PCMDI's* Role in Enabling Climate Science Through Coordinated Modeling Activities

Karl E. Taylor

*Program for Climate Model Diagnosis and Intercomparison (PCMDI)

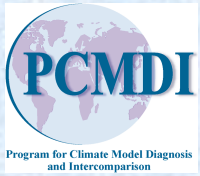
Lawrence Livermore National Laboratory

Briefing of BERAC

Washington D.C.

16 October 2012

U.S. DEPARTMENT OF ENERGY | Office of Science



PCMDI's dual mission is unique and appropriate for a national lab

- Advance climate science through individual and team research contributions.
  - Perform cutting-edge research to understand the climate system and reduce uncertainty in climate model projections.

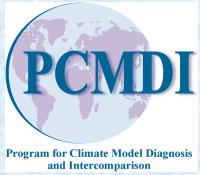
- Provide leadership and infrastructure for coordinated modeling activities that promote and facilitate research by others.
  - Plan and manage "model intercomparison projects" and provide access to multi-model output.

PCMDI's work is funded by the Climate and Environmental Sciences Division of BER.

Outline: PCMDI's role in coordinated modeling activities

- Overview of the Coupled Model Intercomparison Project (CMIP)
  - What is CMIP?
  - Historical perspective
  - International context
- PCMDI's role in CMIP
- CMIP's scientific impact
  - Publications
  - Multi-model perspective
- Samples of CMIP research results (PCMDI & LLNL)
- CMIP's future

What is the “Coupled Model Intercomparison Project” (CMIP)?



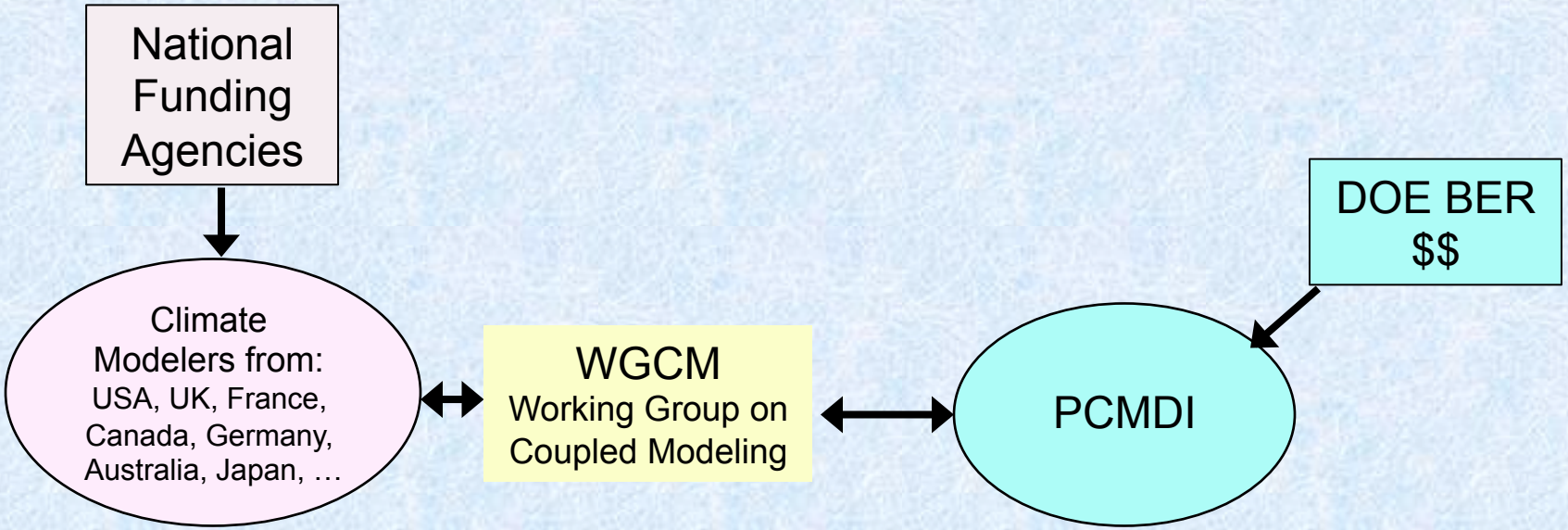
Highlights of "model intercomparison" history

- ca. 1970s and 1980s: climate model evaluation was largely a qualitative endeavor done by modeling groups
- ca. 1991: Atmospheric Model Intercomparison Project (AMIP)
  - Roughly 30 modeling groups from 10 different countries
  - Engaged outside researchers in the evaluation and diagnosis of atmospheric models
- ca. 1995: Coupled Model Intercomparison Project (CMIP)
- CMIP3 (2003 – ca. 2013):
  - Expts: control, idealized climate change, historical, and SRES (future scenario) runs
  - Output largely available by 2005
- CMIP5 (2006 – beyond 2016; ongoing and revisited)
  - An ambitious variety of "realistic" and diagnostic experiments
  - Output largely available by 2012

Model intercomparison and modeling culture has evolved:

- More experiments
  - Address a wider variety of questions
  - Meet the needs of a broader community of users
- More comprehensive models (from atmos. to earth-system)
- More openness in making output available.
- Increased standardization facilitating data exchange
- More model output
- More complete documentation of models/experiments
- New strategies for making output accessible to users

International context for CMIP: A grass-roots collaborative effort

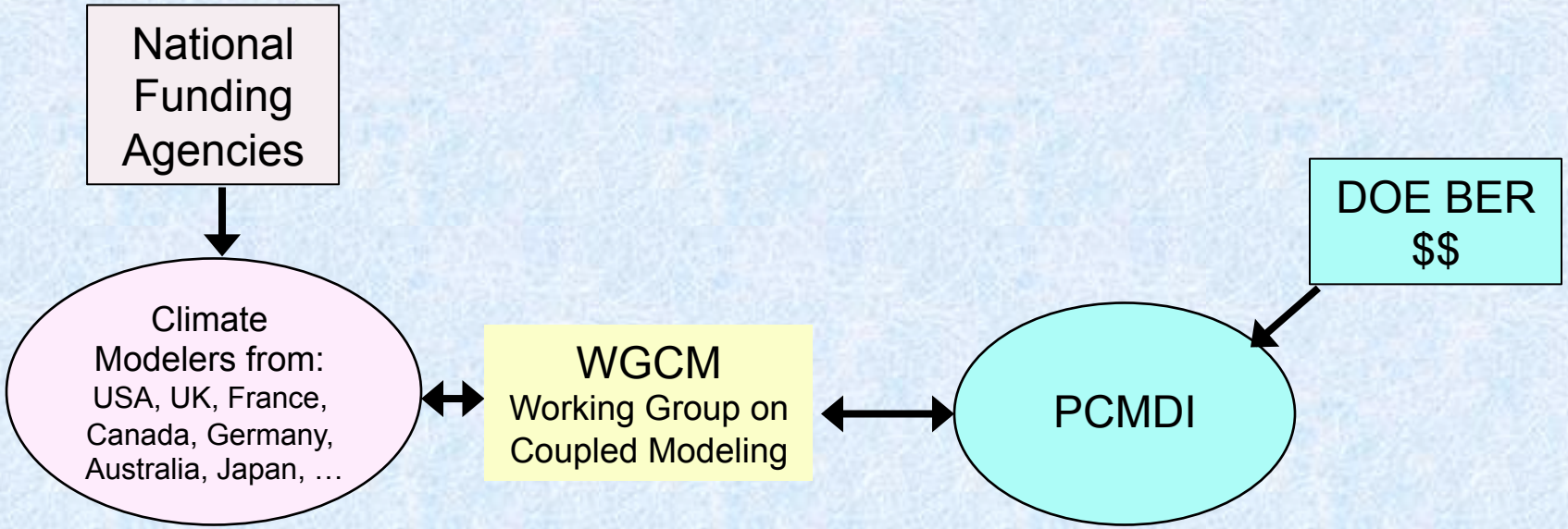


CMIP5 participating groups:
59 models available from 24 groups

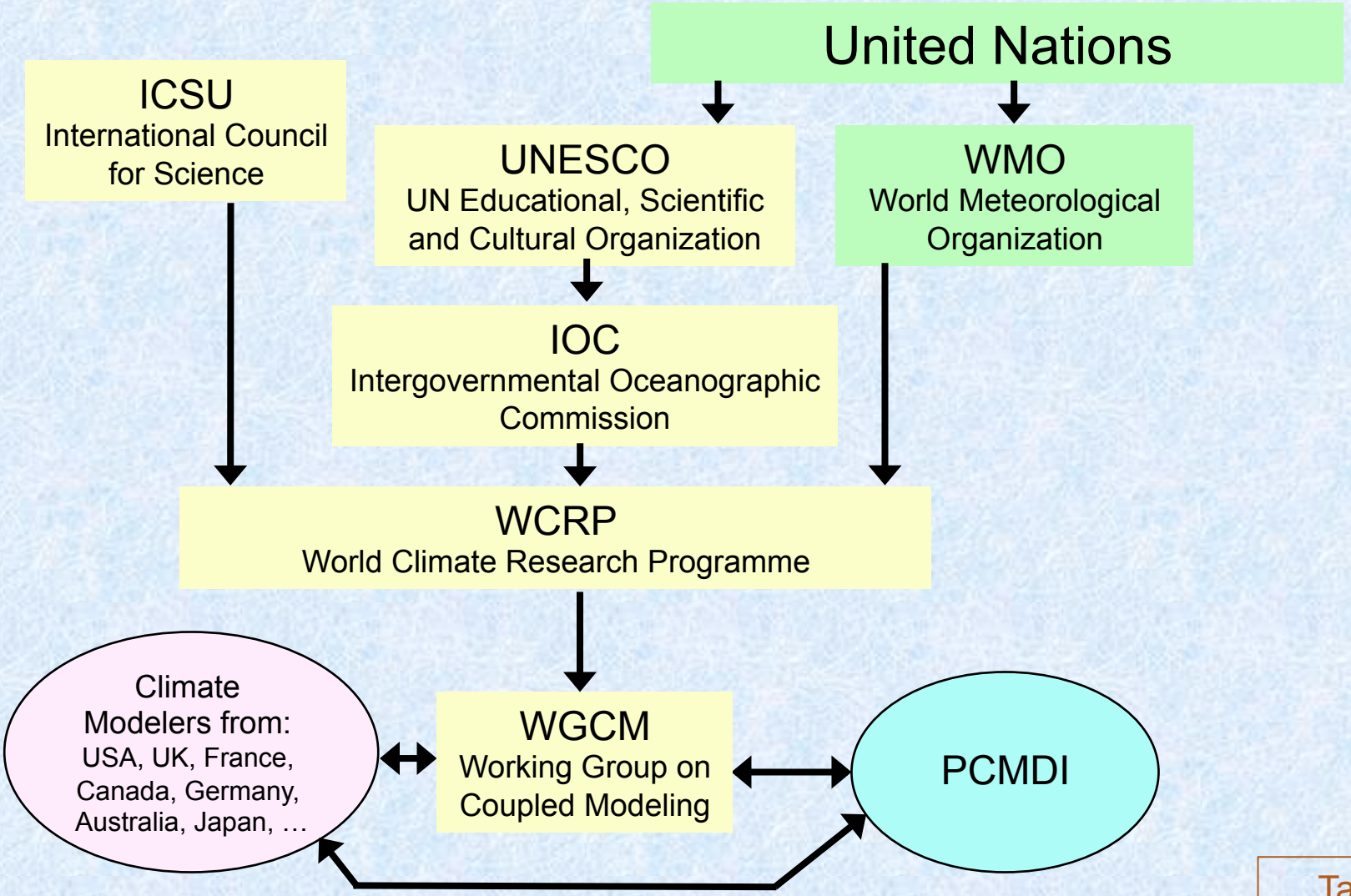
22 Sept. 2012

Primary Group	Country	Model
CSIRO-BOM	Australia	ACCESS 1.0, 1.3
BCC	China	BCC-CSM1.1, 1.1(m)
GCESS	China	BNU-ESM
CCCMA	Canada	CanESM2, CanCM4, CanAM4
DOE-NSF-NCAR	USA	CCSM4, CESM1 (BGC), (CAM5), (CAM5.1,FV2), (FASTCHEM), (WACCM)
RSMAS	USA	CCSM4(RSMAS)
CMCC	Italy	CMCC- CESM, CM, & CMS
CNRM/CERFACS	France	CNRM-CM5
CSIRO/QCCCE	Australia	CSIRO-Mk3.6.0
EC-EARTH	Europe	EC-EARTH
LASG-IAP & LASG-CESS	China	FGOALS- g2, s2, & gl
FIO	China	FIO-ESM
NASA/GMAO	USA	GEOS-5
NOAA 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-LR
MIROC	Japan	MIROC 5, 4m, 4h, ESM, ESM-CHEM
MPI-M	Germany	MPI-ESM- HR, LR, P, ESM-P
MRI	Japan	MRI- AGCM3.2H, AGCM3.2S, CGCM3, ESM1
NCC	Norway	NorESM1-M, NorESM-ME

