INFRASTRUCTURE, SAFETY, AND ENVIRONMENT

Informing Robust Infrastructure Investment Decisions Given Deeply Uncertain Sea Level Rise: PoLA Case Study

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with Robert Lempert & Klaus Keller

Agencies with Coastal Infrastructure Face Major Challenges from Potential Sea Level Rise (SLR)

- **Global sea levels expected to increase in future**
- **But, there is much controversy over extent and timing of SLR**
- **Particularly so for low-probability, high-impact increases of 1+ meters over coming century**

Making infrastructure investment decisions is very difficult under such *deep uncertainty*

Project Addressed Two Key Questions for PoLA

1 What threats does climate change pose to PoLA, and what are some adaptation options?

We used workshops and literature review to develop an inventory of threats and adaptation options

2 What methods should PoLA use to inform infrastructure decisions given deeply uncertain SLR?

We analyzed a terminal hardening decision using two methods, comparing both outcomes and process

- Robust decision making
- Probabilistic analysis

Overview of Key Findings

- **Climate change presents PoLA with serious threats, but there are adaptive responses that can be taken**
- **RDM analysis shows that a PoLA decision to harden terminals against extreme SLR at the next upgrade is not cost-effective**
- **Probabilistic decision analysis reaches similar conclusion**
- **But RDM has significant advantages where there is deep uncertainty underlying decision**

Overview of Key Findings

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We Used Workshops and Literature Review to Inventory Risks and Response Options

Climate Change Manifestation	Example Threat	Example Adaptation
SLR with storm surge	Terminal equipment damage	Harden terminals
More intense river runoff and flooding	Silt deposition in channels	Increase channel dredging
Potential opening of Arctic shipping routes	Changed shipping patterns lead to loss of business for PoLA	Reduce irreversible expenditures (e.g., new capacity investments)
More frequent, more intense, and longer-lasting storms	Dispersion of contaminants	Relocate storage areas

The nature of these adaptation responses varies…

Literature Suggests Useful Taxonomy of Adaptive Responses

Approach	Protect	Accommodate	Retreat
Hard	Dikes, seawalls, breakwaters, salt-water intrusion barriers	Building on pilings, adapting drainage, emergency flood shelters	Relocate threatened port buildings
Soft	Vegetation to strengthen river embankments	New building codes, risk-based hazard insurance	Land-use restrictions, set-back zones

Today's Focus: Should PoLA Consider SLR When Upgrading Its Terminals?

Approach	Protect	Accommodate	Retreat
Hard	Dikes, seawalls, breakwaters, salt-water intrusion barriers	Building on pilings, adapting drainage, emergency flood shelters	Relocate threatened port buildings
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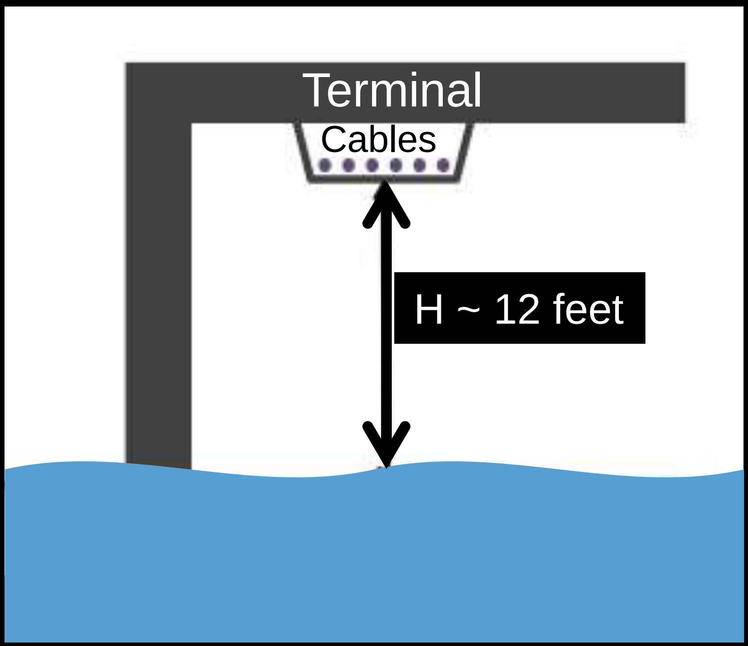
PoLA Is Considering Whether It Makes Economic Sense to Harden Terminals at Next Upgrade

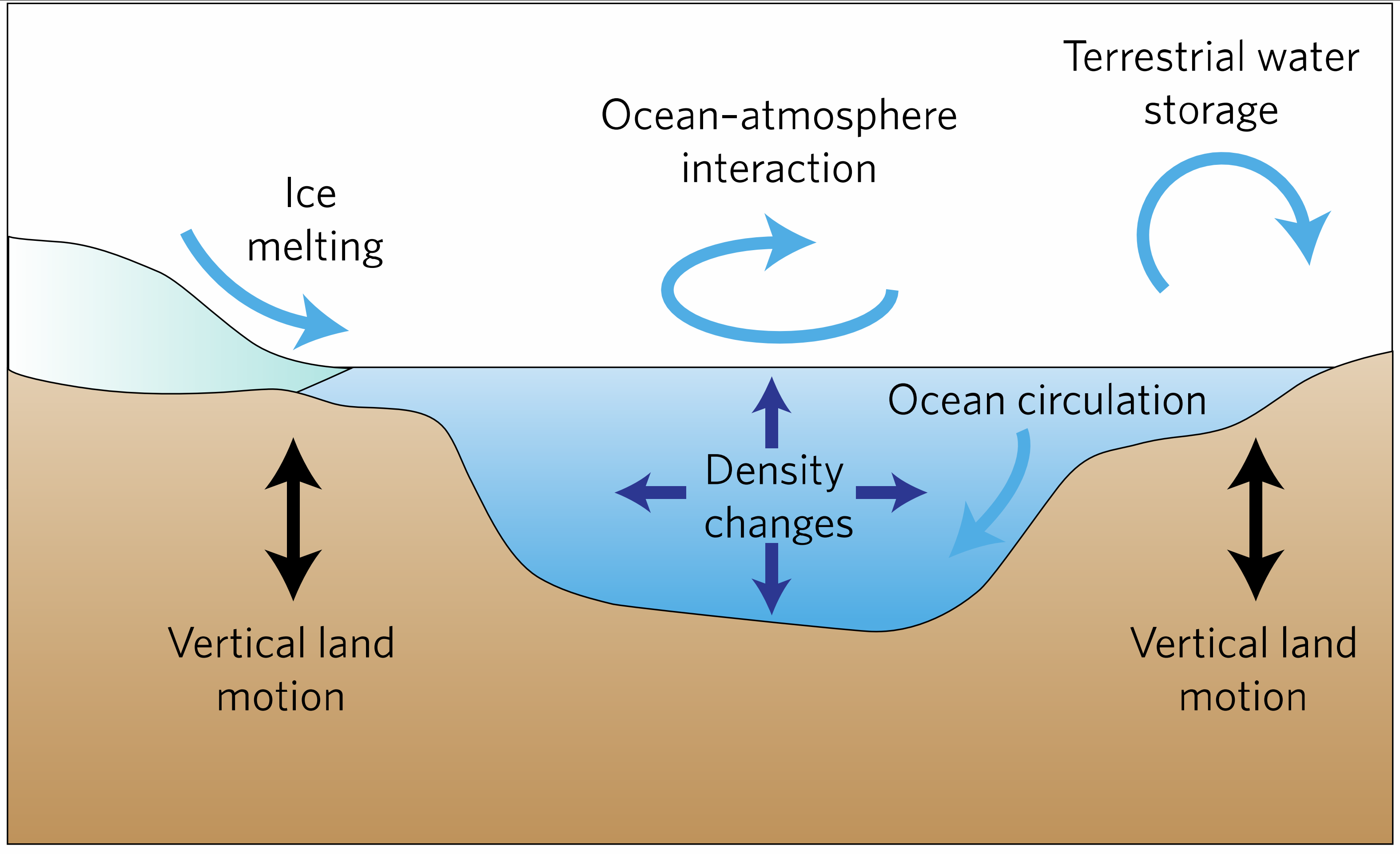


Terminals are high above current sea level, so only vulnerable to extreme SLR

Hardening during a scheduled upgrade is much less costly than hardening between scheduled upgrades

