What can we learn from climate models?

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DOE Climate Change Research Program: Strategic Plan (2009)

- “Priorities for climate change research have moved beyond determining if Earth's climate is changing and if there is a human cause. The focus is now on understanding how quickly the climate is changing, where the key changes will occur, and what their impacts might be. Climate models are the best available tool for projecting likely climate changes, but they still contain some significant weaknesses.”
- “Projections of future climate change . . are the basis of national and international policies concerning greenhouse gas emission reductions.”

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CCSP SAP 3.1 Climate Models: An Assessment of Strengths & Weaknesses

- The science of climate modeling has matured through finer spatial resolution, the inclusion of a greater number of physical processes, and comparison to a rapidly expanding array of observations.

- With increasing computer power and observational understanding, future models will include both higher resolution and more processes.

[3]

Current path for climate modeling (GCMs/ESIMs)

- Increasing resolution and adding complexity
- Fully interactive earth system models (chemical, biogeochemical, land cryosphere); interface with human systems models
- Seamless prediction across timescales; data assimilation and initialization
- Downscaling for regional applications
- Infrastructure
- Communication of climate model results (including uncertainty, credibility); engagement with stakeholders: usefulness for decision making

NRC Project: A National Strategy for Advancing Climate Modeling

JC’s main points

I think there are some deep and important issues that aren’t receiving sufficient discussion and investigation

There is misguided confidence and “comfort” with the current GCMs and projected developments that are not consonant with understanding and best practices from other fields
(e.g. nonlinear dynamics, engineering, regulatory science, computer science).

GCMs may not be the most useful option to support many decision-making applications related to climate change

Is the power and authority that is accumulating around GCMs, and the expended resources, deserved? Is it possibly detrimental, both to scientific progress and policy applications?

Heymann (2010) Studies in History and Philosophy of Modern Physics, Special Issue Modeling and Simulation in the Atmospheric and Climate Sciences

The authority with which climate simulation and other fields of the atmospheric science towards the close of the twentieth century was furnished has raised new questions.

- *How did it come about that extensive disputes about uncertainties did not compromise the authority and cultural impact of climate simulation?*
- *How did scientists manage to reach conceptual consensus in spite of persisting scientific gaps, imminent uncertainties and limited means of model validation?*
- *Why, to put the question differently, did scientists develop trust in their delicate model constructions?*

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Belief/confidence in climate models

- Formal approach: verification & validation; explicit analysis of model errors, including a detailed analysis of model interactions
- Informal approach: GCM modelers personal judgment as to the complexity and adequacy of the models

For GCMs, the informal approach dominates:

- Model complexity limits the extent to which model processes, interactions and uncertainties can be understood and evaluated

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Confidence in climate models

- Confidence derives from the theoretical physical basis of the models, and the ability of the models to reproduce the observed mean state and some elements of variability. Climate models inherit some measure of confidence from successes of numerical weather prediction.

- ‘Comfort’ relates to the sense that the model developers themselves have about their model, which includes the history of model development and the individuals that contributed, the reputations of the various modeling groups, and consistency of the simulated responses among different model modeling groups and different model versions.

Knutti (2007) “So the best we can hope for is to demonstrate that the model does not violate our theoretical understanding of the system and that it is consistent with the available data within the observational uncertainty.”

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Rising discomfort

- Predictions can't be rigorously evaluated for order of a century
- Insufficient exploration of model & simulation uncertainty
- Impenetrability of the model and formulation process; extremely large number of modeler degrees of freedom
- Lack of formal model verification & validation, which is the norm for engineering and regulatory science
- Circularity in arguments validating climate models against observations, owing to tuning & prescribed boundary conditions
- Concerns about fundamental lack of predictability in a complex nonlinear system characterized by spatio-temporal chaos with changing boundary conditions
- Concerns about the epistemology of models of open, complex systems

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Verification and Validation

Verification and validation is the process of checking and documenting that a model is built correctly and meets specifications and is an accurate representation of the real world from the perspective of the intended uses of the model.

NRC (2007) *Models in Environmental Regulatory Decision Making*

Informal approaches are inadequate for models used in environmental regulation and policy making. Fully documented verification and validation (V&V) is needed.

Verification and Validation of GCMs

Arguments for:

- V&V promotes and documents model robustness, which is important for both scientific and political reasons.
- Lack of V&V is major source of discomfort for engineers

Arguments against:

- V&V is overkill for a research tool; inhibits agile software development
- A tension exists between spending time and resources on V&V, versus improving the model.

Verification and Validation of Scientific Models

Recommended approaches:

Roy and Oberkampf (2011) *A comprehensive framework for verification, validation, and uncertainty quantification in scientific computing*

"The framework is comprehensive in the sense that it treats both types of uncertainty (aleatory and epistemic), incorporates uncertainty due to the mathematical form of the model, and it provides a procedure for including estimates of numerical error in the predictive uncertainty."

Sargent (1998) *Verification and validation of simulation models*

"The different approaches to deciding model validity are presented; how model verification and validation relate to the model development process are discussed; various validation techniques are defined; conceptual model validity, model verification, operational validity, and data validity are described; ways to document results are given; and a recommended procedure is presented."

Validation of GCMs

Pope and Davies (2011) *Testing and Evaluating Climate Models*

Range of techniques for validating atmosphere models given that the atmosphere is chaotic and incompletely observed:

- *Simplified tests: against analytical or reference solutions*
- *Single column tests for physics components*
- *Dynamical core tests e.g. numerical convergence, aquaplanet sim*
- *Realistic climate regimes e.g. compare observations, multiple models*
- *Double call tests to assess the impact of model changes*
- *Spin up tendencies to evaluate model biases*
- *NWP tests*

WGNE Climate Model Metrics Panel Gleckler et al. (2008)

Identify a limited set of basic climate model performance metrics based on observations

Climate models: applications

- Numerical experiments to understand how the climate system works; sensitivity studies
- Simulation of present and past states to understand planetary energetics and other complex interactions
- Attribution of past climate variability and change
- Simulation of future states, from decades to centuries
- Prediction and attribution of extreme weather events
- Projections of future regional climate variation for use in model-based decision support systems
- Guidance for emissions reduction policies

science

IPCC

policy

- Projections of future risks of black swans & dragon kings

GCMs: Fit for (what?) purpose

Fit? YES

- Explore scientific understanding of the climate system

Fit? COULD BE

- Attribution of past climate variability and change
- Simulation of plausible future states
- Support for emissions reduction policies

