# *Climate Change and Extreme Weather Vulnerability Assessment and Adaptation Options for the Central Artery/Tunnel, Boston, Massachusetts*

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**Salem Sound Coastwatch**

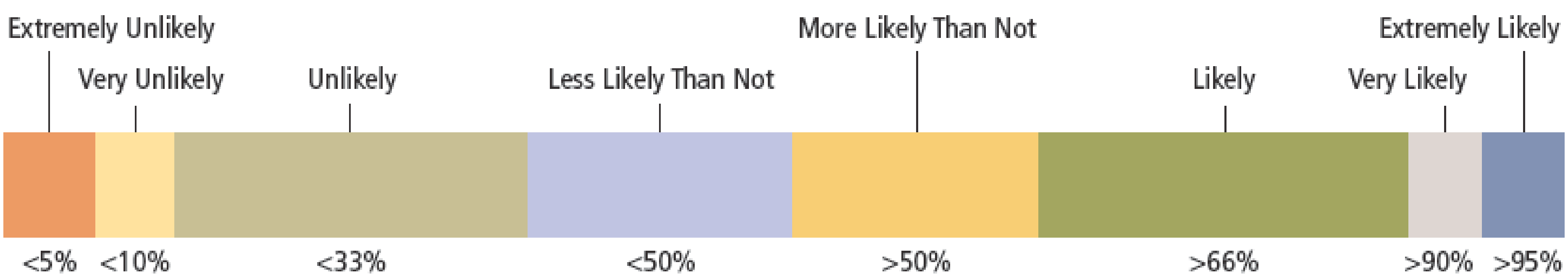
**Finding Solutions to our Coastal Challenges**

**March 18, 2016**

# Climate change is happening and humans are the predominant cause.

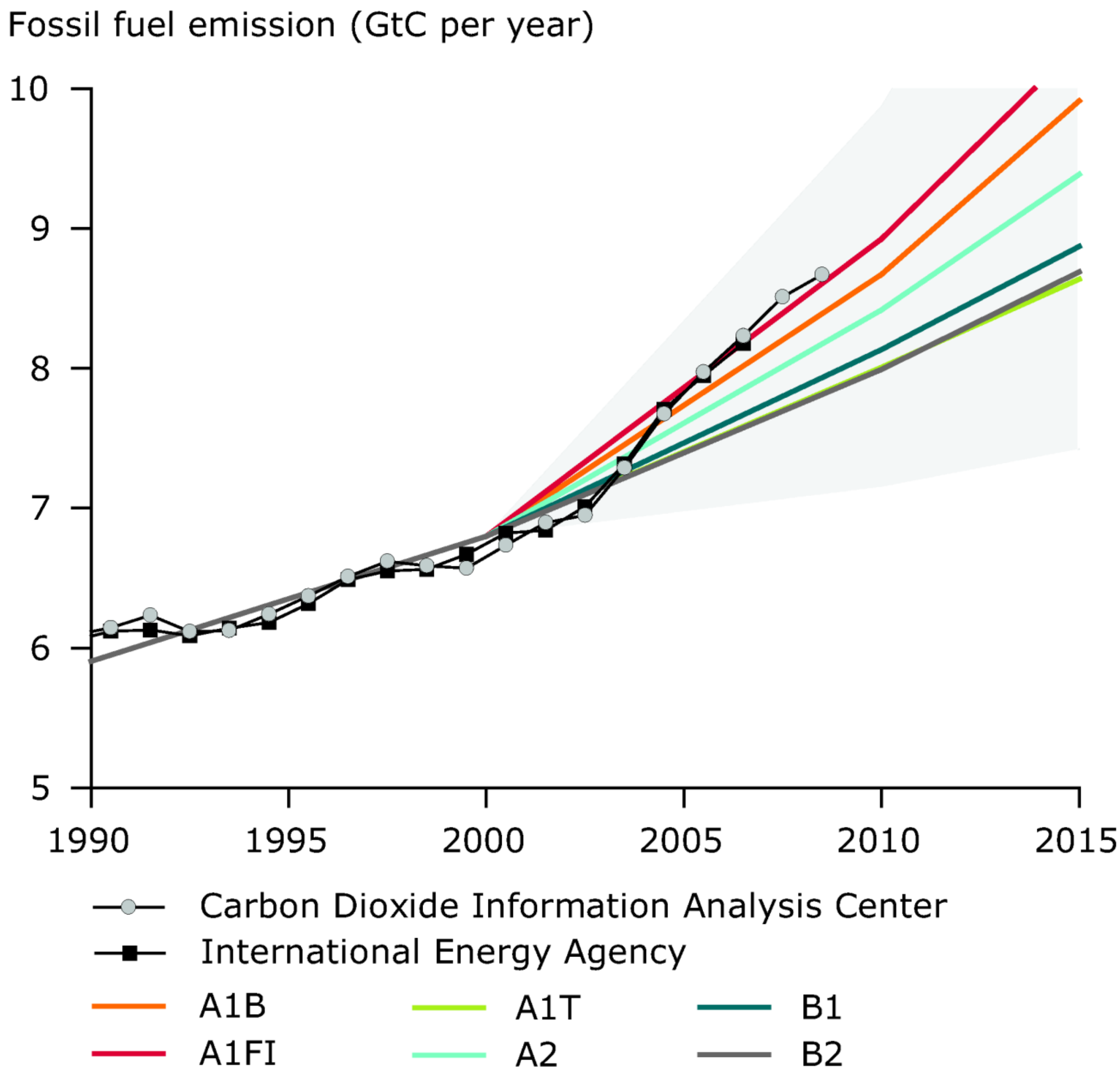
The Intergovernmental Panel on Climate Change **(IPCC AR5, 9/27/13)**

- it is **"unequivocal"** that Earth's climate is warming.
- Since the 1950's, it is **"extremely likely"** that human emission have been the dominant cause of the rise in global temperature.




Source: IPCC *Climate Change 2007: The Physical Science Basis*—Summary for Policymakers.

# Things don't seem to be getting better

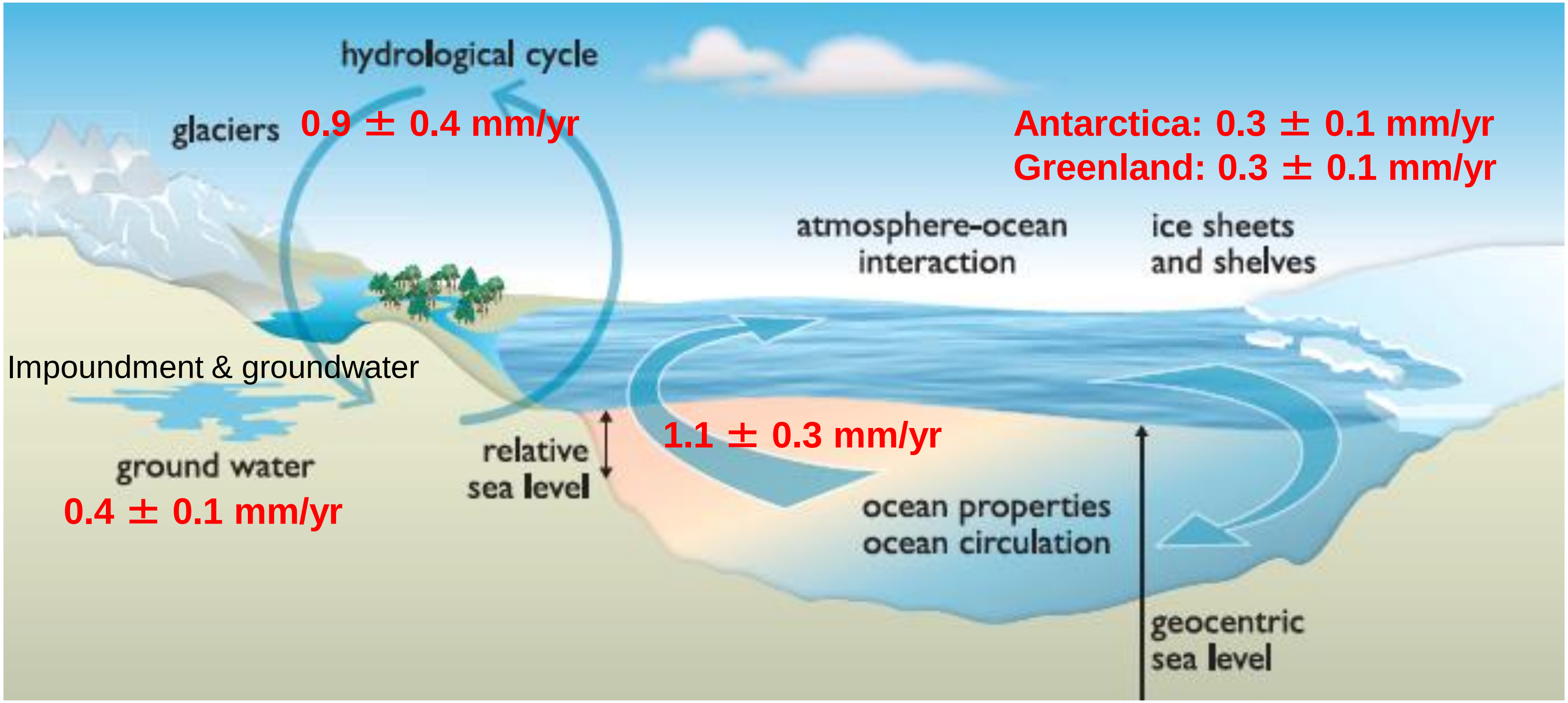



http://www.eea.europa.eu/data-and-maps/figures/observed-global-fossil-fuel-co2

# Climate change is happening and humans are the dominant cause.

- Global temperatures are **likely to rise 0.5-8.6 F** by the end of the century **depending carbon emissions.**
- Most aspects of climate change **will continue for many centuries** even if $CO_2$ emissions stop.
- It's '**'virtually certain**'' that the upper ocean has warmed from 1971 to 2010. The **ocean will continue to warm.** Heat will penetrate from the surface to the deep ocean and **affect ocean circulation.**
- Thermal expansion has dominated SLR in 20$^{th}$ C, but ice-sheet melt will likely dominate later in 21$^{st}$ C.

