Scenario Planning for Sea Level Rise via Markov Decision Processes

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Project Team

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Sea Level Rise

The New York Times

Sep. 25, 2018	Saving Scotland's Heritage From the Rising Seas
Sep. 12, 2018	North Carolina, Warned of Rising Seas, Chose to Favor Development
Feb. 23, 2018	What Land Will Be Underwater in 20 Years? Figuring It Out Could Be Lucrative
Aug. 7, 2017	The Sea Level Did, in Fact, Rise Faster in the Southeast U.S.
Mar. 14, 2016	Rising Sea Levels May Disrupt Lives of Millions, Study Says

The Washington Post

Sep. 20, 2018	At this rate, Earth risks sea level rise of 20 to 30 feet, historical analysis shows
Sep. 6, 2018	Welcome to Virginia Beach, home of the East Coast's fastest-rising sea level
Aug. 20, 2018	Sea level rise is eroding home value, and owners might not even know it
Feb. 13, 2018	Study: Sea-level rise is accelerating, and its rate could double in next century
Sep. 10, 2017	Tampa Bay may escape the worst of its nightmare scenario

Sea Level Rise

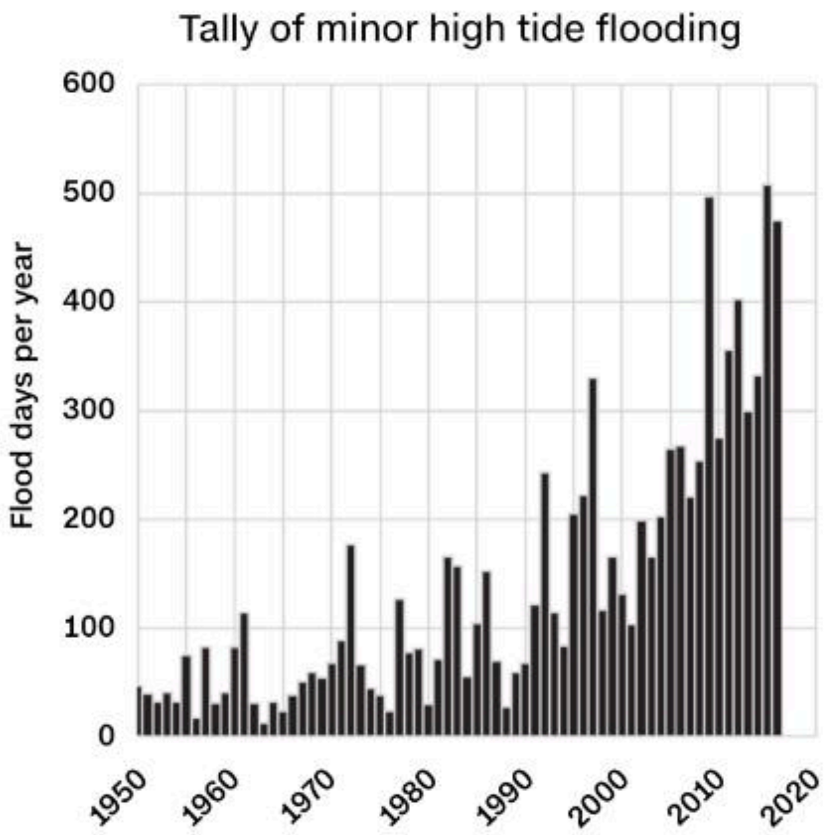
CNN (March 7, 2018)

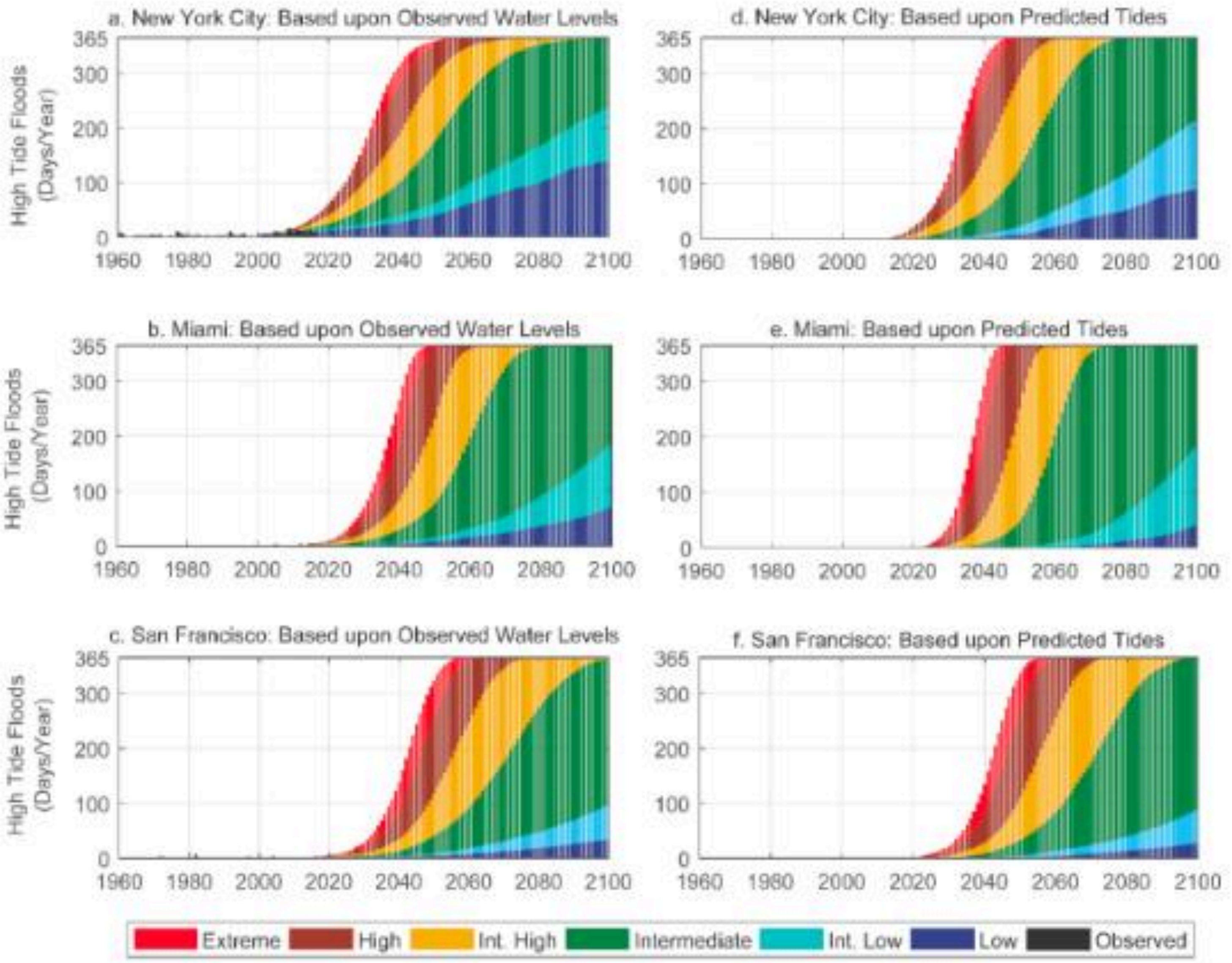
As sea levels rise due to global warming, the kind of flooding currently experienced only in storms will happen during normal high tides. It's known as ***"sunny day flooding."***

"Sunny day flooding, or high tide flooding, is flooding which is increasingly happening with no storm or rain in sight," William Sweet, report author and NOAA oceanographer told CNN.