CMIP: A grass-roots collaborative effort

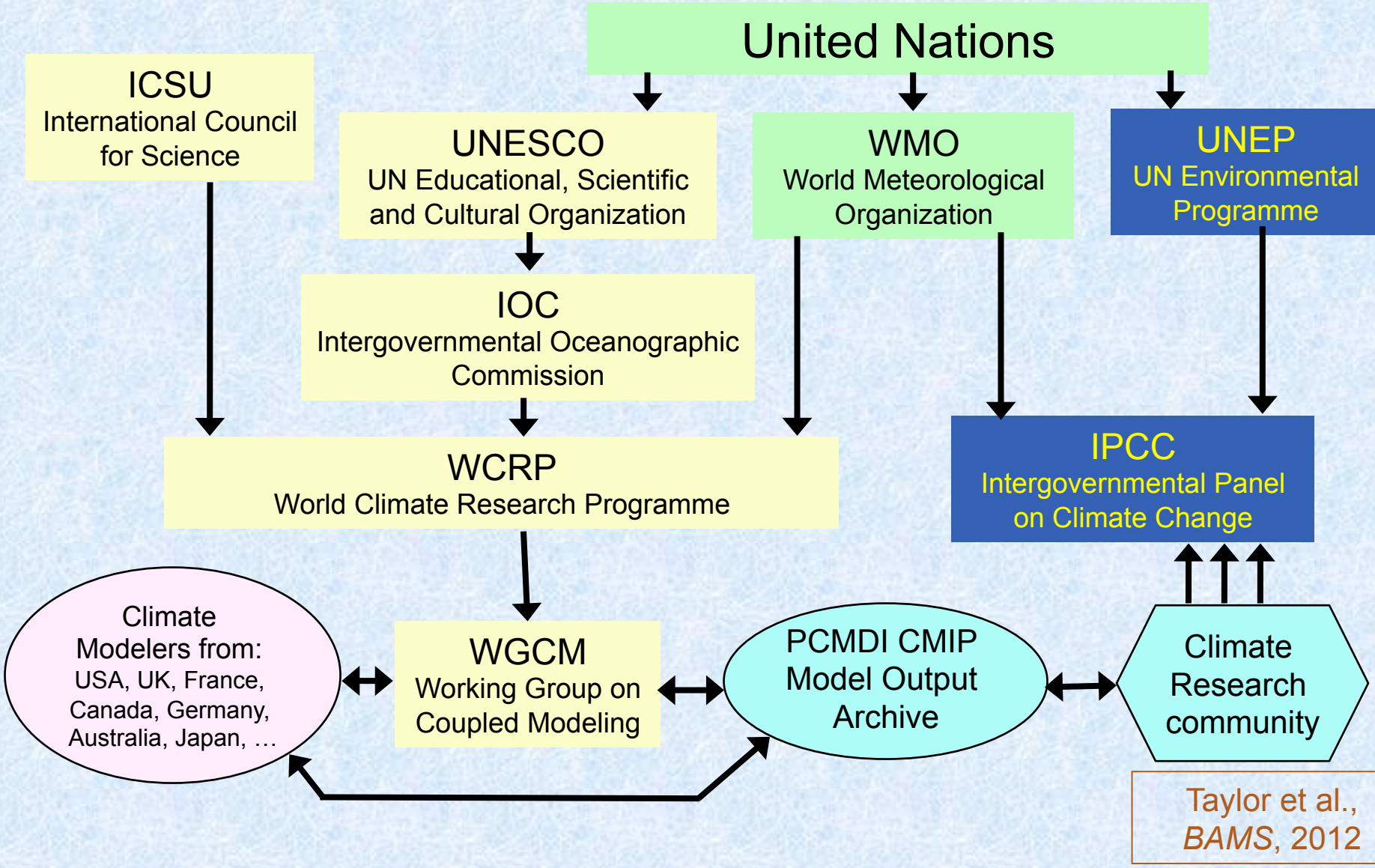


CMIP: Under the umbrella of an internationally-coordinated research program



Taylor et al., *BAMS*, 2012

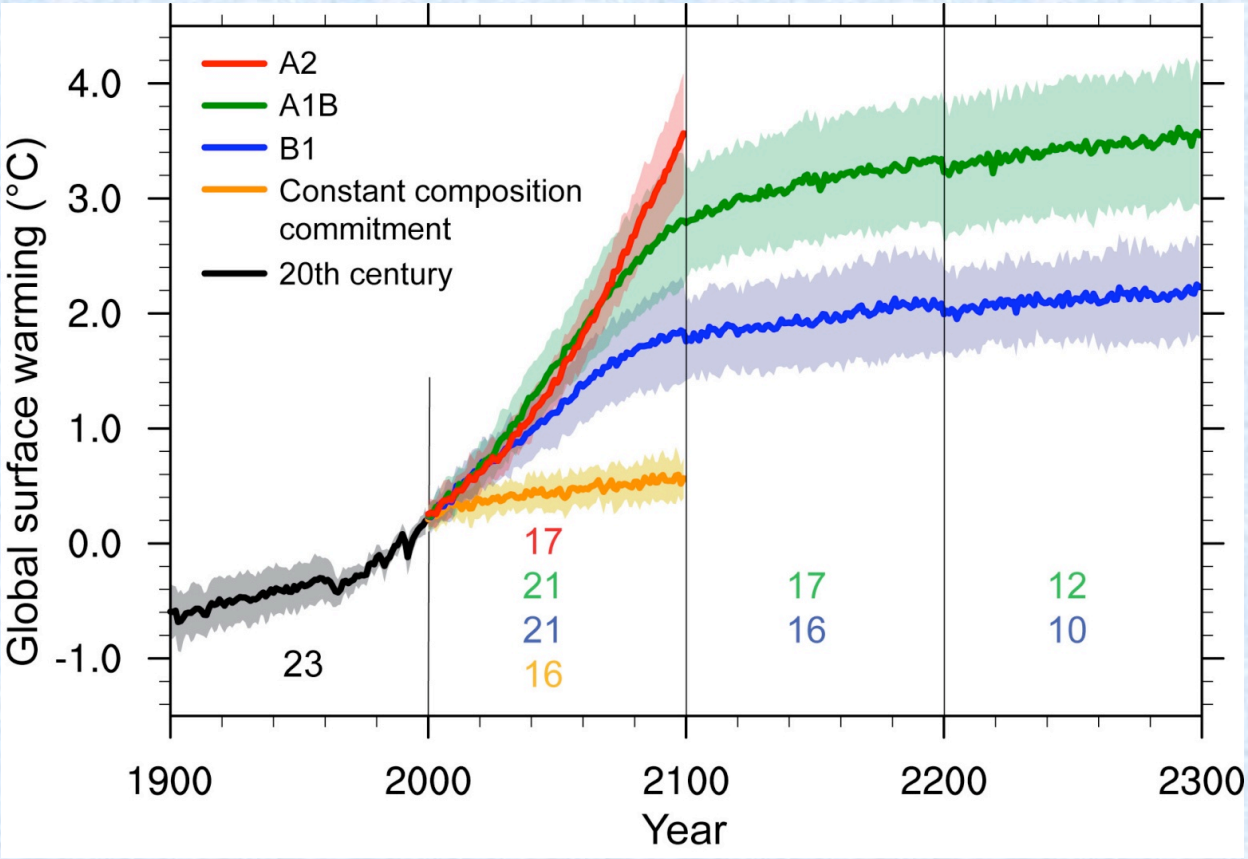
IPCC assessments are separate from the international climate research programs



Taylor et al., *BAMS*, 2012

One component of CMIP: All models make projections of future climate change based on the same set of scenarios

- Different "scenarios" lead to different climate responses
- Models forced similarly exhibit a range of responses



From IPCC AR4 Summary for Policy Makers

K. E. Taylor

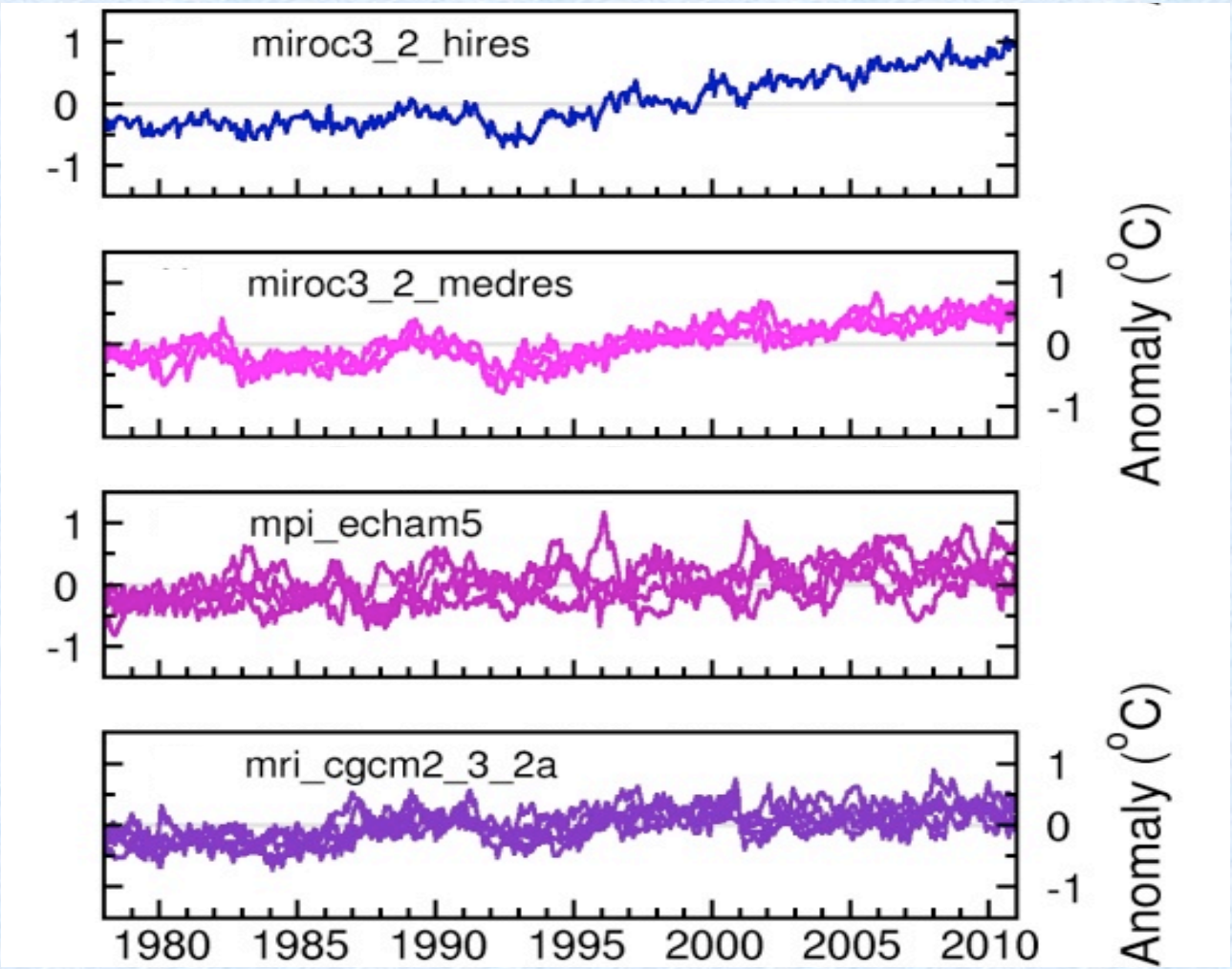
What contributes to the spread in projections?

- Differences in "scenarios" (i.e. different emissions or concentration prescriptions).
- Differences in "radiative forcing" (radiative impact) of changing atmospheric composition.
- Differences in "climate sensitivity" (i.e., differences in climate feedbacks)
- 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

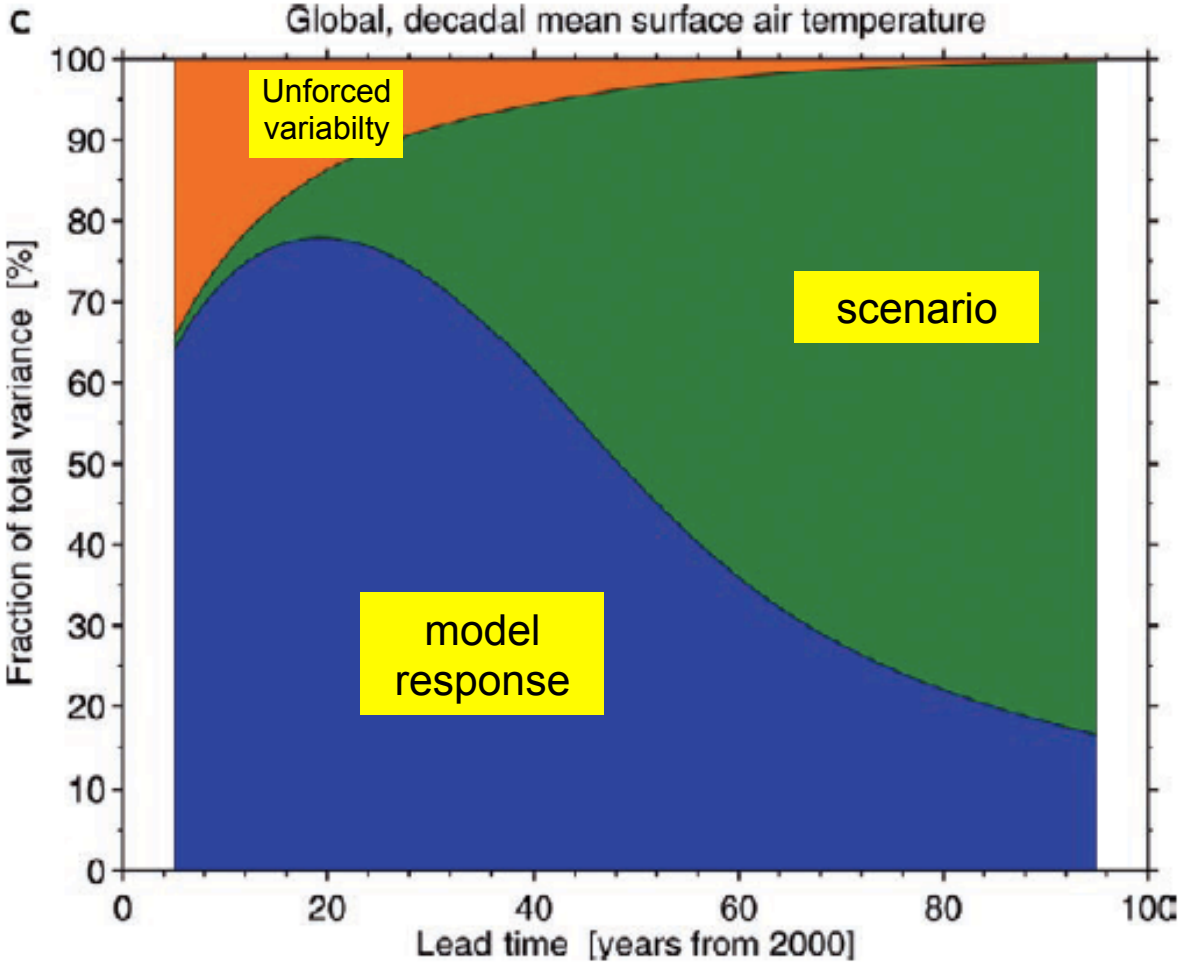
Single simulation

Ensembles of equally likely outcomes



Courtesy of B.Santer

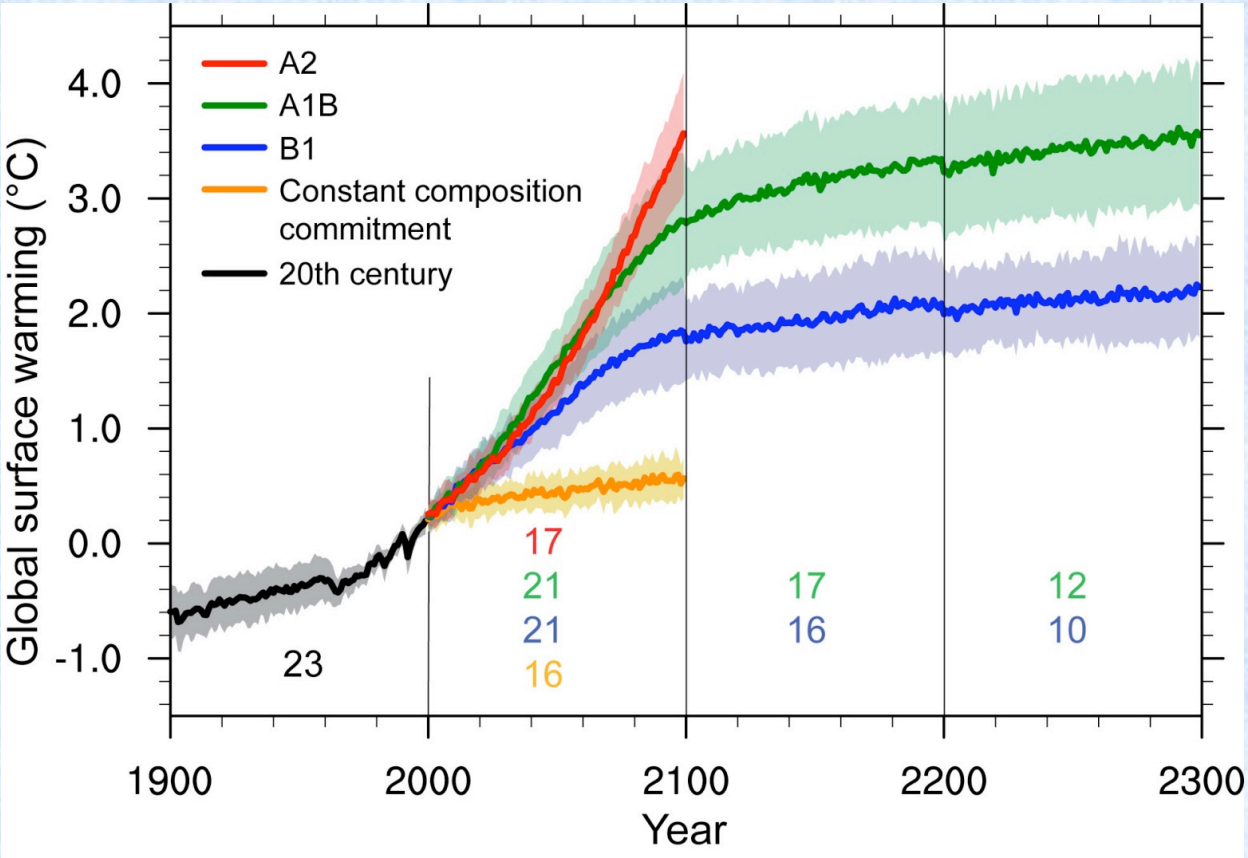
Projection ranges are initially dominated by model "uncertainty"*, but eventually are dominated by scenario



*nb. The "spread" of model results is sometimes without much justification used as a measure of "uncertainty".

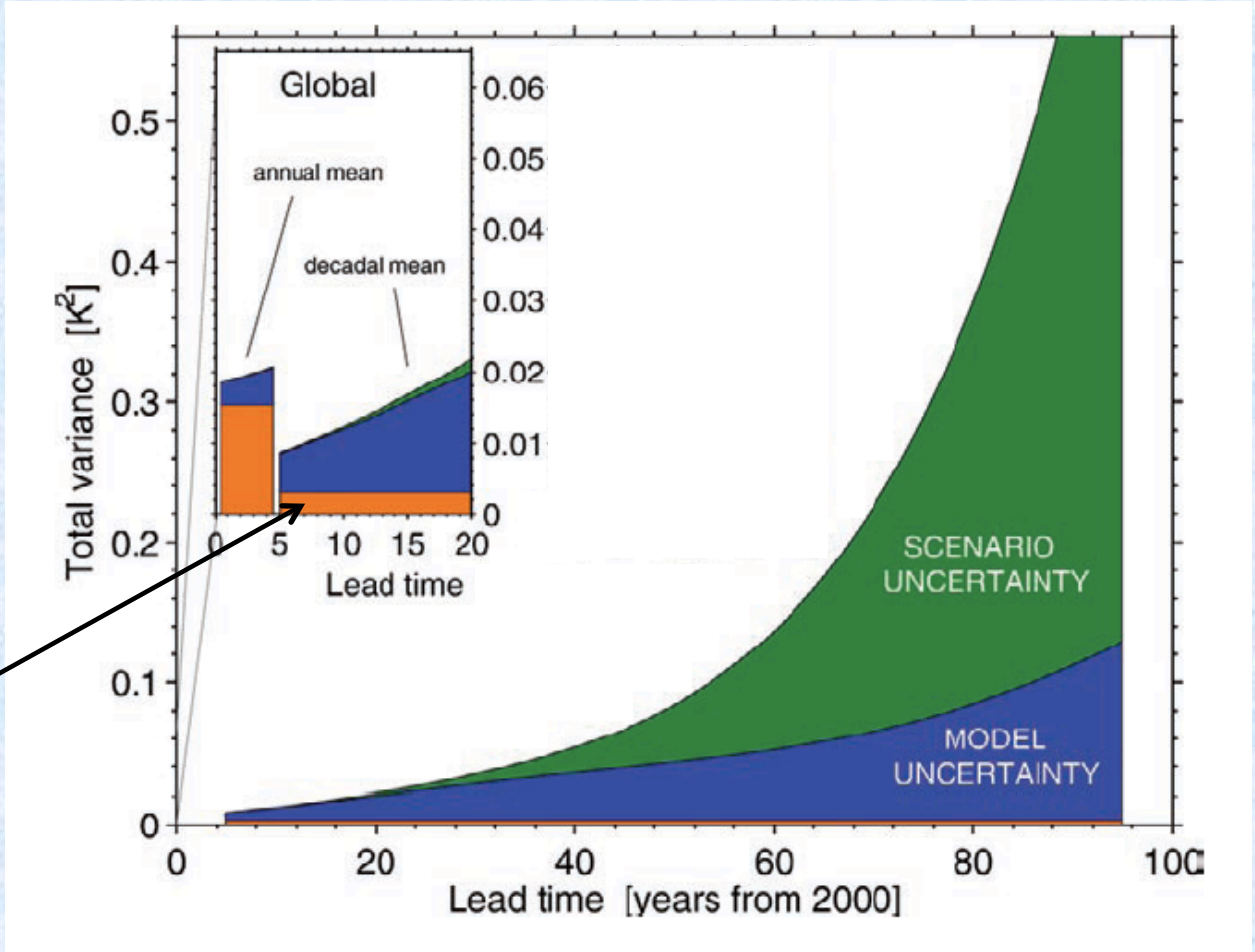
Hawkins & Sutton, *BAMS*, 2009

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



From IPCC AR4 Summary for Policy Makers

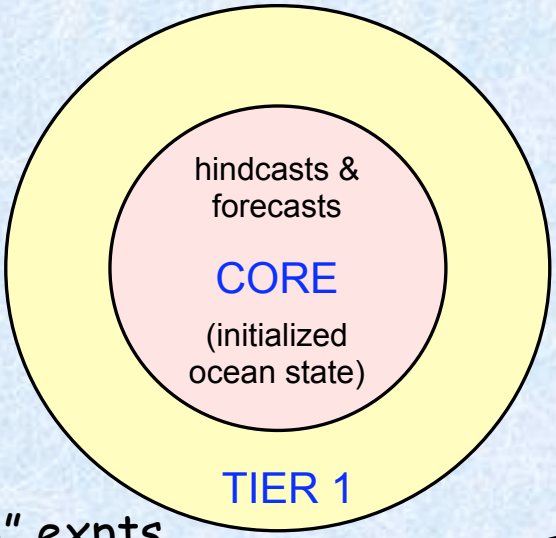
On global scales, the climate future quickly becomes dominated by model and scenario uncertainty.



