Evaluating Future Fisheries Management Scenarios Using Combined Downscaled Climate, Ocean Circulation, and Habitat Suitability Models

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Two Apparently Different Species

- Atlantic bluefin tuna (Thunnus thynnus)
  - Highly migratory oceanic 1000’s km
  - Larvae duration 1-3 day-> ~14days nektonic

- Bonefish (Albula vulpes)
  - Local coastal – shallow flats, 100’s km
  - Larvae duration 41-71 days to settlement in protected shallow areas

Spawning Location – Recruitment Process and Habitat Change Issues

- **One species is likely to change location, due to inhospitable habitat, to a new more hospitable one. Forced out.**
- **One is likely to invade other areas through the advance of their habitat, i.e. improved habitability. Invade.**
- **Both will require adjustments in management**

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Modeling Efforts

- **Bluefin: regionally downscaled climate models and biogeochemical models**
  - Liu, Y. et al., 2015. J. Mar. Syst. 148:56-69.
- **Bluefin: catch -> habitat modeling**
  - **Classification & neural networks**
    - **3D temperature, chlorophyll, depth**
    - Muhling, B.A., 2015. J. Mar. Syst. 148: 1-13.
      - See Muhling et. al., poster using metabolic approach with oxygen and temperature issues
- **Bonefish nowcast-forecasting by He & Zeng**
  - Zeng & He, 2016, J.G.R. Oceans 121:8021-8038
  - Adams et. al., in review

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NASA PROJECT HIGHLIGHTS

Management And Conservation Of Atlantic Bluefin Tuna (*Thunnus Thynnus*) And Other Highly Migratory Fish In The Gulf Of Mexico Under IPCC Climate Change Scenarios: A Study Using Regional Climate And Habitat Models.

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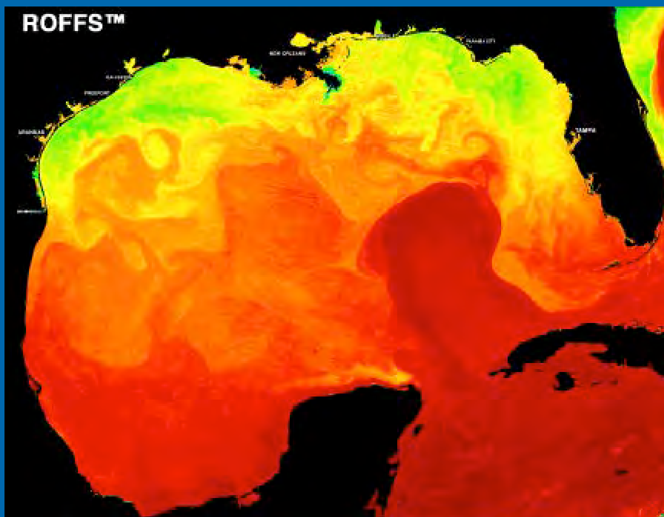
- **Other collaborators added: W. Nero (NOAA), J. Franks (USM), J. Quattro (USC) D. Enfield (NOAA), John F. Walter (NOAA), A. Bakun (UM RSMAS), K. Ramirez (INAPESCA), F. Alemany (IEO), A. Garcia (IEO) . . and growing**
- **Start date September 06, 2011 –End date September 05, 2016**

Multi-sector and multi-disciplinary partnership, including government fishery scientists and managers

Applications Research: Enhancing Management
Gulf of Mexico & North Atlantic Ocean
Larvae and Adults

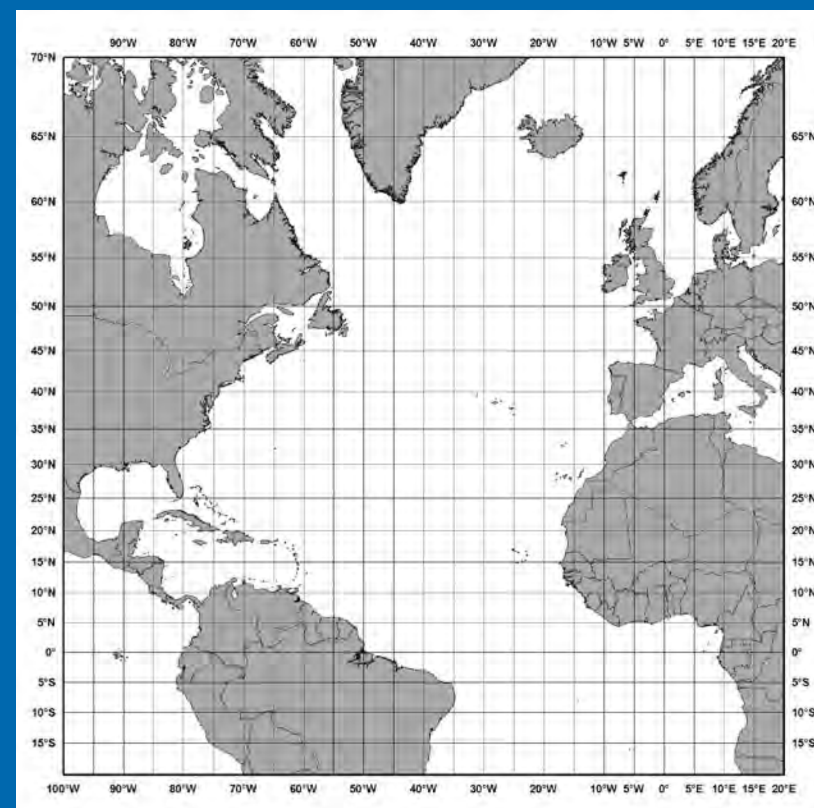


30+ years of NMFS larvae cruise data (larvae, in situ, satellite)

Climate model domain
1000's km

2 m

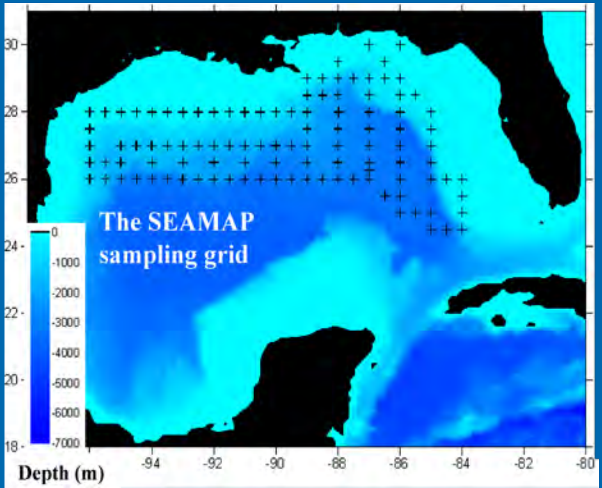
6 mm



25+ years commercial longline data (NOAA + ICCAT)

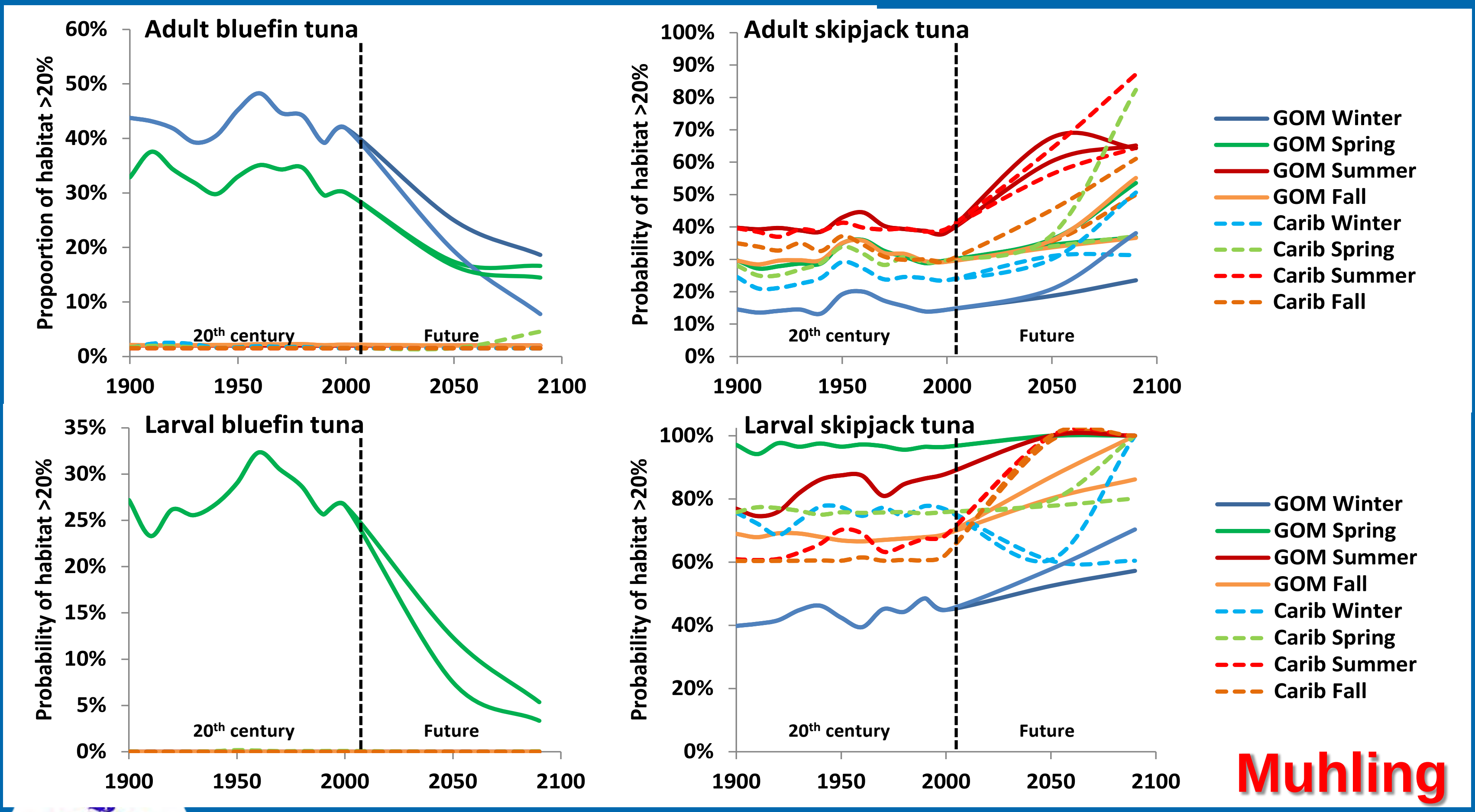
Gulf of Mexico

- Only officially recognized spawning area for US and ICCAT stock assessments in the western North Atlantic Ocean
  - Bluefin tuna larval index derived from NOAA NMFS SEAMAP survey is used to “tune” the virtual population analysis



