NUTRIENT DYNAMICS ACROSS **BLOOM STAGES**

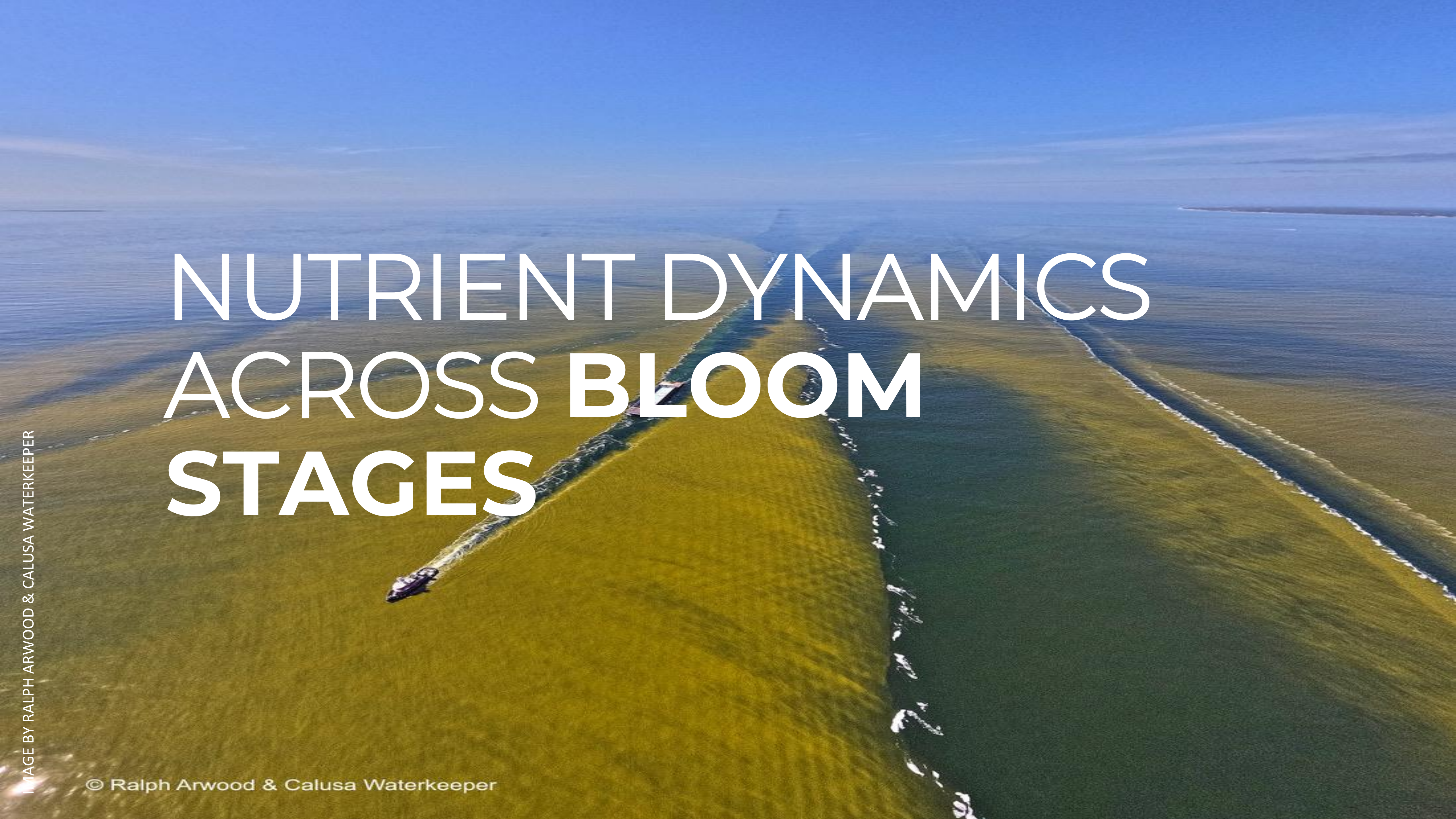


IMAGE BY RALPH ARWOOD & CALUSA WATERKEEPER

Nutrient Dynamics across Bloom Stages | A historical synthesis

Cynthia Heil[1] & Kate Hubbard[2]

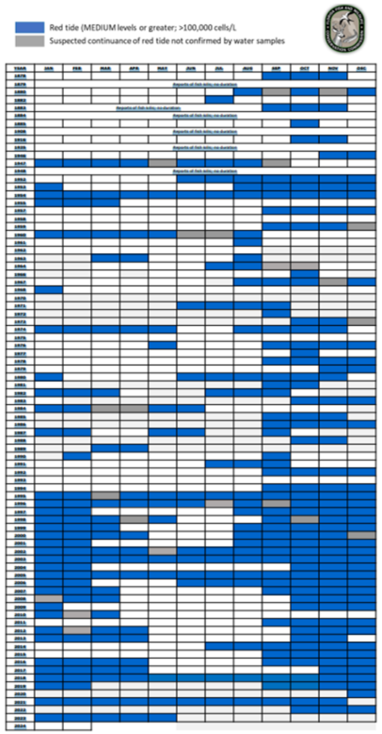
[1]Director, Senior Scientist, Red Tide Institute, Mote Marine Laboratory

[2] Research Scientist, Fish & Wildlife Research Institute, FFWCC


IMAGE BY NOAA-NCCOS

Understanding nutrients and *Karenia brevis* blooms in Florida: a long history

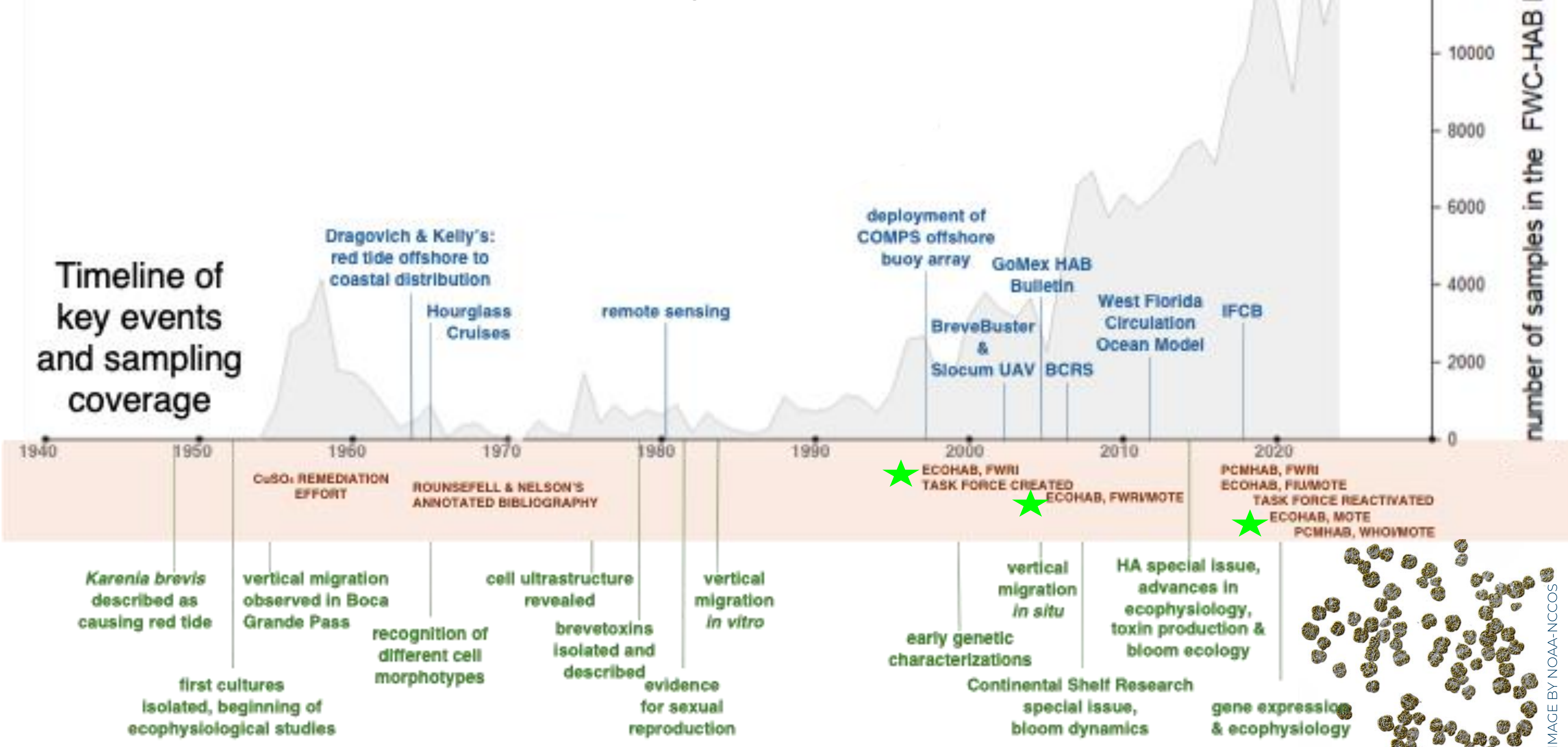
- Nutrients have been a topic of debate since *Karenia brevis* first intensively studied
- Bloom dynamics occur in a series of stages - initiation, peak, maintenance, termination.
- Processes on the West Florida Shelf, along the coasts, within estuaries, and upstream ~ variably important at different stages?
- Blooms can be more or less severe, such that bloom stages do not always align seasonally and may even coincide.
  - e.g., bloom maintenance through summer and summer bloom initiation?
- Bloom timing appears to be trending later in the year – implications for nutrients, impacts