Fit? NO

- Predication and ttribution of extreme weather events
- Projections of future regional climate variation for use in model-based decision support systems
- Projections of future risks of black swans & dragon kings

- **Explore scientific understanding of the climate system**

GCM challenges:

- Resources ($$ and personnel) are being spent primarily on IPCC production runs
- Little time and $$ left over for innovations and scientific studies
- Main scientific beneficiaries are in the impacts area and surrounding sciences

Other approaches:

- The need for plurality in climate model structural form (which is difficult if $$ are focused on GCMs and IPCC production runs)

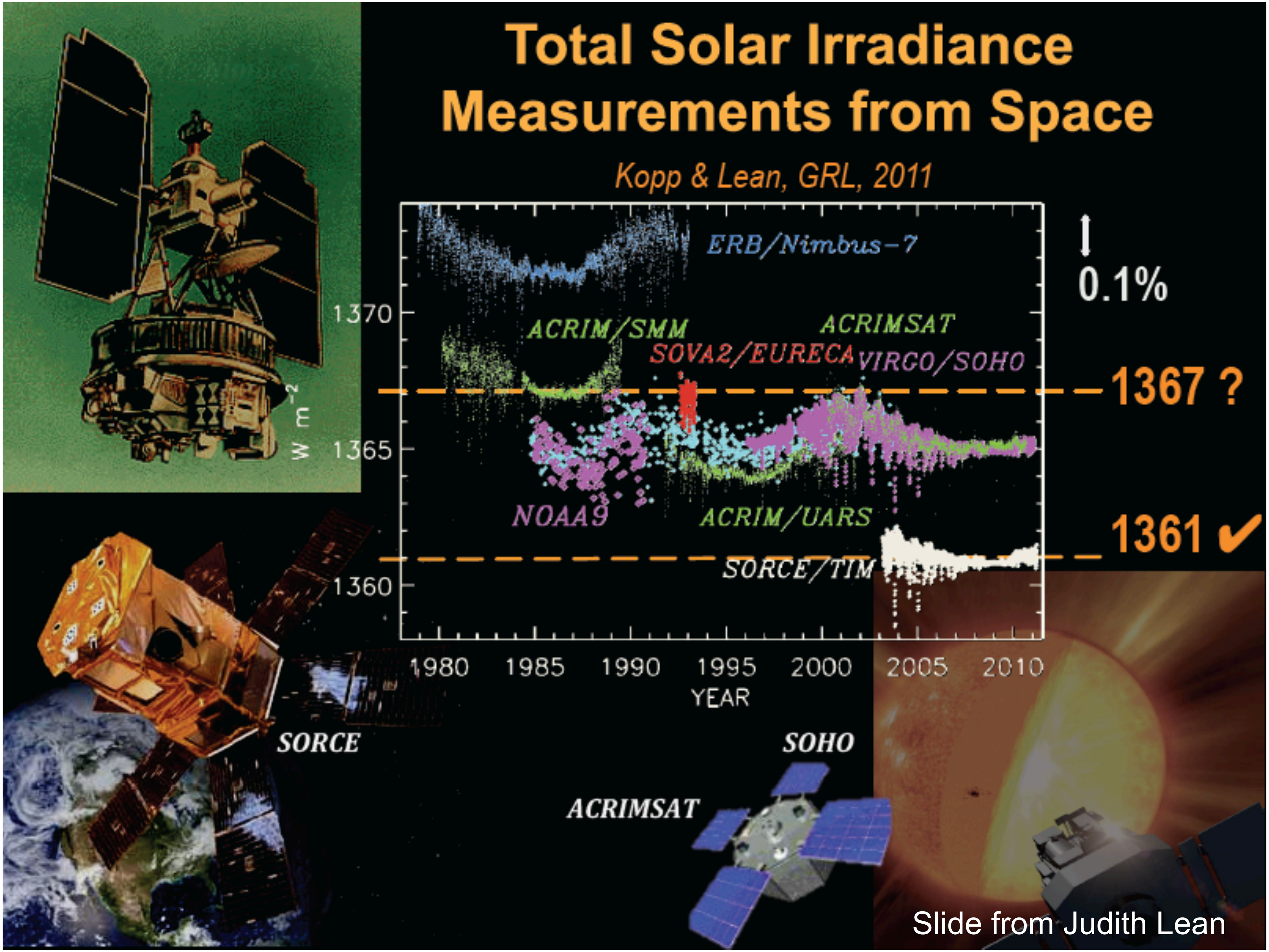
- **Attribution of past climate variability and change**
- **Simulation of plausible future states**
- **Support for emissions reduction policies**