"It is a direct response to years of local relative sea level rise," Sweet said.

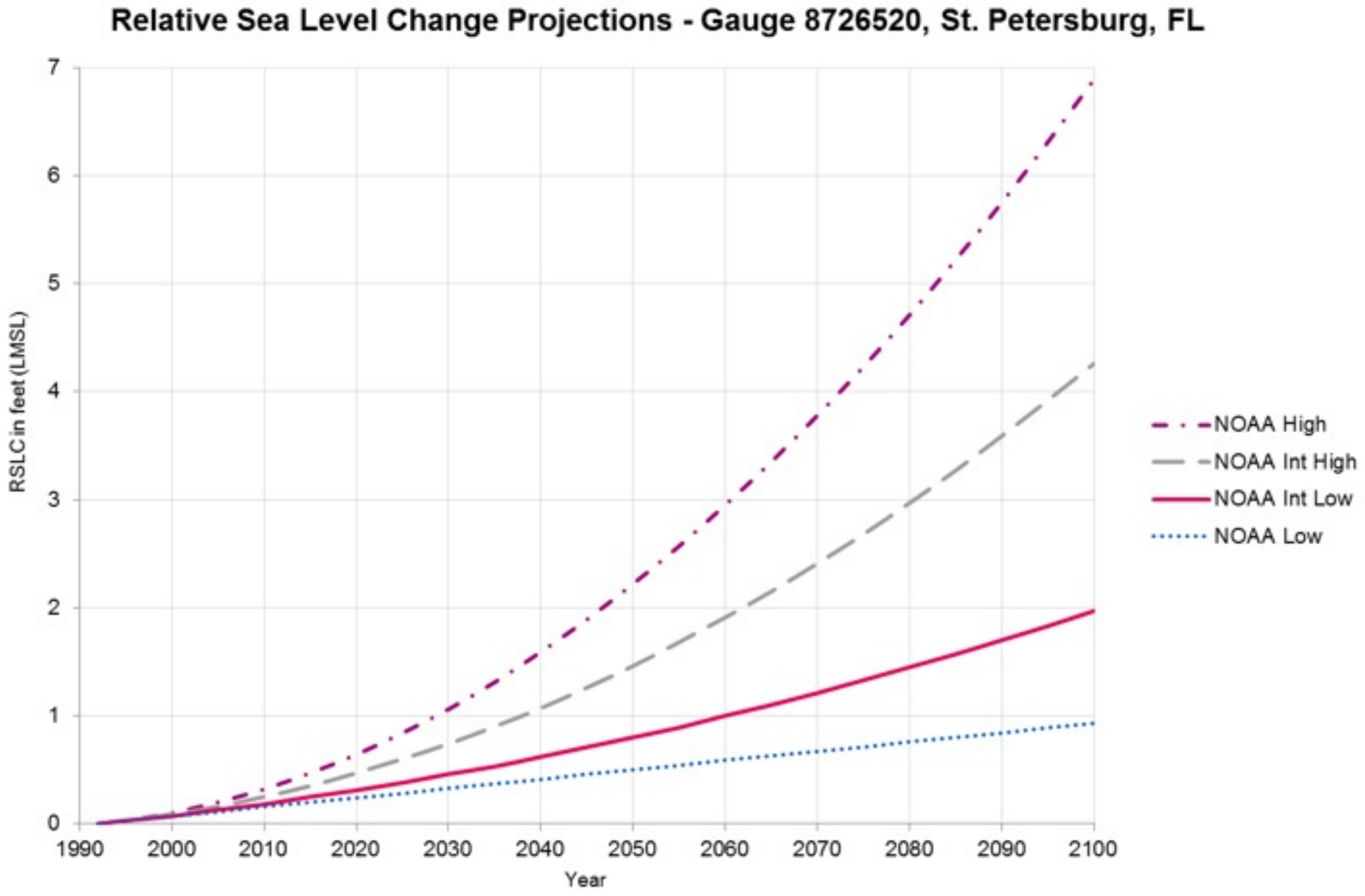
Sea Level Rise





Sea Level Rise in Tampa Bay

- Sea level had risen naturally for centuries, about an inch per decade. But in the mid-1990s, it accelerated
- "Flooding in Florida will eventually cost the state regardless of whether a hurricane hits it" (WP, 9/10/17, Report by Risky Business)
- In 12 years, the value of property that will be lost to sinking land and rising water will amount to $15 billion. By midcentury, that figure is likely to increase to $23 billion, the report said.
- $175 billion loss in a storm the size of Hurricane Katrina
- Tampa Bay one of the 10 most at-risk areas on the globe (World Bank study)



Motivation & Literature Review

- Global climate change and its impacts to the coastal United States and Florida, in terms of sea level rise, have been extensively documented, analyzed and projected [1-6]
- Multiple threats, including increased frequency of compound events - such as
  - storm surge combined with heavy precipitation [7]
  - Threatens particularly underserved communities [8, 9]
  - Stresses coastal ecosystems [10, 11]
  - Impacts local economies by affecting property values, the tax base, and the cost of insurance, among other factors [12]
- Due to uncertainty in SLR impacts, risk assessment tools are needed for governments, planners, coastal managers, etc. [13-17]
- Modeling how stakeholders, such as governments, businesses, and residents, may respond to sea level rise scenarios can assist in the creation of policies tailored to local impacts [18-20]

1. R. K. Pachauri, et al., “Climate change 2014: synthesis report” Intergovernmental Panel on Climate Change . IPCC, 2014.

2. A. Hine, D. Chambers, T. Clayton, M. Hafen, and G. Mitchum, “Sea Level Rise in Florida: Science, Impacts, and Options” University Press of Florida, 2016.

3. A. H. Sallenger Jr, K. S. Doran, and P. A. Howd, “Hotspot of accelerated sea-level rise on the atlantic coast of north america,” Nature Climate Change , vol. 2, no. 12, pp. 884–888, 2012.

4. Tampa Bay Climate Science Adivsory Panel, “Recommended projection of sea level rise in the tampa bay region,” 2015.

5. C. J. Hapke, O. Brenner, R. Hehre, and B. Reynolds, “Assessing hazards along our nation’s coasts,” US Geological Survey, Tech. Rep., 2013.

6. U. D. of the Interior, “National assessment of coastal change hazards: Understanding vulnerability to sea level rise,” US Geological Survey, Tech. Rep., 2014.

7. T.Wahl, S. Jain, J. Bender, S. D. Meyers, and M. E. Luther, “Increasing risk of compound flooding from storm surge and rainfall for major us cities,” Nature Climate Change , vol. 5, no. 12, 2015.

8. S. B. Kashem, B.Wilson, and S. Van Zandt, “Planning for climate adaptation: Evaluating the changing patterns of social vulnerability and adaptation challenges in three coastal cities,” Journal of Planning Education and Research , vol. 36, no. 3, pp. 304–318, 2016.

