IOWA STATE UNIVERSITY

Department of Industrial and Manufacturing Systems Engineering

Enhancing decision making to prevent, prepare for, respond to, and recover from disruptions

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U.S. spending on disasters

- $85 - $136 billion per year (Weiss and Weidman, 2013; Kostro et al., 2013)
- From 1985-2004 (Healy and Malhotra, 2009)
  - $195 million per year on disaster preparedness
  - $3.04 billion per year on disaster relief

Weiss, D.J. and J. Weidman (2013). Disastrous spending: Federal disaster-relief expenditures rise amid more extreme weather. Center for American Progress.

Kostro, S.S., A. Nichols, and A. Temoshchuk (2013). White paper on U.S. disaster preparedness and resilience: Recommendations for reform. CSIS-Pennington Family Foundation Series on Community Resilience, Center for Strategic & International Studies.

Healy, A. and N. Malhotra (2009). Myopic voters and natural disaster policy. *American Political Science Review* 103(3), 387-406.

Cost-benefit analyses

Benefit-cost ratio of FEMA mitigation grants (Rose et al., 2005)

- 1.5 for earthquake mitigation grants
- 5.1 for flood mitigation grants

Rose, A., K. Porter, N. Dash, J. Bouabid, C. Huyck, J. Whitehead, D. Shaw, R. Eguchi, C. Taylor, T. McLane, L.T. Tobin, P.T. Ganderton, D. Goldschalk, A.S. Kiremidjian, K. Tierney, and C.T. West (2005). Benefit-cost analysis of FEMA hazard mitigation grants. *Natural Hazards Review* 8(4), 97-111.

Research questions

- What is the optimal allocation of resources pre-disruption (prevention and preparedness) and post-disruption (response and recovery)?
- How should resources be allocated between different disruptions?
- How can we train decision makers to help them prepare for disruptions?

Outline

1. Resource allocation model
    - Theoretical results: 1 disruption
    - Example: 2 disruptions (oil spill, hurricane)
2. Hurricane decision simulator

Resource allocation model

Normal production

Interdependent matrix

Increased production if no disruption

$$\min \; p\mathbf{x}^{\mathsf{T}}\mathbf{D}\mathbf{c}$$

Probability of disruption

Vector of direct impacts (proportional)

Probability with no resources

Effectiveness of prevention

Pre-disruption allocation

subject to $p = \hat{p}\exp(-k_p z_p)$

Direct impacts with no resources

Allocation to industry

Allocation to benefit all industries

$$c_i = \hat{c}_i \exp(-k_q z_p - k_i z_i - k_0 z_0)$$

Effectiveness of preparation

Effectiveness of recovery allocation

$$z_p + \sum_{i=1}^{m} z_i + z_0 \leq Z$$

Overall budget

$$z_p \geq 0, \; z_i \geq 0, \; z_0 \geq 0$$

Optimal recovery allocation

Consequence * Effectiveness

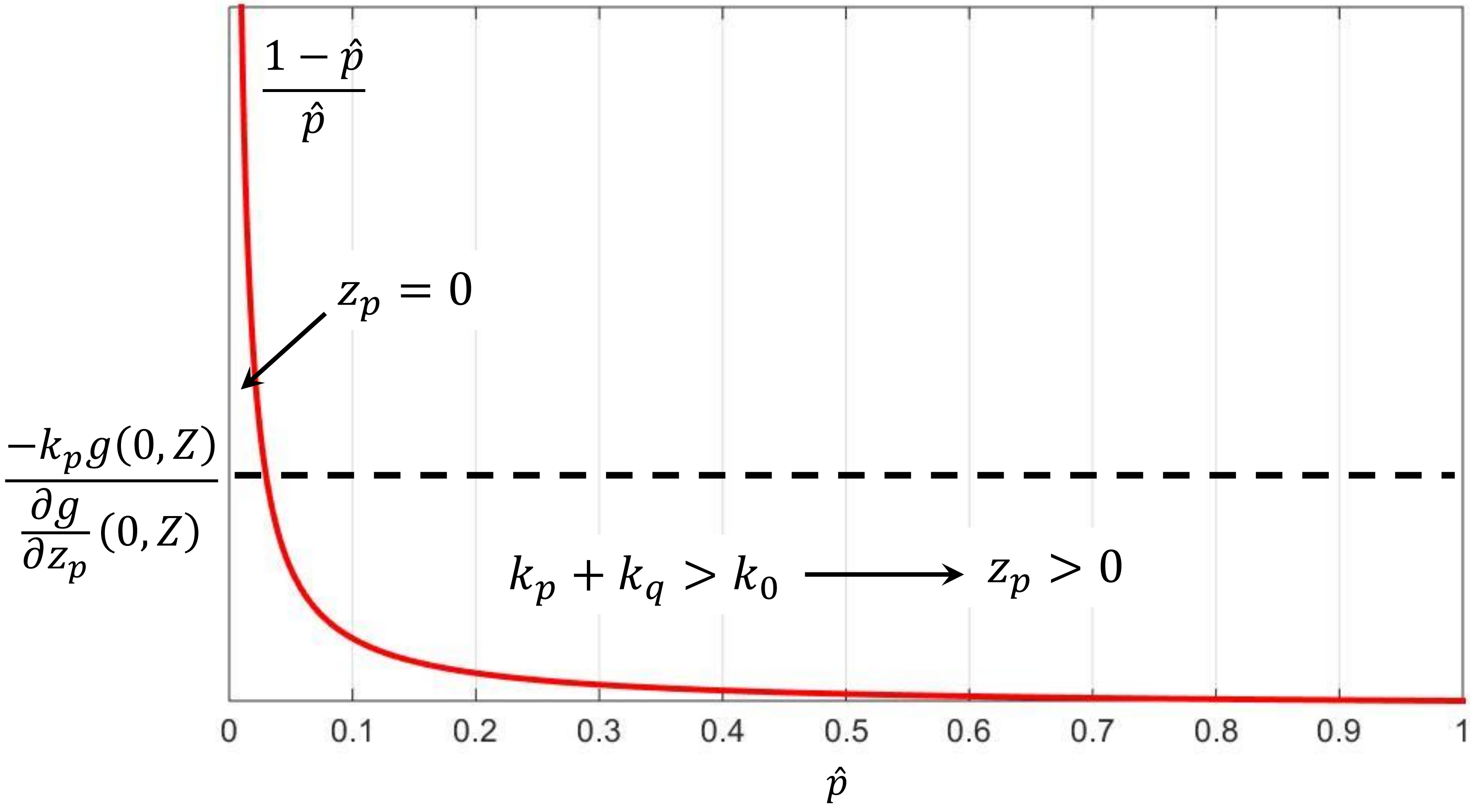
- If $\mathbf{x}^\top \mathbf{d}_{*i} \hat{c}_i k_i \leq \mathbf{x}^\top \mathbf{d}_{*j} \hat{c}_j k_j$ and $z_i > 0$, then $z_j > 0$