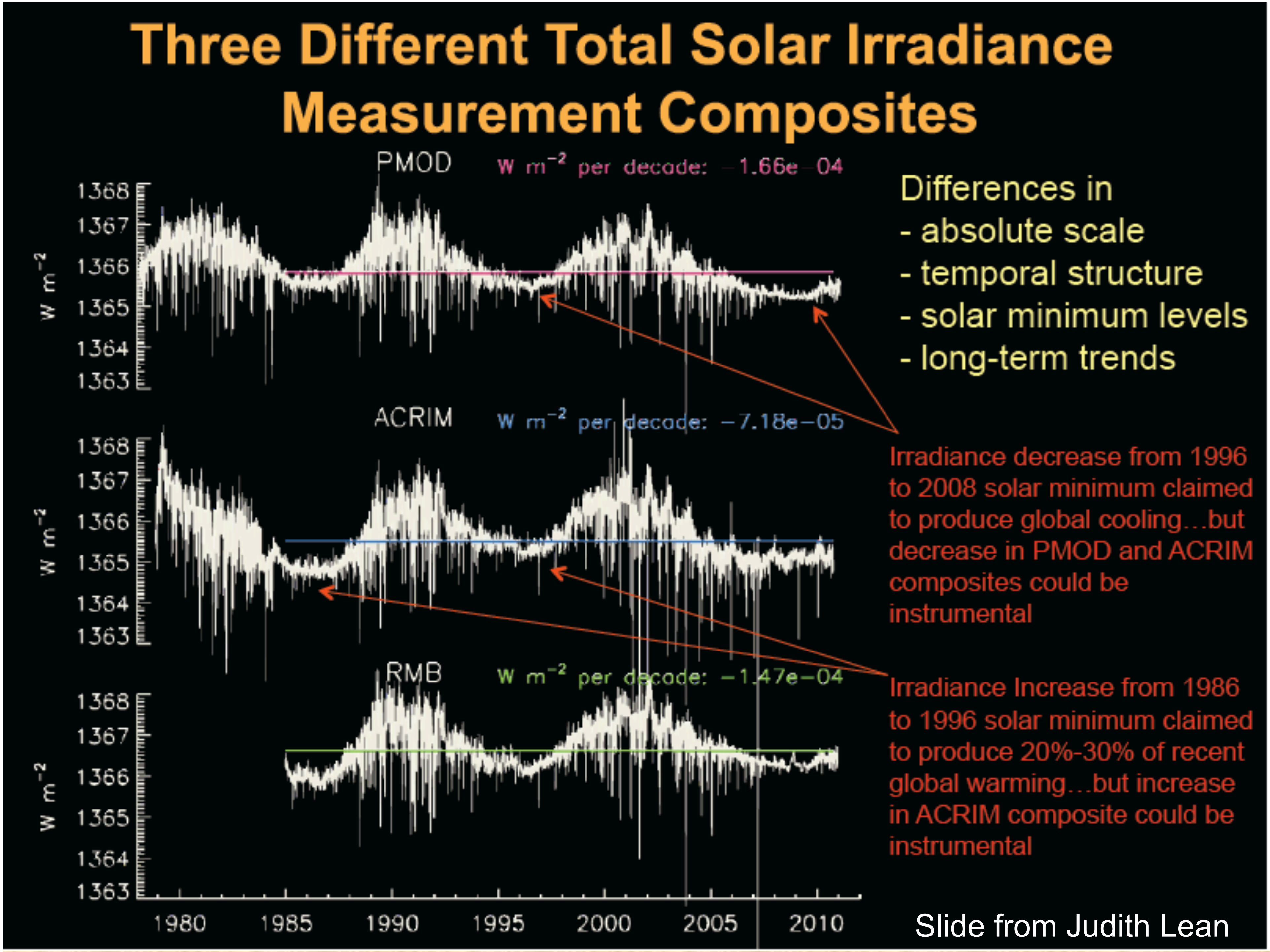
Challenges:

- require adequate simulation of natural internal variability on multi-decadal to century time scales
- solar forcing: better understanding of historical 20^{th} century forcing; solar sensitivity studies conducted as part of attribution assessments; investigation of solar indirect effects; development of scenarios of 21^{st} century solar forcing

Other approaches:

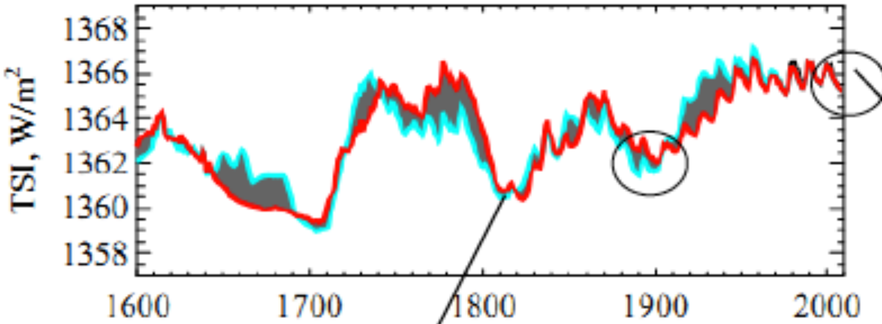
- GCMs may be less effective than intermediate models (with a much greater ensemble size) in developing an understanding of climate sensitivity and attribution

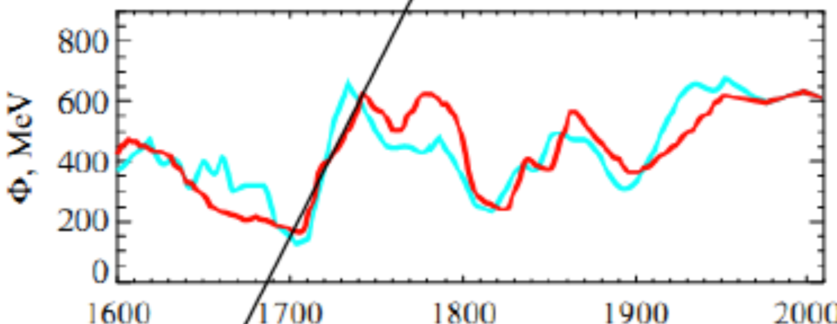

Total Solar Irradiance
Measurements from Space
Kopp & Lean, GRL, 2011
ERB/Nimbus-7
0.1%
1370
ACRIM/SMM
SOVA2/EURECA
ACRIMSAT
VIRGO/SOHO
1367 ?
W m-2
1365
NOAA9
ACRIM/UARS
1361 ✔
SORCE/TIM
1360
1980
1985
1990
1995
2000
2005
2010
YEAR
SORCE
SOHO
ACRIMSAT
Slide from Judith Lean

