Evolution not Revolution: Charting a realistic path forward?

Gavin Schmidt, NASA GISS
Wouldn’t it be great if…

…there was an overarching theory that predicted climate sensitivity from first principles?

…we could design parameterizations that always gave the right emergent response?

… GCMs were more aesthetically pleasing?

…no people were involved in scientific progress?
Global-scale Coupled Climate Models

- Interactive vegetation
- Dust/sea spray/carbon aerosols
- Upper atmosphere
- Atmospheric chemistry
- Atmospheric/land surface
- Ocean
- Sea ice
- Sulphate aerosol
- Biogeochemical cycles
- Carbon cycle
- Marine ecosystems
- Ice sheets


Note: There were some very simplified models before the dates mentioned.
14 Orders of Magnitude

10^{11} s

Sub-scale processes

10^{-6} m

10^{-3} s

10^{8} m

Resolved Physics

Climate Models

Weather Models

Climate Models 1990s

Climate Models 2010s
### GISS-E2 Contributions to CMIP5

<table>
<thead>
<tr>
<th>Experiment</th>
<th>years/expt</th>
<th>No. of simulations</th>
<th>total model years</th>
<th>archive size (TB)</th>
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<tbody>
<tr>
<td>historical+Ext</td>
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<td>36</td>
<td>5832</td>
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<tr>
<td>rcp26</td>
<td>95+200</td>
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<td>885</td>
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<td>15810</td>
<td>13</td>
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<tr>
<td>amip</td>
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<td>12</td>
<td>1860</td>
<td>2.5</td>
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<td>1pctCO2</td>
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<td>abrupt4xCO2</td>
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<td>6</td>
<td>900</td>
<td>0.5</td>
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<td>Spin-ups</td>
<td>~500</td>
<td>~11</td>
<td>~5500</td>
<td>N/A</td>
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<tr>
<td>Controls</td>
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<td>8</td>
<td>8000</td>
<td>3.7</td>
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<tr>
<td>Total</td>
<td></td>
<td>228</td>
<td>~ 66K</td>
<td>~50</td>
</tr>
</tbody>
</table>

6 model versions:
- 2 x oceans
  - Russell
  - HYCOM
3 x atm.
composition:
- non-interactive
- interactive
- including parameterised AIE

Multiple forcings:
- single forcings
- collections
- alternates
Issues/needs

Better coordinated data analytics
GCMs in DA
Parameterization development and tuning
Paleo-climate “out of sample” tests
Complexity and Coherence
Exploration of structural uncertainty
(= “arbitrary and ad hoc coding decisions”)

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The process-based diagnostic challenge

Imagine....

Reanalysis: find mid-latitude storms
Satellites: Create composite
Models: Create composite
Models: Create pseudo-satellite views
Compare processes...

Estimated completion time using current technology?

Years.

Need multivariate/parallel time-space-model-ensemble member filter combined with multi-variate compositing/analysis

Bauer and Del Genio, 2006
Multiple, diverse single column case studies: LES $\rightarrow$ SCM $\rightarrow$ GCM

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Case study</th>
</tr>
</thead>
<tbody>
<tr>
<td>dry convective boundary layer</td>
<td>idealized [Bretherton and Park 2009]</td>
</tr>
<tr>
<td>dry stable boundary layer</td>
<td>GABLS1 [Bretherton and Park 2009]</td>
</tr>
<tr>
<td>marine stratocumulus</td>
<td>DYCOMS-II RF02 [Ackerman et al. 2009]</td>
</tr>
<tr>
<td>marine trade cumulus (shallow)</td>
<td>BOMEX [Siebesma et al. 2003]</td>
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<tr>
<td>marine trade cumulus (deep, raining)</td>
<td>RICO [van Zanten et al. 2011]</td>
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<td>marine stratocumulus-to-cumulus transition</td>
<td>SCT [Sandu and Stevens 2011]</td>
</tr>
<tr>
<td>continental cumulus</td>
<td>RACORO [Vogelmann et al. 2015]</td>
</tr>
<tr>
<td>Arctic mixed-phase stratus</td>
<td>M-PACE [Klein et al. 2009]</td>
</tr>
<tr>
<td>mid-latitude synoptic cirrus</td>
<td>SPARTICUS [MÄ¼hlbauer et al. 2014]</td>
</tr>
<tr>
<td>tropical deep convection</td>
<td>TWP-ICE [Fridlind et al. 2012]</td>
</tr>
<tr>
<td>continental deep convection</td>
<td>EUROCS II [Guichard et al. 2004]</td>
</tr>
</tbody>
</table>
Stratocumulus to trade-cumulus transition