9. G. Schrock, E. M. Bassett, and J. Green, “Pursuing equity and justice in a changing climate: Assessing equity in local climate and sustainability plans in us cities,” Journal of Planning Education and Research , vol. 35, no. 3, pp. 282–295, 2015.

10. R. J. Nicholls, “Planning for the impacts of sea level rise,” Oceanography , vol. 24, no. 2, pp. 144–157, 2011.

11. T. Wahl, F. M. Calafat, and M. E. Luther, “Rapid changes in the seasonal sea level cycle along the us gulf coast from the late 20th century,” Geophysical Research Letters , vol. 41, no. 2, 2014.

12. X. Fu, J. Song, B. Sun, and Z.-R. Peng, “living on the edge: Estimating the economic cost of sea level rise on coastal real estate in the tampa bay region, florida,” Ocean & Coastal Management , vol. 133, pp. 11–17, 2016.

13. T. Beatley, Planning for coastal resilience: best practices for calamitous times . Island Press, 2012.

14. M. K. Buchanan, R. E. Kopp, M. Oppenheimer, and C. Tebaldi, “Allowances for evolving coastal flood risk under uncertain local sea-level rise,” Climatic Change , vol. 137, no. 3-4, 2016.

15. J. Hinkel, C. Jaeger, R. J. Nicholls, J. Lowe, O. Renn, and S. Peijun, “Sea-level rise scenarios and coastal risk management,” Nature Climate Change , vol. 5, no. 3, pp. 188–190, 2015.

16. W. V. Sweet and J. Park, “From the extreme to the mean: Acceleration and tipping points of coastal inundation from sea level rise,” Earth’s Future , vol. 2, no. 12, pp. 579–600, 2014.

17. X. Fu, M. Gomaa, Y. Deng, and Z.-R. Peng, “Adaptation planning for sea level rise: A study of us coastal cities,” Journal of Environmental Planning and Management , vol. 60, no. 2, 2017.

18. J. Tribbia and S. C. Moser, “More than information: what coastal managers need to plan for climate change,” Environmental science & policy , vol. 11, no. 4, pp. 315–328, 2008.

19. P. R. Berke and M. R. Stevens, “Land use planning for climate adaptation: Theory and practice,” Journal of Planning Education and Research , vol. 36, no. 3, pp. 283–289, 2016.

20. A. Drogoul, “Agent-based modeling for multidisciplinary and participatory approaches to climate change adaptation planning,” in Proceedings of RFCC-2015 Workshop, AIT , 2015.

Major Results

- Considering a single-agent MDP problem for government decision making on infrastructure improvements against SLR
  - Theory says a rational government should be proactive by making decisions based on observed sea levels in order to minimize the total cost
  - As opposed to a straightforward government that reacts to observed cost from nature

- Considering NOAA's SLR projections and different government and resident prototypes
  - Show convergence of a Reinforcement Learning algorithm for finding optimum policies
  - Generate SLR scenarios for different government & resident prototypes

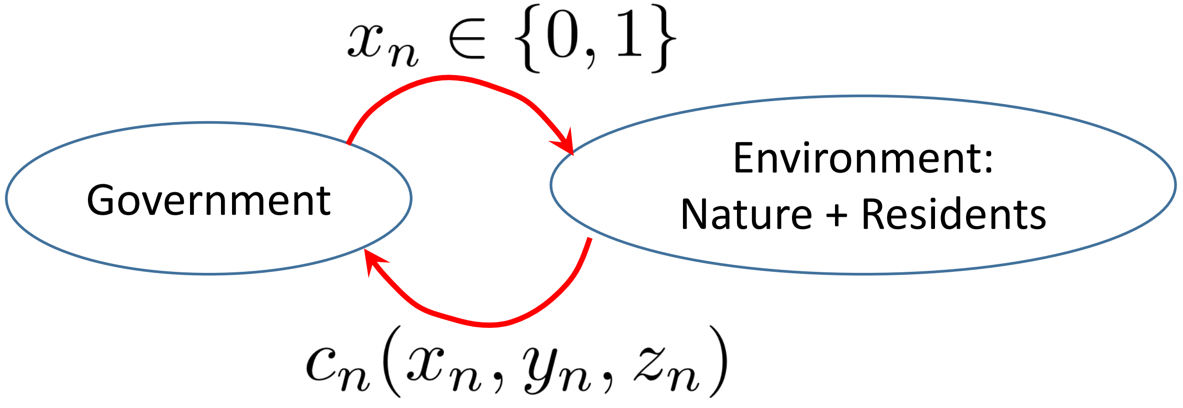
  (value of cooperation)

SLR Board Game based on MDP model

- Atlantis: A Game of Sea Level Rise
  - Focusing on City of Dunedin, FL
  - Nature, government, residents, businesses
  - Emphasizes importance of cooperative actions

