What is the Source of Uncertainty Regarding Global Warming?

AKA "Quantifying the Sources of Inter-model Spread in Equilibrium Climate Sensitivity"; in review at JCli

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What is the Source of Uncertainty Regarding Global Warming?

Mathematically, this question is ~equivalent to asking which terms induce the most inter-model spread in the ECS equation:

Equilibrium **C**limate **S**ensitivity = global-ave equilibrium temperature response to CO_2 doubling

Forcing is taken here to be the fast response to doubling CO_2

$$\boxed{\mathrm{ECS} = \frac{-F}{\lambda_{\mathrm{Pl}} + \lambda_{\mathrm{WV}} + \lambda_{\mathrm{LR}} + \lambda_{\mathrm{Alb}} + \lambda_{\mathrm{SW\ Cld}} + \lambda_{\mathrm{LW\ Cld}}}}$$

Planck feedback

Water Vapor feedback

Lapse Rate feedback

Albedo feedback

Shortwave Cloud Feedback

Longwave Cloud Feedback

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Isolating the impact of individual terms is hard when those terms are in the denominator!

Breaking ECS into a Sum of Terms:

Dufresne + Bony (2008, JCli; hereafter DB08) provide a way to write ECS as a sum of terms:

$$ECS = \frac{-F}{\lambda}$$

net feedback, $\lambda=\Sigma\lambda_i$

$F-\overline{F}$

$$= \frac{-F'}{\lambda} - \frac{\overline{F}}{\lambda}$$

Multi-model mean forcing

$$= \frac{-F'}{\lambda} - \frac{\overline{F}}{\lambda}\frac{\lambda_{Pl}}{\lambda_{Pl}}$$

Planck feedback

$$= \frac{-F'}{\lambda} - \frac{\overline{F}}{\lambda}\frac{\left(\lambda - \sum_{i \neq Pl} \lambda_i\right)}{\lambda_{Pl}}$$

$$= \frac{-F'}{\lambda} - \frac{\overline{F}}{\lambda_{Pl}} + \sum_{i \neq Pl} \frac{\lambda_i}{\lambda_{Pl}} \frac{\overline{F}}{\lambda}$$

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$$ECS = \frac{-F}{\lambda}$$

$$= \frac{-F'}{\lambda} - \frac{\bar{F}}{\lambda}$$

$$= \frac{-F'}{\lambda} - \frac{\bar{F}}{\lambda}\frac{\lambda_{Pl}}{\lambda_{Pl}}$$

$$= \frac{-F'}{\lambda} - \frac{\bar{F}}{\lambda}\frac{\left(\lambda - \sum_{i \neq Pl} \lambda_i\right)}{\lambda_{Pl}}$$

$$= \frac{-F'}{\lambda} - \frac{\bar{F}}{\lambda_{Pl}} + \sum_{i \neq Pl} \frac{\lambda_i}{\lambda_{Pl}}\frac{\bar{F}}{\lambda}$$

Good:

- Breaks ECS exactly into terms associated with each F and λ_i
- Makes physical sense:
  - λ_{Pl} summand is ΔT if Planck was the only feedback operating
  - Other summands are the Planck response needed to balance a given λ_i

Bad:

- Non-unique: why multiply by $\lambda_{Pl}/\lambda_{Pl}$?
- The variance assigned to λ_i is not zero even if var(λ_i)=0 for i≠Pl

An Alternative Decomposition:

$$\mathrm{ECS} = \left(\bar{F} + F'\right)\frac{-1}{\bar{\lambda} + \lambda'}$$

$$= \left(\bar{F} + F'\right)\Bigg[\overbrace{\frac{-1}{\bar{\lambda}} + \frac{\lambda'}{\bar{\lambda}^2} + \text{higher order terms}}^{\text{Taylor expansion about } \lambda'=0}\Bigg]$$

$$= \frac{-\bar{F}}{\bar{\lambda}} + \frac{-F'}{\bar{\lambda}} + \frac{\bar{F}}{\bar{\lambda}^2}\sum_{i=1}^{N}\lambda_i' + \text{higher order terms}$$

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Bad:

- Linearization is inexact
- Constant and higher-order are unrelated to a specific process (so can't be used to analyze contributions to multi-model mean response)

Good:

- var(λ_i)=0 $\Rightarrow$ term i has no contribution to var(ECS)
- Error due to linearization can be rigorously quantified

Linearization error is relatively small. See the paper or ask for details...

So ECS is Decomposed... Now what?

