A Multi-Model Perspective of Climate Uncertainties

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Outline

- Introduction to climate models
- Introduction to model intercomparison projects (MIP's)
- What have MIP's done to advance climate modeling?
- Uncertainty in the evolution of climate
  - Contributions to uncertainty in model projections
  - What do multi-model ensembles contribute to quantifying uncertainty?

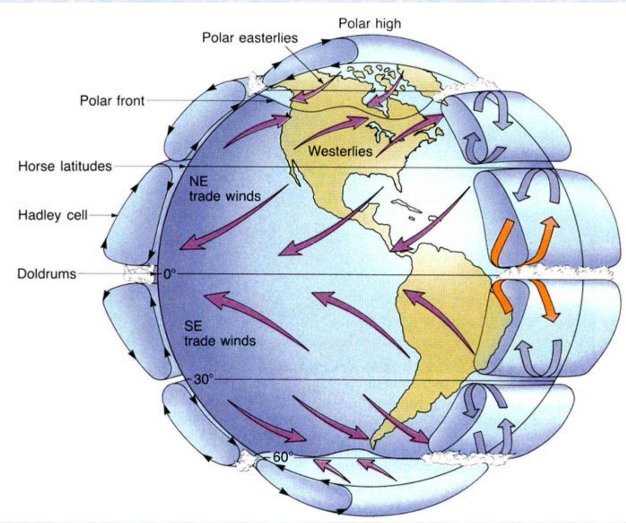
Introduction to climate models

- Physically-based climate models can be used to explore how the climate may evolve as a result of human activities
- Our confidence in climate models stems from rigorous comparisons with observations
- All climate models are imperfect largely because of deficiencies in parameterized physics and missing physics
- We would like to quantify their imperfectness and the uncertainty in their projections.

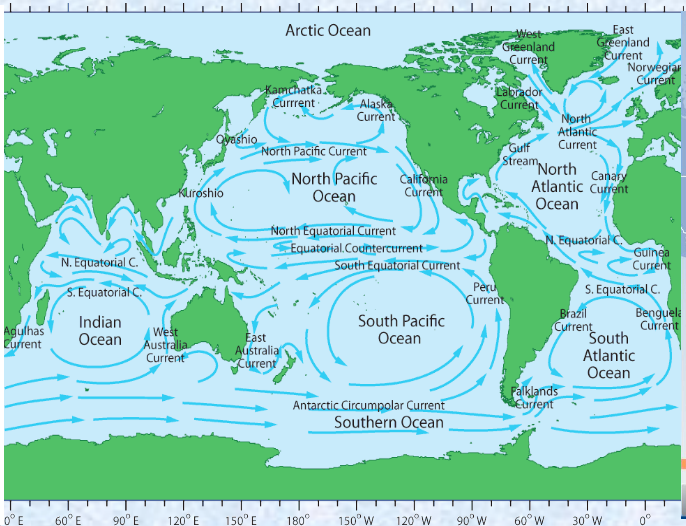
General Circulation Models (GCM's) simulate the large-scale circulation & thermodynamic properties of the atmosphere and ocean

- Based on laws of physics which govern fluid motion and thermodynamics (and chemical processes are also included)
- Systems of differential and other equations
- "Coupled models" result from combining individual component models of the atmosphere, ocean, land and sea-ice
- Development of a new model version can take years

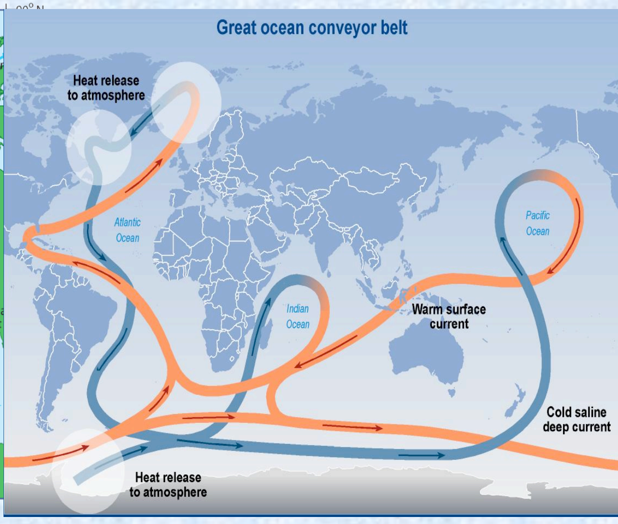
Atmosphere



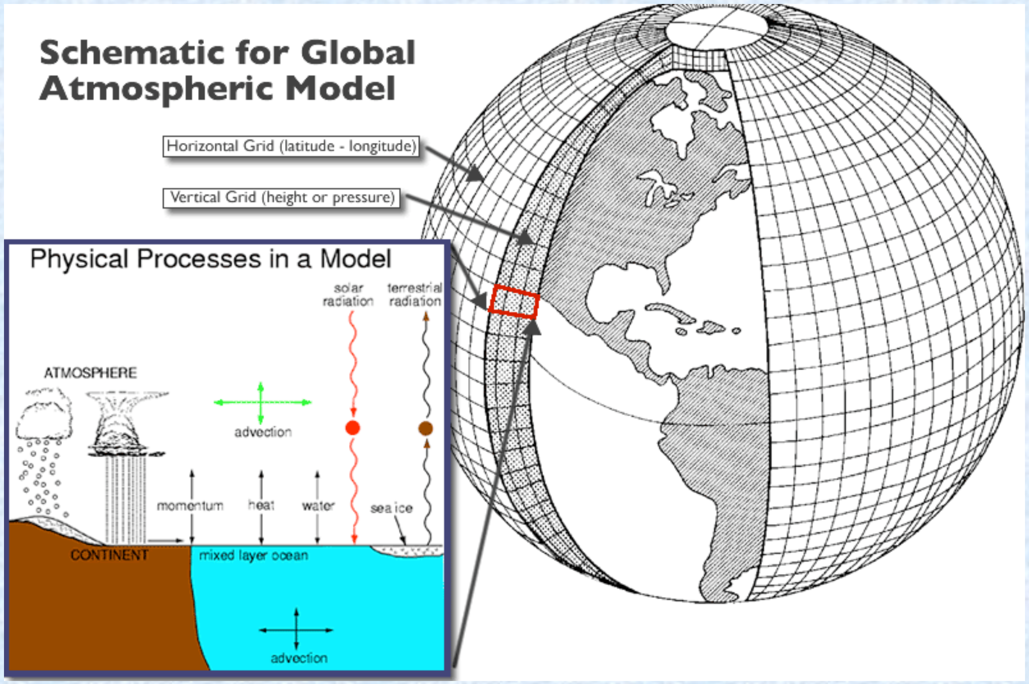
Wind Driven Upper Ocean



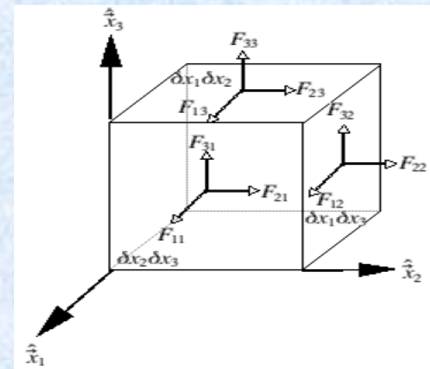
Ocean Thermohaline



Equations are solved numerically on a global grid



Grid cell



Continuity

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = 0.$$

Thermodynamic

$$\rho c_v \frac{DT}{Dt} = -p\nabla \cdot \vec{v} - \nabla \cdot \vec{F} + k\nabla^2 T + \rho \dot{q},$$

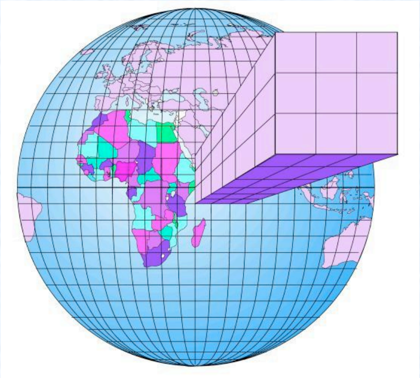
Fluid motion on rotating sphere

$$\vec{F}_{Cor} \approx 2\rho\Omega\delta V \begin{pmatrix} v\sin\phi \\ -u\sin\phi \\ 0 \end{pmatrix} = 2\rho\Omega\delta V\ \sin\phi \begin{pmatrix} v \\ -u \\ 0 \end{pmatrix} = \delta V\ \rho f \begin{pmatrix} v \\ -u \\ 0 \end{pmatrix},$$

where $f \equiv 2\Omega\sin\phi$

GCM "parameterization"

- Treating processes that are too small-scale or complex to be physically represented in the model



- Examples:
  - Convective clouds
  - Cloud microphysics
  - Boundary layer (e.g., surface evaporation)
  - Radiative transfer
  - Ocean eddies
  - …

GCM's reside within a hierarchy of models

- Zero-dimensional models:
  - Energy balance
  - Radiative-convective
- Earth-system Models of Intermediate Complexity (EMICs)
- General Circulation Models, including land and sea-ice models
  - Atmosphere: AGCM
  - Ocean: OGCM
  - Coupled Models: AOGCM
- Earth System Models (e.g., including the carbon cycle)

Introduction to model intercomparisons

- Brief history
- What we can learn from them
- CMIP5: the latest in a series

History: Before the dawn of the MIP's

- In the 1970s and 1980s, the evaluation of climate models was largely a qualitative endeavor (and mostly done by a relatively small group of modelers)
- Often involved purely visual comparison of selected "maps" from a model simulation and observations, with similarities and discrepancies noted.
- No standard benchmark experiments
- Little community involvement in model diagnosis
- Difficult to track changes in model performance over time

History: Establishment of the first MIP

- 1980's: MIP precursors – FANGIO, radiation code intercomparison

- ca. 1991: The Atmospheric Model Intercomparison Project (AMIP), following inception of PCMDI
  - Championed by PCMDI and encouraged/endorsed by the WCRP's Working Group on Numerical Modelling
  - Modeling groups were initially reluctant to share results
  - Roughly 30 modeling groups from 10 different countries
  - Community involvement for the first time in experimental design and diagnosis

- ca. 1995: AMIP2 – tighter experimental protocol, more extensive diagnostics

History: From atmosphere only to coupled models

- CMIP1 (ca. 1995): control run
- CMIP2 (ca. 1997): 1%/year CO_2 increase (idealized climate change)
- CMIP3 (2003 – ca. 2013):
    - Expts: control, idealized climate change, historical, and SRES (future scenario) runs
    - Output largely available by 2005
- [CMIP4 (ca. 2007): "single forcing" experiments for detection/attribution studies]
- CMIP5 (2006 – beyond 2016; ongoing and revisited)
    - An ambitious variety of "realistic" and diagnostic experiments
    - Output largely available by 2012

