Learning from Lionfish: Modeling Marine Invaded Systems

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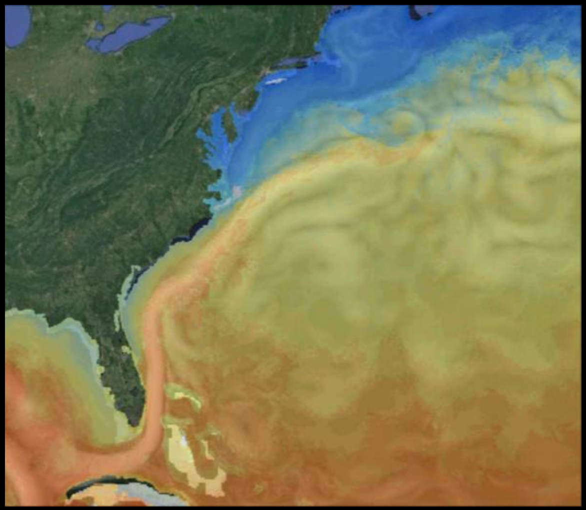

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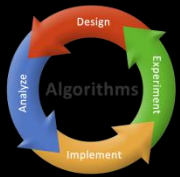
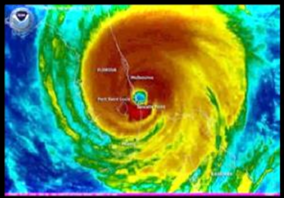
Introduction to Invasives

Model Background/Mechanics



Hurricanes and Lionfish



Lionfish Control

Southern GOM damsels

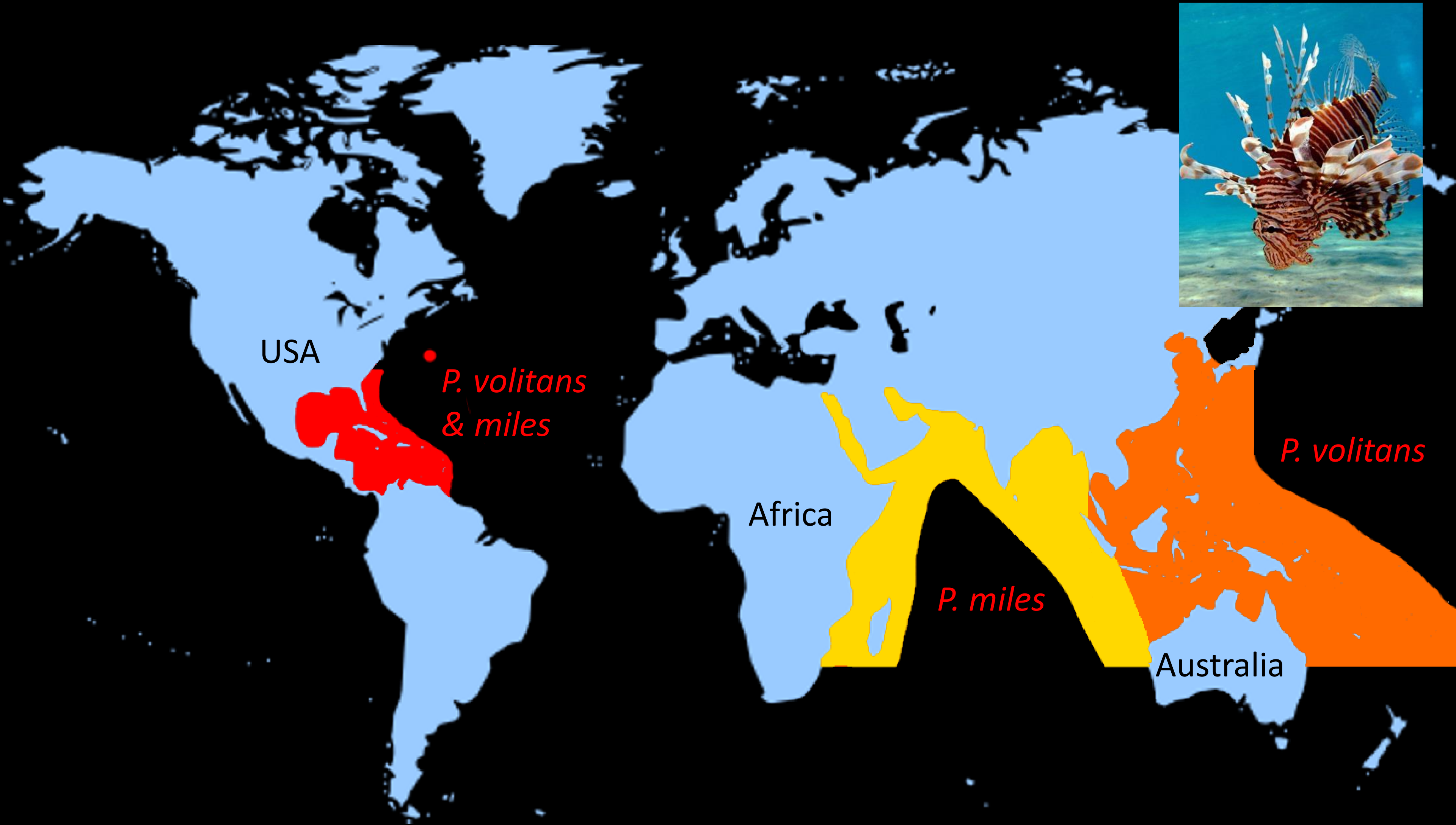
What is an invasive species?

"Animals, plants or other organisms introduced by man into places out of their natural range of distribution, where they become established and disperse, generating a negative impact on the local ecosystem and species." - International Union for the Conservation of Nature

Invasive Species

- 30,000 eggs/four days, buoyant ~30 days
- 10-12 month maturity
- Depth to 300 m
- 10° C

Native and Invasive Range of Lionfish



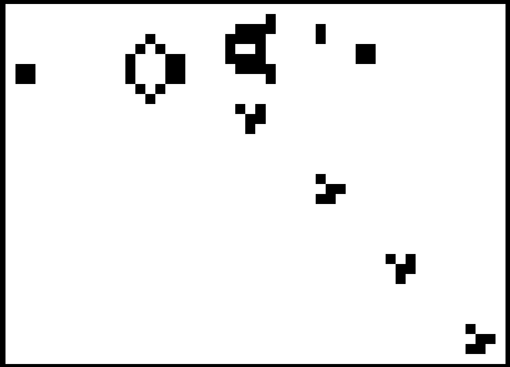
Motivation and Aim of Research

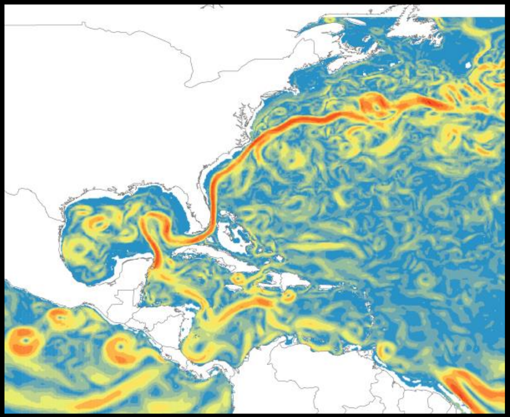
Motivation and Aim of research:

- ***Understand*** the invasion process
- Use mathematical computer simulation to help ***understand and solve*** complex questions in invasion ecology

The Models

- **Cellular automaton** biophysical model
  - Simple rules = complex behavior
- **Lagrangian model**
  - Particle movement in water
- **Physical oceanographic conditions**
  - ocean current, SST, depth
- **Life history traits**
  - *Temporal*: breeding age, life stage mortality, larval duration, egg quantity, breeding frequency





Validated against USGS-NAS

Model Source Data

Ocean Currents (hybrid): HYCOM – monthly and daily averages 1/12° (10km) and 1/25 ° (4km) , monthly 1/3° OSCAR (40 km), daily 1/25 ° ROM (4 km)

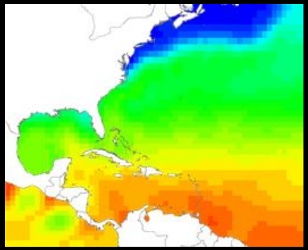
Depth (satellite): ETOPO 1 Global Relief Model (2 km)

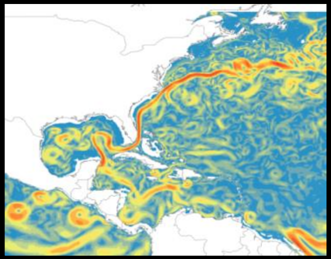
SST (satellite): MODIS - monthly (4 km)

Chlorophyll (satellite): MODIS - monthly (4 km)

Life History Characteristics: Literature

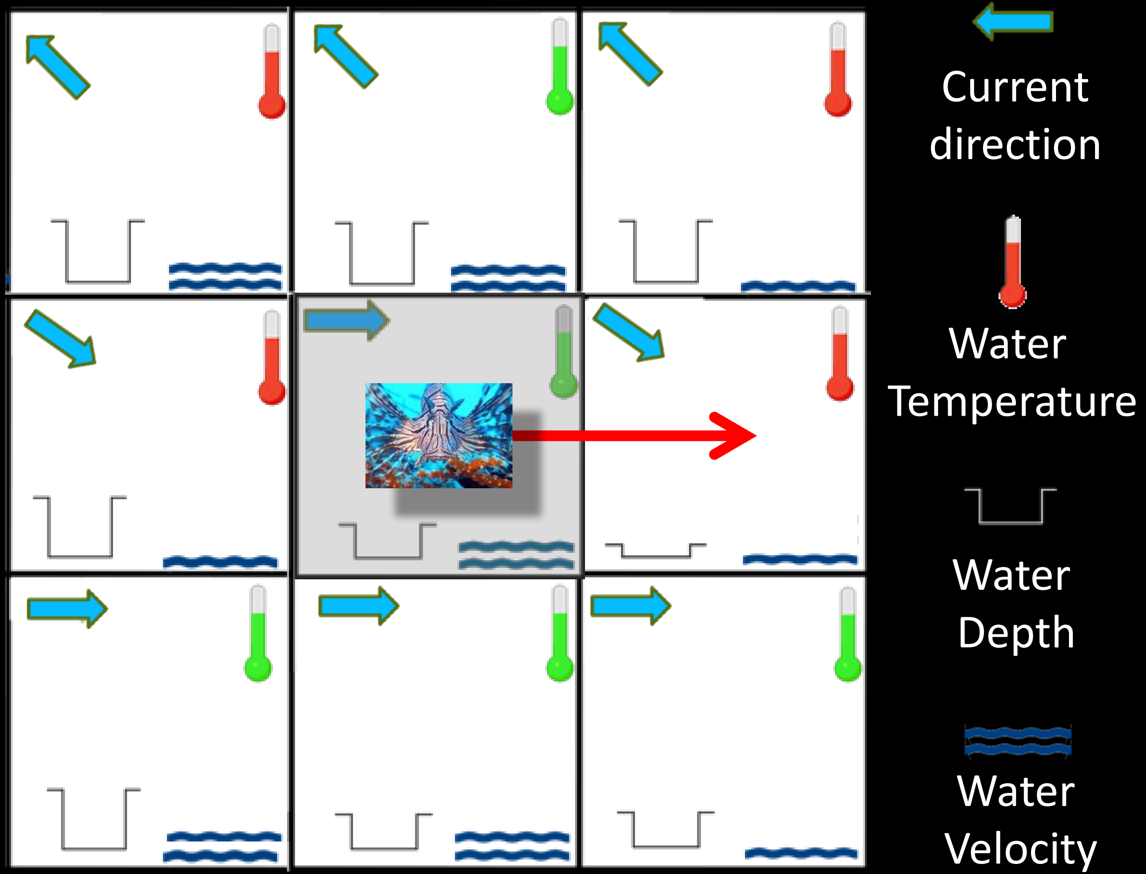
All datasets in public domain





Cellular Automaton Agent-Based Model

- Study area grid
- **4 main logic components:**
- ***conceptual cells***
  - unique parameters
- ***neighborhood cells***
- ***cell state***
- ***rules***
  - downstream
  - Settling dictated by temp/depth



Rules are tested for each step per cycle (30 days) for each larva


Current direction
Water Temperature
Water Depth
Water Velocity

Algorithmic Flow of the Model

Process Steps:

Step 1 : **Select founder population (females)**

Step 2: **Apply mortality**

- Adult
- Egg/larval/juvenile mortality applied to qty larvae produced/female
- If *alive* moves to step 3