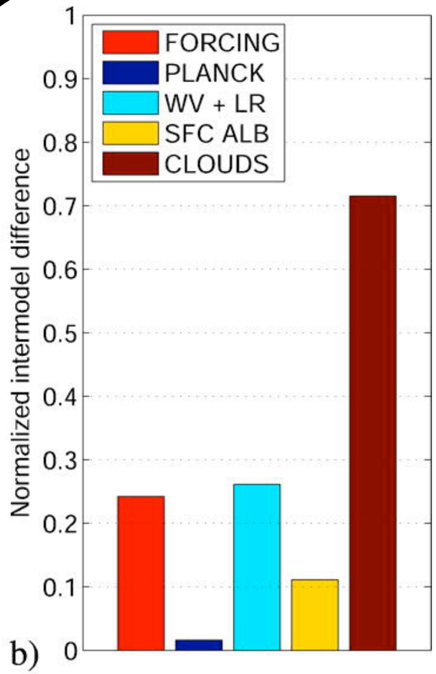


Fig: Normalized inter-model standard deviation of ECS partitioning. Reprinted from DB08.

DB08 use the inter-model standard deviation of each summand as a measure of that term's importance to var(ECS) (see Fig), but formally

$$\mathrm{var}\left(\sum_{i=1}^{N} T_i\right) = \sum_{i=1}^{N}\sum_{j=1}^{N}\mathrm{cov}\left(T_i, T_j\right)$$

$$= \sum_{i=1}^{N}\mathrm{var}\left(T_i\right) + 2\sum_{i=1}^{N}\sum_{j>i}^{N}\mathrm{cov}\left(T_i, T_j\right)$$

so covariances between feedbacks must also be considered!

Viewing Contributions to ECS Spread

$$\mathrm{var}\left(\sum_{i=1}^{N} T_i\right) = \sum_{i=1}^{N}\sum_{j=1}^{N} \mathrm{cov}\left(T_i, T_j\right)$$ is a sum over a covariance matrix… so plot that matrix!

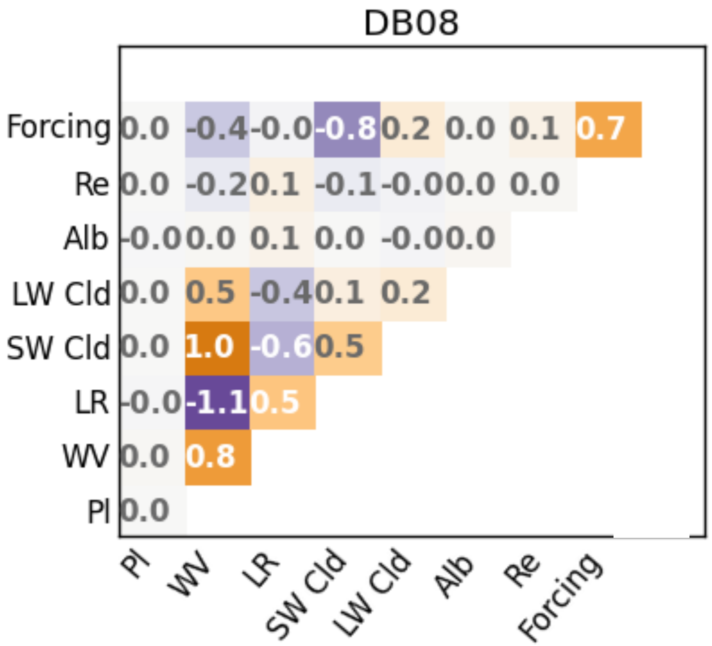


Fig: Normalized covariance matrix for DB08 decomposition using CMIP5 data.

- Colors indicate magnitude
- All elements are normalized by var(ECS) so they sum to 1
- Variances are on the diagonal
- cov(T_i, T_j) = cov(T_j, T_i), so omit ⊿ and multiply ◸ by 2

Enough Theory, Let's Look at Data!

- Use **Gregory** et al (2004) approach to get feedback and forcing components as the slope and y-intercept (respectively) of model response to **abrupt quadrupling of CO_2**
  - **Radiative kernels** used to compute radiative response to Pl, WV, LR, and Alb changes
  - **adjusted cloud radiative effect** used for SW and LW Cld
- ECS is the ratio of net forcing and feedback terms calculated above
- **Analysis are based on 17 CMIP5 models** with SW, LW, and net clear sky kernel errors of < 10%

Results:

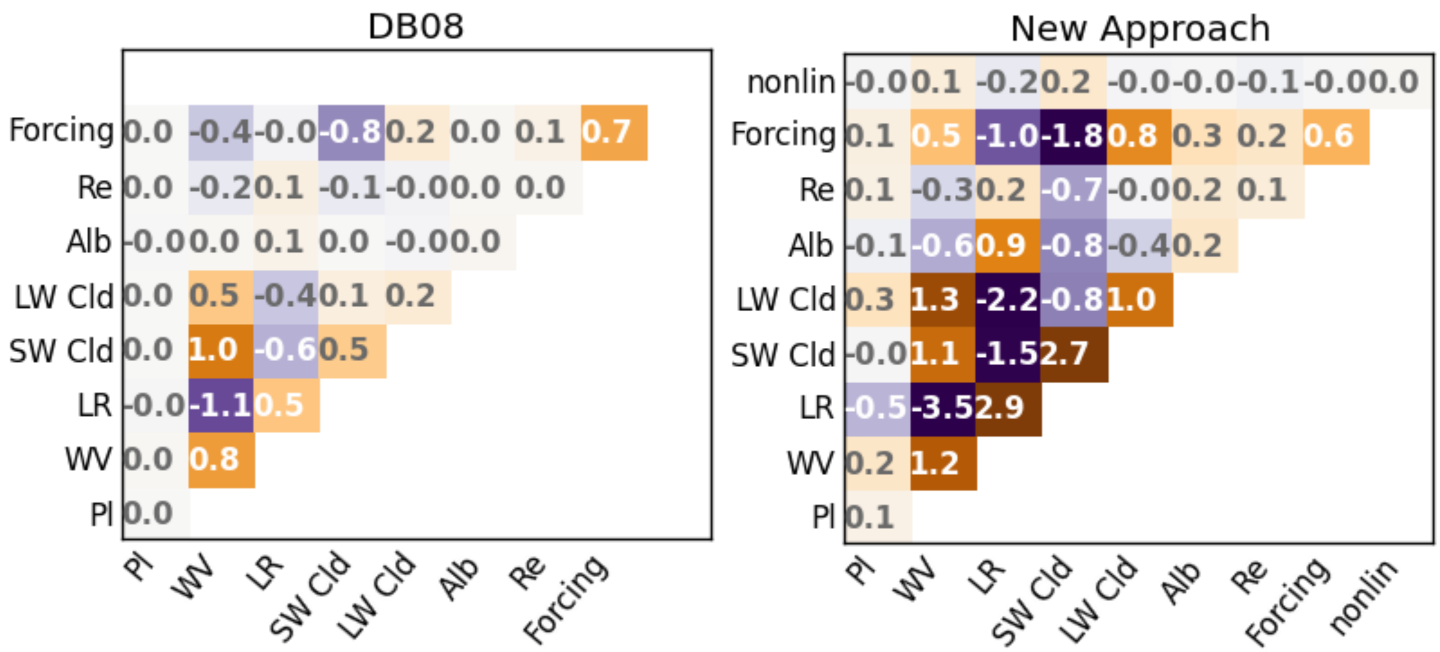


Fig: Normalized covariance matrices for DB08 and the new approach using CMIP5 data.

- Covariance terms are very important
- Partitioning approach makes a huge difference

Better WV + LR Definitions

- WV and LR terms have lots of covariance (see Fig)
- This is expected because RH remains ~constant as the climate changes
- Held and Shell advocate redefining WV feedbacks based on changes in RELATIVE rather than SPECIFIC humidity
- This requires adding the effect of WV change at fixed RH to LR and Pl (for height dependent and independent effects, respectively)

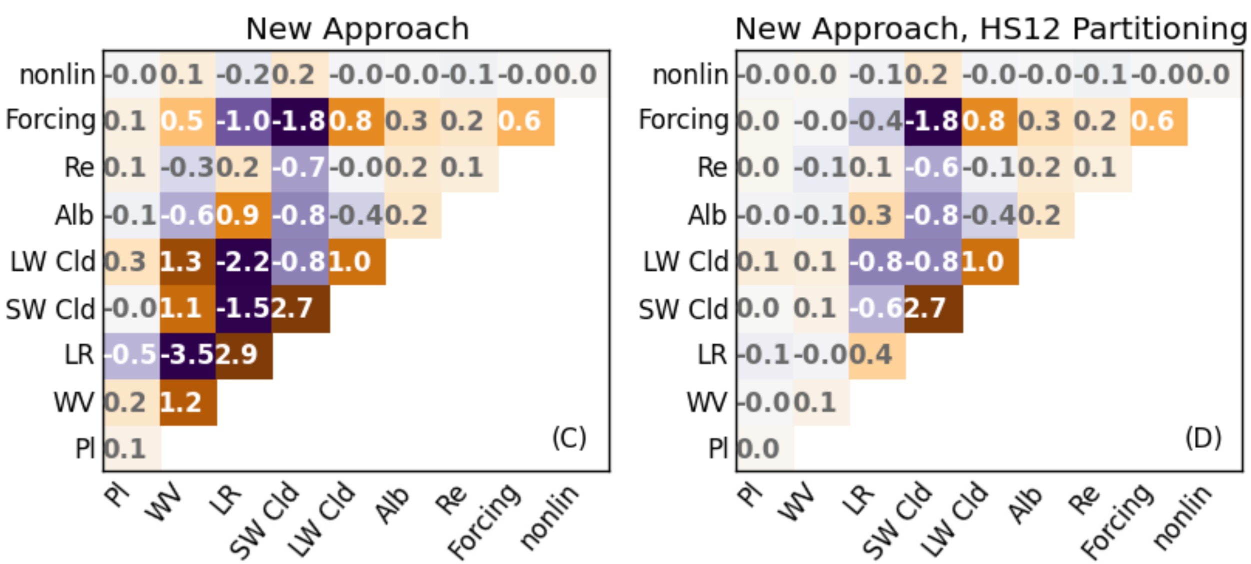


Fig: Cov matrices for new decomposition using traditional and HS12 feedback definitions (in left and right panels, respectively)

Using HS12 definitions makes sense and reduces the magnitude of covariance terms!