CMIP evolution summary: trends toward

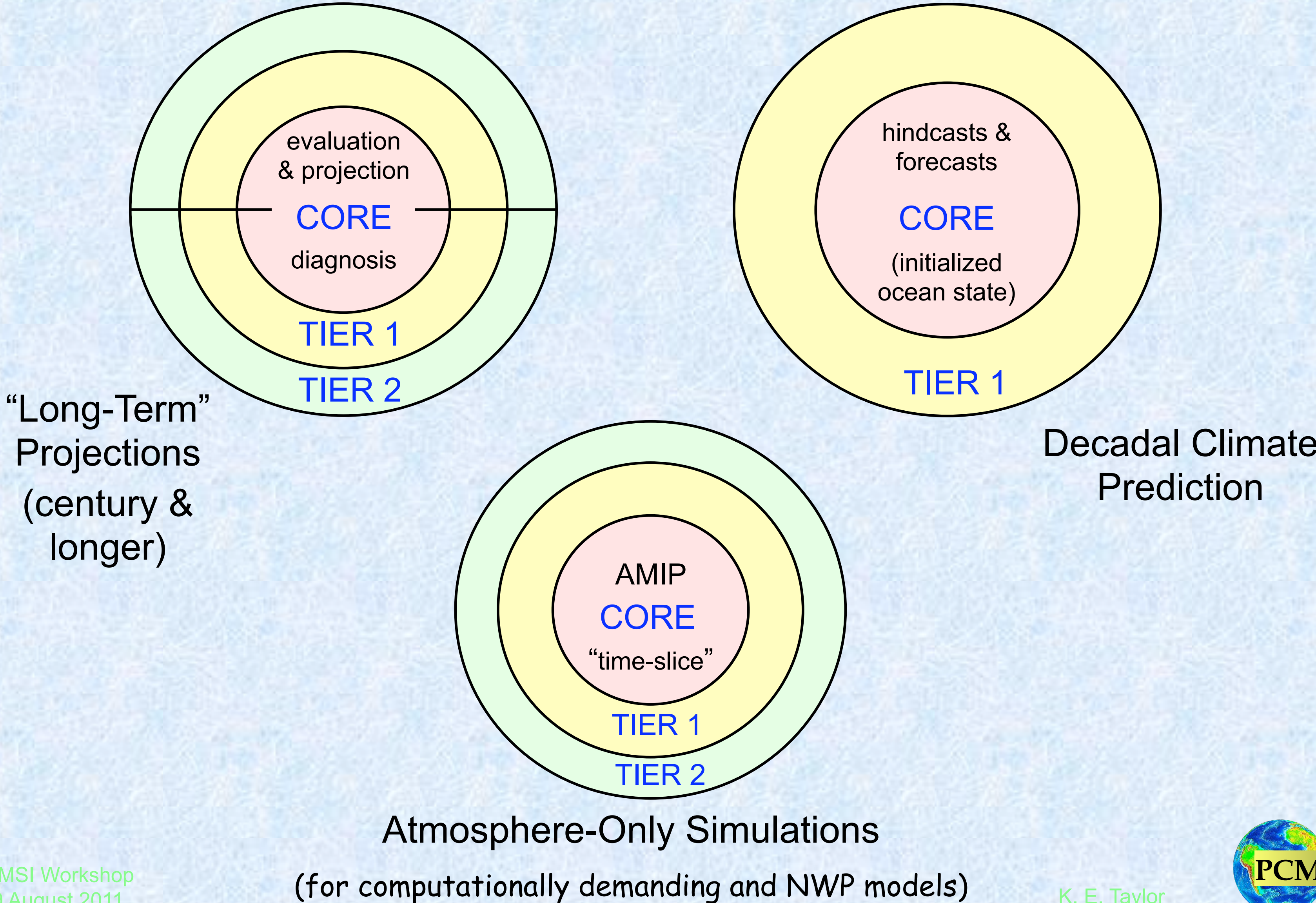
- More openness in making output available quickly
- A wider variety of experiments designed to
  - Address a wider variety of questions
  - Meet the needs of a broader community of users
  - Encompass originally independent MIPs into a single MIP that provides synergistic opportunities for greater scientific understanding
- More comprehensive models (ESMs)
- Increased standardization facilitating scientific exchange (primarily of data)

Continued on next page

CMIP evolution summary: trends toward

- A more complete and diversified set of model output (expecting petabytes of data for CMIP5)
  - Enabling more complete diagnostic process studies (e.g., clouds)
  - Providing information requested by a wider variety of users (e.g., impact studies)
  - For use in dynamical and empirical downscaling
- More complete documentation of models/experiments
- New strategies for making output accessible to users

CMIP5 is organized around three types of simulations



CMIP5 participating groups (23 groups; 50+ models; 13 models available)

Primary Group	Country	Model
CAWCR	Australia	ACCESS
BCC	China	BCC-CSM1.1
GCESS	China	BNU-ESM
CCCMA	Canada	CanESM2, CanCM4, CanAM4
CCSM	USA	CESM1, CCSM4
RSMAS	USA	CCSM4(RSMAS)
CMCC	Italy	CMCC- CESM, CM, & CMS
CNRM/CERFACS	France	CNRM-CM5
CSIRO/QCCCE	Australia	CSIRO-Mk3.6
EC-EARTH	Europe	EC-EARTH
LASG, IAP	China	FGOALS- G2.0, S2.0 & gl
FIO	China	FIO-ESM
NASA/GMAO	USA	GEOS-5
GFDL	USA	GFDL- HIRAM-C360, HIRAM-C180, CM2.1, CM3, ESM2G, ESM2M
NASA/GISS	USA	GISS- E2-H, E2-H-CC, E2-R, E2-R-CC, E2CS-H, E2CS-R
MOHC	UK	Had CM3, CM3Q, GEM2-ES, GEM2-A, GEM2-CC
NMR/KMA	Korea / UK	HadGEM2-AO
INM	Russia	INM-CM4
IPSL	France	IPSL- CM5A-LR, CM5A-MR, CM5B
MIROC	Japan	MIROC 5, 4m, 4h, MIROC- ESM, ESM-CHEM
MPI-M	Germany	MPI-ESM- HR, LR
MRI	Japan	MRI- AGCM3.2H, AGCM3.2S, CGCM3, ESM1
NCC	Norway	NorESM1-M, NorESM-ME, NorESM1-L

What have MIP’s done to advance climate modeling?

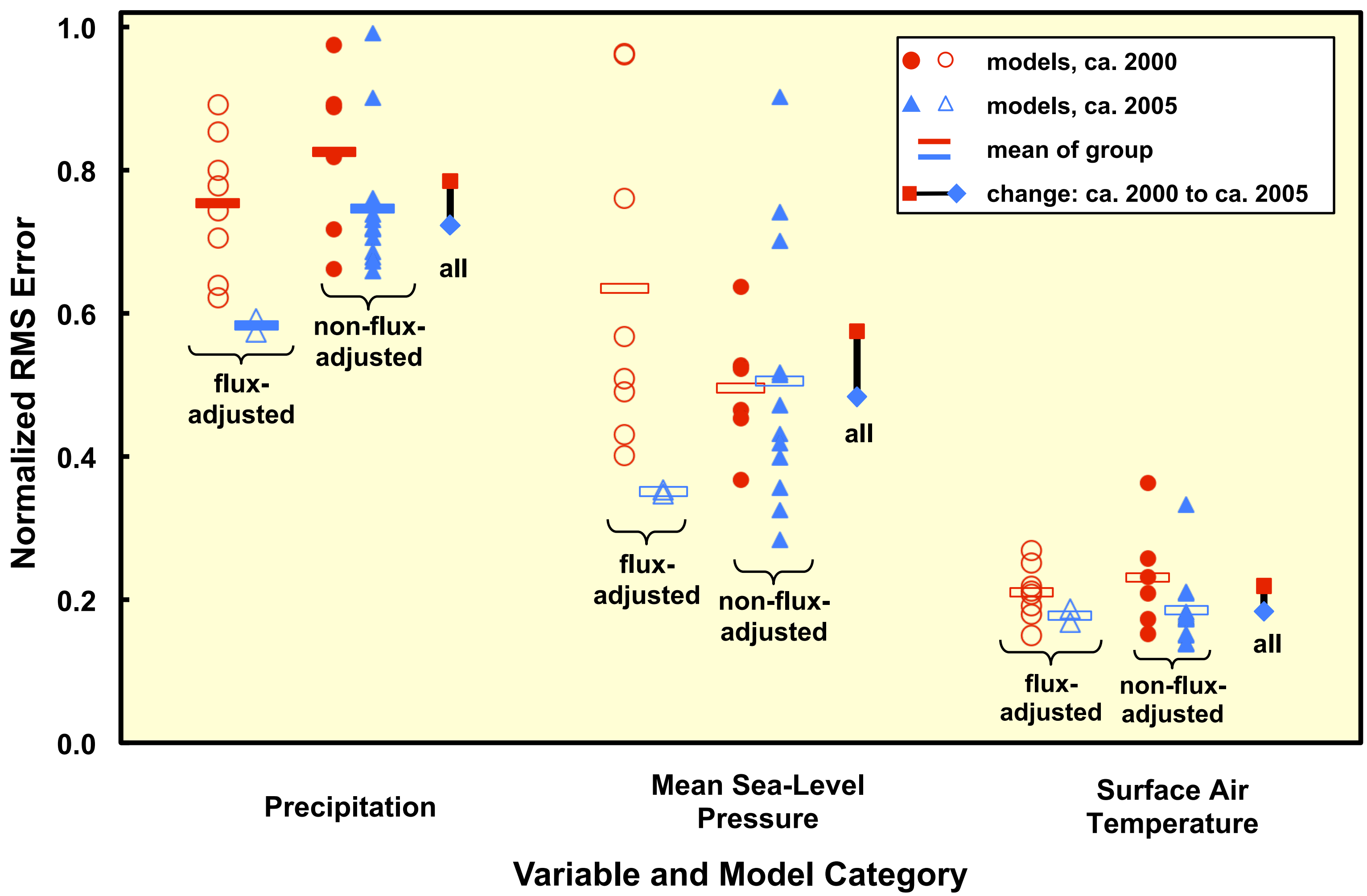
MIP's facilitate more comprehensive scrutiny of model behavior

- Expertise is limited at individual modeling groups
- Broad community of experts can analyze output from multiple models with ease.
- 1000's of scientists have downloaded data from CMIP
- To date, nearly 600 publications have been registered claiming to report on CMIP3 results.

CMIP establishes some benchmark experiments that allow us to gauge changes in model performance.

- AMIP runs (prescribed SST's and seaice)
- CMIP control runs (variability characteristics)
- Historical runs (1850 – present)
- Idealized 1%/yr CO_2 increases (determine climate sensitivity)

Changes in CMIP model errors (ca. 2000 to ca. 2005)

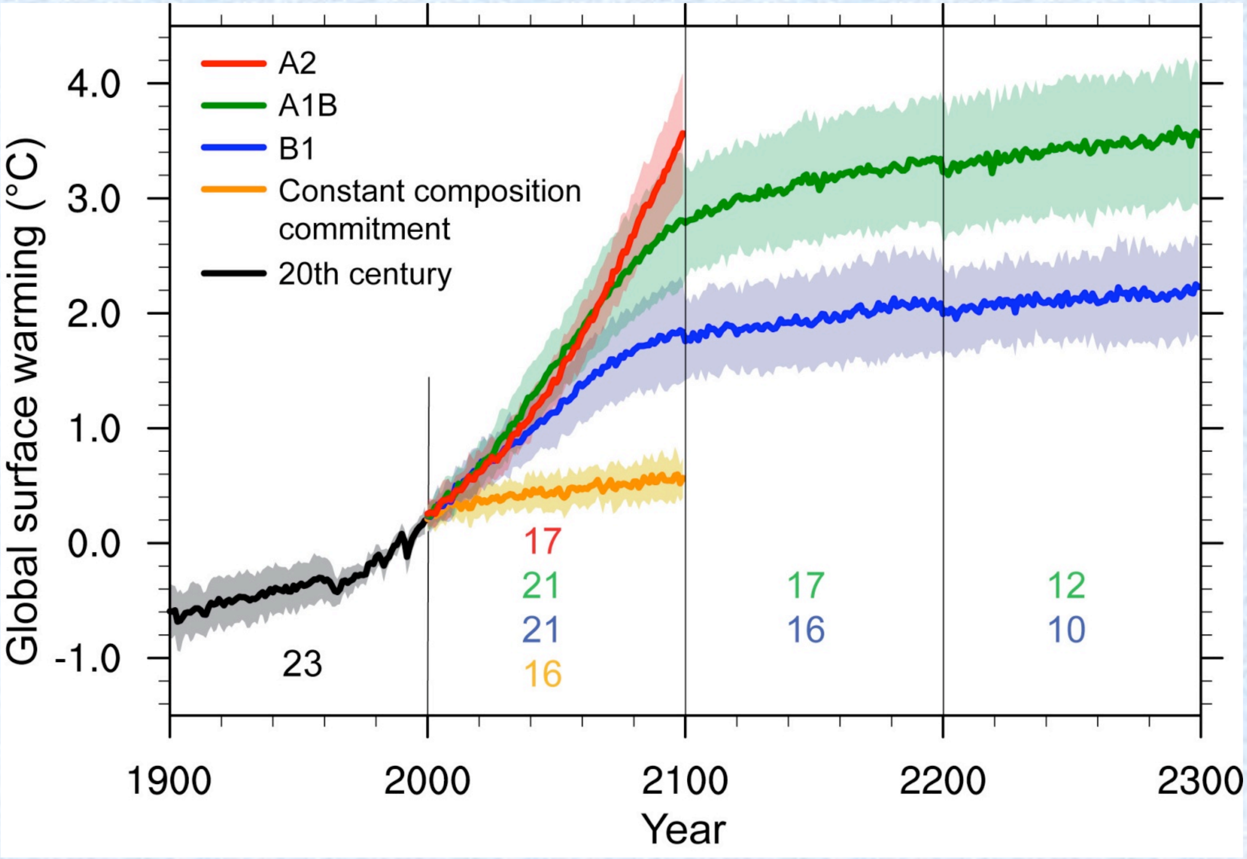


Gleckler, Taylor, & Doutriaux, *JGR*, 2008 (also IPCC AR4)

What has the multi-model perspective yielded?

