

Cyberinfrastructure for Earth-System Modeling

James B White III (Trey)
trey@ucar.edu

Arkansas State University CI-Days
October 31, 2011

Clip art courtesy of "<http://commons.wikimedia.org/>"



U.S. DEPARTMENT OF
ENERGY

Office of
Science

Cyberinfrastructure for Earth-System Modeling

Community Earth System Model (CESM)

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U.S. DEPARTMENT OF
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Intergovernmental Panel on Climate
Change Assessment Report 4
(IPCC AR4)

Prologue

Think back in time 6 generations...



2004



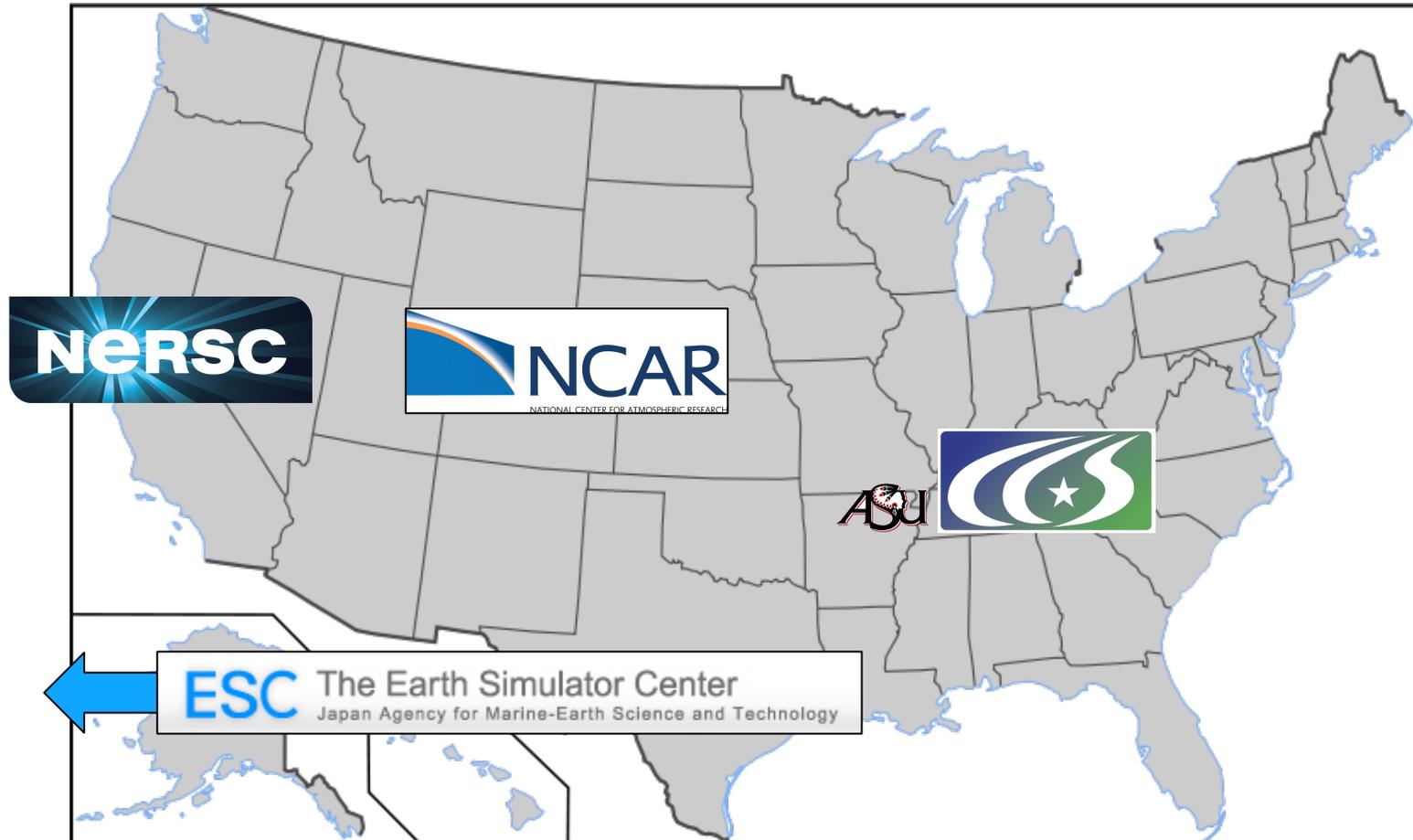
<http://upload.wikimedia.org/wikipedia/commons/1/18/EarthSimulator.jpg>
<https://www.llnl.gov/news/newsreleases/2006/NR-06-11-04.html>
http://commons.wikimedia.org/wiki/File:Roadrunner_supercomputer_HiRes.jpg
<http://www.olcf.ornl.gov/media-center/image-gallery/?album=1&gallery=1>
http://www.china.org.cn/china/2010-11/18/content_21368800.htm
<http://www.fujitsu.com/global/about/tech/k/>



Climate Science, Circa 2004

- Is the global climate warming?
- If so, are people causing the warming?

CCSM3 Runs for AR4



<http://www.jamstec.go.jp/esc/download/index.en.html>

<http://www.nersc.gov/assets/Logos/NERSClogocolor.png>

<https://wiki.ucar.edu/display/wag/Logos+for+Web+and+Print>

http://www.nccs.gov/wp-content/media/gallery/logos/nccs/NCCS_nolettering_logo.jpg

<http://www.sportslogos.net/logo.php?id=6816>

 *You would have been here.*

ORNL CCS Cheetah, Circa 2004

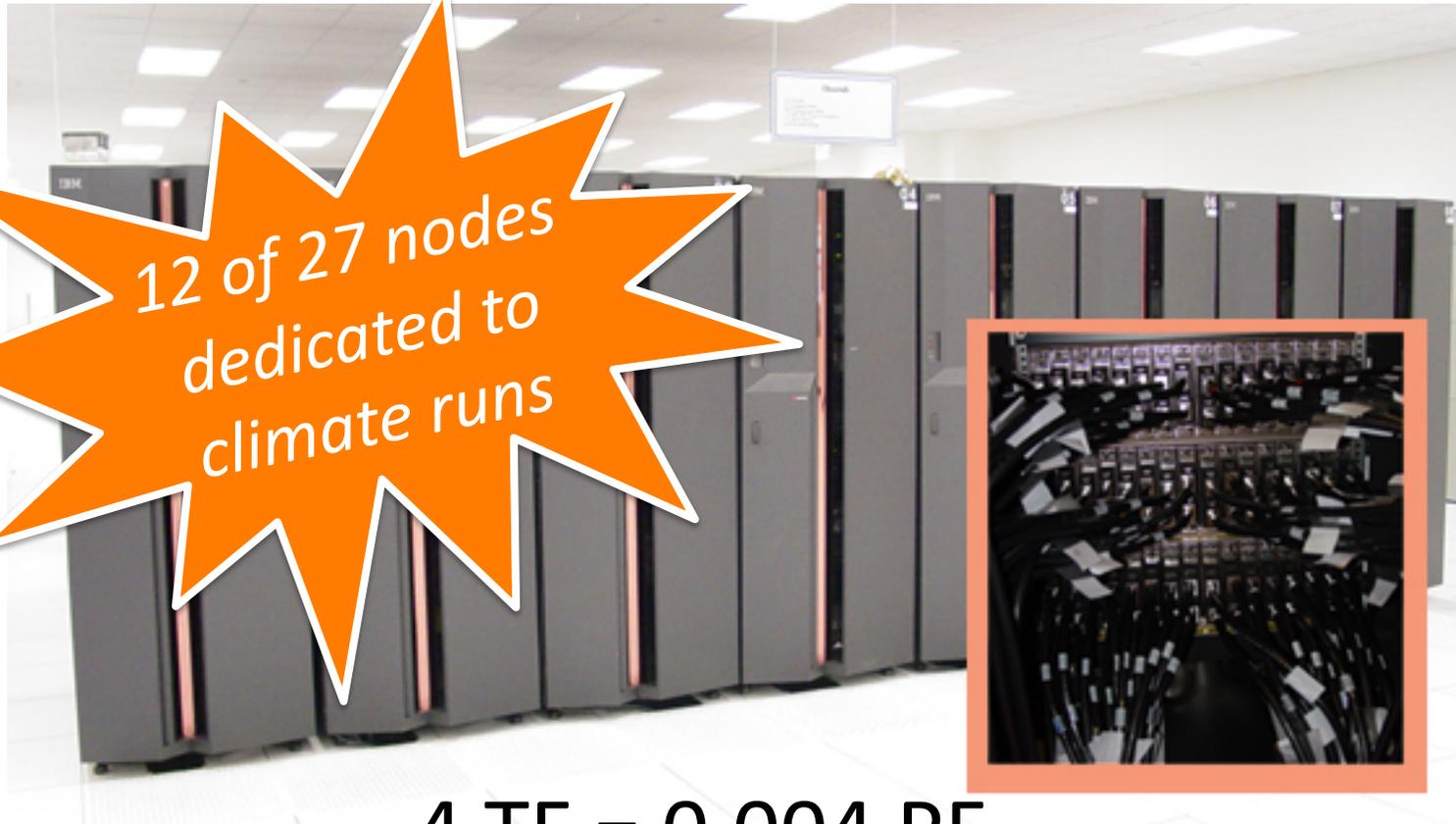
<http://www.ccs.ornl.gov/images/Cheetah-Fed.jpg>



4 TF = 0.004 PF

ORNL CCS Cheetah, Circa 2004

<http://www.ccs.ornl.gov/images/Cheetah-Fed.jpg>



12 of 27 nodes
dedicated to
climate runs

4 TF = 0.004 PF

ORNL CCS Cheetah, Circa 2004

<http://www.ccs.ornl.gov/images/Cheetah-Fed.jpg>

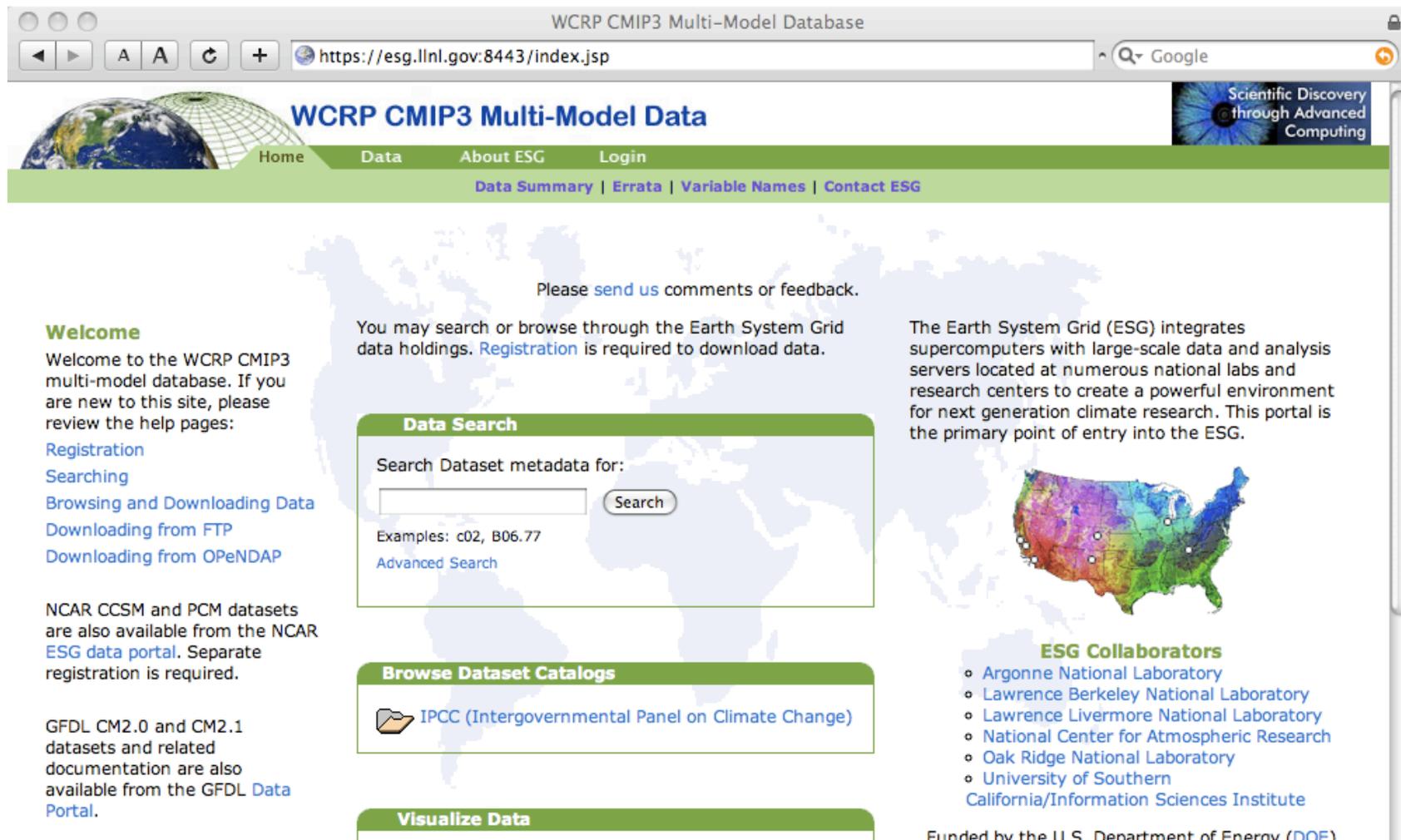


12 of 27 nodes
dedicated to
climate runs

384 cores!

4 TF = 0.004 PF

Earth System Grid



WCRP CMIP3 Multi-Model Database

https://esg.llnl.gov:8443/index.jsp

Google

WCRP CMIP3 Multi-Model Data

Home Data About ESG Login

[Data Summary](#) | [Errata](#) | [Variable Names](#) | [Contact ESG](#)

Please [send us](#) comments or feedback.

You may search or browse through the Earth System Grid data holdings. [Registration](#) is required to download data.

The Earth System Grid (ESG) integrates supercomputers with large-scale data and analysis servers located at numerous national labs and research centers to create a powerful environment for next generation climate research. This portal is the primary point of entry into the ESG.

Welcome

Welcome to the WCRP CMIP3 multi-model database. If you are new to this site, please review the help pages:

- [Registration](#)
- [Searching](#)
- [Browsing and Downloading Data](#)
- [Downloading from FTP](#)
- [Downloading from OPeNDAP](#)

NCAR CCSM and PCM datasets are also available from the NCAR [ESG data portal](#). Separate registration is required.

GFDL CM2.0 and CM2.1 datasets and related documentation are also available from the GFDL [Data Portal](#).

Data Search

Search Dataset metadata for:

Examples: c02, B06.77
[Advanced Search](#)

Browse Dataset Catalogs

 [IPCC \(Intergovernmental Panel on Climate Change\)](#)

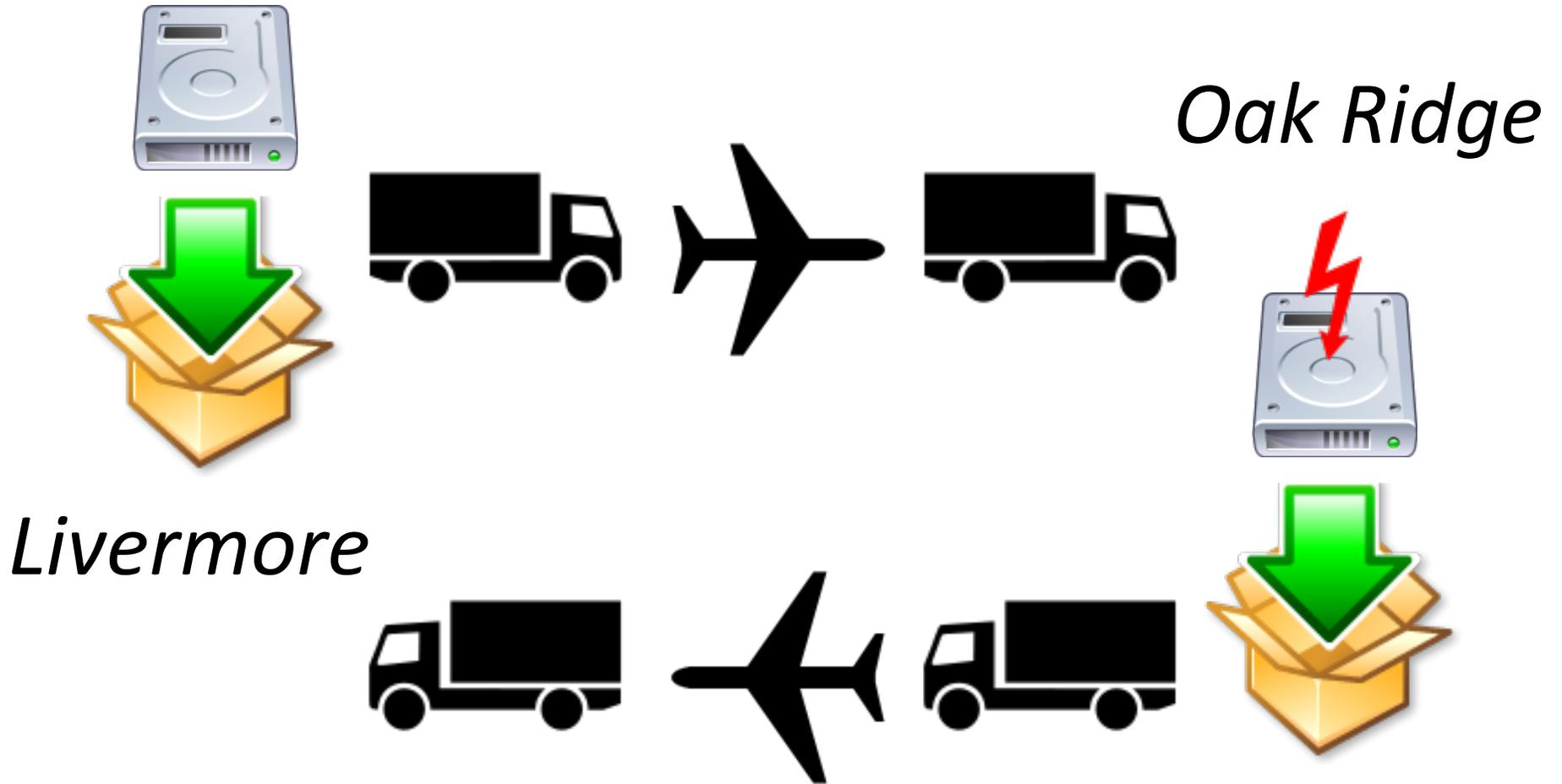
Visualize Data

ESG Collaborators

- [Argonne National Laboratory](#)
- [Lawrence Berkeley National Laboratory](#)
- [Lawrence Livermore National Laboratory](#)
- [National Center for Atmospheric Research](#)
- [Oak Ridge National Laboratory](#)
- [University of Southern California/Information Sciences Institute](#)

Funded by the U.S. Department of Energy (DOE)

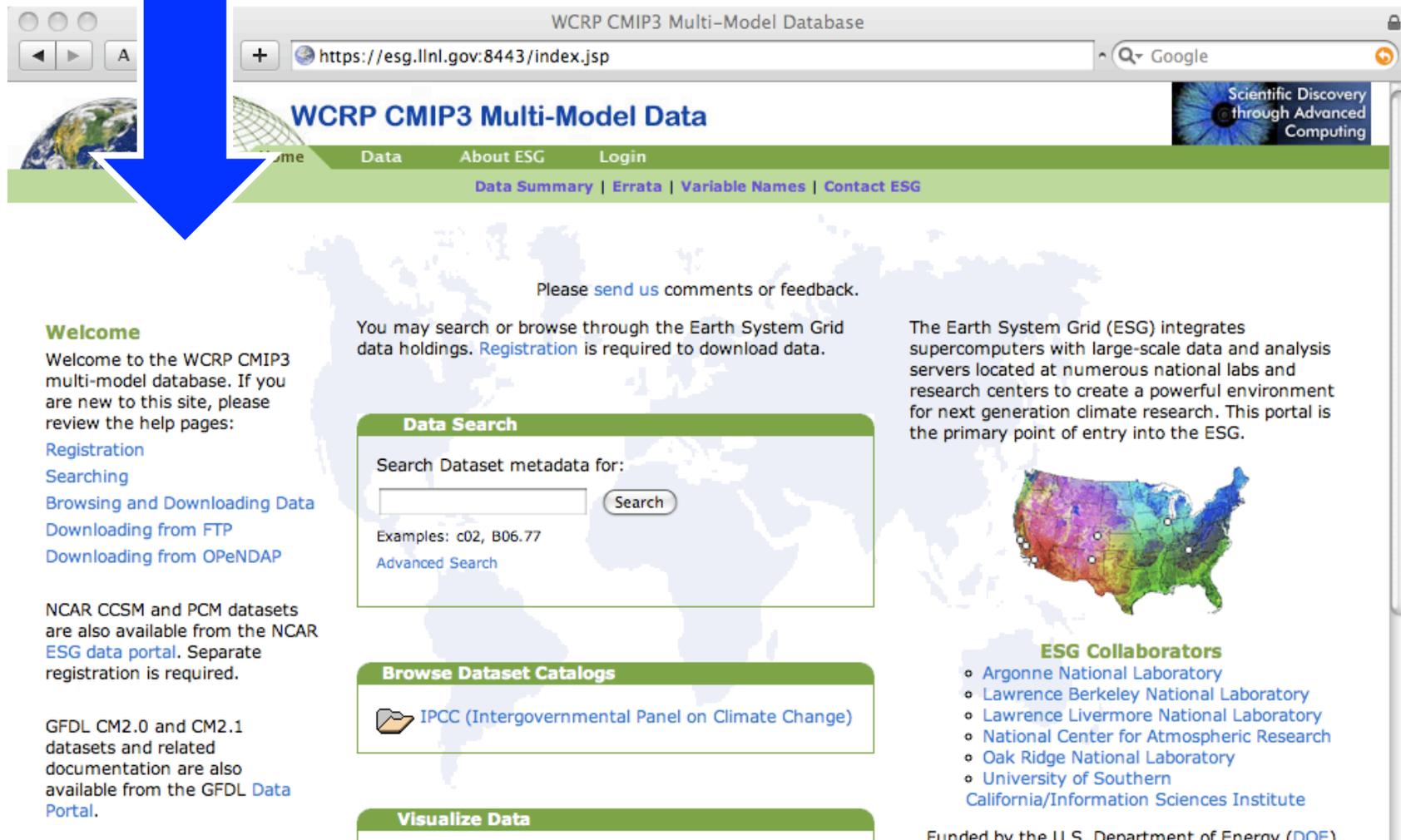
Network Diagram



17 TB

35 TB total

Earth System Grid



WCRP CMIP3 Multi-Model Database

https://esg.llnl.gov:8443/index.jsp

WCRP CMIP3 Multi-Model Data

Scientific Discovery through Advanced Computing

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- [University of Southern California/Information Sciences Institute](#)

Funded by the U.S. Department of Energy (DOE)

Earth System Grid

17 TB

35 TB total

2500+ scientists

550+ papers

WCRP CMIP3 Multi-Model Database

https://esg.llnl.gov:8443/index.jsp

WCRP CMIP3 Multi-Model Data

Home | Data | About ESG | Login

[Data Summary](#) | [Errata](#) | [Variable Names](#) | [Contact ESG](#)

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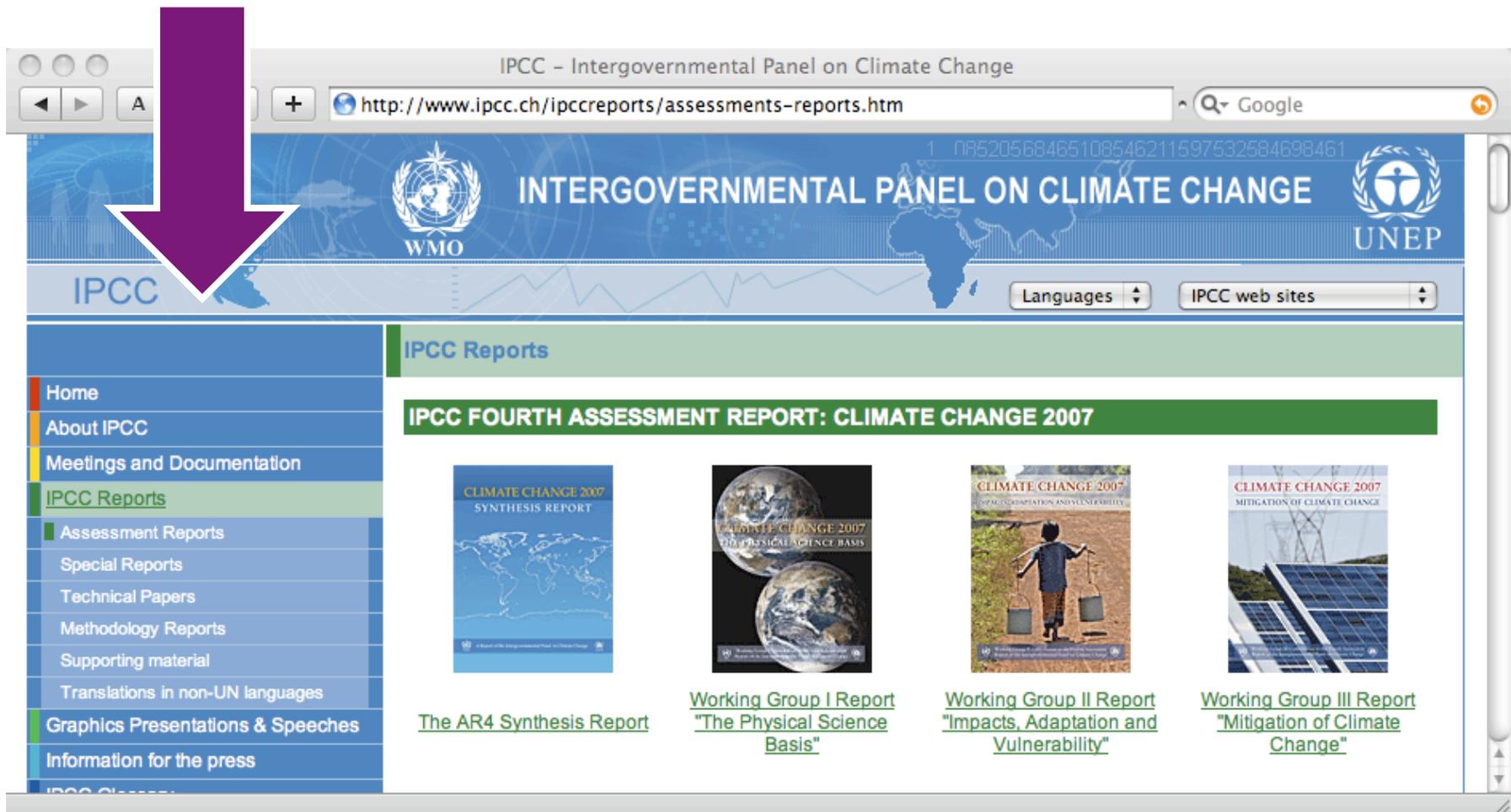
ESG Collaborators

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- Lawrence Livermore National Laboratory
- National Center for Atmospheric Research
- Oak Ridge National Laboratory
- University of Southern California/Information Sciences Institute

Funded by the U.S. Department of Energy (DOE)

Intergovernmental Panel on Climate Change

papers



The screenshot shows the IPCC website interface. At the top, the browser address bar displays the URL <http://www.ipcc.ch/ipccreports/assessments-reports.htm>. The main header features the IPCC logo, the text "INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE", and the logos for WMO and UNEP. Below the header, a navigation menu on the left lists various sections, with "IPCC Reports" highlighted in green. A large purple arrow points from the word "papers" to the "IPCC Reports" link in the menu. The main content area is titled "IPCC Reports" and features a green banner for the "IPCC FOURTH ASSESSMENT REPORT: CLIMATE CHANGE 2007". Below this banner, four report covers are displayed with their respective titles:

- [The AR4 Synthesis Report](#)
- [Working Group I Report "The Physical Science Basis"](#)
- [Working Group II Report "Impacts, Adaptation and Vulnerability"](#)
- [Working Group III Report "Mitigation of Climate Change"](#)

Intergovernmental Panel on Climate Change

papers



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IPCC – Intergovernmental Panel on Climate Change

http://www.ipcc.ch/ipccreports/assessments-reports.htm

Google

1 08520568465108546211597532584698461

INTERGOVERNMENTAL PANEL ON CLIMATE CHANGE

WMO UNEP

IPCC Languages IPCC web sites

IPCC Reports

- Home
- About IPCC
- Meetings and Documentation
- IPCC Reports**
 - Assessment Reports
 - Special Reports
 - Technical Papers
 - Methodology Reports
 - Supporting material
 - Translations in non-UN languages
- Graphics Presentations & Speeches
- Information for the press
- IPCC Glossary

CLIMATE CHANGE 2007 SYNTHESIS REPORT

CLIMATE CHANGE 2007 THE PHYSICAL SCIENCE BASIS

CLIMATE CHANGE 2007 IMPACTS, ADAPTATION AND VULNERABILITY

CLIMATE CHANGE 2007 MITIGATION OF CLIMATE CHANGE

[The AR4 Synthesis Report](#)

[Working Group I Report "The Physical Science Basis"](#)

[Working Group II Report "Impacts, Adaptation and Vulnerability"](#)

[Working Group III Report "Mitigation of Climate Change"](#)

Intergovernmental Panel on Climate Change

papers



Yes. *And yes.*

IPCC Reports

- Home
- About IPCC
- Meetings and Documentation
- IPCC Reports**
 - Assessment Reports
 - Special Reports
 - Technical Papers
 - Methodology Reports
 - Supporting material
 - Translations in non-UN languages
- Graphics Presentations & Speeches
- Information for the press

The AR4 Synthesis Report

Working Group I Report "The Physical Science Basis"

Working Group II Report "Impacts, Adaptation and Vulnerability"

Working Group III Report "Mitigation of Climate Change"

Intergovernmental

Climate

papers



Yes.

All yes.

The screenshot shows the IPCC Reports website. The left sidebar contains a navigation menu with the following items: Home, About IPCC, Meetings and Documentation, IPCC Reports (highlighted), Assessment Reports, Special Reports, Technical Papers, Methodology Reports, Supporting material, Translations in non-UN languages, Graphics Presentations & Speeches, Information for the press, and IPCC Glossary. The main content area is titled 'IPCC Reports' and features four report covers:

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- Working Group I Report "The Physical Science Basis"**: Cover of the 'CLIMATE CHANGE 2007 THE PHYSICAL SCIENCE BASIS'.
- Working Group II Report "Impacts, Adaptation and Vulnerability"**: Cover of the 'CLIMATE CHANGE 2007 IMPACTS, ADAPTATION AND VULNERABILITY'.
- Working Group III Report "Mitigation of Climate Change"**: Cover of the 'CLIMATE CHANGE 2007 MITIGATION OF CLIMATE CHANGE'.

Climate Science, Circa 2004

- Is the global climate warming? *Yes.*
- If so, are people causing the warming? *Yes.*

IPCC Assessment Report 5 (AR5)

IRON CHEF

INTERGOVERNMENTAL

episode 5

IRON CHEF

INTERGOVERNMENTAL

episode 5



Iron Chef Intergovernmental #5

- CMIP5 defines experiments
- Develop a model
- Run experiments
- Provide simulation output
- Scientists worldwide analyze output
- Scientists worldwide publish papers
- AR5 authors cite papers

Iron Chef Intergovernmental #5

???

- CMIP5 defines experiments
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Climate Model Intercomparison Project, Phase 5 (CMIP5)



The image is a screenshot of a web browser window. The address bar shows the URL: http://www.wmo.int/pages/prog/wcrp/documents/WCRPnews_20081015.pdf. The browser's search bar contains the text "Google". The main content area features the WCRP NEWS logo, which includes the text "WCRP NEWS" in a large, bold, pink and grey font, with "World Climate Research Programme" written below it. To the right of the logo is a small globe icon. Below the logo is a horizontal line, and to the right of this line is a solid pink vertical bar. Underneath the logo and bar are the logos for WMO, IOC, and ICSU. The main heading of the article is "CMIP5: Preparing climate simulations and projections for the Fifth IPCC Assessment Report", dated "16.10.2008". The text of the article begins with "The World Climate Research Programme's Working Group on Coupled Modelling (WGCM) held a historic meeting in Paris, France on 22-24 September 2008 where representatives from 20 of the global coupled climate modelling centres from around the world were invited to hear about the next climate model intercomparison project (CMIP5). CMIP5, proposed and". A grey box with the text "Climate model intercomparisons" is partially visible at the bottom right of the page.

http://www.wmo.int/pages/prog/wcrp/documents/WCRPnews_20081015.pdf

WCRP NEWS
World Climate Research Programme

WMO IOC ICSU
International Council for Science

CMIP5: Preparing climate simulations and projections for the Fifth IPCC Assessment Report
16.10.2008

The World Climate Research Programme's Working Group on Coupled Modelling (WGCM) held a historic meeting in Paris, France on 22-24 September 2008 where representatives from 20 of the global coupled climate modelling centres from around the world were invited to hear about the next climate model intercomparison project (CMIP5). CMIP5, proposed and

Climate model intercomparisons

Climate Model Intercomparison Project, Phase 5 (CMIP5)

“The grand challenge of the new set of climate models examined in CMIP5 is to resolve **regional climate changes**, particularly in the **next few decades**, to which human societies will have to **adapt**, and to quantify the magnitudes of the **feedbacks** in the climate system, such as feedbacks in the **carbon cycle**.”

The World Climate Research Programme's Working Group on Coupled Modelling (WGCM) held a historic meeting in Paris, France on 22-24 September 2008 where representatives from 20 of the global coupled climate modelling centres from around the world were invited to hear about the next climate model intercomparison project (CMIP5). CMIP5, proposed and

Climate model intercomparisons

Climate Model Intercomparison Project, Phase 5 (CMIP5)

“The advances of CMIP5 compared to CMIP3 include two classes of models which address two time frames and two sets of science questions: i) **decadal prediction** and predictability for the decade to come until 2035; and ii) **long-term climate prediction** until 2100 and beyond.”