https://myfwc.com/media/dr0fc1sm/bloom-historic-database.pdf

IMAGE BY NOAA-NCCOS

Layering nutrient discovery on our timeline of *K. brevis* key events



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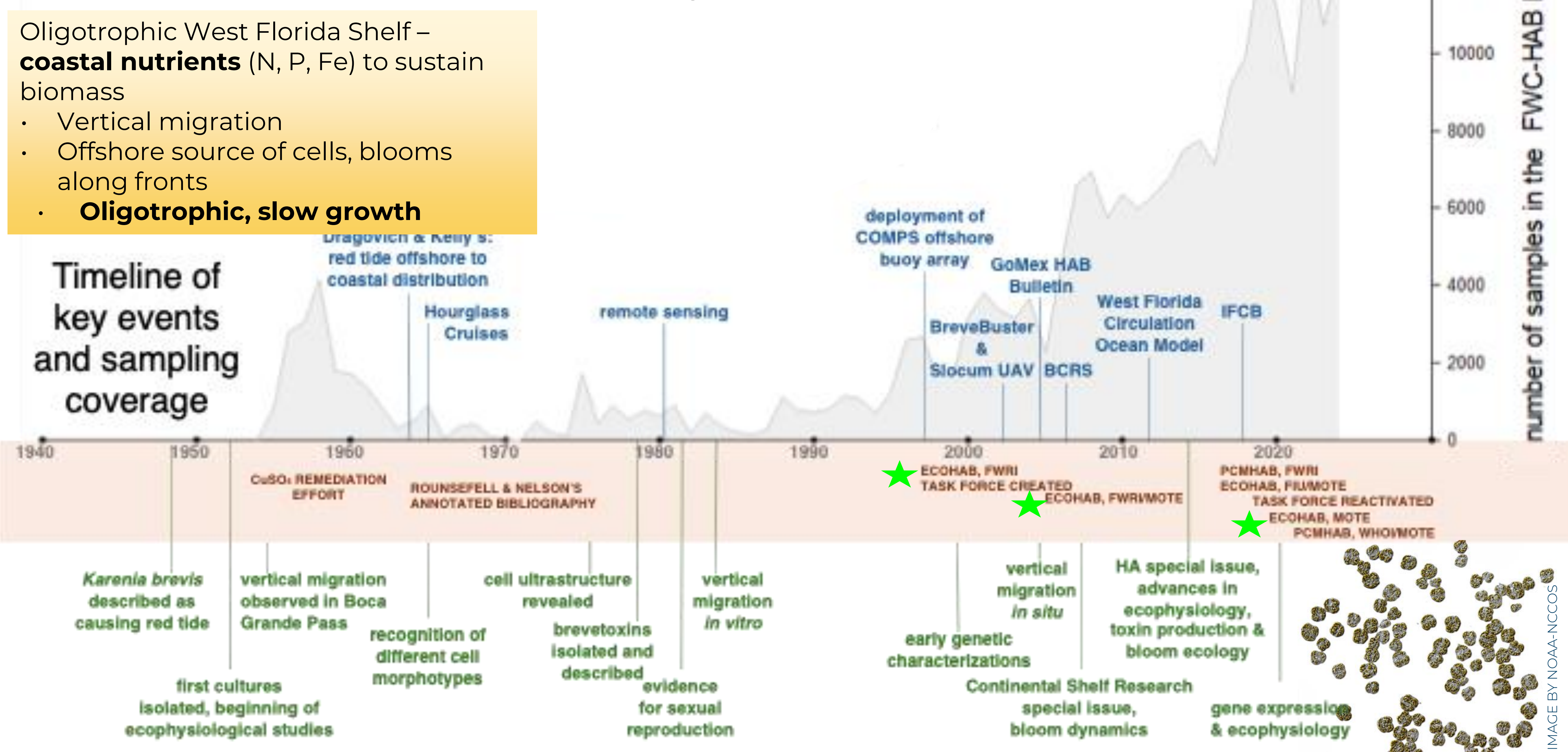
Layering nutrient discovery on our timeline of *K. brevis* key events

Oligotrophic West Florida Shelf – **coastal nutrients** (N, P, Fe) to sustain biomass

- Vertical migration
- Offshore source of cells, blooms along fronts
- **Oligotrophic, slow growth**



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Culturing → complex physiology

- Growth on **varied N, P sources**
- Preference towards **ammonium**
- Potential for **mixotrophy**
- Slow growth, light tolerant

Field studies highlight potential role of diazotrophs, **marine nutrient sources**

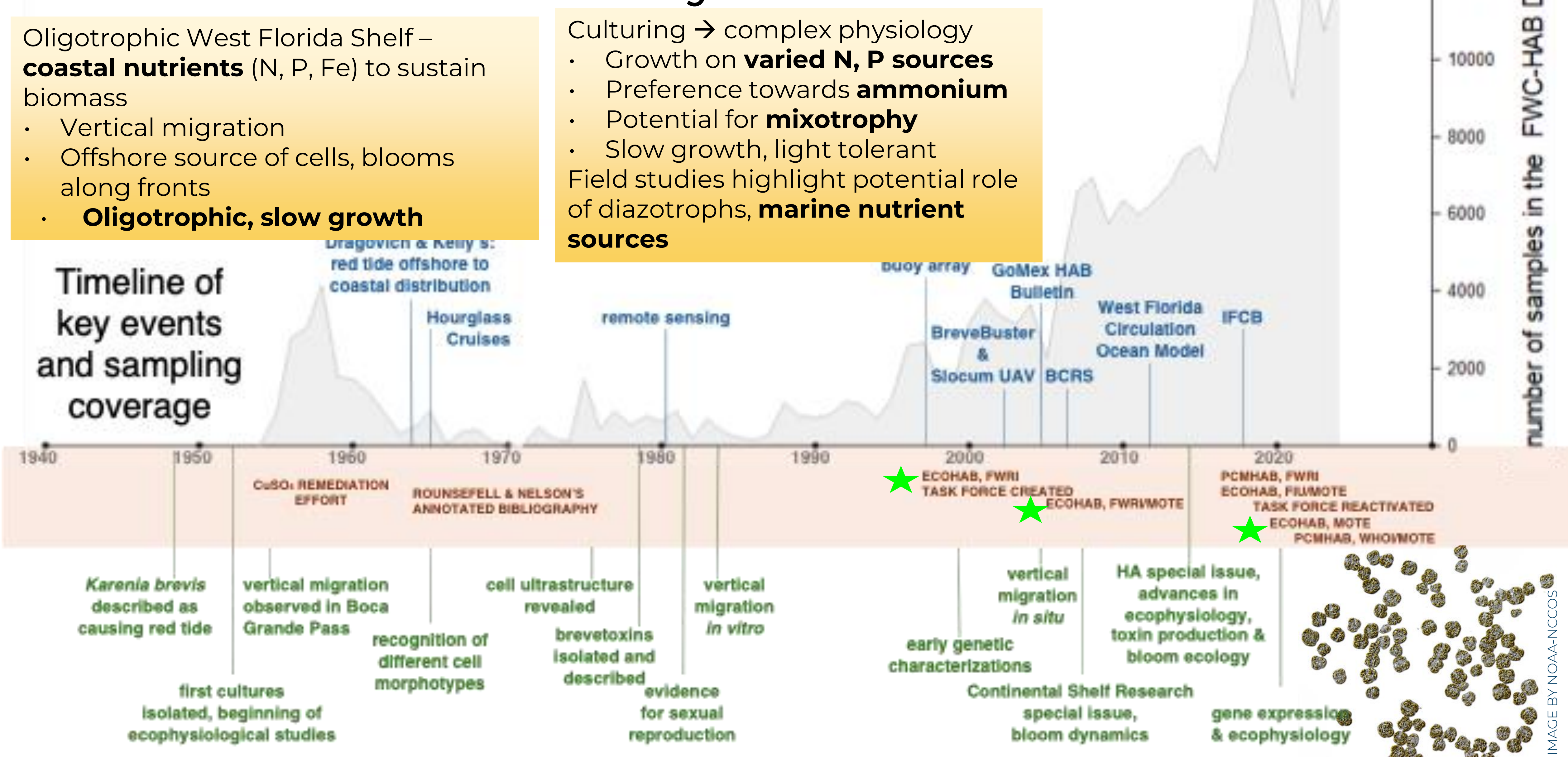

IMAGE BY NOAA-NCCOS

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Initial **ecological models** try to capture complexity
- Nutrient uptake modeled relative to different sources
- Physical dynamics

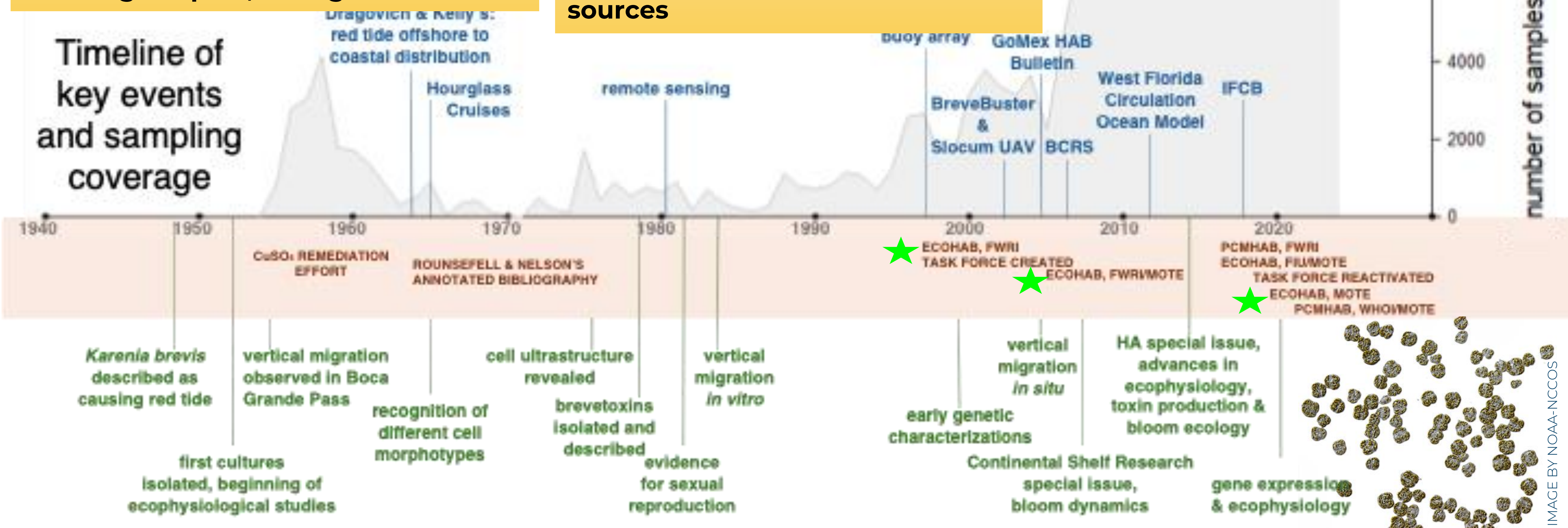


IMAGE BY NOAA-NCCOS

The “Early” Years

Collier (1953): **Caloosahatchee River effluents are important** for blooms: **organic content and physical attributes**

Niimann (1957): "mass outburst of phytoplankton when **fresh-water growth-promoting substances (trace elements, enzymes, other biologically active substances) reach the sea”**

Review by Bein (1957): **P levels in areas with blooms are, at all times, capable of supporting an outbreak**, and cellular P quotas may be lower than expected. Review by Rounsefell & Nelson (1966) caution differences in reports used for P may be partly due to analytical techniques.