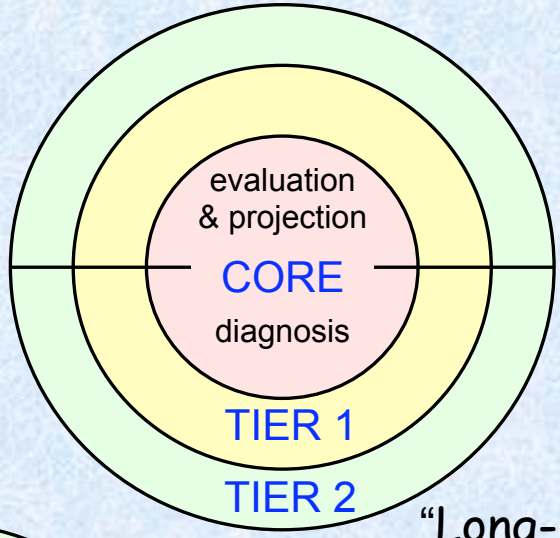
Unforced variability is important only in the near-term.

Hawkins & Sutton, *BAMS*, 2009

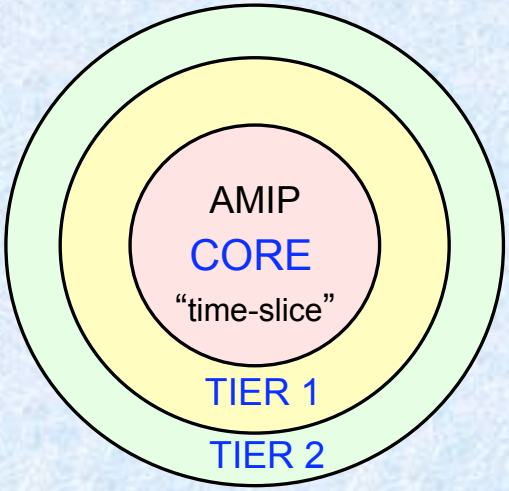
CMIP5 experiments are designed to address the causes of spread in projections and much more.



"Near-Term" expts.
(decadal prediction)



"Long-Term"
traditional expts.
(century & longer)



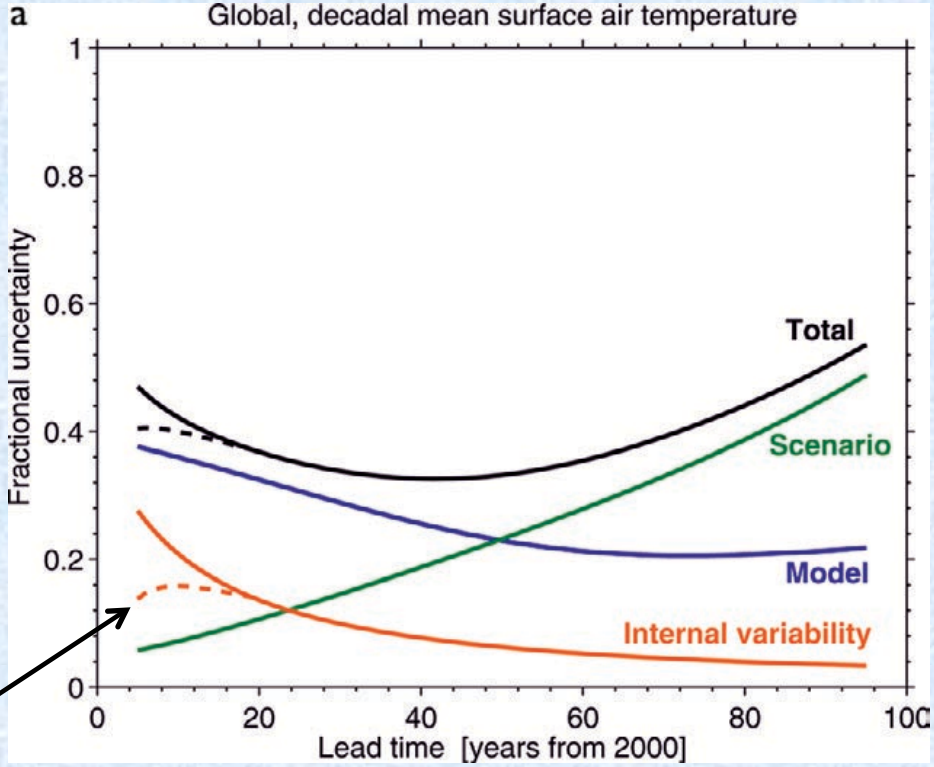
Atmosphere-Only Simulations

(for computationally demanding and NWP models)

Taylor, Stouffer, & Meehl, *BAMS*, 2012

CMIP5 includes models initialized with the observed state (in particular of the upper ocean)

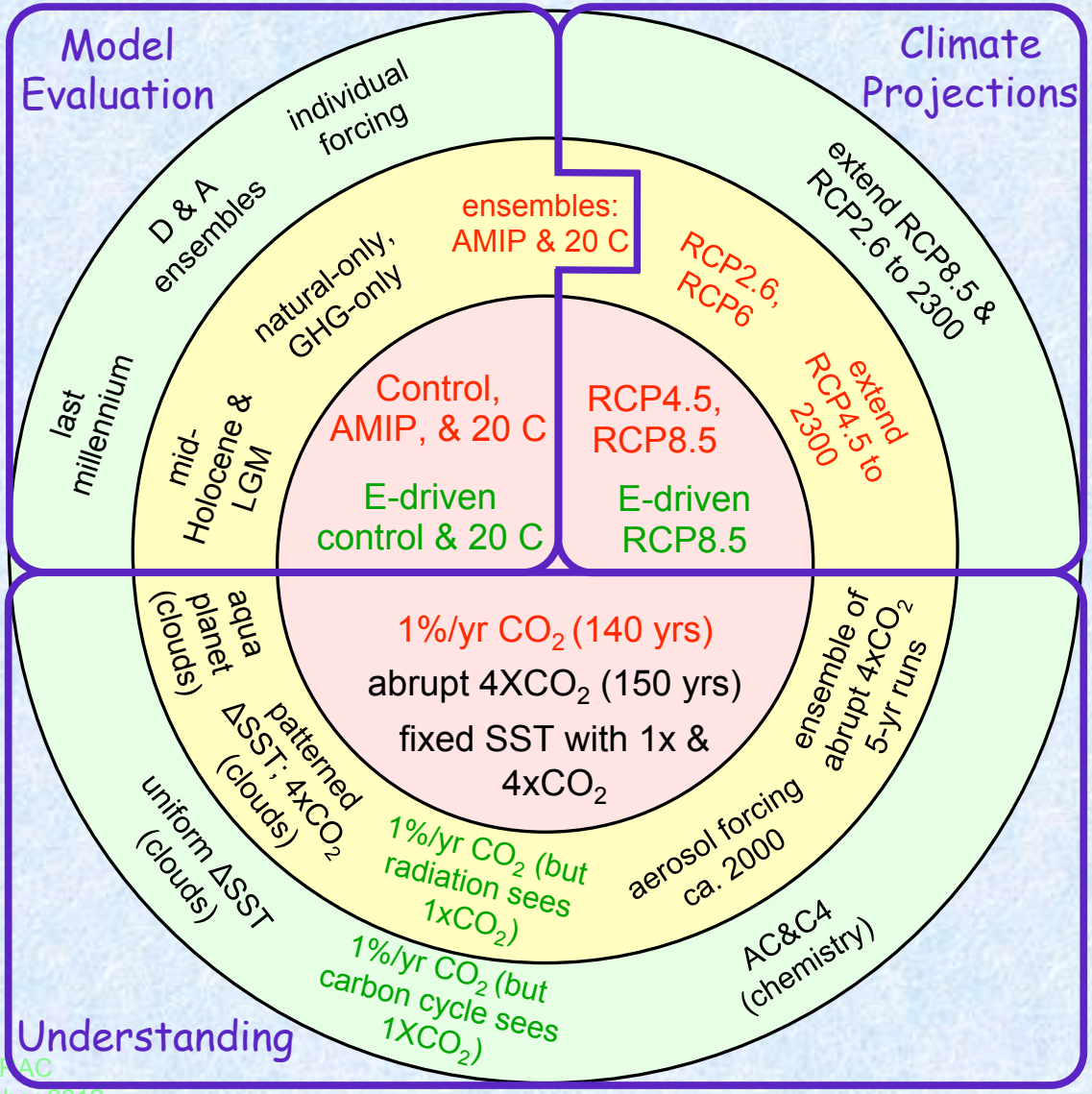
- The hope is that through initialization the models will be able to predict the actual trajectory of "unforced" climate variations.
- The hypothesis is that some longer time-scale natural variability is predictable if the initial state of the system is known



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

Hawkins & Sutton, 2009

The rich set of "long-term" experiments, drawn from several predecessor MIPs, focuses on model evaluation, projections, and understanding



Red subset matches the entire CMIP3 experimental suite

Green subset is for coupled carbon-cycle climate models only

CMIP5 output fields cover all parts of the system and include "high frequency" samples.

- 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

What is PCMDI's leadership role in CMIP?

U.S. DEPARTMENT OF ENERGY | Office of Science

PCMDI
Program for Climate Model Diagnosis and Intercomparison

PCMDI contributes in a variety of ways to CMIP's success

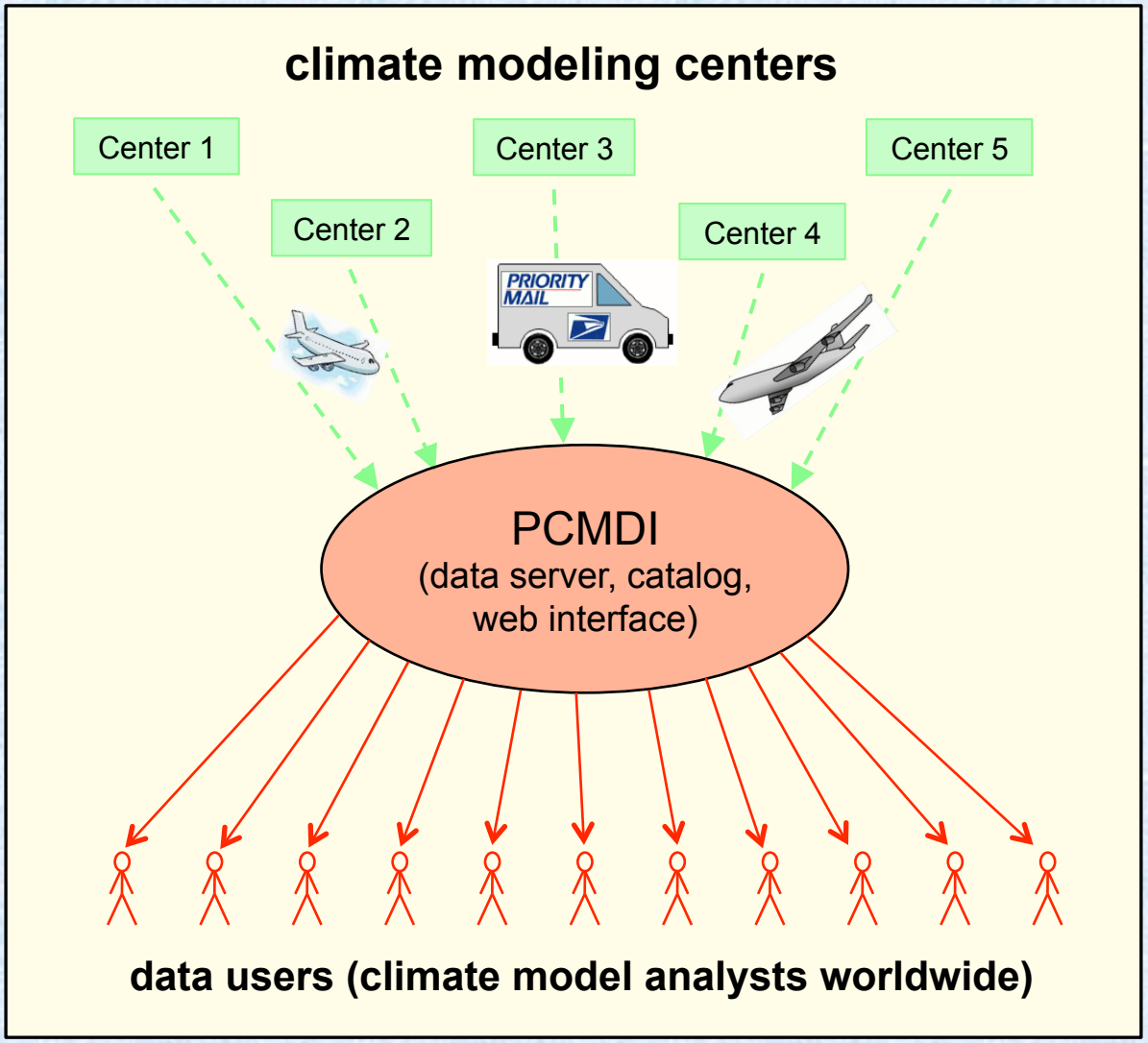
- CMIP5 planning: PCMDI forges community consensus and provides detailed specifications for
  - Experiment design
  - List of requested model output
  - Format and structure of model output, as well as required metadata
- Software infrastructure development and support to enable community analysis of CMIP results
- Web site to provide information needed by modeling groups and users.

Data volumes have grown by many orders of magnitude

- Early 1990's (e.g., AMIP1, PMIP, CMIP1): modest collection of monthly mean 2-D fields: ~1 Gbyte
- Late 1990's (AMIP2): large collection of monthly mean and 6-hourly 2-D and 3-D fields: ~500 Gbytes
- 2004 (CMIP3): fairly comprehensive output from both ocean and atmospheric components; monthly, daily, & 3-hourly: ~36,000 Gbytes
- 2010 (CMIP5) 1000 - 3000 Tbytes (1 TB =1000 GB)

This required new approaches for delivering data to users!