16.10.2008

The World Climate Research Programme's Working Group on Coupled Modelling (WGCM) held a historic meeting in Paris, France on 22-24 September 2008 where representatives from 20 of the global coupled climate modelling centres from around the world were invited to hear about the next climate model intercomparison project (CMIP5). CMIP5, proposed and

Climate model intercomparisons

Climate Model Intercomparison Project, Phase 5 (CMIP5)

“Decadal prediction models are **higher in resolution** (50 km) and will therefore address science questions related to **regional climate** and **extremes**.”

World Climate Research Programme



CMIP5: Preparing climate simulations and projections for the Fifth IPCC Assessment Report

16.10.2008

The World Climate Research Programme's Working Group on Coupled Modelling (WGCM) held a historic meeting in Paris, France on 22-24 September 2008 where representatives from 20 of the global coupled climate modelling centres from around the world were invited to hear about the next climate model intercomparison project (CMIP5). CMIP5, proposed and

Climate model intercomparisons

Climate Model Intercomparison Project, Phase 5 (CMIP5)

“In contrast, the models developed for centennial predictions... will include fully coupled **Earth System Models**, addressing climate feedbacks and other large-scale processes. The latter set of models will be driven by new **emission stabilization (mitigation) scenarios...**”

16.10.2008

The World Climate Research Programme's Working Group on Coupled Modelling (WGCM) held a historic meeting in Paris, France on 22-24 September 2008 where representatives from 20 of the global coupled climate modelling centres from around the world were invited to hear about the next climate model intercomparison project (CMIP5). CMIP5, proposed and

Climate model intercomparisons

Climate Model Intercomparison Project, Phase 5 (CMIP5)

Decadal

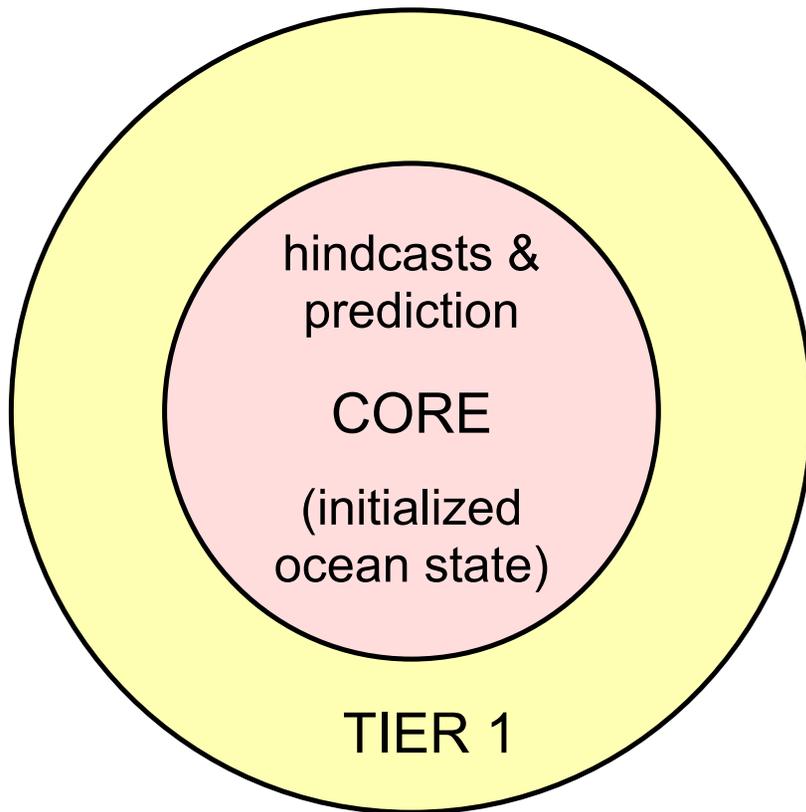
- High resolution
- Regional climate
- Extreme events
- Adaptation

Long Term

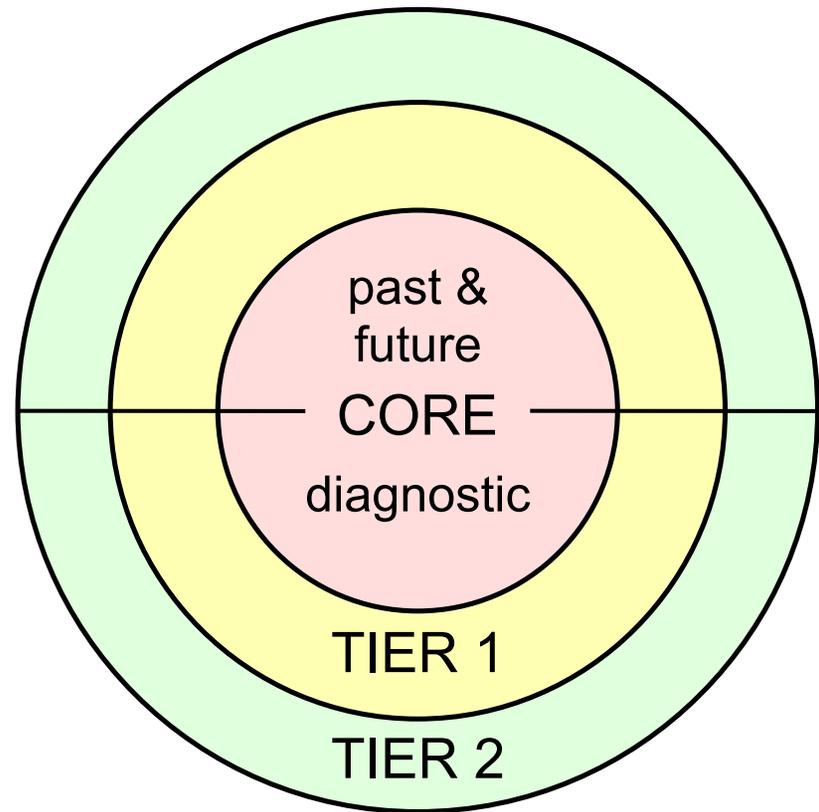
- Earth system
- Climate feedbacks
- Carbon cycle
- Mitigation

CMIP5 Onions

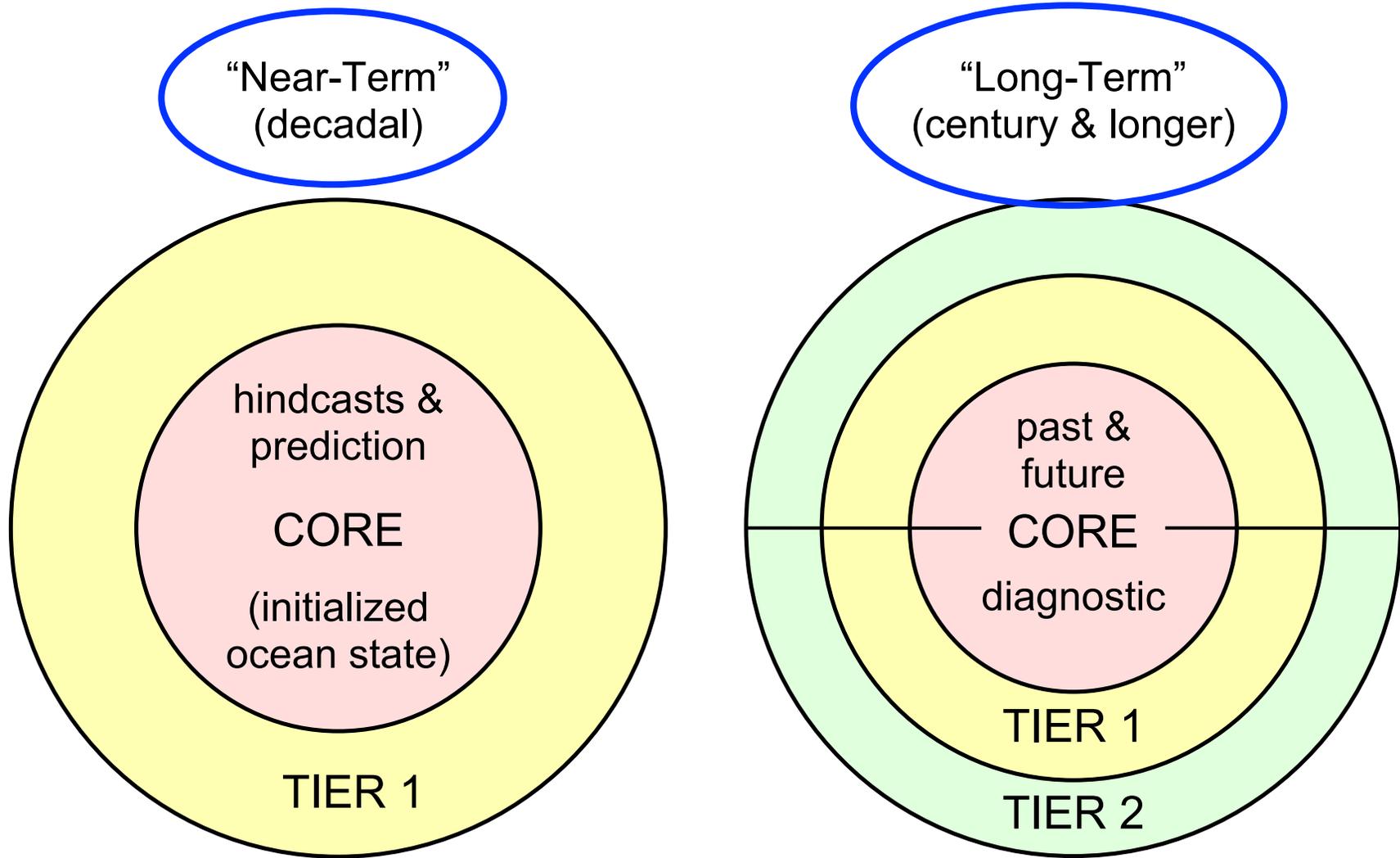
“Near-Term”
(decadal)



“Long-Term”
(century & longer)

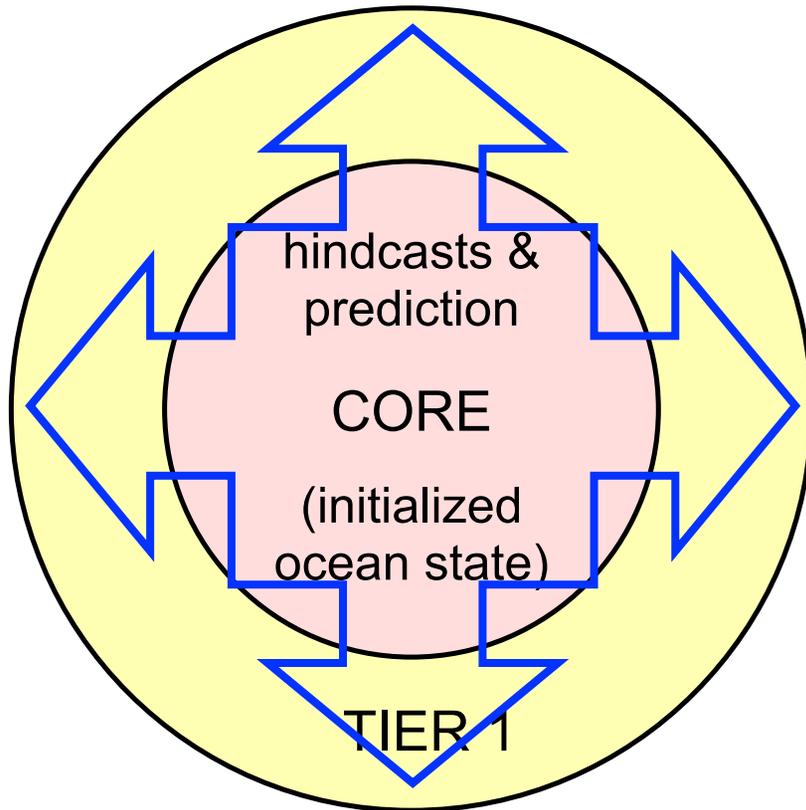


CMIP5 Onions

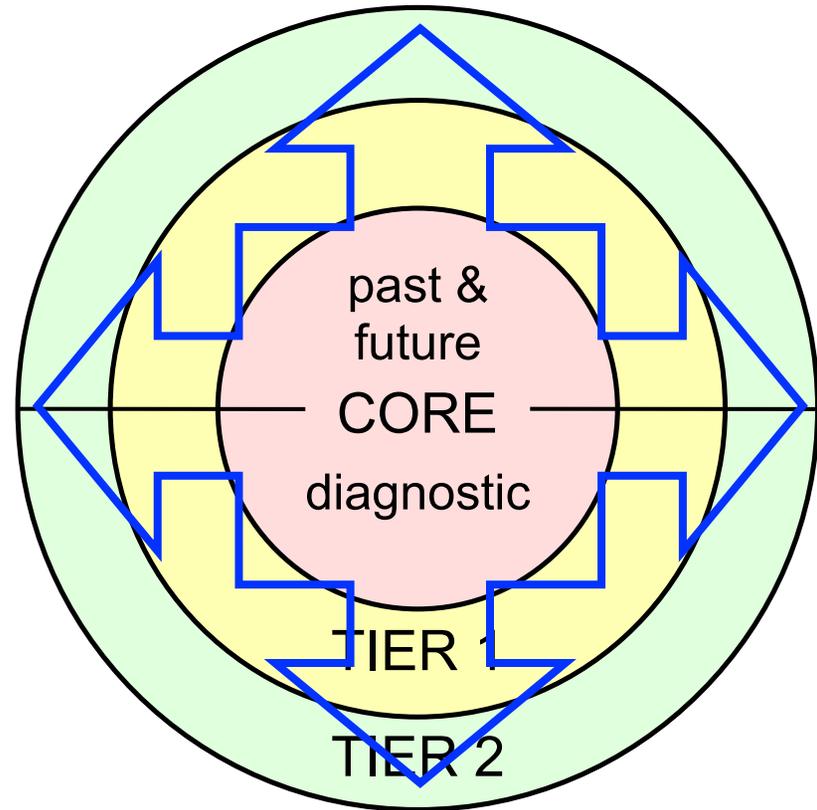


CMIP5 Onions

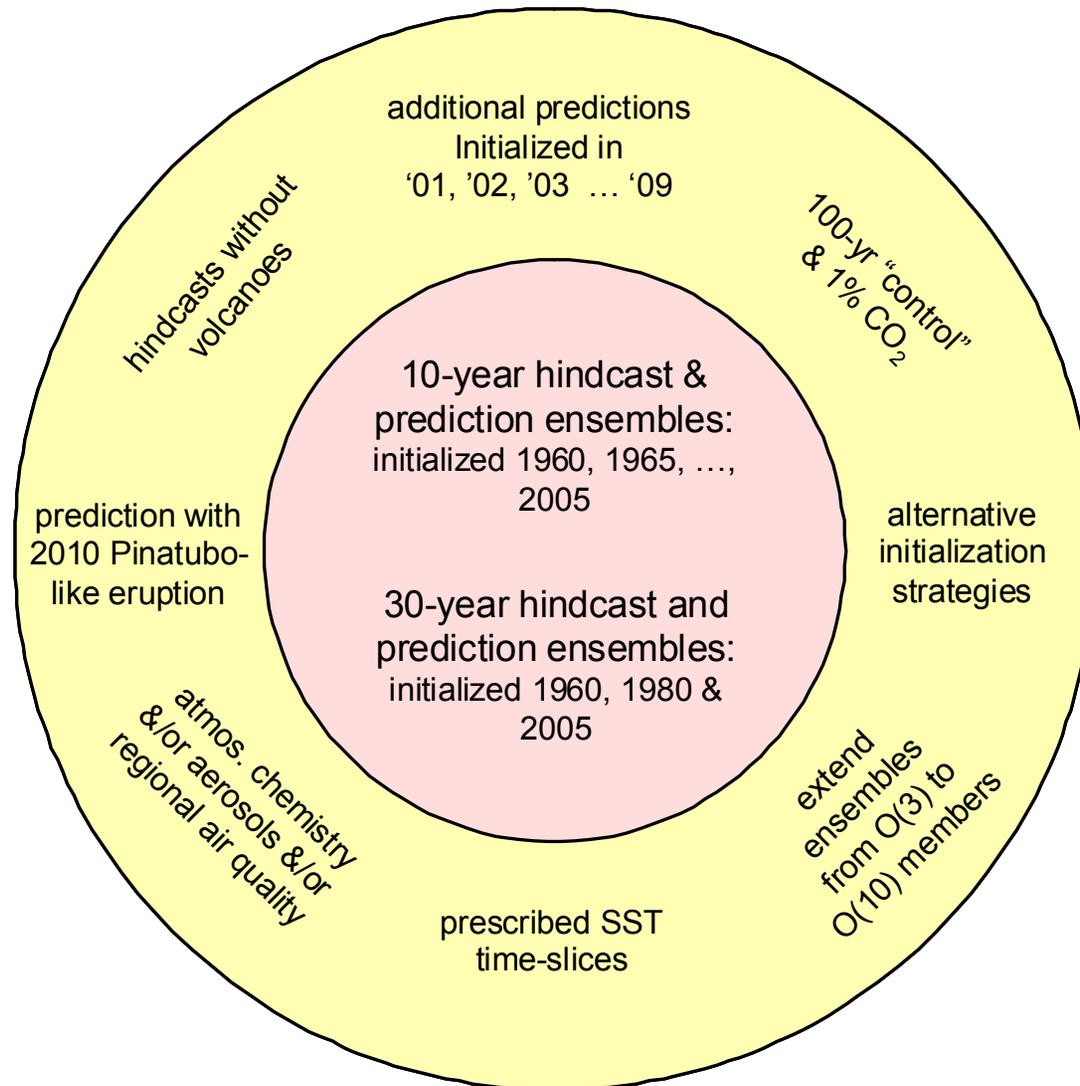
“Near-Term”
(decadal)



“Long-Term”
(century & longer)