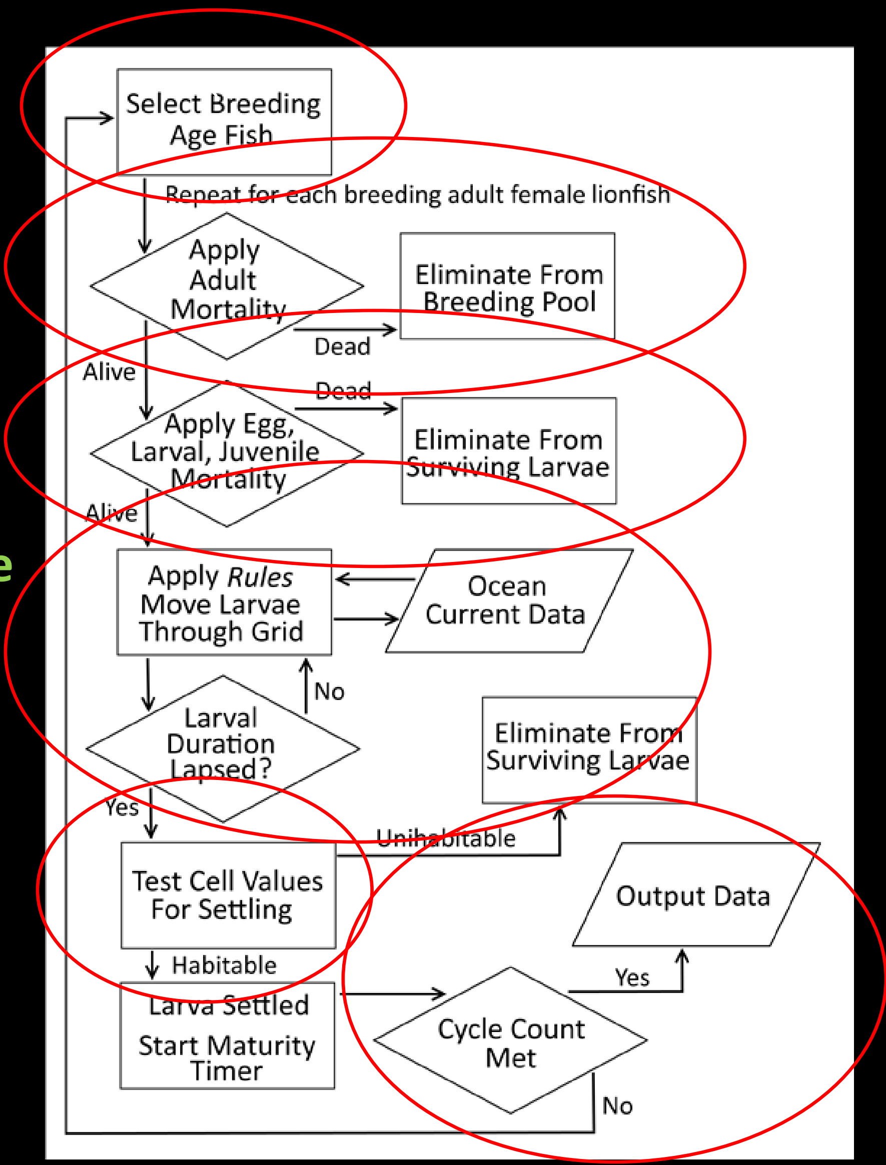
Step 3: **Movement of larvae governed by the *rules***

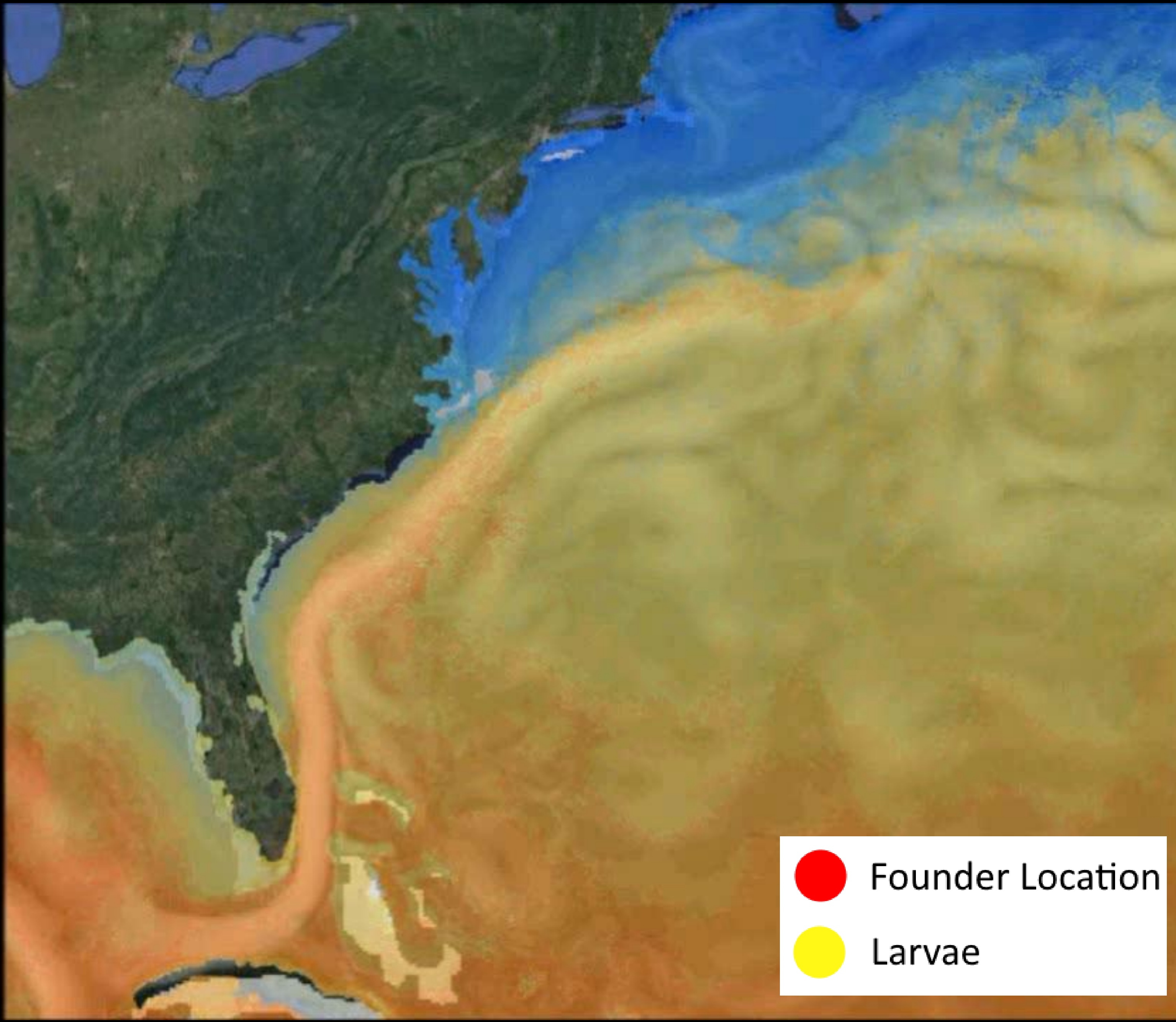
- Process repeats for larval duration period
- Last cell potential settling location

Step 4: **Settlement**

- Parameters tested for settlement

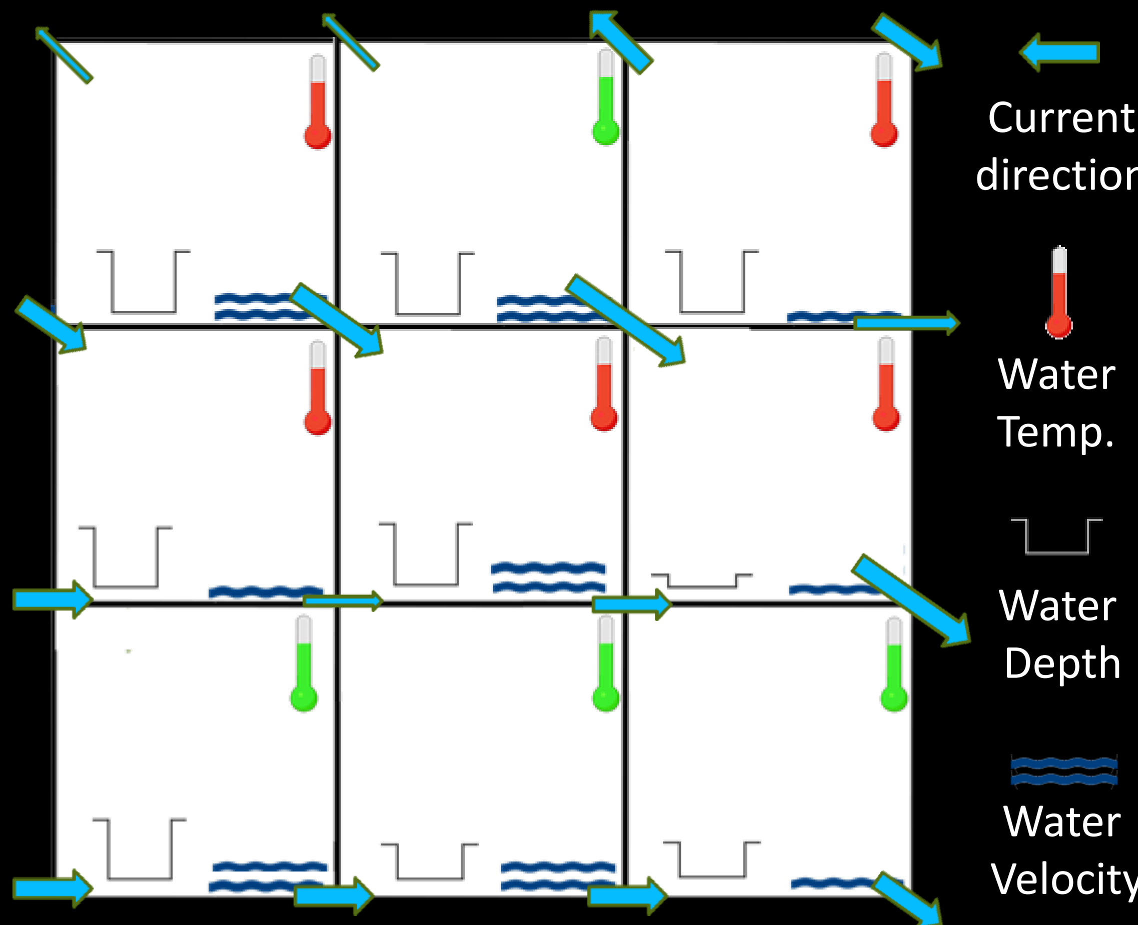
Step 5: **Repeat for duration**




Founder Location
Larvae

Lagrangian Agent-Based Model

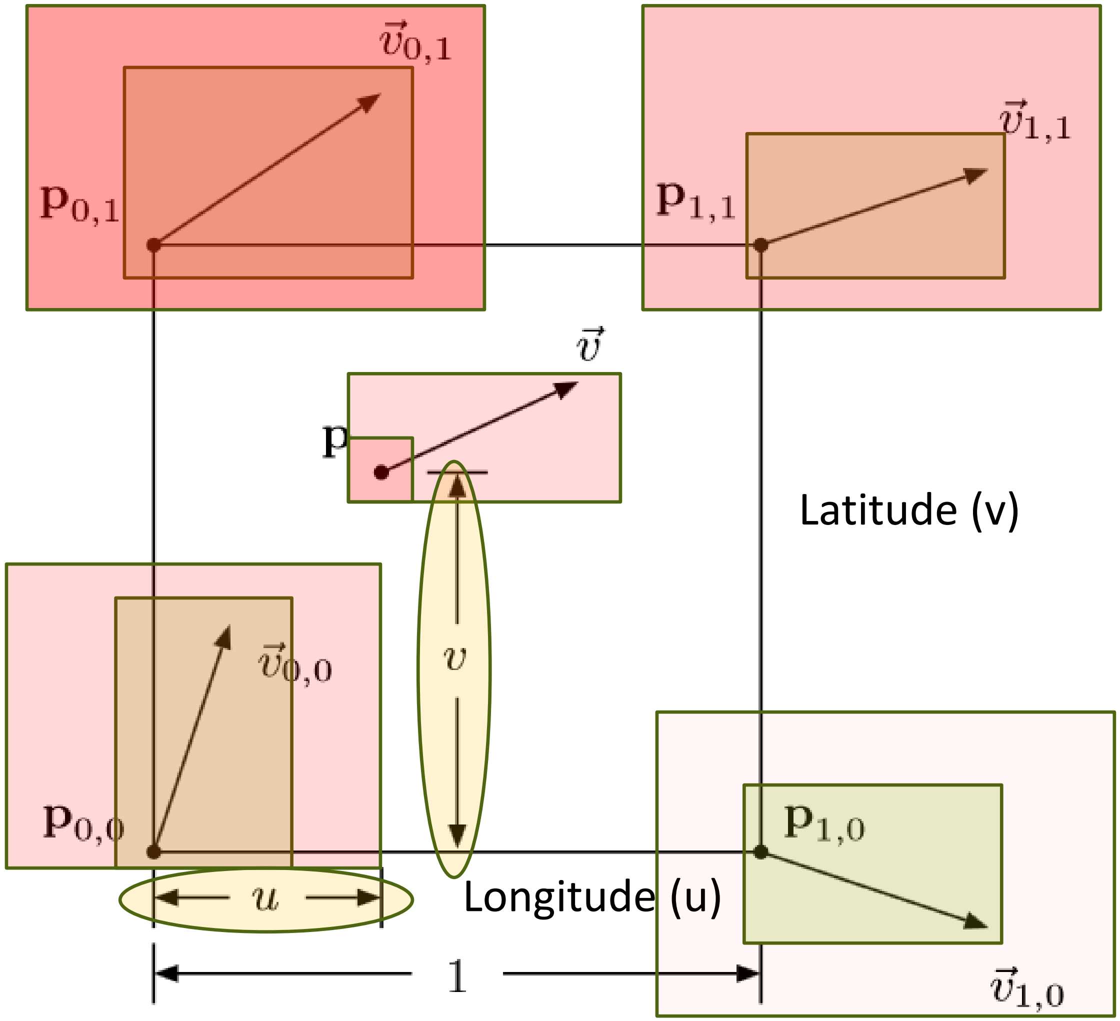
- Grid containing flow vectors derived from **u** (east-west) and **v** (north-south) components
- ***conceptual cells***
  - Unique parameters
- ***rules***
  - Settling dictated by ocean conditions
- ***movement***
  - Euler method
  - Hourly time-steps