Effectiveness to all industries

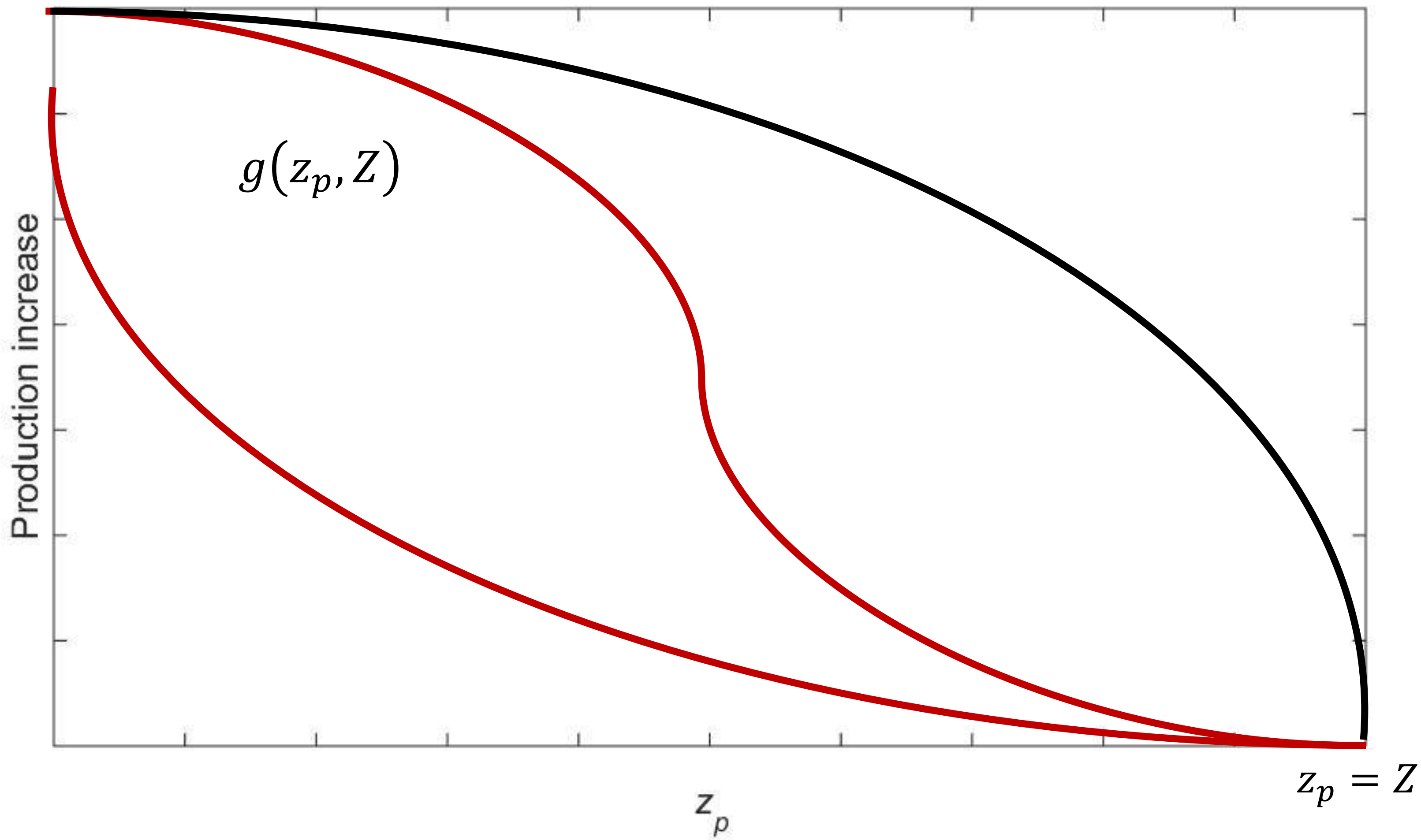
- If $k_0 > \left(\sum_{z_i > 0} {}^1/_{k_i}\right)^{-1}$ then some $z_i > 0$ is not optimal
- If $z_0 > 0$ then

$$z_i = \frac{1}{k_i} \log\left(\frac{\mathbf{x}^\top \mathbf{d}_{*i} \hat{c}_i k_i \left(1 - k_0 \sum_{z_j > 0} {}^1/_{k_j}\right)}{k_0 \sum_{z_j = 0} \mathbf{x}^\top \mathbf{d}_{*j} \hat{c}_j}\right)$$