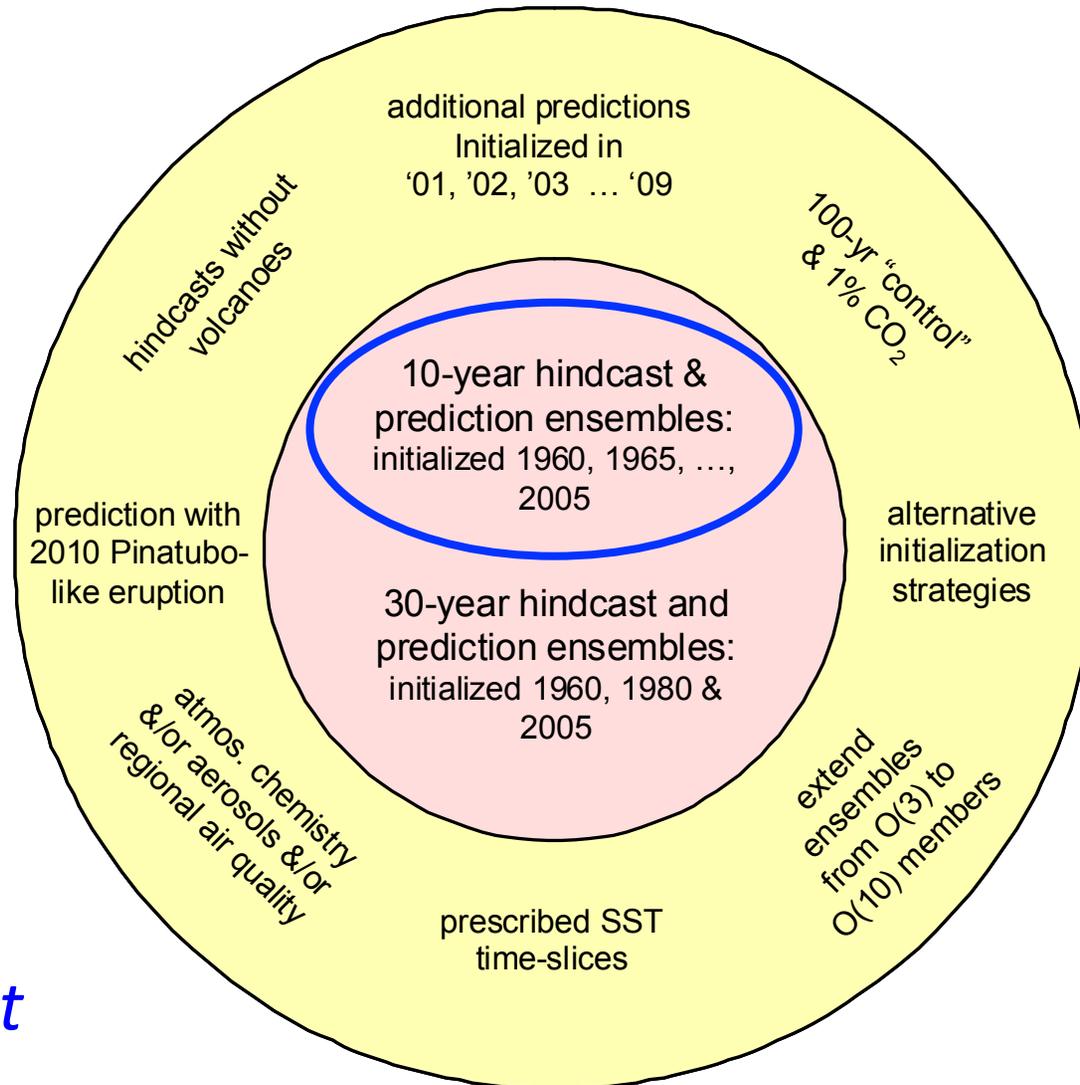
CMIP5 Decadal Onion



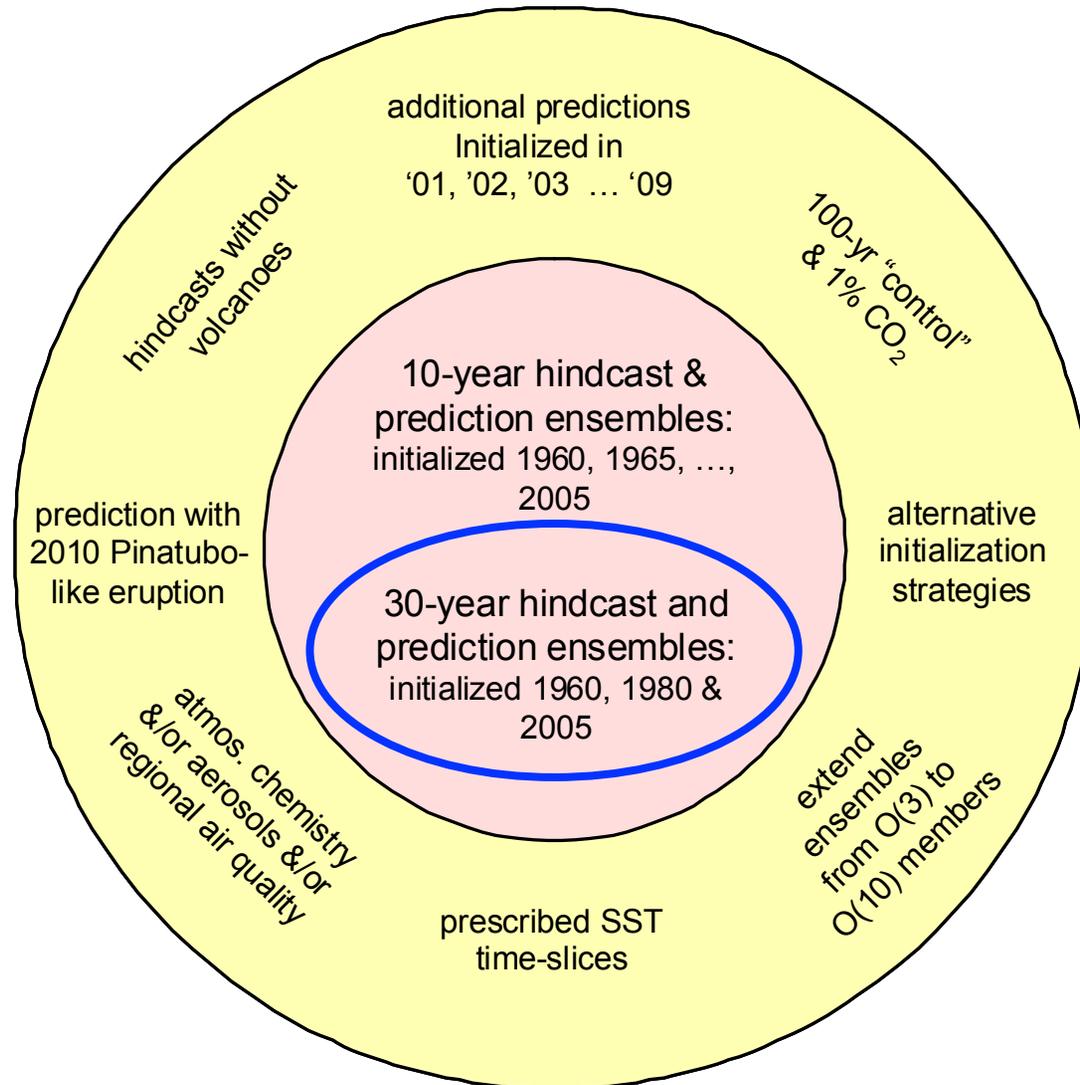
CMIP5 Decadal Onion



*Initial
conditions
matter most*



CMIP5 Decadal Onion

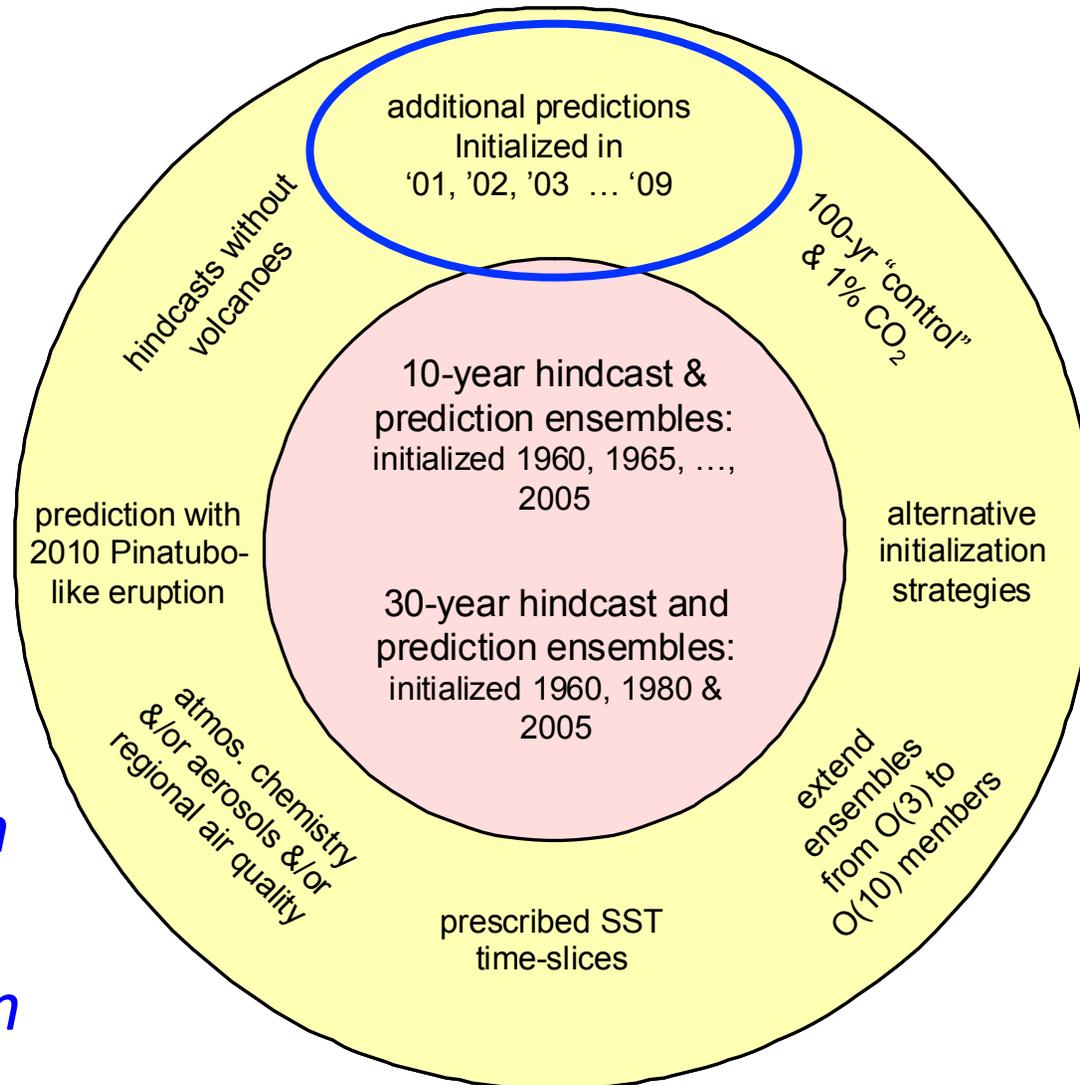


*Forcings
also matter*

CMIP5 Decadal Onion



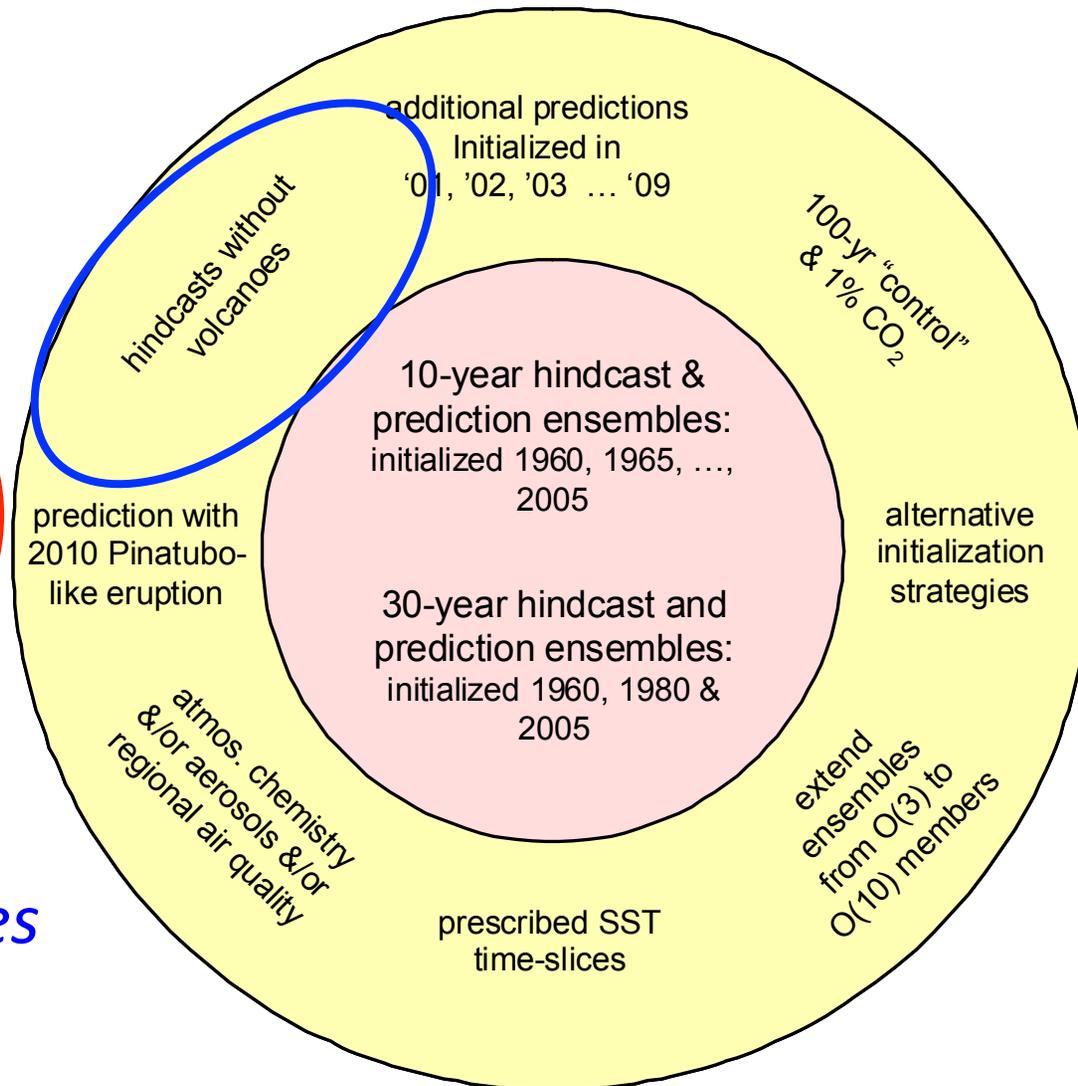
*Good ocean
data for
initialization*



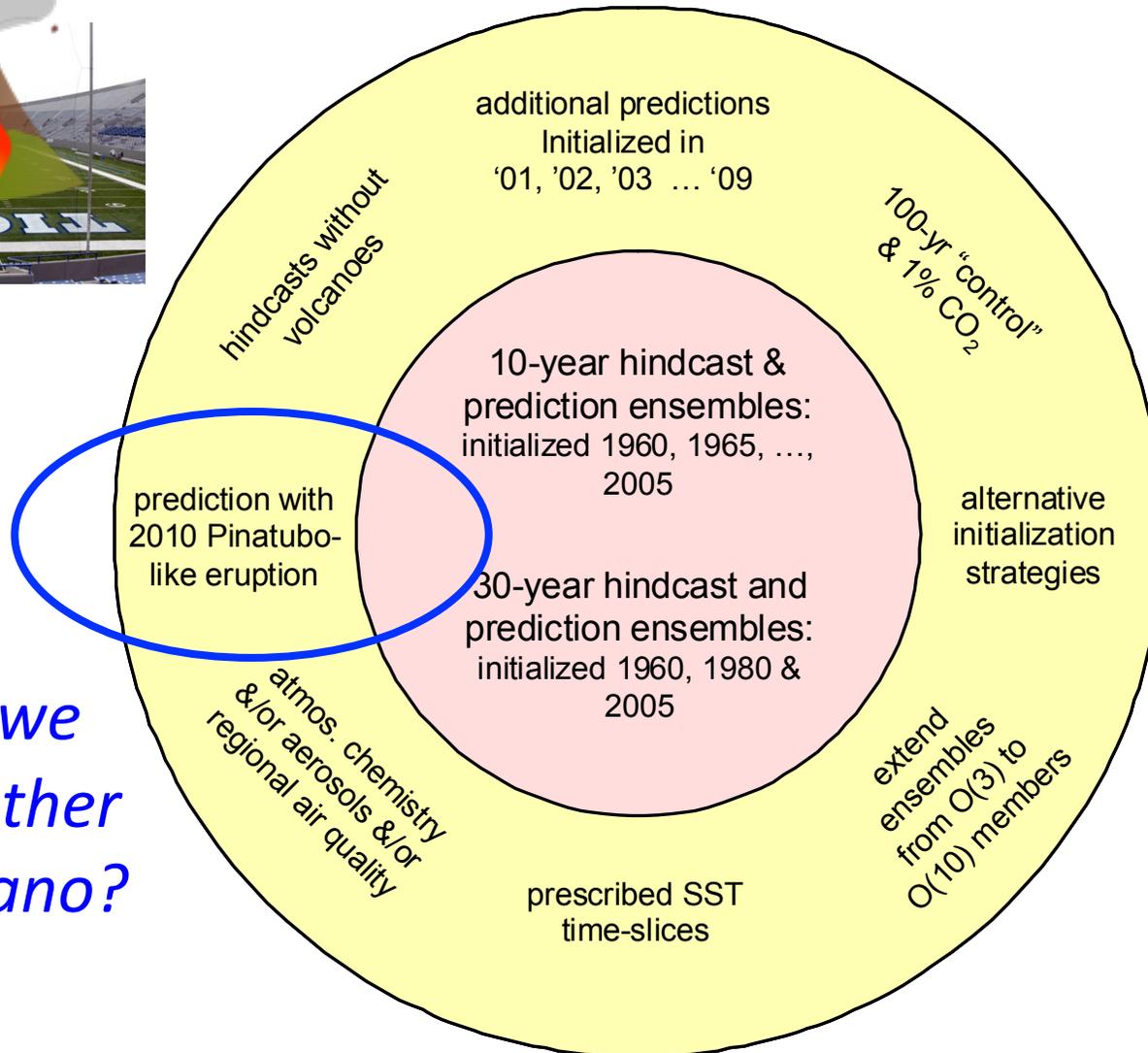
CMIP5 Decadal Onion



*How much
do volcanoes
matter?*



CMIP5 Decadal Onion

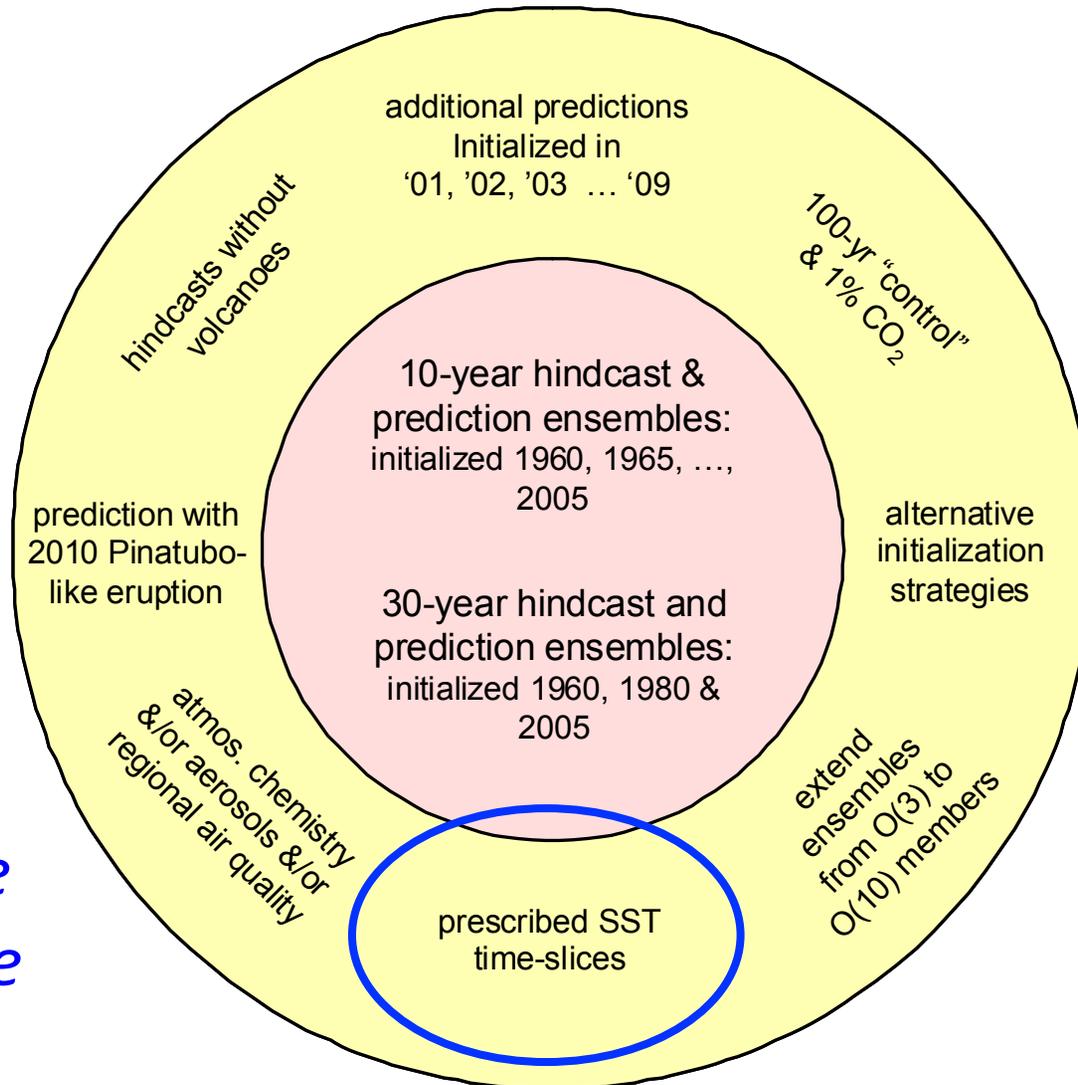


What if we had another big volcano?

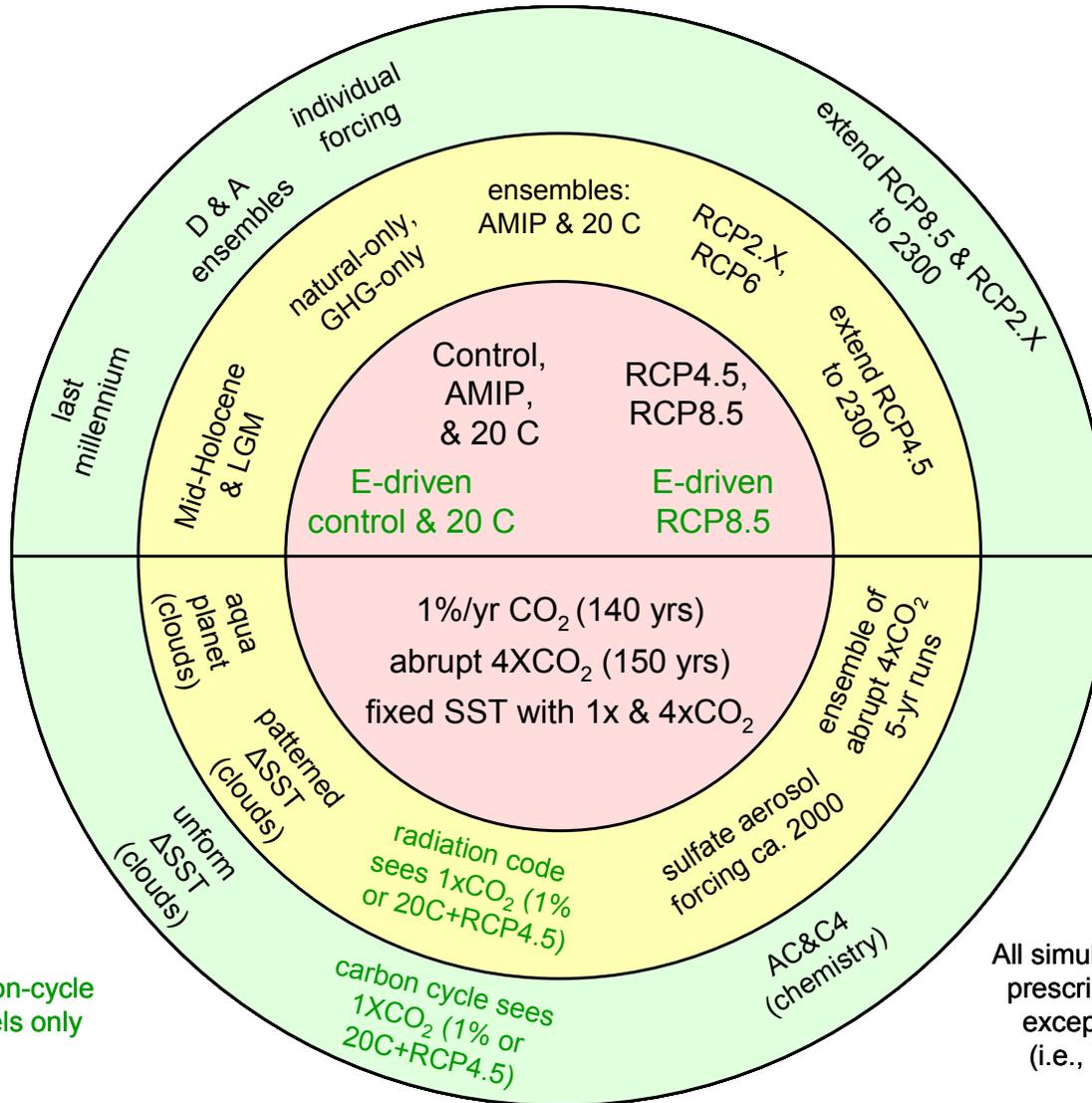
CMIP5 Decadal Onion



*Ultra-high
resolution
atmosphere
or expensive
chemistry*



CMIP5 Long-Term Onion

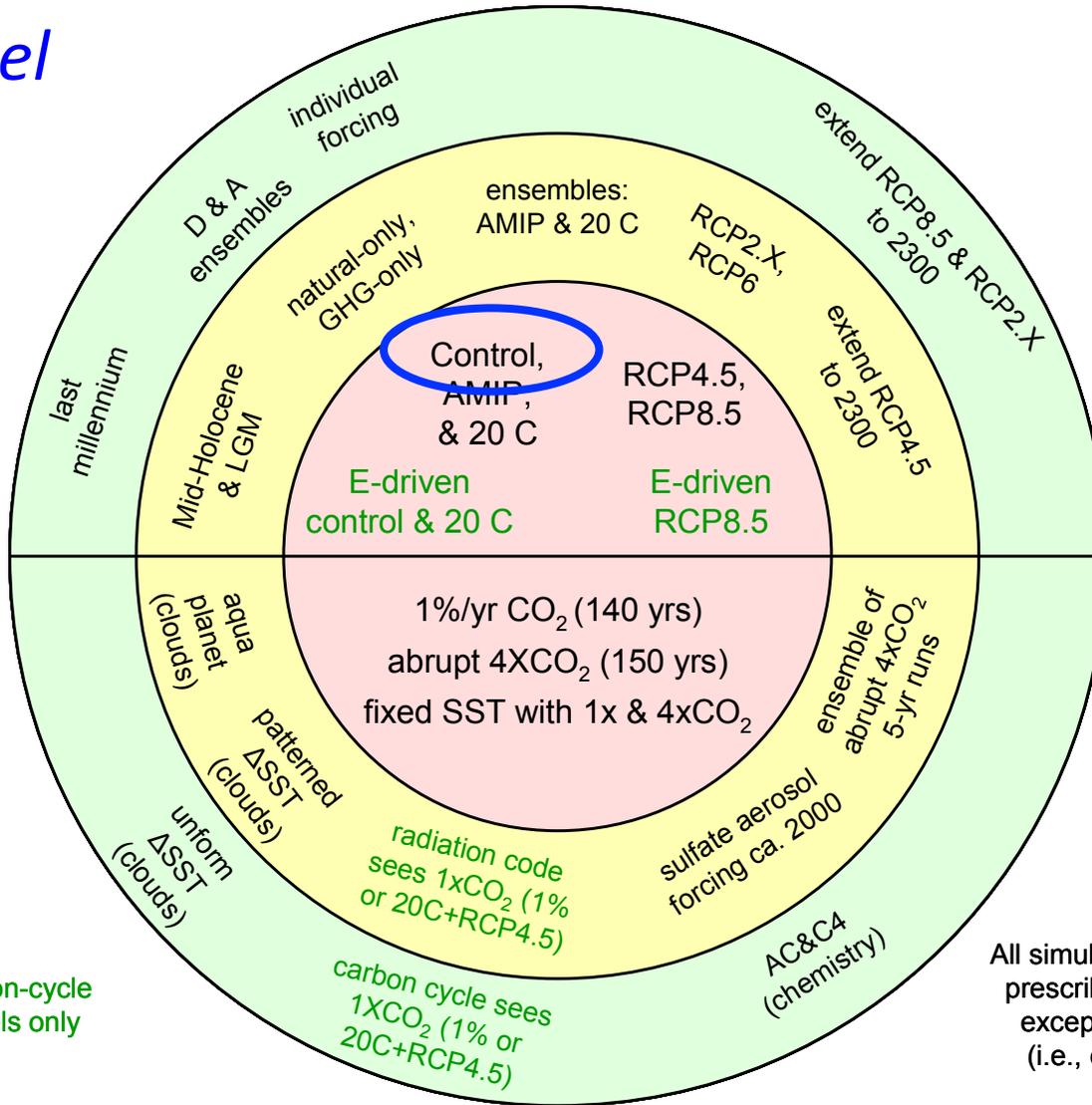
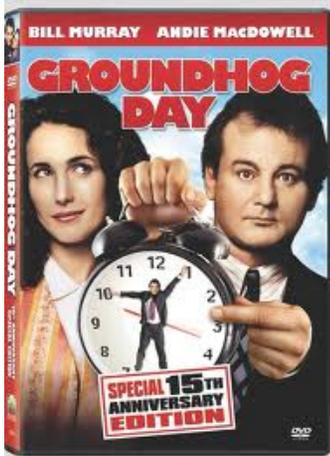


Coupled carbon-cycle climate models only

All simulations are forced by prescribed concentrations except those "E-driven" (i.e., emission-driven).

CMIP5 Long-Term Onion

Is the model stable?

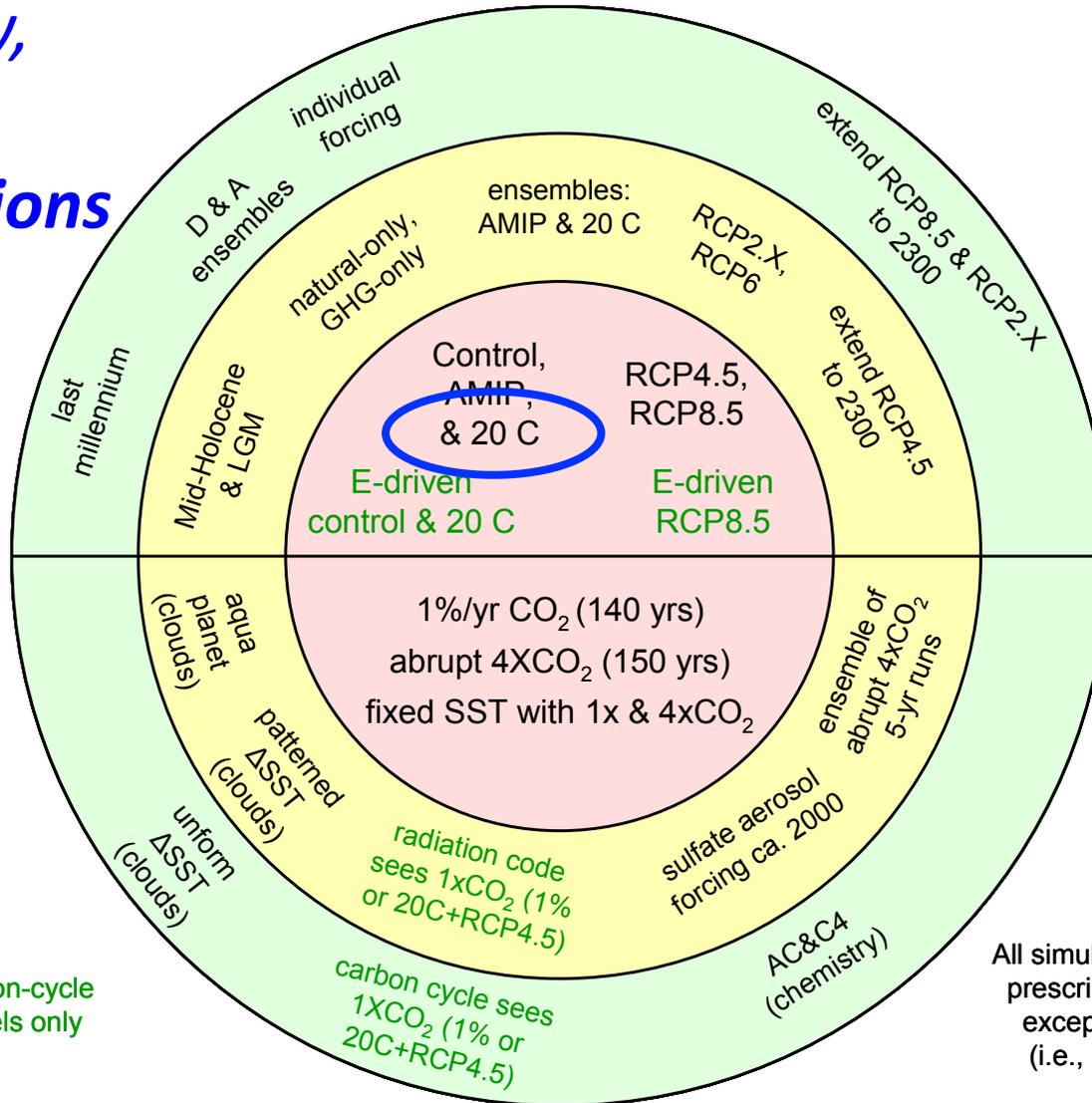


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CMIP5 Long-Term Onion

20th century,
prescribed
concentrations

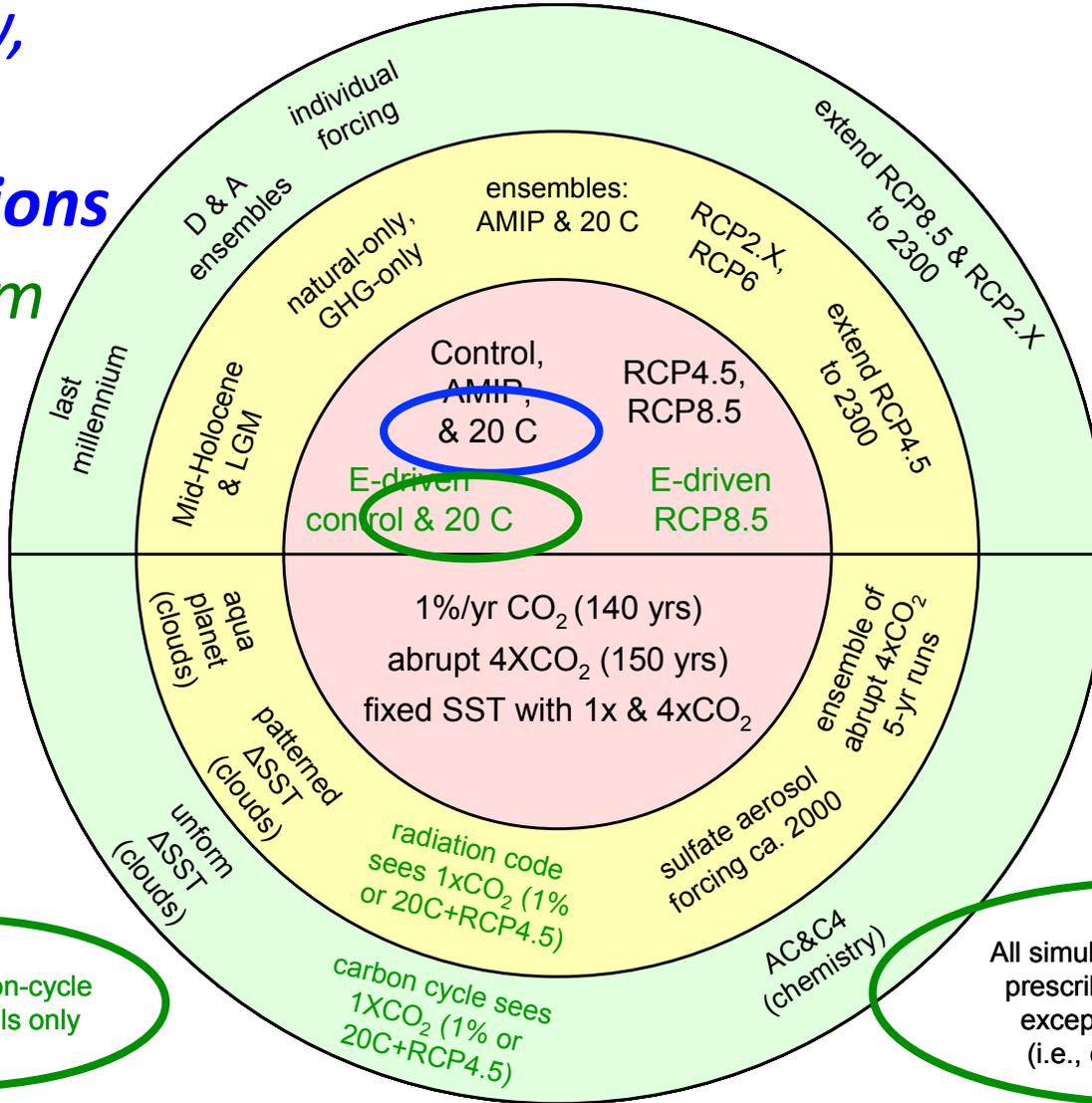


Coupled carbon-cycle
climate models only

All simulations are forced by
prescribed concentrations
except those "E-driven"
(i.e., emission-driven).

CMIP5 Long-Term Onion

20th century,
prescribed
concentrations
Earth System
Models
use
emissions

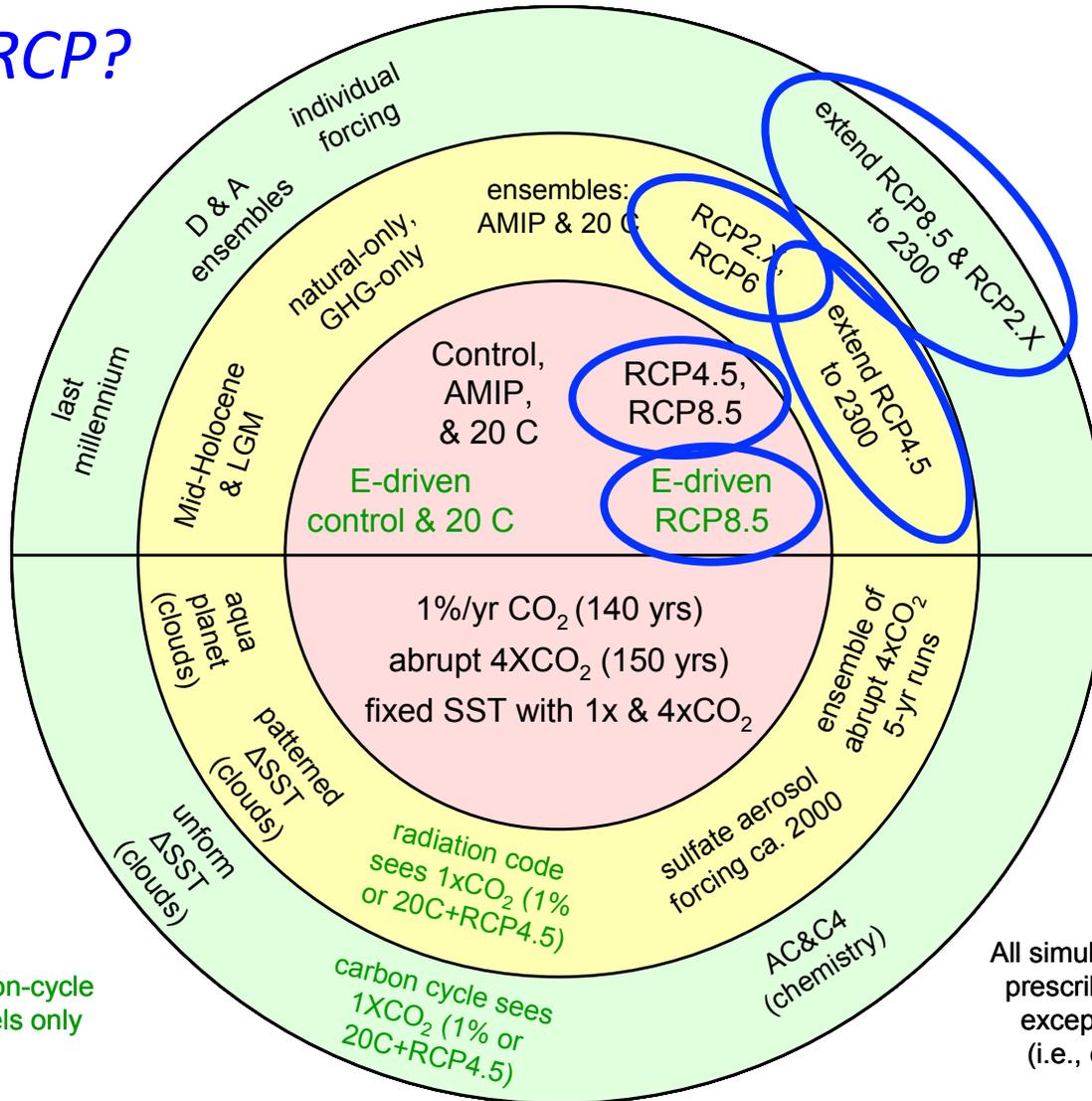


Coupled carbon-cycle
climate models only

All simulations are forced by
prescribed concentrations
except those "E-driven"
(i.e., emission-driven).

CMIP5 Long-Term Onion

What's an RCP?



Coupled carbon-cycle climate models only

All simulations are forced by prescribed concentrations except those "E-driven" (i.e., emission-driven).

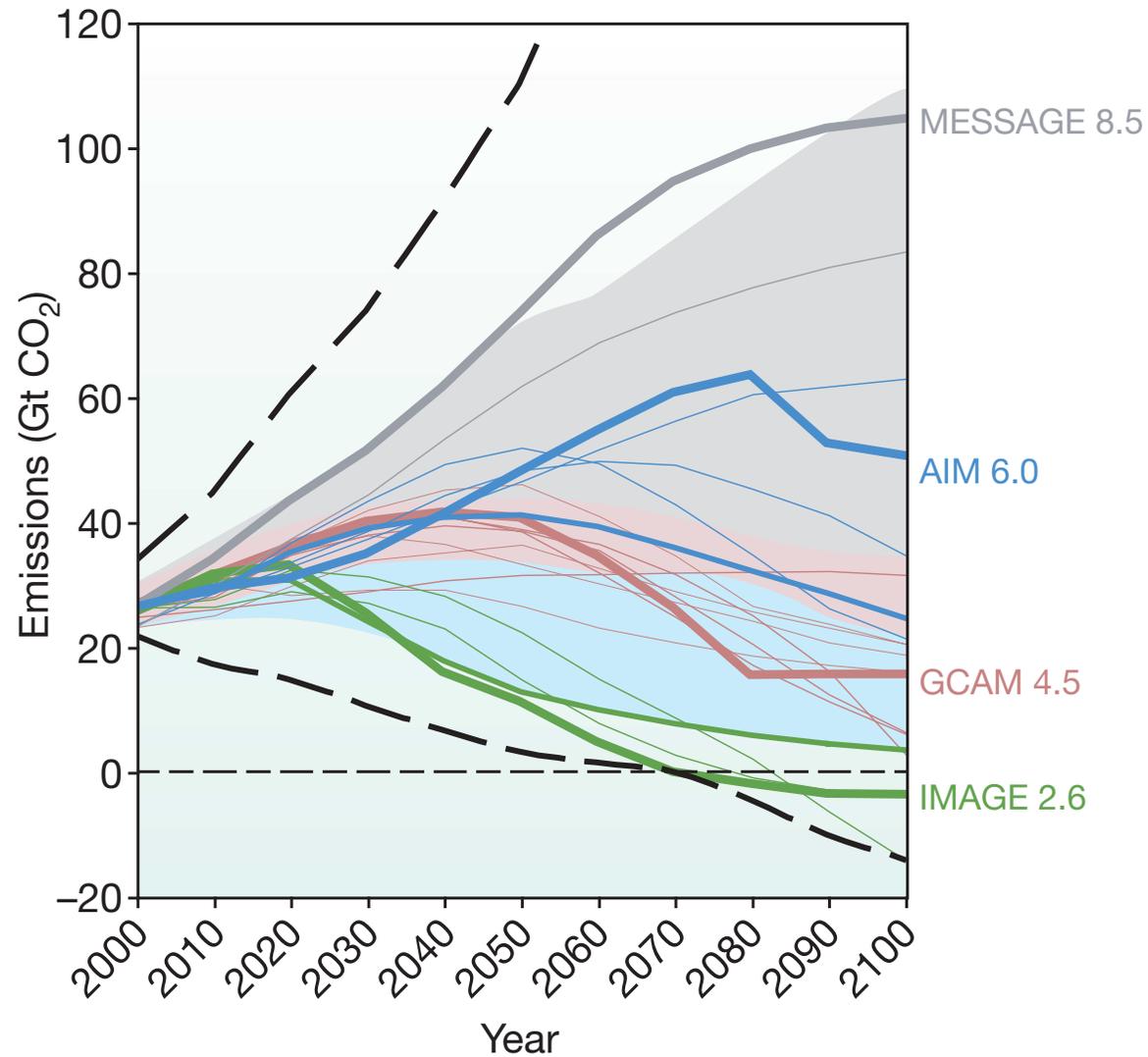
PERSPECTIVES

The next generation of scenarios for climate change research and assessment

Richard H. Moss¹, Jae A. Edmonds¹, Kathy A. Hibbard², Martin R. Manning³, Steven K. Rose⁴, Detlef P. van Vuuren⁵, Timothy R. Carter⁶, Seita Emori⁷, Mikiko Kainuma⁷, Tom Kram⁵, Gerald A. Meehl², John F. B. Mitchell⁸, Nebojsa Nakicenovic^{9,10}, Keywan Riahi⁹, Steven J. Smith¹, Ronald J. Stouffer¹¹, Allison M. Thomson¹, John P. Weyant¹² & Thomas J. Wilbanks¹³

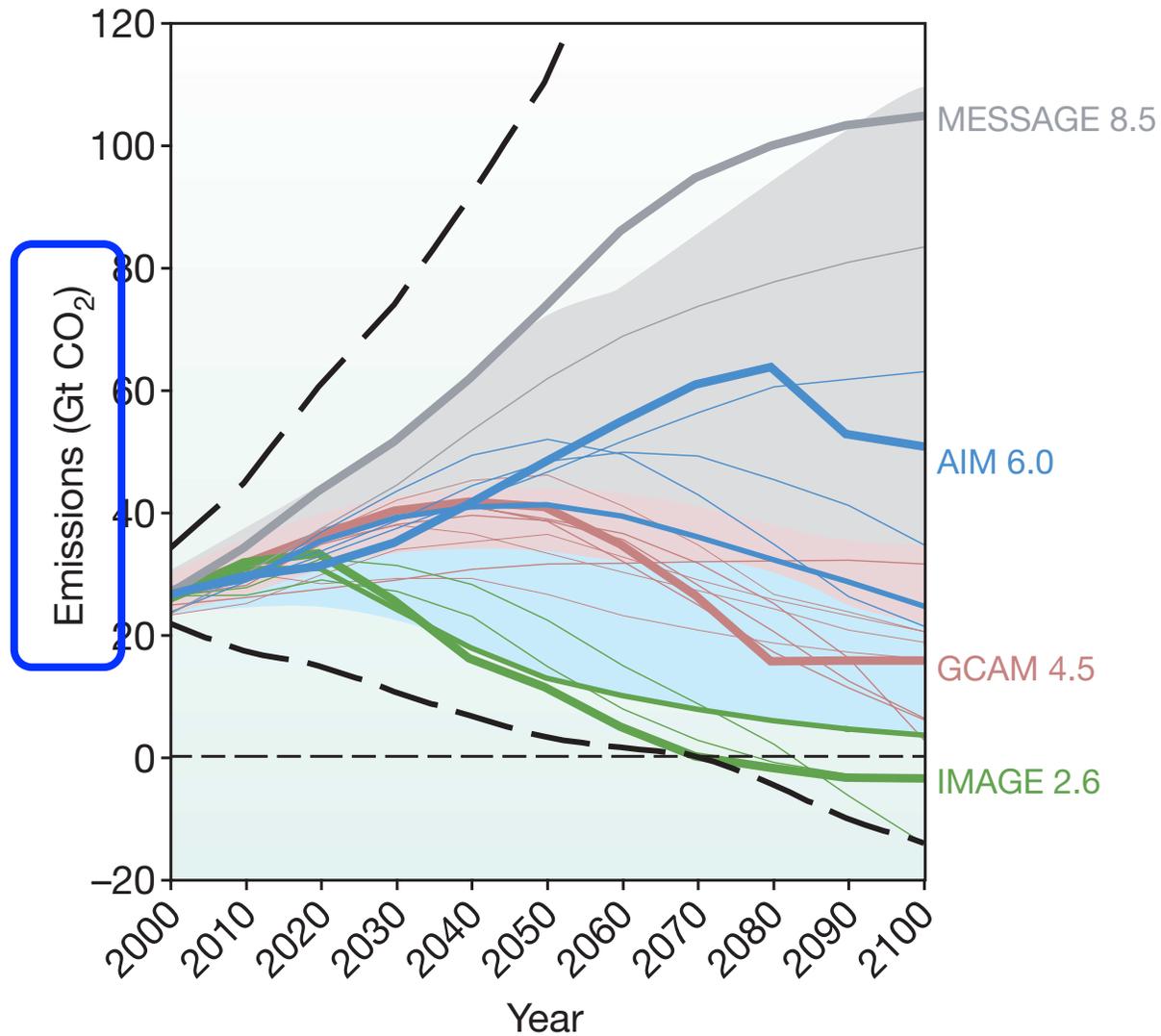
Advances in the science and observation of climate change are providing a clearer understanding of the inherent variability of Earth's climate system and its likely response to human and natural influences. The implications of climate change for the environment and society will depend not only on the response of the Earth system to changes in radiative forcings, but also on how humankind responds through changes in technology, economies, lifestyle and policy. Extensive uncertainties exist in future forcings of and responses to climate change, necessitating the use of scenarios of the future to explore the potential consequences of different response options. To date, such scenarios have not adequately examined crucial possibilities, such as climate change mitigation and adaptation, and have relied on research processes that slowed the exchange of information among physical, biological and social scientists. Here we describe a new process for creating plausible scenarios to investigate some of the most challenging and important questions about climate change confronting the global community.