Future Climate on Bluefin and Skipjack Tuna

Adult and larval habitats in GOM & Caribbean Sea



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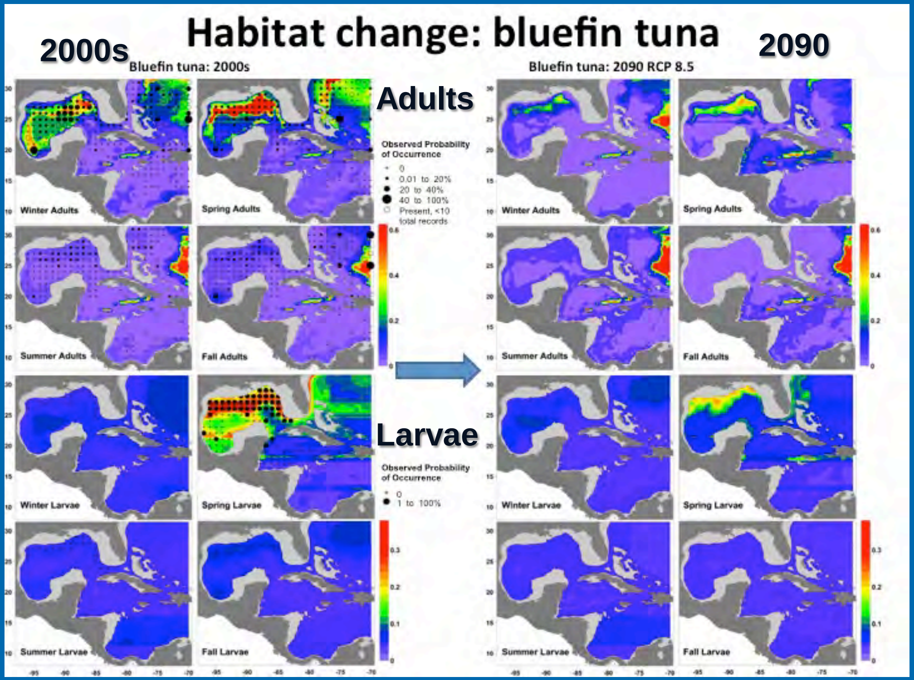
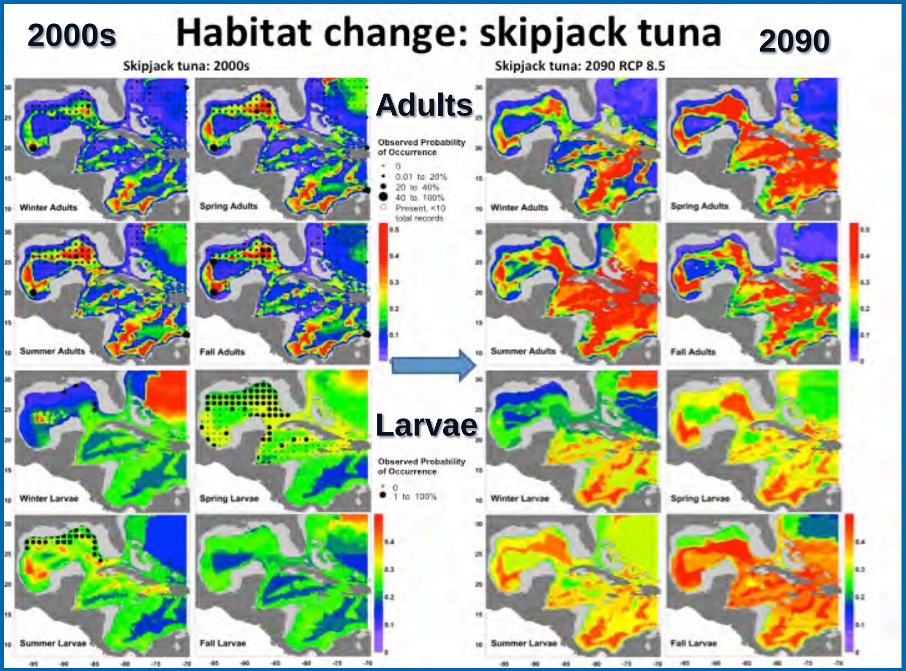
Climate Change Models



Some losers

Some winners



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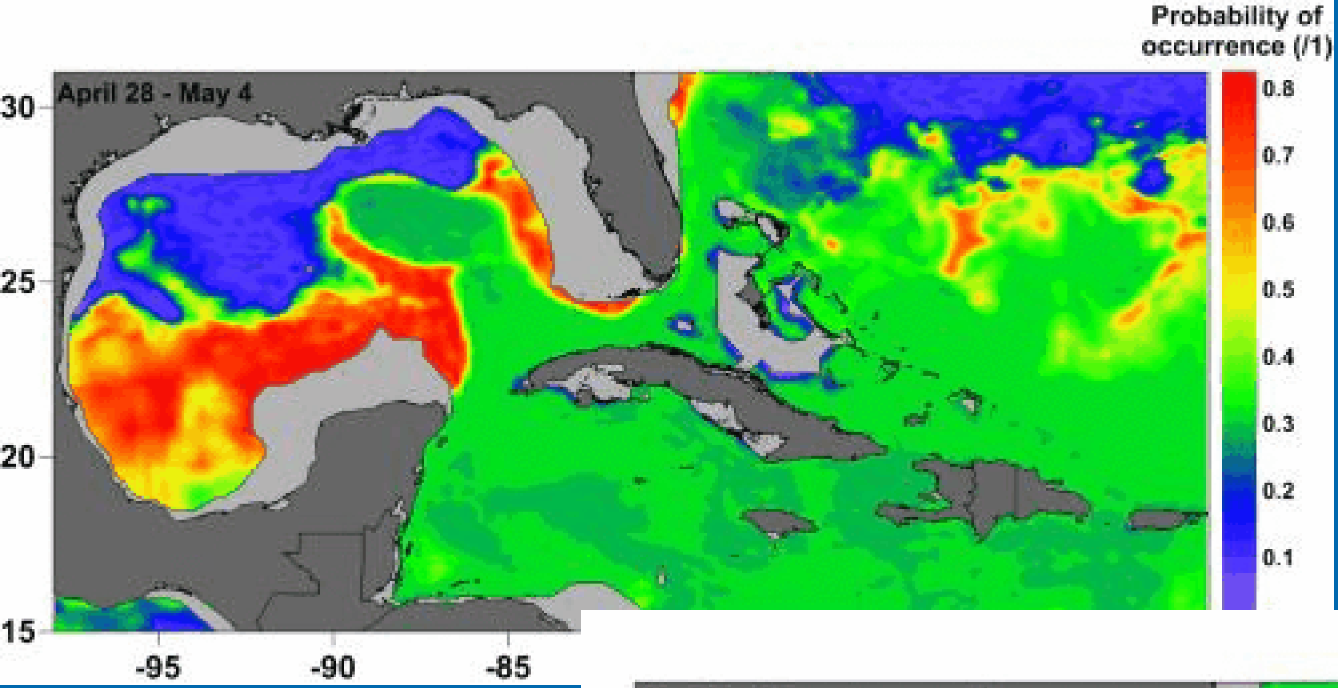
Muhling et al.,