Lagrangian Agent-Based Model – 2D

Vector Interpolation

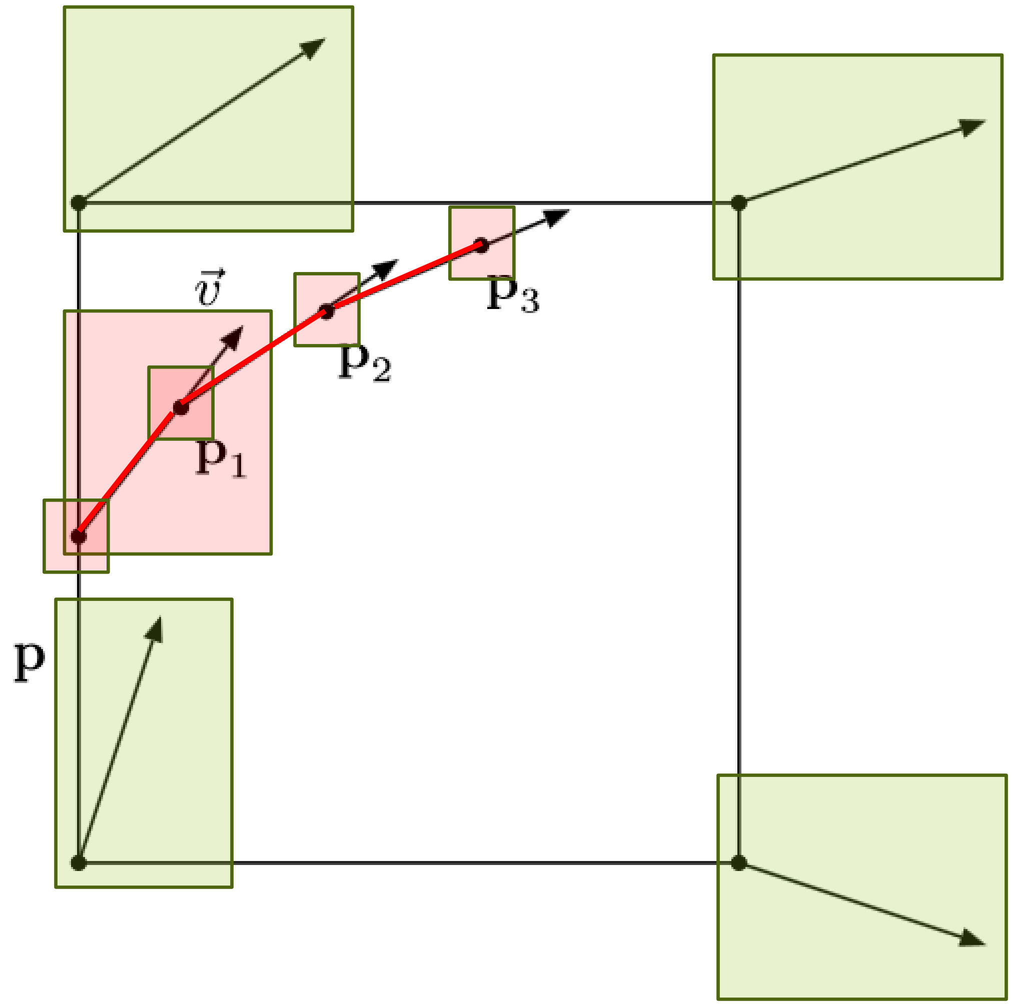
- Position of larva (P) – u and v (or x/y)
- Nearest 4 vectors
- Weighted vector averaging to predict trajectory of particle, i.e. $\vec{v}$
- Bilinear interpolation using the Euler method



$$\vec{v}_i = (1-v)(1-u)\vec{v}_{0,0} + (1-v)u\vec{v}_{1,0} + v(1-u)\vec{v}_{0,1} + vu\vec{v}_{1,1}$$

Calculating Trajectory

- From starting position (P) u/v:
  - 4 nearest vectors
  - Vector path interpolated
  - Particle moved along vector at calculated velocity for one hour i.e., one timestep Δt
  - Process repeats over PLD



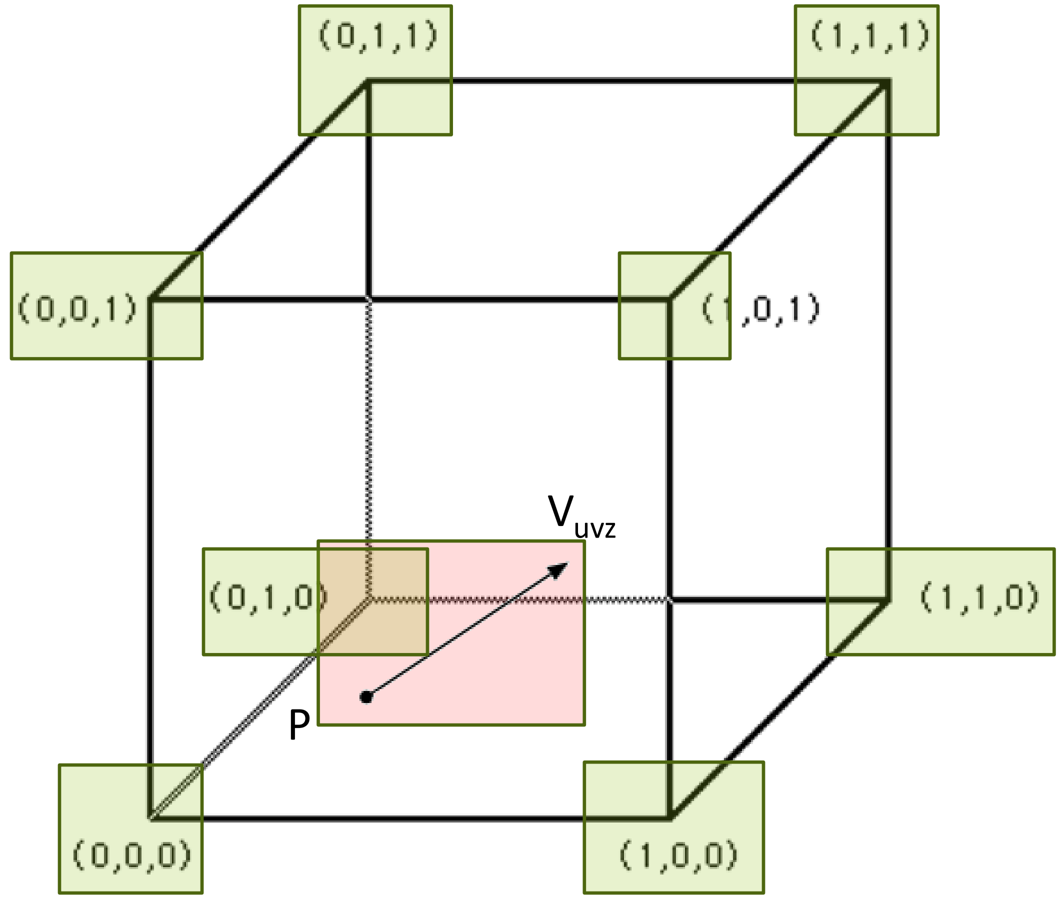
$$\vec{v}_i = (1-v)(1-u)\vec{v}_{0,0} + (1-v)u\vec{v}_{1,0} + v(1-u)\vec{v}_{0,1} + vu\vec{v}_{1,1}$$

$$P_1 = P_0 + \Delta t\vec{v}$$

$$P_{i+1} = P_i + \Delta t\vec{v}_i$$

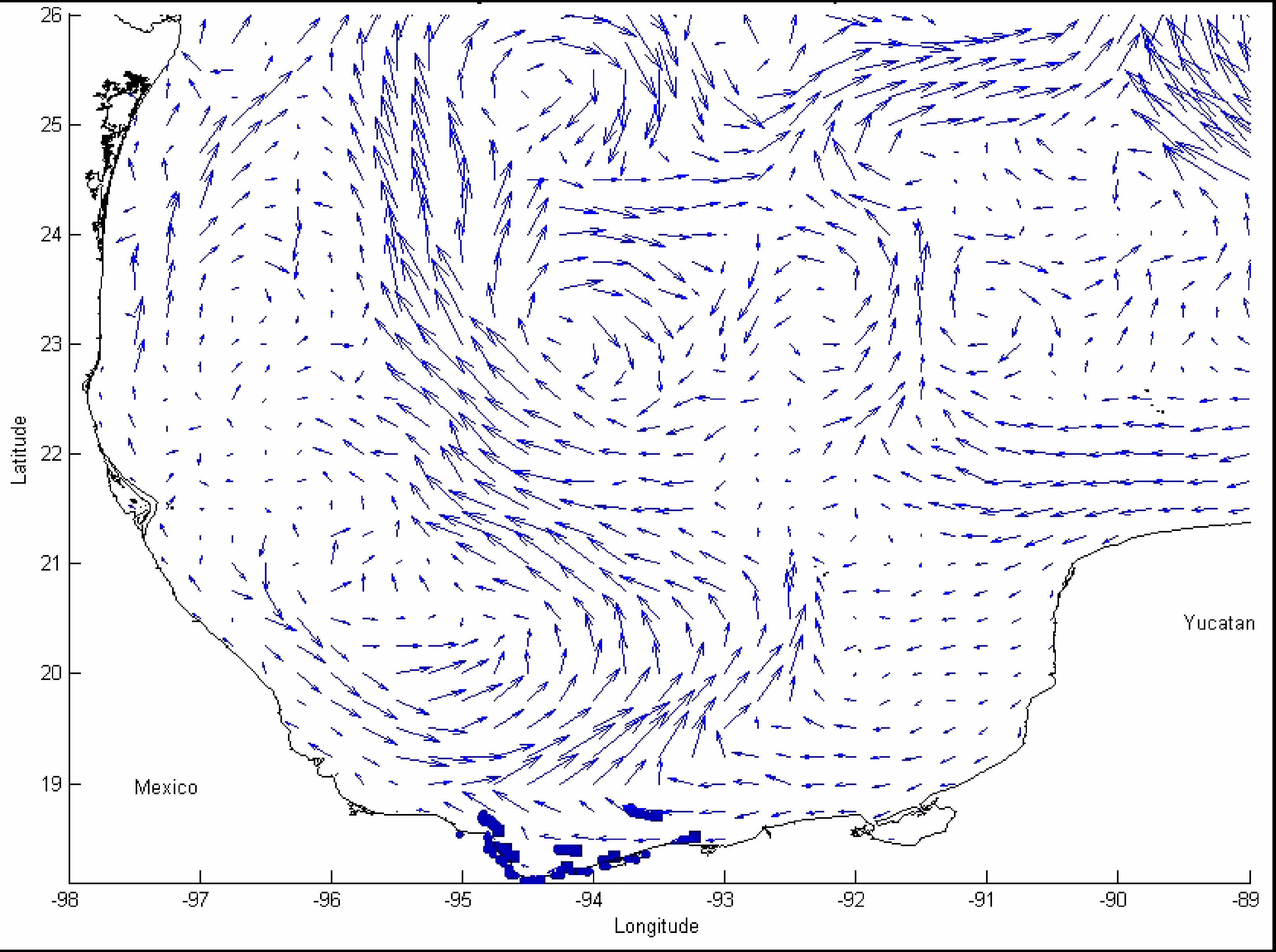
Lagrangian Agent-Based Model – 3D

- Position of larva (P) u/v/z
- Nearest 8 vectors - i.e., trilinear interpolation
- Particle moved along vector at calculated velocity for one hour i.e., one timestep Δt



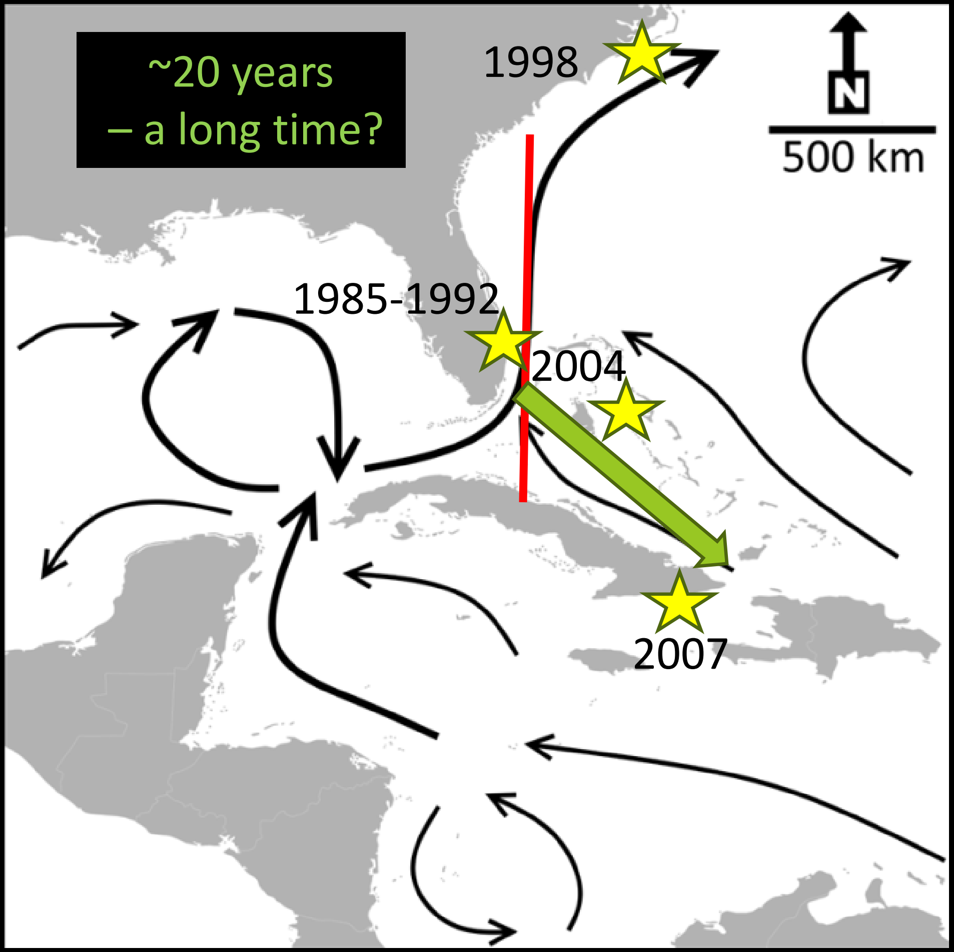
$\mathbf{V_{uvz}} = V_{000}\,(1 - u)\,(1 - v)\,(1 - z) + V_{100}\,u\,(1 - v)\,(1 - z) + V_{010}\,(1 - u)\,v\,(1 - z) + V_{001}\,(1 - u)\,(1 - v)\,z + V_{101}\,u\,(1 - v)\,z + V_{011}\,(1 - u)\,v\,z + V_{110}\,u\,v\,(1 - z) + V_{111}\,u\,v\,z$