Representative Concentration Pathways (RCPs)

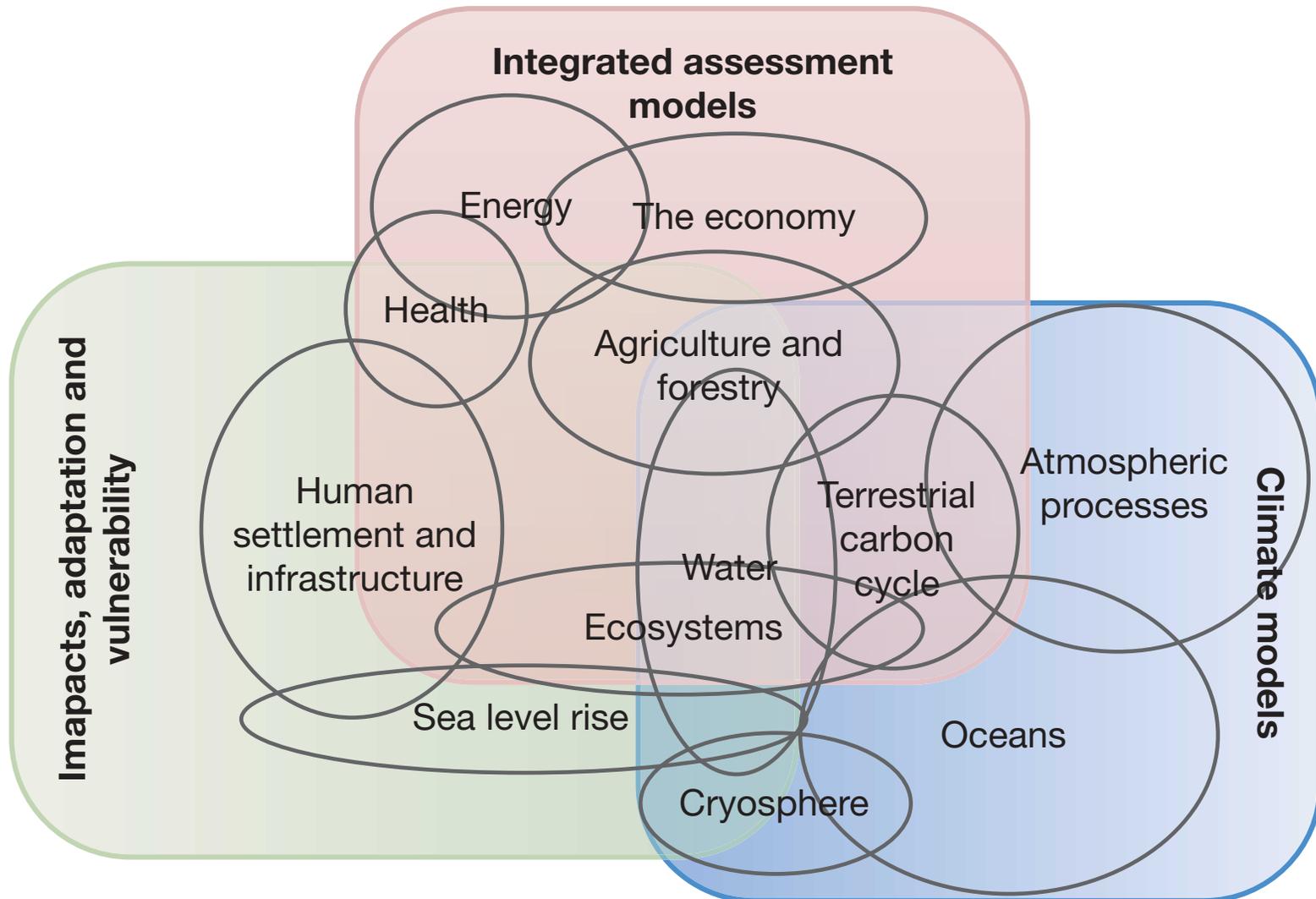


Representative Concentration Pathways (RCPs)

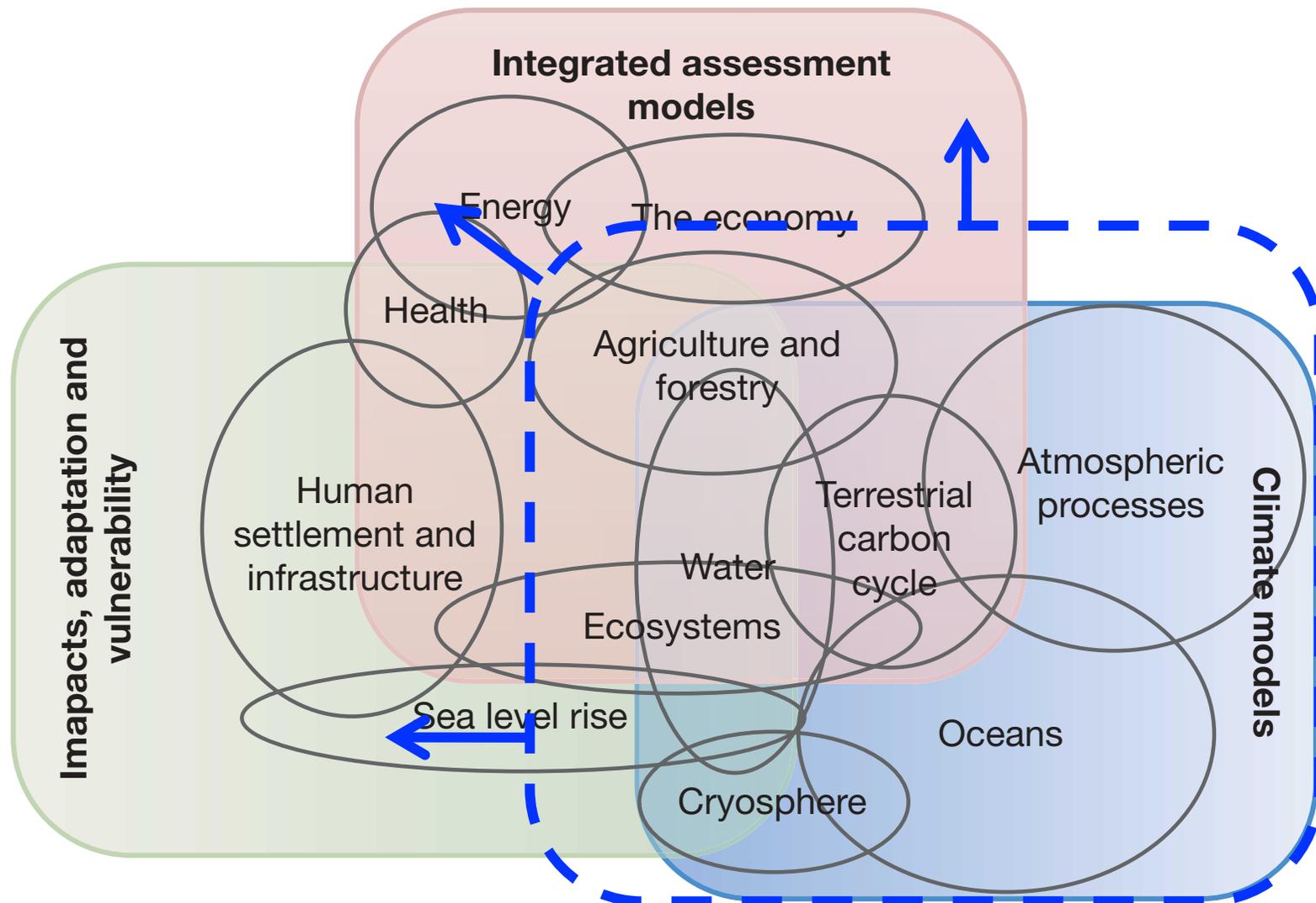
CO₂ emissions predicted by Integrated Assessment Models (IAMs)



What's an IAM?

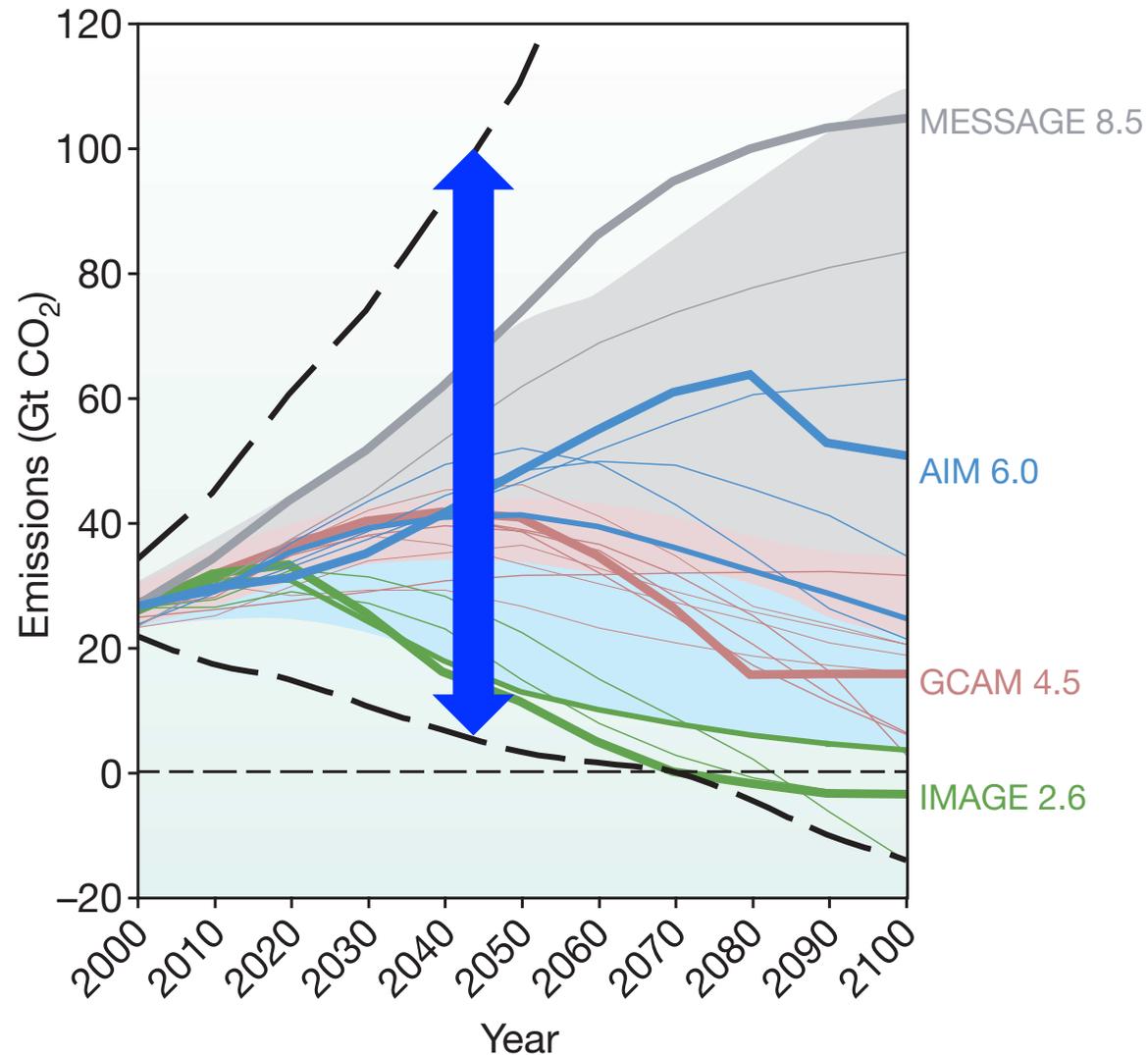


What's an Earth System Model?

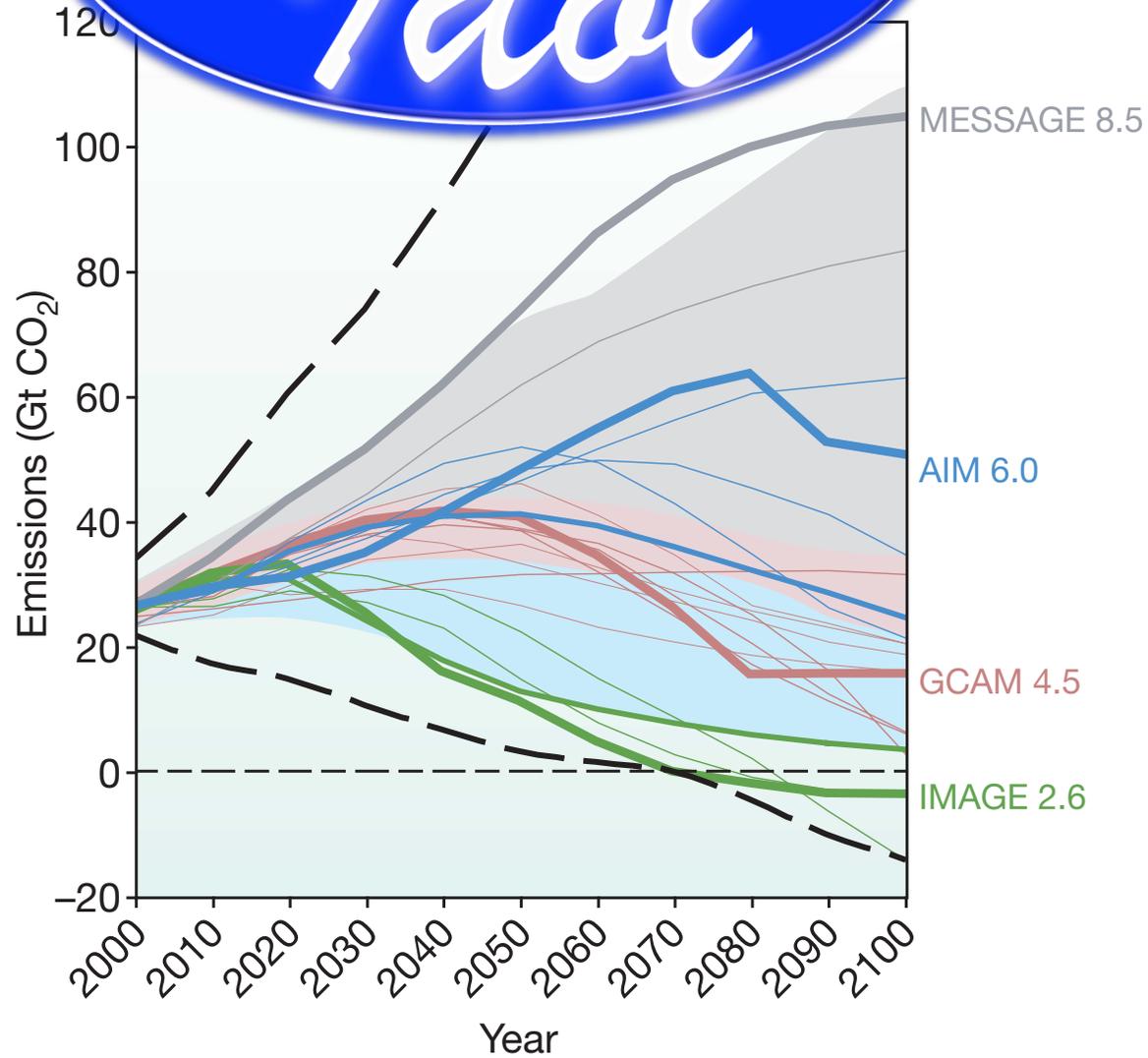


Representative Concentration Pathways (RCPs)

CMIP5 to include full range of predictions from IAMs



Representation





Judging Criteria

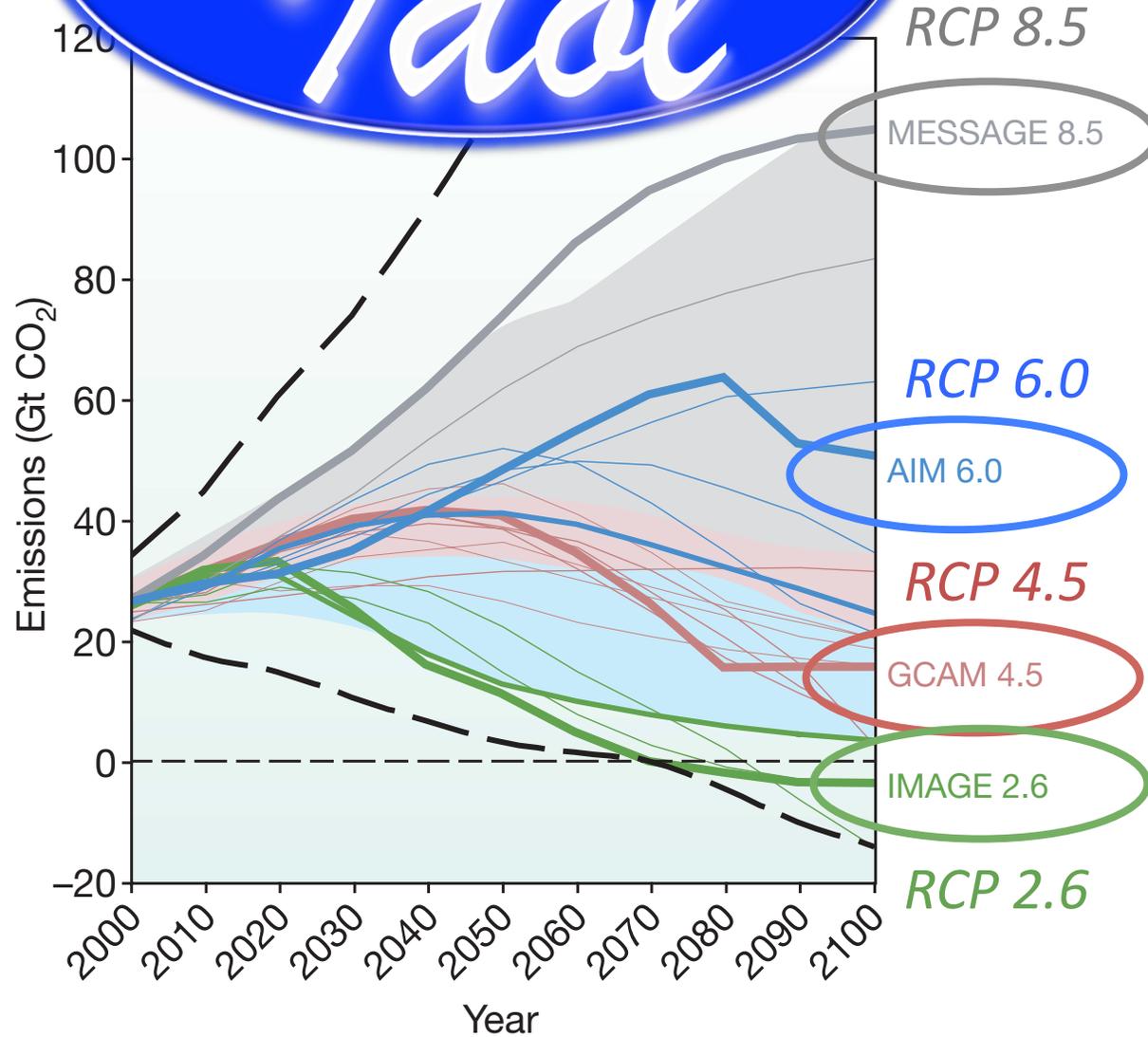
- Winners should represent “the full range of stabilization, mitigation, and reference emissions scenarios available in the current scientific literature”
- Manageable and even number of winners (no “middle one”)
- Far apart from each other
- With available output



Representative Intergovernmental Negotiation

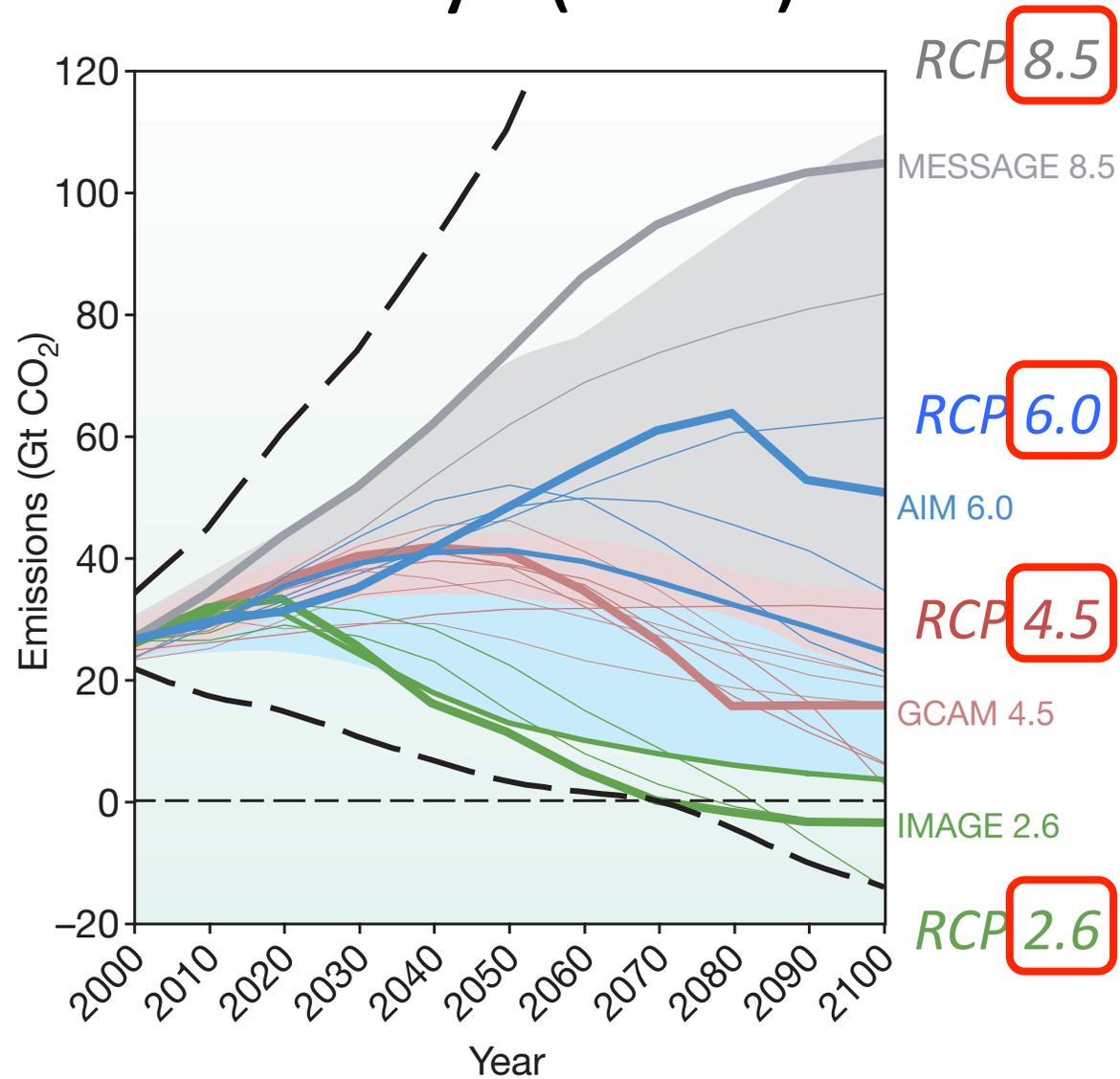
Intergovernmental
Idol

The Winners!

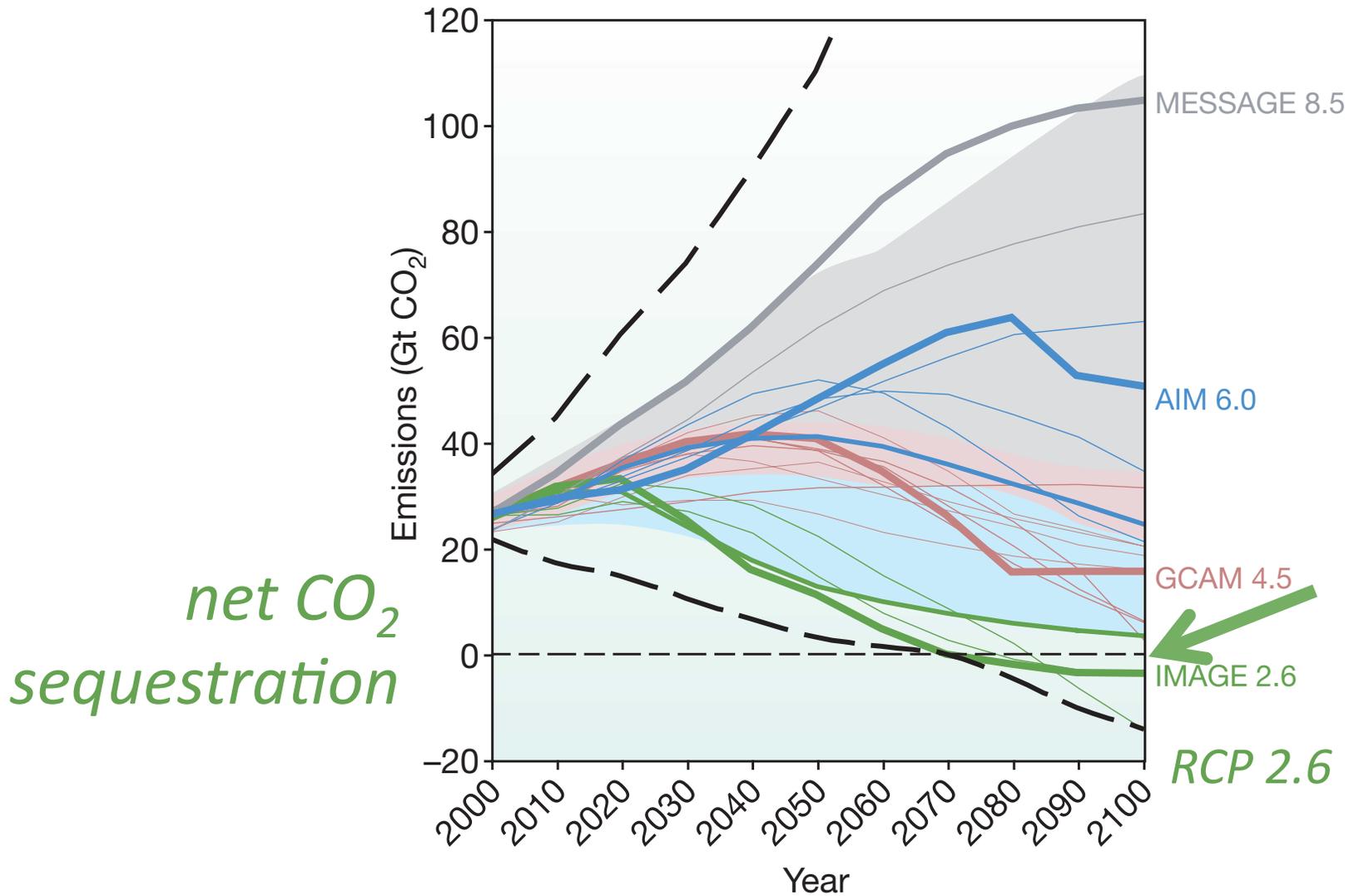


Representative Concentration Pathways (RCPs)

heating produced by 2100 in W/m^2

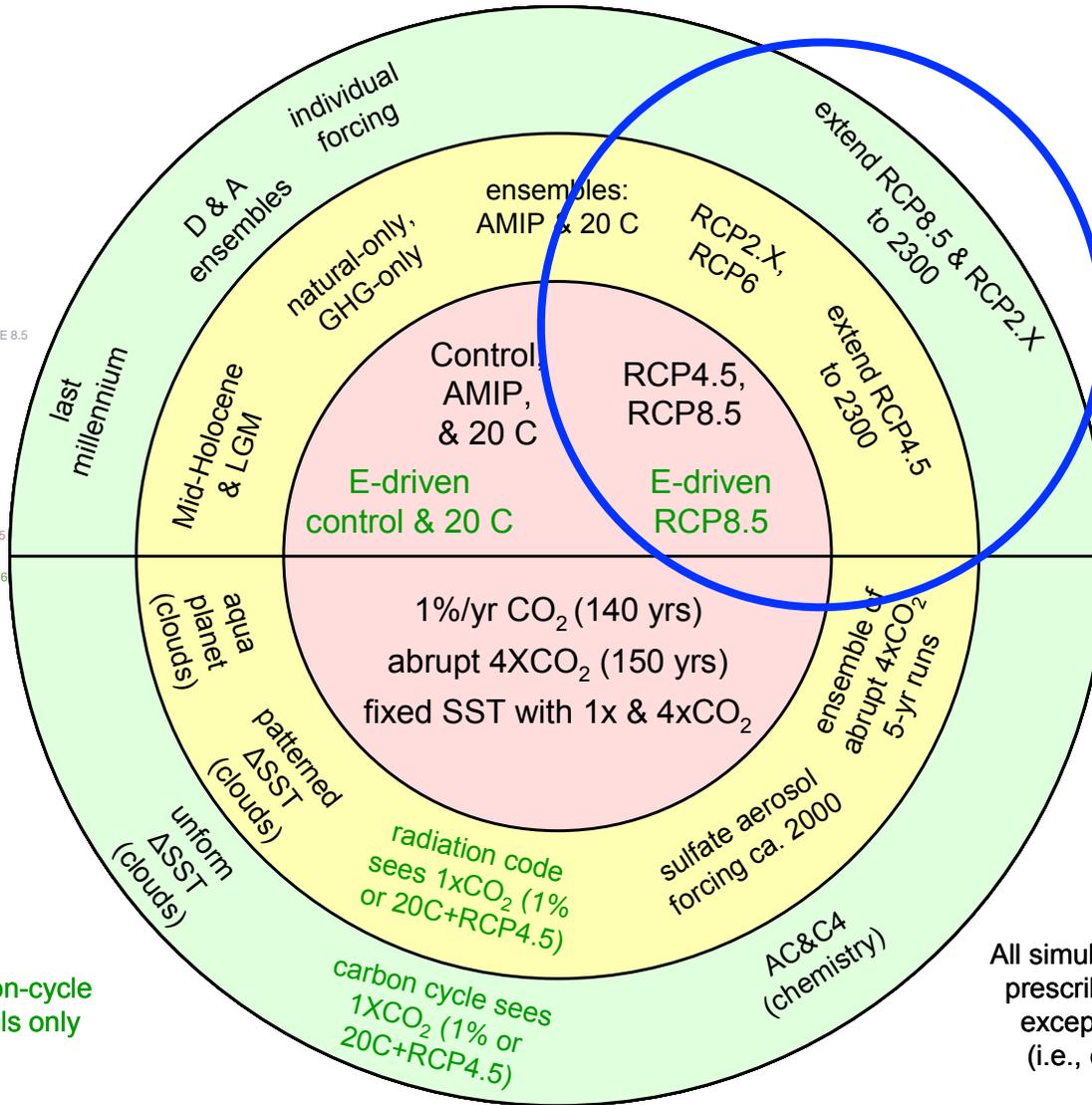
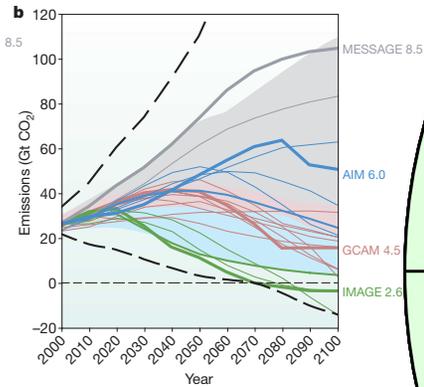


Representative Concentration Pathways (RCPs)



CMIP5 Long-Term Onion

Future mitigation scenarios



Coupled carbon-cycle climate models only

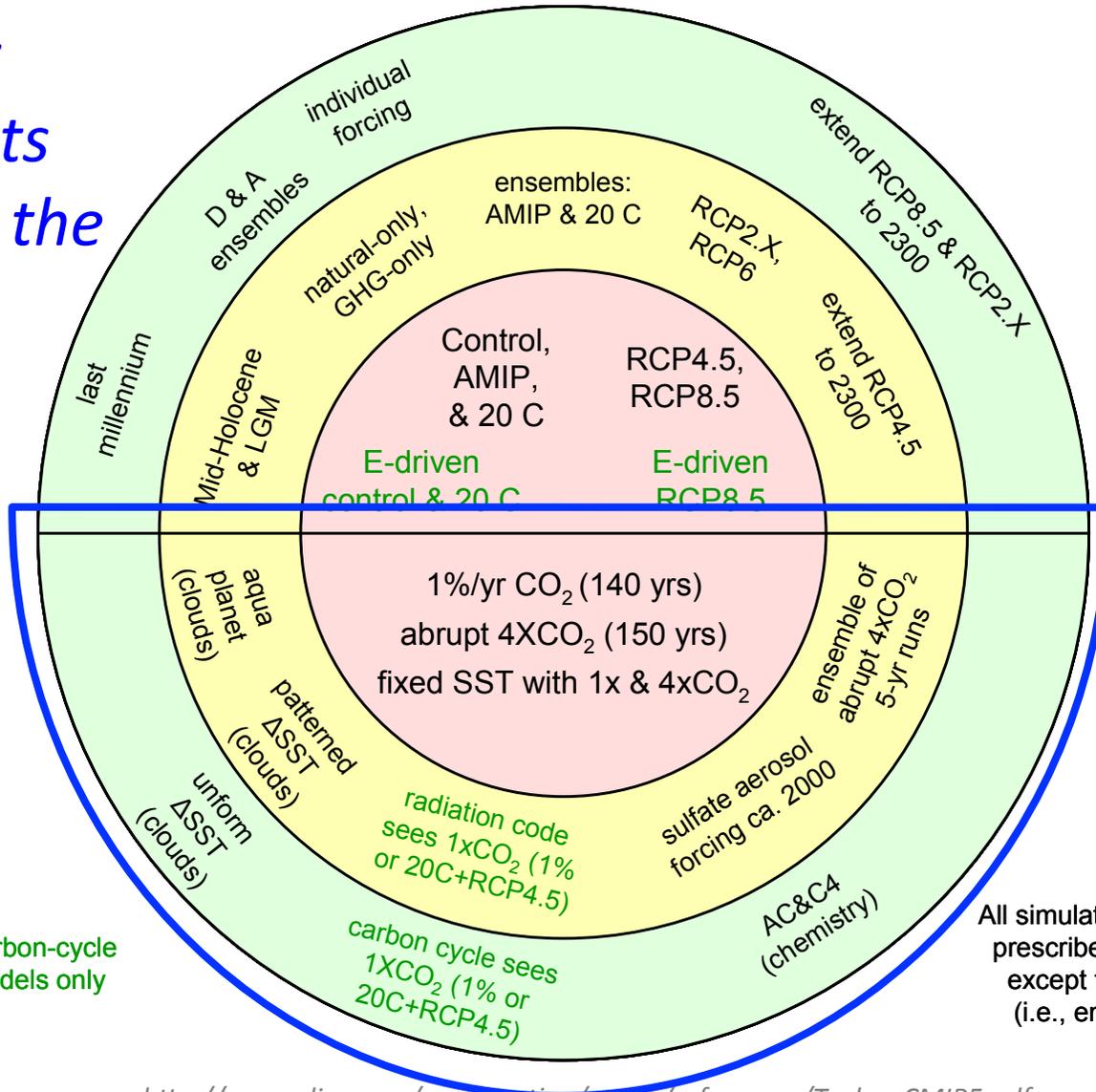
All simulations are forced by prescribed concentrations except those "E-driven" (i.e., emission-driven).