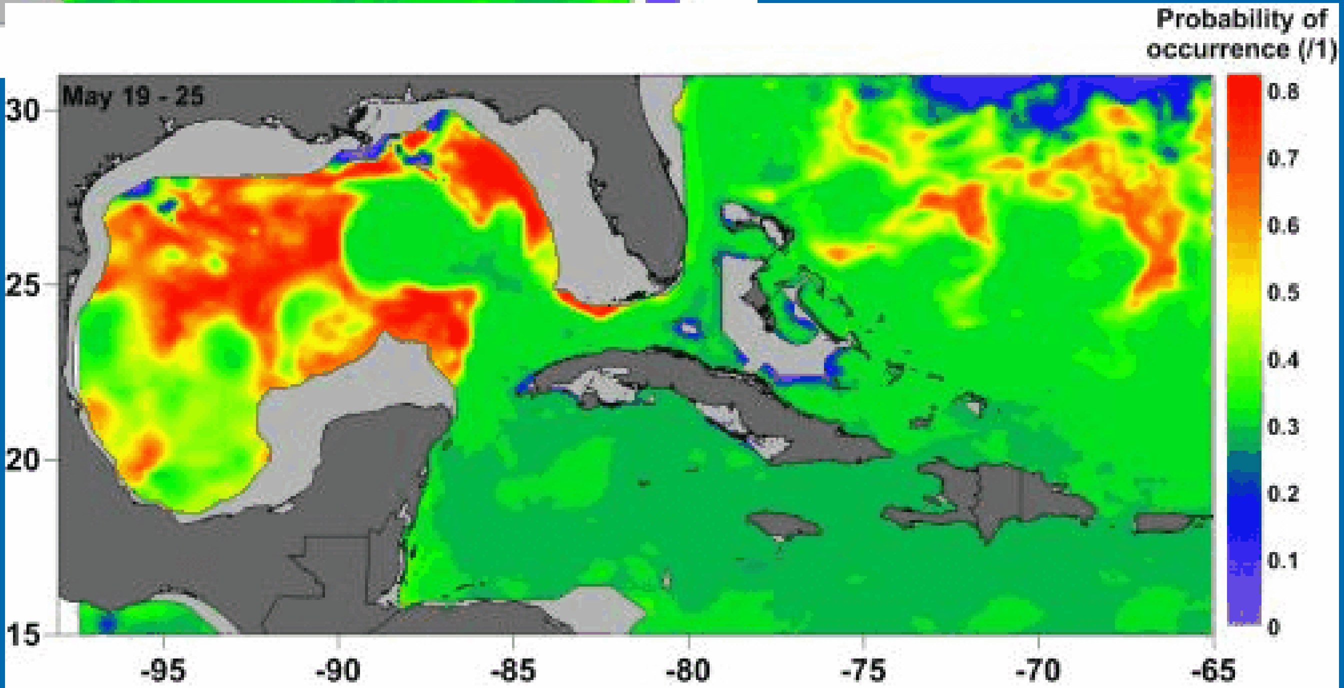
Habitat in GOM, Bahamas, Caribbean 2013



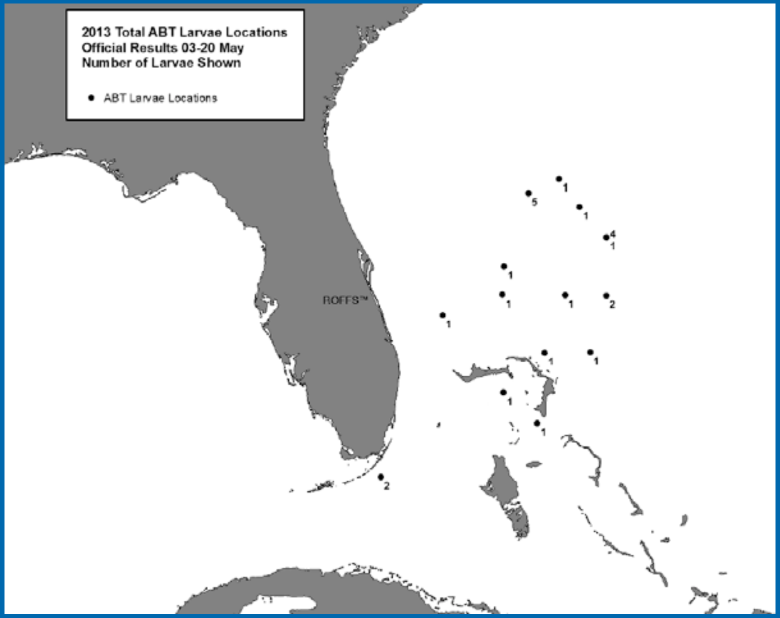
Evaluating New/unknown Spawning areas.

Has transitional phase begun?

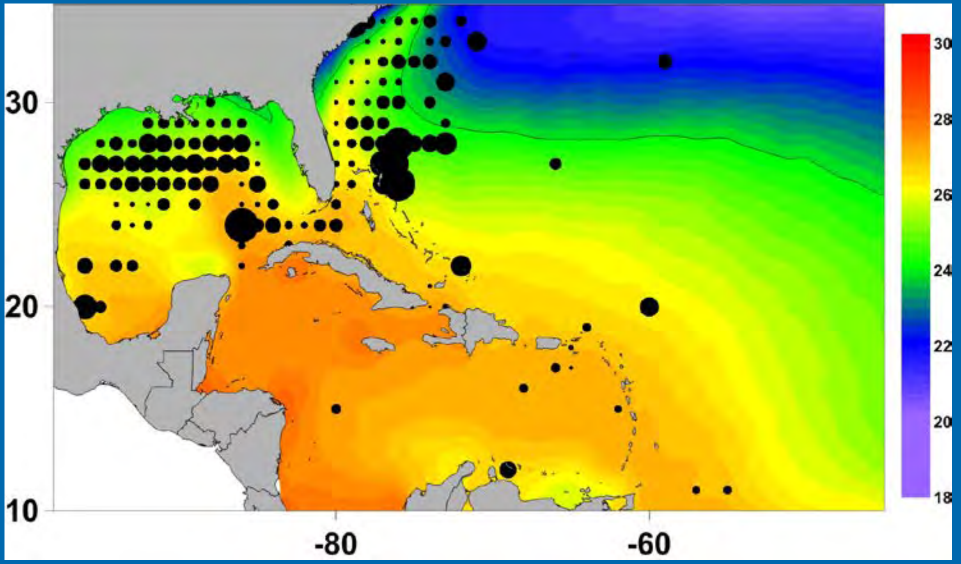
- 2013 habitat model May
- Developed from GOM data!



2013 Results for ABT larvae
16 Positive Stations - 16.5%



Adult Catches 1987-2012



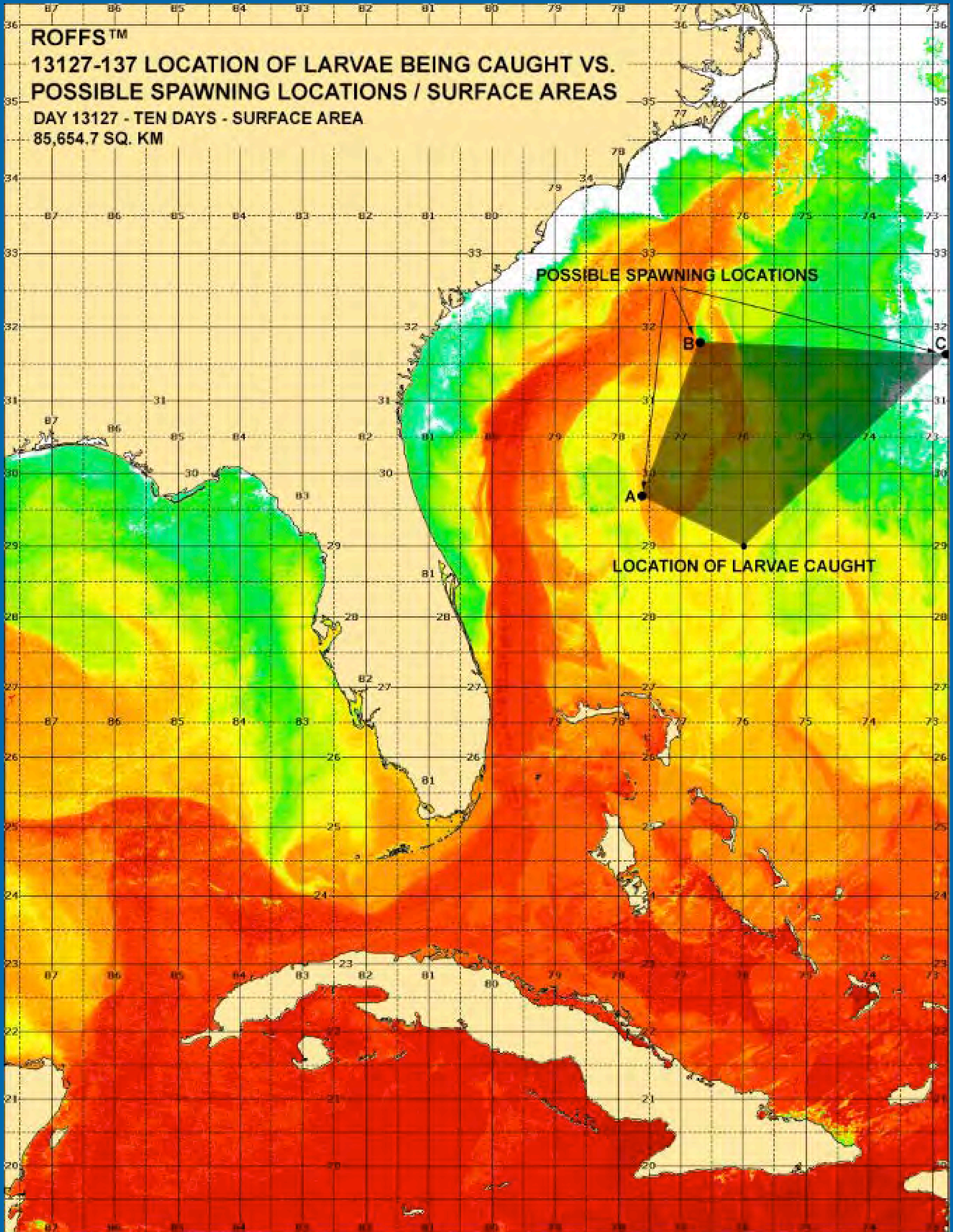
Where were they spawned?

