Workshop Synthesis

136 attendees, #16 breakouts, #104 people on slack, #70 online posters, #60 physical posters

Recent past and near future: Drivers, observations and models

- Drivers of recent past: Forced (GHG, non GHG), unforced
- Implicants for near future as drivers change.
- Model obs discrepancy and sources
- Natural Variability

- Model run wish-list **XMIP**
- Uncertainty quantification in observations
- Paleo & other variables for natural variability
- Models for natural variability

Conceptual & Mechanistic Understanding

- Process understanding: low-freq Pacific variability, SO teleconnections, mean-state 2 trends, positive feedbacks in regions of delated warming
- Frameworks: Definitions, non-GF frameworks, separating linear, nonlinear, temperature dependence
- Links b/w OHU and TOA

- Model wish list continued
- Indices, different spaces
- Theoretical models or nonlinearities
- ?? Process understanding

Empirical Constraints

- Quantify range in models
- What observations and simulations do we need to place an empirical constraint on ECS and pattern effect?
- Observational constraints on near-term and long-term pattern effect

- AMIP + RFMIP simulations & simulators
- What observations? (length, accuracy)
- Continued CERES/ARGO record

Paleo Patterns

- Usefulness of the paleo record for: constraining the equilibrium pattern for our future, ECS, general trust in climate models, constraining decadal internal variability? Transparency of limitations and uncertainties of proxies
- Separating linear (=GF) from non-linear components: Non-linear spatial = “cross-terms” vs. feedback temperature dependence
- More intellectual power into interpreting the observed record
- Records of sea level pressure, digitize obs.
- Paleo-patterns from proxies, inter-calibrate across different proxies

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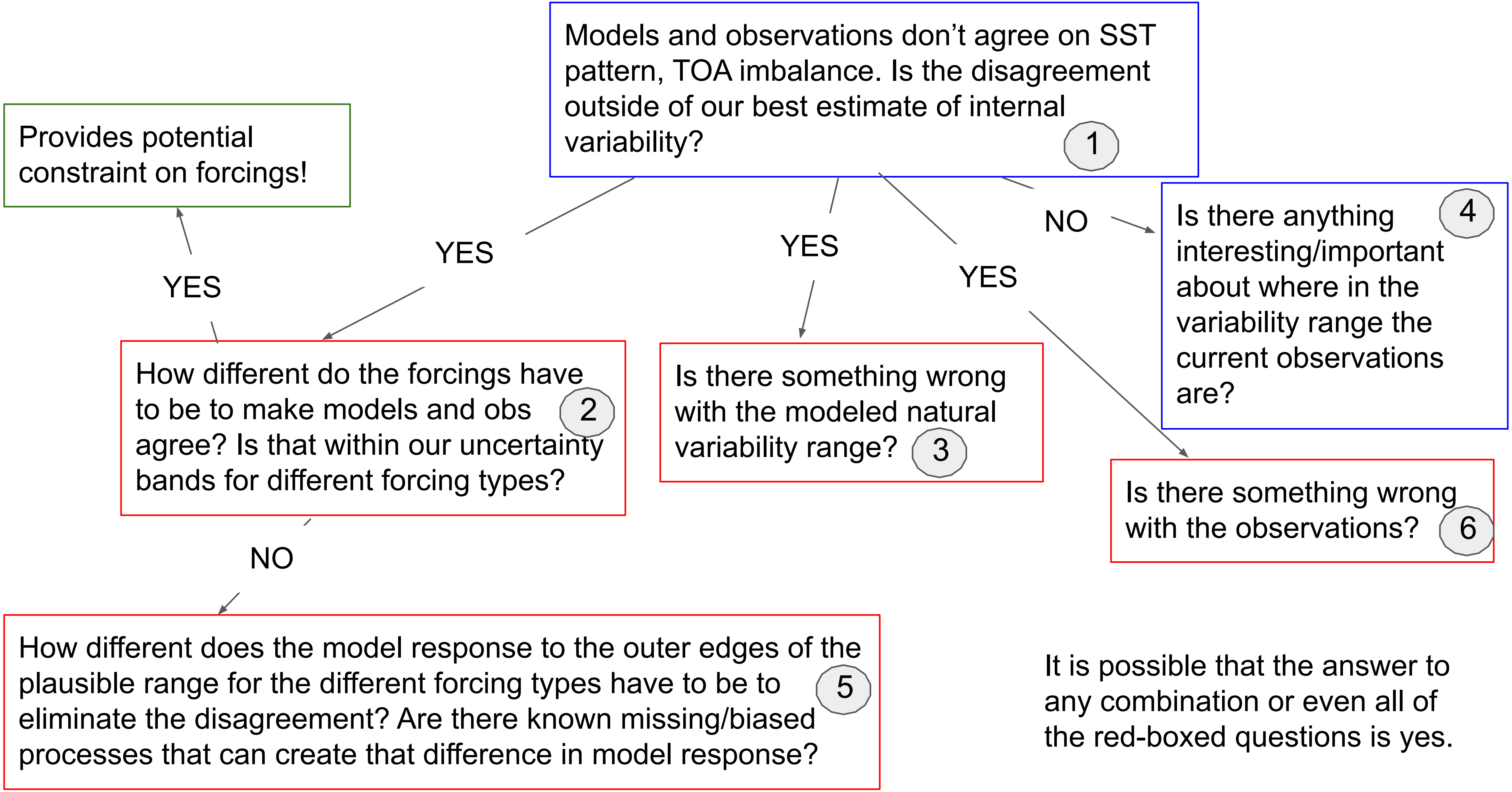
Models and observations don't agree on SST pattern, TOA imbalance. Is the disagreement outside of our best estimate of internal variability?
1
YES
YES
YES
NO
Provides potential constraint on forcings!
YES
How different do the forcings have to be to make models and obs agree? Is that within our uncertainty bands for different forcing types?
2
Is there something wrong with the modeled natural variability range?
3
Is there anything interesting/important about where in the variability range the current observations are?
4
Is there something wrong with the observations?
6
NO
How different does the model response to the outer edges of the plausible range for the different forcing types have to be to eliminate the disagreement? Are there known missing/biased processes that can create that difference in model response?
5
It is possible that the answer to any combination or even all of the red-boxed questions is yes.