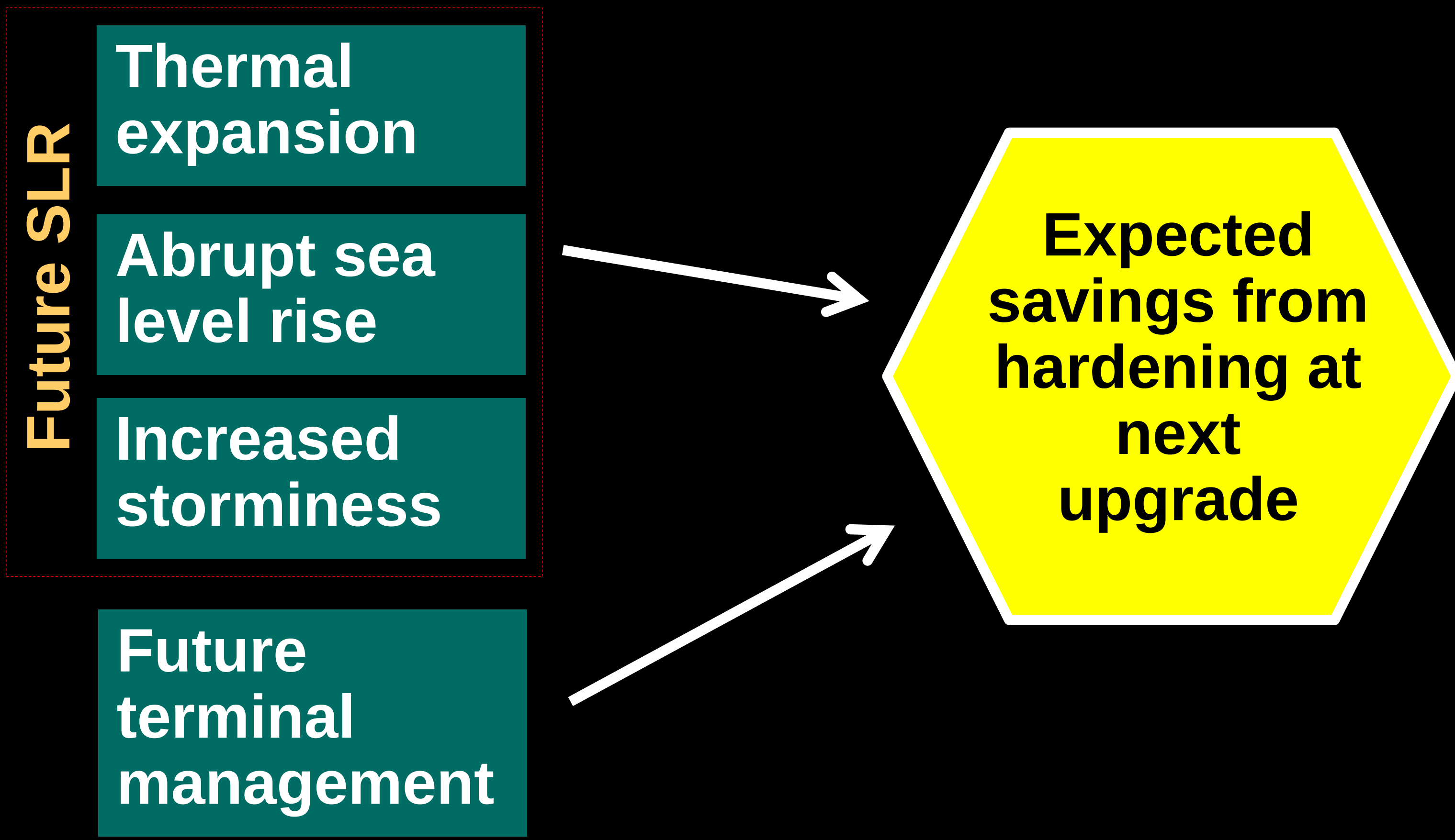
	If PoLA Hardens at next upgrade…
…and future SLR requires hardening	Significant positive savings

Several Factors Determine Future Sea Level



Milne et al., NG (2009)

We Built a Simple Model to Evaluate Decision



PoLA should harden at next upgrade if expected savings are positive

Model Requires Data on Various Parameters

Future SLR

Uncertainty
SLR in 2011
Normal Rate of SLR
Normal SLR Acceleration
Rate of Abrupt SLR
Year Abrupt SLR Begins
Increased storminess

Future Terminal Management

Uncertainty
Lifetime
Maximum Allowable Overtop Probability
Decision Year
Height Above Mean Sea Level
Current Hardening Cost
Discount Rate

Some Parameters Known at Time of Decision

Future SLR

Uncertainty
SLR in 2011
Normal Rate of SLR
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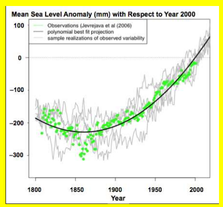
Year Abrupt SLR Begins
Increased storminess

Future Terminal Management

Uncertainty	RDM Characterization of Uncertainty
Lifetime	
Maximum Allowable Overtop Probability	
Decision Year	Known at decision time: e.g. 2020
Height Above Mean Sea Level	Known at decision time: e.g. 2,804 mm
Current Hardening Cost	Known at decision time: e.g. 1%
Discount Rate	Known at decision time: e.g. 5%

Some Parameters Can Be Treated Probabilistically

Future SLR

Uncertainty	RDM Characterization of Uncertainty
SLR in 2011	Well characterized joint probability distribution 
Normal Rate of SLR	
Normal SLR Acceleration	
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Future Terminal Management

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Other Parameters We Regard As Deeply Uncertain

Future SLR

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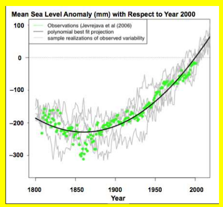
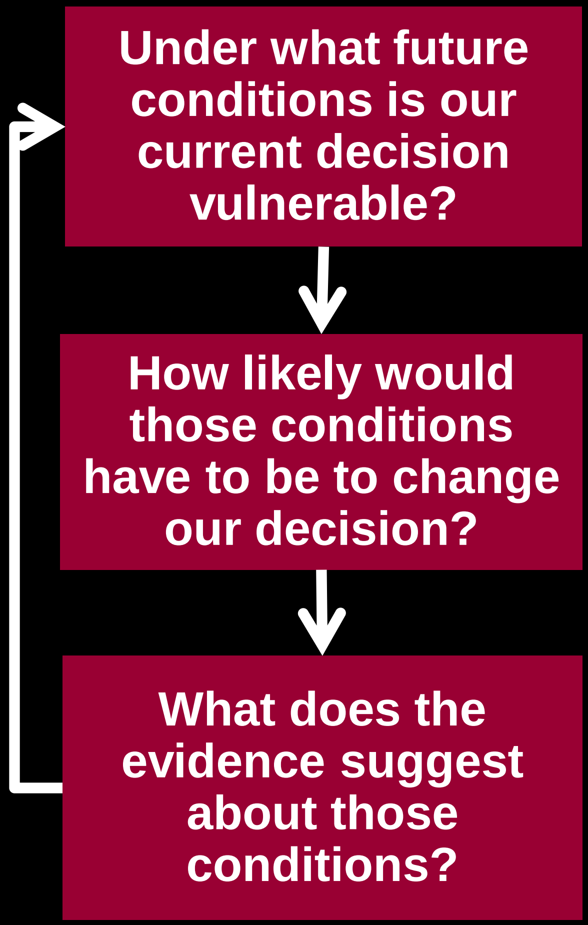
SLR in 2011	Well characterized joint probability distribution 
Normal Rate of SLR	
Normal SLR Acceleration	
Rate of Abrupt SLR	Deeply uncertain: 0 - 30 mm/year
Year Abrupt SLR Begins	Deeply uncertain: 2010 - 2100
Increased storminess	Deeply uncertain: Set of GEV distributions with scale ranging from 517mm to 569 mm;