Understanding the Dynamic Oceanography is Critical

36 hr. surface circulation infrared satellite data

1.1 KM

North of Bahamas

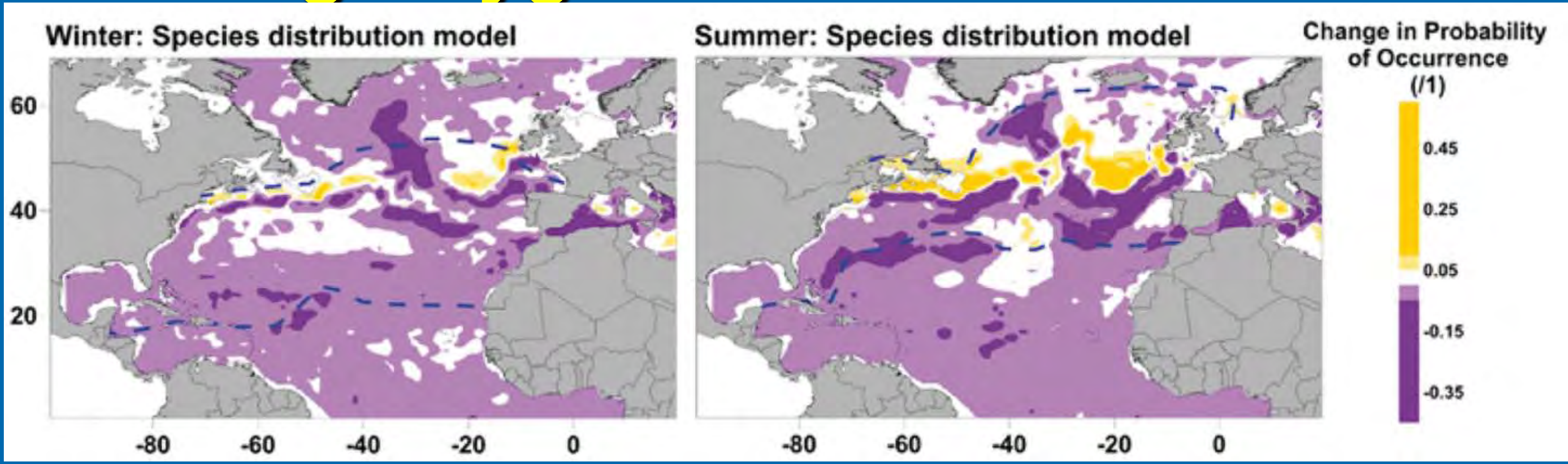


Yes
Bluefin are Spawning Outside the Gulf of Mexico Already

- In Bahamas and north (east of northern South Carolina)
- In Middle Atlantic Bight
  - Discovery of a spawning ground reveals diverse migration strategies in Atlantic bluefin tuna (*Thunnus thynnus*) D.E. Richardson et. al, 2016. PNAS (12) 3299-3304; https://doi.org/10.1073/pnas.1525636113
  - Roffer unpublished research: Backtracking bluefin tuna in Middle Atlantic Bight

1) We don't see good habitat every year.
   a) But climate models suggest these habitats will be hospitable to bluefin in the future
2) Need to repeat surveys in these "new areas" routinely & expand to other areas with the fish or perhaps before they expand.

Future Habitat Distribution Probabilities Using Oxygen – Metabolic Model



Probability of occurrence for bluefin between 2071–2100, from the ESM2M Earth system model. The regions where positive catch rates for bluefin have been recorded in the ICCAT Task II database (1997–2014) are shown as dashed polygons. (From Muhling et al., 2017 and Leung et al., in review).

Poster S10-P5:
Out of tuna: Using metabolic models to estimate future accessibility of bluefin and yellowfin tunas to U.S. fisheries.
B.A. Muhling, R. Brill, J.T. Lamkin[4], M.A. Roffer, S.K. Lee, Y. Liu [7], F. Muller-Karger

Bonefish Larval Drift Modeling

Mitchell A. Roffer, Ph.D.

Aaron Adams:

Bonefish Tarpon Trust

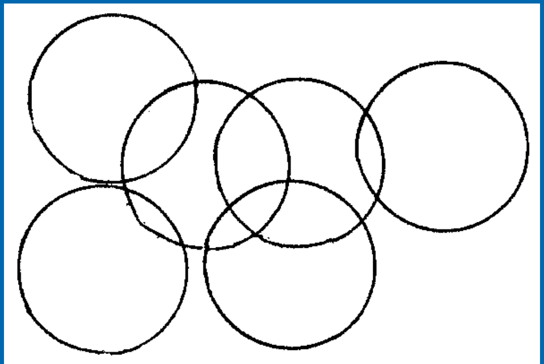
Ruoying He & Xiangming Zeng:

North Carolina State University

THE BIG ISSUE

Management Issue: Are the Bonefish Fisheries Throughout the Caribbean & Florida Unit Stocks

*$0.5 Billion fisheries



- A **unit stock** is essentially a self-contained population with its own spawning area. It is isolated and **fishing** upon one **unit stock** has no effect upon the individuals of other **stocks**.

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http://www.fao.org/docrep/003/f0752e/F0752E08.htm

Is The Localized by Country Unit Stock Concept Appropriate For Bonefish?

- Considering issues between countries:
  - Do we know what the unit stocks are?
  - If they are multi-national could we manage them through an international treaty like other species like tuna?
- What do we need to arrive at an answer?
  - Modeling eggs & larvae

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Methods: Particle Forecasting

- Forward-cast tracked for 53 days
  - Planktonic larval duration 41-71 days
- 4 D ROMS regionally downscaled particle tracking model

4D Ocean Modeling

- ROMS regional Oct. 2009 – May 2015
  - ~ 7 km horizontal grid spacing
  - 36 vertical layers & bathymetry
  - Boundary conditions from HYCOM
  - Surface wind forcing
- Used 26 locations as spawning sites
  - 100 larval “particles”/site were tracked/spawning event
    - 218,400 particles total
  - 0.5 m depth with no vertical migration
  - Released twice a month (new & full moon)
  - Tracked for 53 days

Zeng and He 2016

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Results

- Along trajectory distance
- Straight line distance
- Full moon and new moon distances
- Seasonal: Nov. – Jan. & Feb. – Apr.
- Captured Variance

Site	Mean±STD(Winter)		Mean±STD(Spring)		Significant difference		p-value	
	D1	D2	D1	D2	D1	D2	D1	D2
01	581.33 ± 306.18	172.22 ± 192.02	658.34 ± 351.83	156.15 ± 215.65	1	1	0.00E+00	7.00E-04
02	662.66 ± 262.08	225.84 ± 165.55	864.07 ± 340.40	242.98 ± 169.10	1	1	0.00E+00	0.00E+00
03	752.85 ± 353.46	236.51 ± 150.81	927.05 ± 395.20	265.57 ± 168.07	1	1	0.00E+00	0.00E+00
04	604.36 ± 274.50	153.61 ± 103.55	955.78 ± 468.11	235.51 ± 259.99	1	1	0.00E+00	0.00E+00
05	885.34 ± 499.11	288.99 ± 337.20	1189.40 ± 571.77	379.88 ± 370.39	1	1	0.00E+00	0.00E+00
06	503.09 ± 347.82	172.85 ± 154.43	1114.50 ± 610.77	412.90 ± 415.58	1	1	0.00E+00	0.00E+00
07	288.72 ± 326.44	79.62 ± 105.74	794.24 ± 581.94	293.49 ± 361.89	1	1	0.00E+00	0.00E+00
08	2346.60 ± 1091.40	1567.20 ± 850.12	2662.00 ± 850.42	1764.90 ± 695.17	1	1	0.00E+00	0.00E+00
09	1865.60 ± 1144.40	1263.90 ± 928.50	2132.10 ± 1200.60	1461.20 ± 901.75	1	1	0.00E+00	0.00E+00
10	1576.40 ± 1066.00	863.65 ± 905.33	1697.10 ± 1233.50	1052.00 ± 968.49	1	1	0.00E+00	0.00E+00
11	2003.30 ± 1141.70	1227.10 ± 983.40	1641.90 ± 1113.30	918.88 ± 937.17	1	1	0.00E+00	0.00E+00
12	1022.60 ± 935.74	311.13 ± 377.28	561.75 ± 463.41	146.43 ± 141.71	1	1	0.00E+00	0.00E+00
13	649.33 ± 504.85	230.80 ± 172.62	552.46 ± 448.94	190.94 ± 91.21	1	1	0.00E+00	0.00E+00
14	364.76 ± 269.85	168.65 ± 117.73	221.04 ± 201.69	101.50 ± 90.69	1	1	0.00E+00	0.00E+00
15	866.55 ± 540.53	402.77 ± 241.90	651.03 ± 252.27	316.12 ± 127.96	1	1	0.00E+00	0.00E+00
16	2879.40 ± 1233.20	1572.70 ± 1002.70	3070.90 ± 1037.70	1451.50 ± 938.62	1	1	0.00E+00	0.00E+00
17	2047.50 ± 1447.60	1173.40 ± 973.77	2822.60 ± 1548.50	1479.00 ± 1052.70	1	1	0.00E+00	0.00E+00
18	2221.80 ± 1398.80	1196.40 ± 982.85	3035.30 ± 1512.60	1610.40 ± 1091.10	1	1	0.00E+00	0.00E+00
19	470.36 ± 579.07	223.18 ± 357.69	245.18 ± 287.73	126.04 ± 134.78	1	1	0.00E+00	0.00E+00
20	1082.60 ± 231.78	555.66 ± 208.56	1046.40 ± 164.59	560.06 ± 170.65	1	0	0.00E+00	3.24E-01
21	1060.40 ± 232.39	573.30 ± 205.62	1014.60 ± 243.36	570.33 ± 196.37	1	0	0.00E+00	5.66E-01
22	1095.80 ± 202.99	536.26 ± 197.18	976.36 ± 259.37	529.92 ± 188.78	1	0	0.00E+00	1.80E-01
23	979.77 ± 296.81	593.50 ± 250.39	902.10 ± 301.13	536.34 ± 212.11	1	1	0.00E+00	0.00E+00
24	2065.70 ± 492.92	1531.80 ± 435.90	1987.50 ± 541.79	1451.40 ± 439.48	1	1	0.00E+00	0.00E+00
25	2065.60 ± 447.47	1521.10 ± 443.91	1897.10 ± 524.03	1431.70 ± 414.19	1	1	0.00E+00	0.00E+00
26	2088.50 ± 415.45	1564.40 ± 400.13	1877.70 ± 486.89	1378.60 ± 418.30	1	1	0.00E+00	0.00E+00