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Model Run wish list:

FCMIP - correct climatology
- FAMIP/FFMIP/WNMIP - impose SST trends in a coupled model instead of AMIP
- Different initialization to look at role of disequilibrium
- PPEs
- High Resolution Models
- Explore role of different forcings (single forcing ensembles)
- Simulators (COSP), to better compare to observations

Investigate natural variability:
- Smart use of (recent) paleoclimate record
- Use of alternate observations (SL, SLP, Deep ARGO).
- Statistical methods (LIMs, LFC, D&A)
- Leverage WCRP lighthouse activities attributing decadal changes, clivar effort on tropical basin interaction Pacemaker

Projections for near-future
- Simple models.
- GCMs?

Quantifying uncertainty in observational products
- Reconciling heat fluxes and ocean heat content records
- How do we close global energy budgets on observational timescales? In which terms are we most confident?
- Appropriate error quantification for key records and increasing observational uncertainties
- Quantifying necessary length of record for constraining the forced response, pattern effect, variability, …

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- **Model Run wish list continue:**
  - FCMIP/FAMIP/FFMIP/WNMIP
  - PPEs
  - **Green's functions in coupled models**
  - **Mechanism denial runs**

- Increase understanding of indices and test new ones (SST#, GF-weighted EOFs, A&D)
- Non-geographic spaces (percentile space, ascent space, Bony space)

- Theoretical advances / conceptual models ?!
  - Theoretical frameworks that take into account coupling (?)
  - **Unified view of radiation and ocean heat uptake**
  - Idealized simulations?
  - **Innovative approaches to process understanding?**
  - Interbasin exchange?