- Visibly demonstrates that model results are uncertain
- Provides a range of (equally?) plausible projections for policy makers
- Has been used as a cornerstone for recent IPCC reports:
  - About 75% of 100 figures in AR4 Chapters 8-11 are based on CMIP3
  - 4 of the 7 figures AR4 “Summary for Policy Makers” are based on CMIP3
- Some argue the multi-model ensemble ensures more robust conclusions than can be obtained with a single model

The CMIP3 multi-model ensemble produced a range of responses even when forced similarly

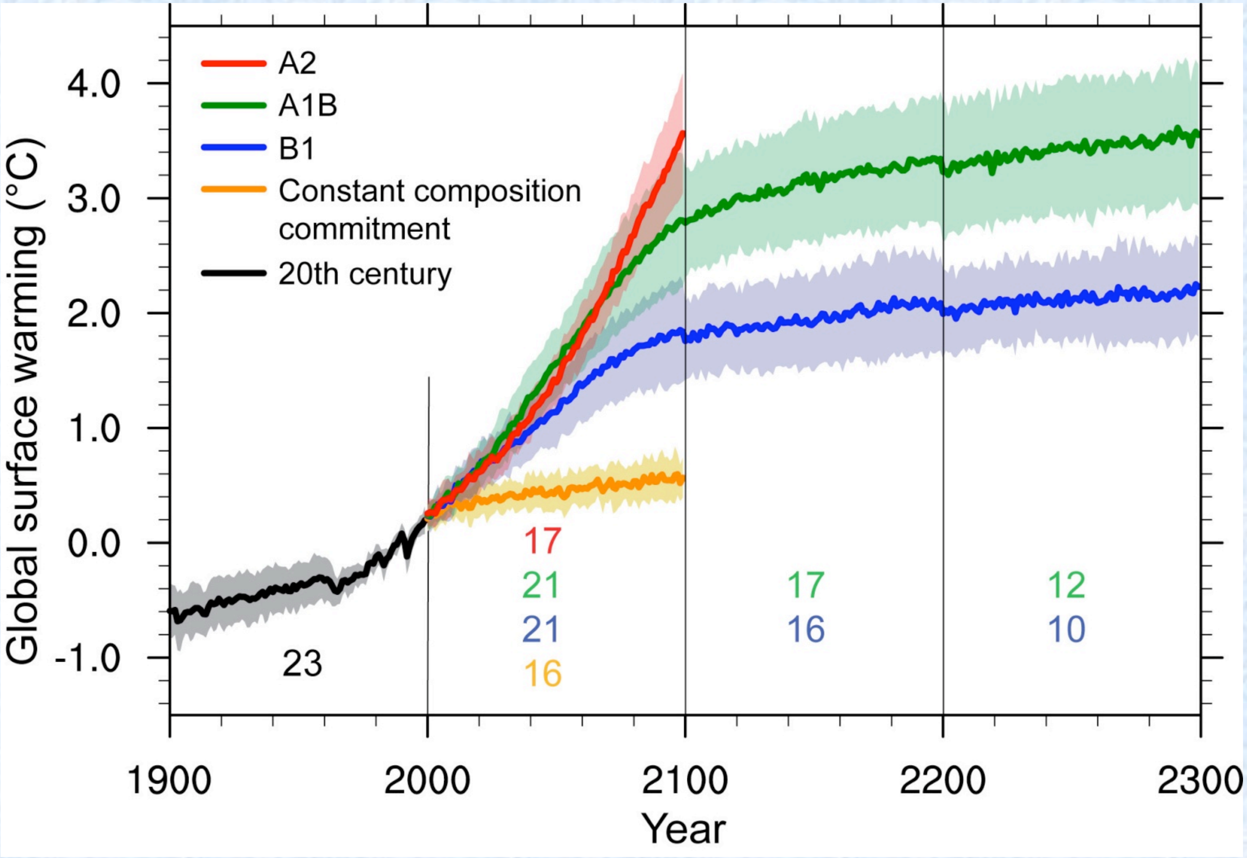


AR4 Summary for Policy Makers

What is "model uncertainty"?

- The "spread" of model results is loosely referred to as "model uncertainty"
- It sometimes is assumed to be an estimate of the range of "possible outcomes" produced by some scnario, with the "truth" presumably contained within the range
- The spread can result from several factors:
  - Differences in "scenarios" (i.e. different emissions or concentration prescriptions), but this is *not* a component of "model uncertainty"
  - Differences in "radiative response" (i.e., the "fast" response to a change in concentrations)
  - Differences in "climate sensitivity" (i.e., the slower responses that are dominated by climate feedbacks)
  - Differences in the (equally likely) paths of unforced variability exhibited by simulations forced in the same way

Different "scenarios" lead to different climate responses



AR4 Summary for Policy Makers

What is "model uncertainty"?

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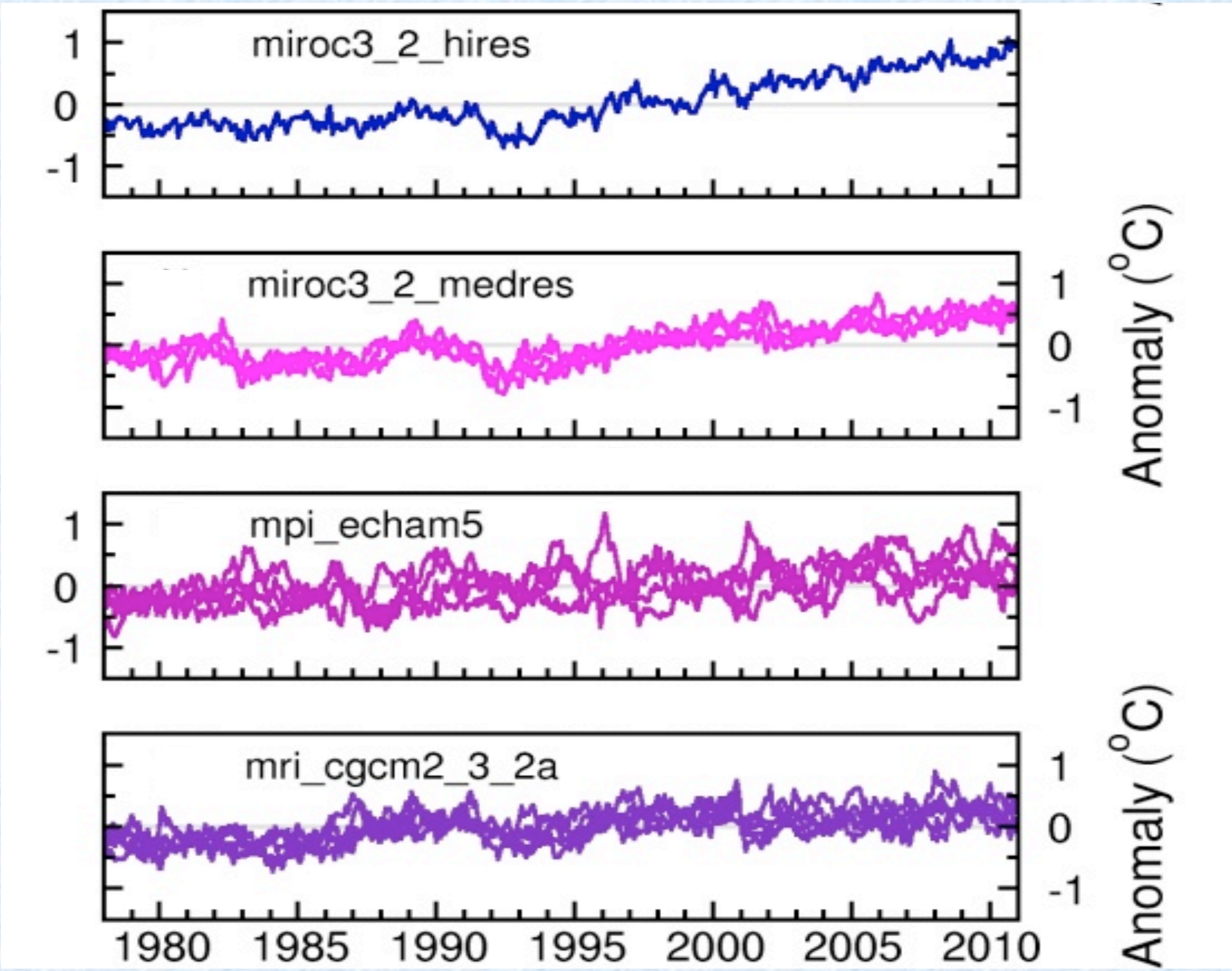
- Remember, the spread can result from several factors:
  - Differences in "scenarios" (i.e. different emissions or concentration prescriptions), but this is *not* a component of "model uncertainty"
  - Differences in "radiative response" and "climate sensitivity"
  - Differences in the (equally likely) paths of unforced variability exhibited by simulations forced in the same way

Forced changes and unforced variability in global mean tropospheric temperature (TLT) in CMIP3 runs