Site	Mean ± STD (both)		Mean ± STD (full moon)		Mean ± STD (new moon)		Significant difference		p-value	
	D1	D2	D1	D2	D1	D2	D1	D2	D1	D2
01	626.52 ± 346.02	169.11 ± 217.94	634.37 ± 337.15	166.64 ± 211.00	618.67 ± 354.53	171.58 ± 224.66	1	0	3.85E-02	2.92E-01
02	762.56 ± 324.48	239.29 ± 163.10	736.46 ± 326.85	230.11 ± 157.08	788.67 ± 320.01	248.46 ± 168.43	1	1	6.68E-16	1.78E-09
03	837.16 ± 381.95	250.94 ± 163.21	815.69 ± 397.18	245.16 ± 163.85	858.62 ± 364.88	256.72 ± 162.38	1	1	2.84E-10	3.11E-05
04	721.16 ± 425.00	176.96 ± 193.81	738.40 ± 471.41	189.70 ± 217.02	703.91 ± 372.11	164.21 ± 166.48	1	1	8.49E-07	2.52E-11
05	1045.60 ± 566.31	351.59 ± 370.47	1019.70 ± 552.17	341.84 ± 375.85	1071.40 ± 579.02	361.33 ± 364.79	1	1	8.31E-07	3.33E-03
06	805.96 ± 597.86	298.95 ± 345.35	768.47 ± 580.31	265.23 ± 317.84	843.45 ± 612.69	332.67 ± 367.78	1	1	8.68E-14	3.74E-26
07	524.32 ± 512.94	182.83 ± 277.47	502.59 ± 459.69	169.79 ± 243.86	546.06 ± 560.37	195.86 ± 306.91	1	1	5.63E-08	1.24E-11
08	2363.80 ± 1073.30	1555.10 ± 838.04	2375.90 ± 1033.30	1584.10 ± 815.00	2351.70 ± 1111.80	1526.20 ± 859.59	0	1	2.51E-01	4.10E-04
09	1915.10 ± 1183.00	1277.50 ± 928.78	1955.70 ± 1146.00	1299.70 ± 914.38	1874.60 ± 1217.70	1255.30 ± 942.54	1	1	1.46E-04	7.59E-03
10	1564.40 ± 1113.80	891.16 ± 909.98	1473.30 ± 1063.00	811.68 ± 883.69	1655.50 ± 1155.50	970.63 ± 928.86	1	1	3.54E-16	5.29E-19
11	1742.90 ± 1117.80	999.52 ± 957.19	1830.50 ± 1099.80	1072.20 ± 988.70	1655.40 ± 1128.90	926.79 ± 918.98	1	1	6.53E-20	5.63E-20
12	813.84 ± 778.08	230.57 ± 286.91	867.81 ± 804.16	252.41 ± 323.66	759.87 ± 747.31	208.74 ± 242.77	1	1	1.90E-18	1.85E-16
13	605.48 ± 479.05	216.06 ± 138.37	588.63 ± 476.81	215.51 ± 125.71	622.33 ± 480.74	216.61 ± 149.98	1	0	5.23E-04	7.01E-01
14	316.94 ± 304.78	147.75 ± 118.11	282.86 ± 256.80	132.44 ± 120.89	351.02 ± 342.82	163.05 ± 113.22	1	1	8.50E-32	3.59E-53
15	773.03 ± 516.46	372.61 ± 217.40	833.42 ± 582.85	406.44 ± 224.95	712.63 ± 431.86	338.79 ± 204.07	1	1	3.29E-29	4.82E-48
16	2901.90 ± 1144.30	1444.30 ± 940.41	3123.30 ± 1144.80	1654.90 ± 1005.20	2680.50 ± 1100.30	1233.70 ± 818.41	1	1	7.14E-73	2.52E-92
17	2249.60 ± 1570.60	1231.50 ± 1023.10	2377.40 ± 1501.10	1253.90 ± 968.60	2121.80 ± 1627.30	1209.20 ± 1074.50	1	1	1.17E-19	9.90E-03
18	2470.80 ± 1538.00	1326.70 ± 1052.50	2475.60 ± 1465.80	1261.00 ± 981.81	2466.10 ± 1607.00	1392.40 ± 1115.00	0	1	7.51E-01	2.08E-11
19	356.09 ± 444.12	168.66 ± 255.76	371.08 ± 427.94	174.20 ± 233.69	341.10 ± 459.29	163.11 ± 275.99	1	1	1.35E-04	1.58E-02
20	1068.90 ± 202.94	566.09 ± 190.43	1082.10 ± 200.44	605.80 ± 174.63	1055.70 ± 204.59	526.37 ± 197.19	1	1	4.10E-11	5.76E-98
21	1035.30 ± 242.17	577.91 ± 198.11	1015.10 ± 240.65	599.78 ± 186.37	1055.50 ± 242.03	556.03 ± 206.92	1	1	1.61E-19	1.57E-29
22	1045.00 ± 235.20	535.71 ± 187.57	1029.10 ± 245.32	525.80 ± 184.58	1060.90 ± 223.53	545.63 ± 190.02	1	1	5.03E-13	8.90E-08
23	957.03 ± 305.35	577.75 ± 236.43	948.38 ± 292.40	589.79 ± 215.47	965.67 ± 317.58	565.72 ± 255.13	1	1	7.95E-04	2.79E-08
24	2015.70 ± 608.59	1459.90 ± 461.63	2045.10 ± 673.58	1452.30 ± 494.29	1986.20 ± 534.23	1467.40 ± 426.41	1	0	1.08E-06	1.12E-01
25	1970.60 ± 532.66	1447.70 ± 445.00	2062.00 ± 592.76	1473.60 ± 478.50	1879.20 ± 446.61	1421.80 ± 407.16	1	1	1.40E-76	9.49E-09
26	1958.80 ± 478.97	1444.40 ± 447.21	2003.70 ± 481.48	1476.70 ± 475.27	1914.00 ± 472.26	1412.10 ± 414.82	1	1	4.21E-25	2.11E-15