- Community Engagement & Some Fun
  - Game meeting with Tampa Audubon Society

MDP Model: $(\mathcal{S}, \mathcal{X}, \mathcal{P}, c, a_g)$



Markov state: $\mathcal{S}_n = (s_{n-1} + x_n, \ell_{n-1} + r_n)$

x_n : investment decision

c_n : system cost

$y_n \in \{0, 1\}$: residents' decision of support

$z_n \geq 0$: cost from nature

$s_n \in \{1, 2, ...\}$: infrastructure state

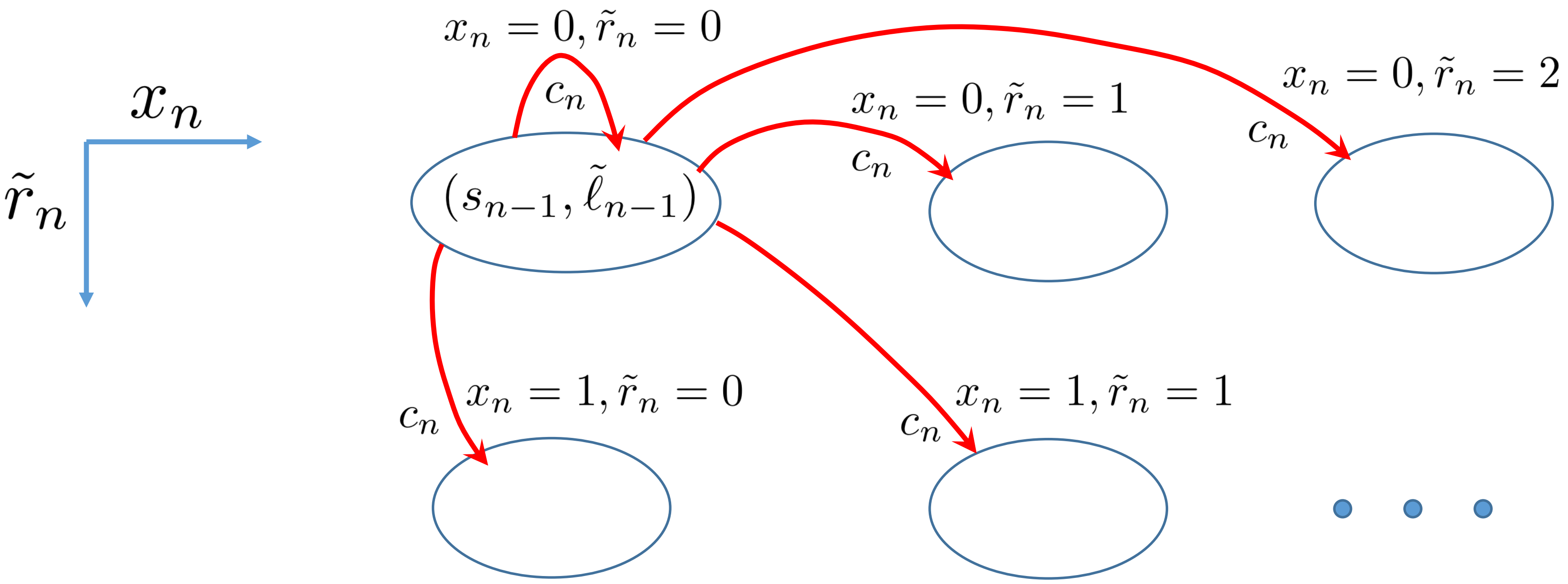
$$s_n = \sum_{m=1}^{n} x_m$$

$\ell_n \geq 0$: sea level

$r_n \geq 0$: sea level rise

$$\ell_n = \sum_{m=1}^{n} r_m$$

MDP Model: State Transition



$\tilde{r}_n \in \{0, 1, 2, \dots\}$: discretized sea level rise

MDP Model: Government

- Government makes a decision $x_n \in \{0, 1\}$ about investing in infrastructure improvement against SLR, e.g., storm water drainage system, sea wall, levee, etc.
- Cost function

$$C_N(\{x_n, y_n, z_n\}) = \sum_{n=0}^{N} a_g^n [(2 - y_n)x_n + z_n]$$

- $y_n \in \{0, 1\}$ denotes residents' decision to support government's investment
- $z_n \geq 0$ denotes cost from nature, e.g., flooding, storm surge, etc.
- $a_g \in (0, 1)$ discount factor denoting also **government's cooperation index**
- Time unit could be a year, two years, …
- Cost unit could be \$100 M, \$1 B, …

MDP Model: Residents

- Residents' decision governed by $y_n \sim \text{Bernoulli}(p_n)$

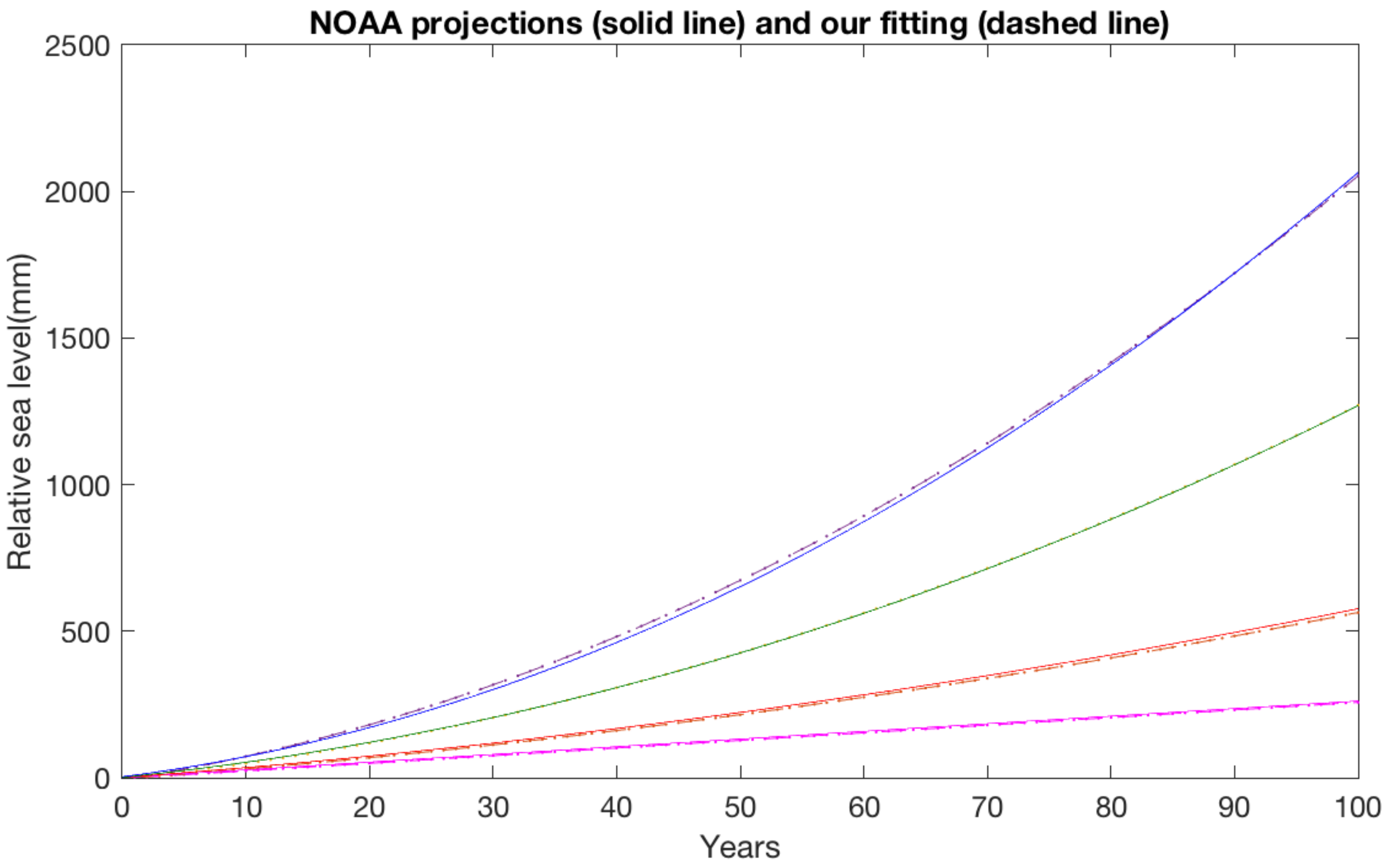
$$p_n = \sigma(q_n) = \frac{1}{1 + e^{-q_n}}$$

$$q_n = \sum_{m=1}^{n-1} a_r^{n-m} x_m z_m$$

- $a_r \in (0, 1)$ denotes **residents' cooperation index**
- For high probability of support, recently there must be both government investments and some serious cost from nature
- *That is, residents are typically followers; they are serious only when both government and nature are serious!*

MDP Model: Nature

- Sea level rise is modeled as
  $$r_n \sim \mathrm{Gamma}(\alpha, \beta)$$
  - $\beta = 0.5$
  - α set to match the mean SLR to different NOAA projections for St. Pete, FL
- Nature's cost is modeled as
  $$z_n \sim \mathrm{GeneralizedPareto}(k, \sigma, \theta)$$
  - $k = -0.001, \quad \theta = 0$
  - $\sigma_n = \dfrac{\eta(\ell_{n-1})^a}{(s_{n-1})^b}$