CMIP5 Long-Term Onion

Diagnostic experiments (how does the model function)



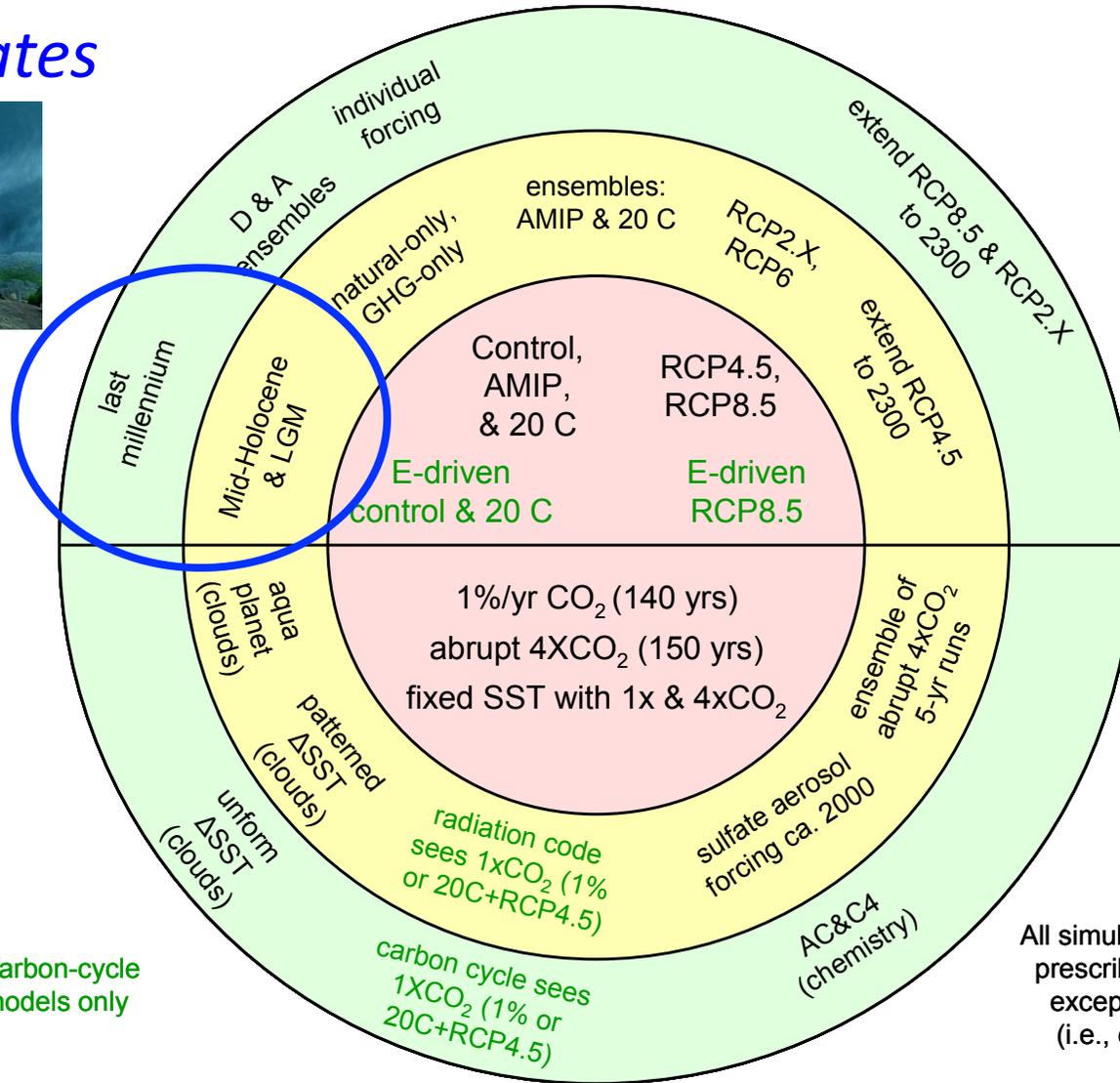
Coupled carbon-cycle climate models only



All simulations are forced by prescribed concentrations except those "E-driven" (i.e., emission-driven).

CMIP5 Long-Term Onion

Past climates

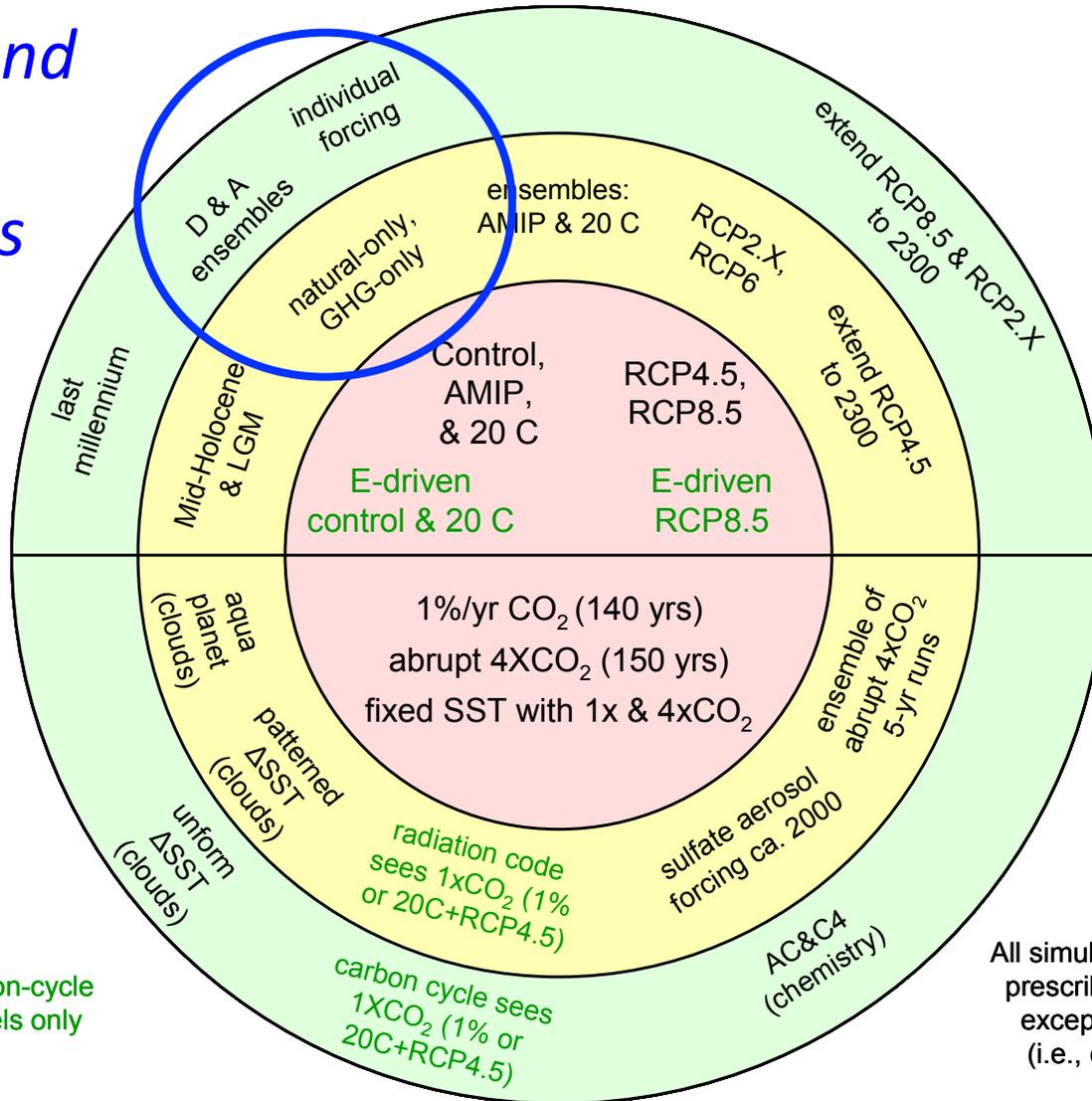


Coupled carbon-cycle climate models only

All simulations are forced by prescribed concentrations except those "E-driven" (i.e., emission-driven).

CMIP5 Long-Term Onion

Detection and attribution (who causes what)



Coupled carbon-cycle climate models only

All simulations are forced by prescribed concentrations except those "E-driven" (i.e., emission-driven).

Iron Chef Intergovernmental #5

- CMIP5 defines experiments
- **Develop a model**
- Run experiments
- Provide simulation output
- Scientists worldwide analyze output
- Scientists worldwide publish papers
- AR5 authors cite papers

MODEL DOCUMENTATION

CESM1.0

[User's Guide](#)

Atmosphere Models

- ▶ Community Atmosphere Model (CAM5)
- ▶ Climatological Data Model (DATM)

Land Models

- ▶ Community Land Model (CLM4)
- ▶ Climatological Data Model (DLND)

Sea Ice Models

- ▶ Community Ice Code (CICE4)
- ▶ Climatological Ice Model (DICE)

Ocean Models

- ▶ Parallel Ocean Program (POP2)
- ▶ Climatological/Slab-Ocean Data Model (DOCN)

Land Ice Models

- ▶ Community Ice Sheet Model (Glimmer - CISM)

CESM Coupler

- ▶ CESM Coupler (CPL7)

External Library Documentation

- Parallel I/O Library (PIO)
- Model Coupling Toolkit (MCT)
- Earth System Modeling Framework (ESMF)

MODEL INPUT DATA

The input data necessary to run the CESM1.0 models is available in the input data repository. Note that the CESM1.0 input data repository is a **DO NOT** attempt to modify the input data. The User's Guide explains how to obtain the input data.

PERFORMANCE AND LOAD BALANCING DATA

MODEL SOURCE CODE

Copyright and Terms of Use

All CESM source code is subject to the following Copyright Notice and Disclaimer.

Acquiring the Code

CESM source code is distributed through a public Subversion code repository. This code can be checked out using Subversion client software, such as the command tool svn, or simply [viewed with a web browser](#).

A short [registration](#) is required to access the repository. After registering, you will receive an email containing a user name and password that is necessary to gain access to the repository.

Acquisition of the code is more fully described in the [CESM1.0 User's Guide](#).

Version Summaries and Known Problems

The following table lists the available versions of code along with their test record and any known problems in the code.

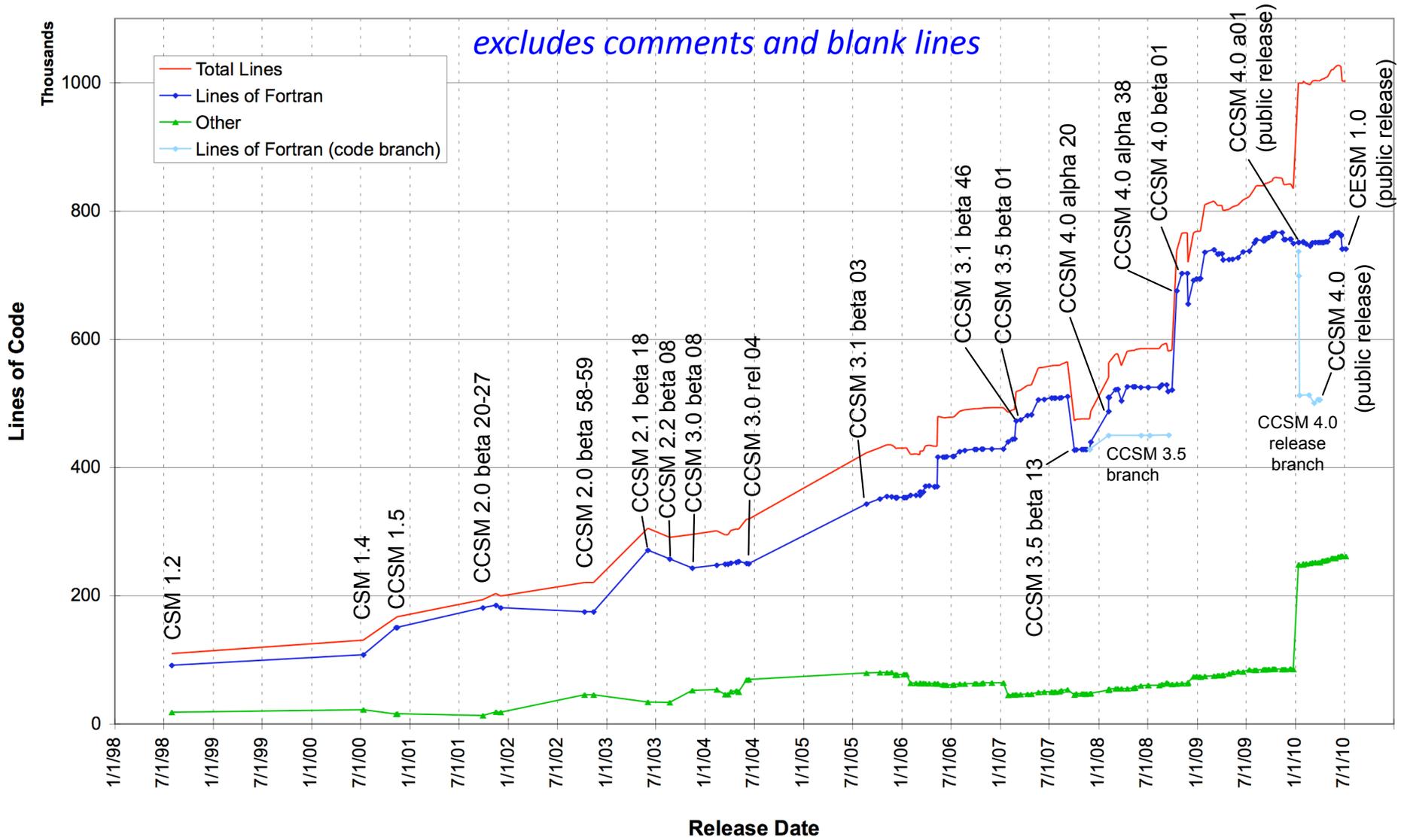
- [CESM1.0 Release Versions](#)

Reporting a Problem

If you have any problems, please first read the User's Guide including the sections on FAQs and Use Cases. Please also refer to the [CESM Bulletin Board](#), which is in place to facilitate communication within the CESM community. Finally, please also refer to the [Known Problems](#) entries that are provided with every release and release update. If questions or problems still exist, then please send an email to cesm-help@cgd.ucar.edu. Support questions will be answered as they are available.

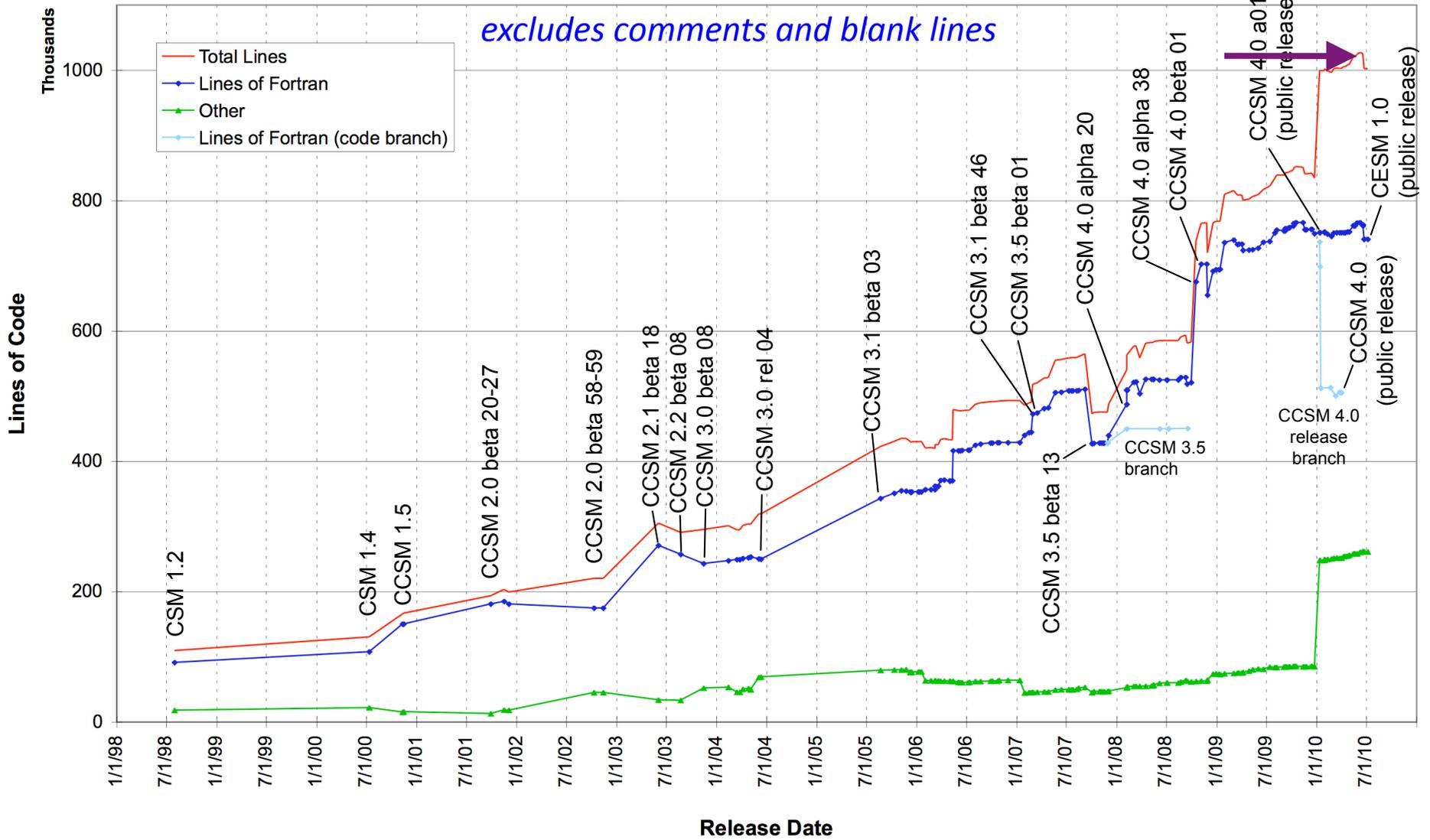
www.cesm.ucar.edu

Growth in Lines of Code for CSM/CCSM/CESM, 1998-2010



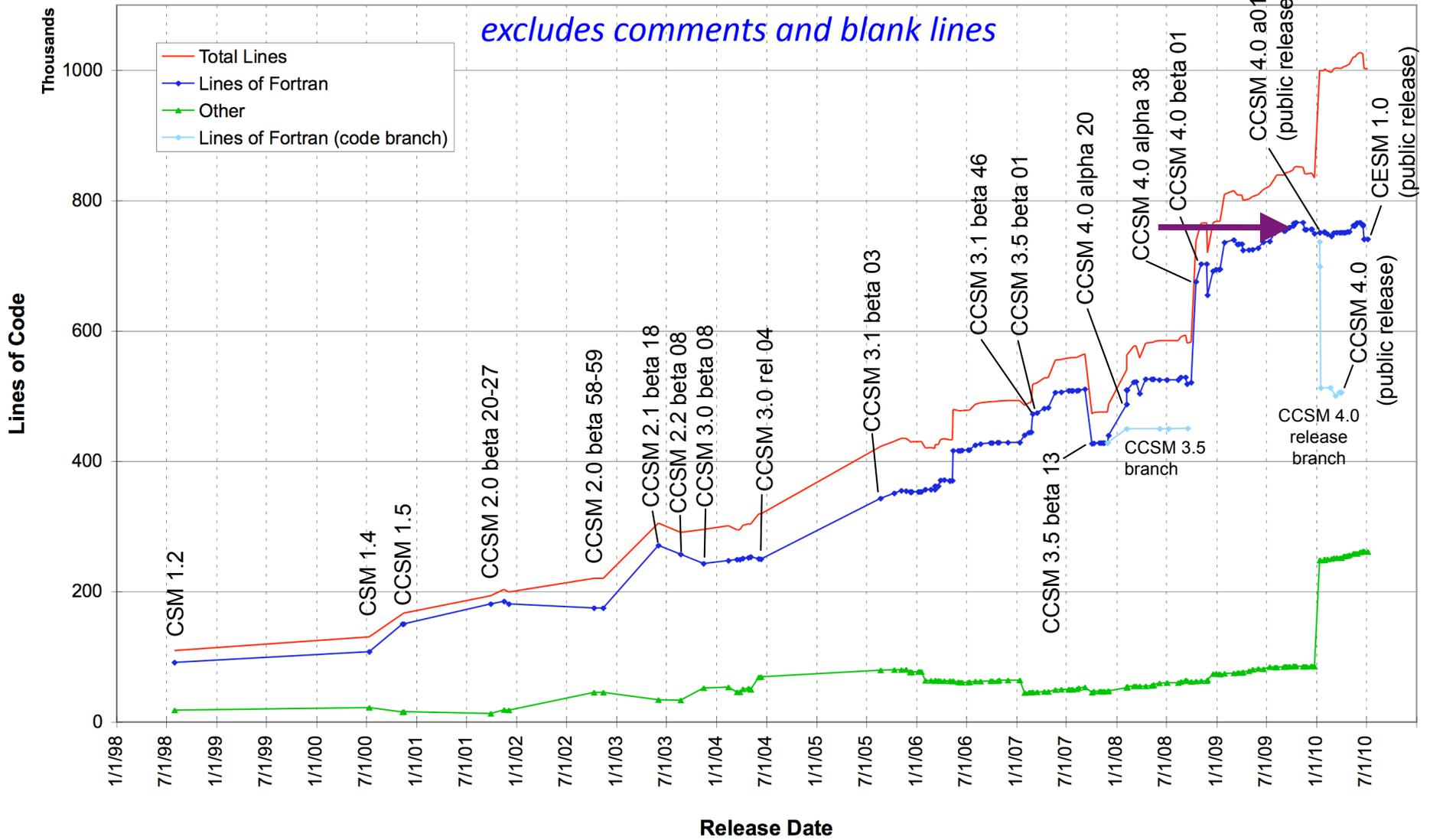
Courtesy of Steve Easterbrook, University of Toronto

Growth in Lines of Code for CSM/CCSM/CESM, 1998-2010



Growth in Lines of Code for CSM/CCSM/CESM, 1998-2010

800k lines of Fortran



Some New Features of CESM

- OpenMP (and MPI) in all components
- Parallel I/O
- New atmospheric physics w/prognostic aerosols
- Full and “fast” atmospheric chemistries
- “High top” atmosphere (stratosphere)
- Dynamic vegetation with carbon & nitrogen biogeochemistry
- Ocean ecosystem
- Land ice-sheet model

Iron Chef Intergovernmental #5

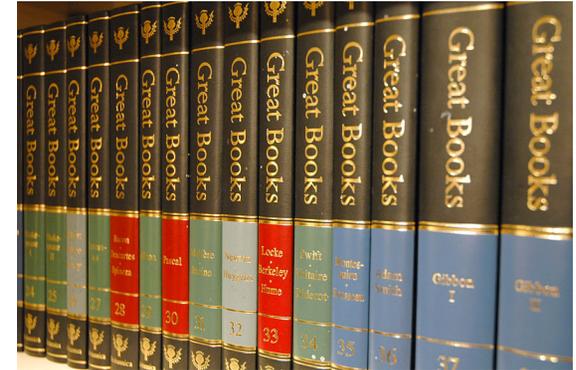
- CMIP5 defines experiments
- Develop a model
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- Scientists worldwide analyze output
- Scientists worldwide publish papers
- AR5 authors cite papers

229 Configuration Variables

- 42 variables for the overall experiment
- 58 variables for the “configure” step
- 34 variables for the parallel layout
- 27 variables for the “build” step
- 68 variables for the “run” step



Input Data



- Initial conditions
- Prescribed quantities
(emissions, concentrations, land use)
- 2 TB, 9400 files, and growing
(increasing resolution and model complexity)
- On spinning disk at each supercomputer site

Example Run: CCSM4 RCP 8.5

- Years 2005-2100 (inclusive, 96 years)
- 1° global resolution, all active components
 - Atmosphere, land, ocean, sea ice
- NCAR Bluefire: 13.6 years/day on 512 cores
 - 7+ days continuous, broken into 6-hour chunks (checkpoint/restart)
- 6 ensemble members
 - 6 different 20th-century runs
- 98 TB of archived data

CCSM4/CESM1 Runs for AR5



<http://www.nersc.gov/assets/Logos/NERSClogocolor.png>

<http://nwsr.ucar.edu/>

<https://wiki.ucar.edu/display/wag/Logos+for+Web+and+Print>

<http://www.anl.gov/>

<http://www.ncsa.illinois.edu/News/Images/logo.html>

<http://www.olcf.ornl.gov/media-center/media-kit/>

<http://www.astateredwolves.com/>



You are here.

High Performance Computing

a digression

Engineering CESM for Portable Performance

- Block-oriented computation
- Hybrid parallelism
- Modular parallel communication
- Flexible task parallelism
- Modular built-in timers

Block-Oriented Computation

- Pass blocks of elements as procedure arguments
- Operate on a block at a time
- More than one element
 - Vectorization (SSE, AltiVec, double hummer, *etc.*)
 - Pipelining
 - Loop unrolling
- Less than whole domain
 - Cache blocking
 - Load balancing
- Tunable block size



Hybrid Parallelism

- MPI (distributed memory) and OpenMP (shared memory)
- OpenMP can target different parallelism
 - 3rd dimension in 2D decomposition
 - Too tightly coupled for distributed memory
 - Allows use of more cores
- Or same parallelism
 - Aggregate MPI messages
 - Fewer, larger messages can be more efficient
- Tunable number of threads/task



Modular Parallel Communication

- Isolate parallel communication
- Allow different programming models
 - MPI, Co-Array Fortran, SHMEM
- Allow different algorithms
 - Performance tuning
 - Workarounds for computer limitations



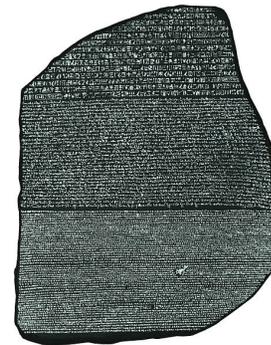
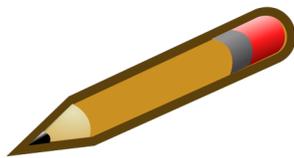
Examples of Different Algorithms

- Sends before receives or vice versa
- Reproducible dot products
- Load balancing options:
on task, on node, nearby nodes, global
- Flow control (critical on largest computers)

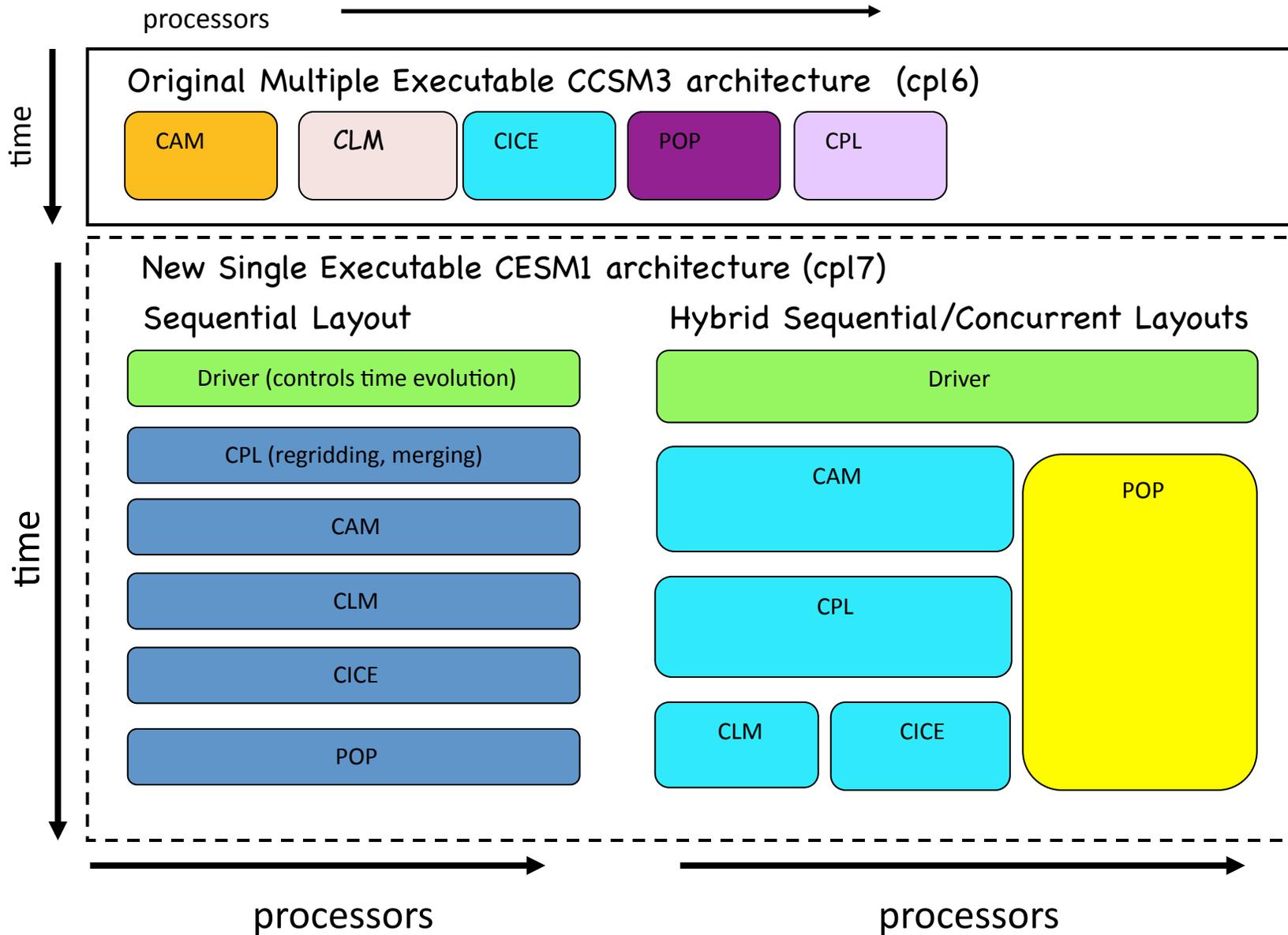


Modular Parallel I/O

- Tunable number and location of I/O tasks
- Choices for underlying implementation: NetCDF3, NetCDF4, pNetCDF, binary
- Potential for asynchronous I/O
- Potential for in-memory checkpoint/restart