Future Terminal Management

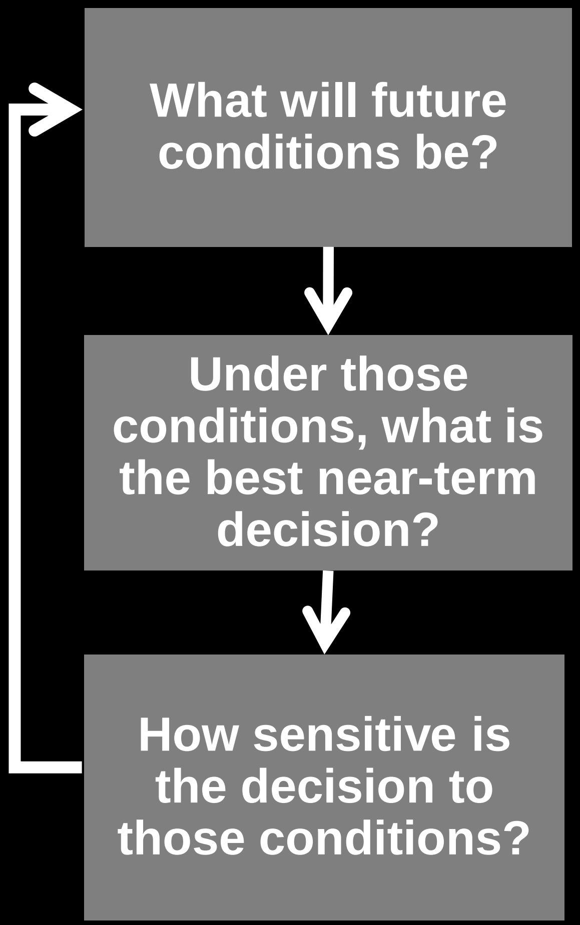
Uncertainty	RDM Characterization of Uncertainty
Lifetime	Deeply uncertain: 30 - 100 years
Maximum Allowable Overtop Probability	Deeply uncertain: 5 - 50%/year
Decision Year	Known at decision time: e.g. 2020
Height Above Mean Sea Level	Known at decision time: e.g. 2,804 mm
Current Hardening Cost	Known at decision time: e.g. 1%
Discount Rate	Known at decision time: e.g. 5%

The Two Methods Differ in Their Approach to Uncertainty

Robust Decisionmaking Process

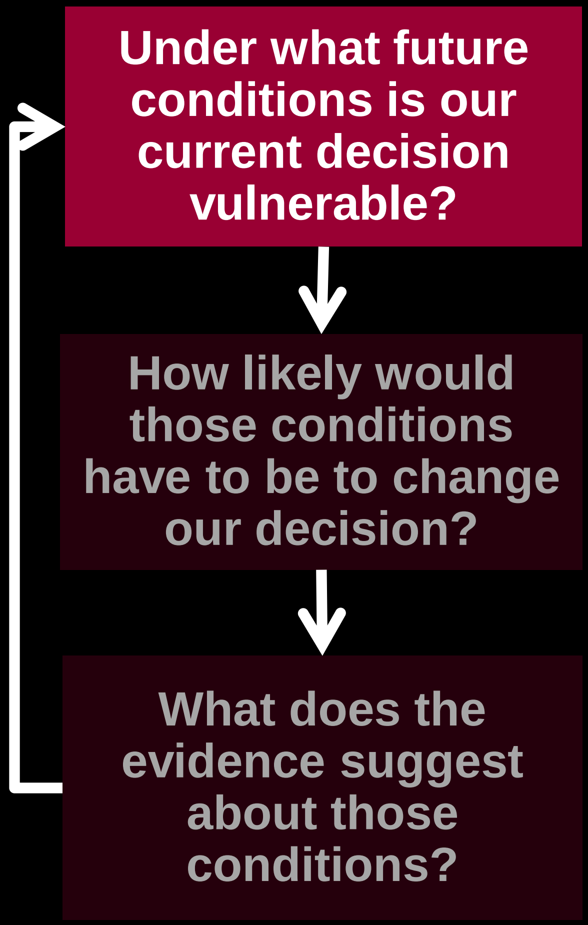


Probabilistic Decision Analysis



Conduct RDM Analysis

Robust Decisionmaking Process

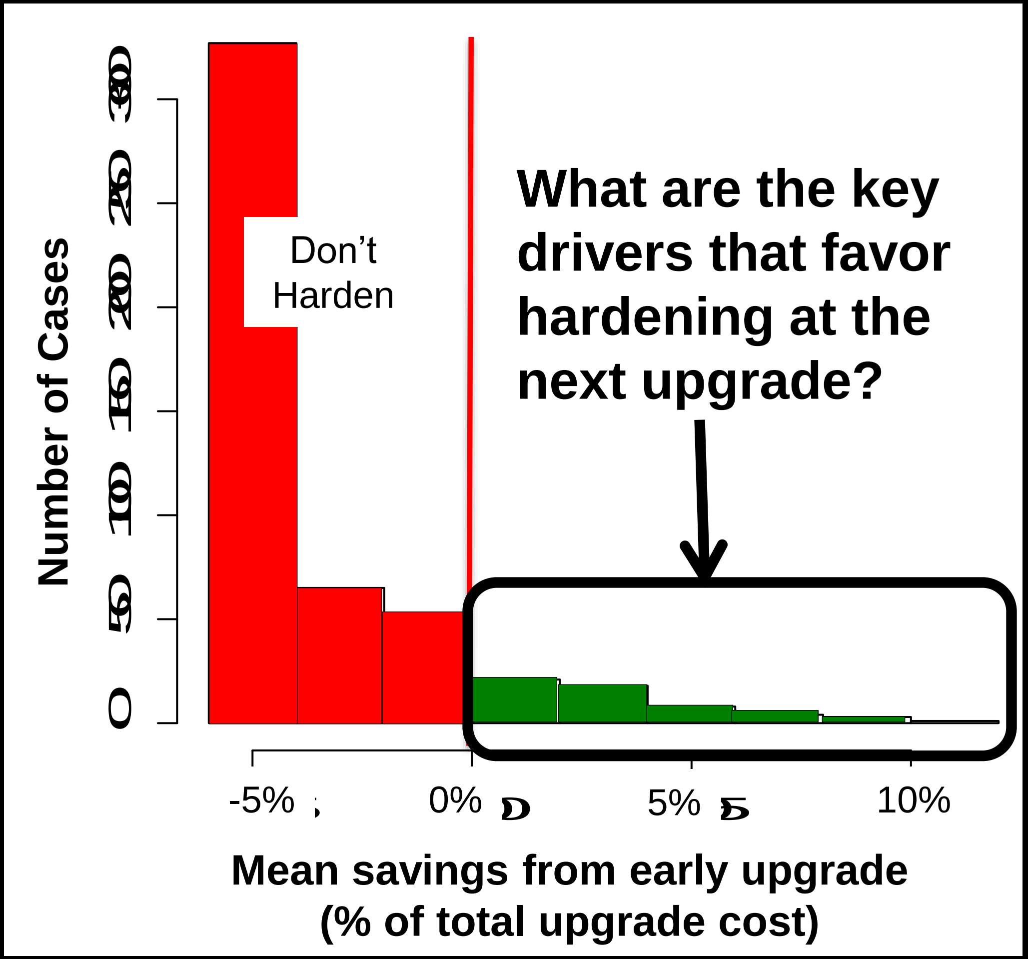


Run model over cases that sample full range of combinations of all uncertainties

Characterize cases where a decision to harden at next upgrade would be cost-effective