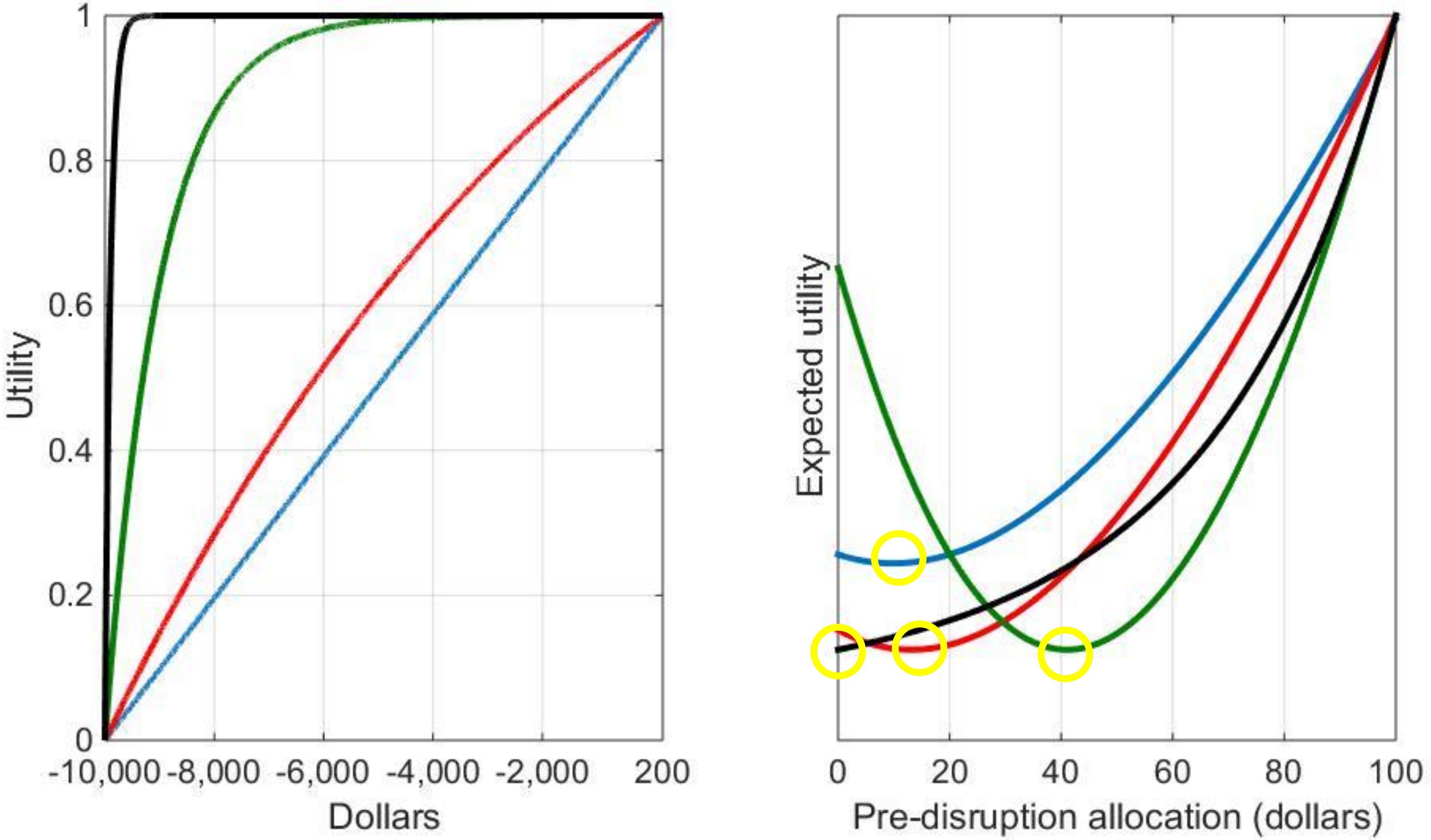
Optimal pre-disruption allocation



Optimal pre-disruption allocation



Risk aversion



Example: multiple disruptions

- Gulf states: Texas, Louisiana, Mississippi, Alabama, Florida
- 2 disruptions: oil spill (*Deepwater Horizon*) and hurricane (Katrina)
  - Probability of each disruption
- Economic losses
  - Demand losses
  - Production shut-down
- Hypothetical decision maker

MacKenzie, C.A., A. Al-Kazimi (2017). Optimal resource allocation model to prevent, prepare, and respond to multiple disruptions, with application to *Deepwater Horizon* oil spill and Hurricane Katrina. Under review.

Input parameters

	Oil spill	Hurricane
Probability	$\hat{p} = 0.045$	$\hat{p} = 0.56$
Prevention	$k_p = 2.8*10^{-4}$	$k_p = 0$
Preparedness	$k_q = 1.6*10^{-4}$	
All industries	$k_0 = 1.1*10^{-5}$	
Directly impacted industries	$m = 5$	$m = 31$
	Fishing, Real estate, Amusements, Accommodations, Oil and gas	Service industries, Farms, Fishing, Construction, Manufacturing industries, Utilities, Ports, Oil and gas,

