

The cognitive science of uncertainty visualization

Lace Padilla, Ph.D.

Assistant Professor, CIS, UC Merced

SPACE Lab

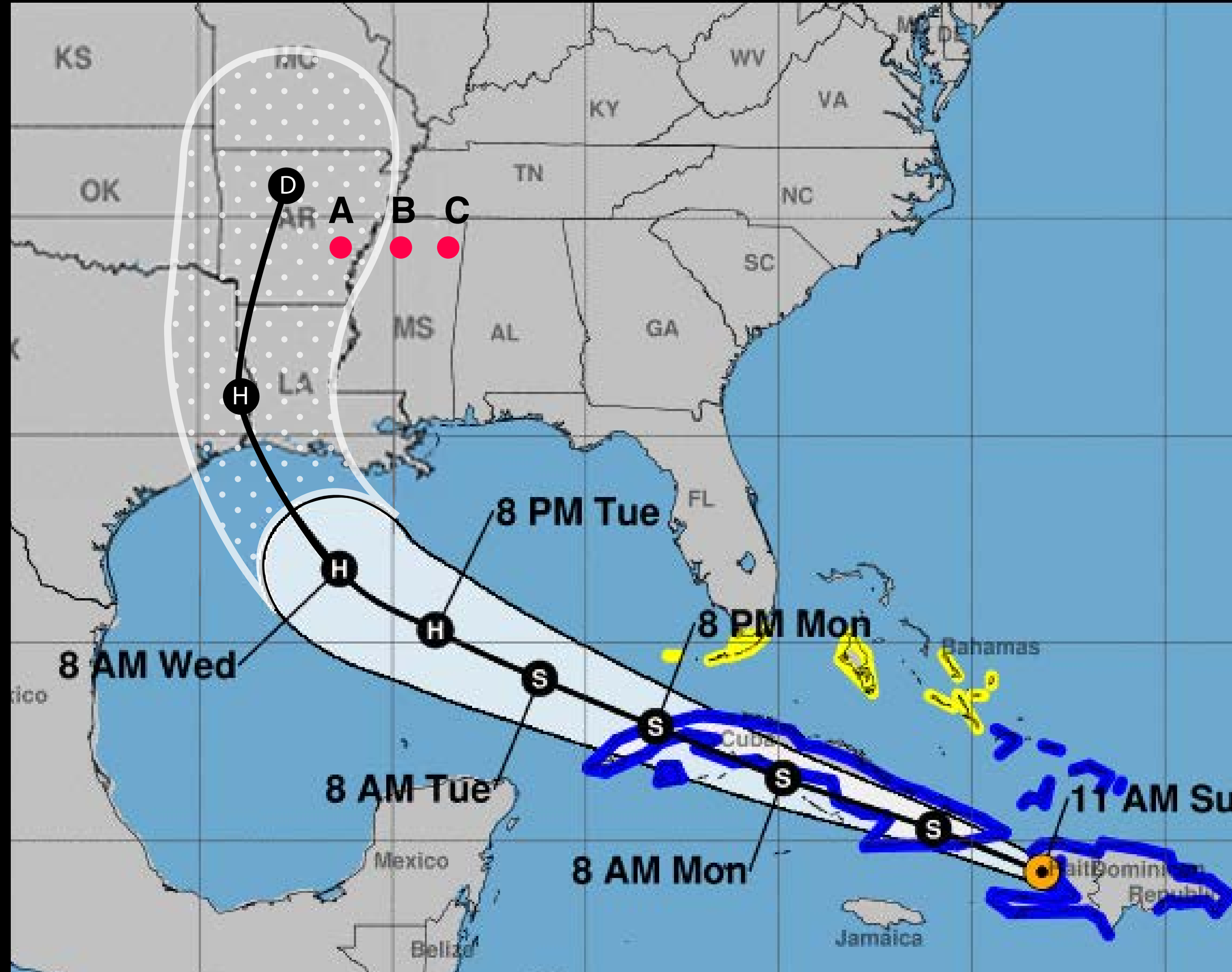
Spatial Perception, Applied Cognition + Education

[SPACE.ucmerced.edu](https://space.ucmerced.edu)

SPACE

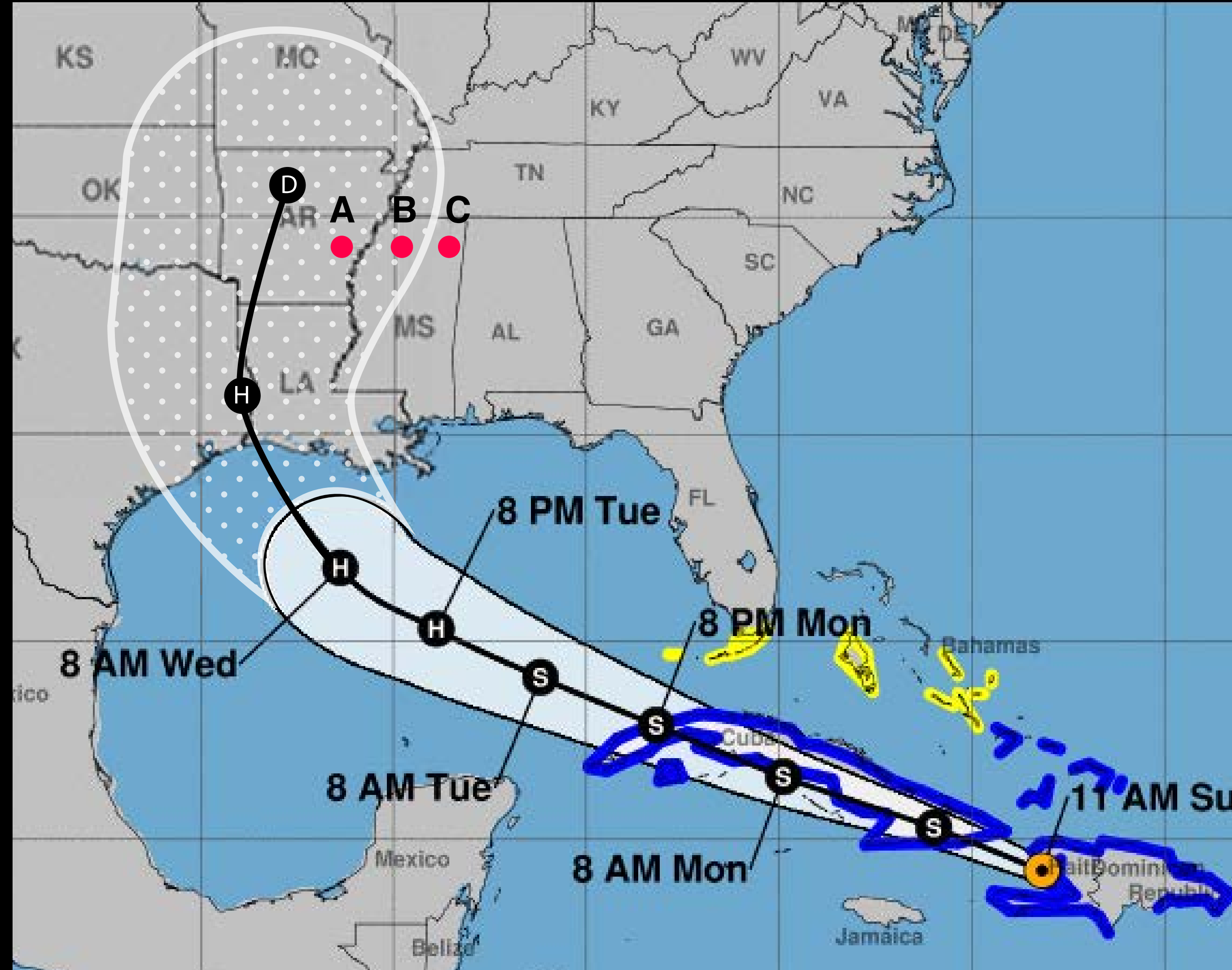


Hurricane 1



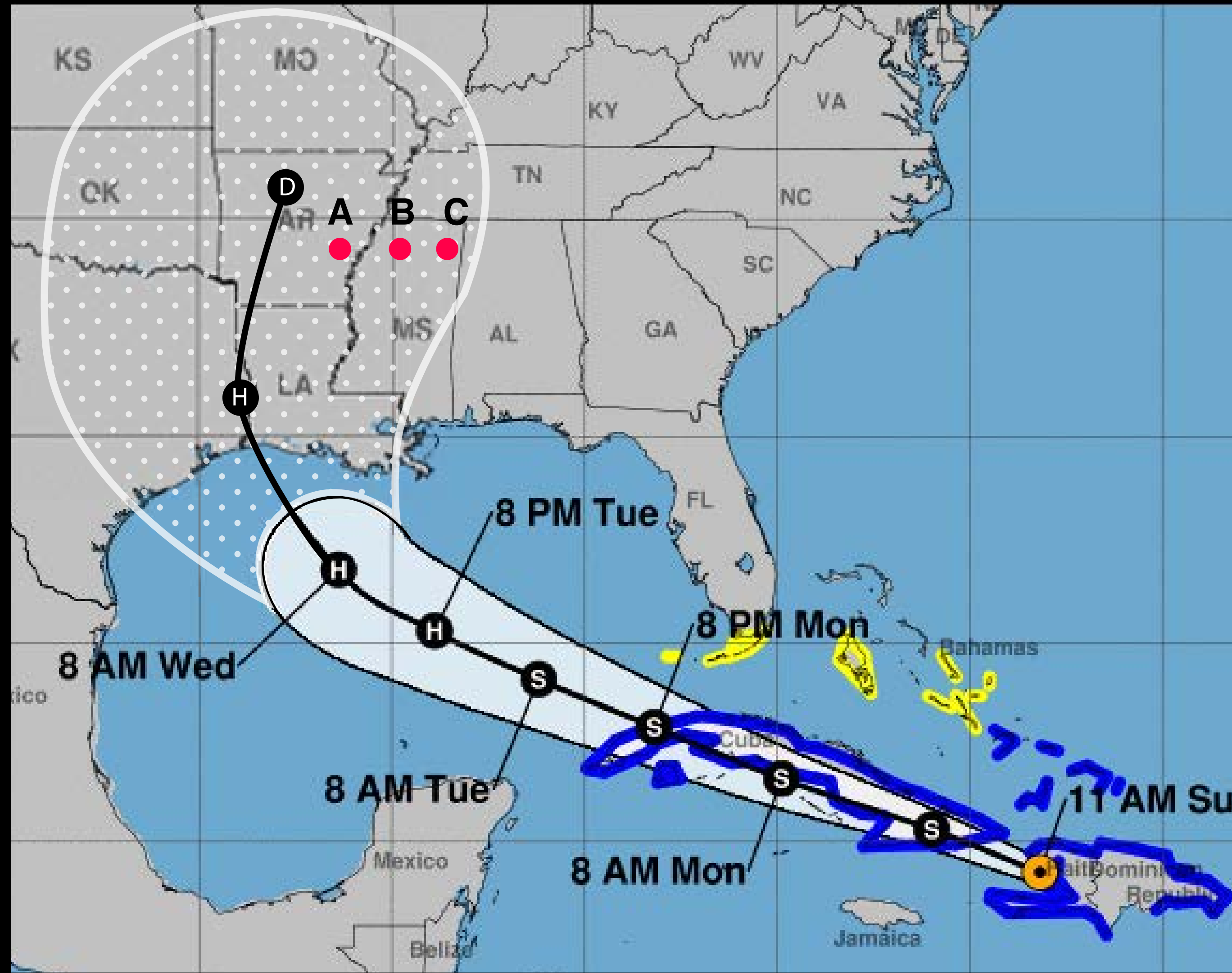
Which locations are in extreme danger?

Hurricane 2

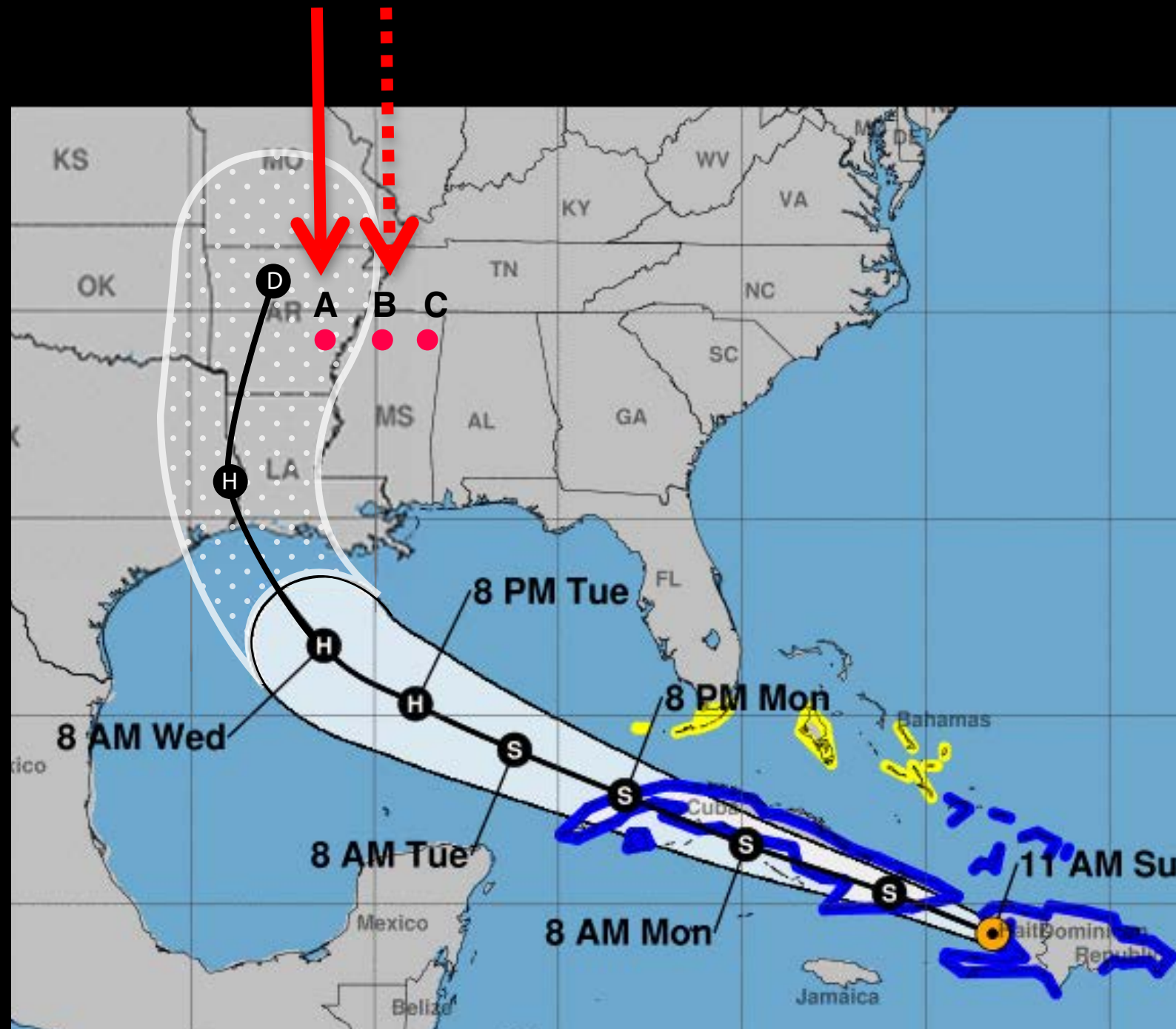


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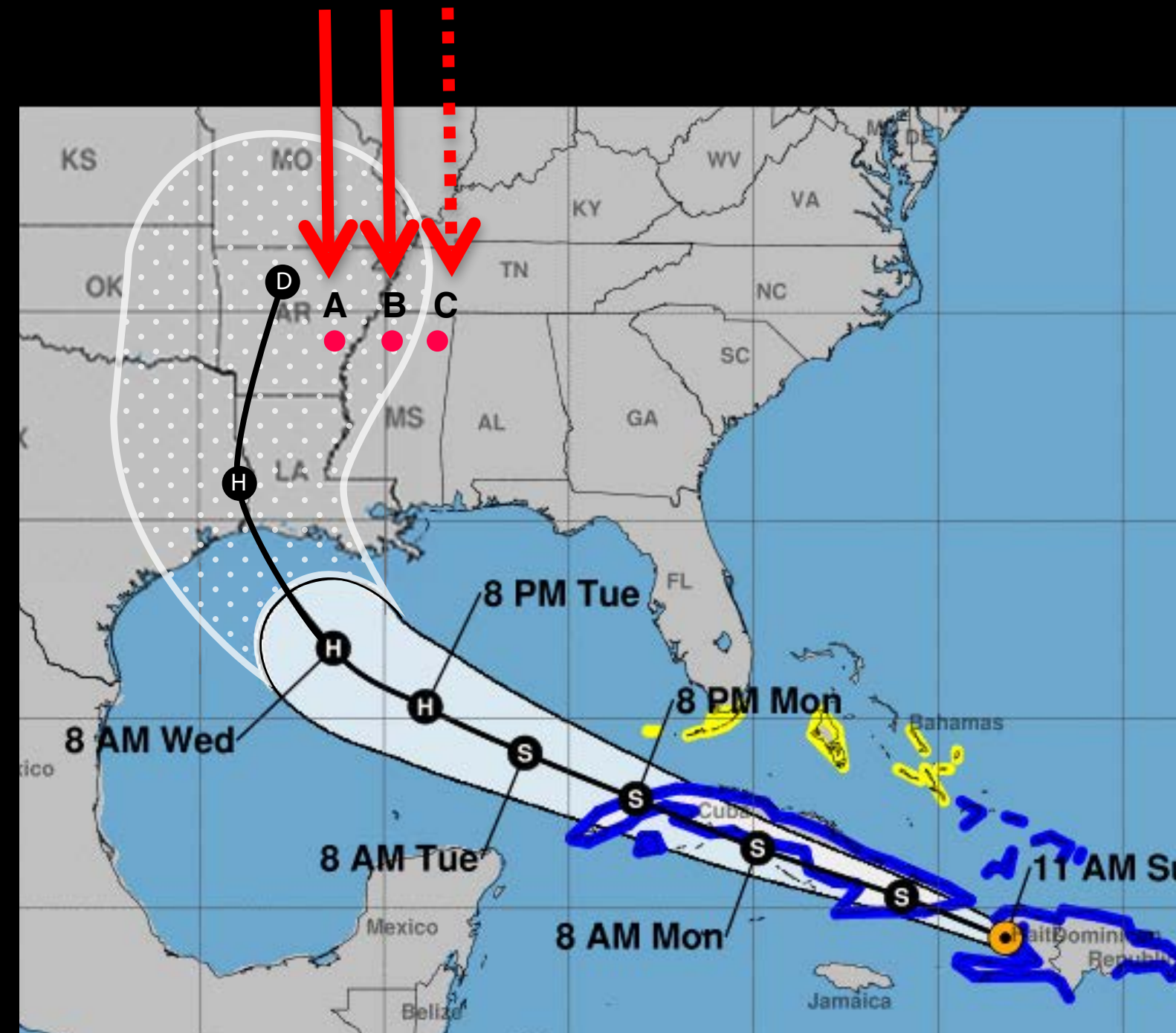
Hurricane 3



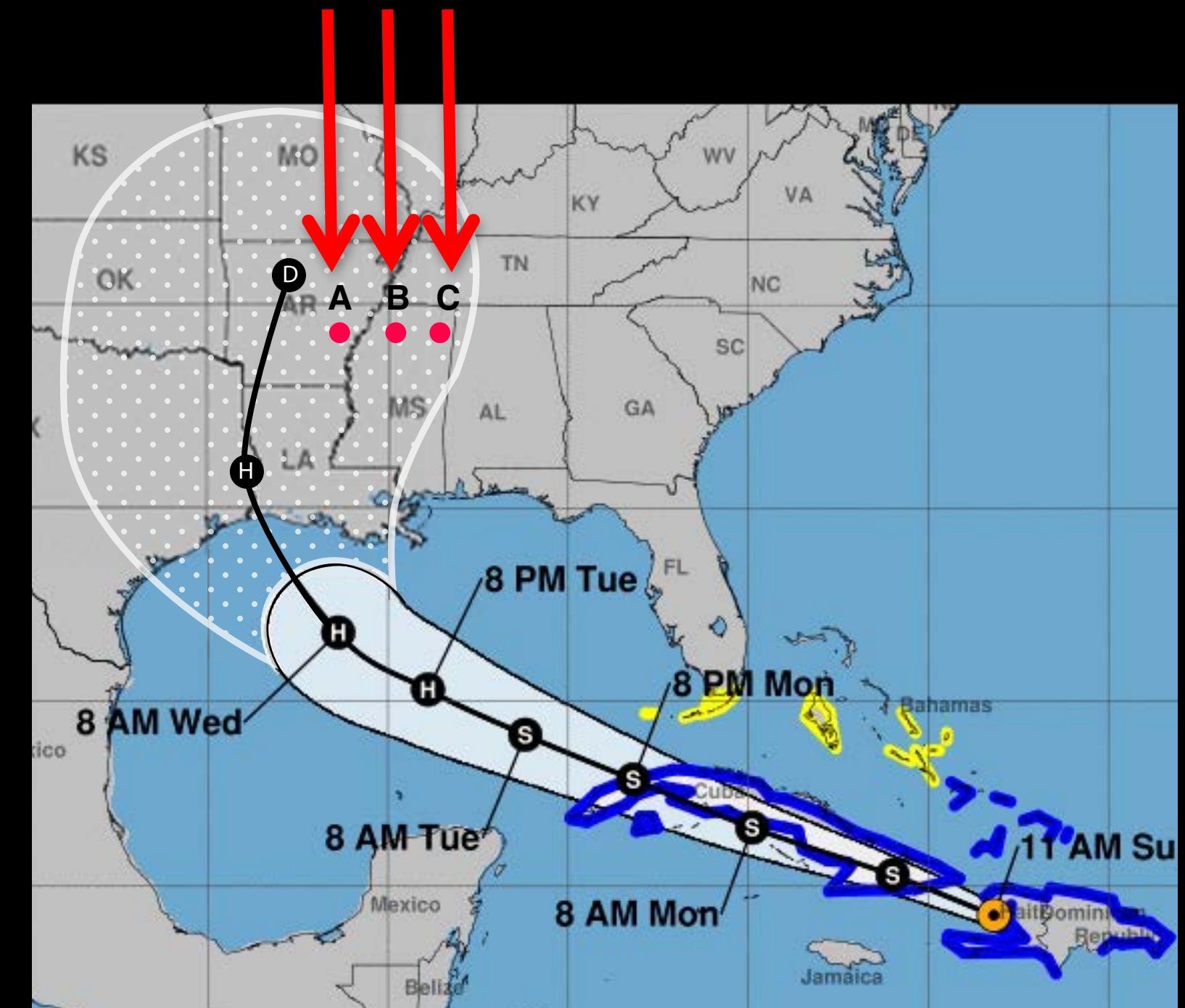
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Hurricane 1



Hurricane 2

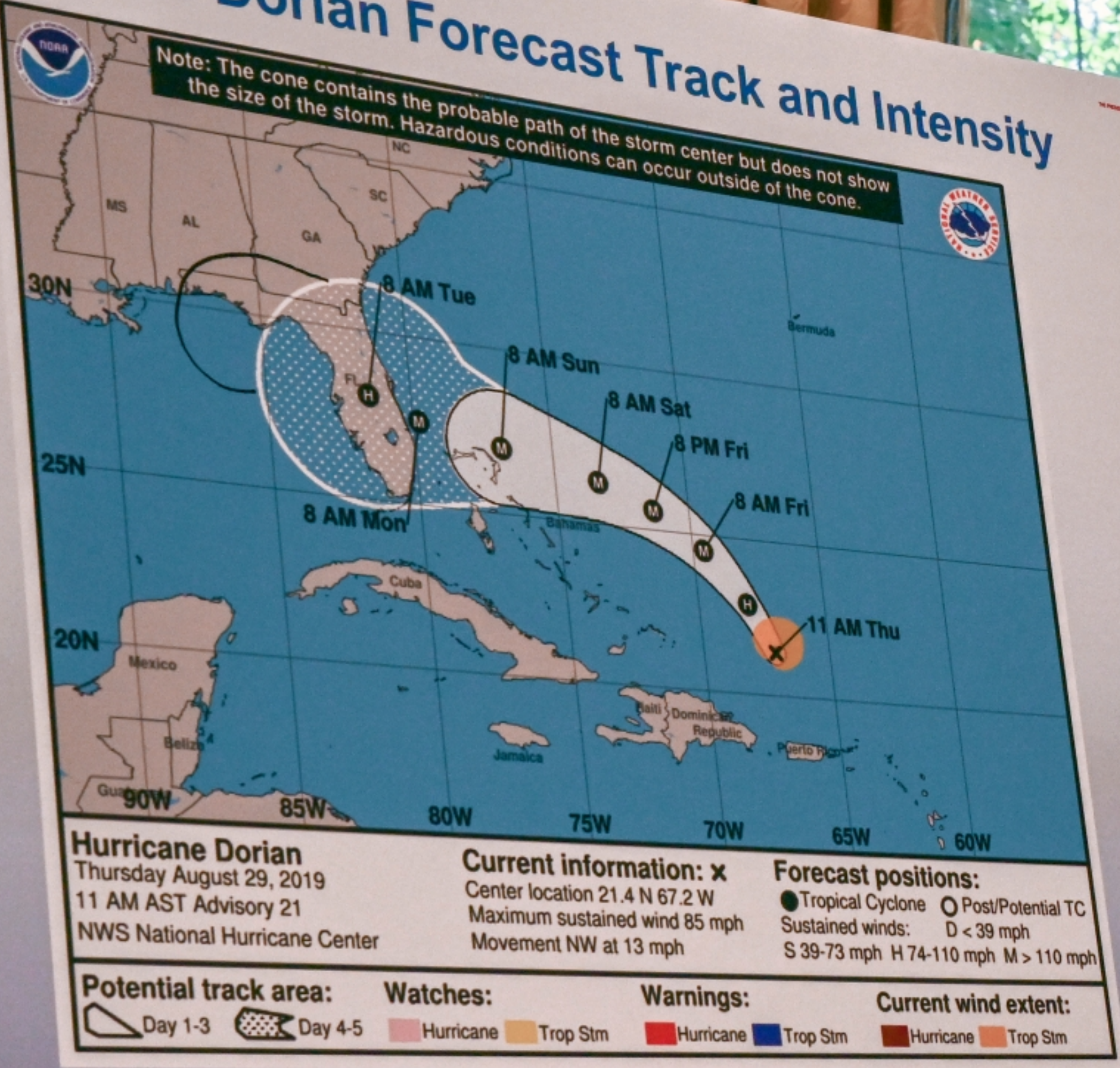


Hurricane 3

Which locations are in extreme danger?

September 4th 2019

Hurricane Dorian Forecast Track and Intensity



COVID-19 Forecasts

Week Ahead

? Help

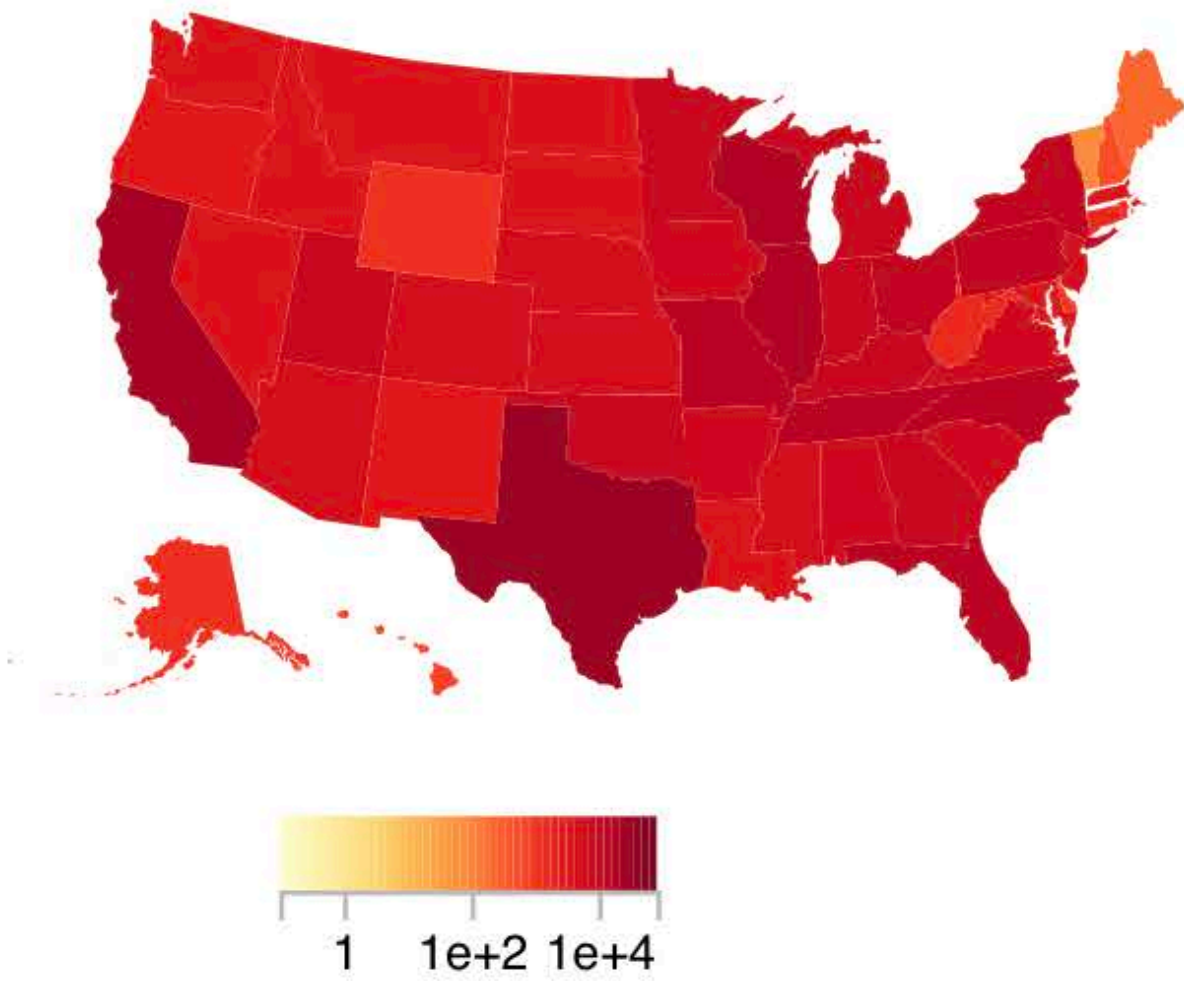
WEEK 42 (2020)

TARGET

Massachusetts

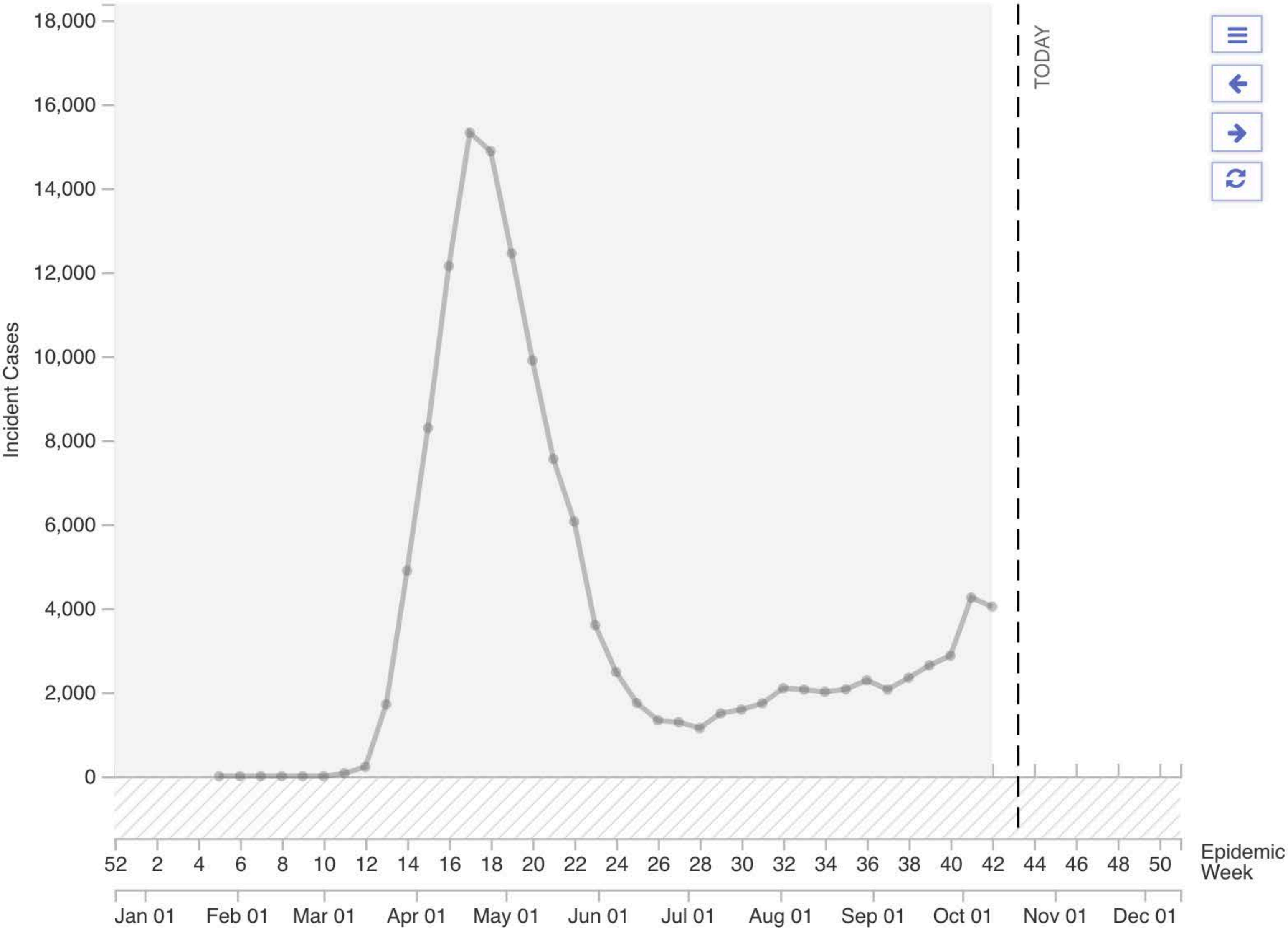
Incident Cases

Incident Cases (Observed)



Time Chart

The **ensemble** forecast combines models unconditional on particular interventions being in place with those conditional on certain social distancing measures continuing. To ensure consistency, only models with 4 week-ahead forecasts ahead are included in the ensemble.



COVID-19 Forecasts

Week Ahead

? Help

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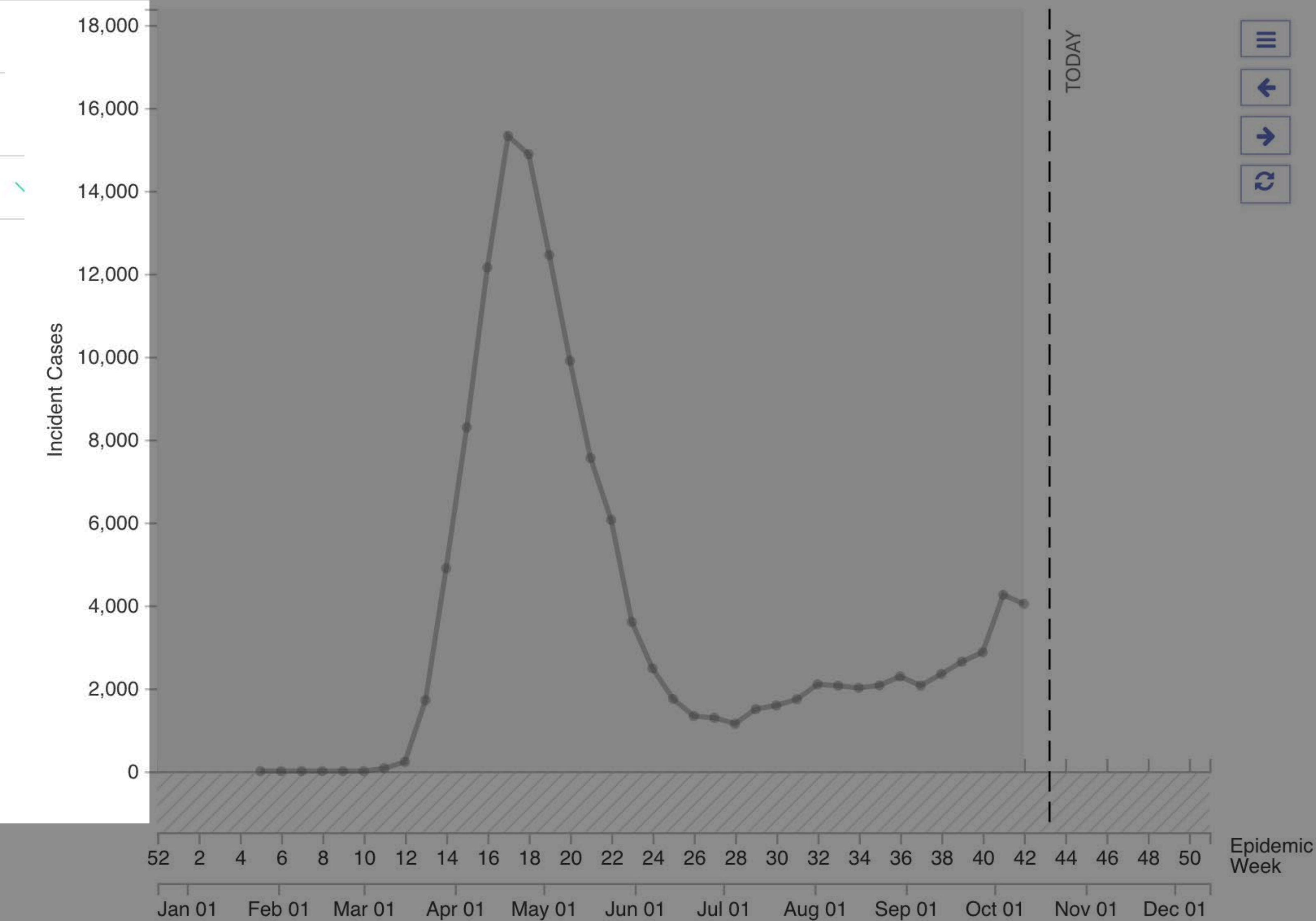
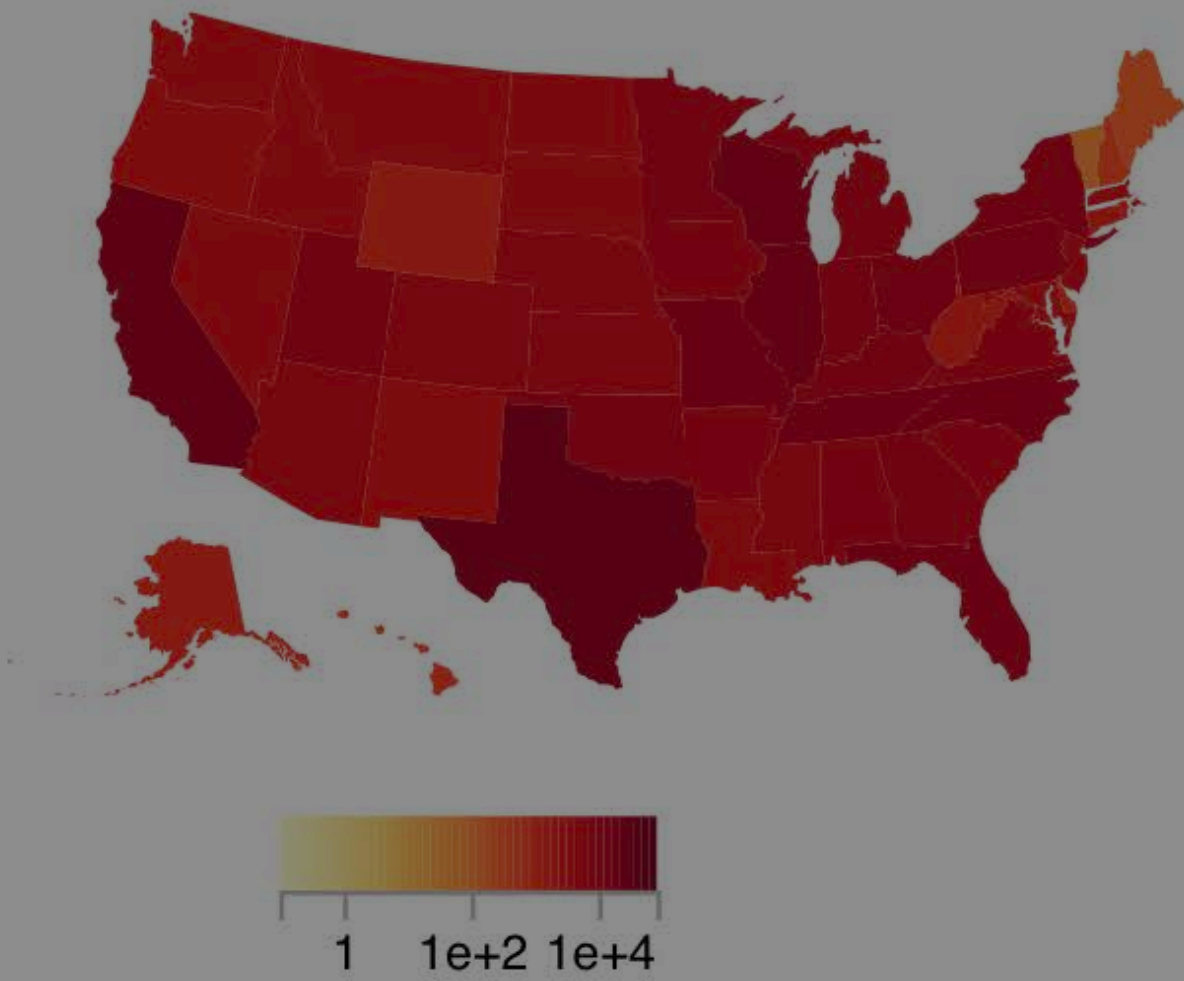
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COVID-19 Forecasts

Week Ahead

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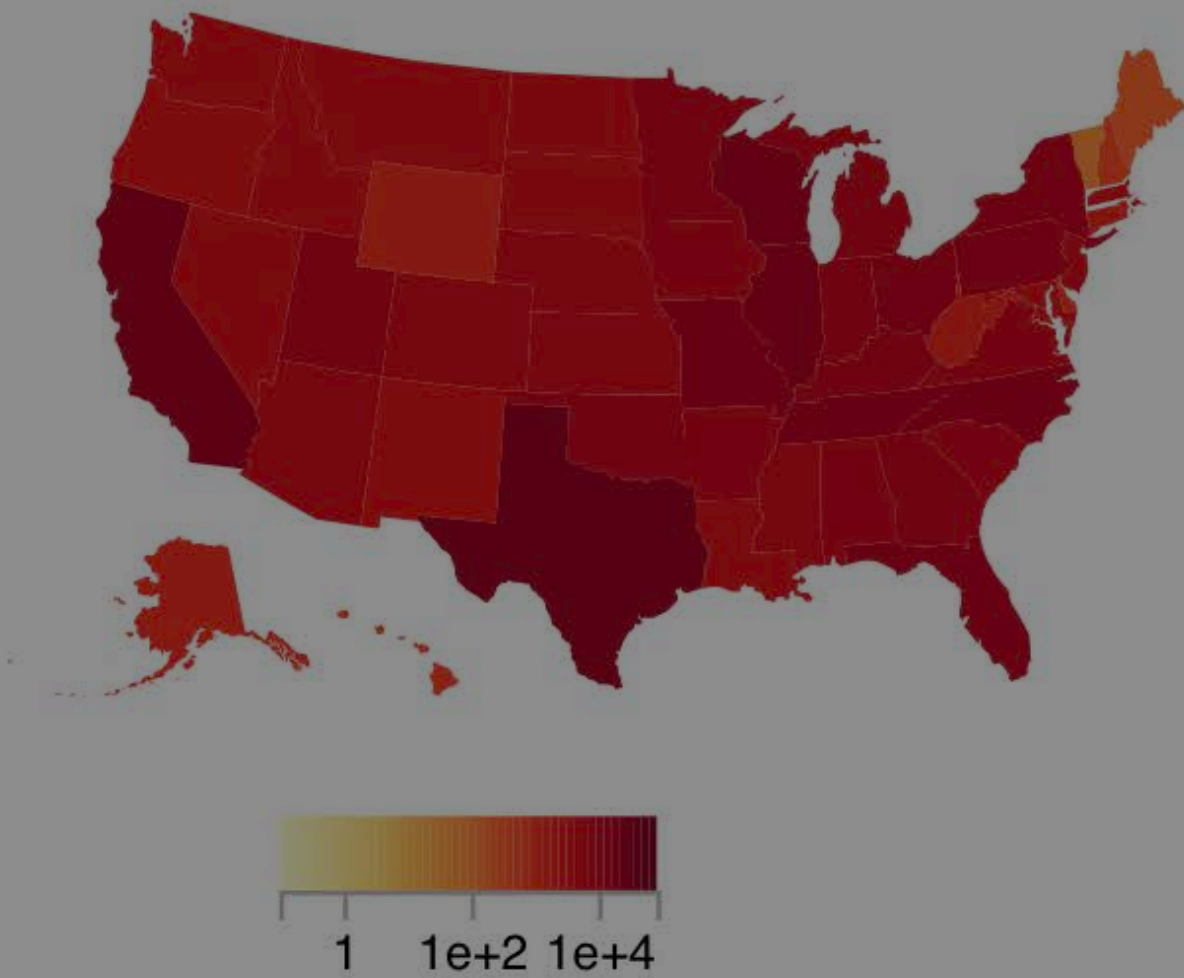
WEEK 42 (2020)

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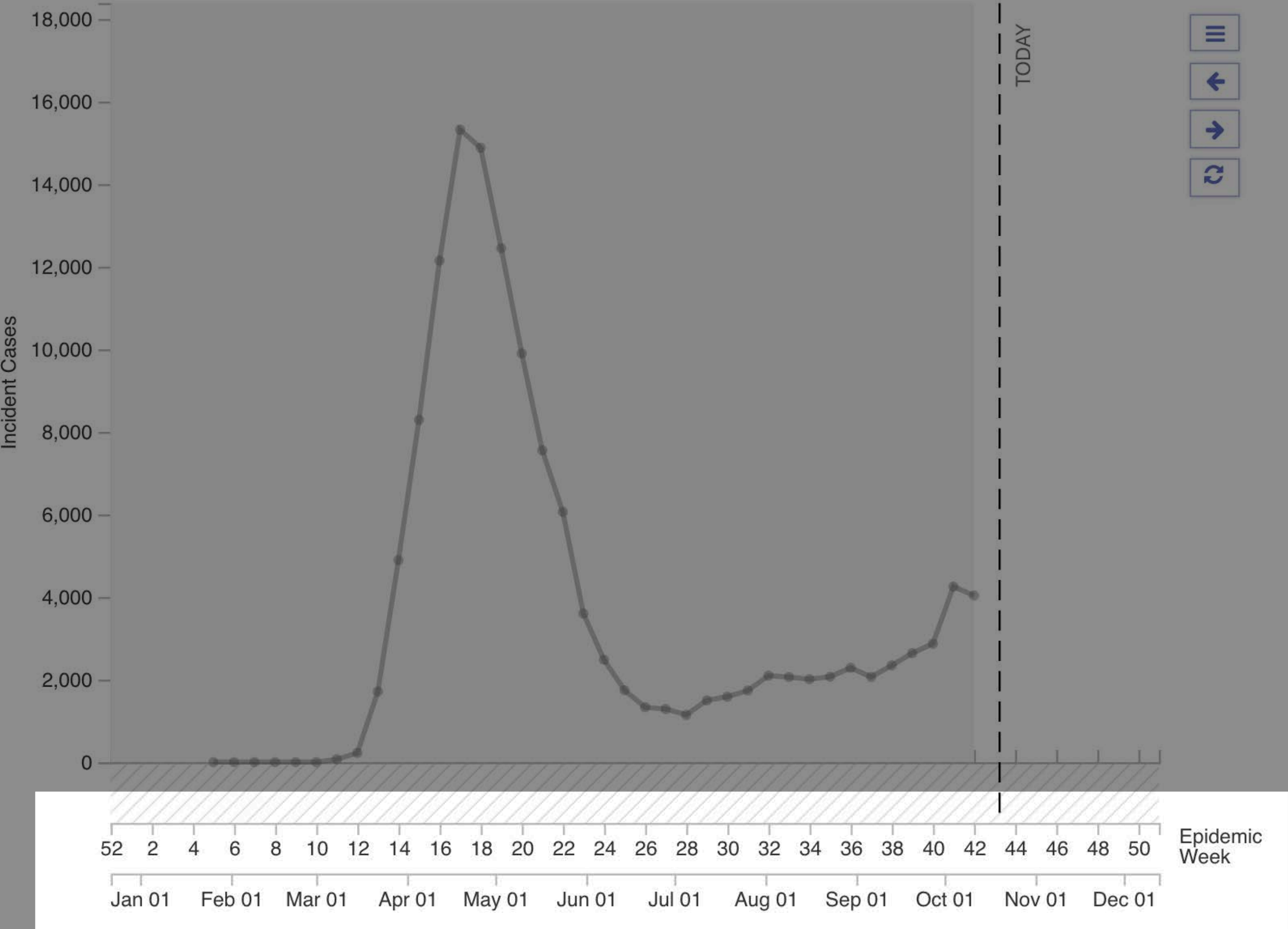
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COVID-19 Forecasts Week Ahead

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Time Chart

Is the COVID-19 risk in Massachusetts decreasing, increasing, or staying the same?

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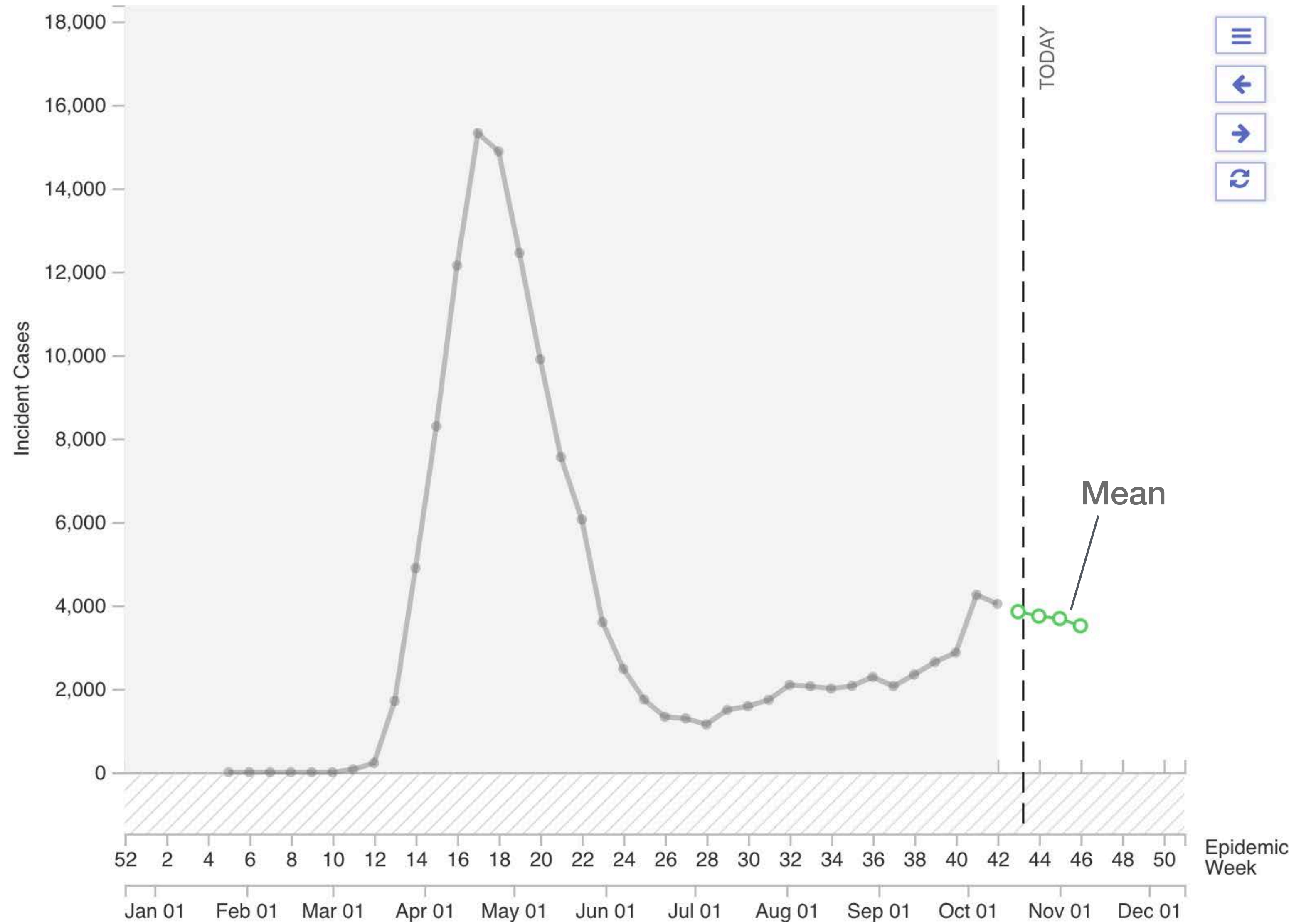
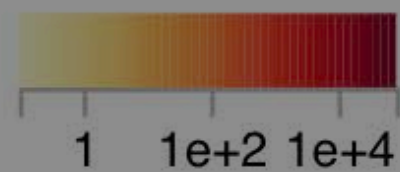
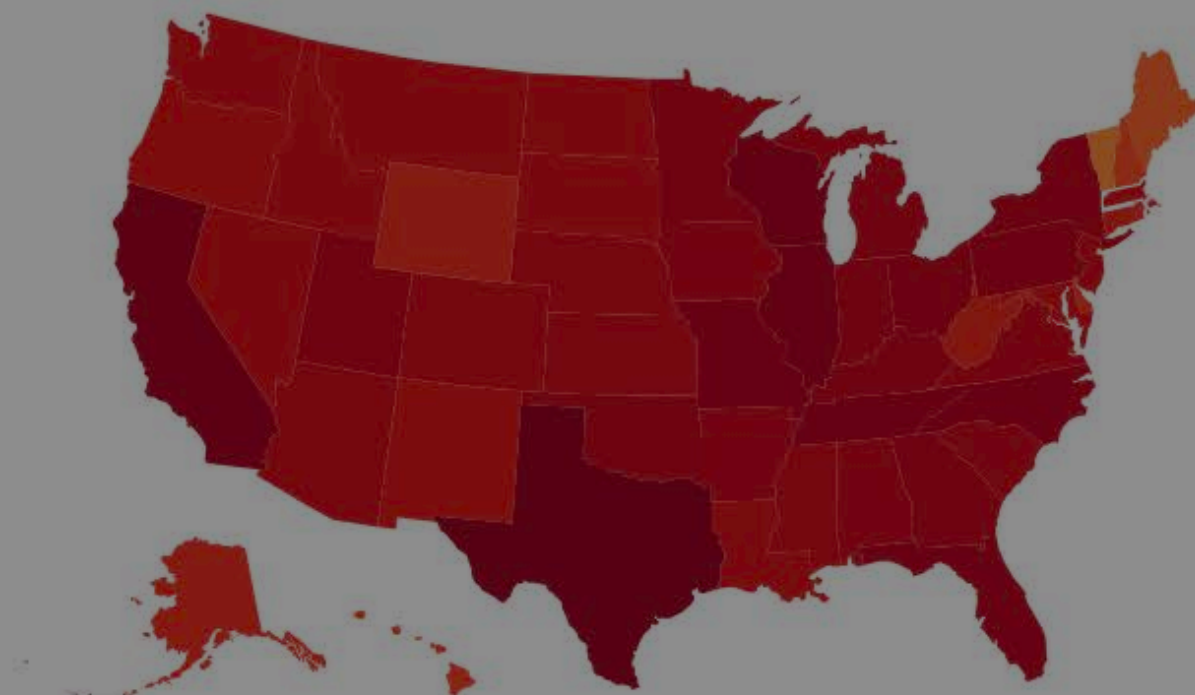
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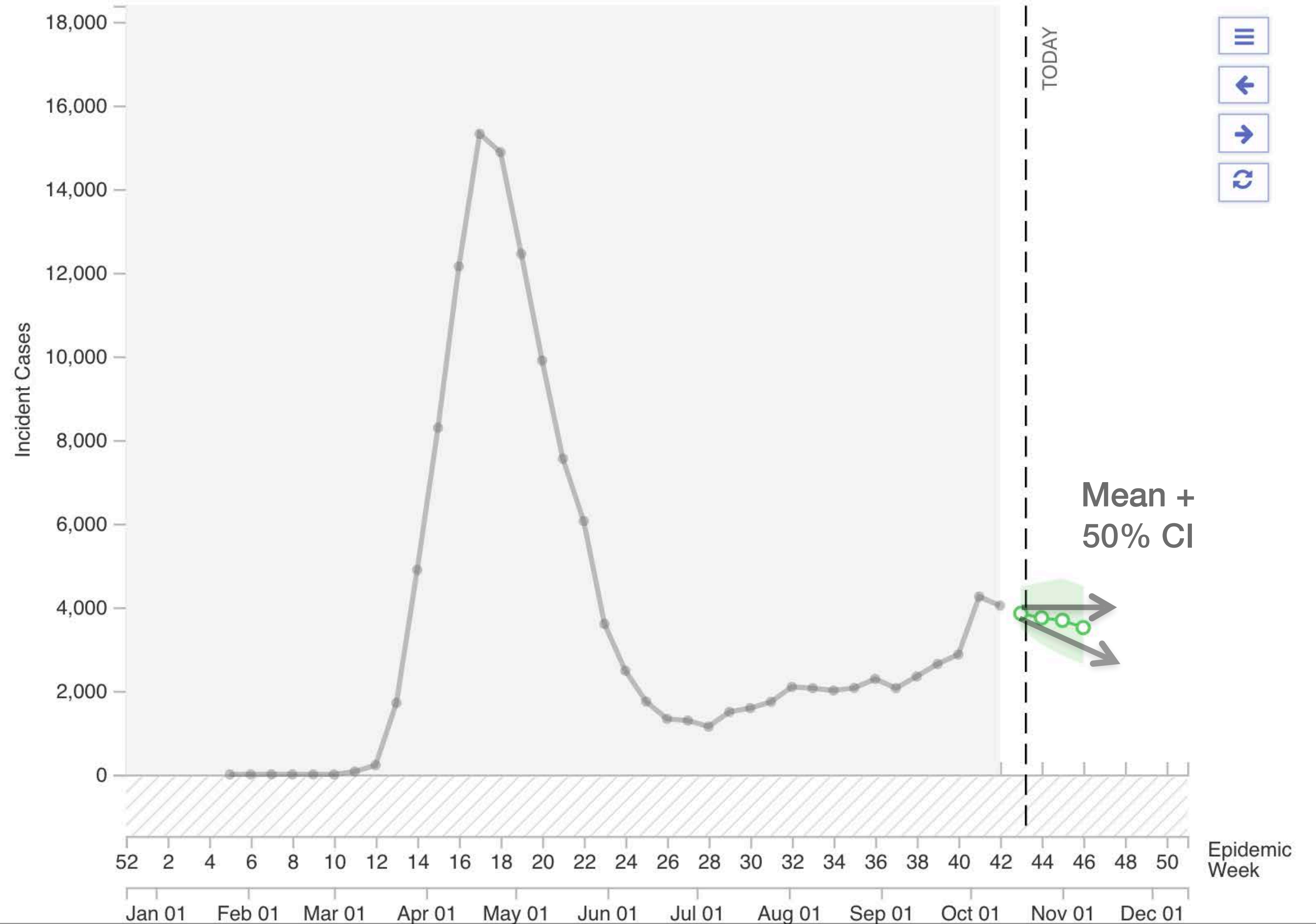
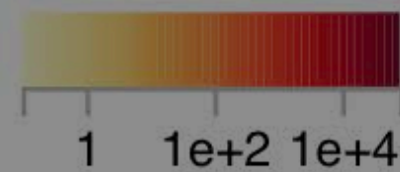
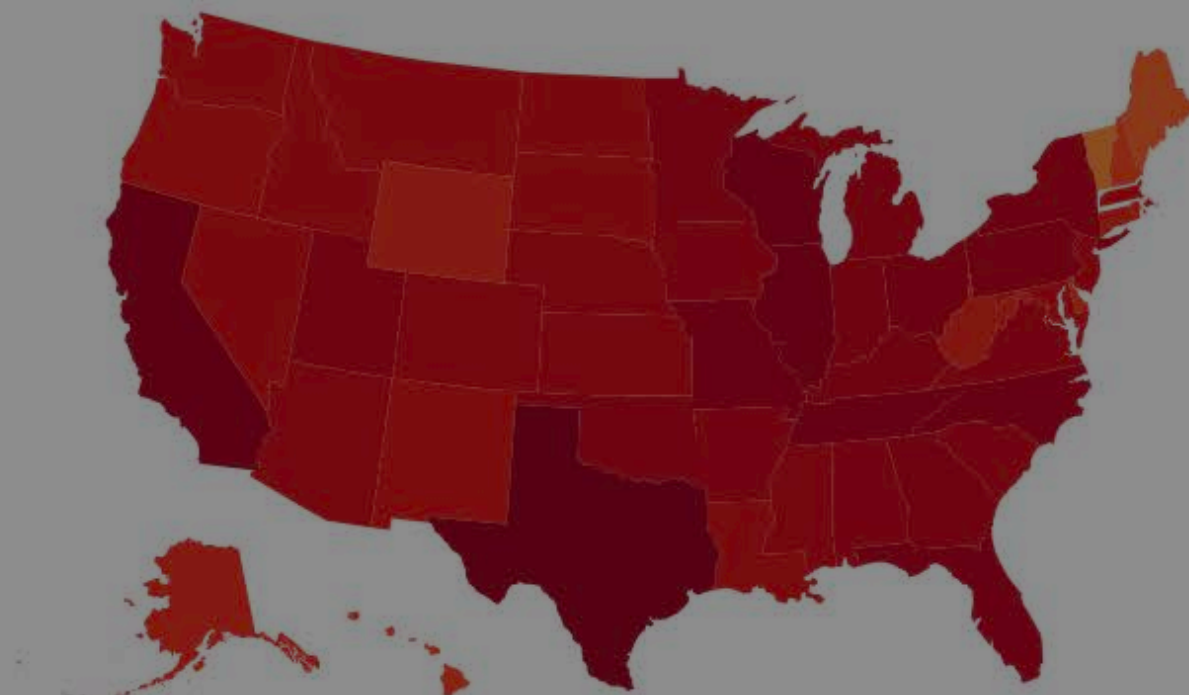
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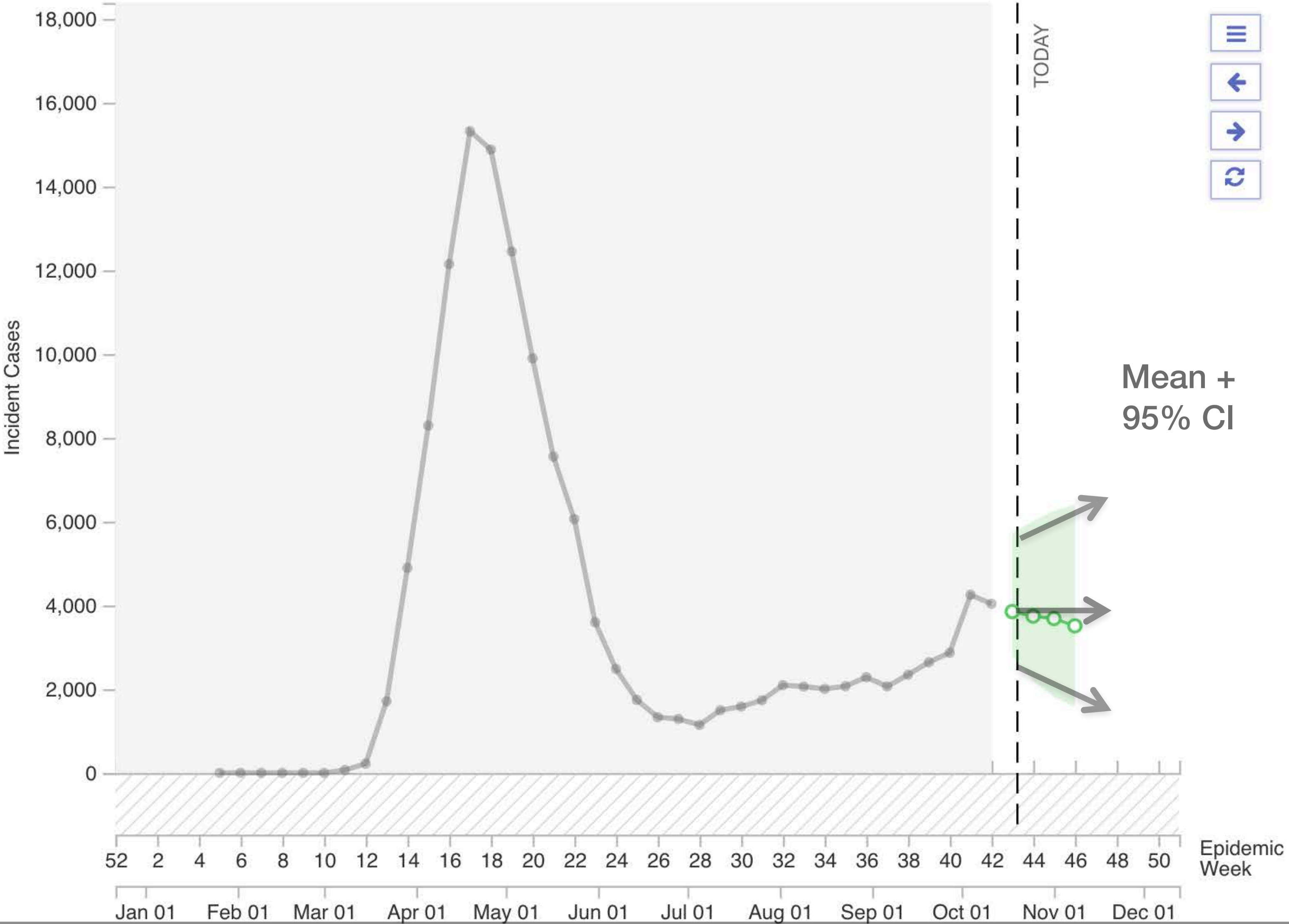
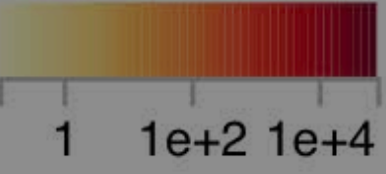
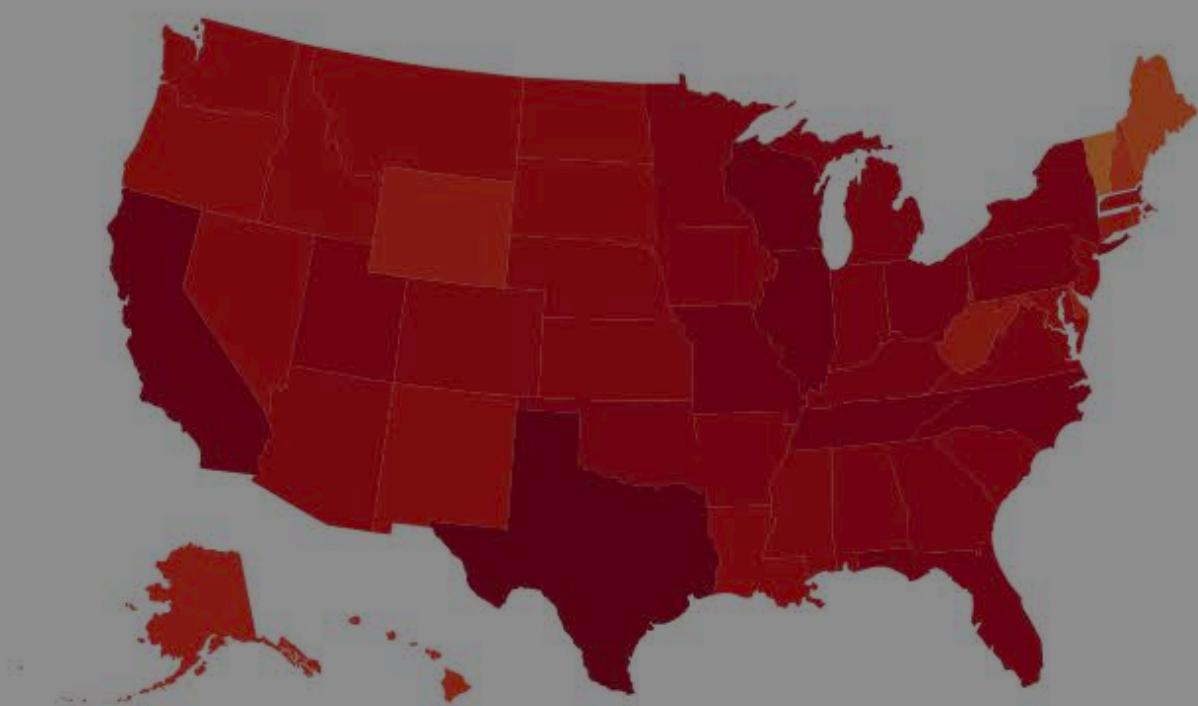
Massachusetts



