



On the application of science systems engineering and uncertainty quantification for ice sheet science and sea level projections

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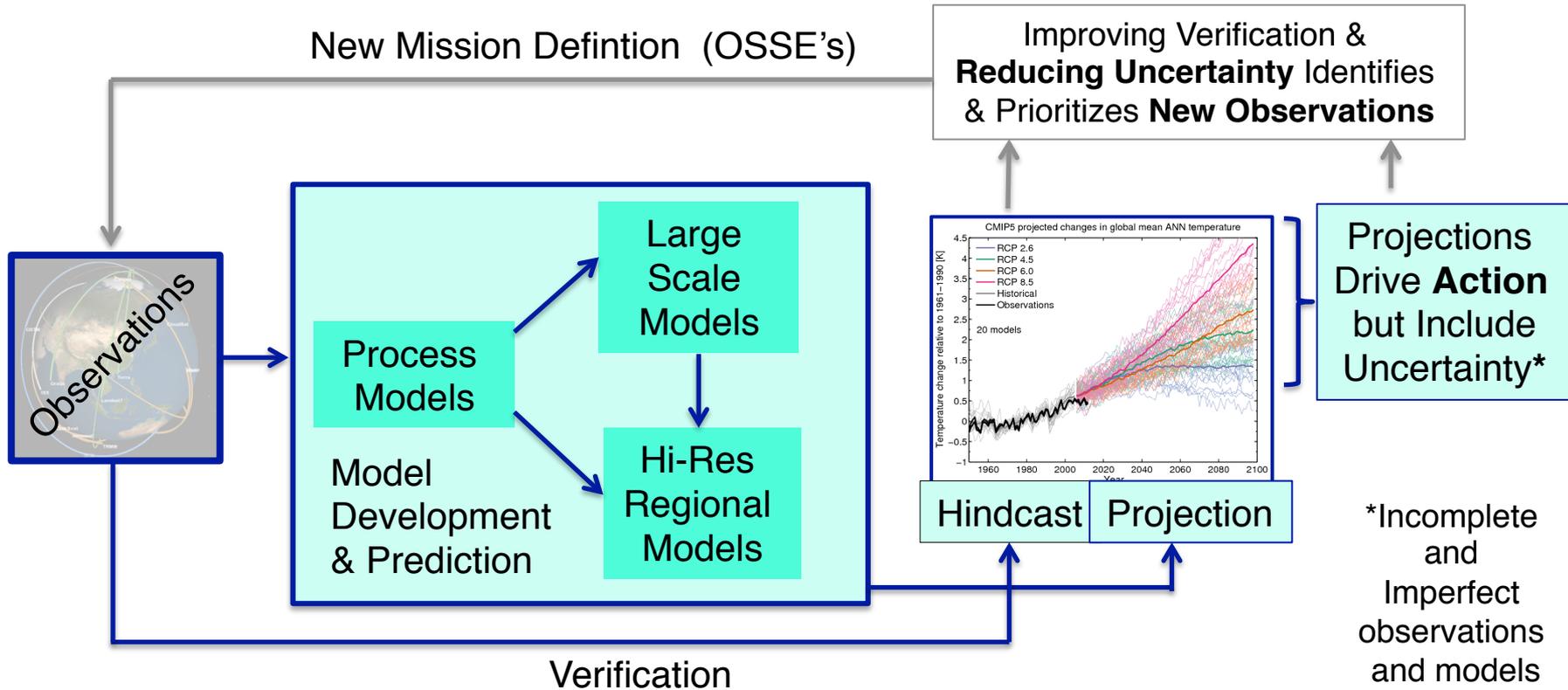
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Motivation

- Two (originally uncoupled) questions:
 1. Why can't we do a better job of quantitatively assessing and optimizing new measurements impact on understanding of the climate system?
 - Significant improvement in quantitatively tracing from measurement to instrument design via system engineering approaches
 - Extend to “science system engineering” at higher level of abstraction
 2. Why can't we have smaller uncertainties in sea level rise by 2100?
 - Range from ~20 cm to ~200 cm