- Through η, a and b we control the impact of SLR over nature's cost (relative infrastructure)

Optimal Policy

- A rational government tries to minimize the expected cost $\mathsf{E}[C_N(x_n, y_n, z_n)]$ by choosing its actions $\{x_n\}$

- Bellman Equation:

$$V(s_{n-1}, \ell_{n-1}) = \min_{x_n} \mathsf{E}[c_n + a_g V(s_n, \ell_n) | x_n]$$

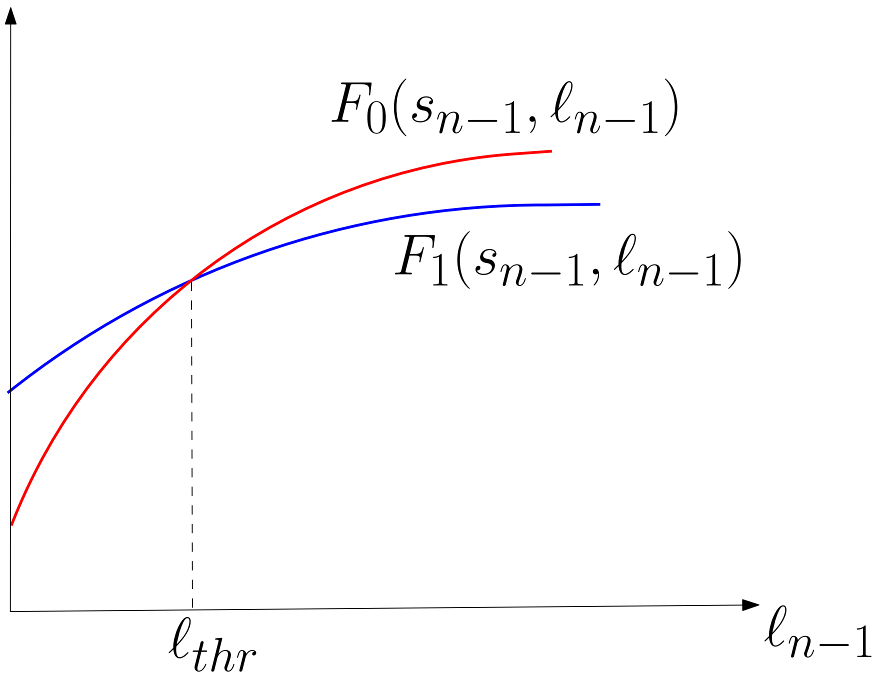
$$= \min \Big\{ \underbrace{\mathsf{E}[z_n + a_g V(s_{n-1}, \ell_{n-1} + r_n) | x_n = 0]}_{F_0(s_{n-1}, \ell_{n-1})},$$

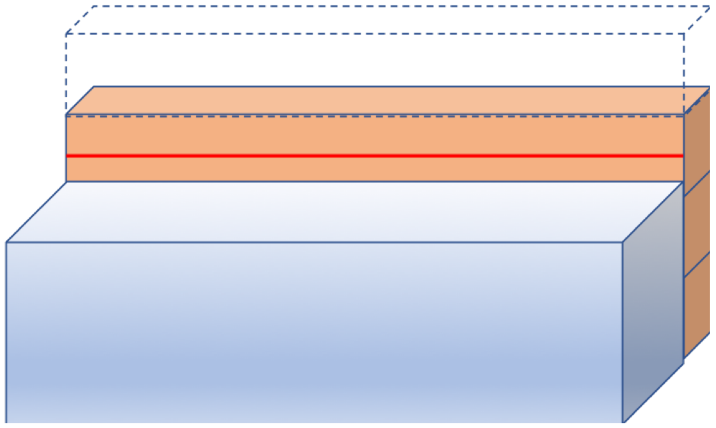
$$\underbrace{\mathsf{E}[2 - y_n + z_n + a_g V(s_{n-1} + 1, \ell_{n-1} + r_n) | x_n = 1]}_{F_1(s_{n-1}, \ell_{n-1})} \Big\}$$

Optimal Policy

Theorem 1: $F_0(s_{n-1}, \ell_{n-1})$ and $F_1(s_{n-1}, \ell_{n-1})$ are *concave, nondecreasing, and bounded* in ℓ_{n-1} for each s_{n-1}, and $\frac{\mathrm{d}}{\mathrm{d}\ell_{n-1}} F_0(s_{n-1}, \ell_{n-1}) > \frac{\mathrm{d}}{\mathrm{d}\ell_{n-1}} F_1(s_{n-1}, \ell_{n-1})$