Incident Cases



Incident Cases (Observed)



Mean +
95% CI

Epidemic
Week

COVID-19 Forecasts Week Ahead

? Help

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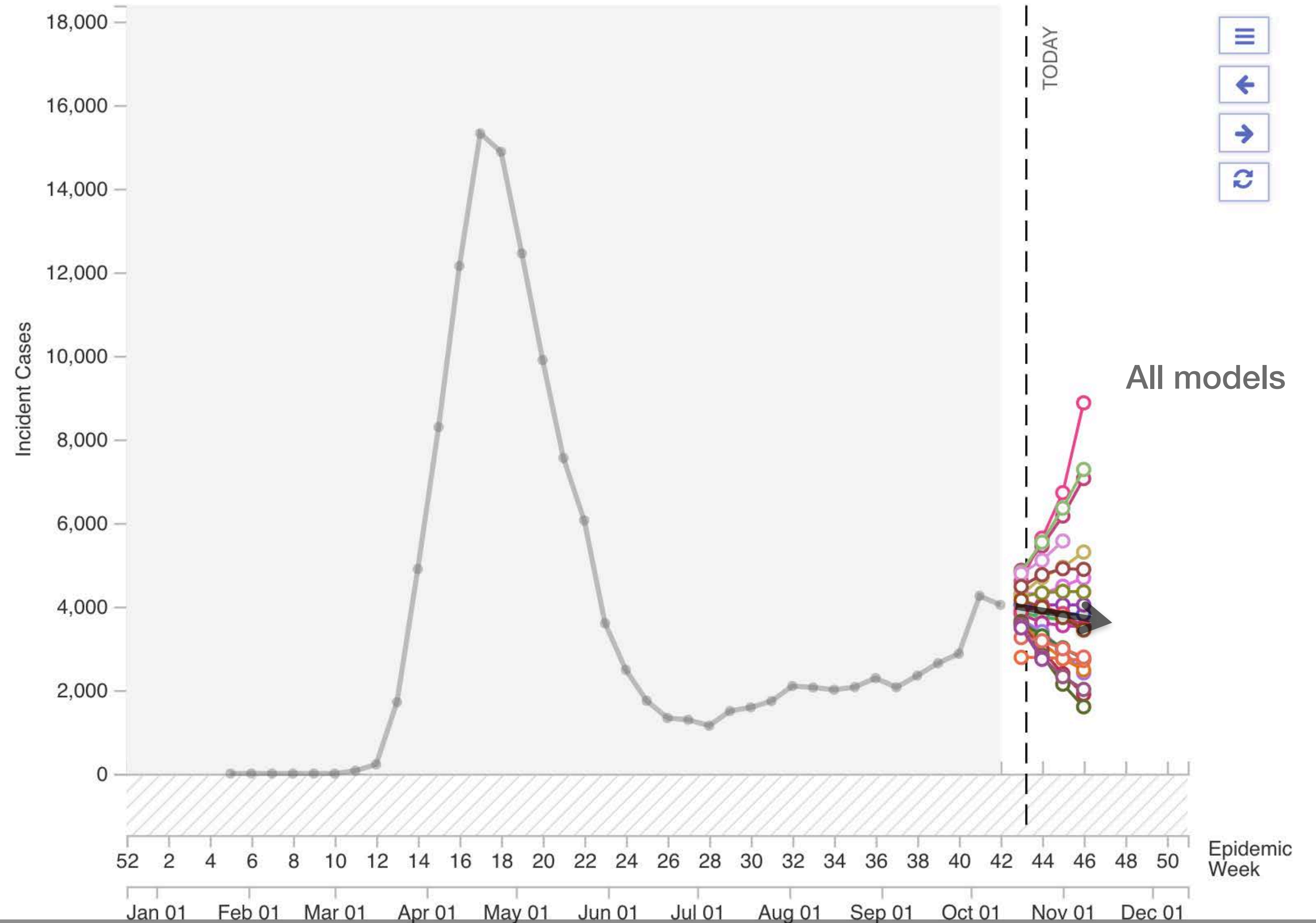
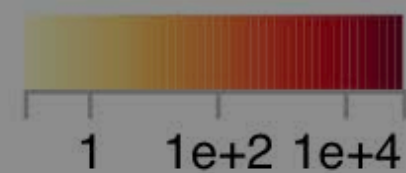
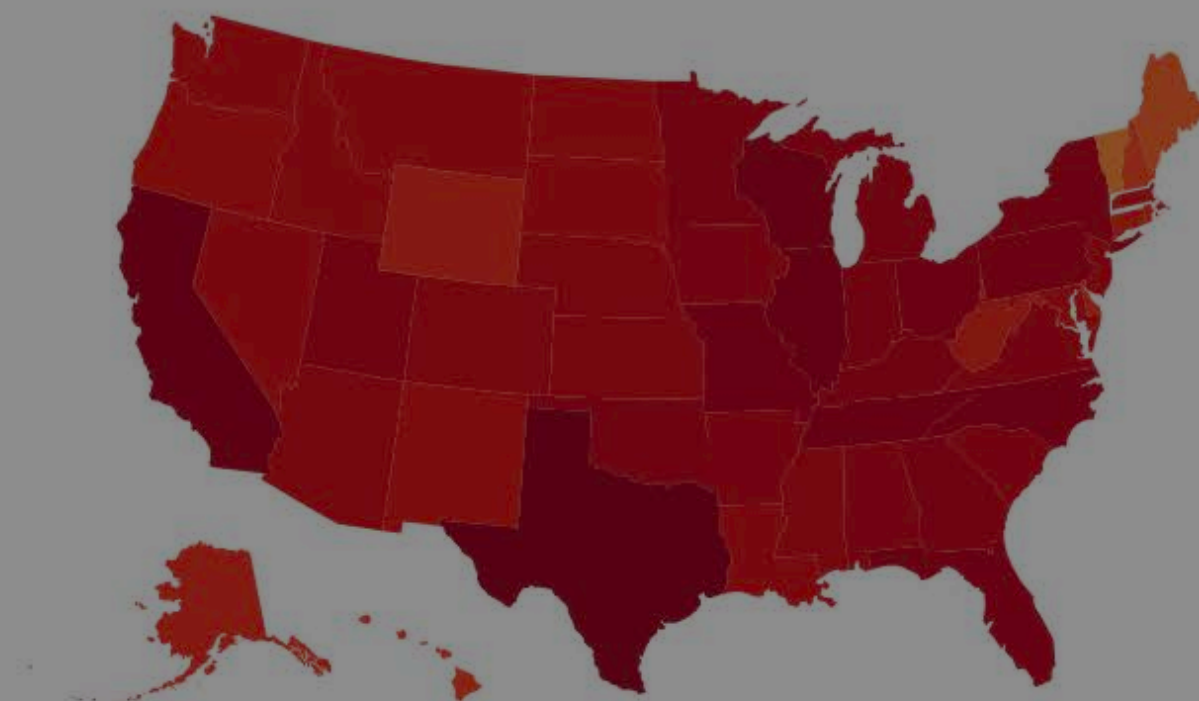
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Massachusetts



Incident Cases

Incident Cases (Observed)



COVID-19 Forecasts

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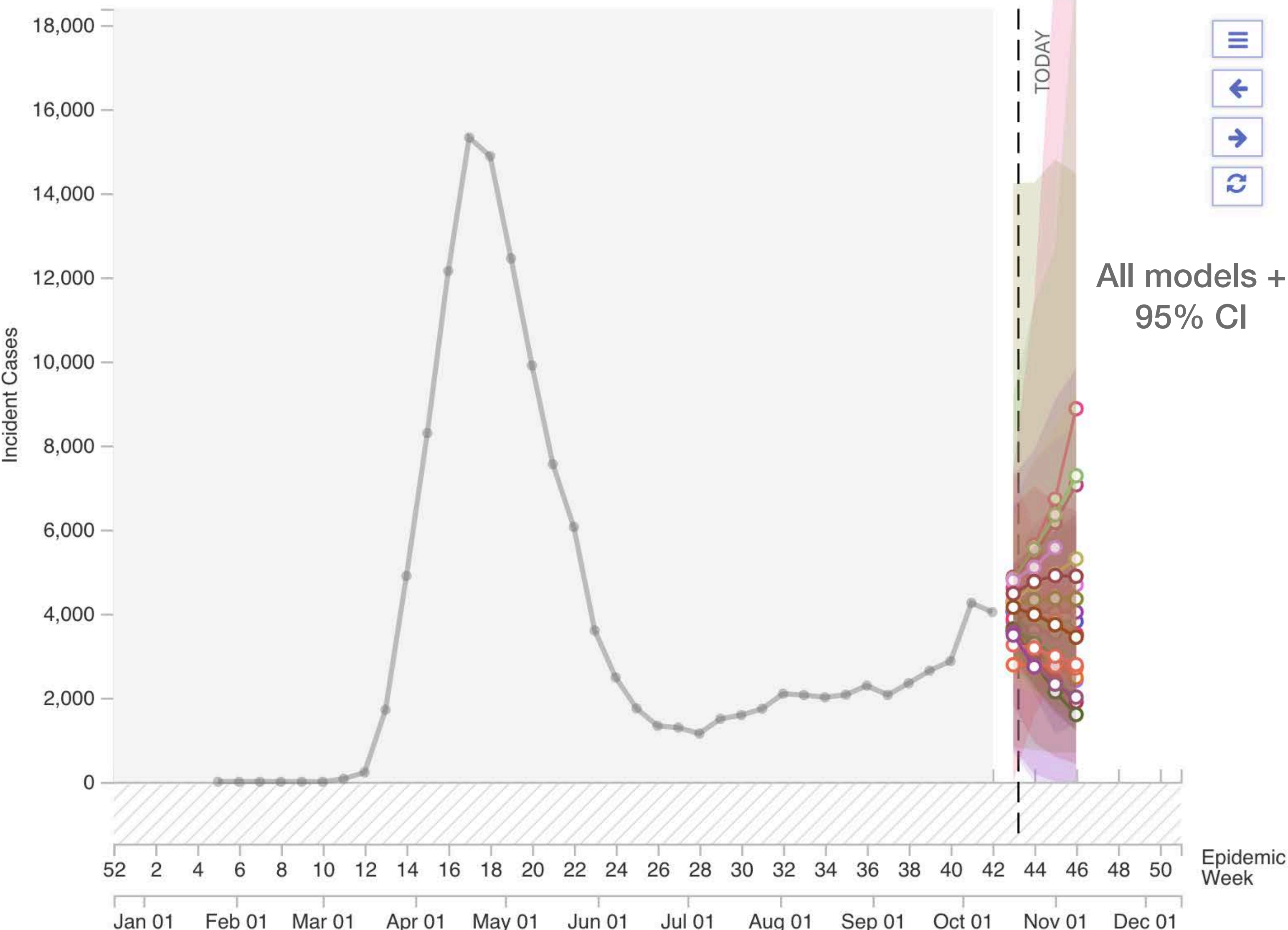
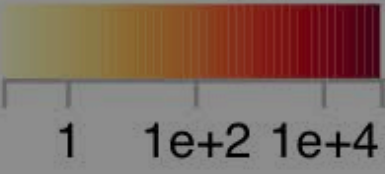
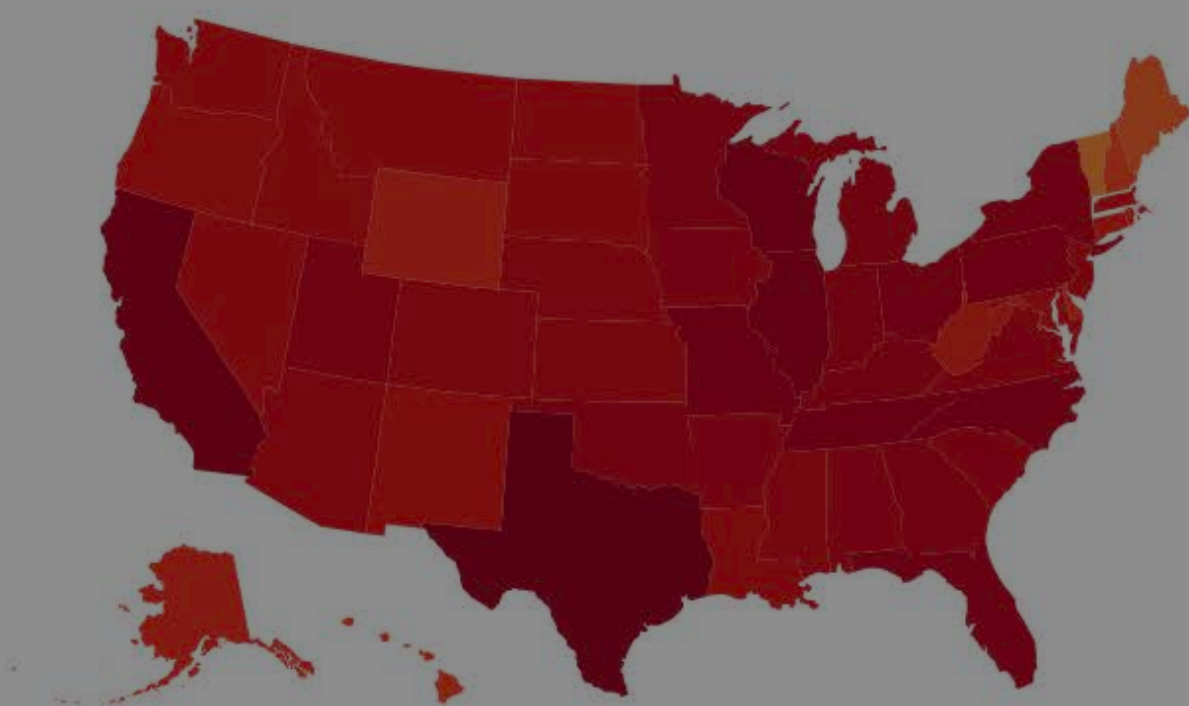
Massachusetts



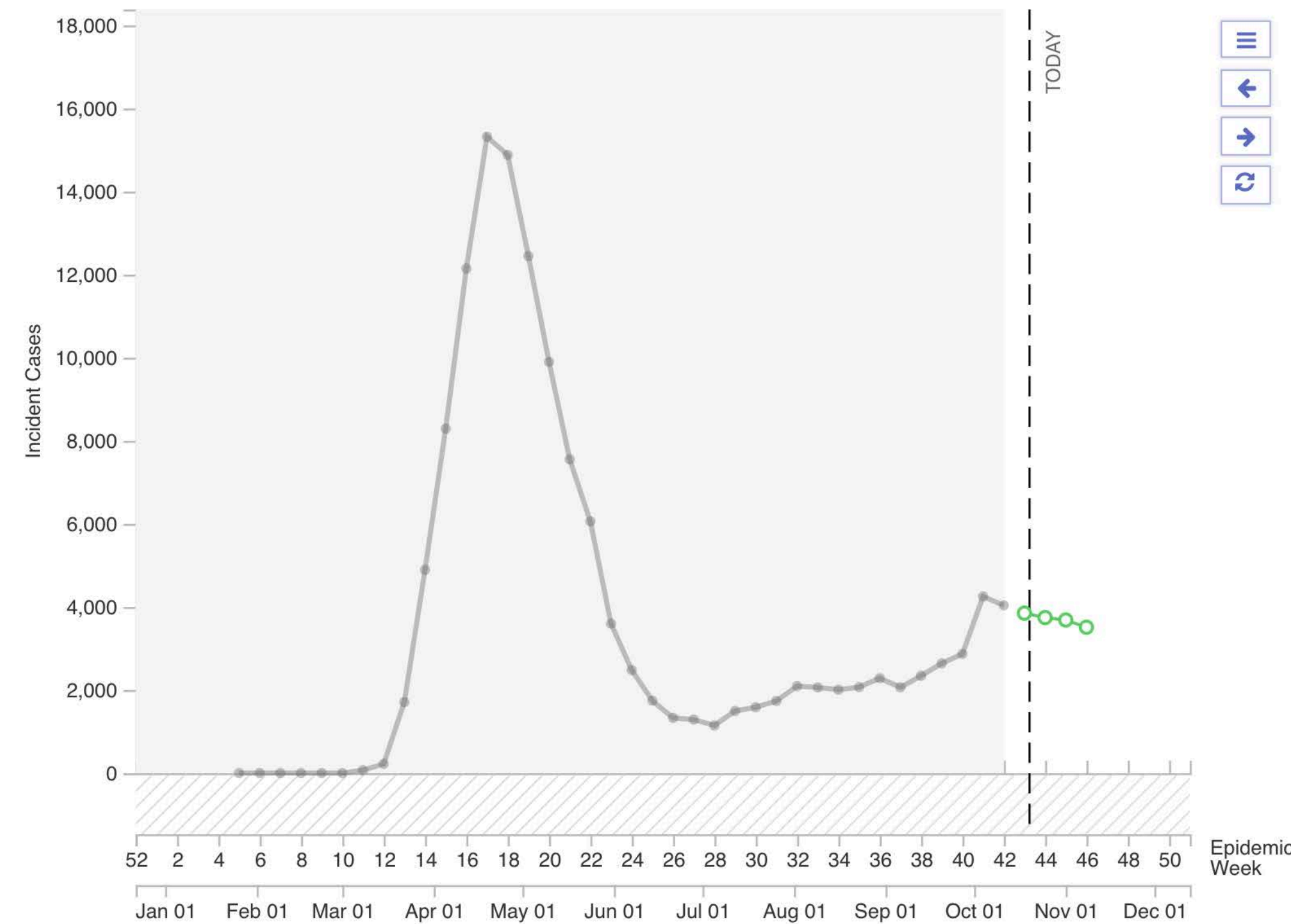
Incident Cases



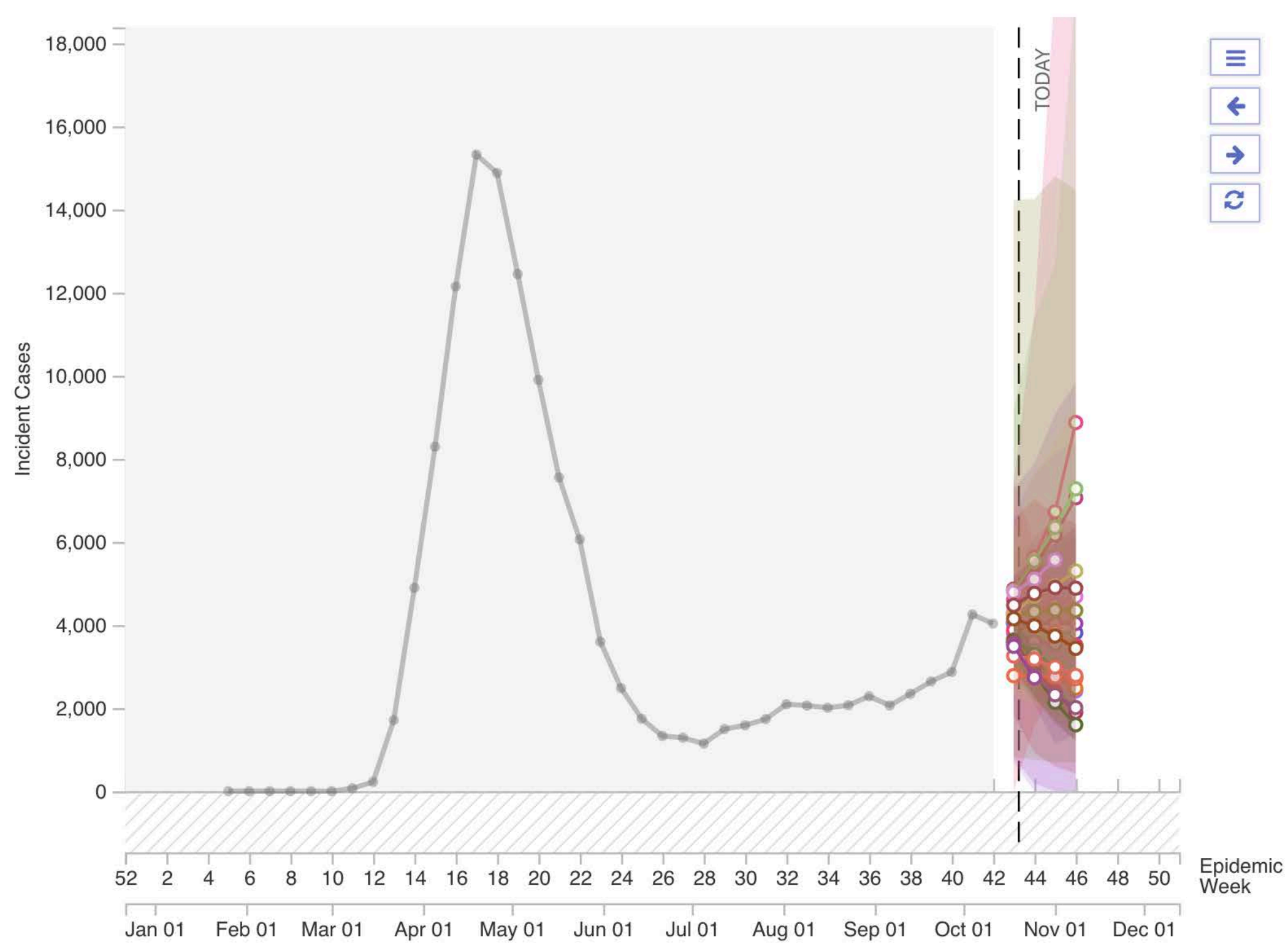
Incident Cases (Observed)



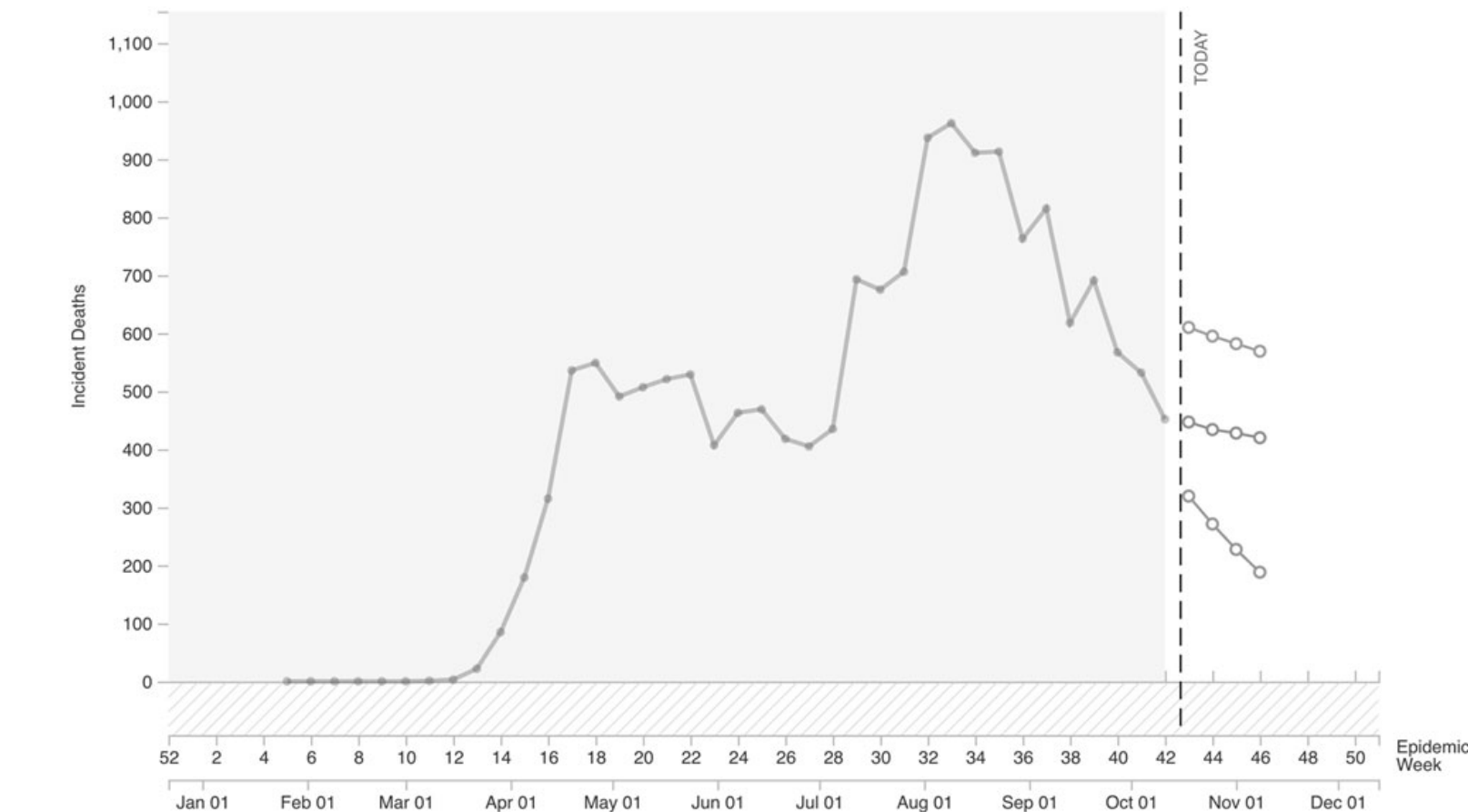
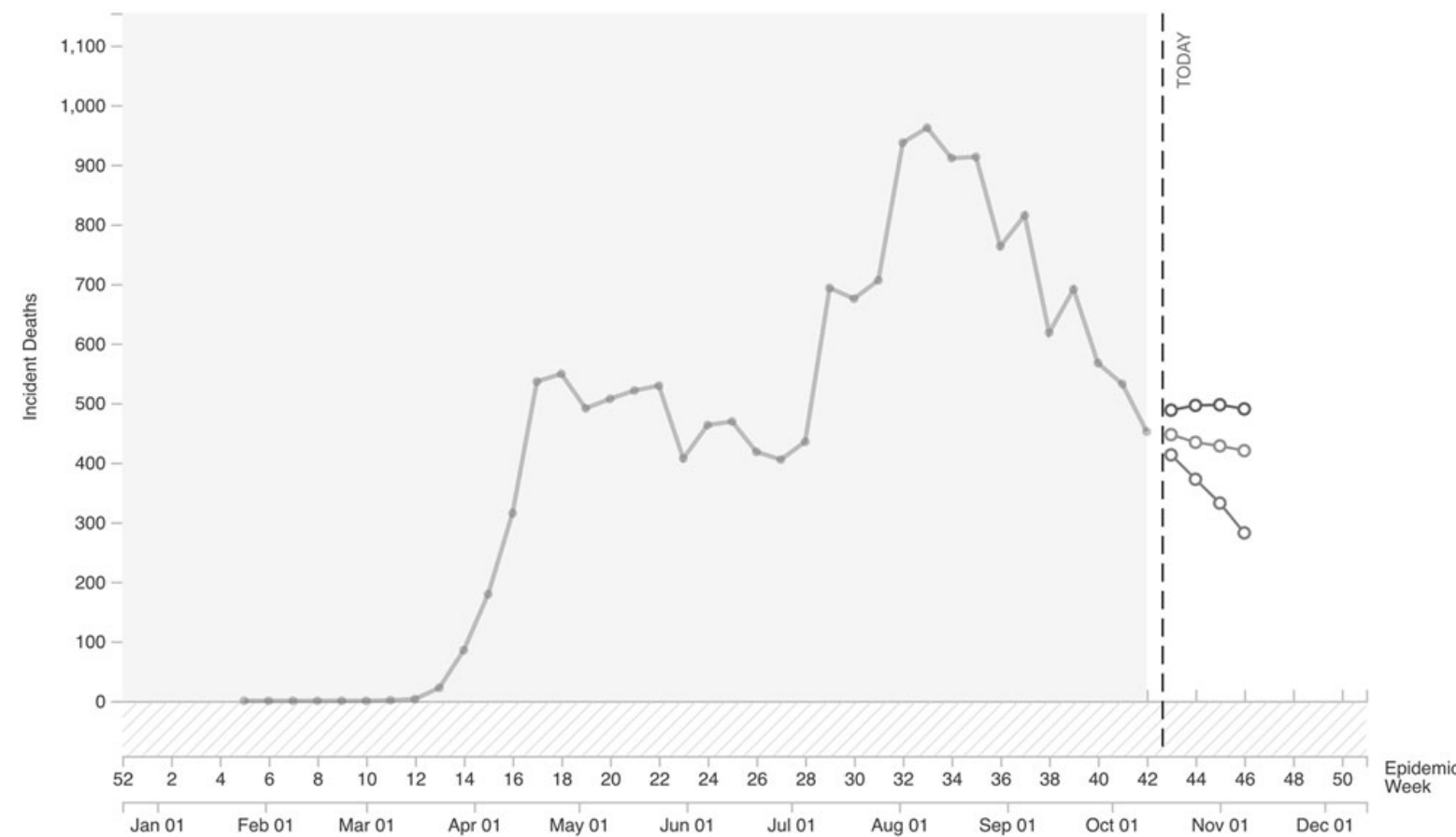
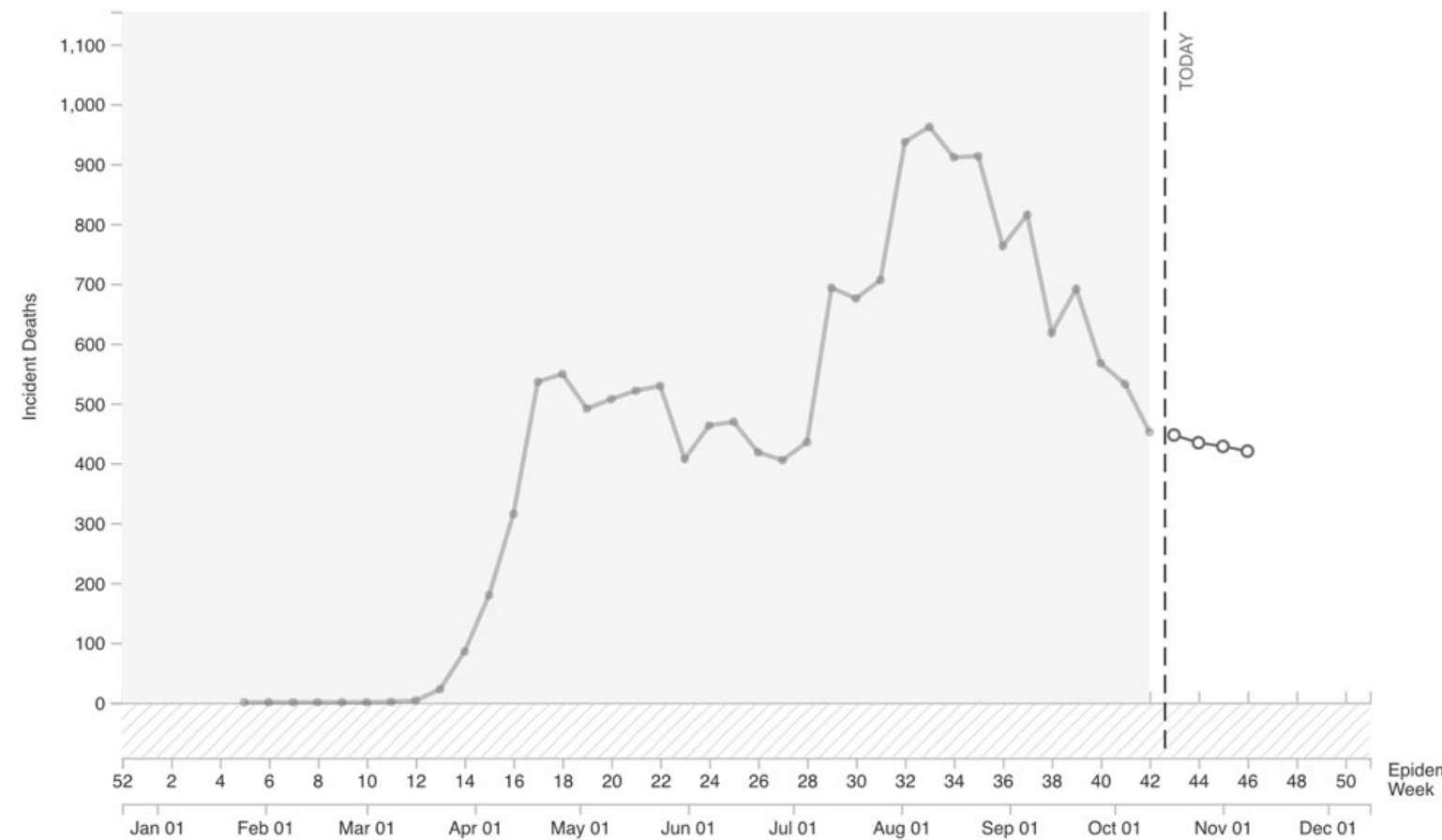
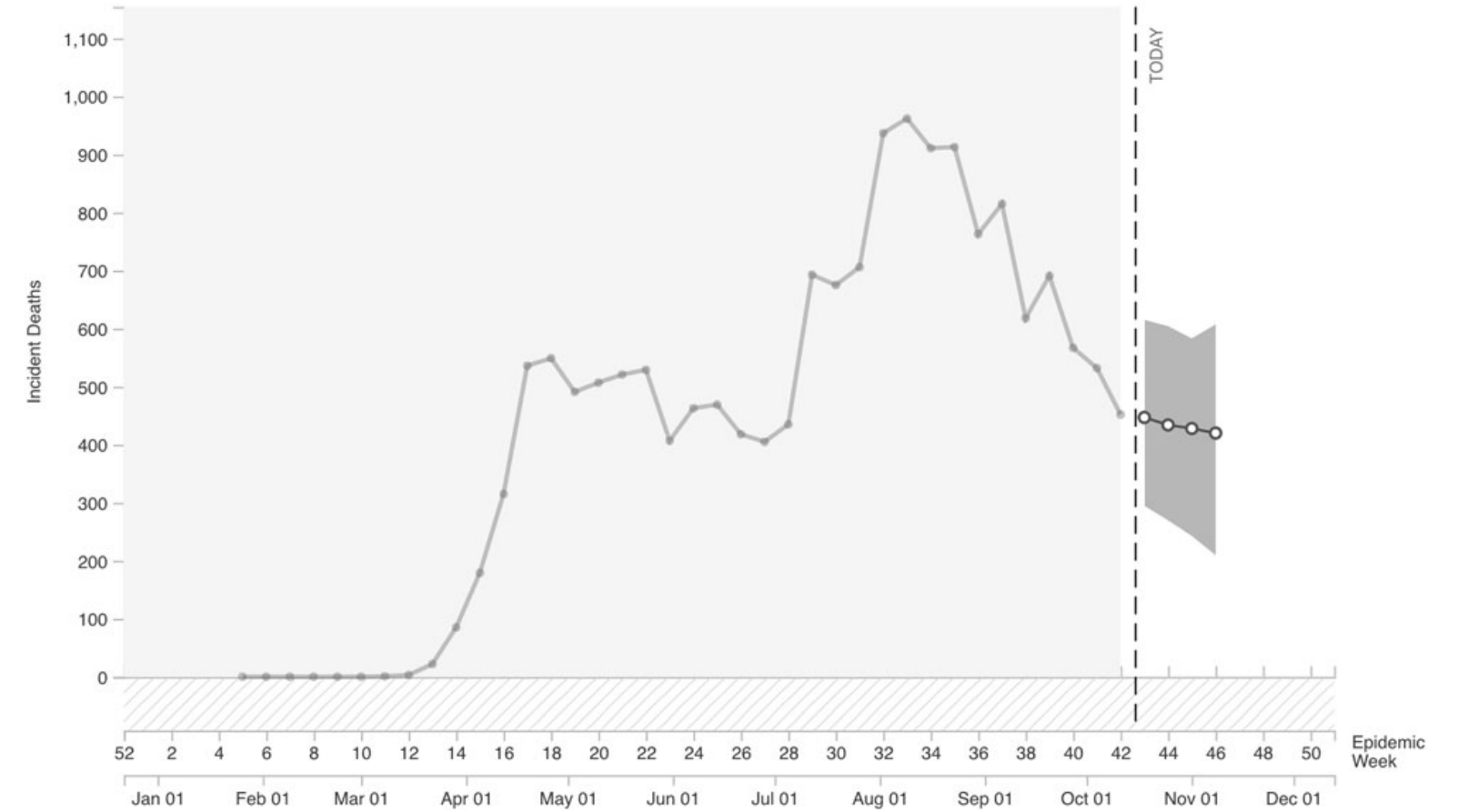
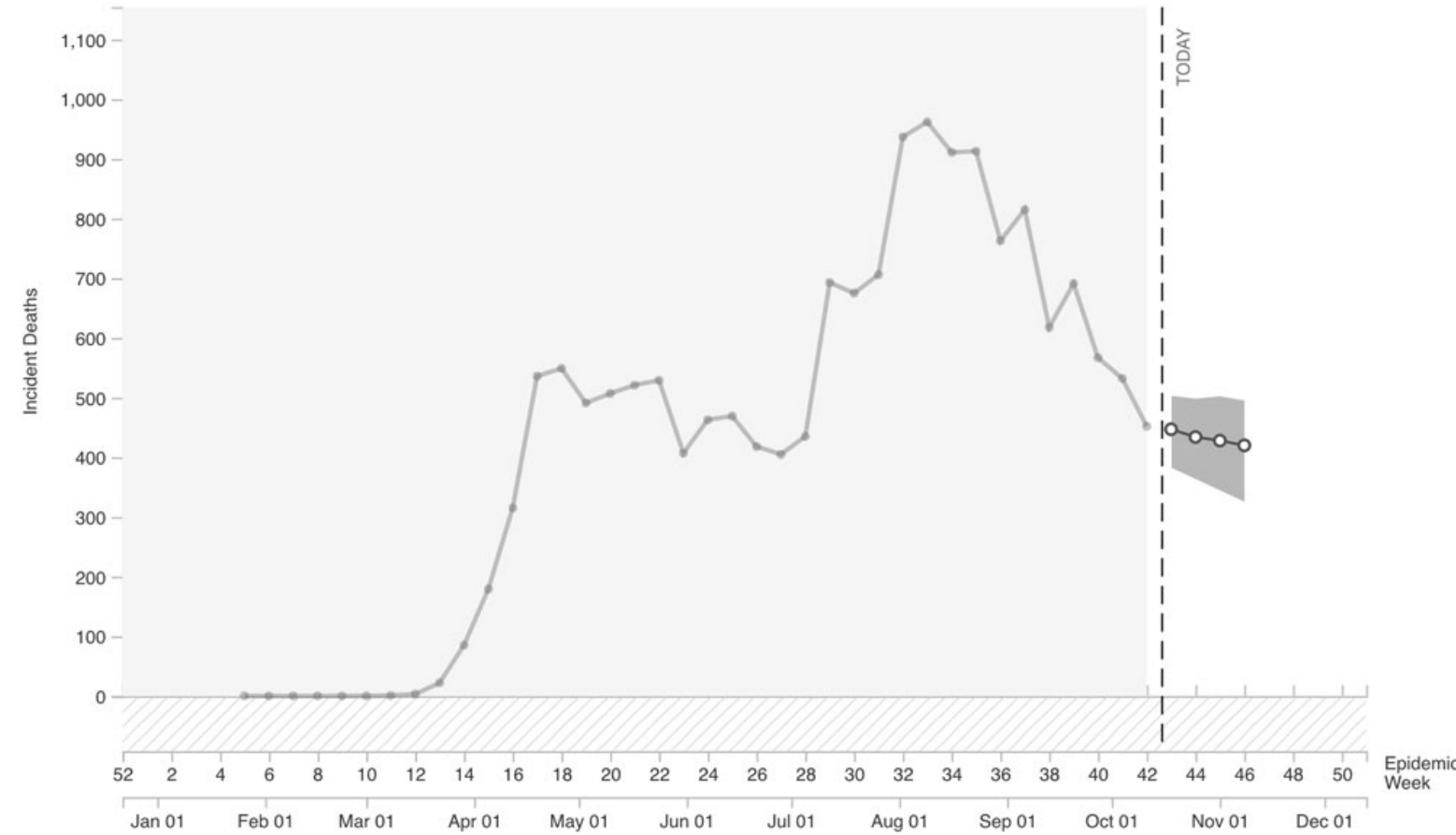
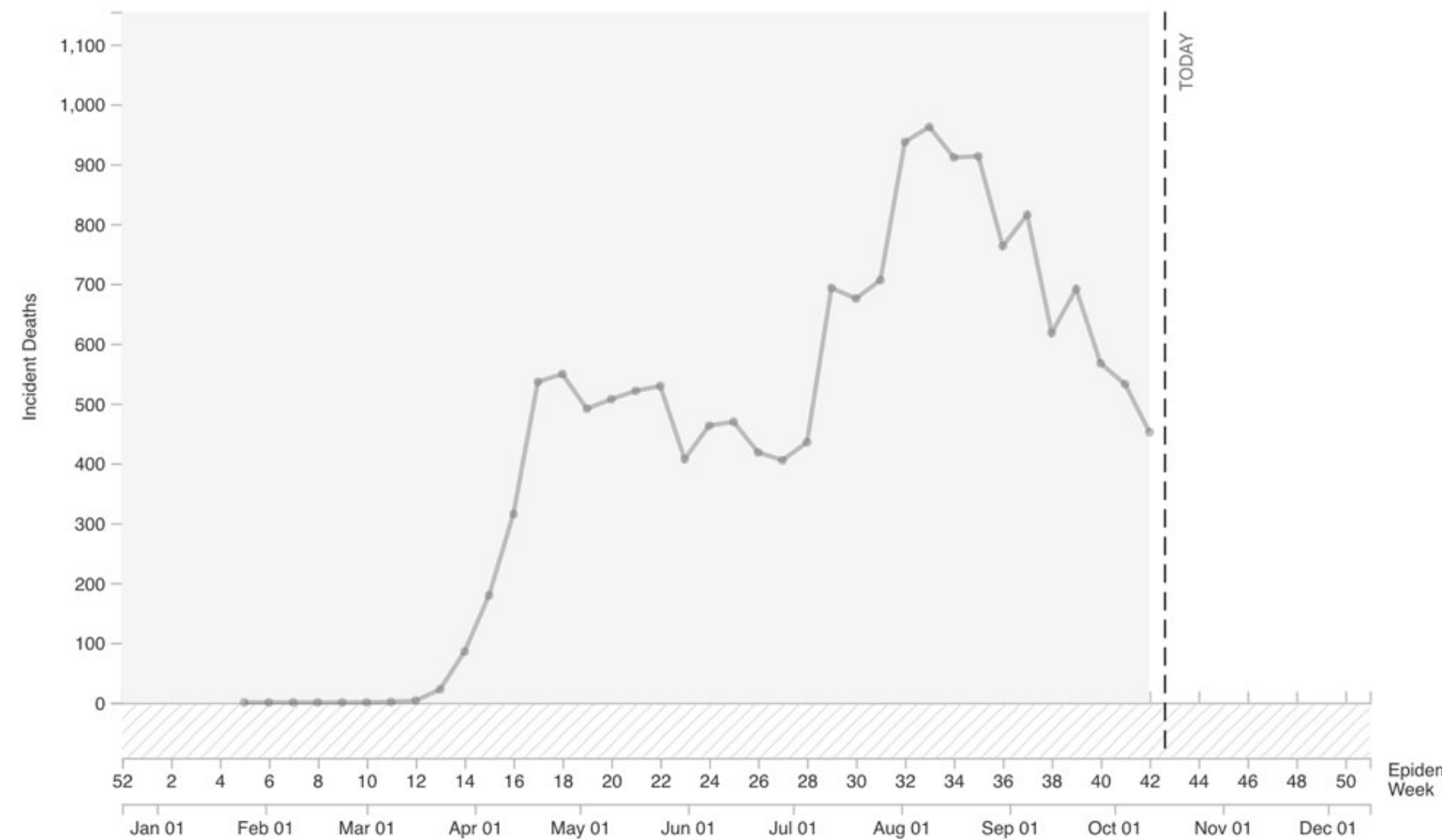
Mean



All Models + 95% CIs



Is the COVID-19 risk in Massachusetts decreasing, increasing, or staying the same?



Online study w/ $n = 1200$



Enrico Bertini
NYU



Rumi Chunara
NYU



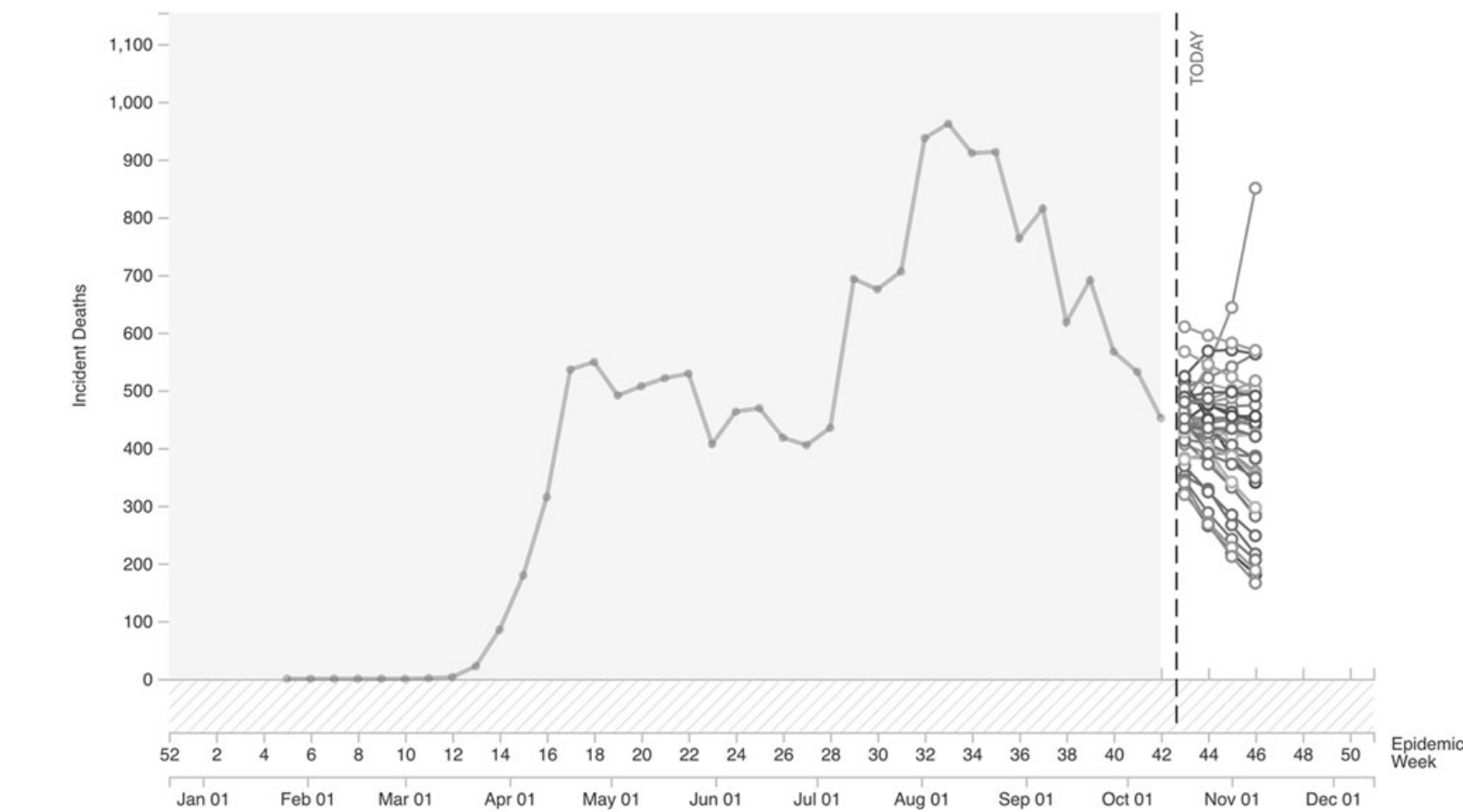
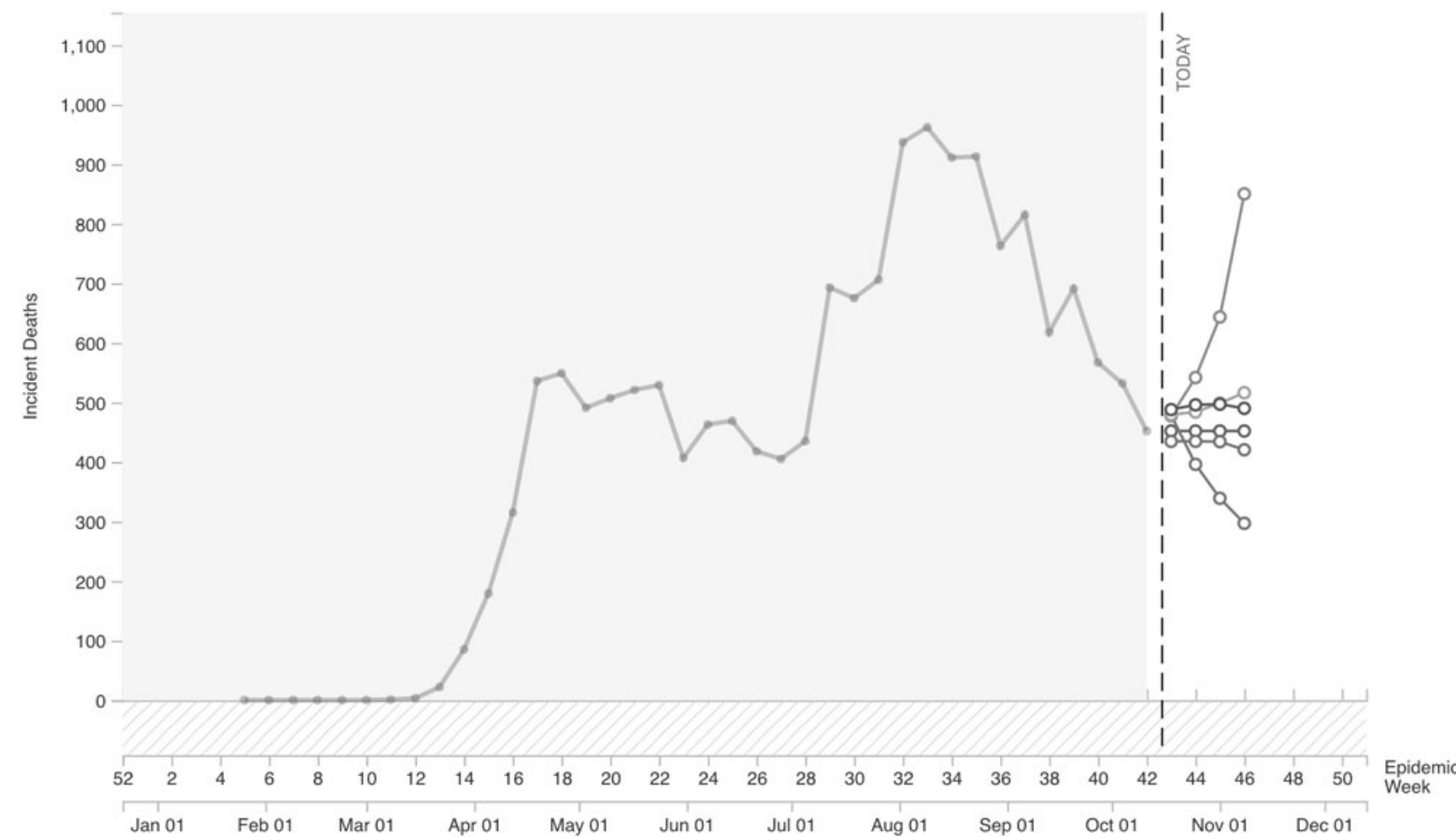
Jenny Howell
UC Merced