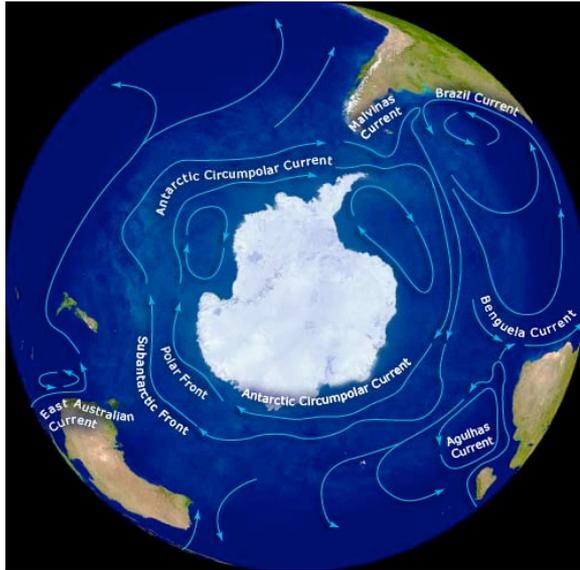
JPL Physics based model/prediction/observing optimization framework



Better quantitative characterization of these complex systems through the application of system engineering and uncertainty quantification methods would enable:

- Improved *science analysis* results
- Improved *science traceability* for optimizing measurement system (mission and instruments) design
- Improved *prioritization* of missions and instruments

