Ecology and management of Atlantic bluefin tuna under climate variability and change

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Outline

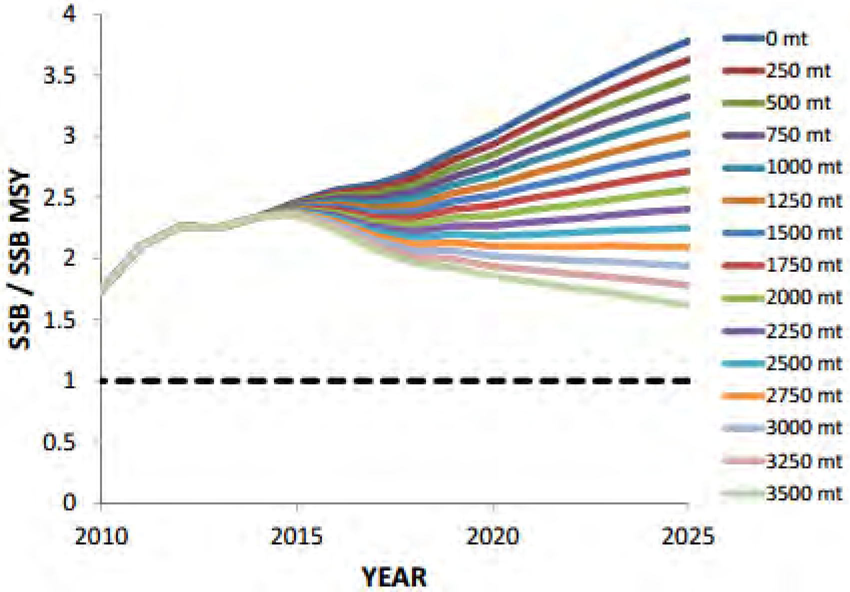
- Management and biology of Atlantic bluefin tuna
- Knowledge gaps and research questions
- Larval studies: distribution and links to recruitment
- Adult studies: habitat and physiology
- Potential climate change impacts
- Conclusions
- Management implications

Current assessment and management

- Atlantic bluefin tuna are managed through the International Commission for the Conservation of Atlantic Tunas (ICCAT)
- Eastern and western stocks separated at 45°W
- Both stocks likely to be overfished, and undergoing overfishing
  - Large uncertainty for western stock, due to lack of understanding of recruitment processes
- Current management does not consider environmental variability or climate change

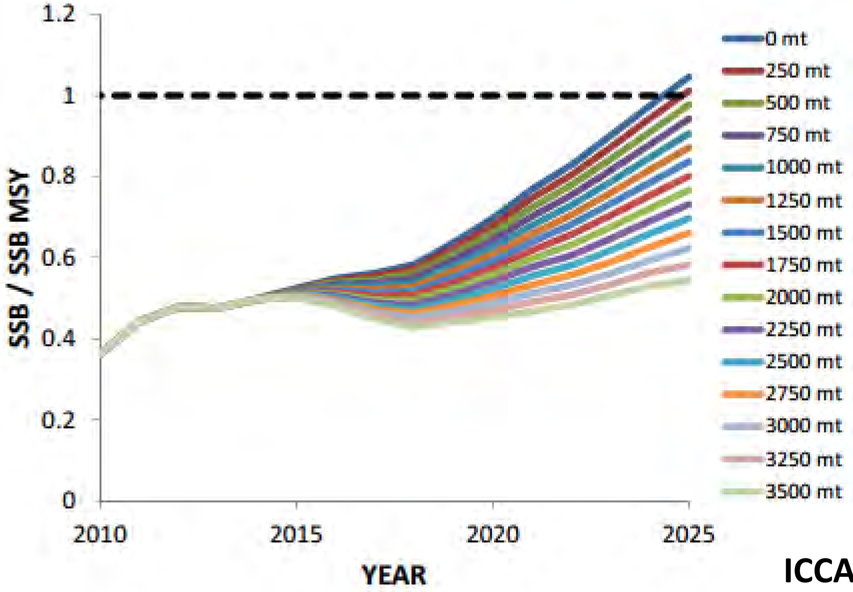
SSB / SSB@MSY: Low recruitment scenario

- Everything is fine



SSB / SSB@MSY: High recruitment scenario

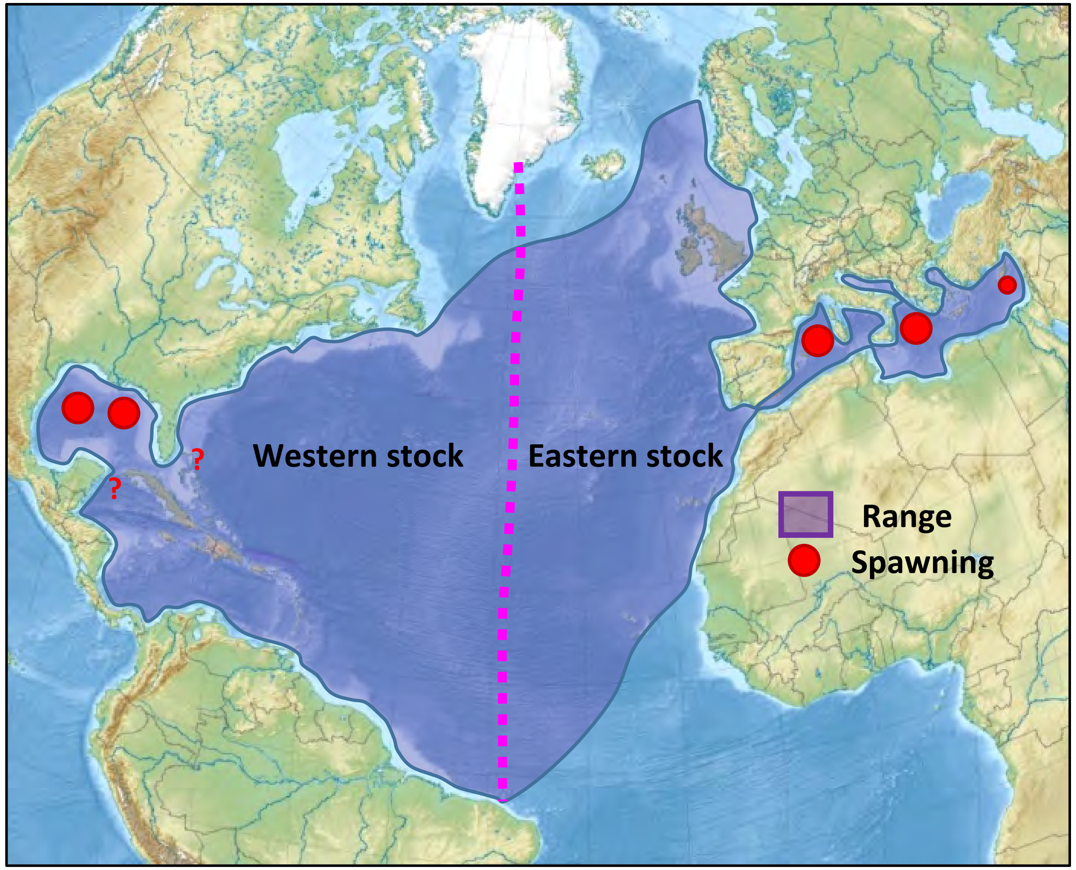
- No chance of rebuilding by 2025



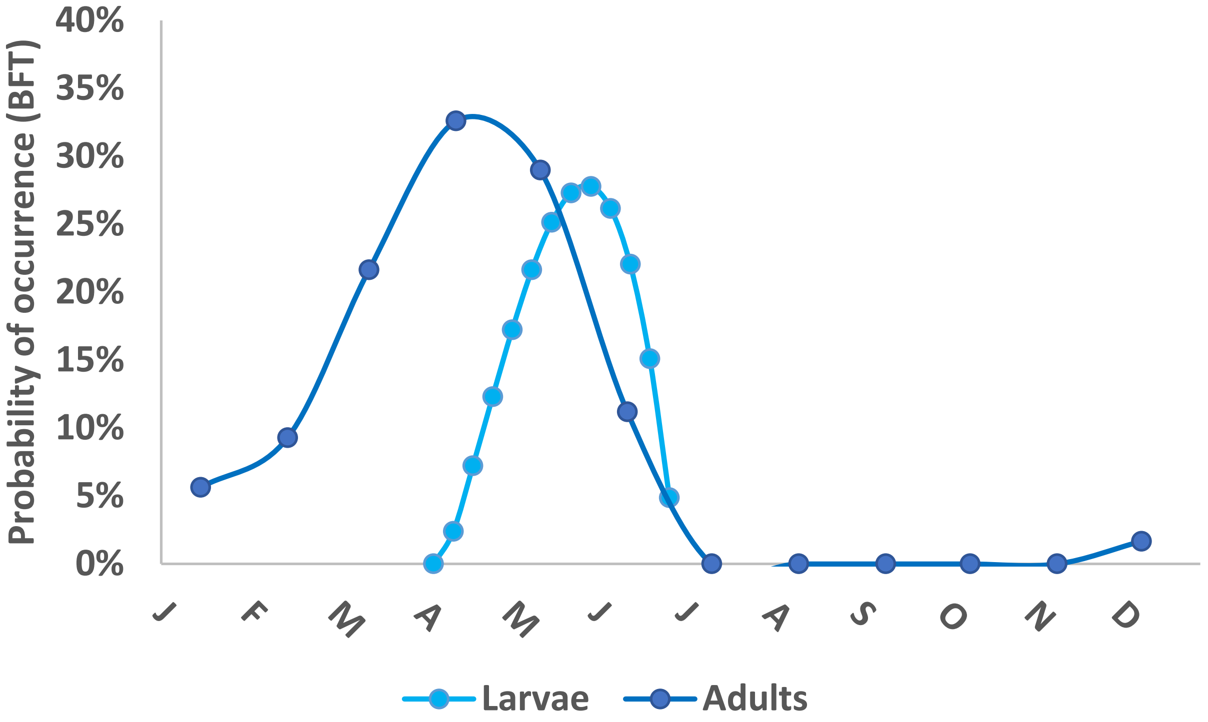
ICCAT, 2015

Migration and spawning

- Atlantic bluefin tuna range from sub-arctic to tropical habitats
- They migrate annually between temperate feeding grounds and subtropical spawning grounds
- Stocks mix in the open Atlantic, but show spawning site fidelity to one of two semi-enclosed seas:
  - The western stock spawns in the Gulf of Mexico region, during spring
  - The eastern stock spawns in the Mediterranean Sea, during summer



Occurrence of adult and larval bluefin tuna in the Gulf of Mexico

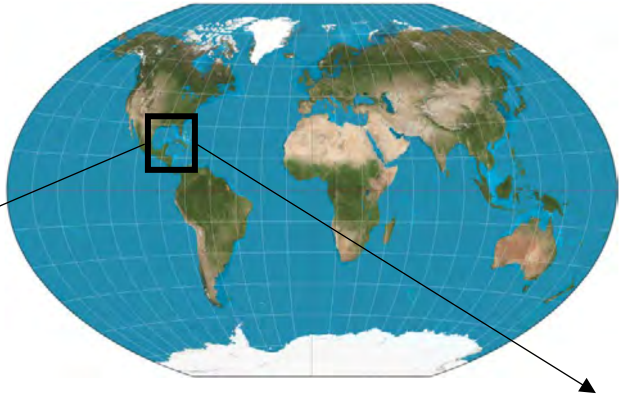


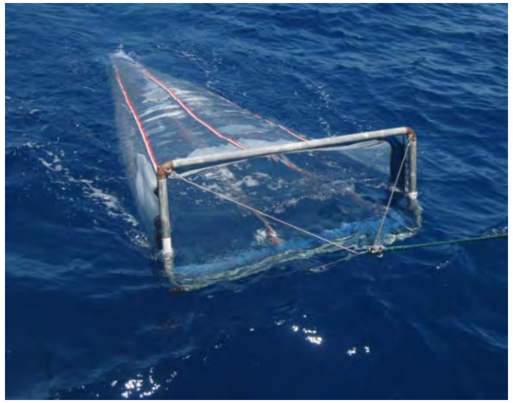
Knowledge gaps and research questions

- Recruitment and larval ecology:
  - What are the links between larvae and environmental conditions?
  - Is there a link between environment and recruitment?
  - Is there spawning outside currently sampled spawning grounds?
- Adult bluefin tuna and environmental conditions
  - What determines adult distributions, and availability to fisheries?
- Climate change impacts
  - How might climate change impact spawning activity? Habitat use? Recruitment? Availability to fishing fleets?

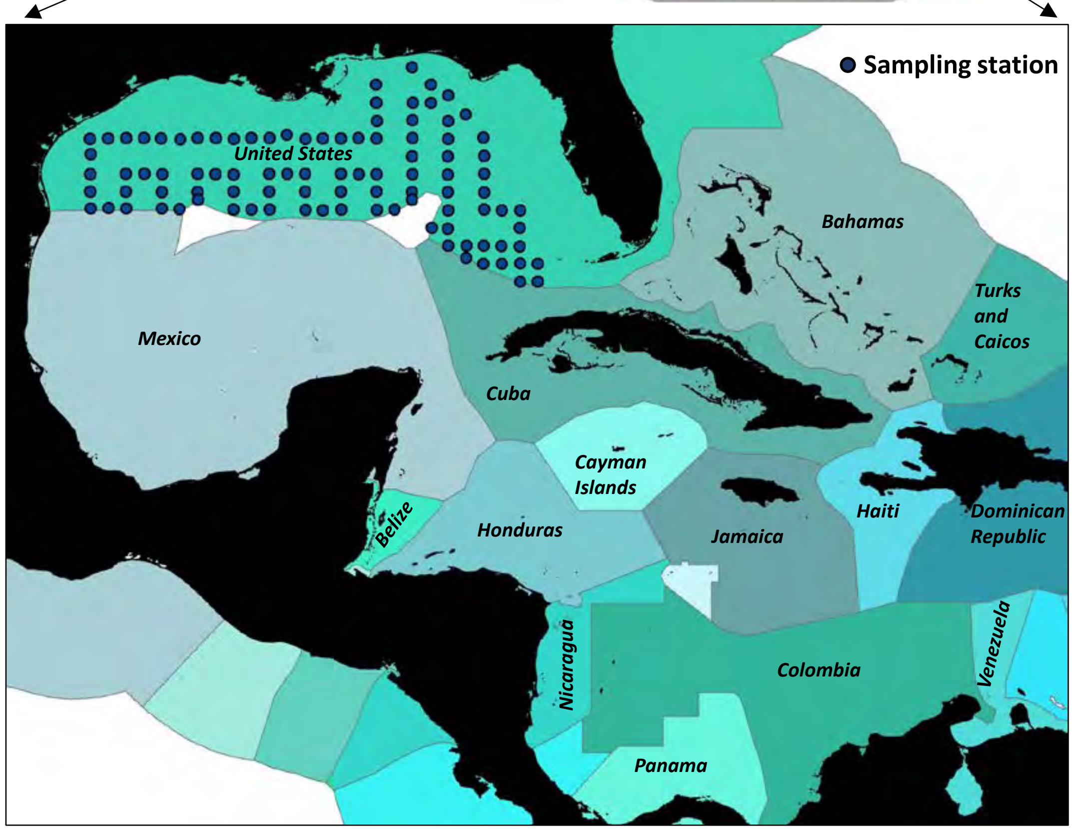
Larval sampling cruises

- Plankton surveys have been completed by NOAA across the northern Gulf of Mexico (US EEZ) since 1977
- Larval bluefin tuna are typically collected between mid April and early June
- Abundances are standardized into an index of spawning stock biomass
  - This is the only fishery-independent index for the western stock
- Concurrent environmental data are available from CTD casts