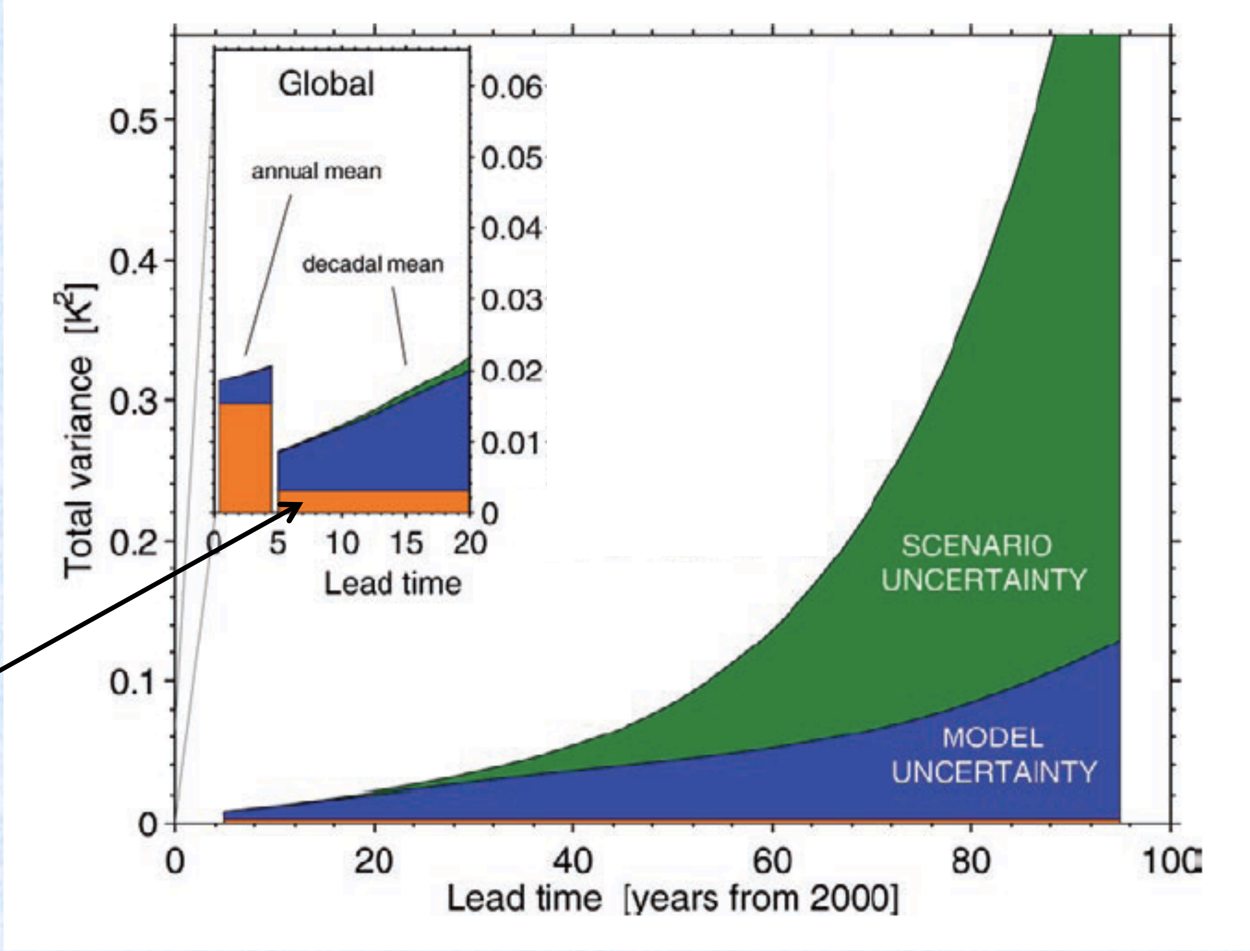
Single simulation

Ensembles of equally likely outcomes



Courtesy of B.Santer

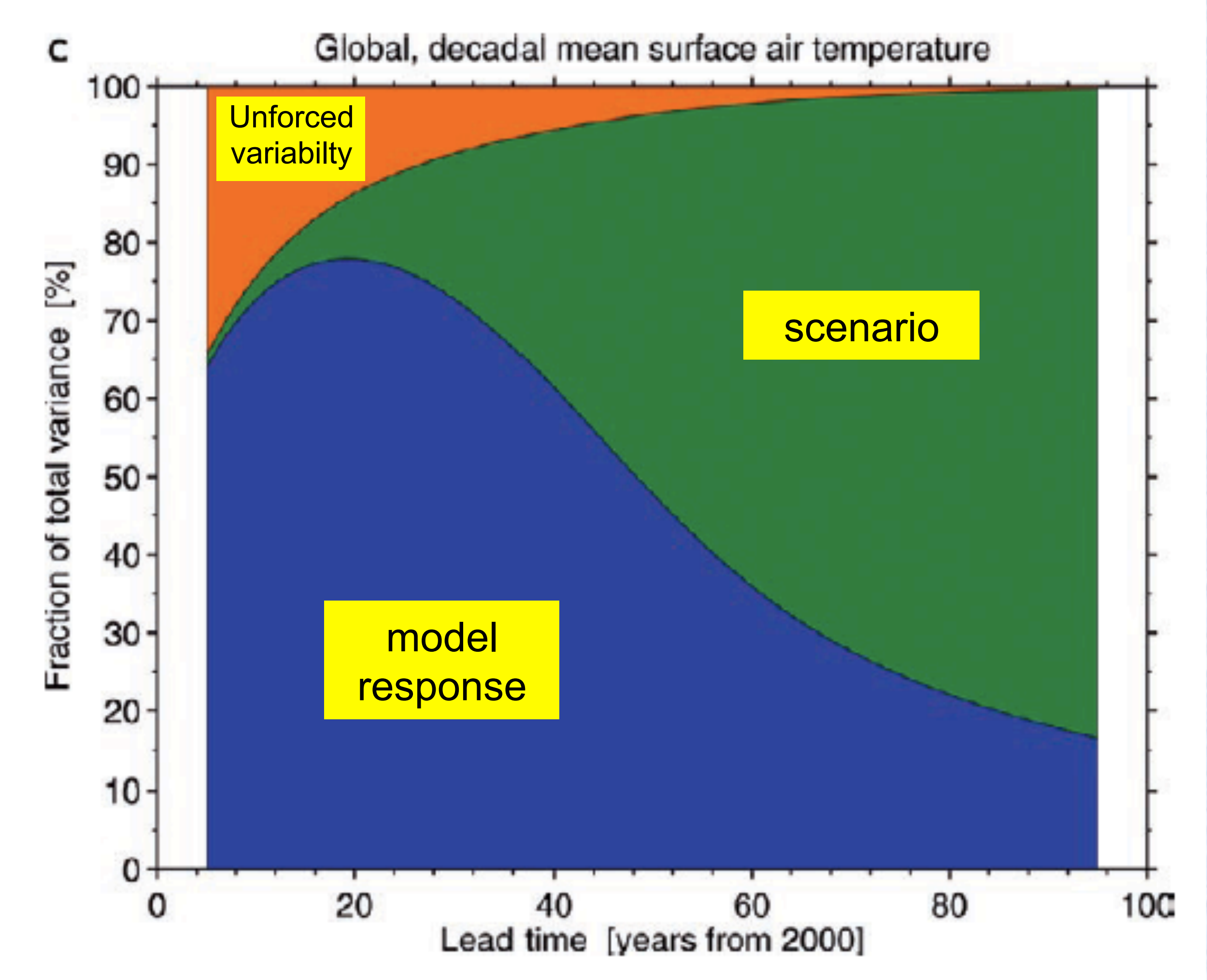
Total range of future climate change estimates depends on scenario, model, and unforced variability



Unforced variability is important only in the near-term.

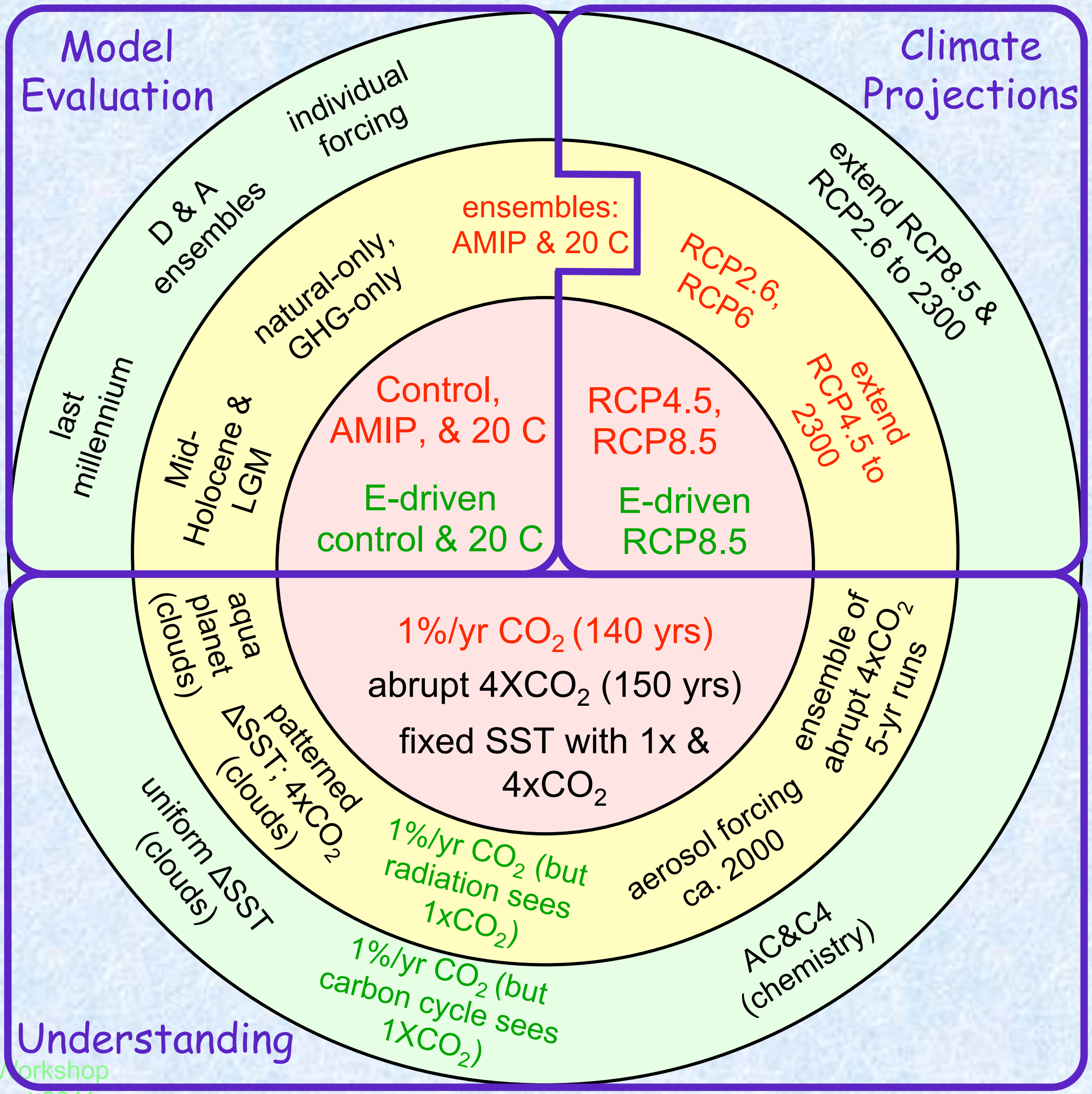
Hawkins & Sutton, *BAMS*, 2009

Projection ranges are initially dominated by model "uncertainty", but eventually are dominated by scenario



Hawkins & Sutton, *BAMS*, 2009

The CMIP5 design provides opportunities for evaluation and understanding model behavior, as well as producing projections



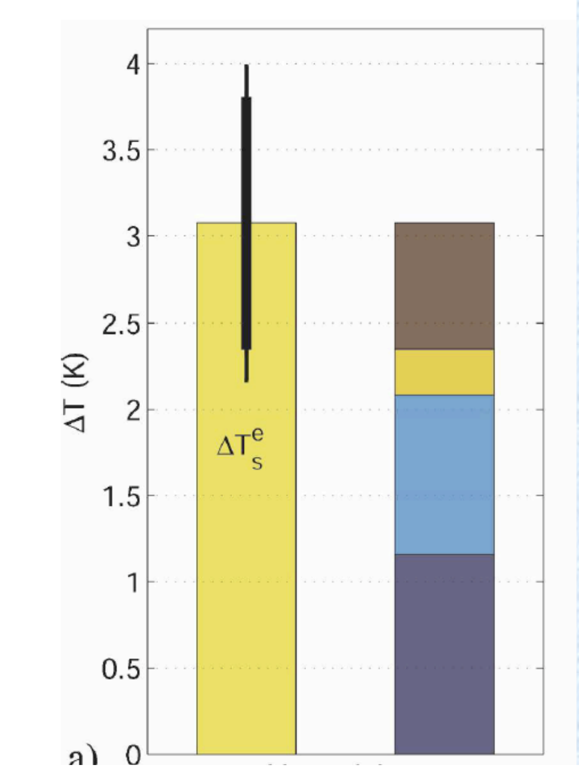
Red subset matches the entire CMIP3 experimental suite

Green subset is for coupled carbon-cycle climate models only

Taylor et al., *BAMS* 2011

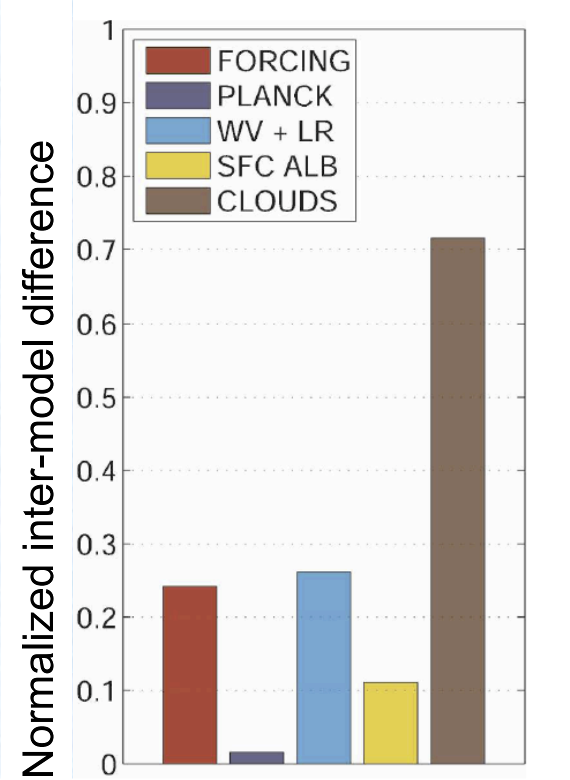
Which feedbacks are responsible for the spread in CMIP3 model responses to a doubling of CO_2 ?

Response



Multi-model mean

Model Spread



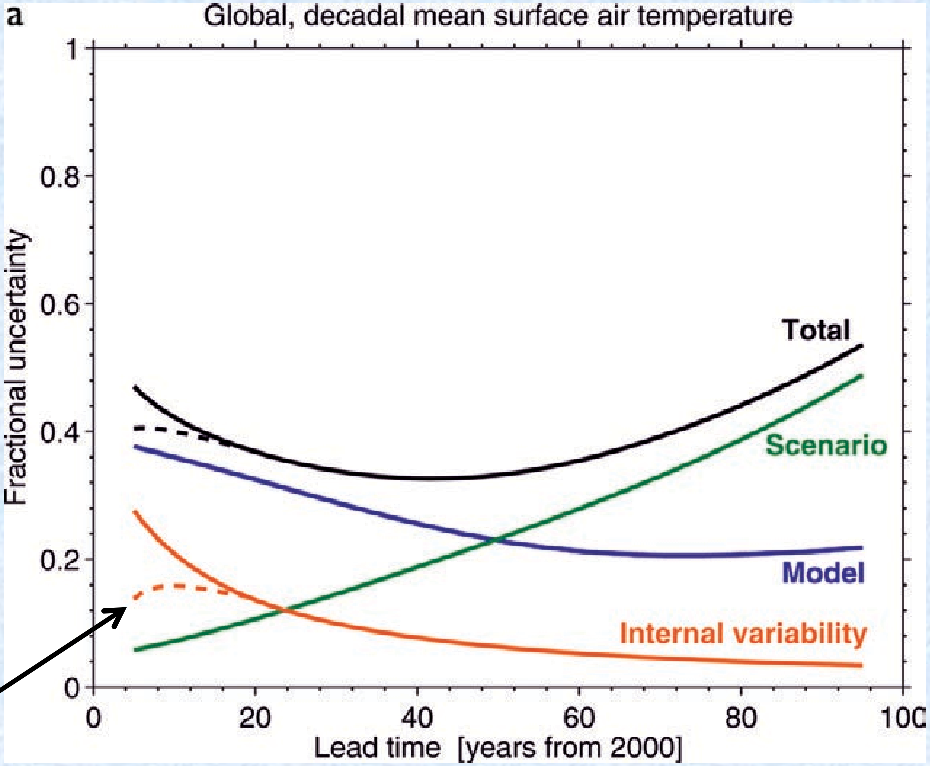
Feedback type

Cloud feedbacks account for the largest fraction of differences in model response