Antarctica



Greenland



Models

ISSM

- Ice Sheet System Model
- Adjoint capabilities
- UQ analysis using DAKOTA framework

ECCO/MITgcm

- Estimating the Circulation and Climate of the Ocean
- Adjoint capabilities

Adjoint capability enables easy integration of real or simulated observations for parameter estimation.



Multi-step Process

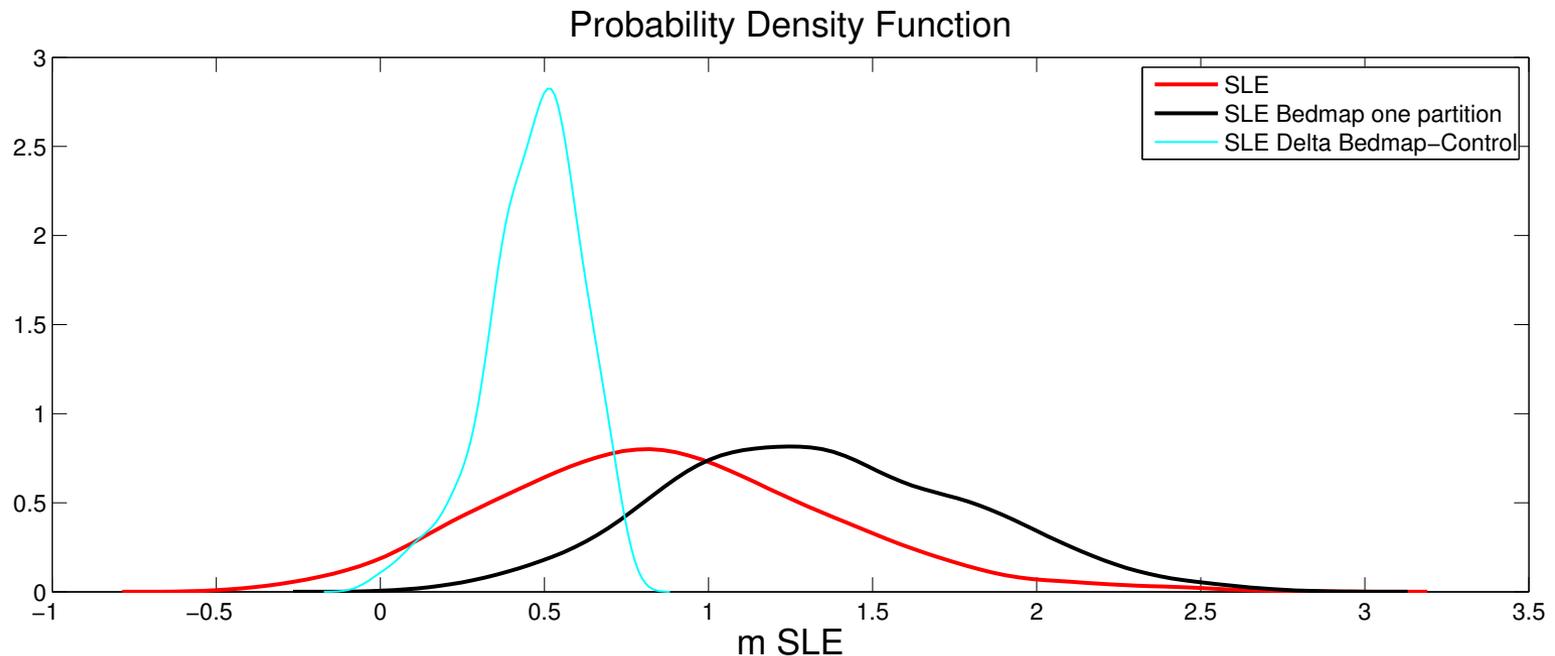
Parameter values applied as constant values for 100 yr durations

