot. IPCC doesn't show them.
Climate models are just beginning to try to produce true fore/hindcasts

Red = observations

10-yr means, 1955-2012

Trenberth, 2010
Are climate models getting better? Reichler & Kim (BAMS 2008) found YES

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**Fig. 1.** Performance index $I^2$ for individual models (circles) and model generations (rows). Best performing models have low $I^2$ values and are located toward the left. Circle sizes indicate the length of the 95% confidence intervals. Letters and numbers identify individual models (see supplemental online material at doi:10.1175/BAMS-89-3-Reichler); flux-corrected models are labeled in red. Grey circles show the average $I^2$ of all models within one model group. Black circles indicate the $I^2$ of the multimodel mean taken over one model group. The green circle (REA) corresponds to the $I^2$ of the NCEP/NCAR reanalyses. Last row (PICTRL) shows $I^2$ for the preindustrial control experiment of the CMIP-3 project.

**CMIP = Climate Model Intercompar’n Project (start 1994)**

Index compares grab bag of predicted var’s to current climate

Index > 1 for underperforming (bad?) models

Better resolution and parameterizations led to better results

Black circles = multi-model means (green = observ’ns)
Kerry Emanuel video on climate (24 min)

https://alum.mit.edu/learn/facultyforum/online/climate-research?destination=node/20702

Starts with Arrhenius and ends with need for going back to basics in climate modeling -- emphasizing basic understanding over black box simulation
“Climate Research: Time for a New Direction

Research aimed at predicting future climate activity has primarily focused on exceptionally large and complex numerical models. While this approach has provided some quantitative estimates of climate change, those predictions can vary greatly from one model to the next and produce significant uncertainties in the projected outcome. Attempts to reduce these uncertainties have largely failed.”
What Are Climate Models Missing?

Bjorn Stevens\(^1\) and Sandrine Bony\(^2\)

Fifty years ago, Joseph Smagorinsky published a landmark paper (1) describing numerical experiments using the primitive equations (a set of fluid equations that describe global atmospheric flows). In so doing, he introduced what later became known as a General Circulation Model (GCM). GCMs have come to provide a compelling framework for coupling the atmospheric circulation to a great variety of processes. Although early GCMs could only consider a small subset of these processes, it was widely appreciated that a more comprehensive treatment was necessary to adequately represent the drivers of the circulation. But how comprehensive this treatment must be was unclear and, as Smagorinsky realized (2), could only be determined through numerical experimentation. These types of experiments have since shown that an adequate description of basic processes like cloud formation, moist convection, and mixing is what climate models miss most.

From GCMs to Earth System Models

Smagorinsky’s GCM was designed around the premise that studies of the general circulation required a model capable of resolving the heat transport from the equator to the poles. Its formulation was the next logical step in a program of hierarchical model development best known for its pioneering contributions to numerical weather prediction (3). The work paved the way for fundamental studies of the atmospheric general circulation, and hence Earth’s climate.

Over the past half century, many of these studies have focused on the types of numerical experiments anticipated by Smagorinsky. Beginning with basic processes like moist convection and cloud formation, which have long been appreciated as central to the energetics of the troposphere, a long succession of processes and couplings have been added to primitive-equation descriptions of the atmospheric general circulation. In so doing, GCMs have gradually morphed into Global Climate Models, and with the more recent incorporation of models of the biosphere and the associated cycles of important chemical nutrients, Earth System Models (4, 5).

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Wide variation. The response patterns of clouds and precipitation to warming vary dramatically depending on the climate model, even in the simplest model configuration. Shown are changes in the radiative effects of clouds and in precipitation accompanying a uniform warming (4°C) predicted by four models from Phase 5 of the Coupled Model Intercomparison Project (CMIP5) for a water planet with prescribed surface temperatures.
What drives modelers crazy?

clouds (a feedback)

precipitation

aerosols (a forcing)

known unknown feedbacks
  -permafrost
  -ocean thermohaline circulation

unknown unknown feedbacks
  -esp. over long timescales
Typical timescales of different feedbacks relevant to equilibrium climate sensitivity