Flexible Task Parallelism



Modular Built-In Timers

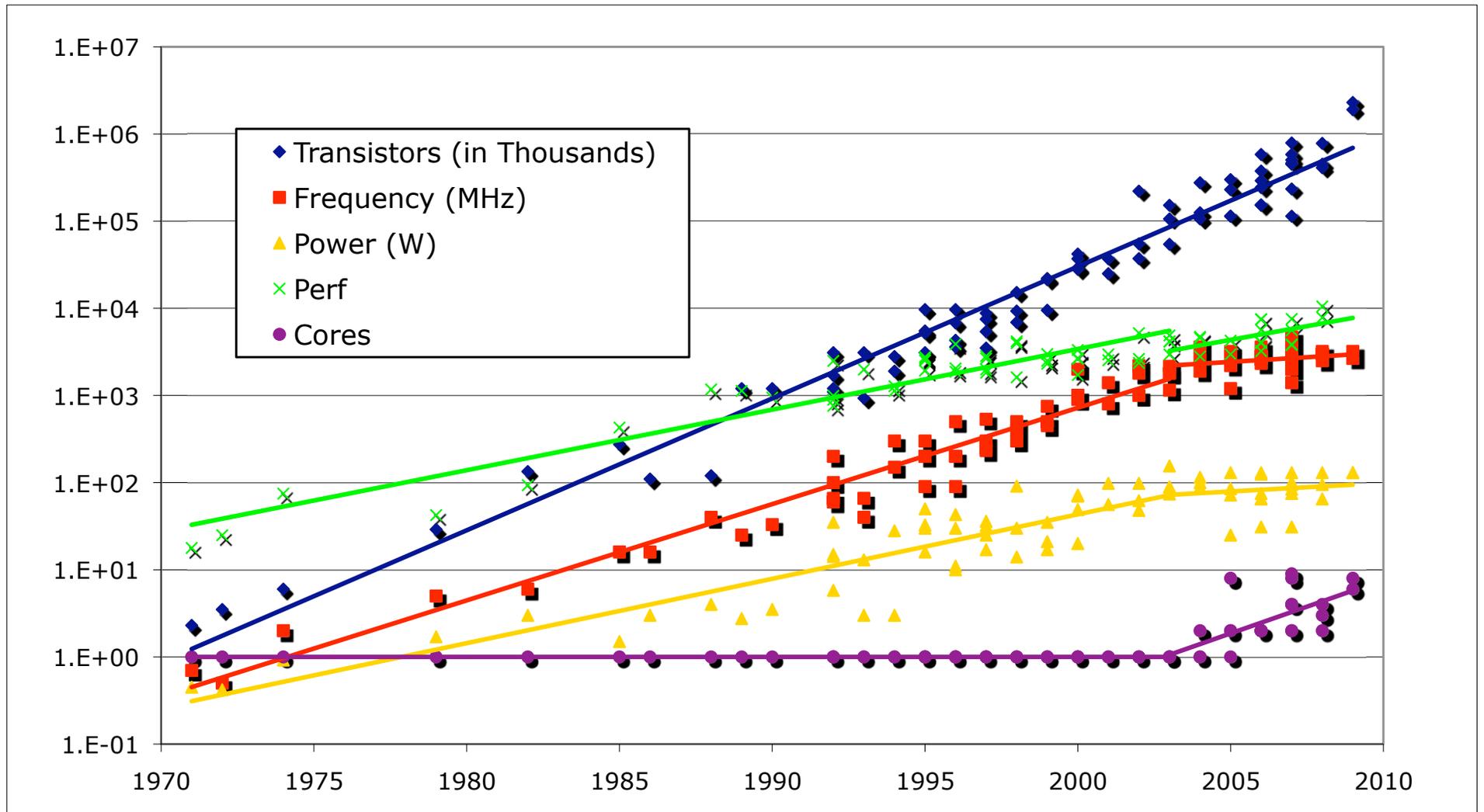
- Portable performance tuning
 - Don't depend on vendor tools
 - Use newest computers
- Configurable level of detail
 - Load balance components
 - Choose tuning parameters for a given component
 - Find tuning “opportunities” and performance bugs
- Opportunity for automatic tuning



Scaling Out CESM

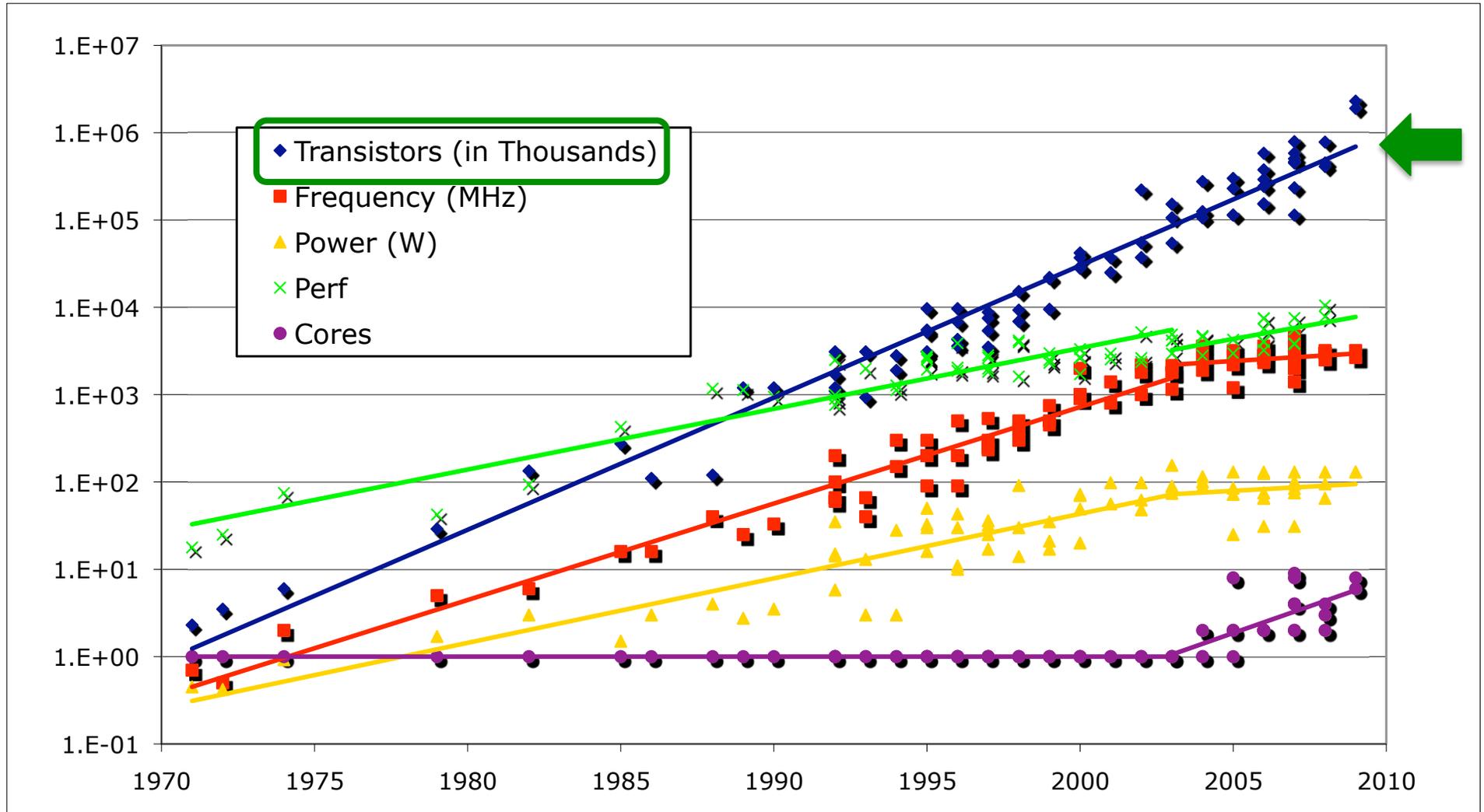
- Flexible, hybrid parallelism
- Parallel I/O
- More-scalable atmosphere grids and dynamics
- Higher resolution
- More physical processes per grid point
 - ➔ Higher computational intensity

Kathy Yelick's Processor Trends



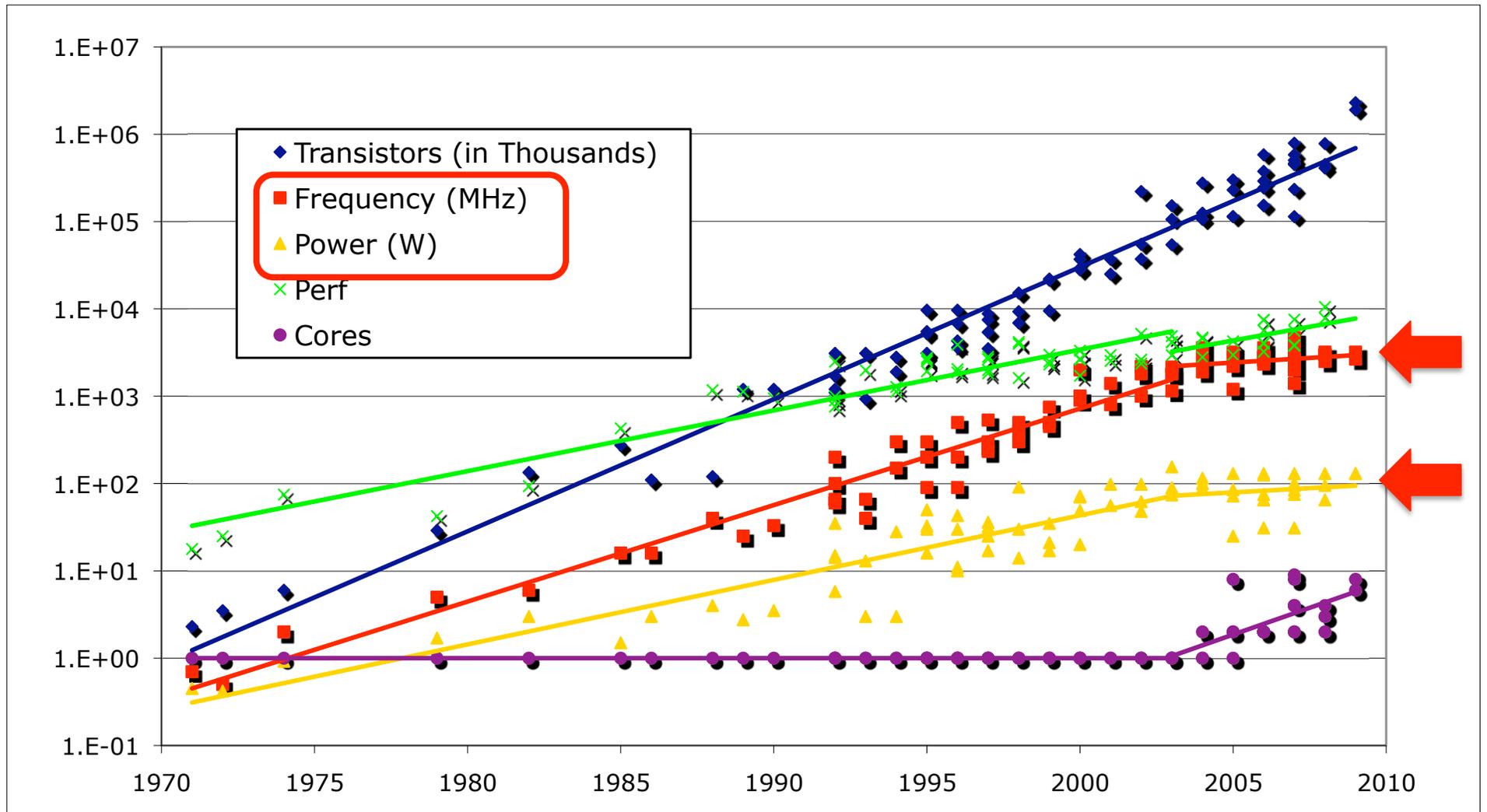
From Kathy Yelick's "Ten Ways to Waste a Parallel Computer", using data from Kunle Olukotun, Lance Hammond, Herb Sutter, Burton Smith, Chris Batten, and Krste Asanovic

Moore's Law Continues



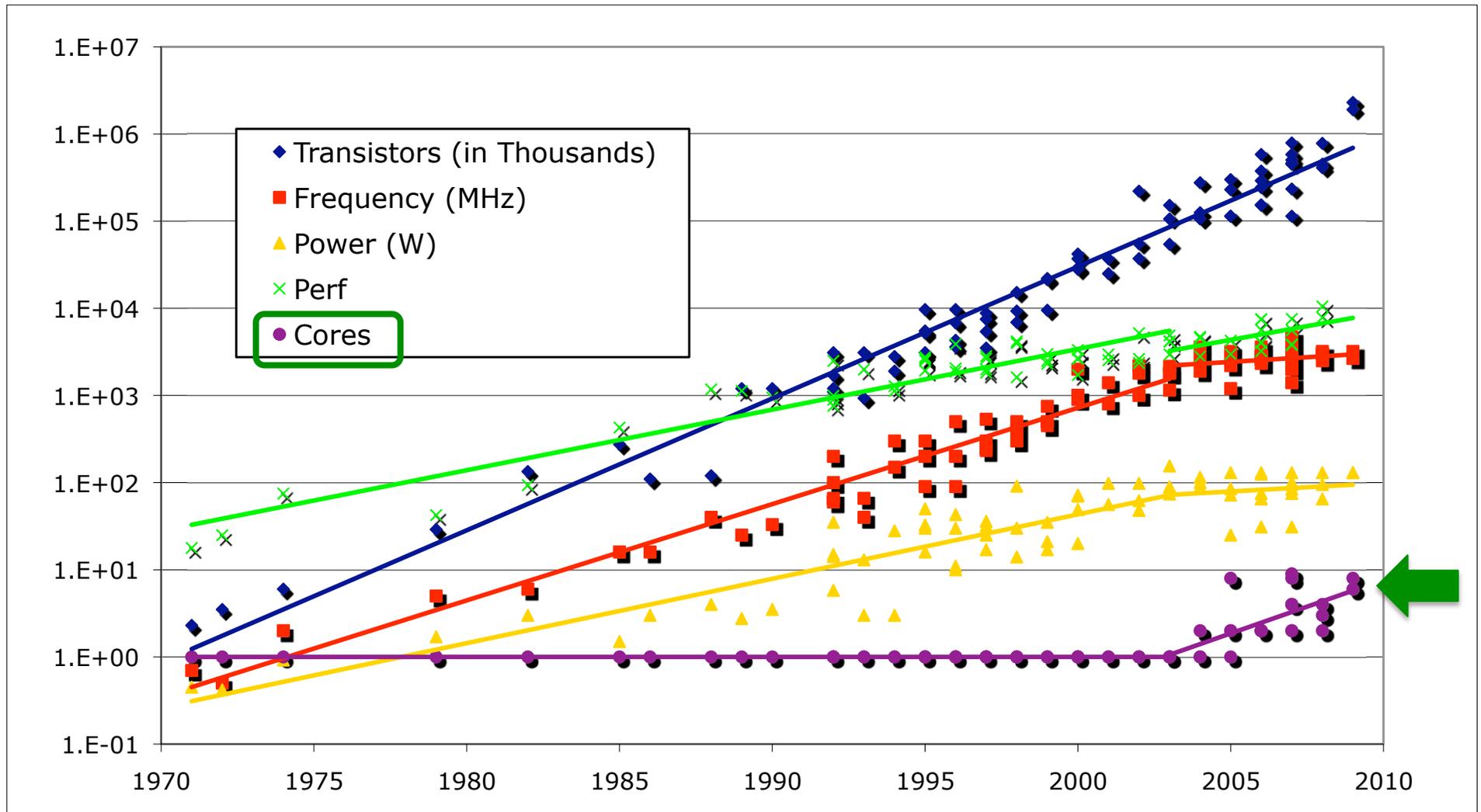
From Kathy Yelick's "Ten Ways to Waste a Parallel Computer", using data from Kunle Olukotun, Lance Hammond, Herb Sutter, Burton Smith, Chris Batten, and Krste Asanovic

Power & Frequency Stagnating



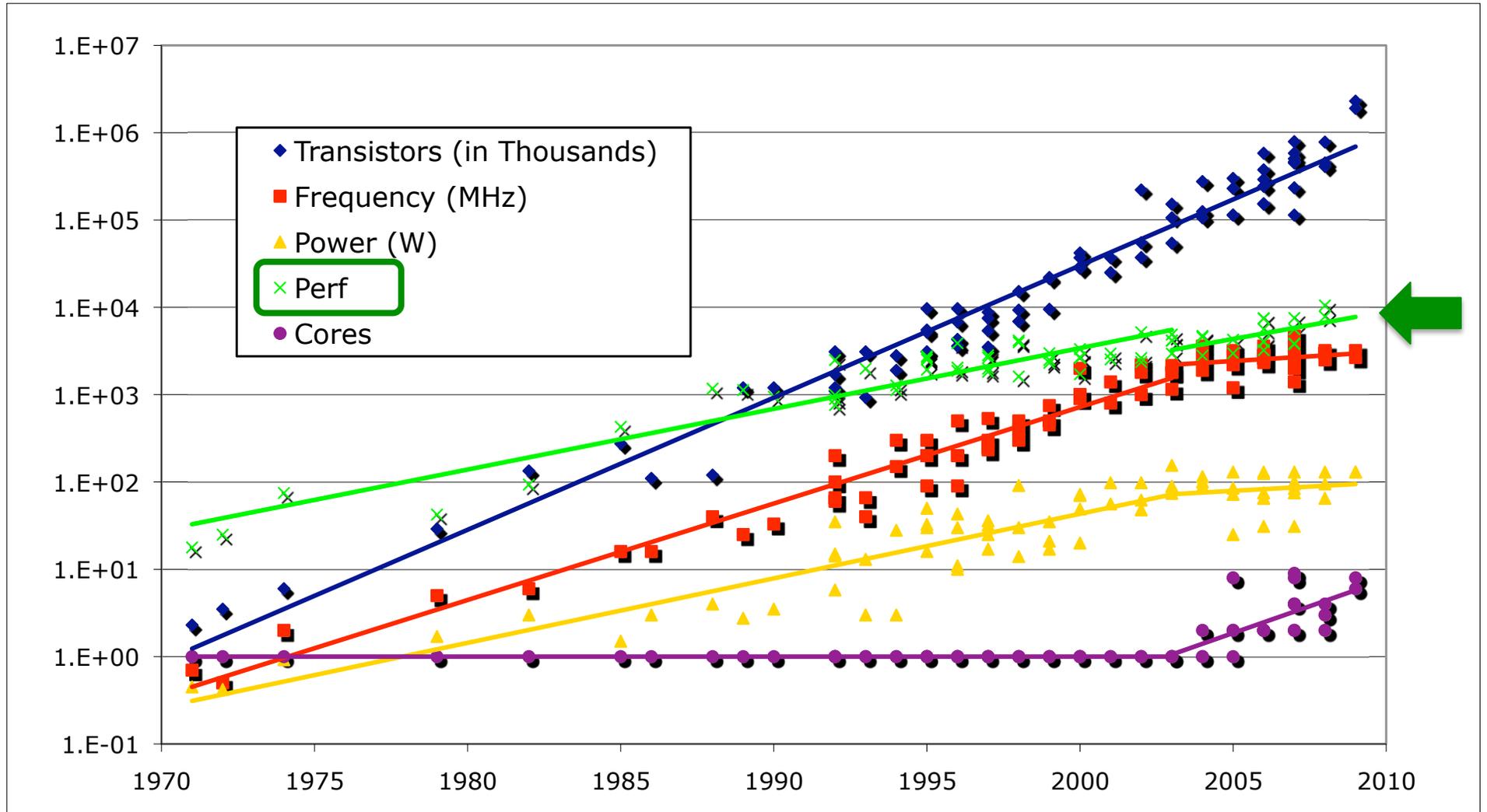
From Kathy Yelick's "Ten Ways to Waste a Parallel Computer", using data from Kunle Olukotun, Lance Hammond, Herb Sutter, Burton Smith, Chris Batten, and Krste Asanovic

Cores Per Socket Increasing



From Kathy Yelick's "Ten Ways to Waste a Parallel Computer", using data from Kunle Olukotun, Lance Hammond, Herb Sutter, Burton Smith, Chris Batten, and Krste Asanovic

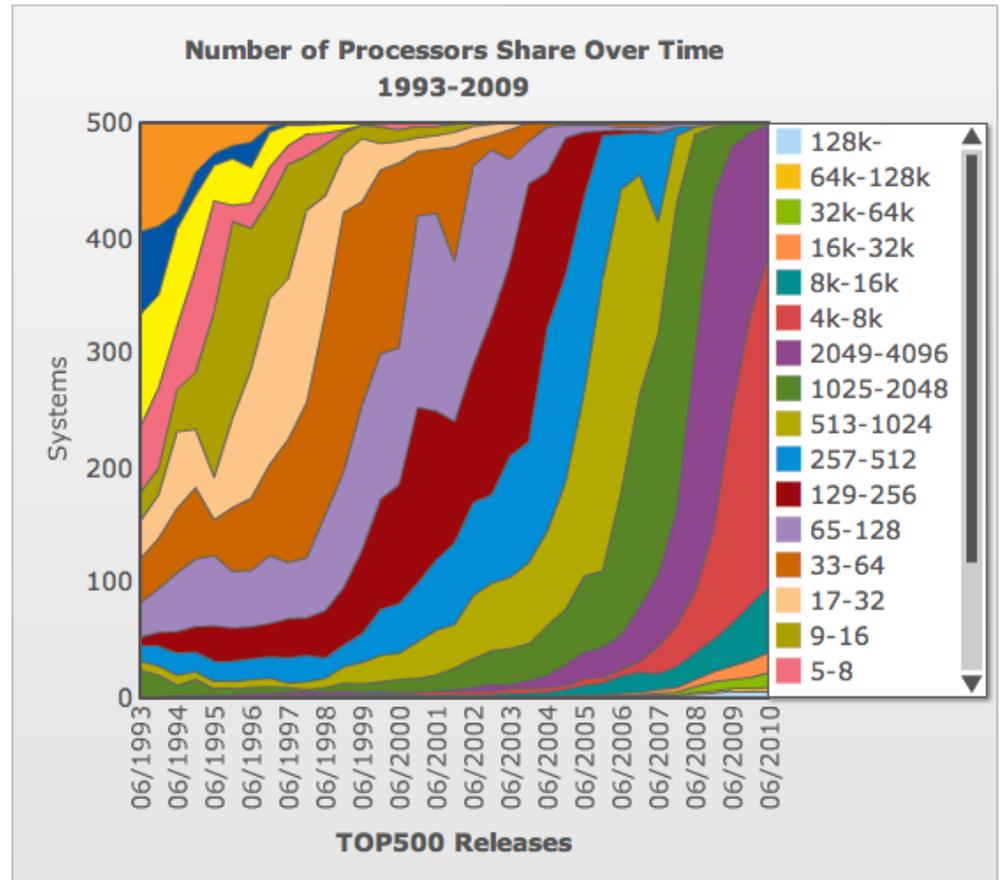
Performance Increasing (Some)



From Kathy Yelick's "Ten Ways to Waste a Parallel Computer", using data from Kunle Olukotun, Lance Hammond, Herb Sutter, Burton Smith, Chris Batten, and Krste Asanovic

Scaling Out

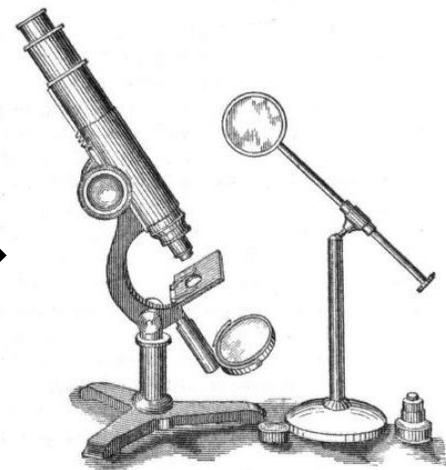
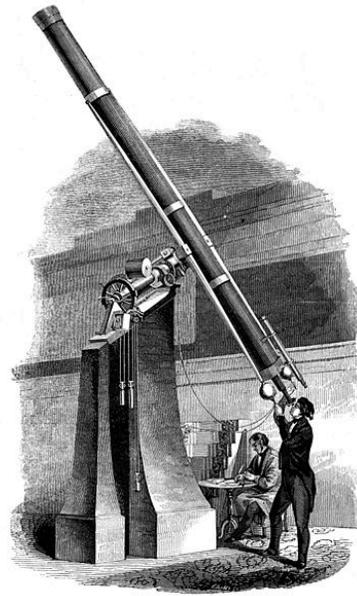
- More cores
- More memory
- More performance
- More space
- More power



Top500.org

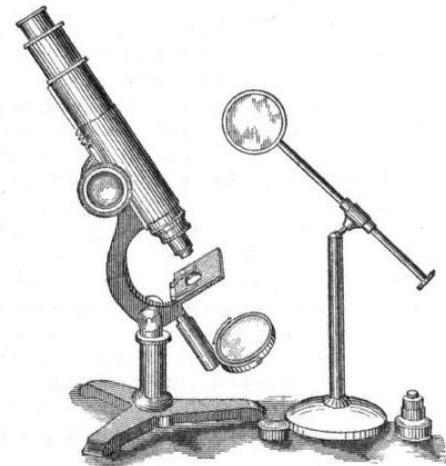
Scaling Out → Scaling In

- More transistors
- More computational need
- Limited space
- Limited power

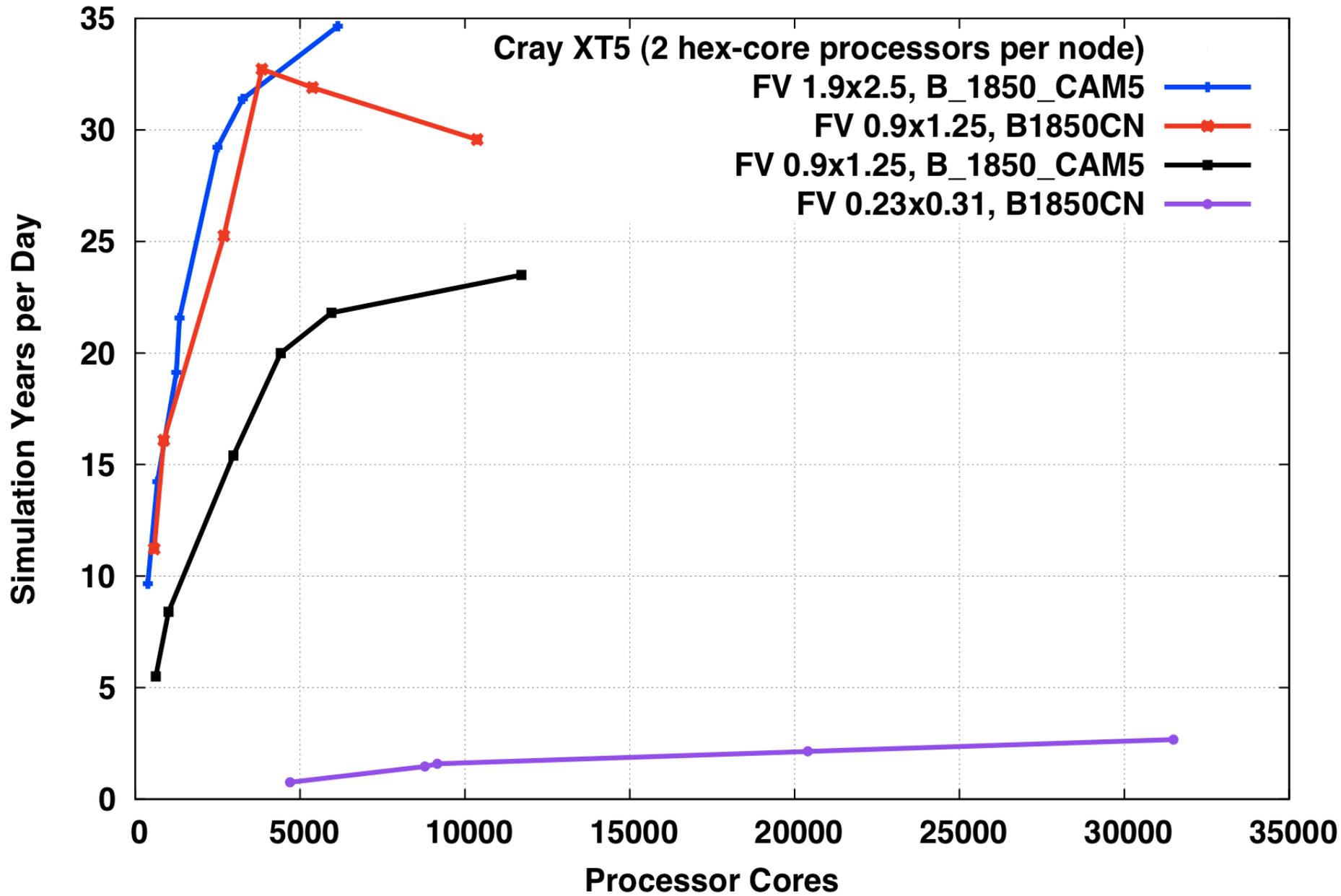


Scaling In

- More cores per chip
- More threads per core
- Longer vector registers (2→4+ doubles)
- Block multithreading (GPUs)
- Heterogeneity on a chip
 - IBM Cell
 - AMD Fusion
 - NVIDIA Project Denver
- Power efficiency
- **More architectural uncertainty**



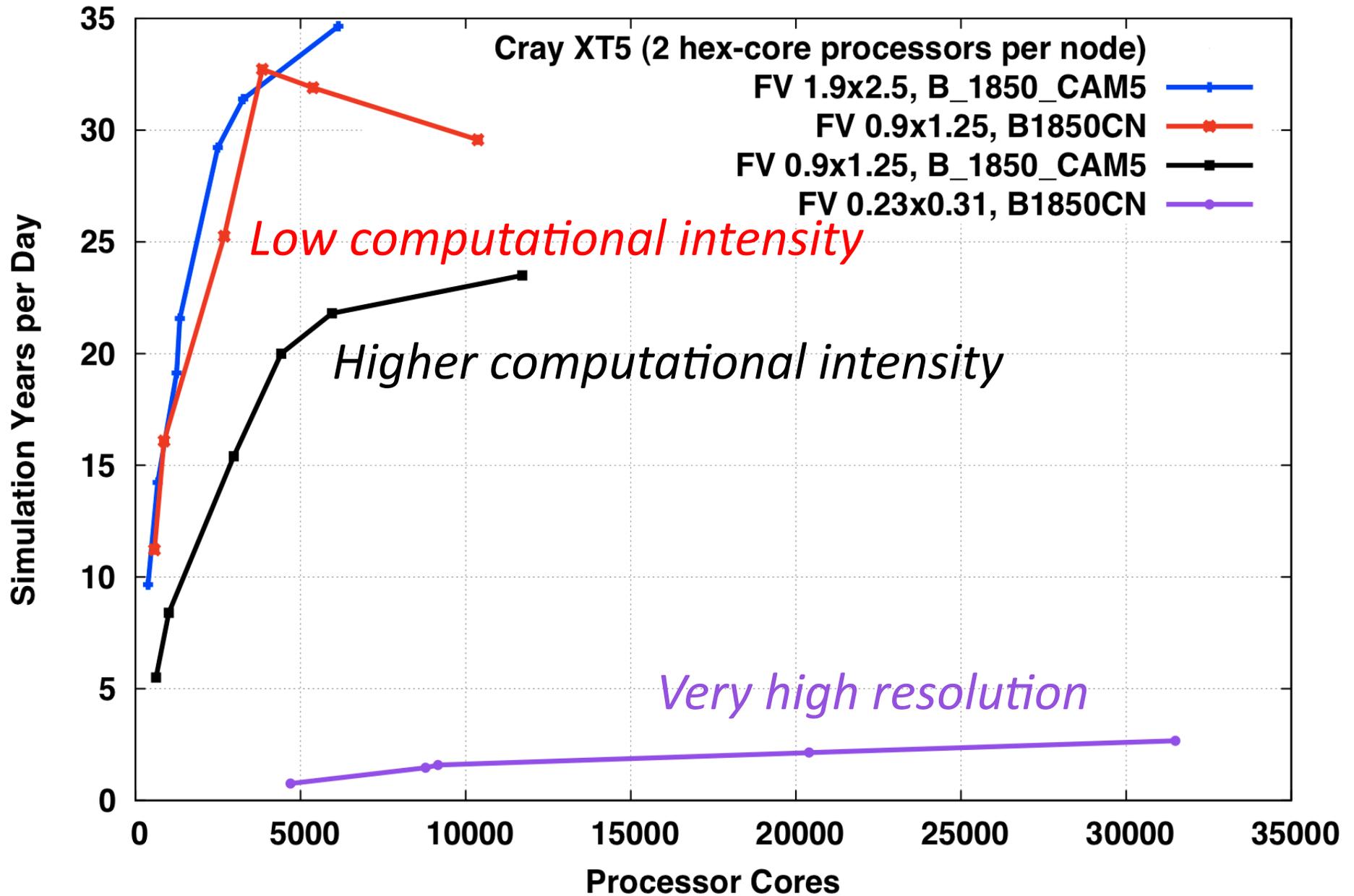
CESM Performance



Courtesy of Pat Worley, ORNL

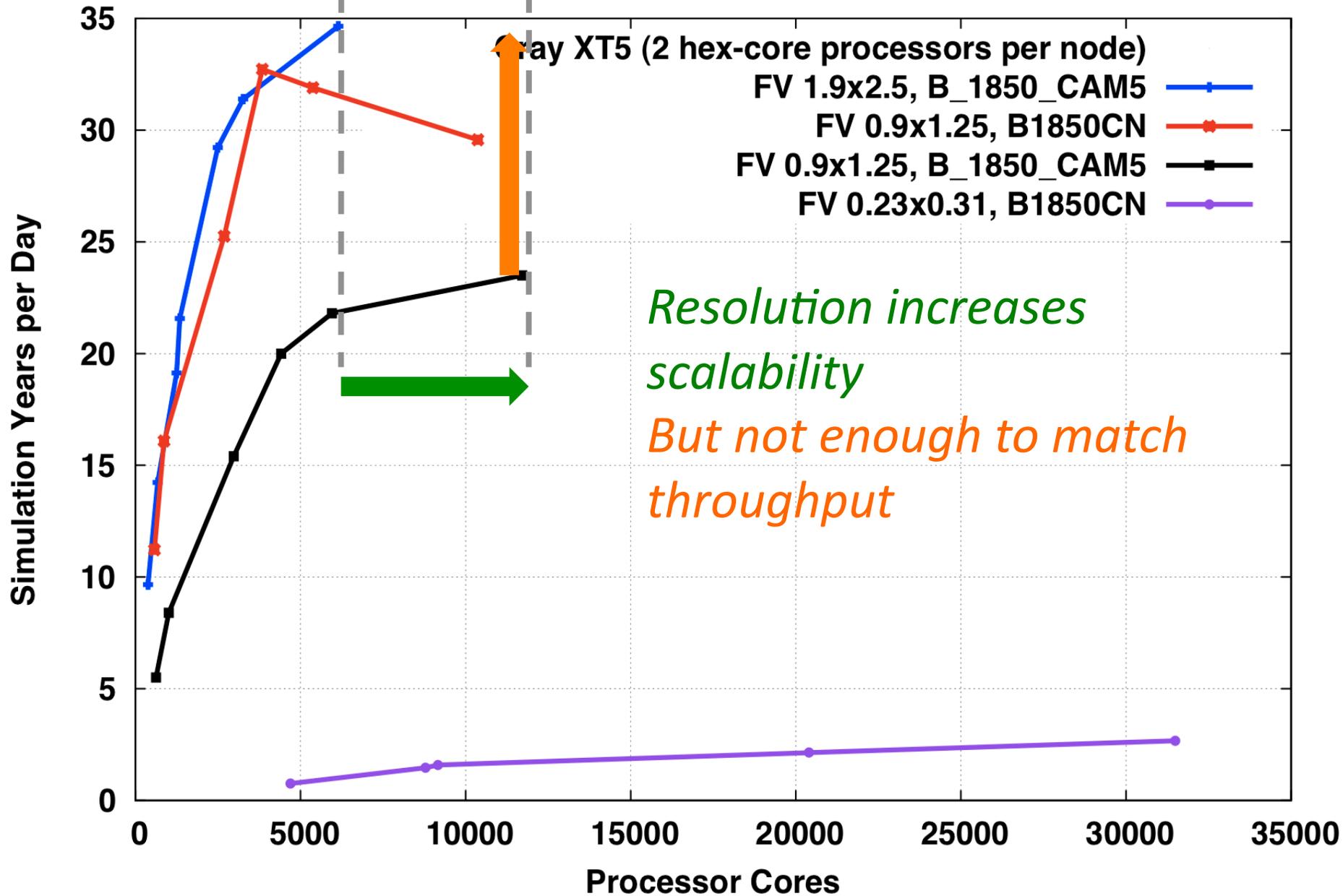
Low resolution

CESM Performance



Courtesy of Pat Worley, ORNL

CESM Performance



Time-Integration Challenge

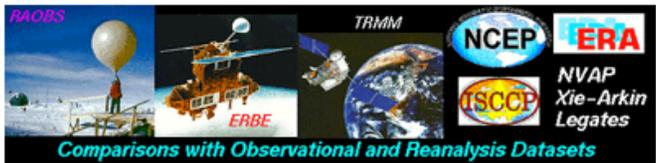
- Explicit methods
 - Scalable and cheap per time step
 - Resolution goes up, time step must go down
 - Single-thread performance no longer improving
- Implicit methods
 - Can be stable for large time steps
 - Expensive: linear and often nonlinear solvers
 - Less scalable: global reductions, latency bound
 - Preconditioning advection?