$$P_{i+1} = P_i + \Delta t \vec{v}_i$$



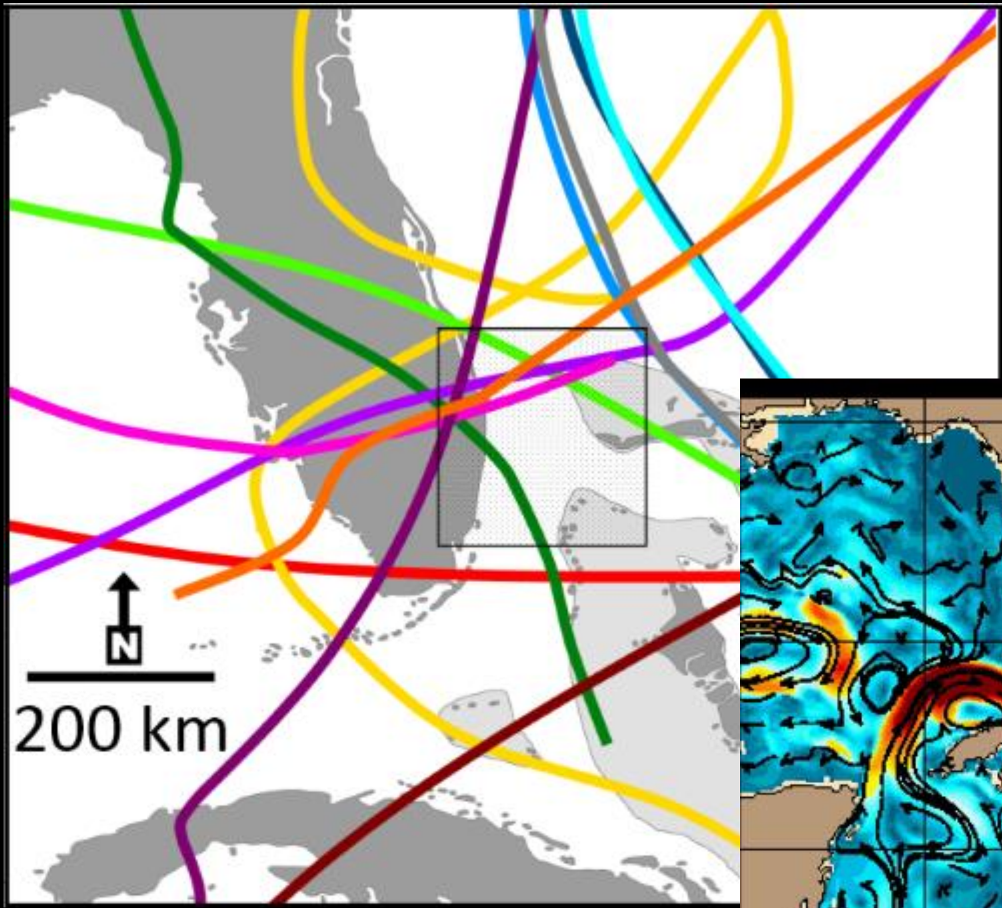
14.5 million larval movements spanning 5 years

Hurricanes accelerated the Florida-Bahamas Lionfish invasion

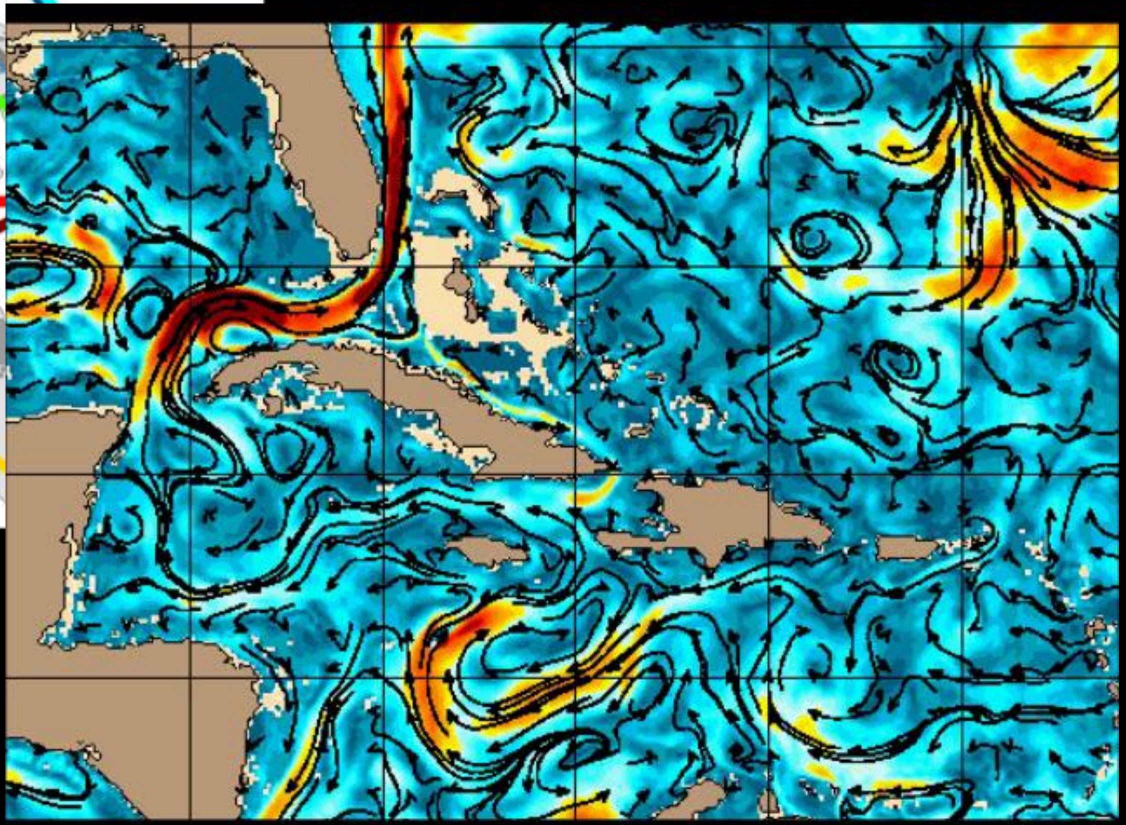


- Curious: Bahamas mean currents run north and west – lionfish moved south east
- Current anomalies?
- Role of hurricanes?

Hurricanes accelerated the Florida-Bahamas Lionfish invasion



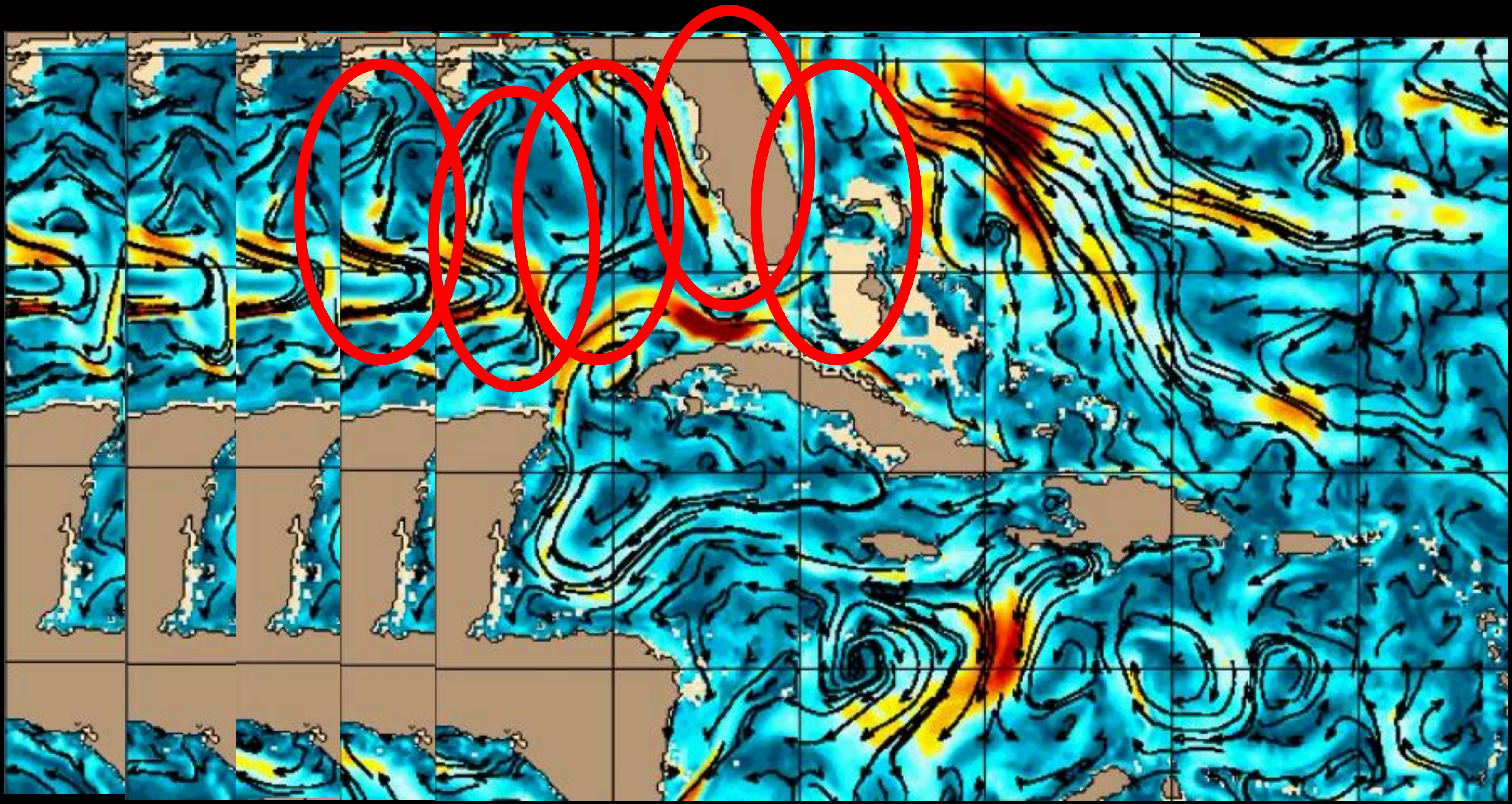
1992 – 2003 (13 storms)



Sandy 2012

Hurricanes accelerated the Florida-Bahamas Lionfish invasion

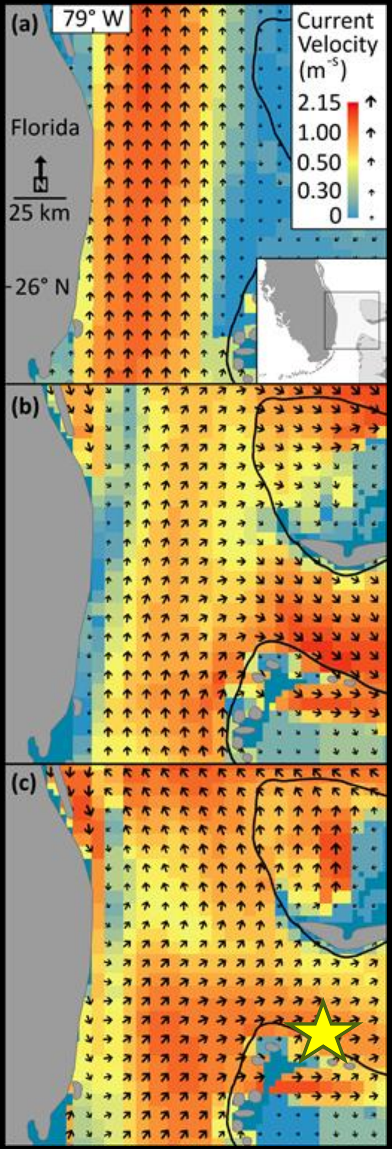
Hurricane Sandy - 2012



24 hour frames

Hurricanes accelerated the Florida-Bahamas Lionfish invasion

- Step 1 - Identify crossover events due to hurricanes
  - Analyze direction/velocity of daily HYCOM data in Florida Straits
- Step 2 – Analyze effect of hurricanes on population size
  - Small founder pop. In NW Bahamas
  - 2000 – 2007
  - Simulations using: monthly mean currents (average year)
  - Simulations using: daily currents for 2004-2005 hurricane seasons
  - Contrasted hurricane vs. non-hurricane