Conceptual & Mechanistic Understanding

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- More models with RFMIP+AMIP / amip-piForcing simulations.
- Extend AMIP to match CERES

- **Asses impact of record length, accuracy, resolution on constraining ECS and pattern effect**

- **Continue records**: CERES, Deep C (and high lat) Argo is absolute key
- Assess utility of longer ERB record (e.g., ERBE) for improved understanding of pattern effect

- **Frameworks for placing empirical constraints**
- Empirical Green's Functions?

Paleo Patterns

- Usefulness of the paleo record for: constraining the equilibrium pattern for our future, ECS, general trust in climate models, constraining decadal internal variability? Transparency of limitations and uncertainties of proxies
- Separating linear from non-linear components: Non-linear spatial = “cross-terms” vs. feedback temperature dependence vs. linear framework (=GF)
- Intellectual power into interpreting the observed record
- Records of sea level pressure, digitize obs.
- Paleo-patterns from proxies, inter-calibrate across different proxies

- Robust uncertainty quantification of paleoclimate patterns: **Holocene variations & quasi-equilibrium patterns**

- Can PAGES come up with patterns, inter-calibrate across different proxies, integrate across observations, include more variables (sea level pressure), digitize obs pre 1950

- Disentangle f**orcing, feedback, boundary conditions**
    a. Paleoclimate Simulations
    b. Frameworks

- More intellectual power into interpreting the observed record

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Going Forward

Online Poster Gallery

Slack - will stay open – please ramble

Workshop Report

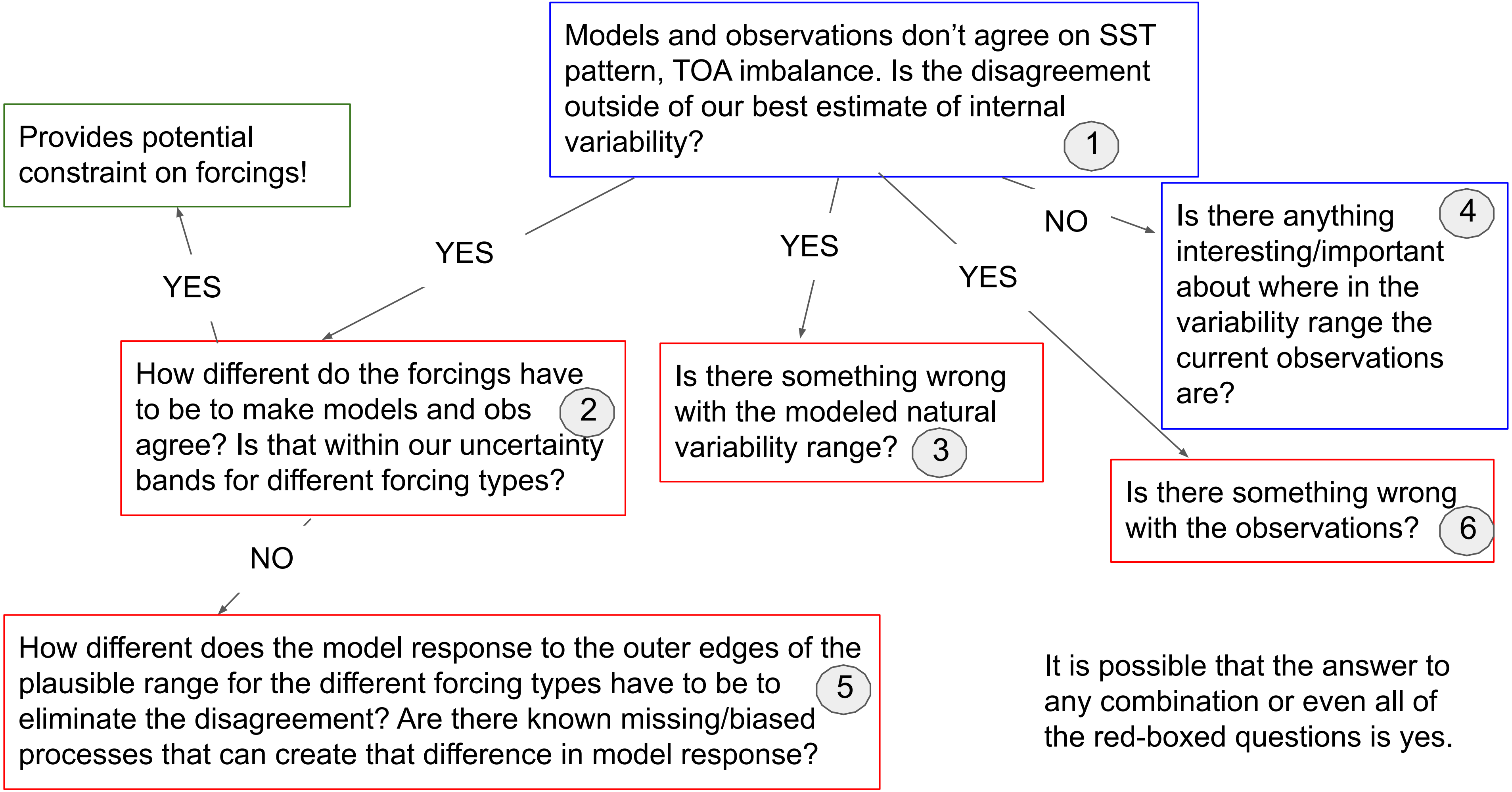
- CLIVAR
- BAMS (?)