Psst...

Iron Chef Intergovernmental #5

- CMIP5 defines experiments
- Develop a model
- **Run experiments** 
- Provide simulation output
- Scientists worldwide analyze output
- Scientists worldwide publish papers
- AR5 authors cite papers

AMWG Diagnostics Package cam3655_t341_preind

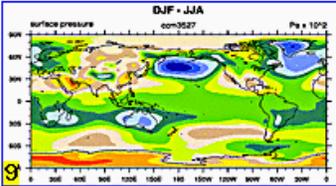
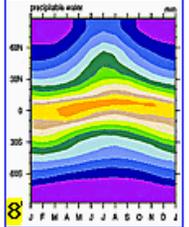
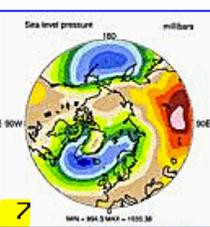
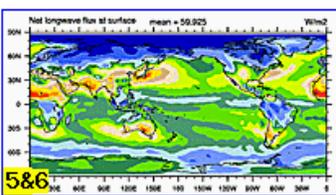
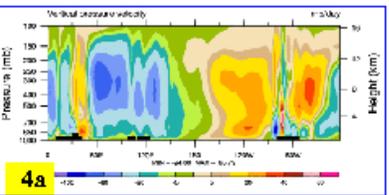
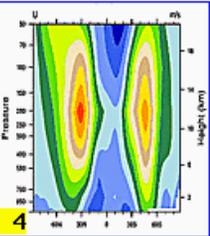
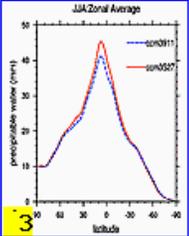
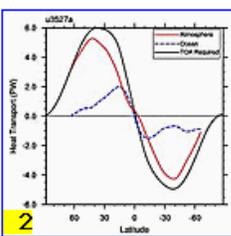


Plots Created
Tue Jan 26 10:40:09 EST 2010

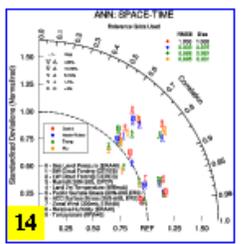
Set Description

- 1 [Tables](#) of ANN, DJF, JJA, global and regional means and RMSE.
- 2 [Line plots](#) of annual implied northward transports.
- 3 [Line plots](#) of DJF, JJA and ANN zonal means
- 4 [Vertical contour plots](#) of DJF, JJA and ANN zonal means
- 4a [Vertical \(XZ\) contour plots](#) of DJF, JJA and ANN meridional means
- 5 [Horizontal contour plots](#) of DJF, JJA and ANN means
- 6 [Horizontal vector plots](#) of DJF, JJA and ANN means
- 7 [Polar contour and vector plots](#) of DJF, JJA and ANN means
- 8 [Annual cycle contour plots](#) of zonal means
- 9 [Horizontal contour plots](#) of DJF-JJA differences
- 10 [Annual cycle line plots](#) of global means
- 11 [Pacific annual cycle, Scatter plot plots](#)
- 12 [Vertical profile plots](#) from 17 selected stations
- 13 [ISCCP cloud simulator plots](#)
- 14 [Taylor Diagram plots](#)

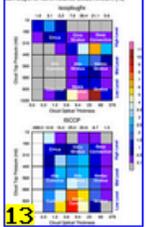
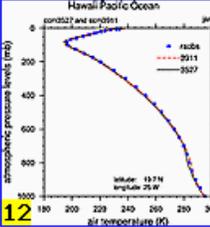
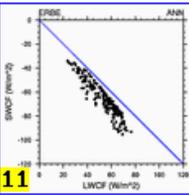
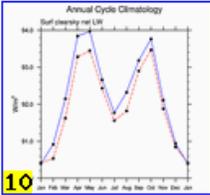
Click on Plot Type

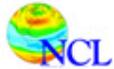


TABLES



METRICS





NCAR Command Language



NCL is an interpreted language designed specifically for scientific data analysis and visualization.

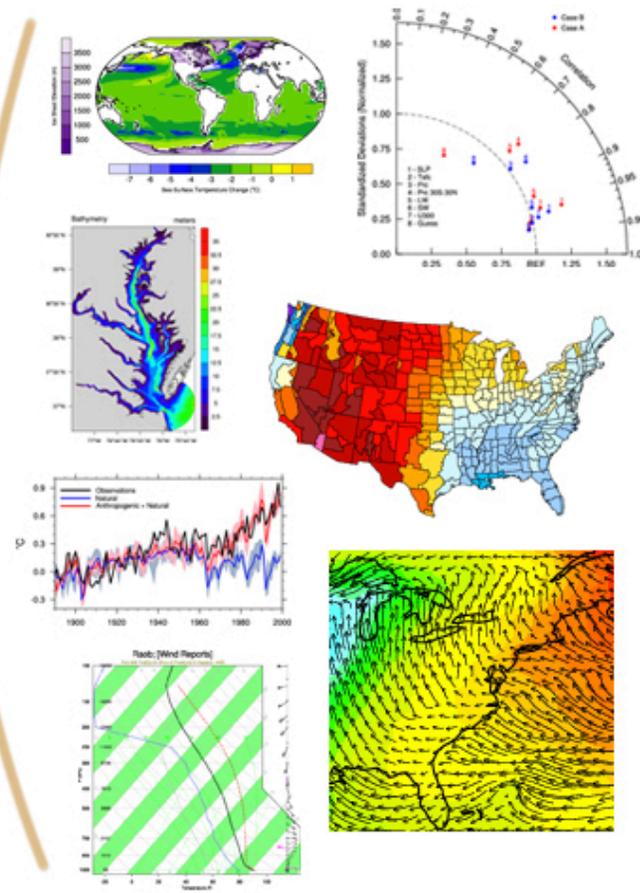
Portable, robust and free, NCL is available as binaries or open source

Supports netCDF3/4, GRIB1/2, HDF-SDS, HDF4-EOS, binary, shapefiles, and ascii files

Numerous analysis functions are built-in

High quality graphics are easily created and customized with hundreds of graphic resources

Many example scripts and their corresponding graphics are available

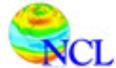


Release Information

Current Version: 5.2.1
Release Date: July 26, 2010

Announcements

Version 5.2.1 now available!



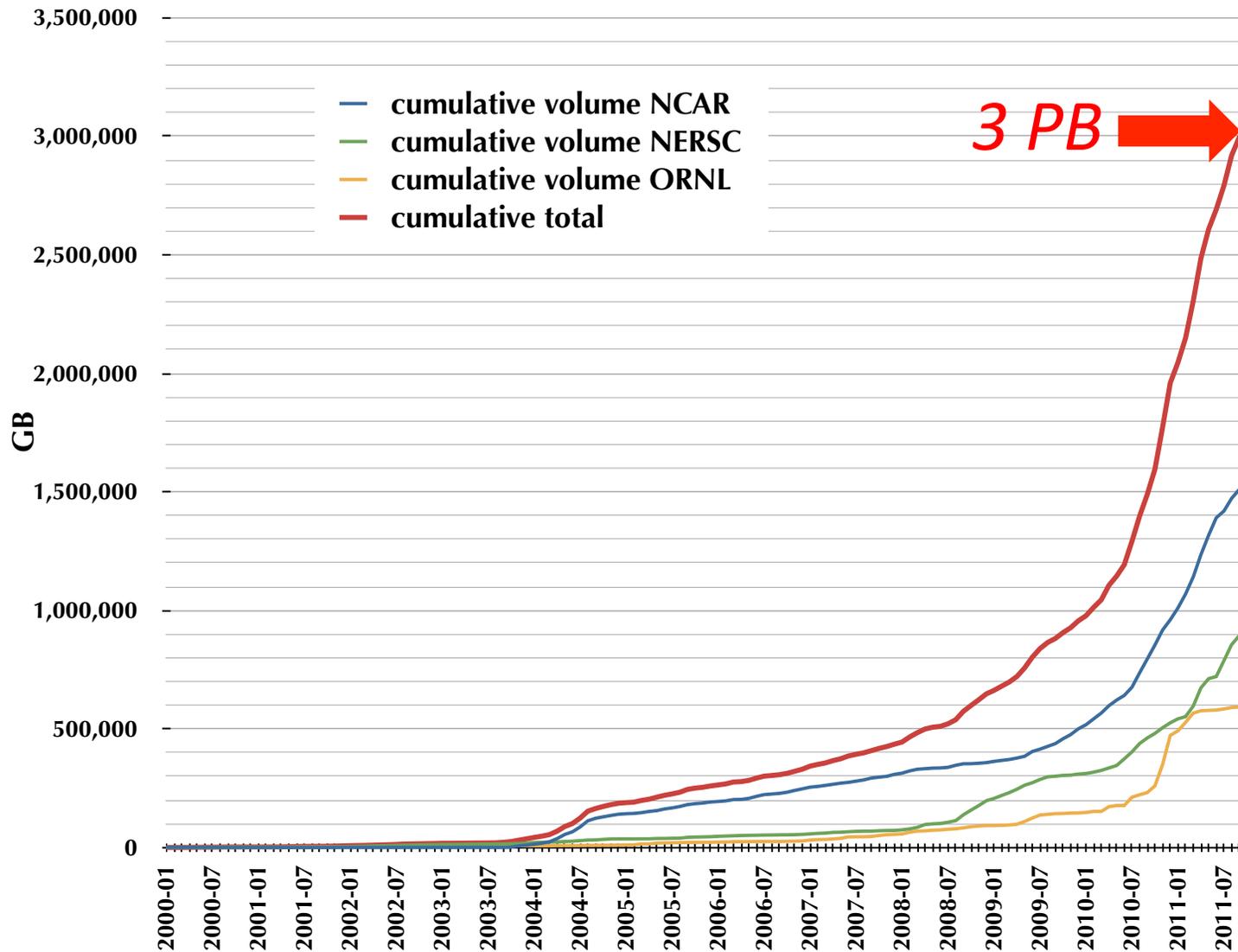
- Serial NCL scripts generate HTML and plots
 - Analysis computers with big I/O
 - Web hosting
- Becoming a bottleneck
 - 8-9 hours for T341 (1/3° resolution)
 - Parallel computers for analysis
 - **Development need:** Parallel analysis scripts
 - Parvis project: <http://trac.mcs.anl.gov/projects/parvis>



Many example scripts and their corresponding graphics are available



CCSM/CESM Output



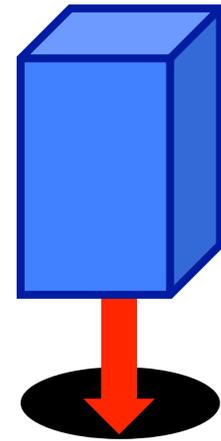
Courtesy of Gary Strand, NCAR

Iron Chef Intergovernmental #5

- CMIP5 defines experiments
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- Run experiments
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Postprocessing Output

- Simulations produce history snapshots
(many fields for a single month)
- Scientists typically want time series
(one field over many years)
- Scientists often want to compare
results from multiple models



NetCDF



- Network Common Data Form
- Portable file format
- Built-in metadata: dimensions, sizes, units
- NetCDF Climate and Forecast (CF) Metadata Convention
- <http://www.unidata.ucar.edu/software/netcdf/>

CMIP5 → CMOR

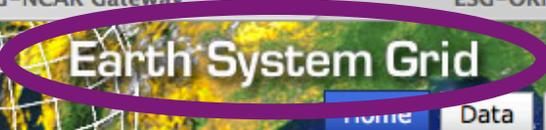


- Climate Model Output Rewriter
- One primary variable per file
 - With coordinate/grid data, attributes, metadata
- Standard variable types defined for CMIP5
- Some CESM fields match CMIP5 one to one
- Others don't
 - Must be derived from model output
 - Must be interpolated to standard vertical coordinate
- <http://www2-pcmdi.llnl.gov/cmor>

typical climate scientist →



*Feed me,
CMOR!*


 Earth System Grid

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ESG Gateway at the National Center for Atmospheric Research

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- > [CMIP5/IPCC AR5](#)
- > [NARCCAP](#)
- > [PCM](#)

+ Model

+ Experiment

+ Frequency

+ Realm

+ Variable

Global Climate Models

Community Earth System Model



[Community Earth System Model \(CESM\)](#)

[CCSM 4.0 Model Output](#)

[CCSM 3.0 Model Output](#)

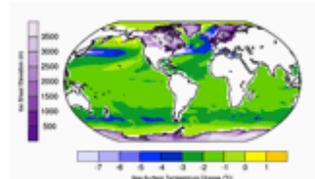
[Parallel Climate Model \(PCM\)](#)

Regional Climate Models



[NARCCAP: North American Regional Climate Assessment Program](#)

Analysis & Visualization Software



[NCL: NCAR Command Language](#)

[PyNGL: Python Interface to the NCL Graphic Libraries](#)

[PyNIO: Python Interface for NetCDF Input/Output](#)

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ESG Gateway at the National Center for Atmospheric Research

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- + Model

- + Experiment

- + Frequency

- + Realm

- + Variable

Global Climate Models

Community Earth System Model



[Community Earth System Model \(CESM\)](#)

[CCSM 4.0 Model Output](#)

[CCSM 3.0 Model Output](#)

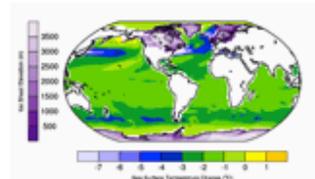
[Parallel Climate Model \(PCM\)](#)

Regional Climate Models



[NARCCAP: North American Regional Climate Assessment Program](#)

Analysis & Visualization Software



[NCL: NCAR Command Language](#)

[PyNGL: Python Interface to the NCL Graphic Libraries](#)

[PyNIO: Python Interface for NetCDF Input/Output](#)

Quick Links

[Create Account](#)
[Browse Catalogs](#)
[Search for Data](#)

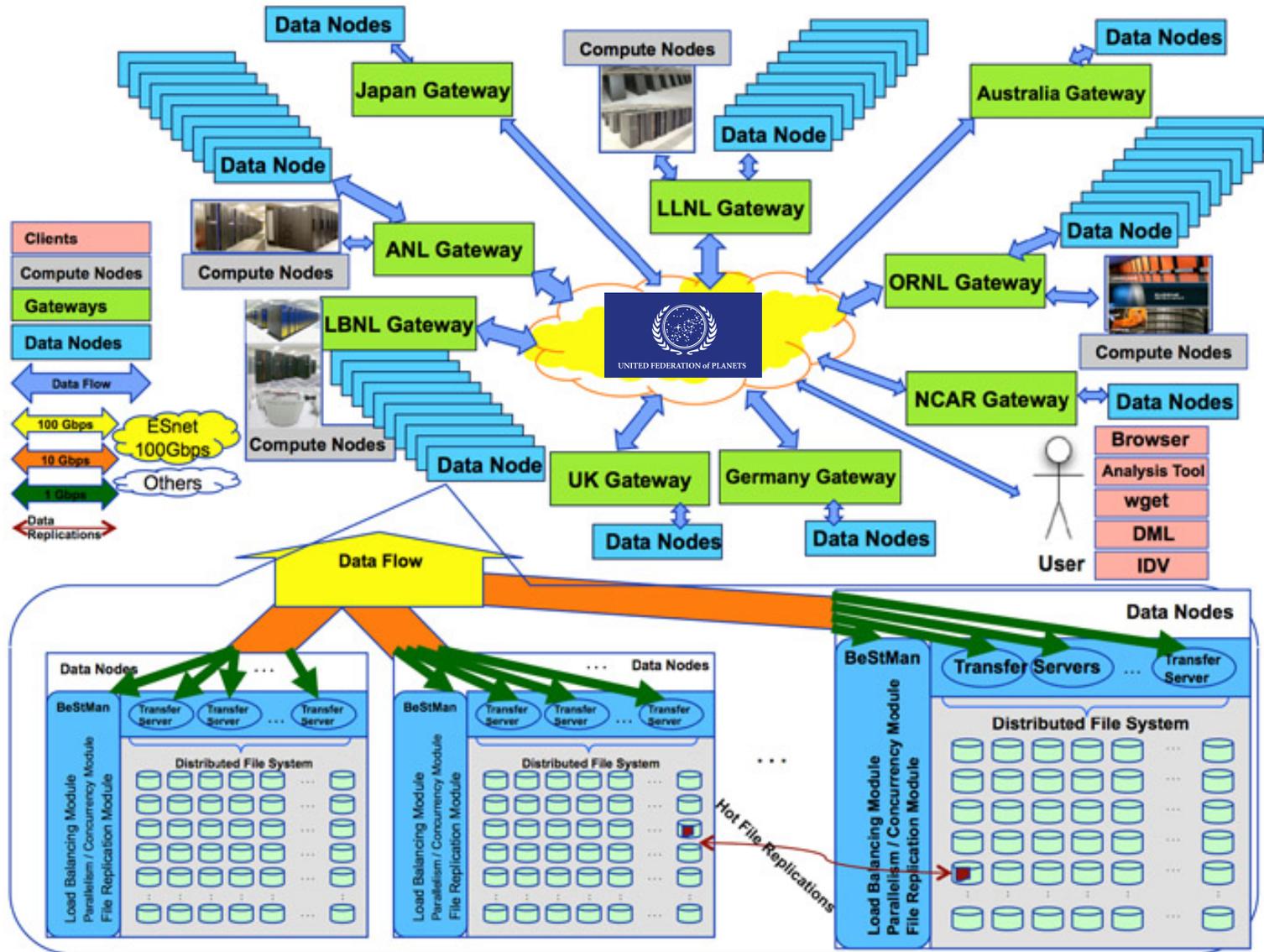
ESG Data Gateways

[NCAR Gateway](#)
[ORNL Gateway](#)
[PCMDI Gateway](#)

Other Gateways

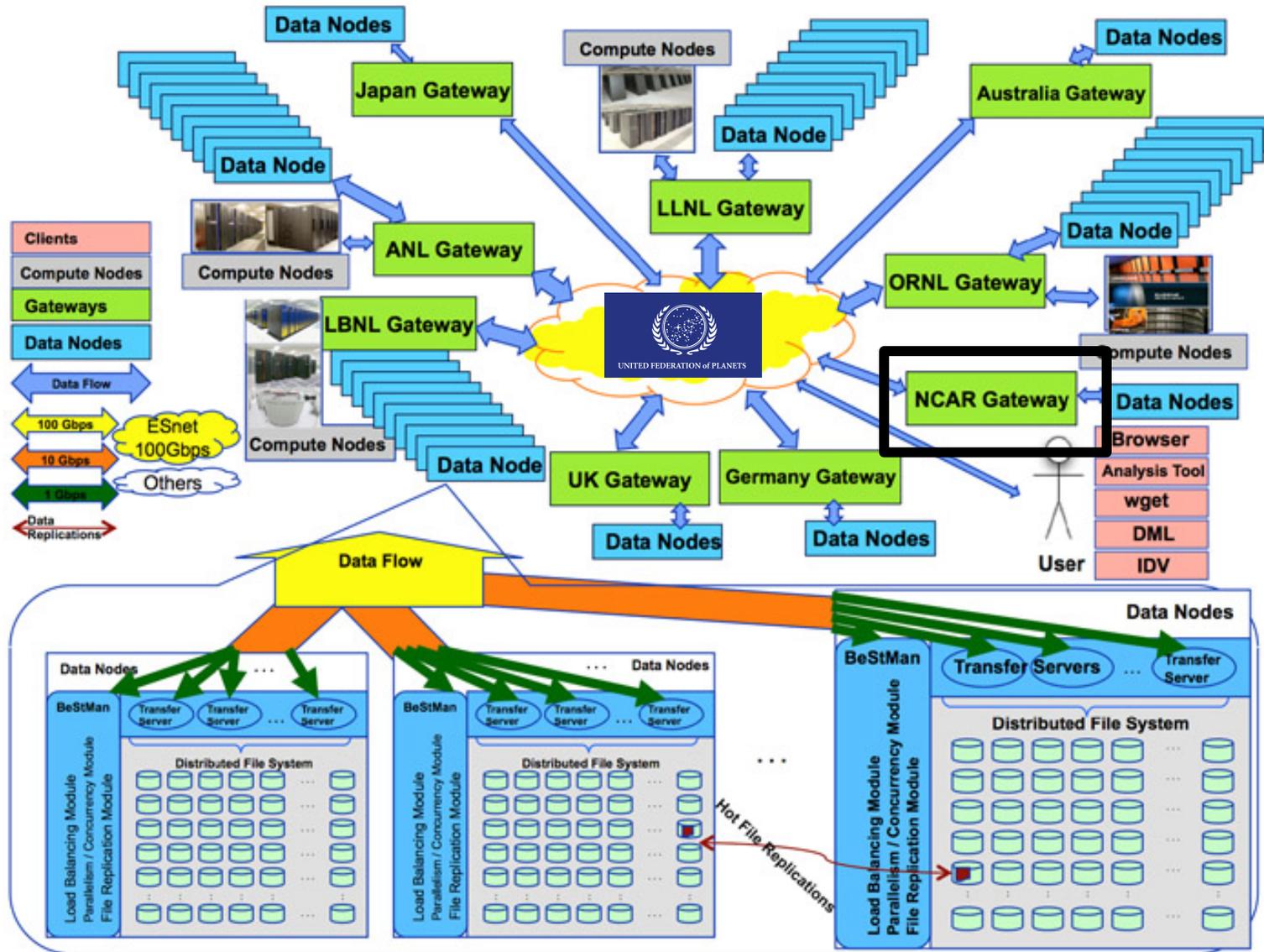
[CADIS \(Arctic\)](#)

ESG Federation



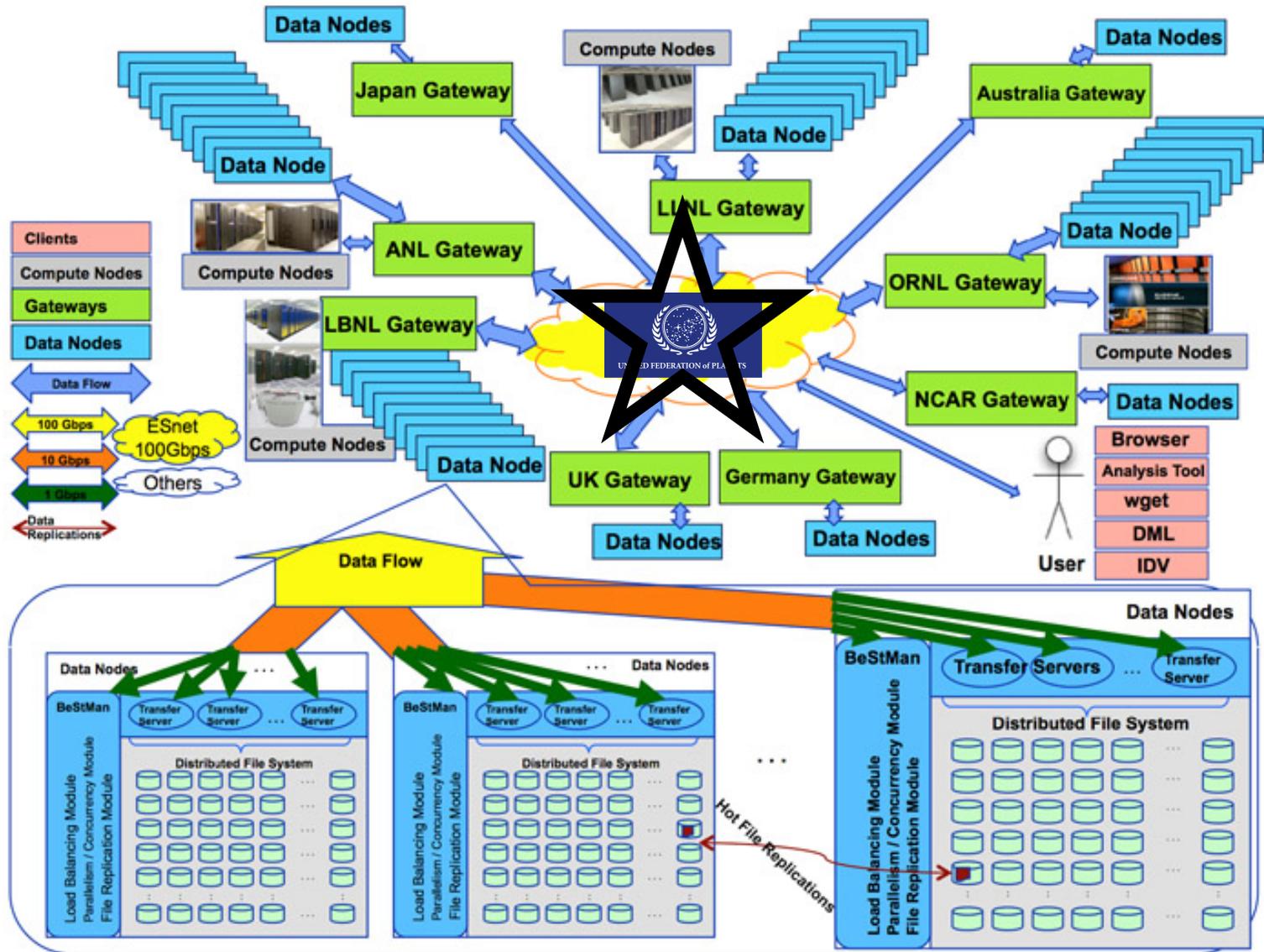
ESG Federation

Data stay at source computer center

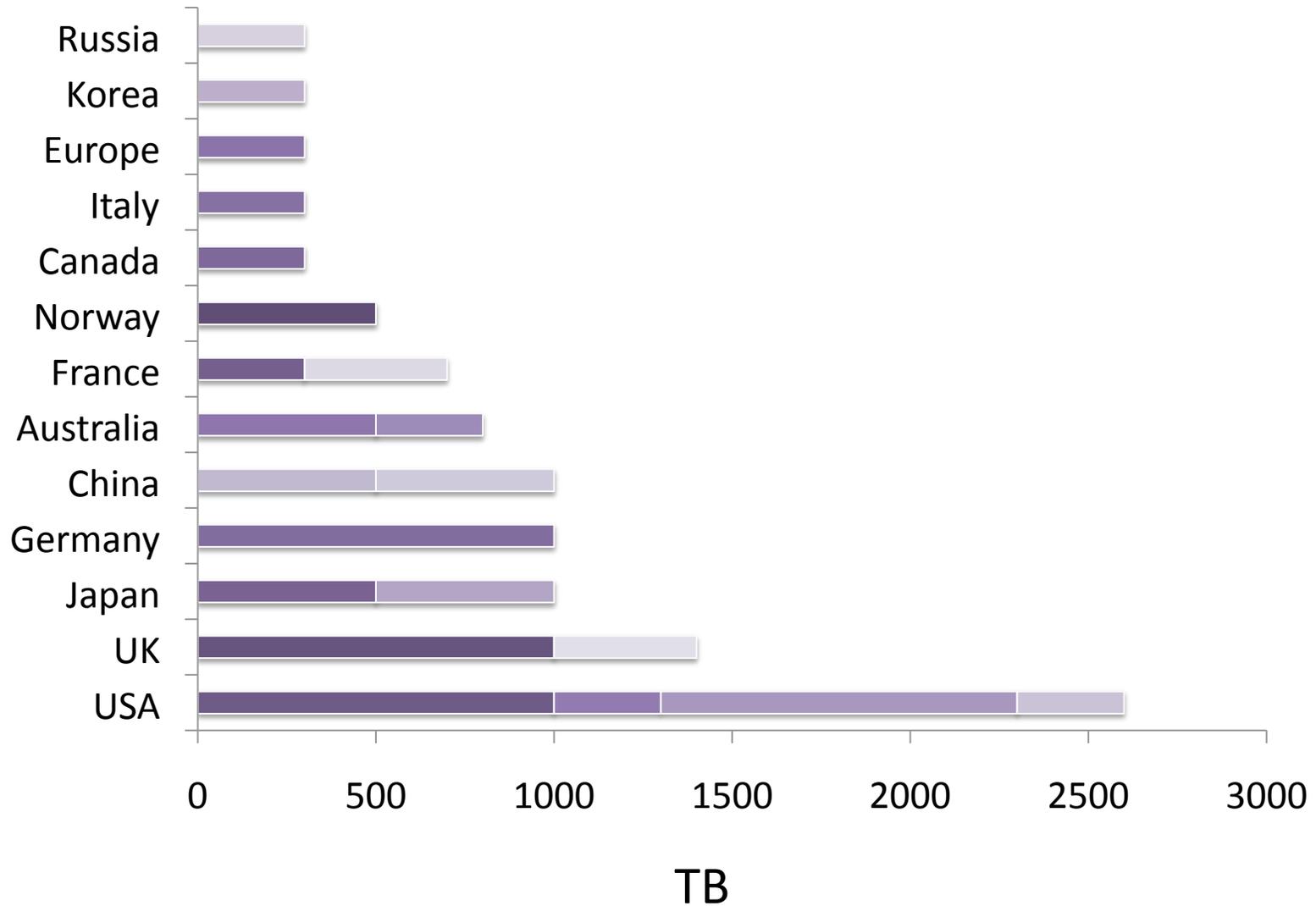


ESG Federation

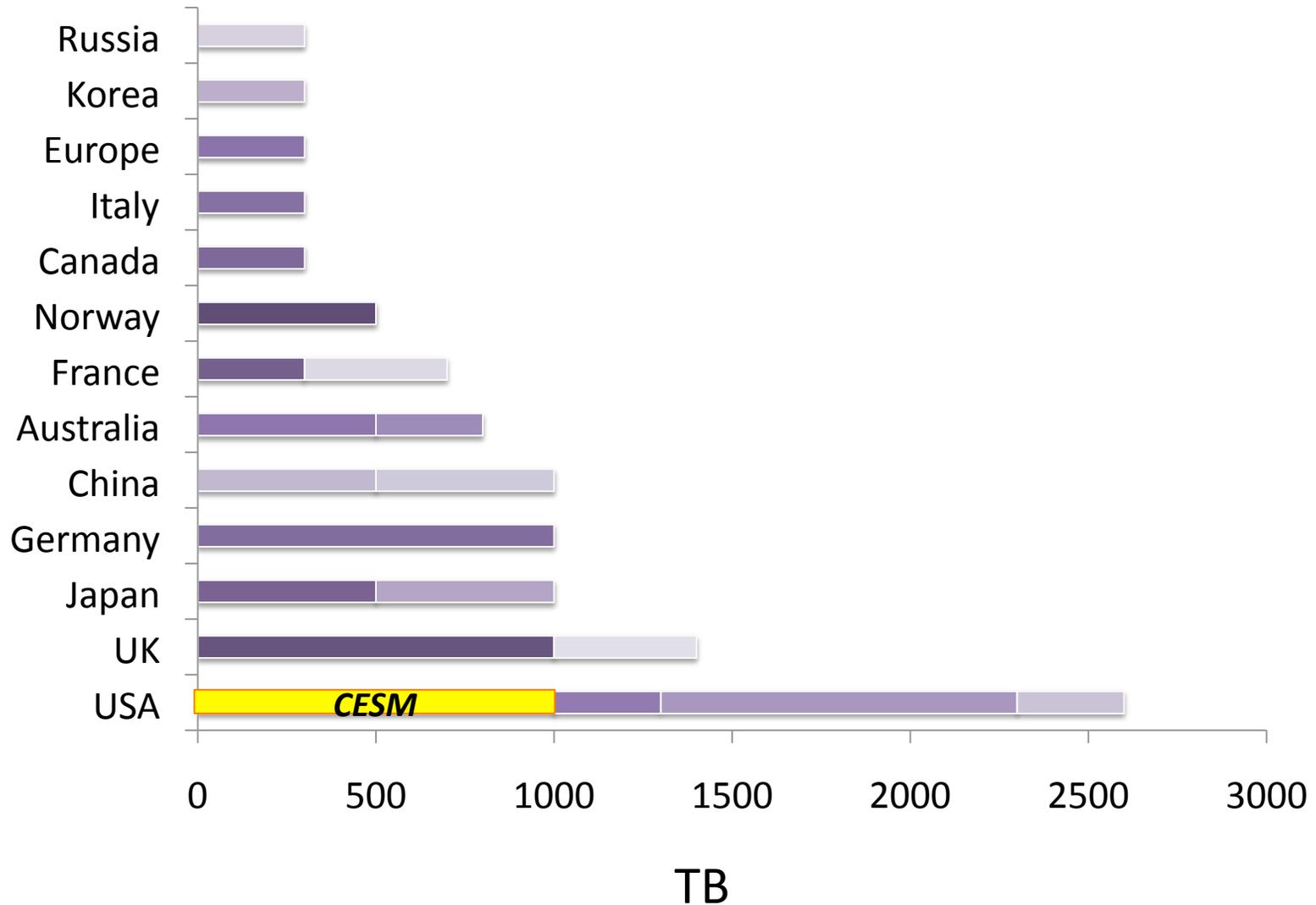
*Locatable from
any portal*



Expected CMIP5 data for ESG



Expected CMIP5 data for ESG



Metafor: Common Metadata for Climate Modeling Digital Repositories

CMIP5 Model Metadata Questionnaire

http://q.cmip5.ceda.ac.uk/cmip5/3/

CMIP5 Metadata Questionnaire (1.11)

Completed data will be sent to the Earth System Grid for inclusion in all official CMIP5 catalogues.