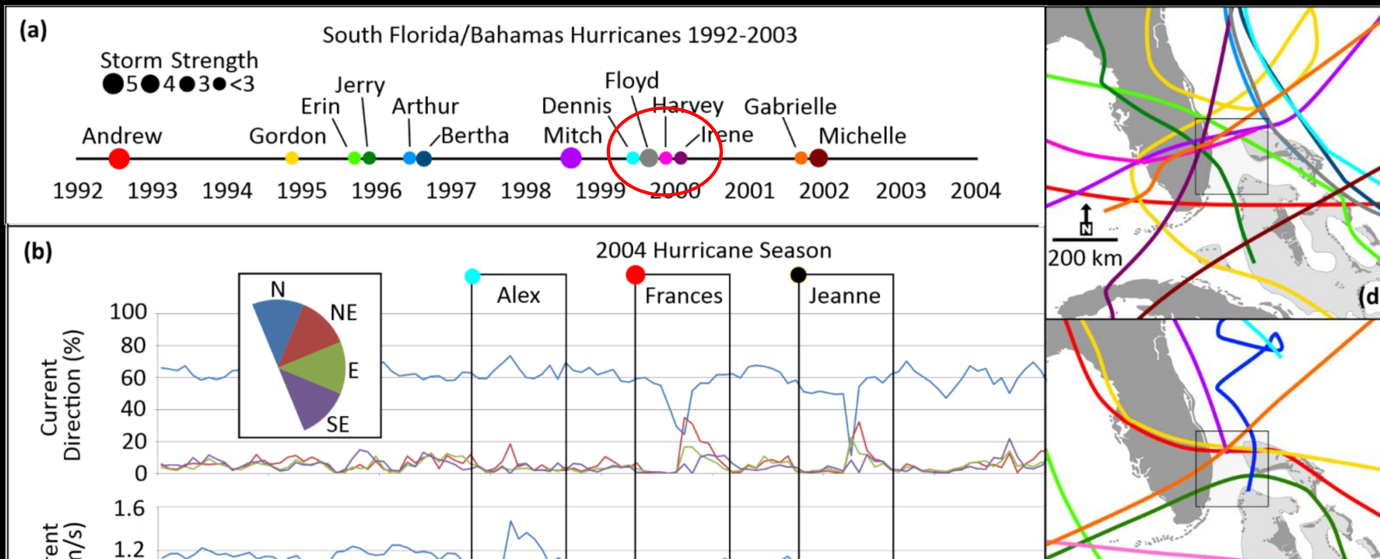


Average Year

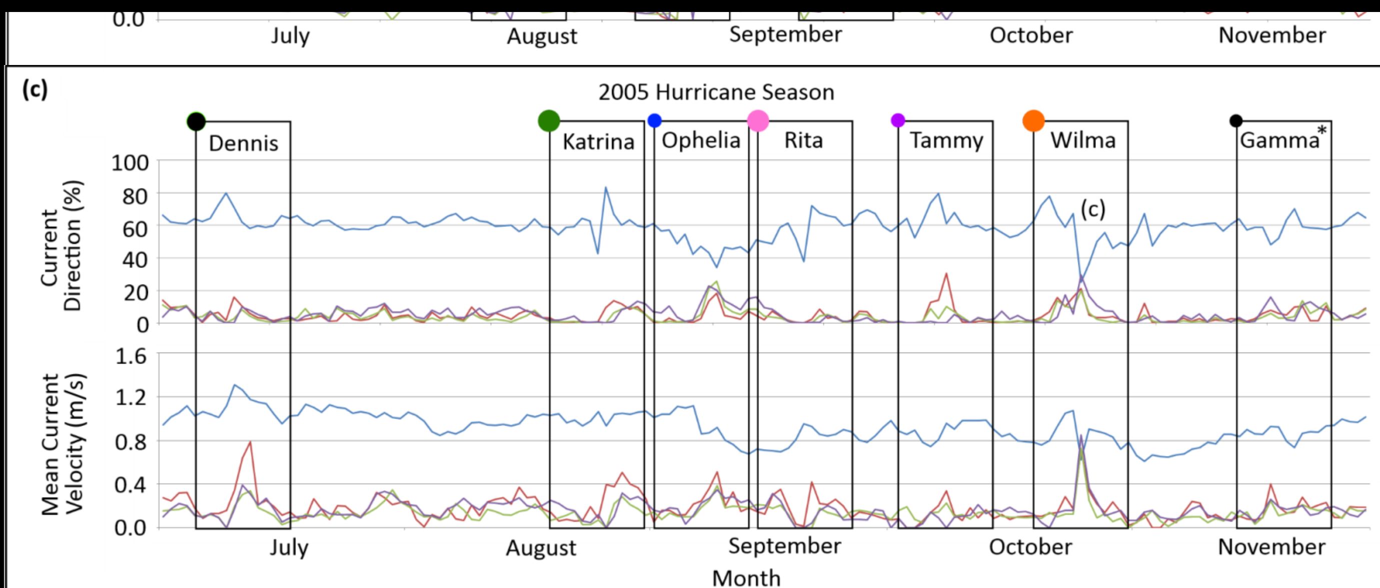
Jeanne 2004

Wilma 2005

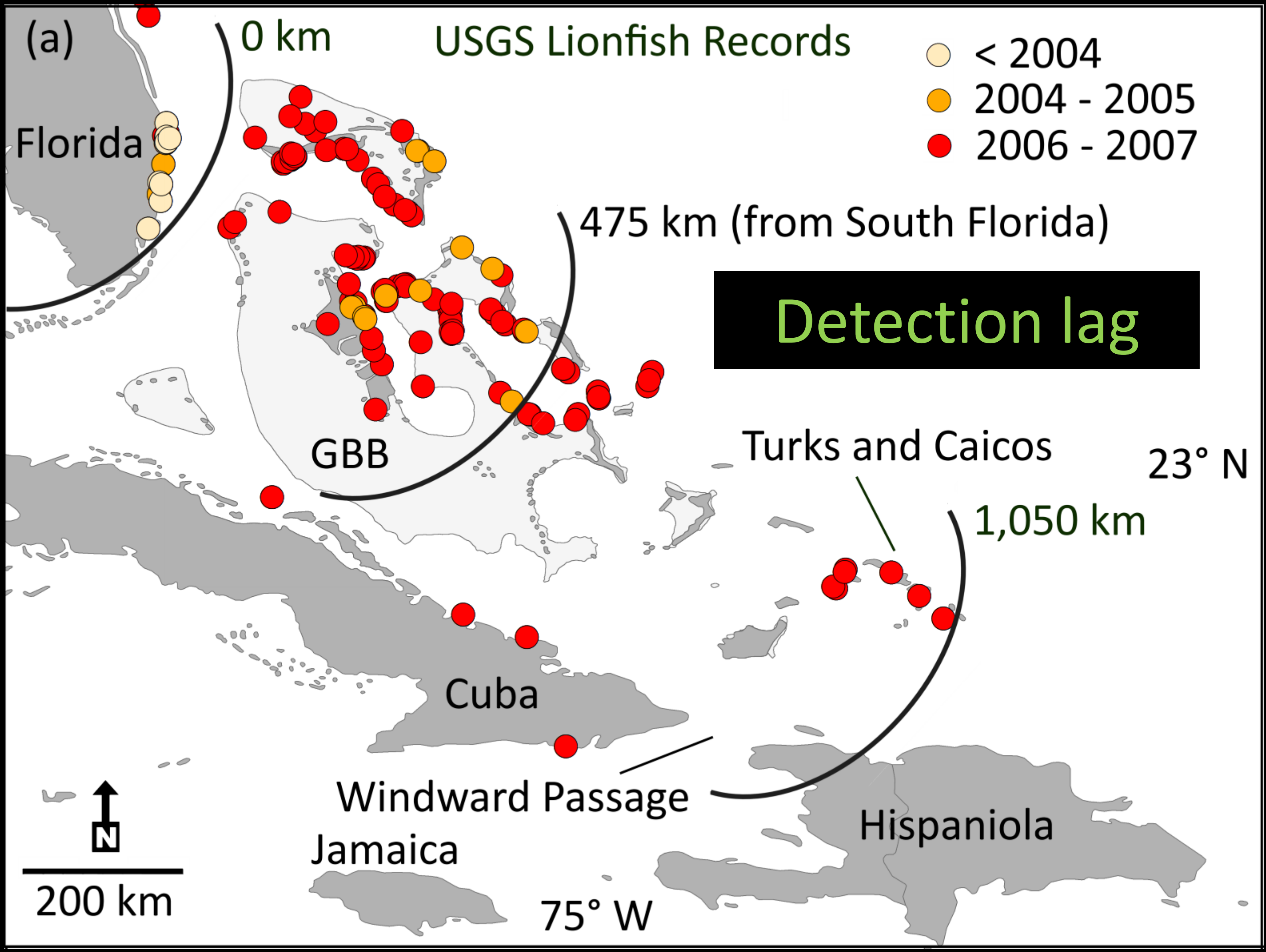
Step 1 - Identify crossover events due to hurricanes



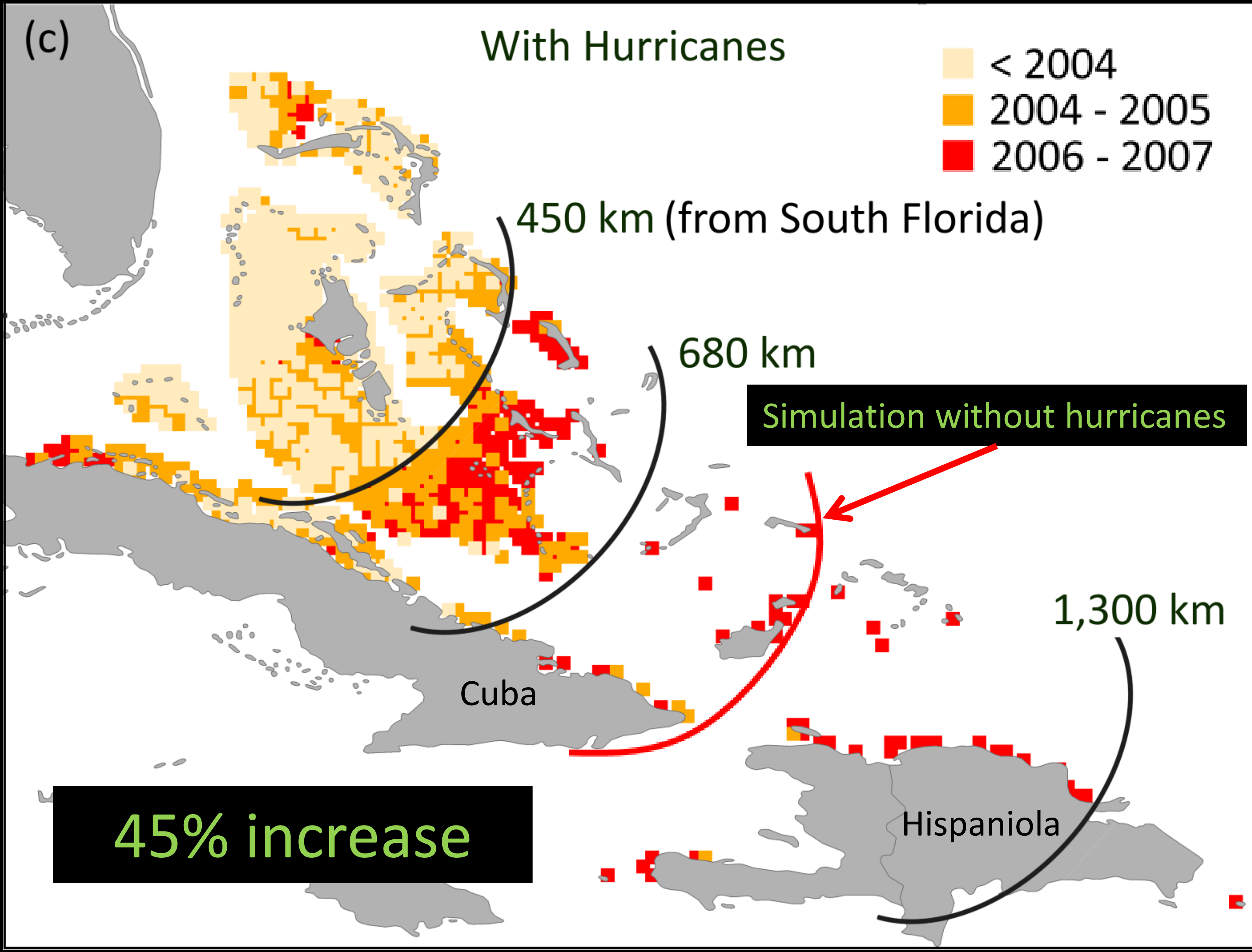
23 opportunities between 1992 - 2005



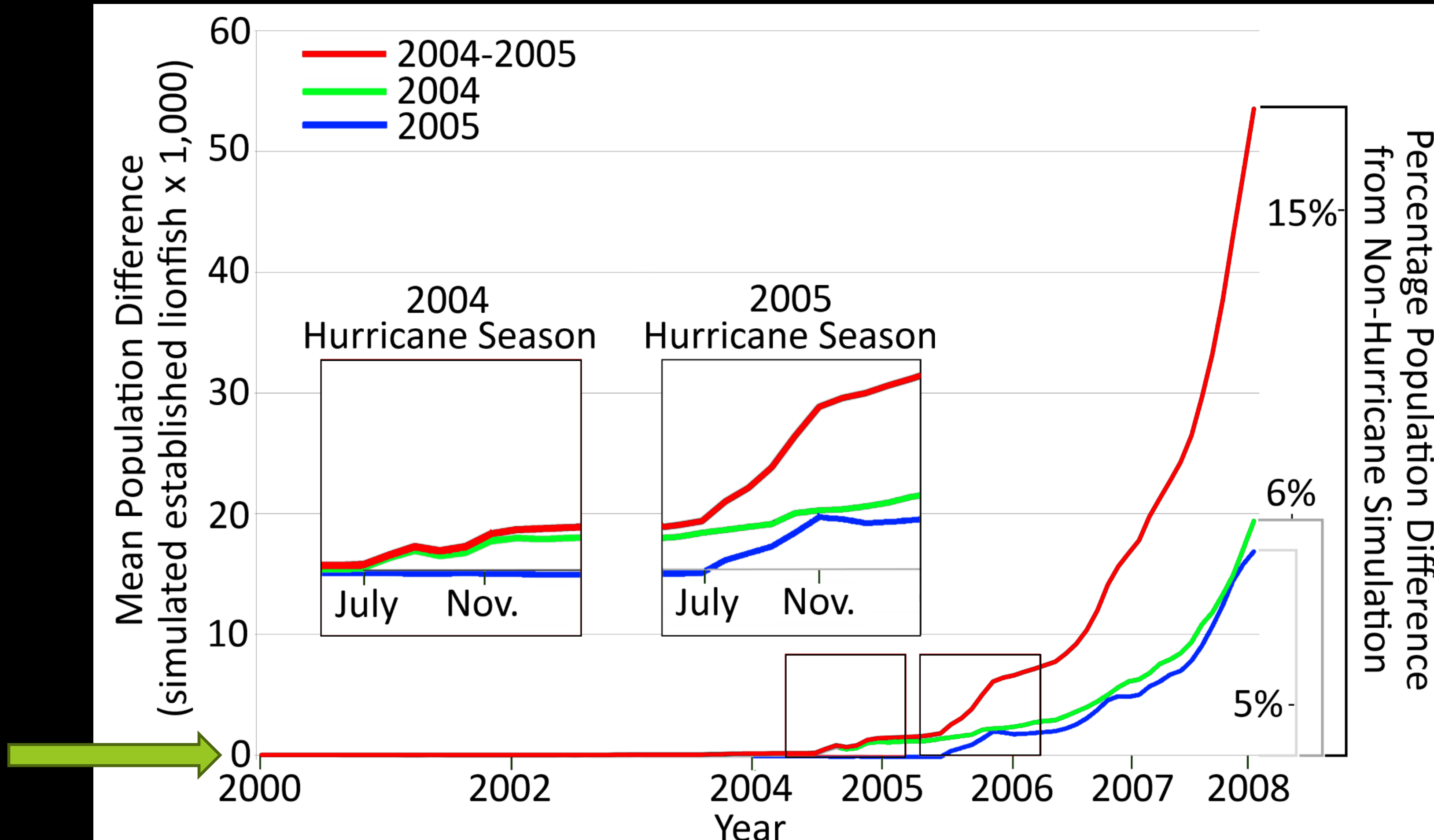
Step 2 – Analyze effect of hurricanes on population size



Step 2 – Analyze effect of hurricanes on population size



Step 2 – Analyze effect of hurricanes on population size



- Difference in pop. from an average year
- 5-6% population increase/storm year
- 15% increase in consecutive years
- First to link hurricanes with marine invasives
- Implications for all species

Lionfish Removals Require a Coordinated International Effort

- Lionfish removals – do they work?
  - Sporadic and incomplete
  - Contemporary controls leave remnant populations
  - What rate, where, how often?
- Previous modelling efforts (Arias-González et al. [2011], Barbour et al. [2011], Morris et al. [2011])
  - Local control only - how does connectivity factor?