CMIP3 data handling: ESG* central archive at PCMDI

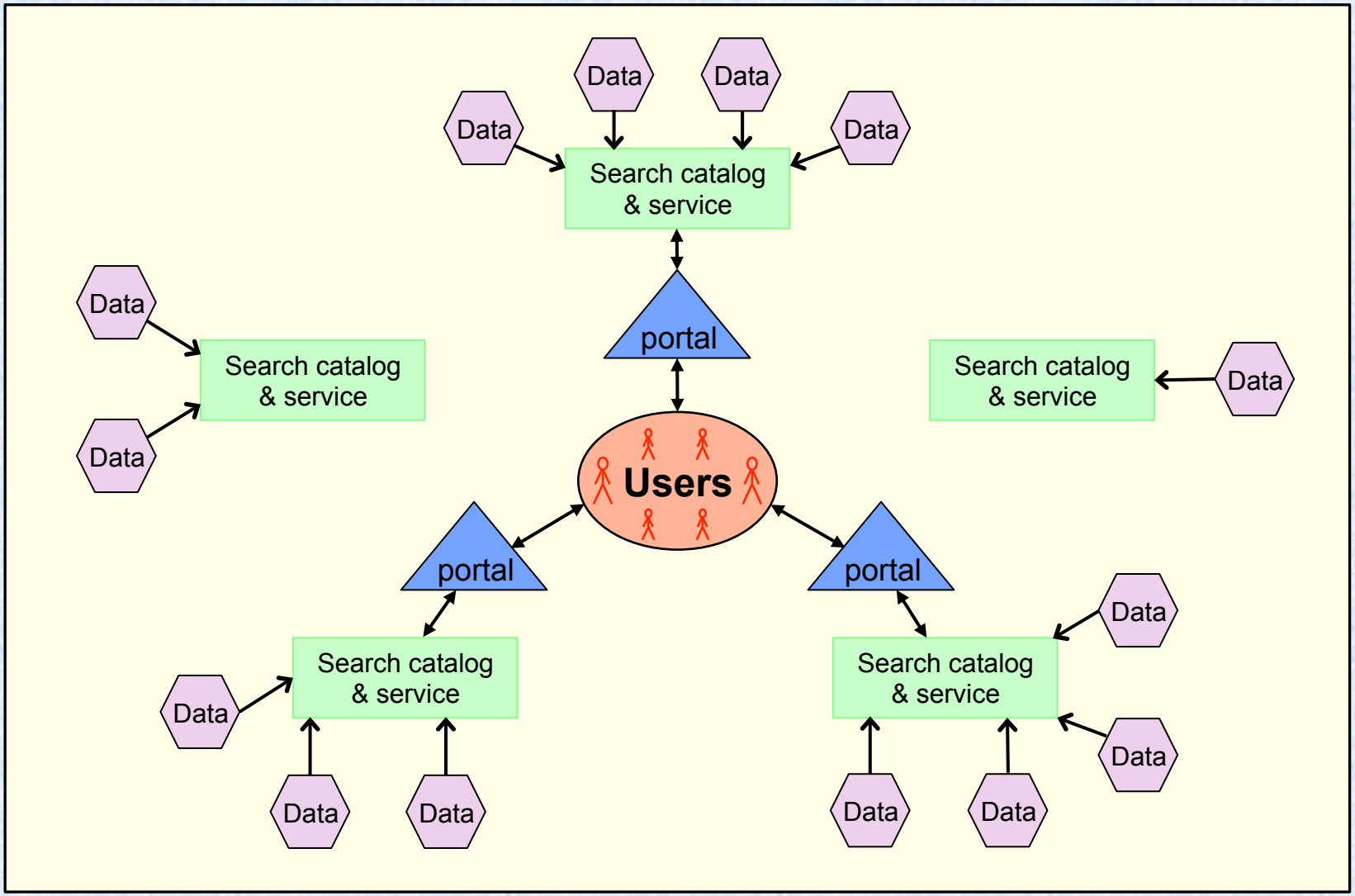


- Data shipped to PCMDI on hard disks
- Delayed availability
- Hindered corrections

- Search service via web gateway
- Download from single location (ftp, http)
- Fragile dependence on a single server.

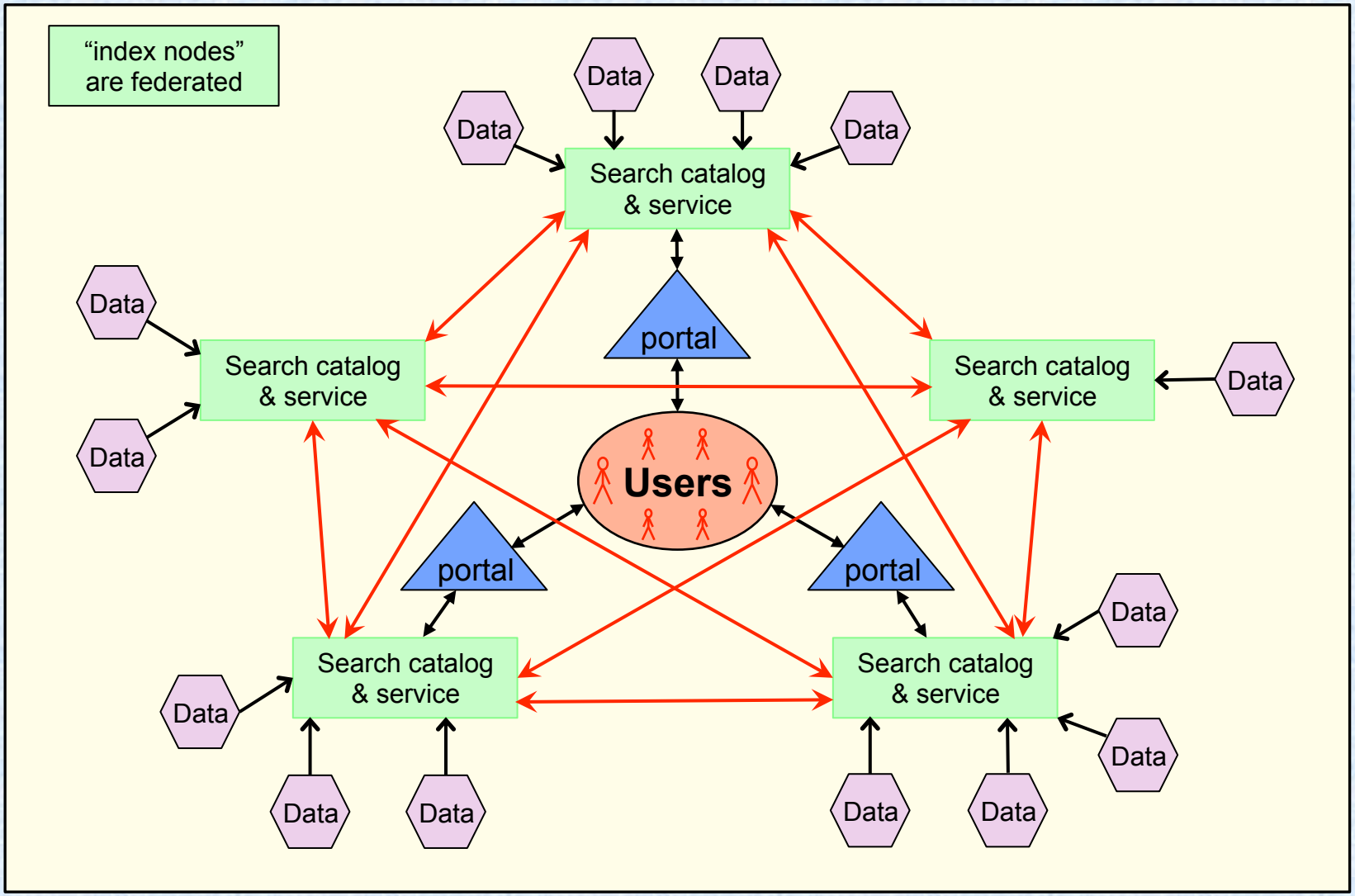
*ESG = Earth System Grid

CMIP5 new approach: Distributed data archive (ESGF*)

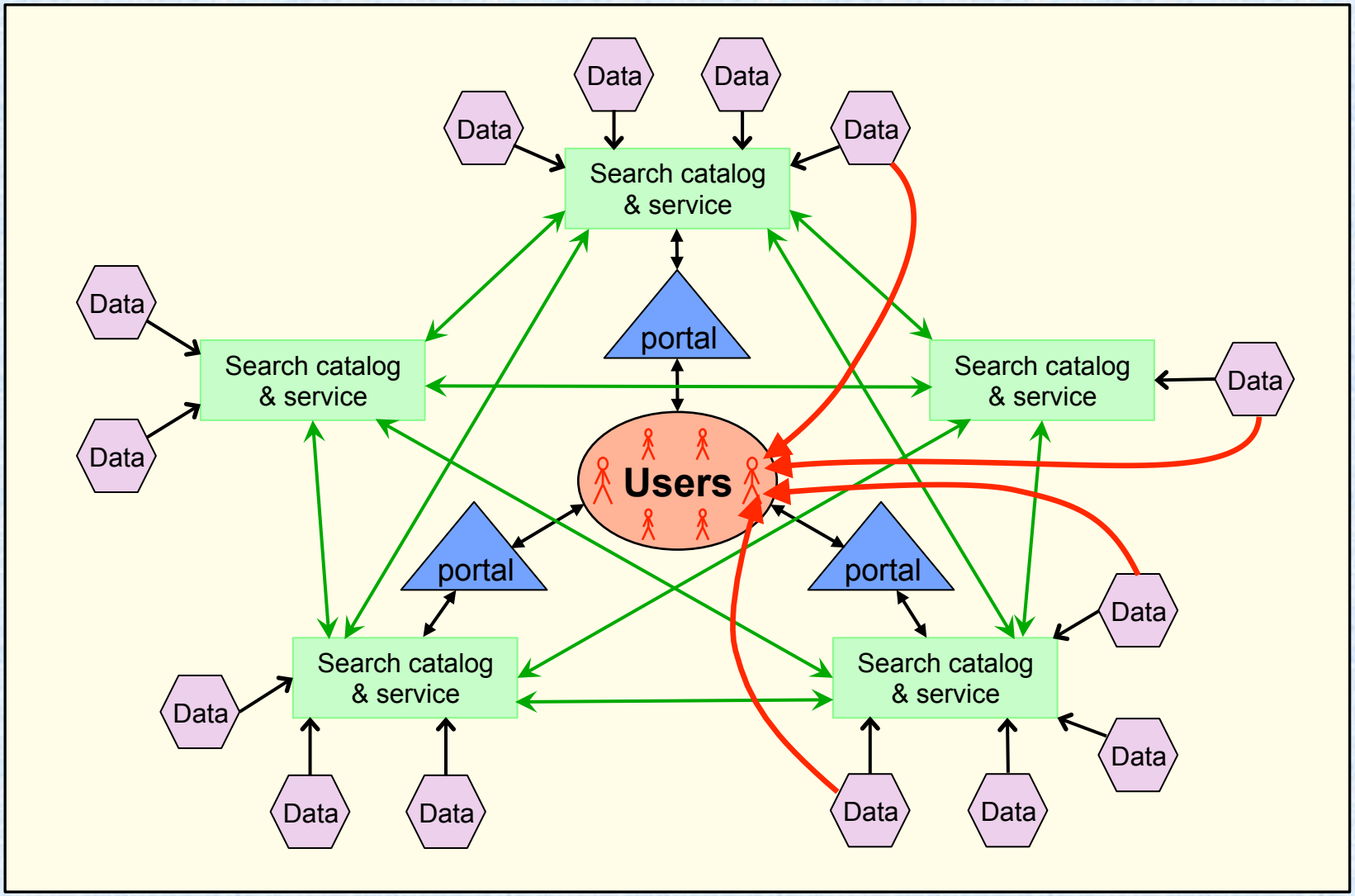


*ESGF = Earth System Grid Federation

All data can be browsed through a single portal because index nodes are federated.

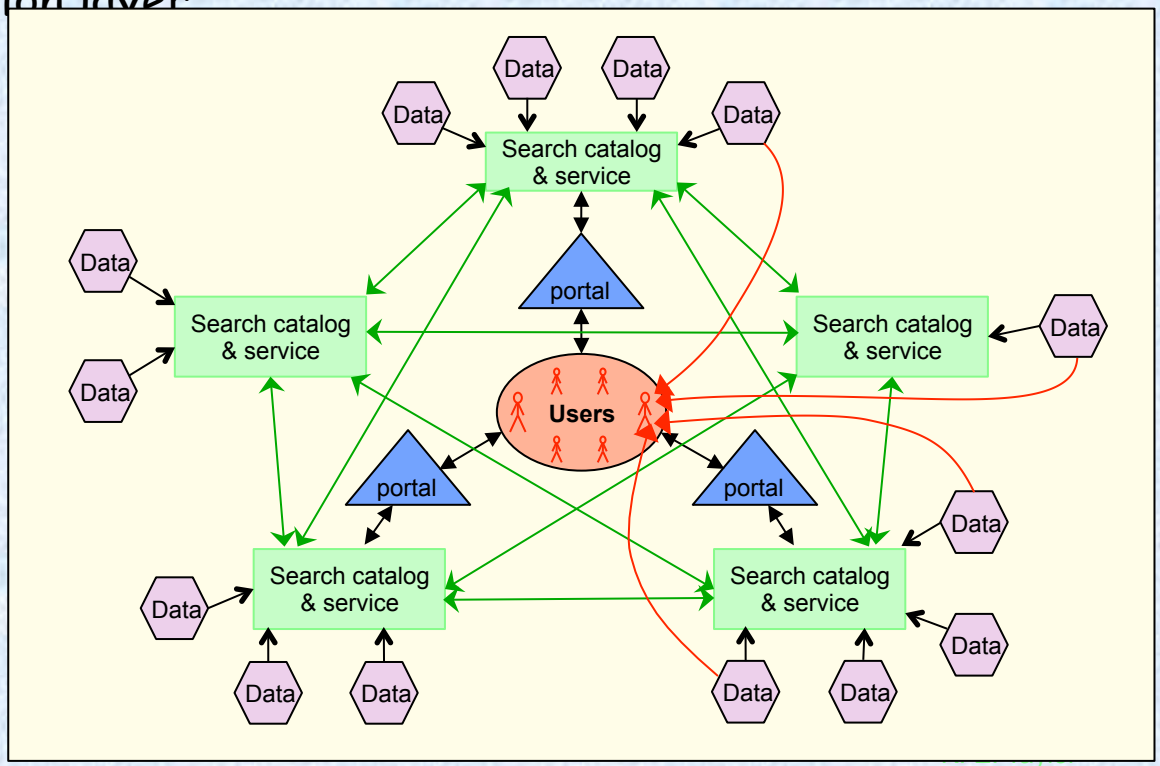


Once desired datasets have been found, user harvests data directly from the nodes.



ESGF is unparalleled in capabilities and complexity

- Diagram does not show:
  - Script-driven direct search and retrieval of data (bypassing portals)
  - Server-side computing services
  - Security & authentication layer
- Also:
  - PCMDI and other major data centers have replicated high-demand datasets.



CMIP5 output can be obtained at **http://pcmdi9.llnl.gov**

What has CMIP done to advance climate modeling?

U.S. DEPARTMENT OF ENERGY | Office of Science

PCMDI
Program for Climate Model Diagnosis and Intercomparison

CMIP facilitates 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, more than 600 publications have been registered claiming to report on CMIP3 results, and more than 250 publications have been prepared based on CMIP5 results (which have been available for only a year or so).

Record of CMIP5 publications

CMIP Coupled Model Intercomparison Project

World Climate Research Programme

U.S. DEPARTMENT OF ENERGY | Office of Science

Submit | Edit | View | Administration

All Publications

Author	Article Title	Journal
?eparovi? L. , A. Alexandru, R. Laprise, A. Martynov, L. Sushama, ...	Present climate and climate change over North America as simulated by the fifth-generation Canadian Regional Climate Model (CRCM5); (Citation) (More Information)	Climate Dynamics
Ahlstr?m A. , G. Schurgers, A. Arneth, B. Smith	Robustness and uncertainty in terrestrial ecosystem carbon response to CMIP5 climate change projections; (Citation) (More Information)	Environmental Research Letters
Ahmed C. B. , S. Sensoy	Assessment of climate change effects on agriculture in the Mediterranean countries; (Citation) (More Information)	
Alan I. , M. Demircan, S. Sensoy	Trends in Turkey climate extreme indices from 1971 to 2004; (Citation) (More Information)	
Anav A. , P. Friedlingstein, M. Kidston, L. Bopp, P. Ciais, ...	EVALUATING THE LAND AND OCEAN COMPONENTS OF THE GLOBAL CARBON CYCLE IN THE CMIP5 EARTH SYSTEM MODELS; (Citation) (More Information)	Journal of Climate
Andrews T. , J. M. Gregory, M. J. Webb, K. E. Taylor	Forcing, feedbacks and climate sensitivity in CMIP5 coupled atmosphere-ocean climate models; (Citation) (More Information)	Geophysical Research Letters
Anstey J. A. , P. Davini, L. J. Gray, T. J. Woollings, N. Butchart, ...	Multi-model analysis of Northern Hemipshere winter blocking and tropospheric jet variability; (Citation) (More Information)	Journal of Geophysical Research

Total Publications Count: 255

Publication Views

- All Publications
- By Journal
- By Publication Type
- By Publication Status
- By Publication Year
- By Model
- By Experiment
- By Variable
- By Keyword
- By Sampling Frequency

See http://cmip.llnl.gov/cmip5/publications/allpublications

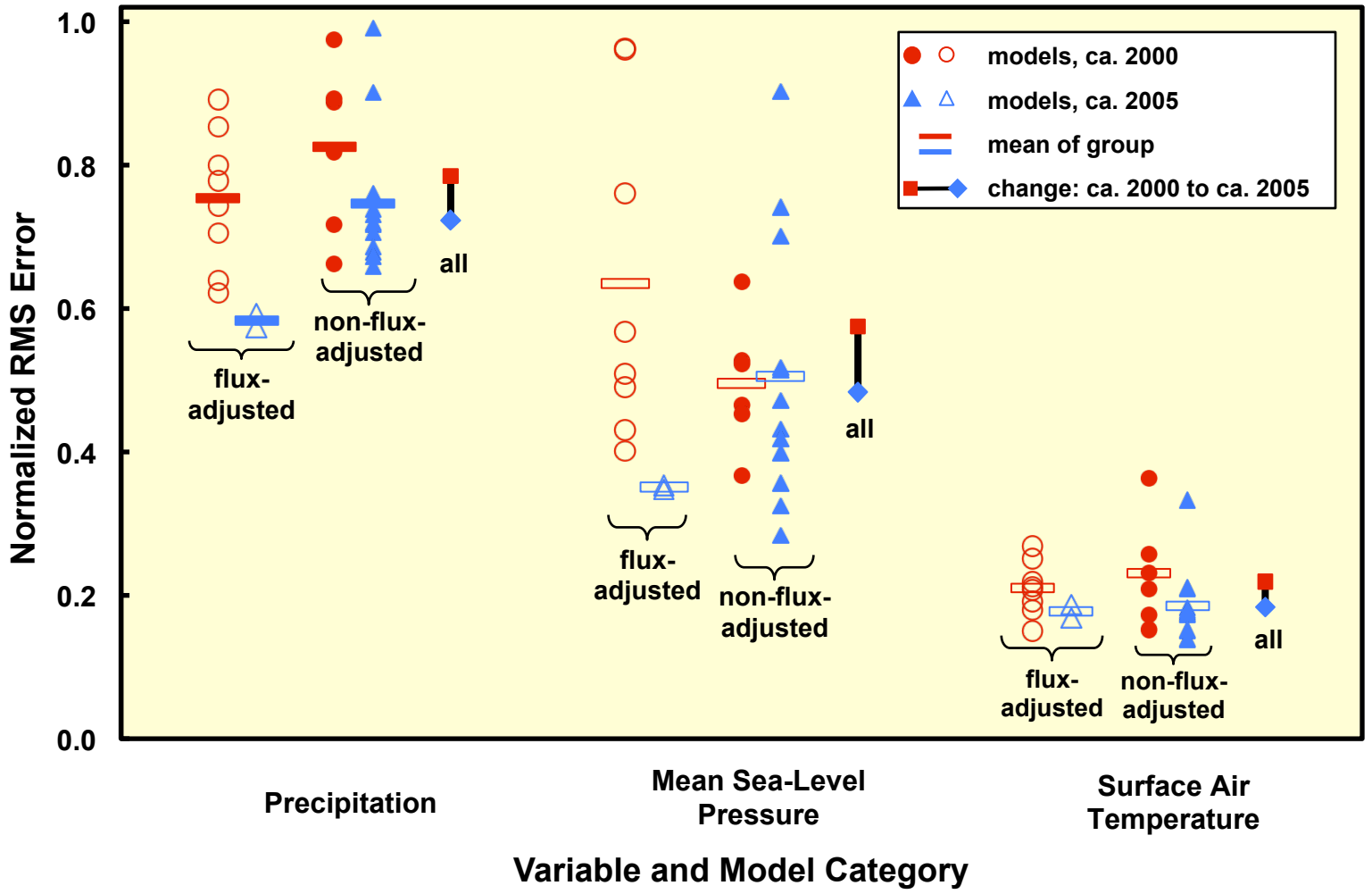
What has the multi-model perspective yielded?