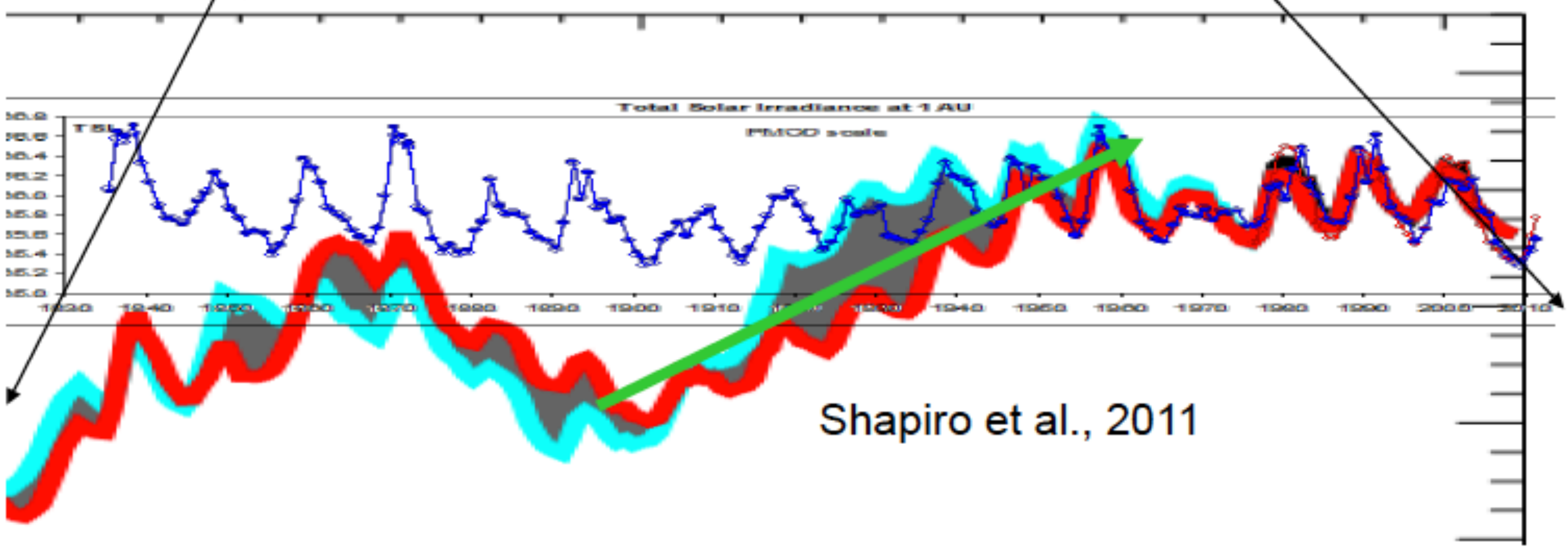

Three Different Total Solar Irradiance Measurement Composites
PMOD
W m^-2 per decade: -1.66e-04
ACRIM
W m^-2 per decade: -7.18e-05
RMB
W m^-2 per decade: -1.47e-04
W m^-2
1368
1367
1366
1365
1364
1363
1980
1985
1990
1995
2000
2005
2010
Differences in
- absolute scale
- temporal structure
- solar minimum levels
- long-term trends
Irradiance decrease from 1996 to 2008 solar minimum claimed to produce global cooling…but decrease in PMOD and ACRIM composites could be instrumental
Irradiance Increase from 1986 to 1996 solar minimum claimed to produce 20%-30% of recent global warming…but increase in ACRIM composite could be instrumental
Slide from Judith Lean

Slide from Leif Svalgaard

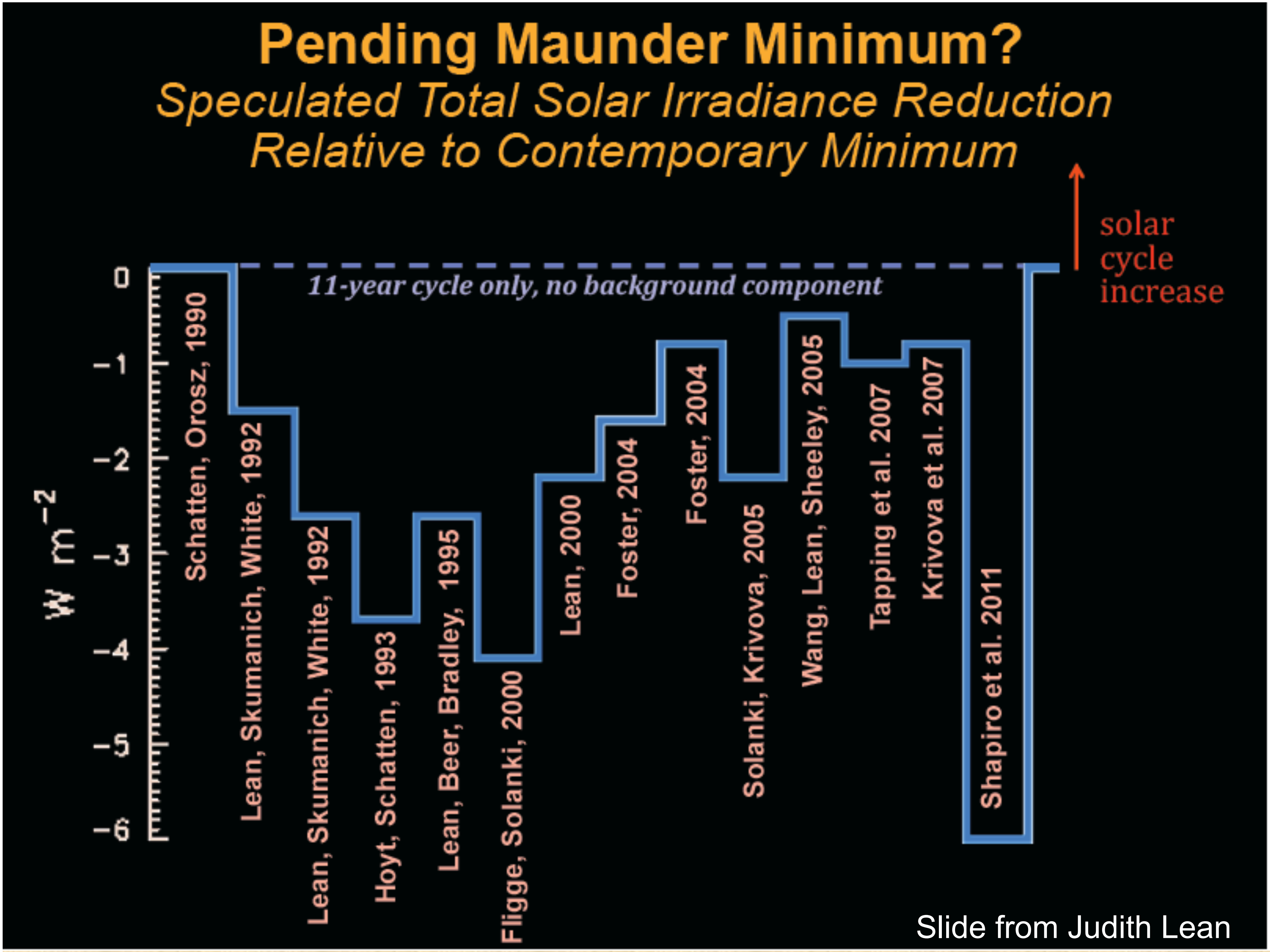
The Discrepancy between Now and 100 years ago, *if real*, is severe







- Experts cannot agree on the long-term variation of solar activity
- Solar influence on climate on shaky ground if we don't even know solar input