<table>
<thead>
<tr>
<th>Timescale</th>
<th>Years</th>
<th>Decades</th>
<th>Centuries</th>
<th>Millennia</th>
<th>Multi-millennia</th>
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<td>Upper ocean</td>
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<td>Land ice sheets</td>
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<td>Carbon cycle</td>
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<td>Plate tectonics</td>
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<td>vegetation types</td>
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PALAEOSENS Nature 491, 683-691 (2012)
Cloud shortwave reflection and infrared absorption are critical for determining planetary climate. Thanks to Daniel Koll.
Cloud processes are not resolved by GCMs, and therefore require parameterization in terms of resolved variables.

Cloud microphysics scale: $\approx 10^{-6} - 10^{-3}$ m

Cloud size: $\approx 10^{1} - 10^{3}$ m
What drives modelers crazy? - 2

Regional climate change

Multiple equilibria?

Why is Earth’s albedo 0.3? Is it stable?

Which ensemble member are we on?

1940 to 1975 cooling (tuned with aerosols)

Dimming and brightening of sunlight@surface
What drives modelers crazy? – 3

Internal variability:

* El Nino / La Nina
* Madden-Julian Oscillation
* other oscillations (vacillations, really)
  - Arctic
  - Pacific Decadal
  - Atlantic
Global warming hiatuses in models: who knew?

Evolution of $T_s$: CCSM4 RCP4.5

NCAR Community Climate Model

Period of no $T_s$ increase for over a decade
Forced climate variations are the goal
Free climate variations are what you get
40 identical experiments with NCAR CCSM3 for 2000-2060 with CO2 and sulfate aerosol forcing

Winter air temperature trends

**Winter Air Temperature Trends 2010-2060**

<table>
<thead>
<tr>
<th>Total</th>
<th>Free</th>
<th>Forced</th>
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<tr>
<td>Run A</td>
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<td>0.8 °C</td>
<td>-1.3 °C</td>
<td>2.1 °C</td>
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<tr>
<td>Run B</td>
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<tr>
<td>3.4 °C</td>
<td>1.3 °C</td>
<td>2.1 °C</td>
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Deser 2013
It matters which ensemble member you are on!

NCAR Model: Future Climate Trends 2010-2060

Winter Air Temperature

Run A
0.8

Run B
3.4

Summer Rainfall

Run C
-0.18

Run D
0.44

Same CO₂ increase

°C

mm/day
Where does the extra energy from rising CO2 go? Bet on the oceans!

Energy Content in the Climate System

Energy Content Change ($10^{22}$ J)

- Blue: 1961 to 2003
- Burgundy: 1993 to 2003

- Glaciers and ice caps
- Greenland Ice Sheet
- Antarctic Ice Sheet
- Continents
- Atmosphere
- Arctic sea ice
- Total Change

from IPCC, Trenberth
Bender 2005: model disparity in Earth albedo

CERES
ERBE
GISS-EH
UKMO-HadGEM1
GISS-ER
UKMO-HadCM3
MIROC3.2(hires)
MRI-CGCM2.3.2
INM-CM3.0
IPSL-CM4
GFDL-CM2.1
PCM
ECH0-G
CGCM3.1(T47)
FGOALS-g1.0
CCSM3
GFDL-CM2.0
CSIRO-Mk3.0
BCCR-BCM2.0
MIROC3.2(medres)
ECHAM5/MPI-OM
CNRM-CM3

0.27 0.28 0.29 0.3 0.31 0.32 0.33
Arctic Oscillation (AO)

= an opposing pattern of pressure between the Arctic and northern middle latitudes

From 1970s to mid-1990s, AO tended to lock into positive phase.

However, since then (as before 1970) has alternated between positive and negative, with record negative phase in 2009-2010 winter.
Arctic Oscillation (AO)

- Colder stratosphere
- Warm, wet
- Cold
- Stronger tradewinds

Less cold stratosphere
- Cold
- Weaker tradewinds
Arctic Oscillation Index, Winter 2011
Regional climate change forecasts?