The Questionnaire Support Team can be contacted on our dedicated email: cmip5qhelp@stfc.ac.uk
Instructions for gaining access to the questionnaire can be found [here](#)

Summary Experiments Model Grid Simulation Files References Parties Help About Log Out

Summary page for US National Centre for Atmospheric Research (NCAR)

Introduction

Each CMIP5 modelling centre performs *Simulations* which run *Models* on *Platforms*. The purpose of this questionnaire is to glean information about these platforms, models and simulations and how the simulations conformed to the CMIP5 experiment requirements. We expect each centre to describe at least one platform, one model and multiple simulations following the workflow listed below:

1. Describe a Platform
2. Describe a Model and Grid
3. Describe some Simulations

It is not possible to start entering simulation information until at least one model and one platform have been described.

Each new platform, grid and model you create will be given a generic name you will need to give these more appropriate short names so they can be distinguished from each other.

Definitions

Models are made up of *Components*.

Simulations conform to the *Numerical Requirements* of *Experiments* via what we call *Conformances*.

Conformances will consist of either specific code characteristics (defined here as *model modifications*) or the use of specific boundary or initial conditions.

Computing platforms associated with NCAR

bluefire			Edit	
franklin			Edit	
jaguarpf			Edit	

Add a new Platform

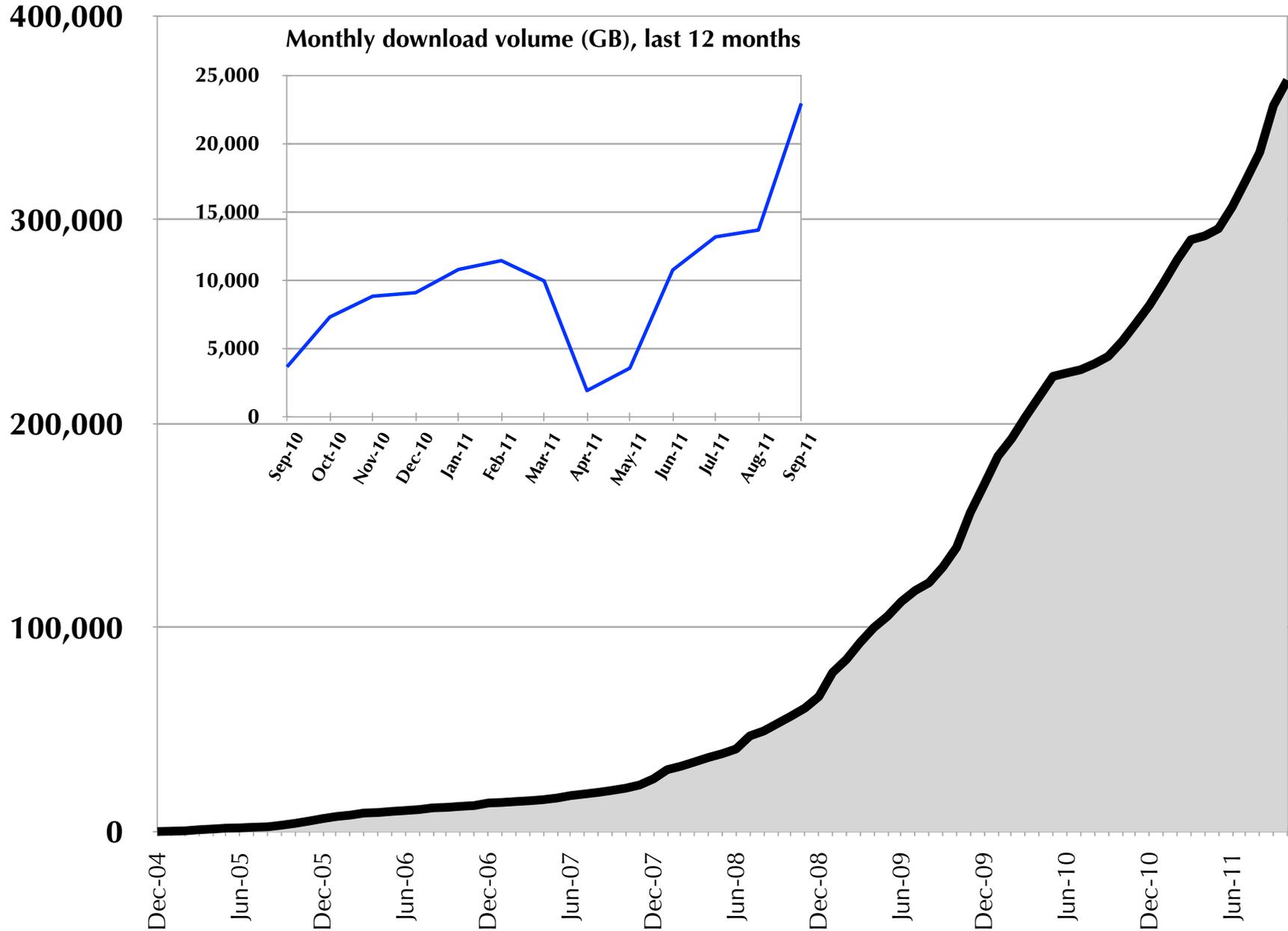
Files, References and Parties

There are 6 references associated with NCAR

Iron Chef Intergovernmental #5

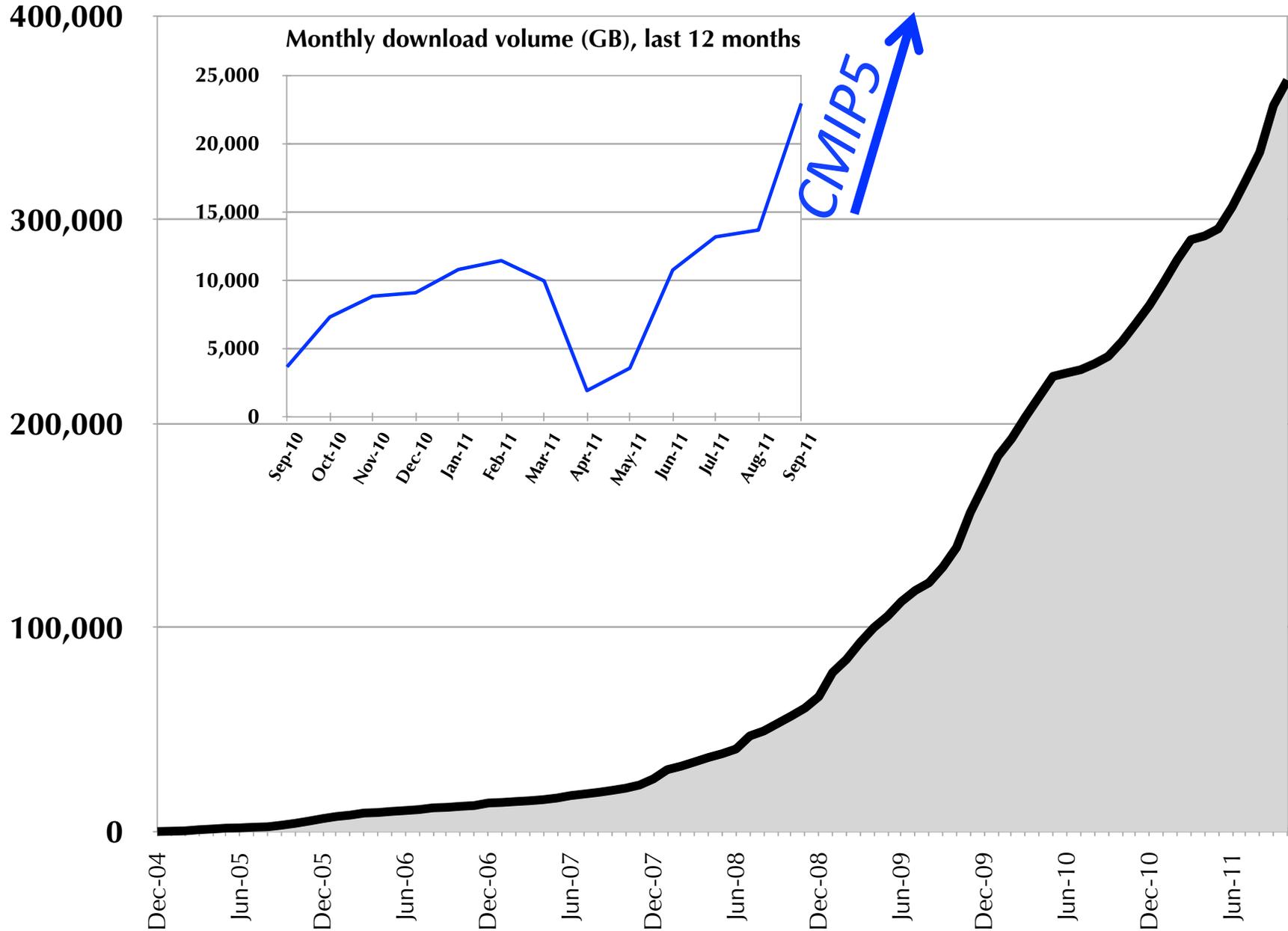
- CMIP5 defines experiments
- Develop a model
- Run experiments
- Provide simulation output
- **Scientists worldwide analyze output**
- Scientists worldwide publish papers
- AR5 authors cite papers

NCAR ESG-CET portal cumulative download volume (GB)



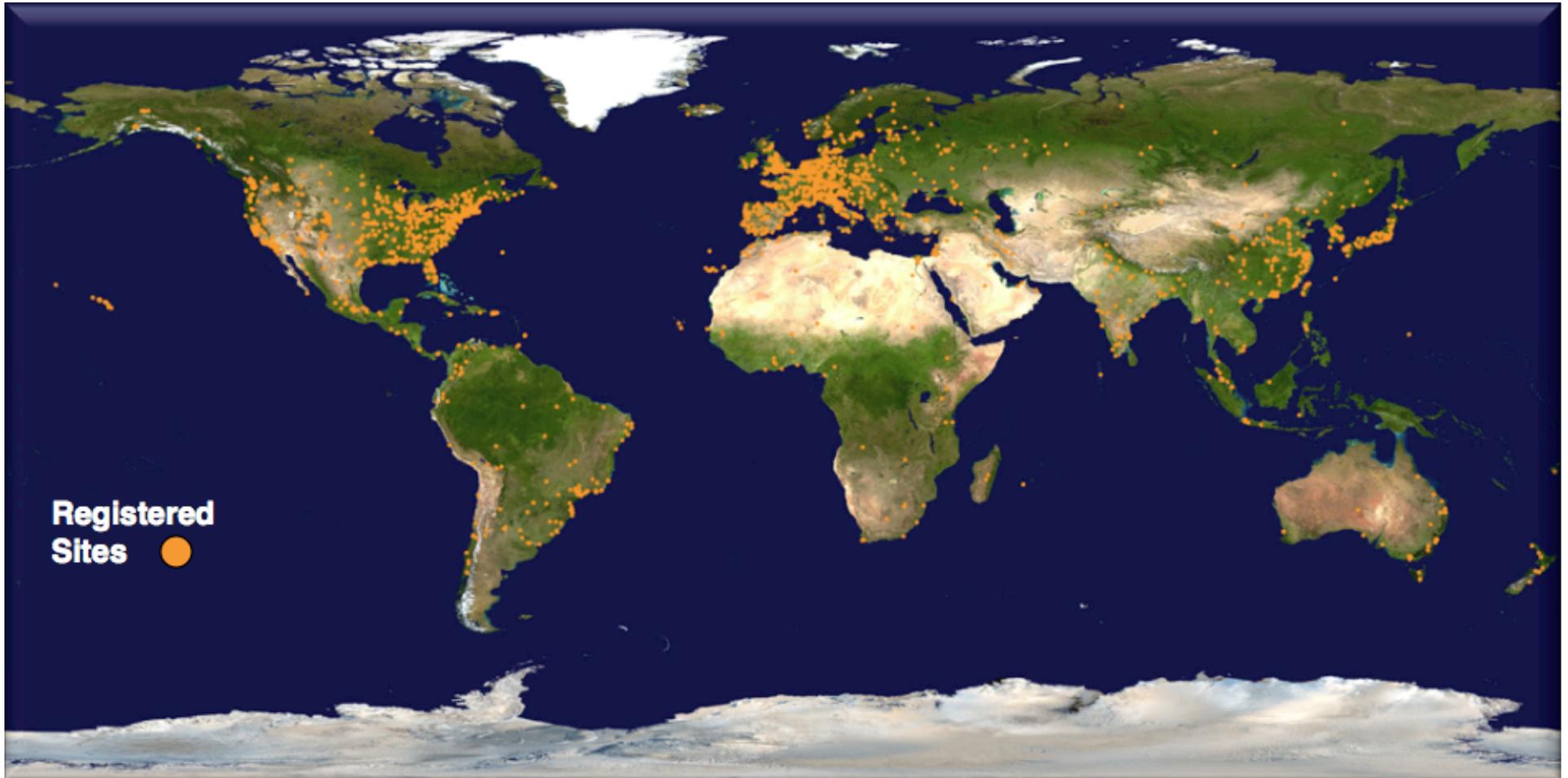
Courtesy of Gary Strand, NCAR

NCAR ESG-CET portal cumulative download volume (GB)



Courtesy of Gary Strand, NCAR

ESG Downloads



From "Climate Science—Enabling Worldwide Access to Petascale Climate Data", by Dean N Williams, Gary Strand, Galen Shipman, and James McGraw, in <http://www.es.net/assets/Papers-and-Publications/BER-Net-Req-Workshop-2010-Final-Report.pdf>.

WAN Bandwidth

Transfer Rate	Time to Transport 1 TB of Data	Time to Transport 1 PB of Data
10-Mbps	9.7days	27.20 years
50-Mbps	1.94 days	5.44 years
100-Mbps	23.3 hours	2.72 years
1-Gbps	2.28 hours	97.1 days
10-Gbps	13.65 minutes	9.7 days
100-Gbps	81.9 seconds	23.3 hours

From "Climate Science—Enabling Worldwide Access to Petascale Climate Data", by Dean N Williams, Gary Strand, Galen Shipman, and James McGraw, in <http://www.es.net/assets/Papers-and-Publications/BER-Net-Req-Workshop-2010-Final-Report.pdf>.

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Weeks to years?

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Output Challenges

- ESG volume and throughput?
- Archive volume and cost
 - Computing centers charging for space, adding quotas
 - Which sites should maintain data? For how long?
- Post-processing and diagnostic throughput
 - Compute jobs can outrun diagnostics and post-processing

Output Opportunities

- Parallel I/O
- Asynchronous I/O
- Output time series directly from simulation
 - Or even CMOR output?
- Parallel analysis tools
- Distributed analysis tools
- Automatic metadata generation and propagation

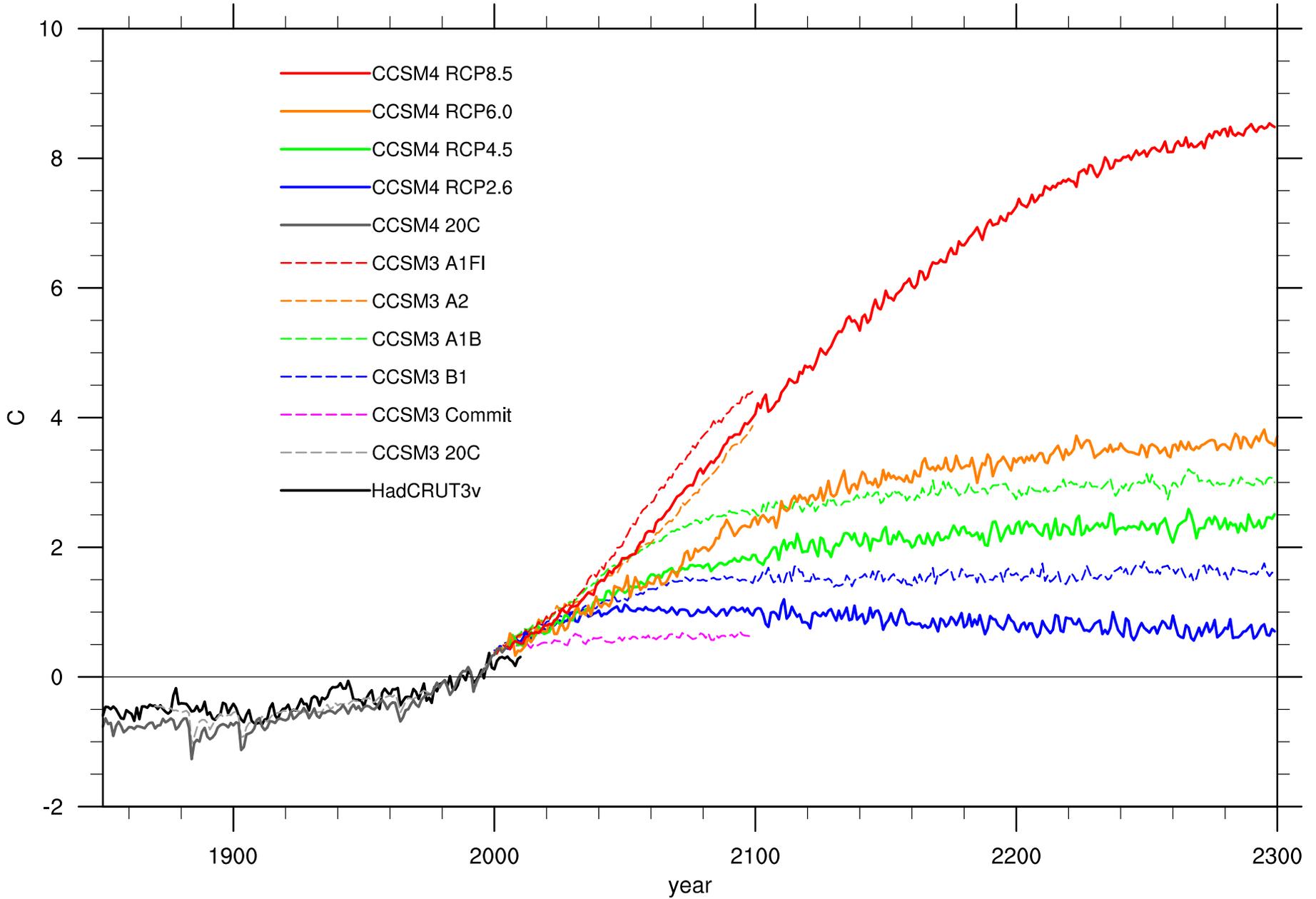
Iron Chef Intergovernmental #5

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Surface temperature

anomaly from 1980-1999, annual and global mean

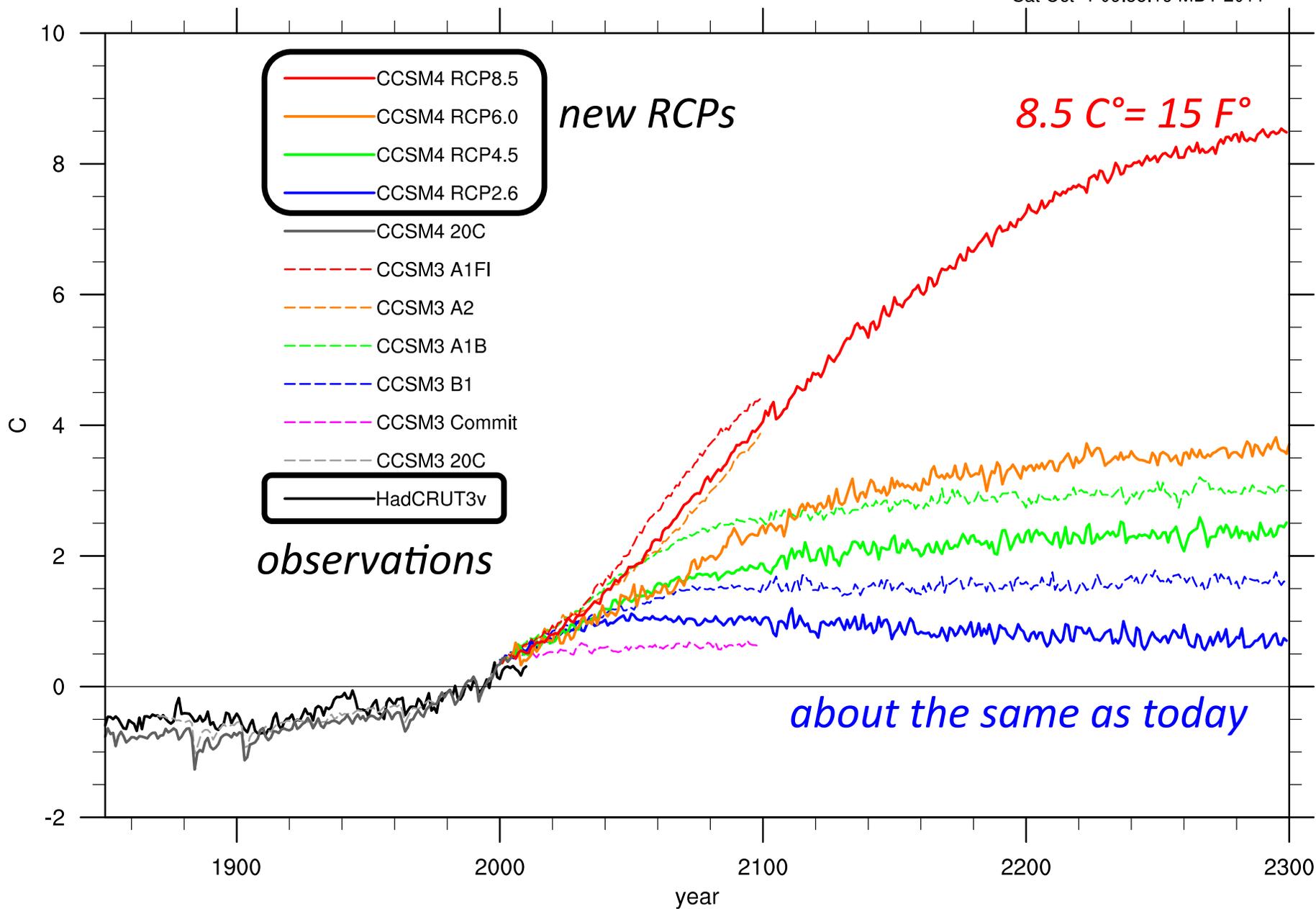
Sat Oct 1 09:58:19 MDT 2011



Surface temperature

anomaly from 1980-1999, annual and global mean

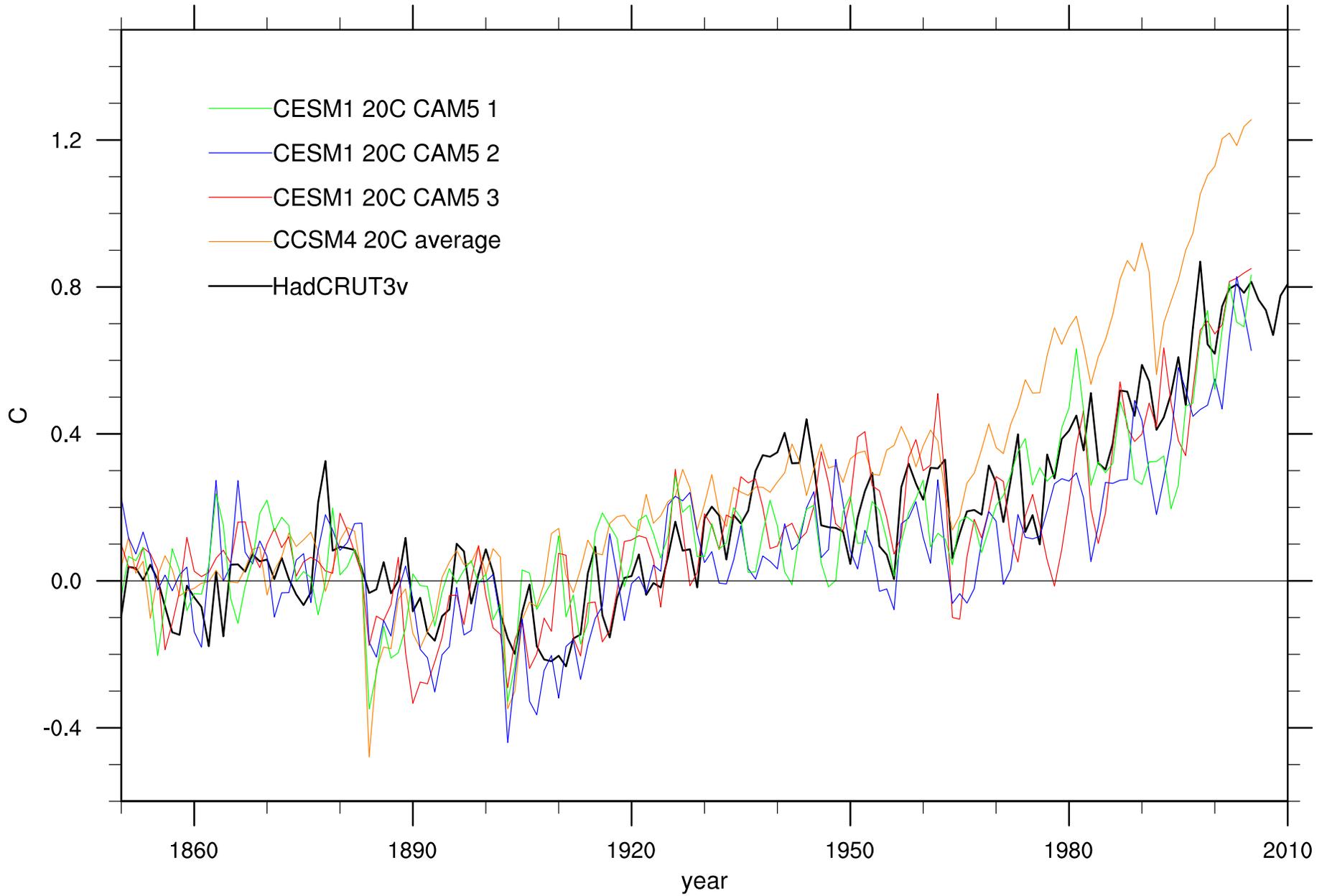
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Surface temperature

anomaly from 1850-1899, annual and global mean

Fri Oct 21 07:36:46 MDT 2011

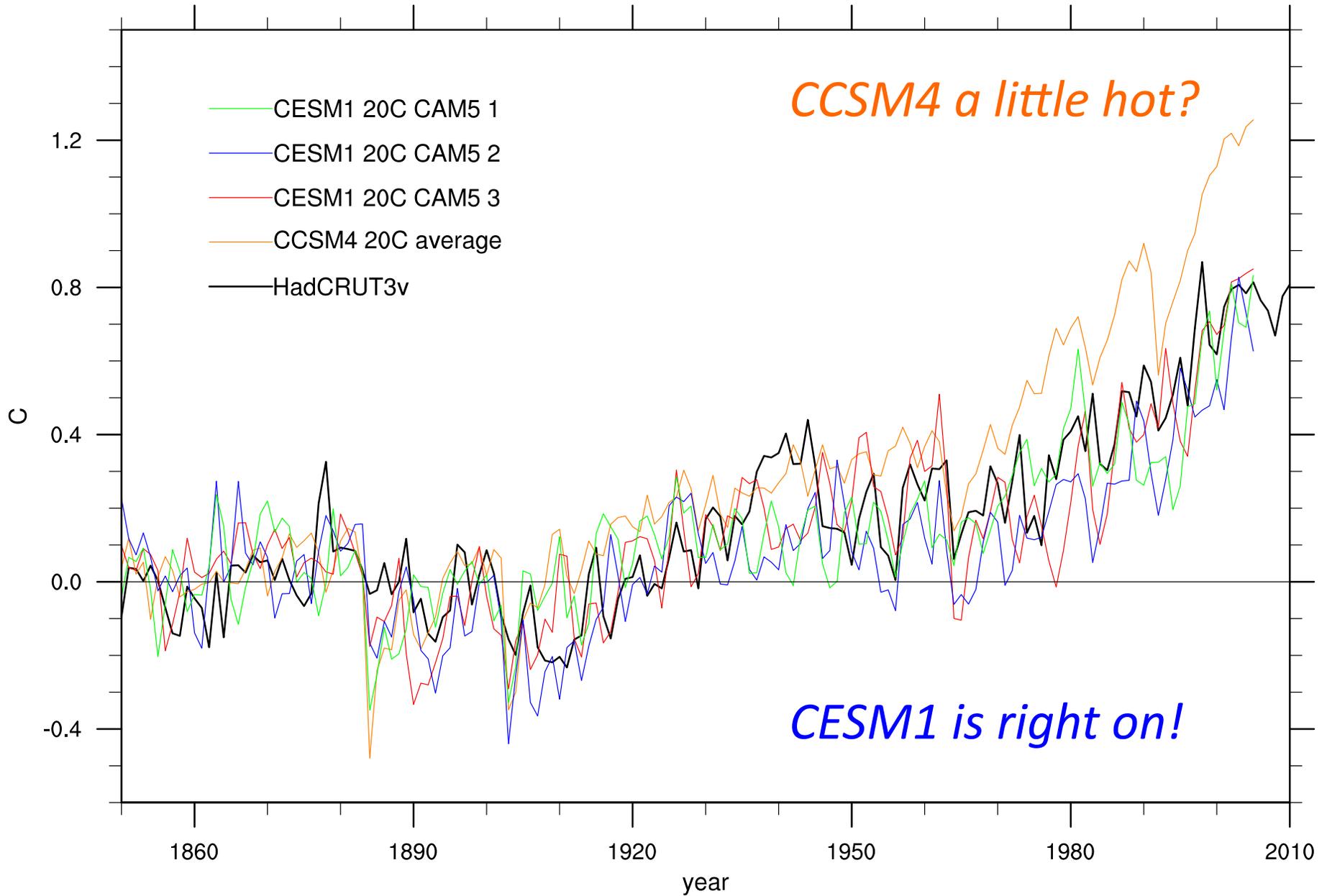


Courtesy of Gary Strand, NCAR

Surface temperature

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Fri Oct 21 07:36:46 MDT 2011



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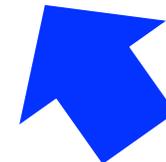
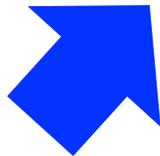
AR5 Deadlines

- Working Group 1: Physical Science Basis
 - Papers submitted before **August 2012**
 - Papers accepted by **March 2013**
 - Assessment Report approved September 2013
- WG2: Impacts, Adaptation, and Vulnerability
WG3: Mitigation of Climate Change
 - Papers submitted before February 2013
 - Papers accepted by September/October 2013
 - Assessment Reports approved in 2014

Psst...



Cyberinfrastructure for Earth-System Modeling



James B White III (Trey)
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Arkansas State University CI-Days
October 31, 2011

Clip art courtesy of "<http://commons.wikimedia.org/>"



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Cyberinfrastructure for CESM

- Petascale supercomputers
- Terascale clusters
- PB and multi-GB/s file systems
- Multi-PB and GB/s archives
- GB/s wide-area networks

Cyberinfrastructure for CESM

- Web repositories for software, input data, and experiment configurations
- Multi-PB distributed output repositories
- Standard output formats
- Metadata models, conventions, and web servers
- Analysis tools (parallel?) (distributed?)
- State-of-the-science million-line simulation software

Questions?

Cyberinfrastructure for Earth-System Modeling

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