Lackey and Hynes (1955) described **lack of nitrate-nitrogen** in red-tide water samples from October 6, 1953. Dragovich (1960) found **no relationship between nitrate/nitrite and incidence of cells**.

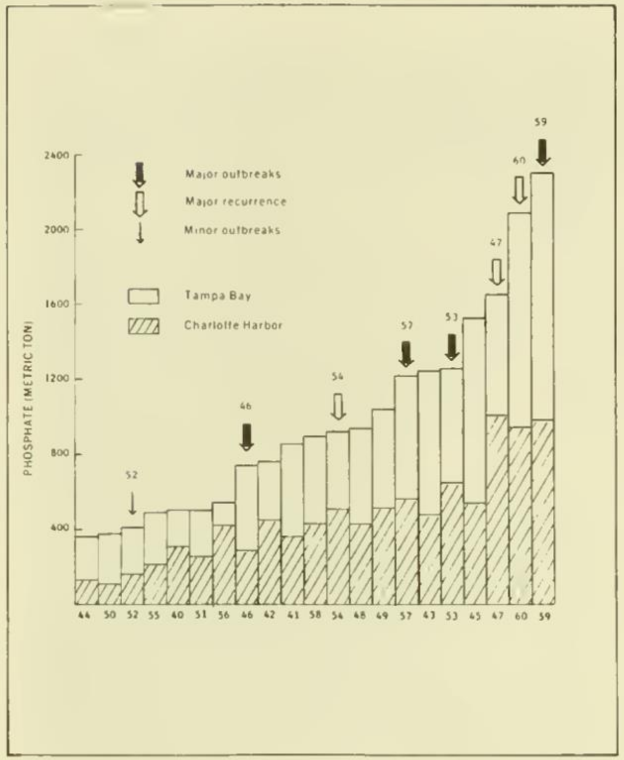


Figure 4.--Red-tide years in relation to phosphorus intrusion into Tampa Bay and Charlotte Harbor due to river discharge, March-September, 1940-60.

Rounsefell and Nelson 1966

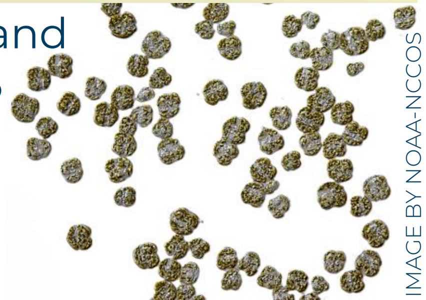
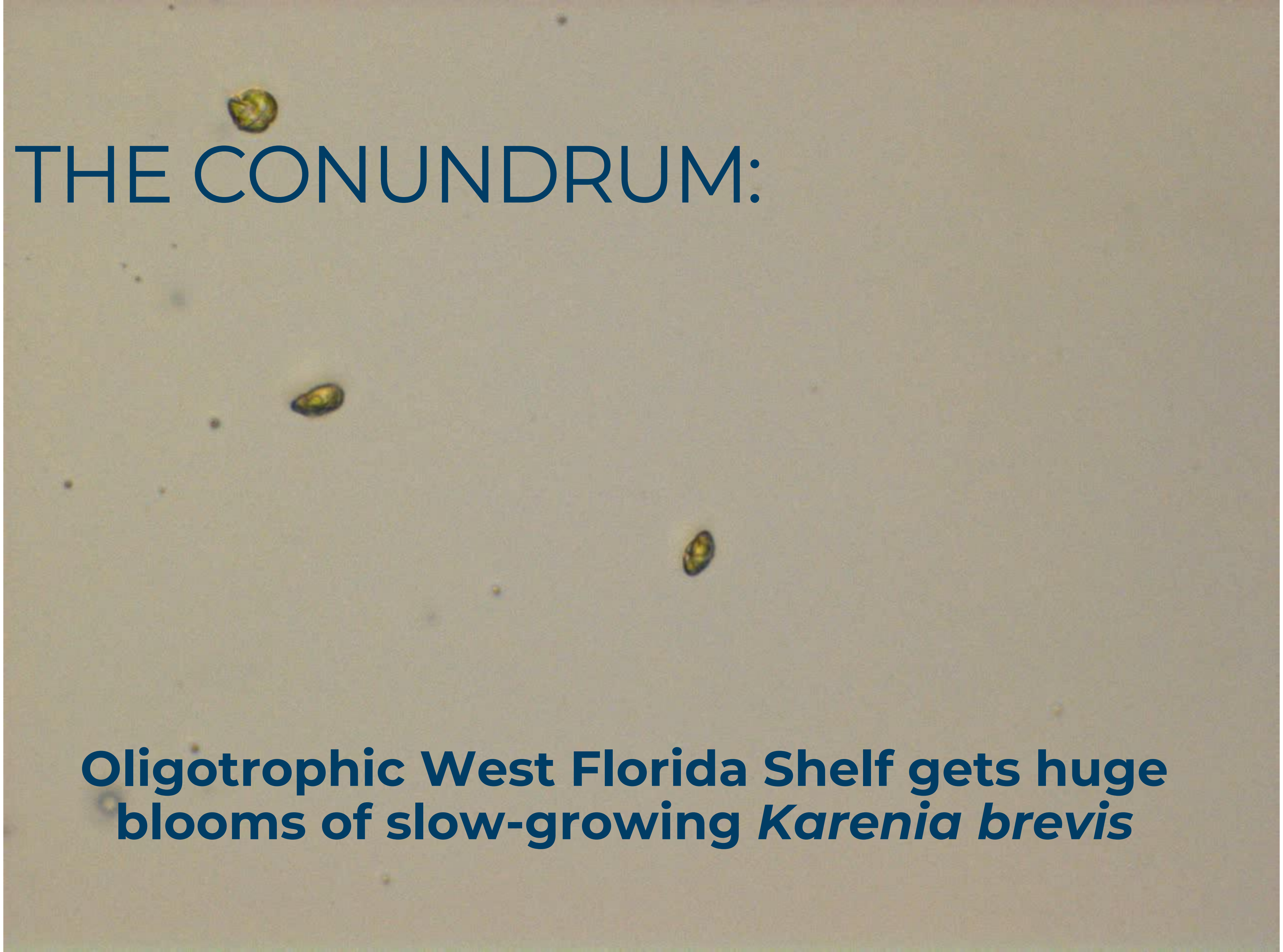


IMAGE BY NOAA-NCCOS

THE CONUNDRUM:



Oligotrophic West Florida Shelf gets huge blooms of slow-growing *Karenia brevis*

IMAGE BY NOAA-NCCOS

HYPOTHESIZED: 20+ RED TIDE **CAUSES**

- 7 are related to **rainfall, runoff, and/or riverine flux**
- 6 invoke the benthos or **bottom flux**
- 7 involve **water column hydrodynamics** or are unrelated to either the benthos or land sources
- 4 are primarily **chemical/allelopathically** (plant to plant interaction) based

From Vargo (2009)

Is there one central hypothesis that can explain all aspects of *Karenia brevis* blooms in the Gulf of Mexico?

- **No** – *Karenia brevis* is well adapted for life in an oligotrophic ocean and the coastal zone. A combination of **multiple factors (including varied nutrient sources) leads to the initiation, growth, and maintenance of blooms** in the unique SW Florida estuarine, coastal and shelf environment, and **not all blooms are the same.**

IMAGE BY NOAA-NCCOS

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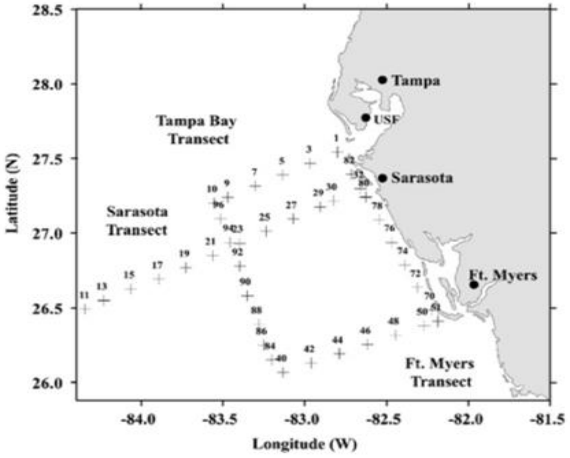
The shifting baseline syndrome (SBS) describes a gradual shift in how people perceive the state of nature, leading to a lowered expectation of what constitutes a healthy ecosystem. Don't reinvent the wheel. We are in times of unprecedented observations, change, and communication.