Review Paper

Online Breakout

Forced or unforced that is the question

What can we do to answer just that simple binary question?



It is possible that the answer to any combination or even all of the red-boxed questions is yes.

Things we could do scientifically to progress through the flowchart

Forced or unforced–that is the question! What can we do to answer just that simple binary question?

1. Large ensemble experiments to better sample the modeled natural variability. Nudged wind coupled experiments?
2. Series of simulations exploring various combinations of upper and lower end of uncertainty range for various forcing types; Matrices of historical single-forcing experiments for aerosols, land use change, e.g: full coupled hist-aer, amip with observed or fully coupled all forced SST and hist-aer atmospheric forcing, amip with hist-aer SST and pi forcing,
3. Initialize coupled models with observed SST, etc. in 1980 – ones that drift farthest are the worst at natural variability??? [Not sure if that's what the group meant]; See if increasing model resolution reduces atmosphere and ocean biases and improves simulation of tropical variability
4. Update AMIP experiments to as near real-time as possible so we at least know if this effect is sticking around or going away
5. Does high resolution ocean/atmosphere help? Perturbed parameter experiments ala Ken Carslaw's A-CURE?
6. Look to new types of observations/ salinity, upper troposphere. Data assimilation, Proxy data constraints. Independent observations of same metrics (e.g. AIRs and CERES for longwave TOA)

Breakout 1

CMIP and other modeling

- Get more modeling groups participating in RFMIP and AMIP – key for pattern effect quantification in models
- Extend AMIP simulations to keep up with observations
- Support GFMIP and get more groups involved
- Does degree of PI disequilibrium project onto pattern effect? Initialize models earlier.
- Flux corrected runs. Fixing mean-state may fix model forced response and variability. FCMIP
- Freshwater forcing MIP
- Pacemaker simulations MIP (or SO/tropical wind nudging MIP?)
- Better understanding of role of non-CO2 forcings in setting SST patterns in paleoclimate record (i.e., how good of an analogue is the Pliocene for future warming?)
- PPEs on top of AMIP simulations (historical and paleo)

- More speculative:
  - Maybe models initialized with obs, though model drift issues
  - GFMIP PPEs
  - Pattern effects in high resolution models (issues with mean state changes)
  - OMIP simulations with novel boundary conditions (fluxes instead of SAT?)