Pending Maunder Minimum?
Speculated Total Solar Irradiance Reduction
Relative to Contemporary Minimum
solar
cycle
increase
11-year cycle only, no background component
W m^-2
0
−1
−2
−3
−4
−5
−6
Schatten, Orosz, 1990
Lean, Skumanich, White, 1992
Lean, Skumanich, White, 1992
Hoyt, Schatten, 1993
Lean, Beer, Bradley, 1995
Fligge, Solanki, 2000
Lean, 2000
Foster, 2004
Foster, 2004
Solanki, Krivova, 2005
Wang, Lean, Sheeley, 2005
Tapping et al. 2007
Krivova et al. 2007
Shapiro et al. 2011
Slide from Judith Lean

- **Projections of future regional climate variation for use in model-based decision support systems**

GCM challenges:

- GCMs currently have little skill in simulating regional climate variations; unclear how much increased resolution will help
- Dynamical & statistical downscaling adds little value, beyond MOS to account for local effects on surface variables

Other approaches:

- Improve understanding of historical/paleo regional climate dynamics and black swan events
- Broader range of future scenarios of natural forcing changes (e.g. solar, volcanoes) and natural internal variability
- Creative, regional approach to scenario development, including population and land use changes and alternative policy scenarios

- **Prediction and attribution of extreme weather events**

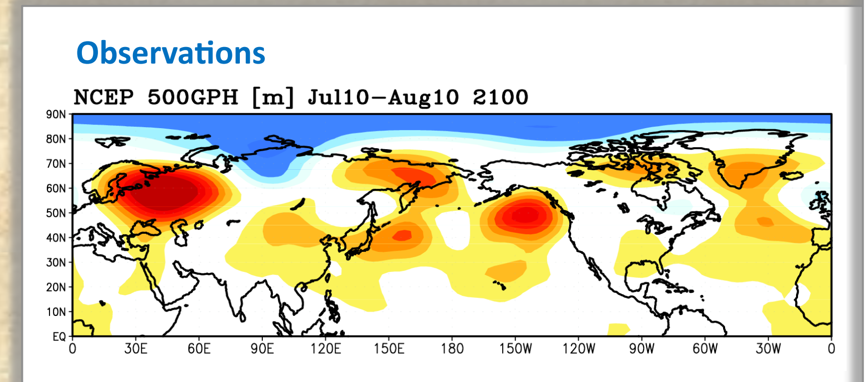
Challenges:

- Climate models do not currently predict explicitly many types of extreme weather events (e.g. hurricanes, flash floods, tornadoes)
- Much higher resolution climate models with much larger ensemble sizes are necessary (but probably not sufficient)

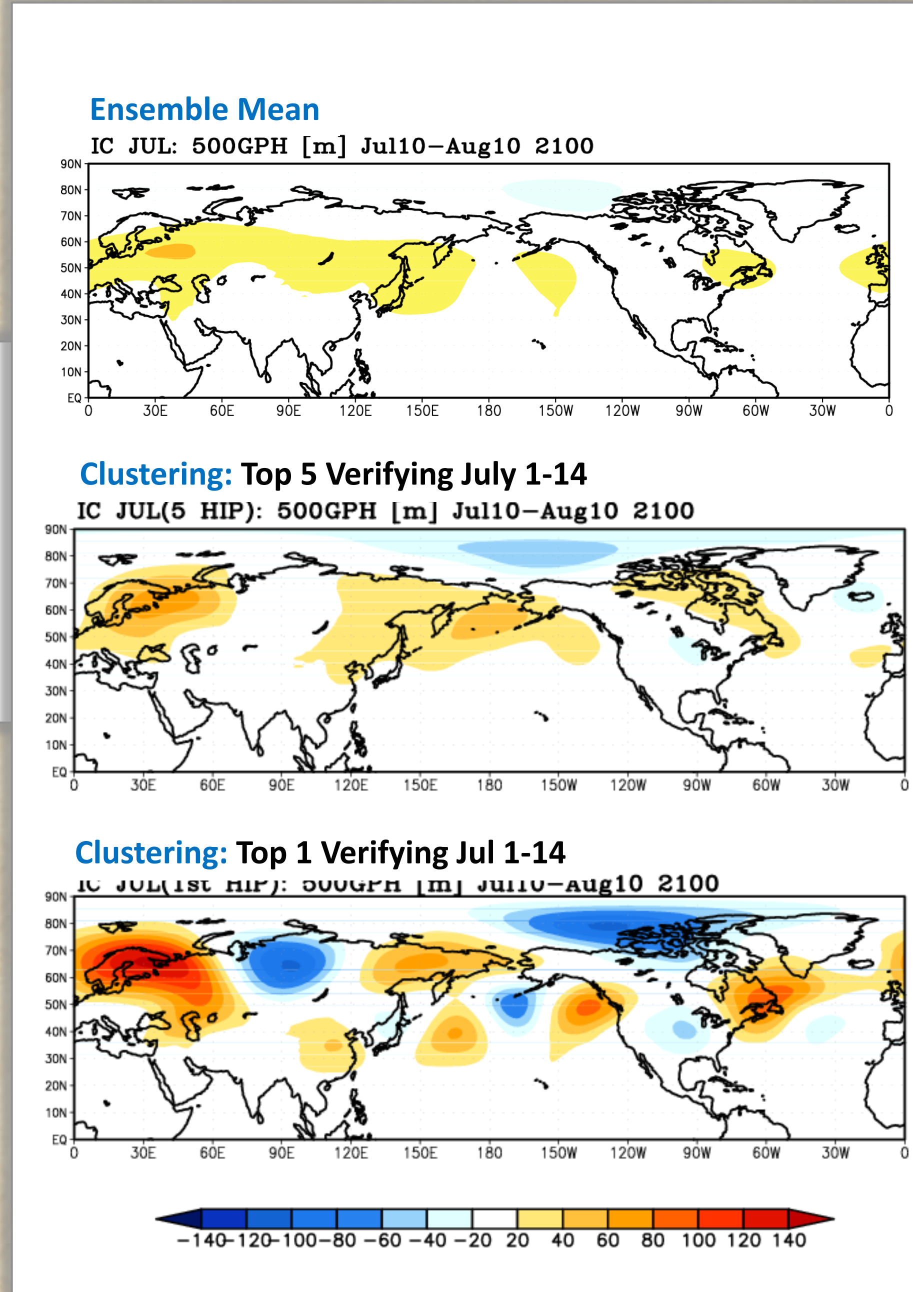
Other approaches:

- Greatest short term contribution would come from regional historical and paleo analyses of extreme events
- Climate dynamics approach, interpreting past extreme events in context of teleconnection and climate regimes, blocking patterns

Outlook for the Russian Heat Wave



- **Sub-Seasonal** Time Scale (Days 10-40):
  - ✓ CFAN's clustering of ensembles based on the best match to hemispheric 500 hPa pattern for first two weeks of the forecast captures well the geopotential anomalies pattern up to 40 days in advance.
  - ✓ The 500 hPa geopotential height represents the signature of the blocking pattern associated with the Russian heat wave.