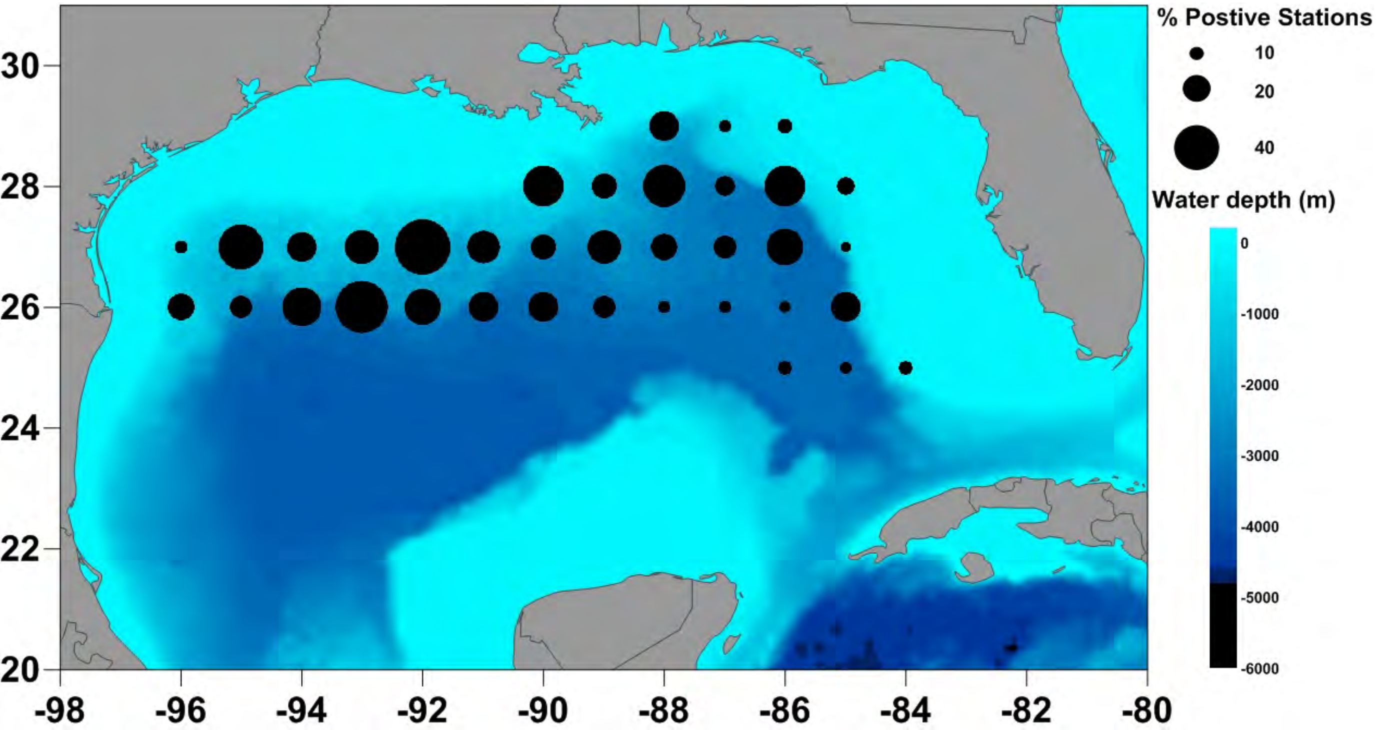




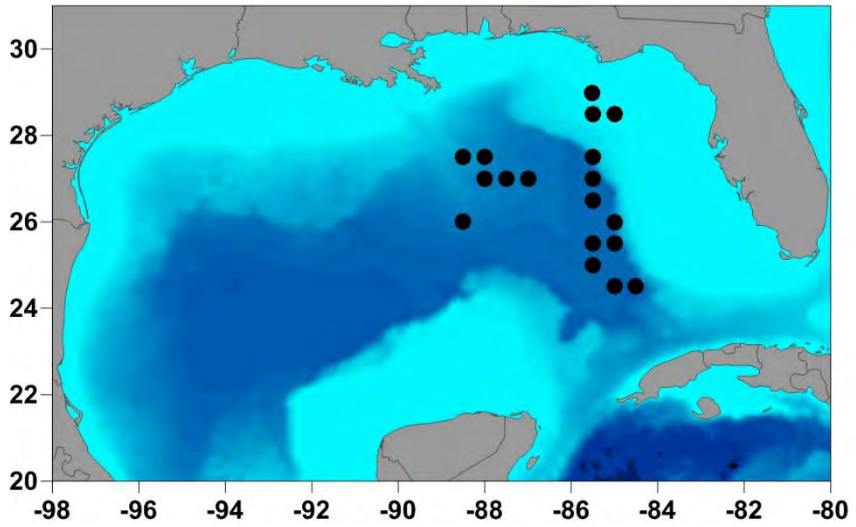


Larval distribution

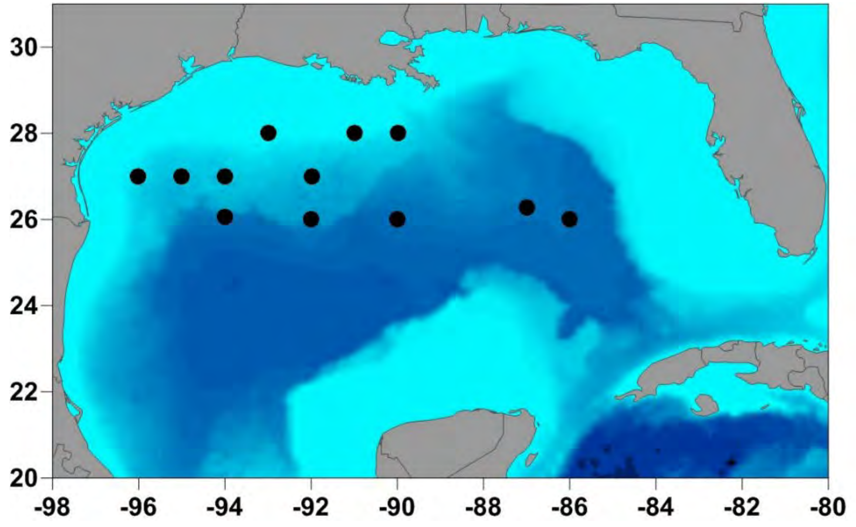
- In the last ~30 years of cruises, larval bluefin have been collected across much of the northern Gulf of Mexico
- However, distributions vary from year to year
- Adult fishes often target specific environmental conditions for spawning
- We used predictive habitat models to see if this was the case for bluefin tuna in the Gulf of Mexico



Eastern distribution: 1983

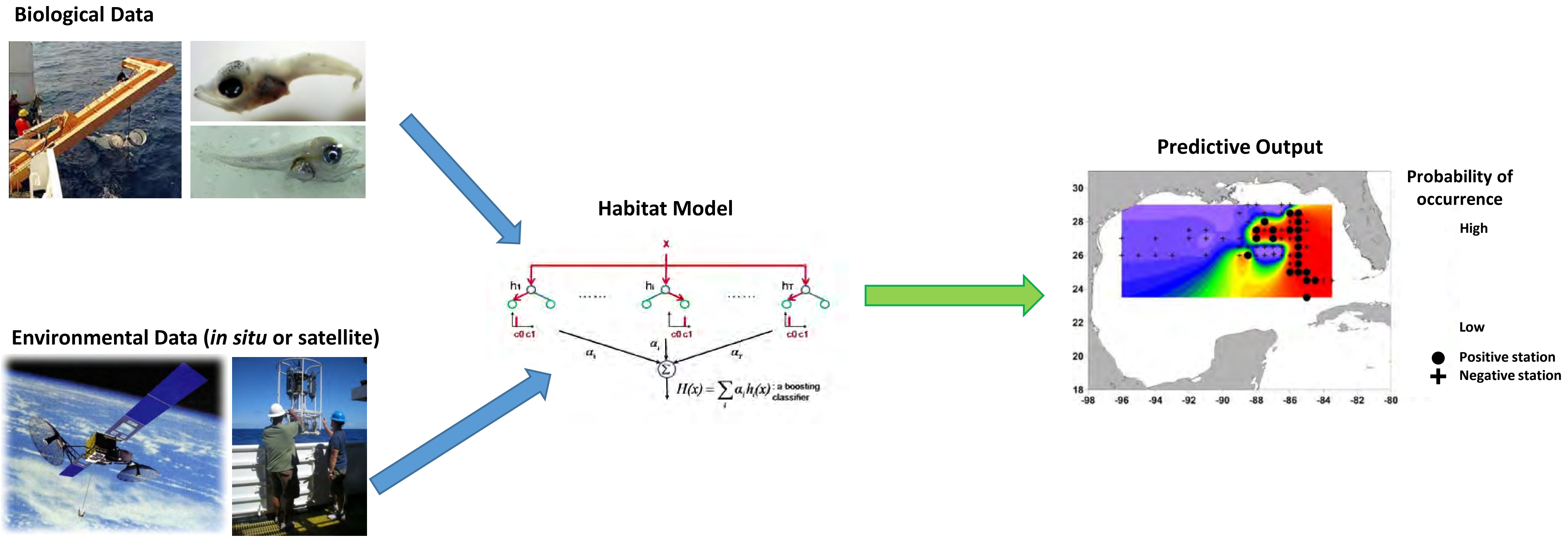


Western distribution: 2003



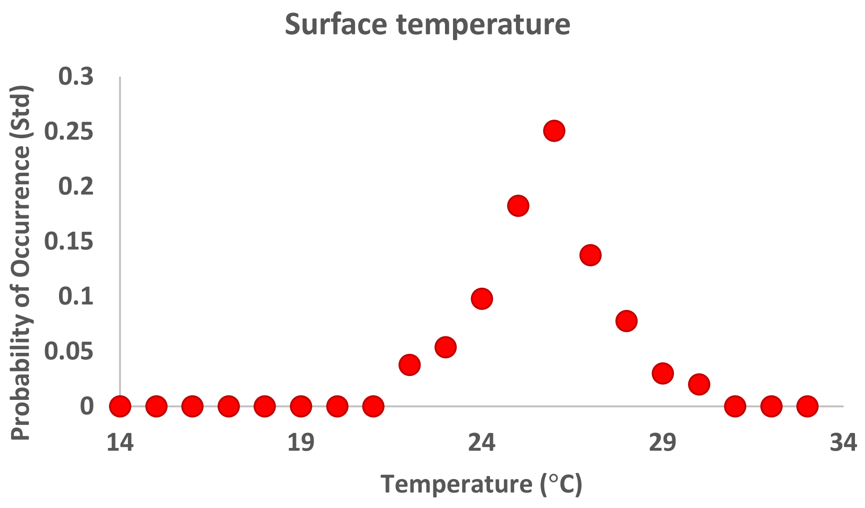
Habitat modeling

- Habitat models predict probability of occurrence, or abundance, in space and time, based on oceanographic conditions
- Environmental data can be sourced from *in situ* CTD casts, or extracted from satellite data or ocean models
- Common modeling methods include Generalized Additive Models (GAMs), Artificial Neural Networks (ANNs) and Classification and Regression Trees (CARTs)
- Ability to include non-linear relationships and interactions is important

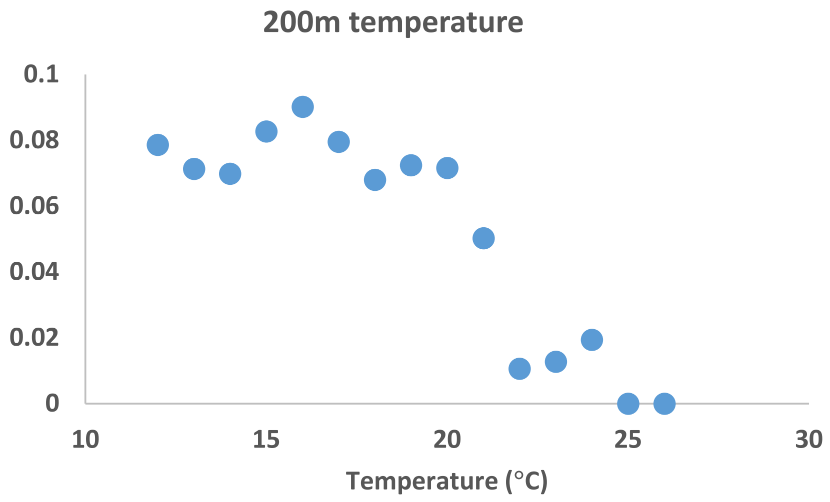


Habitat modeling results: individual predictors

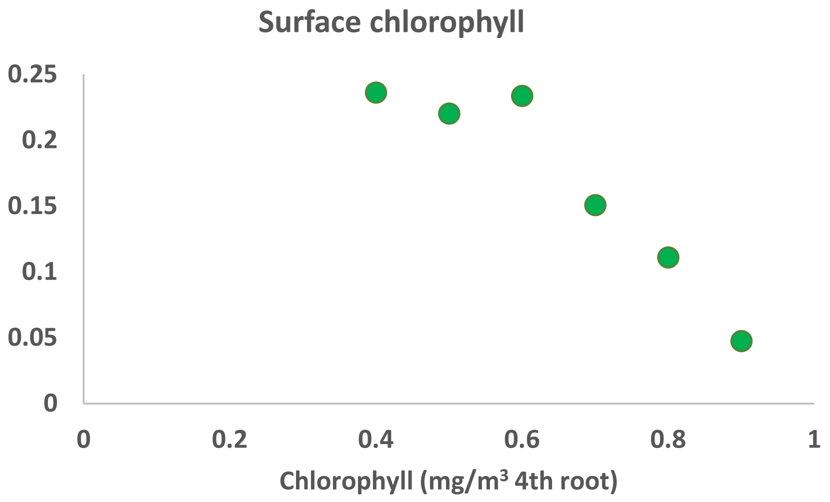
- We constructed several different habitat models for larvae using different predictors
  - Some variables (e.g. temperature at depth) are available only from *in situ* CTD casts or ocean models
  - Some variables (e.g. surface chlorophyll) are most easily sourced from satellites
- Different modeling methods were used, mostly from the machine-learning family
  - Artificial neural networks, boosted regression trees, linear model trees
- Several common themes emerged from these models:



Bluefin larvae were associated with particular sea surface temperatures: ~24-28°C



… and low temperature at depth (areas outside the Loop Current and anticyclonic rings)



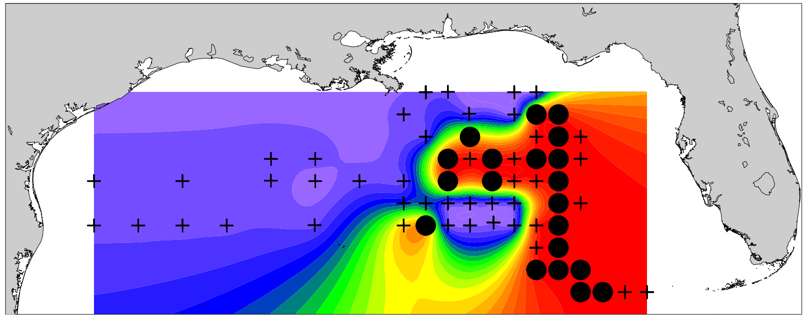
… and low surface chlorophyll

Habitat modeling results: CTD vs. satellite

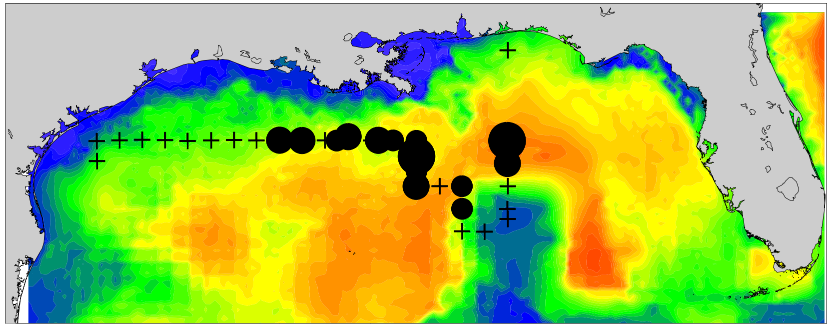
CTD cast data

Satellite data

Predicted and actual larval distribution from CTD model: 1983



Predicted and actual larval distribution from satellite model: 2010



Probability of larval occurrence (/1)

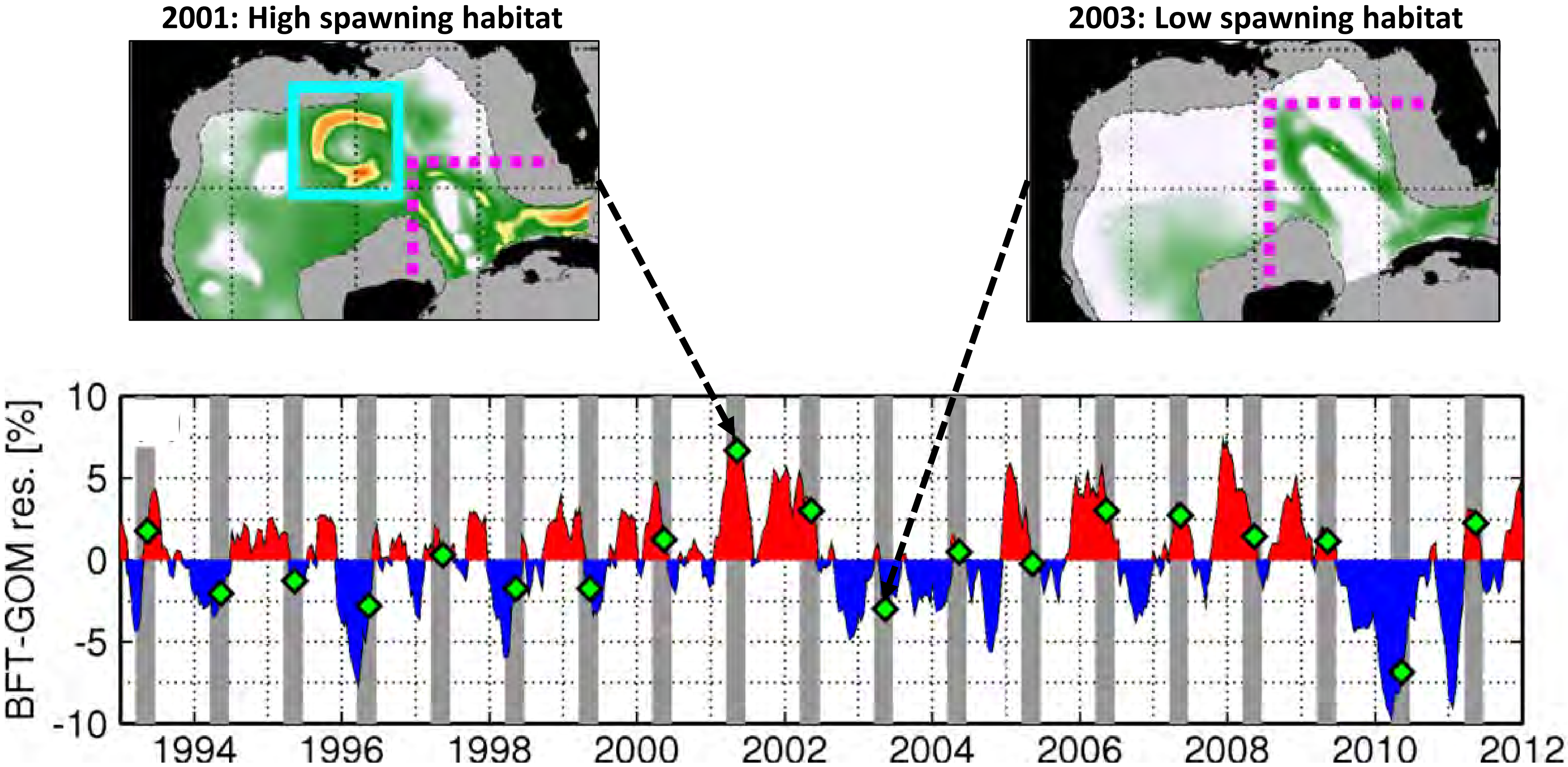
● Positive station
+ Negative station

- Habitat models based on both *in situ* and remotely sensed data explained observed larval distributions well
- Oceanographic variability drove variability in larval catch locations
    - e.g. a cold western Gulf in 1983 restricted spawning to the eastern Gulf
    - e.g. high chlorophyll on the Texas shelf in 2010 resulted in low larval catches in the northwest Gulf

Muhling et al., 2010, 2012

Spawning habitat variability

- The spatiotemporal extent of “favorable” larval habitat varies from year to year, depending on seasonal warming and oceanographic structure
- Domingues et al. (2016) assessed interannual variability in spawning habitat extent in the northern Gulf of Mexico using satellite data

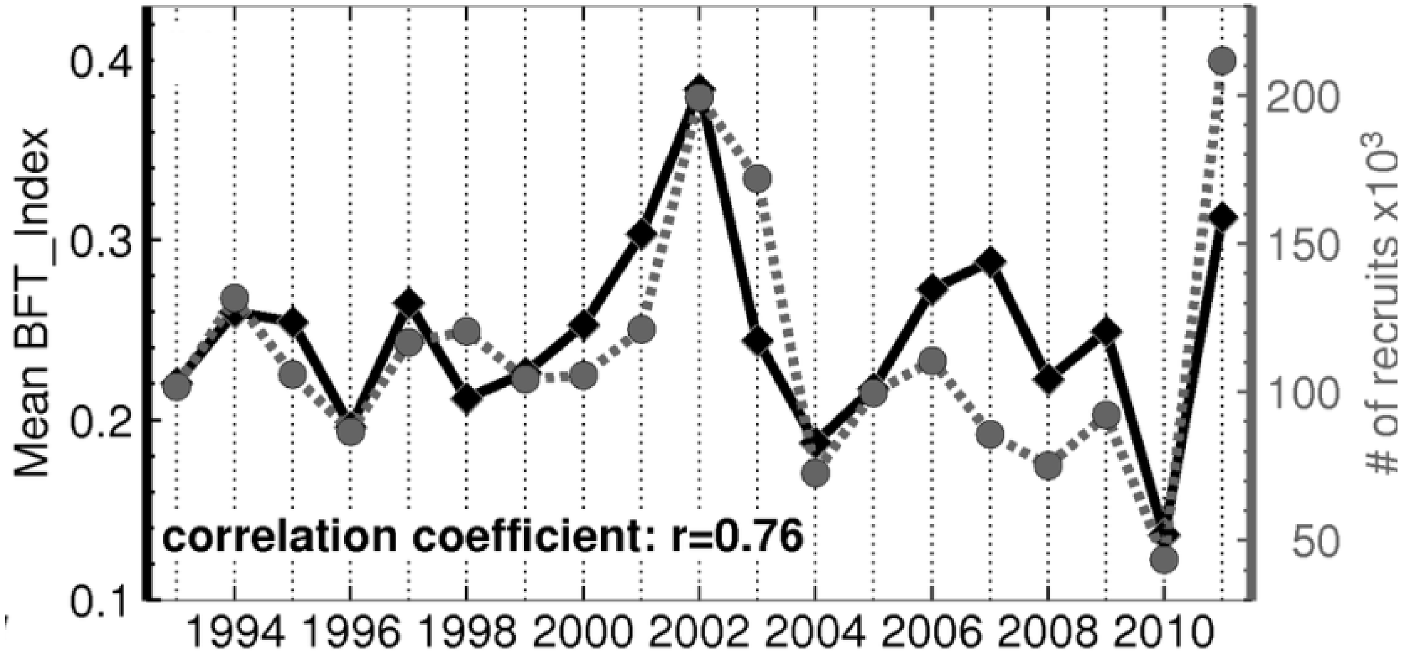


Lindo et al., 2012
Domingues et al., 2016

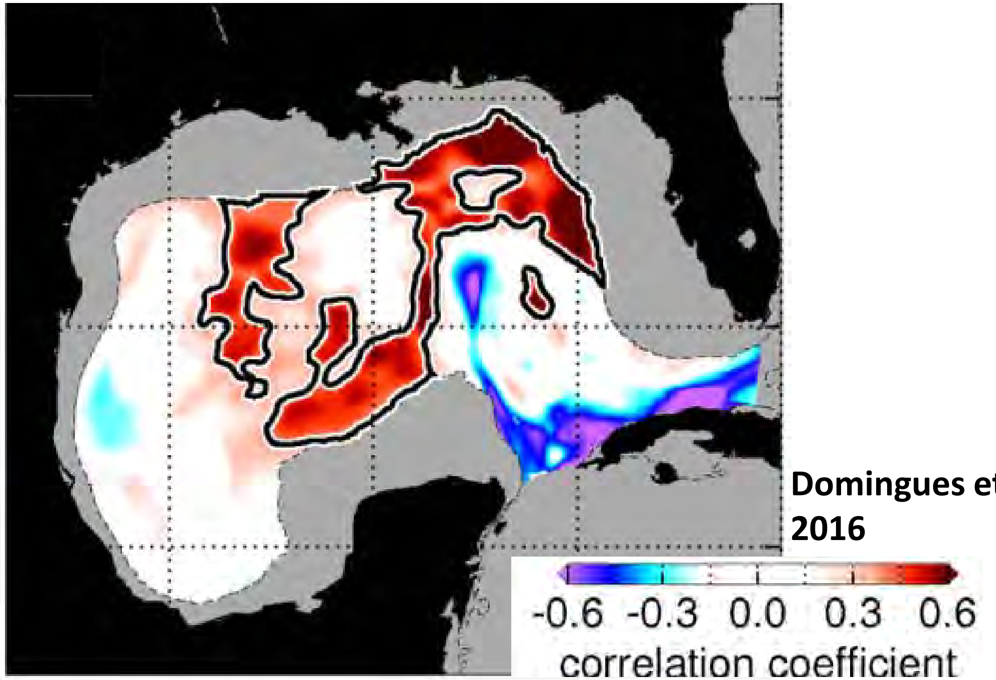
Links to recruitment

- The spawning habitat index was correlated with recruitment time-series
- This correlation had a spatial component:
  - Persistence of spawning habitat in the northeast and western Gulf was associated with *high* recruitment
  - Restriction of spawning habitat to the southeast Gulf was associated with *low* recruitment
- Management implications:
  - Recruitment may be partially driven by oceanographic characteristics on spawning grounds

Recruitment (VPA) vs index of spawning habitat



Recruitment vs. spawning habitat: spatial

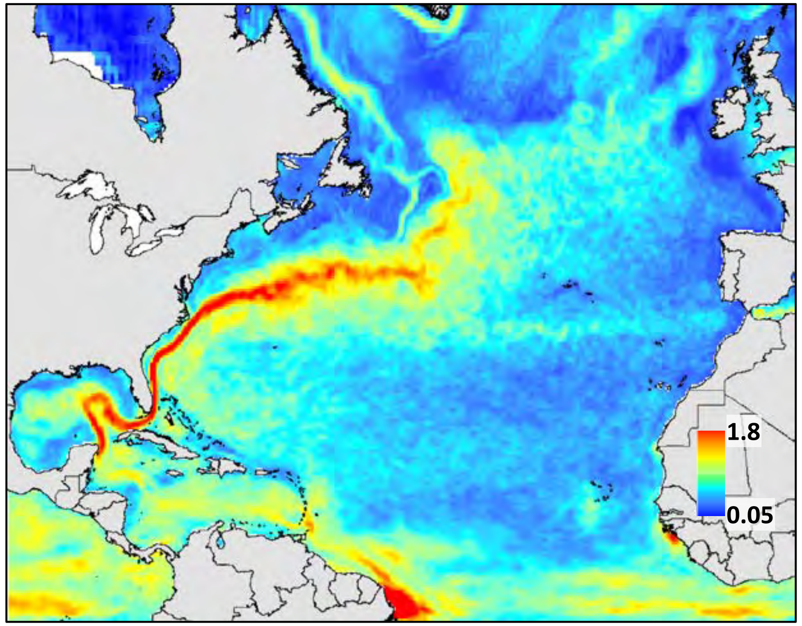


Domingues et al., 2016

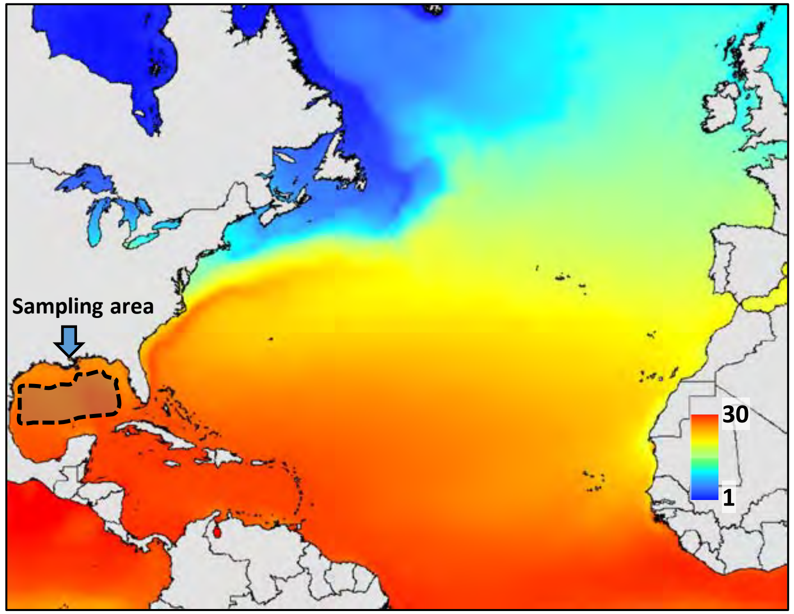
Is there spawning outside of the Gulf of Mexico?