A Few Cases in the Sample Favor Hardening at the Next Upgrade

- Ran 500 case sample
  - Varied five deeply uncertain parameters
  - Used distributions for parameters with well-characterized uncertainties
- Calculated expected savings for each case



Three Factors Drive the Cases Where Savings Are Expected

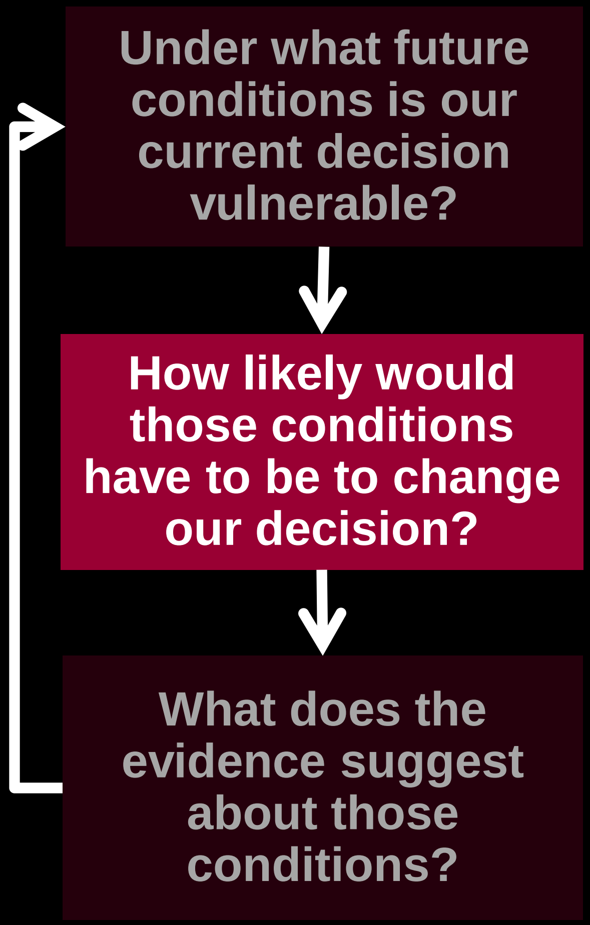
Parameter	Range of Possibilities
Abrupt SLR	0-30mm/year between 2010-2100
Increased Storminess	517-569mm
Terminal Lifetime	30-100 years

Three Factors Drive the Cases Where Savings Are Expected

Parameter	Range of Possibilities	Condition
Abrupt SLR	0-30mm/year between 2010-2100	≥ 14mm/year in 2020 ≥ 30mm/year in 2060
Increased Storminess	517-569mm	> 533mm
Terminal Lifetime	30-100 years	> 50 years

Conduct RDM Analysis

Robust Decisionmaking Process



How likely does this vulnerable scenario have to be for it to make sense to harden now?

PoLA Might Reasonably Harden at Next Upgrade If Probability of This Scenario Is >7%

- **The expected savings from a decision to harden is:**

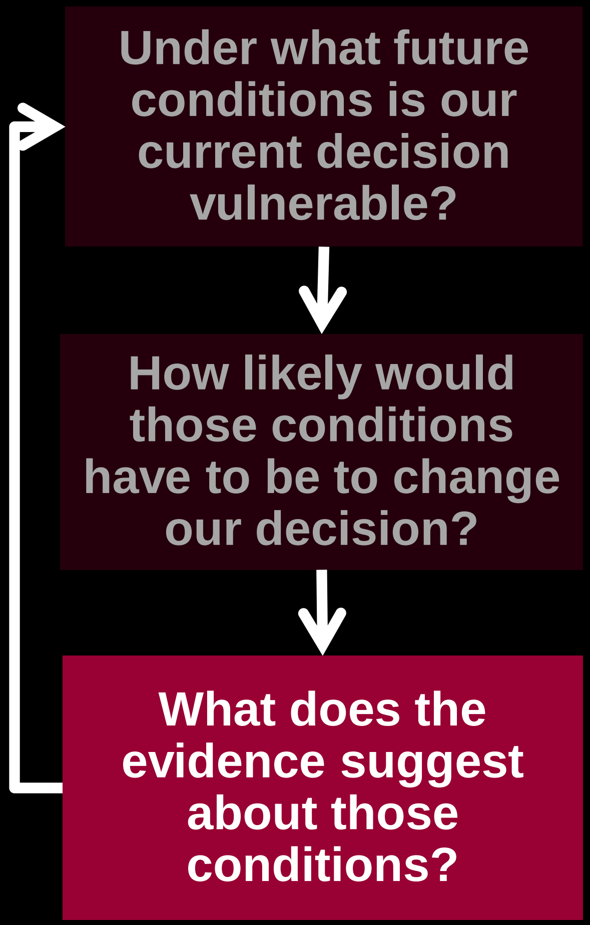
$$P_{scenario} \times Savings_{scenario} + (1 - P_{scenario}) \times Savings_{\substack{all\ other \\ scenarios}}$$

- **What is the smallest value of $P_{scenario}$ for which expected savings are positive?**

- **Answer: 7%**

Conduct RDM Analysis

Robust Decisionmaking Process



What is the evidence about each of our three conditions on abrupt SLR, storminess, and terminal lifetime?

What Does Scientific Evidence Say About Each of These Conditions?

Parameter	Condition	Evidence
Abrupt SLR (rate and year)	≥ 14mm/year in 2020 ≥ 30mm/year in 2060	≤ 14 %, suggested by data from two bounding cases
Increased Storminess (hourly anomaly)	> 533mm	Some studies suggest storminess will increase, but none as high as suggested by this scenario
Terminal Lifetime	> 50 years	Condition on lifetime is longer than those PoLA has previously experienced

What Does Scientific Evidence Say About Likelihood of Our Scenario?

- **We have three factors: abrupt SLR, storminess, and terminal lifetime**
- **We have information about abrupt SLR, so if we bound that, we can "solve" for the probability of other two**
- **The likelihood of the scenario > 7% when there is a 67% probability that:**
  - **Terminal lifetime > 50 years** ← **Longer than past lifetimes**
  - **Storminess > 533 mm** ← **Not much evidence**

Thus, PoLA might reasonably choose *not to harden its terminals at the next upgrade*

RDM Was Also Used to Analyze "Harden at Next Upgrade" Decision for Three Other PoLA Facilities

Top of Terminals (12 ft above MSL)	✗ **Don't harden at next upgrade**
Berths 206-209 (8 ft above MSL)	✗ **Don't harden at next upgrade**
Alameda and Harry Bridges Crossing (6 ft above MSL)	? **Consider hardening at next upgrade**

Overview of Key Findings

- Climate change presents PoLA with serious threats, but there are adaptive responses that can be taken
- RDM analysis shows that a PoLA decision to harden facilities against SLR at the next upgrade is not cost-effective
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- But RDM has significant advantages where there is deep uncertainty underlying decision

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How Do RDM and Full Probabilistic Analysis Compare?

