PISM
Parallel Ice Sheet Model

Using Gaussian Process Emulators to Reduce Uncertainty in Sea Level Projections with Ice Sheet Models

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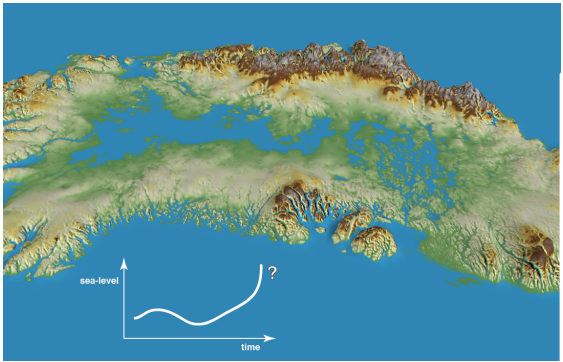
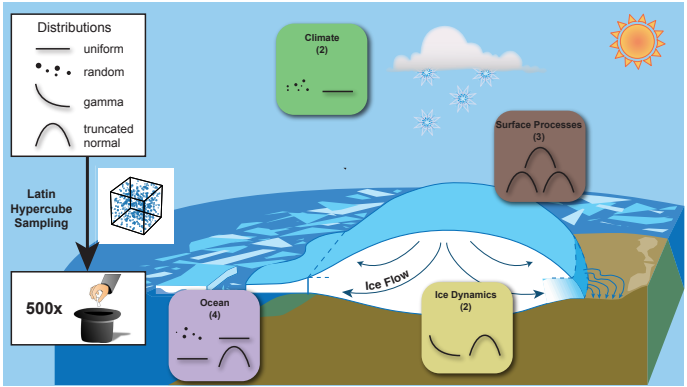
Background

- Ice sheet melt rates are increasing with higher global temperatures
- Greenland ice sheet (GrIS) has 7.2 m sea level equivalent
- 5-33 cm sea level contribution by 2100 (Aschwanden *et al.* 2019)



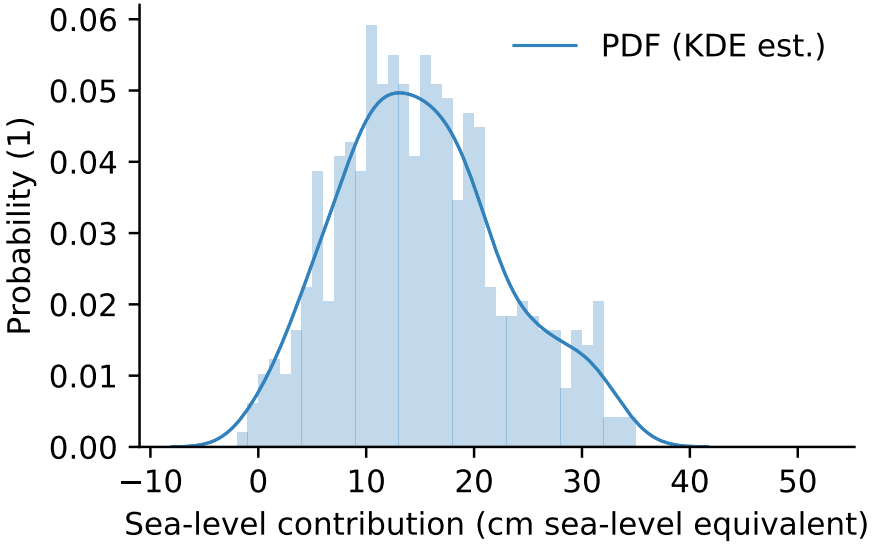
(RCP 8.5, Year 3000)

Background



- Numerical models predict mass loss as function of geophysical parameters: $y = f(\mathbf{x}), \mathbf{x} = x_1, x_2, x_3, \ldots$
- Models have uncertainties (e.g. structural, parametric)
- Parametric: vary parameter values in simulation runs ("ensemble members") of model