- Adult bluefin tuna migrate long distances to reach the Gulf of Mexico and spawn
  - This implies enhanced conditions for larval survival
- The Gulf is warm and low in surface chlorophyll during spring, with moderate mesoscale eddy activity
- Temperature at depth is moderate compared to the Caribbean and the rest of the sub-tropical Atlantic
- Sampling historically concentrated in the US EEZ
  - But is it possible that spawning is also occurring in similar conditions outside the northern Gulf of Mexico?
  - We used habitat models developed in the Gulf to assess other possible spawning areas

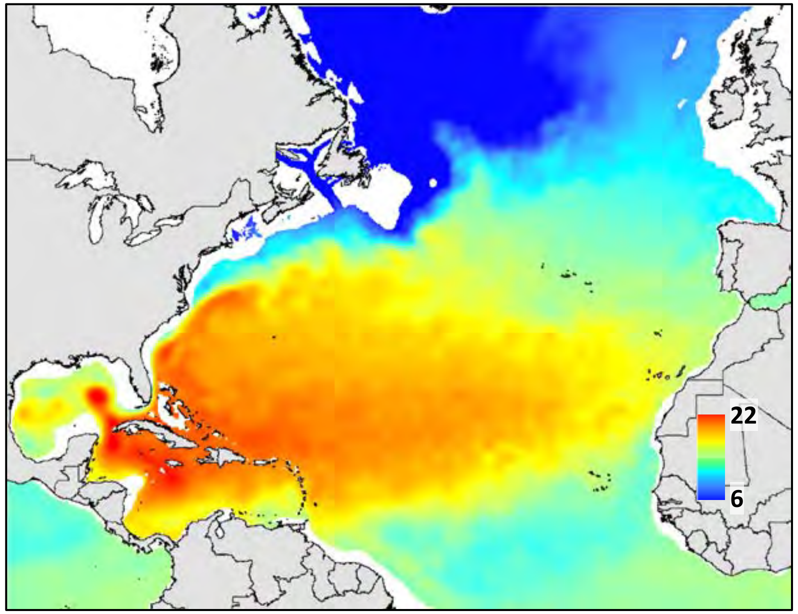
Moderate eddy kinetic energy



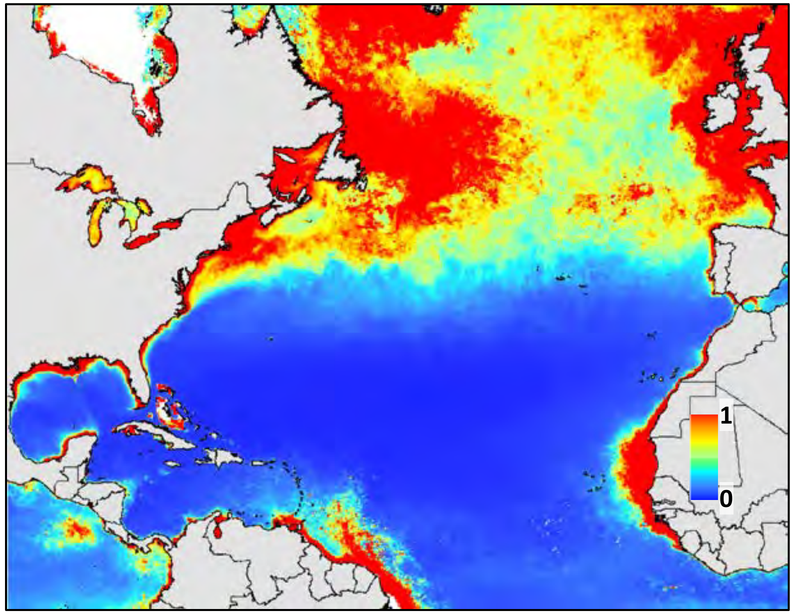
Warm surface temperature



Moderate 200m temperature

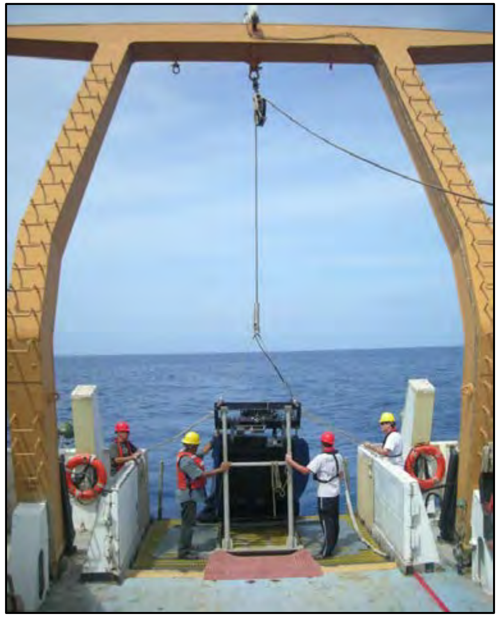


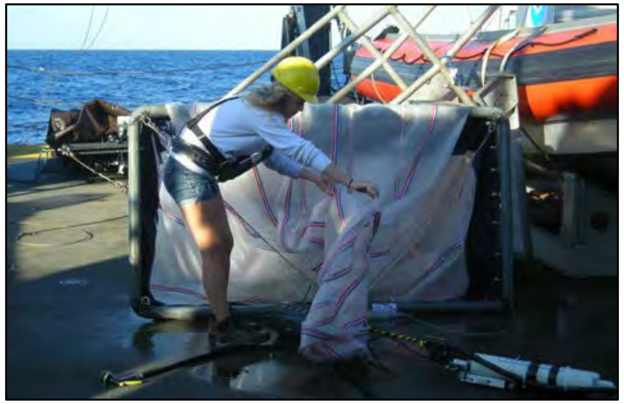
Low surface chlorophyll

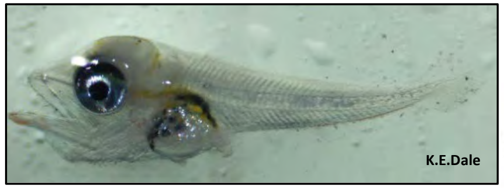


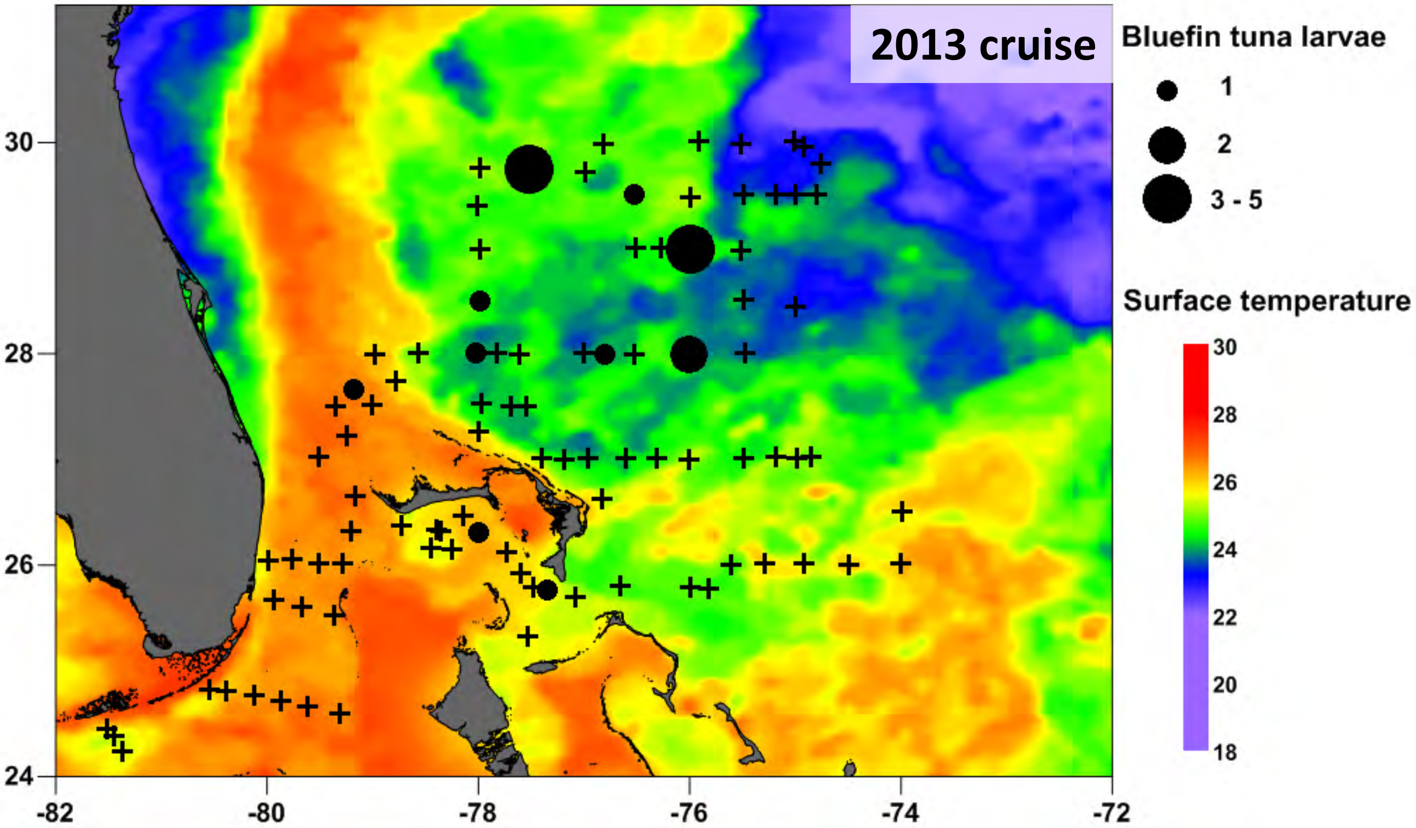
Exploratory cruises

- Starting in 2009, the Early Life History lab at the NOAA SEFSC was provided with extra shiptime to complete exploratory cruises
- We sampled the southern Gulf of Mexico, Caribbean Sea, and around the Bahamas
- Sampling was guided by real-time satellite imagery, and ocean model outputs





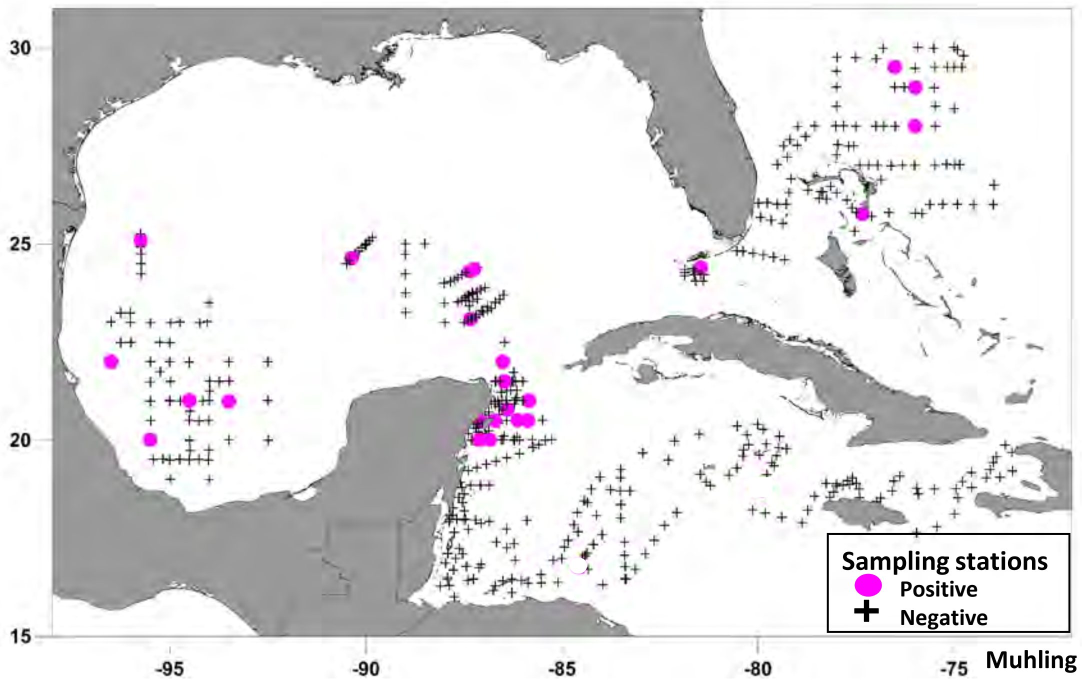




Cruise results

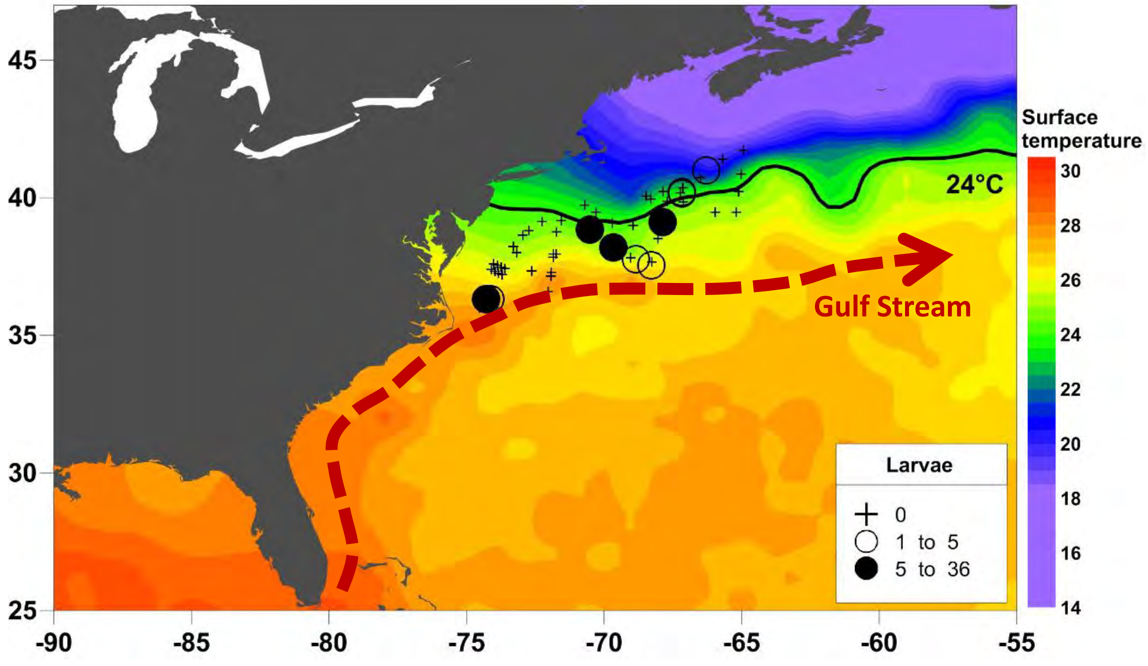
- Bluefin tuna larvae were collected in several locations outside of known spawning grounds
- Backtracking analyses suggest that larvae were mostly spawned close to collection sites
- Larval abundances were generally much lower than in the northern Gulf of Mexico
- Implications for management:
  - Age/size at maturity may be *lower* than currently assumed
  - The western stock may be *less productive* than previously supposed
  - Adults may have considerable plasticity in spawning behavior