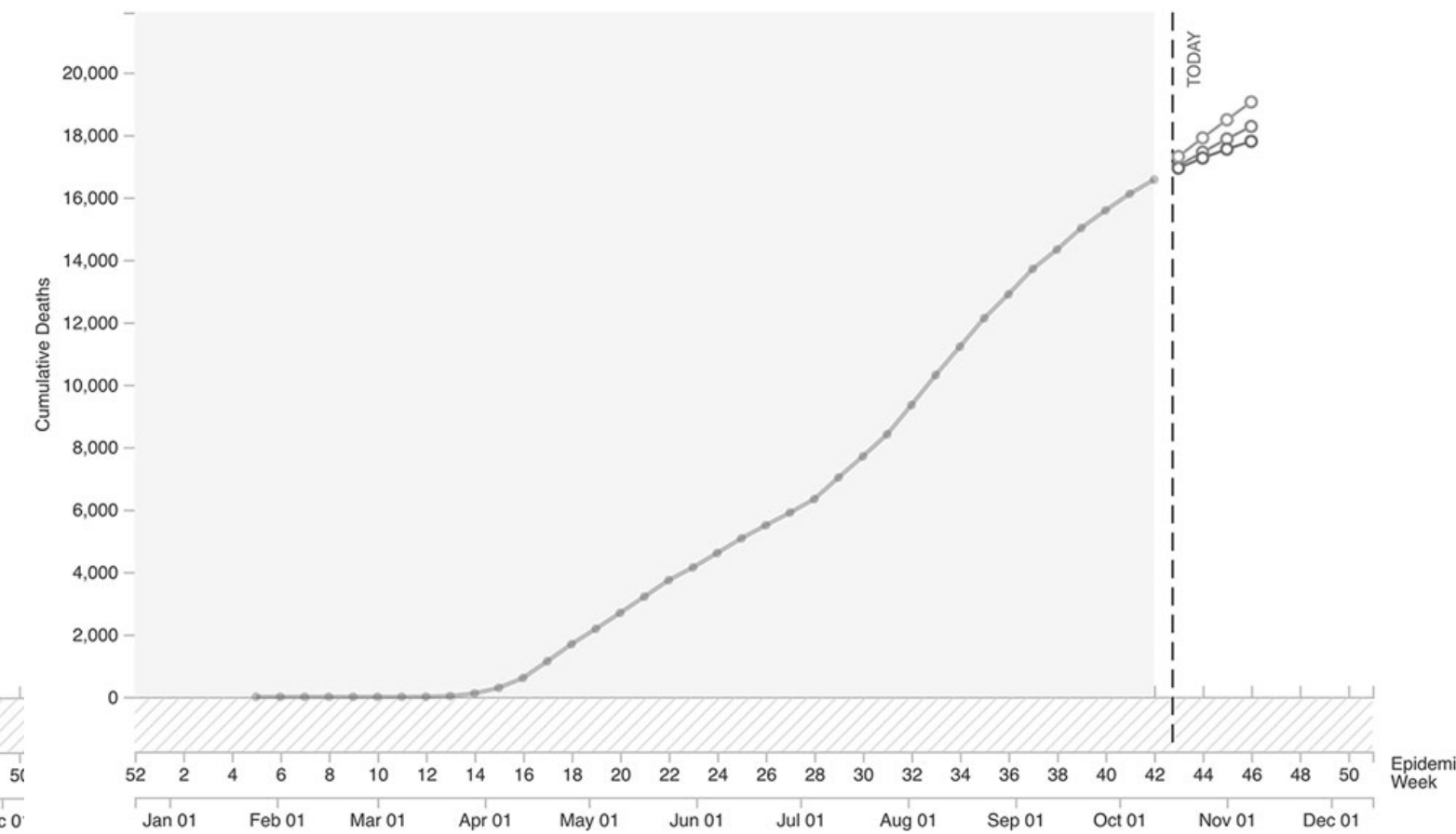
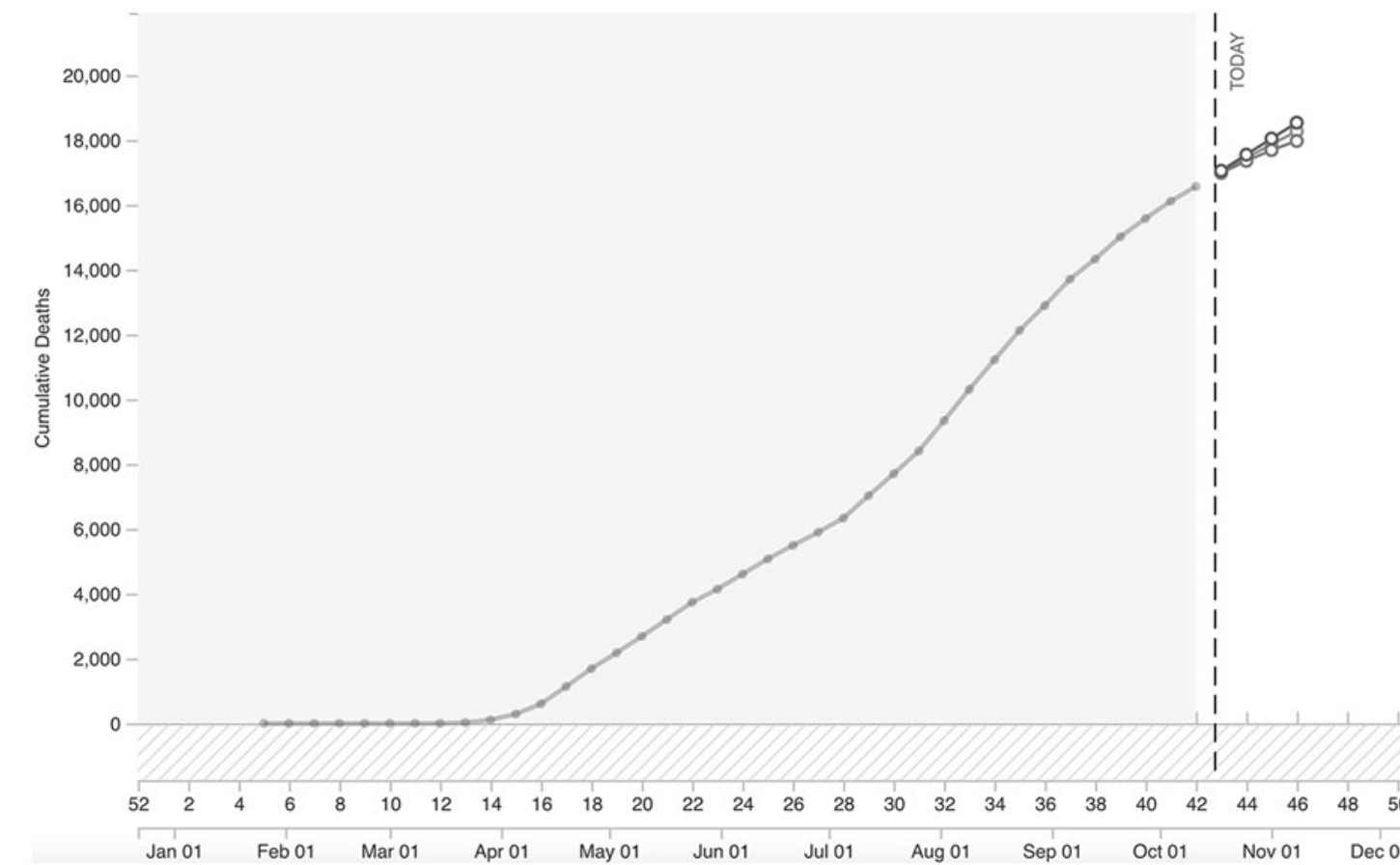
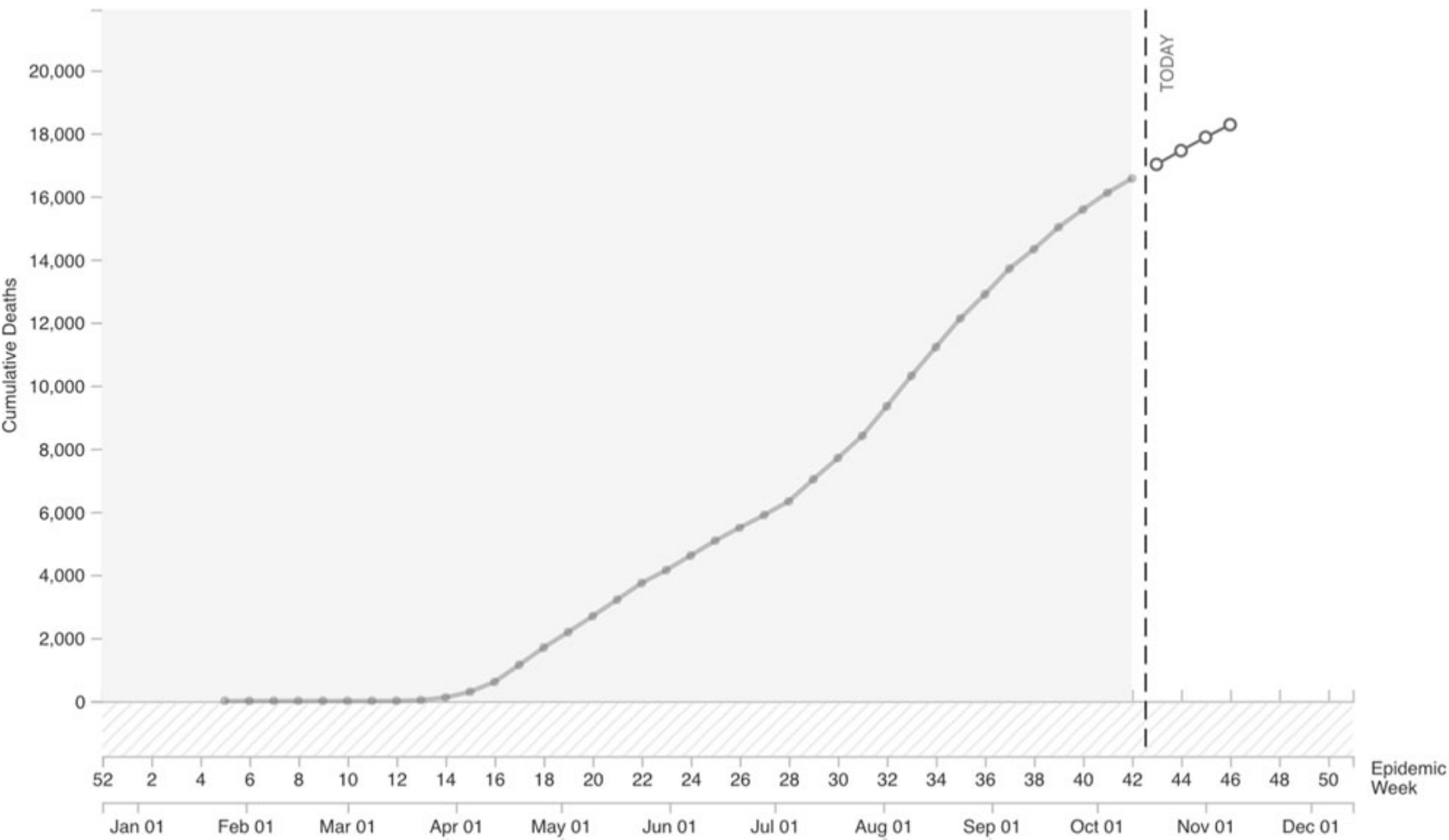
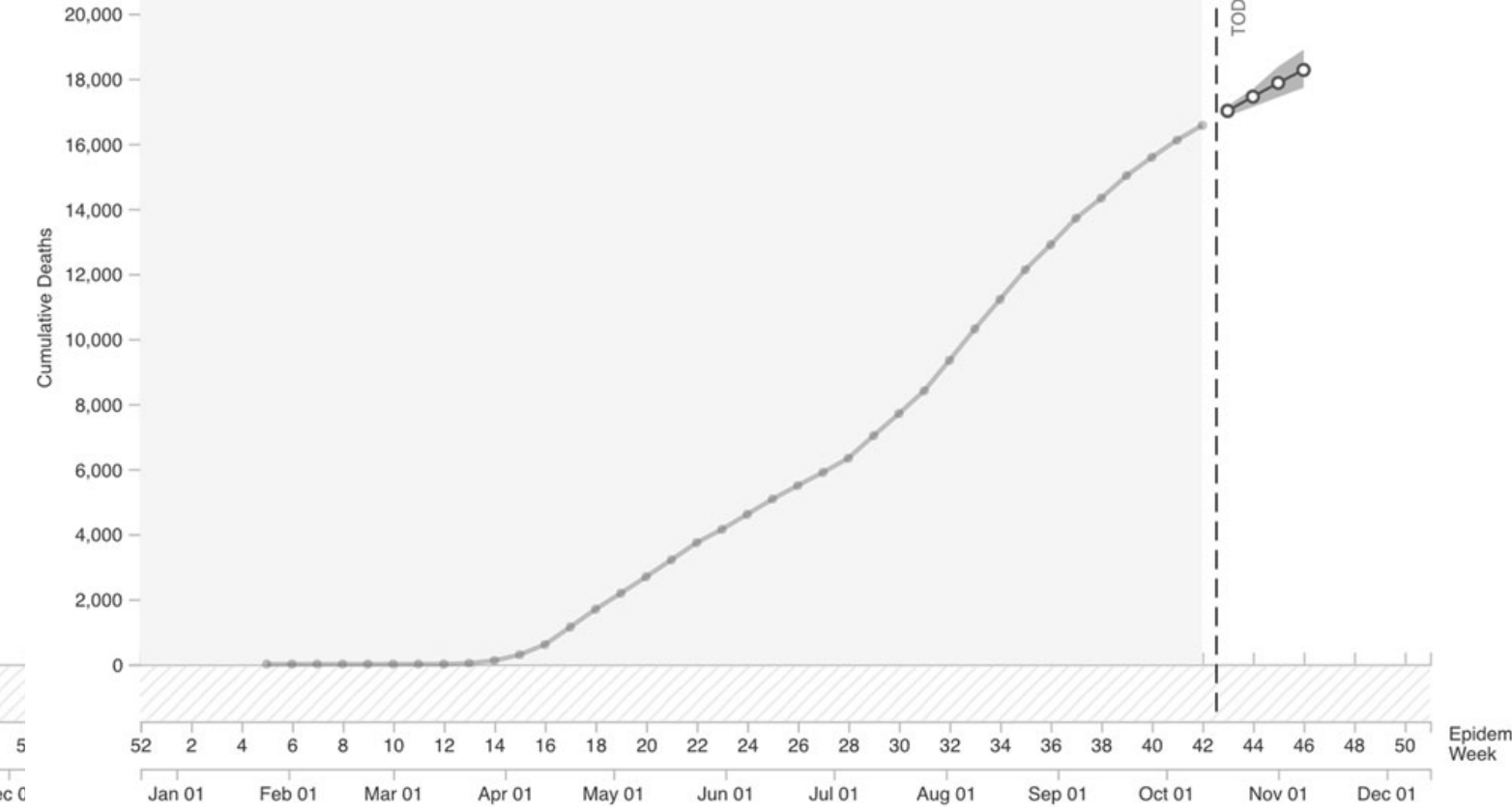
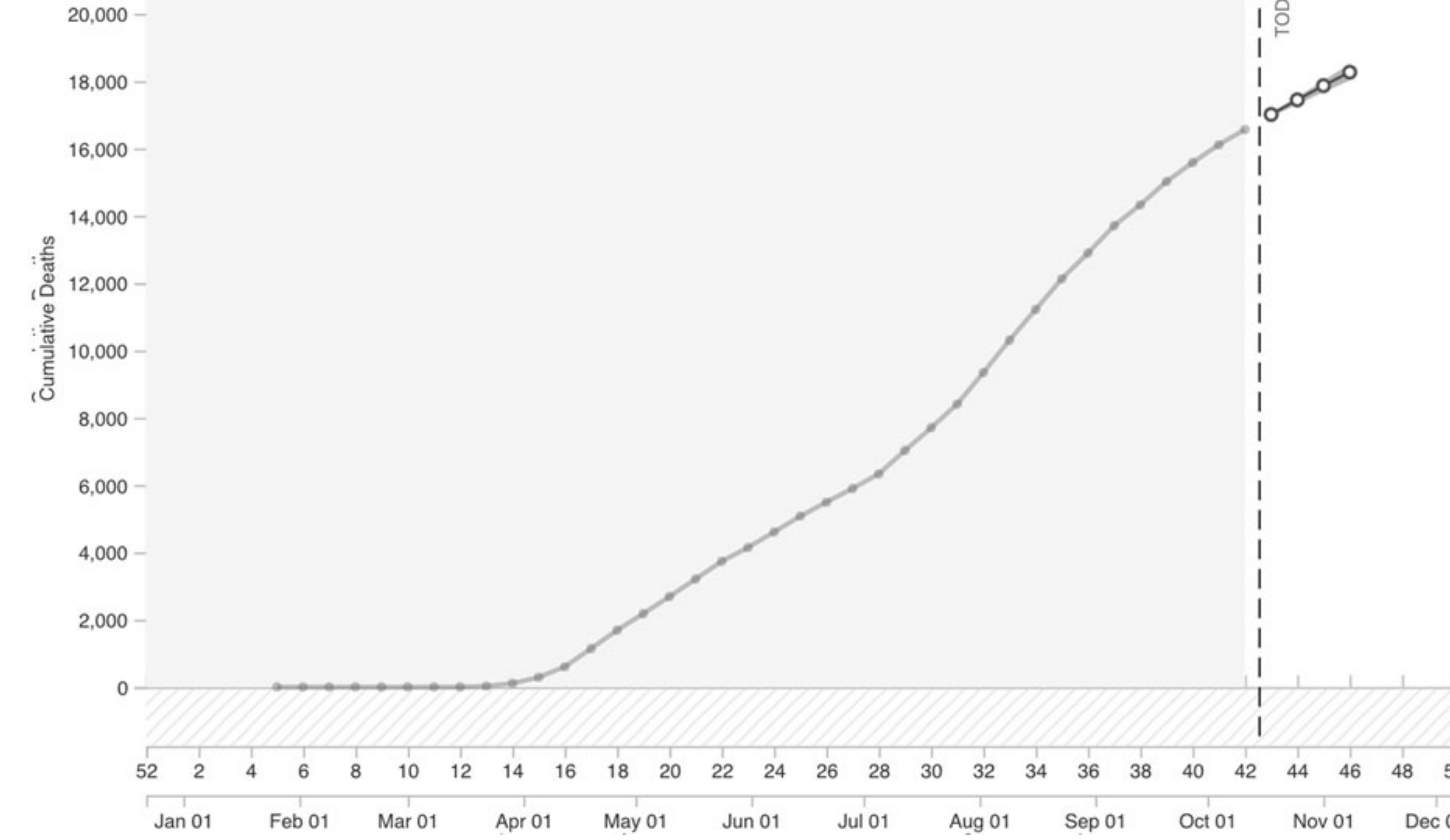
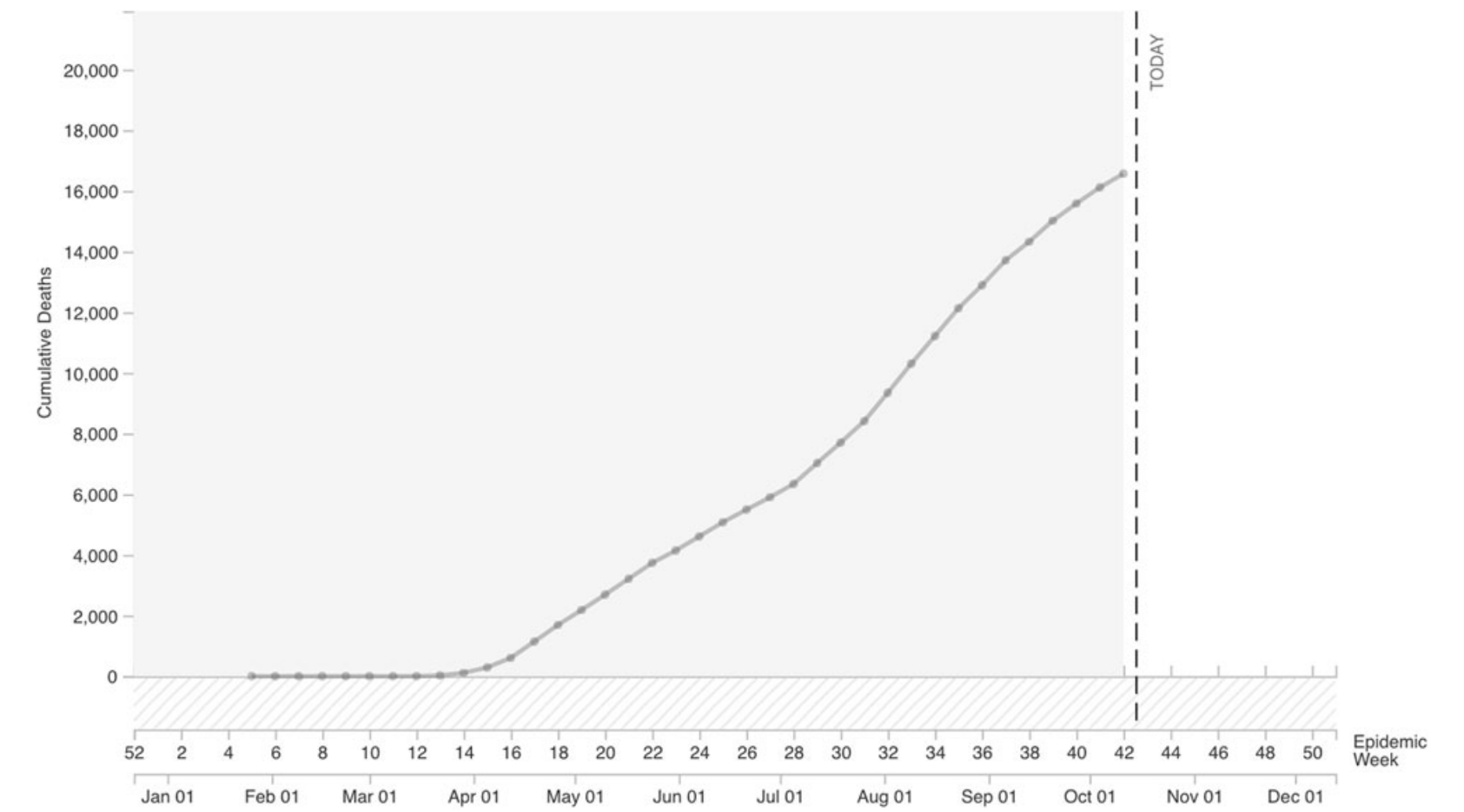


Helia Hosseinpour
UC Merced



Racquel Fygenon
NYU





Online study w/ $n = 1200$



**Enrico
Bertini**
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Chunara**
NYU



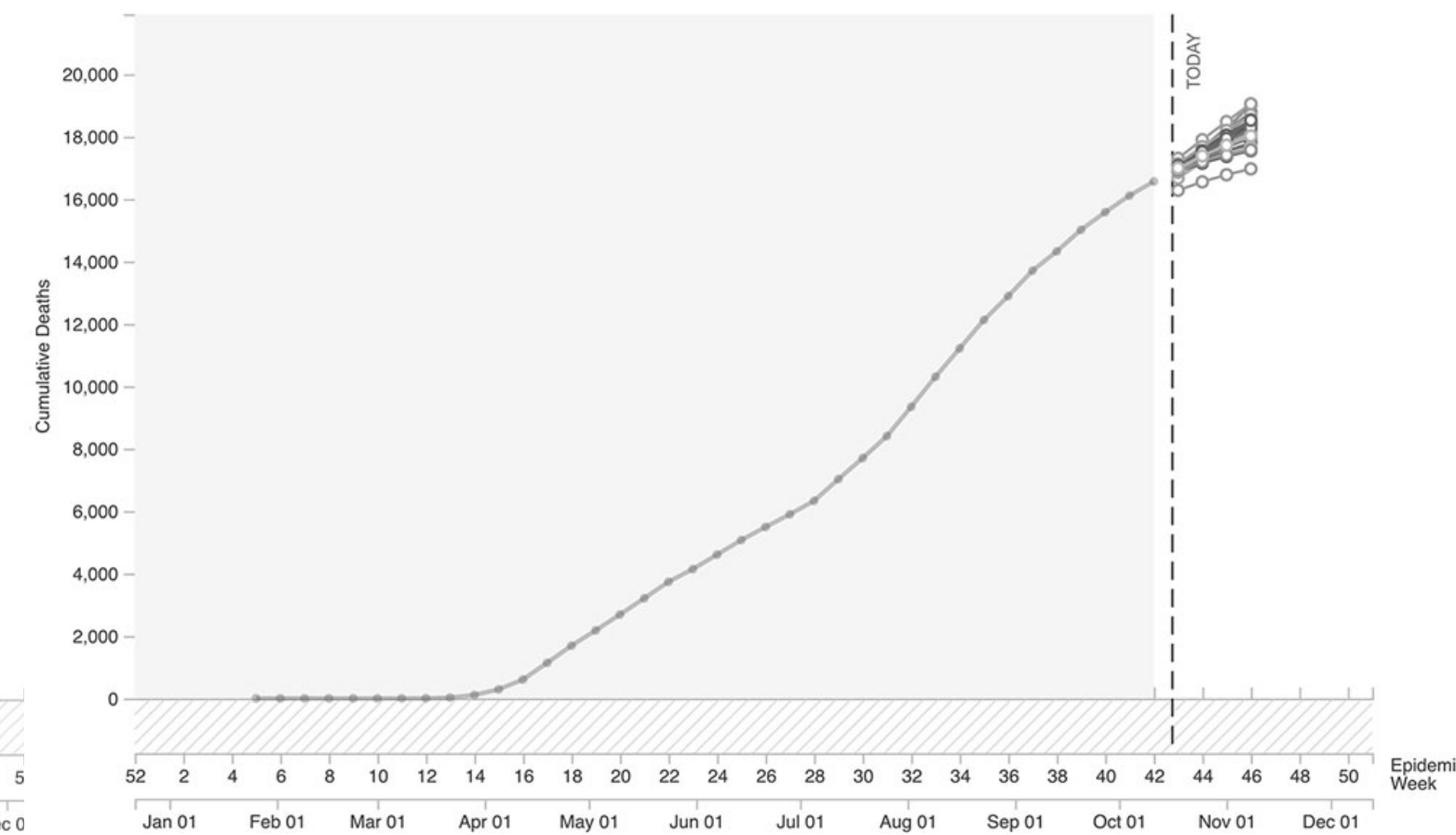
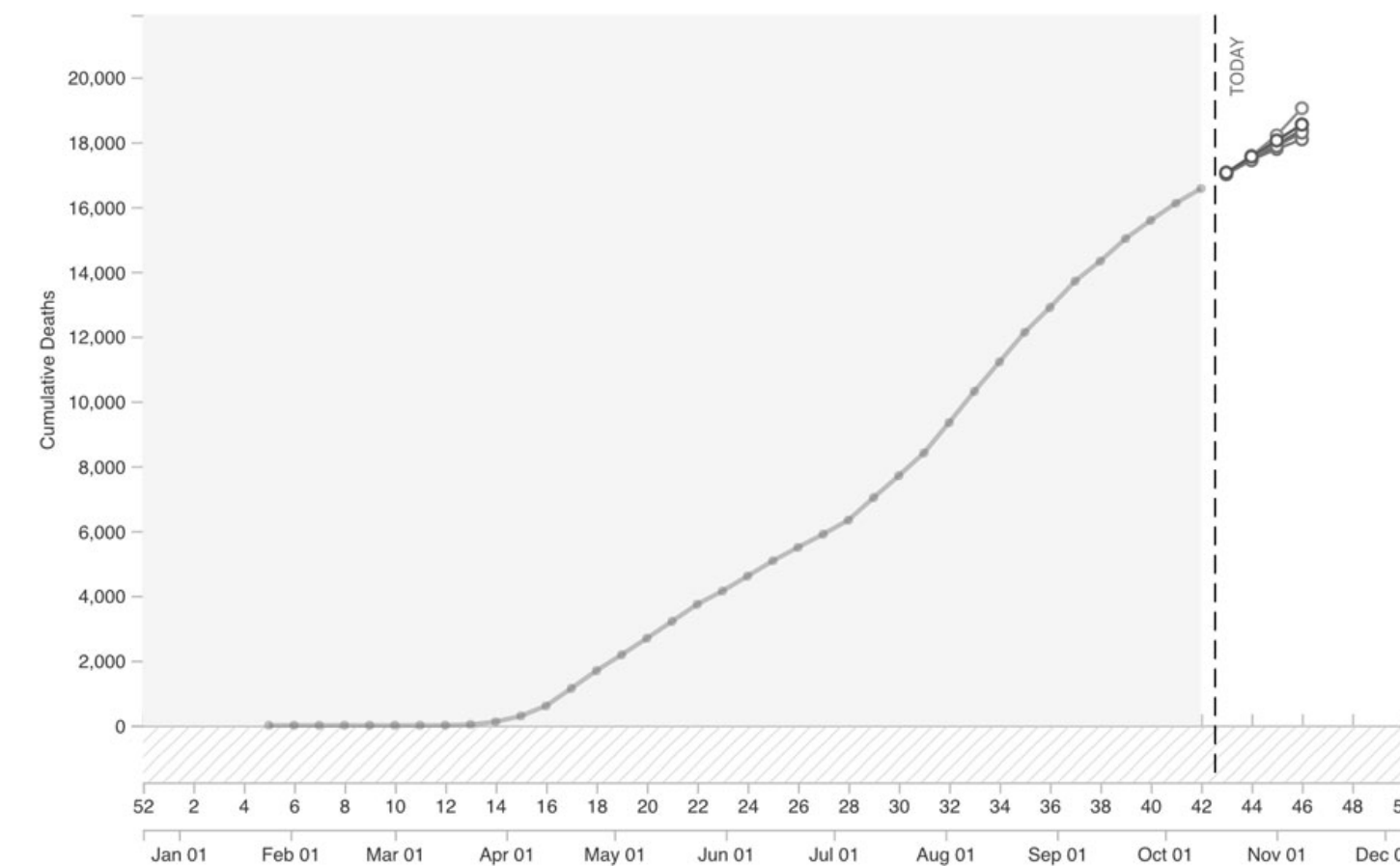
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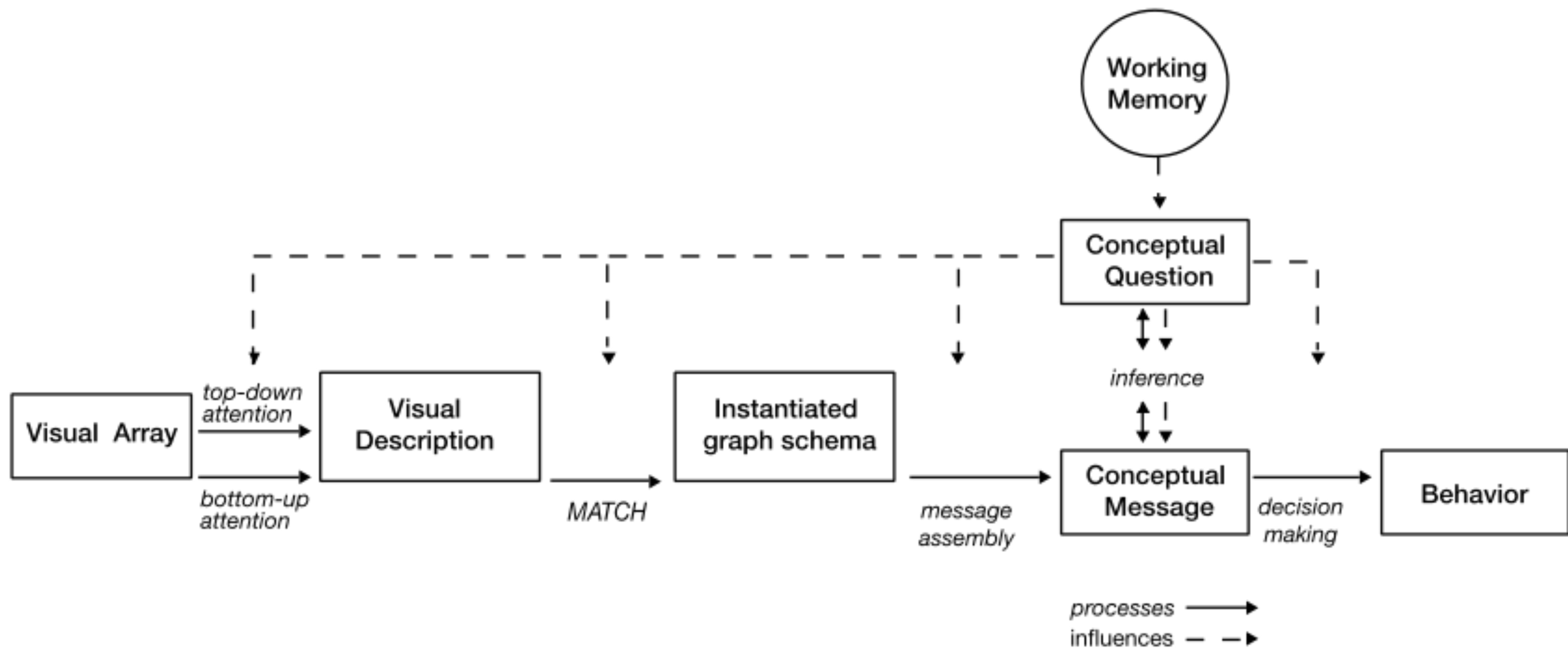
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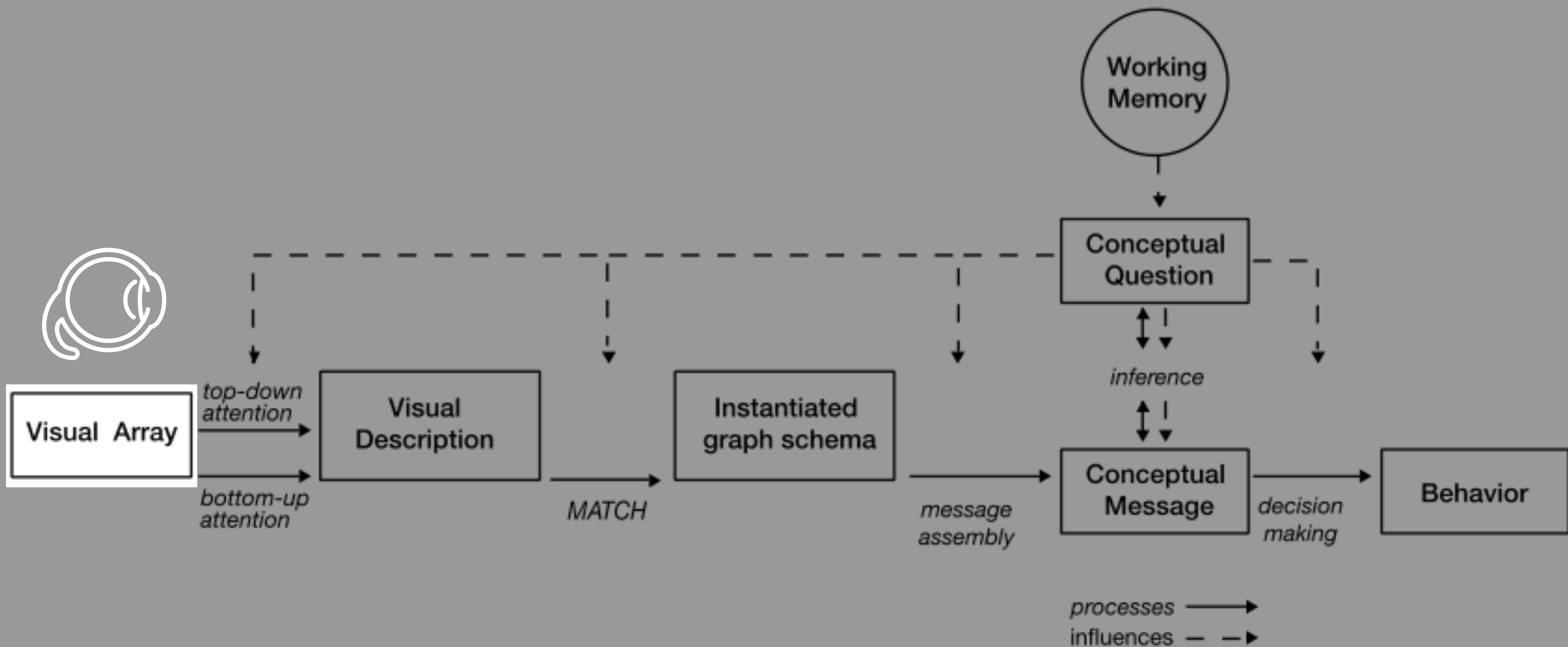


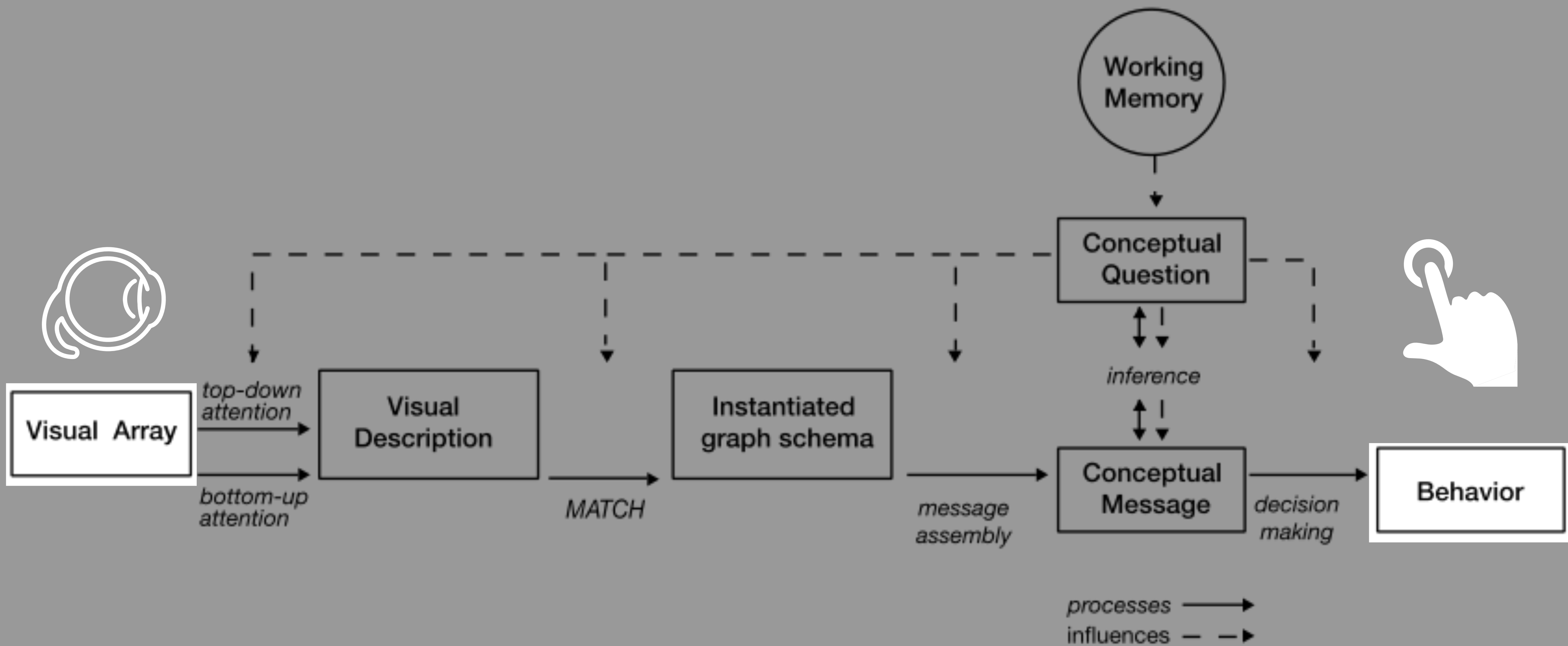
**Racquel
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NYU

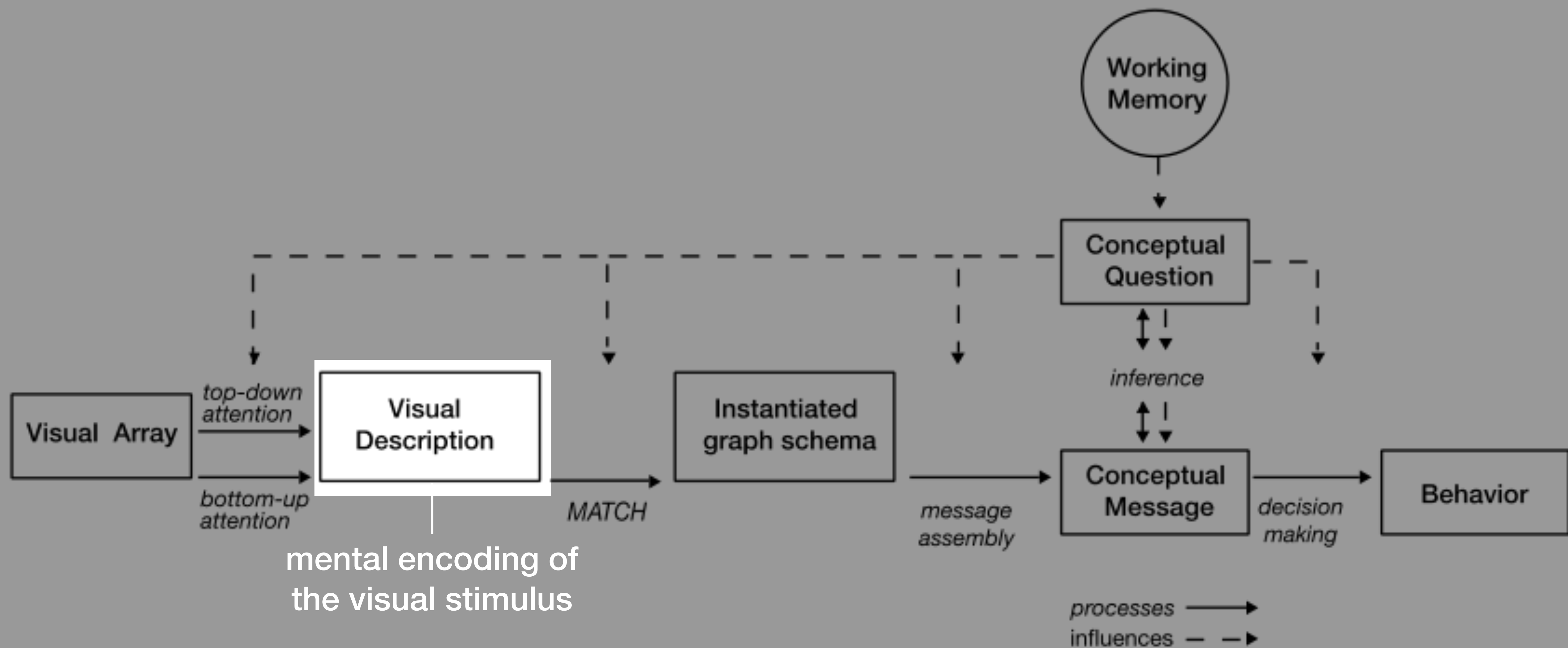


The way that uncertainty is presented has a profound influence on our judgments



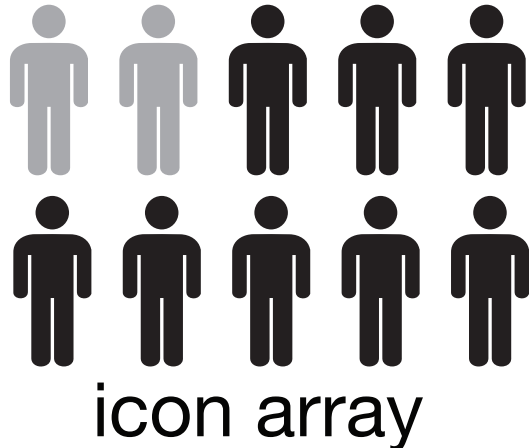
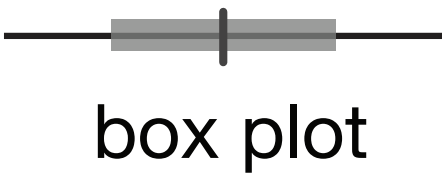
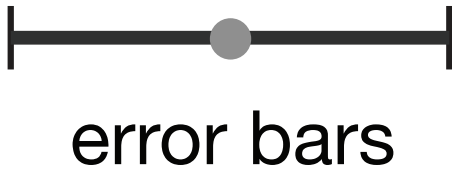




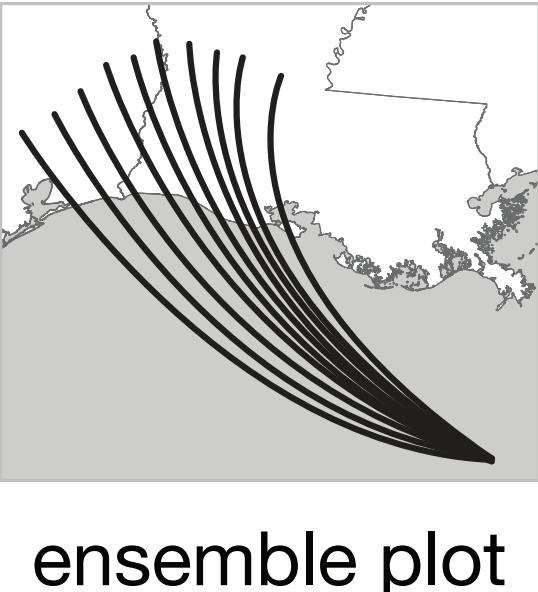
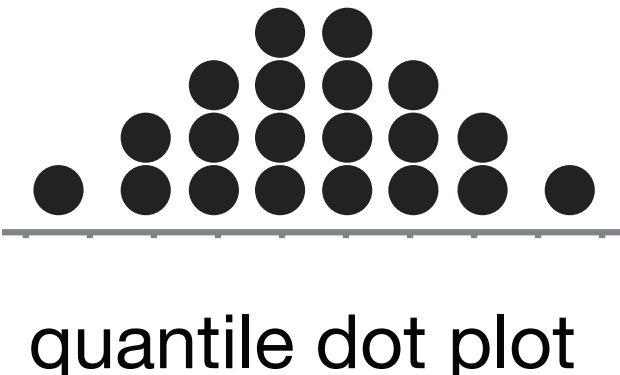
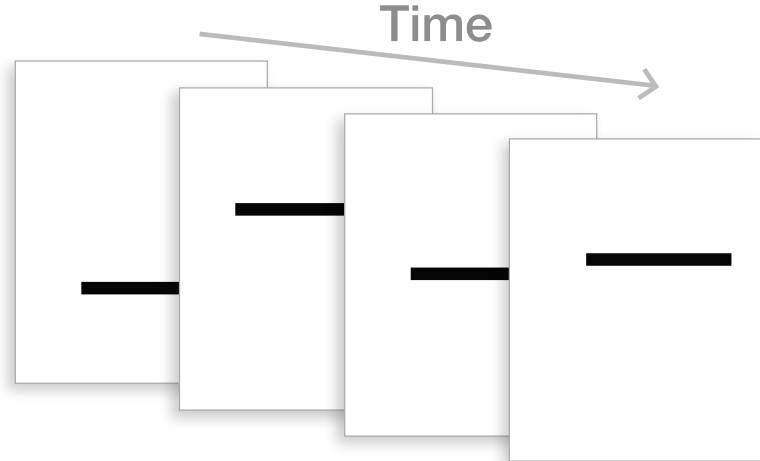
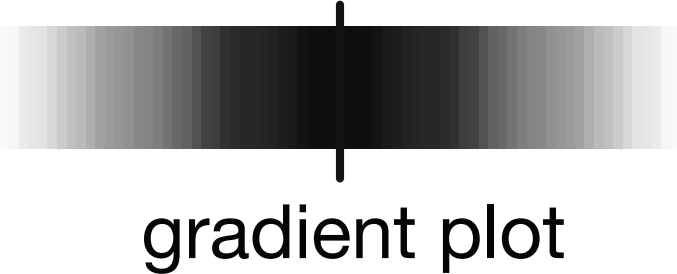
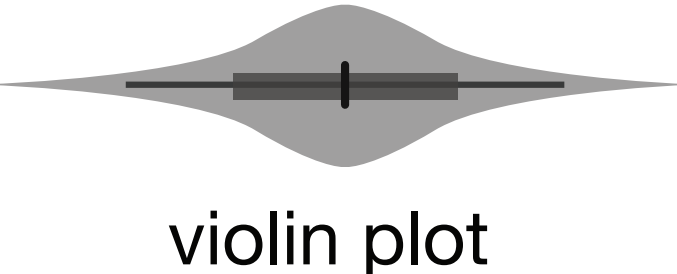


Graphical Annotations of Distributional Properties

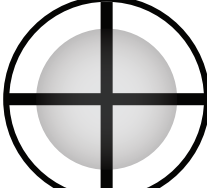
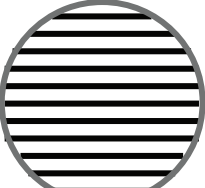
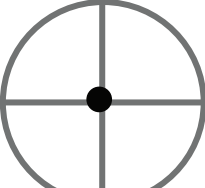
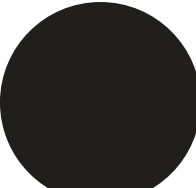
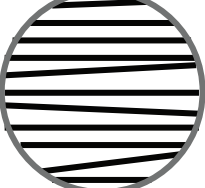
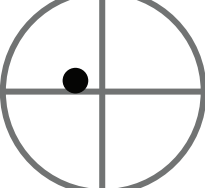
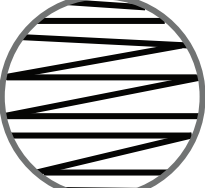
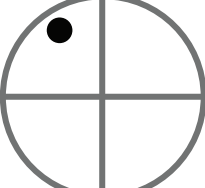
Intervals and Ratios



Distributions

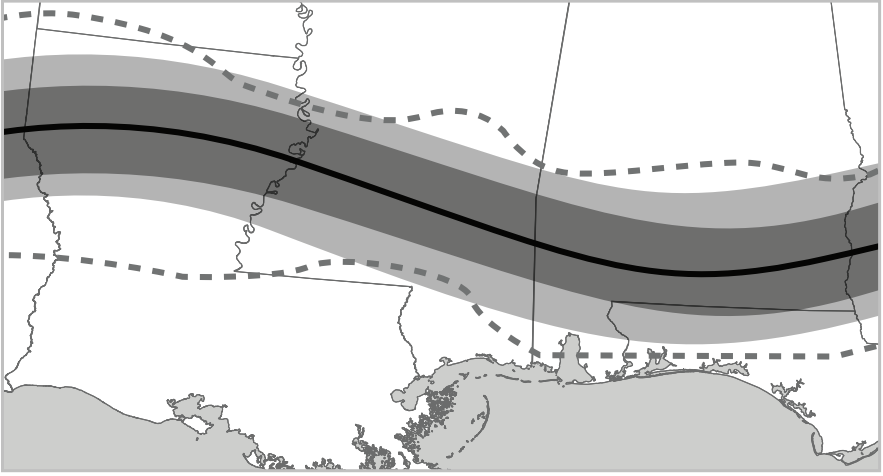


Visual Encodings of Uncertainty

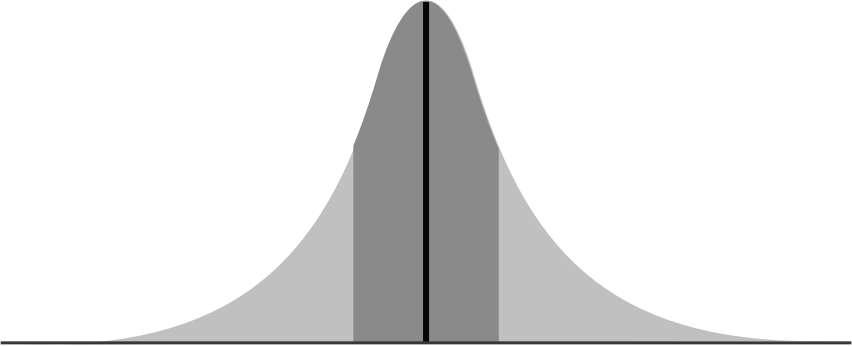


fuzziness location arrangement size transparency

Hybrid Approach



contour boxplot

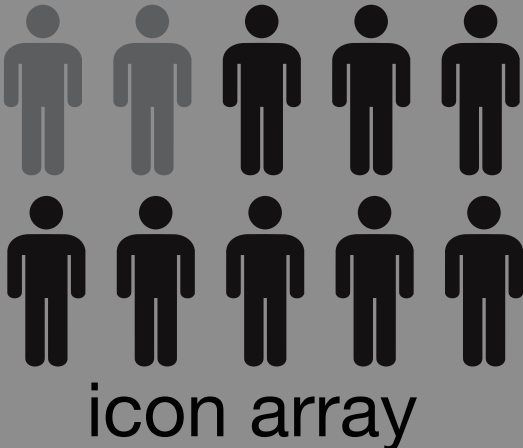
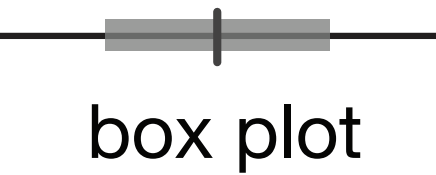
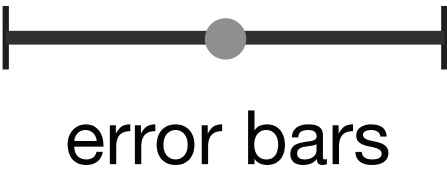


probability density and interval plot

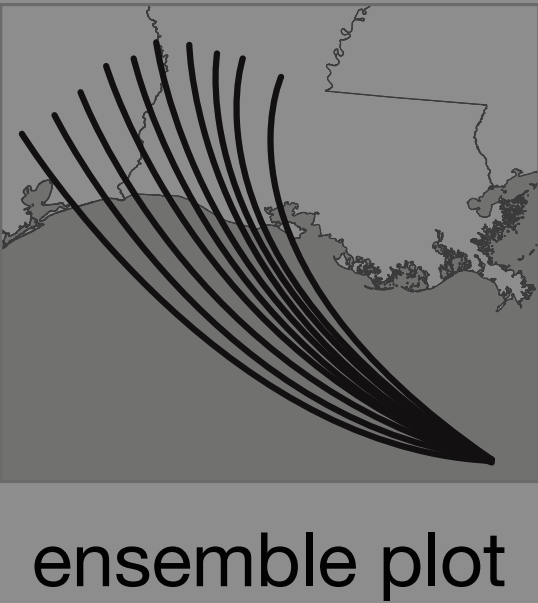
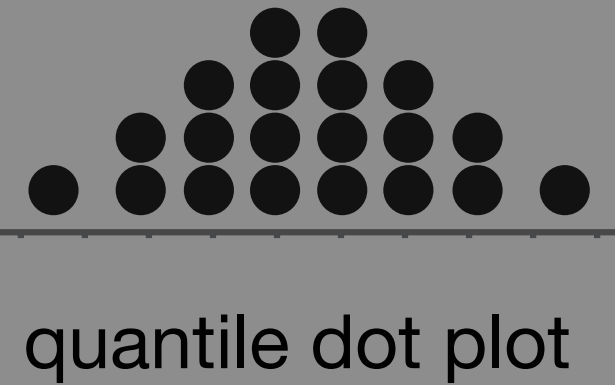
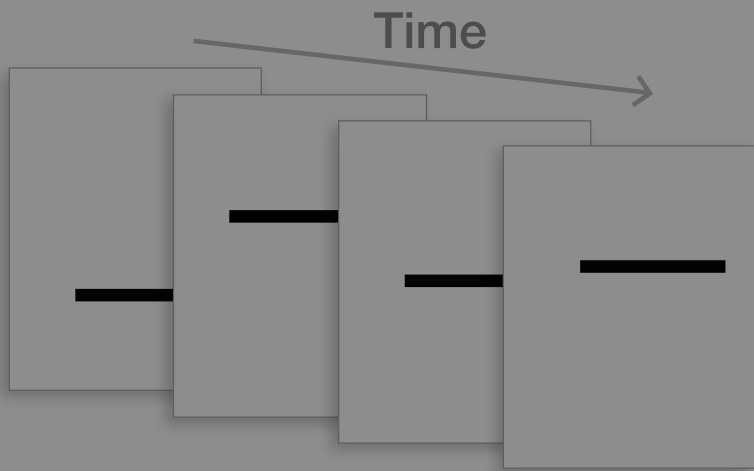
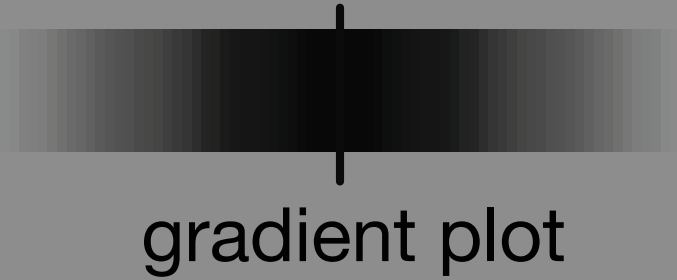
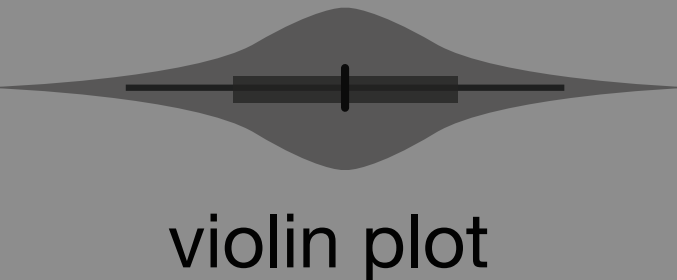
visual description mental encoding of
the visual stimulus

Graphical Annotations of Distributional Properties

Intervals and Ratios



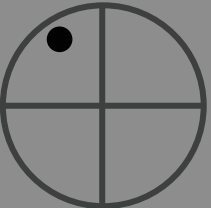
Distributions



Visual Encodings of Uncertainty



fuzziness



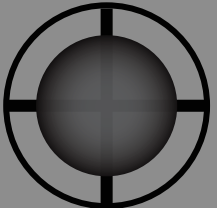
location



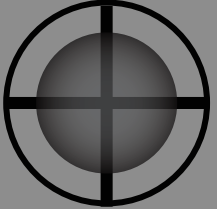
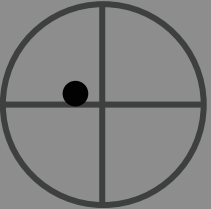
arrangement



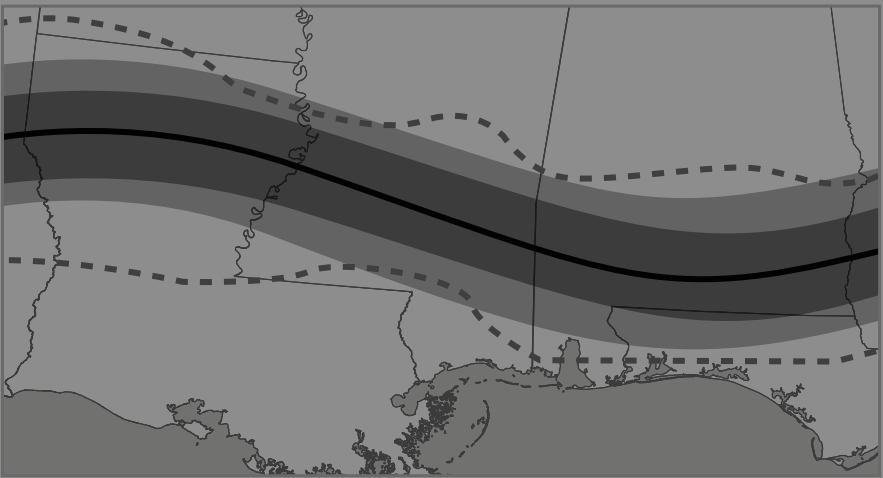
size



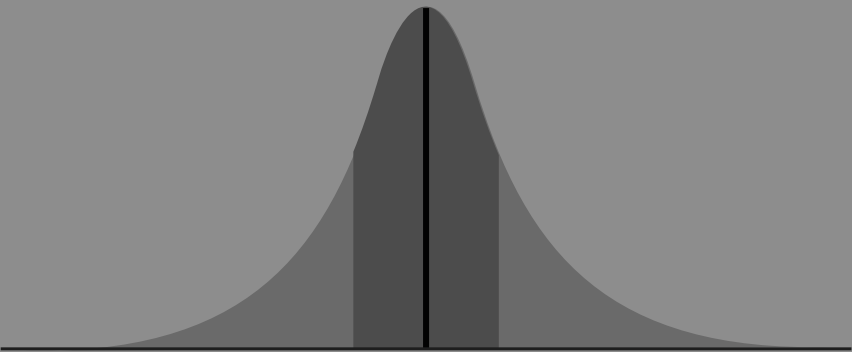
transparency



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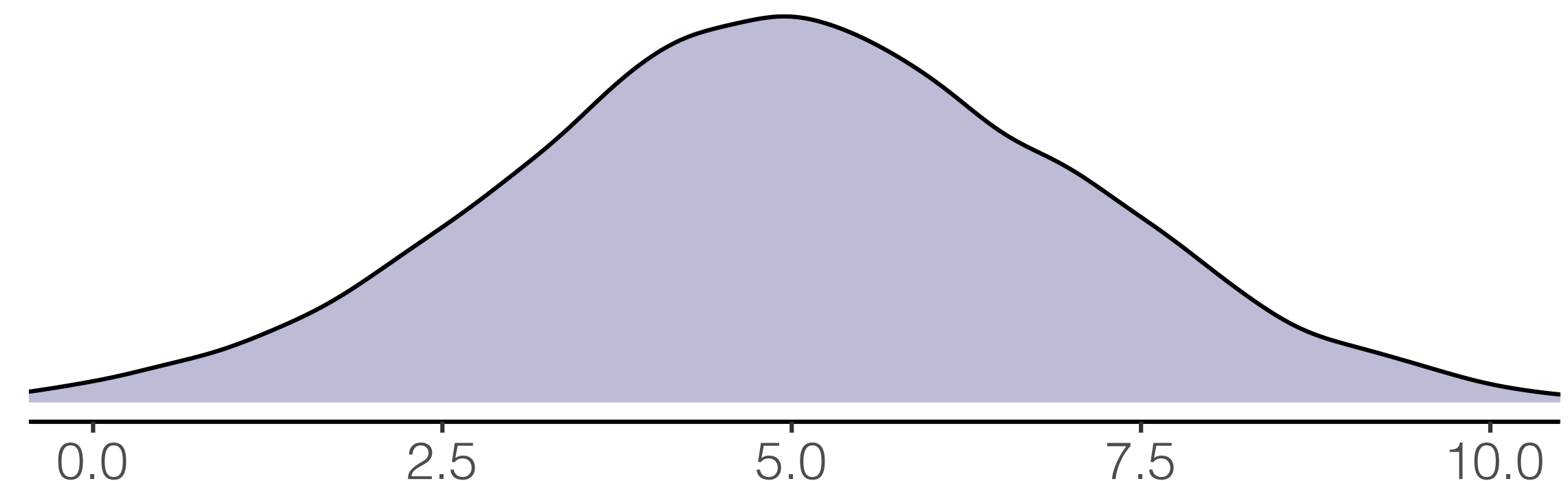
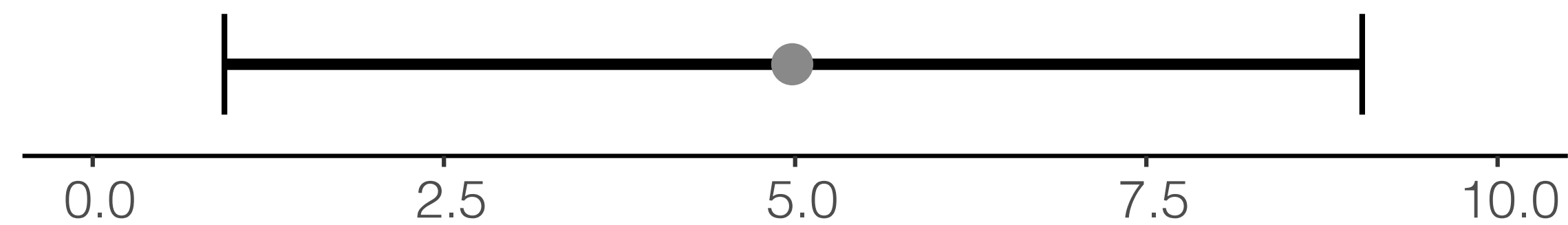


contour boxplot

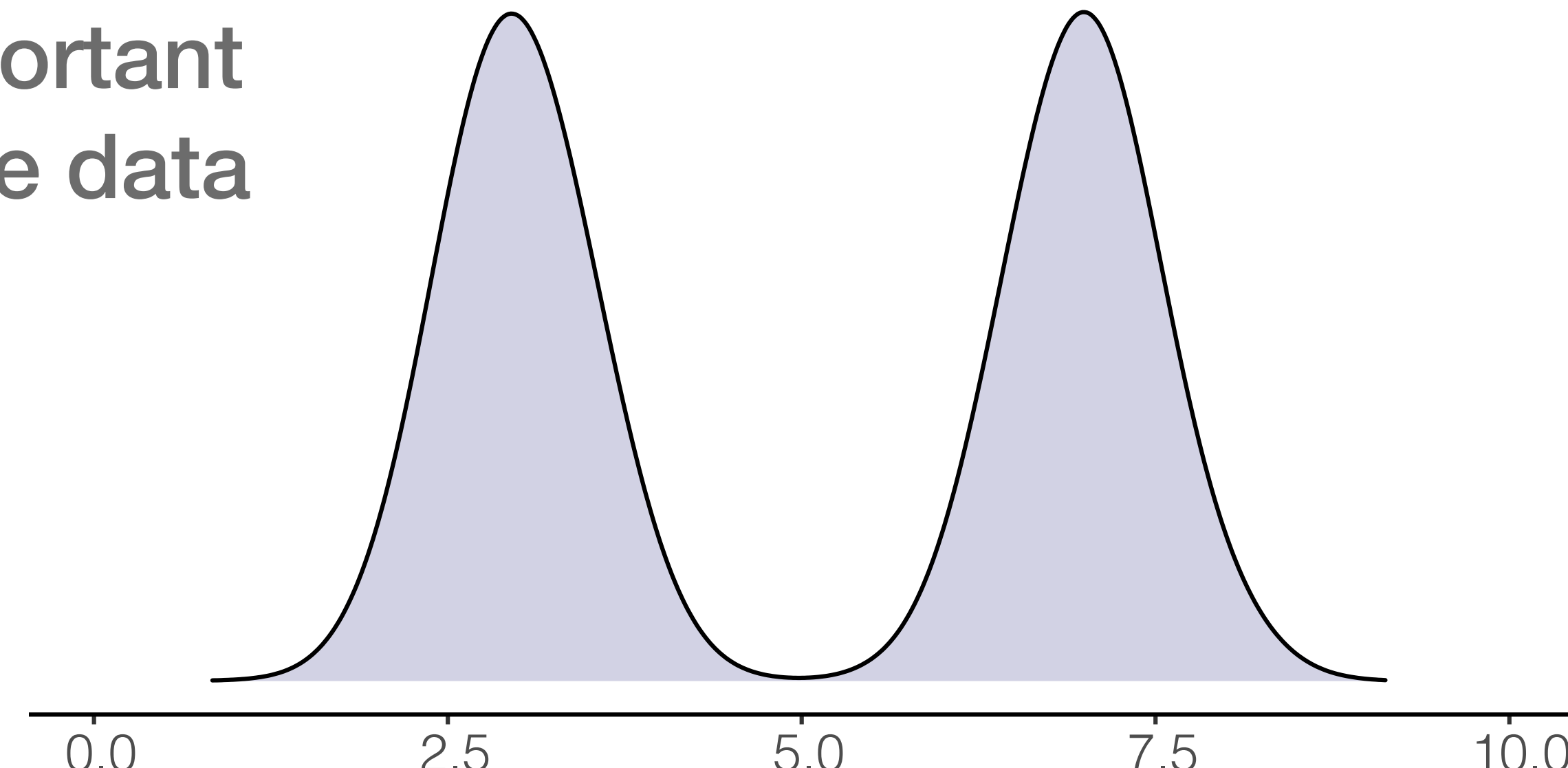
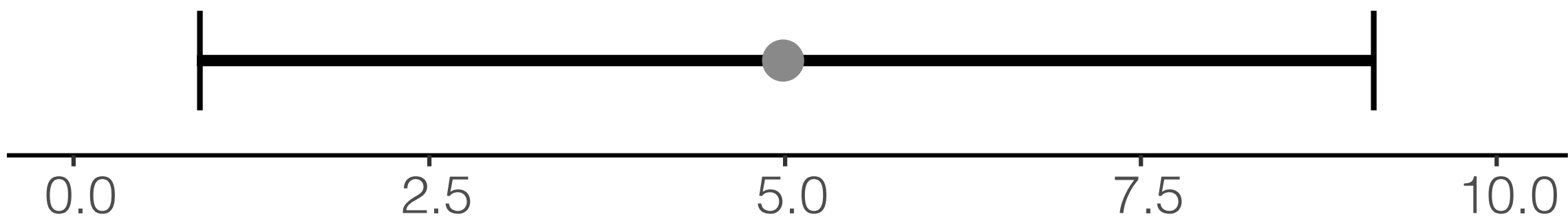


probability density and interval plot

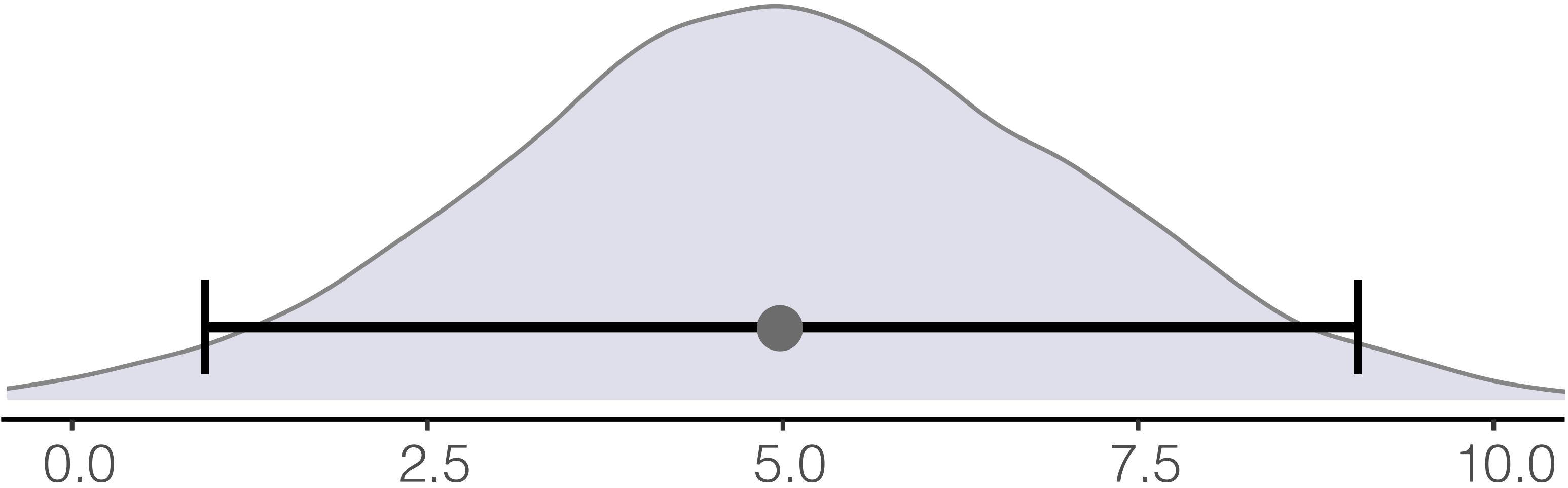
Intervals (95% CI)