- Step 1 – single parameter sensitivity experiments
 - Ocean/ice melt rate; viscosity; basal drag; Surface Mass Balance
- Step 2 – Initial Monte Carlo analysis
 - varying most influential parameters from step 1, over extreme (high SLR) min/max range
 - 1 and 2000 partition runs - equal area
- Step 3 – refined Monte Carlo analysis
 - More credible parameter mix/max for next 100 yrs
 - 27 “smart” partitions – designed around drainage basins and climate regions
- Step 4 – scenario driven / time evolved parameter change
 - Future work

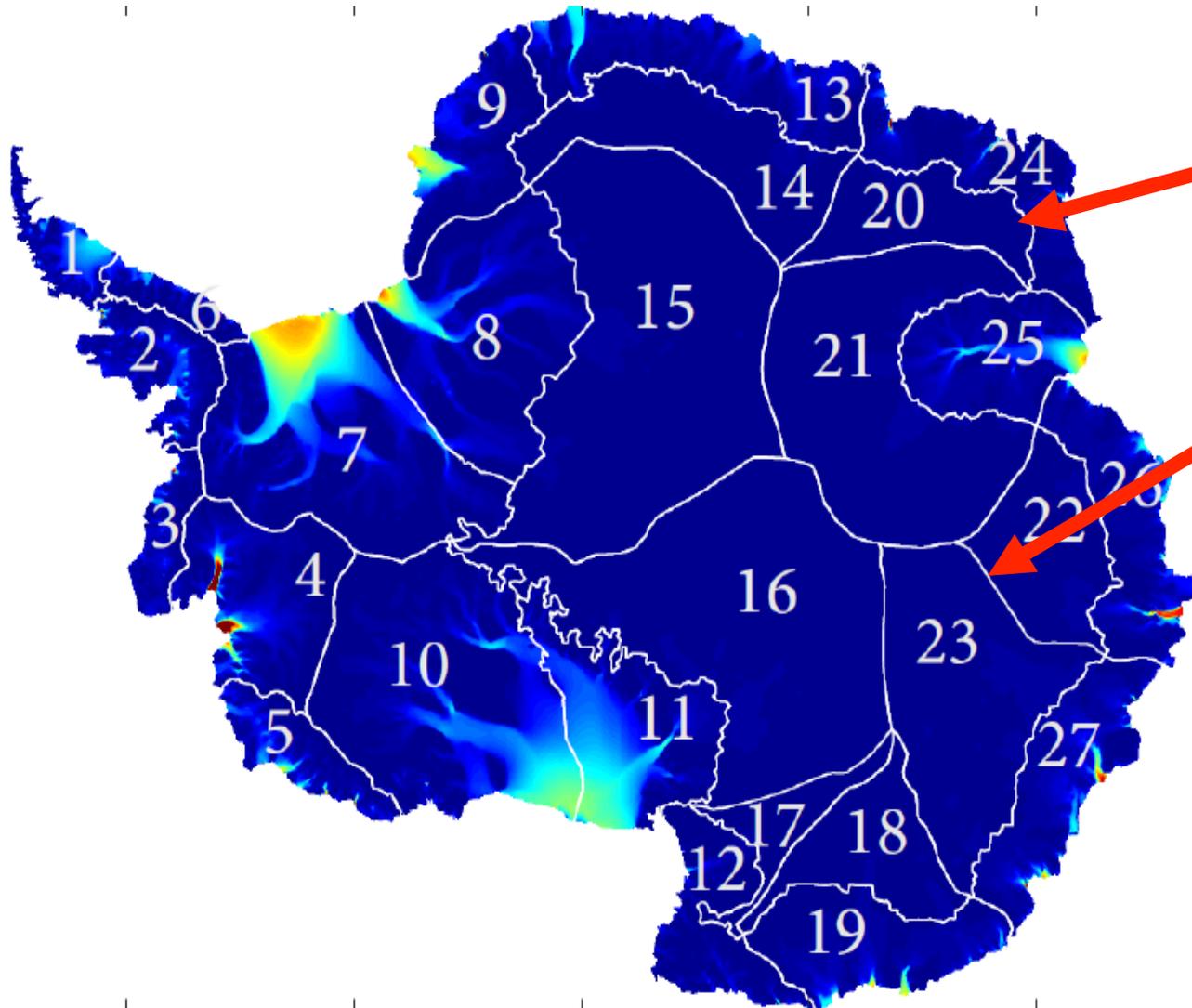
Each AIS UQ Monte-Carlo Experiment: Varied 4 parameters, 200 values each, 800 runs total for each experiment