Sampled stations and catch locations: 2009-2013



Muhling et al., 2011

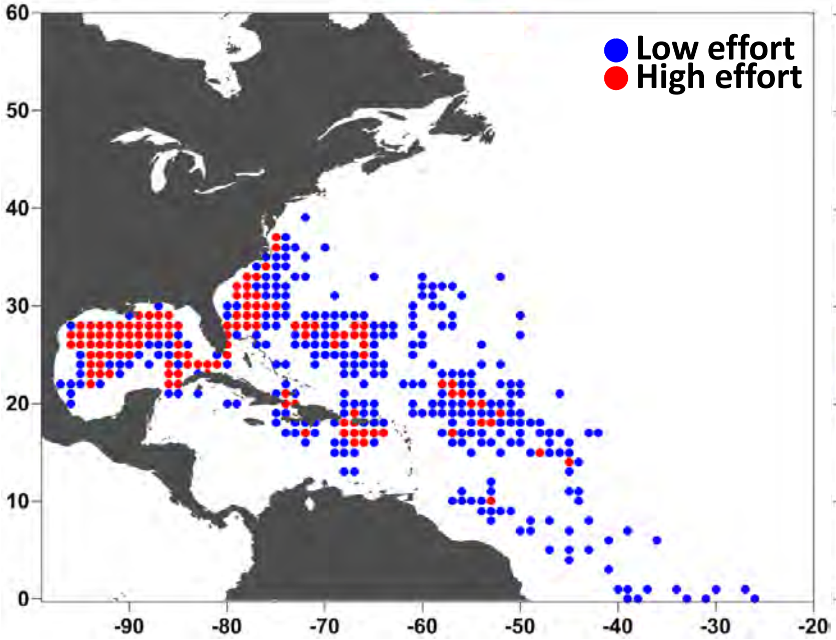
Bluefin tuna larvae in the Mid-Atlantic Bight (Richardson et al., 2016)



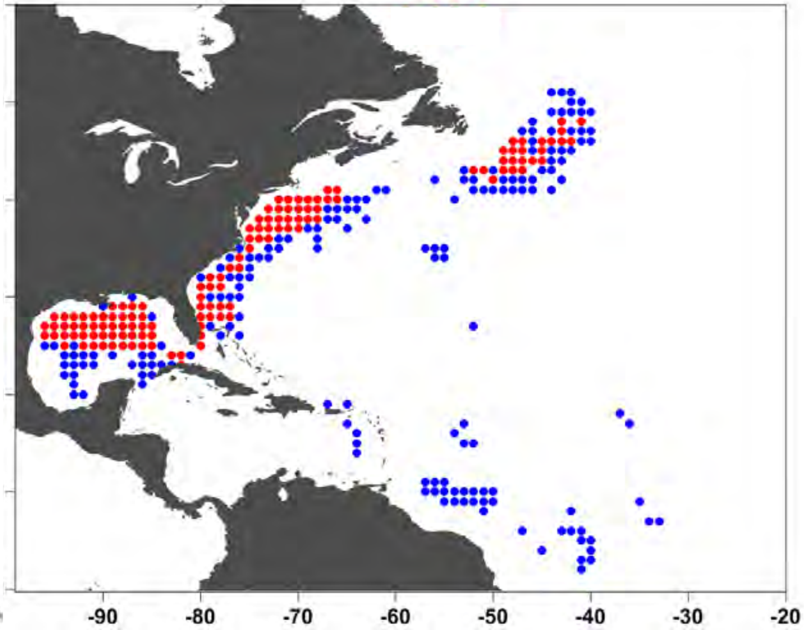
Adult bluefin tuna habitat

- Bluefin tuna have very broad environmental tolerances, and occupy a wide range of habitats
- However, some limits on their distribution have been proposed
  - Potential oxygen stress in very warm waters (Blank et al., 2004)
  - Potential cardiac stress in very cold waters (Brill, 1994)
- Implications for accessibility to fisheries, and responses to climate change
- We used logbook records from the US pelagic longline fishery to build predictive habitat models
- Model results were then applied across the North Atlantic, and overlaid on ICCAT 5x5 catch data

Winter pelagic longline effort

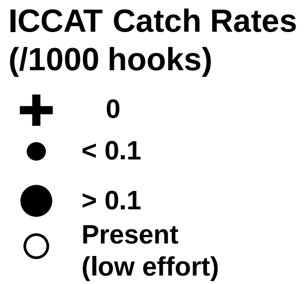


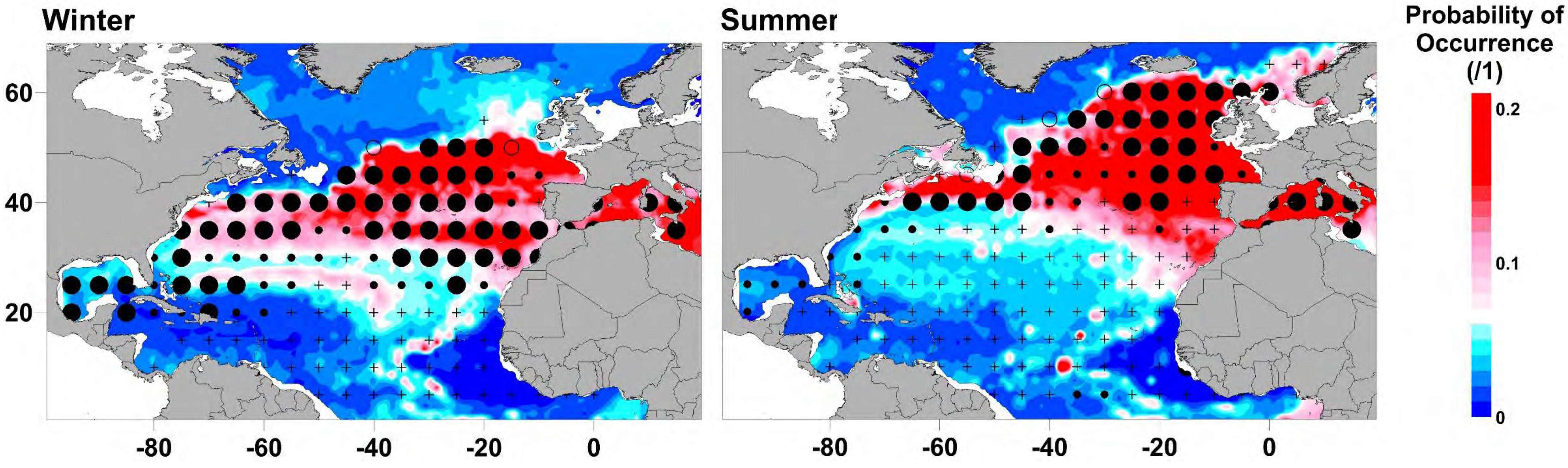
Summer pelagic longline effort



Habitat model results

- The habitat model corresponded fairly well with ICCAT catch rate data
    - Gulf of Mexico spawning grounds outside "core habitat"
- Adult bluefin tuna were most abundant south of 50°N during winter, but extended their distribution up to near Iceland in the summer
- Warming summer temperatures also appeared to restrict subtropical distributions
- There was generally more favorable habitat in the eastern Atlantic than in the west



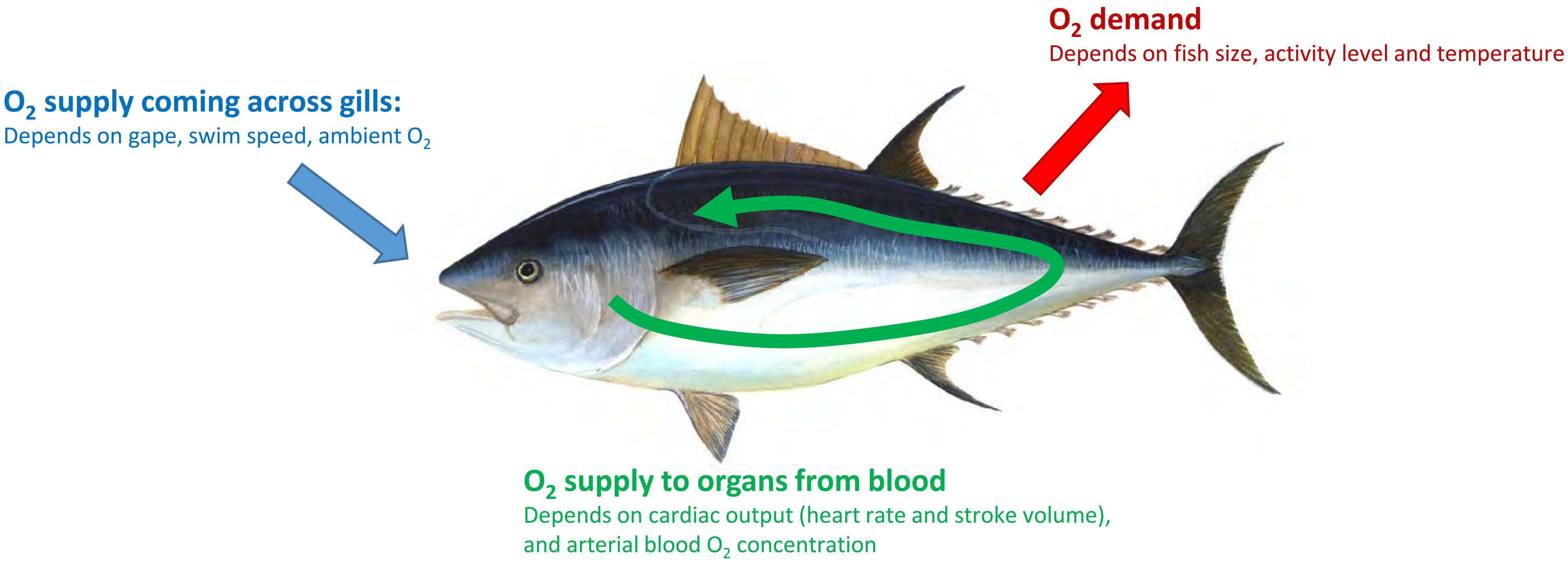


Correlative vs. mechanistic models

- However, there are several disadvantages to using correlative habitat models:
  - Correlations between species distributions and environmental variables can be spurious, or region-specific (or missed completely)
  - Models are only as good as the input training data
    - Fisheries-dependent data can be strongly biased
  - Can be difficult or impossible to extrapolate in space, or time
    - e.g. for climate change impact studies
- It has been hypothesized that bluefin tuna primarily occupy regions where their metabolic costs are low
- We used published data from tuna physiological studies to build a mechanistic metabolic scope model , and compared results to the correlative habitat model

Bluefin tuna oxygen supply and transport

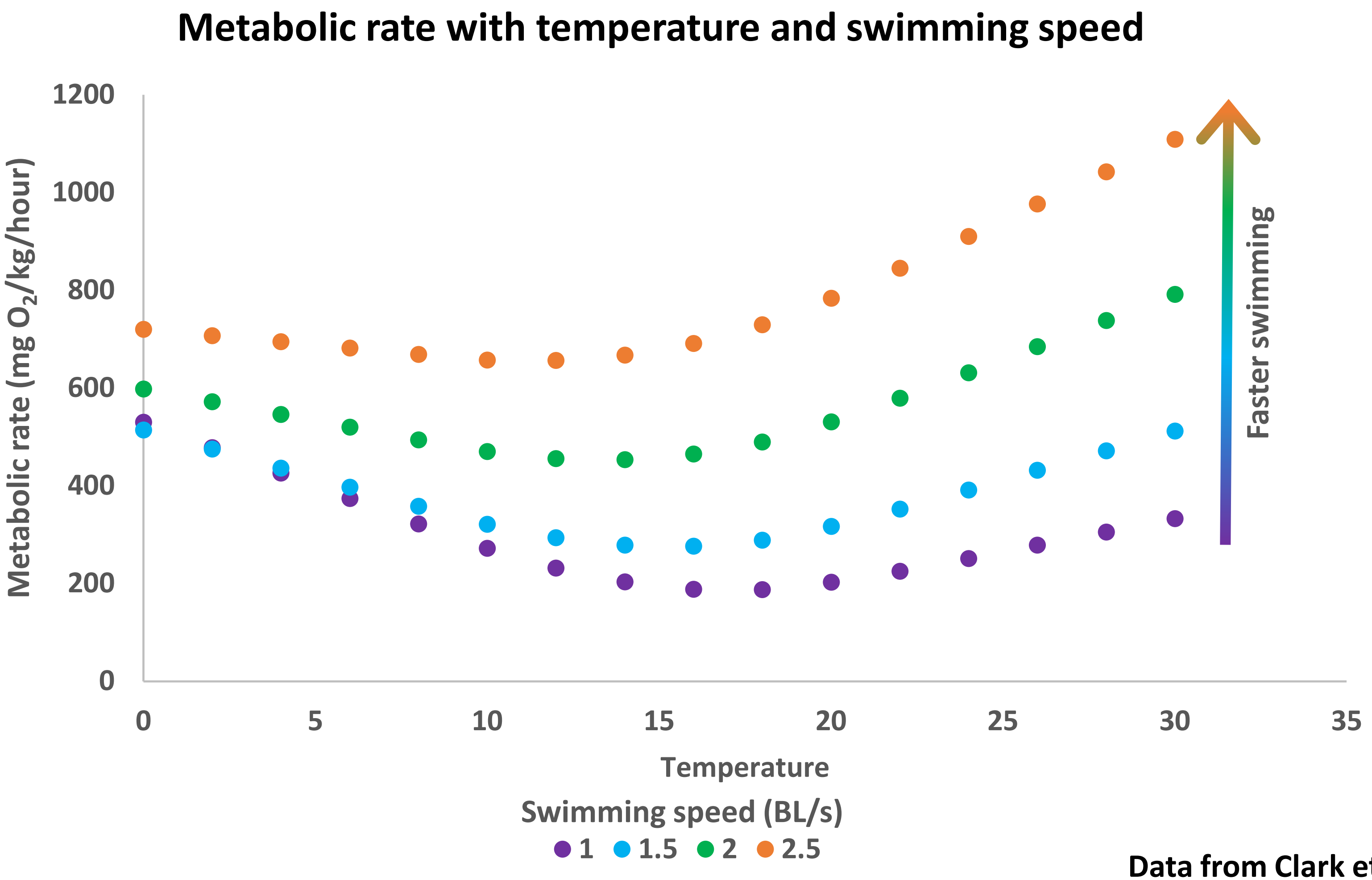
- Oxygen is delivered through the gills as the tuna swims, and is then transported to tissues via the circulatory system
- Both supply and demand are affected by ambient water temperature and oxygen concentration
  - Low oxygen concentrations lead to lower overall delivery through the gills
  - Warm temperature increase cardiac output, but also increase metabolic demand
  - Cold temperatures reduce cardiac output, but decrease metabolic demand