Theoretical and analysis frameworks

- Explore use of different reference periods in EffCS calculations to periods when SST patterns are more well known; but then need to quantify energy imbalance better, and need to account for role of internal variability and possibly larger pattern effects
- Further develop theories for which pattern metrics to focus on. SST# and others. In general, can we come up with simple ways of relating SST patterns to radiation that work for historical record as well as 4xCO2 and paleo?
- Data Assimilation methods for paleo and historical record reconstructions to get dynamically consistent patterns
- Revisit theories for tropical Pacific E-W gradient and walker circulation in light of model failures; is it fixed simply by correcting mean state biases?
- Better theories for (i) ocean/atmos coupling, do lambda and gamma covary, with what sign and on what timescales? Can we observe these energy flows in the system (CERES + Argo + Reanalyses) and do models accurately capture them? (ii) Why curvature is consistently the way it is? (why slow warming in positive feedback regions)
- Continue to develop statistical methods to isolate forced response from variability in models and in observations

Additional observations and proxies

- Maintain critical observations over the next 5-10 years (SSTs from satellites and in-situ, Argo, continue CERES, cloud observations, precipitation products, surface heat flux products, atmospheric reanalyses, sea ice datasets); *Which have been most useful so far? CERES, SST datasets, sea ice datasets, atmospheric reanalyses, radiative forcing datasets*
- Better quantification of historical and future freshwater input from Antarctica, and where spatially/with depth
- Paleoclimate isotope measurements to reconstruct walker circulation; isotope enabled modeling DA. Particularly to reconstruct Southern Ocean variability since ~1850. Antarctic ice cores.
- Data Assimilation methods to reconstruct SSTs and sea ice in a dynamically consistent way, particularly 19^{th} C and early 20^{th} C
- Multidecadal variability in tropical temperatures in paleo records, for context for recent obs; better analyses to get patterns of variability rather than gridpoint, SST# proxy?
- Revisit SST dataset uncertainties, much better quantification of uncertainty needed

Breakout 2

What experiments would you suggest to CMIP and/or other modeling efforts?

Experiments to elucidate how the TOA imbalance changes are related to changes in ocean heat uptake
FAFMIP - prescribed the surface fluxes, how the ocean might drive patterns and feedbacks -> experiments that highlight the ocean's role in pattern formation
Changing the slab ocean q-flux to scale ocean heat transport - for pattern mechanism verification
Experiments changing the patterns without warming - CFMIP
Updated AMIP experiments with observed SST/sea ice through the present.
Coupling of the atmosphere and ocean is important. Doesn't need to be in every experiment don't ignore it.

What theoretical frameworks should be pursued?

Review paper on the pattern effect

Theoretical frameworks that take into account coupling

Unified view of ocean heat uptake and what sets ocean heat uptake?

Patterns of ocean heat uptake and cloud feedback.

Trace energy flux anomalies through pathways.

Energy Budgets that must close. What is the residual term? What are you most confident in?

What additional observations and proxies might be most useful?

Appropriate error quantification for the key records

Reconciling heat fluxes and ocean heat content records

Integrating different types of observations - can we do budgets across observational products - what we know versus relying the residual

Records we have to continue - CERES, Deep Argo, surface obs to calibrate (we need them, getting rid of them is misguided), records of sea level pressure, digitize the observations that are actually out there before 1950 (would make a huge difference), intercalibrate the different SST products, more intellectual effort into historical temperature reconstructions, citizen science, HMS Challenger data, online platforms to help the science be done (citizen science), Can PAGES come up with patterns – we need to inter-calibrate across different proxies, how to integrate across observations to go after patterns

High latitudes and deep ocean heat content. Argo is great but its only really recent.

Ocean heat uptake, SST patterns with observational uncertainty. (ECCO, ARGO important in this regard).