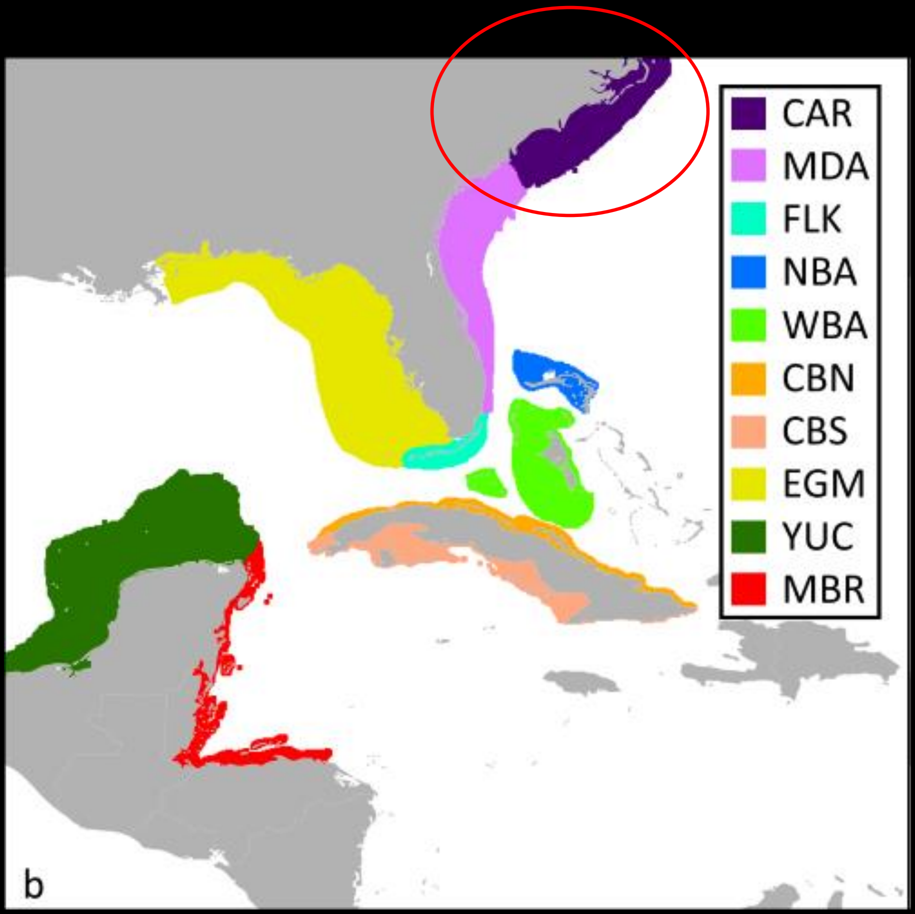
Lionfish Removals Require a Coordinated International Effort

- Two goals - quantify:
  - Connectivity between regions
    - Identify importer/exporter relationships
  - Removal rates required to contain invasion
    - Target 100% of population or just the majority (95%)
- Focus: impact of removals on Carolinas lionfish populations

Lionfish Removals Require a Coordinated International Effort

Goal 1 - Quantify connectivity between regions

- Identify all 10 precincts linked to CAR (i.e. Johnston and Purkis 2014b)
- 5 years
- 10 random locations, 100 lionfish each
- Track exporter vs. importer location
- Identify exporter/importer links – major exporters supply 95% to an importer precinct



Lionfish Removals Require a Coordinated International Effort

Goal 2 - Quantify Removal Rates Required to contain invasion

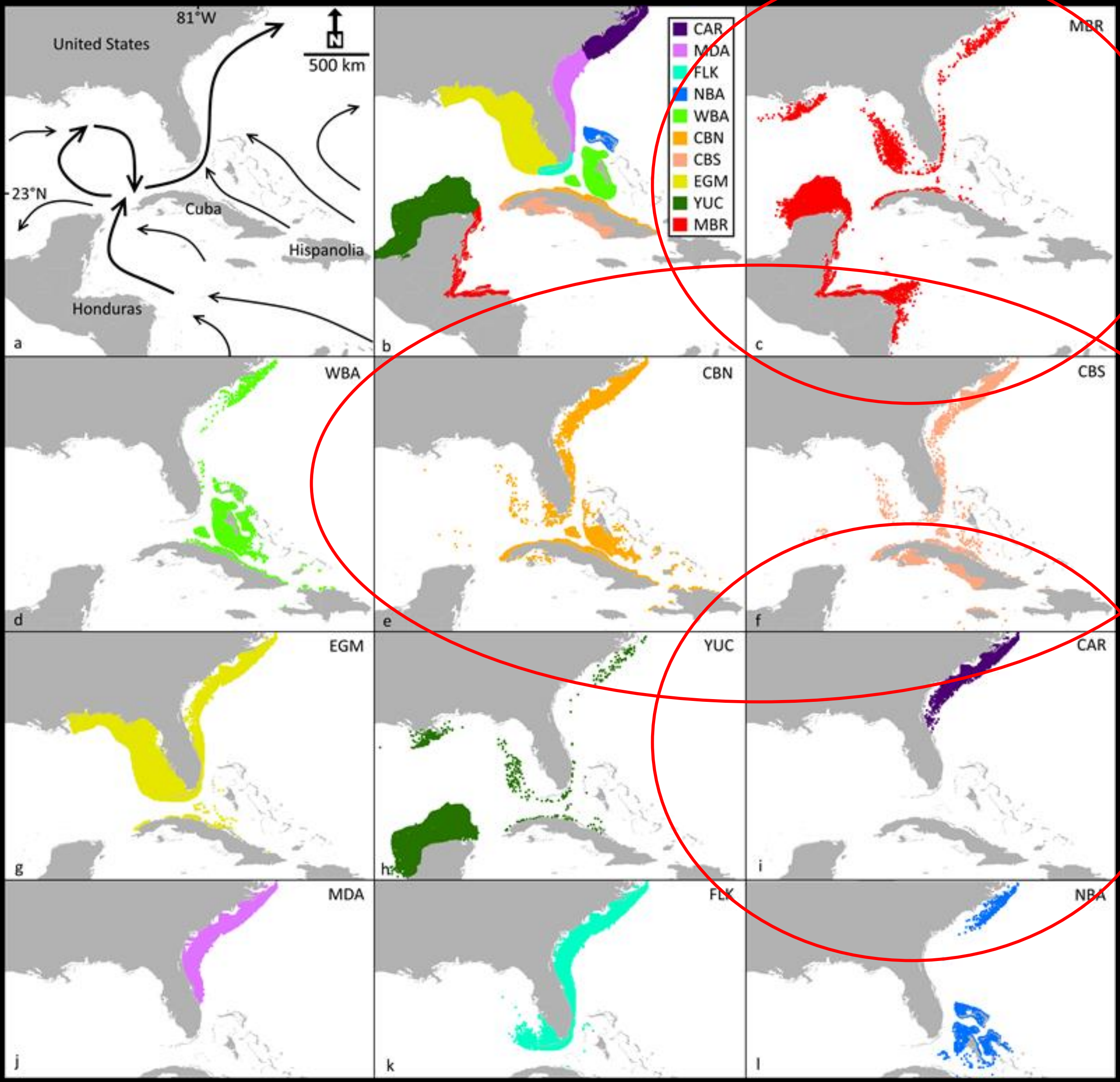
- Step 1
  - Model virtual culls performed in the major exporter precincts - i.e., those that supply 95% of lions to the Carolinas
  - 5 years, 10 random locations, 100 lionfish each
  - Perform culls at varied rates
    - Annual (i.e. derbies) 50% - 90%
    - Monthly – 10% - 60%

- Step 2
  - Repeat basin-wide for all 10 precincts that provide 100% of lionfish to the Carolinas

Tests sporadic vs. continuous culls targeting 95% or 100%

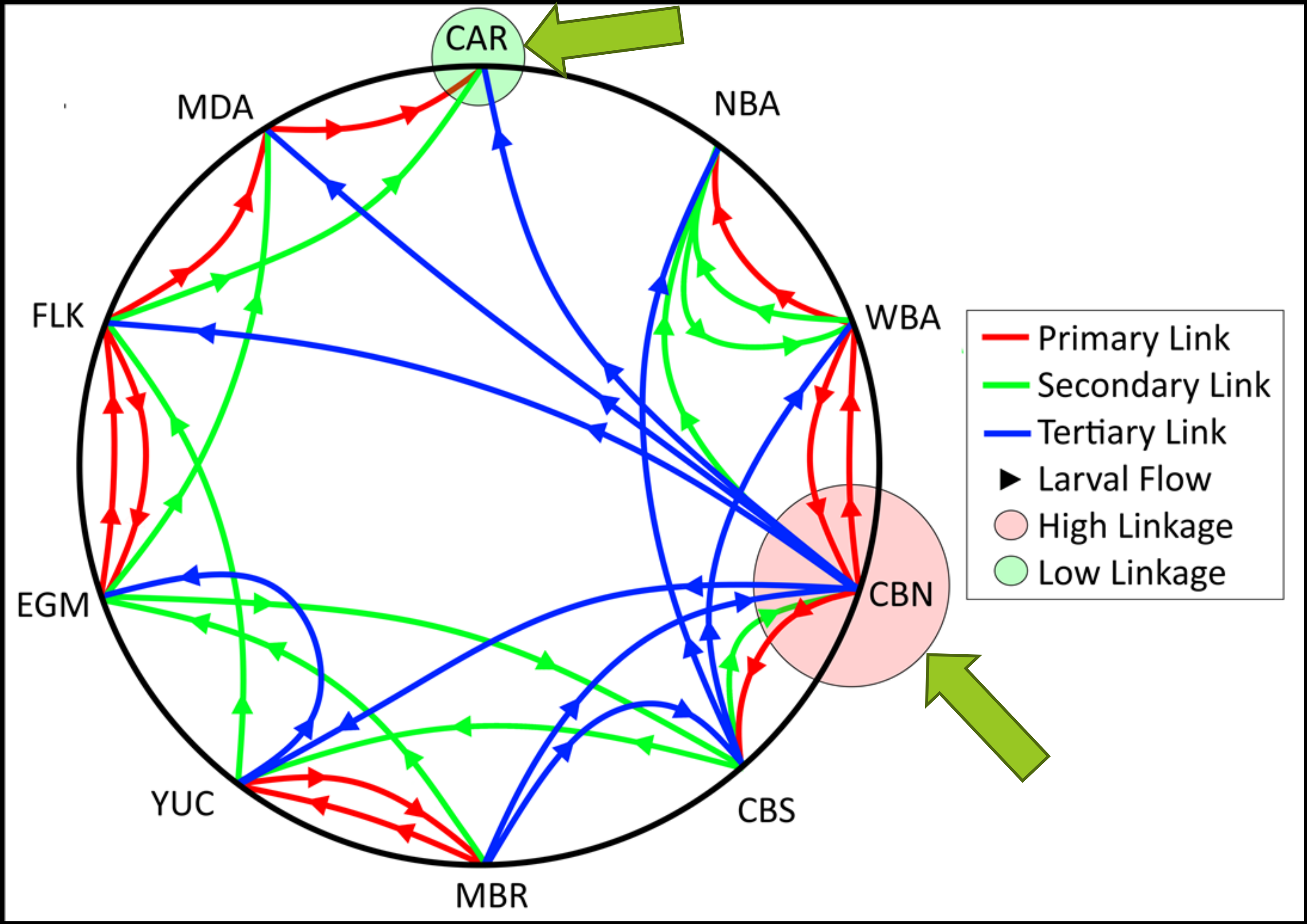
Lionfish Removals Require a Coordinated International Effort

Results (step 1)