Estimates of GrIS Sea Level Contribution



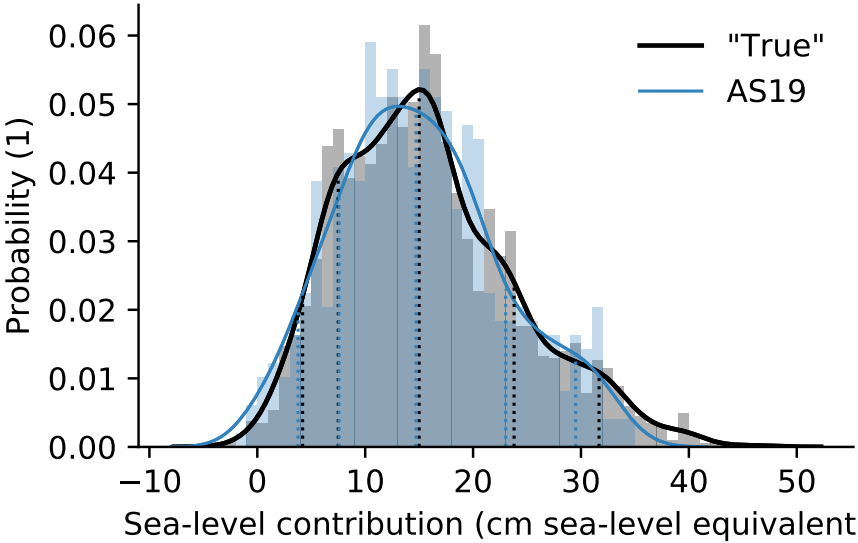
RCP 4.5, Year 2100 from Aschwanden *et al.* 2019

11 critically important parameters in Parallel Ice Sheet Model (PISM)

Research Question

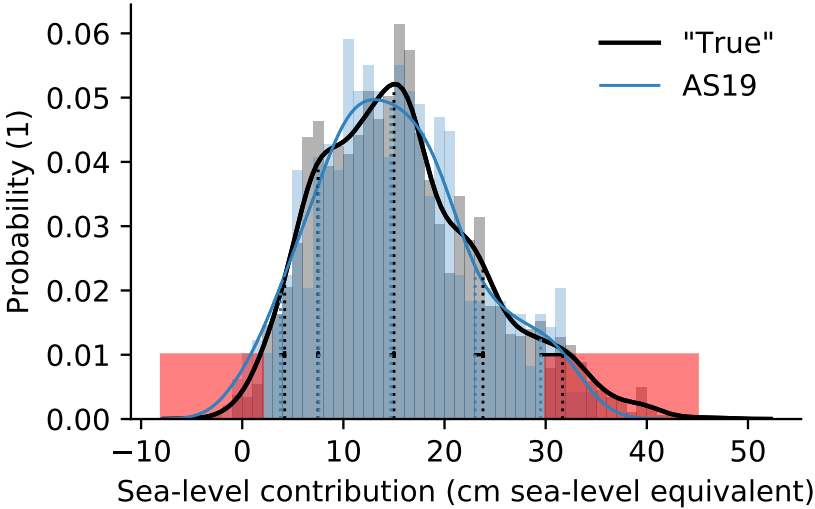
How well does the 500-member ("AS19") ensemble characterize the "true" (or complete) probability density function (PDF)?

Validation Ensemble (RCP 4.5, Year 2100)



"True" 4,000-member ensemble close to complete PDF

Validation Ensemble (RCP 4.5, Year 2100)

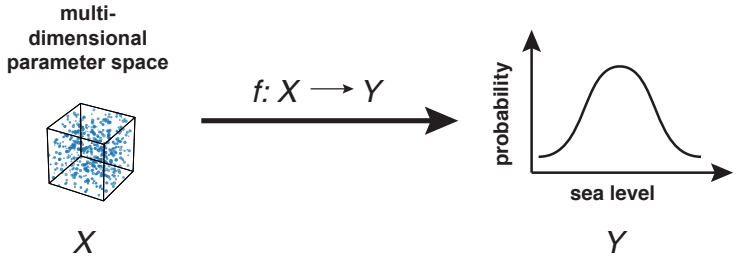


Problem: Infeasible supercomputing time, underestimates tails of "True" PDF

Need: Computationally efficient approximation that captures uncertainty

Solution: Gaussian Process (GP) Emulators

- Following Edwards *et al.* 2019
- Trained on 500 members, predictions with 4,000 members
- **Benefits: computationally cheaper, provides uncertainty estimates of predictions**



*Assume PISM is validated

Gaussian Process

- Infinite set of random variables
  - Subset has joint multivariate normal distribution