Which Terms are Important?

- var($\lambda_{SW\ Cld}$) dominates (as expected)

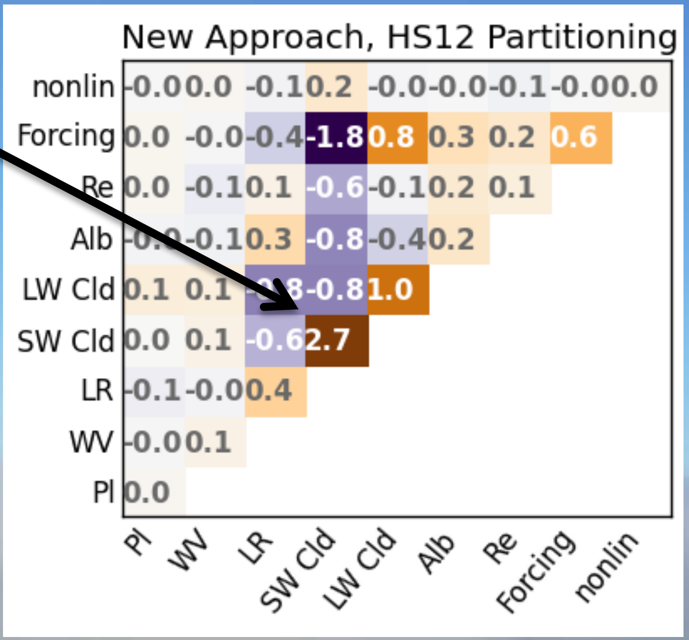


Fig: Cov matrix for new decomposition using HS12 definitions (from last slide)

Which Terms are Important?

- var($\lambda_{SW\ Cld}$) dominates (as expected)
- var($\lambda_{LW\ Cld}$) and var(*F*) are also important

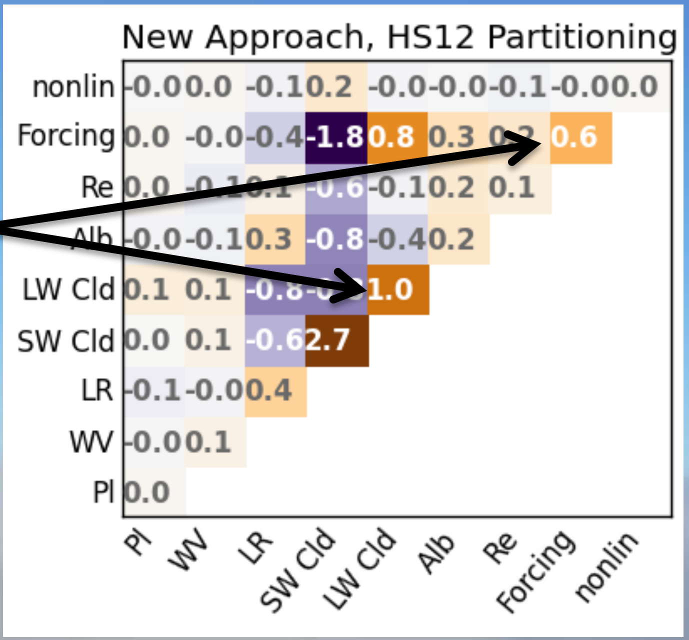


Fig: Cov matrix for new decomposition using HS12 definitions (from last slide)

Which Terms are Important?

- var($\lambda_{SW\ Cld}$) dominates (as expected)
- var($\lambda_{LW\ Cld}$) and var(F) are also important
- cov($\lambda_{SW\ Cld}$, F) and cov($\lambda_{LW\ Cld}$, F) are big but compensate (see also Ringer et al, 2014 GRL)