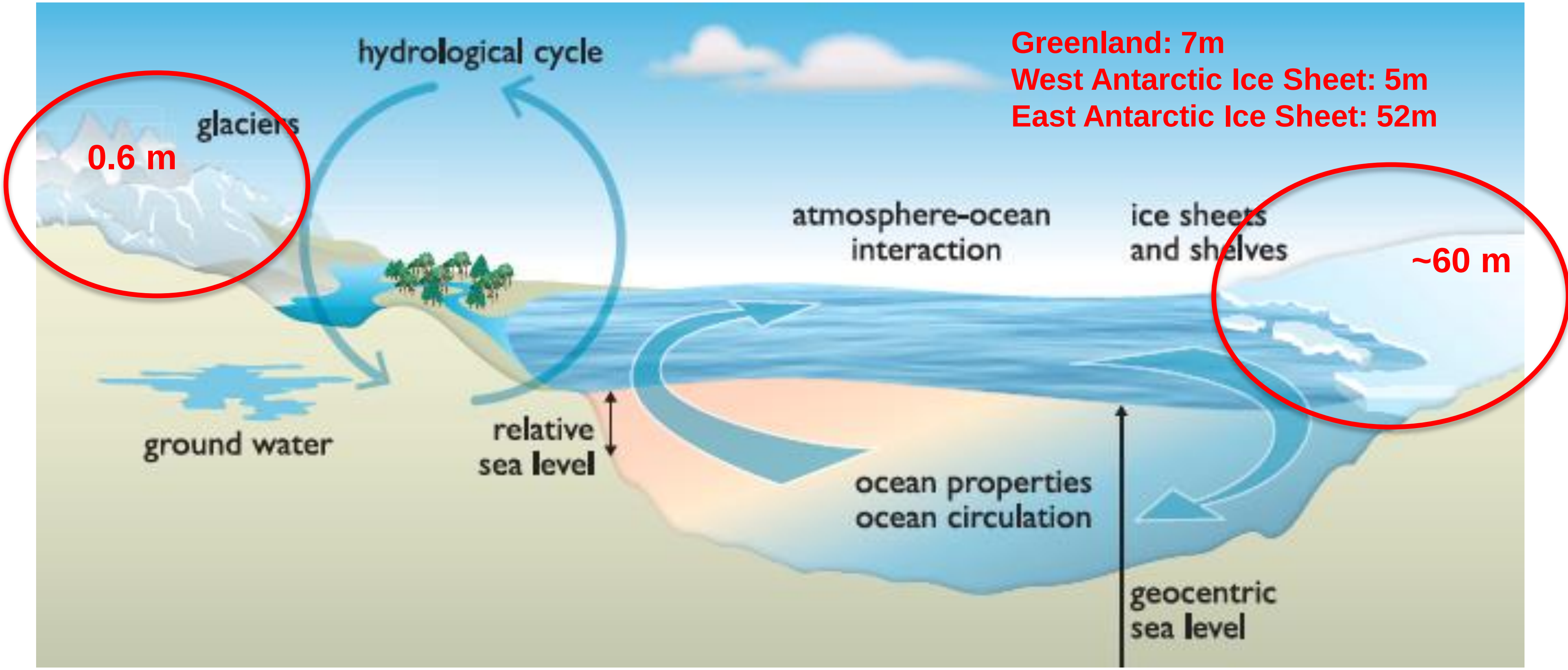
# 20th century contributors to GMSL rise




Thermal expansion of ocean water and glacier melt has been the biggest contributor to GMSL.

IPCC AR5 2013

# Potential 21$^{st}$ century contributors to GMSL rise

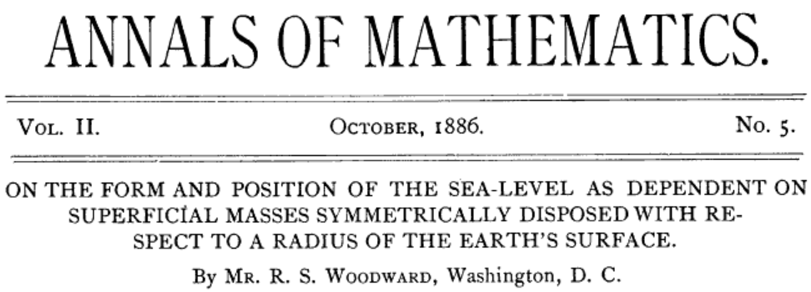



Ice sheet melt and the ice-sheet "finger print is potentially the biggest contributor in 21$^{st}$ C.

IPCC AR5 2013

# Sea-level rise in New England is not (and will not) be the same as GMSL rise

- Mass redistribution (elastic gravitational and rotational effects)

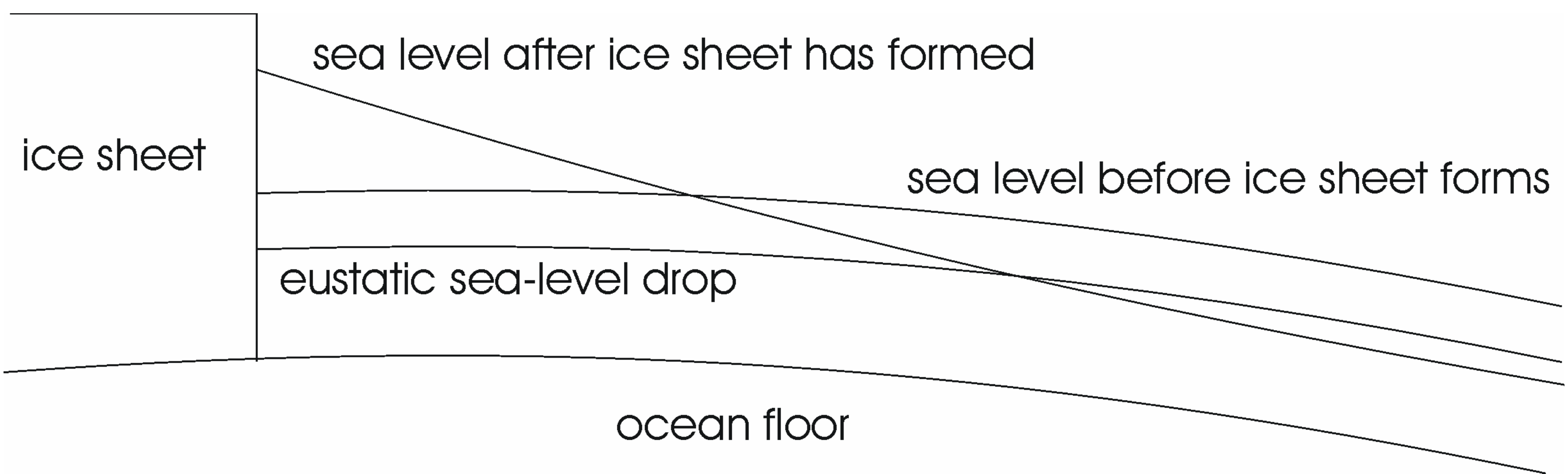


ANNALS OF MATHEMATICS.

Vol. II. | October, 1886. | No. 5.

ON THE FORM AND POSITION OF THE SEA-LEVEL AS DEPENDENT ON SUPERFICIAL MASSES SYMMETRICALLY DISPOSED WITH RESPECT TO A RADIUS OF THE EARTH'S SURFACE.

By Mr. R. S. Woodward, Washington, D. C.