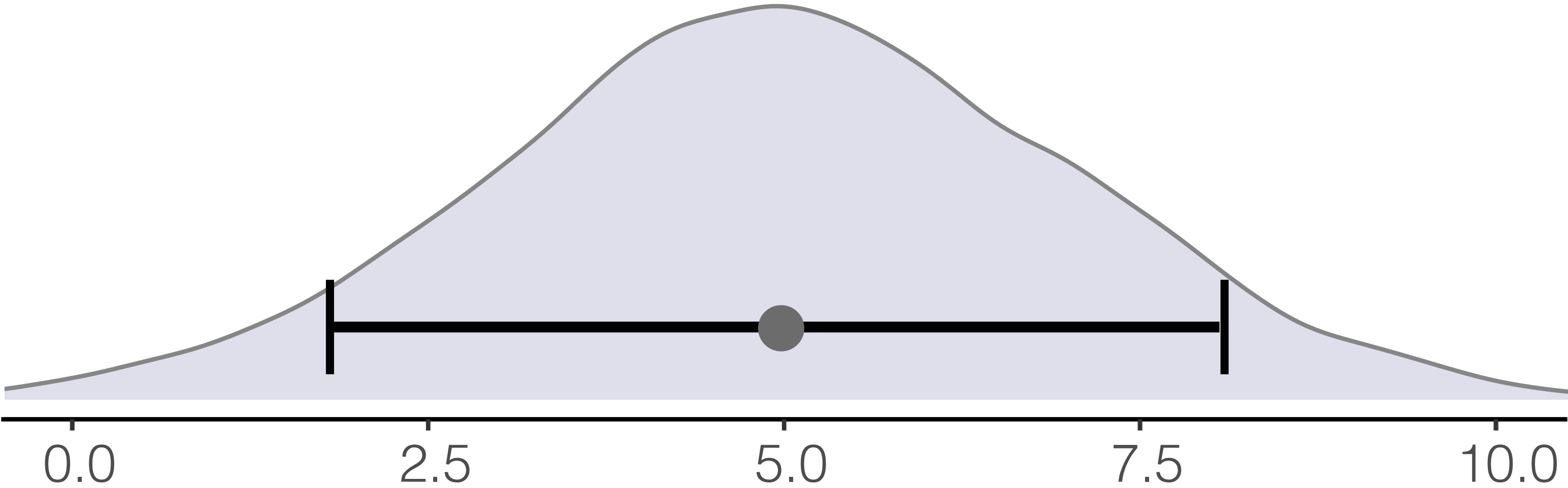
Can hide important features of the data



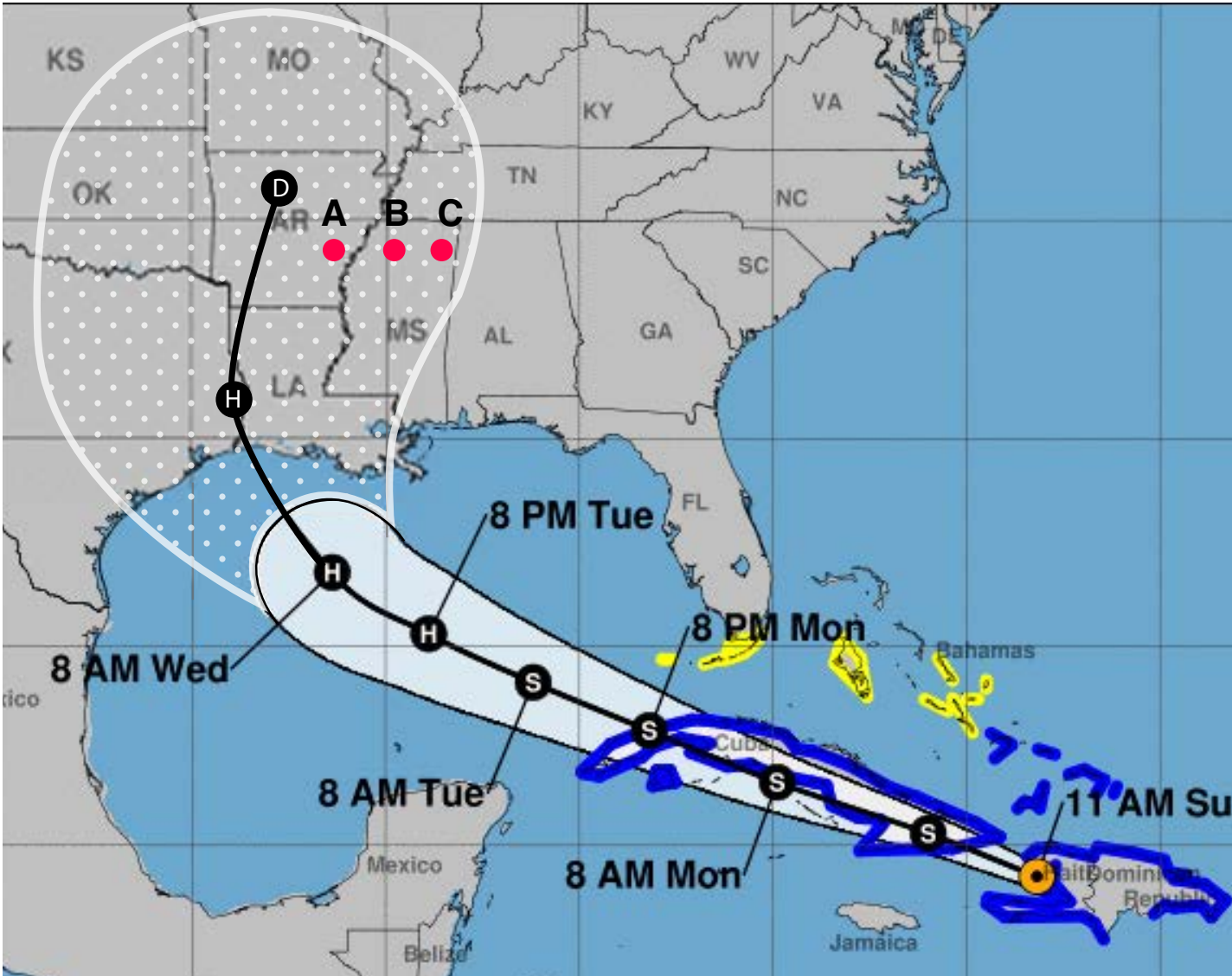
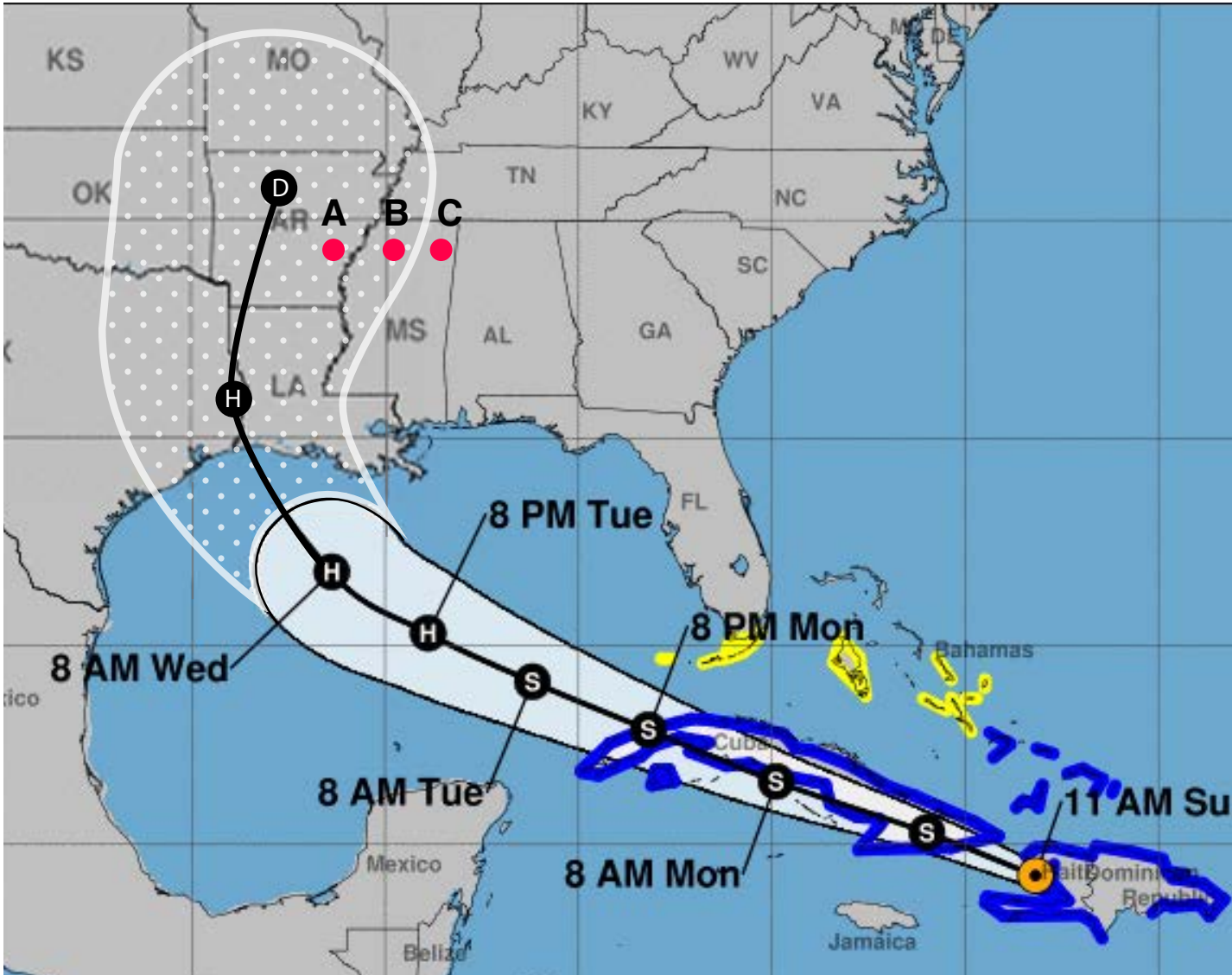
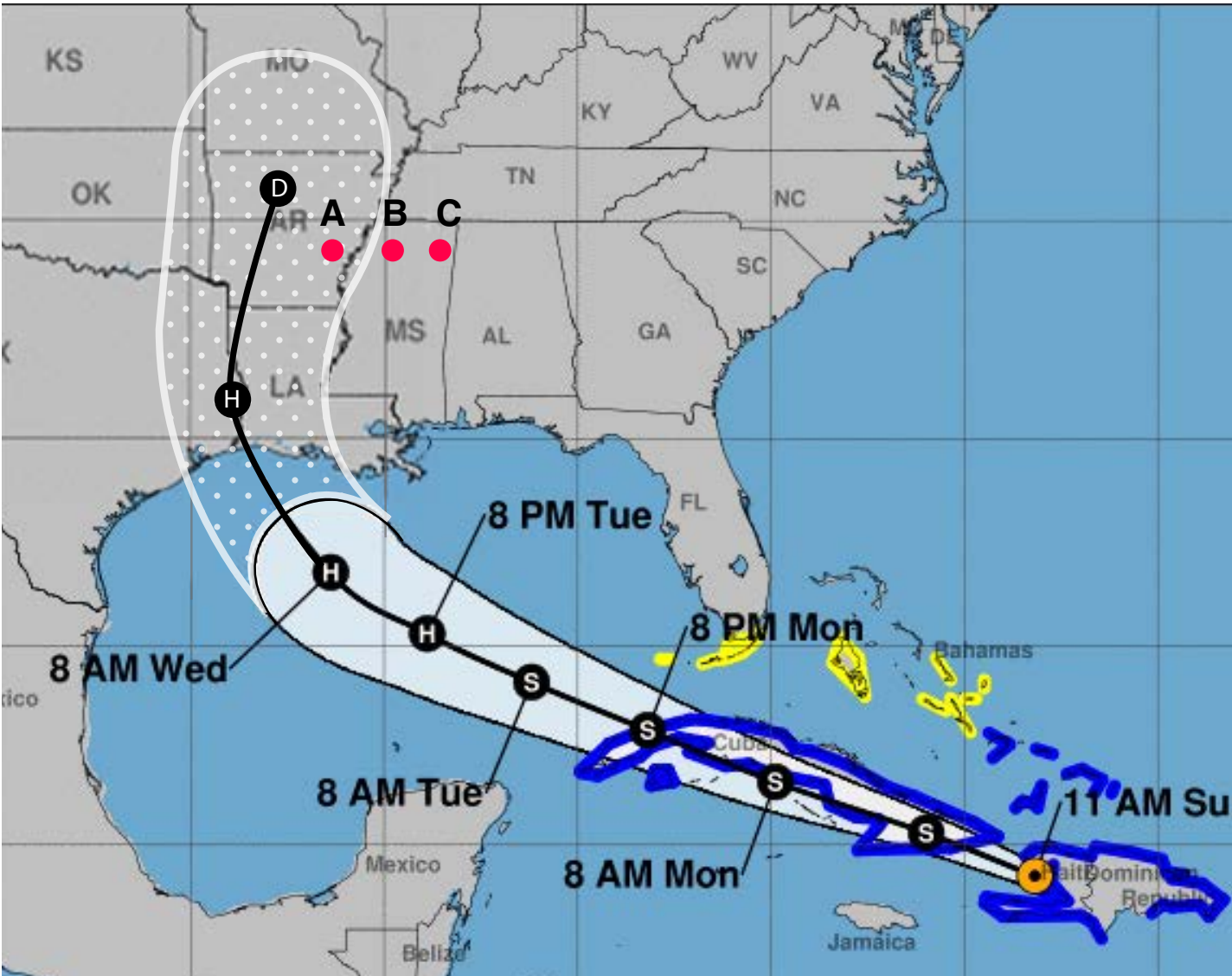
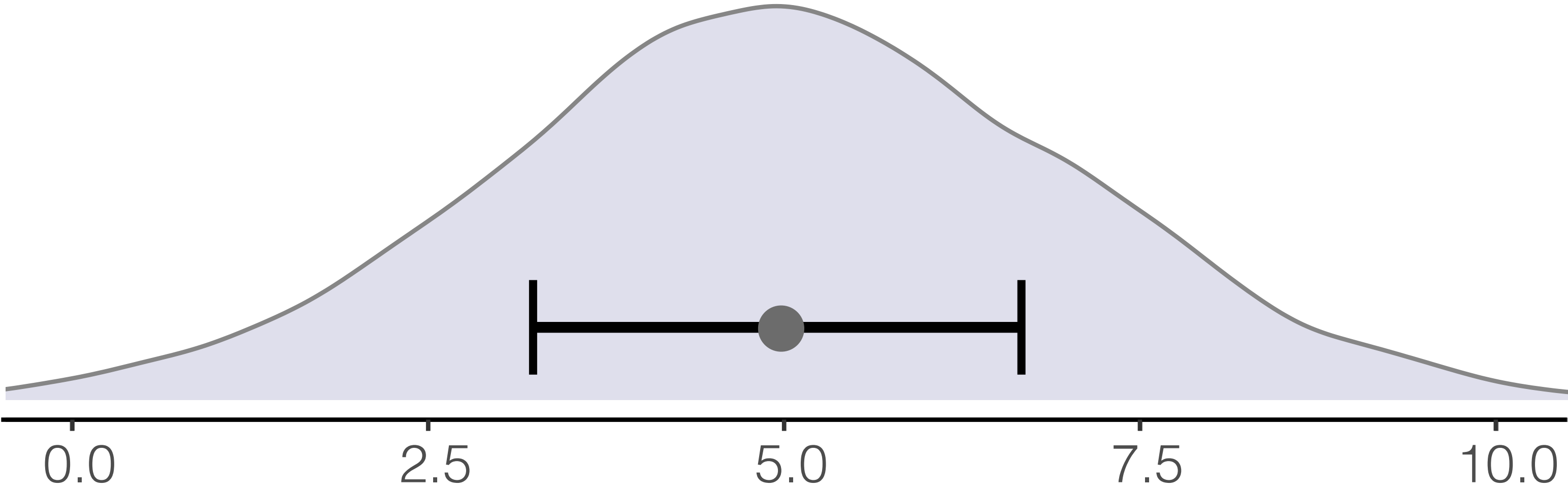
Intervals



Intervals

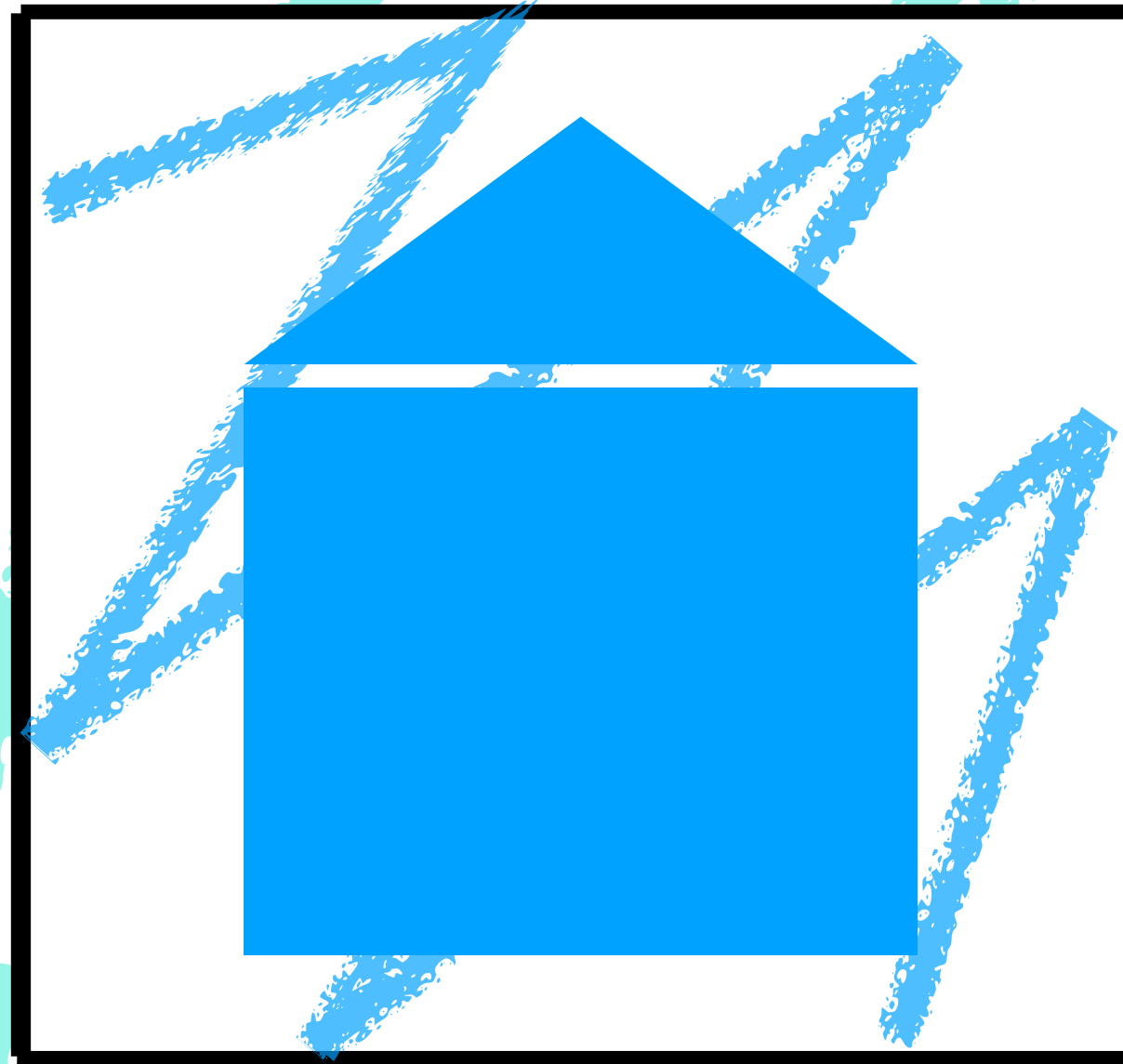


Intervals



Intervals create conceptual categories

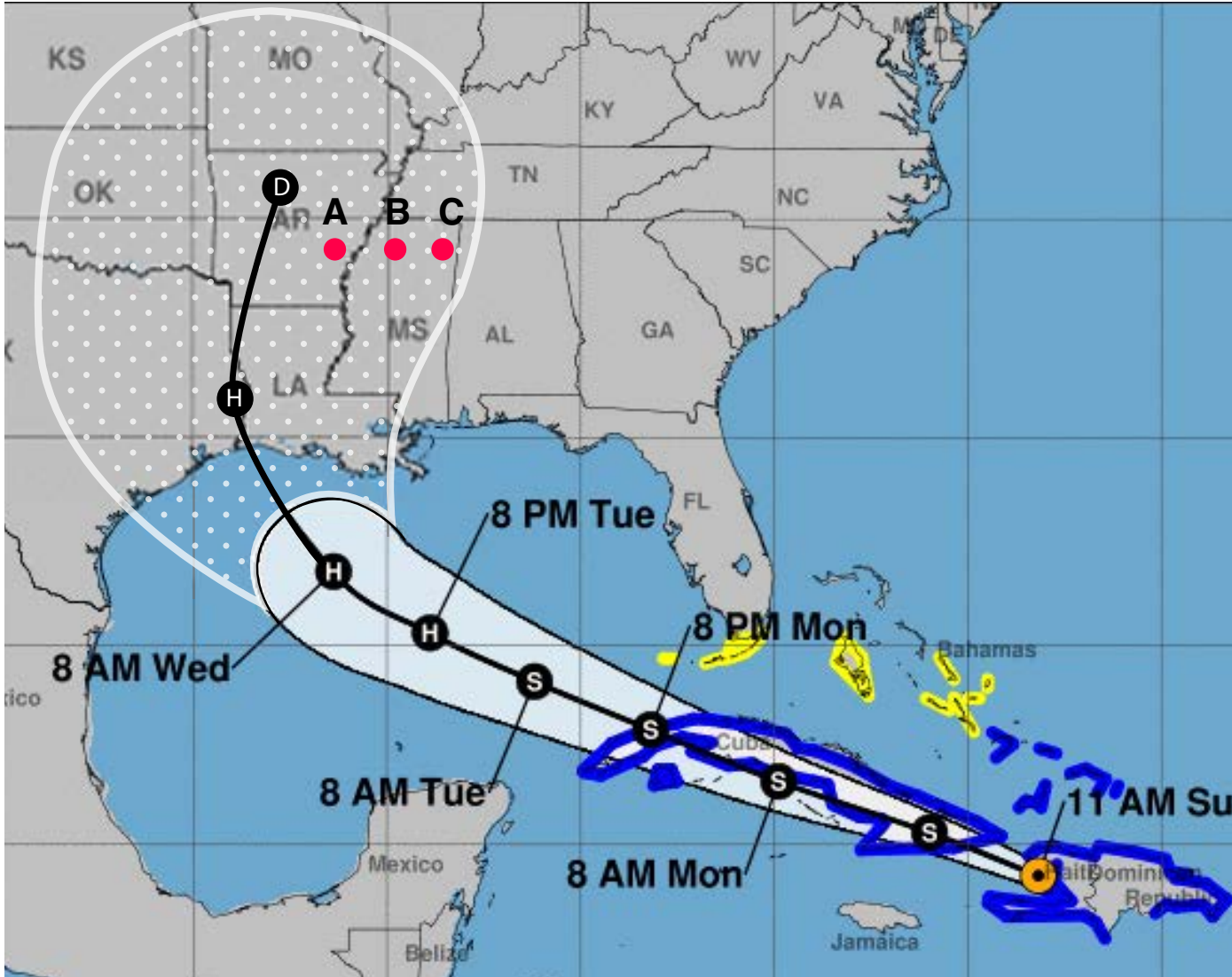
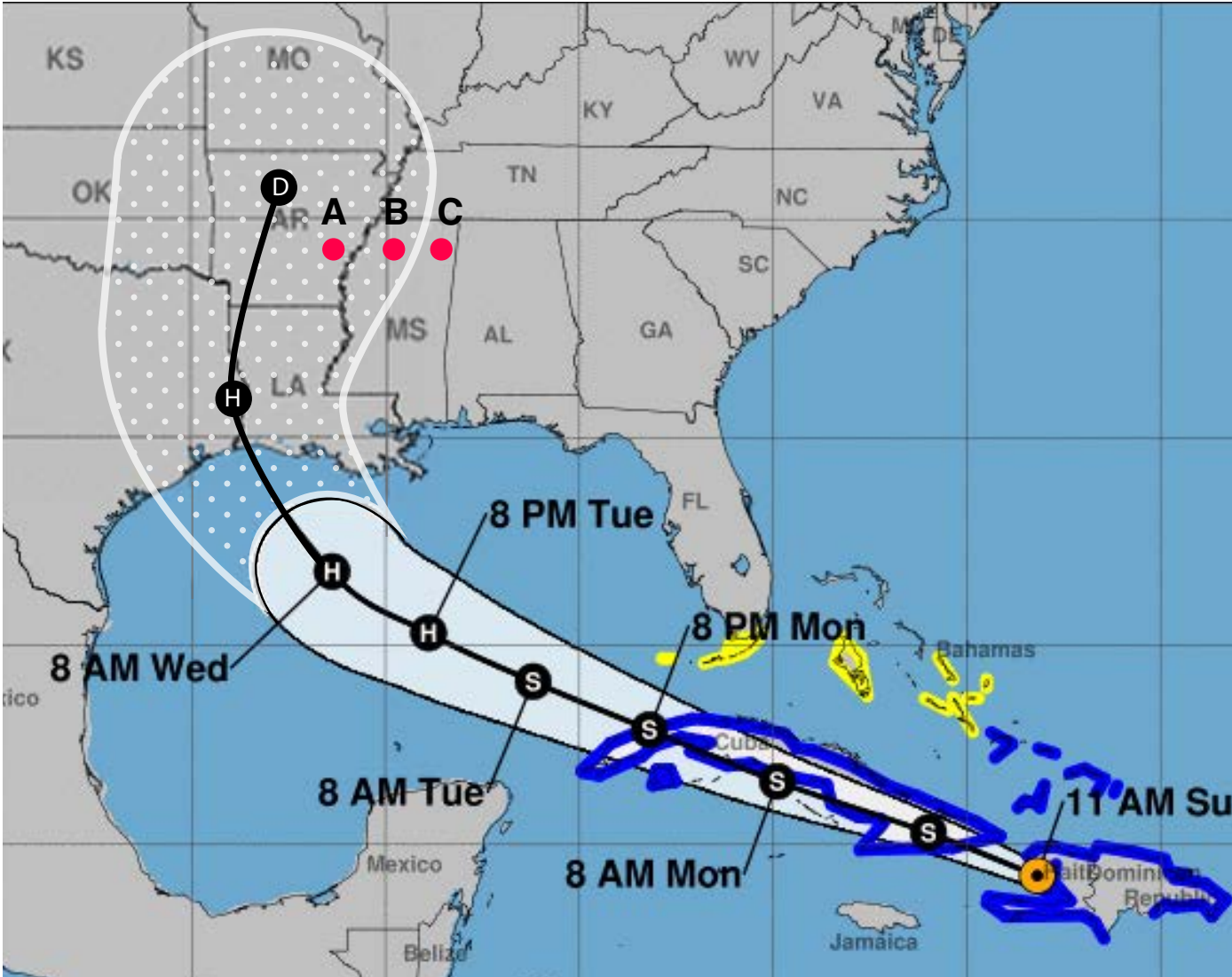
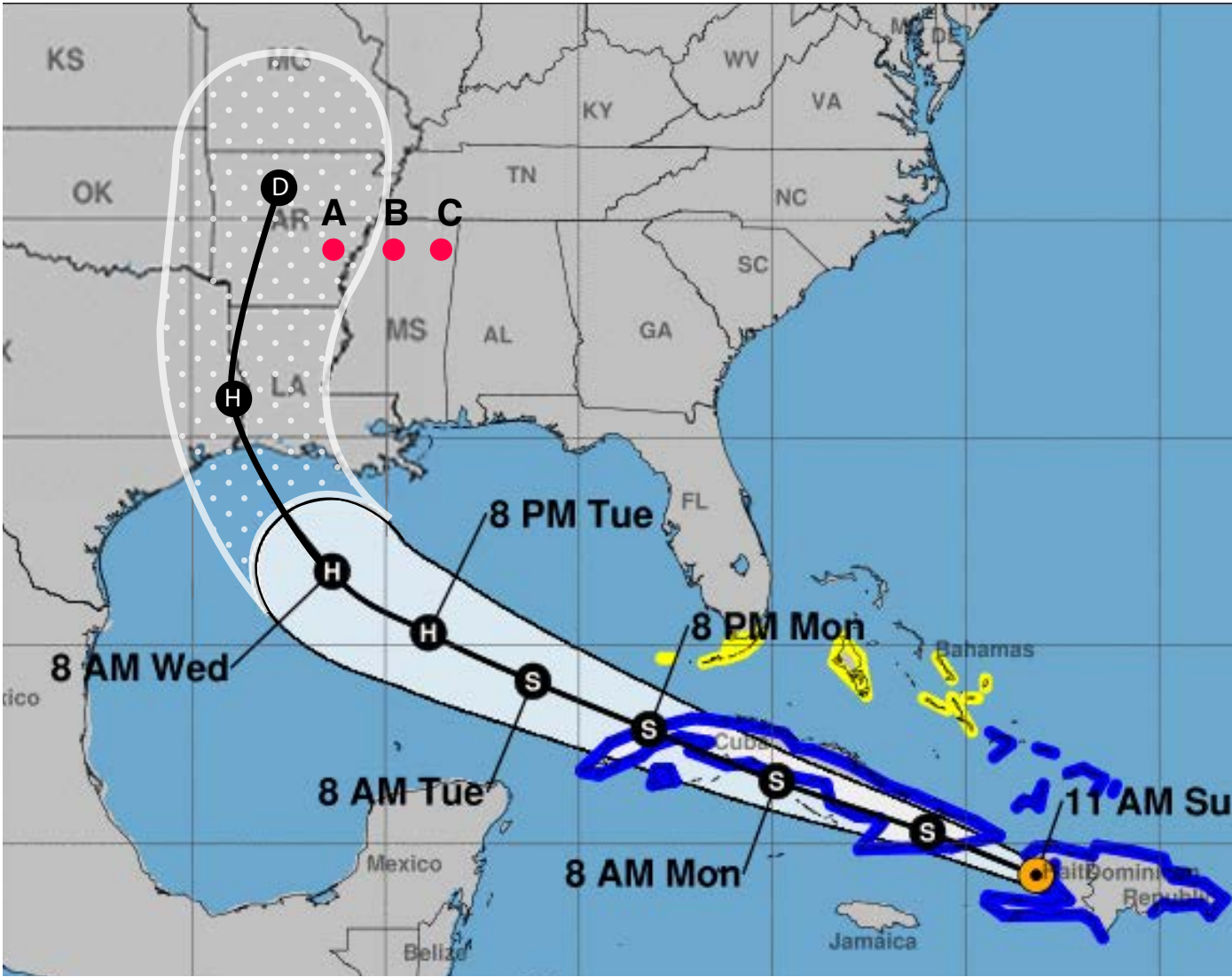
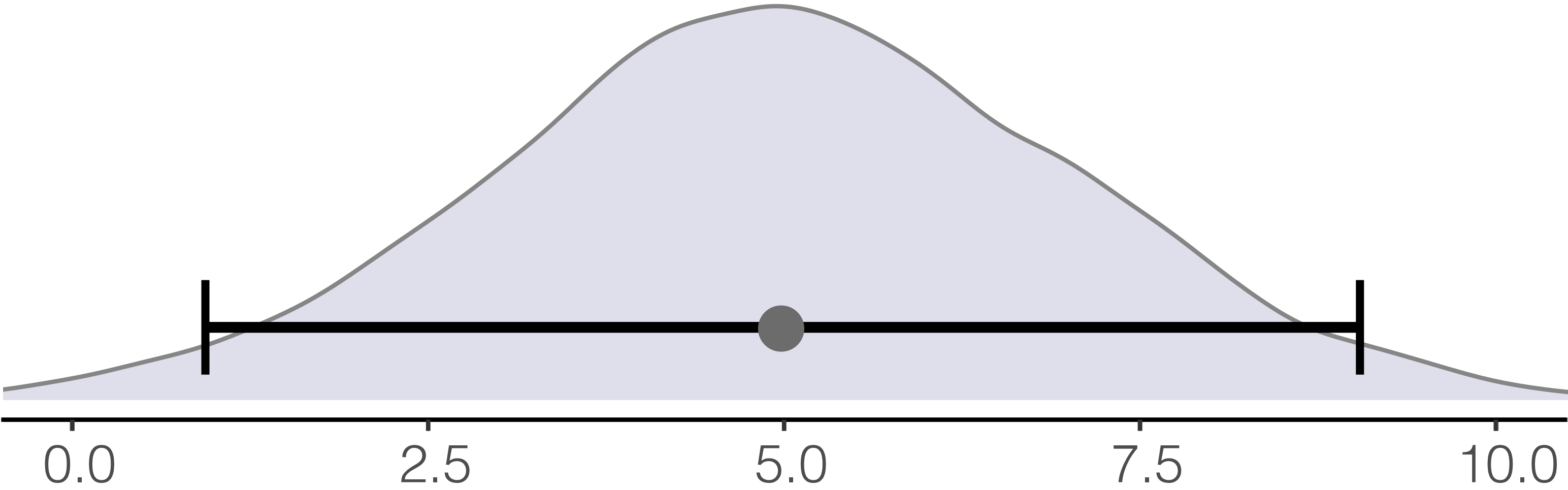
Intervals create conceptual categories



Framing a picture is a way
of saying that what is
inside the picture has a
different status from what
is outside the picture

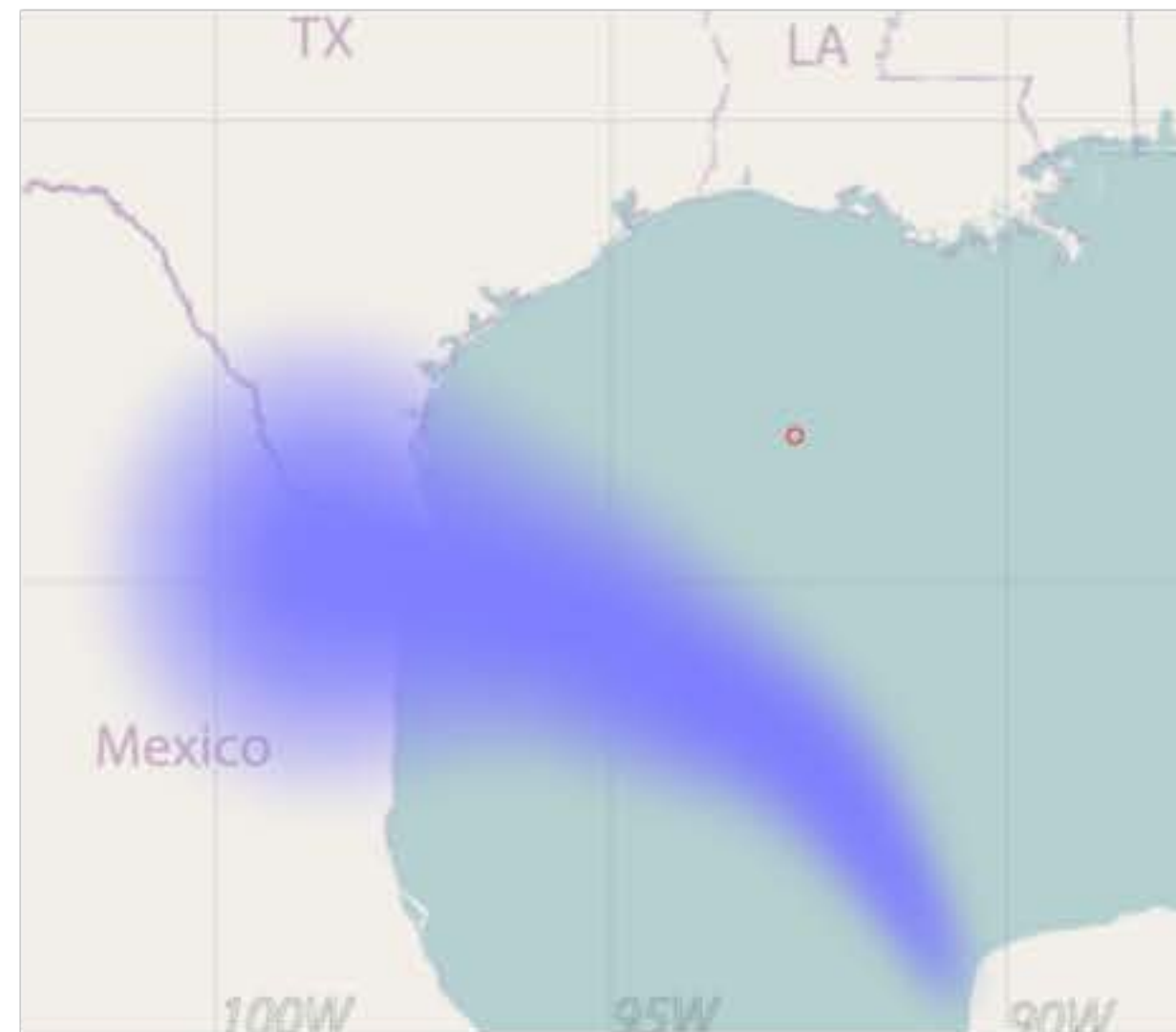
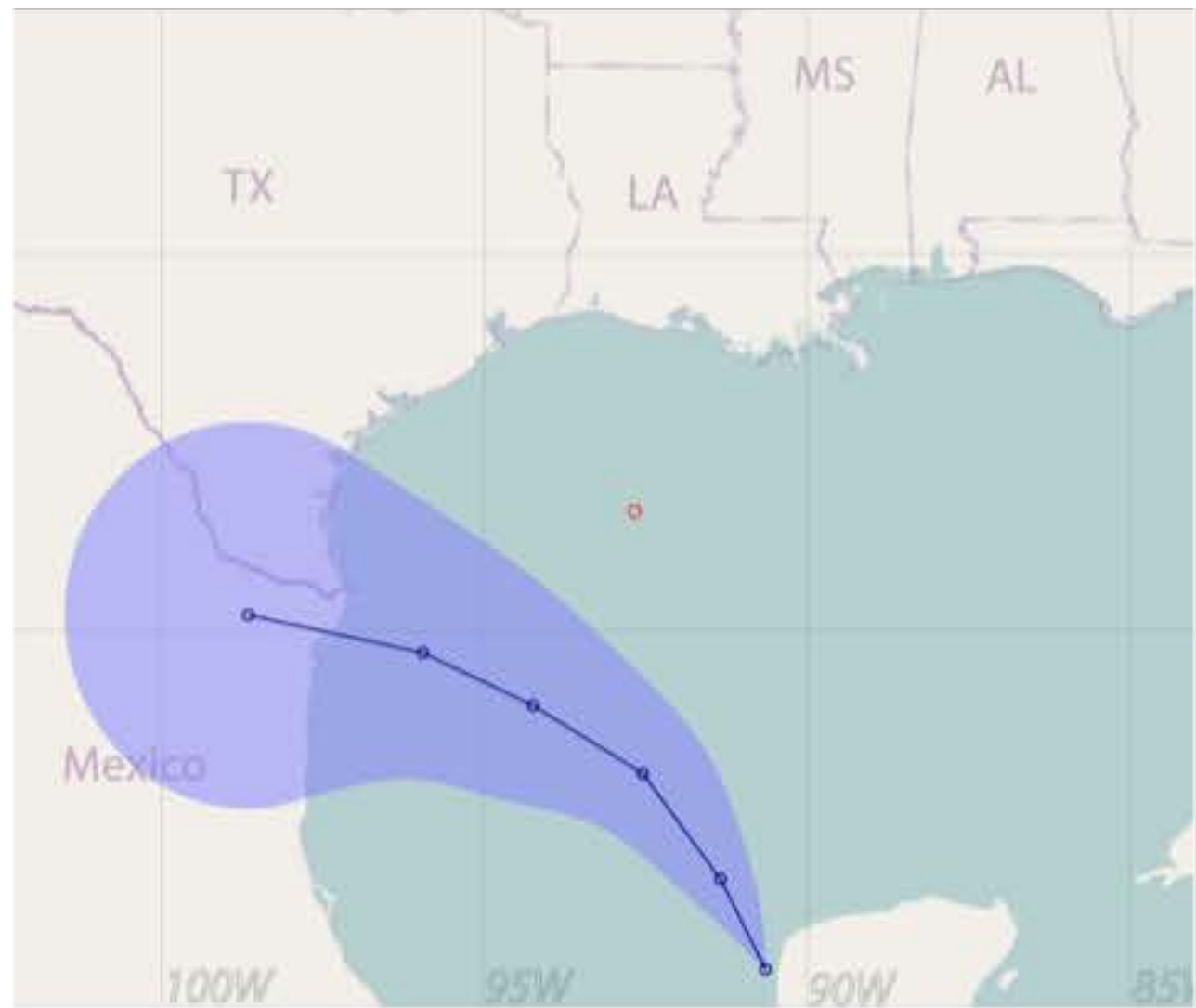
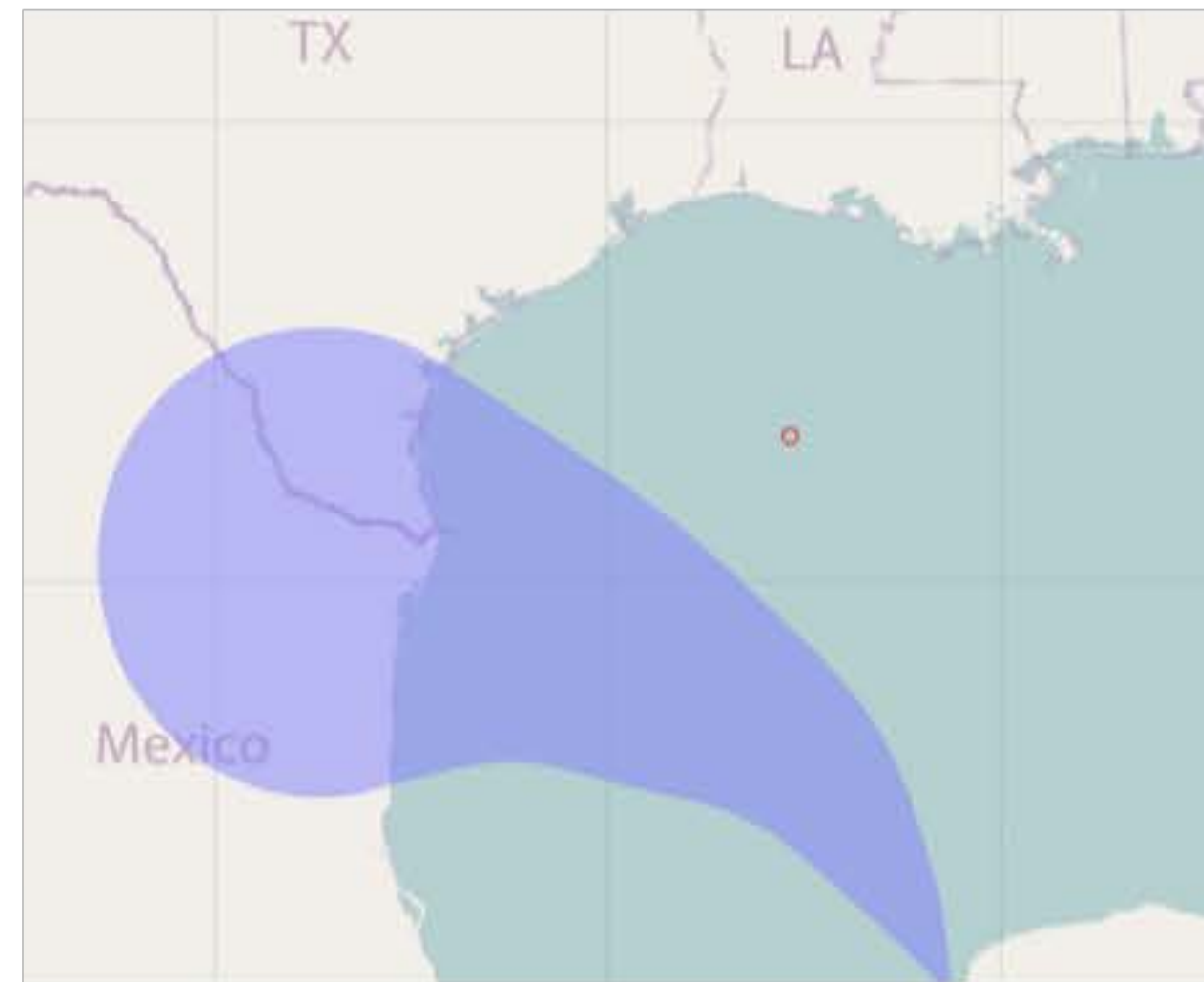
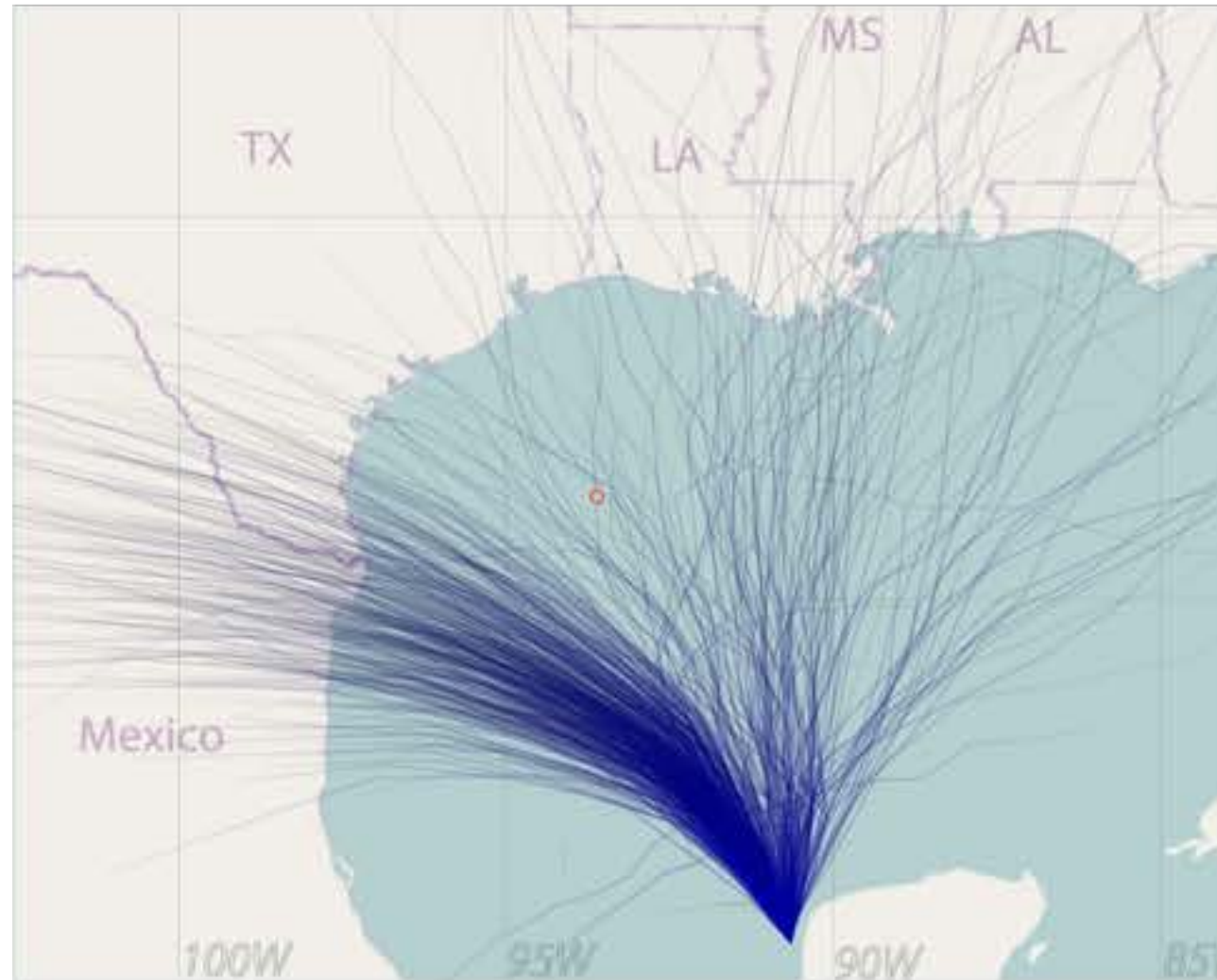
- Barbara Tversky (2011)

Intervals



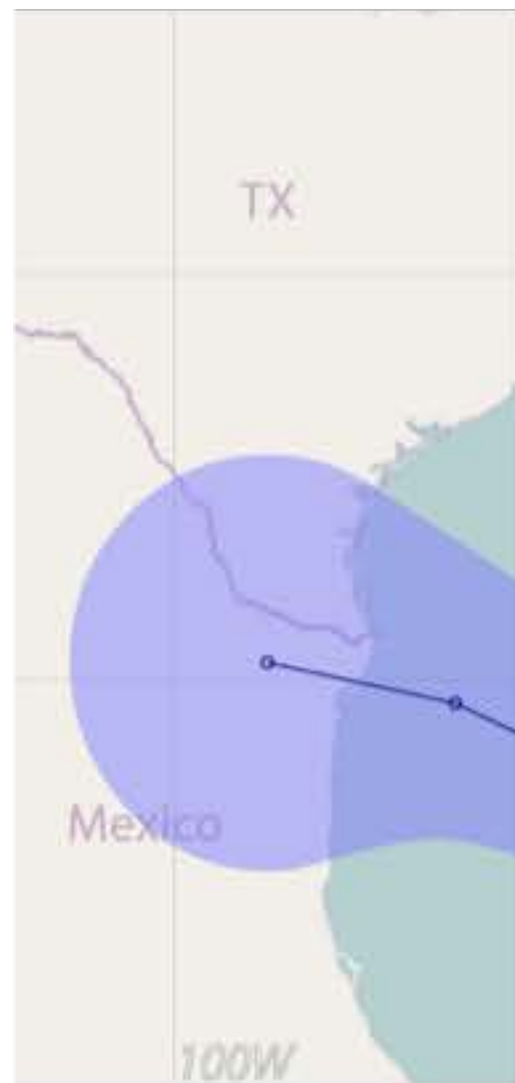
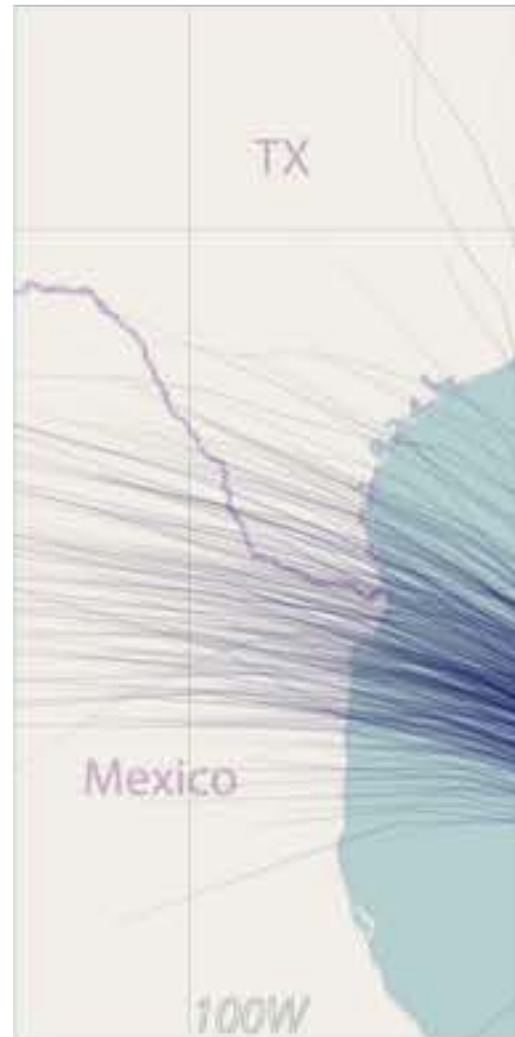
Non-expert interpretations of hurricane forecast uncertainty visualizations

Ian T. Ruginski, Alexander P. Boone, Lace M. Padilla, Le Liu, Nahal Heydari, Heidi S. Kramer, Mary Hegarty, William B. Thompson, Donald H. House & Sarah H. Creem-Regehr



Non-expert interpretations of hurricane forecast uncertainty visualizations

Ian T. Rugin
Heidi S. Kra
Sarah H. Cr

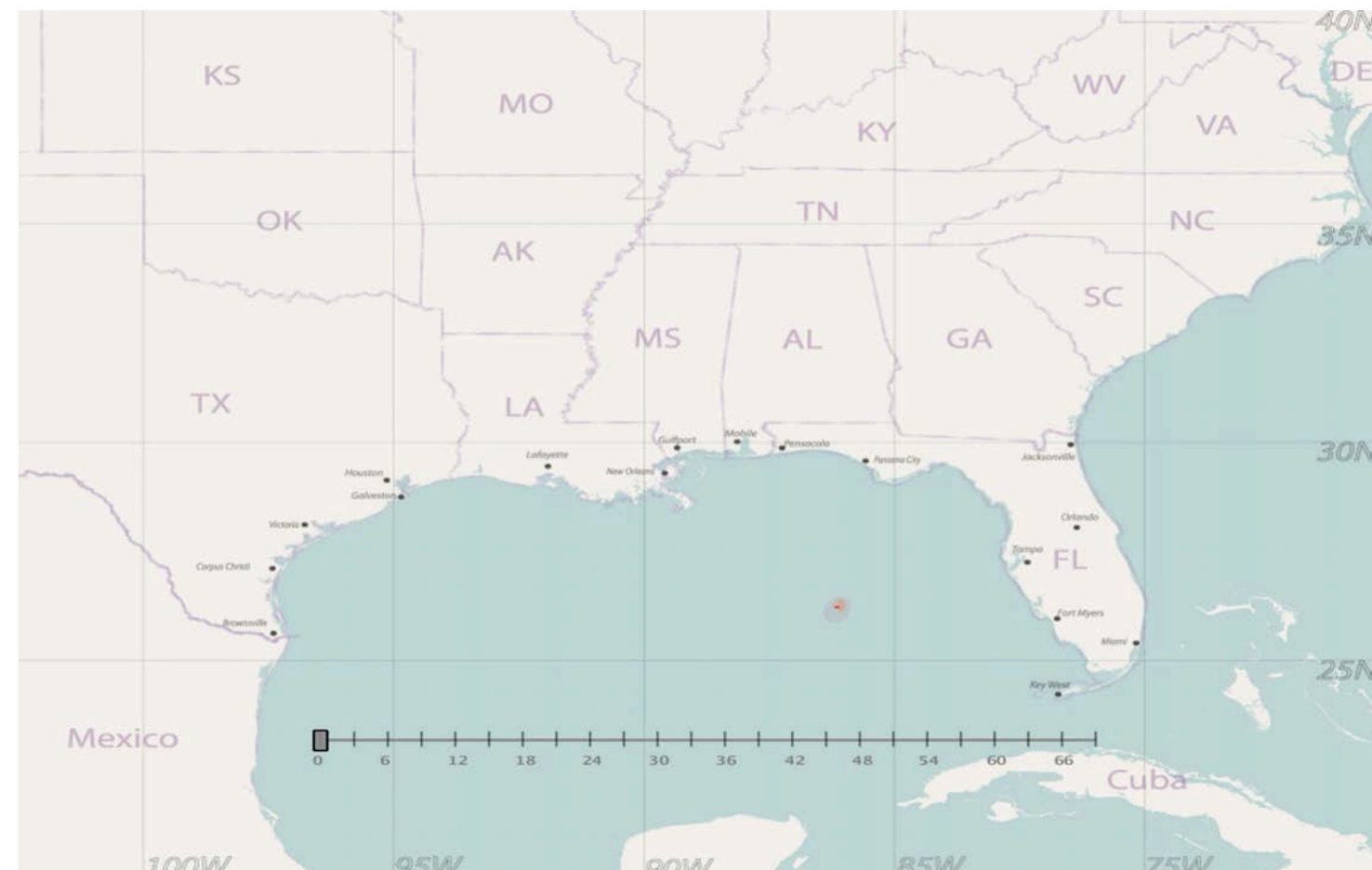


IEEE TRANSACTIONS ON VISUALIZATION AND COMPUTER GRAPHICS, VOL. 23, NO. 9, SEPTEMBER 2017

2165

Uncertainty Visualization by Representative Sampling from Prediction Ensembles

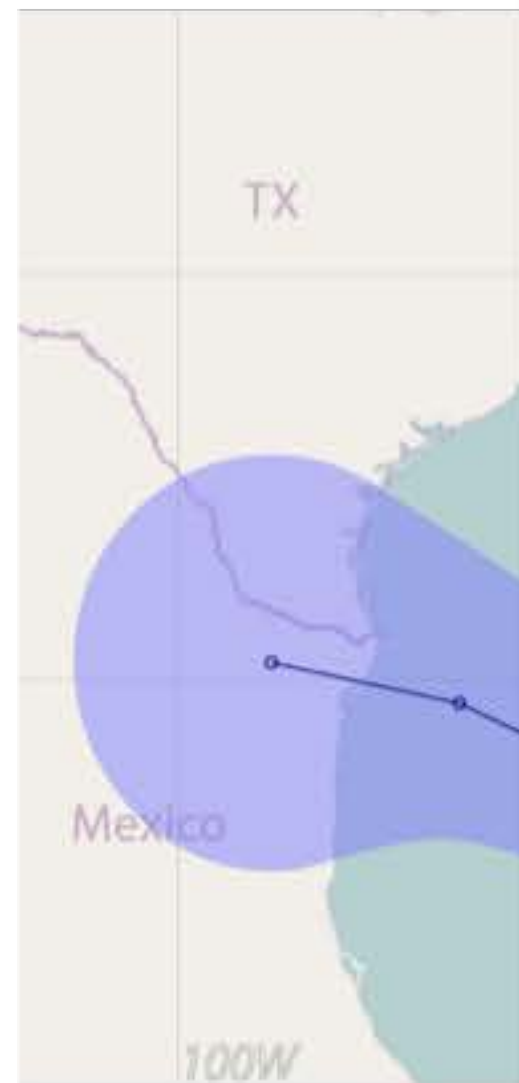
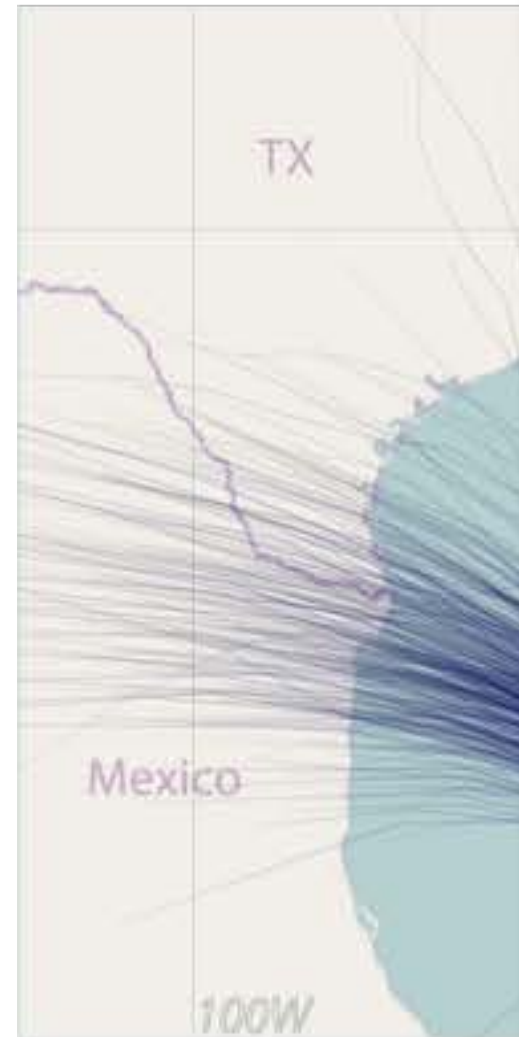
Le Liu, *Student Member, IEEE*, Alexander P. Boone, Ian T. Ruginski, Lace Padilla, Mary Hegarty, Sarah H. Creem-Regehr, William B. Thompson, Cem Yuksel, and Donald H. House, *Member, IEEE*



Hurricane Icon Visualization

Non-expert interpretations of hurricane forecast uncertainty visualizations

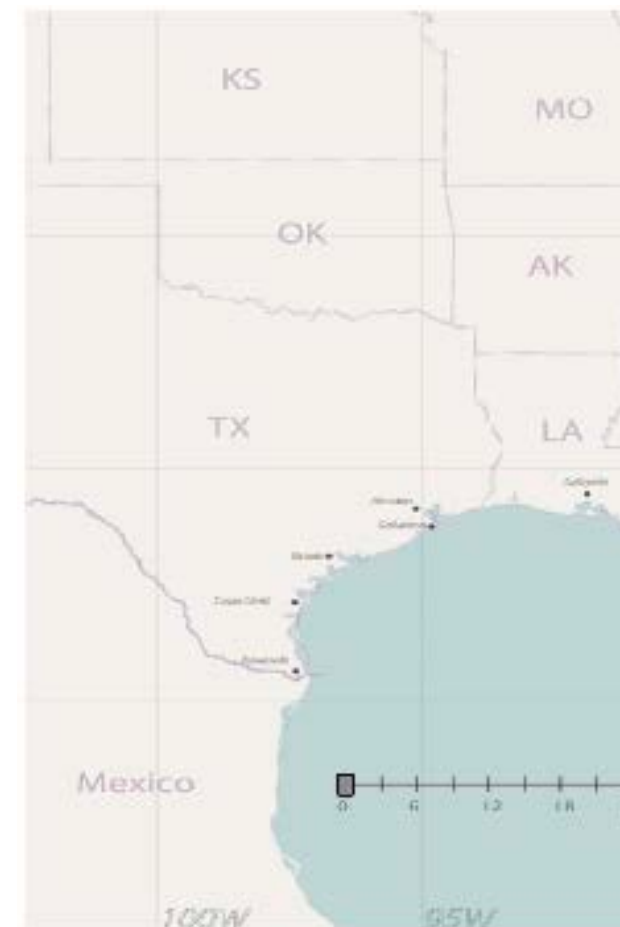
Ian T. Rugin
Heidi S. Kra
Sarah H. Cr



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Uncer Sa

Le Liu, Student
Sarah H. Creer



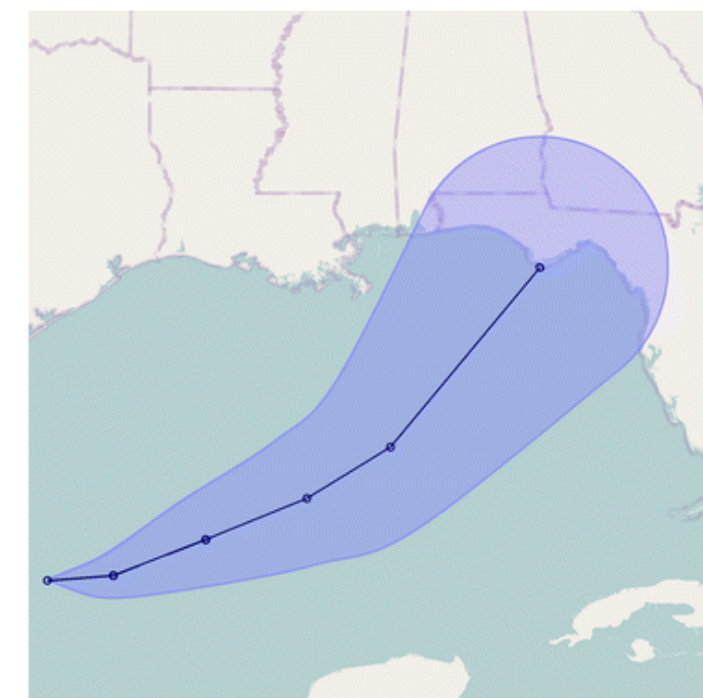
ORIGINAL ARTICLE | OPEN ACCESS

Effects of ensemble and summary displays on interpretations of geospatial uncertainty data

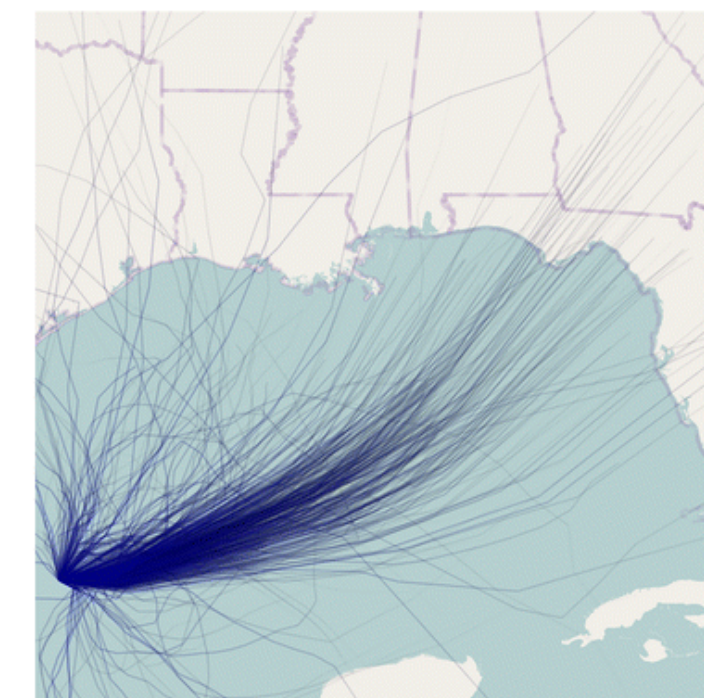
Lace M. Padilla ✉, Ian T. Ruginski and Sarah H. Creem-Regehr

Cognitive Research: Principles and Implications 2017 2:40 | <https://doi.org/10.1186/s41235-017-0076-1> | © The Author(s) 2017

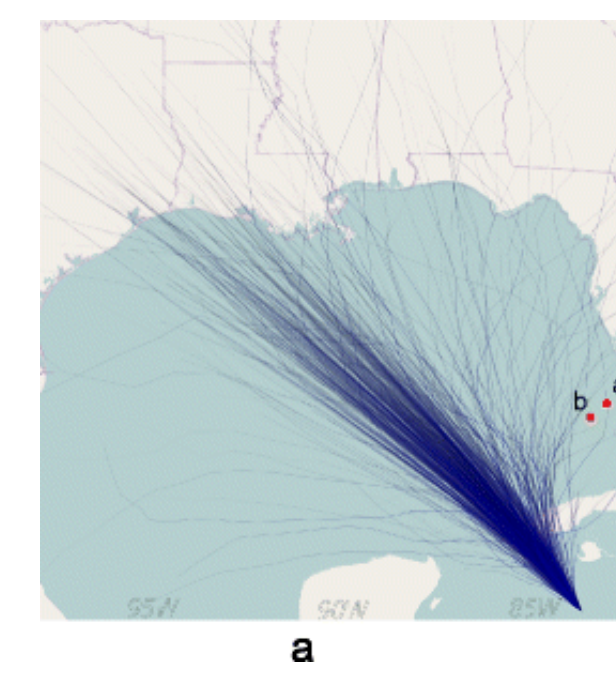
Received: 26 January 2017 | Accepted: 30 August 2017 | Published: 4 October 2017



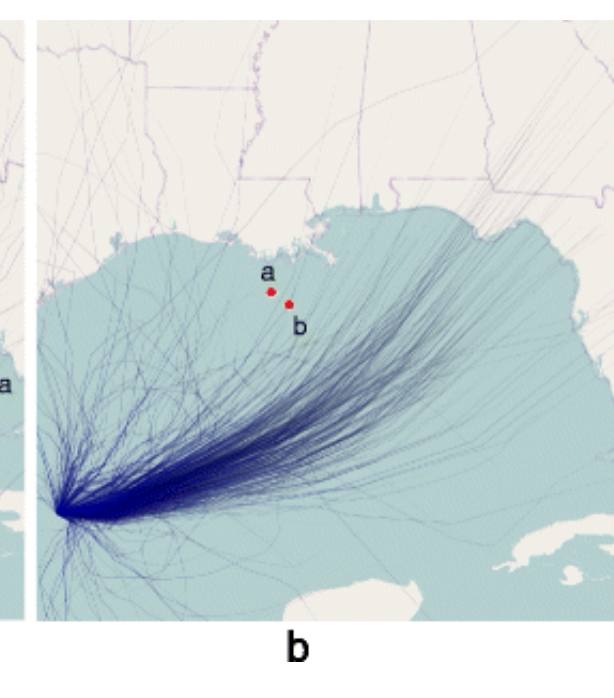
a



b



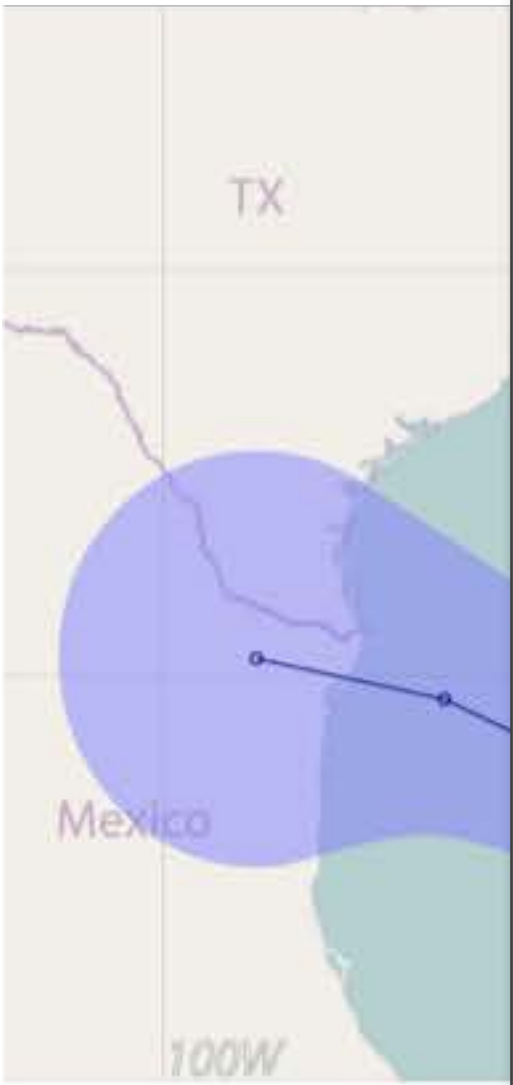
a



b

Non-expert interpretations of hurricane forecast uncertainty visualizations

Ian T. Rugin
Heidi S. Kra
Sarah H. Cr



IEEE TRANSACTIONS ON VISUALIZATION AND COMPUTER-BASED INFORMATION, VOL. 22, NO. 9, SEPTEMBER 2012

Uncer Sa

Le Liu, Student
Sarah H. Creer



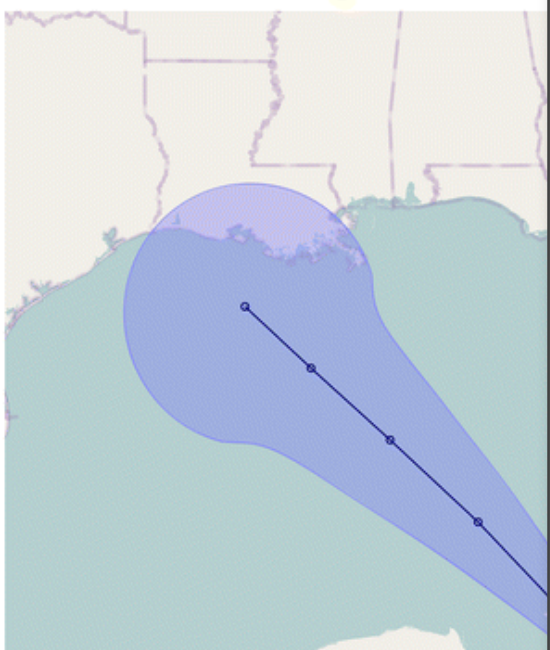
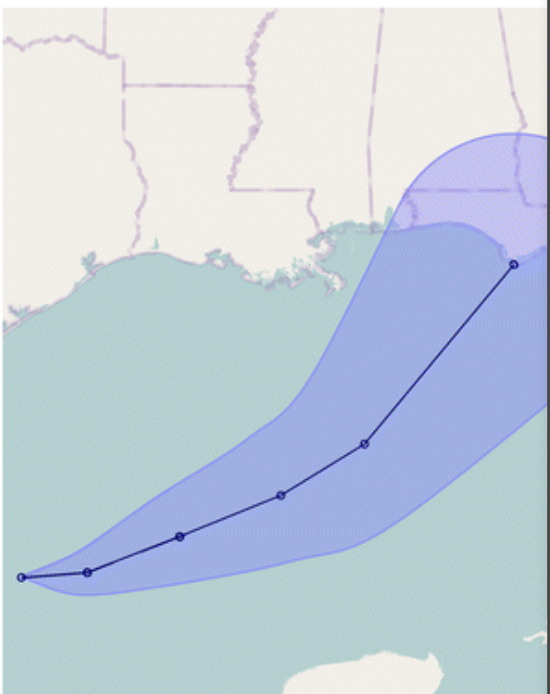
ORIGINAL ARTICLE