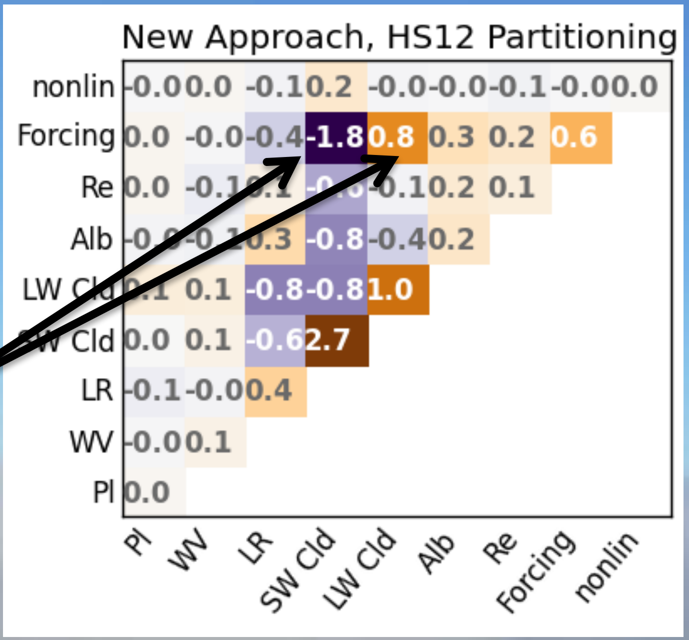


Fig: Cov matrix for new decomposition using HS12 definitions (from last slide)

Which Terms are Important?

- $var(\lambda_{SW\ Cld})$ dominates (as expected)
- $var(\lambda_{LW\ Cld})$ and $var(F)$ are also important
- $cov(\lambda_{SW\ Cld}, F)$ and $cov(\lambda_{LW\ Cld}, F)$ are big but compensate (see also Ringer et al, 2014 GRL)
- $cov(\lambda_{SW\ Cld}, \lambda_{Alb})$ and $cov(\lambda_{LR}, \lambda_{LW}$ Cld) are important sinks of ECS variance (see also Huybers, 2010 JCli and Mauritsen et al, 2013 ClimDyn)

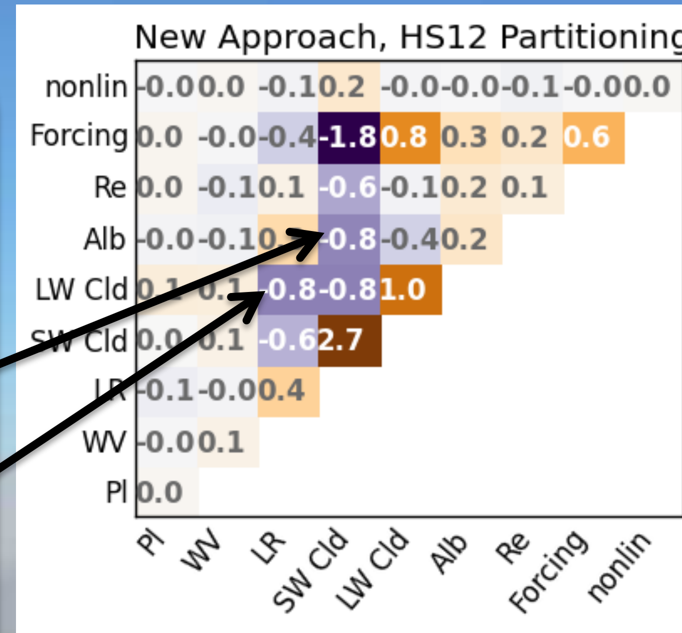
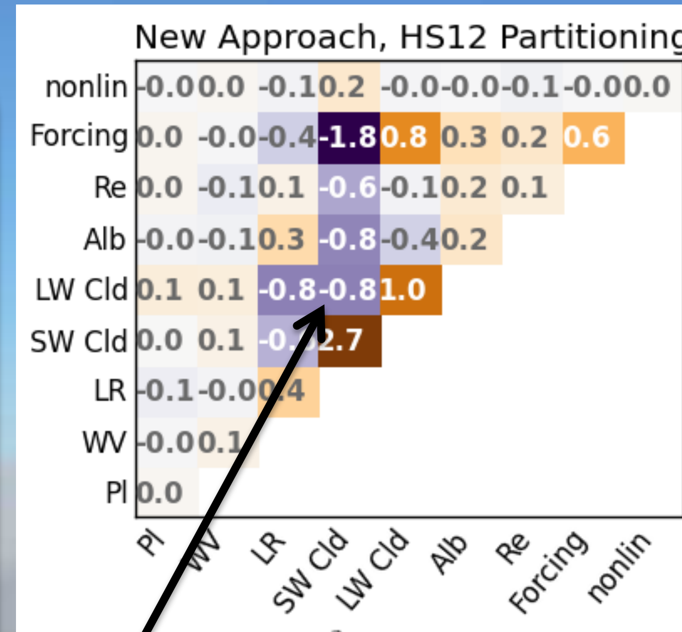


Fig: Cov matrix for new decomposition using HS12 definitions (from last slide)

Which Terms are Important?