IMAGE BY NOAA-NCCOS

ECOHABs: Regional (and targeted) Studies

- **ECOHAB: Florida Program (1998-2002) - Funding Agency(s): NOAA, EPA, NSF, supp. State $**
  - 1) Model bloom stages, describe physical habitat, ID nutrient sources, evaluate intersection of cellular, behavioral, life cycle & community regulation with environmental forcing, production, occurrence, fate & effects of brevetoxins
  - 2) Monthly sampling (~63 stations), annual process cruises, lab expts
- Characterized biological (Chl *a*, *K. brevis*), chemical (NO_3, PO_4, SiO_4, DON, DOP) & physical conditions



(from Vargo et al., 2008)

Continental Shelf Research
2008, Vol. 88

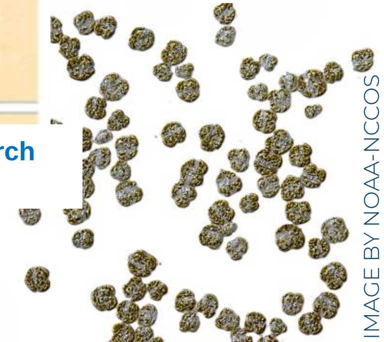


IMAGE BY NOAA-NCCOS

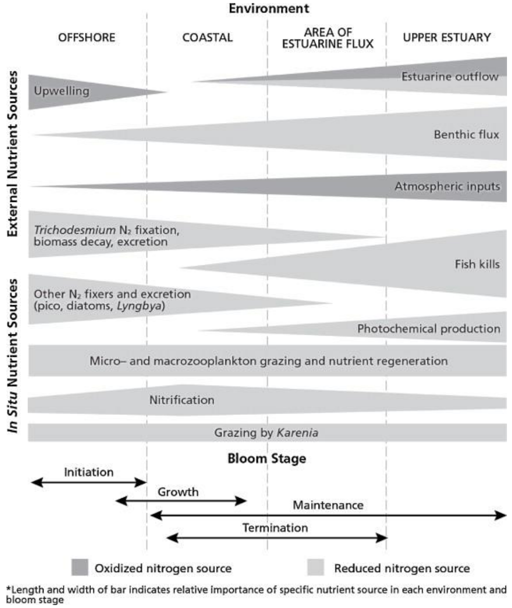
ECOHABs: Regional (and targeted) Studies

ECOHAB: *Karenia* (2006-2012) - Funding Agency: NOAA, supplemental state funding

1) What are the N & P nutrient sources fueling massive, persistent biomass *Karenia* accumulations?

2) Examined 5 blooms, in 3 stages, with varying sizes and locations

- Identified & quantified 12 different nutrient sources available to blooms, model parameterization
- Project Database: ambient conditions & rate processes (C, N, & P uptake & regeneration, bacterial & primary production, micro- & macrozooplankton grazing) in 3 different blooms + 1 non-bloom



(from Heil et al., 2014)

Harmful Algae 2014, Vol. 38

IMAGE BY NOAA-NCCOS

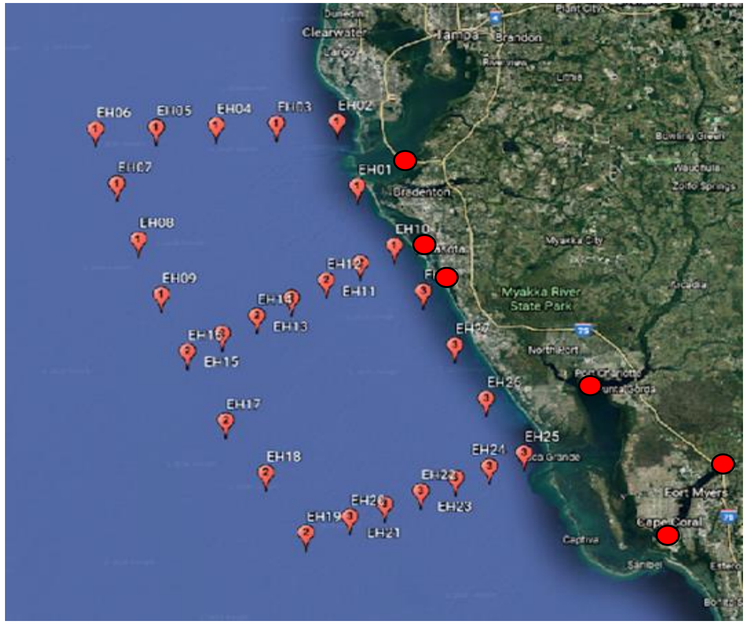
ECOHABs: Regional (and targeted) Studies

ECOHAB: Life & Death (2019-2025) - Funding Agency(s): NOAA

1) What is role of extreme events in magnifying directly or indirectly the intensity and/or duration of blooms and what are the factors that ultimately lead to bloom decline?

2) Monthly sampling (~29 coastal, 6 land-based stations), process cruises, lab & field based expts

- Characterized biological (genomics, phyto counts, HPLC, virus, bacteria), chemical (NO_3, NH_4, PO_4, SiO_4, DON, DOP, $\delta^{15}N$, $\delta^{13}C$) & physical conditions pre, bloom & post-bloom
- Model parameterization, bacterial & viral bloom interactions, mixotrophy, improved ^{18}O based P & R mmts, temperature effects, nutrient uptake & regeneration
- Long-term data analyses: bloom patterns, large-scale perturbations impacts (hurricanes, Piney Pt), climate change & eutrophication, regime shifts, role of weather in bloom termination



Special Issue (2026-2027?)

IMAGE BY NOAA-NCCOS

What fuels a bloom?

Which nutrients does *Karenia brevis* need?
- Sunlight+
- Nitrogen, Phosphorus, Carbon
- Trace Metals
- Vitamins

Which nutrients can *Karenia brevis* use?

Inorganic N & P: NO_3, NO_2, NH_4, PO_4

Organic N & P & C: DON, DOP, DOC, Urea, Humics/Tannins

Particulate N & P & C: mixotrophic: ingests *Synechococcus* (& others?)

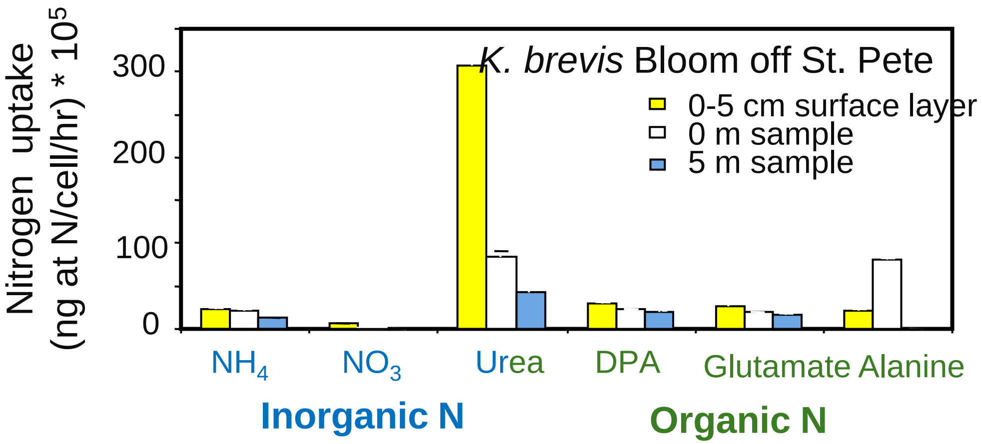


Figure from Heil et al (2014)

nanoSIMS confirmation of *Synechococcus* grazing by *K. brevis*

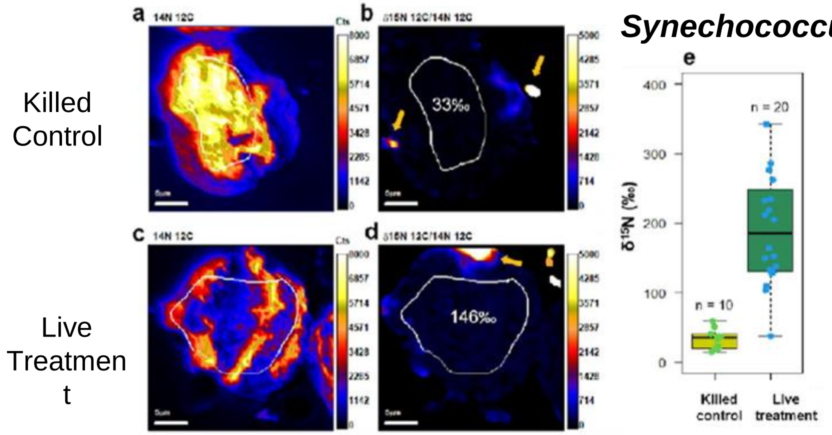
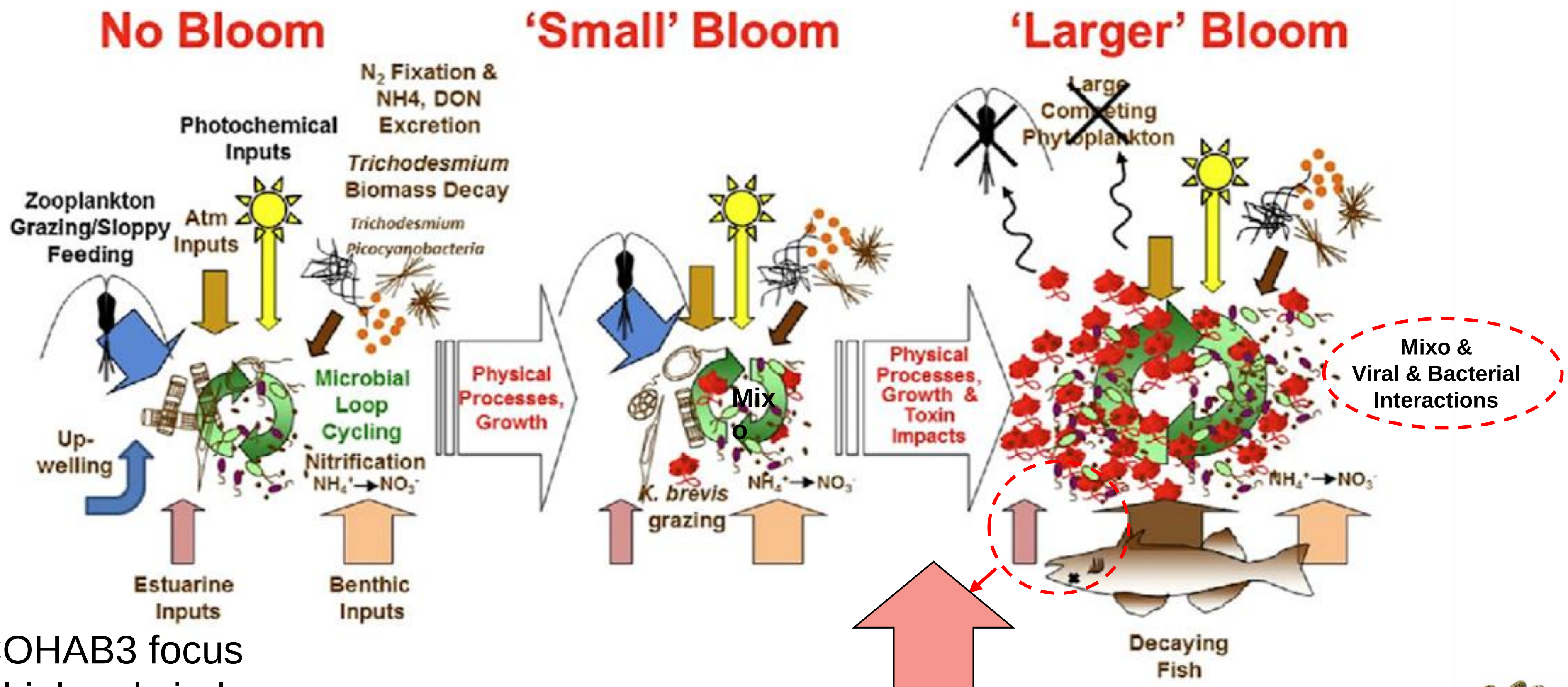


Figure from Ahn (2023)

IMAGE BY NOAA-NCCOS

Bloom severity and potential underlying processes: (how) can a bloom sustain itself?