Uncertainties in Bedrock Topography

- Bedmap 1 vs Modified Bedmap 2: $\sim 0.4\text{m}$ ($\sim 33\%$) mean SLR difference at 100yrs for extreme climate scenario
- Residual uncertainty in AIS topography is \sim Bedmap1 / Bedmap 2 correction
- **Completing high resolution bedmap of AIS is a quantifiably low risk / high pay-off measurement**



“Smart” Partitions



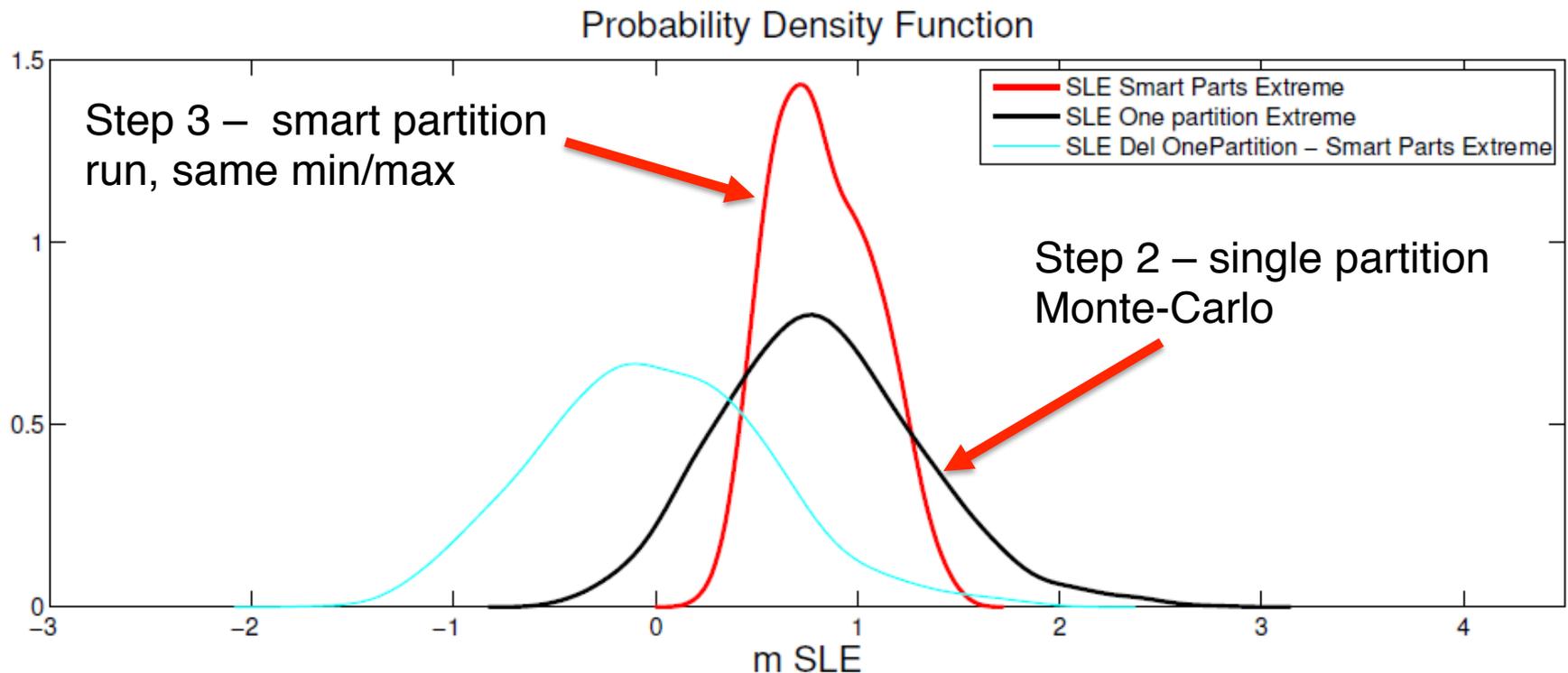
Climate split
~@2km based
boundary

Drainage basin
based boundary

- Climate zone - per Palerme et al 2016 (CMIP5 comparison / summary paper)
- Surface melt regions from DeConto et al., 2016
- Drainage basins per Bamber / Rignot / Zwally
- Ocean regions per discussions with M. Schodlok (ECCO2)

Single Partition vs “Smart” Partitioning

- General effect is **reduction in the spread of sea level contribution** since now not all parts of AIS are assumed to have the same parameter values