- Visibly demonstrates that model results are uncertain
- Provides a range of (equally?) plausible projections for planners
- Has been used as a cornerstone for recent IPCC reports: In the 4th Assessment Report
  - 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

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

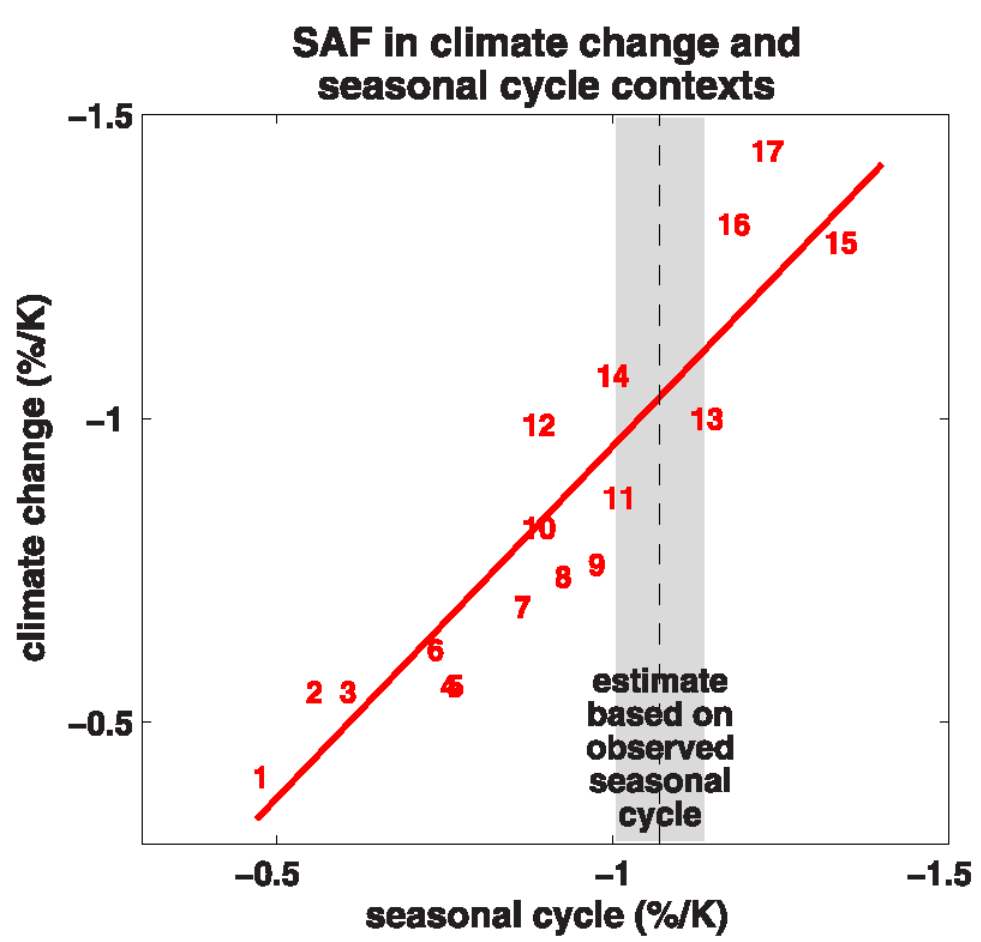
- AMIP runs (prescribed SST's and seaice)
- CMIP control runs (variability characteristics)
- Historical runs (1850 – present)
- Idealized 1%/yr CO_2 increases (determine climate sensitivity)

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



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

Relationships between observables and projections have been gleaned from CMIP results, that indicate which models might be reliable



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

Hall and Xu, *GRL*, 2006

Can important research questions be addressed by analysis of CMIP5 results?

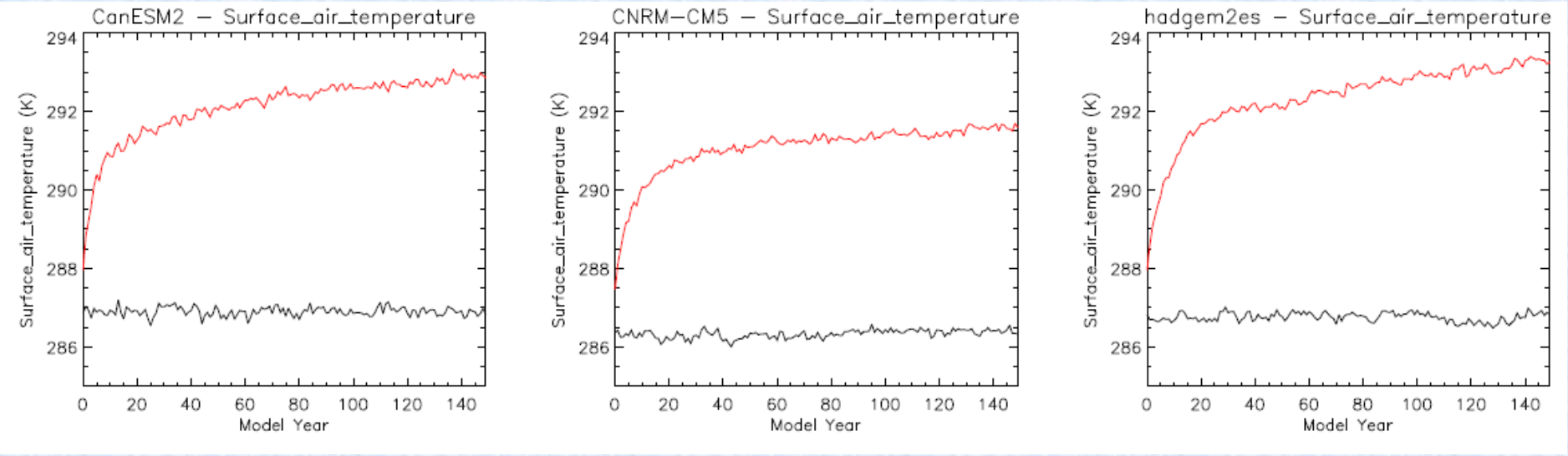
U.S. DEPARTMENT OF ENERGY | Office of Science

PCMDI
Program for Climate Model Diagnosis and Intercomparison

Example: What causes the spread in climate responses by models and is the uncertainty narrowing?

- One of the CMIP5 experiments was designed to answer this question
  - The CMIP5 equilibrium pre-industrial control is subjected to an abrupt quadrupling of CO_2.

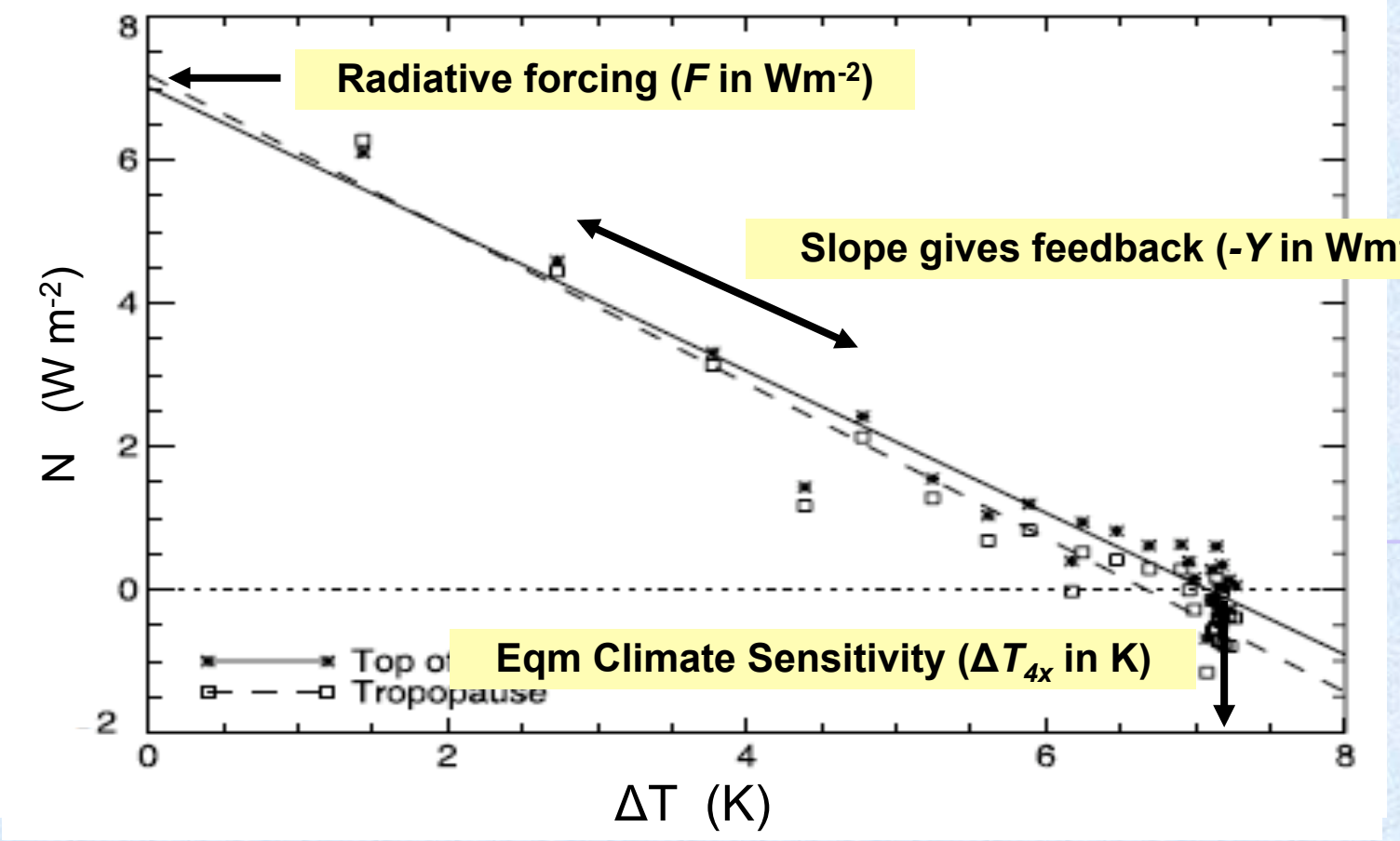
Temperature approaches a new equilibrium over many decades.



The net flux of global radiation is approximately proportional to surface temperature

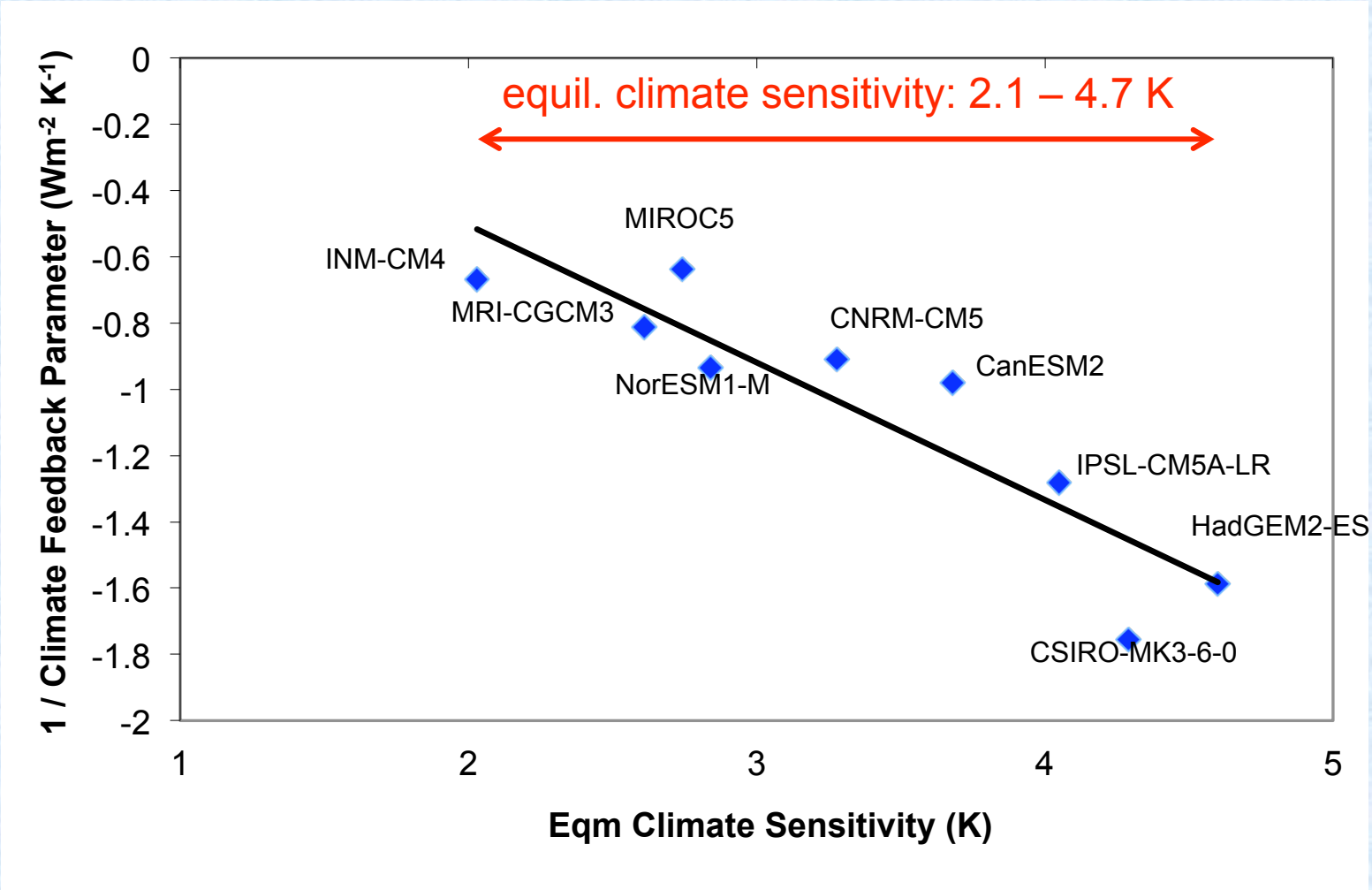
Following Gregory et al. (2004), express the energy balance of the climate system as:

$$N = F - Y\,\Delta T$$



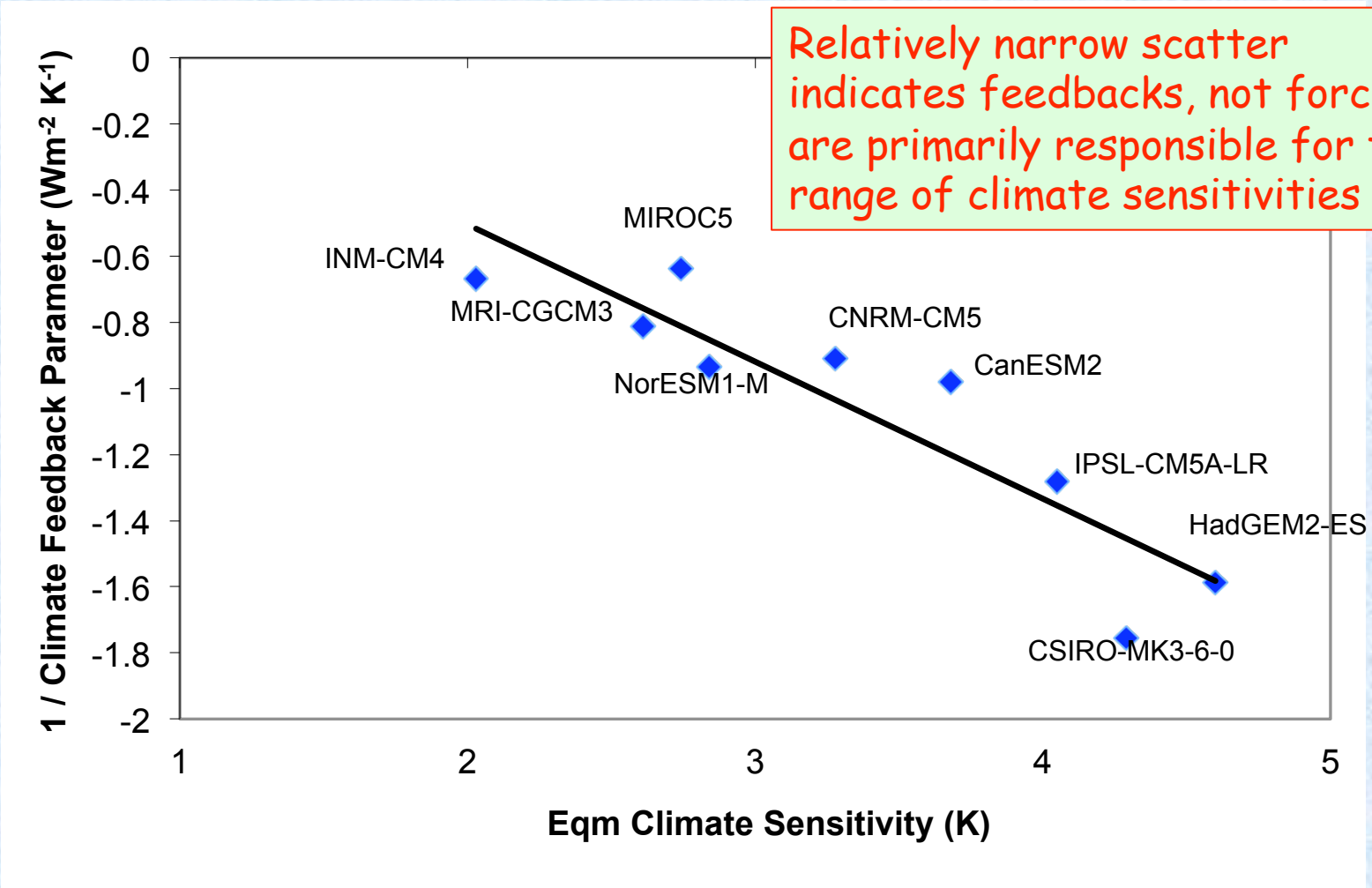
In CMIP5, we will only be part way along this curve…

We diagnosed climate sensitivity and feedback parameters for available CMIP5 models.



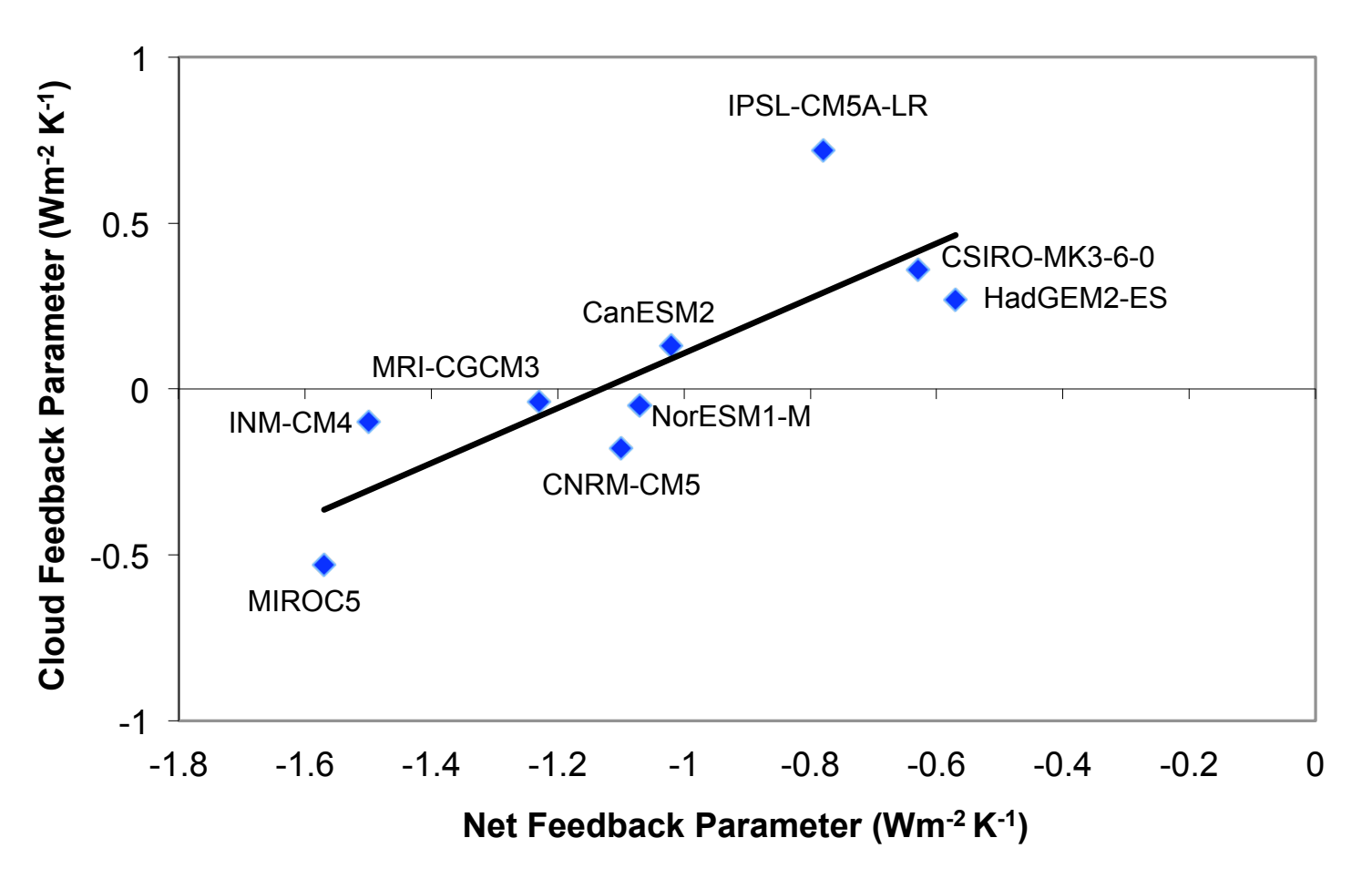
Andrews et al., *GRL*, 2012

We diagnosed climate sensitivity and feedback parameters for available CMIP5 models.



Andrews et al., *GRL*, 2012

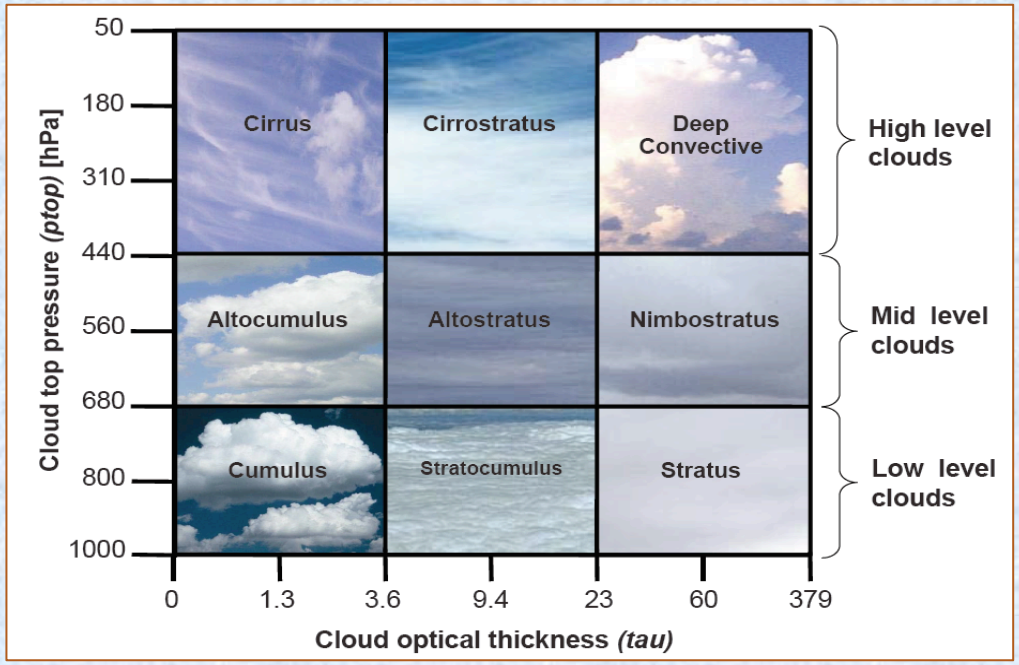
Differences in cloud feedback are responsible for a large fraction of the range of feedback strengths



Andrews et al., *GRL*, 2012

CMIP5 offers opportunities to evaluate and diagnose reasons for differences in cloud feedback among models

- "Satellite simulator" output collected for the first time.
- The "ISCCP simulator" code diagnoses from model cloud vertical distribution and optical properties the fraction of clouds occupying each of ISCCP's cloud "categories"



Courtesy of Swati Gehlot

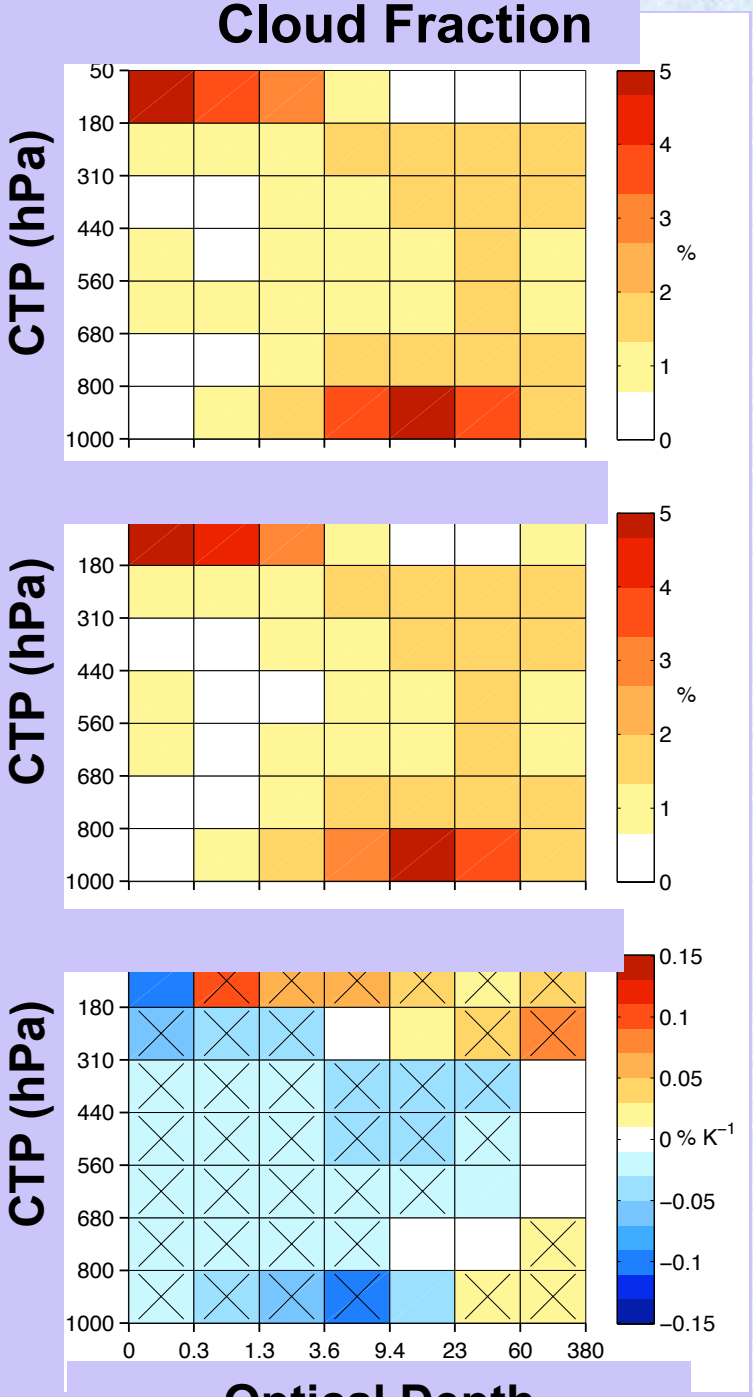
Cloud Fraction

[Multi-model mean of CFMIP1 results]

1xCO$_2$ 58.1 %

2xCO$_2$ 56.8 %

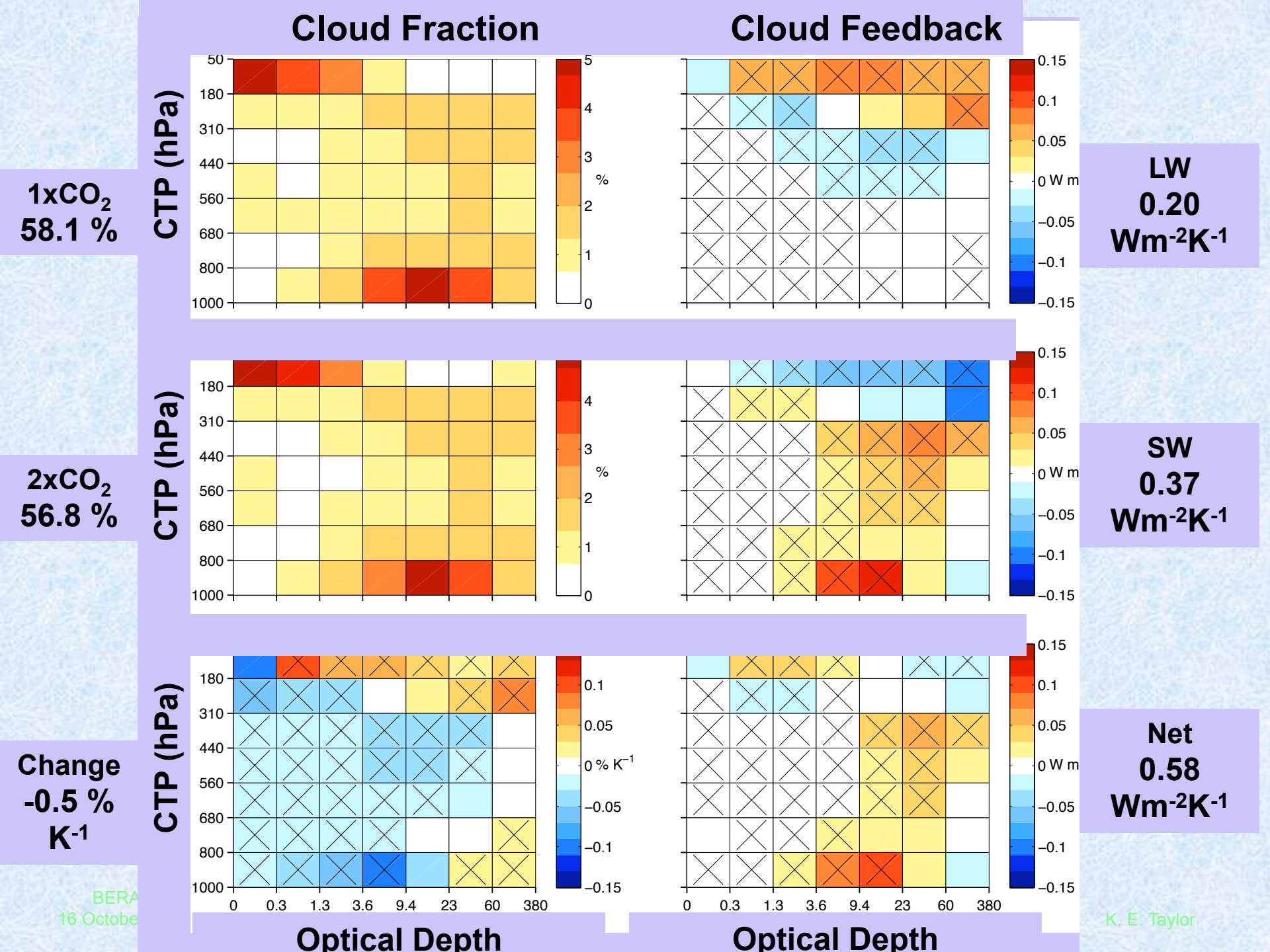
Change: -0.5 % K^{-1}



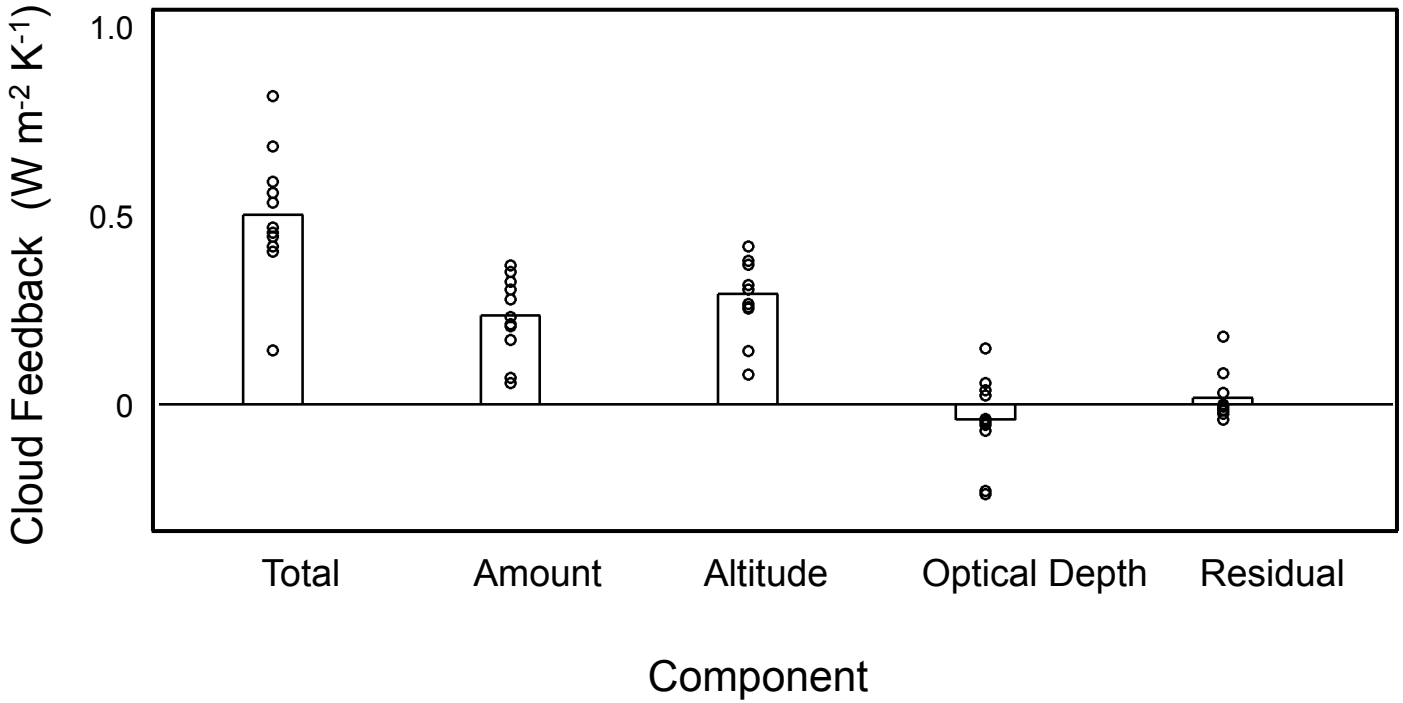
Each cloud fraction shown is "visible" from space (i.e., the non-overlapped cloud fraction)