- **Projections of future risks of black swans & dragon kings**

GCM challenges:

- GCMs are currently incapable of predicting emergent phenomena, e.g. abrupt climate change
- Will more complex or higher resolution GCMs be able to generate counterintuitive, unexpected surprises?

Other approaches:

- Synchronization in spatio-temporal chaos
- Other theoretical developments from nonlinear dynamics, network theory

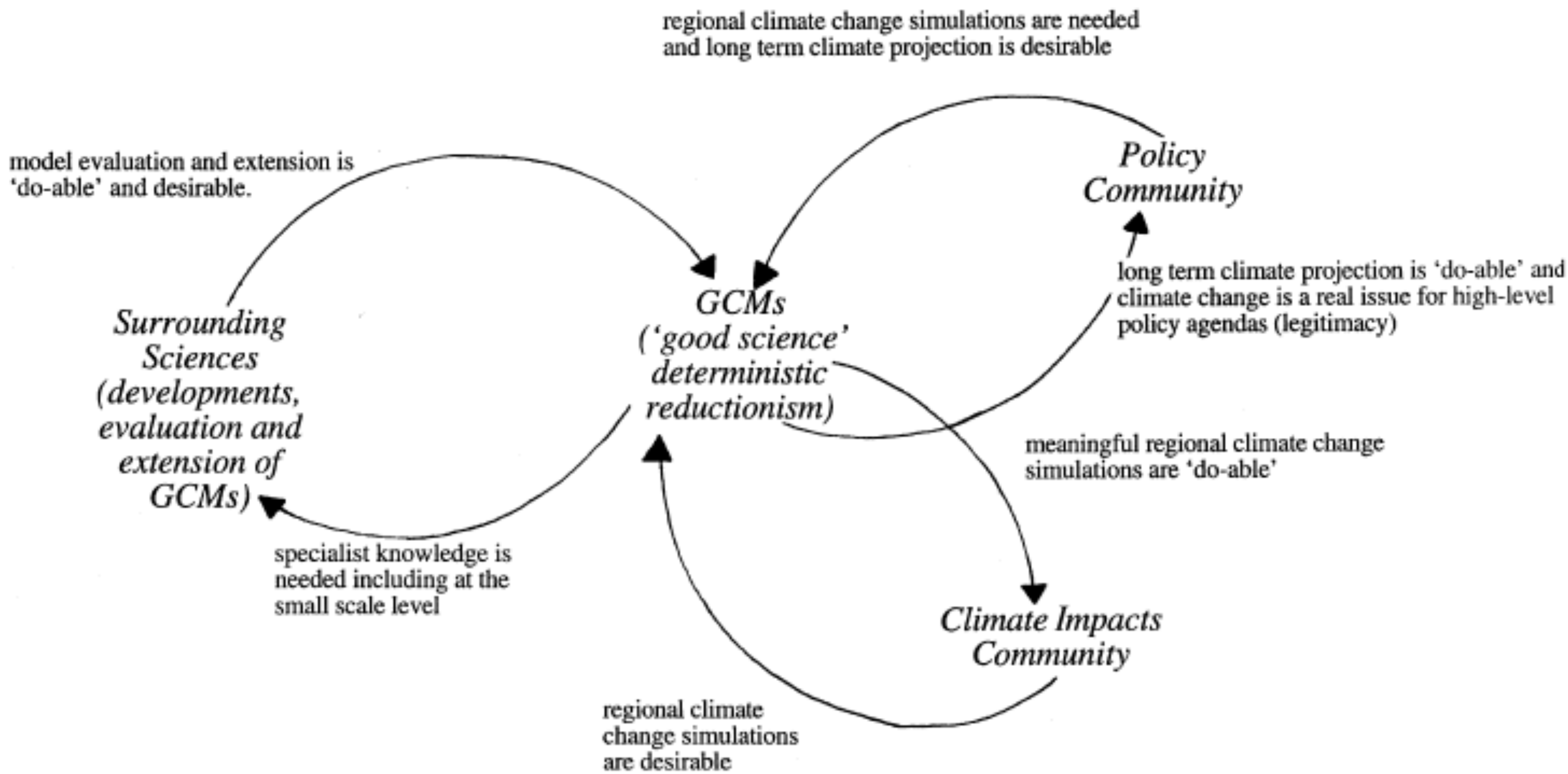
Climate models: fit for purpose?

A completely general, all encompassing climate model that is accepted by all scientists and is fit for all purposes seems to be an idealistic fantasy

We need a plurality of climate models that are developed and utilized in different ways for different purposes.

For decision support, the GCM centric approach may not be the best approach

Given the compromises made for multiple purposes, GCMs may not be the optimal solution for any of these purposes



Shackley et al. 1998

Are GCMs especially policy useful?

Main advantage:

- *potential* for providing regional climate change scenarios (this potential is currently unrealized)
- perception that complexity = scientific credibility; sheer complexity and impenetrability, so not easily challenged by critics

Disadvantages:

- demands massive computing and personnel resources; creates dependency on a few centers and their experts
- slow to incorporate new scientific insights or understanding
- precludes conducting extensive sensitivity and uncertainty analyses
- precludes rapid exploration of different model assumptions and policy scenarios
- not user friendly for advisory scientists or policy makers