New models in ECOHAB3 focus on capturing microbial and viral dynamics, etc.
(Glibert presentation)

NO_3 → NO_3/NH_4 → NH_4

New N bloom

Regenerated N bloom

Figure adapted from Heil et al (2014)

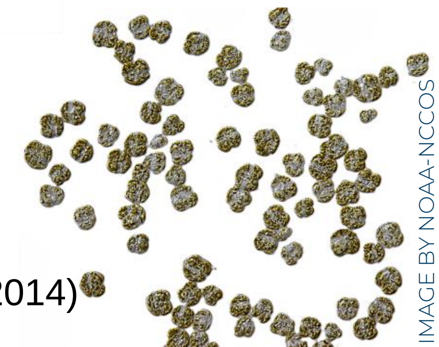


IMAGE BY NOAA-NCCOS

Complex relationship with N and P

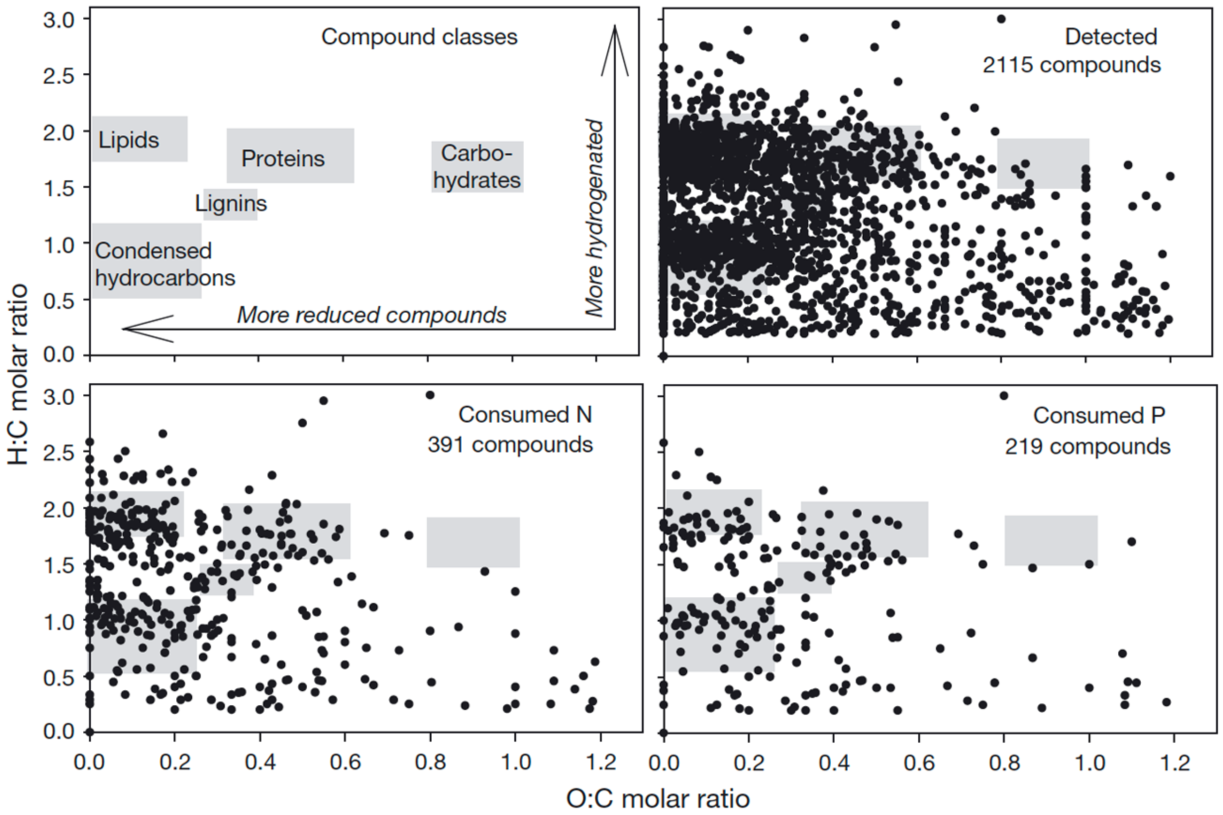
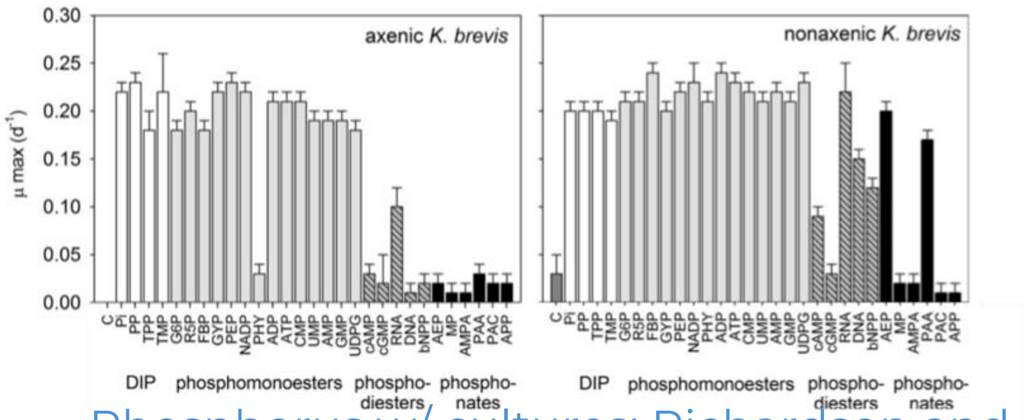


Fig. 3. Van Krevelen diagrams of general compounds classes redrawn from Kim et al. (2003) and Bhatia et al. (2010); all formula assigned for +*Trichodesmium* sp. cellular exudates (+TCE) bioassays, N-containing organic compounds consumed, and P-containing organic compounds consumed

Bioassays: Sipler et al. (2009)



Phosphorus w/ cultures: Richardson and Corcoran (2015)

1) >8 inorganic and organic N substrates used by *K. brevis*
2) NH4+>NO3>urea>humic-N>amino acids in order of preference
3) *K. brevis* may be able to modulate N-uptake

Killberg-Thoreson et al. (2014)

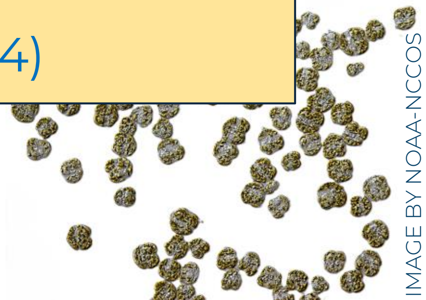
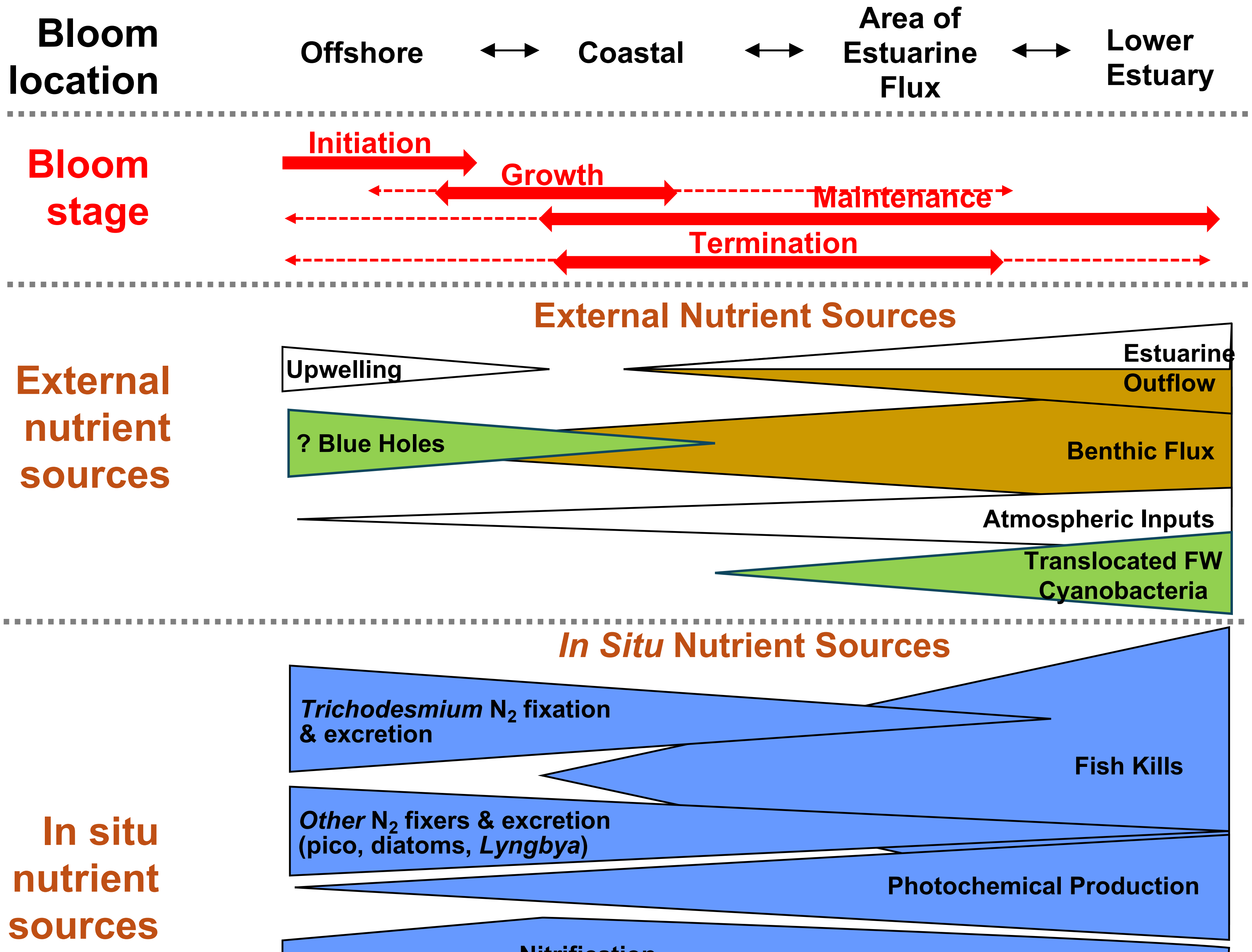
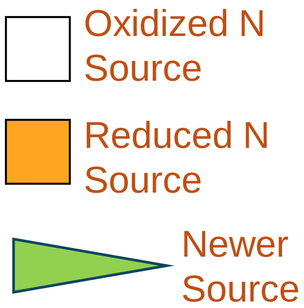