- RDM gives more information about conditions where hardening at next upgrade might be appropriate
- RDM provides precise information about vulnerabilities
    - Allowing decisionmakers to consider potential responses to those vulnerabilities
    - Before evaluating evidence about likelihood of those scenarios
- RDM is an emerging methodology, particularly well-suited for stakeholder involvement

Conclusions

- Full probabilistic analysis works well when we are confident in best estimates of probability distributions
- But future SLR is deeply uncertain, making it hard to assess investment decisions
- In these cases, RDM may be a more convenient and transparent way to:
  - Organize relevant scientific information
  - Apply it to decision
  - Draw on stakeholder knowledge

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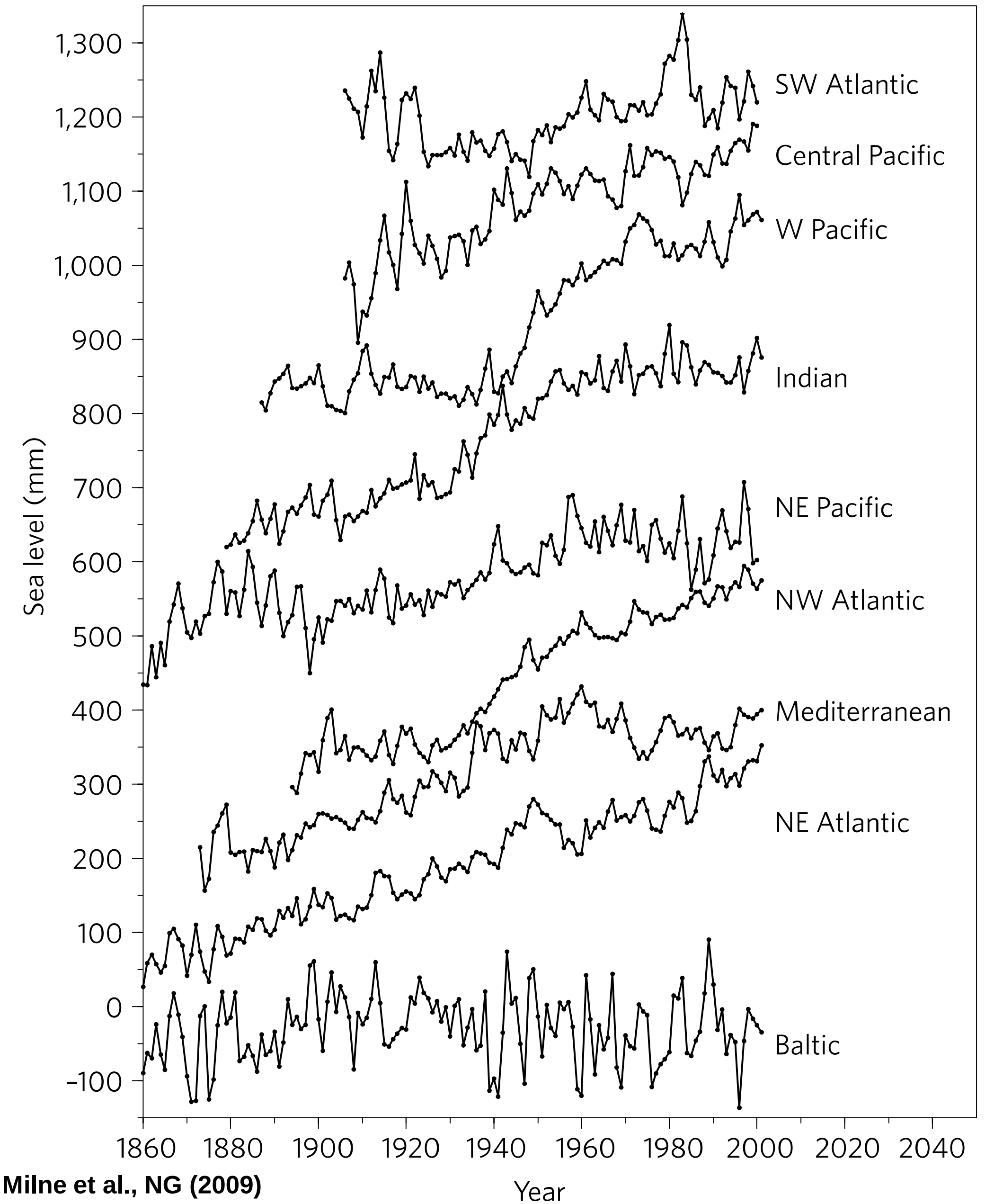
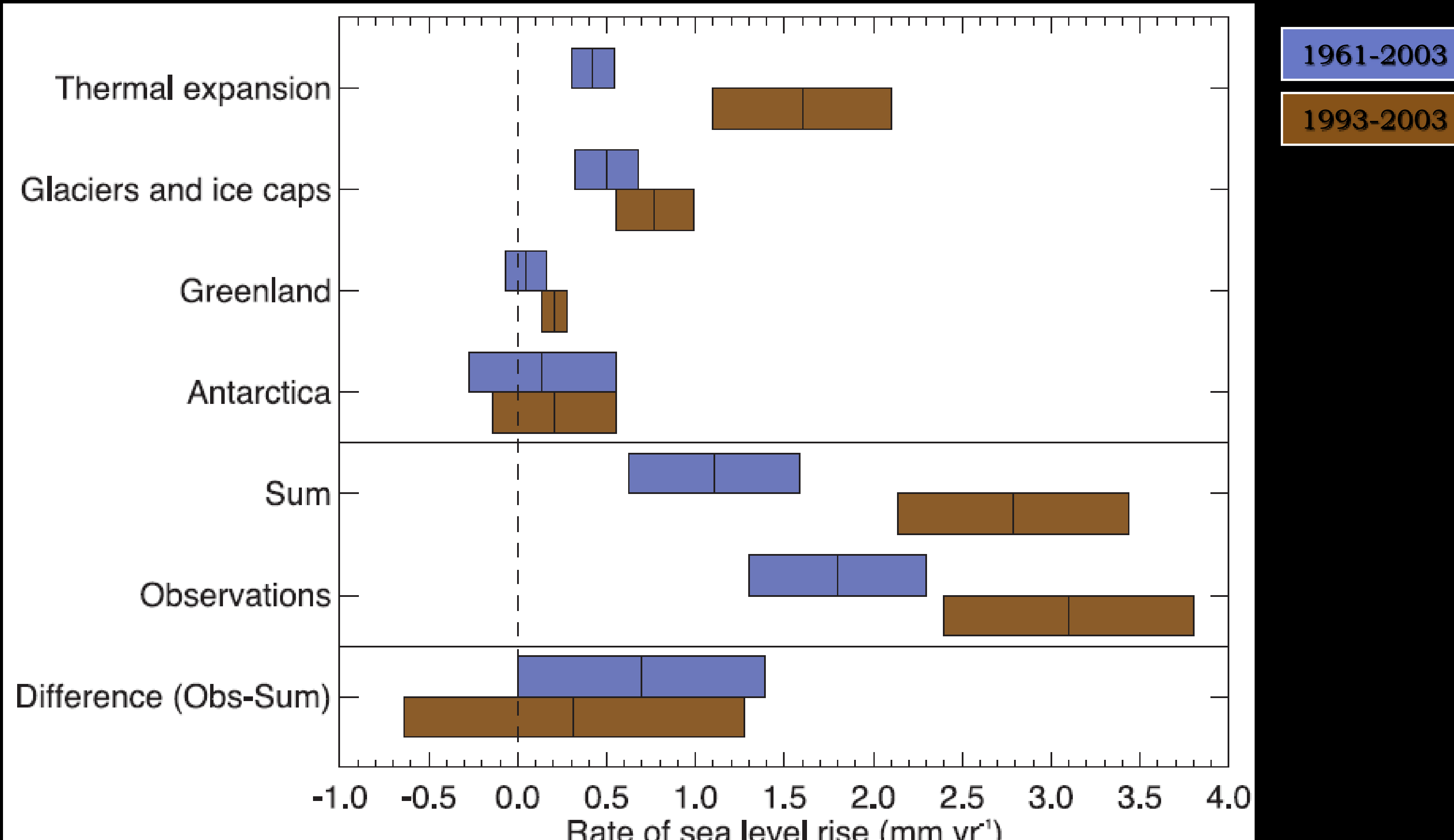
SLR SCIENCE