Multiply by Cloud Radiative Kernels at each location and month, then averaged annually, globally, and across models…

Zelinka et al., *J. Climate*, 2012a

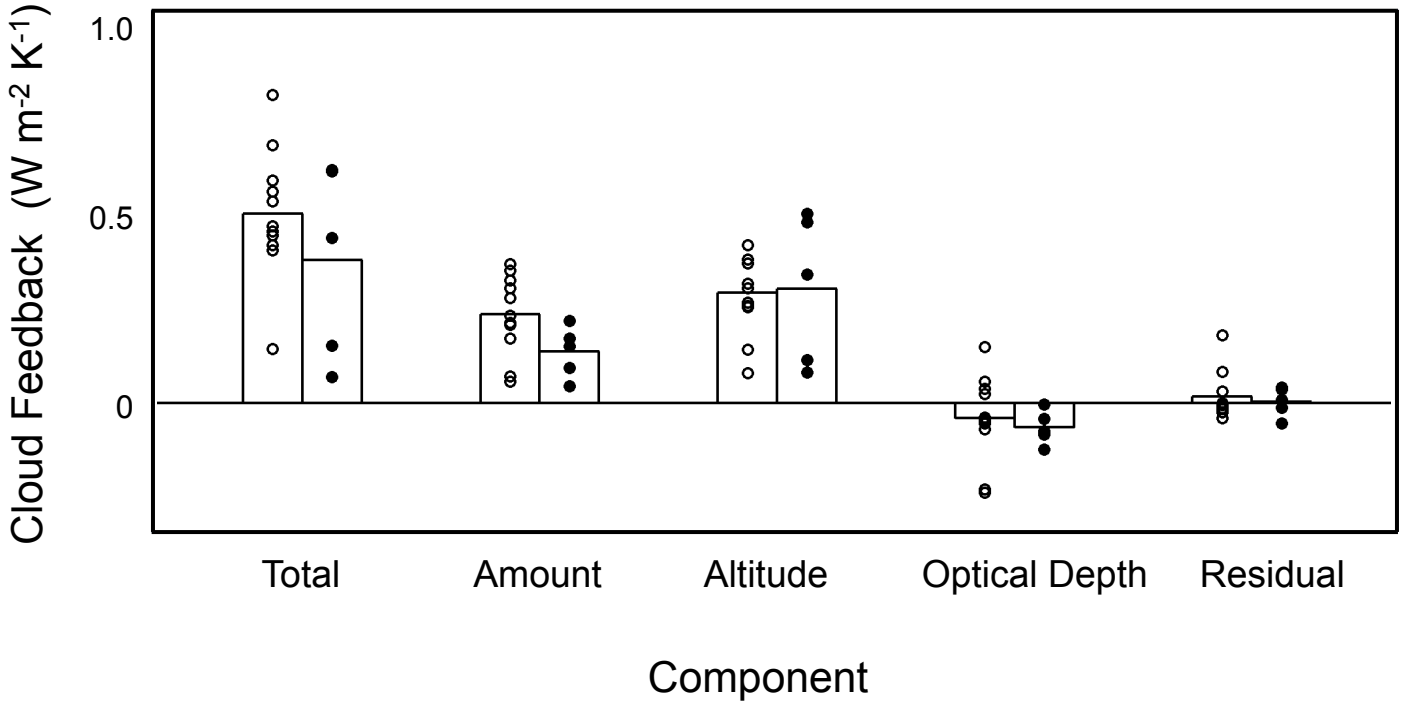

Cloud Fraction
Cloud Feedback
1xCO2
58.1 %
2xCO2
56.8 %
Change
-0.5 %
K-1
LW
0.20
Wm-2K-1
SW
0.37
Wm-2K-1
Net
0.58
Wm-2K-1
CTP (hPa)
50
180
310
440
560
680
800
1000
%
W m
% K−1
0
0.3
1.3
3.6
9.4
23
60
380
Optical Depth
Optical Depth
BERA
16 Octobe
K. E. Taylor

Using kernel method, CMIP cloud radiative effect can be resolved into components.



Zelinka et al., *J. Climate*, 2012a

Spread and mean of cloud components has not changed much between CMIP3 and CMIP5



Zelinka et al., *J. Climate*, submitted

Cloud-induced net radiation anomalies plotted for CMIP5 models

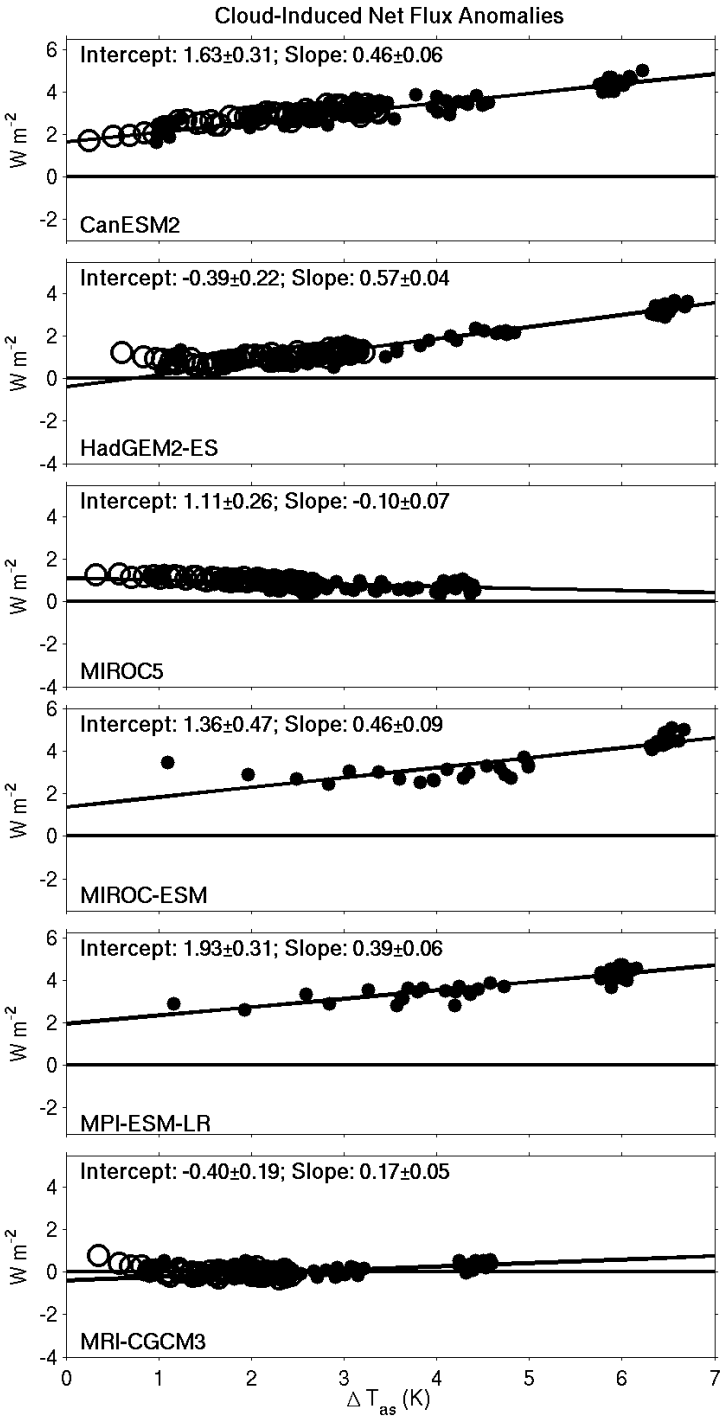
(Positive = heating)

$$\Delta R_C = F + \alpha_C \Delta T_S$$

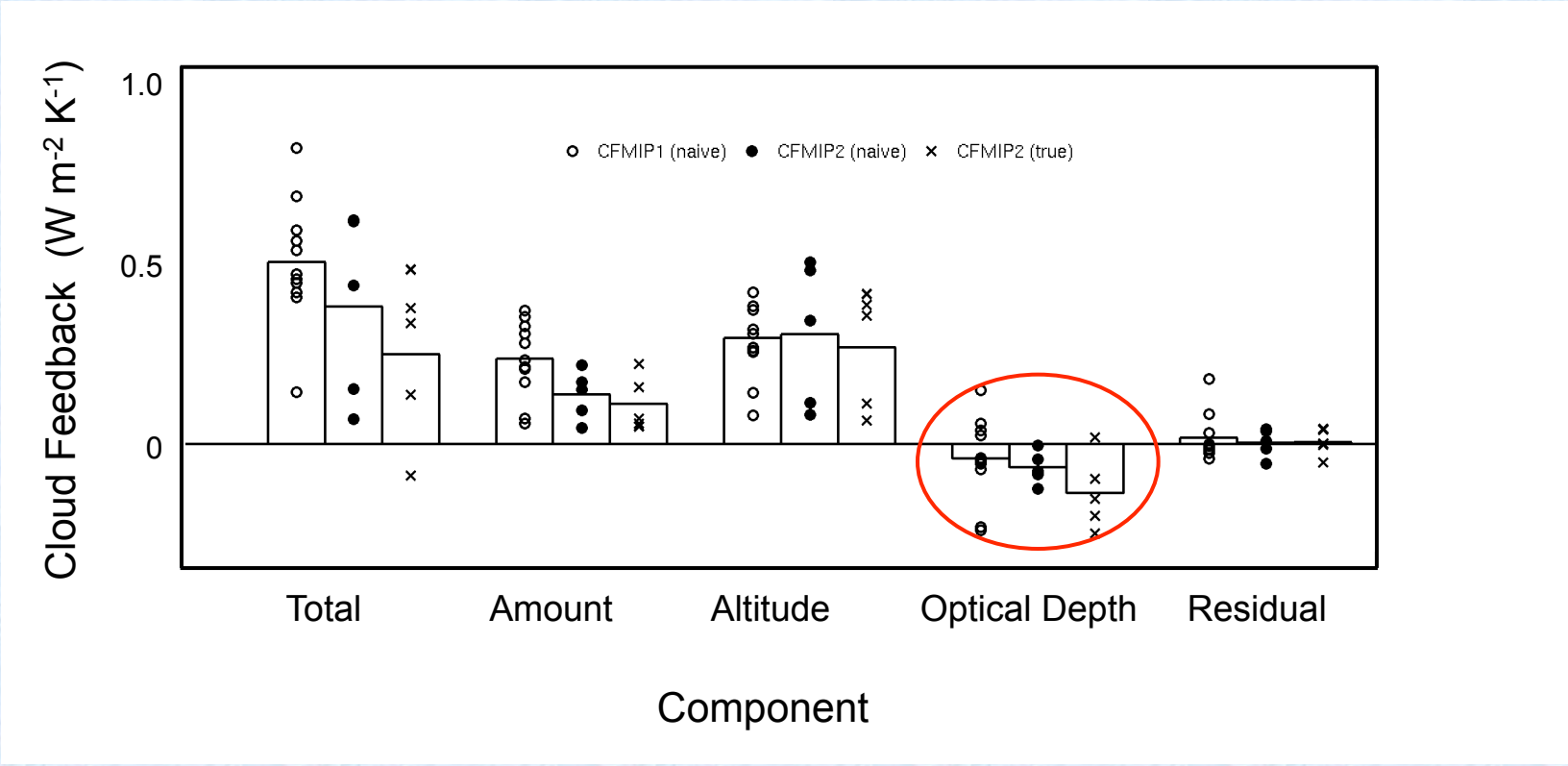
→ intercept (F_C) = "fast" adjustment
→ slope (α_C) = feedback

-Robust positive cloud "fast" adjustments
-Positive cloud feedbacks in 5 out of 6 models
-Some early departures from linearity

Zelinka et al., *J. Climate*, submitted



Accounting for the "fast adjustments" results in a stronger negative optical depth feedback (optical depth increases with warming): So total cloud feedback may be weaker than in earlier models.



Zelinka et al., *J. Climate*, submitted

If inter-model spread in cloud feedbacks remains large, does this imply a lack of improvement in the simulation of clouds?

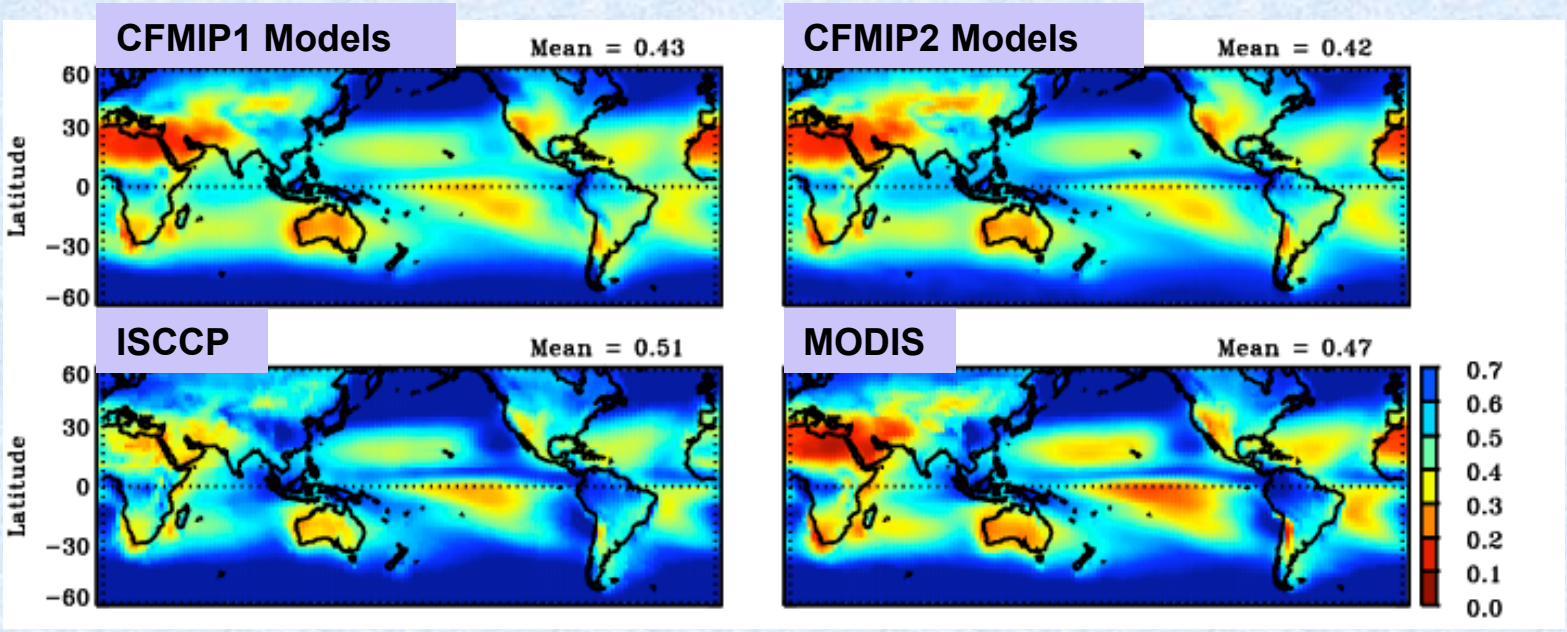
- We consider the simulation of the climatological distribution of clouds against satellite observations from two recent model ensembles
  - CFMIP1 (~CMIP3) – ca. 2000-2005
  - CFMIP2 (~CMIP5) – ca. 2012

How often does a cloud occur?