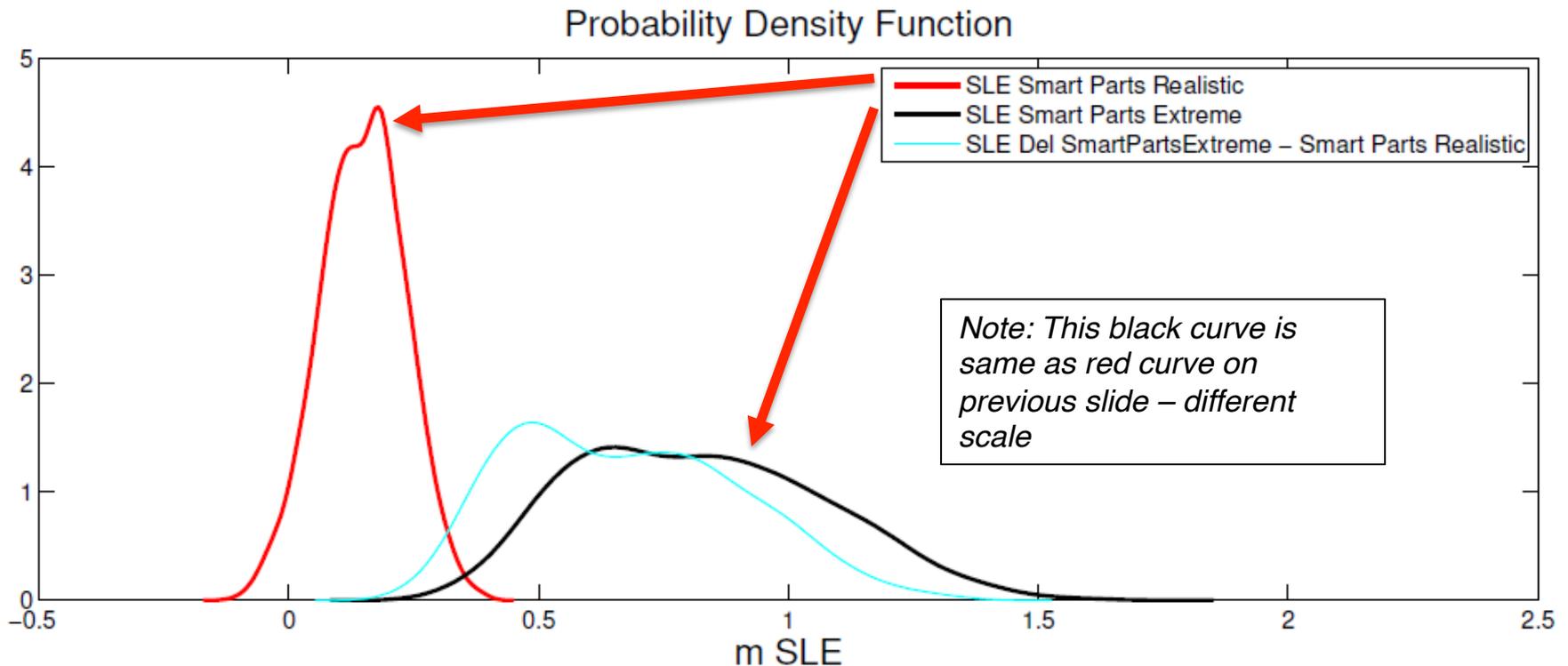
“realistic” min/max parameter value selection for smart partitions

- All min/max values are % **multipliers** relative to control
- Literature review for **RCP 8.5 climate predicts** for each of the 27 smart partition areas
 - RCP 8.5 regional GCM model predicts used to derive SMB and ice viscosity (based on surface temperature)
 - Minimum +/- on viscosity set to 5% to reflect floor uncertainty value
- Basal drag min/max derived from **range of basal drag inversion solutions** for different model resolutions and optimization levels -> resulted in +/- 15% to +/-25% estimate, region dependent
 - Assumed that over 100 yr time scale our present uncertainty, and not substantial new lubrication / warming, is what drives the range
- Basal (ocean i/f) melt rate – min based on present day mean observation best fit, max based on results of our basal melt sensitivity experiment – multiplied calculated **sensitivity per deg C, by available delta T from CDW** outside each of the cavities
 - Assumes worst case scenario that warmest present day CDW water makes it into ice cavity everywhere around AIS