LES

E2.1

E3 alpha

E3
Big improvements in representation of MJO

The most significant improvement that AR5a has compared to AR4a is its simulation of the Kelvin mode. The Kelvin mode in AR5a is similar to that in observations in the tropics. This result is consistent with those of Kim et al. (2011b), who showed that models with stronger MJOs also had a cold bias in the upper troposphere relative to observations.

The strong-MJO period is characterized by enhanced stability in the troposphere. This is consistent with the decrease in entrainment rate (from AR5a_Ent1 to AR5a) as the MJO cooling below so that the mass-weighted average of the tropospheric temperature from the first day of simulation.

The warming aloft is greater than the cooling below so that the mass-weighted average of the tropospheric temperature from the first day of simulation. It is also had a cold bias in the upper troposphere relative to observations and several versions of Model E2. Our focus is on the signals distinct from the background spectrum in the wavenumber–frequency spectra of equatorial precipitation from observations and several versions of Model E2.

The symmetric component of precipitation divided by the background spectrum for the space–time spectrum of the 15-day (the last being defined as wavenumbers 1–3, periods 30–60 days) that can be found in the observations.

CMIP6: GISS-E2.1-R uses higher horizontal resolution than that in AR5a. C_AR5a (Fig. 3d) represents a version of Model E2 that lacks the MJO mode.

(Wheeler-Kiladis diagrams extended from Kim et al, 2012)
Self-generating stratospheric QBO

Tropical winds in lower stratosphere

102 Layers + Model Top 0.002 hPa

Rind et al (2014)
Comparison of vertical profile of cloud ice w/CloudSat

![Comparison of vertical profile of cloud ice w/CloudSat](image)
Representation of Volcanic Forcings: CMIP5 to CMIP6

CMIP5: Prescribed Stratospheric Volcanic AOD, Sato et al 1993, and updates
CMIP6: Prescribed Stratospheric Volcanic AOD, Luo et al (CMIP6 protocol)
Emission driven: Historical VolcanEESM (Neely, Schmidt, 2016)
Solar-only regression (~70 cycles)

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Solar cycle response of temperature (Lag 0)

Solar cycle response of specific humidity (Lag 2)
GISS modeling summary

Major improvements in atmospheric properties since CMIP5
Better representation of key modes of variability
Deeper understanding of forcing mechanisms and uncertainties
Greater potential for exploring interactions (solar/QBO/MJO/AO, Volcano/QBO/ENSO etc.)
**GCM Parameterization Tuning: incorporating knowledge of observational uncertainty**

Incorporate obs. bias into \( W \) (i.e. key component of our work: develop a regime- or region-aware weighting; penalize model less where observational biases are larger)

\[
E^2 = \frac{1}{W} \sum_i \sum_j \sum_t w_{i,j,t} (F_{i,j,t} - R_{i,j,t})^2
\]

\( E \) is “model goodness” metric; \( F \) is the model field; \( R \) is the reference/truth; \( W \) is the weighting term.

*Observational bias \( \neq \) retrieval product uncertainty estimates.

Use smart sampler to adjust parameters and find local maxima in goodness…

Elsaesser et al (in prep)
Relationship between different measures of present-day model skill

Santer et al, 2012
“… from what has actually been, we have data for concluding with regard to that which is to happen thereafter.”

James Hutton (1788)
Land-Ocean contrasts are robust in past and future

Masa Kageyama (Schmidt et al, 2014)
A lake burst 8000 years ago...

...changed ocean circulation and left traces in Greenland ice...

... providing an out-of-sample test for the same models that predict ocean, dust and CH$_4$ changes in the future.
Points I’d like to make

Enhanced data analytics goes hand in hand with more efficient model development

Paleo-climate “out of sample” tests remain essential for building credibility in projections

Need to increase complexity and coherence

Exploring structural uncertainty is essential

Current efforts may not be totally optimal, but they are headed in the right direction