Climatological distribution of cloud amount ($\tau > 1.3$)

Multi-Model Mean

Satellite Observations



Klein et al., submitted

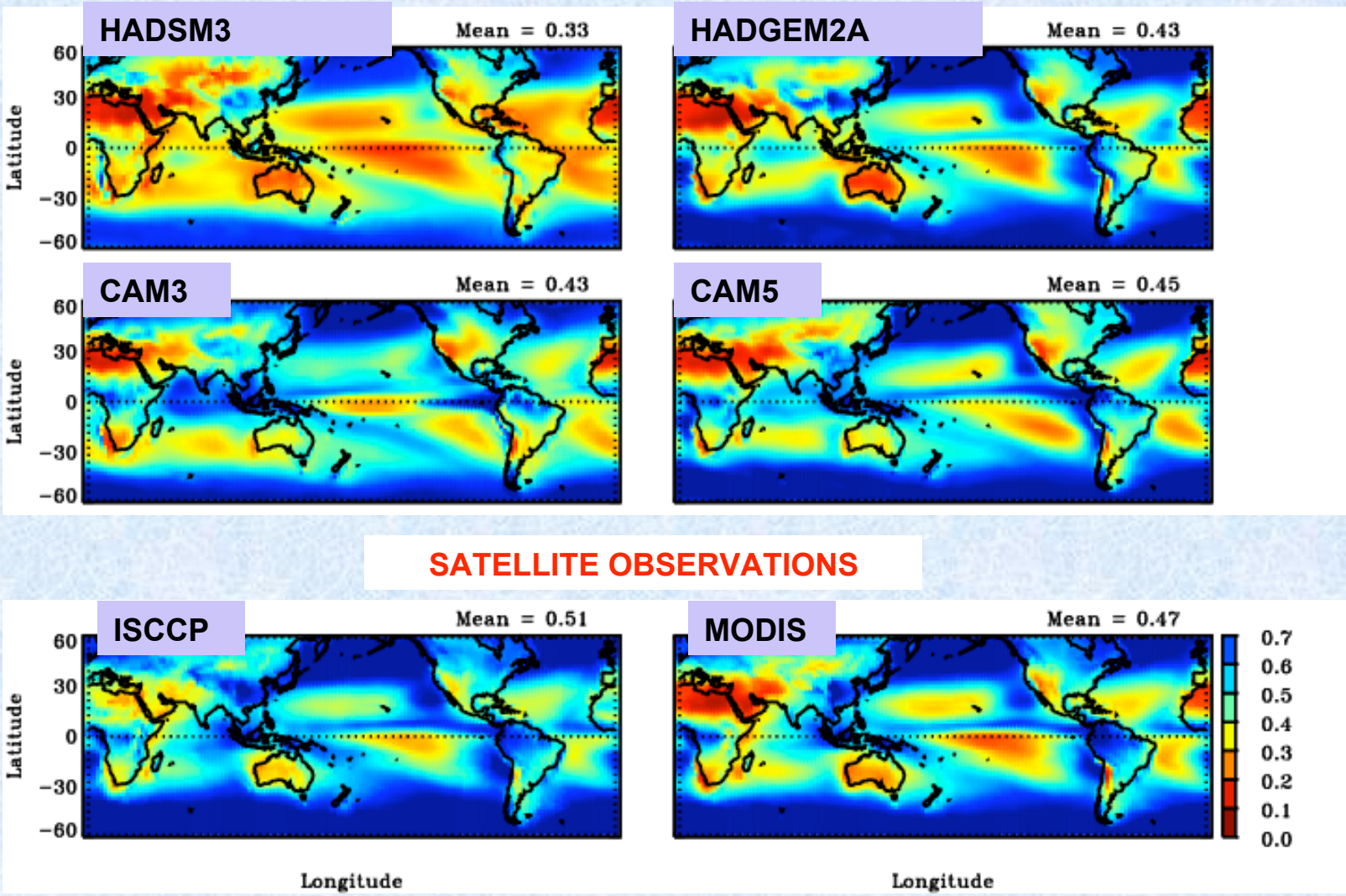
Despite multi-model mean, some individual models have improved.

model ca. 2004

model ca. 2011

MET OFFICE MODELS

COMMUNITY ATMOSPHERE MODELS

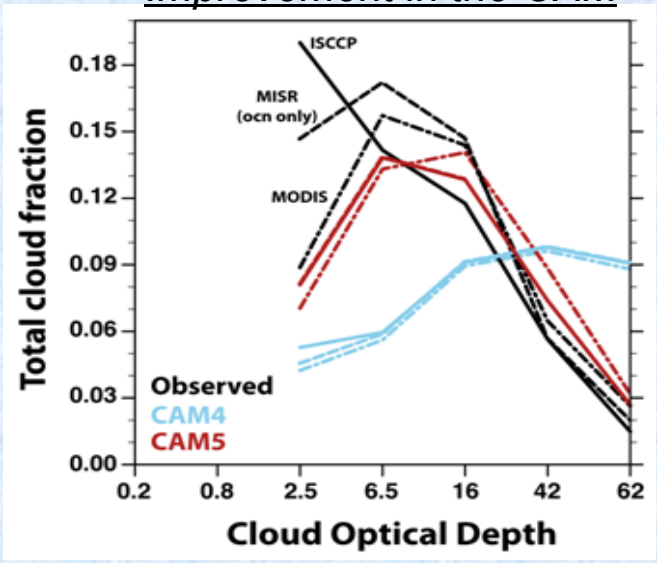


Klein et al., submitted

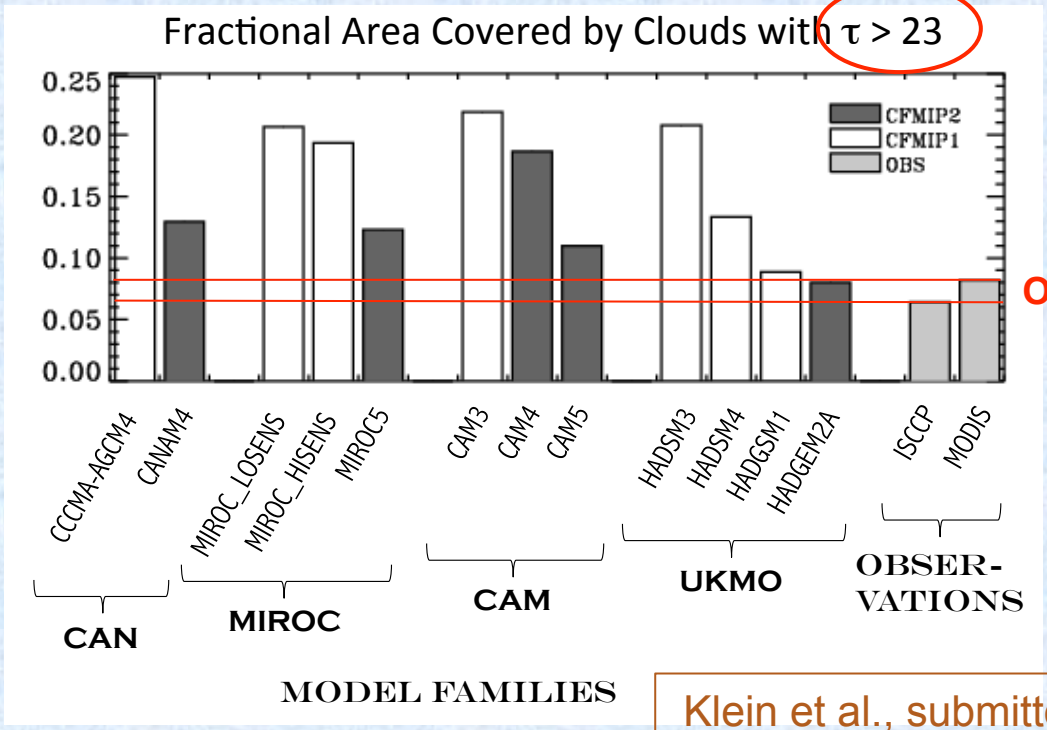
Models have improved simulation of optical depths

- Climate models often have a compensating error between cloud amount and cloud optical depth (Zhang et al. 2005)
  - Models are tuned to the time-mean radiation balance
  - They commonly achieve this by simulating too many optically thick clouds and too few optically thin ones to offset too little cloud cover

Improvement in the CAM



Kay et al., 2012

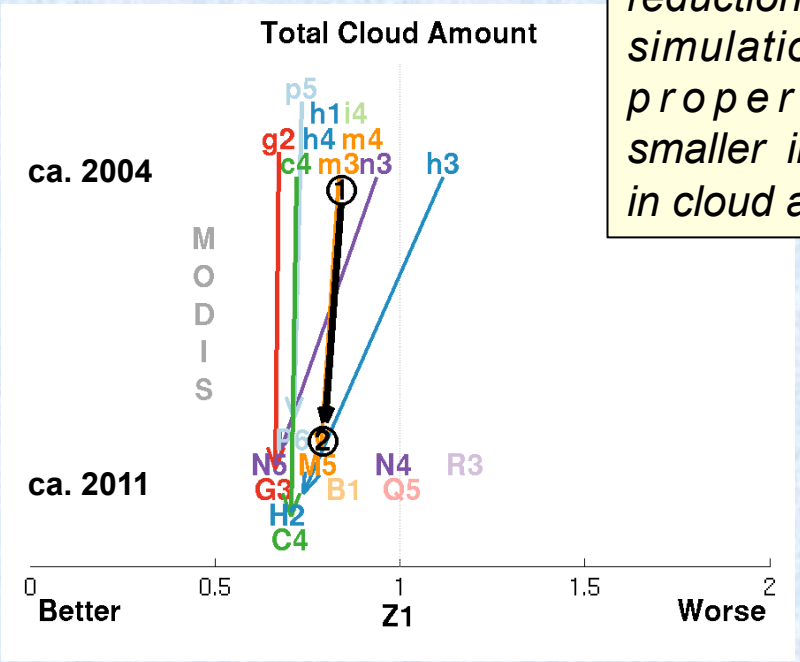


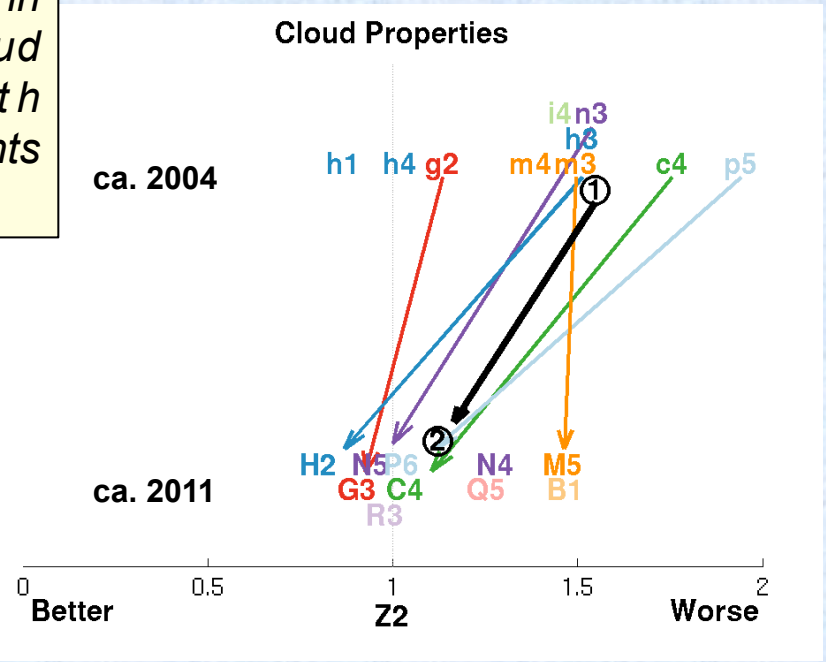
Klein et al., submitted

The good news is that models have quantitatively improved in the simulation of clouds!

- Consider the annual cycle of the global distributions of cloud amount and cloud properties (CTP and τ)
- For each model, compute the normalized root-mean square errors.

Widespread error reduction of 10-50% in simulation of cloud properties, with smaller improvements in cloud amount.





Klein et al., submitted

Where is CMIP headed?

U.S. DEPARTMENT OF ENERGY | Office of Science

PCMDI
Program for Climate Model Diagnosis and Intercomparison

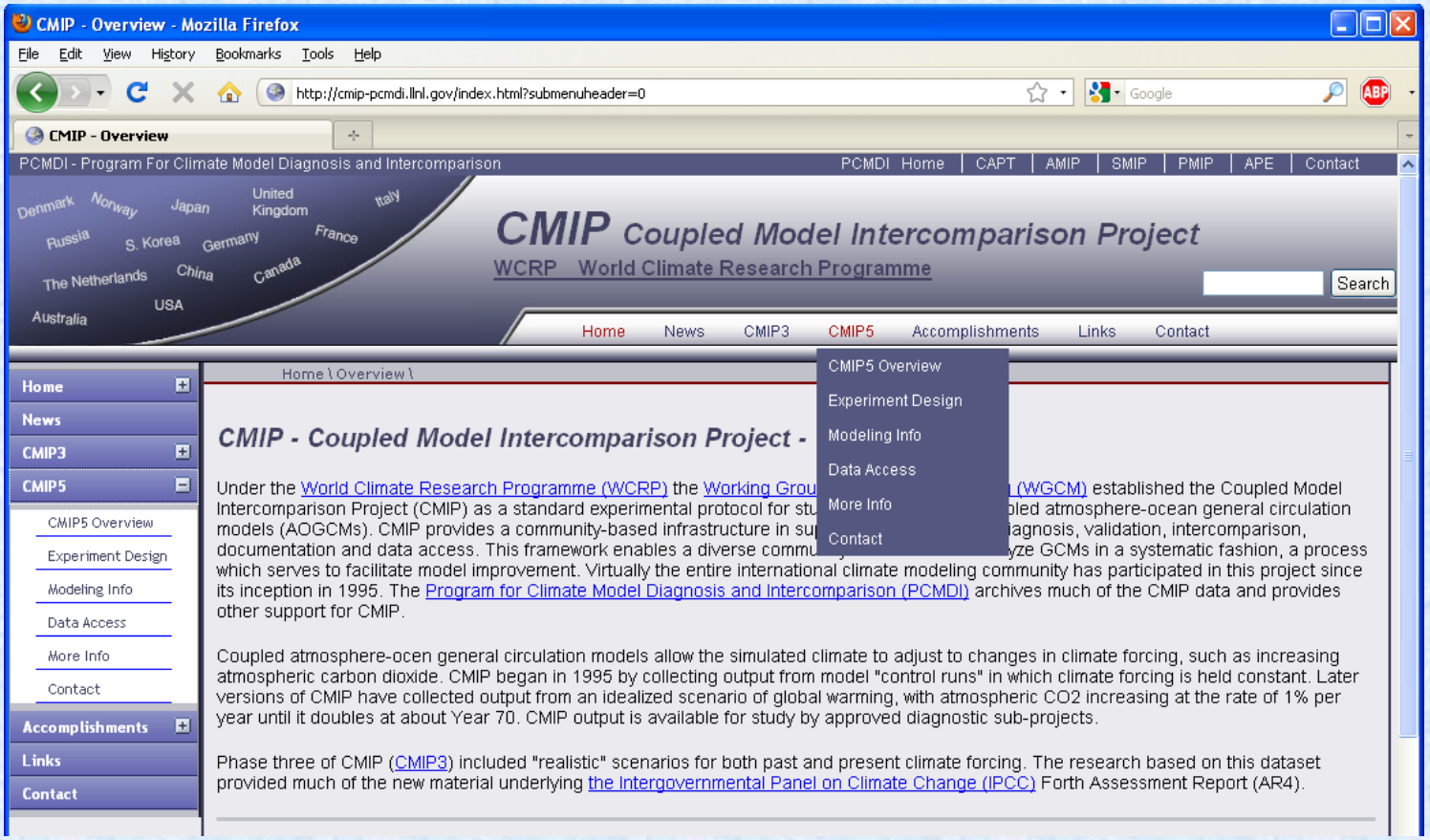
CMIP has become an integral part of climate modeling

- Modeling groups perform the core CMIP experiments as part of their model improvement efforts
- The IPCC continues to provide top-down incentives to provide projections based on common scenarios
- The scientific benefits of providing multi-model output for community analysis are now well established
- PCMDI, in cooperation with the WCRP, is working to establish climate model metrics that can be used to identify merits and shortcomings of models, relative to one another models.
- It can be anticipated that there will be a CMIP6, but that it will unlikely attempt to take on more than CMIP5.

Concluding remarks

- With BER's support, PCMDI has made essential contributions to the success of coordinated modeling activities.
  - Research contributions
  - Project "management" responsibilities
- CMIP has enabled a diverse community of researchers to evaluate models from a variety of perspectives and use model simulations in an enormous breadth of research.
- The ongoing uncertainty in projection accuracy stems from model treatment of clouds.
  - A target of BER's Atmospheric Radiation Measurement (ARM) program
- A distributed data archive infrastructure has ben developed that could serve other projects and scientific communities

CMIP website: http://cmip-pcmdi.llnl.gov



U.S. DEPARTMENT OF ENERGY | Office of Science

PCMDI
Program for Climate Model Diagnosis and Intercomparison