Dufresne and Bony, *J. Climate*, 2008

CMIP5 will also include models initialized with the observed state (in particular of the upper ocean)

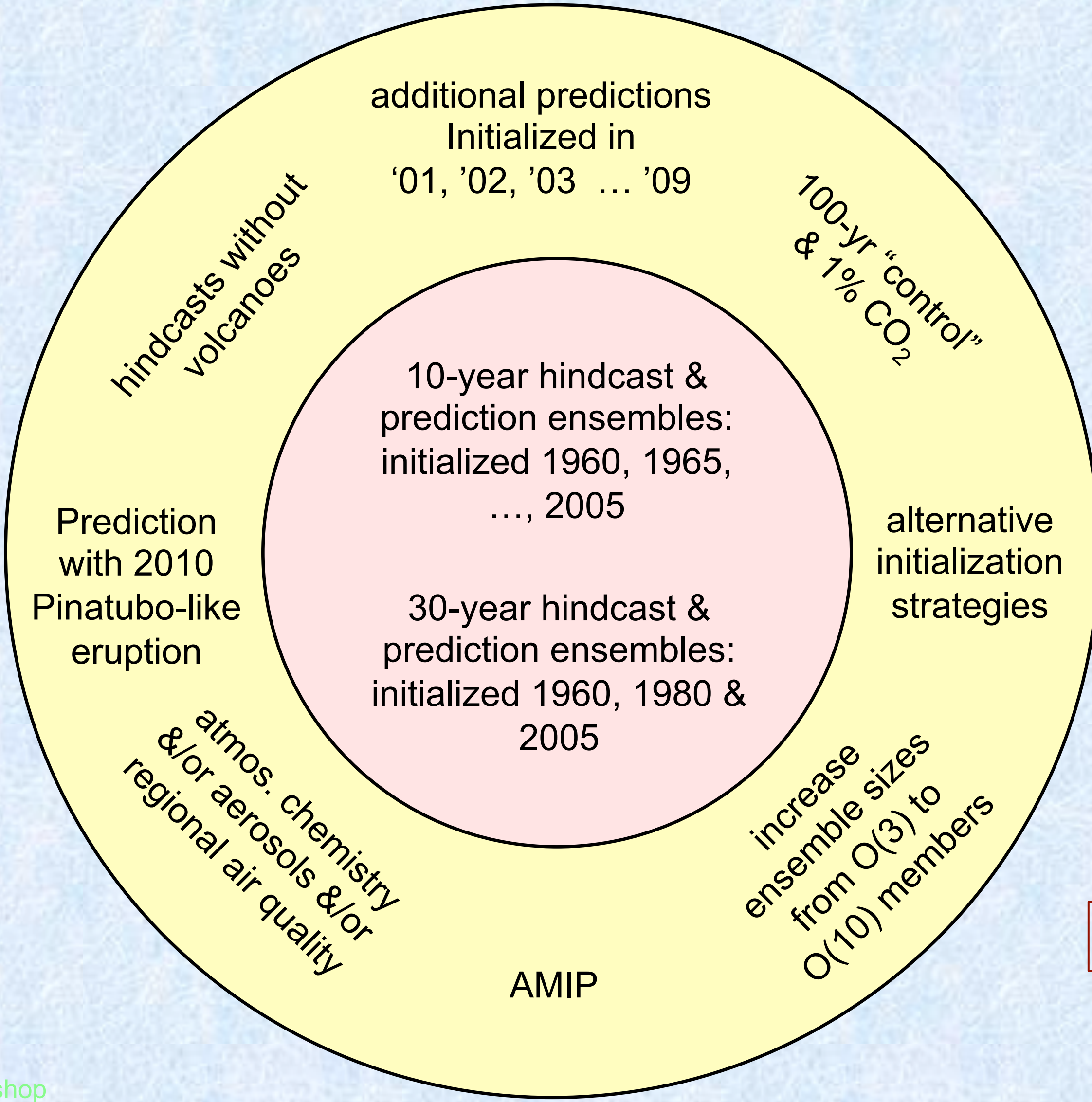
- The hope is that through initialization the models will be able to predict the actual trajectory of "unforced" climate variations.
- The hypothesis is that some longer time-scale natural variability is predictable if the initial state of the system is known



The deviation from observations caused by unforced variability can potentially be reduced through initialization.

Hawkins & Sutton, 2009

CMIP5 new near-term experiments attempt true climate "predictions" by initializing models with observations.

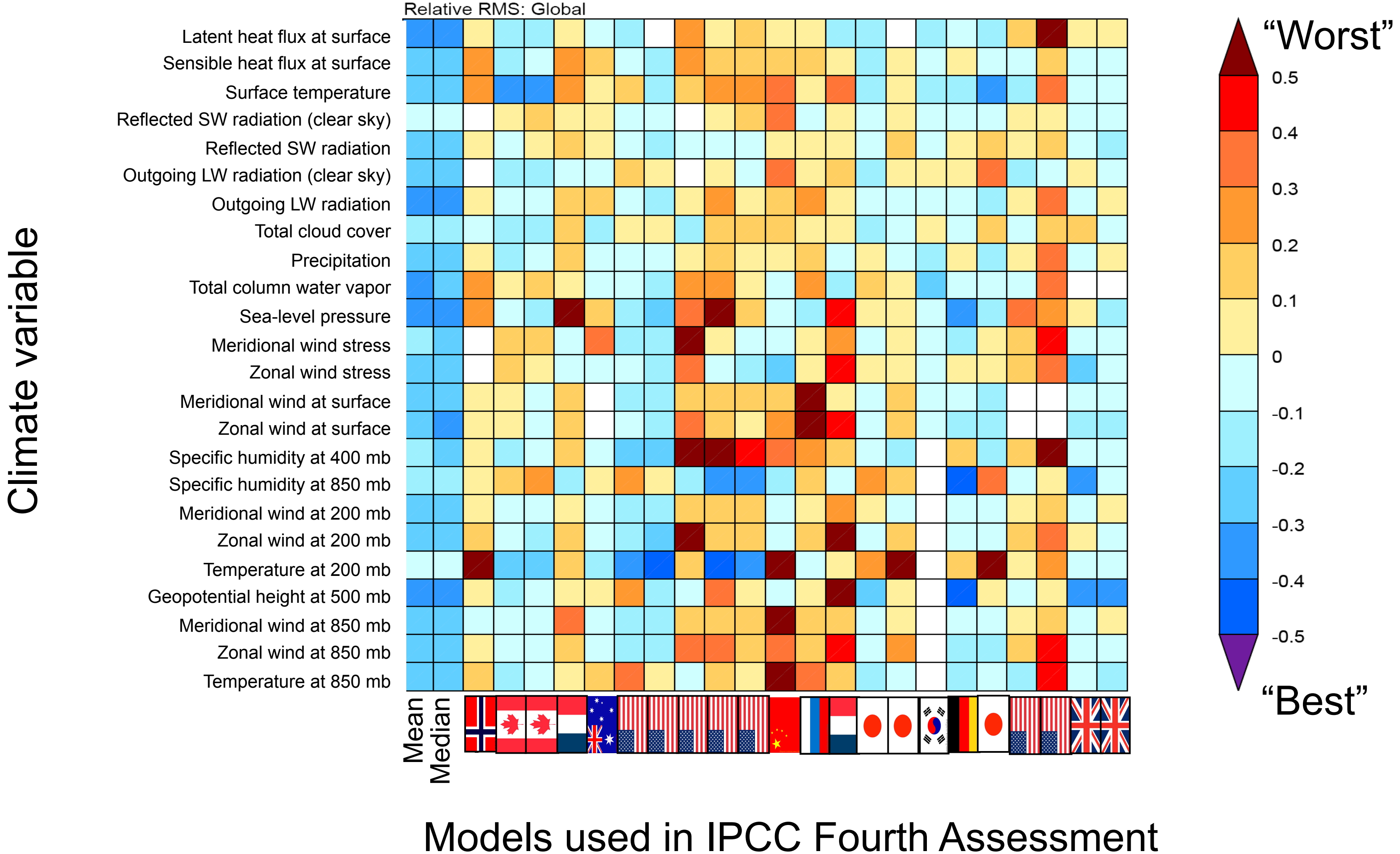


Taylor et al., *BAMS* 2011

Is "uncertainty" based on spread of model results misleading?

- It doesn't include possibility of a common bias across models
  - If the common bias is zero, then the multi-model mean provides a good estimate of the "truth"
  - If the bias is not zero, the truth may lay outside model results

The "mean" model simulates climatology better than individual models, and some believe the consensus projection is also superior



Gleckler, Taylor and Doutriaux, *J.Geophys.Res.* (2008)

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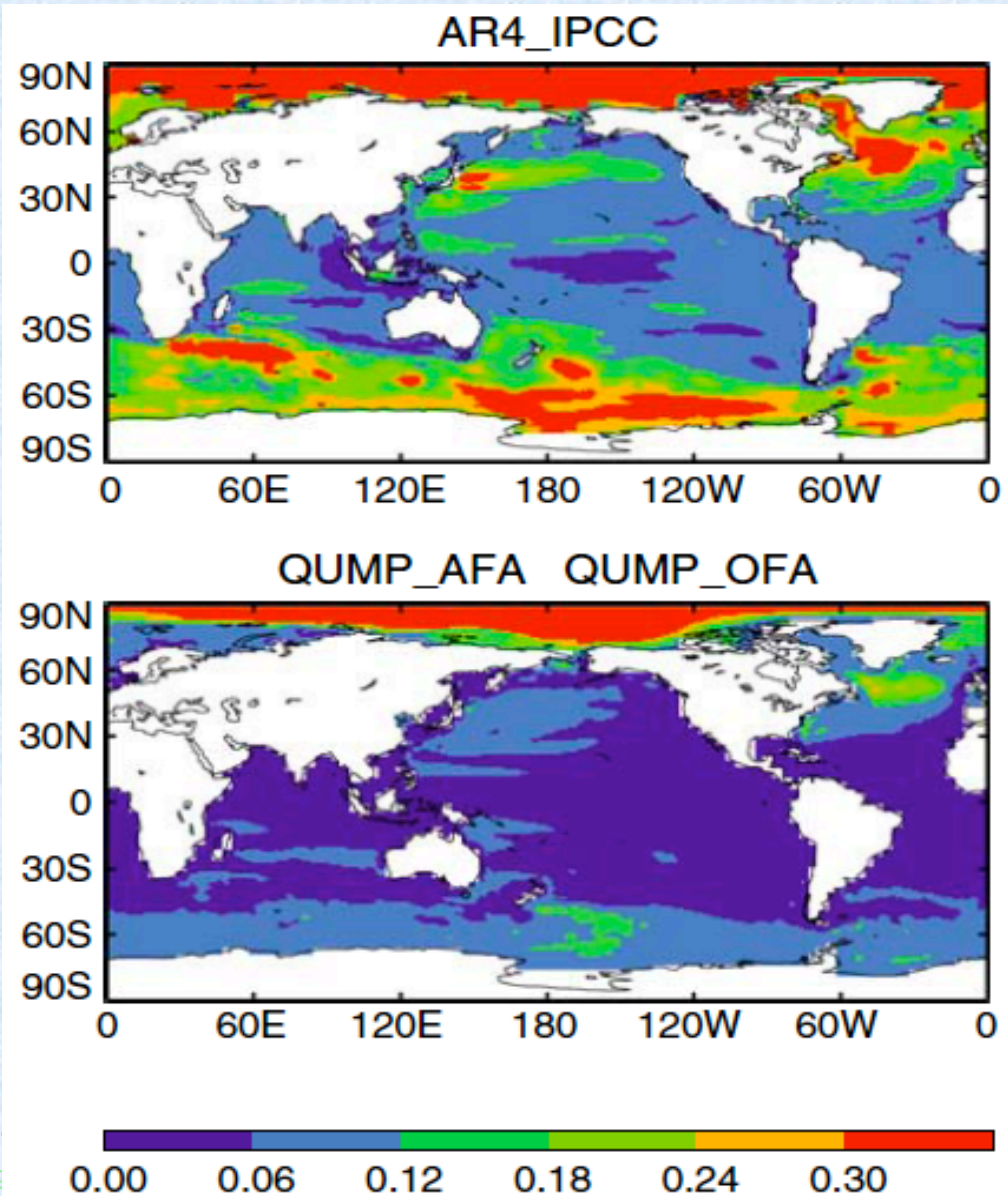
- It doesn't include possibility of a common bias across models
  - If the common bias is zero, then the multi-model mean provides a best estimate of the "truth"
  - If the bias is not zero, the truth may lay outside model results
- It assumes that existing models constitute a "representative sample" of all possible models that are equally consistent with physical laws and observations.
  - If some of the models are inconsistent with observations, then eliminating/down-weighting those models should improve uncertainty estimation
  - If "social pressures" decrease the spread of model results, "model uncertainty" will be unjustifiably perceived as being reduced