$$g(z_p, Z) = 1.6(Z - z_p)$$

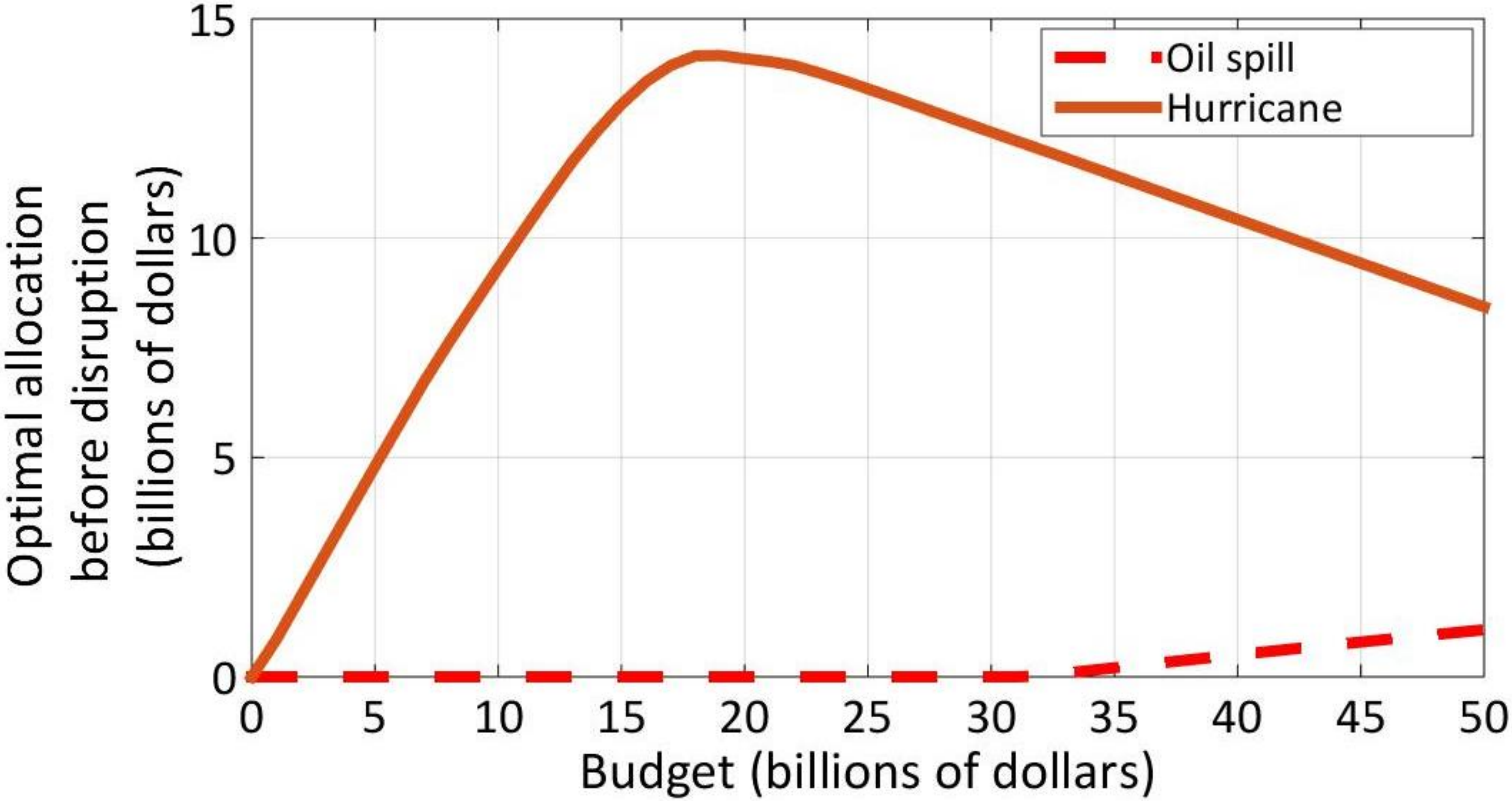
Parameter estimation for fishing

$62 million lost sales from Gulf Coast fishing
→ 0.84% of region's fishing and forestry production

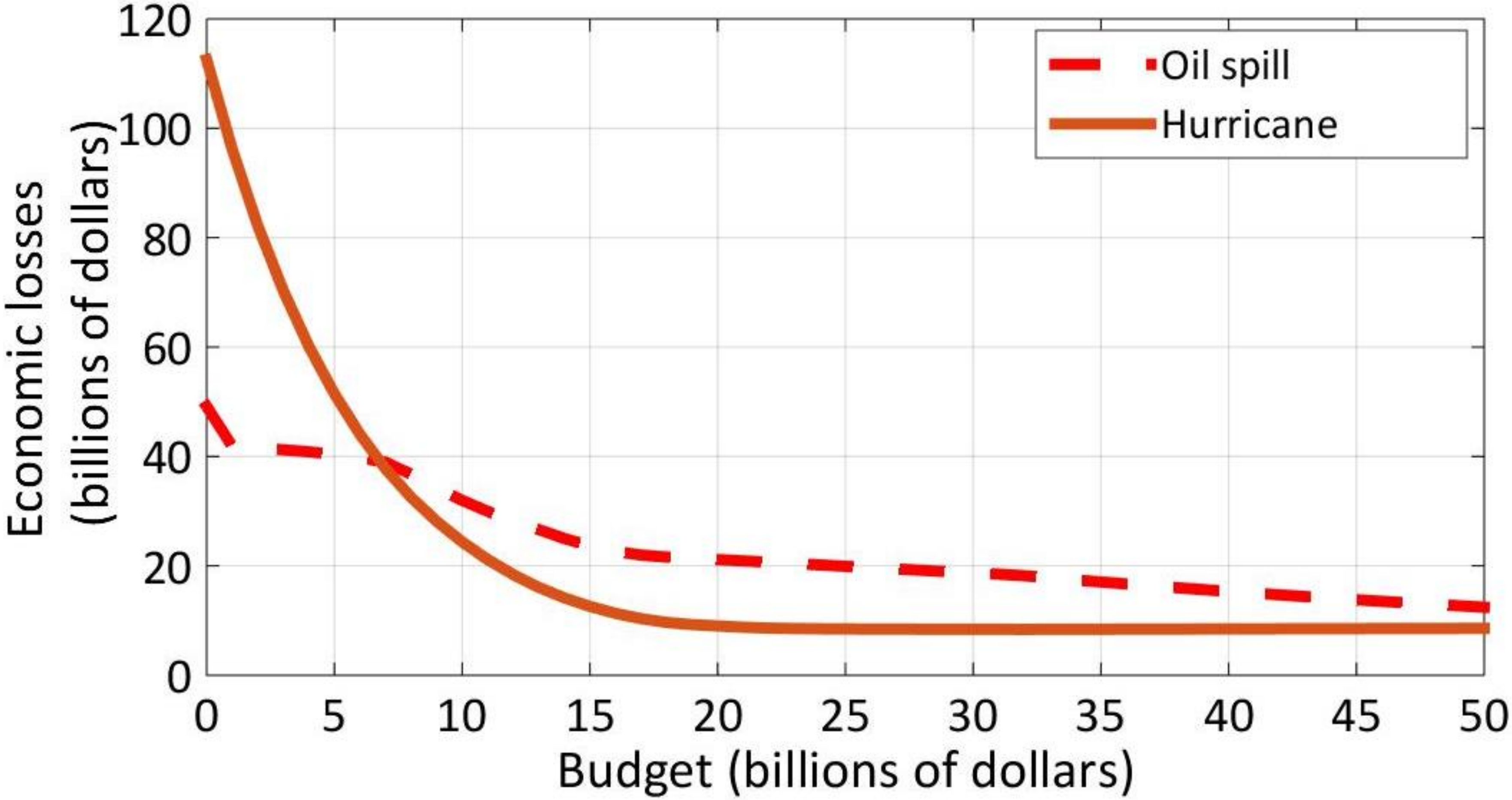
Studies on food safety and impact of positive media stories
→ $792,000 to reduce losses by $40 million