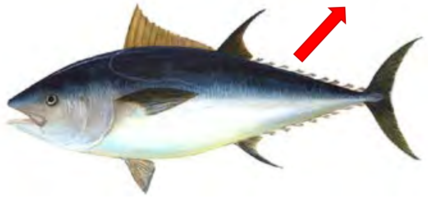


O_2 supply – O_2 demand = metabolic scope

Modeling metabolic demand

- We combined results from three published swim tunnel studies on metabolic rates in small Pacific bluefin tuna into a generalized additive model (GAM: R^2=0.91)
- Results showed a metabolic minimum zone at 15-20°C, and a logarithmic effect of swimming speed

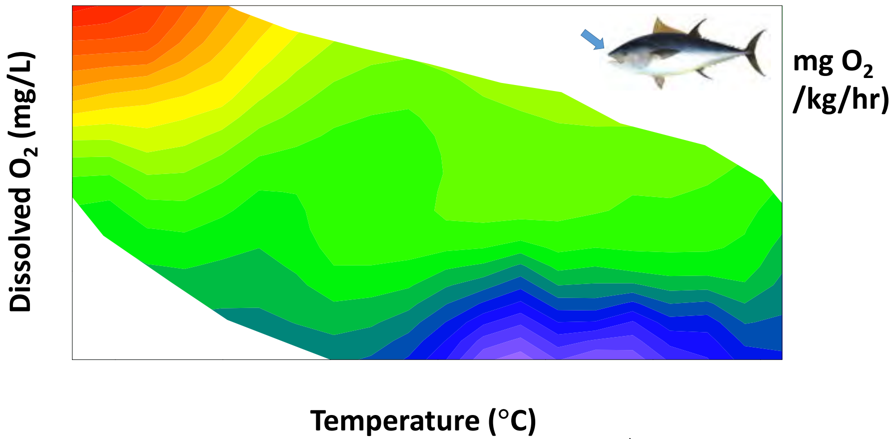


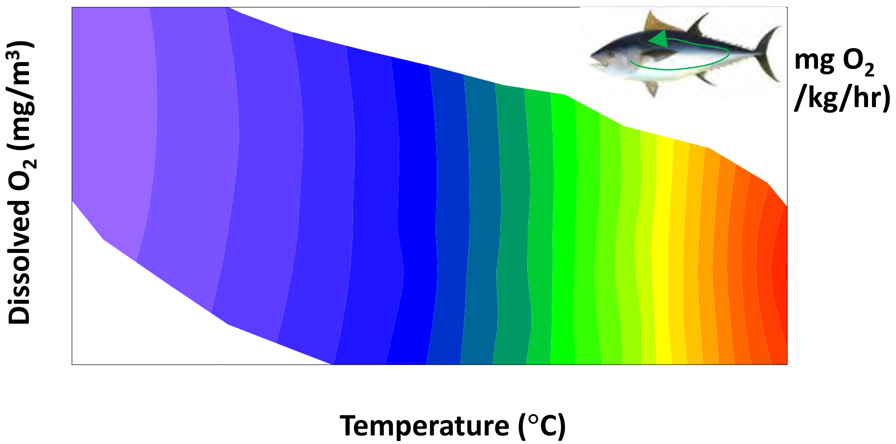


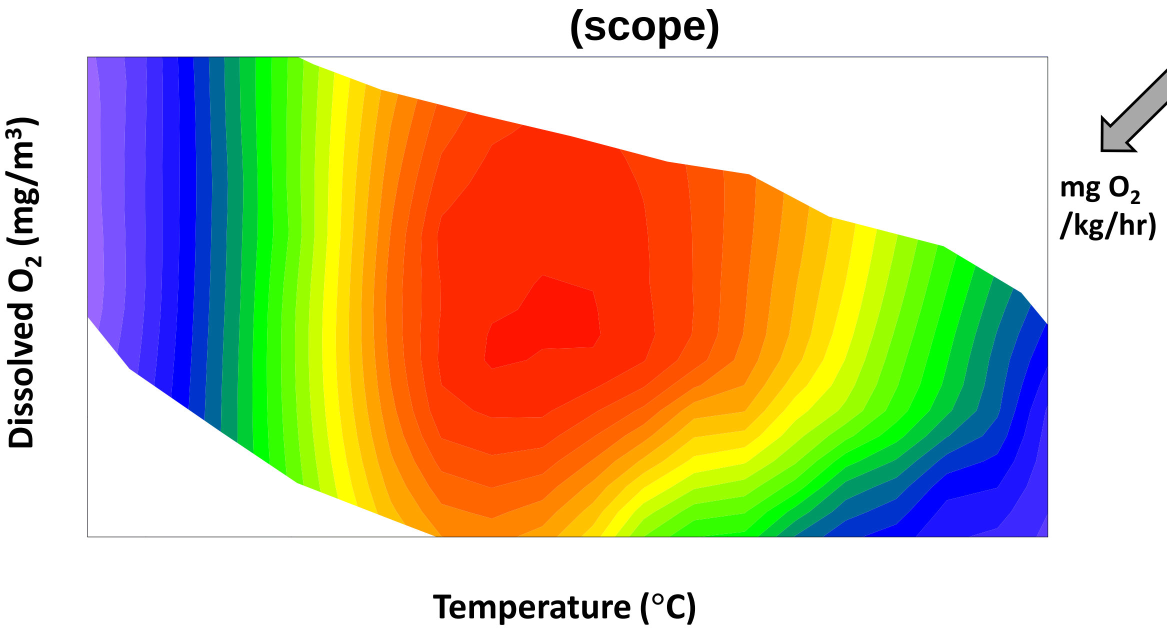
Data from Clark et al. (2013), Blank et al. (2007a,b)

Oxygen supply and metabolic scope

- Oxygen supply and transport were modeled using published observations of gape, blood O_2 and cardiac output
- Metabolic scope for the upper 50m was then calculated across the North Atlantic (temperature and oxygen climatologies from WOA)
- Results shown assuming a swimming speed of 2 BL/s



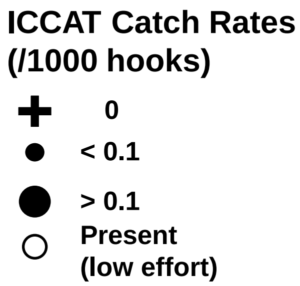


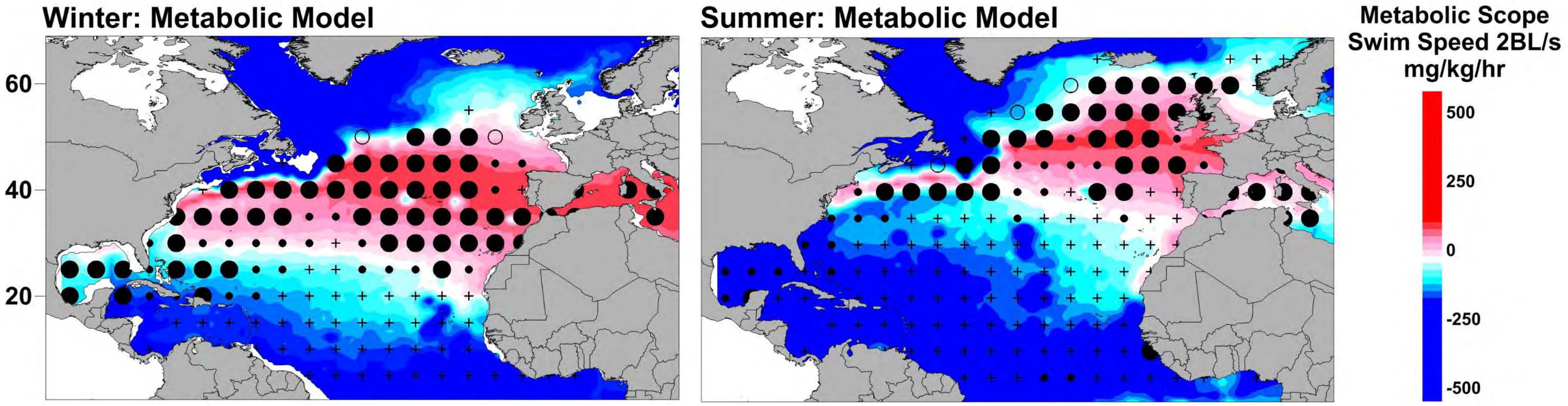


Equations adapted from:
Bushnell & Brill, 1991, 1992, Korsmeyer et al., 1997, Brill & Bushnell, 2001, Blank et al., 2002, 2004, 2007a,b, Clark et al., 2013

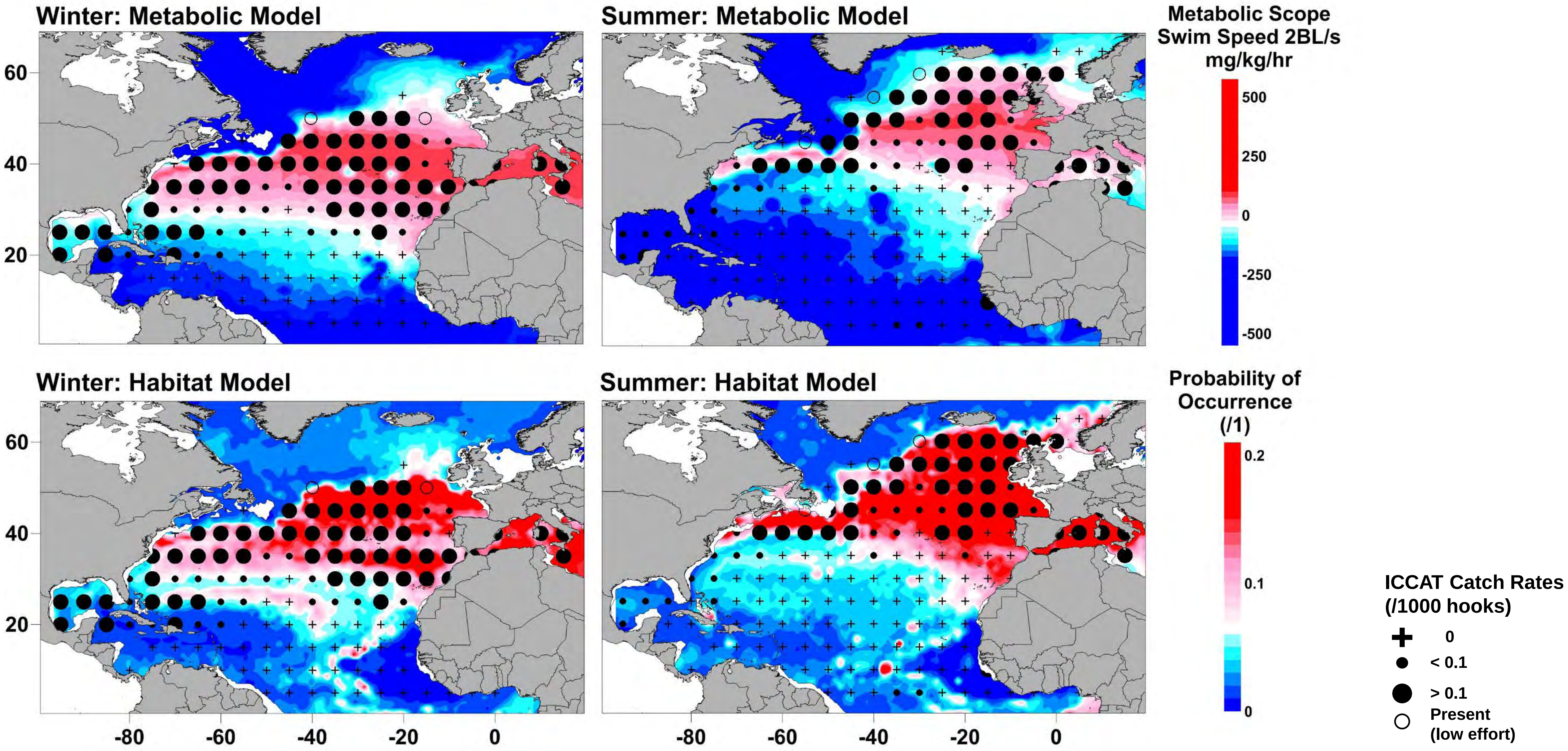
Metabolic model results

- Distributions of adult bluefin tuna corresponded with areas of maximum metabolic scope
- Cold waters north of the Gulf Stream wall were predicted to be metabolically stressful via effects on cardiac function and oxygen supply to tissues
- Warm waters near the tropics were predicted to be stressful because of high metabolic demands