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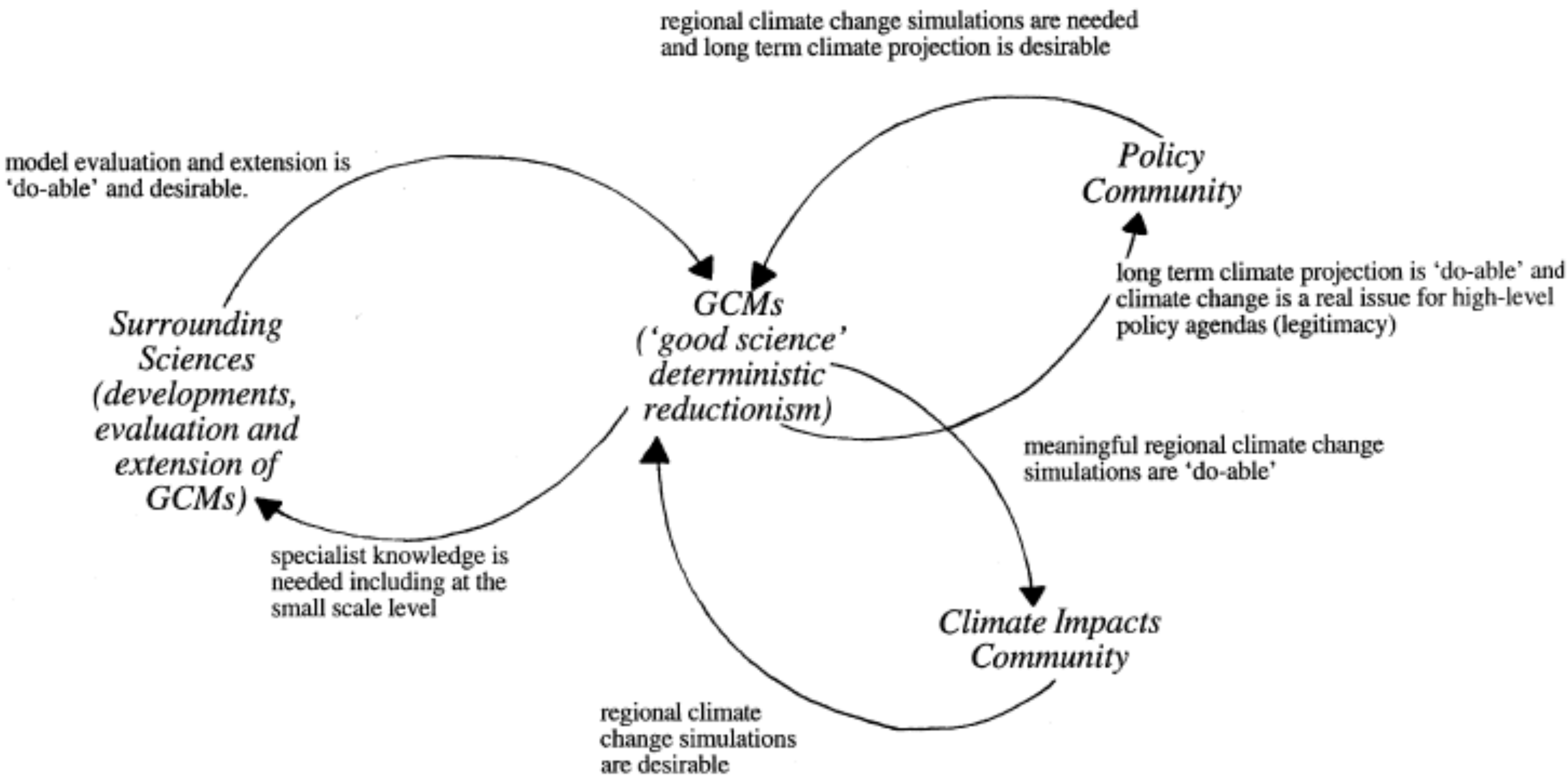
Key policy needs:

CO2 mitigation policies:

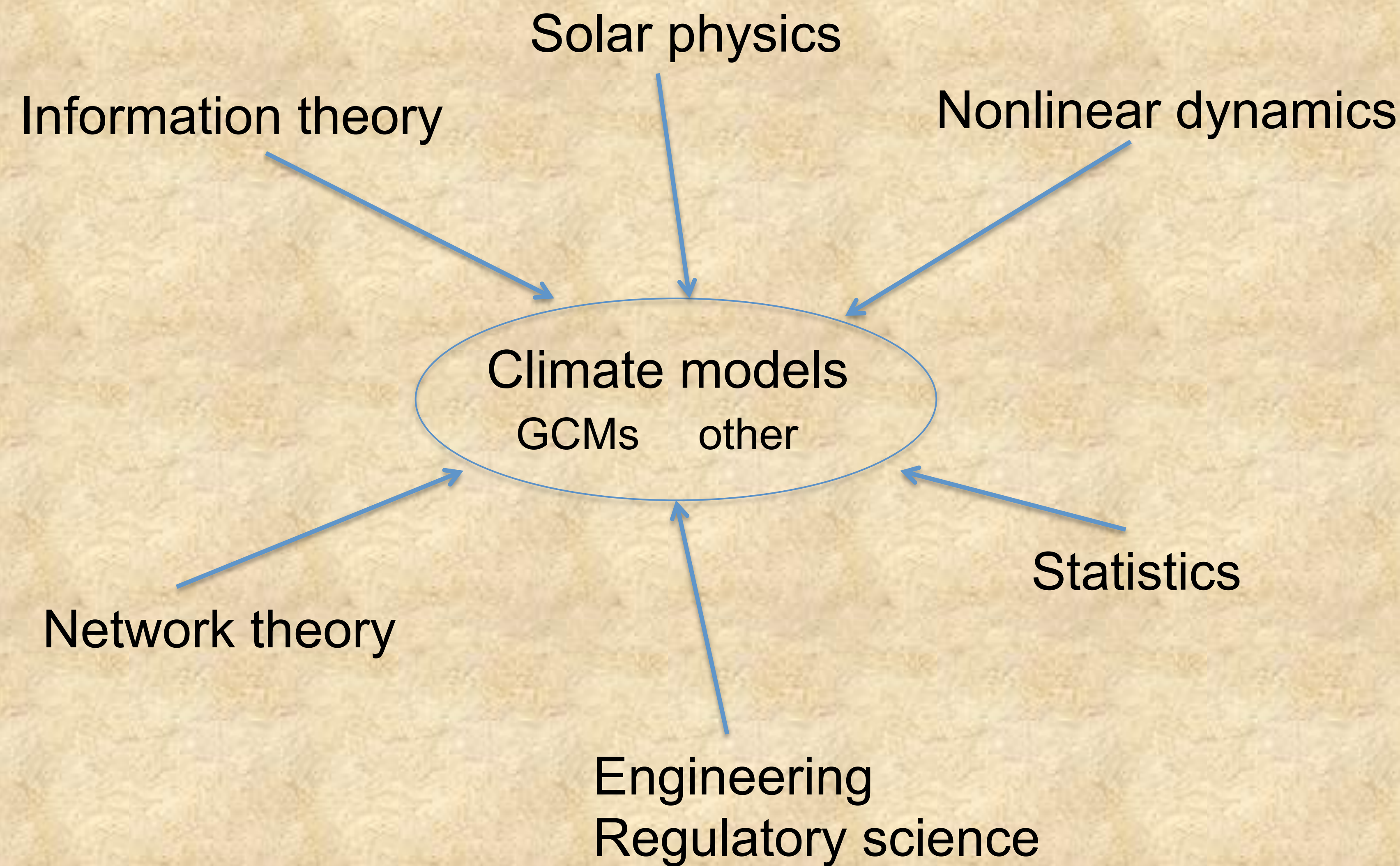
- GCMs have a role to play, but large ensembles from lower order models with interactive carbon cycle may be the best solution for determining sensitivity