Effects of en geospatial u

Lace M. Padilla, Ian T

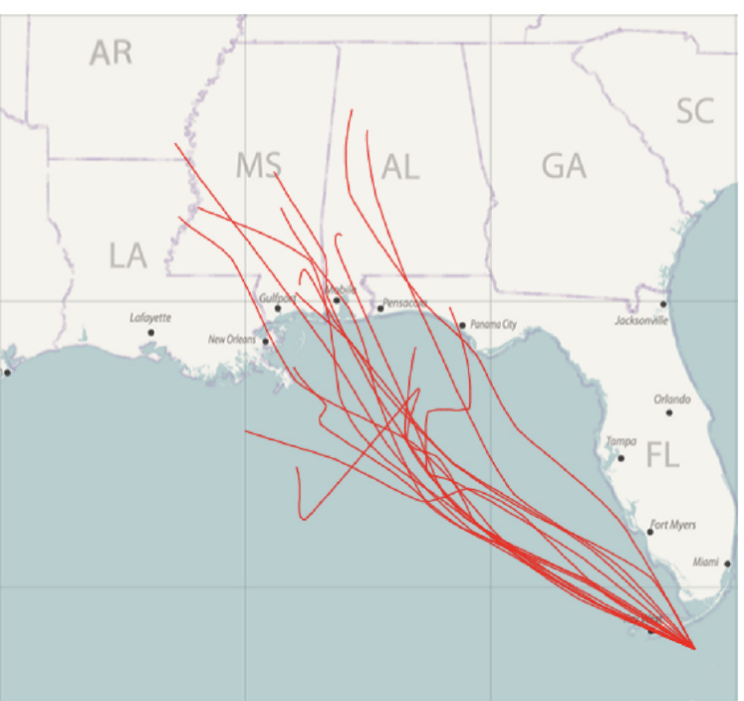
Cognitive Research: Princ

Received: 26 January 201

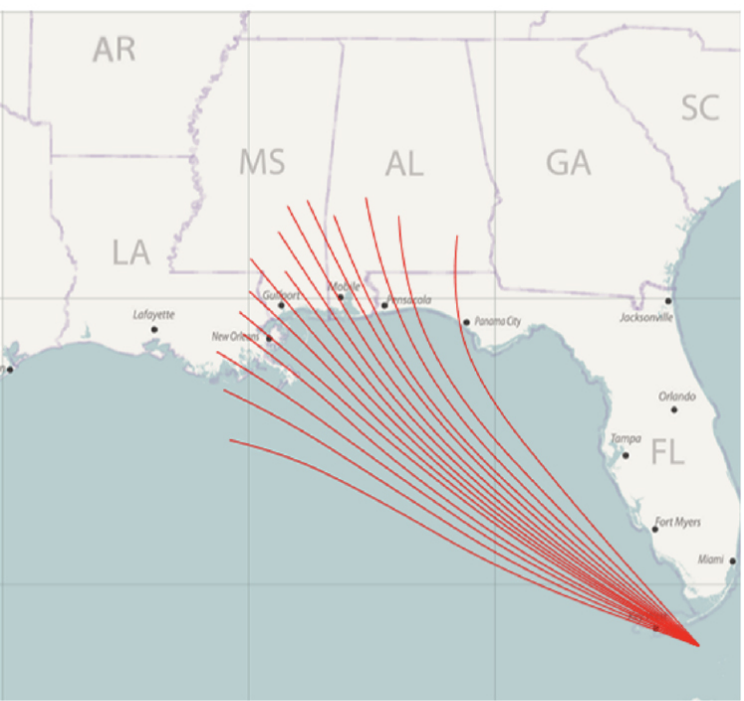


Visualizing Uncertain Tropical Cyclone Predictions using Representative Samples from Ensembles of Forecast Tracks

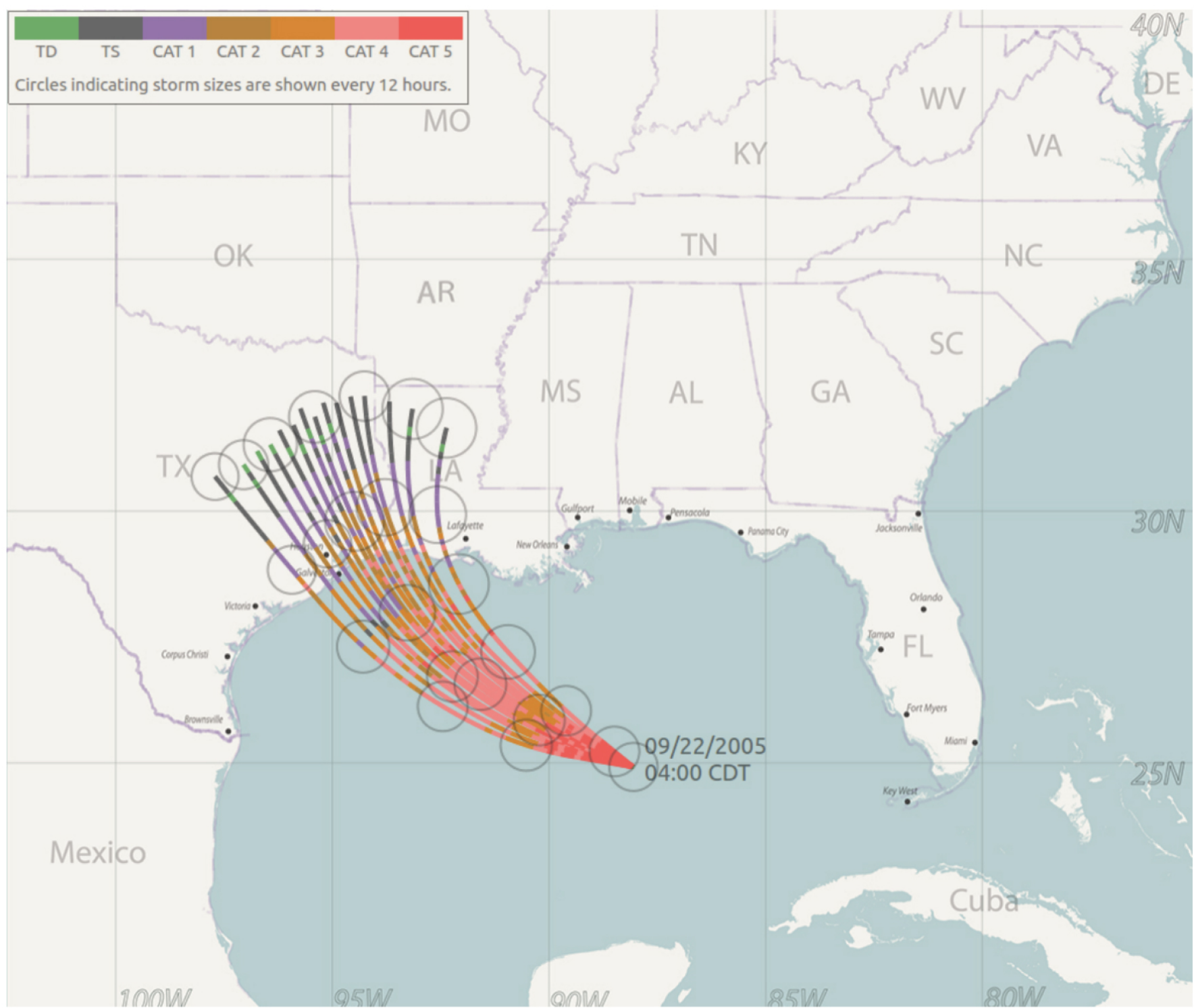
Le Liu, *Member, IEEE*, Lace Padilla, Sarah H. Creem-Regehr, and Donald H. House, *Member, IEEE Computer Society*



(a) randomly selected paths



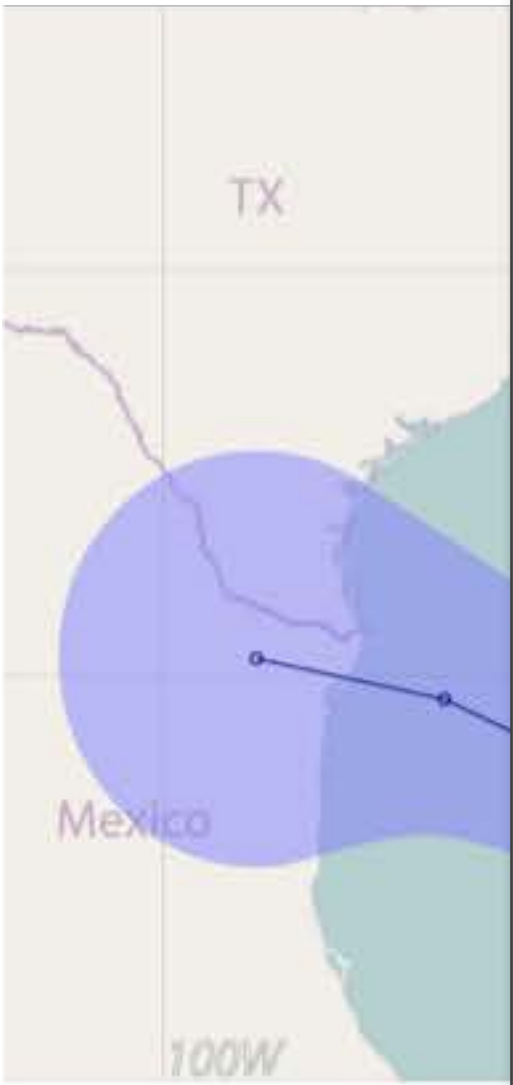
(b) reconstruction of paths



(c) path, size, and category data for Hurricane Rita. 4AM CDT. 09/22/2005, advisory 17

Non-expert interpretations of hurricane forecast uncertainty visualizations

Ian T. Rugin
Heidi S. Kra
Sarah H. Cr



IEEE TRANSACTIONS ON VISUALIZATION AND COMPUTER-BASED INFORMATION, VOL. 22, NO. 9, SEPTEMBER 2012

Uncer Sa

Le Liu, *Student*
Sarah H. Creer

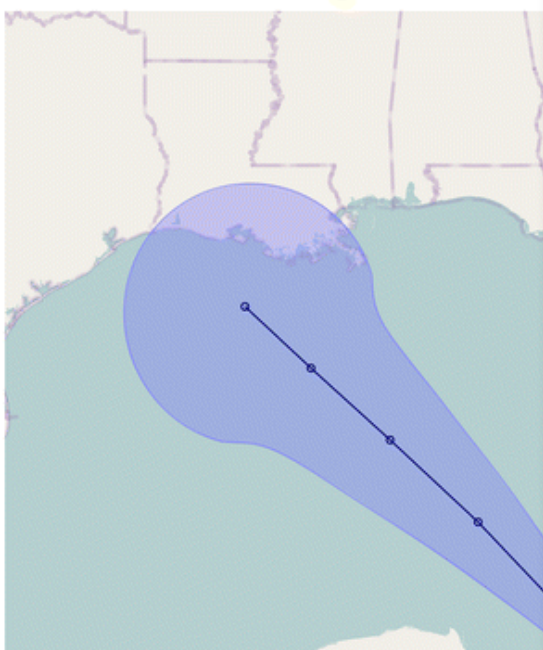
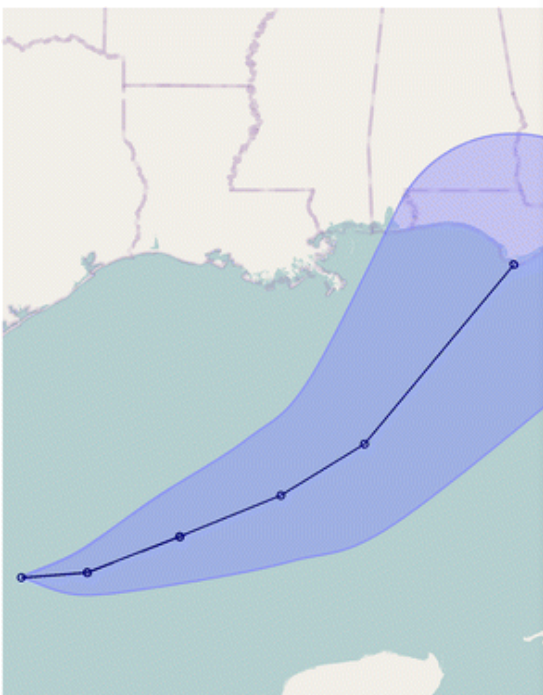


ORIGINAL ARTICLE

Effects of en geospatial u

Lace M. Padilla ✉, Ian T

Cognitive Research: Princ
Received: 26 January 201

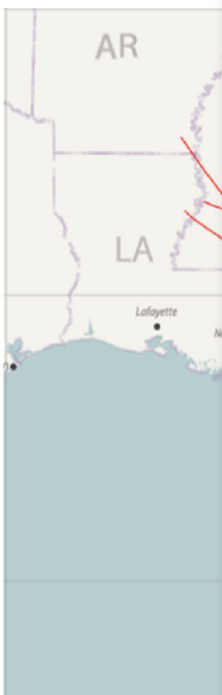


Visualizing Uncertain Tropical Cyclone Predictions using Representative Samples from Ensembles of Forecast Tracks

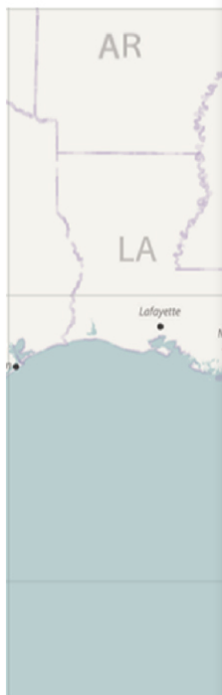
JEP: Applied

The Powerful Influence of Marks: Visual and Knowledge-Driven Processing in Hurricane Track Displays

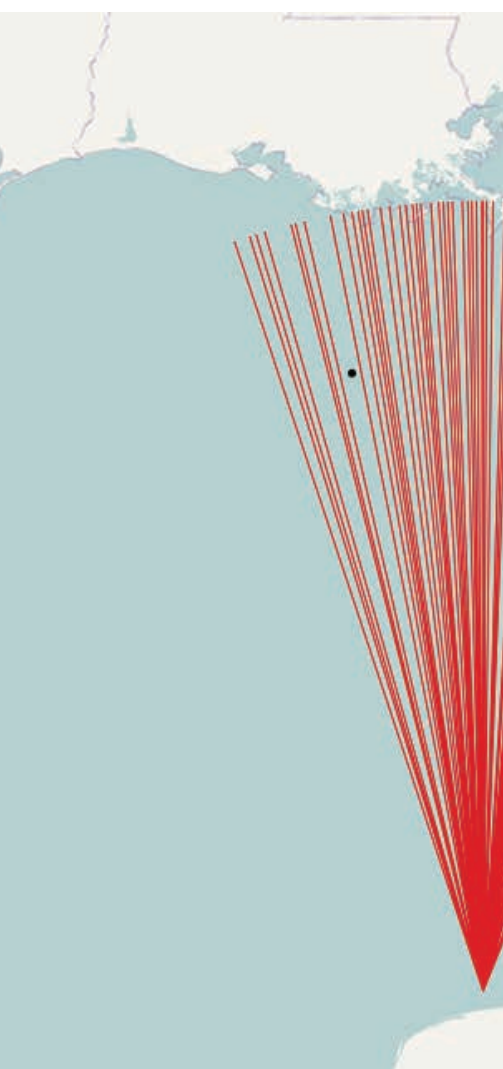
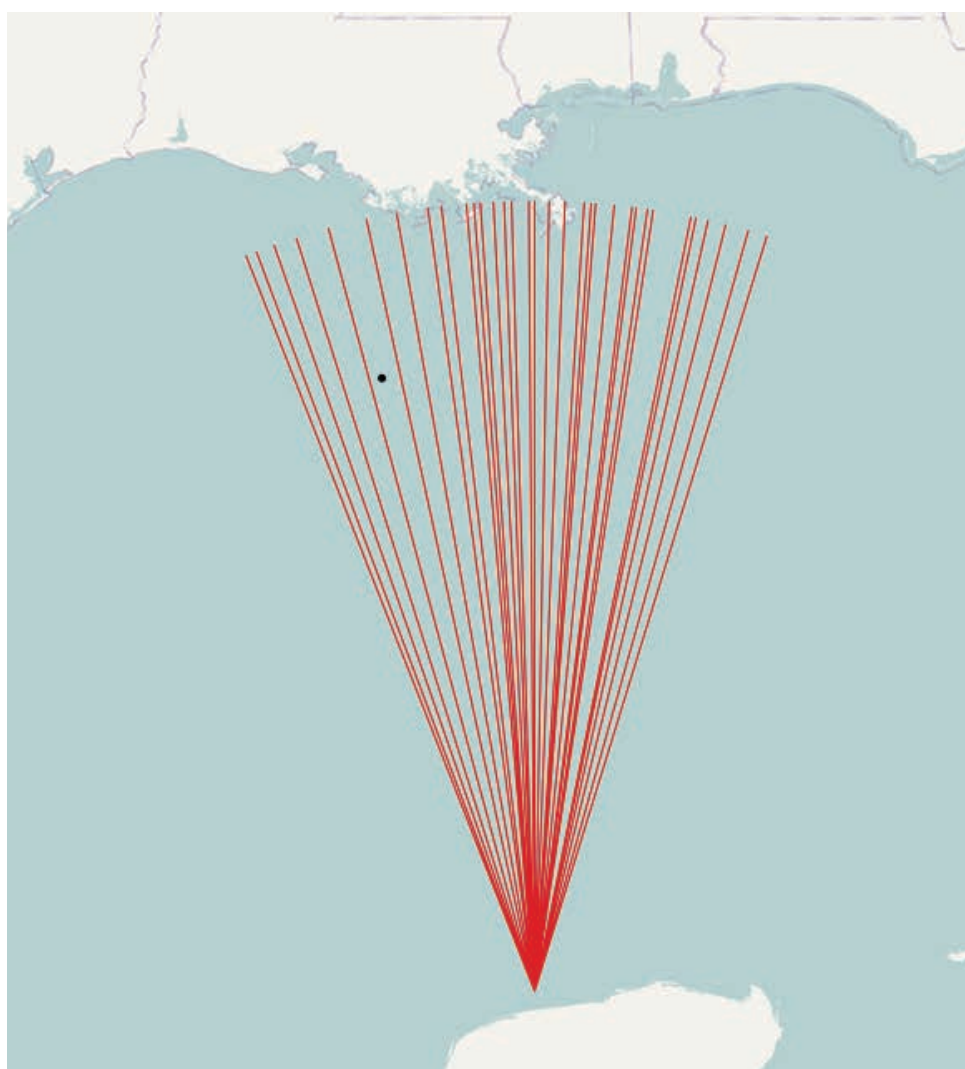
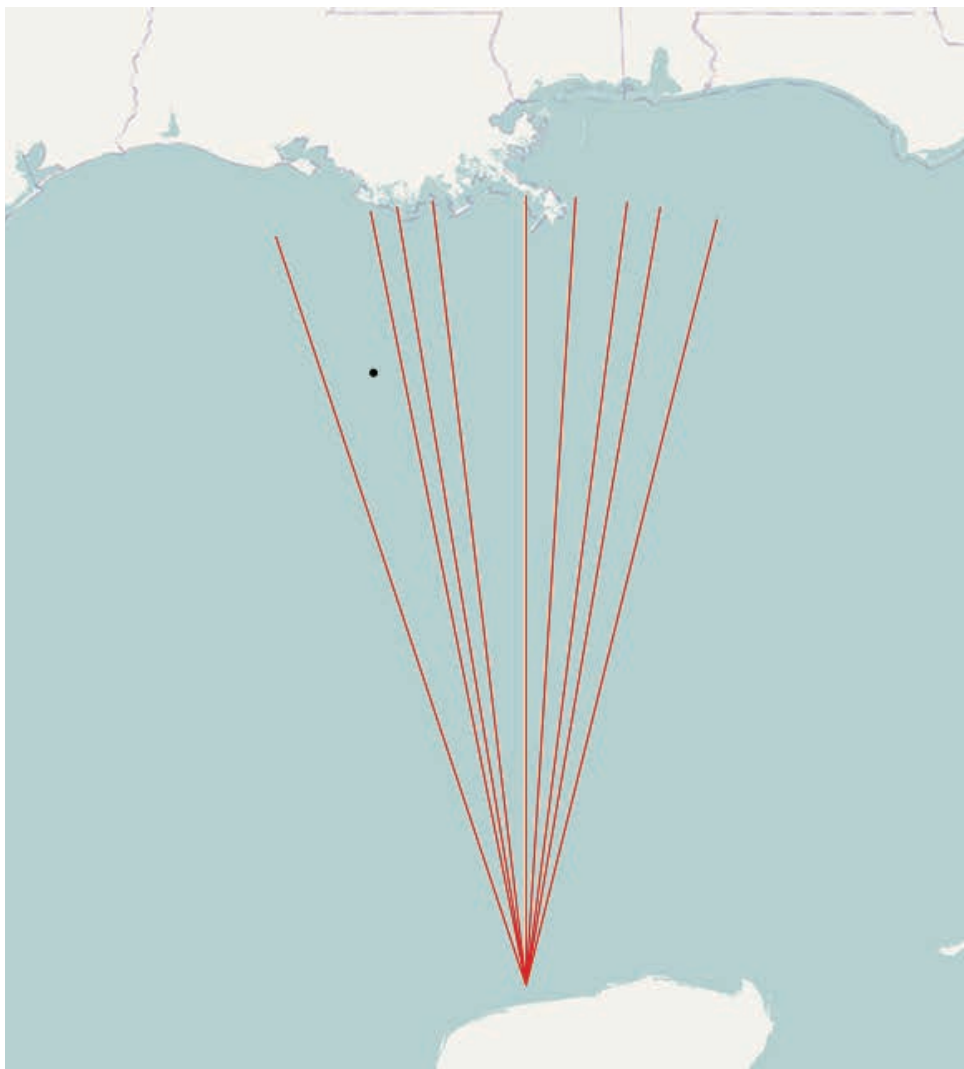
Lace M. Padilla, Sarah H. Creem-Regehr, and William Thompson



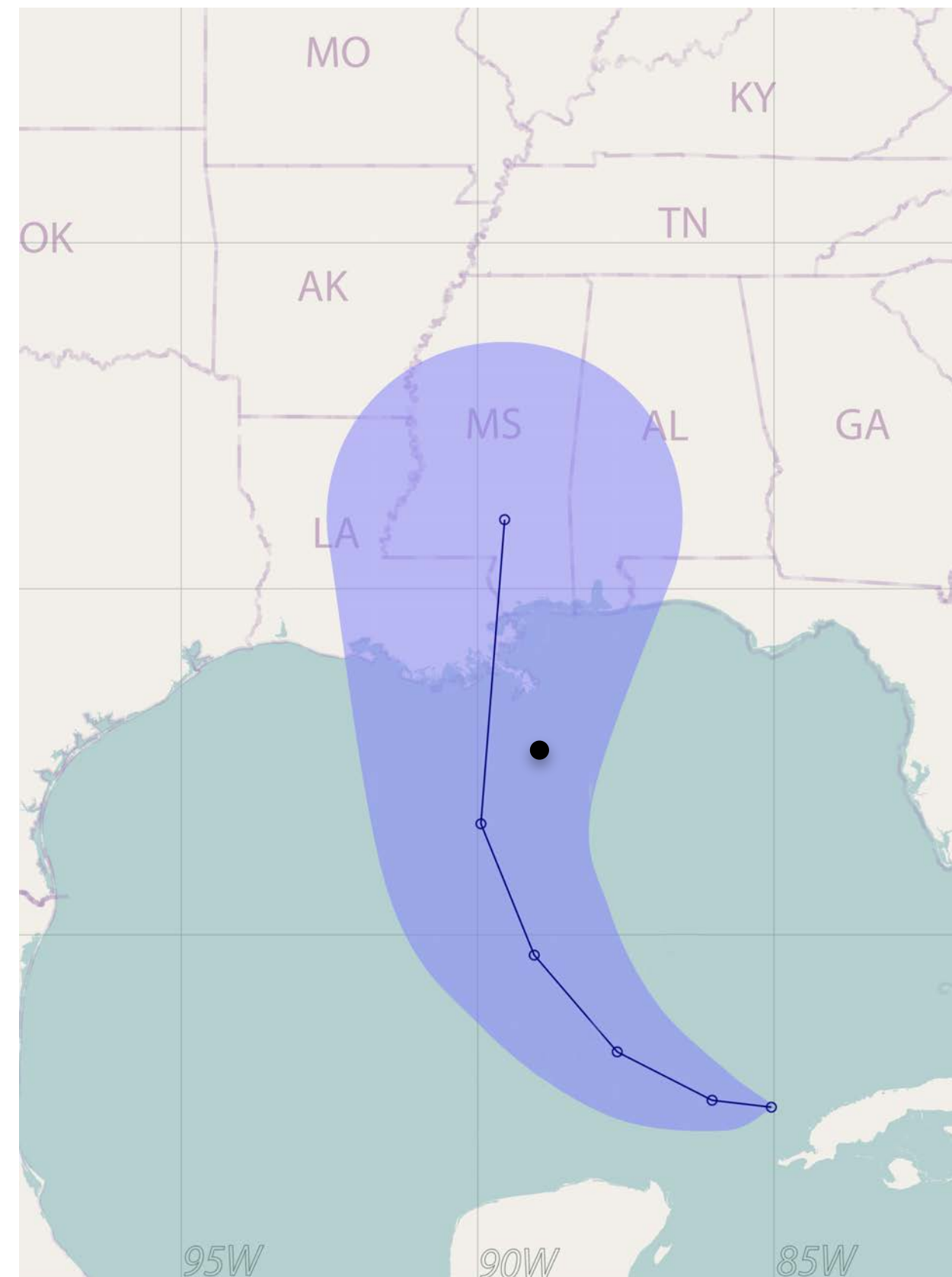
(a) ran



(b) rec



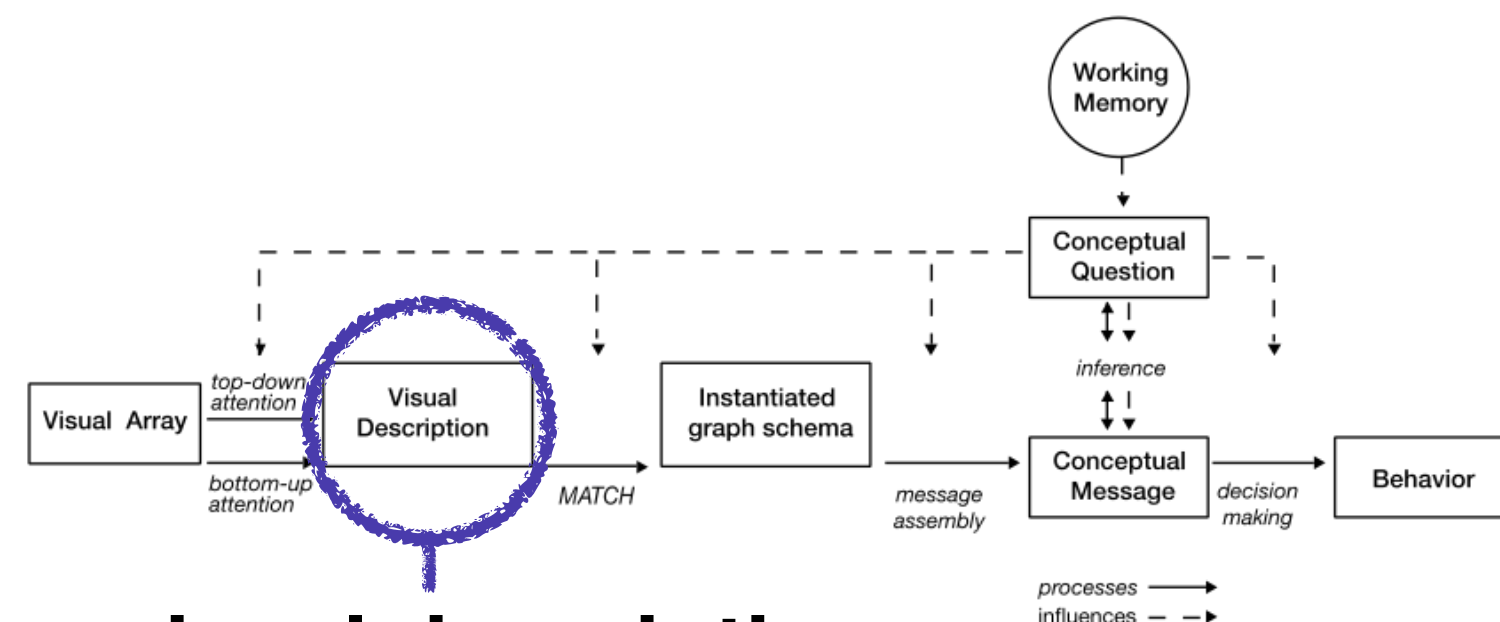
Behavioral Measures (probability judgments)



1 2 3 4 5 6 7
(no damage) (severe damage)

Behavioral Measures (probability judgments)

200 students at the
University of Utah and
UC Santa Barbara w/
minimal description
of the visualization

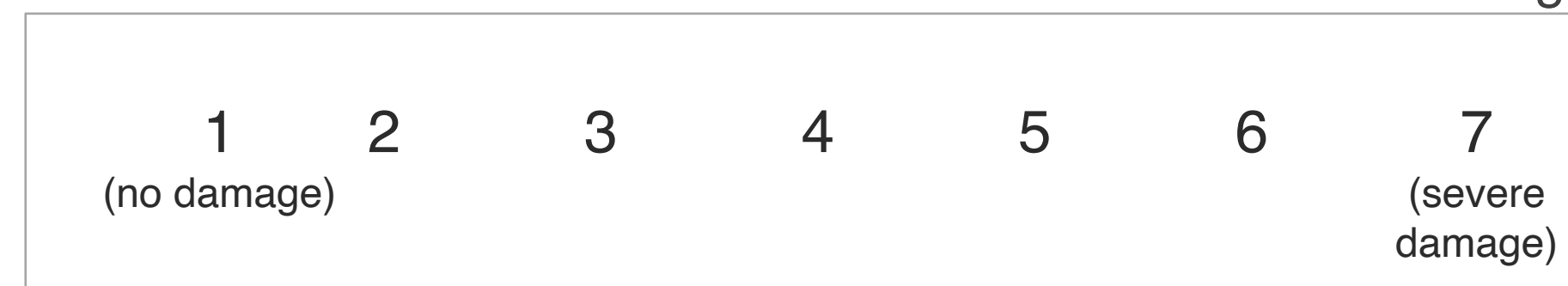


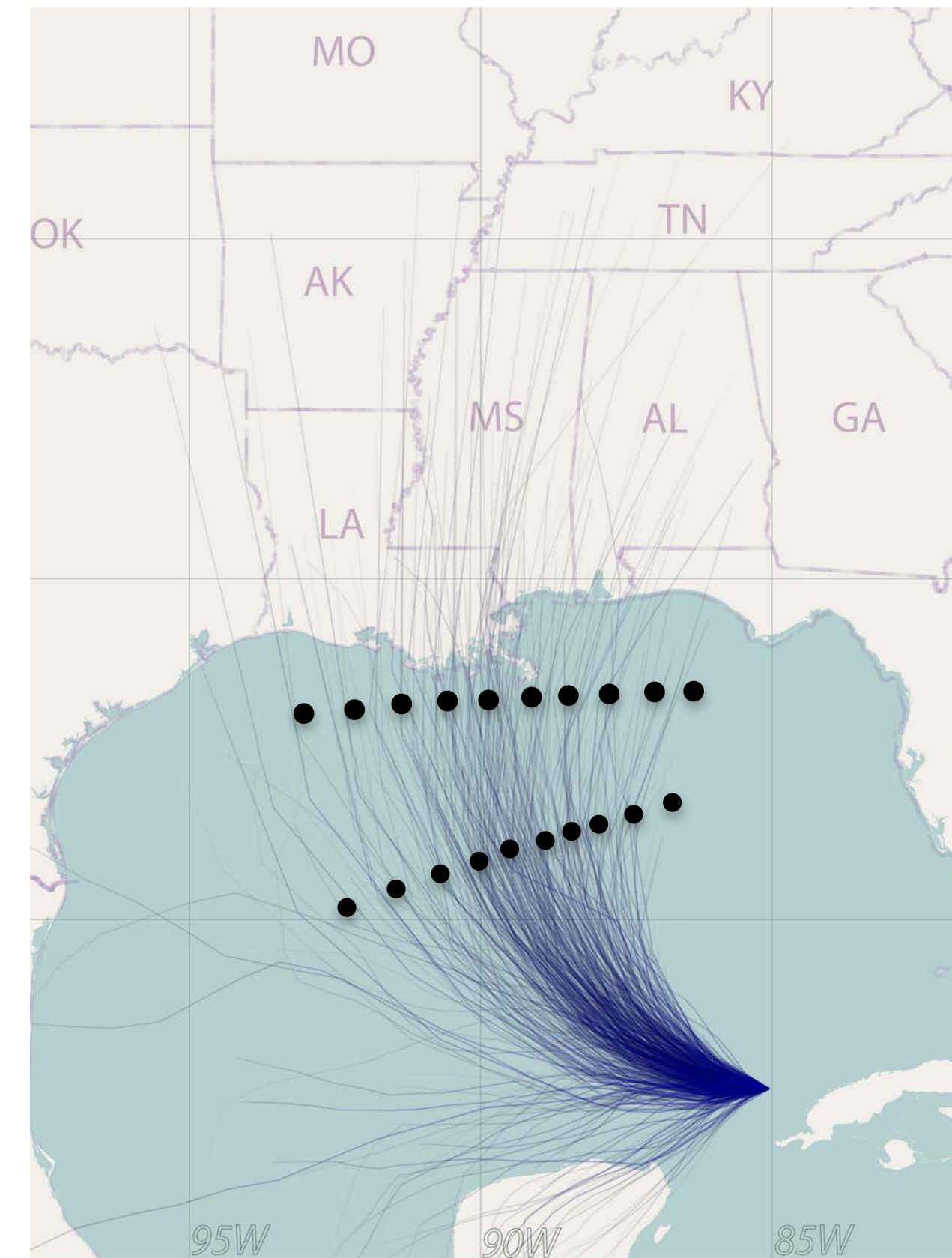
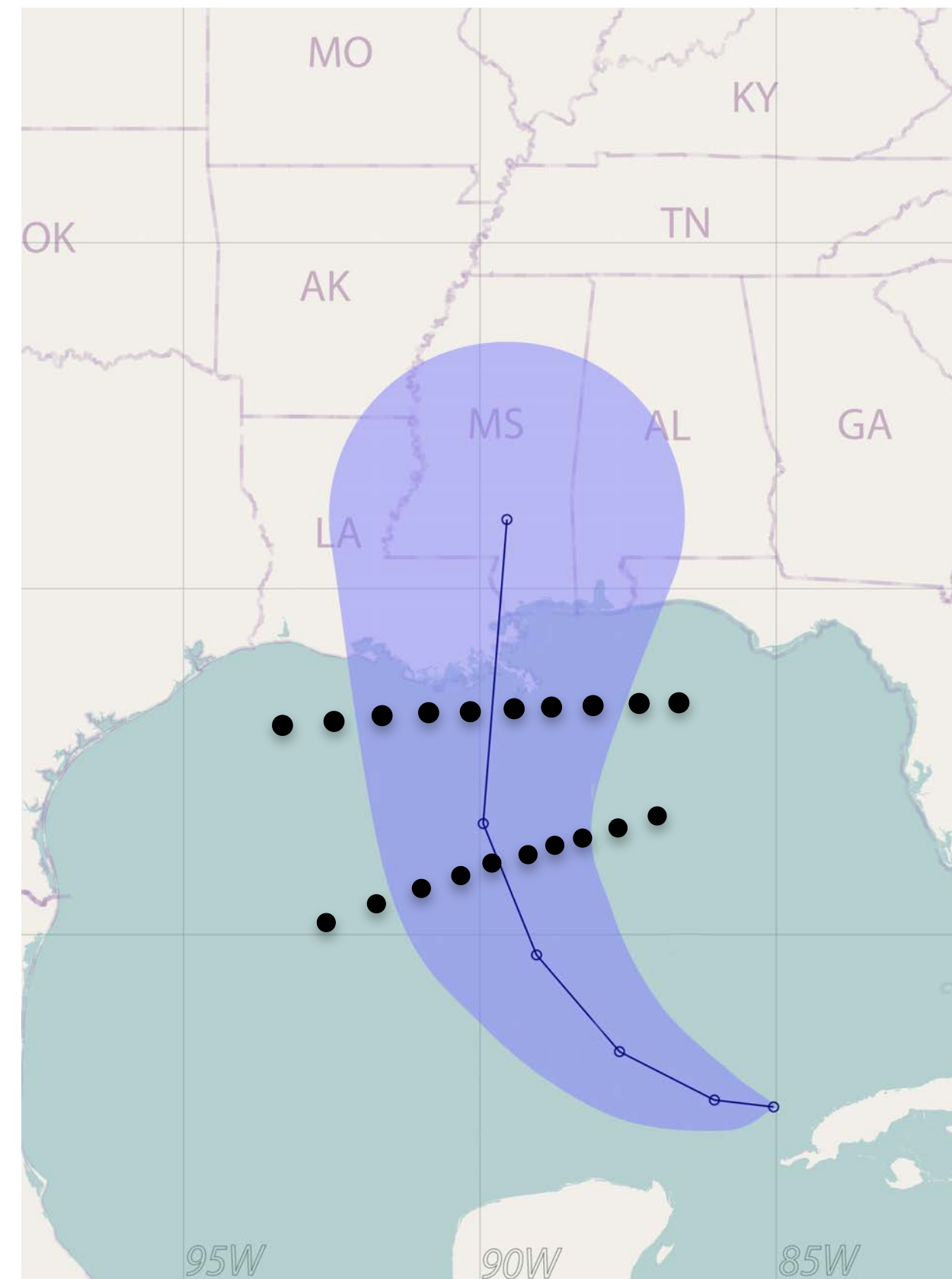
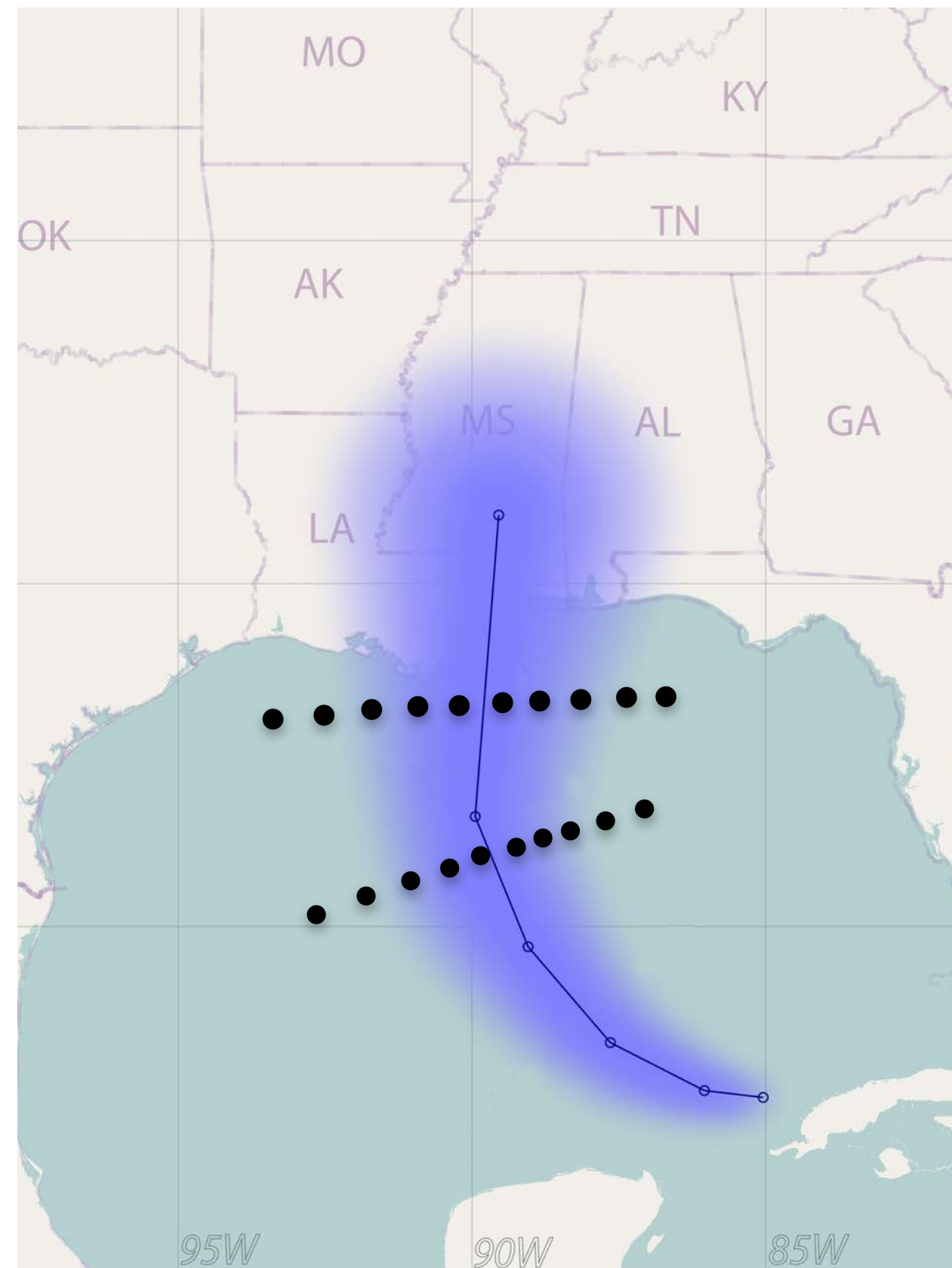
visual description
(mental encoding of
the visual stimulus)

Instructions:

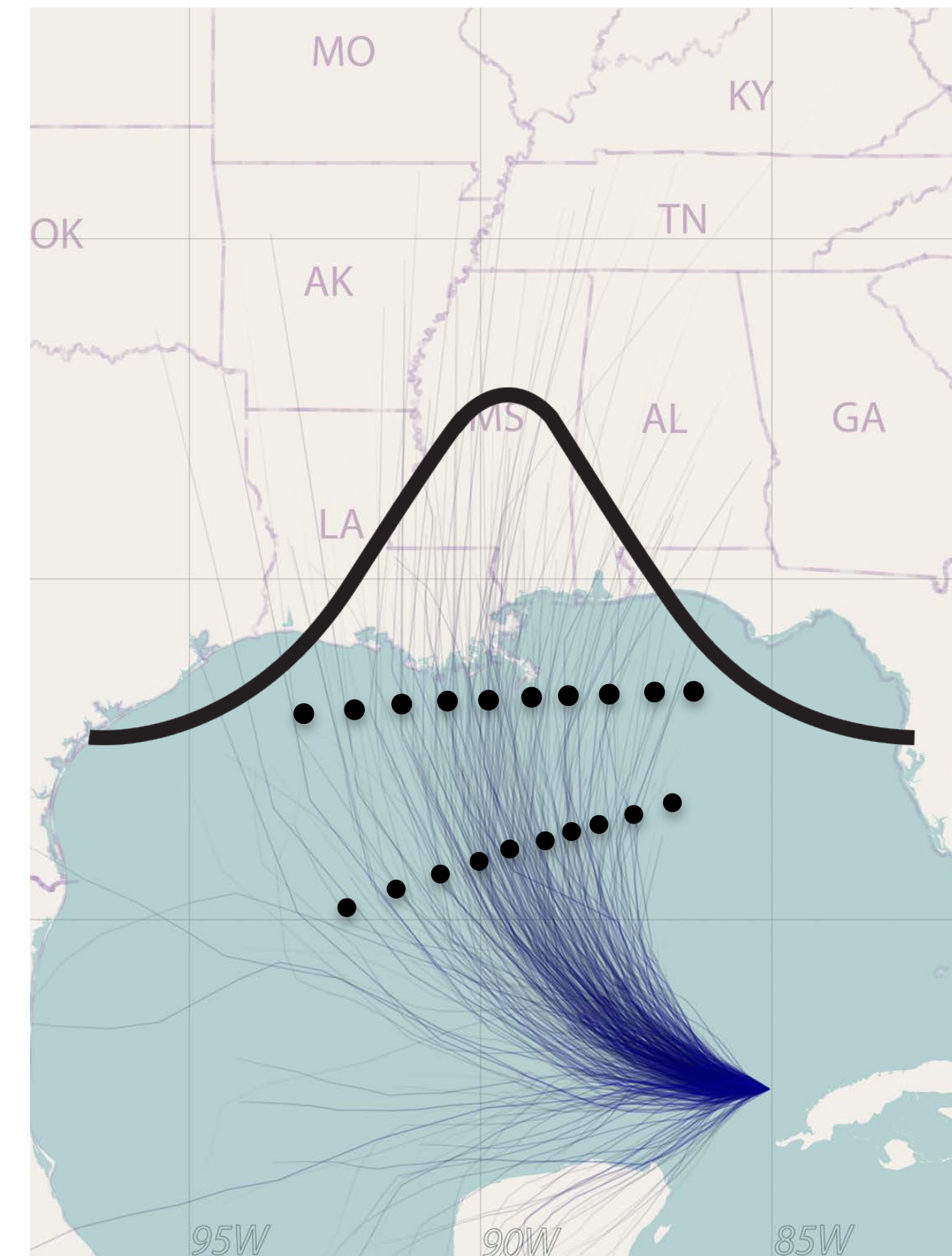
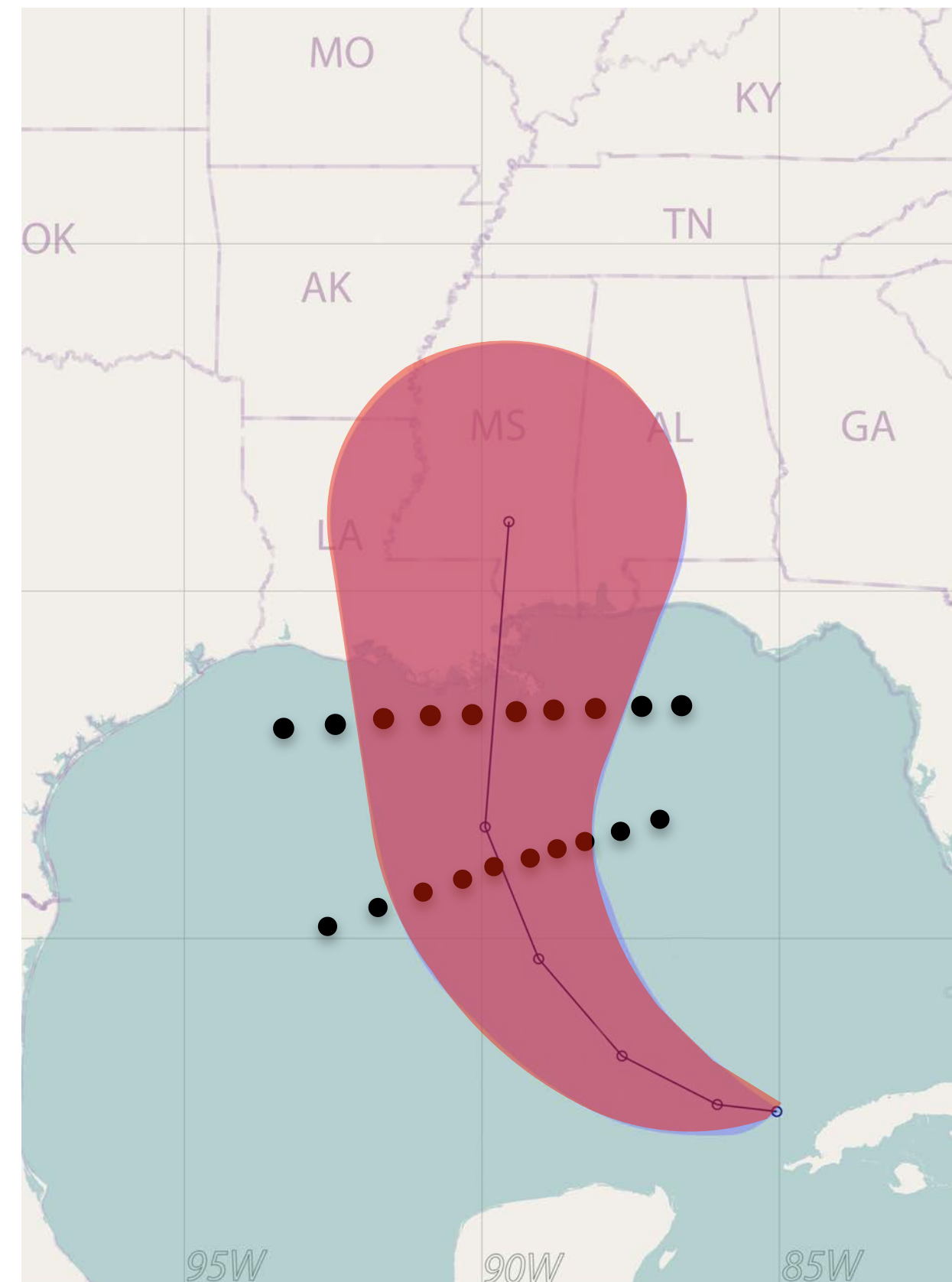
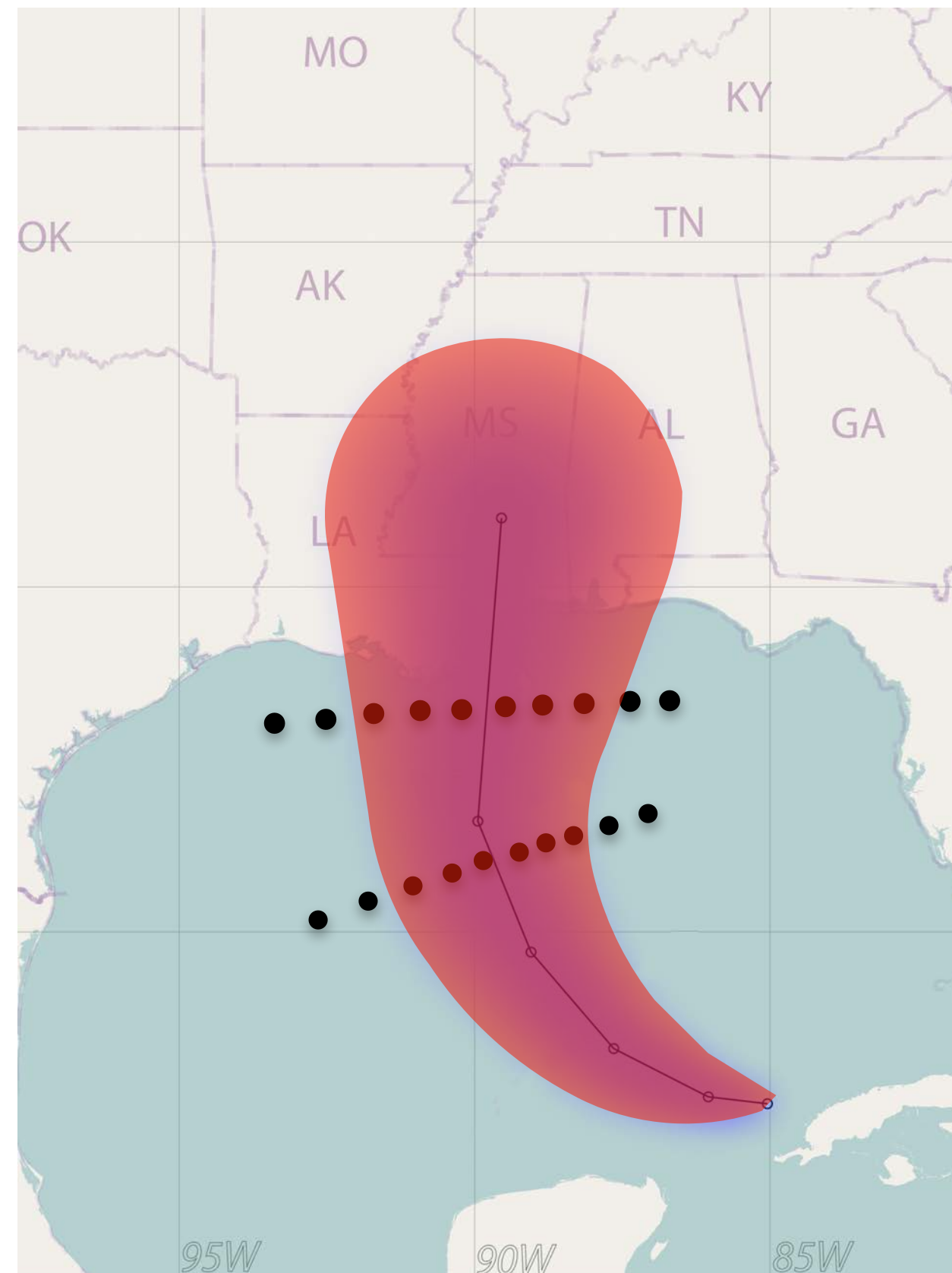
In the following experiment, you will view maps showing the forecast path of different hurricanes as they travel over the Gulf of Mexico, towards land. The maps will also show the location of one offshore oil platform in the Gulf. Oil platforms are large structures on the surface of the water with components that extend to the ocean floor for drilling and storing oil.

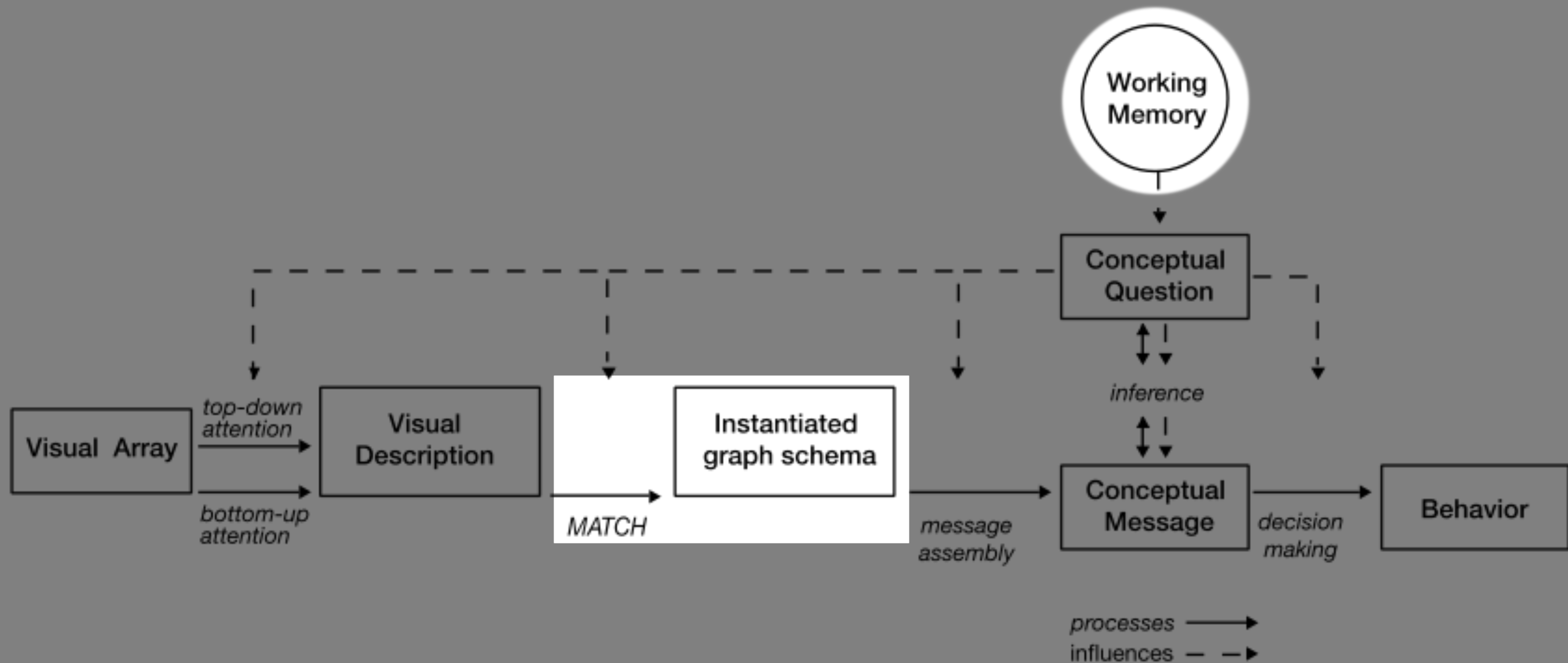
The forecast path of where the hurricane will move in the next three days is shown in blue and the location of the oil platform is shown by a small red circle. Your task is to estimate the level of damage that the platform will incur based on the depicted forecast of the hurricane path on a scale of 1 to 7 where 1 is no damage and 7 is severe damage.