IMAGE BY NOAA-NCCOS

How do nutrient sources vary with respect to:

- **Bloom location**
- **Bloom stage**
- Seasonal processes





How do nutrient sources vary with respect to seasonal processes?

"typical" bloom stages in nutrient/growth space
Bottom-up approach = growth, nutrient structure and form

	Summer/fall **initiation**	Late fall/winter **peak**	Winter/spring **demise**
Nearshore	• End of wet season • Stratification • Cyanobacteria season peak to demise (benthic and fresh)- nutrient source?	• Dry season with periodic precipitation • *K. brevis* often dominant, transported into estuaries • Regenerated nutrients	• Dry season with periodic precipitation • *K. brevis* concentrations and distribution decline
Offshore	• Horizontal fronts • After/during dust deposition events • During/after peak diazotroph abundance (?)	• Bloom transported through multiple watersheds along coast • Oligotrophic further offshore	• Oligotrophic
Both	• Warmest months • Peak storm activity • Cloud cover vs. peak radiation • Downwelling gives way to local/ regional upwelling • Nitrate mostly scarce	• Cold fronts • Localized wind-driven upwelling/downwelling • Erosion of fronts? • Less cloud cover, shortest days, least radiation	• Cold fronts with gradual seasonal warming, after transition from coldest time of year • Less cloud cover • Days start to lengthen

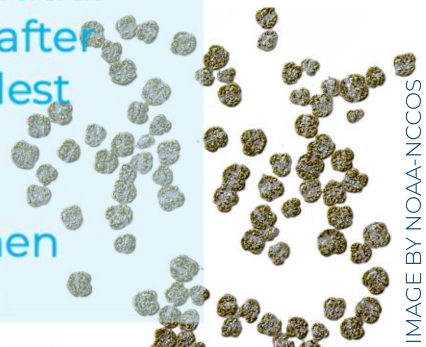


IMAGE BY NOAA-NCCOS

How do nutrient sources vary with respect to seasonal processes?

“typical” bloom stages in nutrient/growth space
Bottom-up approach = growth, nutrient structure and form

	Summer/fall **Initiation/Peak 3**	Late fall/winter **Peak 1**	Winter/spring **Peak 2**
Nearshore	• End of wet season • Stratification • Cyanobacteria season peak to demise (benthic and fresh)- nutrient source?	• Dry season with periodic precipitation • *K. brevis* often dominant, transported into estuaries • Regenerated nutrients	• Dry season with periodic precipitation • *K. brevis* concentrations and distribution decline
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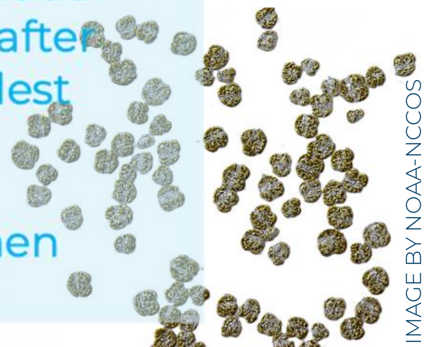


IMAGE BY NOAA-NCCOS

The availability of nutrients varies with:

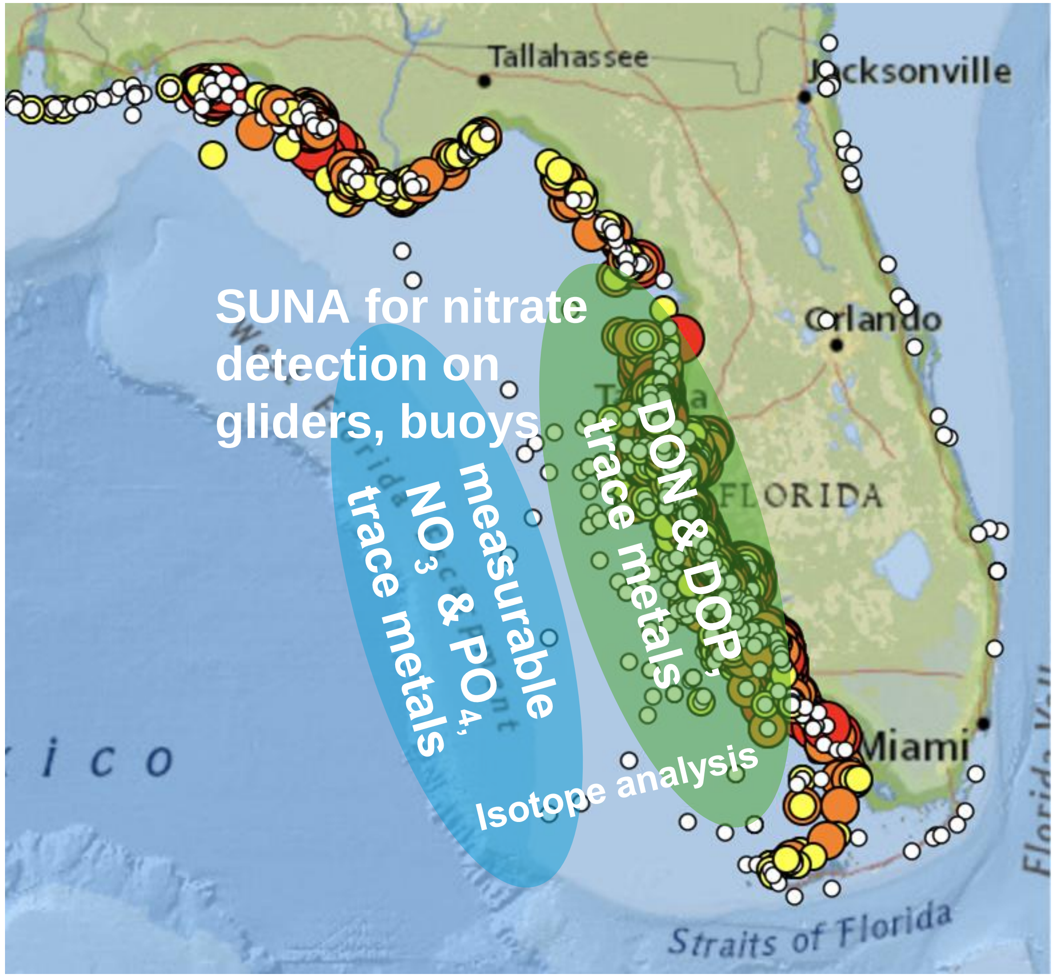
- bloom location
- bloom stage
- time of year
- nutrient & nutrient form & delivery
- physiological stresses
- physical processes
- climate processes
- management actions
- benthic processes
- life history
- estuarine dynamics

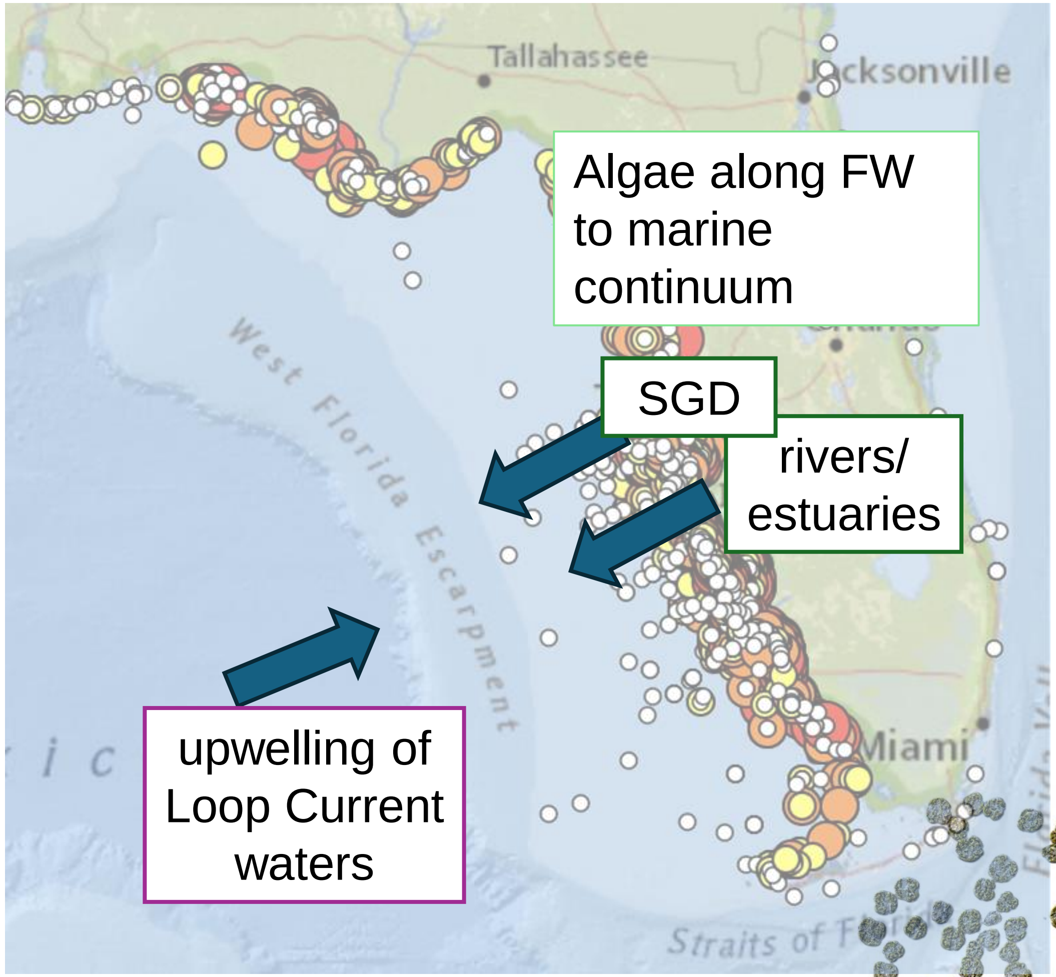
Historical rates and data may no longer be valid-- do we need to update rate measurements and nutrient budget(s)?