Proof *via Value iteration and Mathematical induction.*





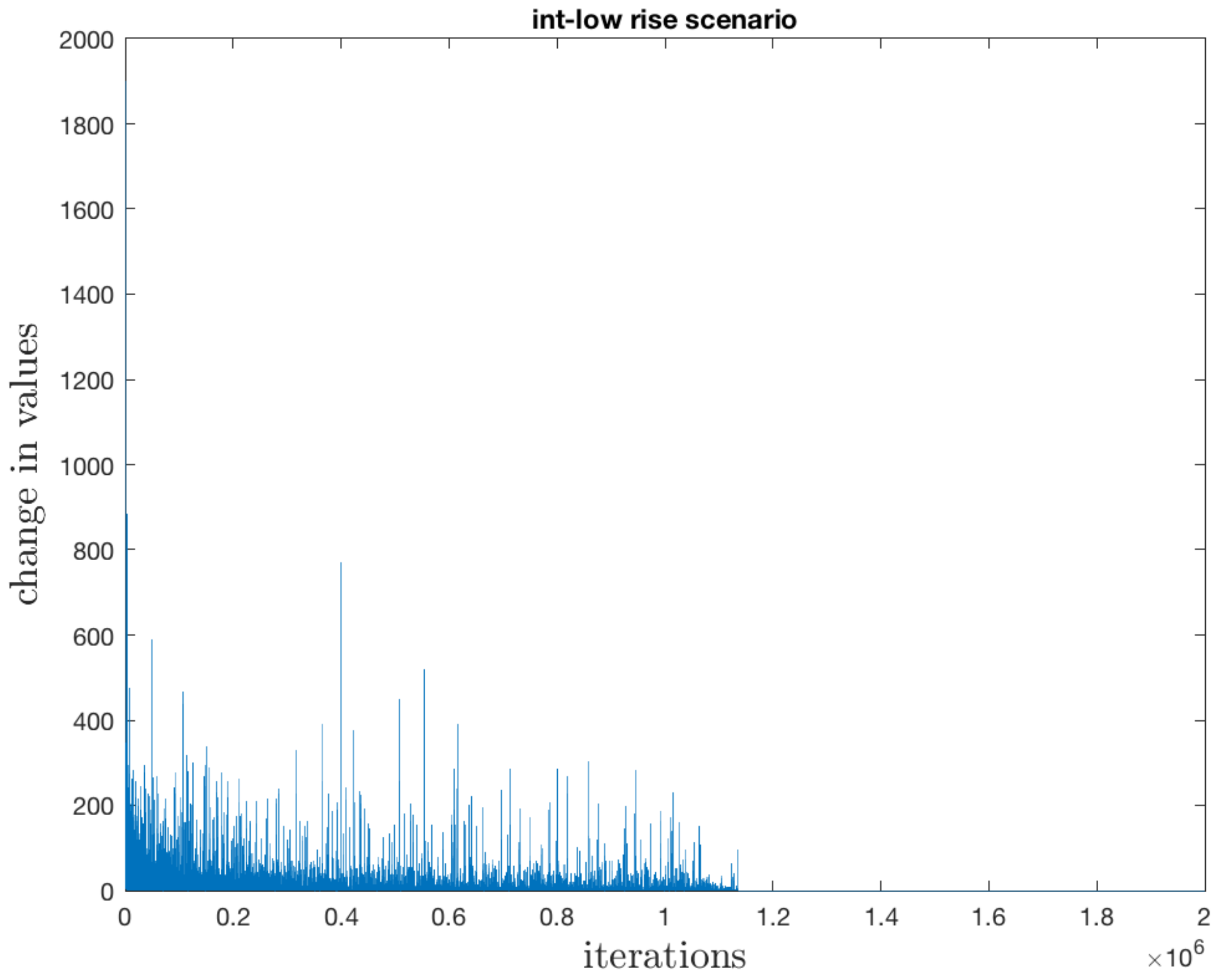
Finding Optimal Policy

- Reinforcement Learning, e.g., *Value iteration by Monte Carlo*

Theorem 2: Value iteration algorithm converges to a limit.

Proof: $V^i(s_{n-1}, \ell_{n-1})$ concave, nondecreasing in ℓ_{n-1} and bounded from Theorem 1.

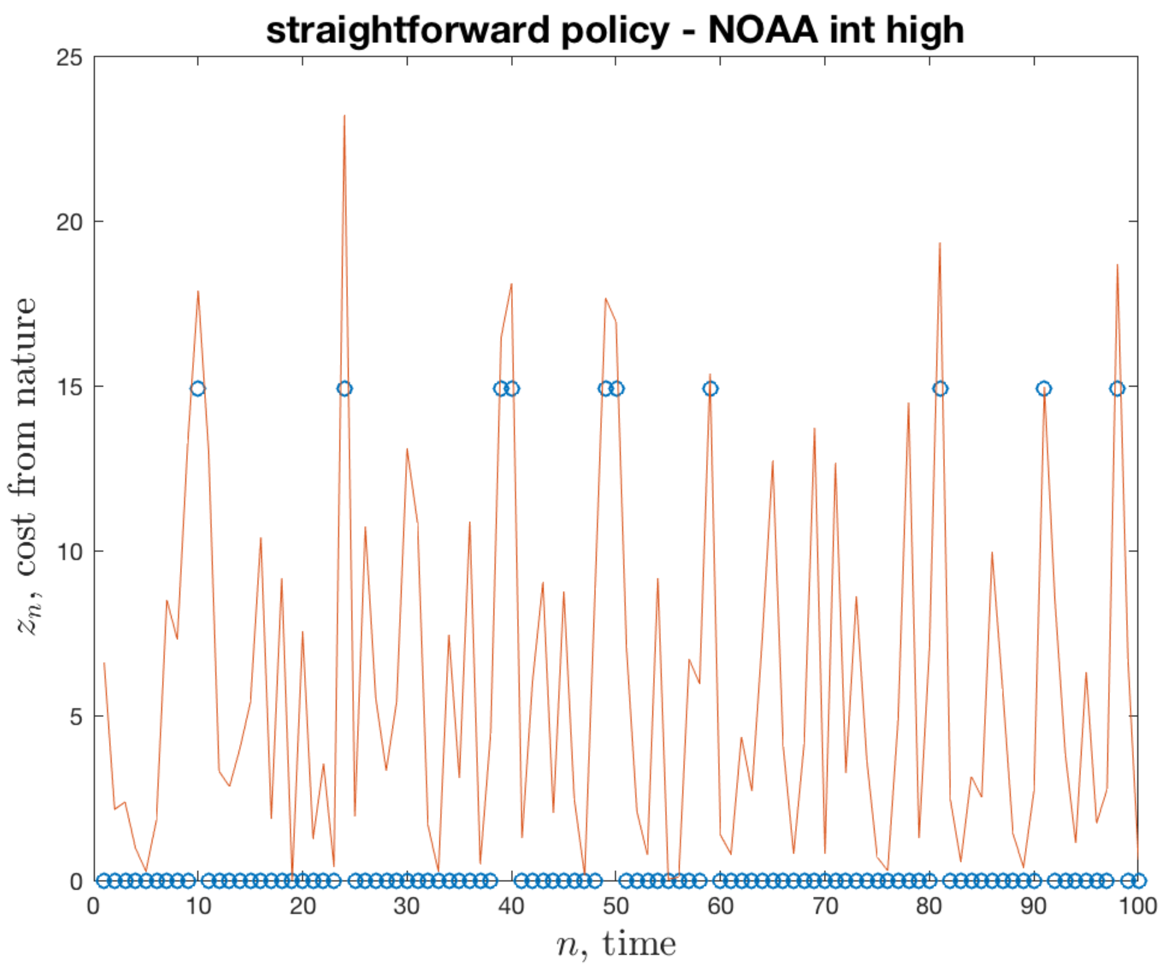
Show also nondecreasing in iteration i using mathematical induction.