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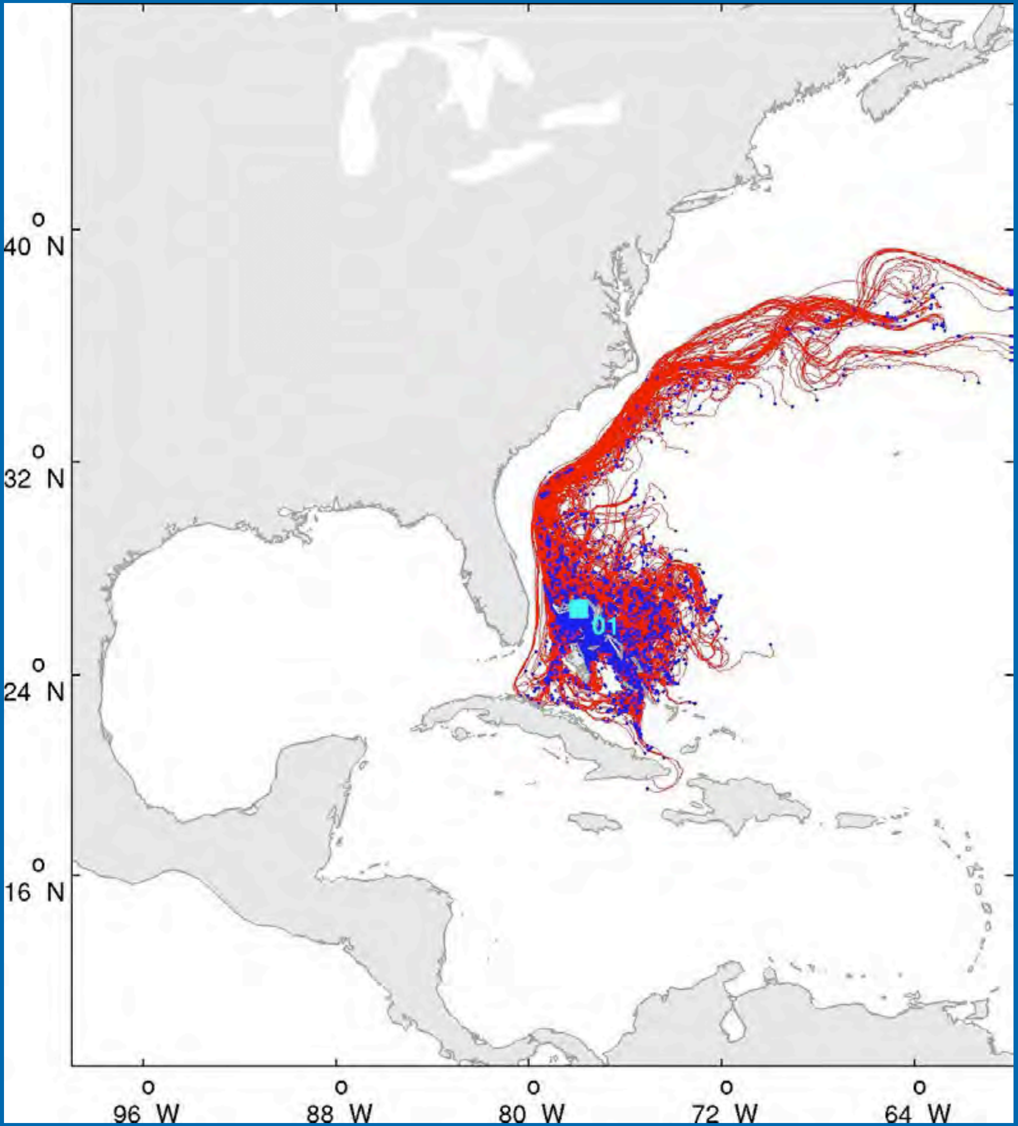
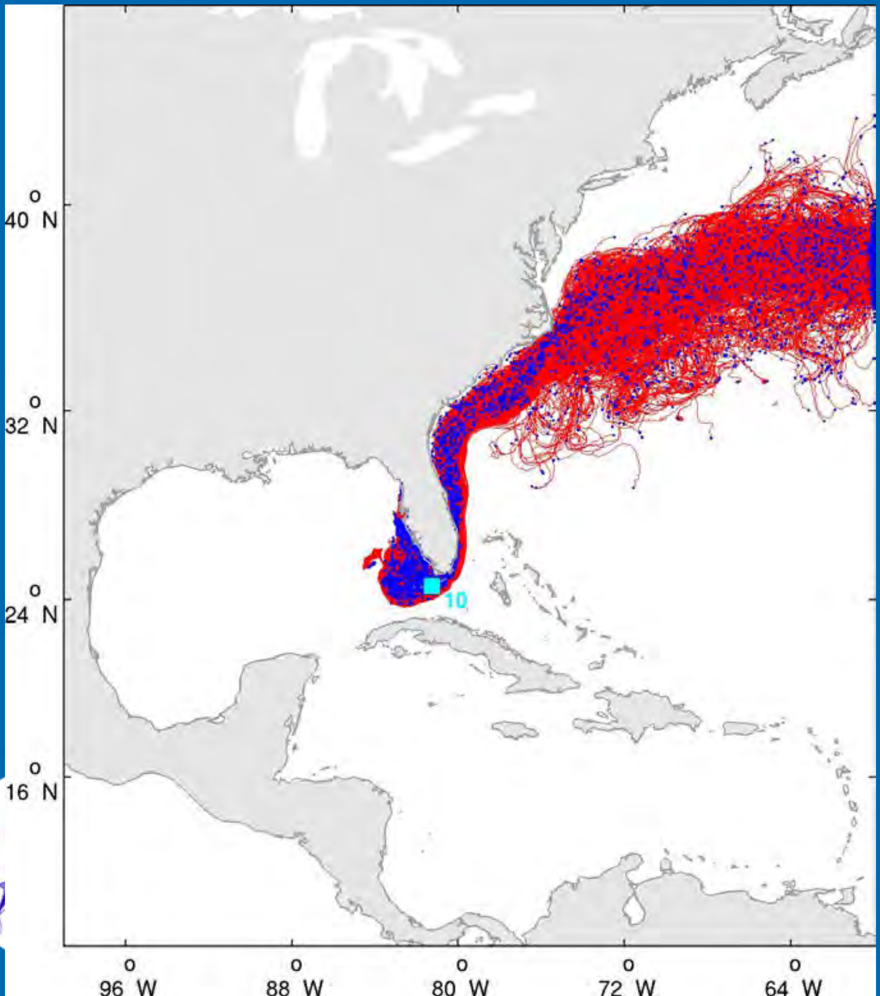
Presently No Reproductive Populations North of Bahamas