- var($\lambda_{SW\ Cld}$) dominates (as expected)
- var($\lambda_{LW\ Cld}$) and var(F) are also important
- cov($\lambda_{SW\ Cld}$, F) and cov($\lambda_{LW\ Cld}$, F) are big but compensate (see also Ringer et al, 2014 GRL)
- cov($\lambda_{SW\ Cld}$, λ_{Alb}) and cov(λ_{LR}, λ_{LW} Cld) are important sinks of ECS variance (see also Huybers, 2010 JCli and Mauritsen et al, 2013 ClimDyn)
- cov($\lambda_{SW\ Cld}$, $\lambda_{LW\ Cld}$) is large but spurious – the correlation between these quantities is ≈ 0



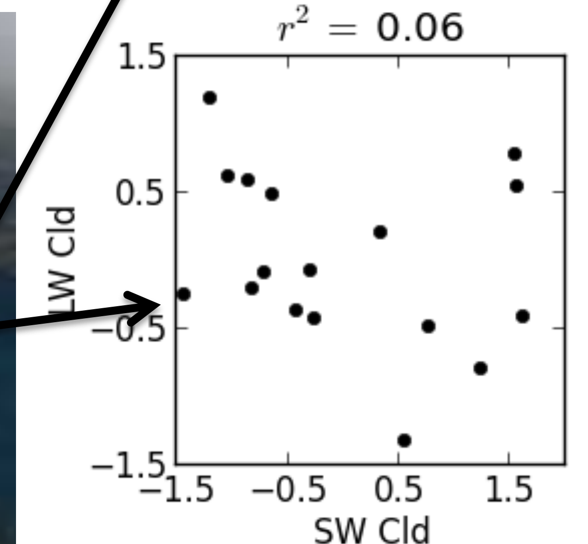


Fig: scatter plot of $\lambda_{SW\ Cld}$, $\lambda_{LW\ Cld}$

Conclusions:

1. Asking "What causes global warming uncertainty?" ≈ asking "which quantities in the ECS equation dominate var(ECS)?"
2. Isolating the impact of individual terms is hard when those terms are in the denominator!
3. The DB08 partitioning is
   a. non-unique and
   b. does not isolate variance from individual processes
4. Our new partitioning solves these problems; comparing methods shows that subjective partitioning choices have a big impact
5. Covariances are important!
6. Held and Shell (2012, JCli) definitions are useful
7. $\lambda_{SW\ Cld}$ is still the dominant source of ECS spread, but other terms play an important role

Extra Slides

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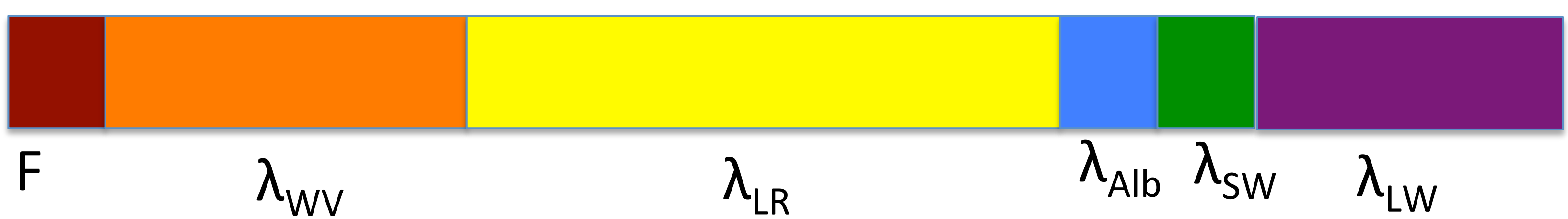
ECS Decomposition for Emergent Constraints

$$\mathrm{corr}(ECS, X) = \mathrm{corr}\left(\sum_{i=1}^{N} T_i, X\right)$$

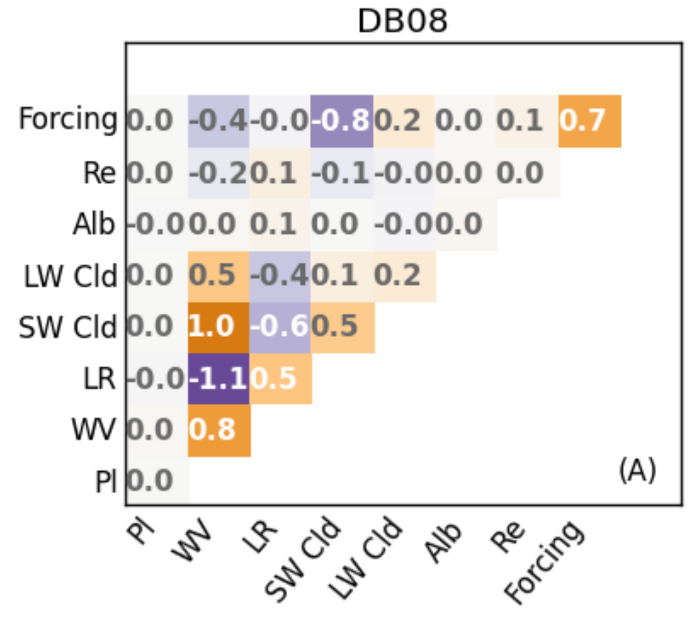
$$= \sum_{i=1}^{N} \mathrm{corr}(T_i, X)$$



Real constraints should be associated with a single physical mechanism (or an explainable set of mechanisms). Partitioning uncovers what those are.