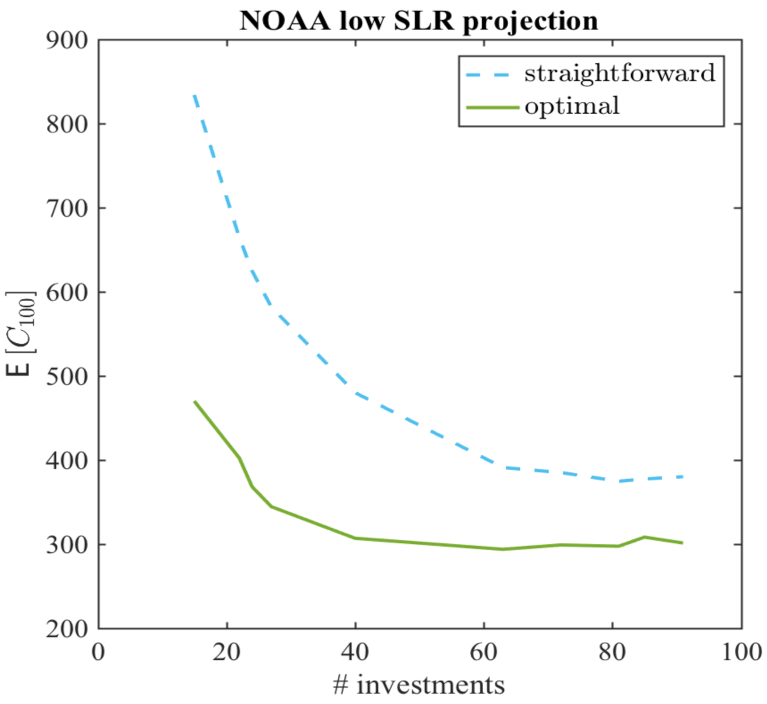
Simulations

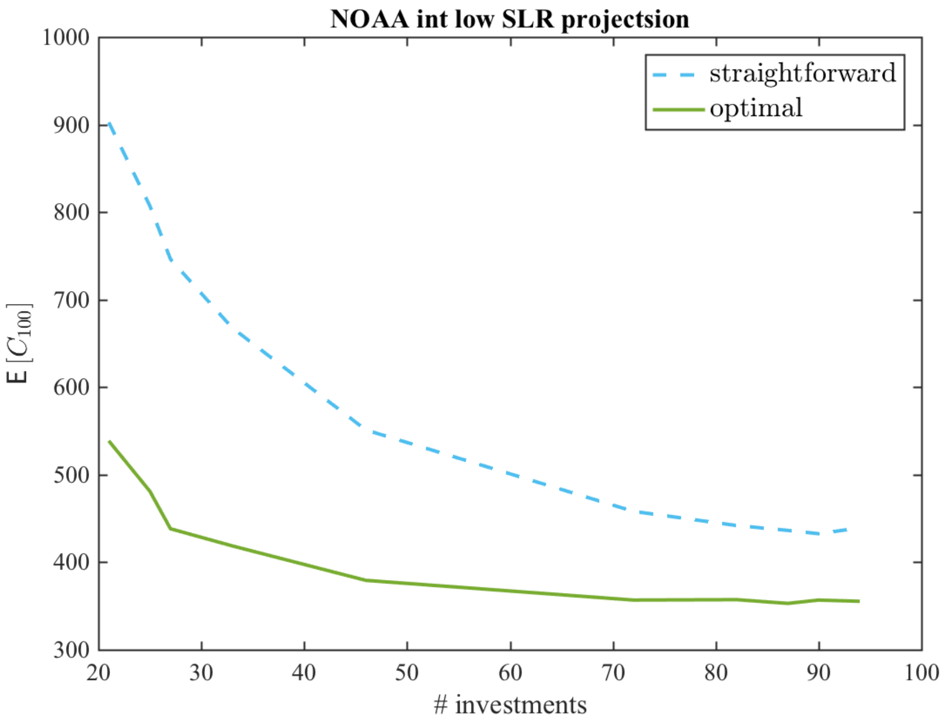
Optimal policy:

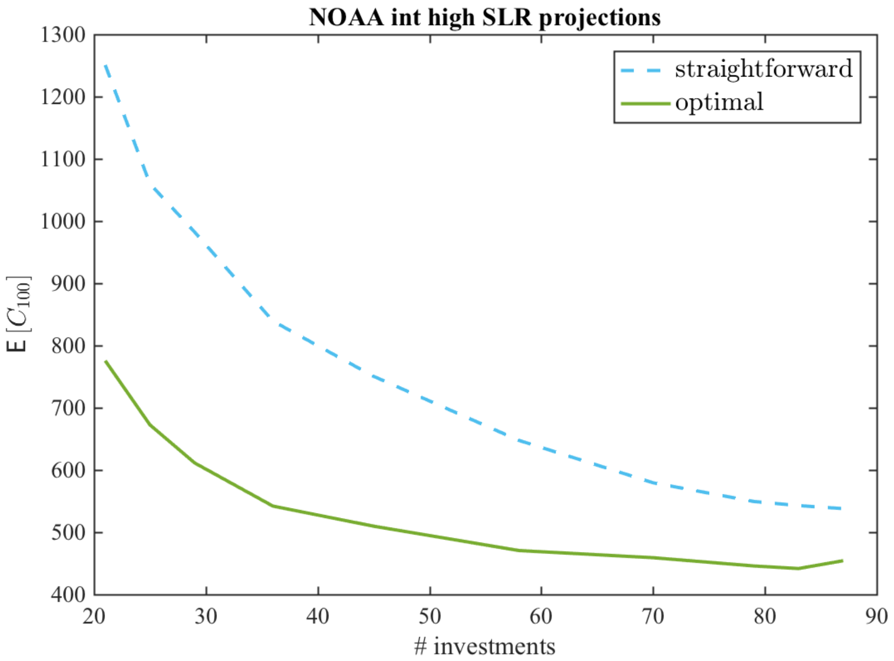
$$\sigma_n = \frac{2(\ell_{n-1})^{0.2}}{(s_{n-1})^{0.5}}$$