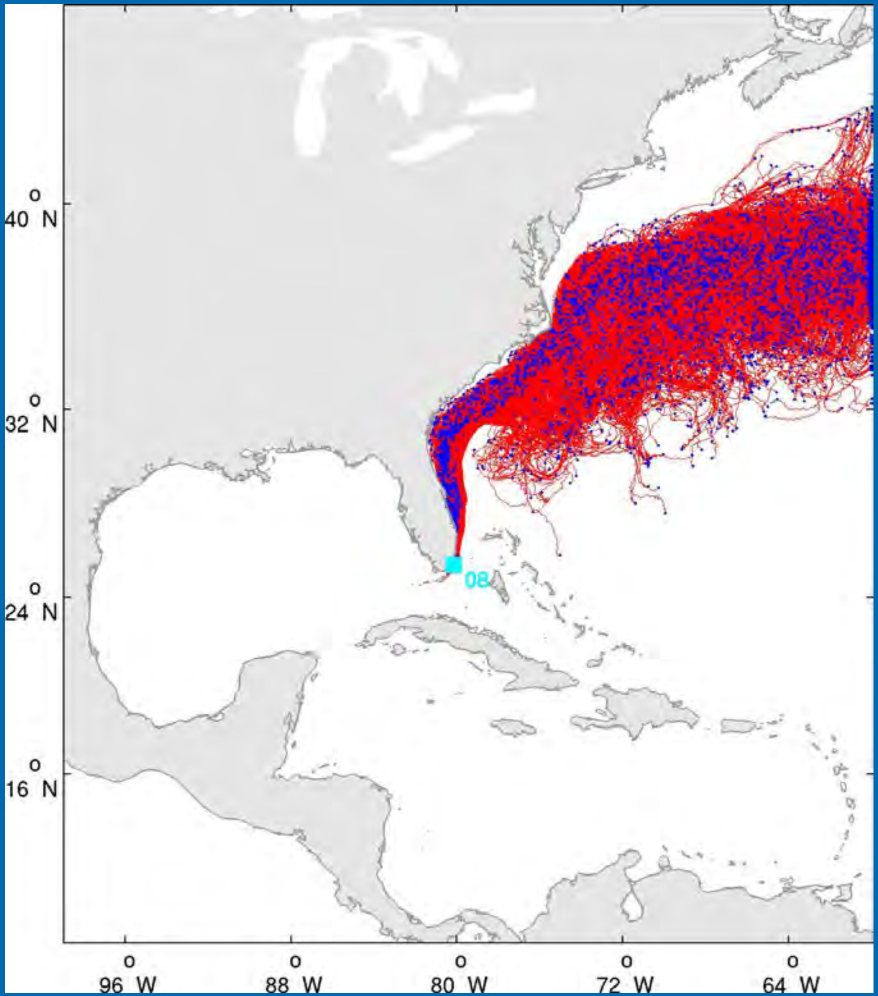


Movie of results

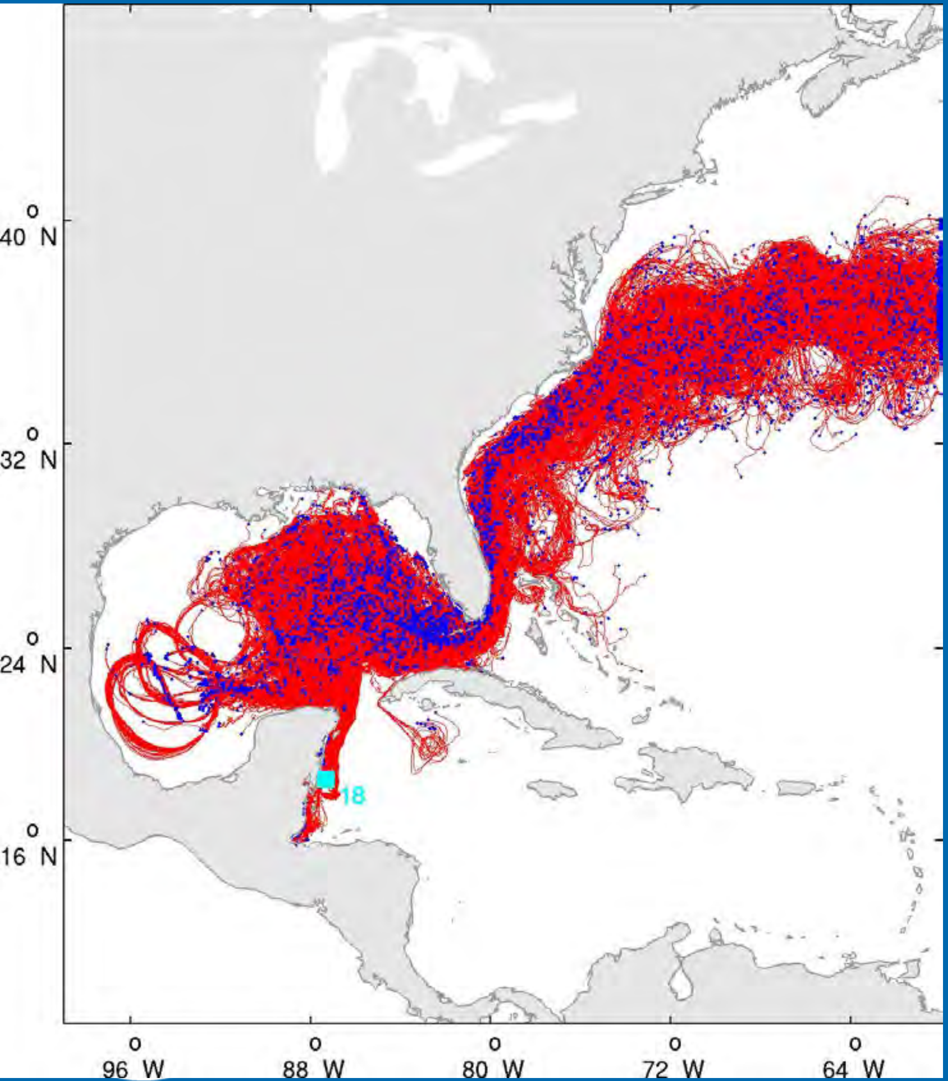
Presently Lots of Lost Recruitment

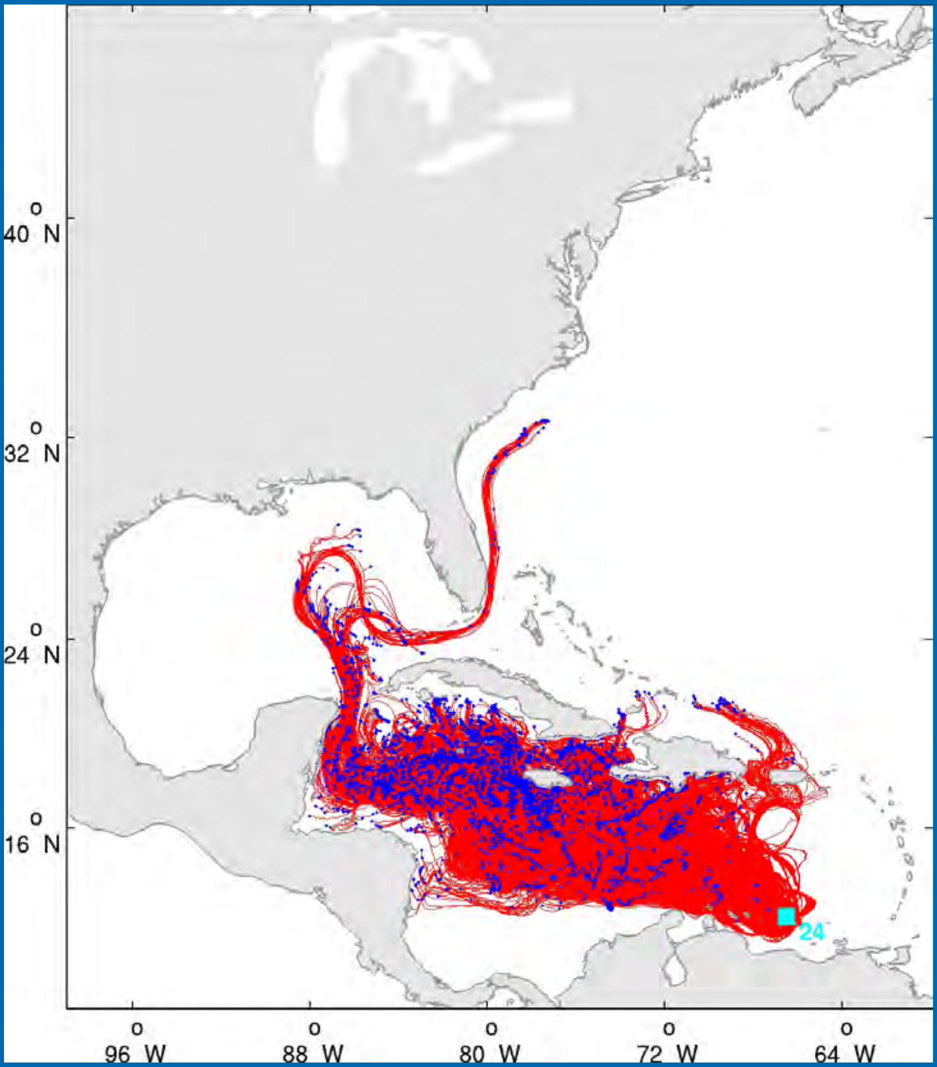
- Eggs and larvae to areas where no reproduction occurs presently