MacKenzie, C.A., H. Baroud, and K. Barker (2016). Static and dynamic resource allocation models for recovery of interdependent systems: Application to the *Deepwater Horizon* oil spill. *Annals of Operations Research*, 236, 103-129.

Optimal pre-disruption allocation

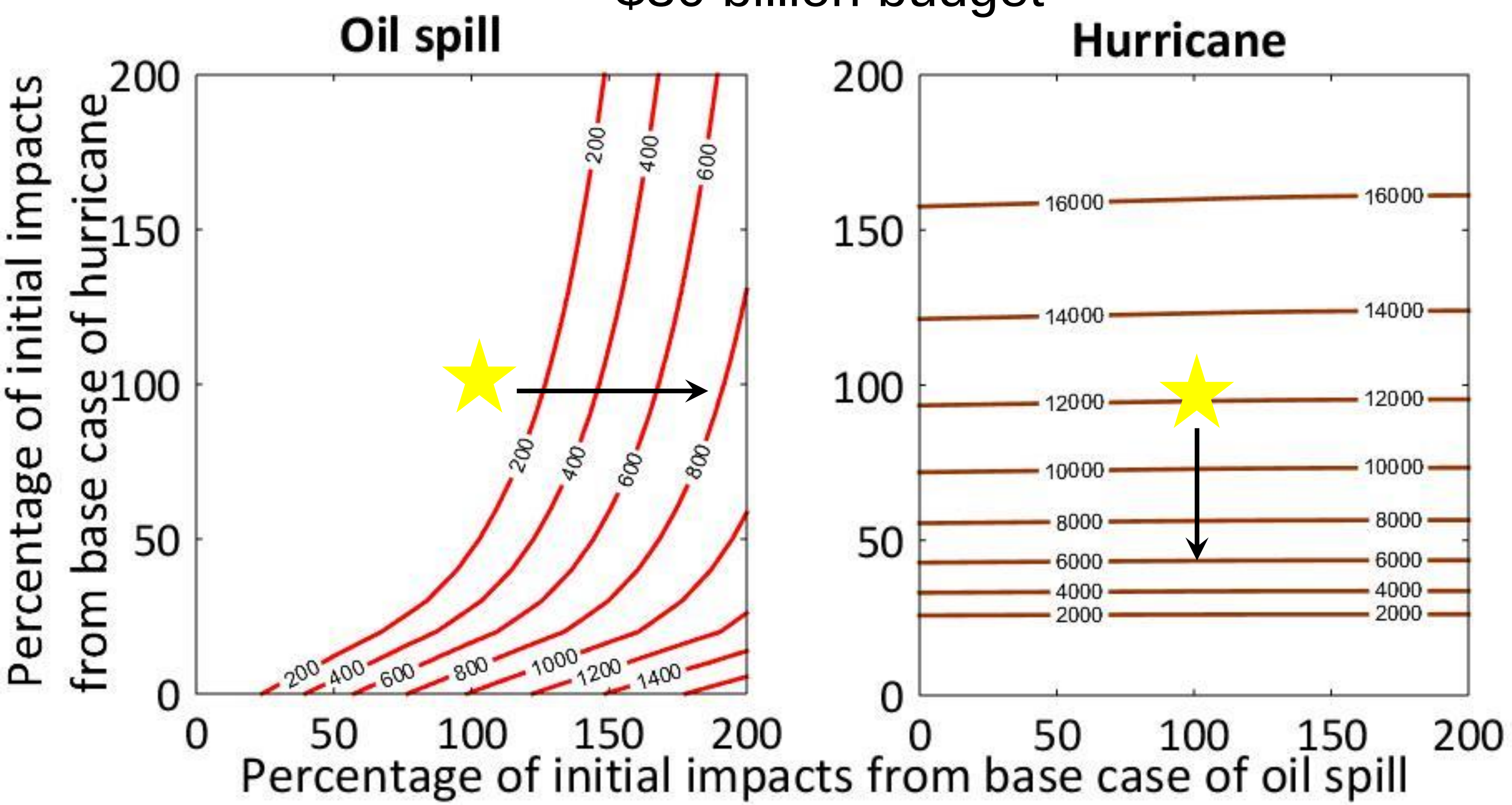


Economic losses



Sensitivity analysis (pre-disruption allocation)

$30 billion budget

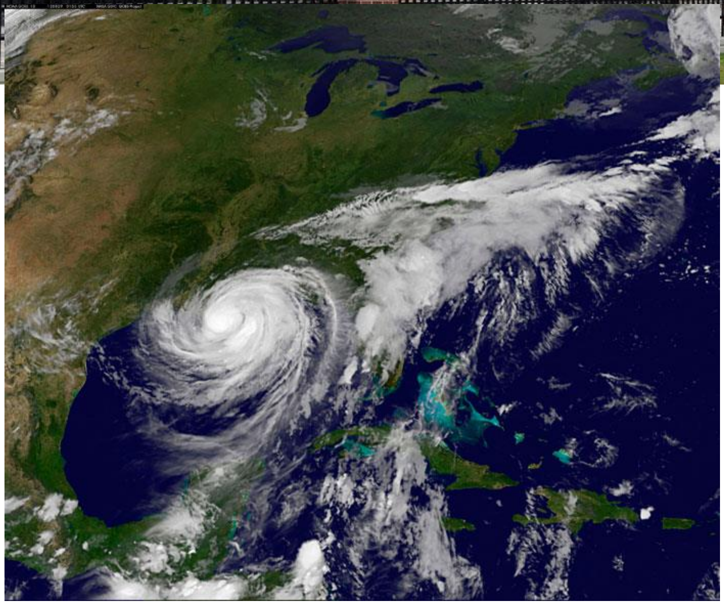


Conclusions

- Model benefits
  - Consider one disruption versus another disruption
  - Pre versus post-disruption allocation
  - Consider spending on disruptions versus other priorities
- Decision maker should allocate more for hurricane than oil spill → more probable and more consequential