Sea Levels Are Generally Rising Around the World



Milne et al., NG (2009)

Our Current Understanding of Past Sea-Level Changes Is Incomplete



IPCC 4AR (2007)

RISKS AND ADAPTATION OPTIONS

Many Expected Changes Pose Risks for PoLA (1)

Climate Change Manifestations	Threats for PoLA
SLR with added storm surge	• Chronic flooding or inundation of connecting highway, rail • Chronic flooding of open storage areas • Reduced bridge clearance • Liquefaction of substrate soils • Dispersion of buried contaminants
More intense river runoff and flooding	• Increased dredging requirements • Increased flooding of adjacent low-lying areas
Potential opening of Arctic shipping routes	• Changed shipping patterns leading to loss of business for PoLA

Many Expected Changes Pose Risks for PoLA (2)

Climate Change Manifestations	Threats for PoLA
More frequent, more intense, and longer-lasting storms (greater precipitation, surge, waves, and wind)	• Ship/wharf collisions • Containers and other cargo from open storage physically dislodged • Wharf/pier structures damaged • Specialized terminal equipment damaged or destroyed • Pavement and foundations damaged or undermined • Flooding of connecting highway, rail • Stormwater system capacity overwhelmed • Increased storm-related PoLA closures • Increased underwater debris buildup, blockages, or loss of markers hindering channel navigation • Increased dredging requirements

Appropriate Responses Depend on the Specific Threat (1)

Port Area/Funct ion	Threat	Adaptation Strategy
Port Planning	• Investment risk due to uncertain climate effects	• Reduce irreversible expenditures • Reduce lease lengths
	• Loss of business due to Arctic routes	• Reduce irreversible expenditures (i.e., new capacity investments)
Entire Port Complex	• Damage due to storm surge and waves	• Put in surge barrier • Strengthen and elevate breakwater
	• Permanent inundation or frequent flooding due to extreme SLR	• Put in floating port • Relocate port

Appropriate Responses Depend on the Specific Threat (2)

Port Area/Function	Threat	Adaptation Strategy
Navigation Channels	• Silt deposition, debris, and blockages	• Increase channel dredging
Wharves, Piers	• Damage due to storm surge, wave action	• Strengthen/raise wharves and piers
	• Ship collisions during storms	• Add or strengthen fenders
Terminal Equipment	• Damage due to storm surge, wave action	• Strengthen equipment, foundations
Chemical Storage	• Dispersion of contaminants	• Relocate storage areas • Remove contaminants

Appropriate Responses Depend on the Specific Threat (3)

Port Area/Function	Threat	Adaptation Strategy
Terminal Buildings	• Damage due to storm surge, wave action	• Strengthen buildings • Use easy-to-repair materials
	• Liquefaction, weakened foundations	• Strengthen foundations
	• Flooding	• Elevate buildings • Plan nonessential or flood-tolerant functions at ground level
Open Container Storage	• Containers dislodged by surge, wave action	• Elevate or relocate container storage areas
Connecting Roads/Rail	• Inundation or frequent flooding	• Elevate roads, rails
Bridges	• Reduced clearance	• Elevate bridges

UNCERTAIN PARAMETERS

Model Requires Data on Various Parameters

Future SLR

Uncertain Parameter
SLR in 2011
Normal Rate of SLR
Normal SLR Acceleration
Rate of Abrupt SLR
Year Abrupt SLR Begins
Increased storminess

Future Terminal Management

Uncertain Parameter
Lifetime
Maximum Allowable Overtop Probability
Decision Year
Height Above Mean Sea Level
Current Hardening Cost
Discount Rate

Some Parameters Known at Time of Decision

- Some terminal management parameters are known at time of decision
- We consider a particular case here

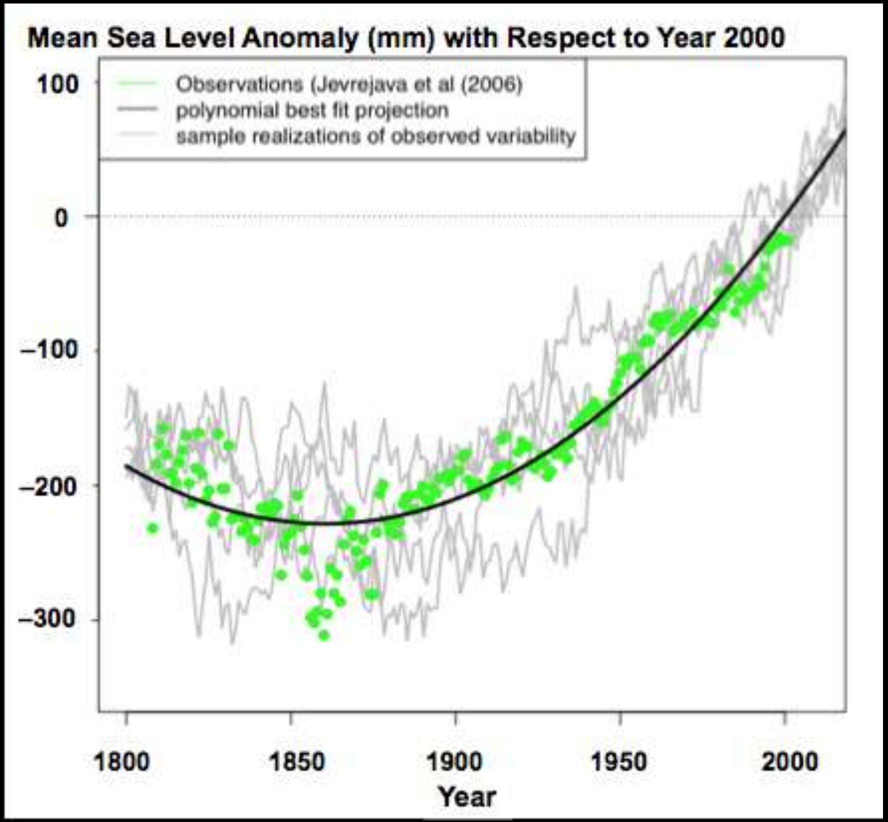
Future Terminal Management

Uncertainty	RDM Characterization of Uncertainty
Decision Year	Known at decision time
Height Above Mean Sea Level	Known at decision time
Current Hardening Cost	Known at decision time: 1%
Discount Rate	Known at decision time: 5%