Is "uncertainty" based on spread of model results misleading? (continued)

- Some of the model spread results from unforced variability
  - Unforced variability accounts for some discrepancy between models and observations
    - This is *not* "model uncertainty"
    - This is largely unpredictable "noise"
- The common (but not rigorously grounded) aspects of model formulation may (misleadingly) limit the spread

Structural uncertainty may be underestimated in perturbed physics ensembles (perhaps also in multi-model ensembles)



← CMIP3 ensemble

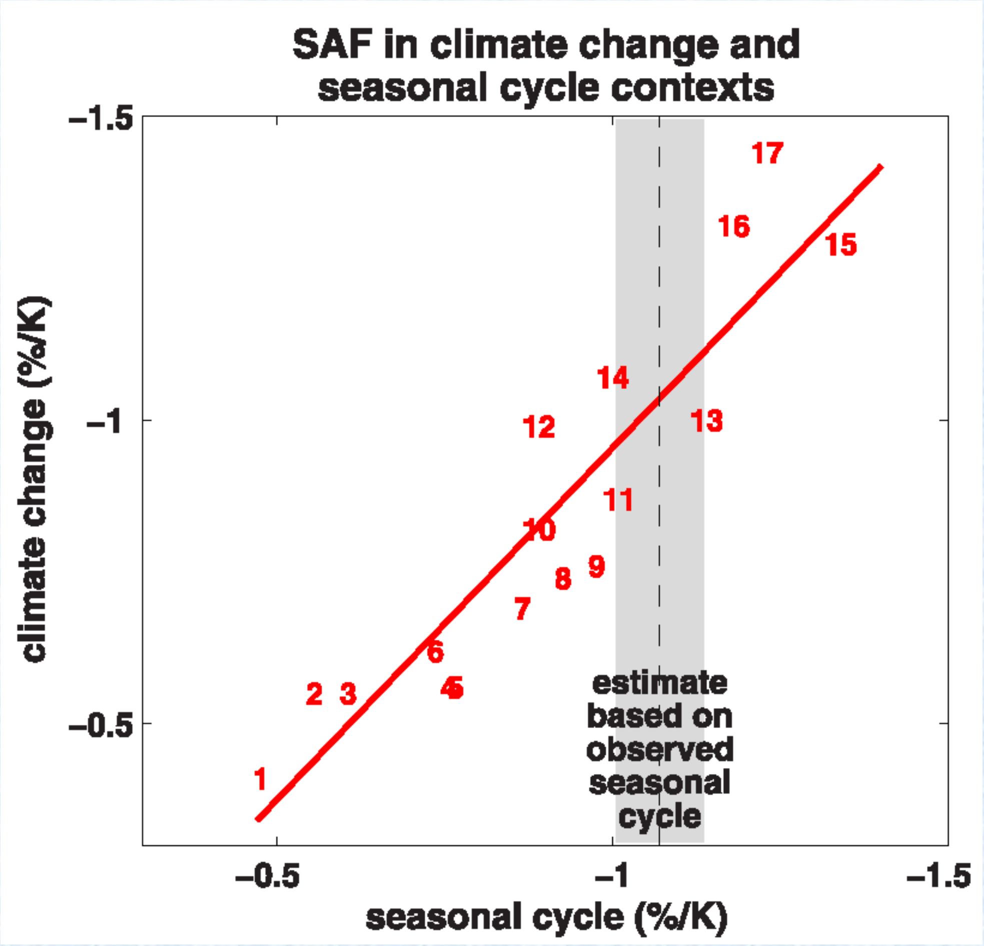
Sea level rise pattern (with global mean removed)

← Perturbed physics ensemble

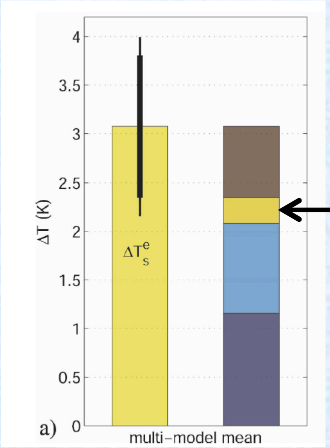
Pardaens, Gregory, and Rowe, *Clim. Dyn.*, 2010

If the multi-model ensemble can't provide rigorous estimates of the total uncertainty, what *can* it do?

Relationships between observables and projected climate responses can sometimes be discovered



Response of snow cover to global warming in models is related to their snow response to spring warming



But recall that surface albedo feedback is relatively weak

Hall and Xu, GRL, 2006

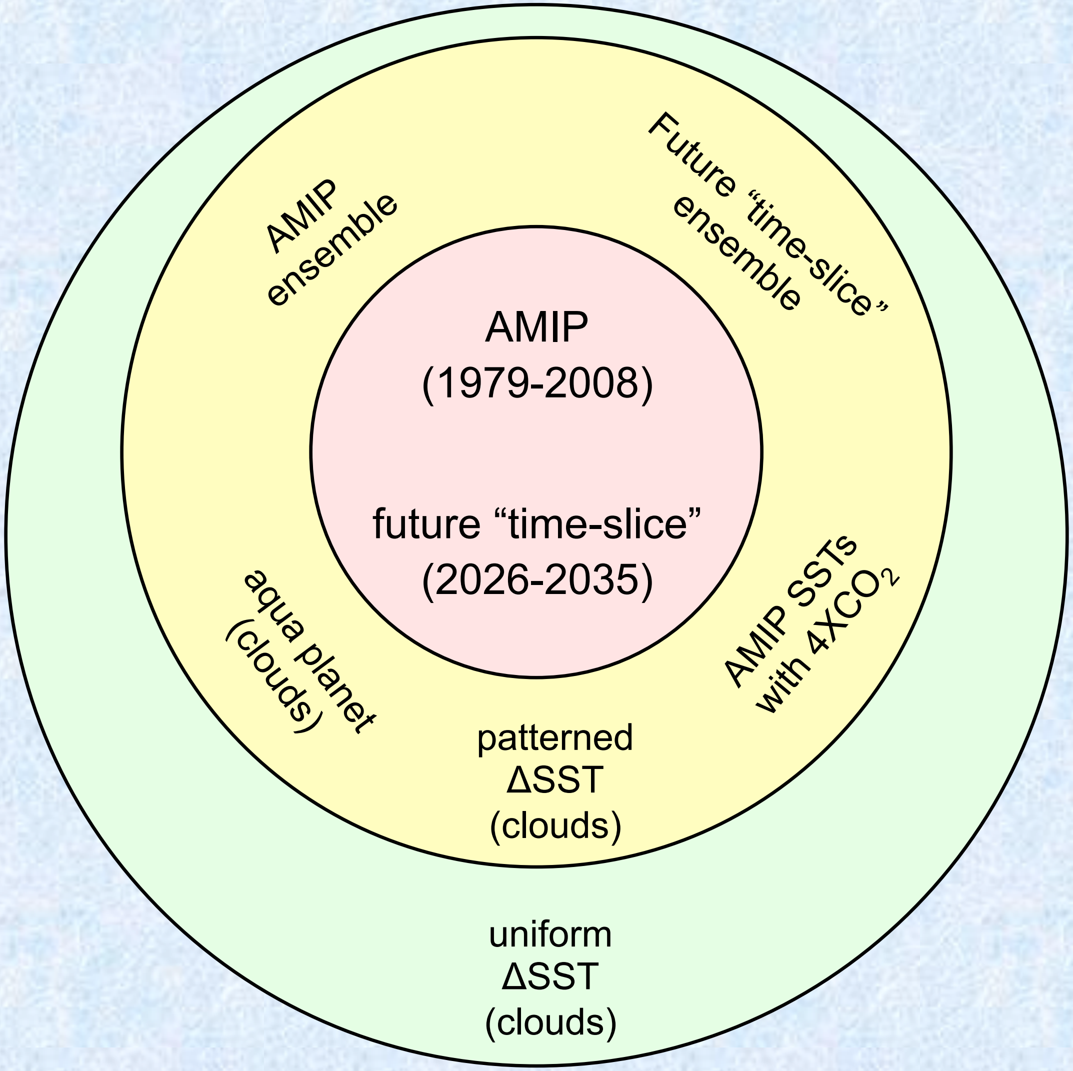
Summary

- Climate model intercomparisons have advanced climate modeling
- The multi-model perspective clearly shows that there is uncertainty in model projections
- The spread of model results cannot provide a rigorous estimate of how reliable the model projections are

Why should we believe any of the models?

Perhaps ensemble of models provides a better projection.

CMIP5 atmosphere-only experiments (targeted for computationally demanding and NWP models)



~14 models plan to do core runs

(10 of these will also do long-term and/or decadal simulations)

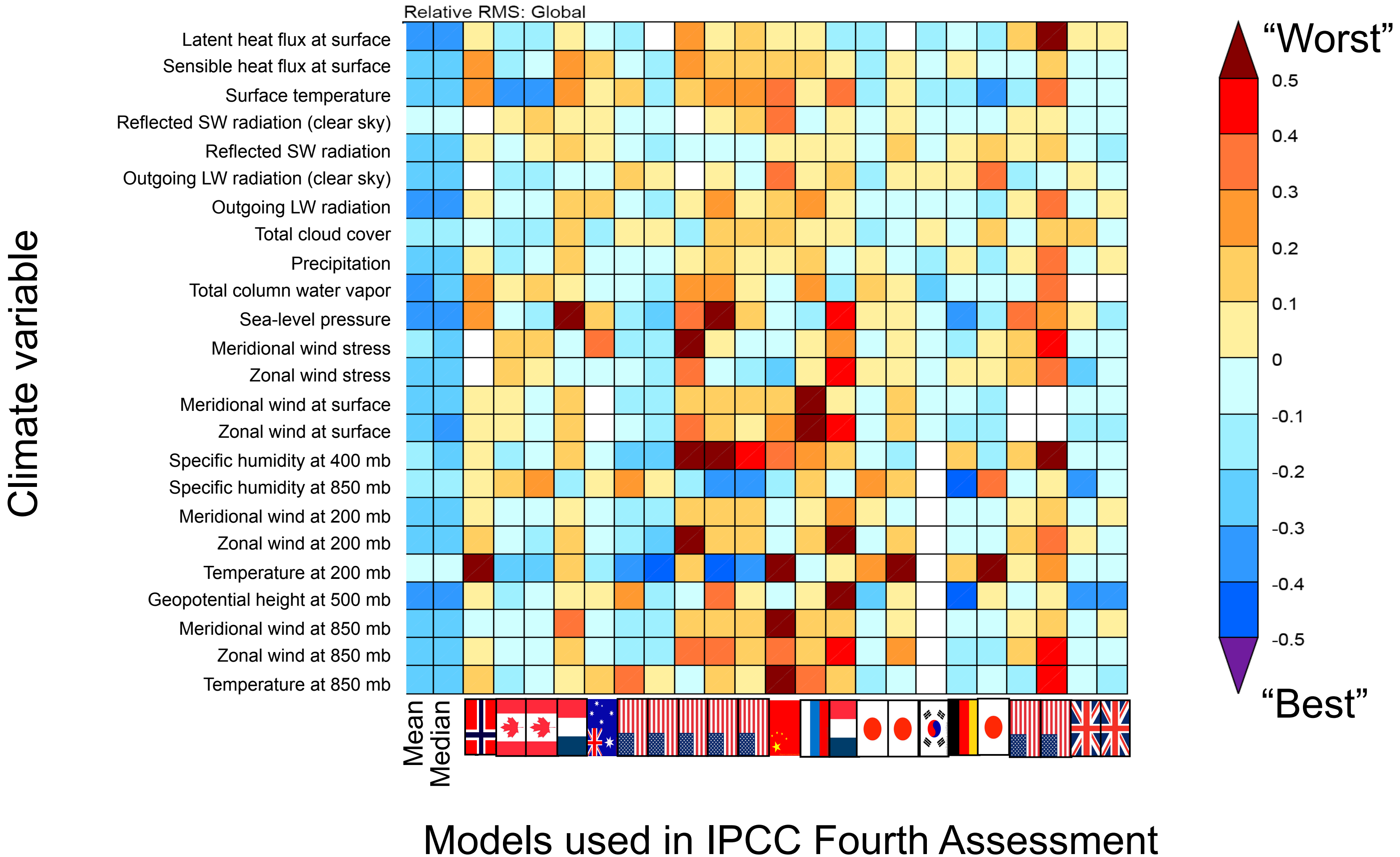
History: Proliferation of “MIP’s”

- The value of performing common experiments and subjecting them to wide-spread and systematic analysis is now deeply imbedded in the research community

- PCMDI provides leadership and infrastructure support to a number of other MIPs.
    - Paleoclimate MIP (1995)
    - Coupled Carbon Cycle Climate MIP (2001)
    - Aqua-planet MIP (2002)
    - Cloud Feedback MIP (2004)
    - Geoengineering MIP (2010)
    - Integrated Assessment Model (2010)