Why isn't λ_{Cld} Dominant in DB08?

- Because WV+LR are anti-correlated and SW+LW Cld are positively correlated



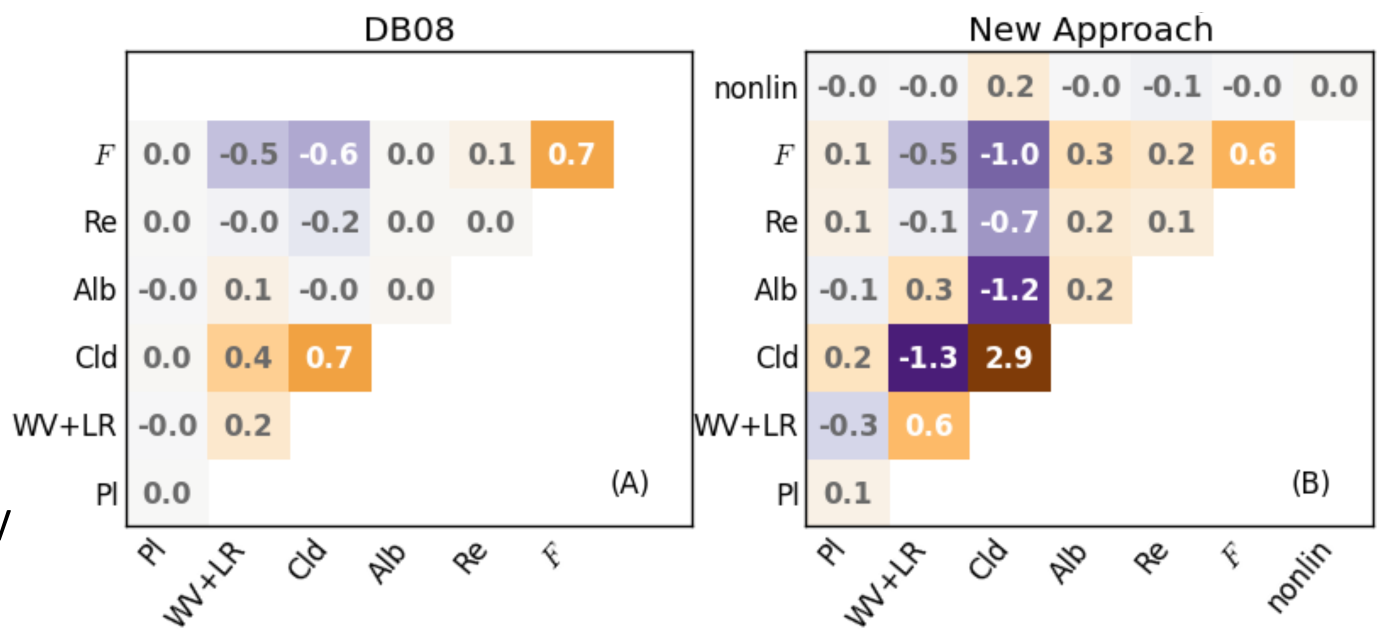
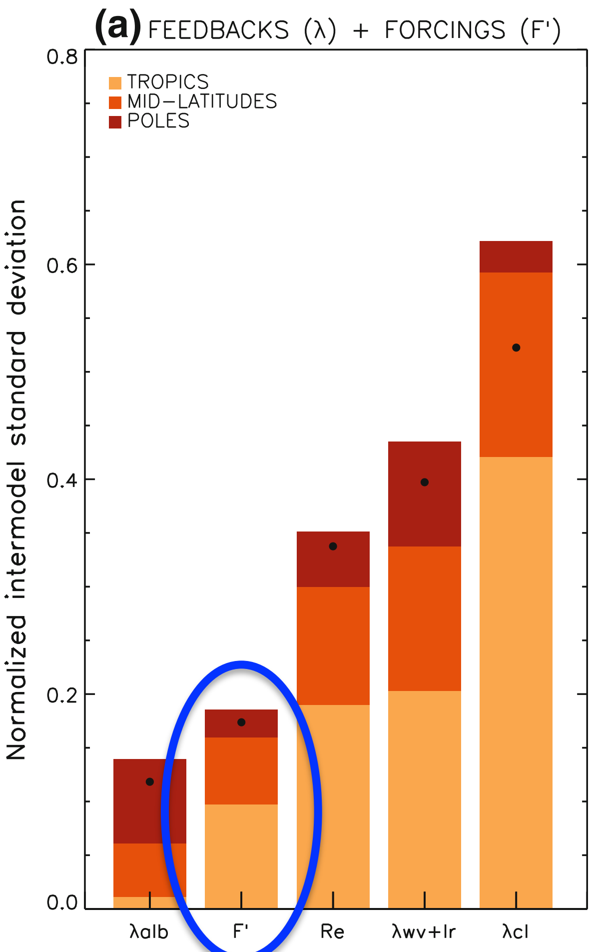


Fig: Cov matrices for CMIP5 with Cld and WV +LR terms combined

But Vial et al (2013) says Forcing isn't Important!