## ICE SHEET “FINGERPRINT’

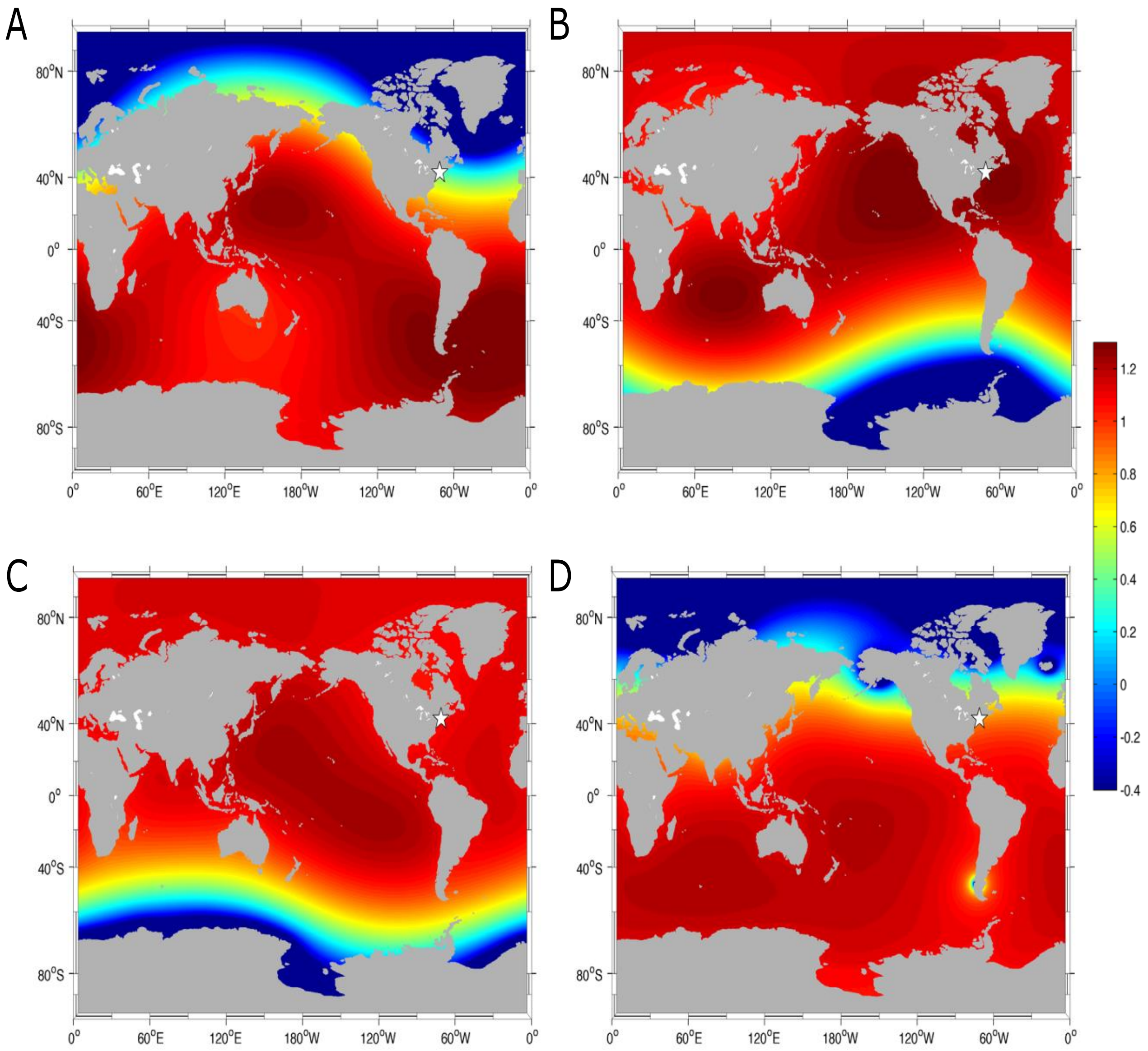



***Figure 1-1.*** *Fingerprints of spatially variable sea-level rise arising from melting of the Greenland Ice Sheet (A), the West Antarctic Ice Sheet (B), the East Antarctic Ice Sheet (C) and alpine glaciers and ice caps (D). The location of Boston is shown with a star. Shading represents the meters (arbitrary units) of sea-level rise that would occur if each of these land-based ice reservoirs were to contribute a meter of equivalent GMSL rise. (DeConto et al., 2016: Chapter 1 in BRAG report)*

# Project Overview

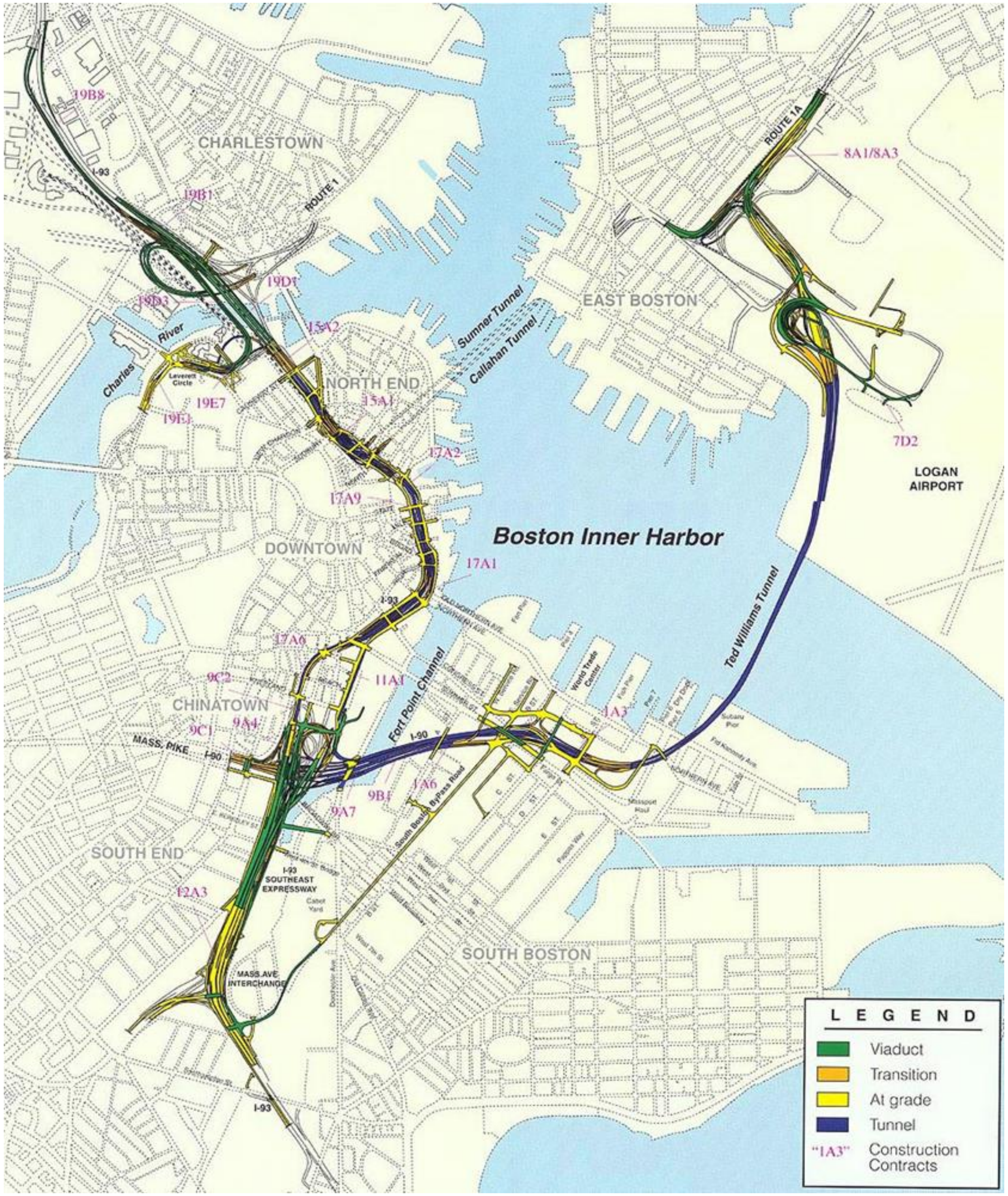
The **Central Artery/Tunnel (CA/T)** system is a critical link in regional transportation and a vitally important asset in the Boston metropolitan area. It is potentially vulnerable to flooding from an extreme coastal storm under present and future climate.

## Project Objectives:

- Assess vulnerability of CA/T to present climate and future sea level rise and extreme storm events
- Investigate options to reduce identified vulnerabilities through local and regional adaptation
- Support an emergency response plan for tunnel protection and/or shut down in the event of a major storm

# Project Team

- Ellen Douglas, UMass Boston
  - Project Manager, Climate Change, Hydrology
- Kirk Bosma, Woods Hole Group
  - Hydrodynamic Modelling, Engineering
- Paul Kirshen, UNH/UMass Boston
  - Climate Change, Vulnerability, Adaptation
- Chris Watson, UMass Boston
  - Assistant Project Manager, GIS, Database, Survey
- Steven Miller, MassDOT
  - Project Manager
- Katherin McArthur, MassDOT
  - Assistant Project Manager


CHARLESTOWN
EAST BOSTON
NORTH END
DOWNTOWN
CHINATOWN
SOUTH END
SOUTH BOSTON
LOGAN AIRPORT
Boston Inner Harbor
Sumner Tunnel
Callahan Tunnel
Ted Williams Tunnel
Fort Point Channel
Charles River
ROUTE 1
ROUTE 1A
I-93
I-90
MASS. PIKE
I-93 SOUTHEAST EXPRESSWAY
MASS AVE INTERCHANGE
South Boston ByPass Road
19B8
19B1
19D1
19D3
19E7
19E1
15A2
15A1
17A2
17A9
17A1
17A6
11A1
9C2
9C1
9A4
9B1
9A7
1A6
1A3
12A3
8A1/8A3
7D2
LEGEND
Viaduct
Transition
At grade
Tunnel
"1A3" Construction Contracts

Boston Harbor & Tip O'Neill Tunnel Exit/Entrance Ramps
http://www.flickr.com/photos/pictometry/6220376808/

# Project Realities

## Phase 1: Define Geographical Scope

- GIS-based delineation too unwieldy
- Redefined scope with "Institutional Knowledge" (IK) approach
  - District 6 staff provided significant insight into the CA/T
- Created "mini-pilot" project approaches to:
  - Develop preliminary vulnerability assessment methodology using a subset of tunnel assets to identify key assets
  - Field work to identify structures and measure heights of openings
  - Interacted with IK to augment field work and GIS data analysis
- "Discovered" several databases (i.e., Maximo)
  - defined a common language and identifiers across datasets and personnel.
- Final project domain defined by IK team
  - Face-to-face meetings with maps to decide what was in and what was out.

→Lesson learned: allow 3 months for "discovery"

# Project Realities

## Phase 2: Inventory of Assets

- Devised GIS hierarchical framework to incorporate interconnectedness and to facilitate vulnerability analysis

Structural Systems ← Structures ← Facilities ← Assets

- Inventory limited to Structures and Facilities
- Created GIS database (CATDB) of Facilities and Structures
  - Maximo not georeferenced, locations not accurate enough for VA.
  - As-Built Record Drawings not compatible with project needs
  - Identified ~25% more structures than contained in Maximo.
  - Field work alone was ~500 man-hours or ~3 months FTE additional time.
  - IK team instrumental in this process.