Some Parameters Can Be Treated Probabilistically

Future SLR

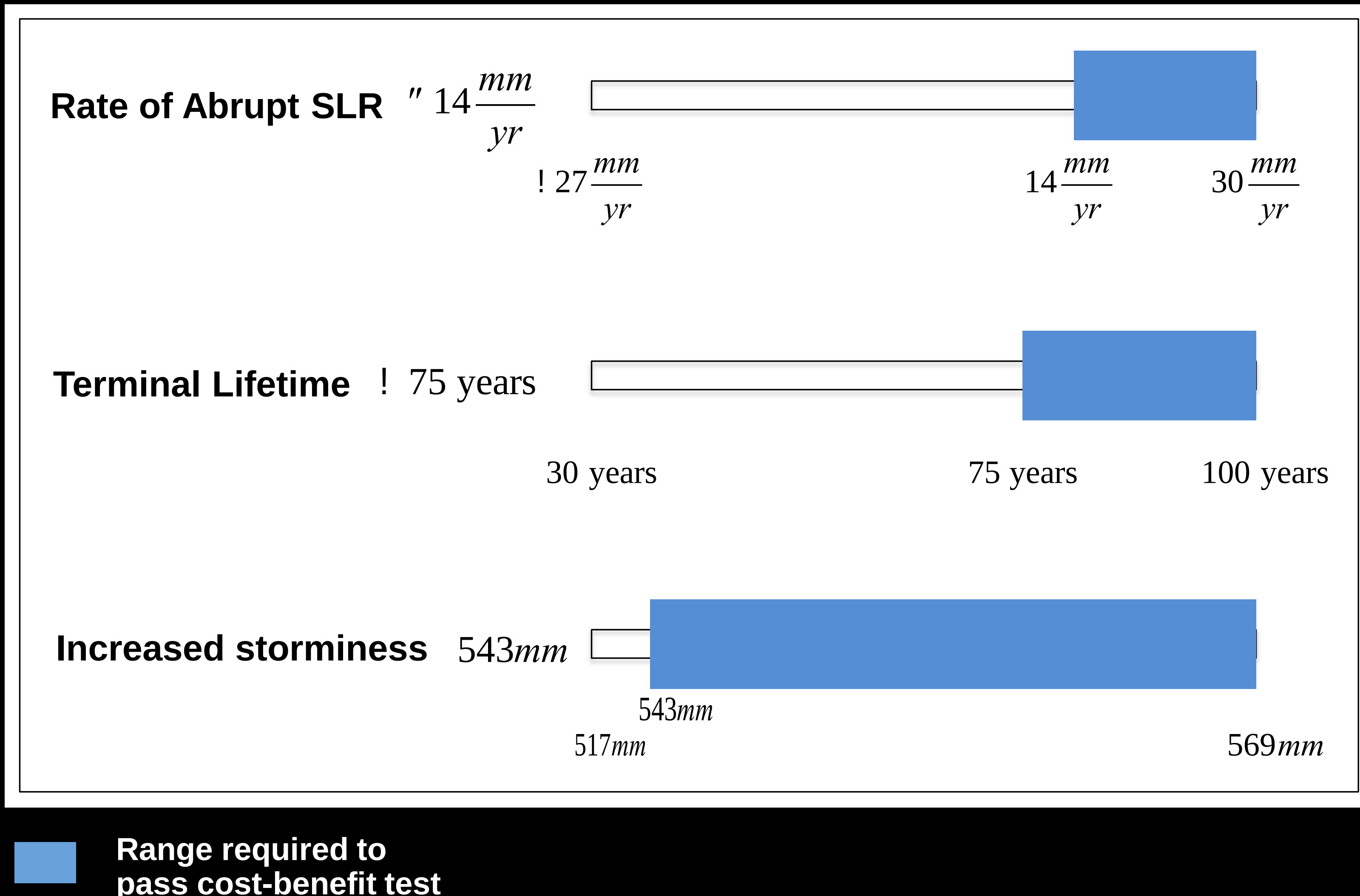
Uncertainty	RDM Characterization of Uncertainty
SLR in 2011	Well characterized joint probability distribution
Normal Rate of SLR	
Normal SLR Acceleration	



Observations of past sea level give info about thermal expansion

SCENARIO CONDITIONS

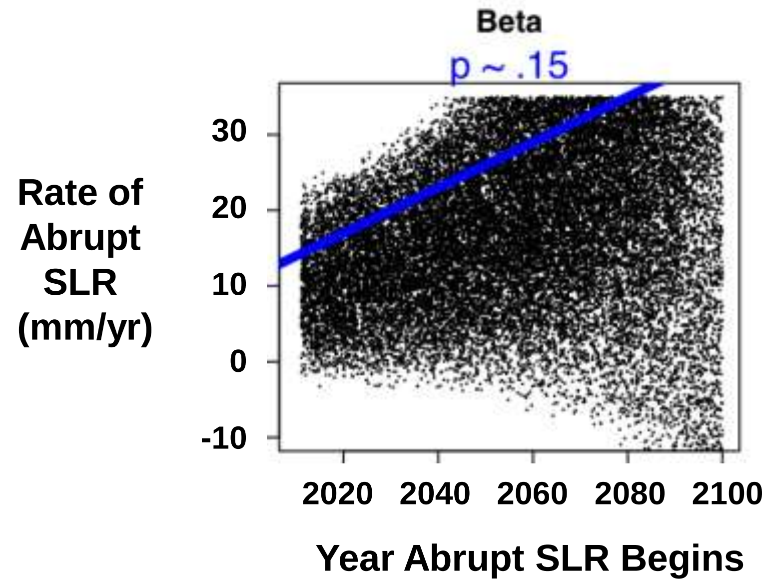
A Scenario Exists Where Hardening at Next Upgrade Passes Cost-Benefit Test



Scientific Evidence for Abrupt SLR

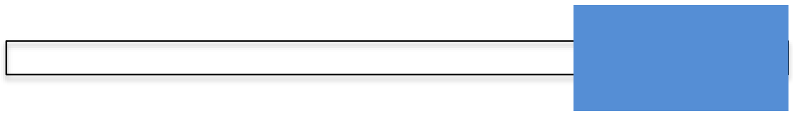
Future SLR

Uncertainty
Rate of Abrupt SLR
Year Abrupt SLR Begins



Data from two bounding cases suggests probability of sufficiently abrupt sea level rise is no greater than about 14%