U.S. Marine Forces Reserve (MFR)

Lt. Gen.
Rex McMillian

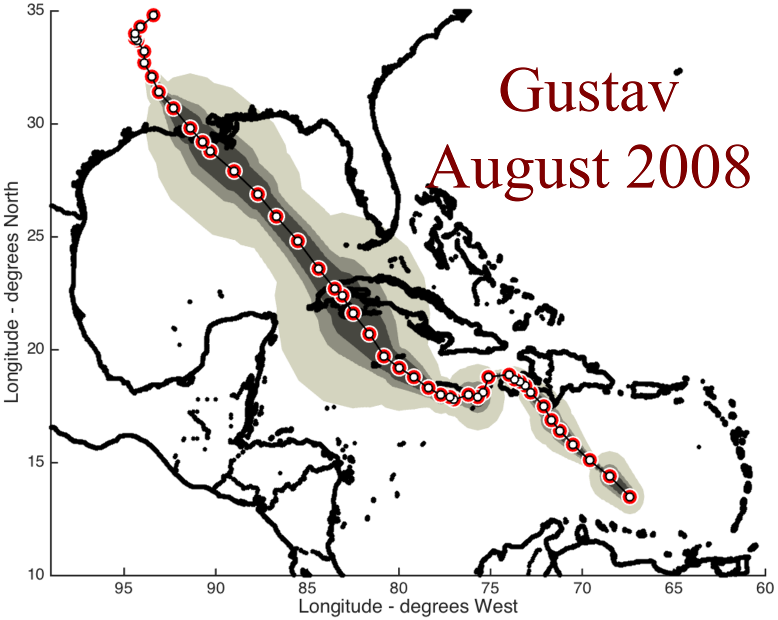


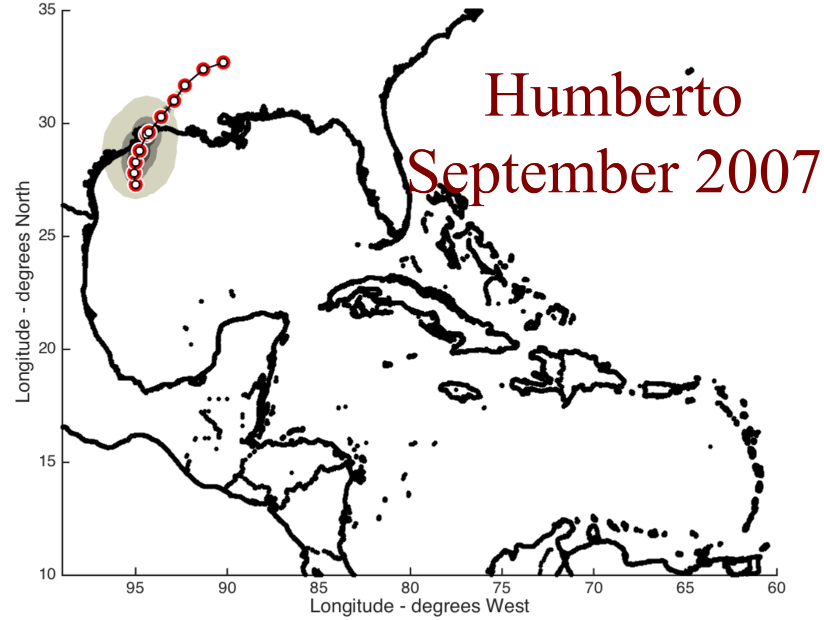
MFR Decision Support Matrix

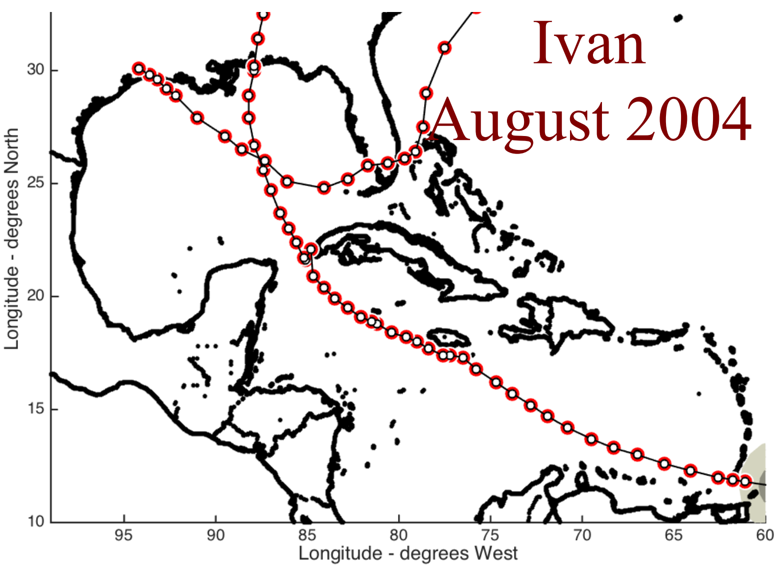
Hours before arrival of 36-mph winds

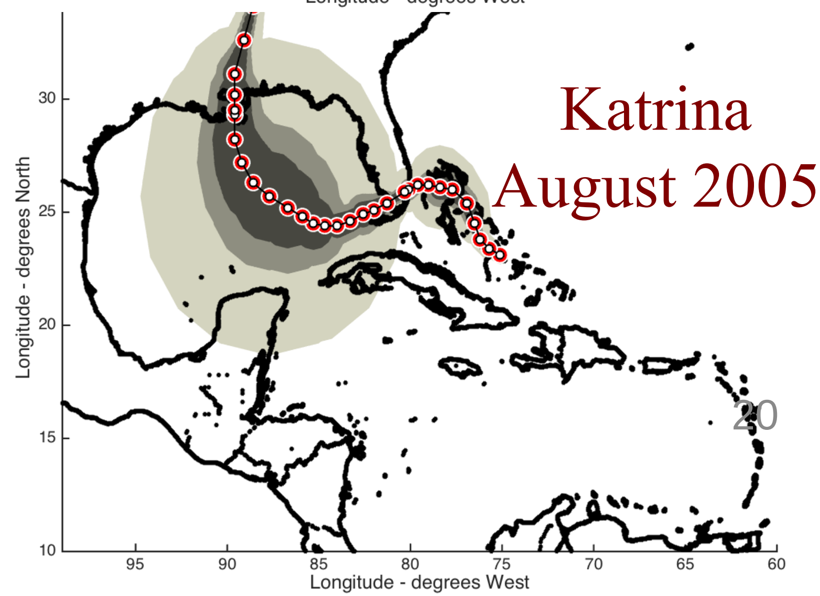
1. 96 hours: Send advance emergency relocation staff (ERS) to alternate headquarters
2. 96 hours: Send liaison officers to local municipal emergency operations centers
3. 72 hours: Send rest of ERS to alternate headquarters
4. 72 hours: Activate remain behind element to stay if evacuation ordered
5. 60 hours: Evacuate or shelter in place
6. 48 hours: Transfer command and control to alternate headquarters

Every storm is different









Challenges in hurricane preparation

Task environment

- Too much information
- Uncertainty
  - Storm intensity
  - Storm path
  - Storm timing
- Dynamic information sources (frequent updates)

Formation of expertise

- Highly variable context
- Dynamic information sources
- Few learning opportunities
- Ambiguous feedback

Training tool for hurricane preparations

Key characteristics

- Storm model (storm and forecasts)
- User decisions
- Actions of other entities
- Consequences of storm plus decisions
- Quickly experience many storms

Storm model

- Synthetic storms
  - Realism – storms should <u>feel</u> believable
  - Features should <u>span</u> realistic ranges
  - Unusual events <u>should</u> occur in synthetic storms
- Storm forecasts in 6-hour increments
  - Most likely path (forecast track)
  - Probability forecasts for next 120 hours
    - 38-mph winds (tropical winds)
    - 58-mph winds (destructive force winds)
    - 74-mph winds (hurricane-force winds)
- Realistic forecasts: forecast errors consistent with recent NHC forecasts