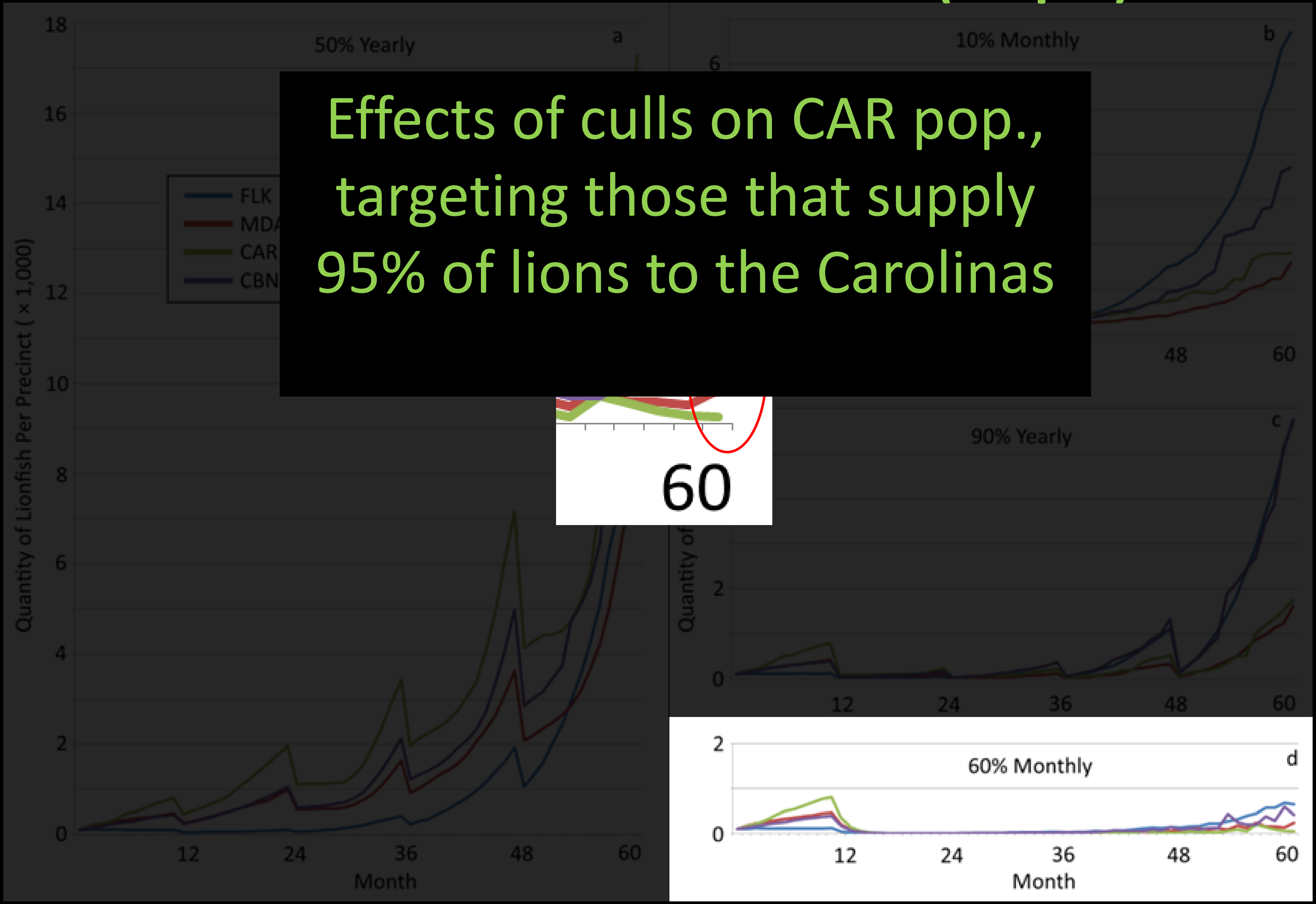
Lionfish Removals Require a Coordinated International Effort

Results (step 1)



- Linkages between regions
- Cuba - major exporter
- Carolinas imports almost all

Lionfish Removals Require a Coordinated International Effort : Results (Step 2)



Effects of culls on CAR pop., targeting those that supply 95% of lions to the Carolinas

Lionfish Removals Require a Coordinated International Effort : Results (Step 2)

Not doing enough!

Are we causing more damage (i.e. recruitment compensation) – just "pruning the trees" ??

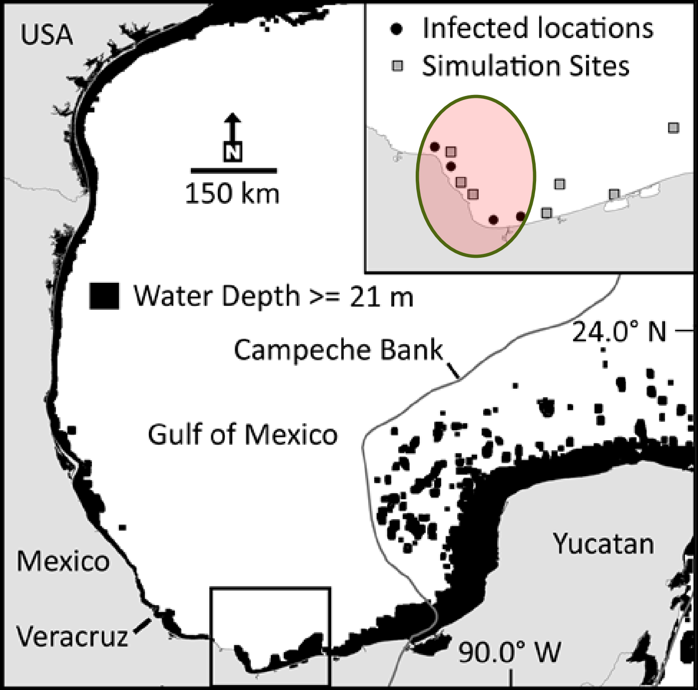
Needed:

1. Monthly culls
2. Basin wide
3. Target 20% of the entire population

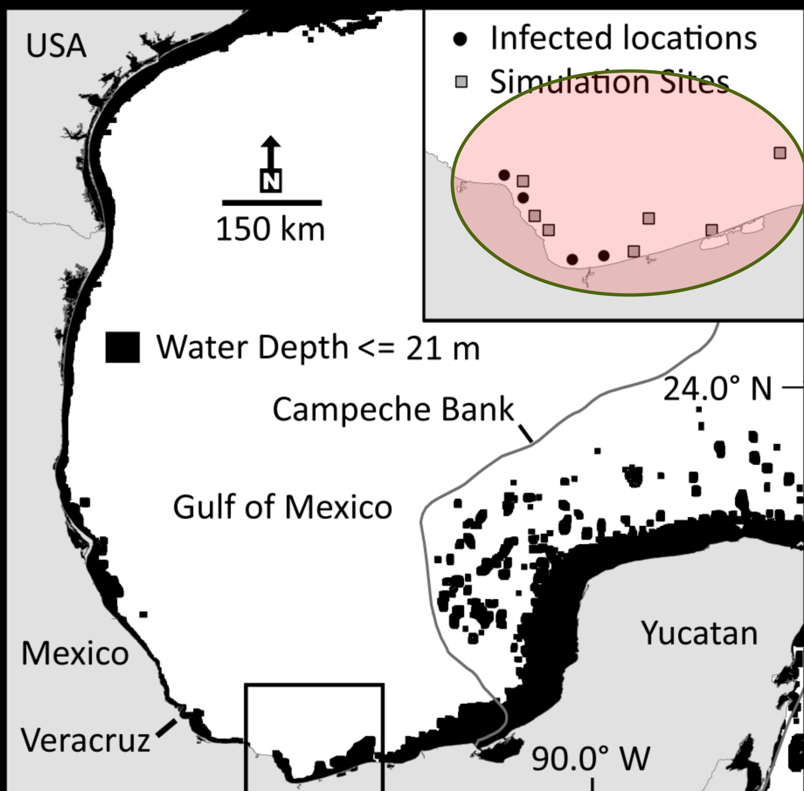
- 25% remnant populations
- 20% basin-wide/monthly

Royal Damsel (*Neopomacentrus cyanomos*) in the Southern Gulf of Mexico

- First sighted in 2012 near Veracruz
- Common to aquaria, widespread
- Found in large numbers
- Non-predatory
  - Competition with native damsels
- Shallow <= 21 m
- Pelagic larvae

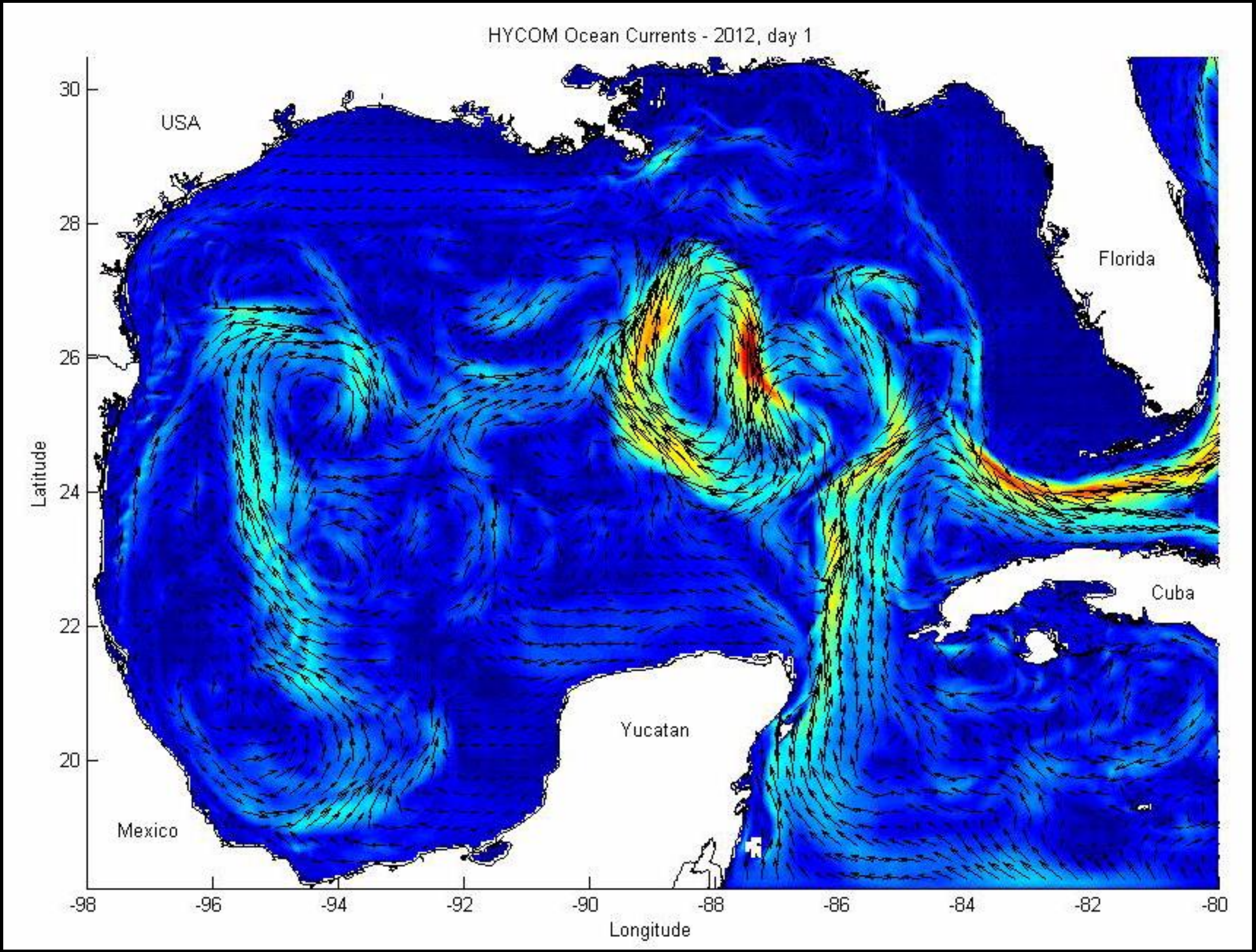


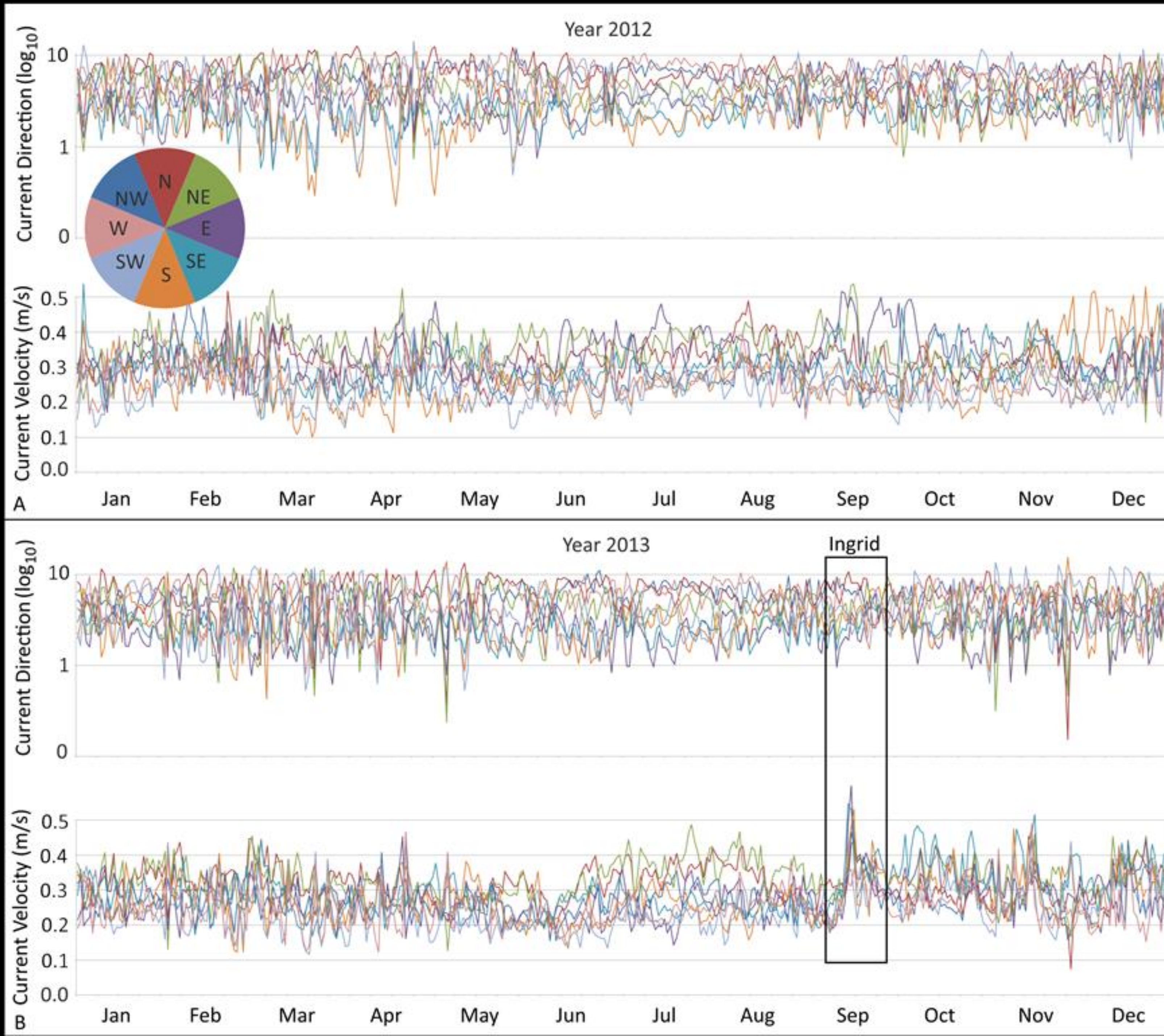
Royal Damsel (*Neopomacentrus cyanomos*) in the Southern Gulf of Mexico