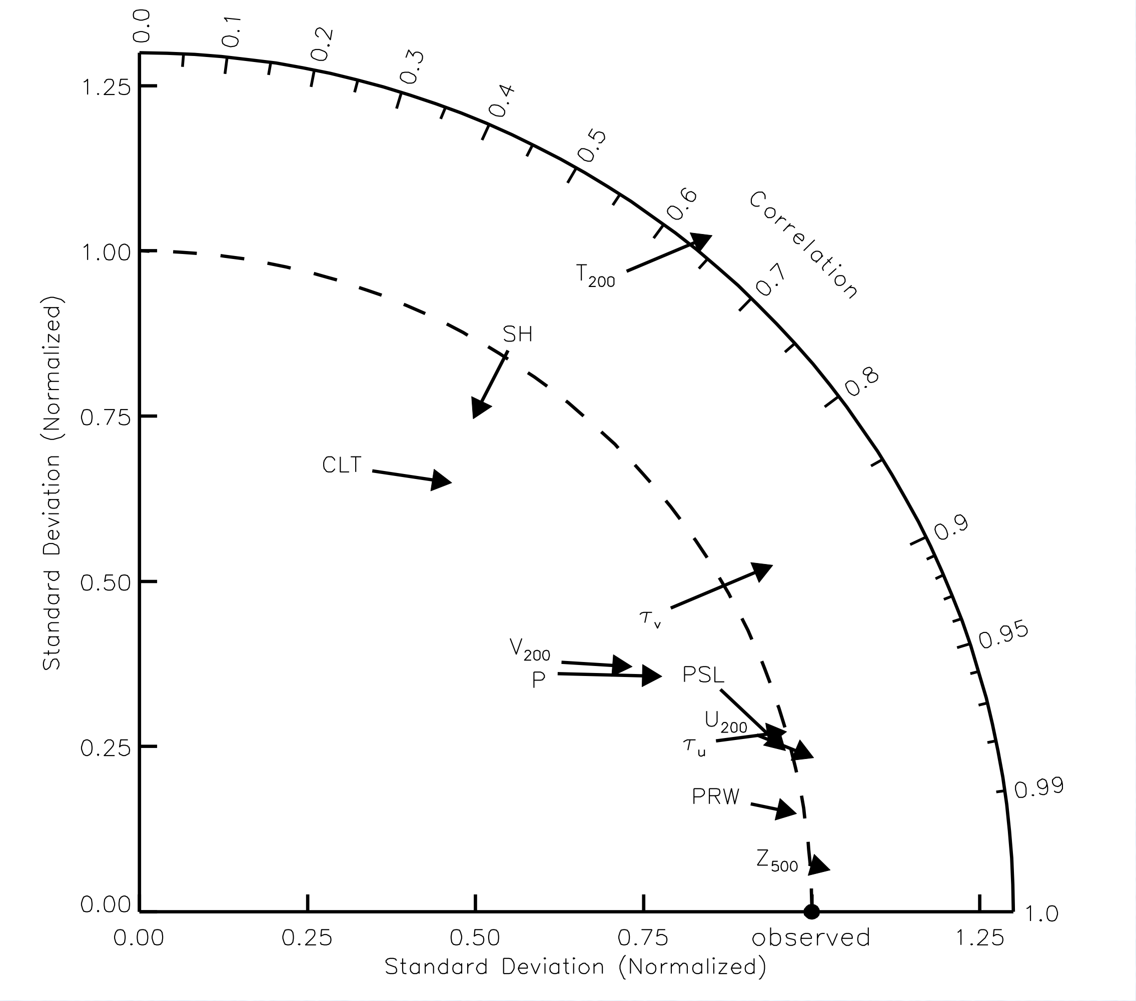
- Others (C-LAMP, OCMIP, AOMIP, AeroCom, PlioMIP, CORDEX, TransCom, SIMIP, ISMIP, ALMIP, MISMIP, ARMIP, DMIP, LakeMIP, MareMIP, BGCMIP, SGMIP, McMIP, SnowMIP, …)

Quantitative performance measures spur competition and provide objective criteria for judging the quality of simulations



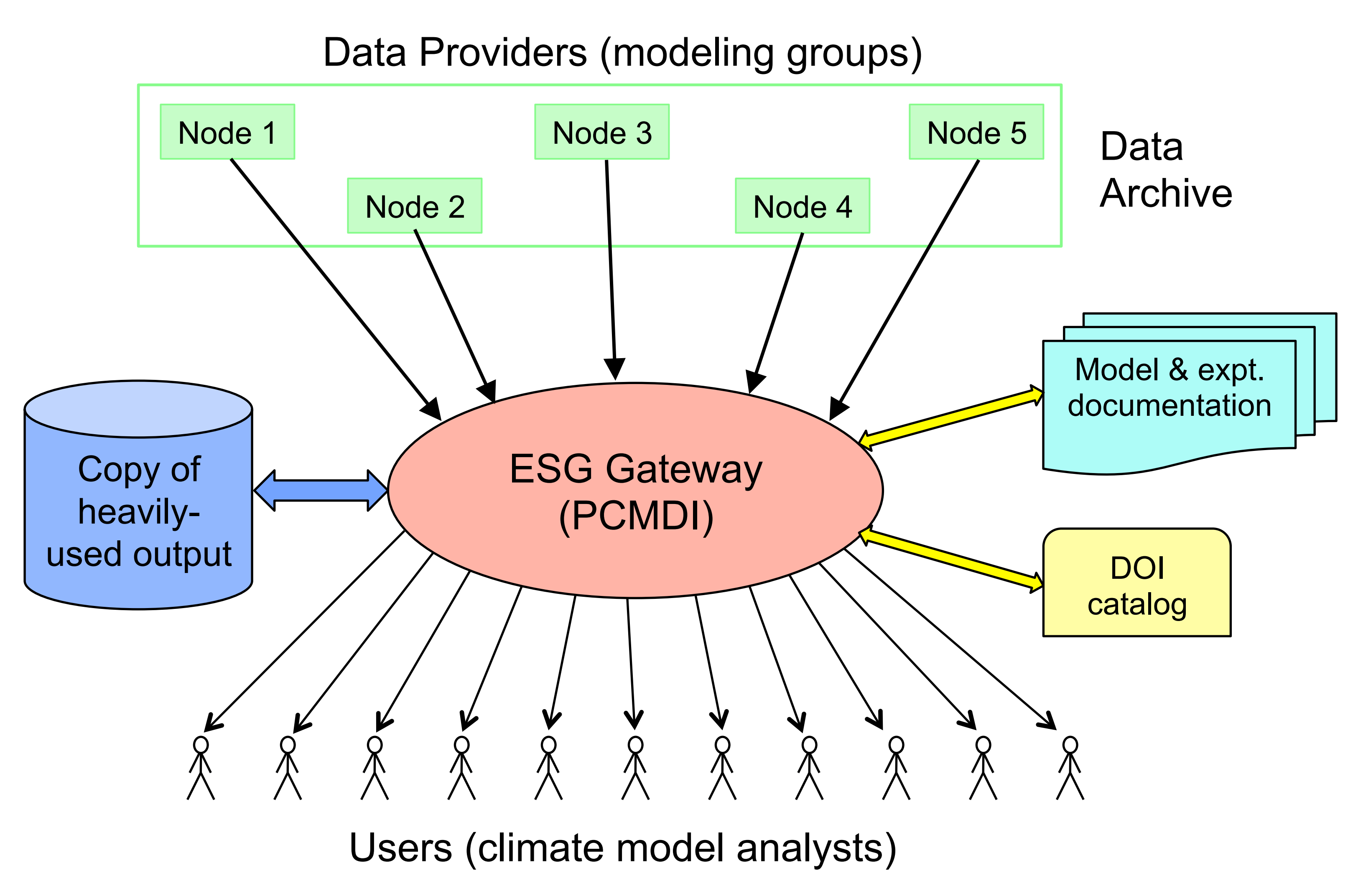
Gleckler, Taylor and Doutriaux, *J.Geophys.Res.* (2008)

Change in AMIP median model performance from early to late 1990's

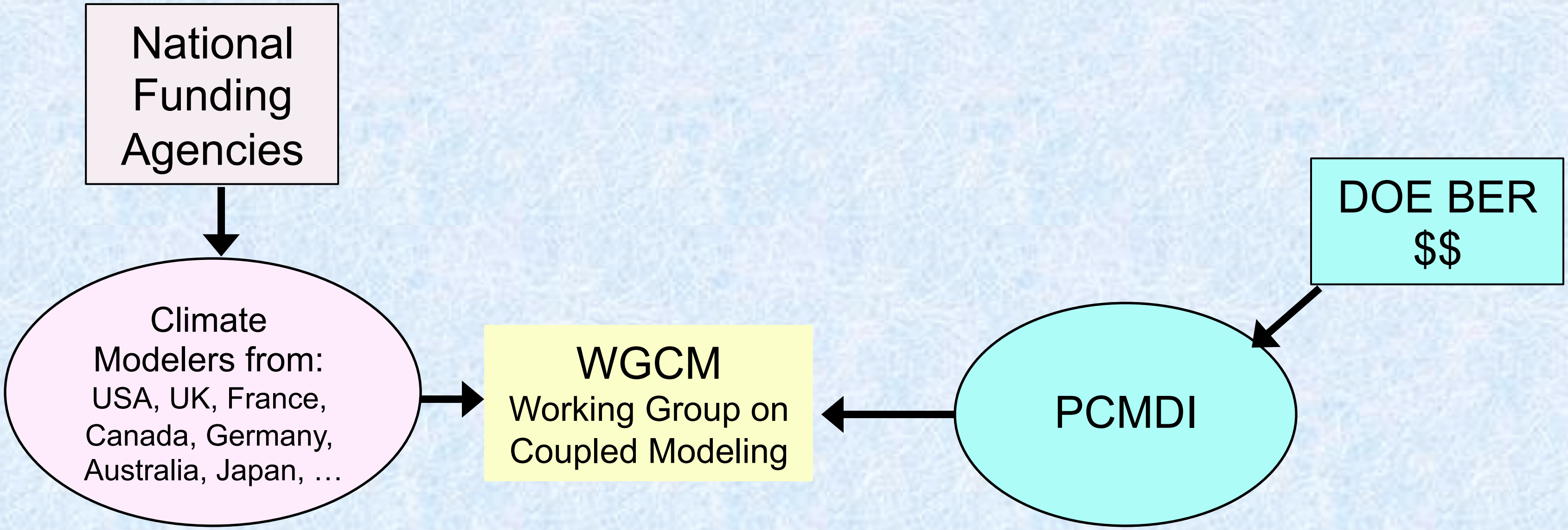


PCMDI

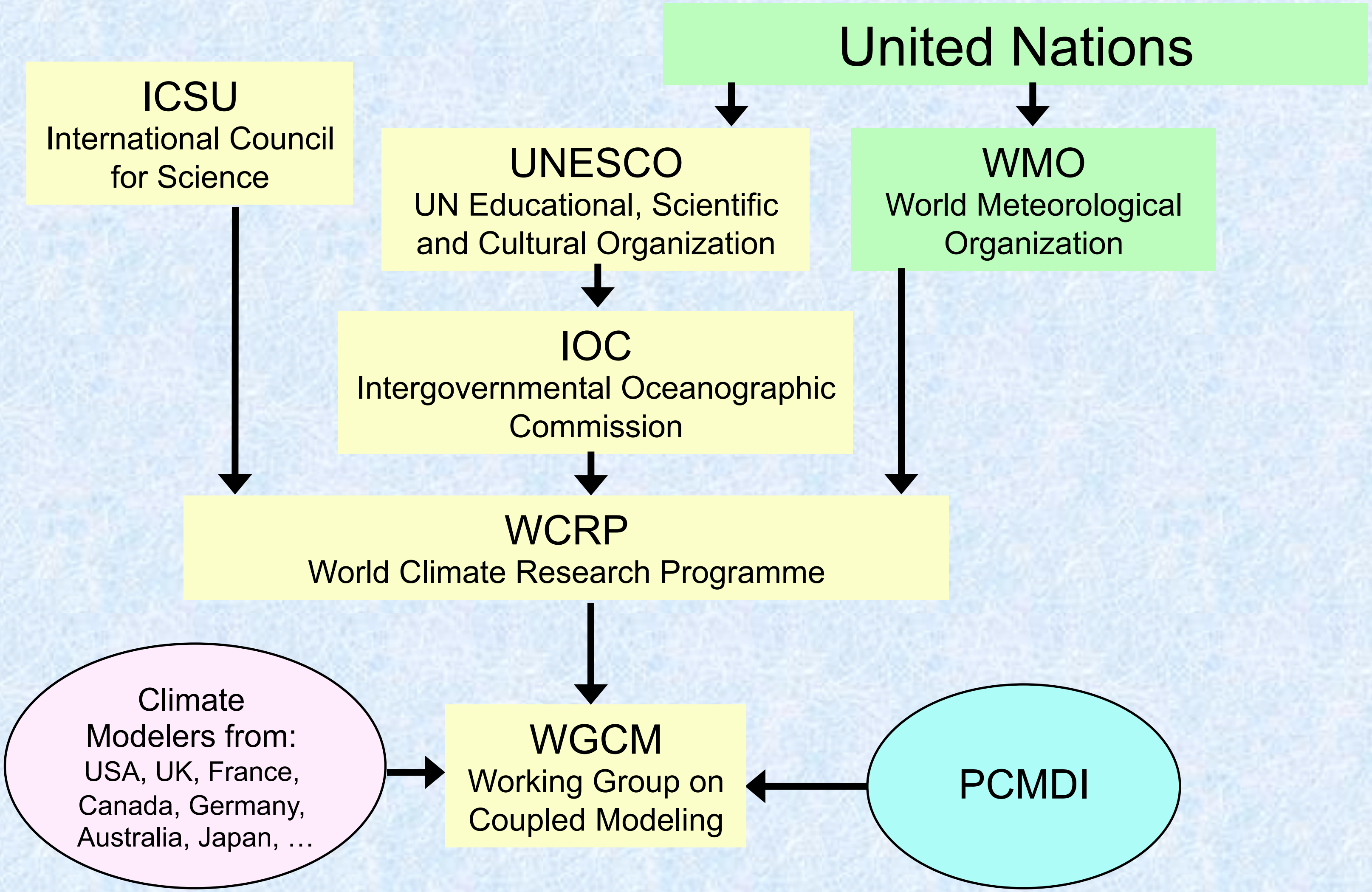
CMIP5 output from many of the world's climate centers is now served to users through a single gateway