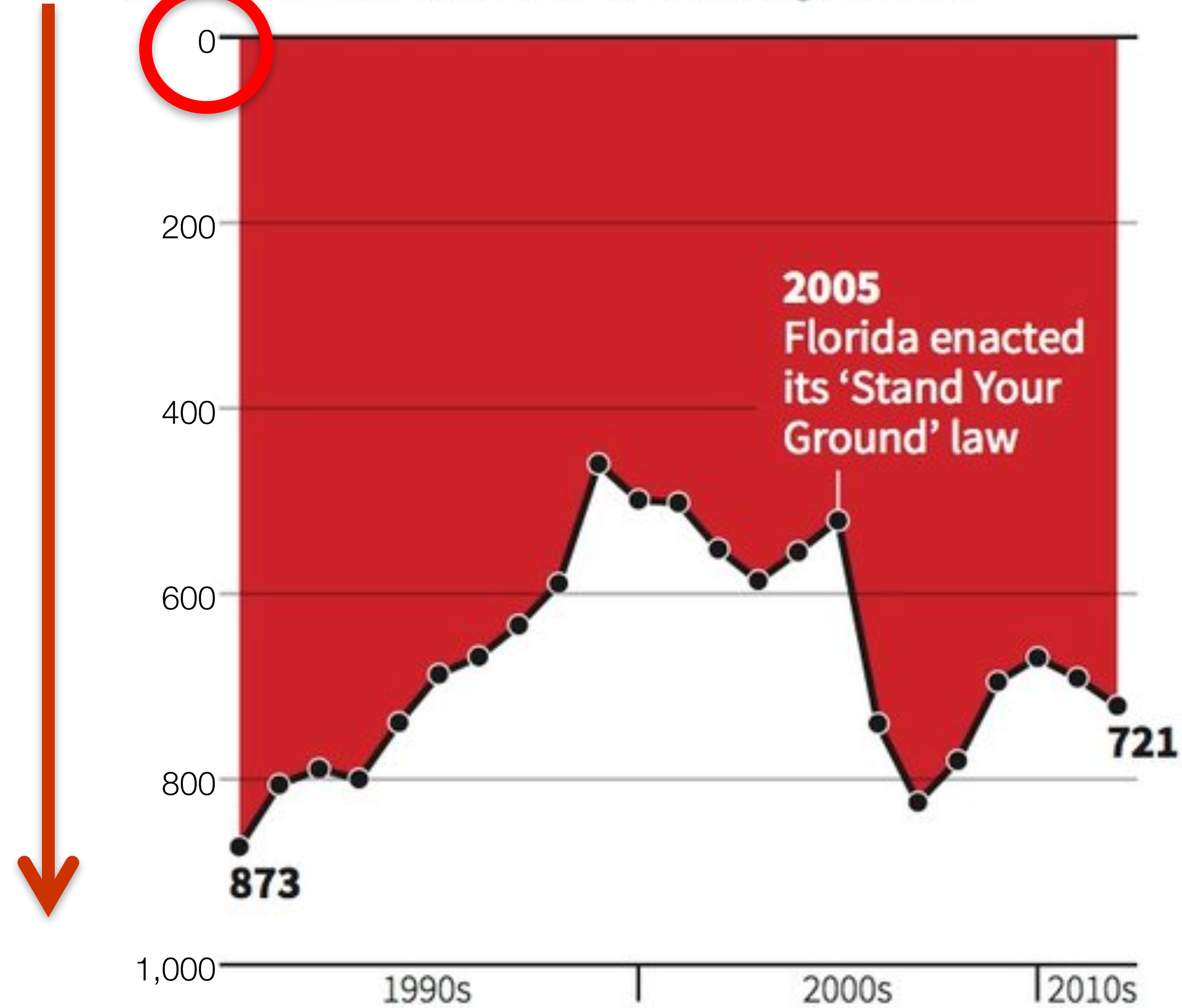
Intervals create conceptual categories





Gun deaths in Florida

Number of murders committed using firearms

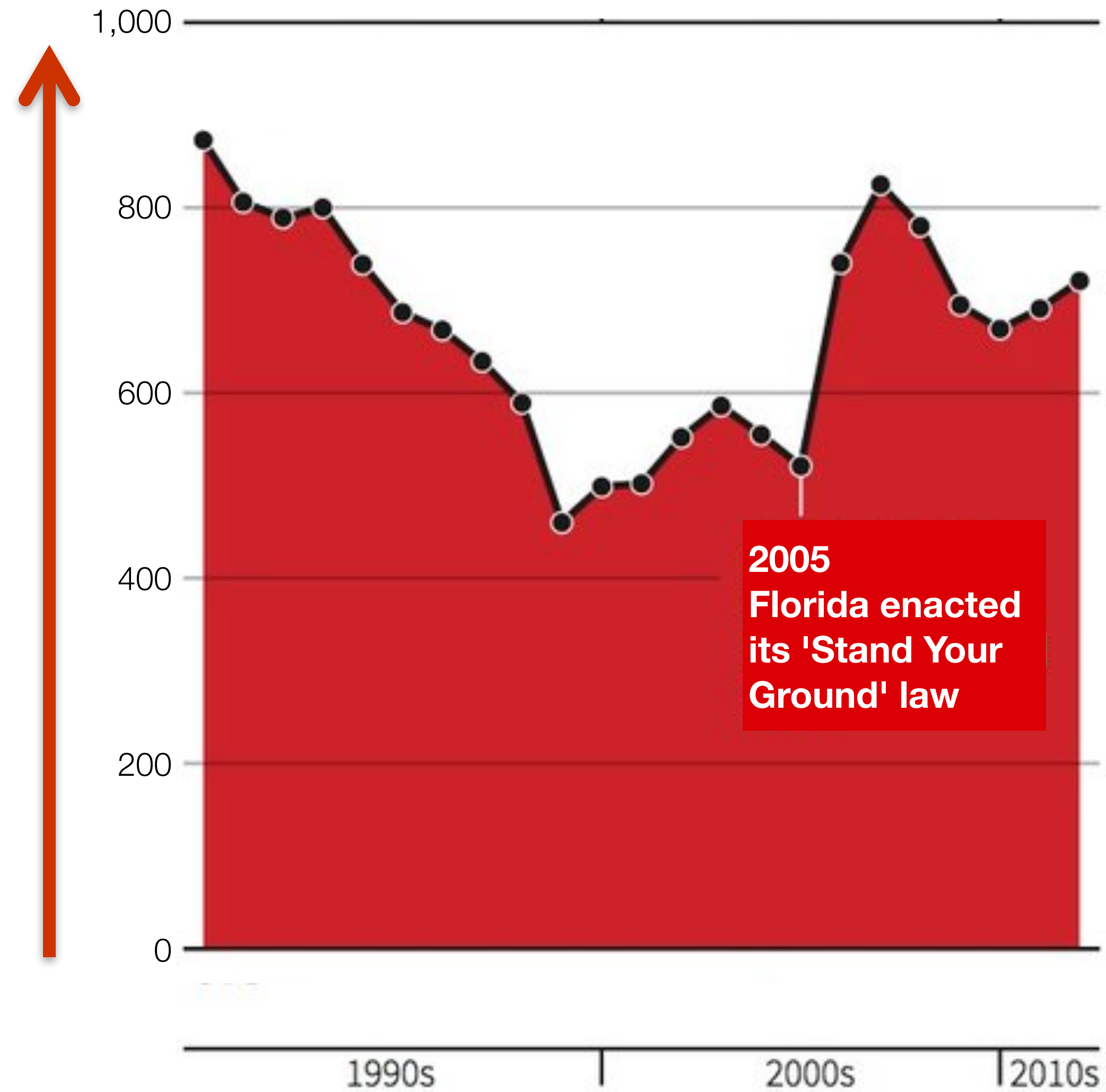


Source: Florida Department of Law Enforcement

C. Chan 16/02/2014

REUTERS

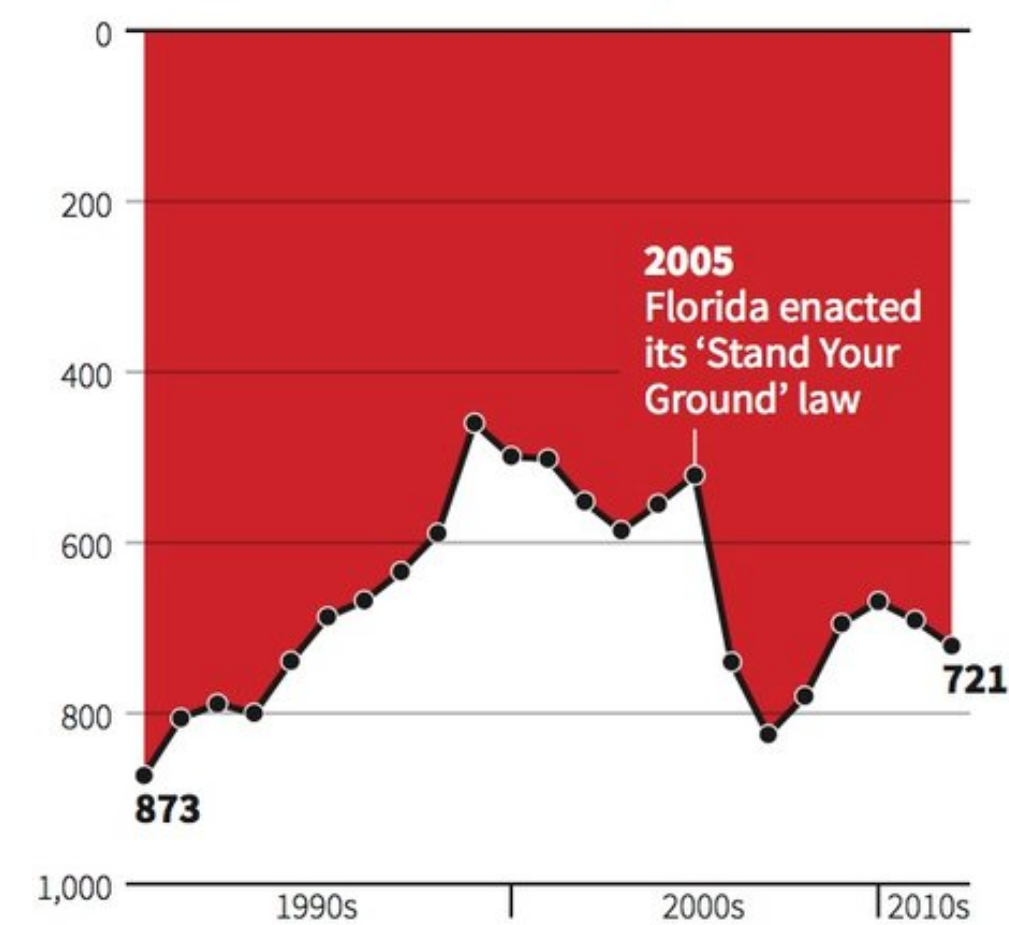
Gun deaths in Florida



Source: Florida Department of Law Enforcement

Gun deaths in Florida

Number of murders committed using firearms



Source: Florida Department of Law Enforcement

C. Chan 16/02/2014

REUTERS

Visualization

\neq

Y

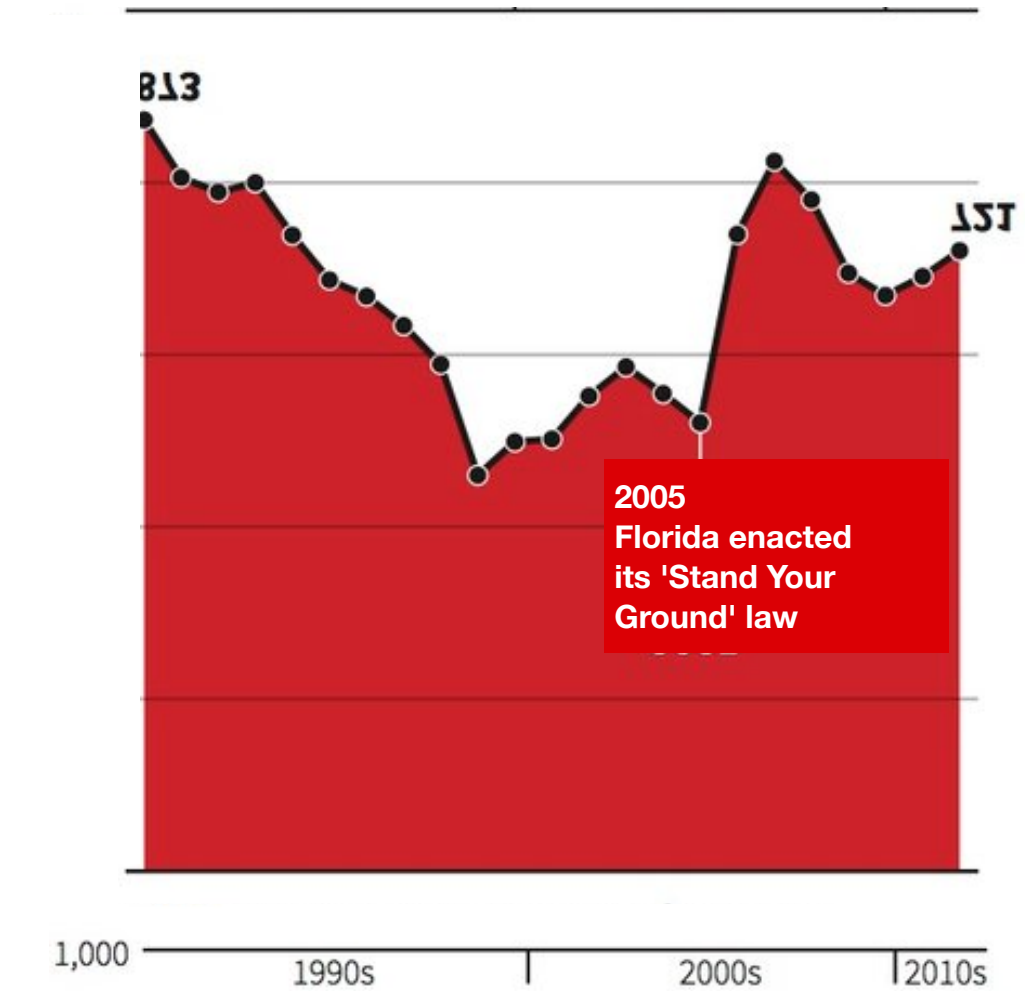
$=$

X

Graph Schema

(e.g.,. conventions,
templates, rules of
thumb, strategies)

Gun deaths in Florida



Source: Florida Department of Law Enforcement

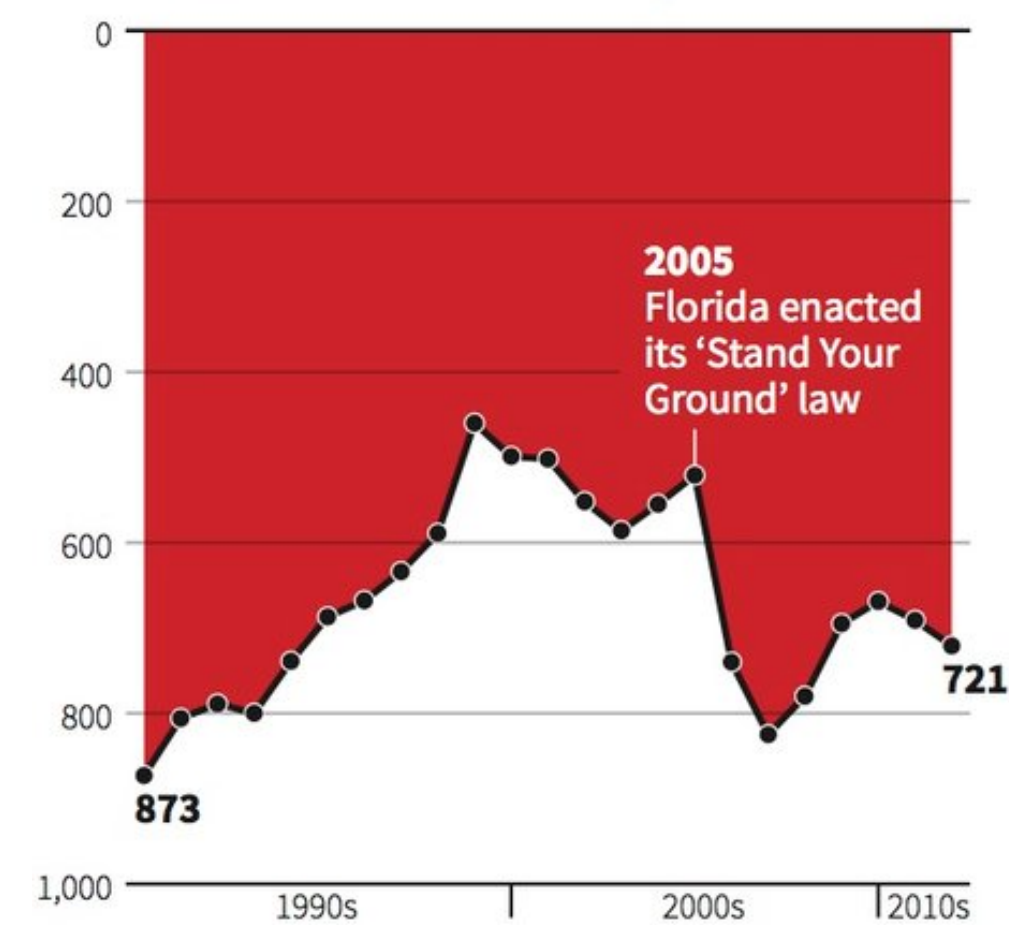
C. Chan 16/02/2014

REUTERS

Instantiated Schema

Gun deaths in Florida

Number of murders committed using firearms



Source: Florida Department of Law Enforcement

C. Chan 16/02/2014

REUTERS

Visualization

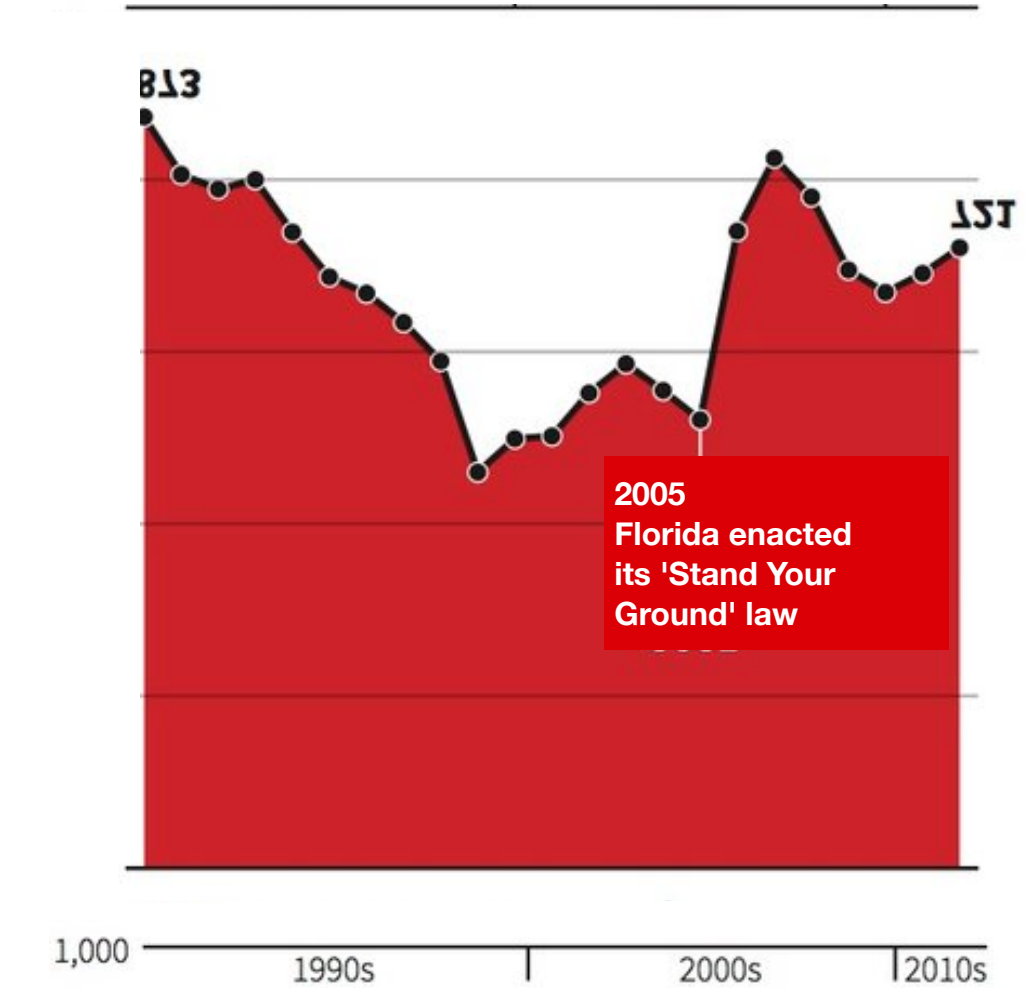
\neq

Y

$=$

X

Gun deaths in Florida



Source: Florida Department of Law Enforcement

C. Chan 16/02/2014

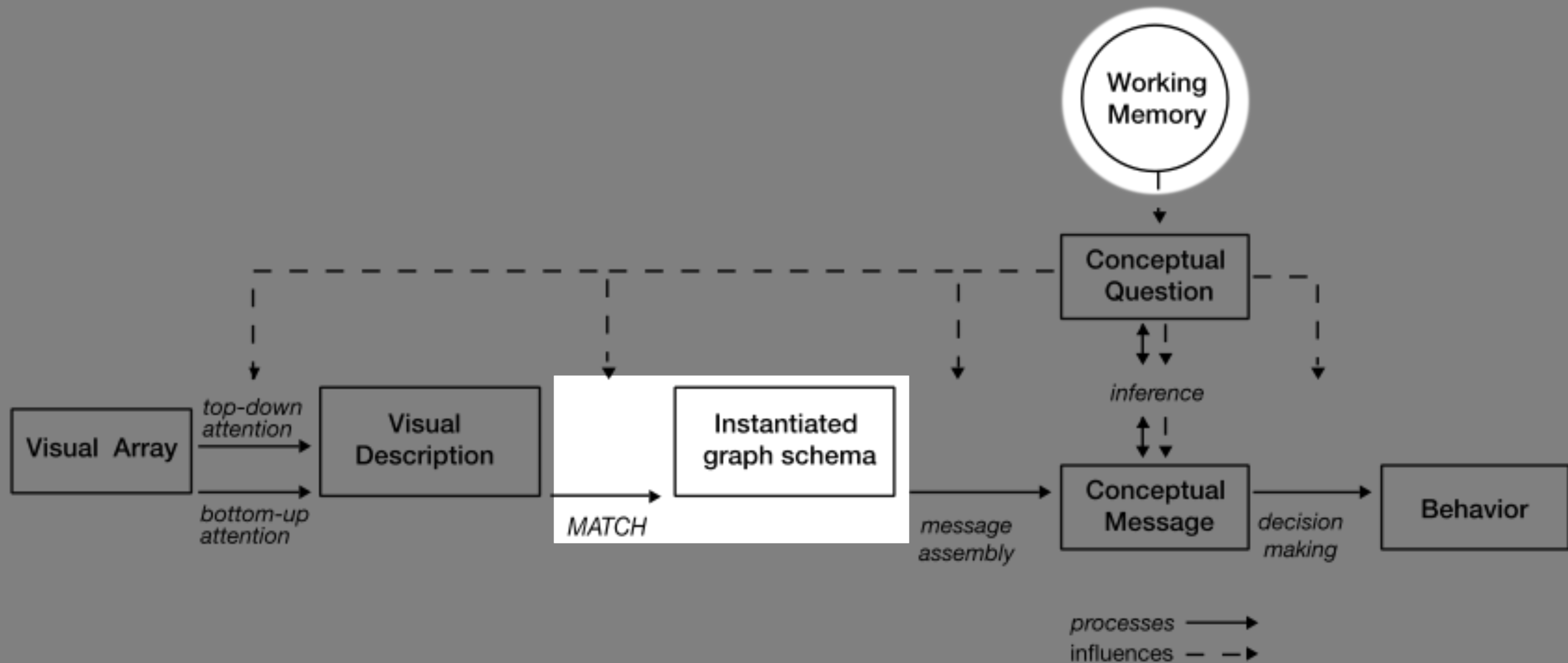
REUTERS

Instantiated Schema

Working

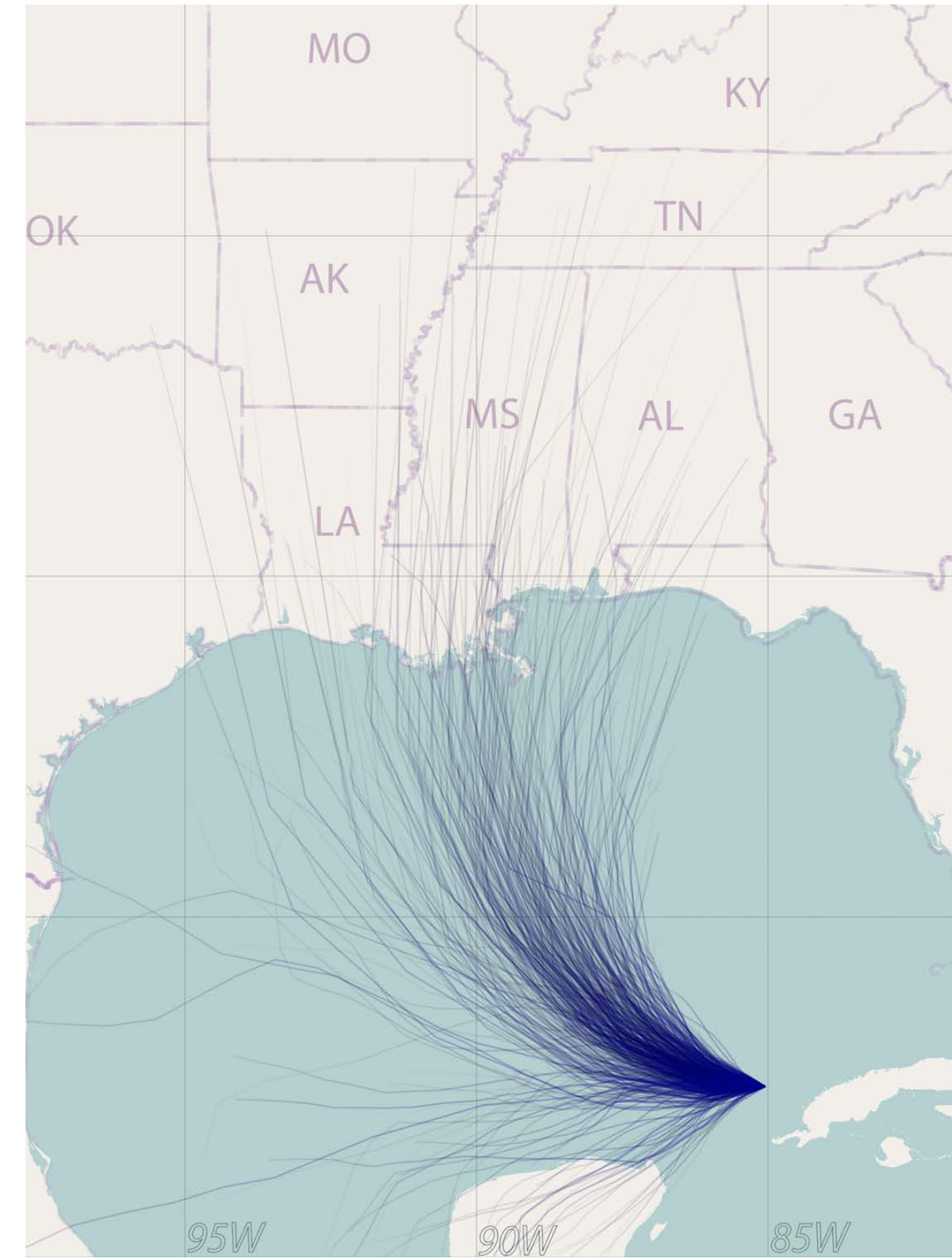
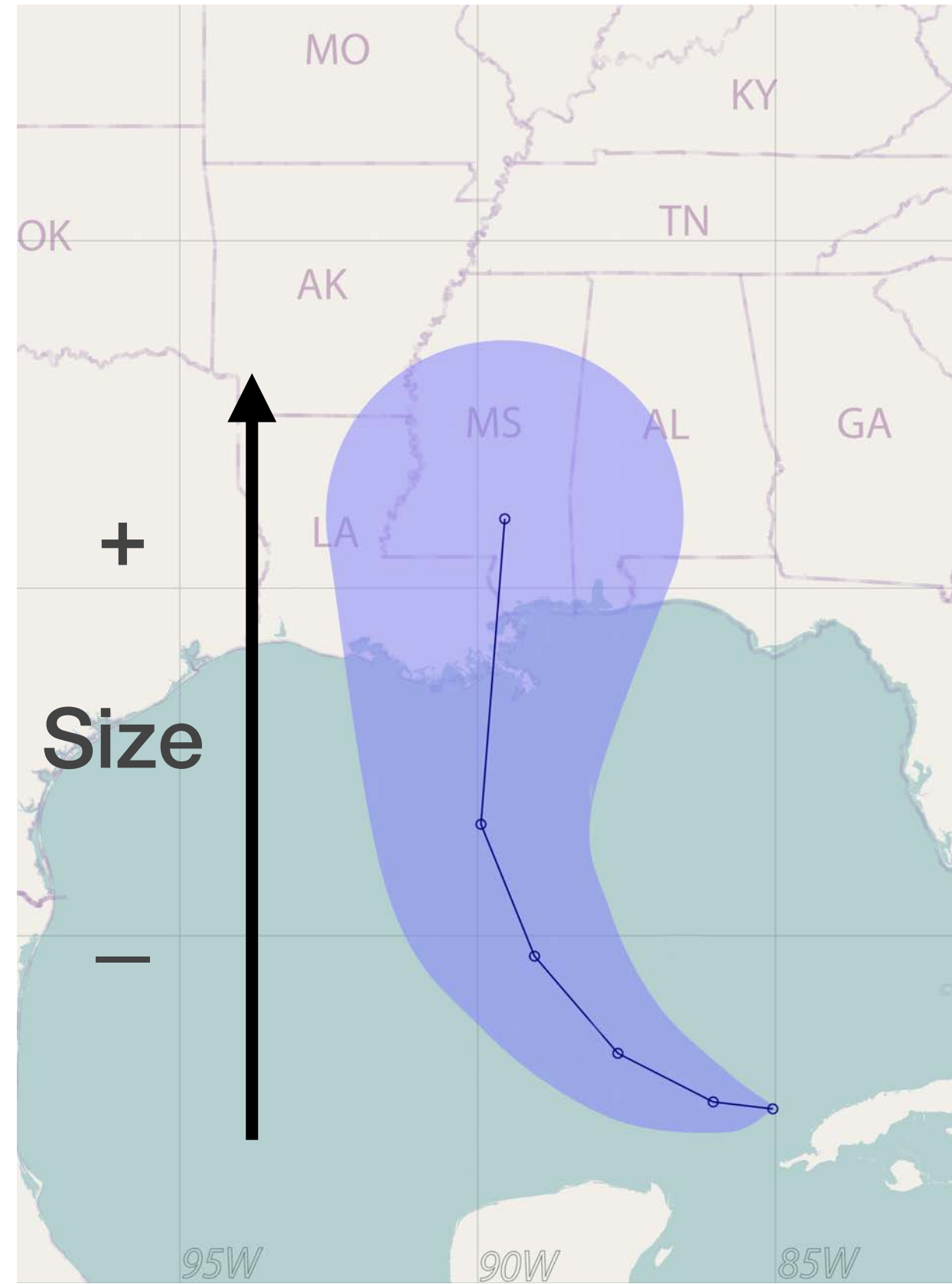
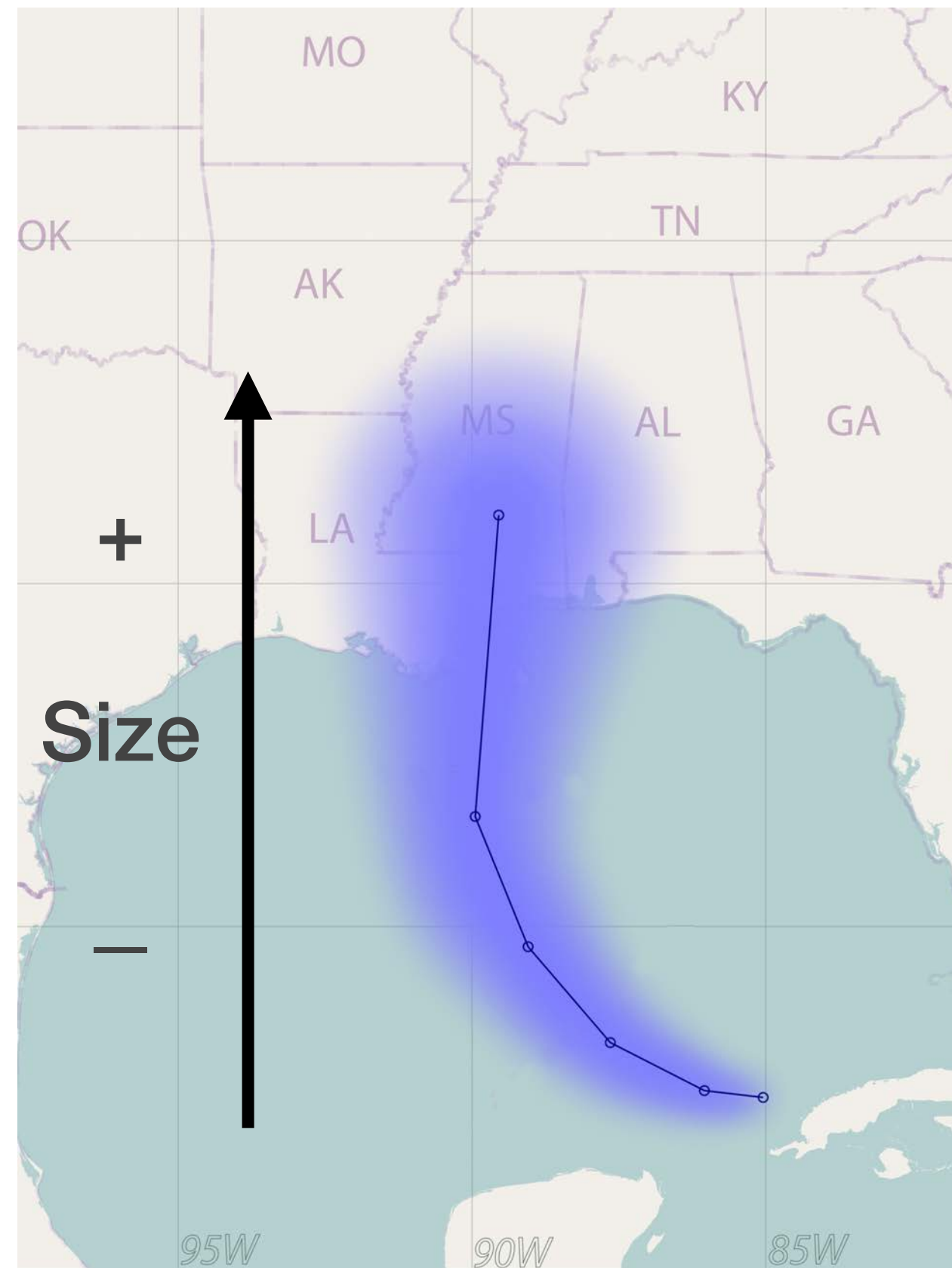
Memory

AKA mental effort



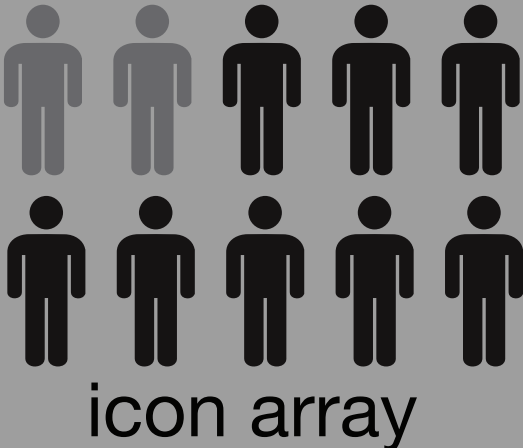
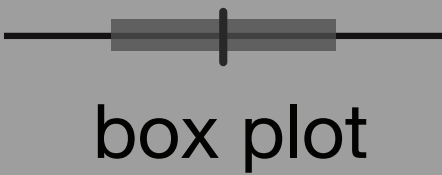
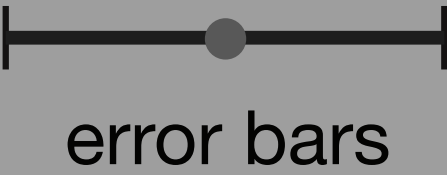
Errors arise when the visualization evokes the wrong schema

Why? Because of **working memory**

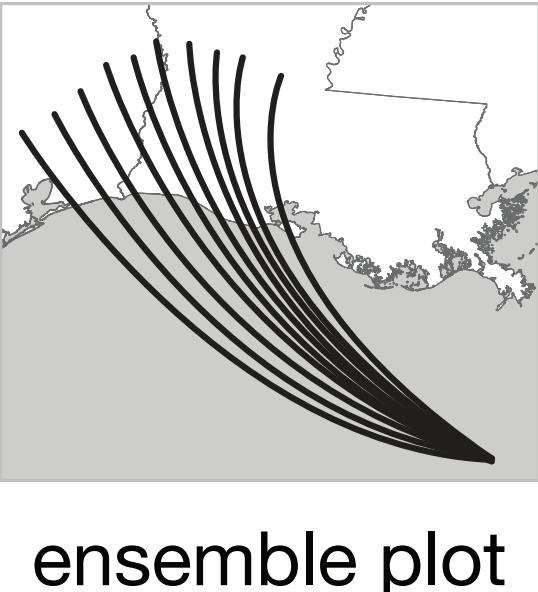
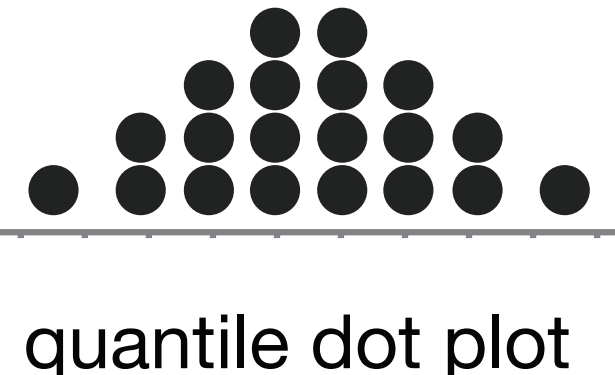
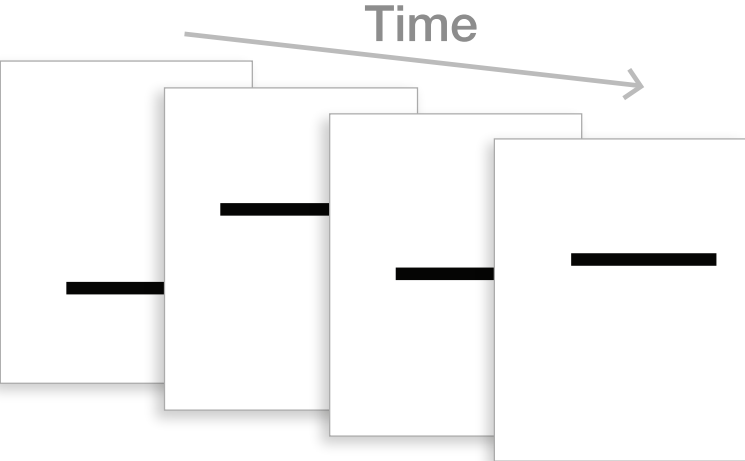
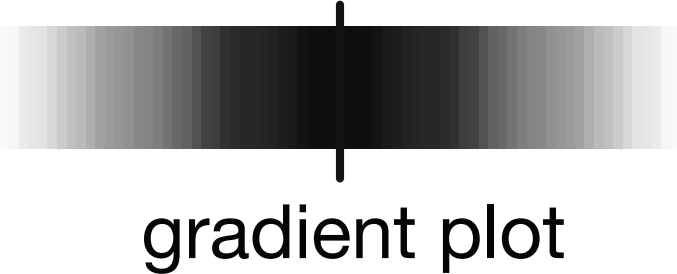
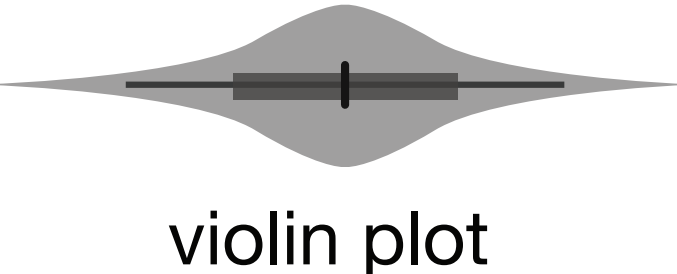


Graphical Annotations of Distributional Properties

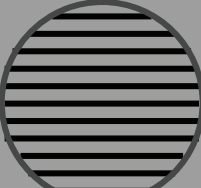
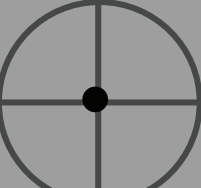
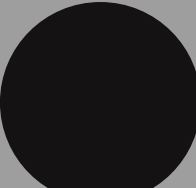
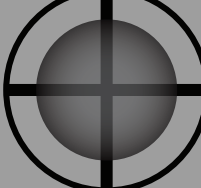
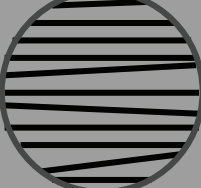
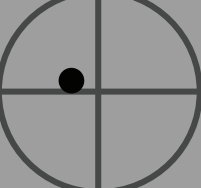
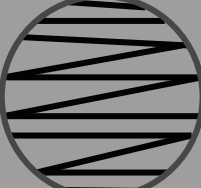
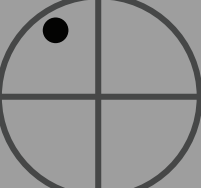
Intervals and Ratios



Distributions



Visual Encodings of Uncertainty



fuzziness

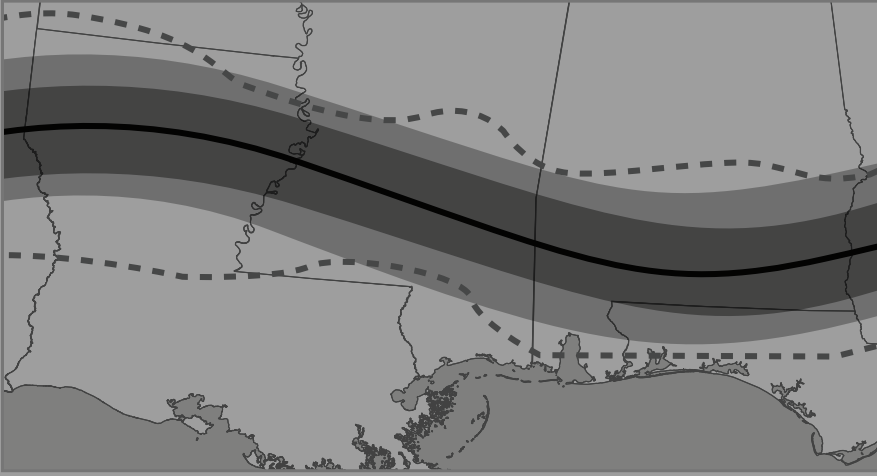
location

arrangement

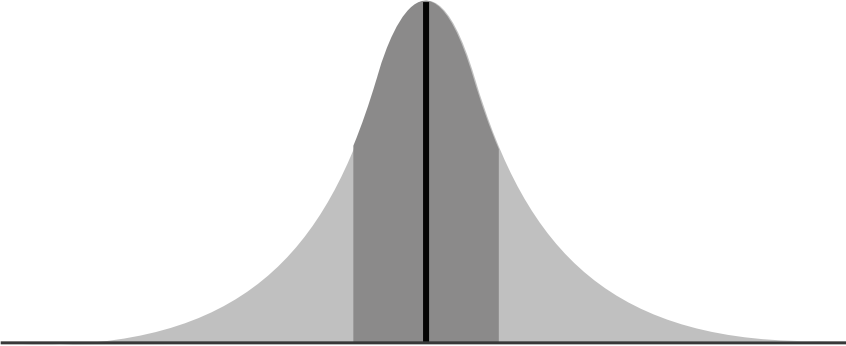
size

transparency

Hybrid Approach



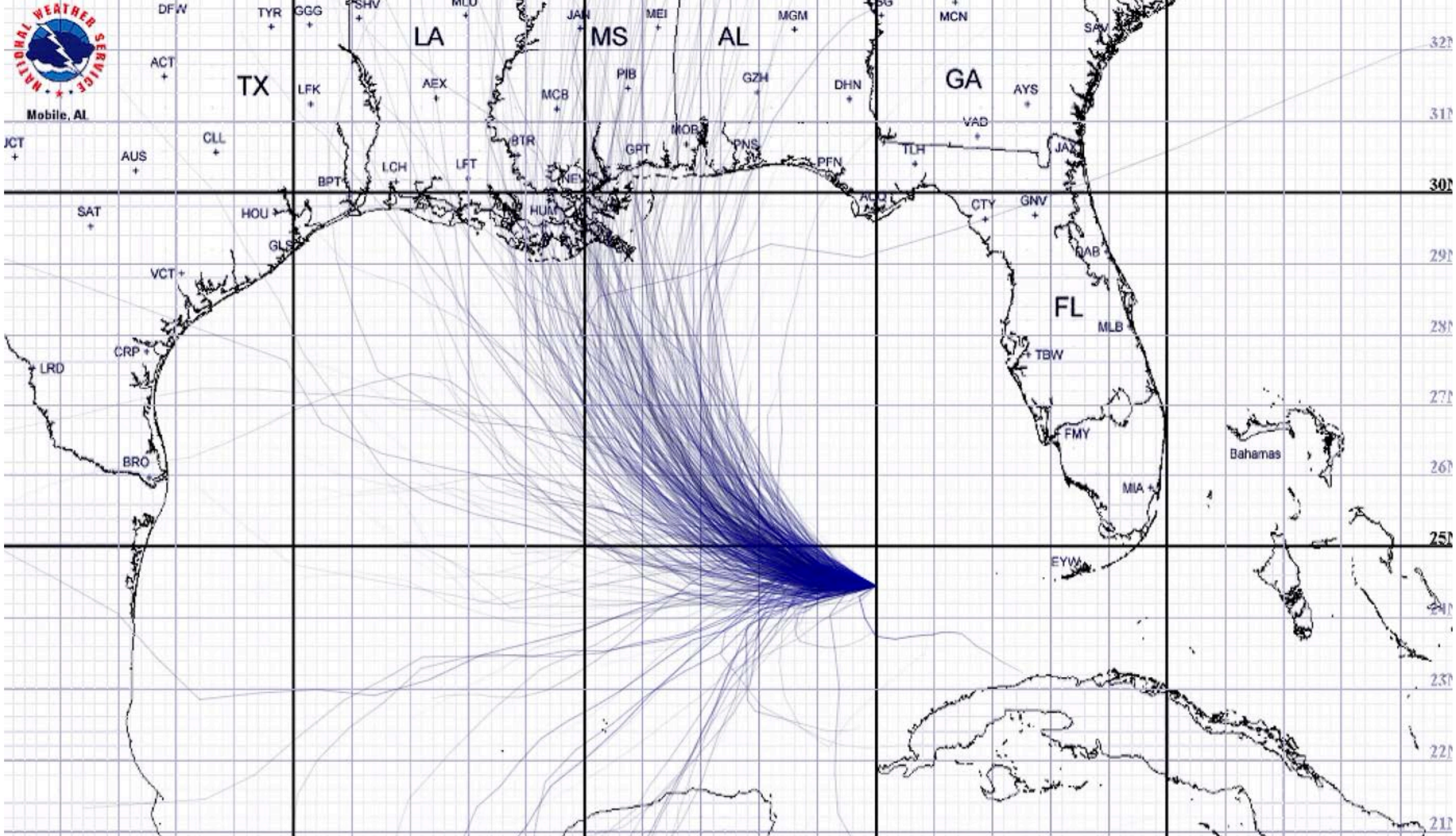
contour boxplot



probability density and interval plot



Mobile, AL



JCT

AUS

CLL

SAT

HOU

GLS

VCT

LRD

CRP

BRO

BPT

LCH

LFT

BTR

MCB

AEX

PIB

MOB

GPT

NEV

HUM

GZH

MGM

DHN

PNS

PFN

GA

AYS

VAD

TLH

JAX

FL

MLB

TBW

FMY

MIA

EYW

Bahamas

320

310

300

290

280

270

260

250

240

230

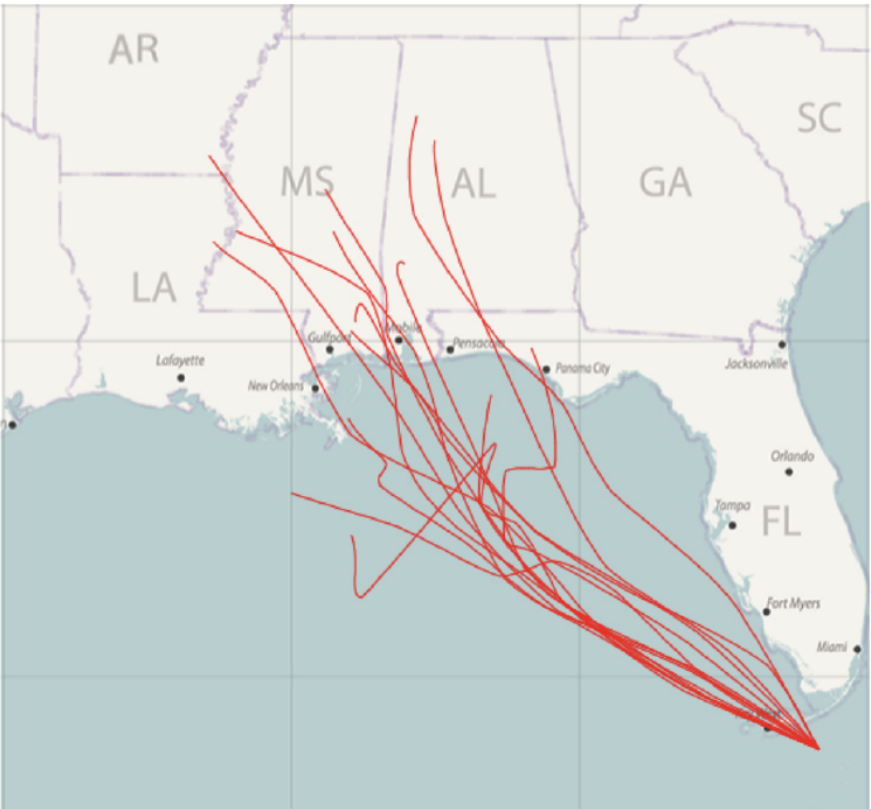
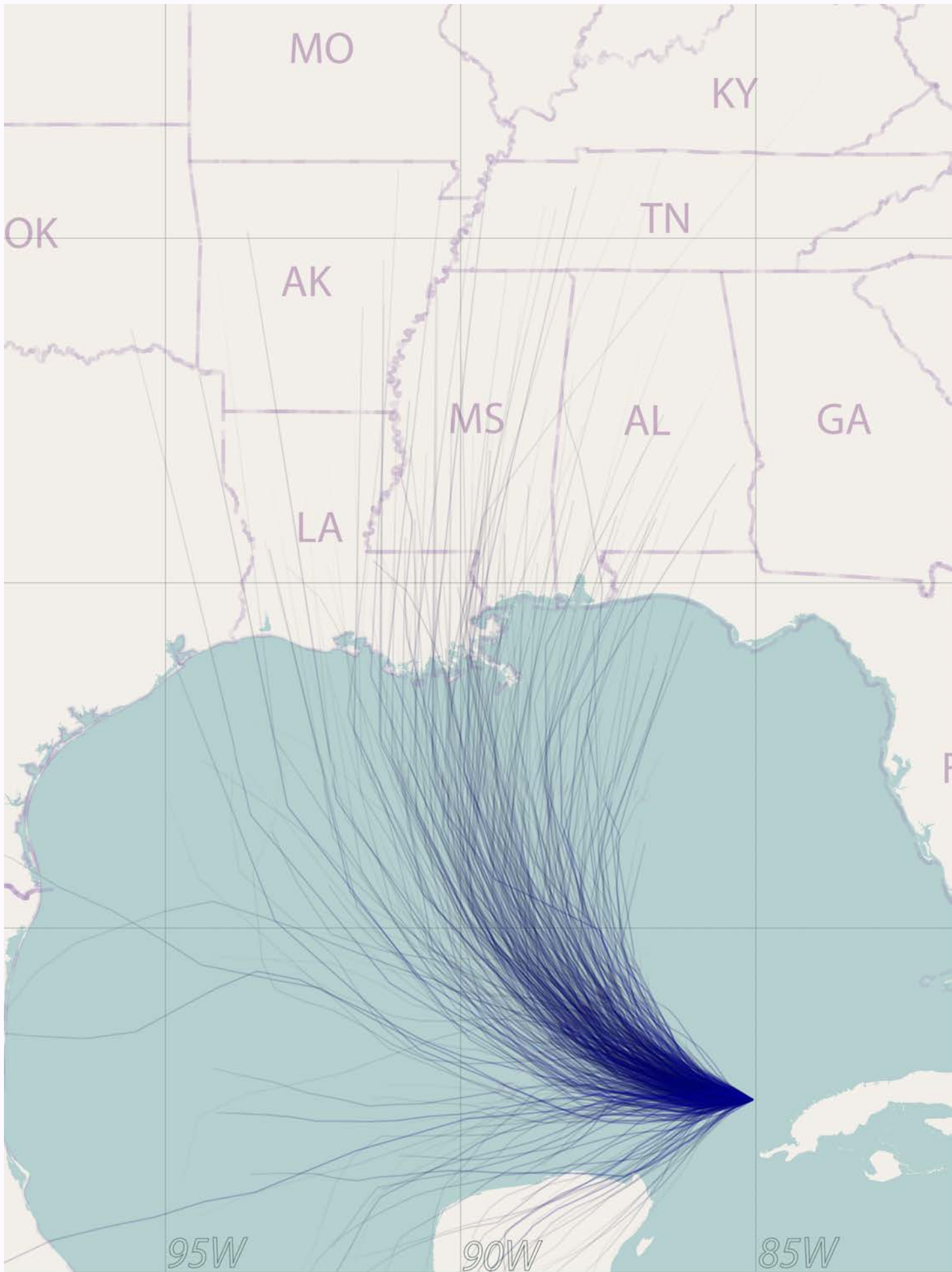
220

210

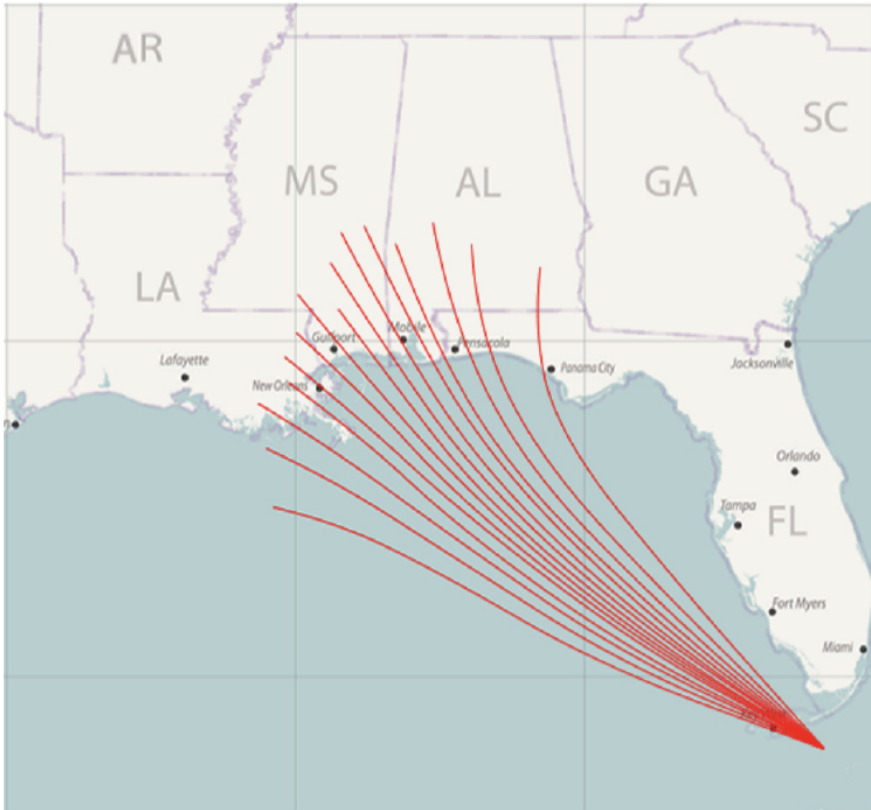
Distributions (ensemble plot)

Visualizing Uncertain Tropical Cyclone Predictions using Representative Samples from Ensembles of Forecast Tracks

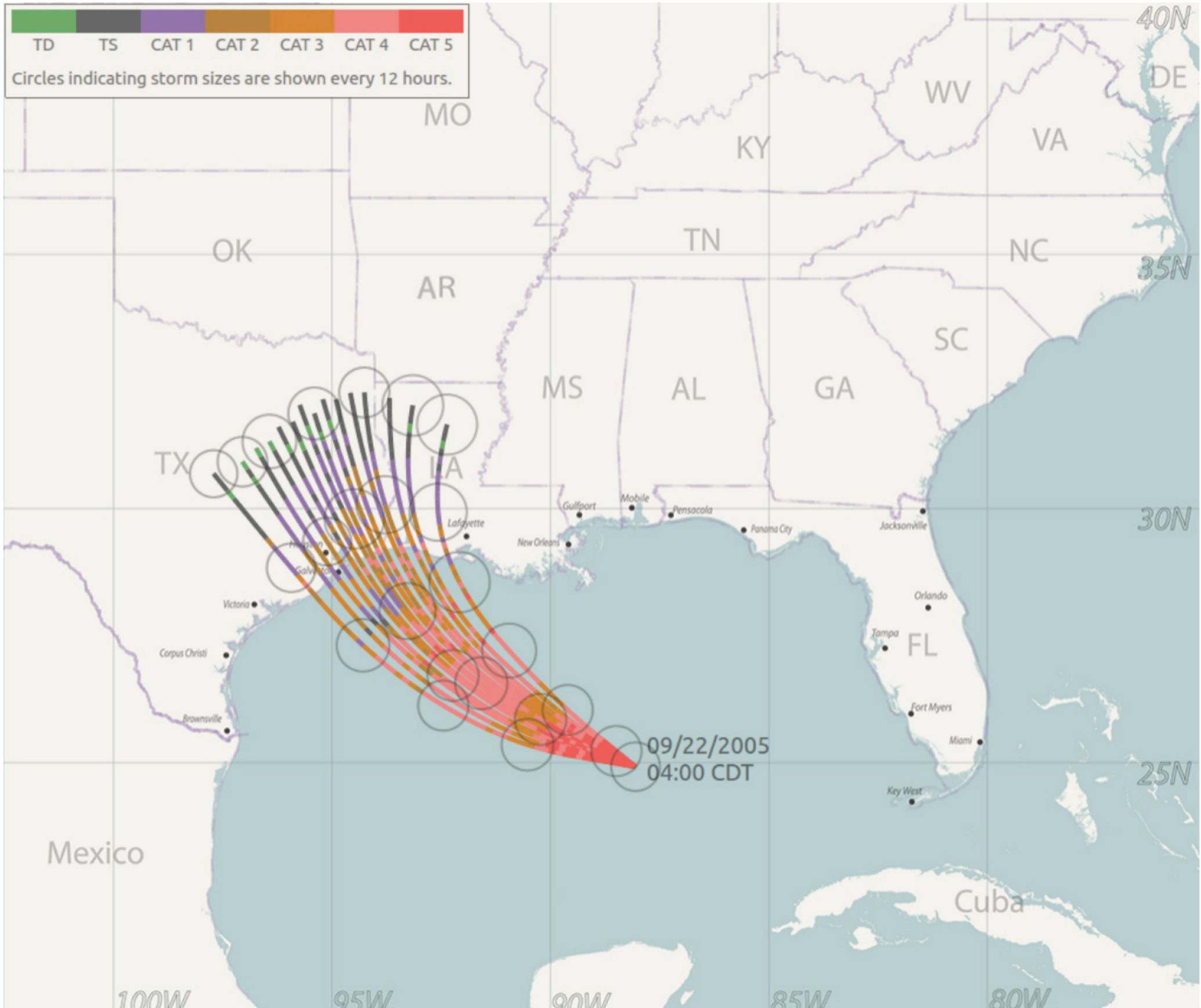
Le Liu, *Member, IEEE*, Lace Padilla, Sarah H. Creem-Regehr, and Donald H. House, *Member, IEEE Computer Society*



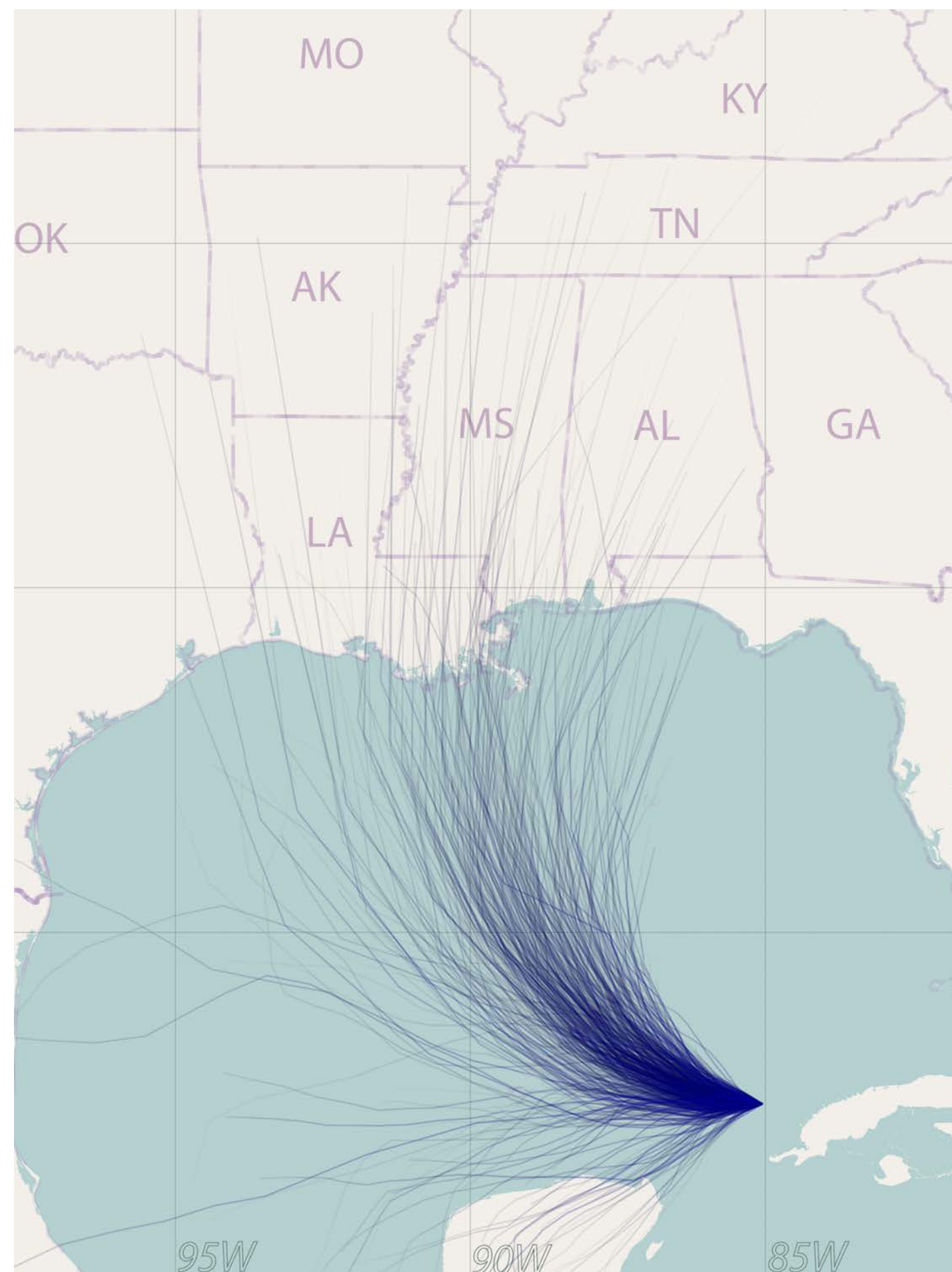
(a) randomly selected paths



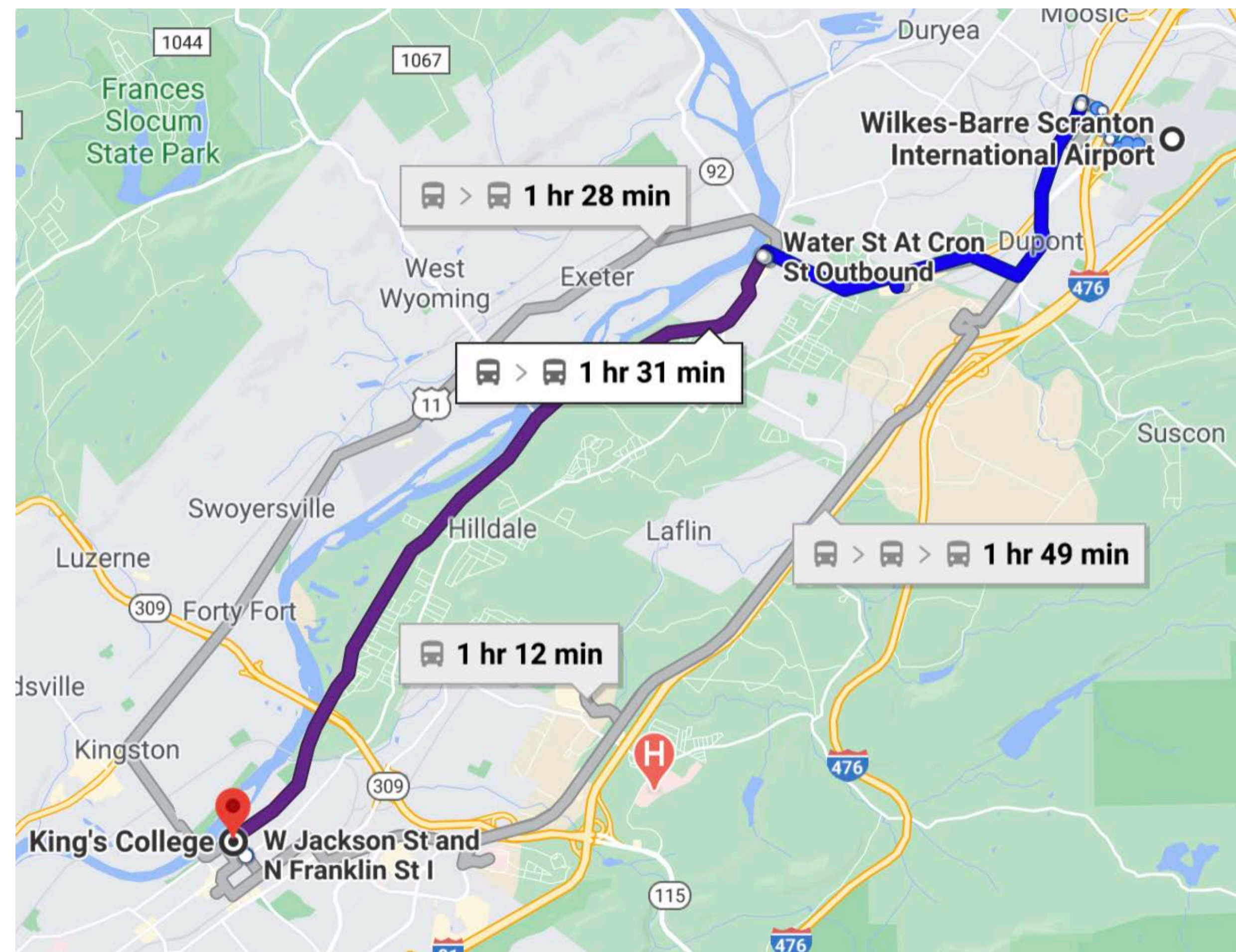
(b) reconstruction of paths

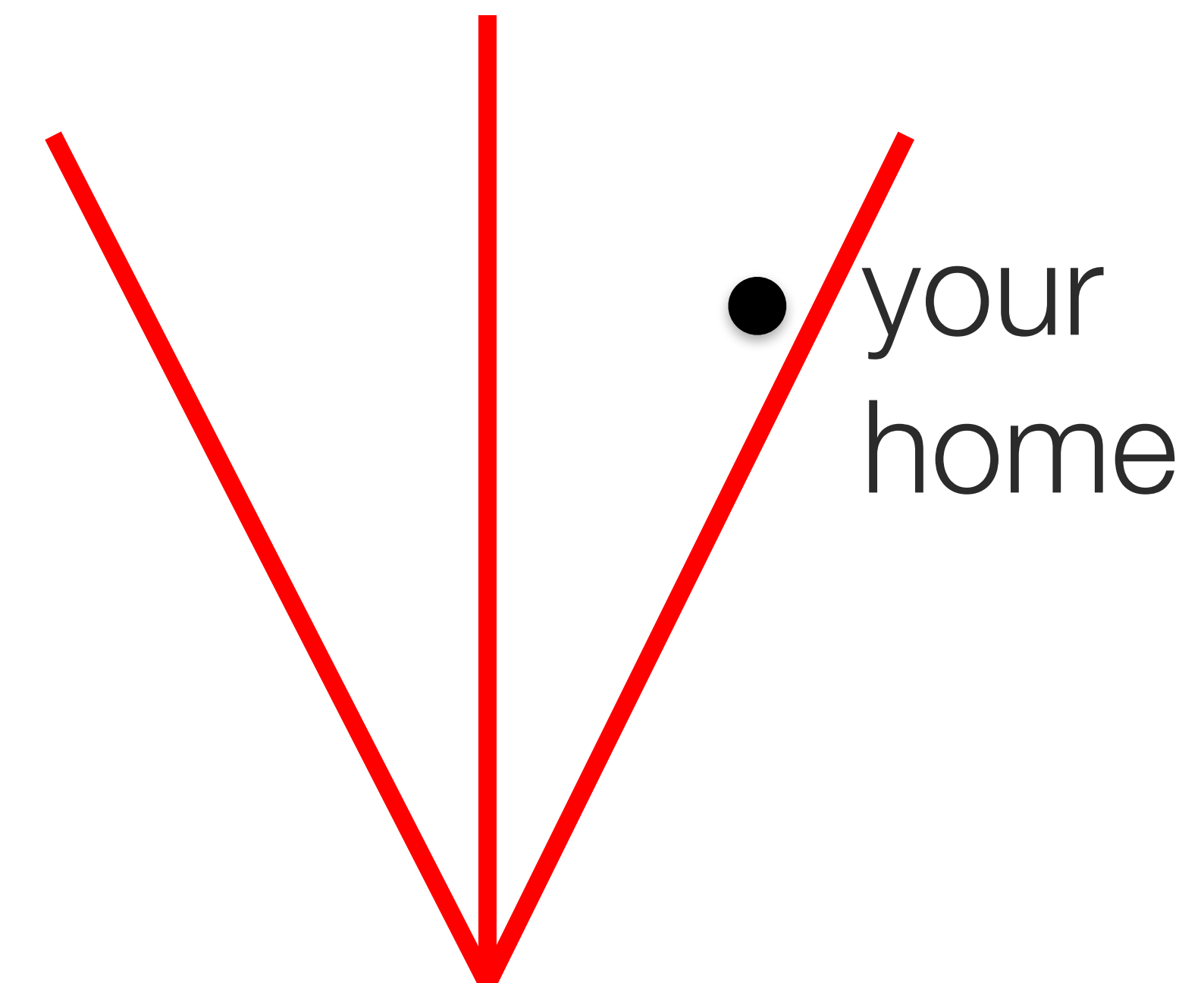
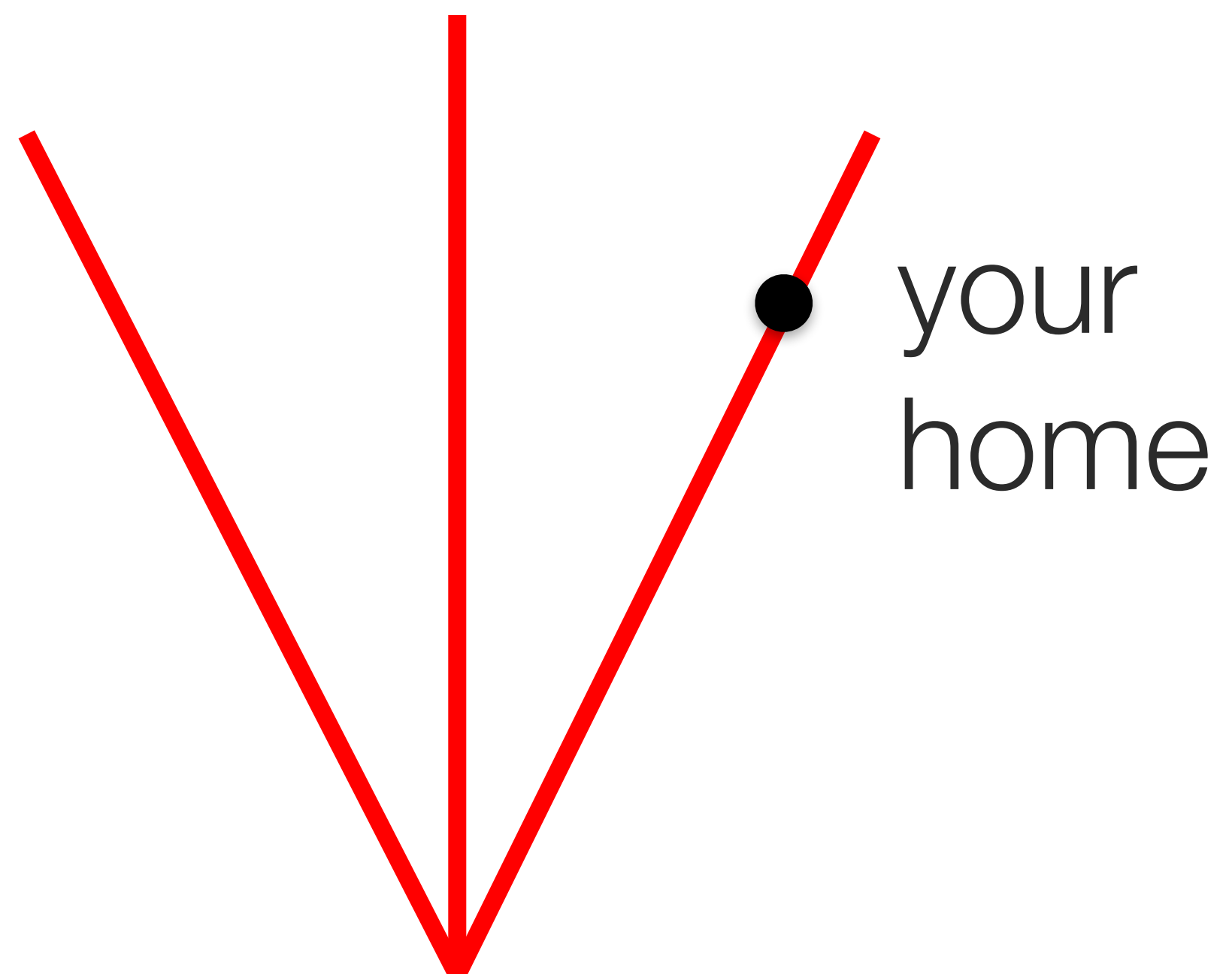


(c) path, size, and category data for Hurricane Rita. 4AM CDT. 09/22/2005, advisory 17



schema?