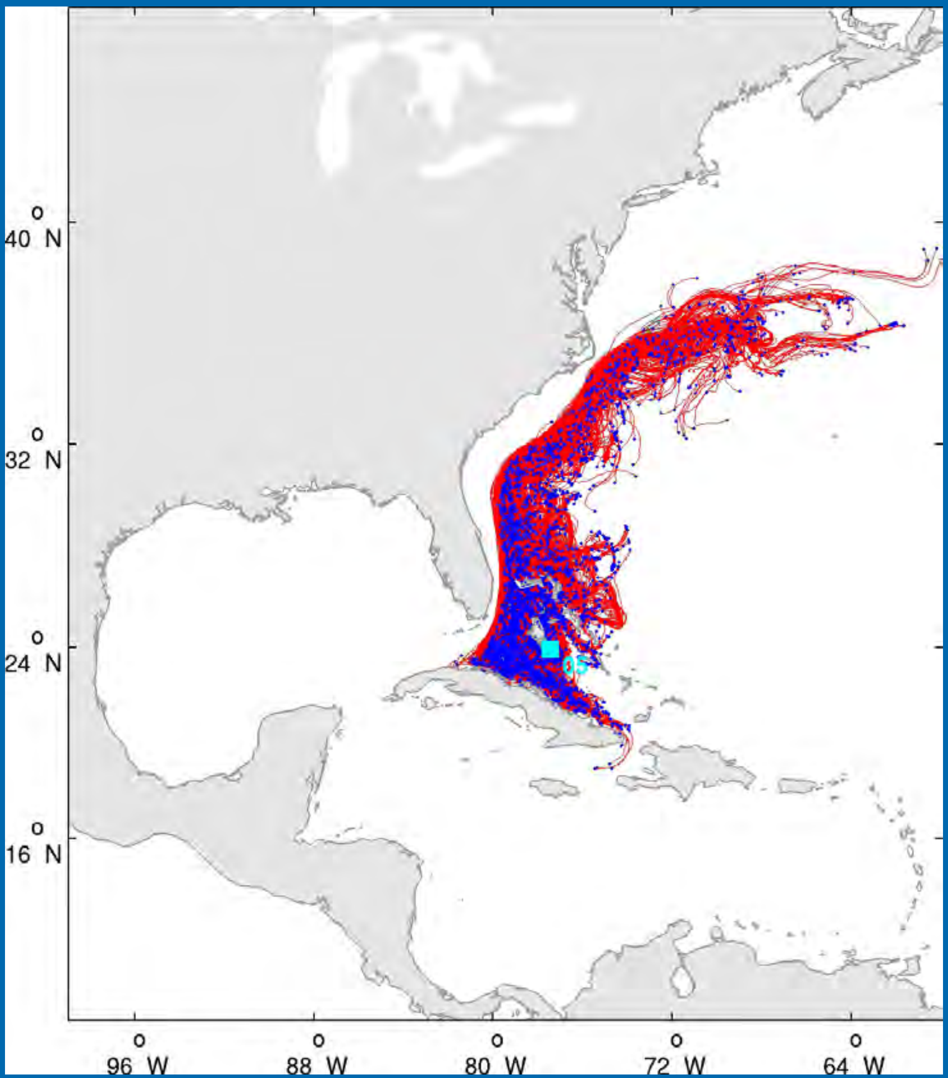


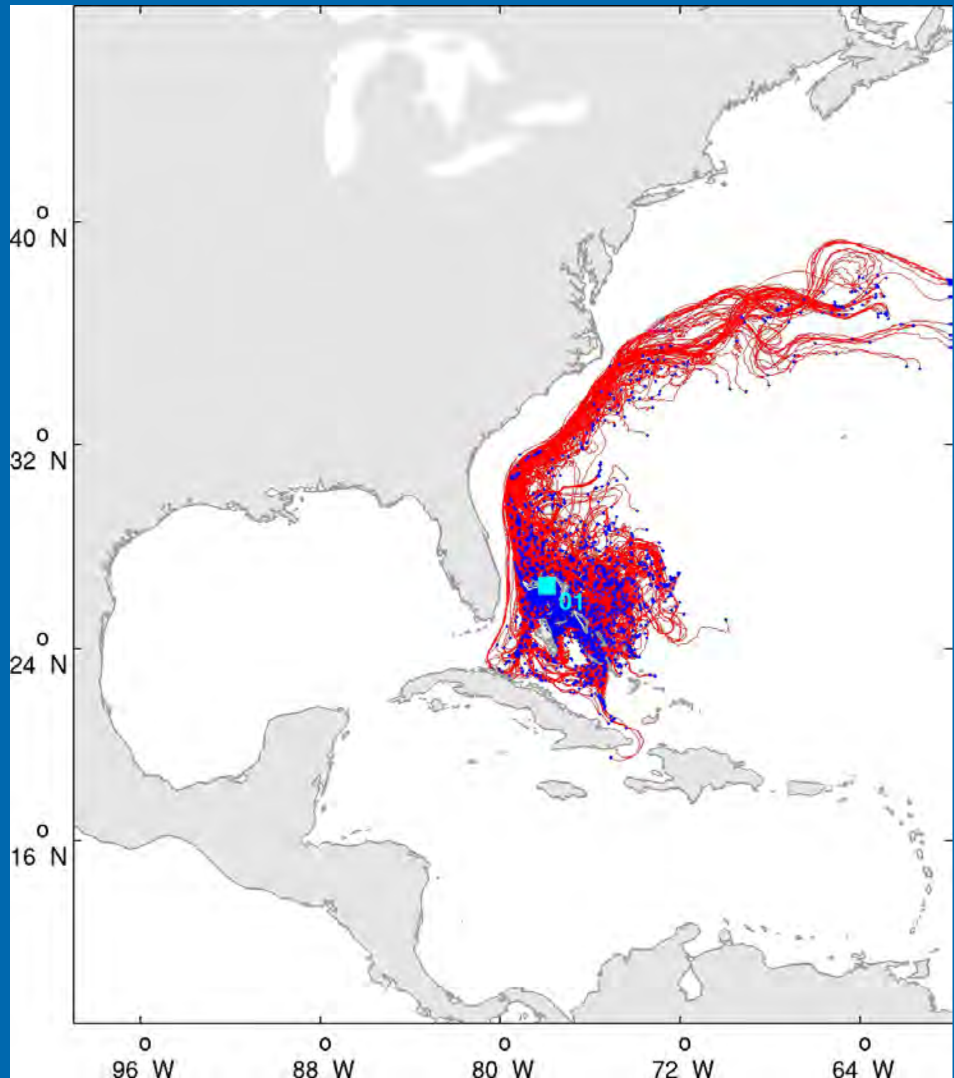
Lots of Variation





Bahamas Spawning





Eggs Carried Away By Gulf Stream

- Eggs "lost" under present conditions.
- But what about climate change?
  - Eggs & larvae travel to areas where there is no fishery now.
    - But there likely will be in the future.

Management Implications

- **Habitat change creates new transboundary issues.**
- **Should we generate larger reproductive reserves (N) through reduced catch during transitional times, i.e. until populations recover?**
  - **Assuming that there will be a reduction in total recruitment success as habitats move?**
- **How many species are like tuna and already spawn in presently unfavorable habitats? “Covering their reproductive survival bets”**
- **Issues of uneven environmental change**
  - **Non-linear changes in temperature, chlorophyll, current expected**

Challenges with Change

- **How do we plan for the marine reserves of the future?**
  - **When & where do we propose them?**
  - **How do we do this with confidence w buy in ?**
- **Fishery independent surveys need to re-evaluated as to where they should occur.**
  - **Additional recent work* with north Atlantic mackerel (Scomber sombrous) showed the need for revised surveying techniques as the fish (immature and mature) are not always in the trawl survey area.**

Final report to the Mid-Atl. Fish. Manage. Council. Collab. Res. Prog: *Collaborative Development of a Winter Habitat Model for Atlantic Mackerel, "version 2.0", for the Identification of "Cryptic" Habitats and Estimation of Population Availability to Assessment Surveys and the Fishery*. By G. DiDomenico, W. Bright, P. Moore, J. Kohut, M. Roffer, J. Manderson, & J. Pessutti. 2017. Contract Number: 16-0405

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Contemplation

- Need for quantitative catchability coefficients derived from environmental – habitat condition co-variants.
- While this is suggested in ecosystem based fisheries management, this isn't being done as much as needed.
  - Noteworthy exceptions
    - Ingram et al., for US and Spanish bluefin
    - Manderson et al., north Atlantic mackerel
    - Muhling et al., grey triggerfish
    - Others

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Thank You

- NASA Earth Science Program
  - Biodiversity and Ecological Forecasting
- NOAA SEFSC, Miami & NEFSC, Narragansett
- Bonefish & Tarpon Trust
- ROFFS™

Poster S10-P5:

Out of tuna: Using metabolic models to estimate future accessibility of bluefin and yellowfin tunas to U.S. fisheries.

B.A. Muhling, R. Brill, J.T. Lamkin[4], M.A. Roffer, S.K. Lee, Y. Liu [7], F. Muller-Karger

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4D Ocean Modeling: Bonefish

- ROMS regional Oct. 2009 – May 2015
  - ~ 7 km horizontal grid spacing
  - 36 vertical layers & bathymetry
  - Boundary conditions from HYCOM
  - Surface wind forcing
- Used 26 locations as spawning sites
  - 100 larval "particles"/site were tracked/spawning event
    - 218,400 particles total
  - 0.5 m depth with no vertical migration
  - Released twice a month (new & full moon)
  - Tracked for 53 days

Zeng and He 2016

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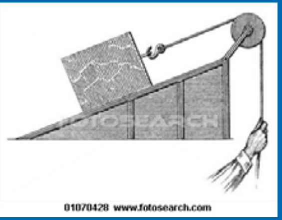
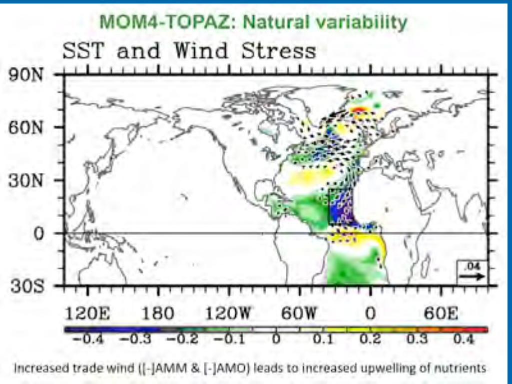
Summary of Bluefin Methods

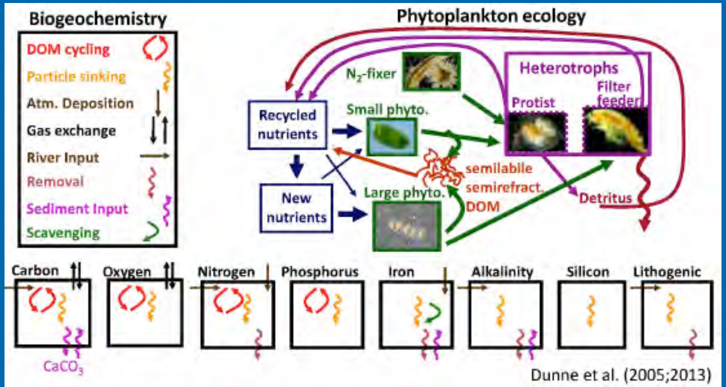
1. Developed habitat models of larvae and adults using boosted classification tree and neural network models
   a. Multivariate, non-parametric methods
2. Downscaling climate models for 100 year forecasts
   a. CMIP5 simulations using MOM4 (GFDL Modular Ocean Model) – Grid: 0.1° in GOM, 0.25° outside
   b. Now MOM4/5-TOPAZ biogeochemical model.
      a. 1° x 1° North Atlantic -> 0.08° in GOM, 0.25°
3. Satellite IR, ocean color, (NASA-MODIS, NOAA, JPSS-VIIRS), altimetry
   a. In habitat model development
   b. Provide strategic and tactical cruise work
   c. Climatology of GMex & North Atlantic
   d. Validation of climate models

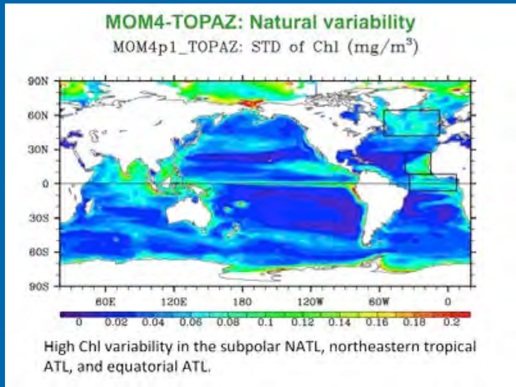


Methods: MOM-TOPAZ

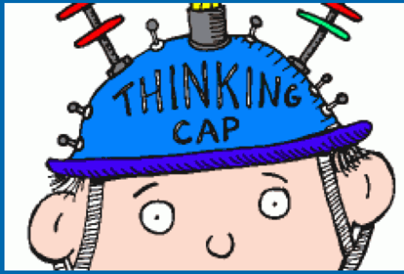
- Yanyun Liu and Sang-Ki Lee (Univ. Miami CIMAS – NOAA_AOML)
- MOM4.1 with TOPAZ biogeochemical model
- Temperature and salinity fields initialized from WOA, integrated for 500 years using CORE2 surface flux fields.
- After 500 years of spin-up, integrated for 1948-2009 using real-time surface flux fields.
- Environmental variables output at 1°x1° resolution by year and season:
  - Surface temperature
  - Temperature at 100m depth
    - Used to calc. temp. difference between surface and 100m
  - Current magnitude (m/s)
  - Oxygen at 100m depth (mg/L)
  - Surface chlorophyll (mg/m^3)
- We chose variables shown previously to be important to the physiology and habitat preference of our HMS pelagic fishes
- Downscaling to 0.08° in GOM. Model domain (100ºW-60ºW, 10ºN-45ºN).







Conclusions



- Florida Keys not a unit stock.
- Habitat conditions in SW Florida are critical.
  - So are the entire Caribbean basin.
  - Water quality issues a great concern.
- Ocean circulation models are critical.
  - Behavior of eggs and larvae next step.
    - Vertical movements in the water.
    - But not likely to change these results.
- Genetic study important to better understand the outside contribution.