Extreme vs More Realistic min/max

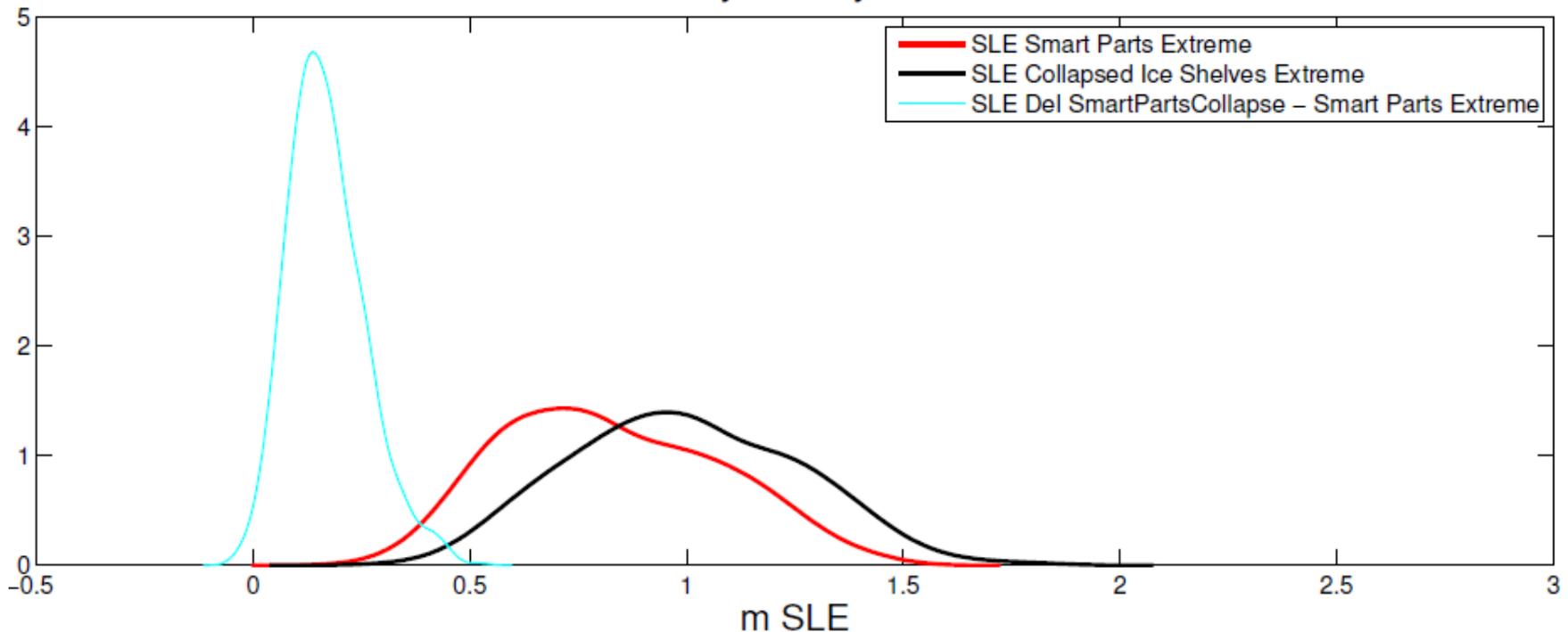
- Examples of parameter range differences for “realistic” vs “extreme” runs (% relative to control, which is “best estimate of current conditions”):
 - Basal drag: (-15 to -25%) to (+15 to 25%); 0 to -40%
 - Viscosity: (-5 to -10%) to +5%; -60% to 0
 - Melt rate: 0 to (2x to >200x) ; 0 to 10x



Impact of Ice Shelf Buttressing

- Experiment to look at 100 yr SLR impact of “instant loss of all AIS ice shelves” (removing backstress)
 - Achieved by new fixed ice shelf at current grounding line. As grounding line retreats, shelf can slowly re-form
 - Max. 95% difference case: ~ 0.4 m