Tip O'Neill Tunnel Exit & Entrance Ramps

Tip O’Neill Tunnel Exit Ramp

Vent Building 1

Vent Building 1 – Detail of Air Exchange Vent

# High Resolution Hydrodynamic Modeling

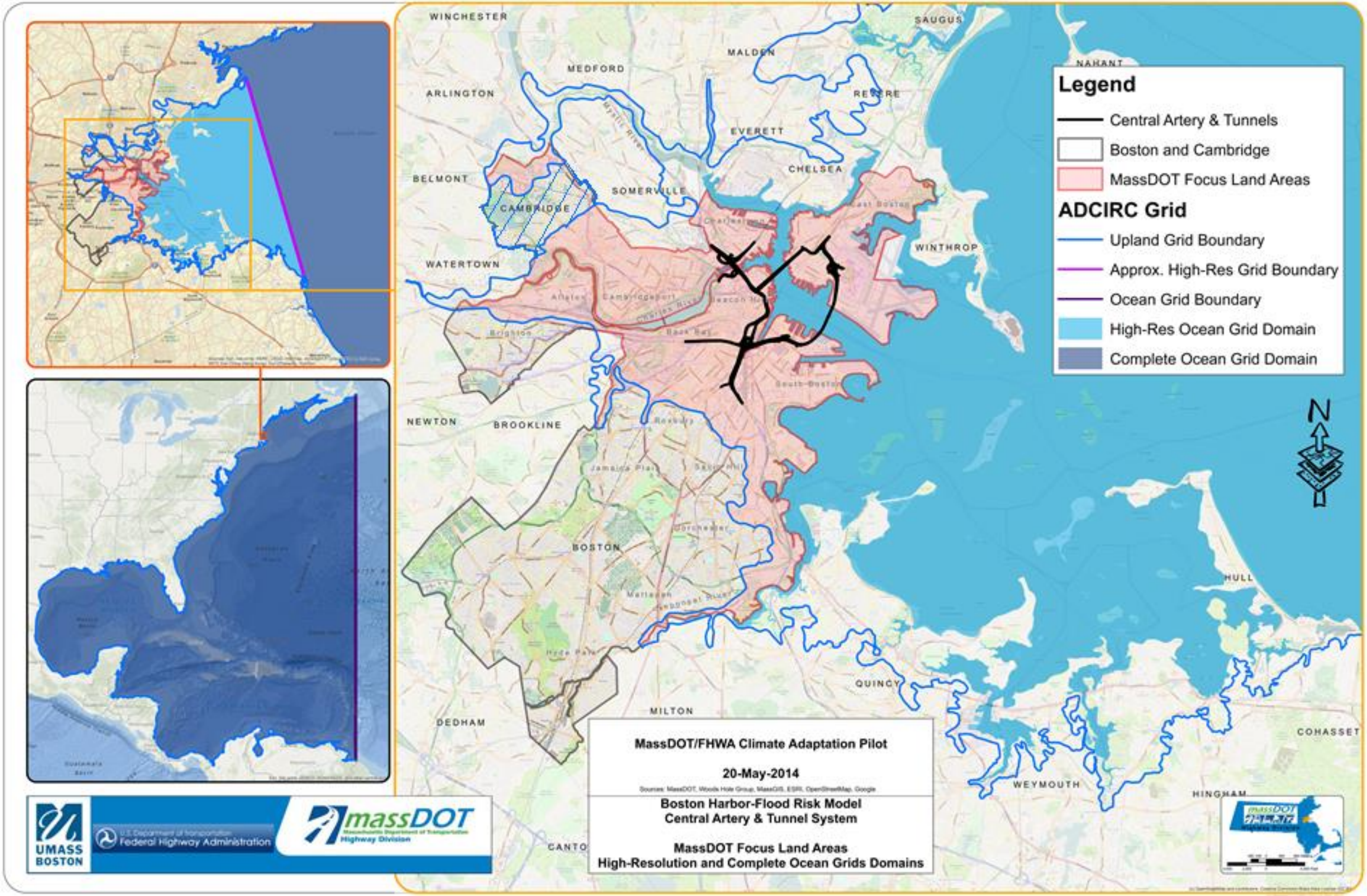
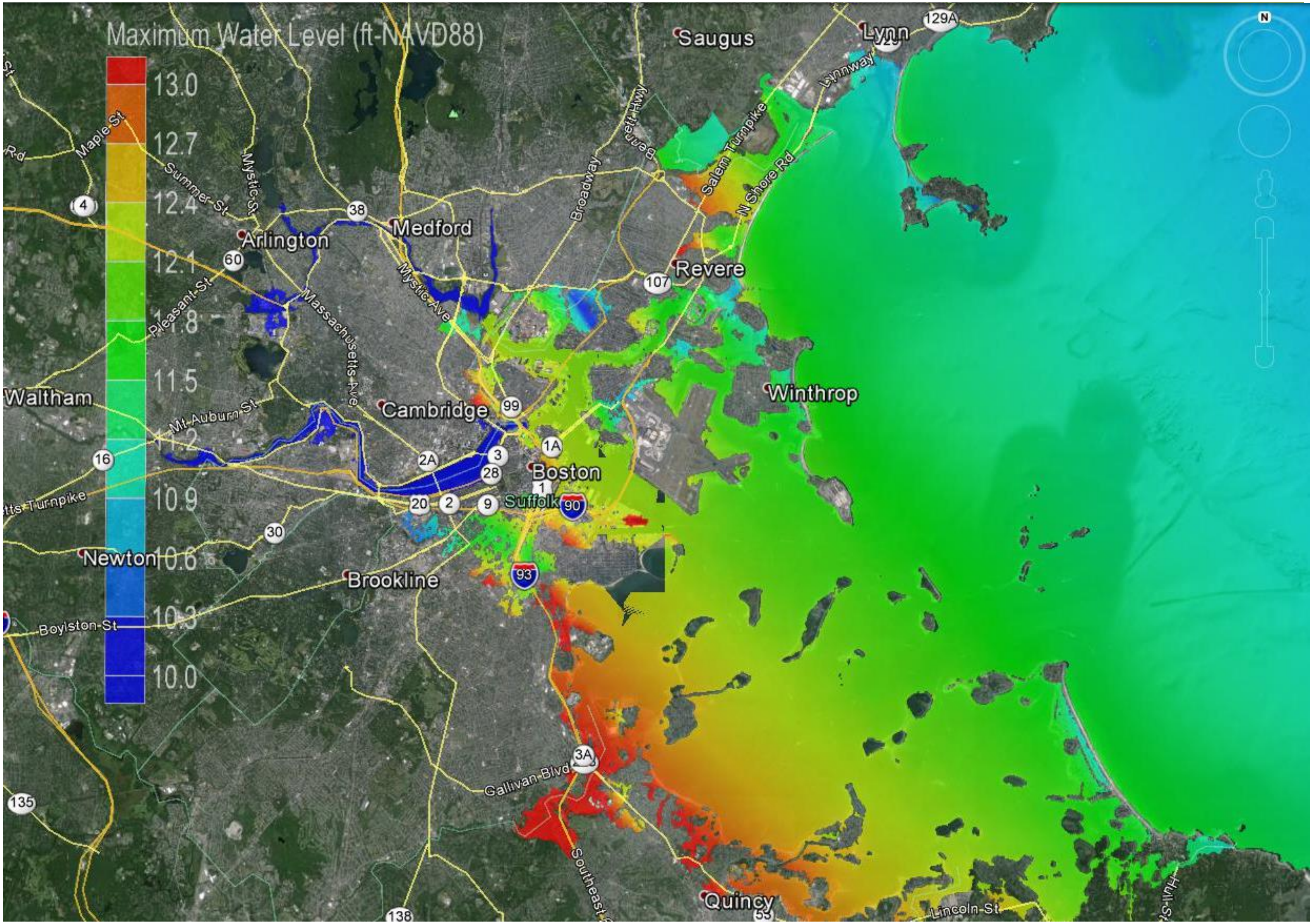
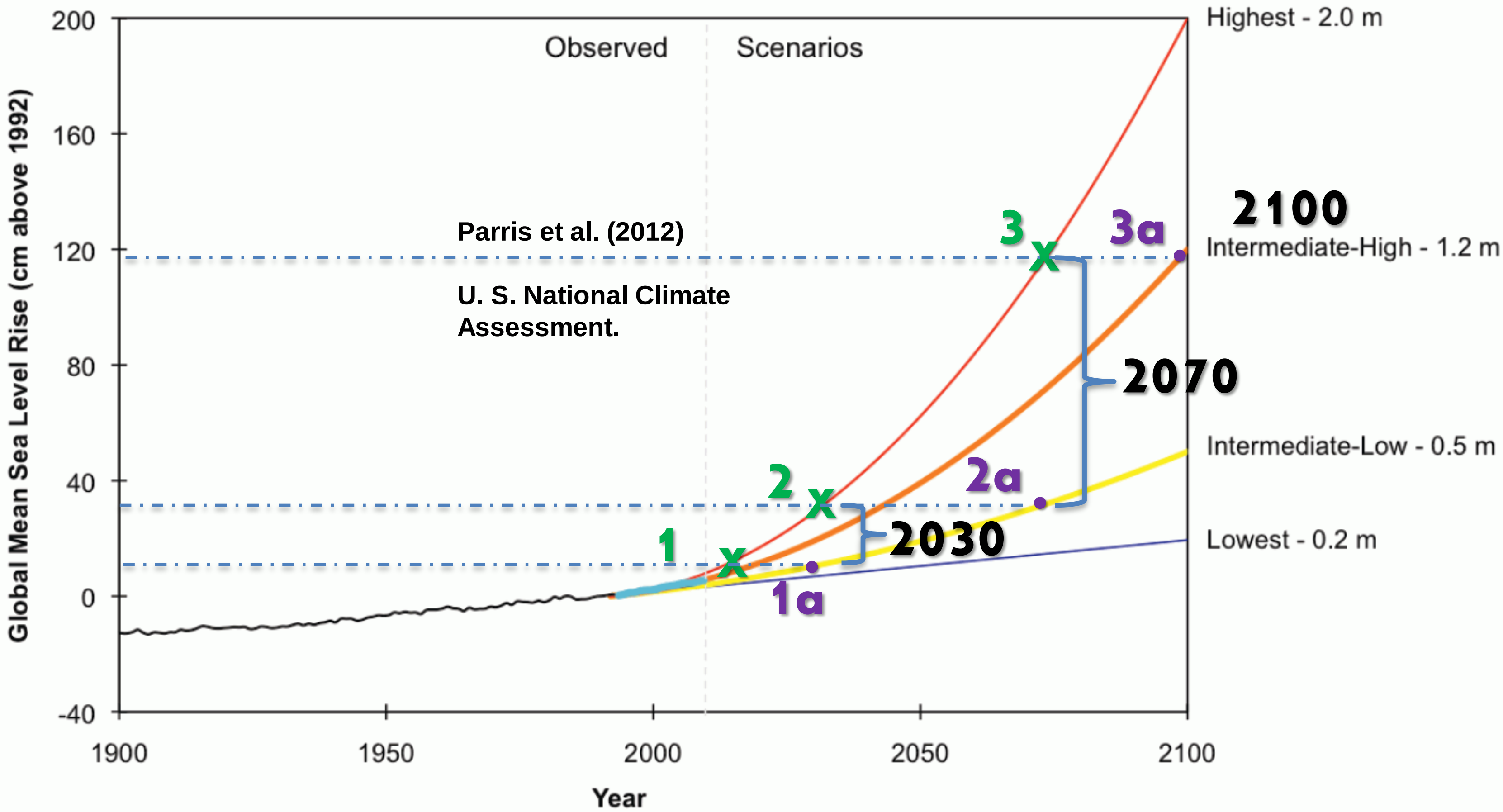



Image Landsat
Google earth

# “Bathtub” vs hydrodynamic model



# SLR Scenarios - Using Projections to Bracket Risk



# Estimating annual maximum exceedance probabilities

- Model generates a series of water surface elevations (WSE) for hurricanes and for nor'easters.
  - Independent series due to Monte Carlo approach

- Estimate average annual frequency ($\lambda$) of each storm type.