IMAGE BY NOAA-NCCOS

Routine offshore observations since 2020

Knapp, Buck, Hall presenting at this SOS
State funded partnerships





2020-2024FWC CELL COUNTS PLOTTED W/ NOAA HABSOS, https://habsos.noaa.gov/; slide modified from Chelsie Bowman and Angie Knapp, TAMU

Modeling blooms and ocean physics

nutrient concentrations and fluxes are impacted on seasonal to event time scales

- Forecasts focus on **upwelling** on the WFS and related to the Loop Current (NOAA initiation and USF seasonal)
- ECOHAB3 integrates **microbial loop** within ROMS
- FL HAB Task Force funded grant: **coupled physical and ecosystem models** within WFCOM for *K. brevis* dynamics (initiation, intensification)
- Statistical models for **inshore dynamics**

IMAGE BY NOAA-NCCOS

Can we forecast and hindcast blooms using models to investigate variability in severity and potential drivers at varied time scales and across bloom stages?

- **Yes** – A suite of models, culture studies, and observations have helped parameterize *Karenia brevis*, however, more work is needed to better connect models that account for environmental variability, bloom stage, biological transformations, and/or *K. brevis* physiology/life history.
- **We need organized and routine data.**

IMAGE BY NOAA-NCCOS

Routine sampling for *K. brevis* dynamics 2020 onward

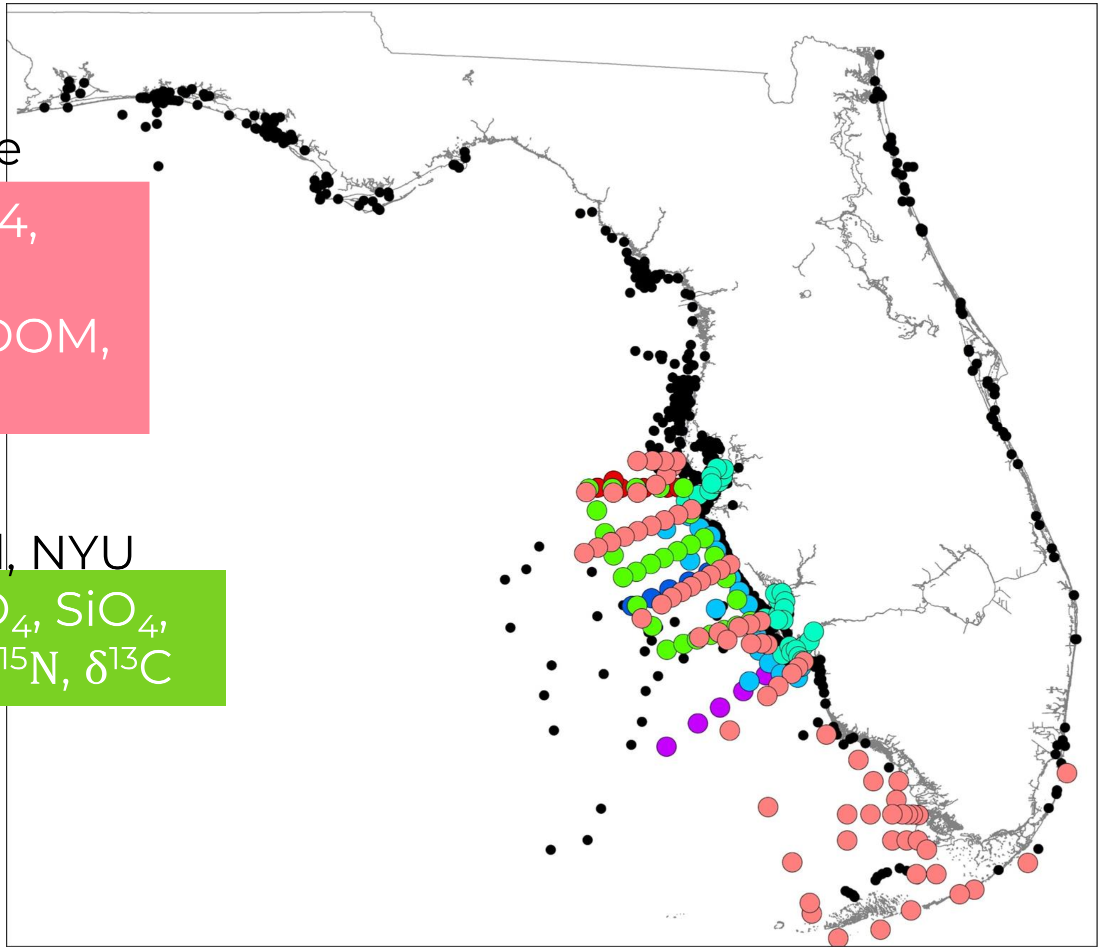
TAMU, USF, Mote

NO2,3, PO4, SiO4, TDN, TDP, dN15, trace metals, CDOM, PN, PC, DOC

U. Maryland, NYU

ECOHAB

NO_3, NH_4, PO_4, SiO_4, DON, DOP, $\delta^{15}N$, $\delta^{13}C$



TAMU, USF

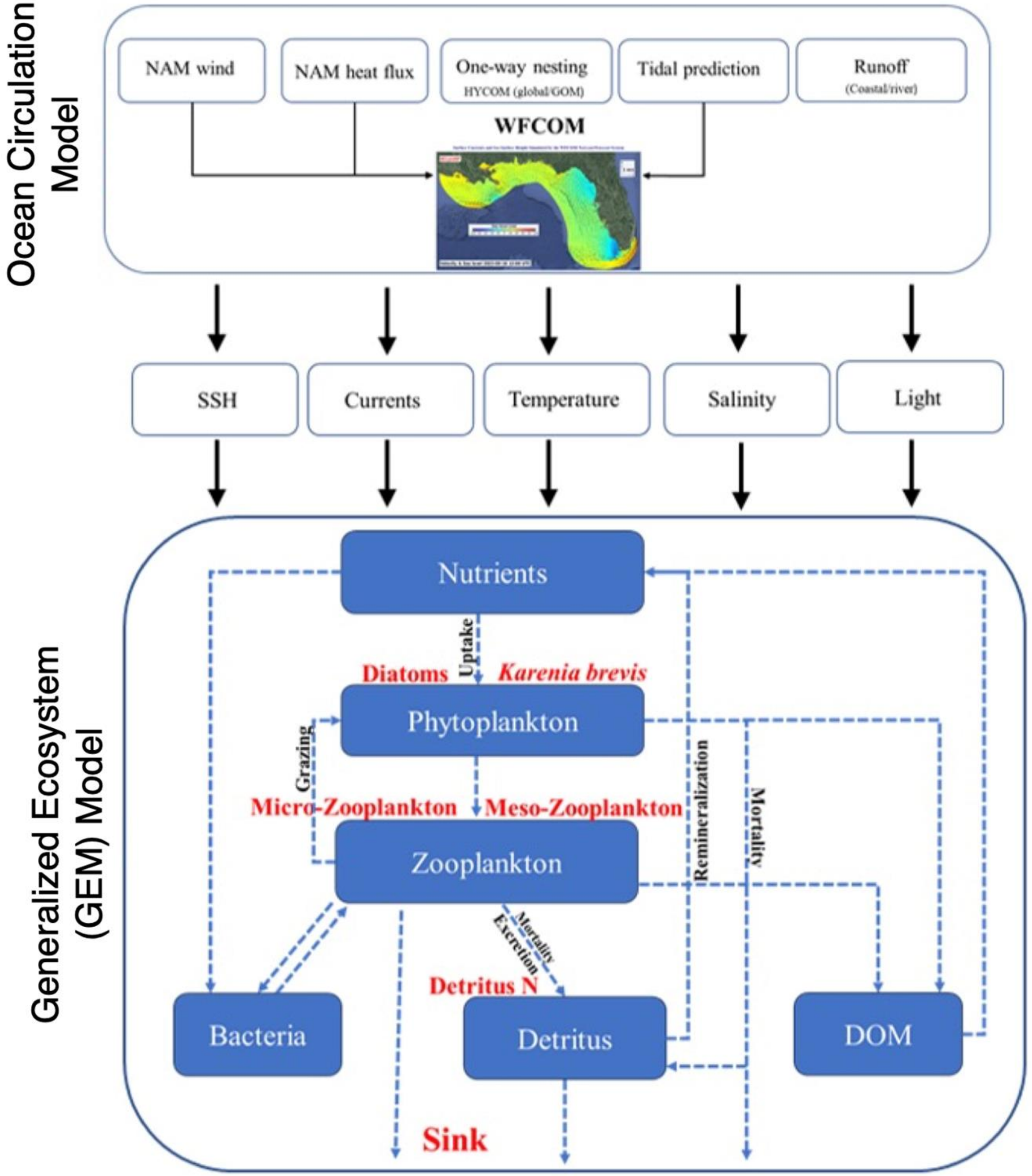
$NO_{2,3}$, PO_4, BioSi, TDN, TDP, dN15

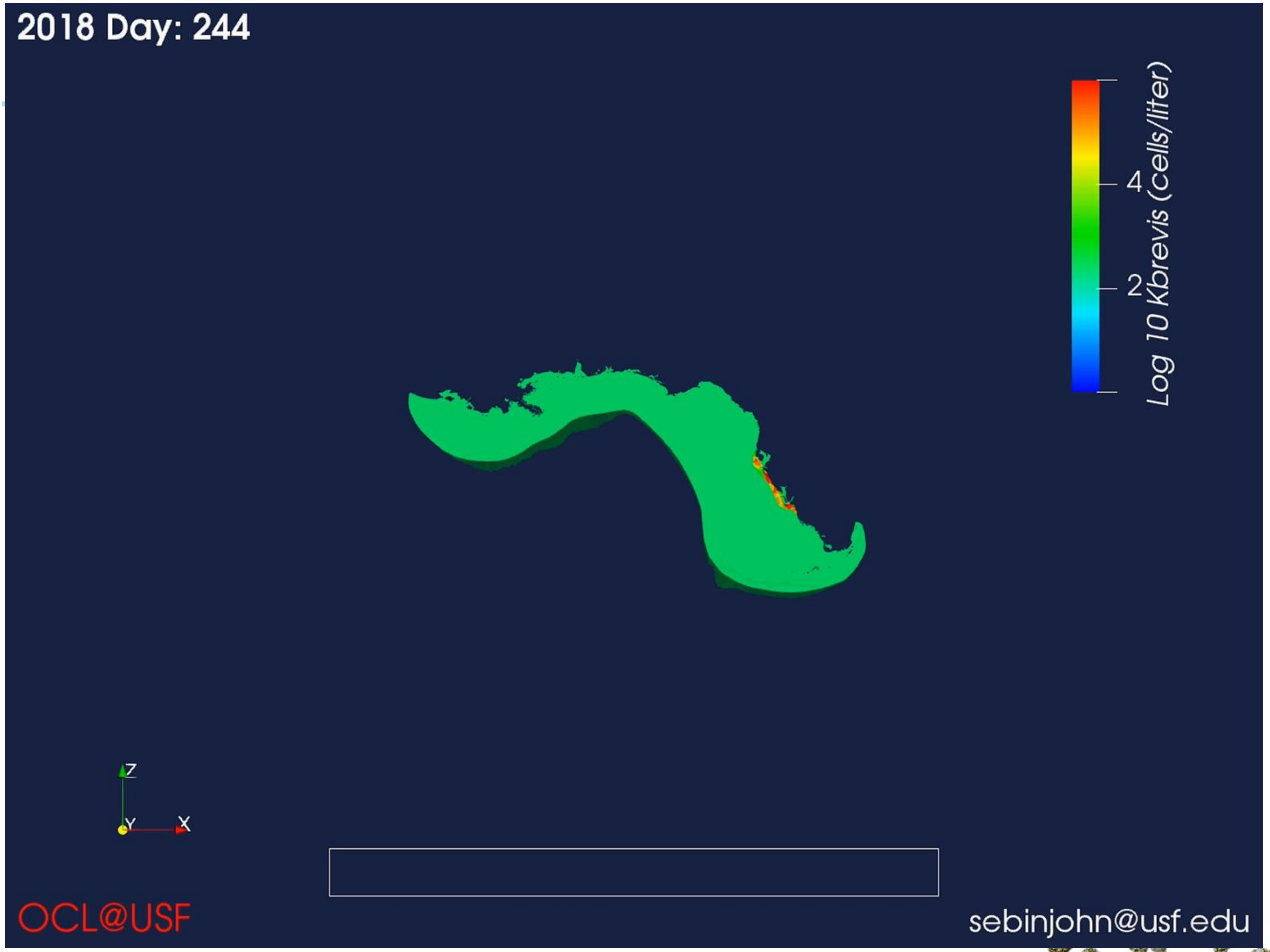
NH4, NO2,3, PO4, CDOM, PN, PC, DOC, DSiO2, PSiO2 , DTP, PP, pHT

NH_4, $NO_{2,3}$, PO_4, SiO_4

IMAGE BY NOAA-NCCOS

Modeling transport and bloom dynamics



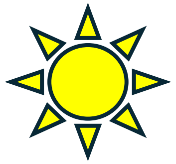


Database needs: disparate nutrient-relevant sources

1. FL HAB Specific DBs
   - FWRI State HAB DB (1953-present): (https://myfwc.com/research/redtide/monitoring/database/)
   - FWRI Fish Kill DB (1998-present): State fish kill data: (https://myfwc.com/research/saltwater/health/fish-kills-hotline/)