Fort Myers

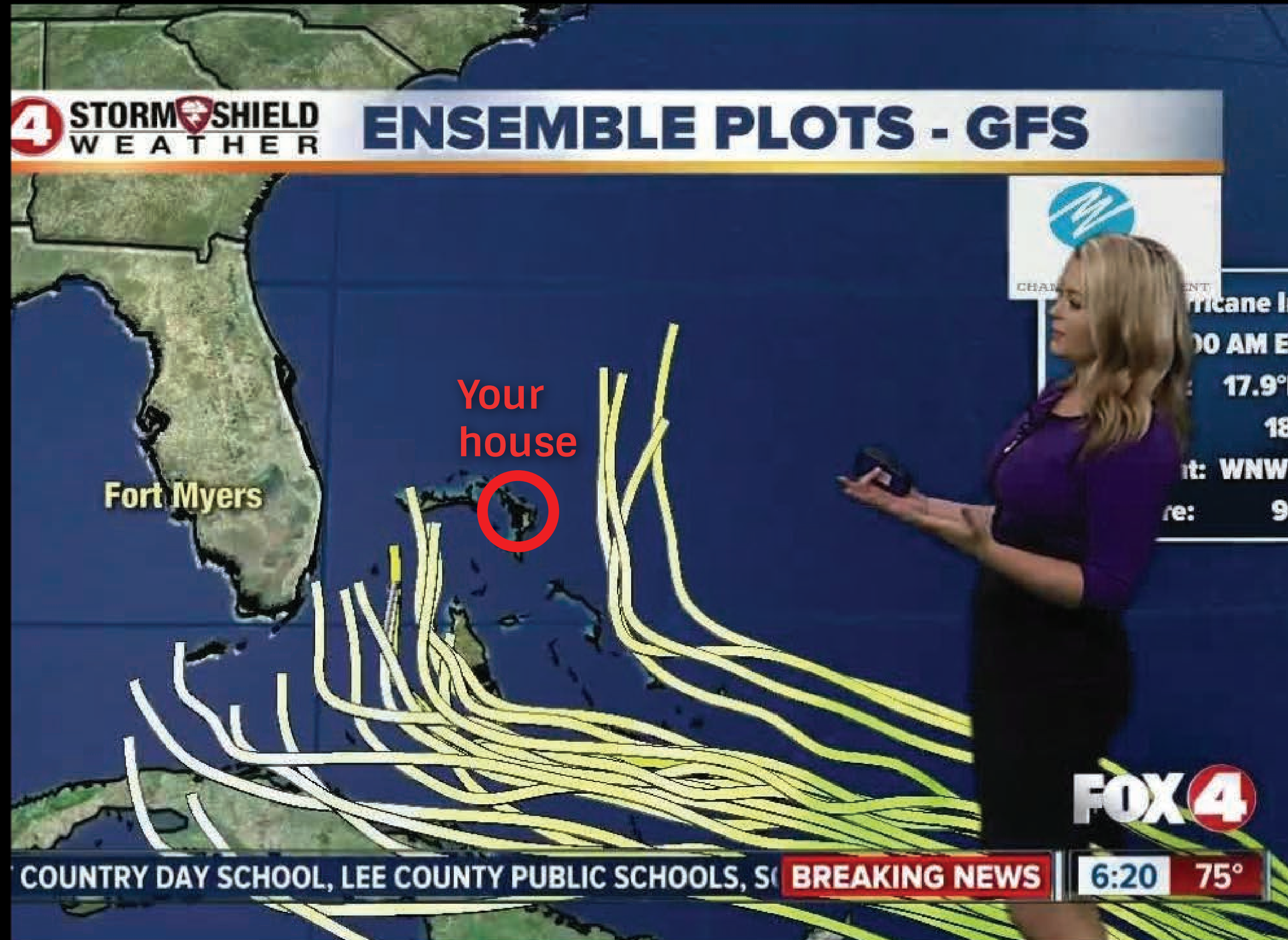


COUNTRY DAY SCHOOL, LEE COUNTY PUBLIC SCHOOLS, SC **BREAKING NEWS**

6:20

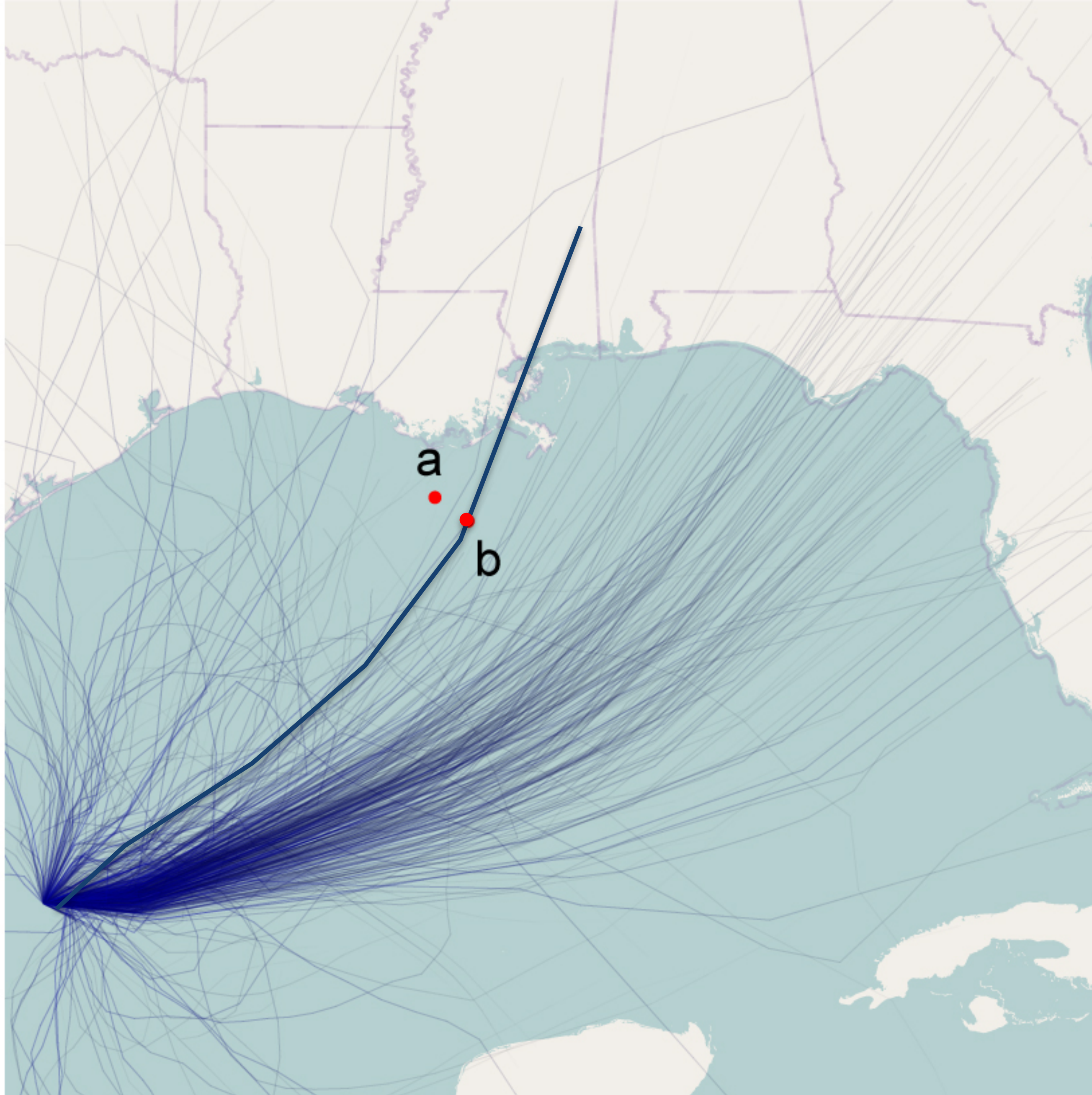
75°

What do you do?



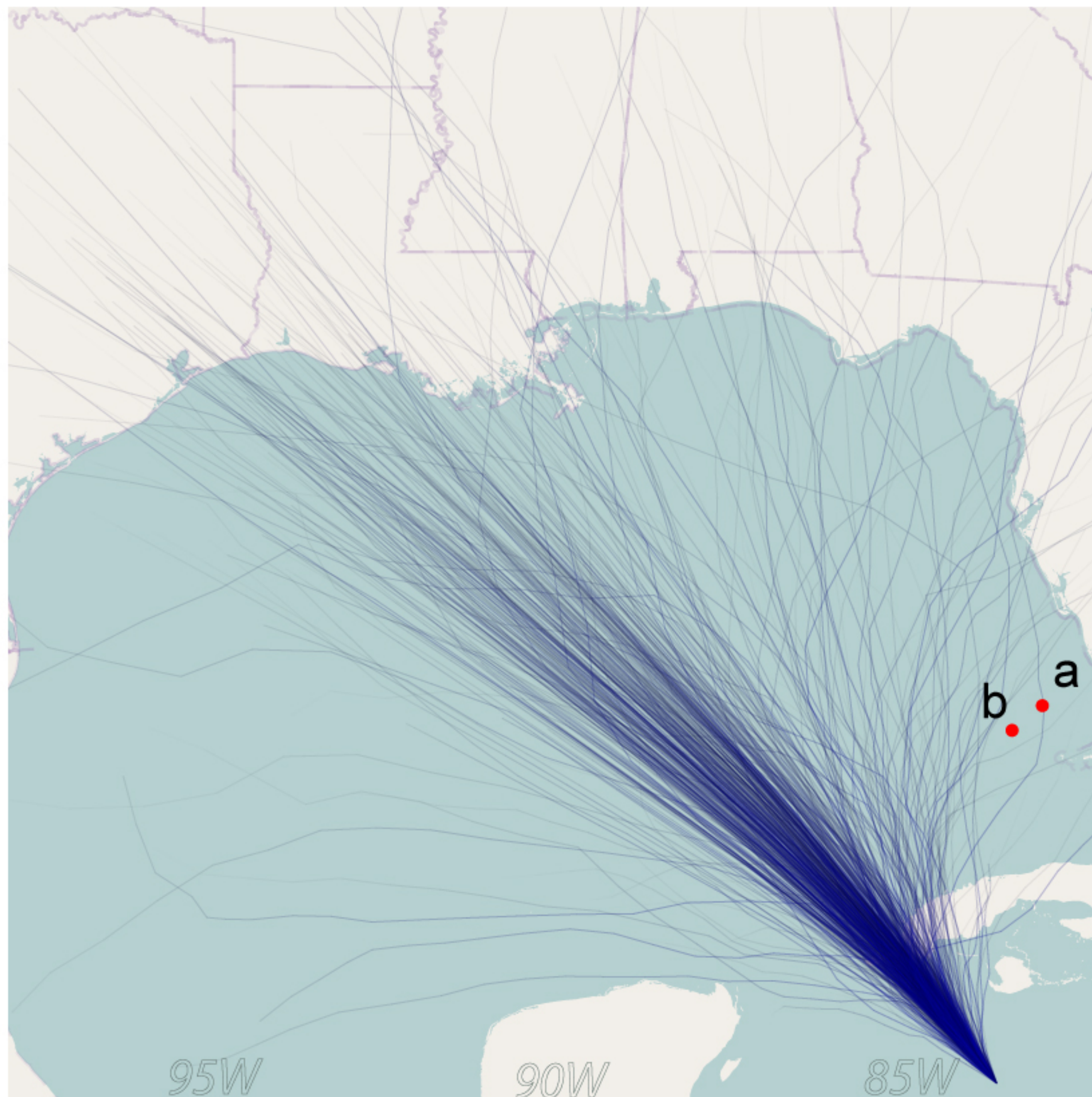
What do you and grandma do?



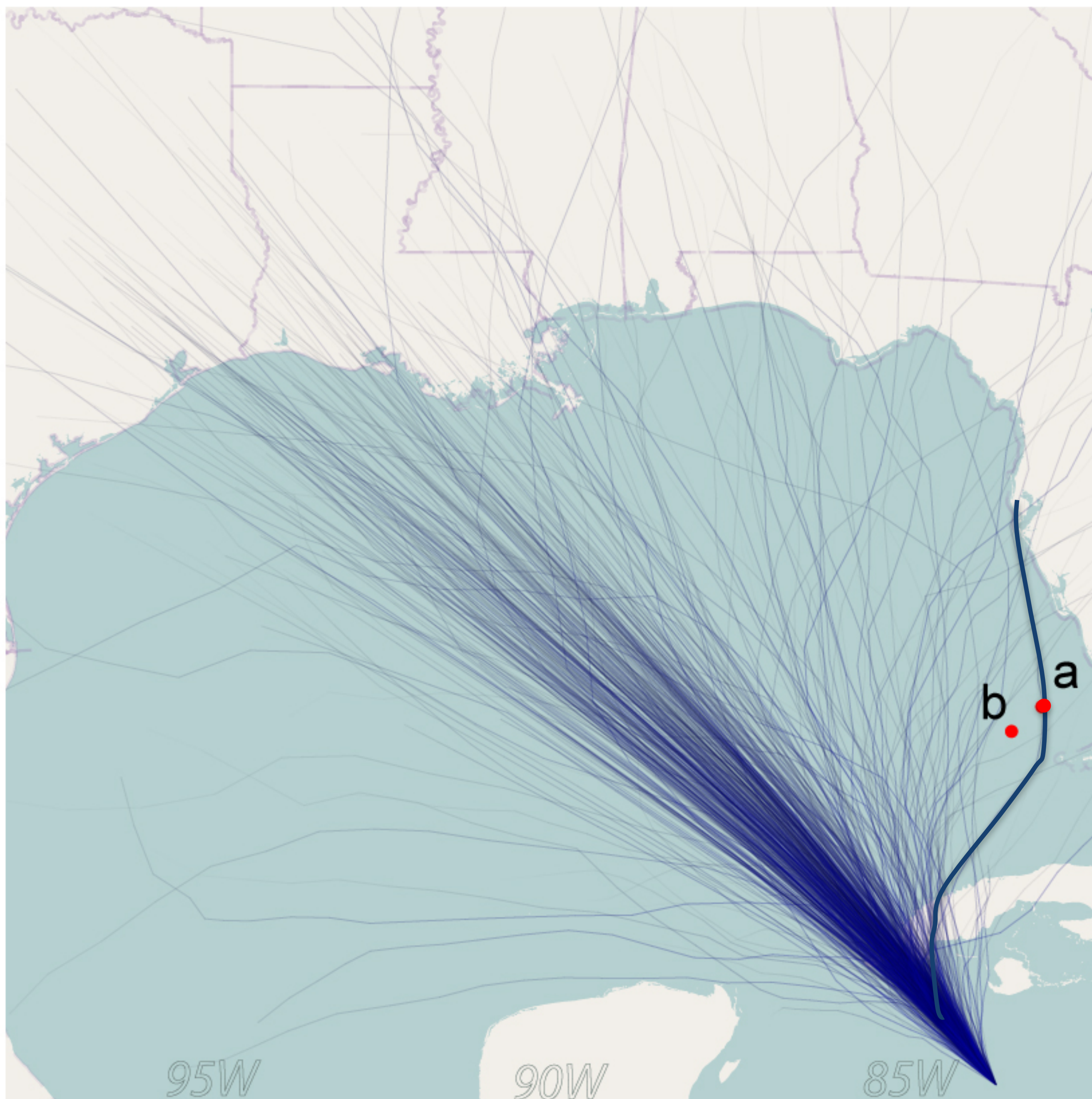


Which location would receive the most damage?

B: 99.68%



Which location would receive the most damage?

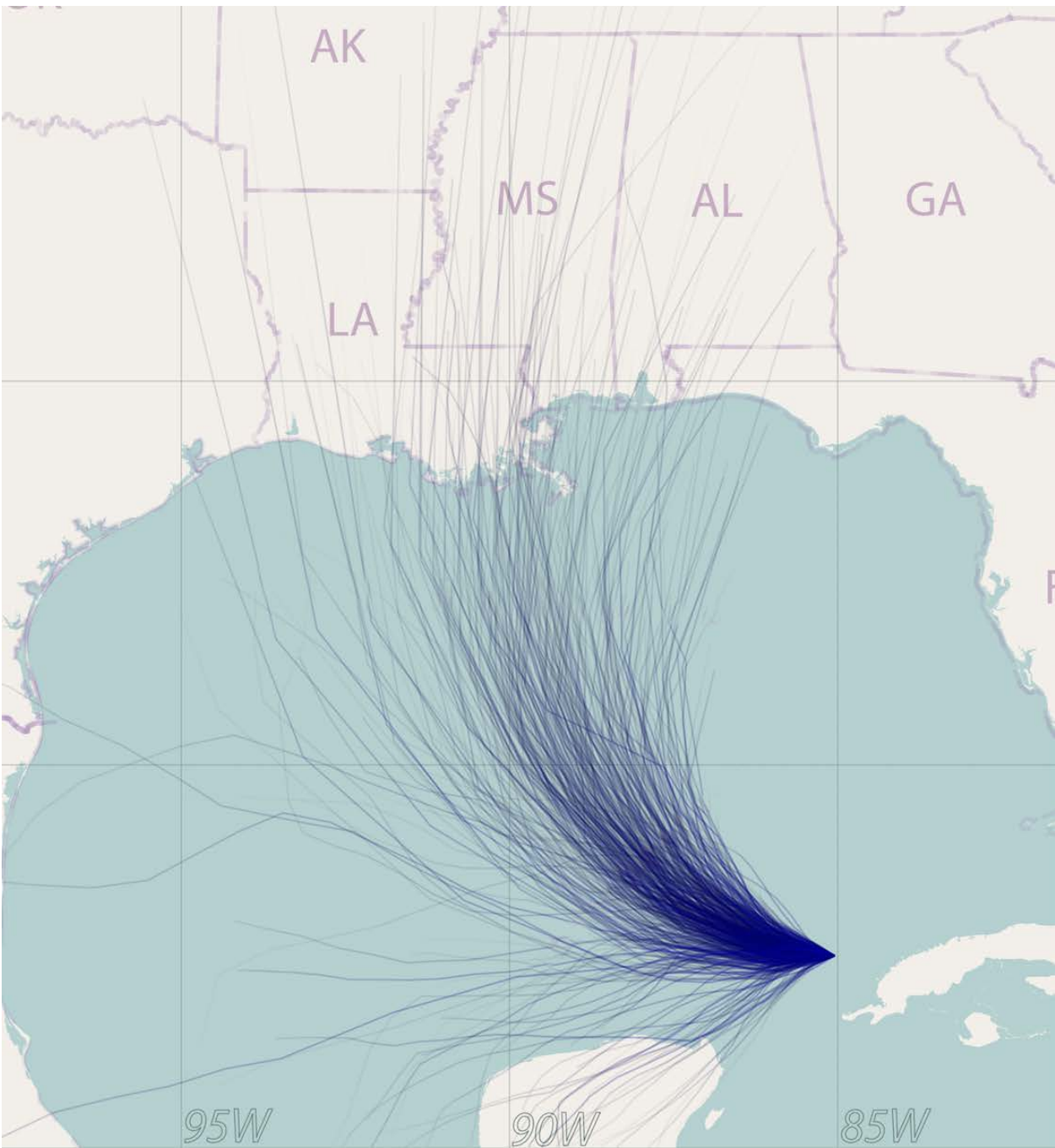
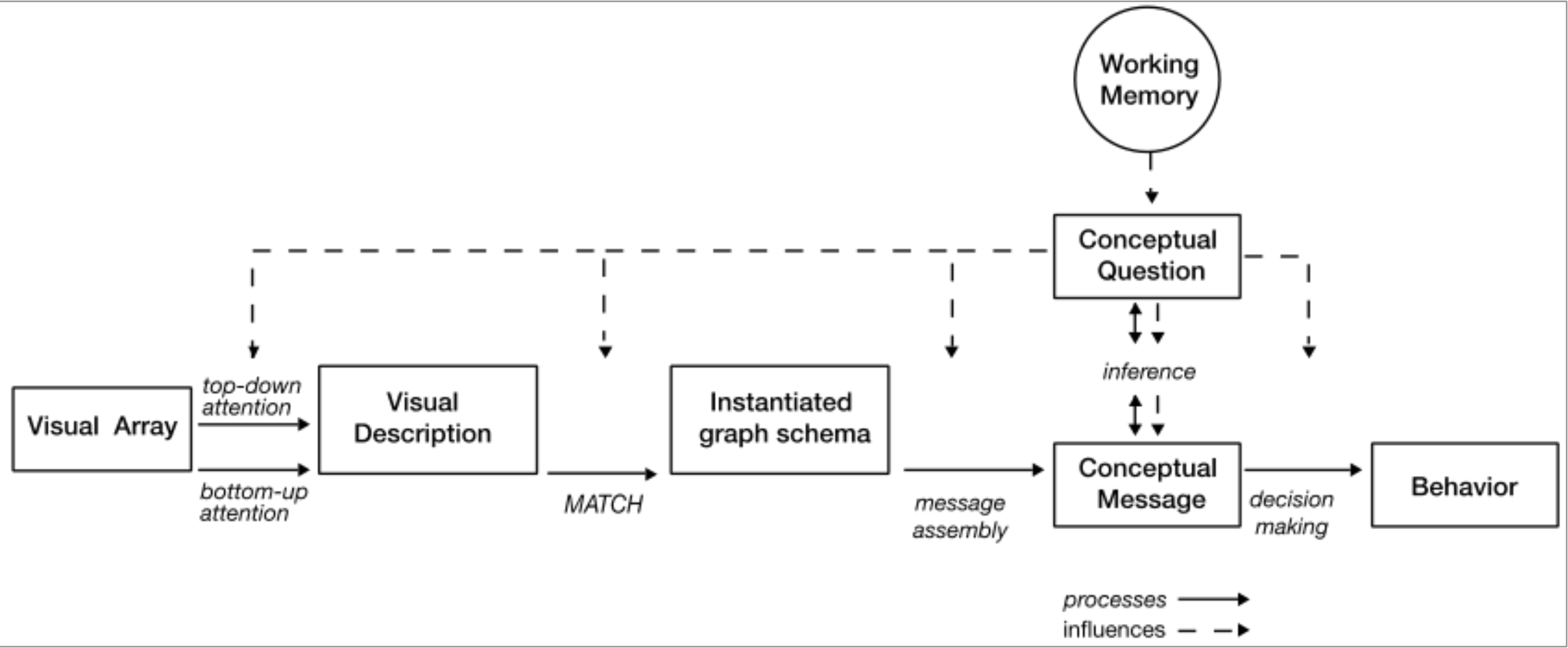
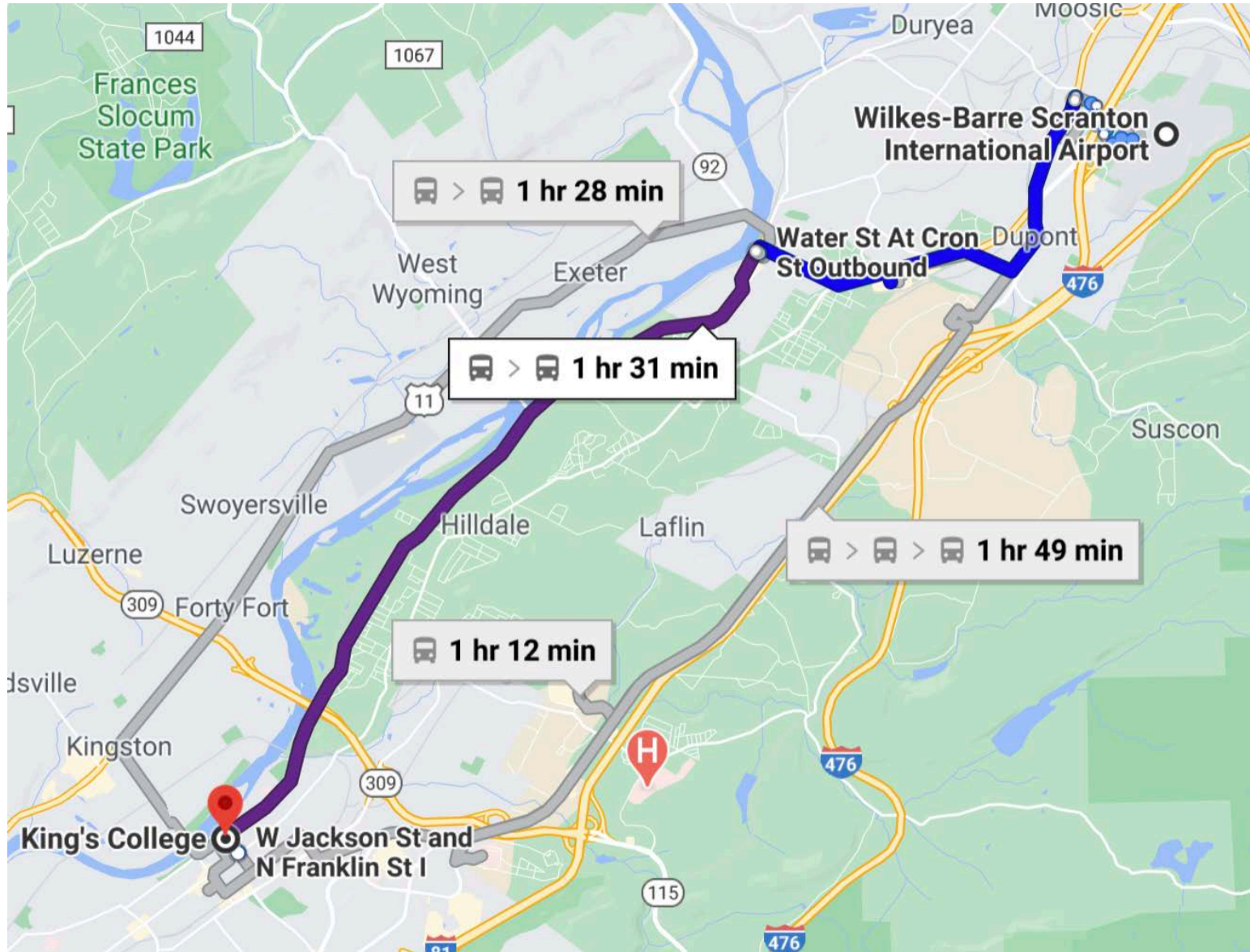


Which location would receive the most damage?

A: 36%

B: 64%

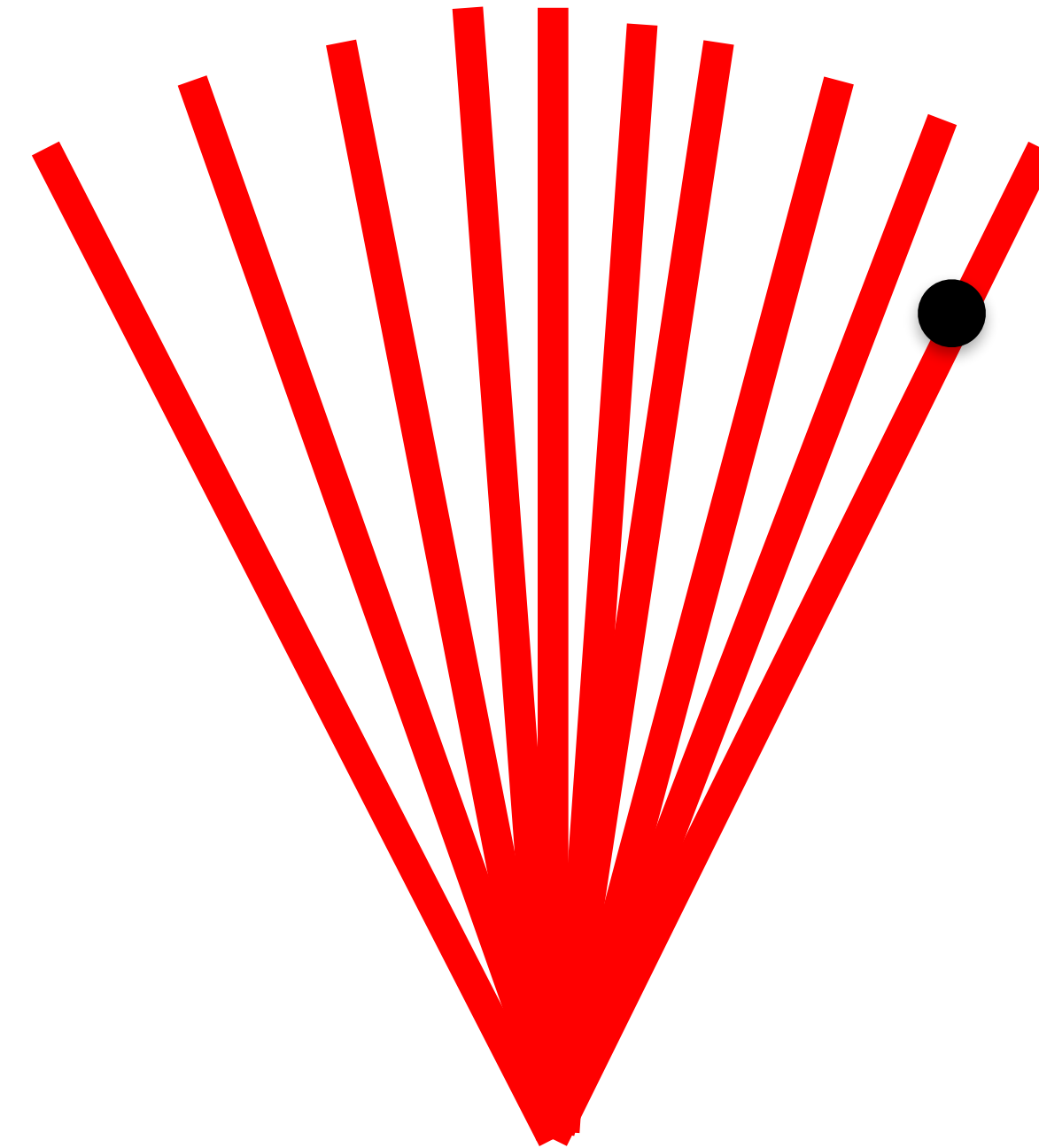
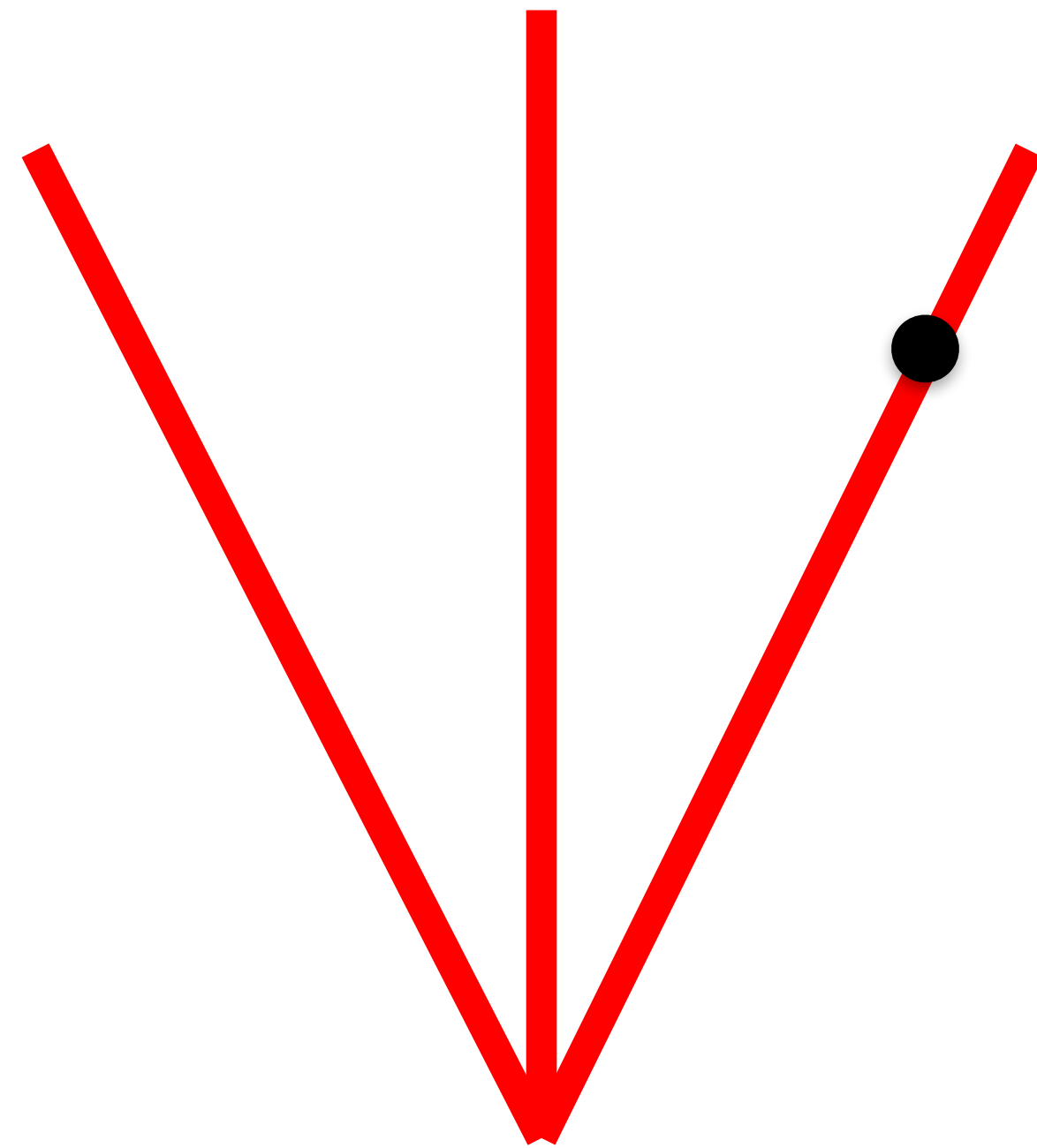
Graph Schema



33%

vs.

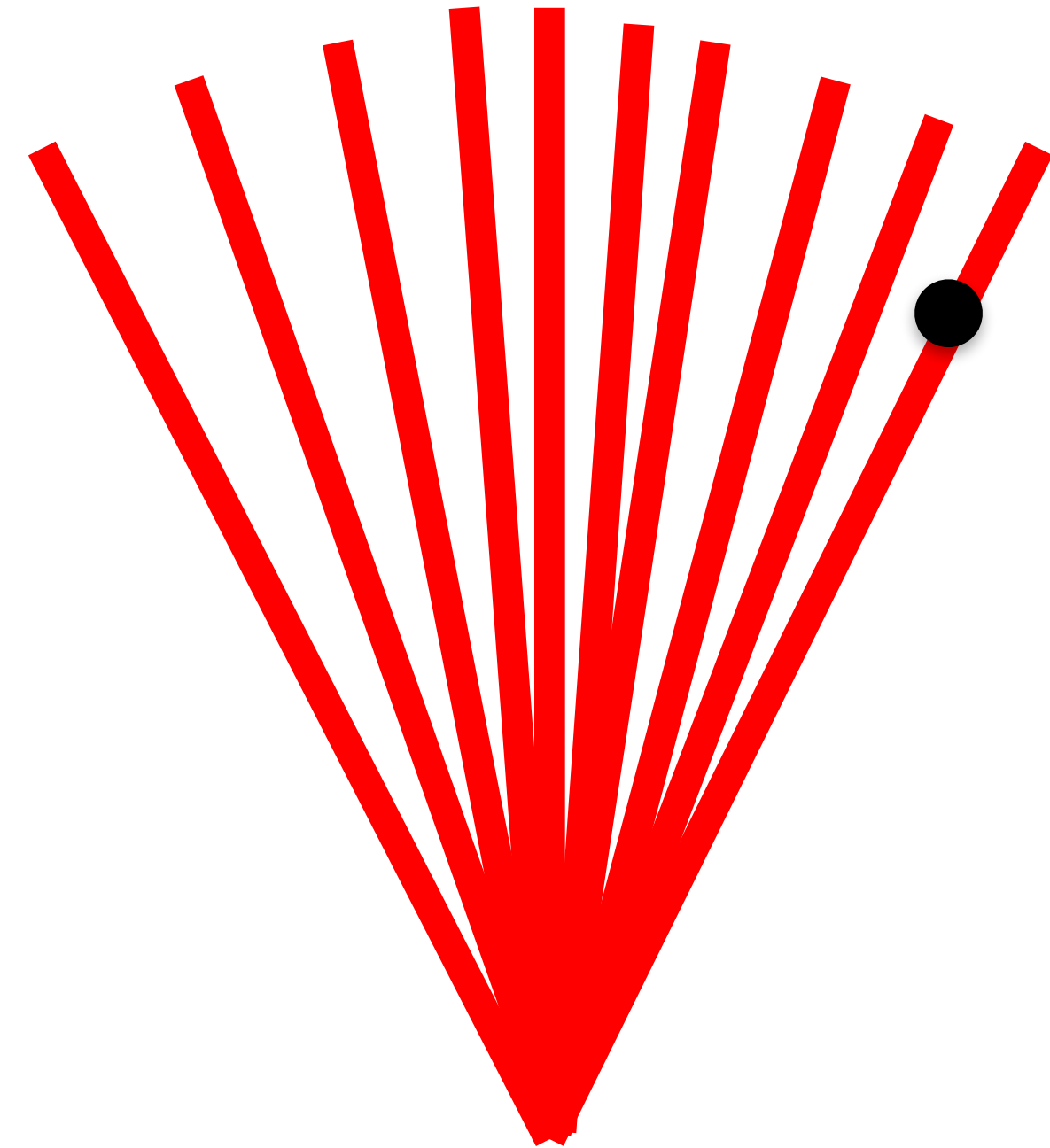
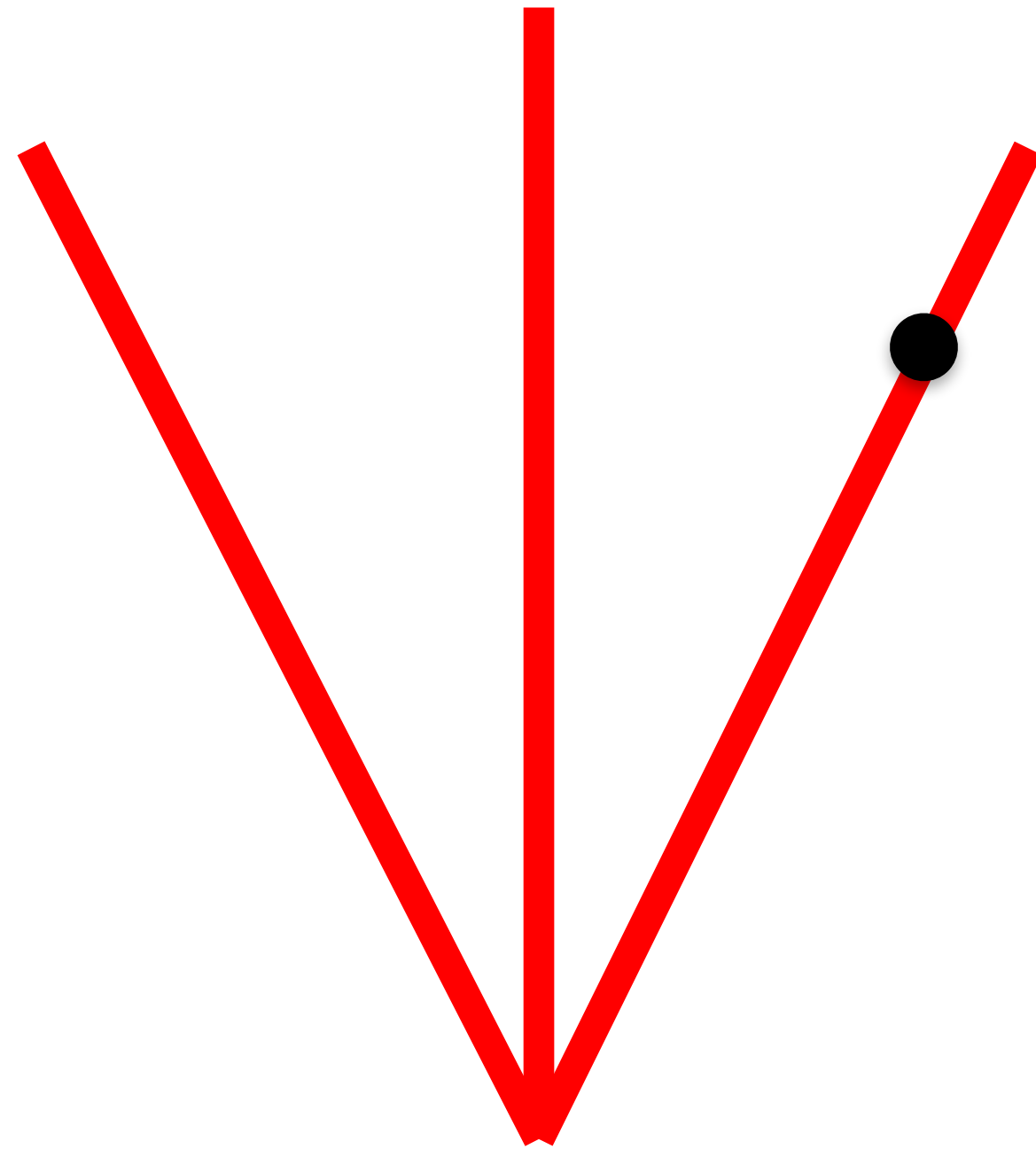
10%



33%

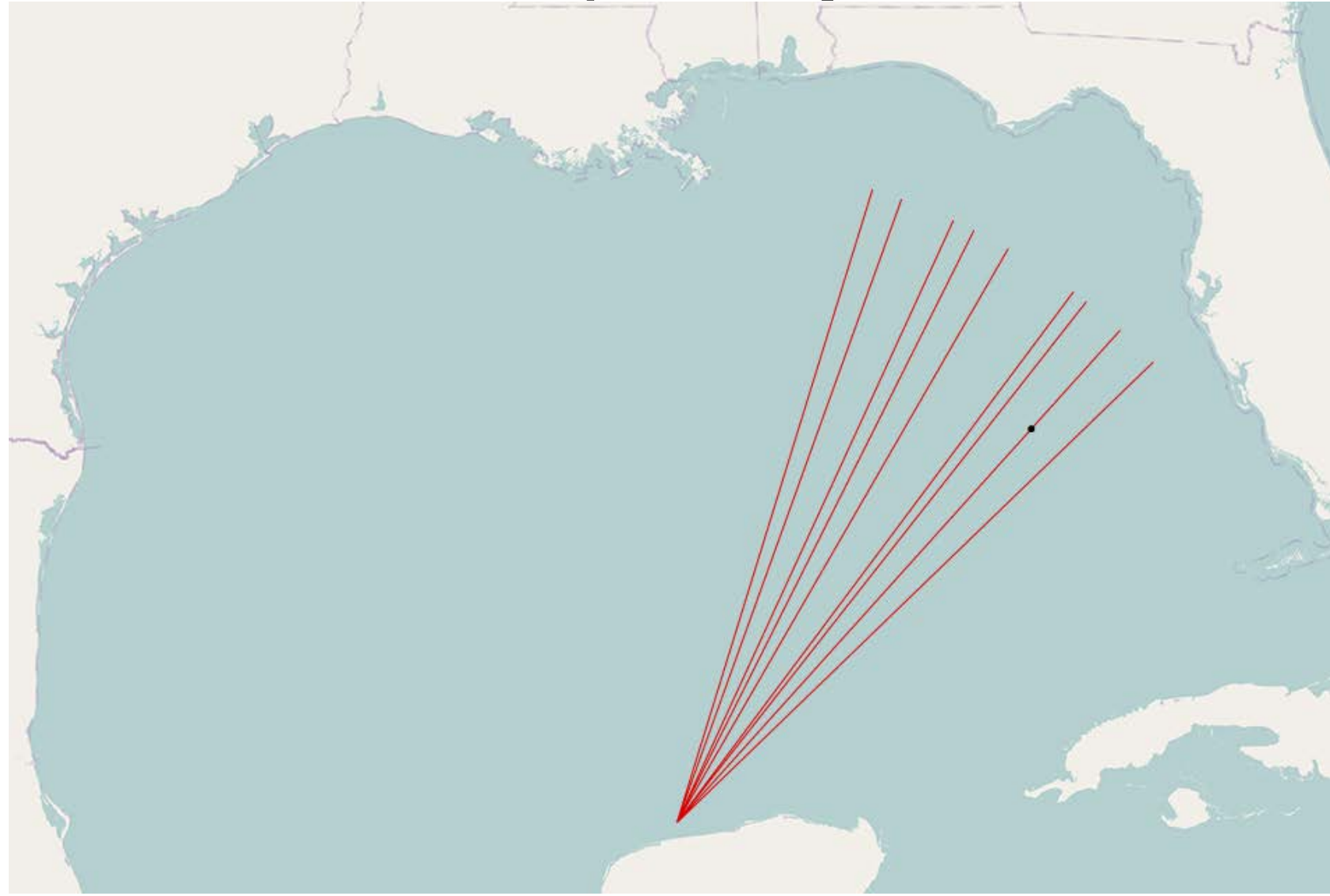
vs.

10%

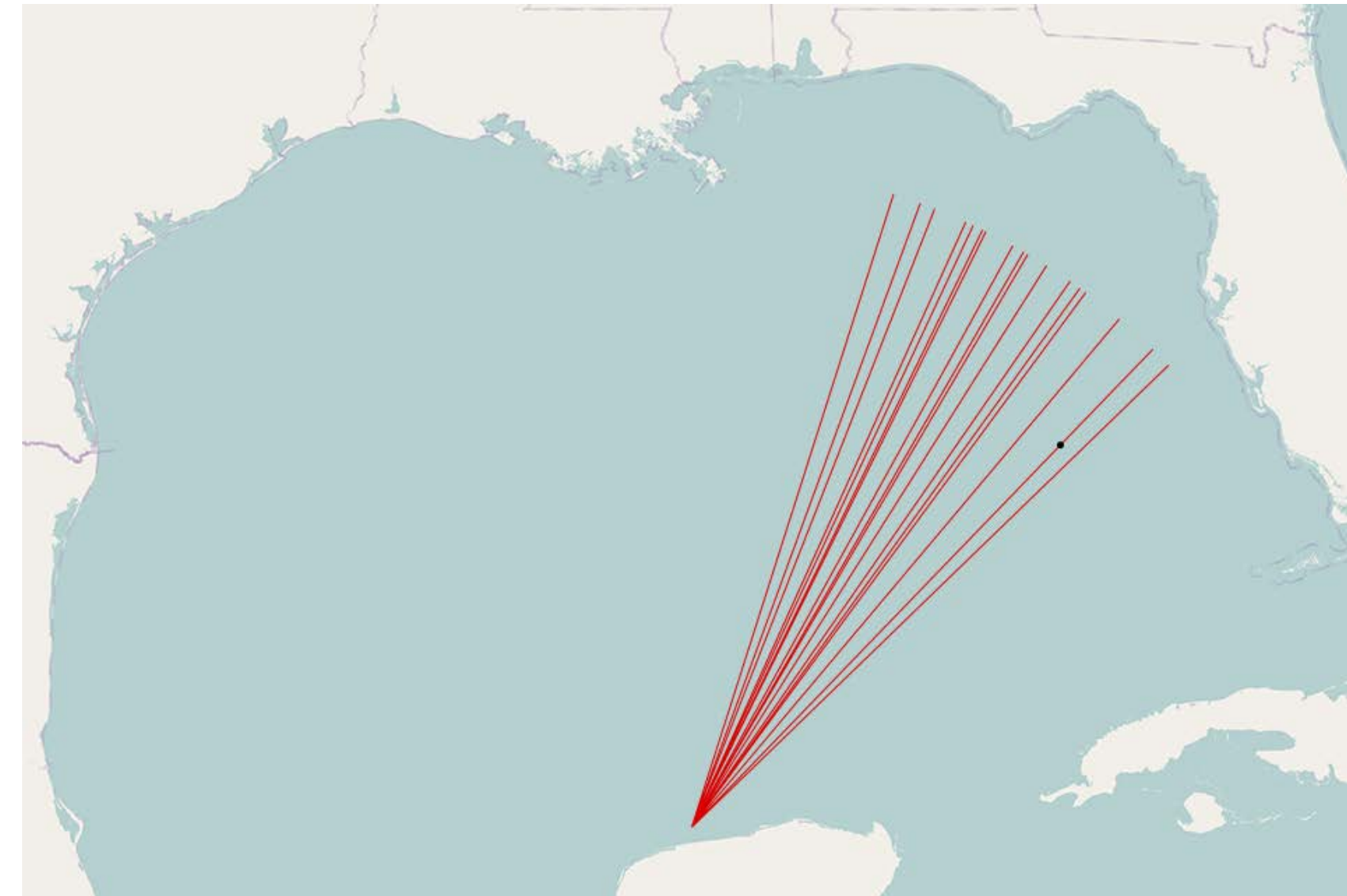


Between-subjects

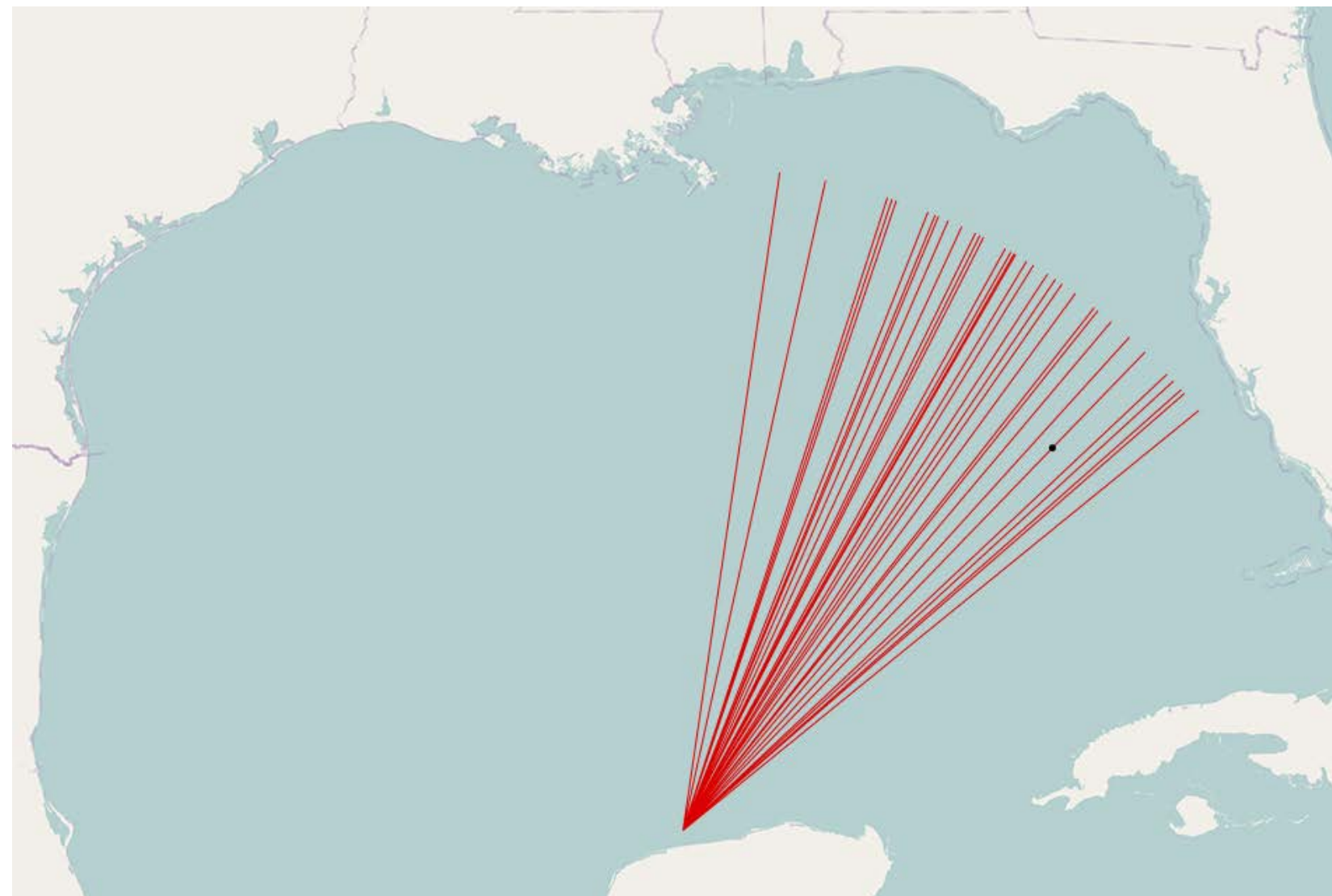
Group 1: 9 paths



Group 2: 17 paths

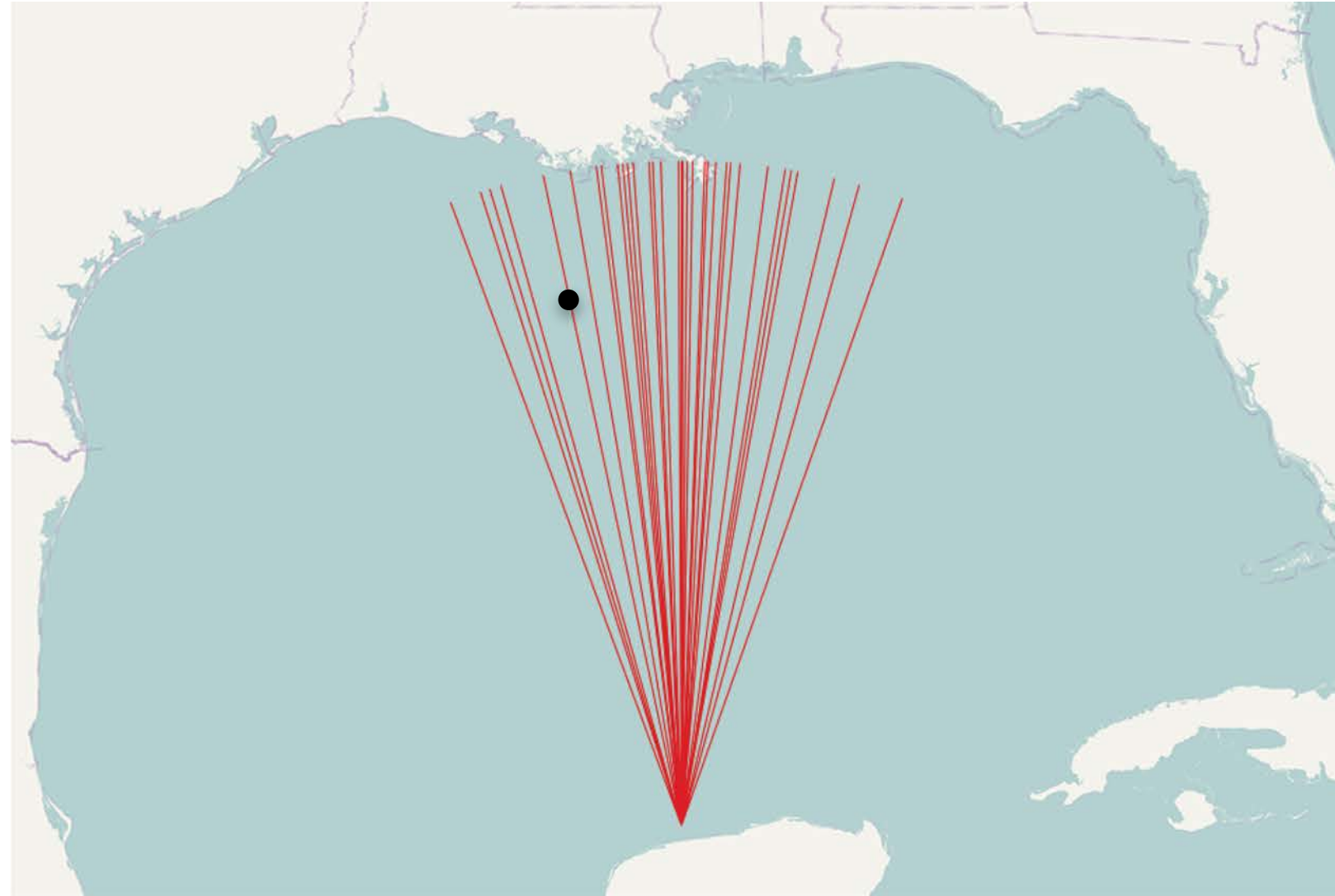


Group 3: 33 paths

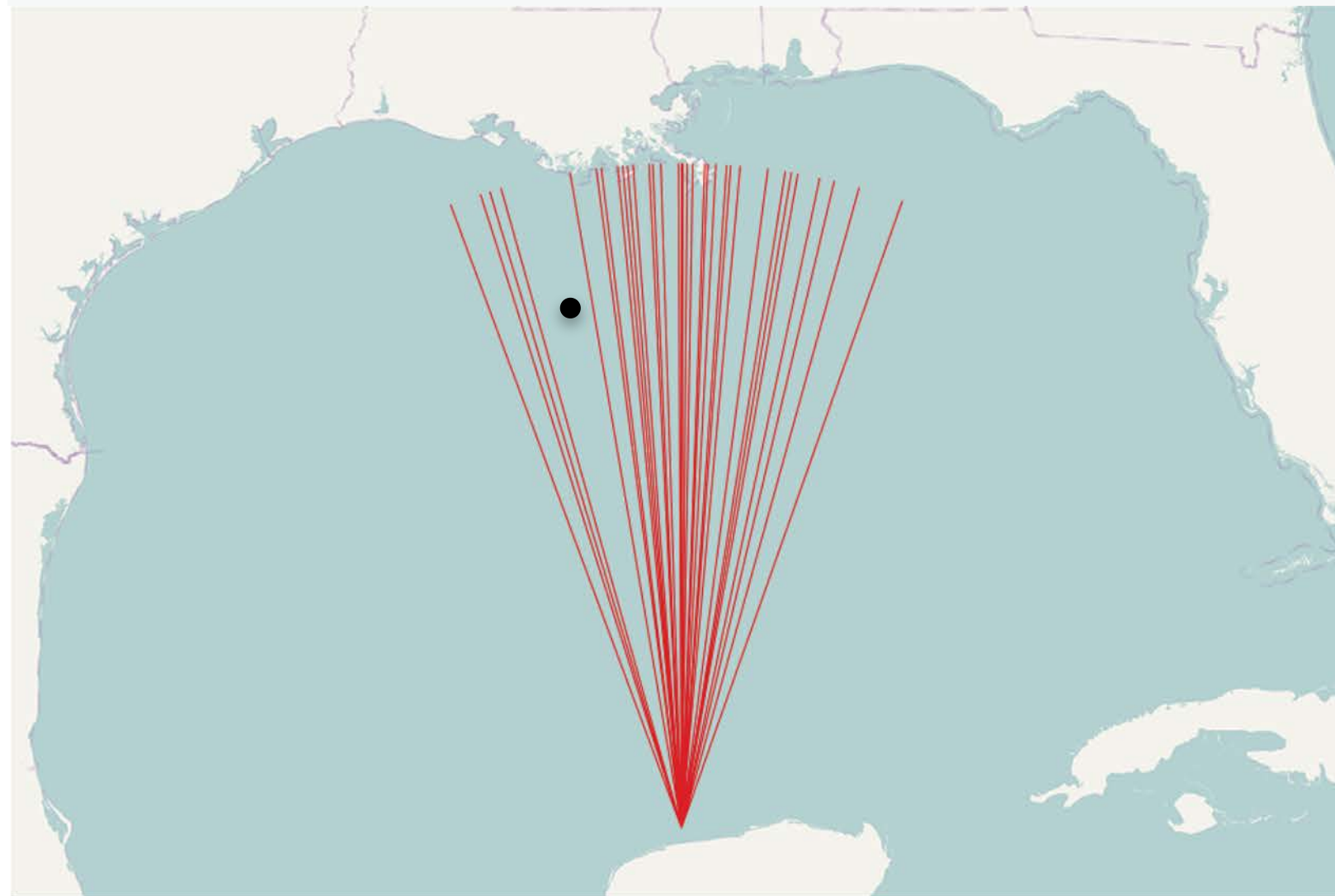


Within-subjects

On line



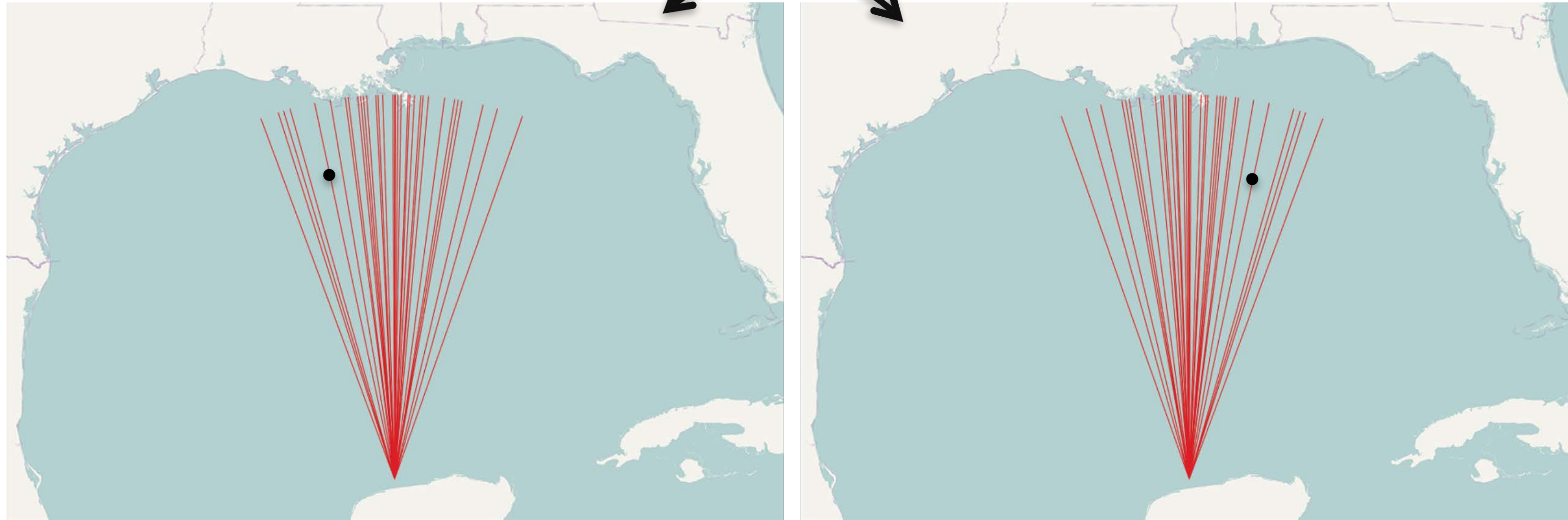
Off line



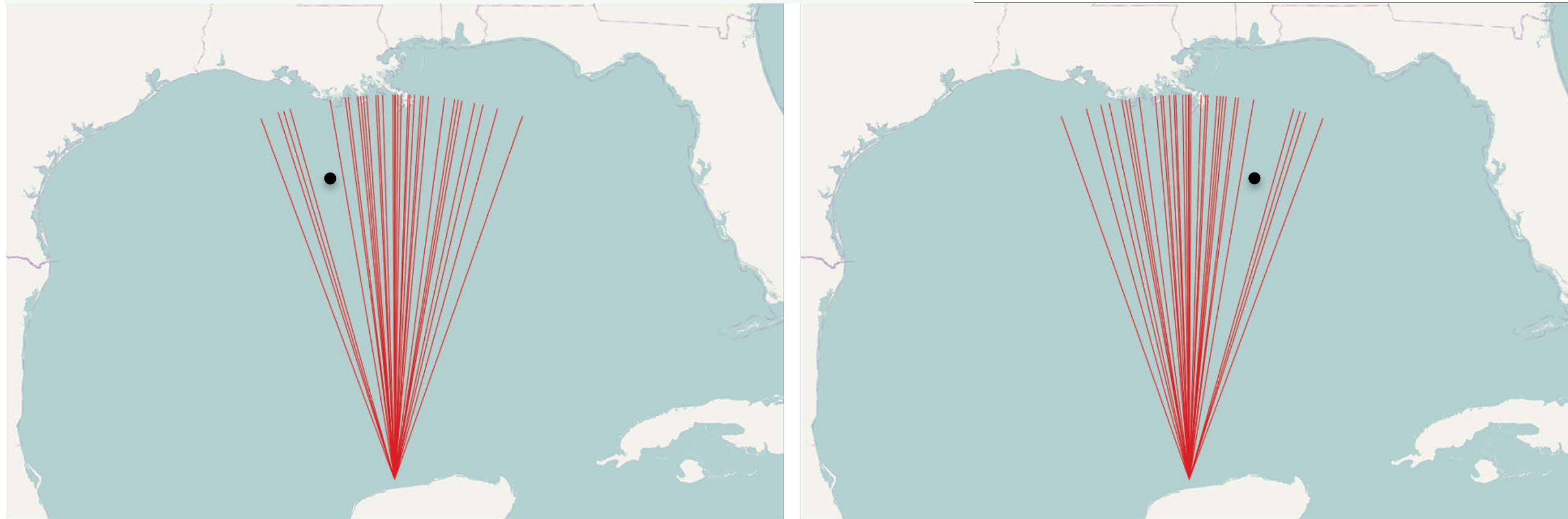
Within-subjects

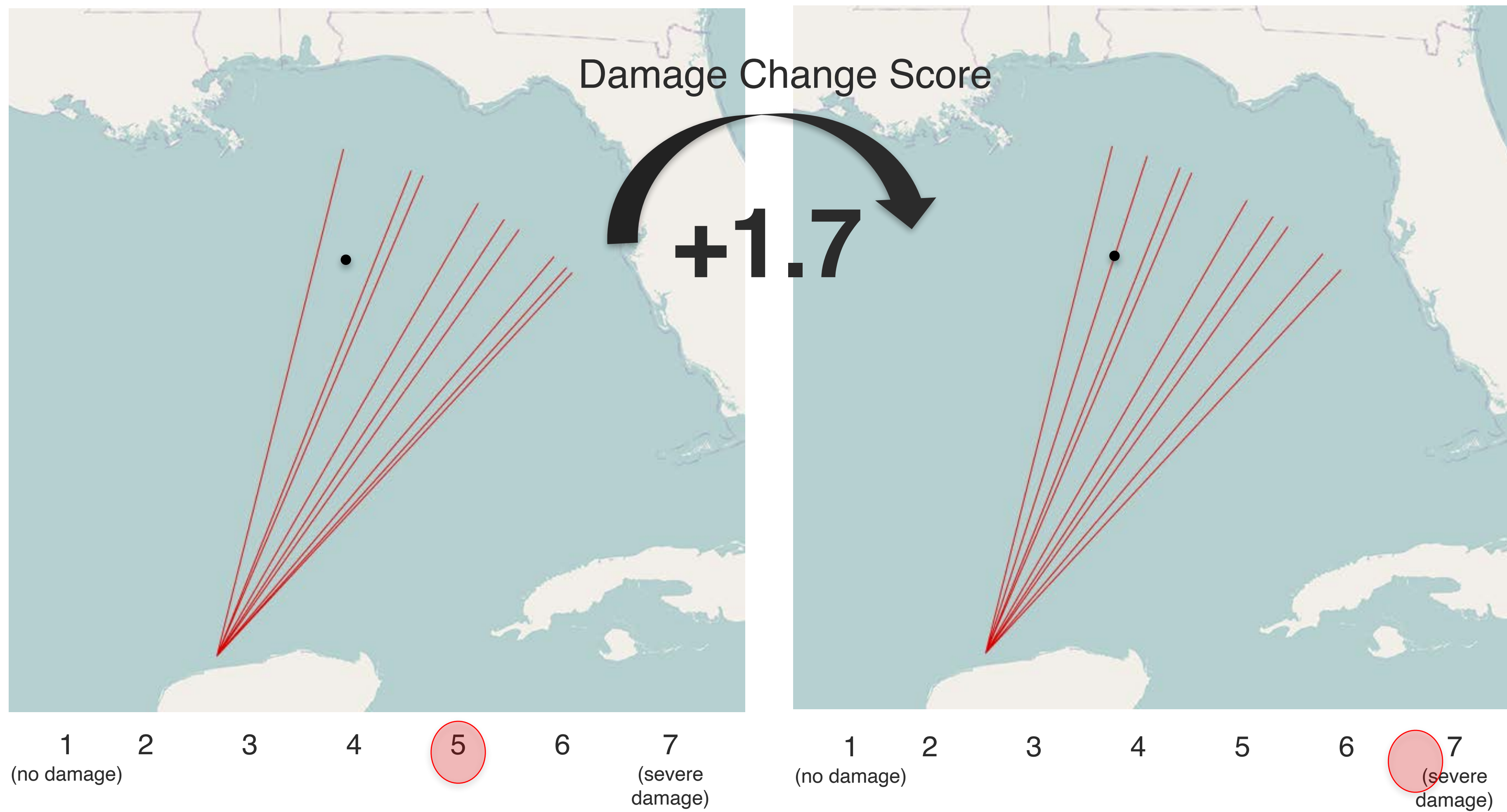
Mirrored image (reflection)