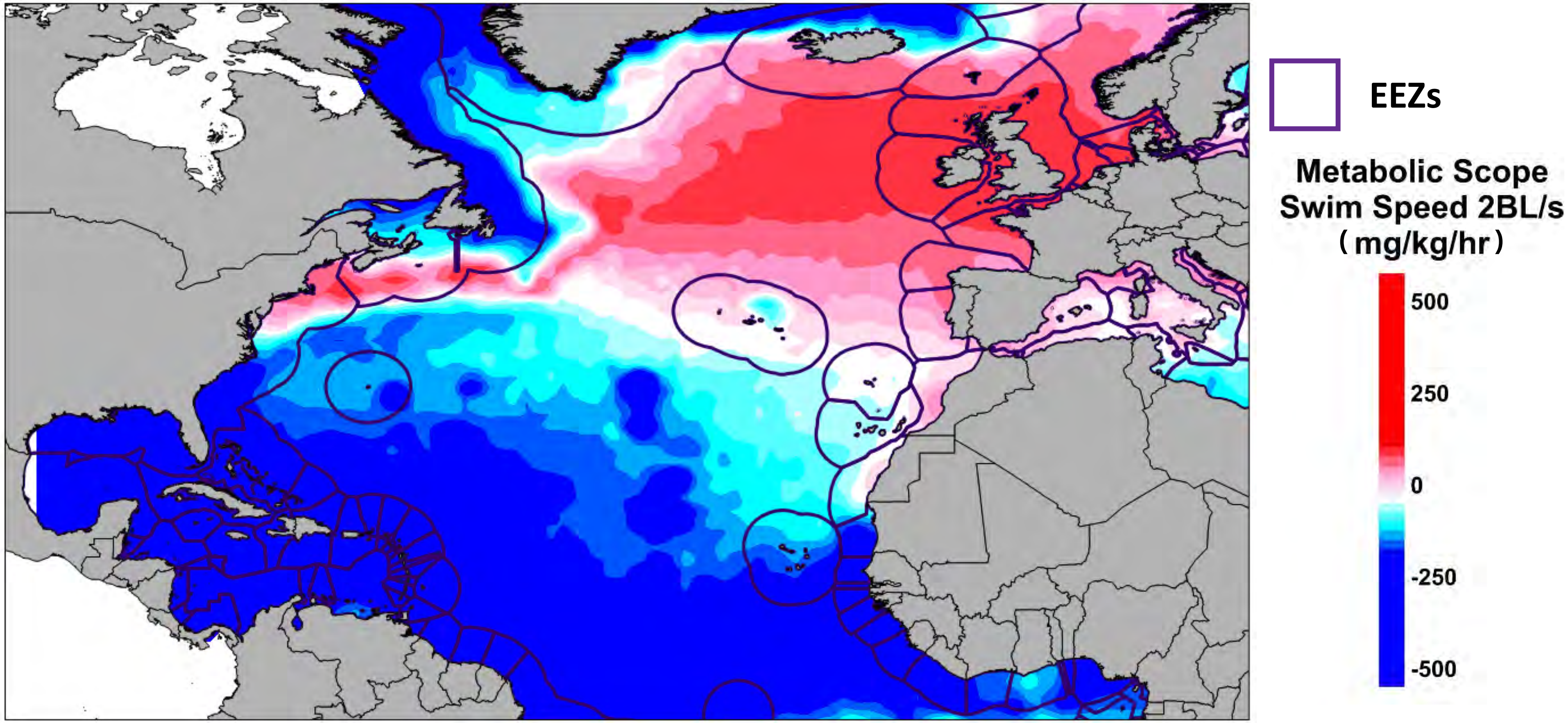


Mechanistic vs. correlative model comparison

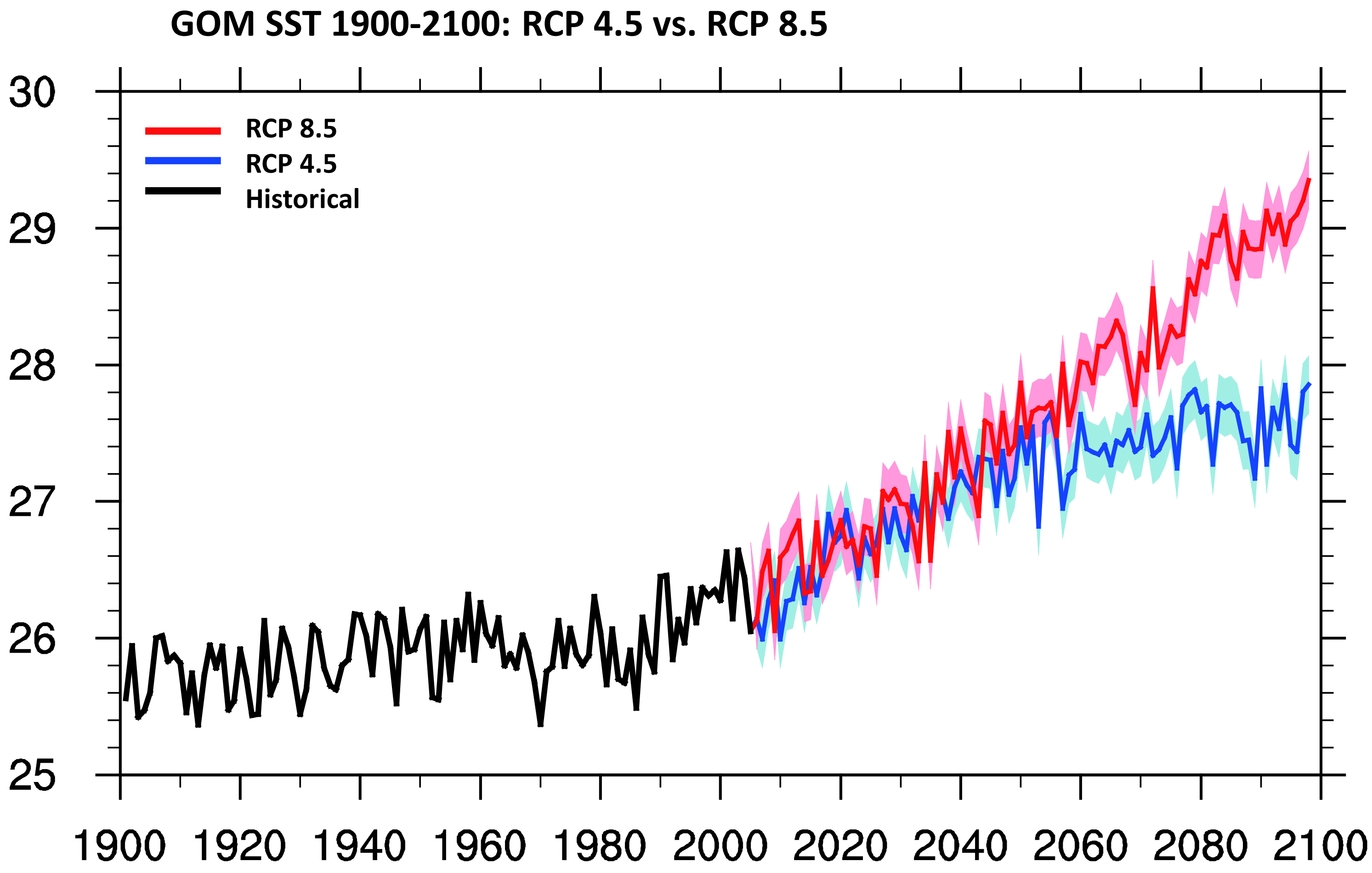


Management Implications

- Results suggest that distributions of adult bluefin can be predicted from environmental variables
- Suitable habitat often corresponds to areas of maximum metabolic scope
- Bluefin tuna interact with fisheries across multiple EEZs throughout their range
- Environmental variability and climate change are likely to affect availability to different fishing fleets, fulfilment of quotas, and reliability of abundance indices



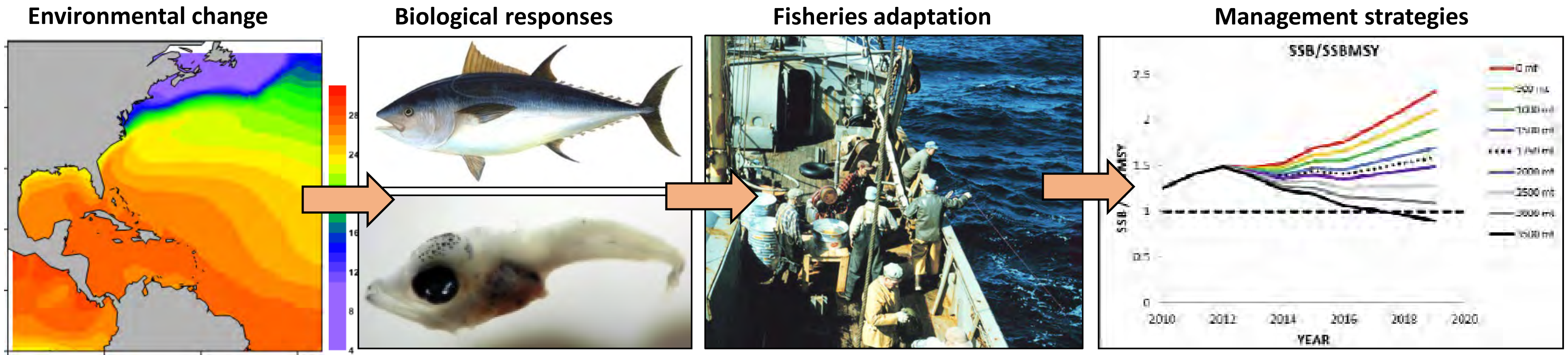
And so what about climate change…?



Liu et al., 2015

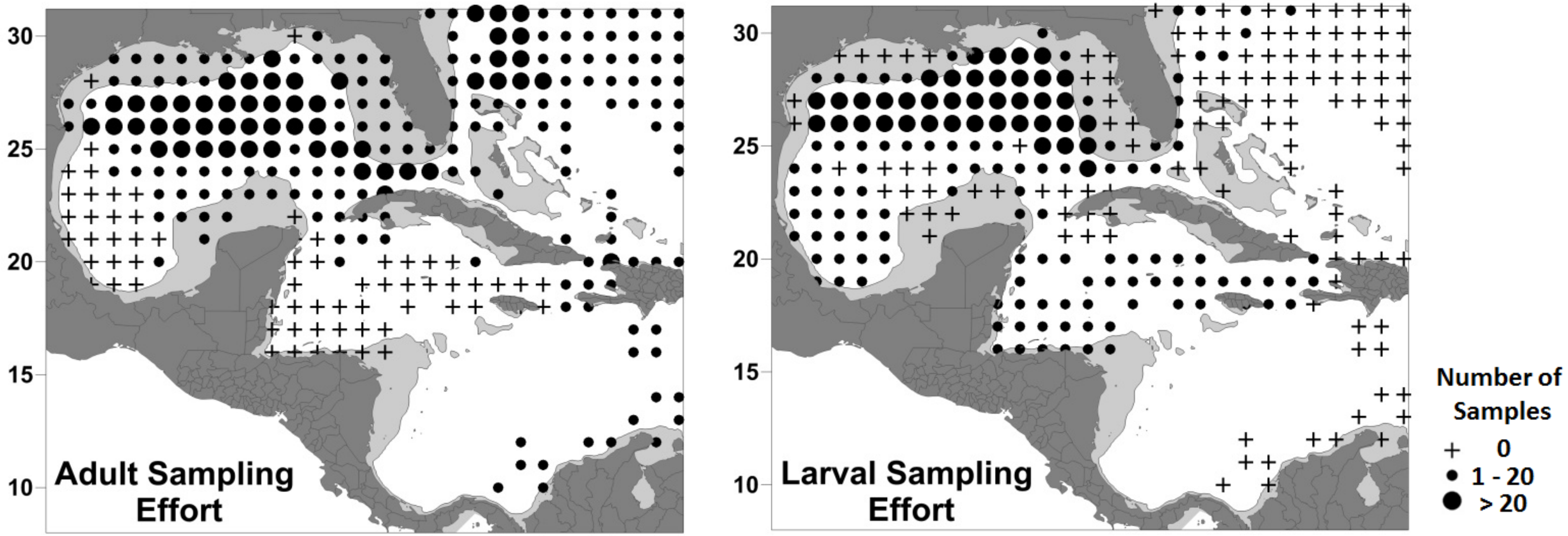
Potential climate change impacts

- Direct effects of temperature on physiological processes
  - Cardiac rates, metabolism
- Changes in distribution and abundance of prey organisms
- Changes in depths of oxygen minimum layers affecting diving and foraging behaviors
- Altered spatiotemporal spawning behaviors
- Temperature and ecosystem impacts on larval survival and recruitment
- Changes in migration patterns
- Effects relevant to fisheries management:
  1) Changes in spatial distribution or availability of target organisms
  2) Changes in larval survival, recruitment, stock size and resilience to exploitation



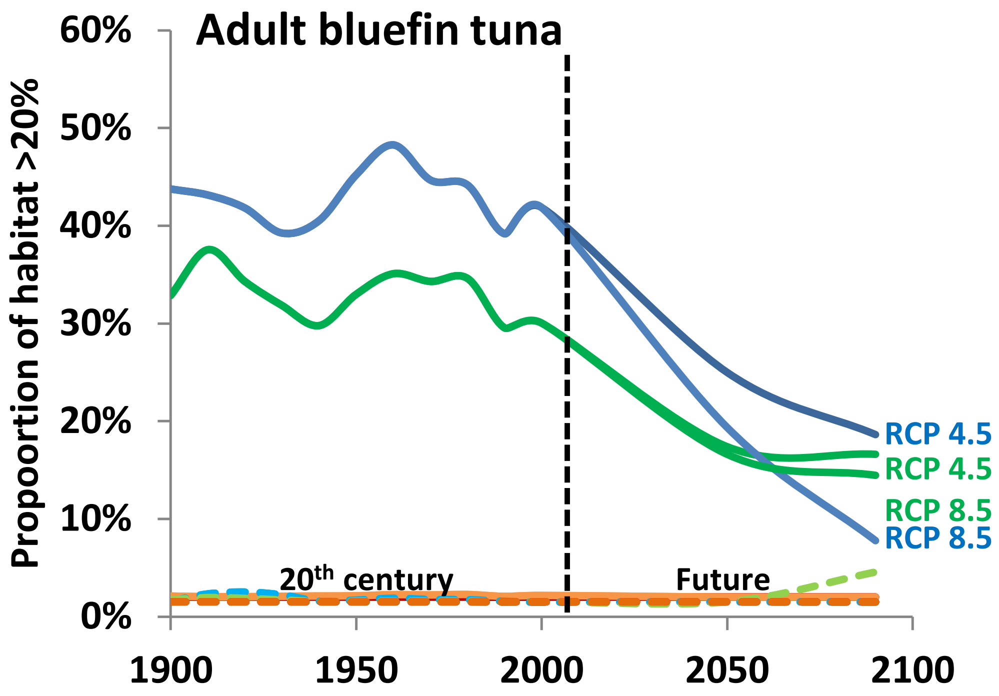
Bluefin tuna and climate change in the Intra-Americas Sea