Breakout 3

The pattern effect in the historical record

- SST mean state biases potentially hinder **inter-basin connectivity** and thereby variability. Suggest **flux-corrected control simulations** to properly sample internal variability in a less biased system.
- <u>Extending CMIP6 AMIP simulations after 2014</u>: Takes advantage of a longer well-observed period post-2000 to evaluate radiative response to changing in SST patterns. Use different SST datasets in the AMIP simulations.
- <u>Better mechanistic understanding</u> of SO & TP in terms of internal variability and forced response. Maintain the observing system: T, SSS, surface fluxes. Leverage WCRP lighthouse activity attributing decadal changes, attributing decadal changes-Single forcing large ensembles (POC: Doug Smith). Also, leverage CLIVAR tropical basin interaction Pacemaker MIP (POC: Ingo Richter).
- Better mechanistic understanding of teleconnections in historical record and forced scenarios.
- <u>Initialized climate model simulations</u>: Can we leverage existing efforts (NMME, coupled atmosphere-ocean reanalysis at GMAO and ECMWF) to assess what processes in models are deficient/need improvement in the context of the pattern effect? **For example, focus on simulations initialized using present-day observations and compare with observations at different time intervals from when models were initialized.** How far back in time can we go? Drift-free decadal prediction systems via anomaly assimilation to predict future evolution of SST pattern (Yoshi Chikamoto). NCAR decal prediction large ensemble to assess model biases on longer timescales (Steven Yeager).
- Continuation of satellite cloud and Earth Radiation budget observations is key progress on radiative pattern effect.

- Continuation of satellite cloud and Earth Radiation budget observations is key progress on radiative pattern effect.
- Assess utility of longer ERB record (e.g., ERBE) for improved understanding of pattern effect.
- Continued and expanded use of simulators (e.g., CFMIP) is highly valuable to understanding cloud feedback.
- Need more transient benchmark indices that we can use to evaluate models with observations (e.g., atmospheric response to SST (AMIP).
- Further work evaluating whether T# is the most meaningful framework for improved understanding of radiative feedback. What are variations in T# relate to processes in a coupled system? Can we tie T# to geographical distributions (zonal redistribution of tropical convection).
- Higher-resolution modeling: how can that help better represent SST patterns and atmospheric response?

The pattern effect in the historical record

- We need to get better understanding of what our actual uncertainties are, even if it expands our error bars.

- Getting the Southern Ocean/high latitudes right can help get the tropical Pacific right. **The pathway between the Southern Ocean and the tropics is not clear.** Are there biases in the winds in the Southern Ocean that would affect this? The dynamics haven't been looked at yet (like Ekman transports resulting from the wind biases).
    - Regions of delayed warming = cooling, because of WES and other feedbacks? (Ulla's hypotheses?)

The pattern effect in projected long-term warming

- <u>Initialized climate model simulations</u>: Can we leverage existing efforts (NMME, coupled atmosphere-ocean reanalysis at GMAO and ECMWF) to assess what processes in models are deficient/need improvement in the context of the pattern effect? For example, focus on simulations initialized using present-day observations and compare with observations at different time intervals from when models were initialized. How far back in time can we go?
- <u>Extending CMIP6 AMIP simulations after 2014</u>: Takes advantage of a longer well-observed period post-2000 to evaluate radiative response to changing in SST patterns.

Summary of big open questions
(to be summarized in talks

Transient, equilibrium, and paleo pattern information

- Does the paleo record help
    a. constraining the equilibrium pattern effect for our future?
    b. ECS?
    c. general trust in climate models?
    d. constrain decadal internal variability?
    e. What are limitations and uncertainties of the proxies on time and spatial scales?
    f. How can we make data aggregation and assimilation transparent enough for end-users to understand the uncertainty?
    g. How do we produce robust uncertainty quantification?
- What are frameworks and experiments to separate non-linear components of how radiation depends on temperature:
    a. Linear component = GF
    b. Non-linear spatial component = “cross-terms”
    c. Feedback temperature dependence

What has driven the patterns observed over the historical record?

Our projections of future pattern effect, and future warming depend critically on what we think has driven the recent past. Different drivers of recent patterns imply very different futures.

Question 1: What is the role of different mechanisms in setting recent SST patterns:

- GHG forcing
- Non-GHG forcing (aerosols, meltwater, ozone, volcanoes?)
- Internal variability (PDO, Southern Ocean, AMOC)

Question 2: Why do the SST patterns over the last 40 years fall outside or at the edge of the simulated model range?

- Observational error?
- Extremely unusual recent patterns?
- Inadequate model response to forcing
- Insufficient internal variability.

Question 3: If models are biased, how do we infer natural variability form a short uncertain instrumental record and a sparse and noise proxy record?