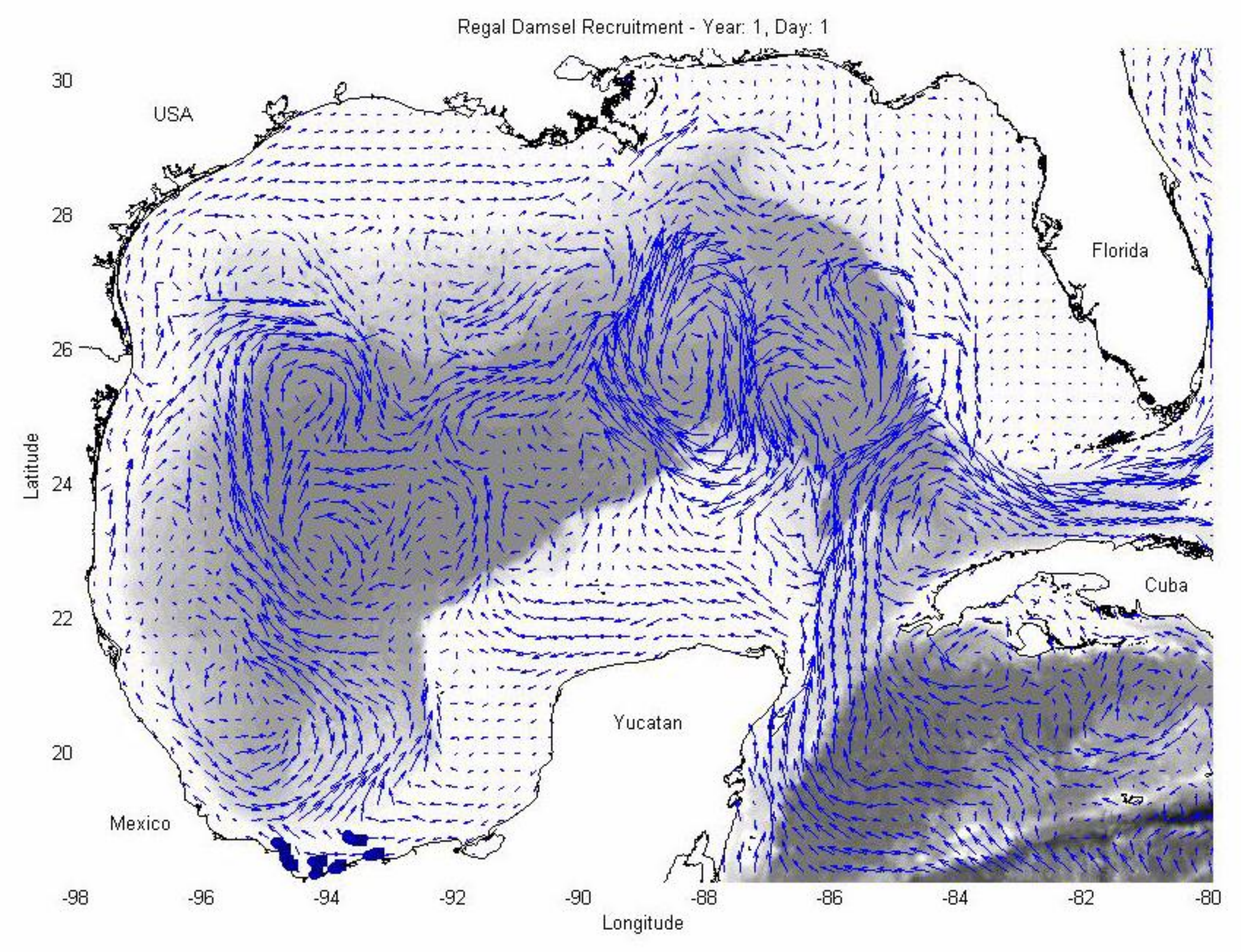
- Rapid risk assessment
- Create simulations for 5 years
- 8 Random founder populations
- Literature values for fecundity/habitat preferences
- Daily 1/25° HYCOM, 2010 - 2014
- Analyze ocean current trends

Royal Damsel (*Neopomacentrus cyanomos*) in the Southern Gulf of Mexico

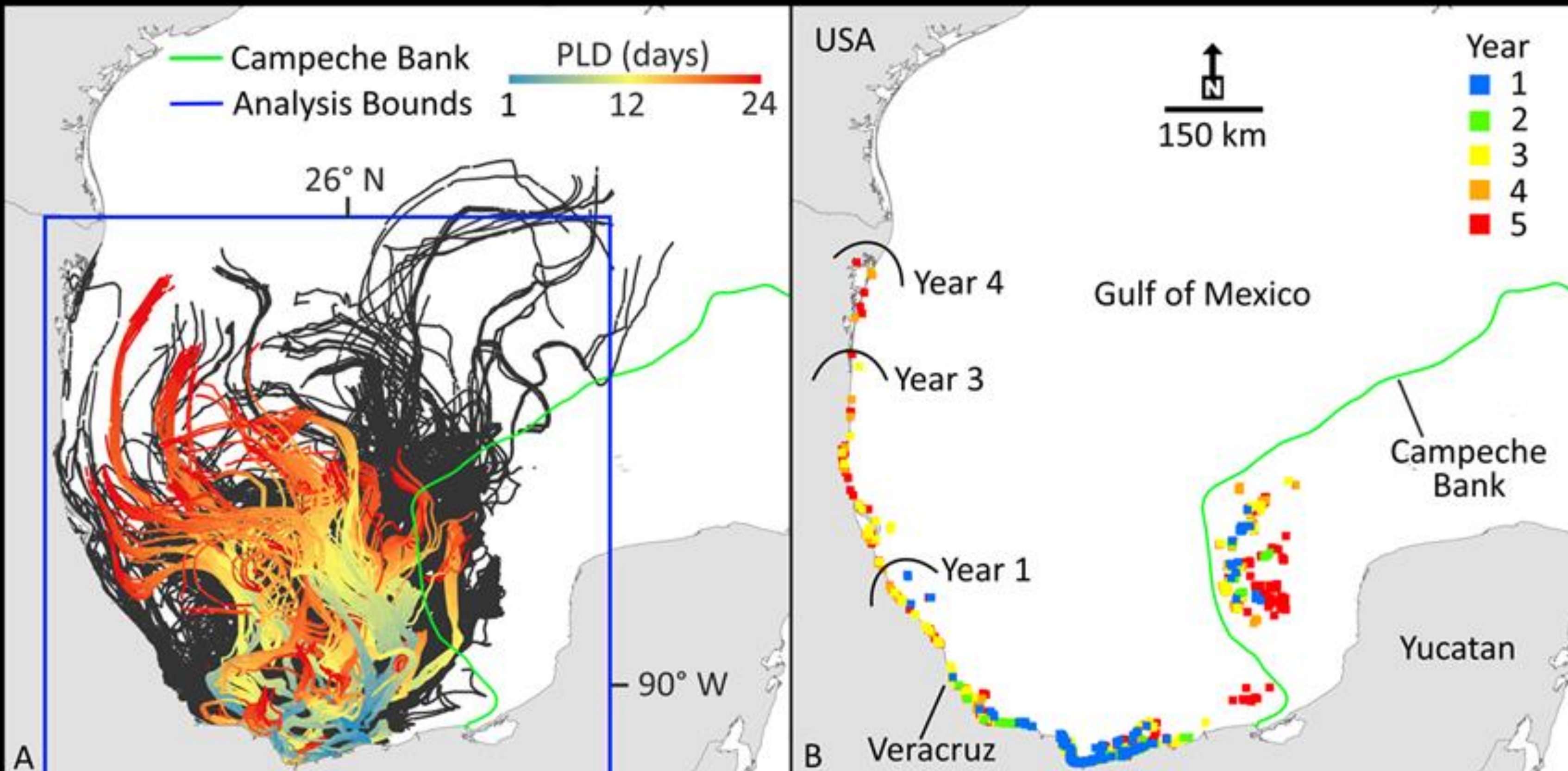




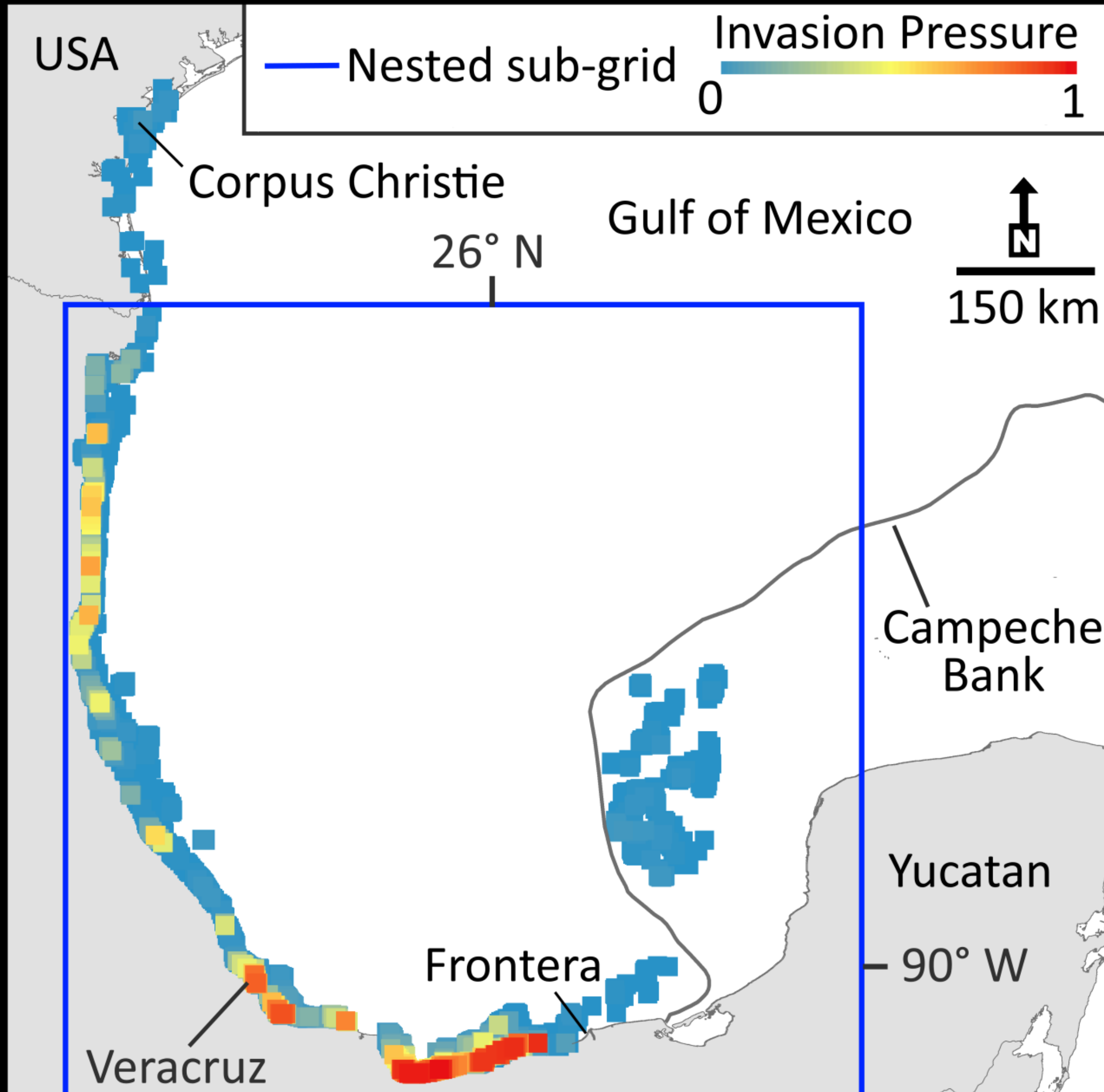
Year 2012
Current Direction (log10)
10
1
0
N
NE
E
SE
S
SW
W
NW
Current Velocity (m/s)
0.5
0.4
0.3
0.2
0.1
0.0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
A
Year 2013
Ingrid
Current Direction (log10)
10
1
0
Current Velocity (m/s)
0.5
0.4
0.3
0.2
0.1
0.0
Jan
Feb
Mar
Apr
May
Jun
Jul
Aug
Sep
Oct
Nov
Dec
B


Regal Damsel Recruitment - Year: 1, Day: 1
USA
Florida
Cuba
Yucatan
Mexico
Latitude
30
28
26
24
22
20
-98
-96
-94
-92
-90
-88
-86
-84
-82
-80
Longitude

Royal Damsel (*Neopomacentrus cyanomos*) in the Southern Gulf of Mexico



- Limited spread over 5 years
- Connectivity break from greater GOM



- Low invasion risk over 5 – 15 years
- Control efforts should be focused near Veracruz extending to the western Campeche Bank and Mexican Shoreline

Thank you!

More information: http://www.mattspace.com