GLOBAL CHANGE

Forecasting Regional Climate Change Flunks Its First Test

The strengthening greenhouse is warming the world, but what about your backyard, or at least your region? It’s hard to say, climate researchers concede. Modelers have sharpened their tools enough to project declining grape yields in a warmer, drier California wine country and to forecast that the Mediterranean region will be getting drier in coming decades. But just how reliable such localized projections might be remains unclear.

Now, a group of global, rather than regional, modelers has tested a widely used model of the Earth’s climate and found it can’t reproduce regional climate changes. The researchers’ efforts, published today in the Journal of Geophysical Research: Atmospheres, are yet another indication that climate models, while powerful tools for understanding the world’s climate, are limited in what they can project for regions of the world.

The researchers tested a regional model, called WRF (short for Weather Research and Forecasting), against observations from North America. Their goal was to see if WRF could accurately simulate regional climate changes. The model did not do well, they report. "skill capturing climateology does not translate into skill capturing climate change," Shindell concludes, echoing the group’s paper of late last year in the Journal of Geophysical Research: Atmospheres. “There is modest improvement over the [global] model, but it’s not so large.” And most of that improvement came only when the global model was periodically allowed to “nudge” the wandering regional model back toward a more realistic broad-scale pattern of climate.

Kerr, Science, 8 Feb 2013
Cryosphere
Ice on Land Today – January
Ice on Land Today - July
The Two Basic Climate States: Nonglacial and Glacial

Glacial states: multiple expansions of continental ice sheets into midlatitudes
- last tens of thousands of years
- occasional abrupt climate change

Continental drift, sea level change, and CO2 all contributed to planetary temperature shifts on the million-yr timescale
Evidence of glacial:

- Striations
- Till
- Erratics

U-shaped valleys
Fluctuations of ice sheets in last 3M yr correlate with Earth-orbit-induced changes in solar radiation distribution with latitude.

Terrestrial feedbacks (ice sheet dynamics, ocean temperatures, CO2) modulate the orbital signal.
Greenland and Antarctica contain enough water to raise sea level by over 73 m.

Measurements of ice elevation and volume were poorly known until IceSAT and GRACE.

(Older satellites missed poles.)
Ice and Snow Strongly Affect Climate

During Northern Hemisphere winter, they
- blanket up to 15% of the Earth’s surface,
- reflect up to 80% of sunlight back to space.

During Southern Hemisphere winter, they
cover only 8% of the surface, . . .

but their influence is far larger than their
areal coverage would indicate.
Global Warming and the Cryosphere

Ice-albedo feedback

Meltback of sea ice would increase ocean heat flux to atmosphere, again amplifying the warming.

It would also increase vapor flux to atmosphere, which might enhance clouds. What would that do?

Climate Models (not all...) have been predicting amplified Arctic warming since Manabe in late 1960’s. But...the observational data were too sparse to tell.
Meltdown in the North

By Matthew Sturm, Donald K. Perovich and Mark C. Serreze

Sea ice and glaciers are melting, permafrost is thawing, tundra scientists are struggling to understand how these changes will affect not just the Arctic but the entire planet.
Arctic warming is currently underway...
Models predict even more warming in this century...

Projected Surface Air Temperature Change 2000-2100

Melting ice and sea level rise

Permafrost Thaw

Current Vegetation  Projected Vegetation (by 2100)

Northward migrating boreal forest

An ice-free Arctic Ocean by 2100?
SHEBA, 1998: early warning of Arctic sea ice collapse

the first extensive sea ice experiment ...
- since AIDJEX in 1972, in which I was involved

icebreaker, frozen for a yr in Arctic ice
helicopter, aircraft, under-ice robot surveys
confirmed what U.S. nuclear submarines had seen: dramatic thinning of pack ice
- Major climate change initiative
- NSF, ONR funded
- SHEBA team
  - ~150 researchers
  - ~20 institutions
- Collaborate with other groups
  - ARM, FIRE, SCICEX
Ice Station SHEBA

- Year long drift
- CCGC Des Groseilliers
- 2 Oct 1997: 75 N, 142 W
- 11 Oct 1998: 80 N, 166 W
- Total drift ~ 2800 km
- Displacement ~ 800 km
Seasonal evolution

April 17

August 8
Net mass loss during SHEBA year!