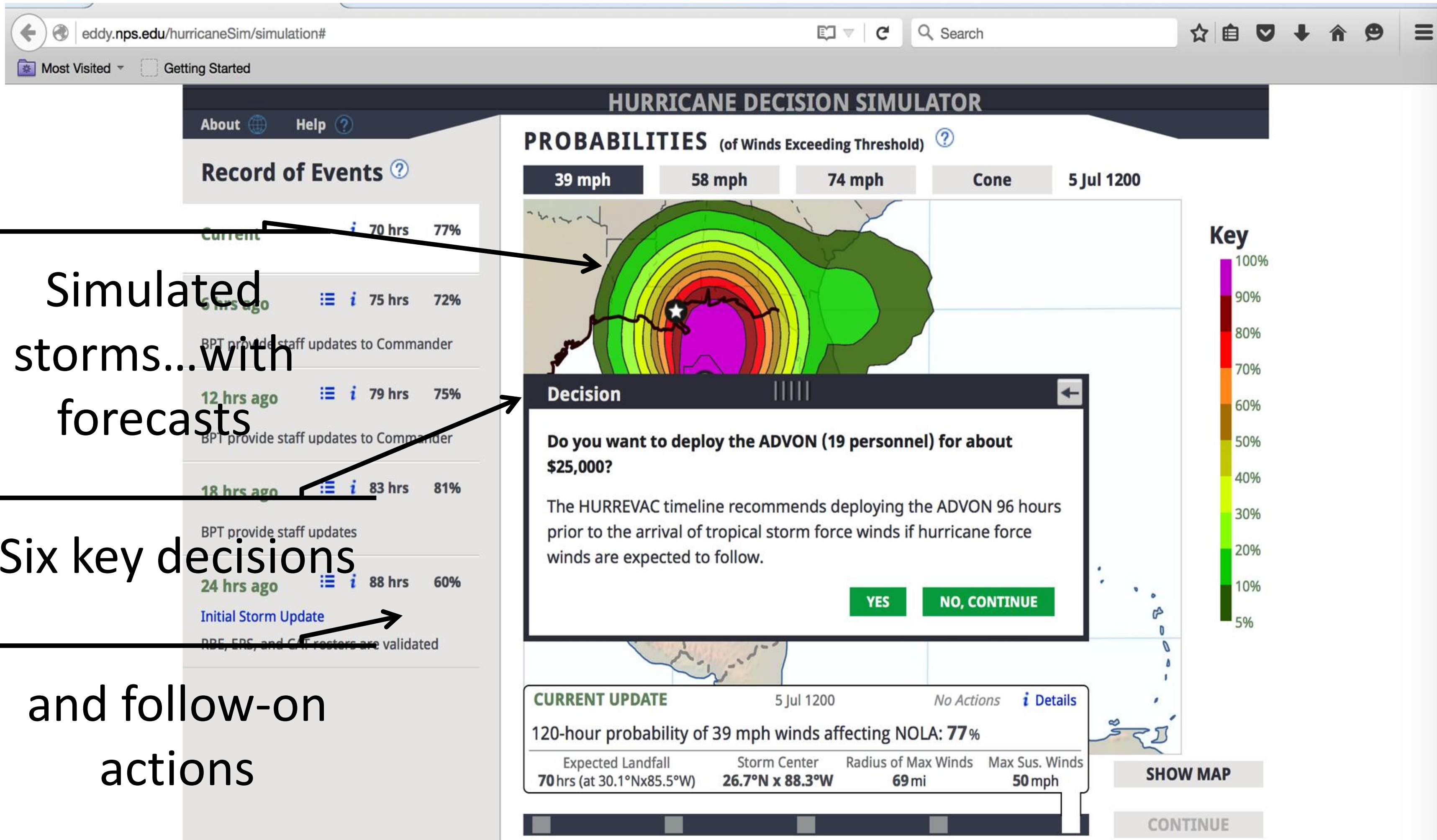
Storm model

- Features
  - Tracks – center position over time
  - Intensities – maximum sustained winds
  - Size – radius of maximum winds
- Forecasts
  - Forecasts of track, intensity, and size
  - Wind-speed probability plumes
  - Storm surge at New Orleans

Storm model

- Data set
  - National Hurricane Center best tracks 1980-2014
  - 542 storms → 14,882 observations
- Markov chain model for center of storm
  - 1500 states defined by k-means clustering algorithm
  - Transition probabilities = observed relative frequency
- Predictors for forecast
  - Current storm center position
  - Prior speed and bearing
  - Overland or on water

Hurricane Decision Simulator for Marine Commands in New Orleans