Question 4: How do we make near term predictions, given the possible magnitude of historical pattern effects and model biases

Conceptual and Mechanistic Understanding

- We need better theoretical/conceptual <u>process understanding</u>
  - Conceptual models of low-frequency modes of variability (IPO/PDO)
  - Pathways between Southern Ocean and low-latitudes?
  - What sets the magnitude and timescales of regions of delayed warming
  - What are links between biases in mean state and trends?
  - Does delayed warming in upwelling regions lead to cooling though feedbacks between temperature gradients, wind, evaporation, and upwelling

- What are other <u>frameworks</u>?
  - What are the most relevant patterns and indices?
  - Can we use other decompositions? (percentile space, precip, omega500).

- Develop transient benchmark indices (opposed to ECS) to evaluate models with observations, e.g., atmospheric response to prescribed SST?

- What is the link between the patterns-dependence of radiative feedbacks and pattern dependence of OHU
  - Is ocean heat uptake dependent (beyond the global mean) on the SST pattern?
  - (How) do changing feedbacks relate to changing ocean heat uptake efficiencies (amplifying or counteracting radiative pattern effect)?
  - How is TOA imbalance partitioned into OHU at different depths and in different regions

Empirical constraints on the pattern effect magnitude?

- What is the possible range of the pattern effect across climate models?
  - for the historical period?
  - for step forcing simulations?
  - for specific paleo timescales?
- How do we place observational constraints on the magnitude of the pattern effect?
  - Lambda_hist - lambda_4xCO2?
  - Green’s Functions?
- What observations do we need?
  - How long of a record? How precise?
  - What observations (SSTs, ARGO, CERES, CLOUDs)?
- How do we empirically constrain on near-term warming

What is the magnitude of natural variability?

How do we infer natural variability from a short and uncertain instrumental record and a sparse, noisy, and (also) uncertain proxy record?

What assumptions do you need to make in order to disentangle forced and unforced variations? / What theoretical frameworks can we use (LIMs?) (e.g. Do we need to rely on GCM large ensembles? Can we leverage other statistical tools (e.g. Robb Wills LFC), that make other assumptions).

How long do we need to extend records such as CERES and ARGO to observe forced response?

What other observations we can use?

- What are variations in T# relate to processes in a coupled system? Can we tie T# to geographical distributions (zonal redistribution of tropical convection) or processes?

Continue and expand work on large ensembles

- Continue to develop statistical methods to isolate forced response from variability in models and in observations
- Better use of paleocliamte record.

Model wish list

1. Experiments to elucidate how the TOA imbalance changes are related to changes in ocean heat uptake
2. FAFMIP - prescribed the surface fluxes, how the ocean might drive patterns and feedbacks -> experiments that highlight the ocean's role in pattern formation
3. Changing the slab ocean q-flux to scale ocean heat transport - for pattern mechanism verification
4. Experiments changing the patterns without warming - CFMIP
5. Updated/extend AMIP experiments with observed SST/sea ice after 2014 through the present.
   a. takes advantage of a longer well-observed period post-2000 to evaluate radiative response to changing in SST patterns.
   b. Use different SST datasets in the AMIP simulations.
6. Flux-corrected control simulations
7. Initialized climate model simulations
   a. leverage existing efforts (NMME, coupled atmosphere-ocean reanalysis at GMAO and ECMWF) to assess what processes in models are deficient/need improvement in the context of the pattern effect? For example, focus on simulations initialized using present-day observations and compare with observations at different time intervals from when models were initialized. How far back in time can we go?
   b. Drift-free decadal prediction systems via anomaly assimilation to predict future evolution of SST pattern (Yoshi Chikamoto).
   c. NCAR decal prediction large ensemble to assess model biases on longer timescales (Steven Yeager).
8. Continued and expanded use of simulators (e.g., CFMIP) is highly valuable to understanding cloud feedback.
9. Higher-resolution modeling: how can that help better represent SST patterns and atmospheric response?
10. More GFMIP
11. Q-Flux Greens Functions in coupled models to attribute origins of patterns

General theme: think coupled and uncoupled, GF is only one side of the path