Regional climate change and extreme events:

- natural climate variability is at least as important as AGW, particularly on decadal time scales
- much to be learned from the climate dynamics of past and paleo regional climates and extreme events
- regional impact models can be forced by wide range of creatively produced scenarios



Shackley et al. 1998


Solar physics
Information theory
Nonlinear dynamics
Climate models
GCMs
other
Network theory
Statistics
Engineering
Regulatory science

[27]

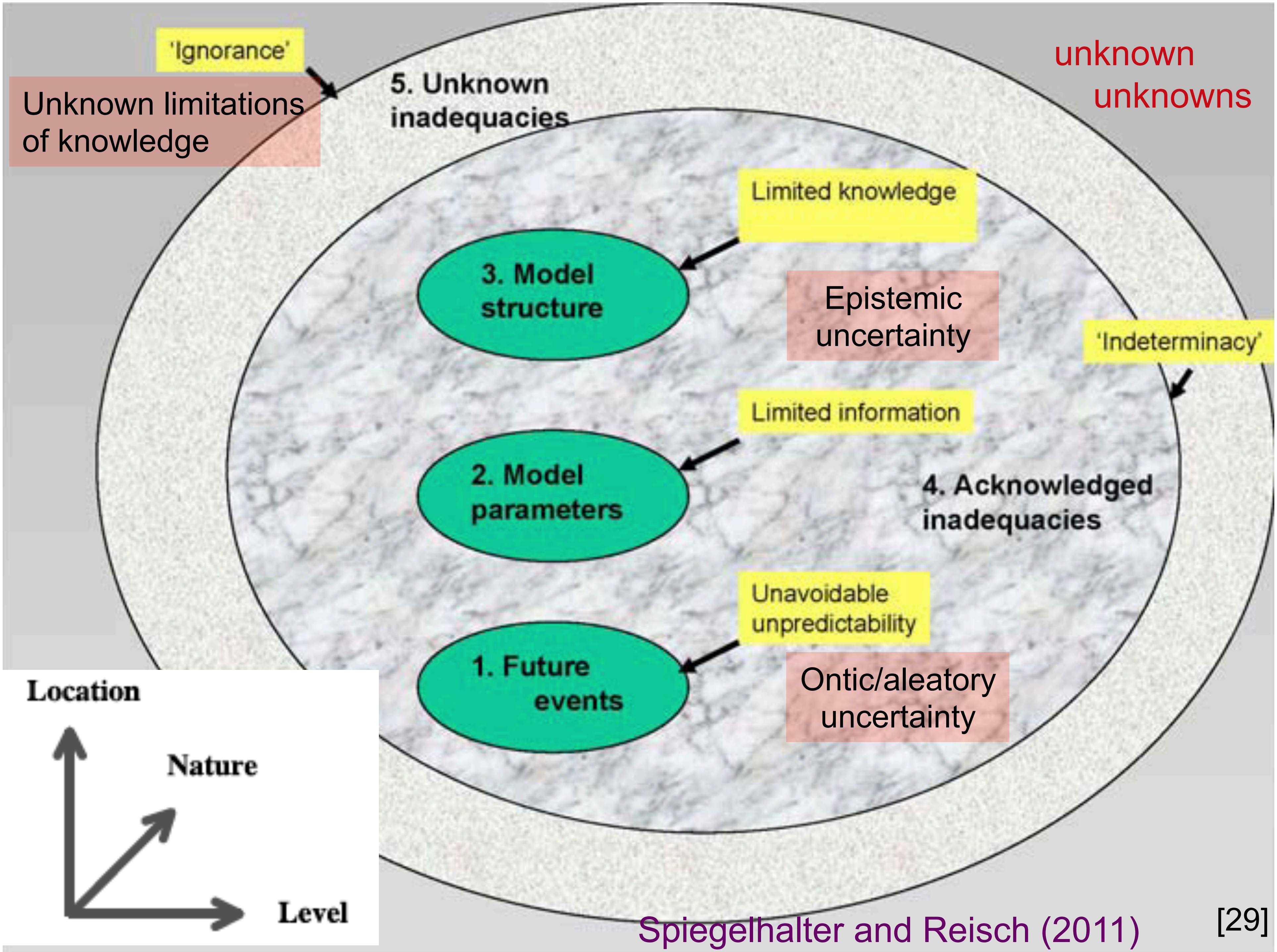
Understanding and representing uncertainty

Challenge:

- Uncertainty and ignorance assessment is a critical element for decision making strategies
- Parameter and parameterization uncertainty is inadequately assessed for individual models or MME
- Ensemble size for initial condition uncertainty is far too small
- Uncertainty associated with model structural form is rarely assessed

Other approaches:

- Stochastic models; stochastic parameterizations
- Monte Carlo techniques and sensitivity analysis
- Uncertainty management approaches such as NUSAP



Spiegelhalter and Reisch (2011)

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Climate models: fit for purpose?

A completely general, all encompassing climate model that is accepted by all scientists and is fit for all purposes seems to be an idealistic fantasy

Increasing complexity (adding additional sub models) is less important for many applications than ensemble size

We need a plurality of climate models that are developed and utilized in different ways for different purposes.

For many issues of decision support, the GCM centric approach may not be the best approach

Given the compromises made for multiple purposes, current GCMs may not be the optimal solution for any of these purposes