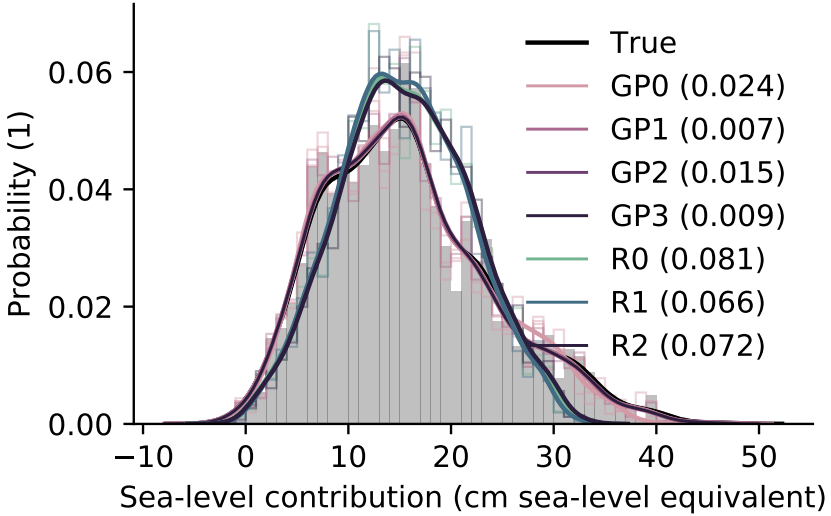
$$f(\mathbf{x}) \sim \mathcal{N}(m(\mathbf{x}), K(\mathbf{x}, \mathbf{x}_i))$$

where $\mathbf{x}$ is a finite collection of sample points

Specified by mean function $m(\mathbf{x})$ and covariance function $K(\mathbf{x}, \mathbf{x}_i)$

- Mean function: expected values of $f(\mathbf{x})$
- Covariance function: outputs of highly correlated inputs are close together

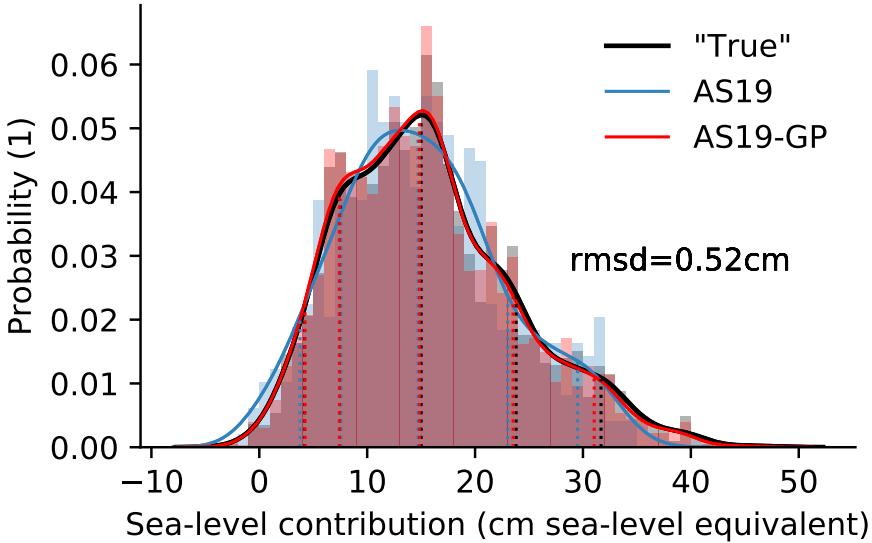
Emulators vs. Fixed-Parameter Linear Models



Kullback-Leibler divergence - information lost in approximation of "True" PDF

Emulators outperform other regression methods (R0-R2)

GP1 Emulator vs. Numerical Model



Conclusion

- Numerical models are computationally expensive to run and do not capture complete probability distribution well
- Emulators enhance value of numerical models and decrease uncertainty in sea level projections
- Lots of other applications for emulators!

References

- Aschwanden, A., Fahnestock, M. A., Truffer, M., Brinkerhoff, D. J., Hock, R., Khroulev, C., Mottram, R., & Khan, S. A. (2019). Contribution of the Greenland Ice Sheet to sea level over the next millennium. Sci. Adv. **5**(6).

- Edwards, T. L., Brandon, M. A., Durand, G., Edwards, N. R., Golledge, N. R., Holden, P. B., Nias, I. J., Payne, A. J., Ritz, C., & Wernecke, A. (2019). Revisiting Antarctic ice loss due to marine ice-cliff instability. Nature **566**:58-64.

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