Probability Density Function



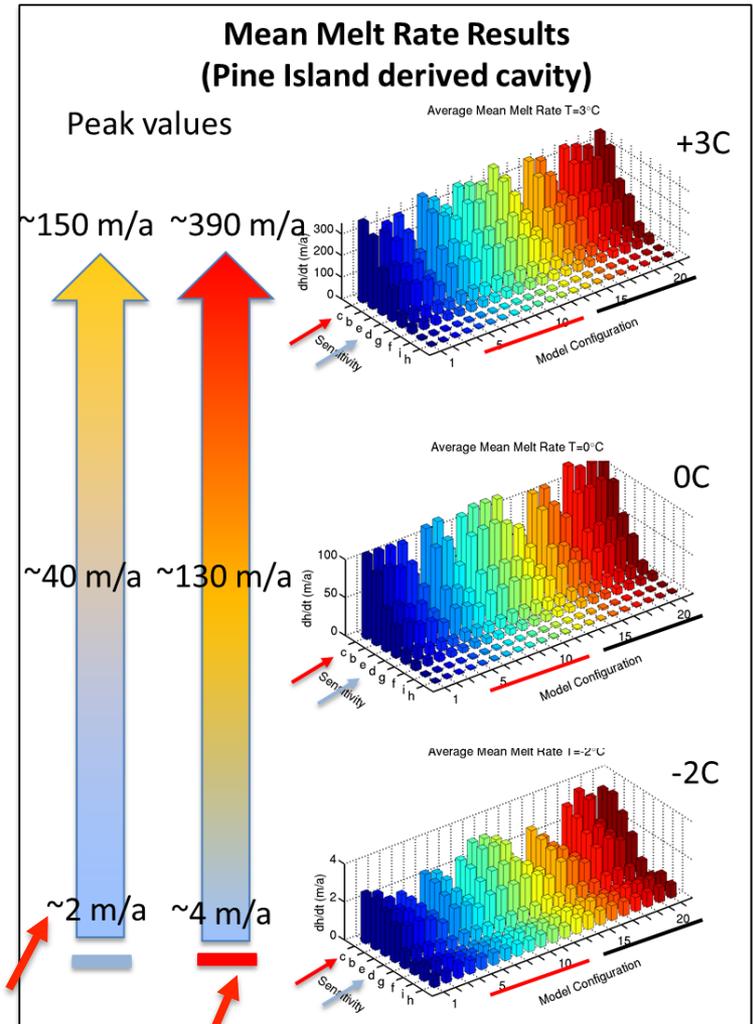
Basal Melt Rate Sensitivity

Ocean warming at ice interface potentially important for large SLR cases

- Ice shelf cavity interface water temperature increase of 2°C can result in 20x to 30x increase in melt rate
 - Credibility / Likelihood of 2°C rise in Southern Ocean ice boundary water in next 100 yrs is very low, but impact is high
- Measurement and prediction of evolution of AIS ice cavity interface water temperature is important for constraining future worst-case SLR

Current best estimate heat exchange coefficients

High end heat exchange coefficients





Sea Level Rise Budget Implications

Pfeffer et al, 2008

Source for 2m upper bound in NCA. 1.1m of which comes from AIS + GIS

Table 3. SLR projections based on kinematic scenarios. Thermal expansion numbers are from (22).

	SLR equivalent (mm)		
	Low 1	Low 2	High 1
<i>Greenland</i>			
Dynamics	93	93	467
SMB	71	71	71
Greenland total	165	165	538
<i>Antarctica</i>			
PIG/Thwaites dynamics	108		394
Lambert/Amery dynamics	16		158
Antarctic Peninsula dynamics	12		59
SMB	10		10
Antarctica total	146	128	619
<i>Glaciers/ice caps</i>			
Dynamics	94		471
SMB	80		80
GIC total	174	240	551
Thermal expansion	300	300	300
Total SLR to 2100	785	833	2008

Likely extreme upper bound - Our results indicate it is difficult to get this much ice out of GIS, even under extreme conditions

Reasonable but not extreme upper bound: Our results agree with there upper bounds given conservative, but not extreme, AIS parameters and boundary conditions. However, if un-expected / extreme conditions develop, AIS is capable of dynamically sourcing substantially more ice in 100 yrs (+1m)



Conclusions

- Extreme worst-case scenarios show values > 1 m for Antarctica; with “realistic worst case” ~ 0.25 - 0.4 m
- Range of sea level PDFs highly dependent on regional dependencies (one vs. “smart” partitions)
- Loss of backstress leads to contribution of < 0.5 m (given physics used)
- Early results are useful for identifying some of the most promising new measurements for the sea level rise prediction problem, including
 - Finishing high resolution mapping of AIS bed topography
 - Monitoring heat exchange at AIS ocean / ice interface
- Funding for ice sheet models
 - Proper funding of model development to address missing physics (e.g. ice shelf calving)
 - Computational resources for high resolution Monte Carlo runs



Thank you!