Since Vial doesn't separate *forcing* variability from λ variability:

Vial eq 24:

$$\Delta T^{e}_{s,\Delta SST} = \frac{-1}{\lambda_p}\left[F + F_{adj} + \left(\sum_{x \neq p} \lambda_x + Re^{\lambda}\right)\Delta T^{e}_{s,\Delta SST}\right]$$

Divides by λ_{Pl} instead of λ

Uses F instead of $\overline{F}$

DB08:

$$ECS = \frac{-F'}{\lambda} - \frac{\overline{F}}{\lambda_{Pl}} + \sum_{i \neq Pl} \frac{\lambda_i}{\lambda_{Pl}} \frac{\overline{F}}{\lambda}$$

Fig: After partitioning ECS into components listed on x-axis, Vial computes Inter-model standard deviations and normalizes by the standard deviation of ECS. This is Fig. 6 from Vial et al. (2013)

Linearizing 1/λ is ok

- ECS predicted from the linearized equation looks very similar to that from the full model with fixed F (compare red and green lines on left)
- The importance of individual summands is largely unaffected by linearizing (right panel).

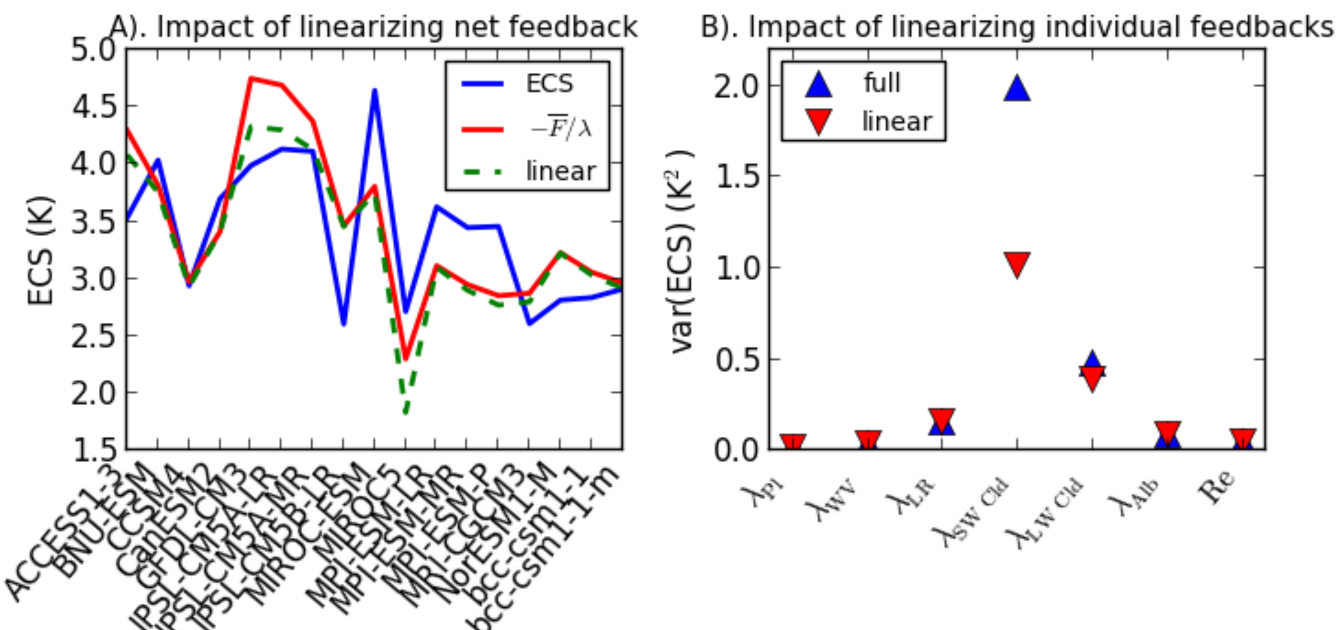


Fig: Panel A= actual model ECS (blue), ECS neglecting F' (red), and linearized 1/λ + neglected F' (green). Each triangle in Panel B denotes var(ECS) neglecting perturbations in all terms except the one listed on the x axis. Red triangles use linearization, blue triangles do not. HS12 partitioning is used for this plot.

Which Terms are Important?