Rate of Abrupt SLR $'' 14\frac{mm}{yr}$



$! 27\frac{mm}{yr}$ $14\frac{mm}{yr}$ $30\frac{mm}{yr}$

Scientific Evidence for Increase Storminess

Future SLR

Uncertainty
Daily Anomaly Location
Daily Anomaly Scale
Daily Anomaly Shape

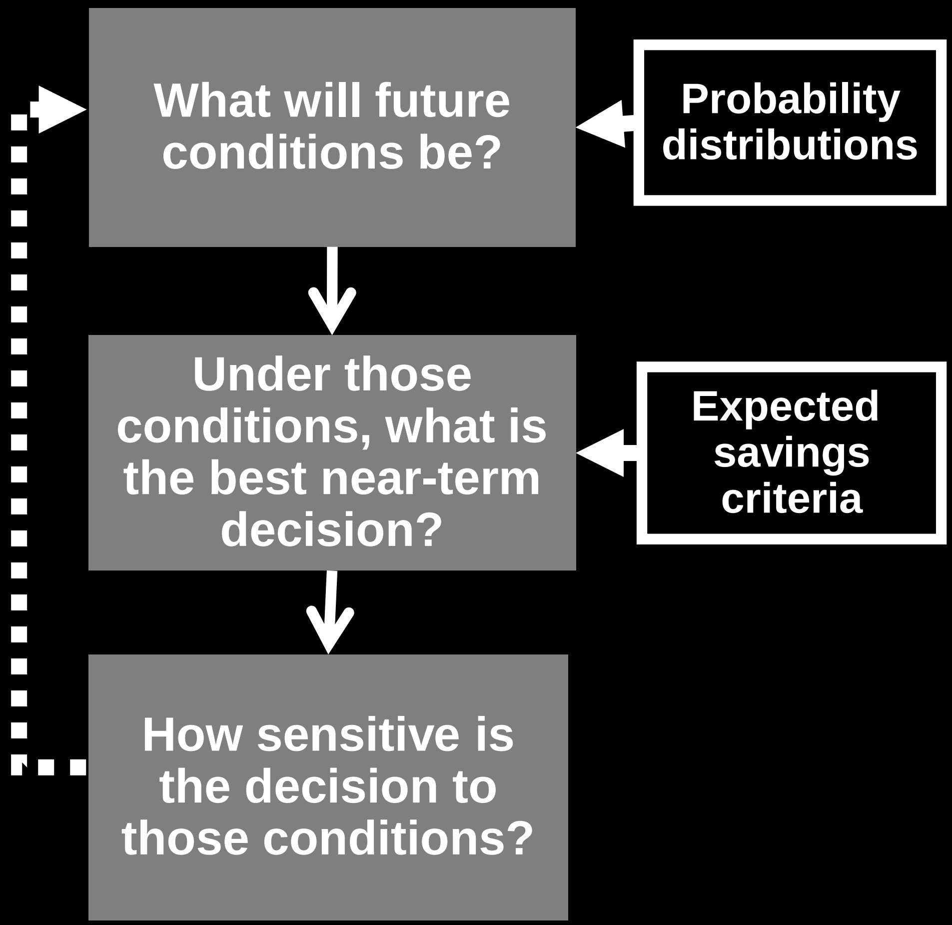
Some studies suggest storminess will increase, but none as high as suggested by this scenario

Hourly Anomaly Scale 543*mm*

PROBABILISTIC ANALYSIS

We Repeated PoLA Analysis Using Full Probabilistic Analysis

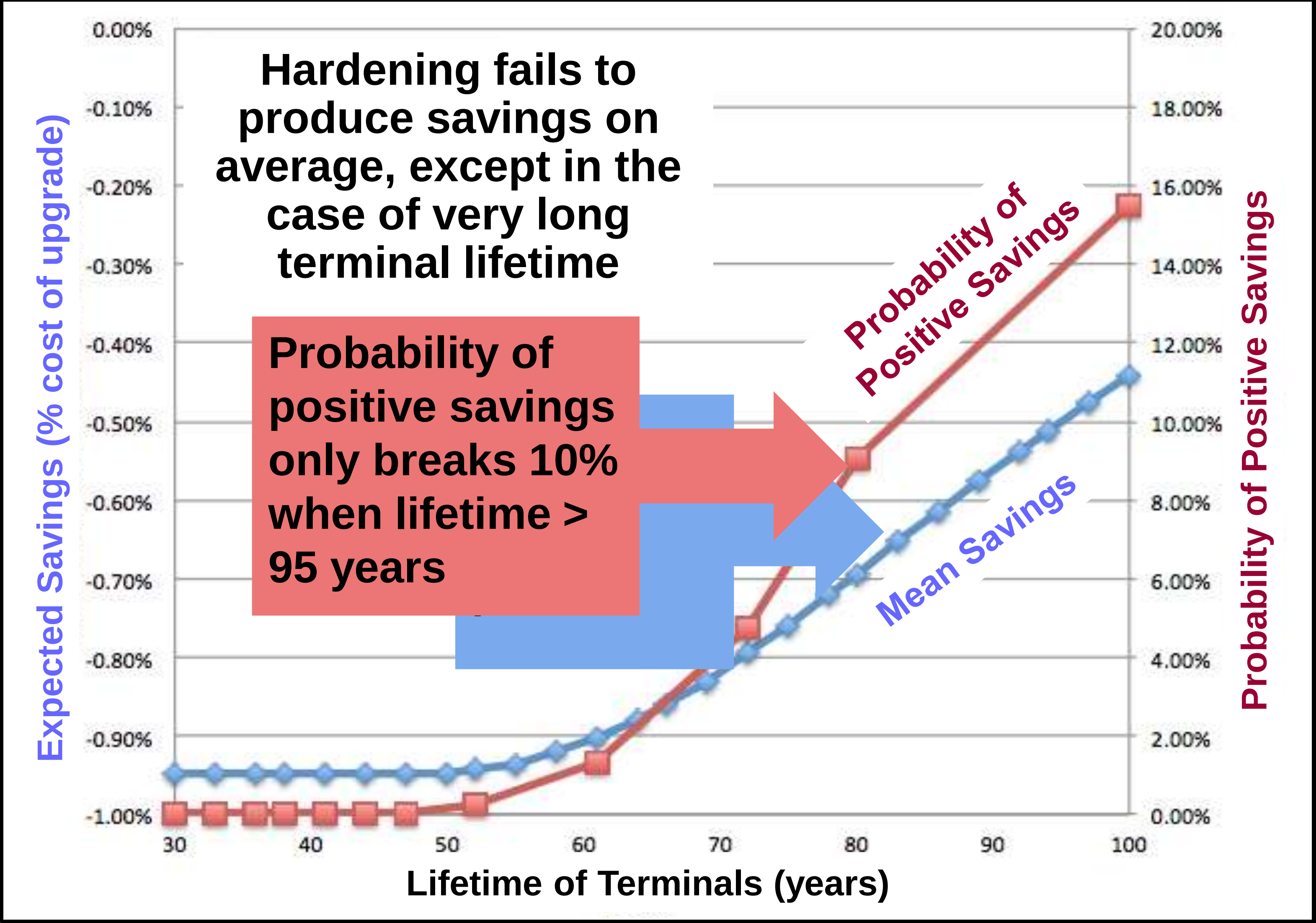
Probabilistic Decision Analysis



- **Estimates a single joint probability distribution for all uncertain input parameters**

- **Uses Monte Carlo sampling over inputs to calculate distribution of savings from hardening at the next upgrade**

Probabilistic Analysis Yields Same Finding as RDM Analysis



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OTHER FACILITIES

RDM Was Also Used to Analyze "Harden at Next Upgrade" Decision for Three Other PoLA Facilities

- **Three facilities considered:**
  - **Top of terminals, which lie 12.14 ft (3,700 mm) above mean sea level (MSL)**
  - **Berths 206-209, which lie 7.62 ft (2,323 mm) above MSL**
  - **Alameda and Harry Bridges Crossing, which lies 6.13 ft (1,868 mm) above MSL**

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  - **Alameda and Harry Bridges Crossing, which lies 6.13 ft (1,868 mm) above MSL**
- **Analysis suggests two main conclusions**
  - **Alameda and Harry Bridges Crossing is only facility that merits serious consideration to harden against rapid SLR at currently estimated costs**
  - **PoLA would have to develop strategies for hardening 5–250 times lower than current estimates to make hardening at next upgrade reasonable for other facilities**

CONFIDENCE

How Do RDM and Full Probabilistic Analysis Treat Information About Levels of Confidence?

- **Both make clear PoLA's decision depends more strongly on scientific estimates in which we have low confidence**
- **But probabilistic analysis does not distinguish between levels of confidence . . .**
- **. . . Whereas RDM explicitly does**