  $\lambda(H) = 0.337$ (2030 climatology)

  $\lambda(N) = 2.3$ (historical)

- Transform PDS to AMS using:

$$p_e = 1 - \exp(-\lambda \cdot q_e)$$ HoH 18.6.3a

- Now we have the empirical annual maximum exceedance probability series (AMS) for each storm type ($p_e$ vs WSE)

# Develop composite exceedance probability distribution for WSE

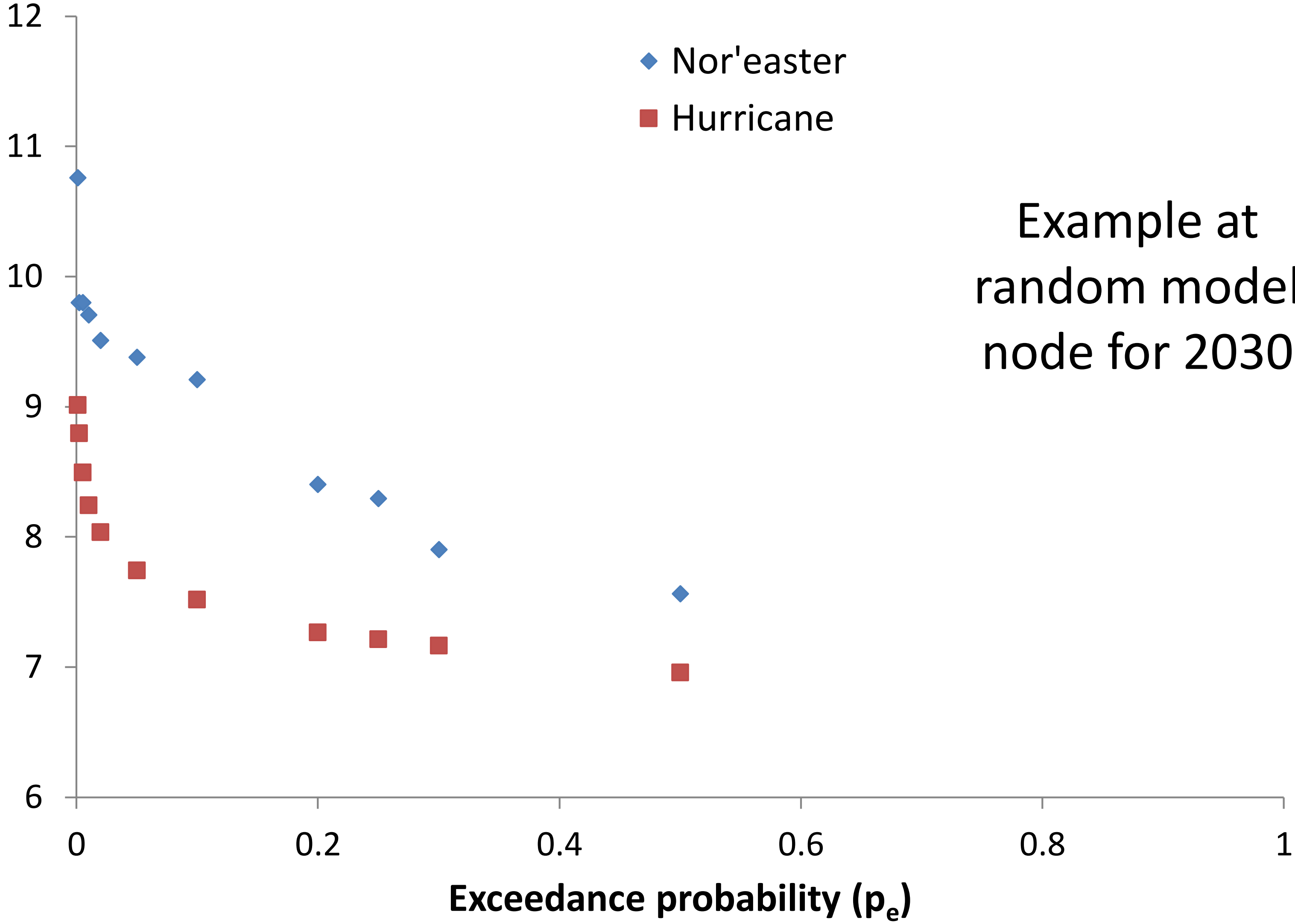
- Following Vogel and Stedinger (1984):

$$F_S(q_m) = F_H(q_m) \cdot F_N(q_m)$$

- Which is equivalent to

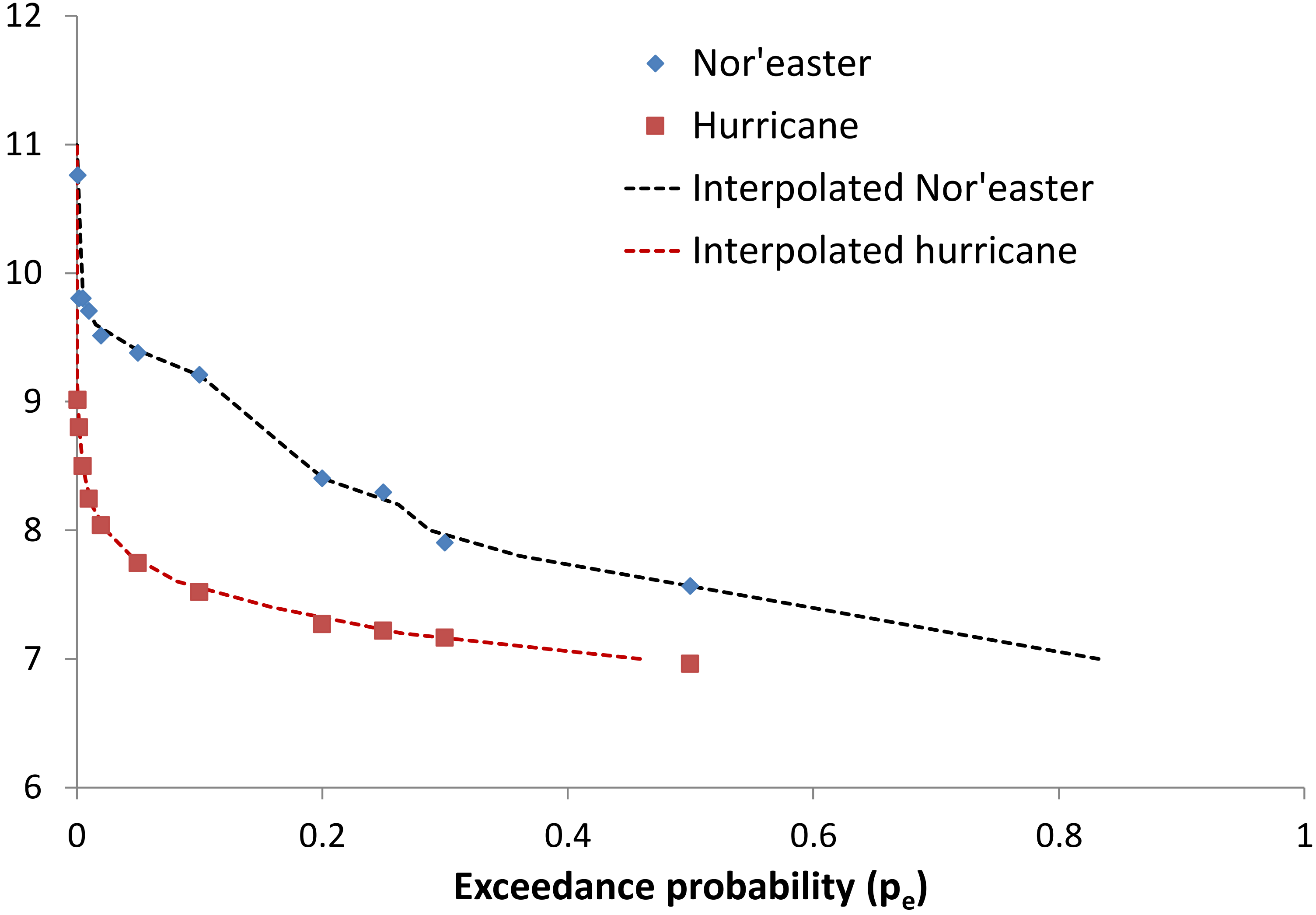
$p_s$ (WSE) = $p_N$ (WSE) + $p_H$ (WSE) – $p_N$ (WSE) $p_H$ (WSE)

(Douglas, Vogel and Bosma, in preparation)