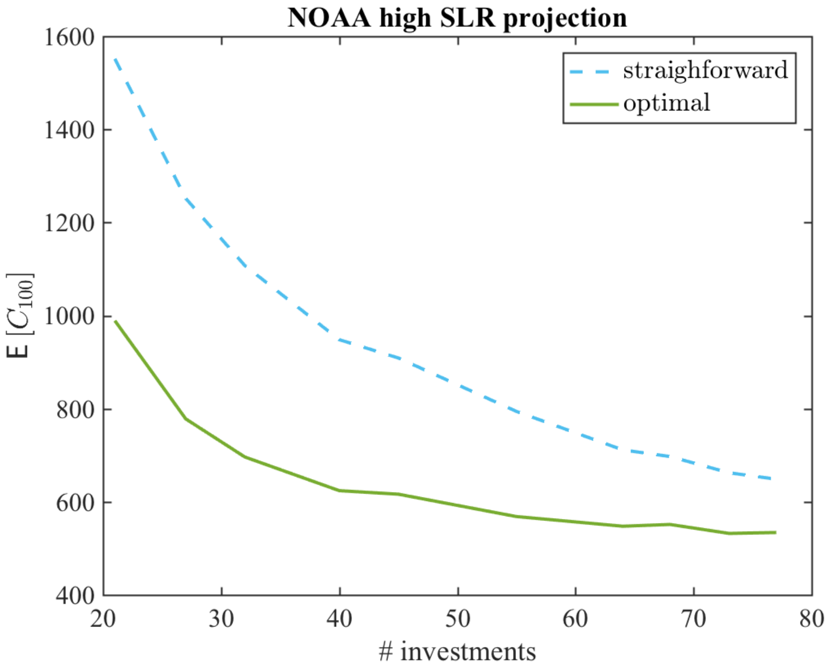


Simulations

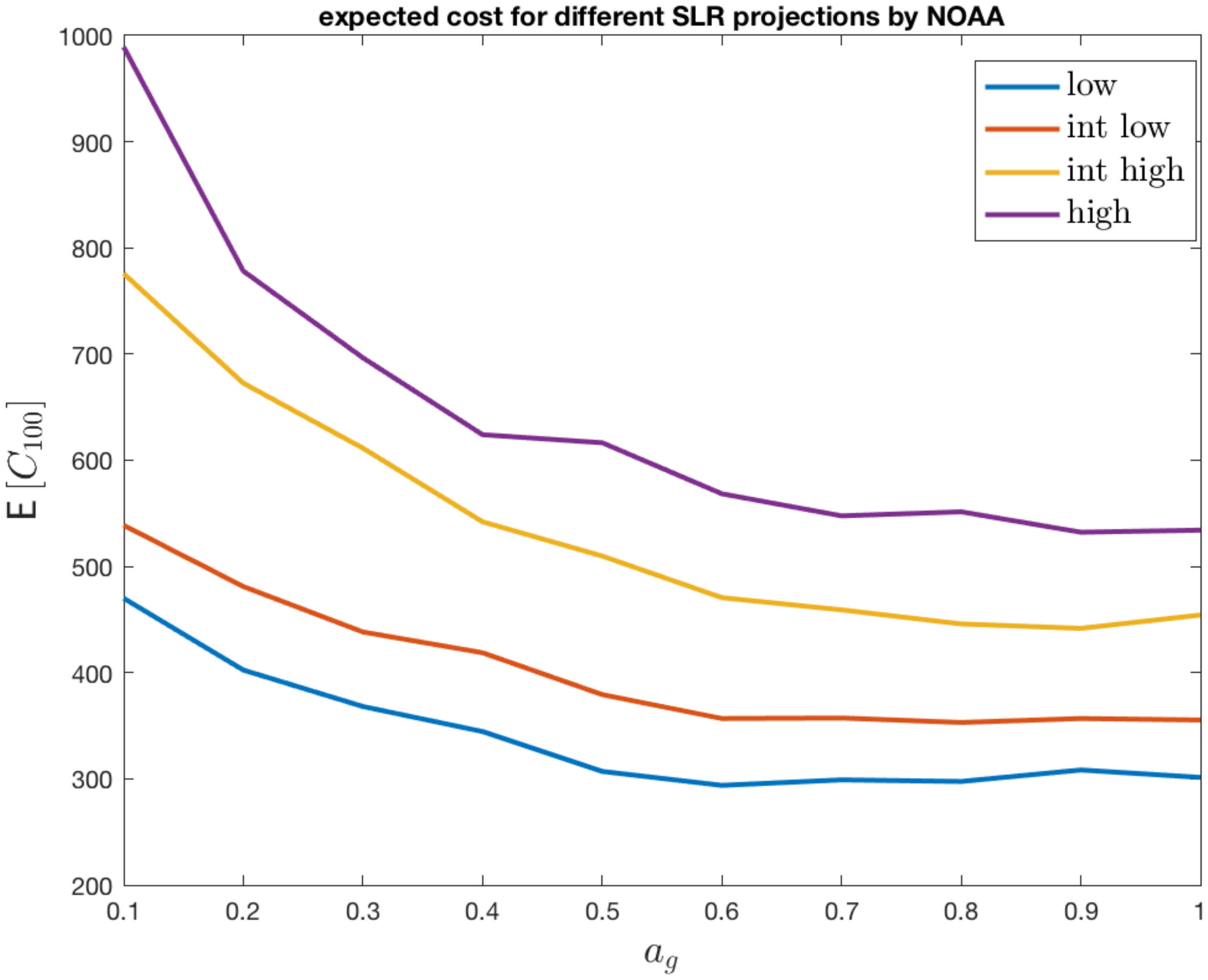








Scenario Simulations



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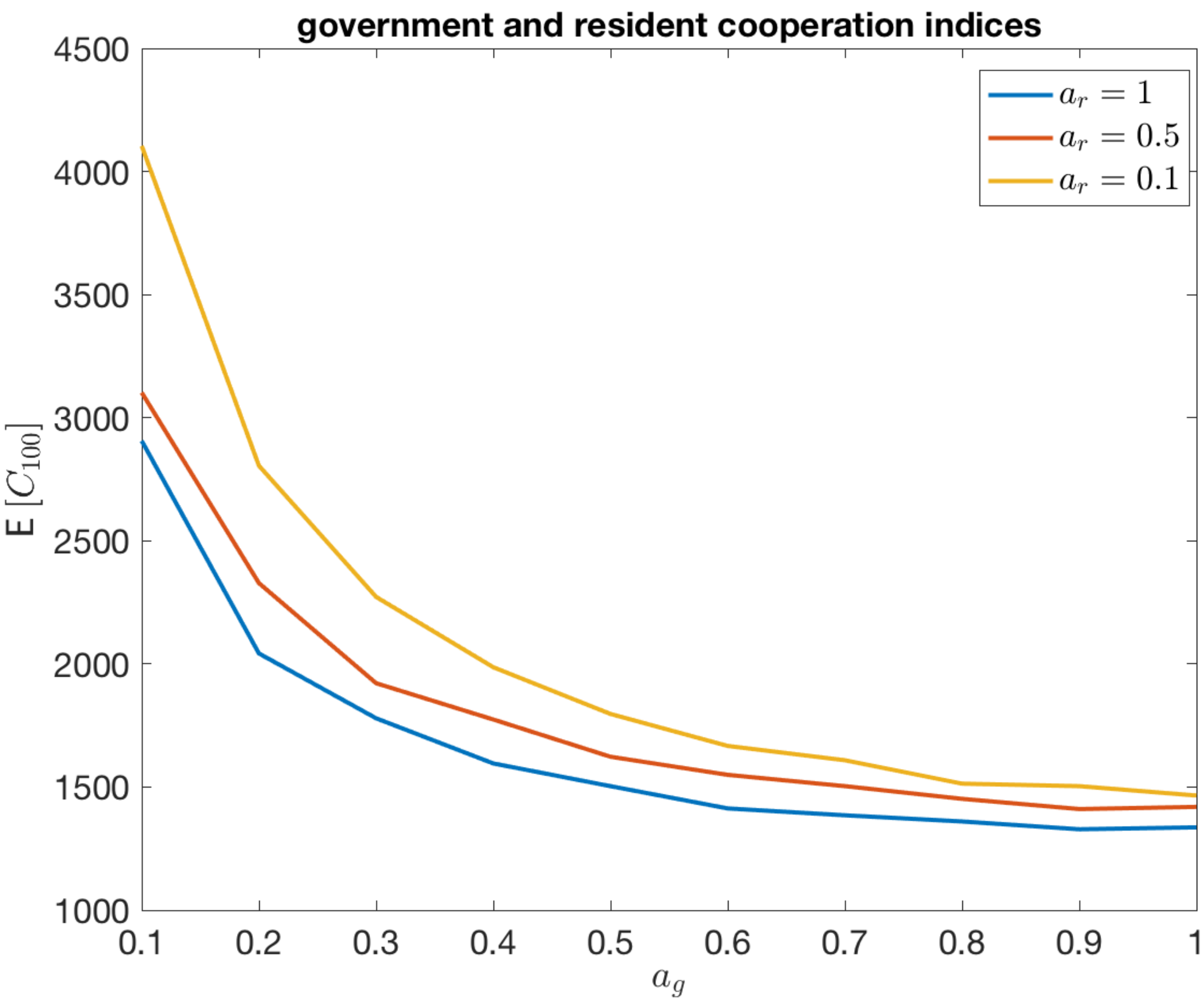

Concluding Remarks

- MDP model for government’s investment decisions
- Optimal policy is proactive: monitors sea level
- Convergence proof for RL algorithm that finds optimal policy
- Optimal policy achieves much less cost than straightforward policy
- Cooperation matters: responsive governments and residents significantly decrease the expected cost
- Future work: multi-agent modeling with more agents, such as businesses
- Future work: modeling of SLR’s impact on nature’s cost
- Future work: modeling of cooperation indices of gov. & res. by decomposing into a number of fundamental traits, such as political, ethical, sociological, and religious.