Growth: 0 -100 cm
Net loss: 20 -200 cm
Sea ice thickness, 1955-76 vs 1993-97

Nuclear submarines measured it, but it was a Cold War secret!

Declassified in mid-90s.
International Polar Year: 50th Anniversary of International Geophysical Year (IGY)
News on the Antarctic Warming Front

Earth’s fastest warming trend on Antarctic Peninsula: 2.5°C in 50 yr

But Antarctica as a whole is not warming

Antarctic sea ice area not decreasing

Some huge West Antarctic outflow ice streams are accelerating and slumping

Some monster Antarctic icebergs have calved recently... but our history is short.
On northern thumb of Antarctica, warming surface temperatures created melt ponds on the surface. Surface water filled crevasses, then froze, cracking the ice entirely through.

21 Feb 2000 Landsat 7 image
Larsen-B Ice Shelf Collapse

January 31, 2002

February 17, 2002

March 5, 2002

March 17, 2002

size of Rhode Island
Wilkins Ice Shelf Collapse, Feb 2008
Wilkins Ice Shelf Collapse, Feb 2008
News on the Arctic warming front

40% thinning, Arctic sea ice, 1950s to 2007

10%/decade reduction in surface area, sea ice

0.6°C/decade temperature increase since 1960s in high northern latitudes

Greenland warming has finally surpassed the warmth of the 1930s.

Greenland melted all over, July 2012.
IPY Movie: Changes in the Arctic
Themes from movie

GLIMS glaciers: 97% shrinking

Arctic sea ice shrinking

Permafrost

Greenland; Jacobshaven retreat accelerating

Snow cover; water storage

Colorado: green 2003, drought 2004 + fires

Snow/ice keep Earth cool
Jacobshavn Glacier retreat to 2006
Arctic avg temp change, 1900 to 2000
Observed Arctic climate change fingerprints

Polar amplification: Arctic air temp’s rising 2-3x faster than rest of world

Arctic sea ice thickness, extent collapsing

Arctic glaciers retreating

Shrubs expanding, tree line moving north

Tundra shifting from CO2 sink to source

Permafrost temp’s rising
Global Land Ice Meas’t from Space (GLIMS)

160,000 glaciers

Vast majority not monitored on ground

GLIMS uses mainly ASTER data

Over half of glaciers now outlined

Many errors, eg stopping at political boundary
Rapidly declining sea ice minimum – 1984
Rapidly declining sea ice minimum – 2012
18 IPCC models, 2007

No summer ice by 2030?
Permafrost: soil/rock below 0°C for 2+ yr

Permafrost:
Soil or rock that remains below freezing for two or more years

IPA Permafrost Distribution Map

Continuous (90 – 100% coverage)
Discontinuous (50 – 90%)
Sporadic (10 – 50%)
Isolated (0 – 10%)

Brown et al. 1998
CCSM3 Projections of Degradation of Near-Surface Permafrost

CCSM3 Modeled Near-Surface Permafrost
- 1980-1999 (20thC)
- 2080-2099 (SRES A1B)

Area Containing Near-Surface Permafrost

- 20thC
- SRES A2
- SRES A1B
- SRES B1
- Commit

Summer 2013
Release of carbon stored in permafrost

- 200 – 800 Pg C

More wetlands $\rightarrow$ CH4

More drylands $\rightarrow$ CO2

At one Swedish bog, ~50% rise in CH4, 1970 to 2000

\[ \text{Release of Soil Carbon Frozen in Permafrost} \]

- ~200 – 800 Pg C frozen in permafrost soil
- Increased wetlands, anaerobic microbial activity $\rightarrow$ CH4 emissions
- Dry, well-drained soil, aerobic decomposition $\rightarrow$ CO2 emissions
- At one Swedish mire, permafrost and vegetation changes linked with 22-66% rise in CH4 emissions (1970 to 2000, Christensen et al. 2004).