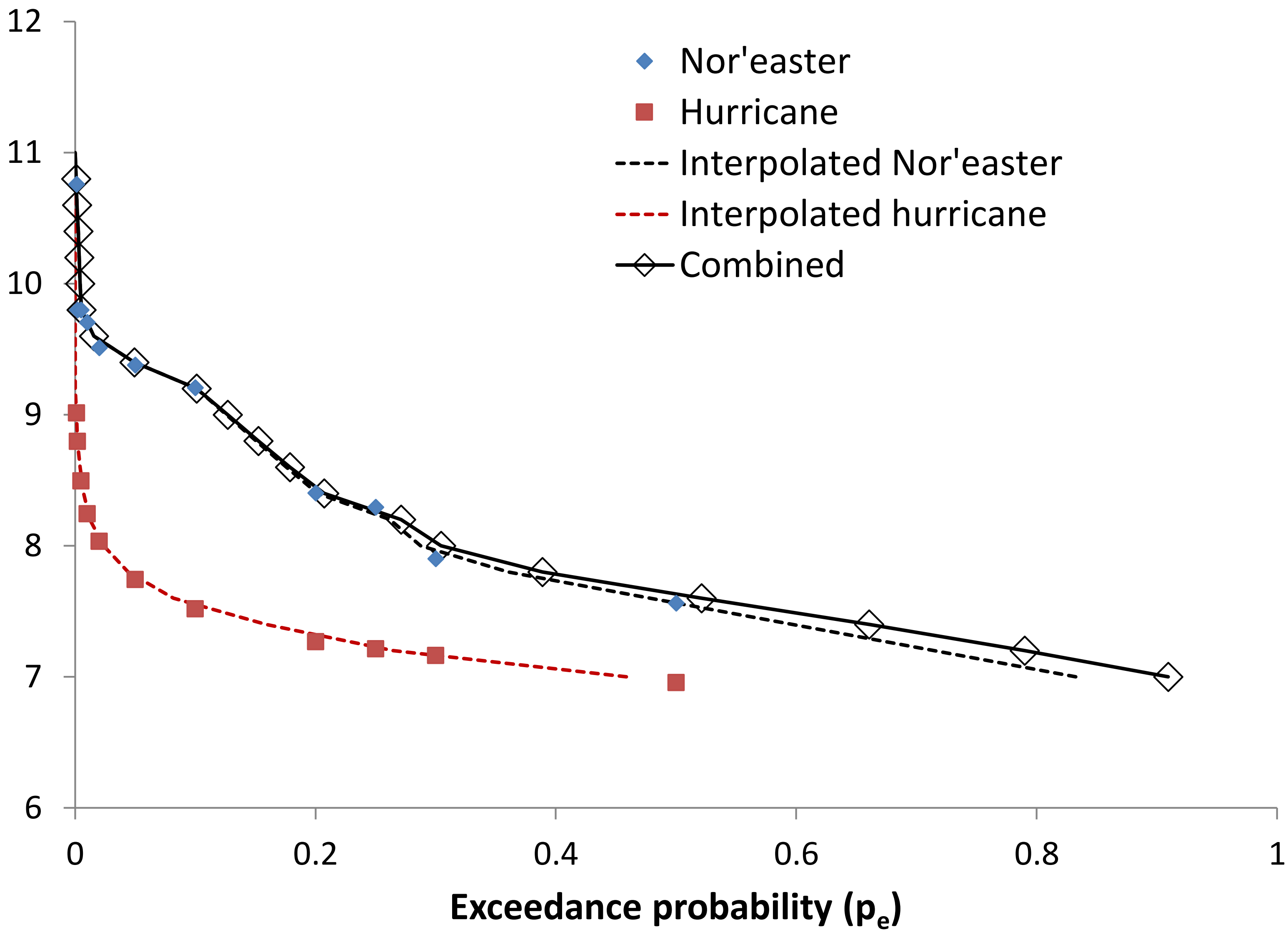



Example at random model node for 2030

(Source: Douglas, Vogel and Bosma, in preparation)

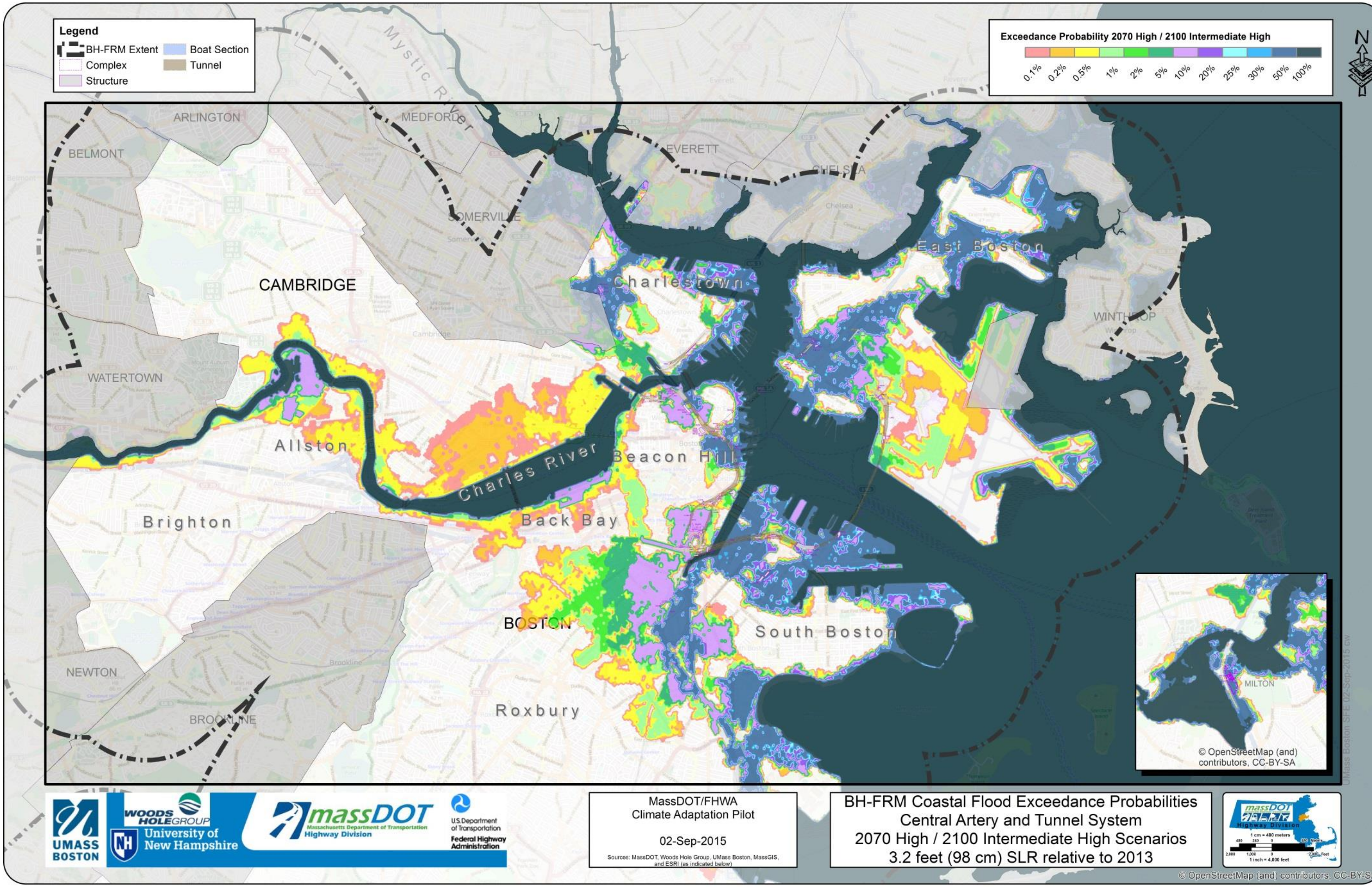



(Source: Douglas, Vogel and Bosma, in preparation)

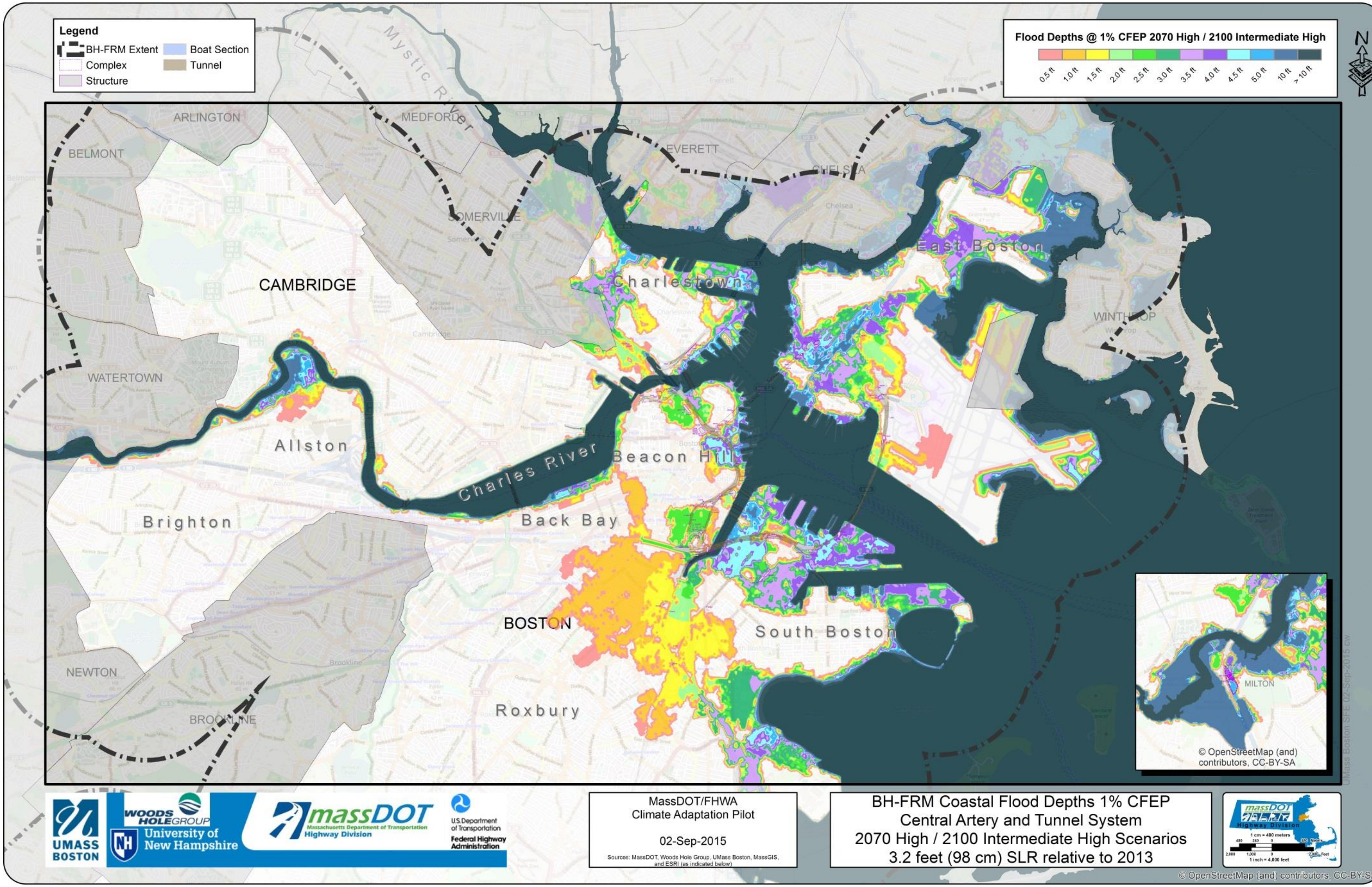



(Source: Douglas, Vogel and Bosma, in preparation)