On line

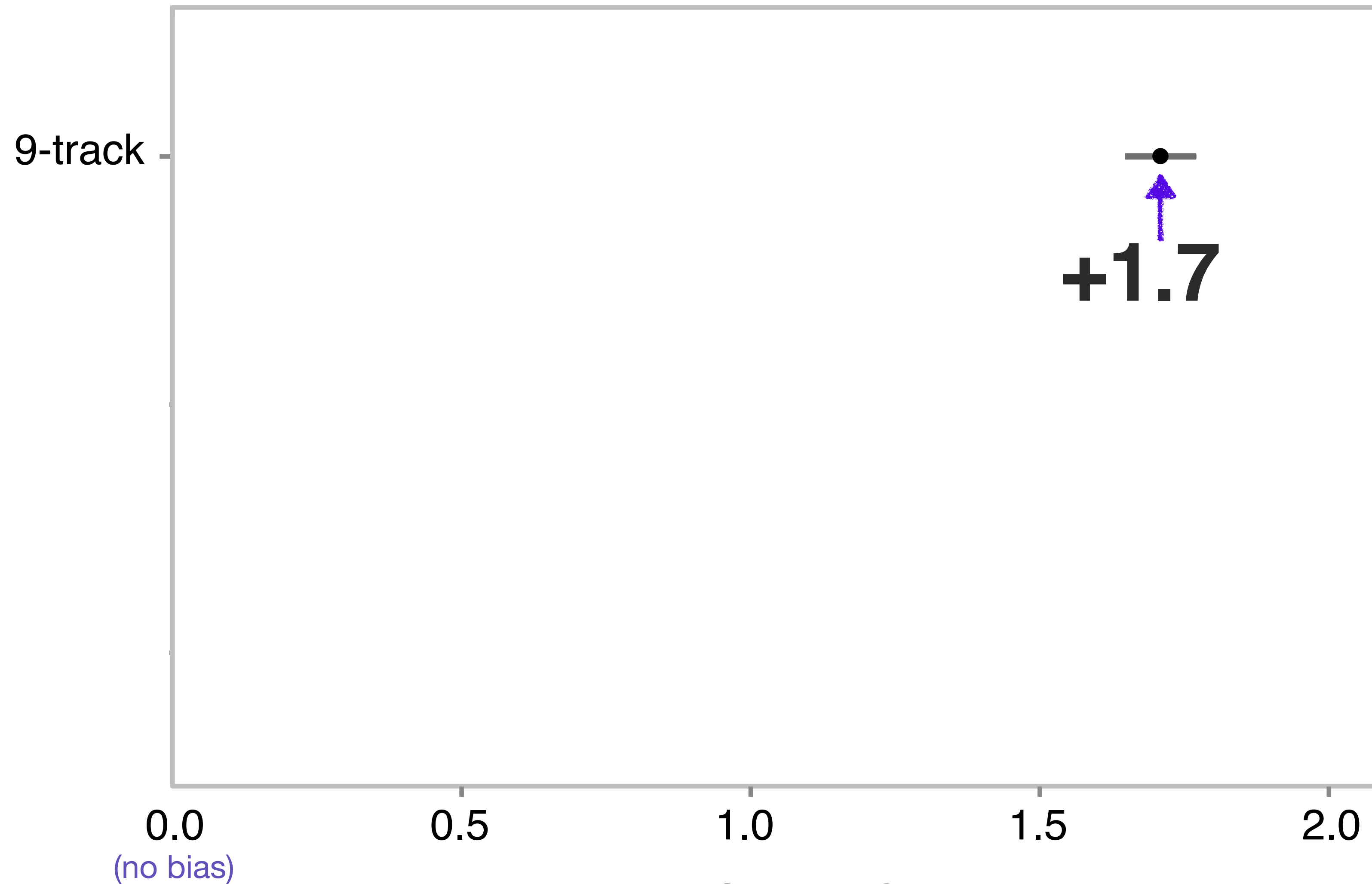


Off line



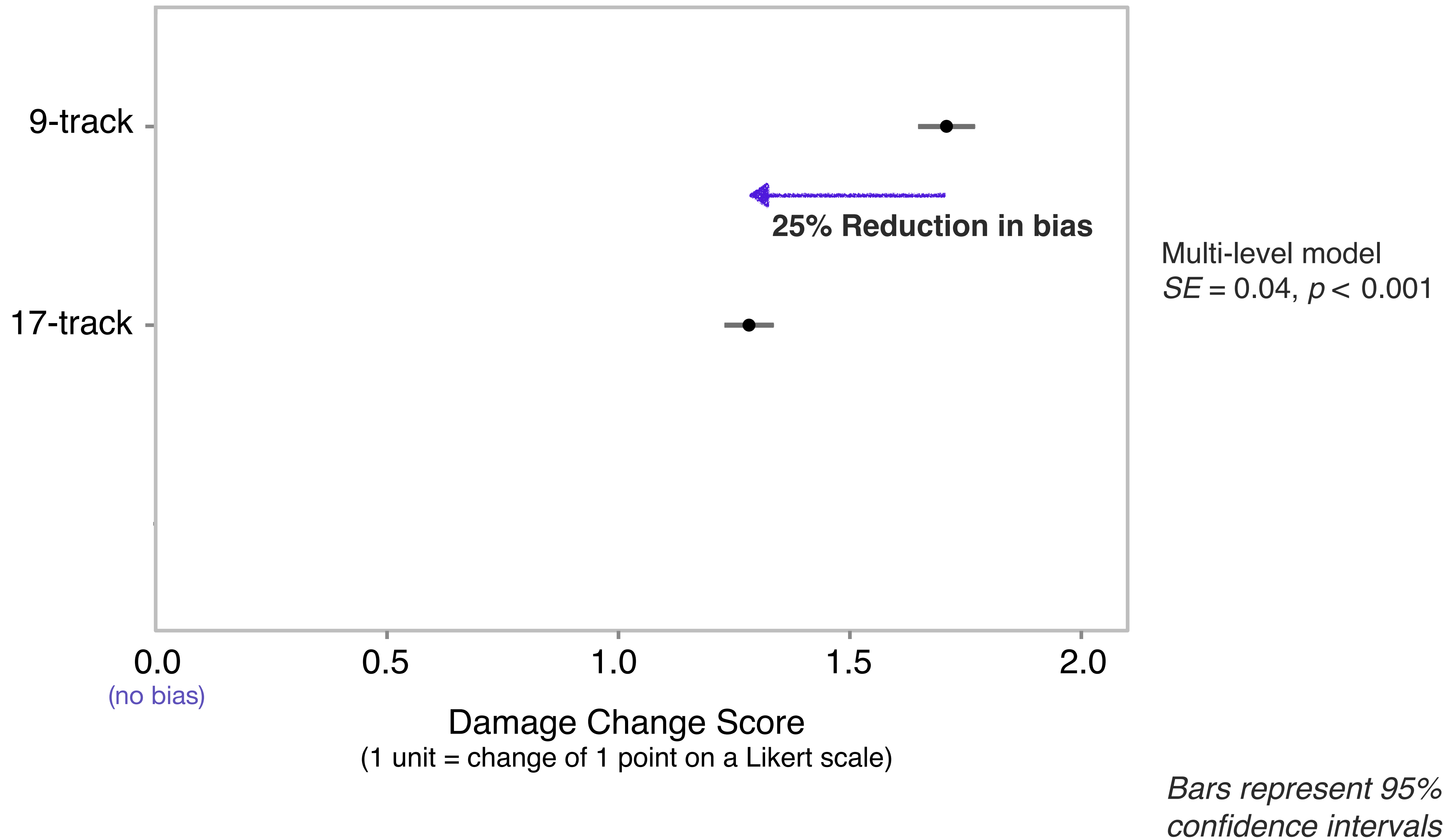


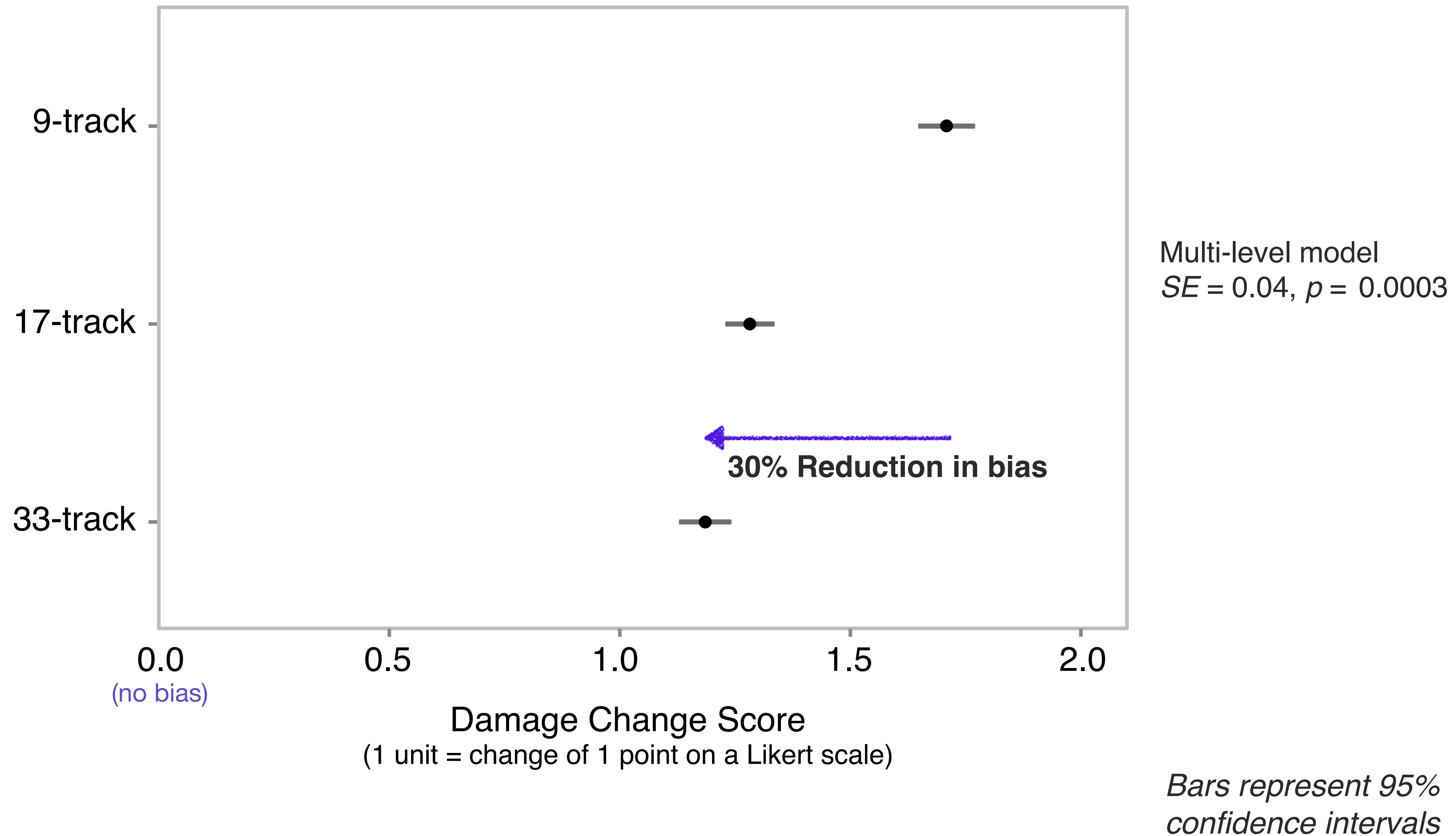
Multi-level model, $SE = 0.02$, $p < 0.001$

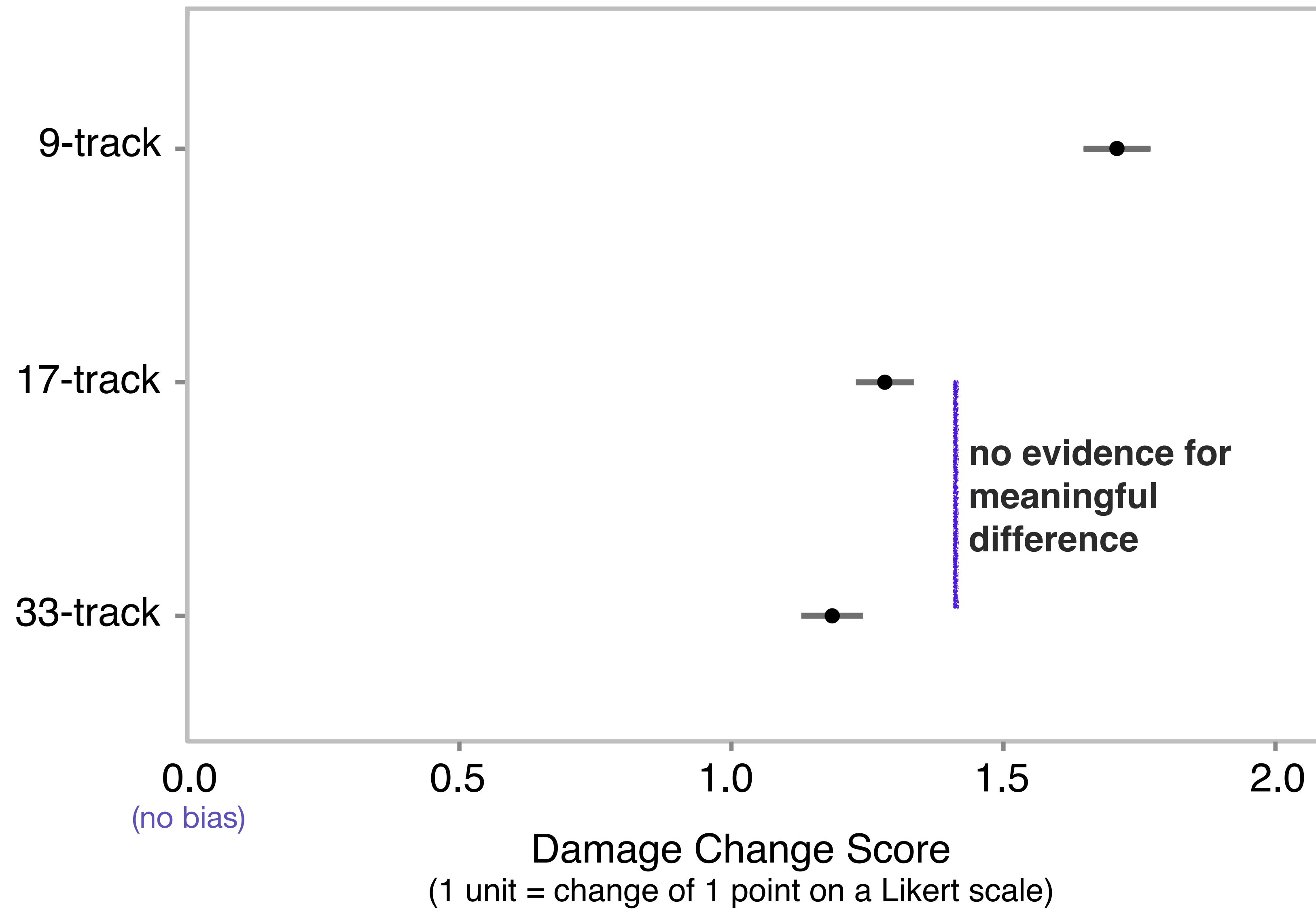


Damage Change Score
(1 unit = change of 1 point on a Likert scale)

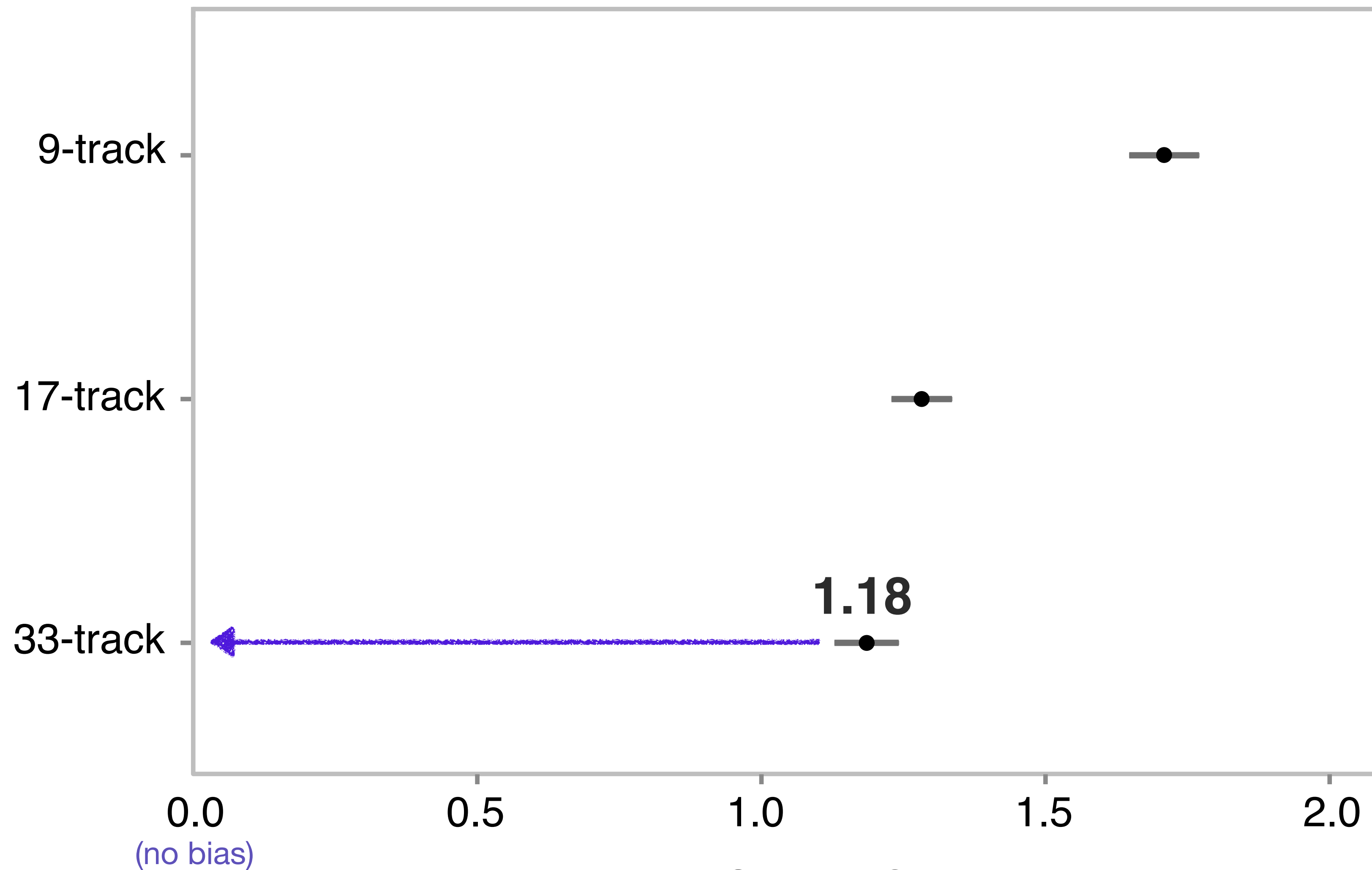
Bars represent 95% confidence intervals







Bars represent 95% confidence intervals

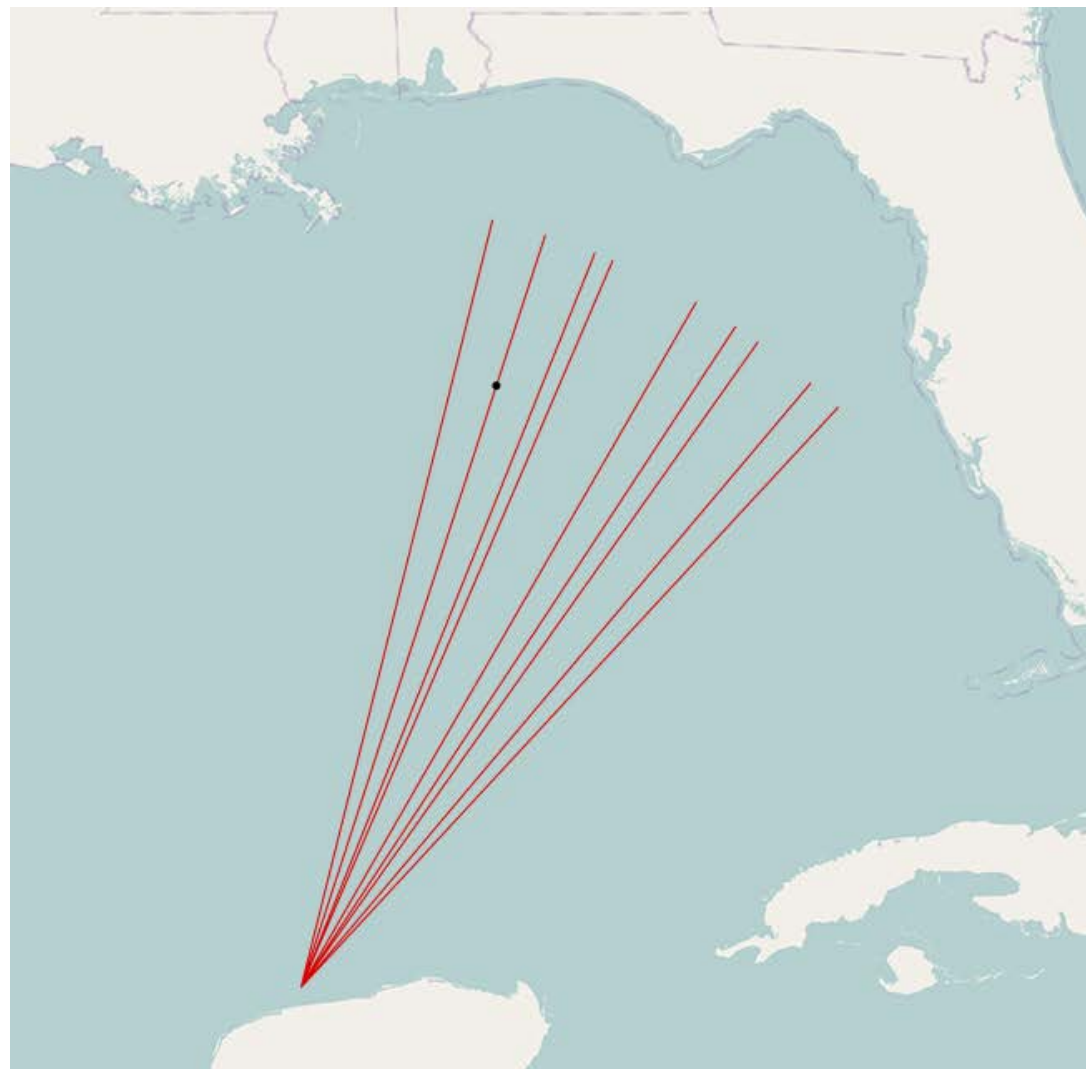


Damage Change Score
(1 unit = change of 1 point on a Likert scale)

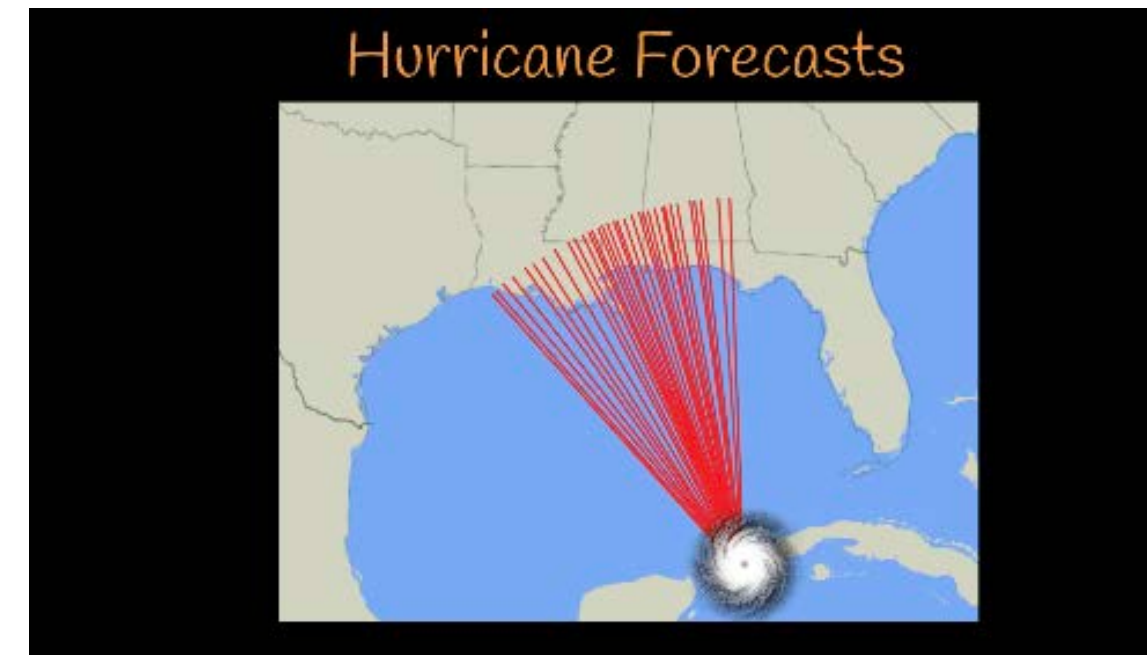
Bars represent 95% confidence intervals

Between-subjects

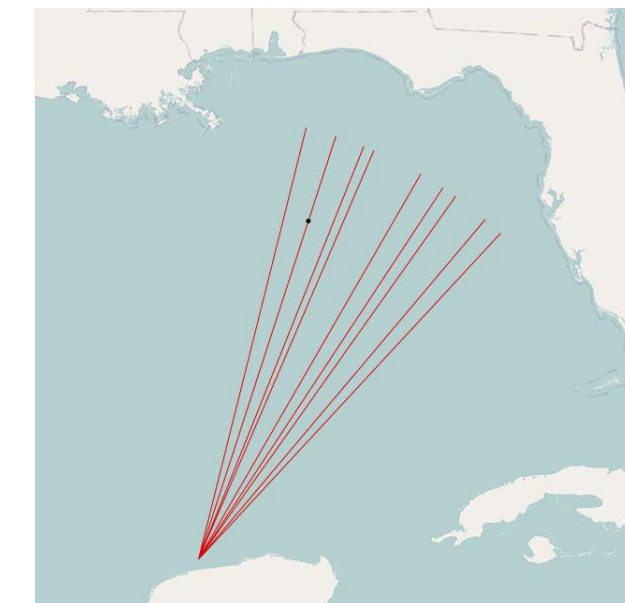
Group 1: No instructions



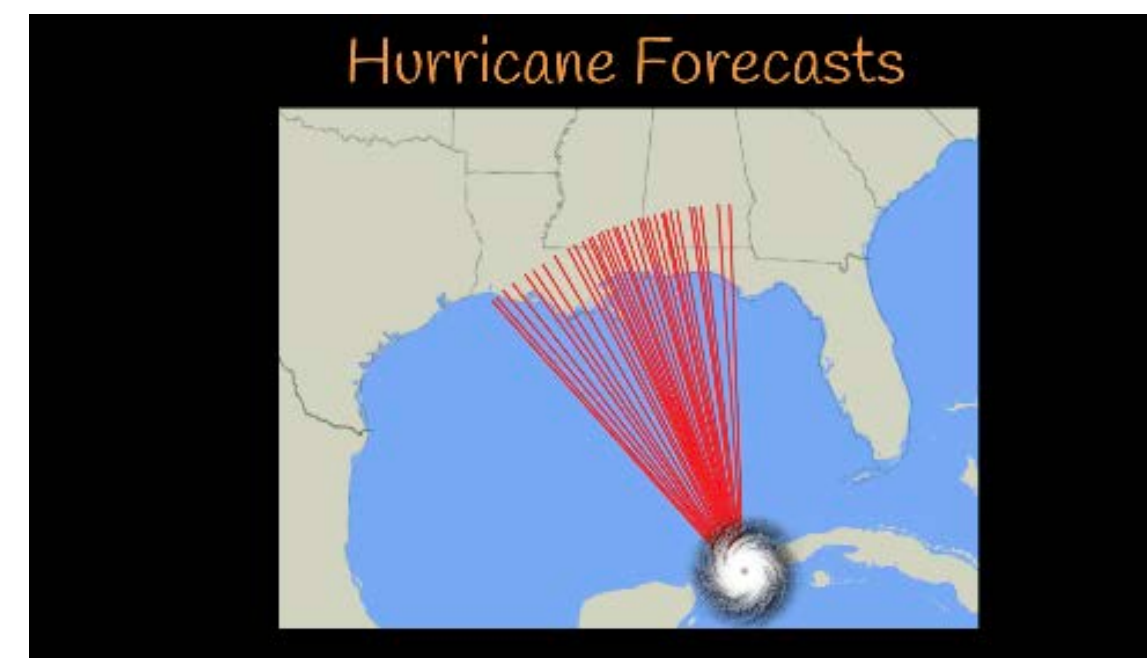
Group 2: Visualization instructions
(**1:37** minutes)



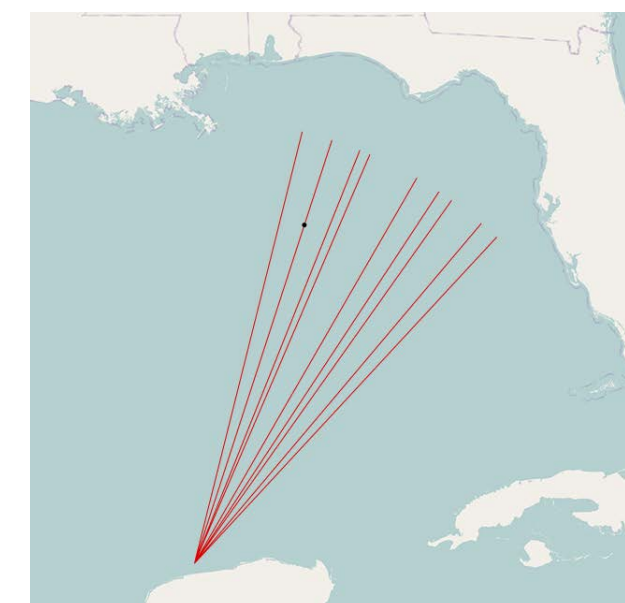
+



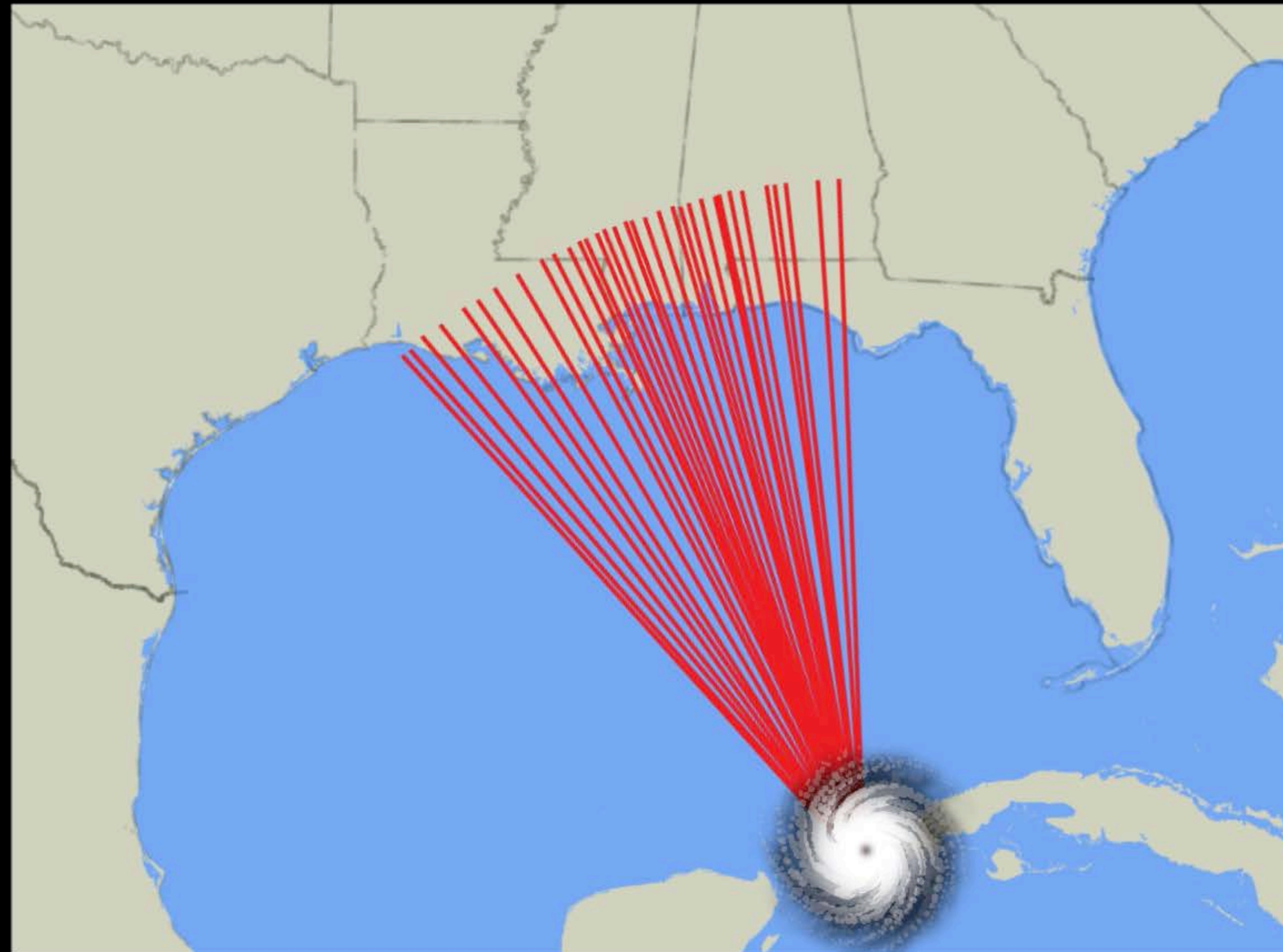
Group 3: Task-specific instructions
(**3:13** minutes)



+

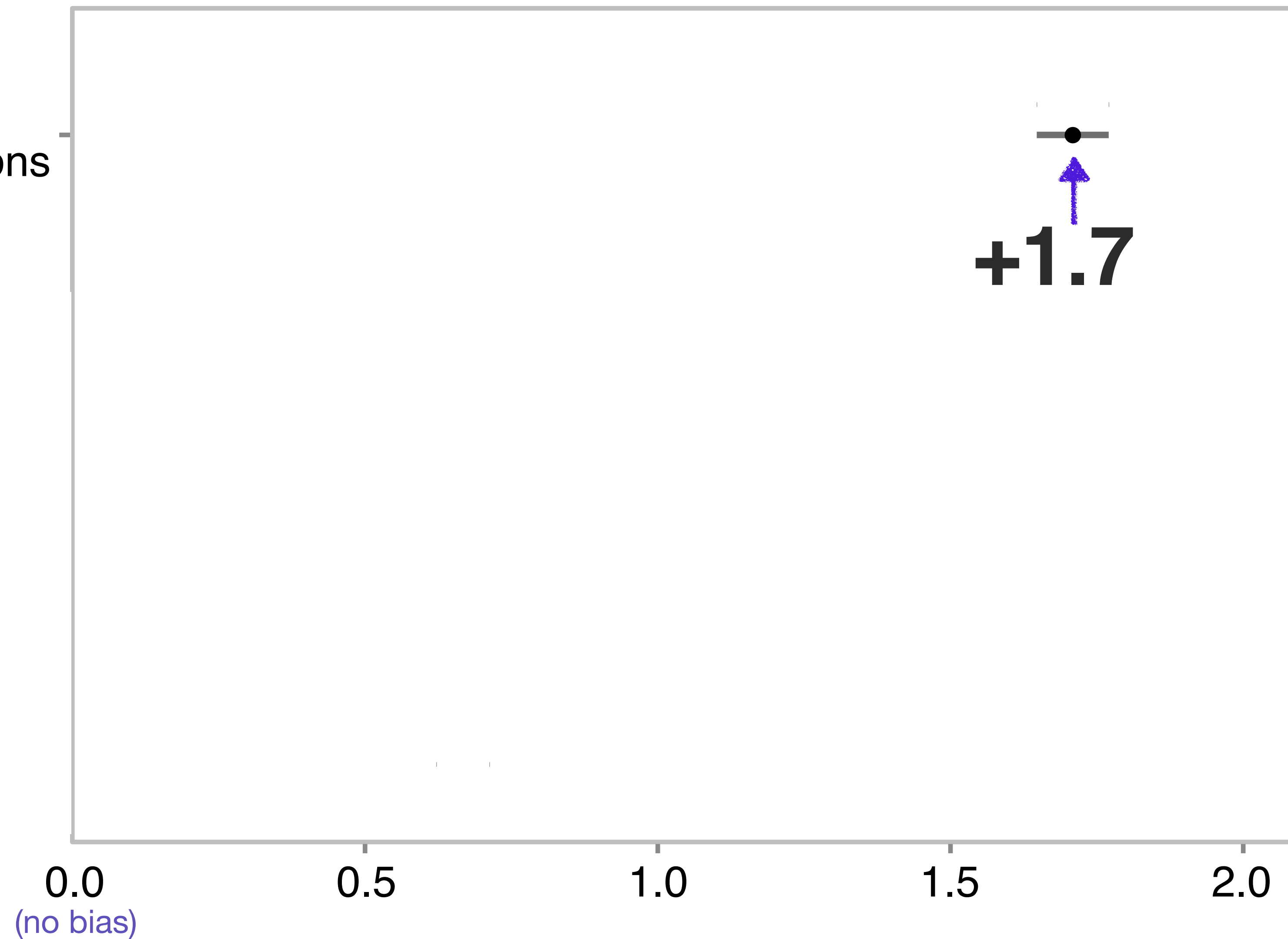


Hurricane Forecasts



Based on guidelines in Zapata-Rivera, Zwick, and Vezzu (2016). *Exploring the Effectiveness of a Measurement Error Tutorial in Helping Teachers Understand Score Report Results*

9-track
No Instructions



Damage Change Score
(1 unit = change of 1 point on a Likert scale)

Bars represent 95% confidence intervals

9-track
No Instructions

9-track
(1:37 min)
Visualization
Instructions

0.0
(no bias)

0.5

1.0

1.5

2.0

Damage Change Score
(1 unit = change of 1 point on a Likert scale)

43% Reduction in bias

Multi-level model
 $SE = 0.05, p < 0.001$

*Bars represent 95%
confidence intervals*

9-track
No Instructions

9-track
(1:37 min)
Visualization
Instructions

9-track
(3:13 min)
Task-specific
Instructions

0.0
(no bias)

0.5

1.0

1.5

2.0

Damage Change Score

(1 unit = change of 1 point on a Likert scale)

Multi-level model
 $SE = 0.04, p < 0.001$

60% Reduction in bias

*Bars represent 95%
confidence intervals*

9-track
No Instructions

9-track
(1:37 min)
Visualization
Instructions

9-track
(3:13 min)
Task-specific
Instructions

0.0
(no bias)

0.5

1.0

1.5

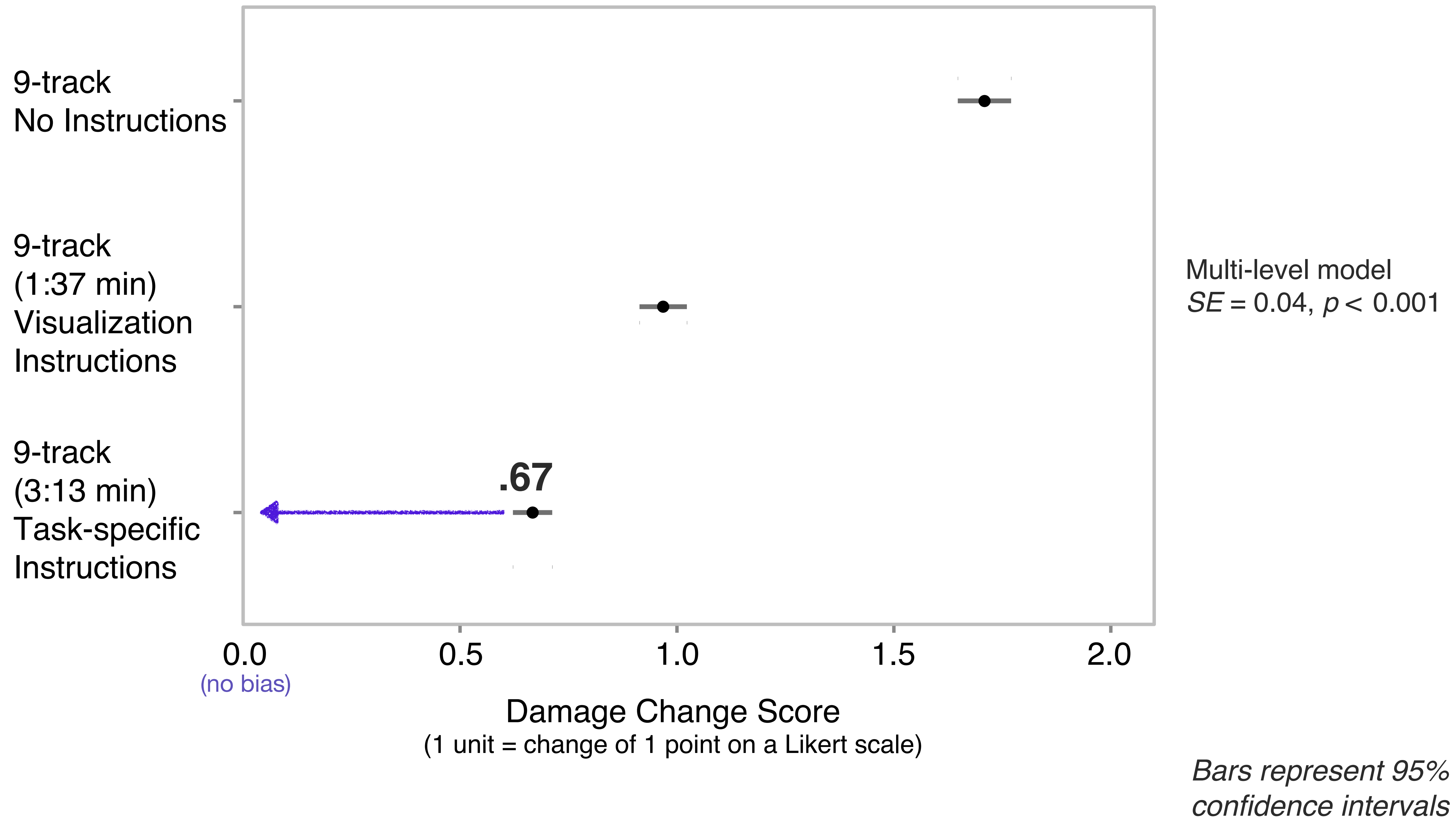
2.0

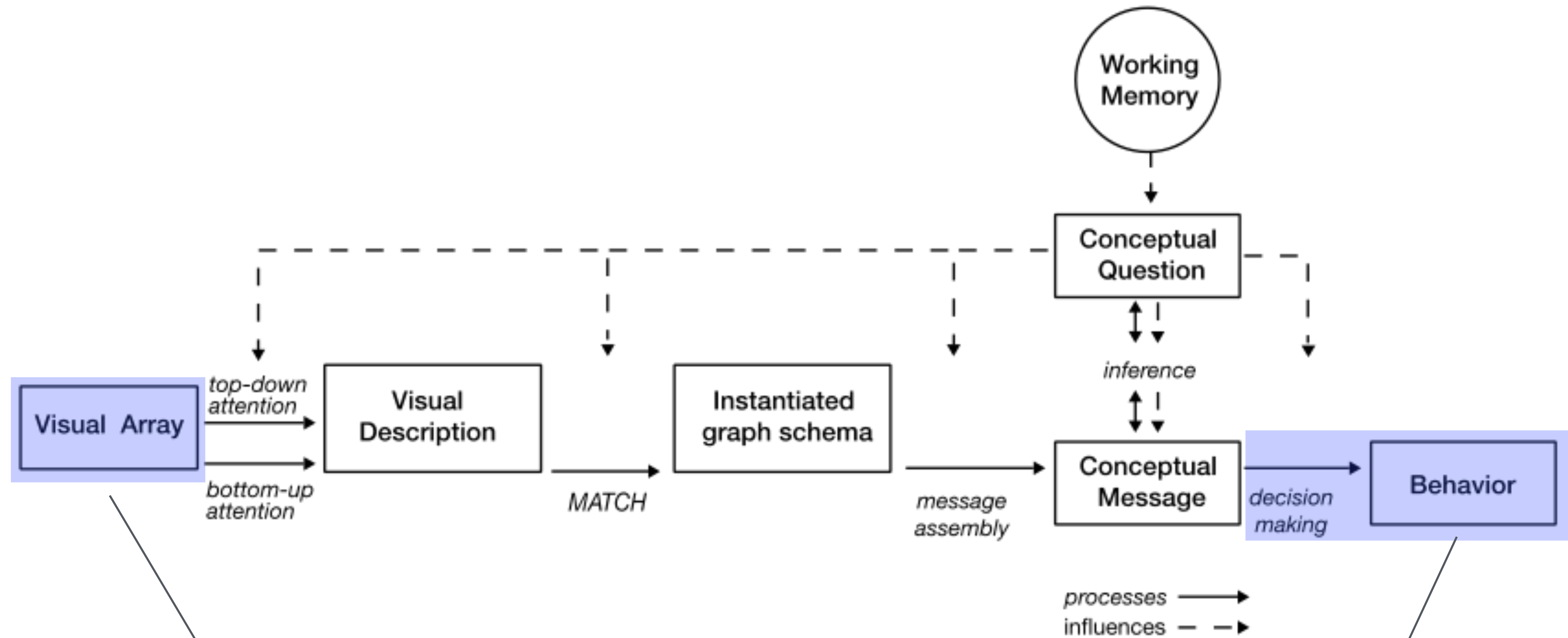
Damage Change Score
(1 unit = change of 1 point on a Likert scale)

meaningful
difference

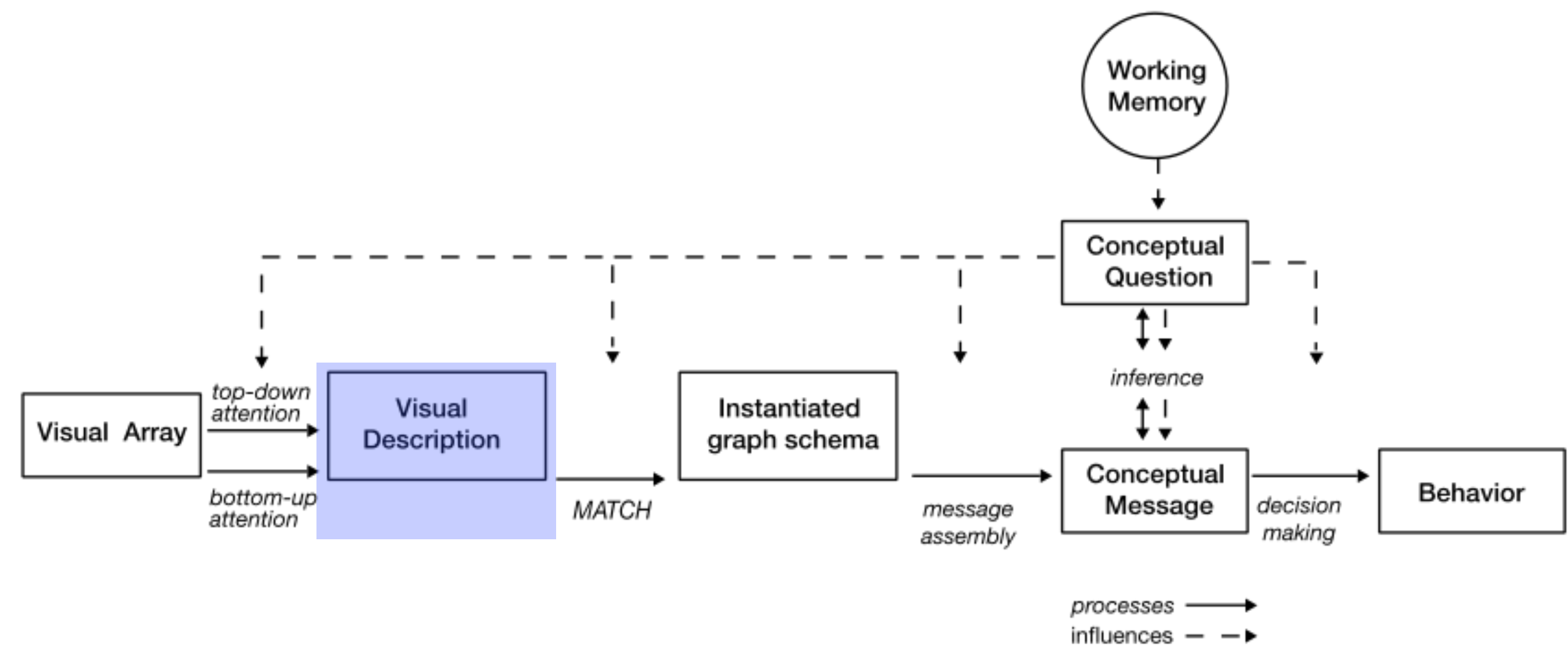
Multi-level model
 $SE = 0.04, p < 0.001$

*Bars represent 95%
confidence intervals*

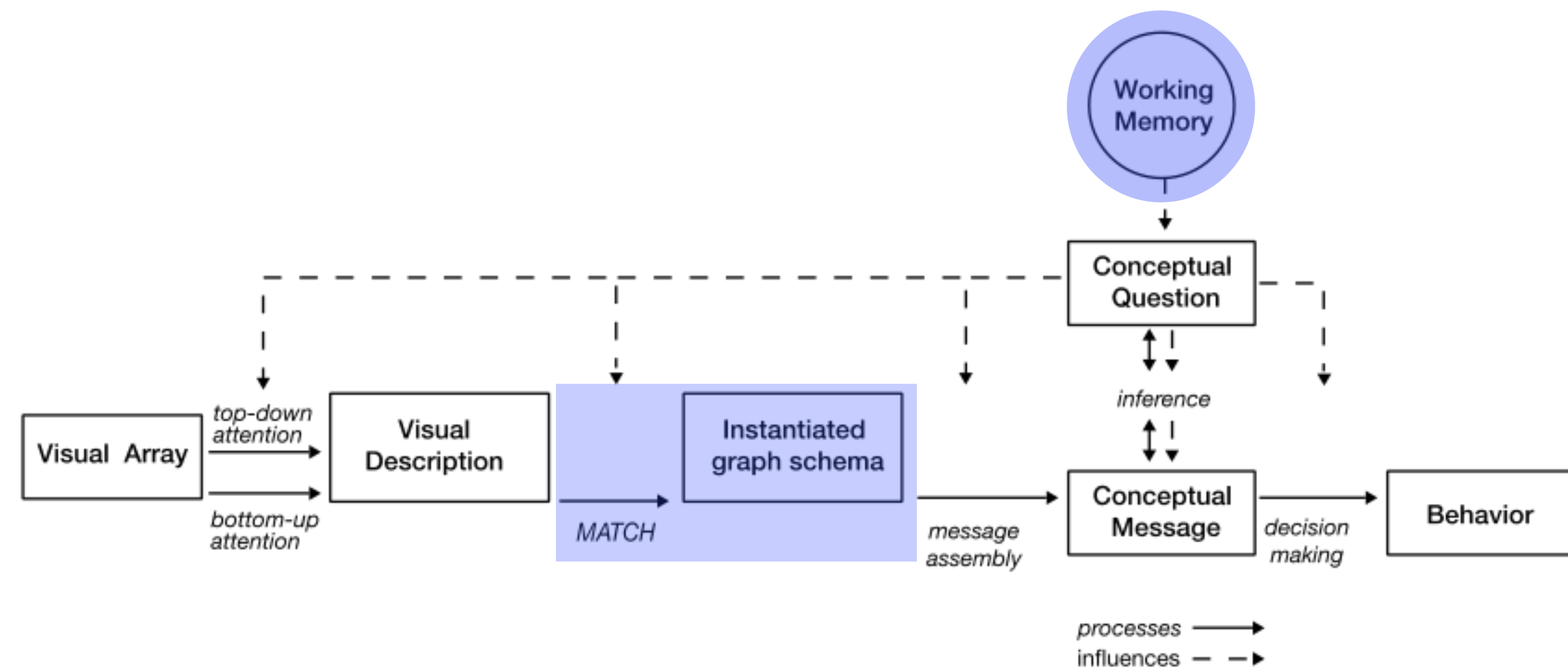




Fix the visualization, not the viewer's behavior

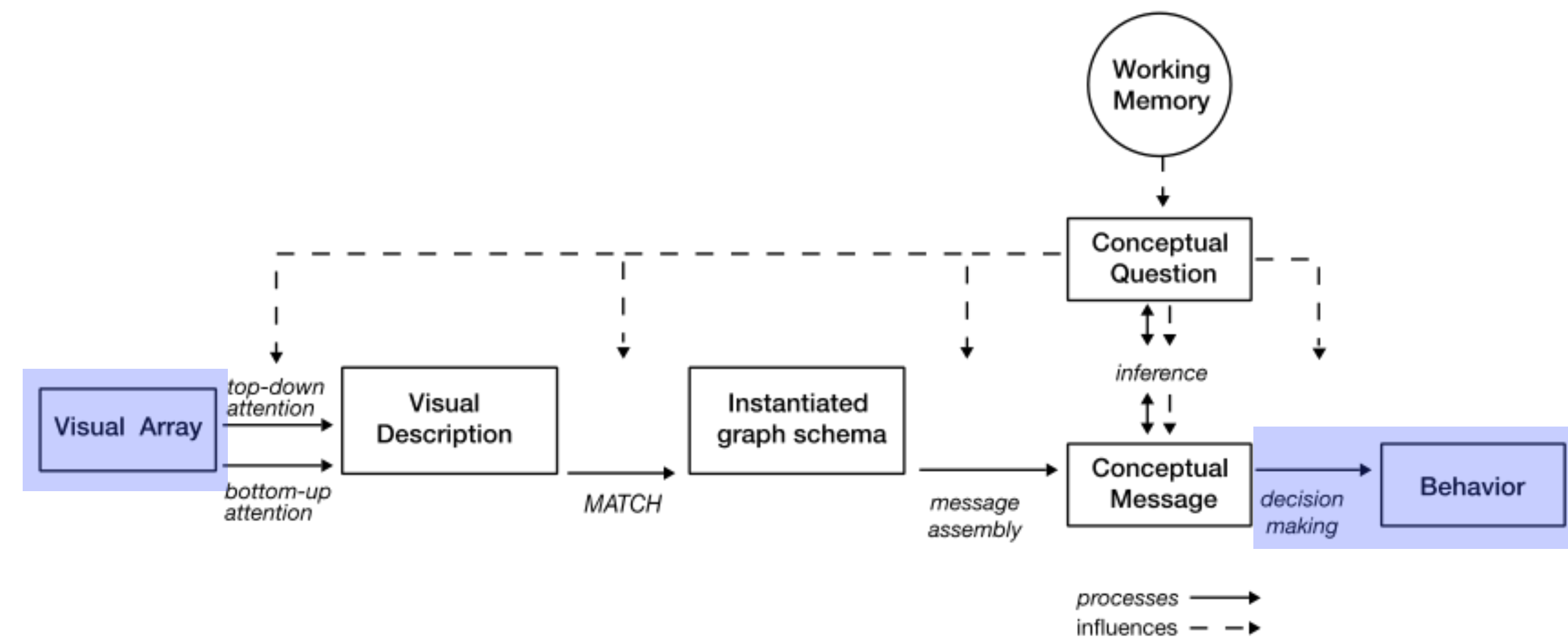


Intervals create conceptual categories



Intervals create conceptual categories

Errors arise when the visualization evokes the wrong schema



Intervals create conceptual categories

Errors arise when the visualization evokes the wrong schema

Fix the visualization, not the viewer's behavior

The way that uncertainty is presented has a
profound influence on our judgments

Special thanks to



Matthew Kay
Northwestern



Jessica Hullman
Northwestern

SPACE.UCMerced.edu
Accepting graduate students!
@LacePadilla



Mary Hegarty
UCSB



Sarah
Creem-Regehr
University
of Utah



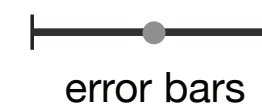
Jeanine Stefanucci
University
of Utah

NSF Award: 2028374

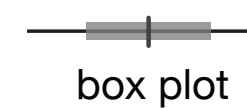
Padilla, Kay, & Hullman (in press). **Uncertainty Visualization.**
To appear in, *Handbook of Computational Statistics and Data.*

Graphical Annotations of Distributional Properties

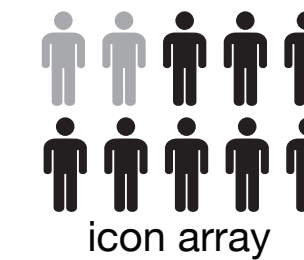
Intervals and Ratios



error bars

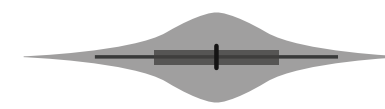


box plot



icon array

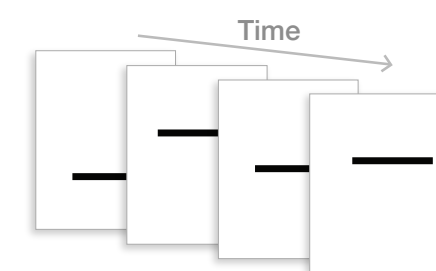
Distributions



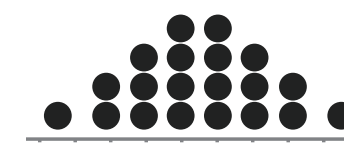
violin plot



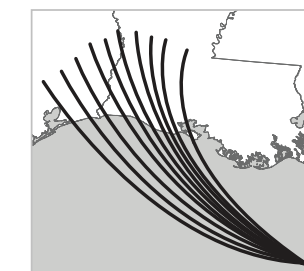
gradient plot



hypothetical outcome plot

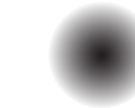


quantile dot plot

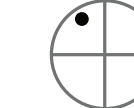


ensemble plot

Visual Encodings of Uncertainty



fuzziness



location



arrangement

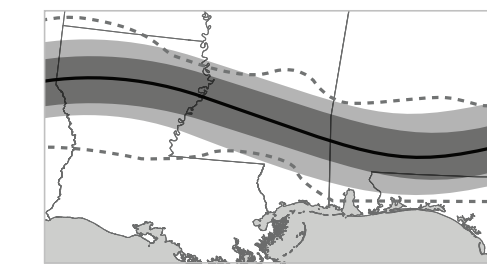


size

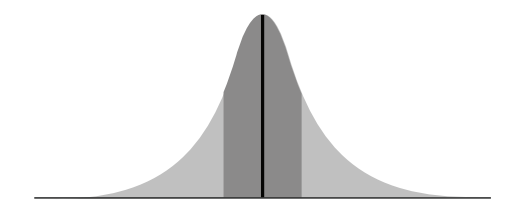


transparency

Hybrid Approach



contour boxplot



probability density and interval plot

Padilla, Creem-Regehr, Hegarty, & Stefanucci (2018). Decision making with visualizations: a cognitive framework across disciplines. CRPI