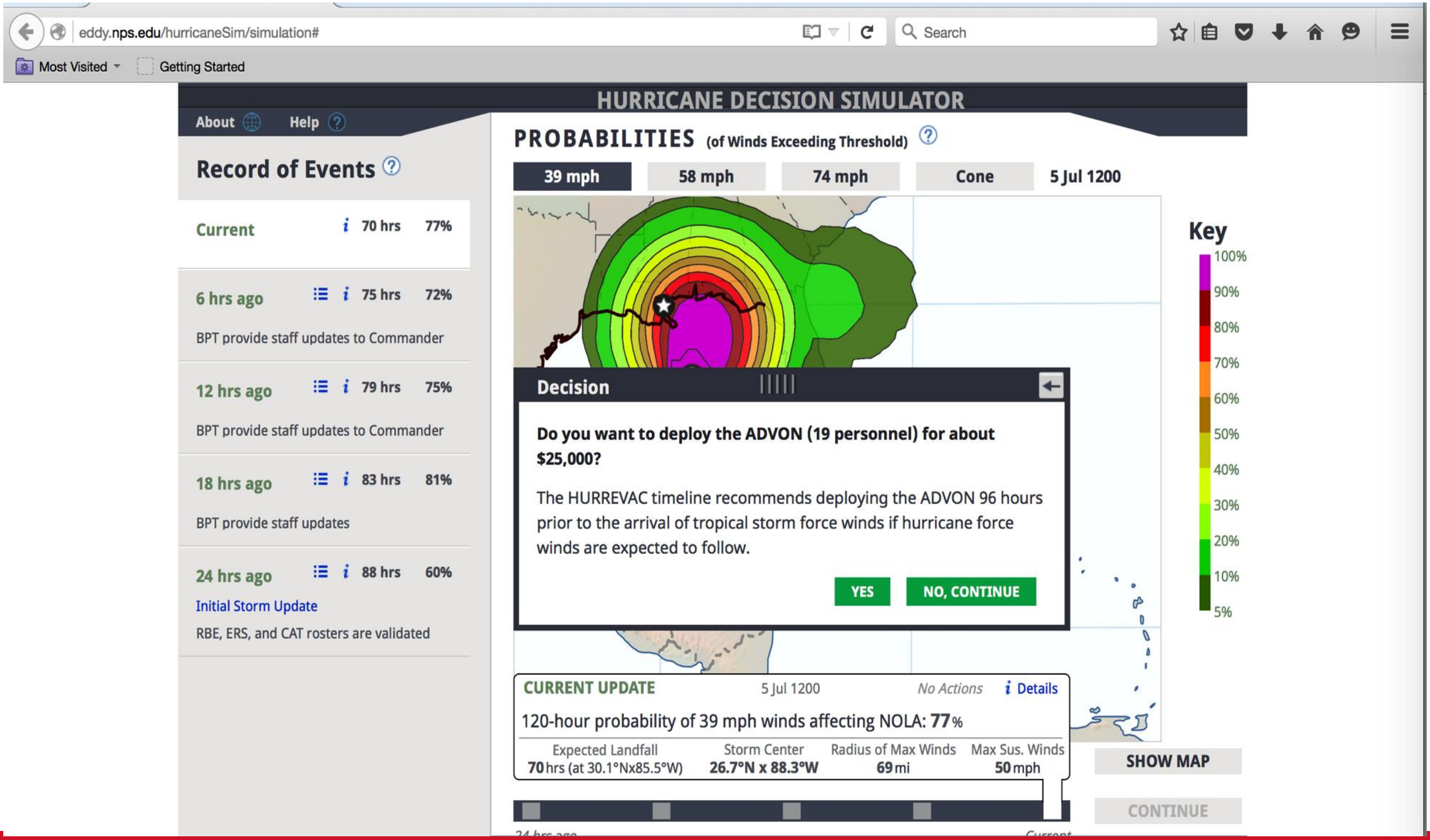


Simulated storms…with forecasts

Six key decisions

and follow-on actions

Hurricane Decision Simulator for Marine Commands in New Orleans



Results so far

- Fall 2015, used in crisis action team group exercise
- Shared with continuity of operations planning team
- In use for individual training by crisis action team and emergency relocation team (almost 200 people)
- Used in developing annual (team) specialized hurricane exercises
- Interest from additional sites/agencies
  - II Marine Expeditionary Force (North Carolina)
  - City of New Orleans
  - Federal Executive Board in New Orleans

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