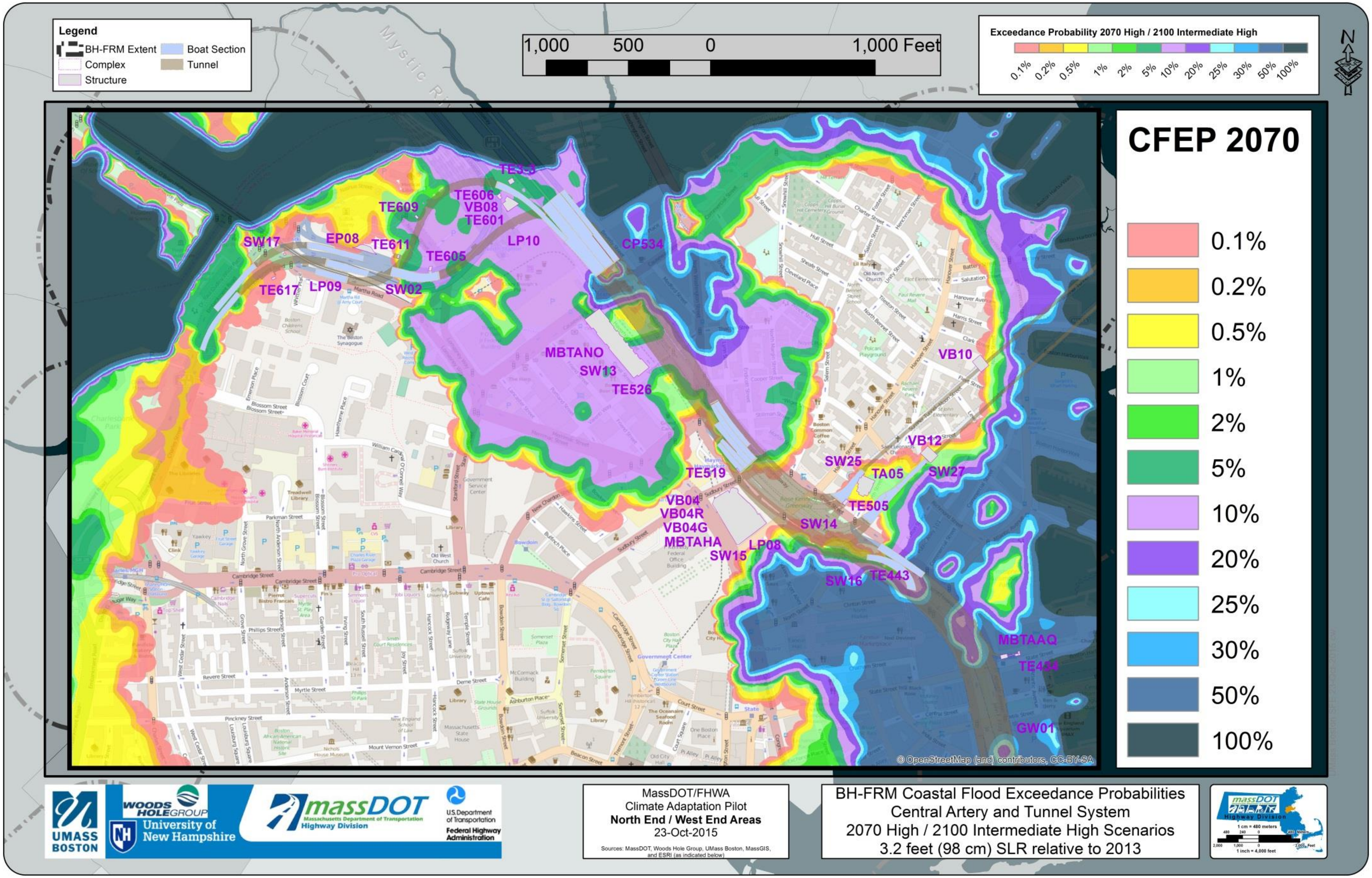
# Flood exceedance probabilities



# 1% Flood depths



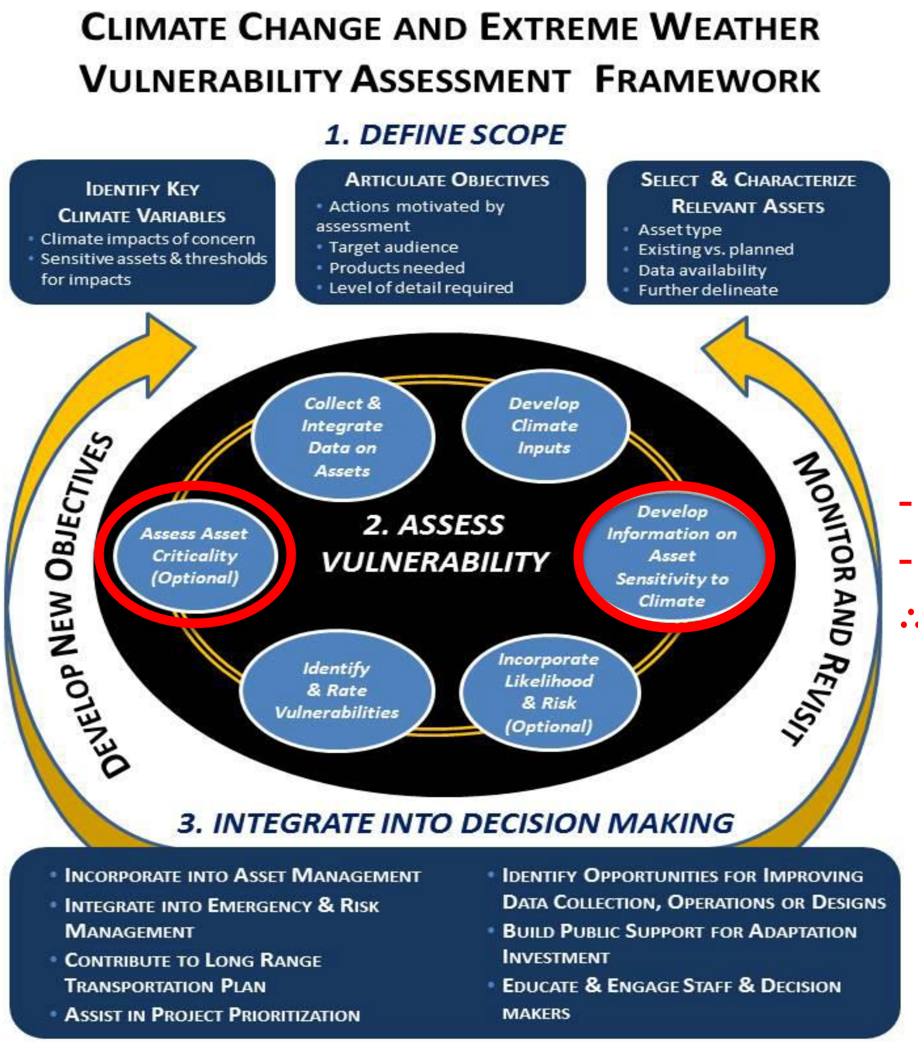
# Flood exceedance probabilities



FHWA framework for assessing the vulnerability of transportation systems to climate change and extreme weather (Source: Fig 1 from FHWA, 2012, pg. 2)

- All components are equally critical
- Any flooding could impact system.