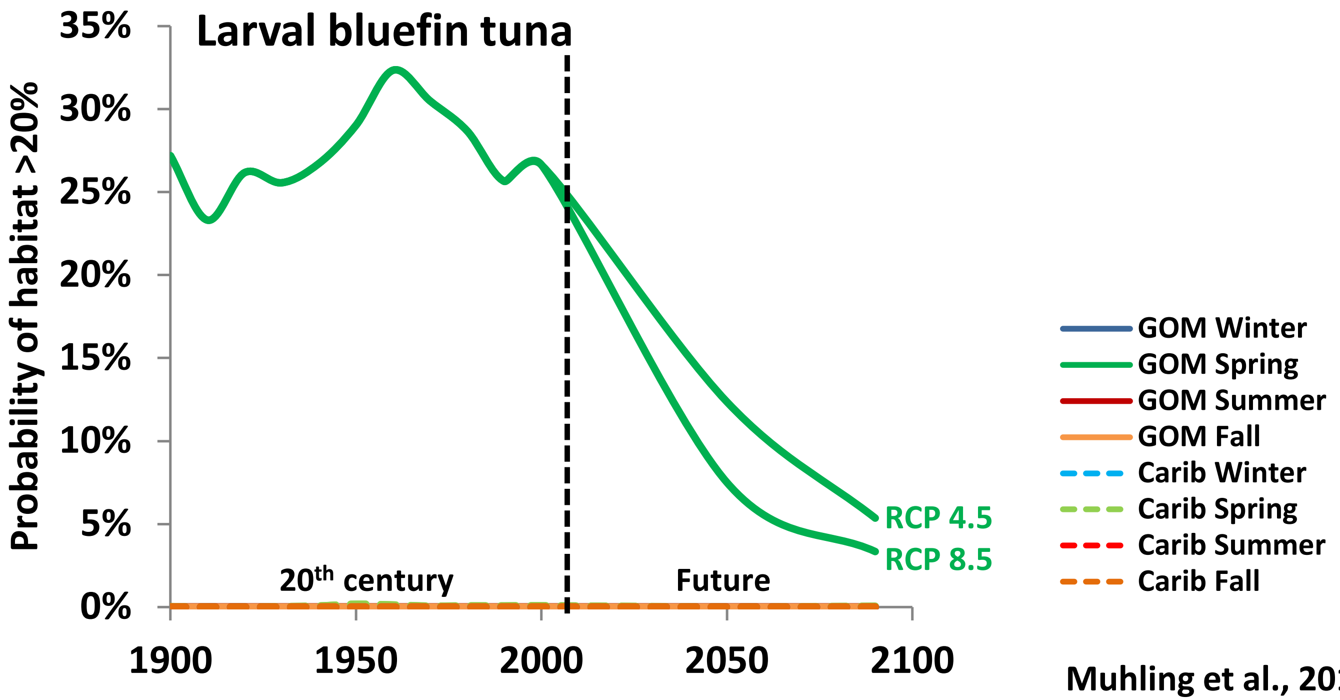
- As a first step, we looked at projected habitat shifts for bluefin tuna in the IAS
- Predictive habitat models for adults and larvae were built using:
  - Species data from NOAA surveys and fisheries data (ICCAT)
  - Water temperatures from satellite and ocean models
- We applied habitat models to projected temperatures from a dynamically downscaled regional climate model (0.1 x 0.1° spatial resolution)
- We considered two CO_2 Representative Concentration Pathways (RCPs):
  - RCP 4.5 (moderate emissions)
  - RCP 8.5 (high emissions)



Predicted habitat change: 1900 - 2100

- The magnitude of projected future habitat change quickly exceeded observed 20th century variability
- Habitat for both adults and larvae was projected to decrease substantially

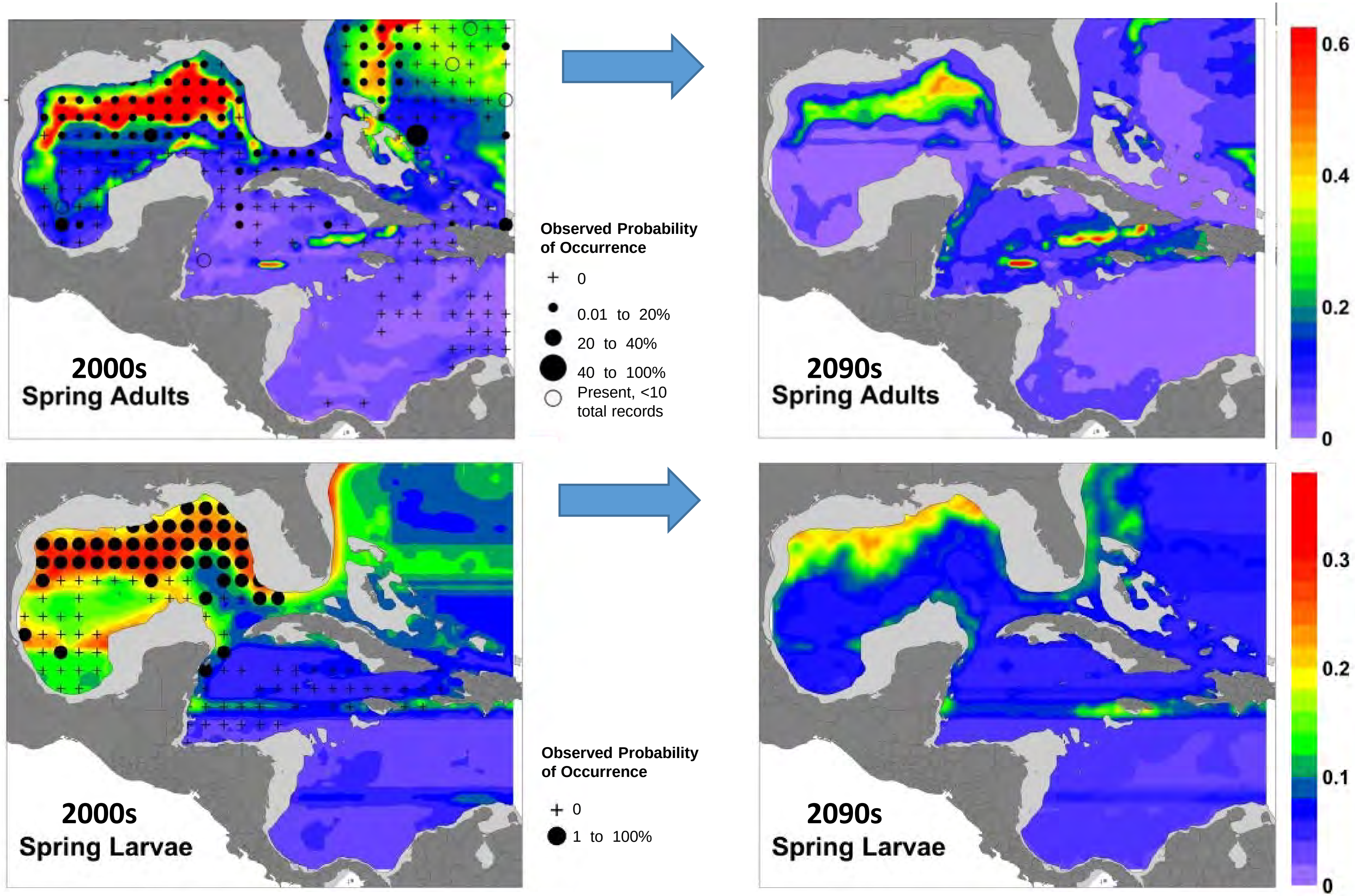




Muhling et al., 2015

Predicted habitat change: 2000s- 2090s

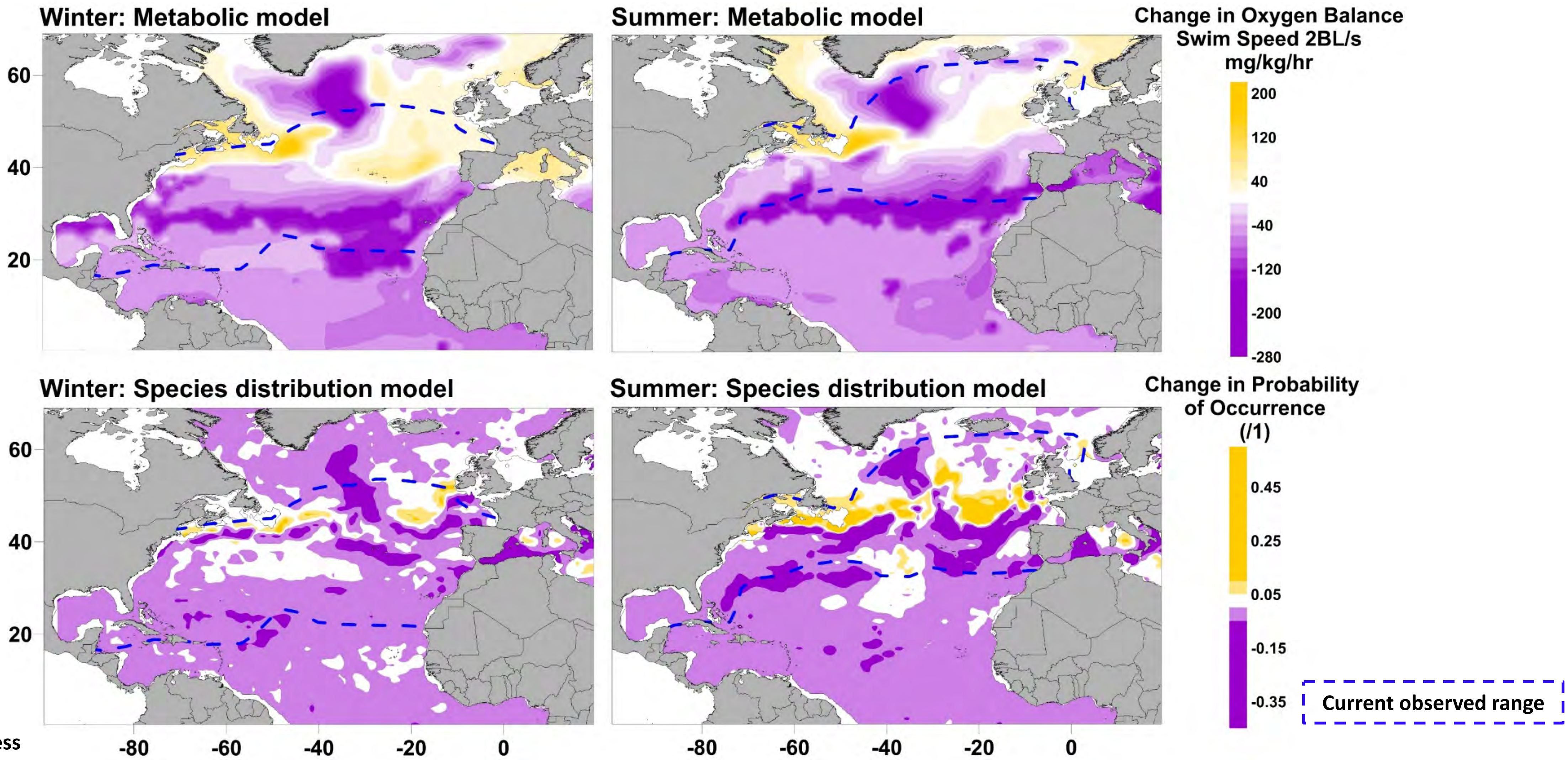
- During the spring spawning season, models predicted loss of habitat for both adult and larval Atlantic bluefin tuna



Muhling et al., 2015

What about the rest of the North Atlantic?

- We compared habitat quality between the recent historical (1970-1999) and end century (2071-2100) time periods
- Both the correlative species distribution model and the mechanistic metabolic model projected habitat loss south of 40°N
- Models differed more in sub-artic waters north of 40°N

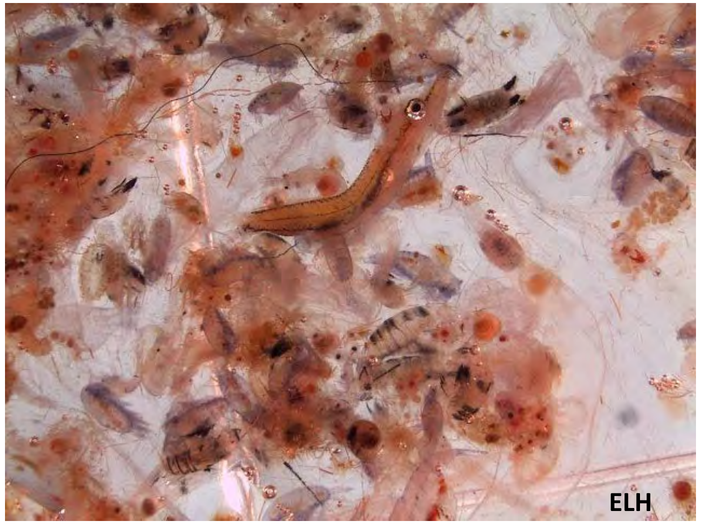


Muhling et al., in press

Conclusions to date

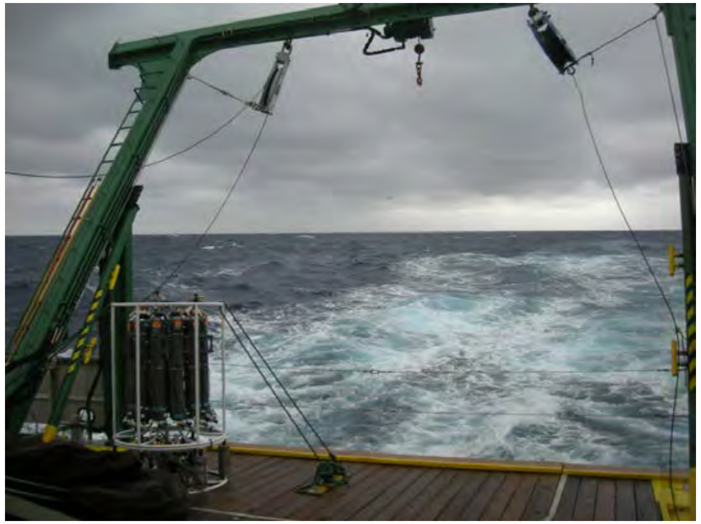
- Bluefin tuna spawning seems associated with specific environmental conditions
- Oceanographic processes on spawning grounds may contribute to recruitment variability
- The entire spawning range is likely under-sampled
- Adult bluefin tuna distributions may be partially driven by metabolic costs
- This sensitivity to environmental conditions across life stages may increase vulnerability to climate change
- Unless adaptation is possible, there may be substantial loss of habitat as climate changes

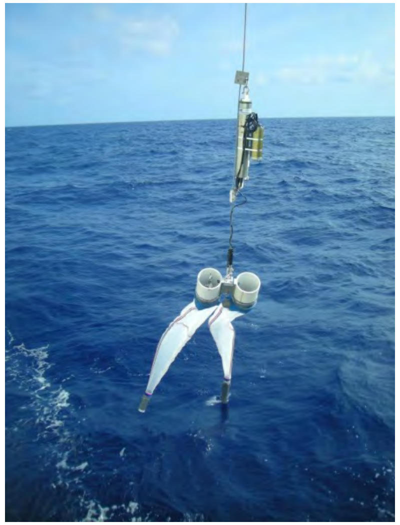




Management implications

- Current larval surveys are likely not capturing all western spawners
- Some parameters in the current stock assessment model may need revision
  - The western stock may be less productive than previously supposed
  - Age/size at maturity may be lower than currently assumed
- Prediction of recruitment from environmental variable may be possible
  - And used to address the high/low recruitment debate
- Constant recruitment, spawning behaviors, distribution and availability to fisheries should not be assumed as climate changes





Further research needs

- Results from correlative models are a good first step, but give little information on physiological processes, future recruitment, or implications for fisheries management
- Models that can project larval survival, recruitment, and population dynamics are also required
- Incorporation of environmental and habitat information into the stock assessment process can be difficult
  - Depends on current assessment model
  - Addition of environmental variables can increase uncertainty
  - Resistance from stakeholders



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