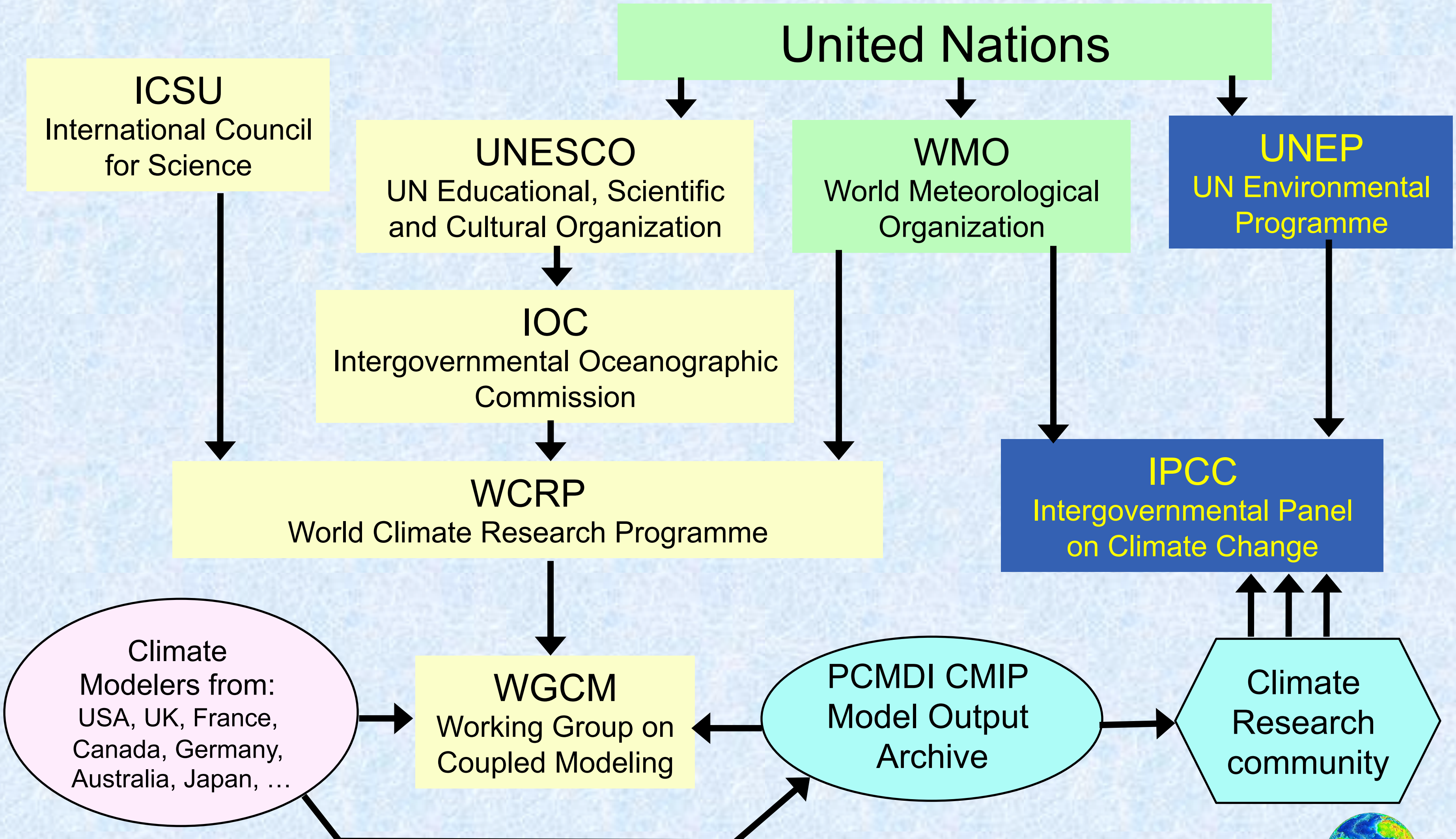
CMIP: A grass-roots collaborative effort



CMIP: Under the umbrella of an internationally-coordinated research program



IPCC assessments are separate from the international climate research programs



For each suite of experiments: model participation and model latitude resolution

Suite(s) of experiments	Number of models	Atmos. resol. (deg)			Ocean resol. (deg)		
		max	min	mean	max	min	mean
Longterm *and* decadal	13	0.8	2.8	1.4	0.4	2.0	0.8
Only longterm	19	1.0	4.5	1.9	0.4	2.0	0.9
Only decadal	7	0.6	2.5	1.4	0.3	1.3	0.9
Only “Time slice”	4	0.2	0.6	0.4	-	-	-

Requested output: 3.3 Pbytes

"Long-term" experiments: planned contributions

* Core simulations (# available as of July 14, 2011)

Experiment(s)	# of models
* Control & historical	35 (9)
* AMIP	26 (6)
* RCP4.5 & 8.5	29 (6)
RCP2.6	18 (5)
RCP6	13 (3)
RCP's to year 2300	10 (?)
* 1% CO2 increase	28 (7)
* Fixed SST CO2 forcing diagnosis	16 (3)
* Abrupt 4XCO2 diagnostic	22 (6)

Experiment(s)	# of models
Fast adjustment diagnostic	9 (?)
Aerosol forcing	9 (2)
*ESM control, historical & RCP8.5	18 (3)
Carbon cycle feedback isolation	9 (2)
Mid-Holocene & LGM	11 (2)
Millenium	7 (0)
CFMIP runs	7-9 (1-4)
D & A runs	15 (5)

"Decadal" experiments: planned contributions

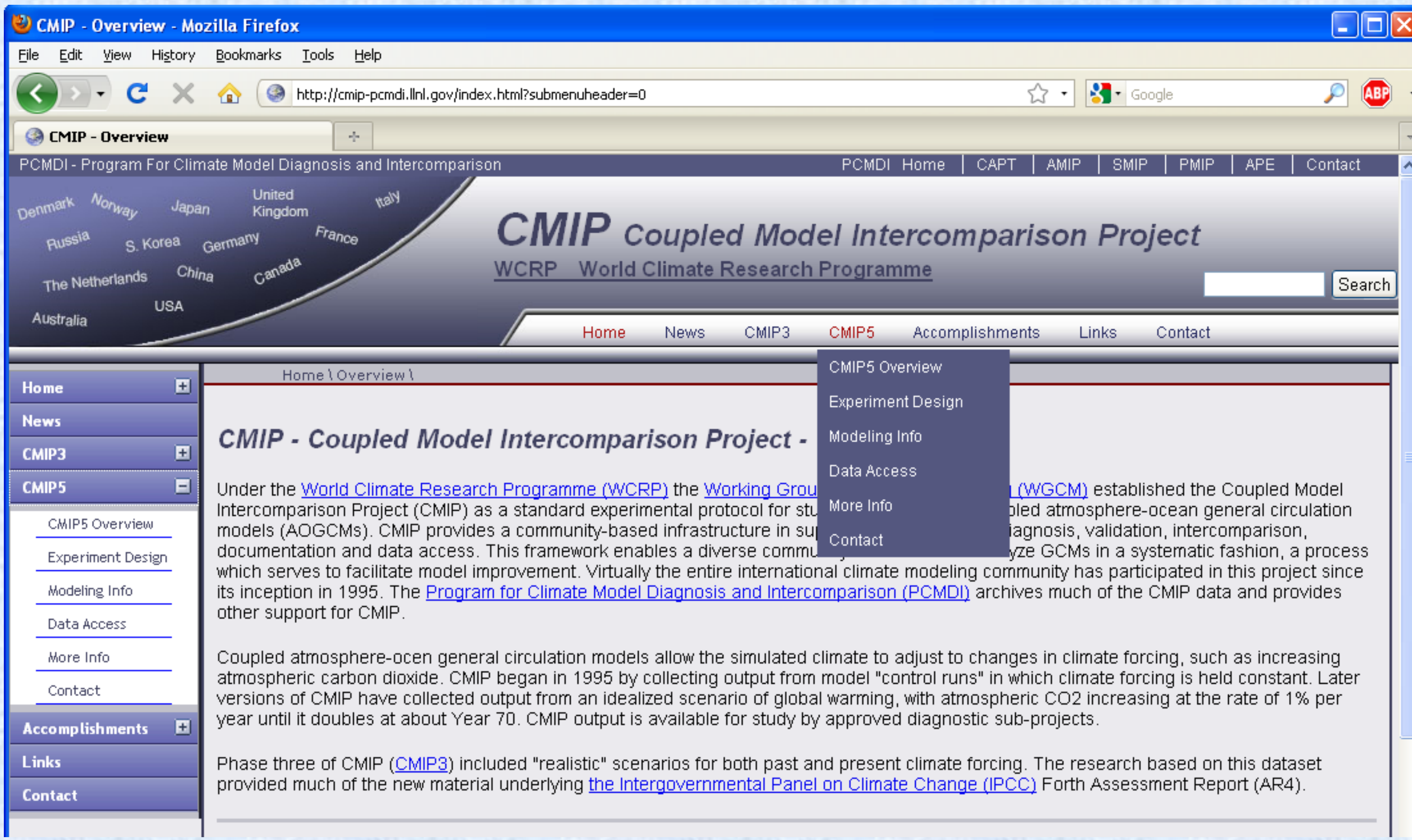
** Core simulations*

Experiment(s)	Number of models
*Hindcasts and predictions	18 (2)
AMIP	3 (1)
Volcano-free hindcasts	3 (0)
2010 "Pinatubo-like" eruption	1 (0)
Initialization alternatives	5 (?)
Pre-industrial control	10 (1)
1% CO2 increase	9 (1)

CMIP website:

http://cmip-pcmdi.llnl.gov

(or search on “CMIP5”)



Getting started with CMIP5 output

http://cmip-pcmdi.llnl.gov/cmip5/data_getting_started.html

CMIP5 output fields requested (goes well beyond what was available from CMIP3)

- Domains (number of monthly variables*):
  - Atmosphere (60)
  - Aerosols (77)
  - Ocean (69)
  - Ocean biogechemistry (74)
  - Land surface & carbon cycle (58)
  - Sea ice (38)
  - Land ice (14)
  - CFMIP output (~100)
- Temporal sampling (number of variables*)
  - Climatology (22)
  - Annual (57)
  - Monthly (390)
  - Daily (53)
  - 6-hourly (6)
  - 3-hourly (23)

*Not all variables will be saved for all experiments and time-periods

http://cmip-pcmdi.llnl.gov/cmip5/output_req.html

CMIP5 decadal predictions are in an exploratory stage

- Some think it likely that most of the predictive skill for most of the next decade (and beyond) will come from the “forced” response, not the initial climate state.

- New results from “initialized” climate simulations often require corrections:
  - Application of these corrections is not trivial, so there is danger for incorrect interpretation.
  - For non-experts it would be safer (and perhaps just as informative) to consider the output of the first few decades of the “long-term” experiments.

CMIP5 timeline

- Late 2013: IPCC AR5 published
- Journal articles accepted – 15 March 2013
- Journal articles submitted – 31 July 2012
- April 2012: Data not already in the CMIP5 archive will probably not be included in publications cited by the AR5
- March 2011: First model output became available to users