∴Exposure = risk of getting wet at any structure or facility




- Sensitivity = 1
- Adaptive Capacity = 0

∴ Vulnerability = Exposure

# Vulnerable boat-sections

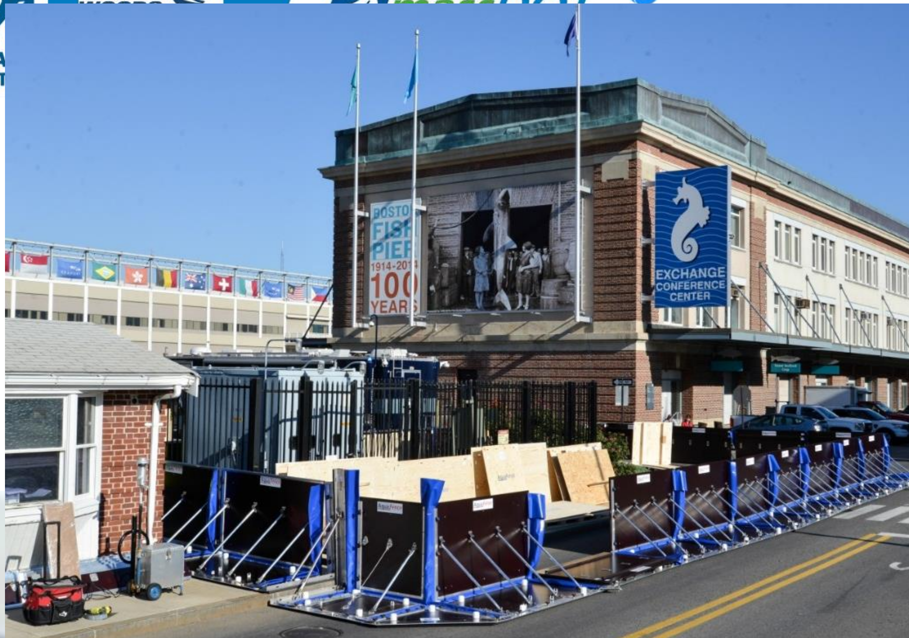
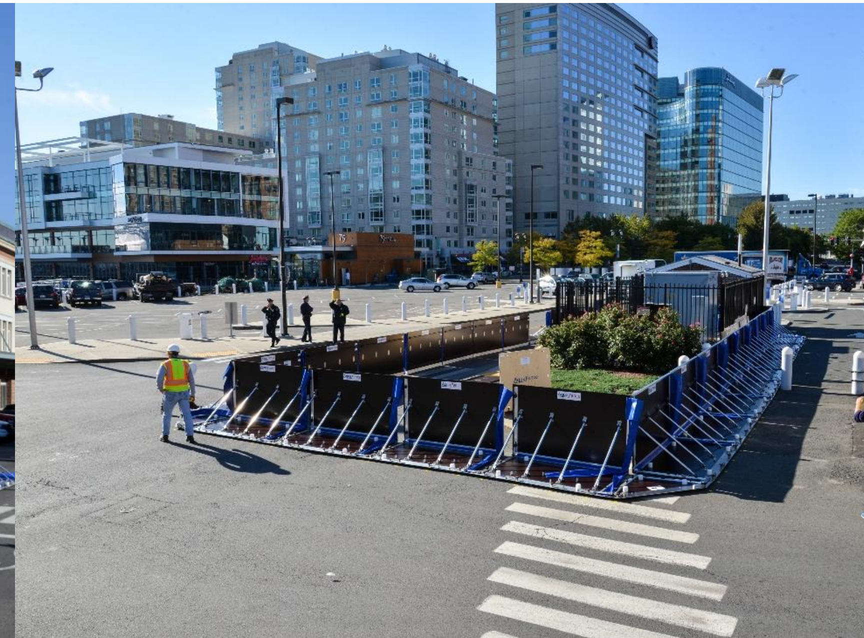
| Structure_ID | 2013 0.1 Depth (ft) | 2013 to 2030 0.1 Depth (ft) | 2030 to 2070/2100 0.1 Depth (ft) | Ramp Area or Roadway Area and Notes |
|---|---|---|---|---|
| **BIN5UR -POR** | 0 | 0 | *0 to 3.2 | Ramp CS-SA Central Artery Southbound to Surface Artery |
| **BIN5VQ-POR** | 0 | 0 | *0 to 1.4 | Rose Kennedy Greenway Parcel 18:<br>Ramp A-CN<br>Atlantic Avenue to I-93 Northbound |
| **BIN5VA-POR** | *0 to 1.0 | *0 to 1.7 | *0 to 4.4 | Rose Kennedy Greenway Parcel 12:<br>Ramp CN-SA<br>Central Artery Northbound to Surface Artery |
| **BIN59Y-POR** | 0 | 0 | *0 to 2.3 | Ramp CN-S Central Artery Northbound to Storrow Drive |
| **BIN5AF-POR** | 0 | 0 | *0 to 1.6 | Storrow Drive Northbound entrance to Leverett Circle Tunnel |
| **BIN5K2-POR** | 0 | 0 | *0 to 1.5 | Storrow Drive Northbound exit from Leverett Circle Tunnel |
| **BIN59K-POR** | 0 | 0 | *0 to 1.7 | Ramp L-CS Leverett Circle to Central Artery Southbound |
| **BIN7BC-POR** | 0 | 0 | *0 to 2.8 | Ramp B Massport Haul Road to I-90 Westbound |
| **BIN7BB-POR** | 0 | 0 | *2.2 to2.8 | Ramp D Congress Street to I-93 from Ramp Area F |
| **BIN7BL-POR**<br>**BIN7BM** | 0 | 0 | *0 to 2.8 | Ramp L<br>I-93 North Bound to I-90 Eastbound – includes a short underpass from BIN7BM to BIN7BL |
| **BIN7DE-POR**<br>**BIN7D5-POR**<br>**BIN7DX-POR**<br>**BIN7BN-POR** | 0 | 0 | *0 to 3.4 | I-90 / I-93 Interchange:<br>Ramp D tunnel exit to I-93 Southbound,<br>I-90 West Bound tunnel exit,<br>I-90 East Bound tunnel entrance and<br>Ramp C entrance to I-93<br>Northbound / Tip O'Neill Tunnel |
| **BIN7GA-POR**<br>**BIN7FX-POR**<br>**BIN7FL-POR** | 0 | 0 | *0 to 1.9 | Sumner Tunnel Exit:<br>Ramp ST-CN to Central Artery Northbound, and Ramp ST-S to Storrow Drive<br>Also, door to D6-SW25-FAC is located<br>in the Boat Section outside (upstream)<br>of BIN7GA-POR |
| **BIN7HV-POR** | 0 | 0 | *0 to 3.3 | I-93 Northbound entrance to Ted Williams Tunnel |
| **BIN7EK-POR**<br>**BIN7E7-POR**<br>**BIN7F6-POR**<br>**BIN7FQ-POR**<br>**BIN7FN-POR** | 0 | 0 | *0 to 3.0 | Rose Kennedy Greenway Parcel 6:<br>Ramp SA-CS Surface Artery to Central Artery South,<br>Ramp SA-CN Surface Artery to Central Artery North,<br>Ramp SA-CT Surface Artery to Callahan Tunnel<br>Ramp ST-SA Sumner Tunnel to Surface Artery<br>Ramp ST-CN Sumner Tunnel to Central Artery North |
| **BIN6HB** | 0 | 0 | *0 to 3.3 | I-93 Southbound exits from Ted Williams Tunnel and I-90 Collector |

# Local Adaptation

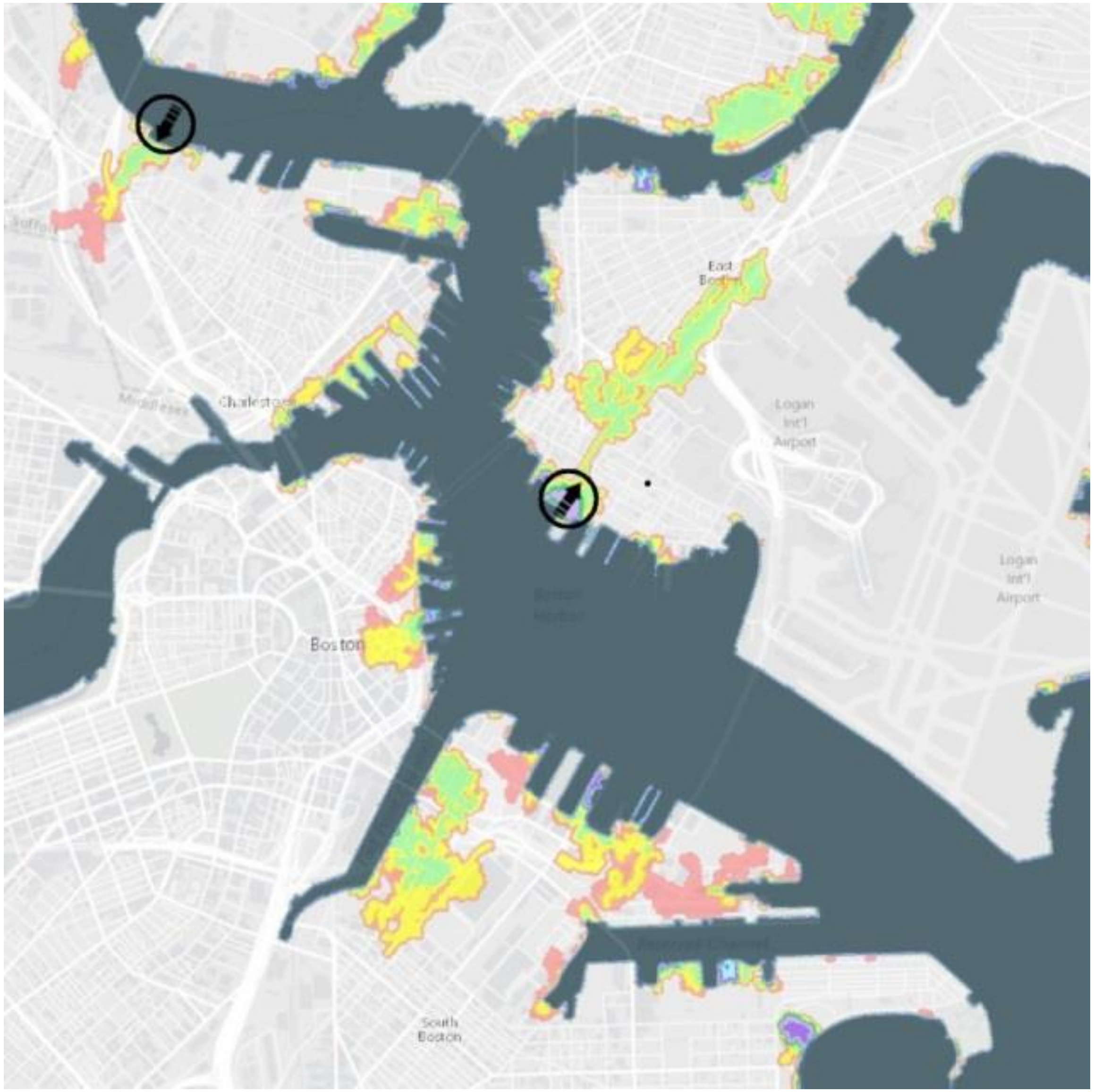

Type A1.1
(> 4 ft. Water)

Type A2.2
(< 4 ft. Water)

Type B2.1
(< 4 ft. Water)


EXCHANGE
CONFERENCE
CENTER



# Regional Adaptation



# Summary and Lessons learned

- Inventoried large number of CA/T Facilities & Structures
  - →Big lessons: Institutional Knowledge and field work were key allow ~3 months for “discovery”
- Assessed MassDOT’s preferences for flood management and vulnerability definition
  - →Big lesson: uncertainty requires flexibility in approach
- Developed high resolution hydrodynamic model simulate the impacts of extratropical and tropical storms, freshwater inflows and flood-control dam operations
- Applied a Monte Carlo approach to estimate probability of flooding under current and future sea level rise scenarios.
  - →Big lesson: computational time grows exponentially with time

# Good News and Bad News

The good news:

- Extent of flooding under current conditions is fairly limited with low exceedance probabilities. This allows MassDOT to focus their efforts on reducing the vulnerability of individual Structures and on local adaptation strategies.
- Regional adaptation can prevent flooding in some areas

The bad news:

- Vulnerable Structures under current conditions include some Tunnel Portals; the number of vulnerable Portals triples by 2070.

The plan:

- Currently meeting to present results and inform personnel.
- Develop strategies for prioritizing and implementing adaptation approaches over short and long term.

- Final report submitted to FHWA end of May 2015.
- Report available on MassDOT website.
- Data layers available upon request (may be a cost).

# QUESTIONS?