   - **ECOHAB**: *Karenia* (2006-2012) – Access DB: 4 blooms at 4 stages, variety of parameters (nutrients, uptake, regeneration, bacterial, primary & secondary production, macro & micro-zooplankton grazing): Model parameterization, Hypothesis testing
   - **ECOHAB**: Florida (1998-2002) – field data, monthly 69 stations between Tampa Bay and Ft. Myers to the 200 m isobath
2. Federal & International HAB DBs
   - Harmful Algal Information System, HAIS
   - CDC One Health Harmful Algal Bloom System (OHHABS)
3. Water Quality DBs
   - SF Water Atlases: TB, CHNEP
   - EPA & USGS DB: STORET, now Water Quality Portal (https://www.waterqualitydata.us/)
   - State DBs: SFWMD DBHYDRO DB,
4. Other relevant DBs- storms, climate indices, hydrology, land use, etc.
   - Florida Hurricane Event Descriptions (Wikipedia), ENSO historical episode data (NOAA National Weather Service, 1950-present)
   - Florida precipitation & temperature (USDA/NRCS – Nat'l Geospatial Center of Excellence PRISM raster data, 1981-2010), National
   - Storm Events Database (NOAA National Weather Service)
   - Florida Geology (USGS - USGS Mineral Resources, 2005),
   - Florida regional Land Use/ Land Cover (Florida DEP) and Florida fertilizer sales (Florida FDACS),
   - Florida regional cropland data (USDA-NASS Cropland Data Layer, 2012)
   - Florida Hydrologic unit delineations (USDA/NRCS - National Geospatial Center of Excellence),
   - Stream Flow/Hydrologic conditions (USGS Surface-Water Historical Instantaneous Data for the Nation)
5. Relevant data that SHOULD be available in DBs

Database needs: Estimates of *K. brevis* biovolume, growth, nutrient quotas → models

Cell size is dynamic



Diel

Determined via in situ Imaging FlowCytobot Muhlbach et al., in prep

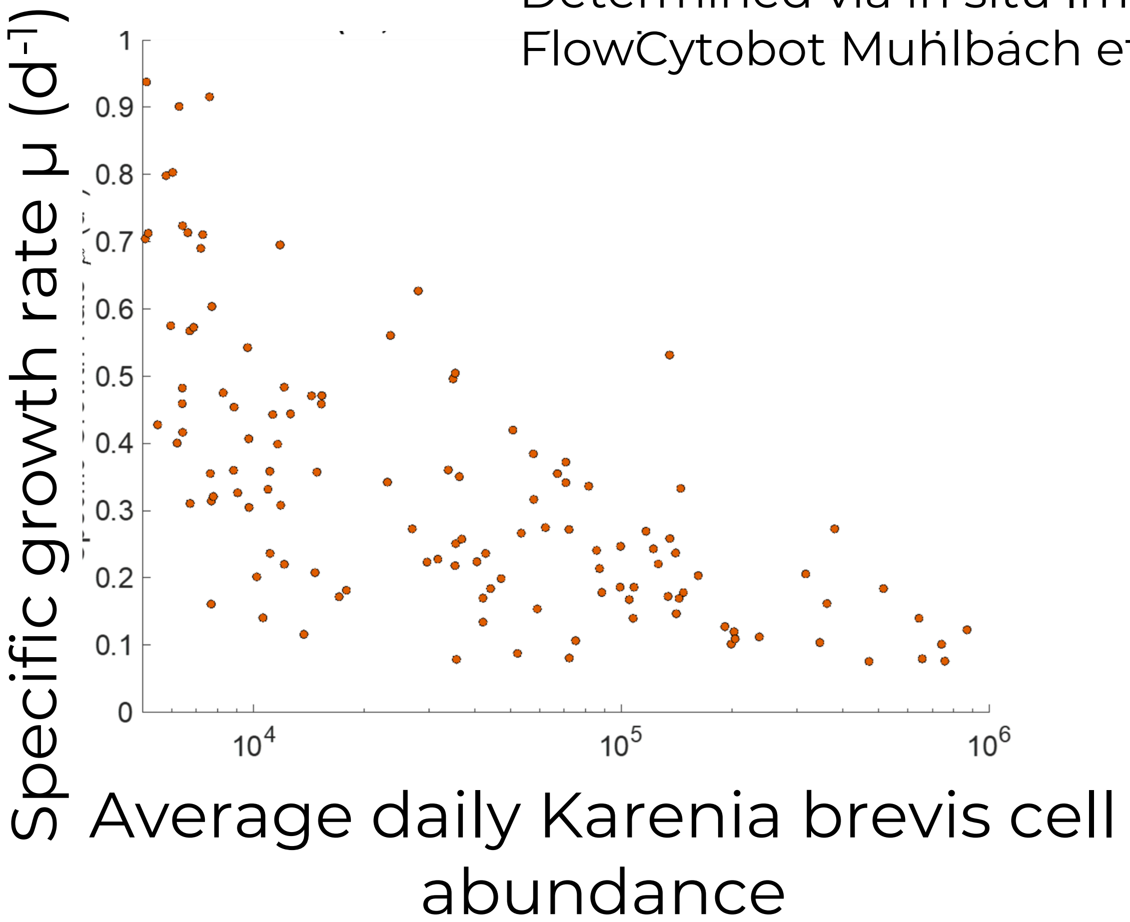


IMAGE BY NOAA-NCCOS

Progress: bloom severity indices

Multi-year interpretation of FWC HAB Database

- Location, occurrence, intensity – cell abundance, Stumpf et al. 2021
- Remote sensing-based assessments of bloom extent, MODIS, Hu et al. 2022, VIIRS Yao et al. 2023
- Bloom duration, concentration, and frequency by subregion, FWC Fishery Assessments for Red Drum, Snook
- Concentration and duration, Kurtz et al. 2023

IMAGE BY NOAA-NCCOS

TAKE AWAY MESSAGES

- Our questions have shifted and our methods have evolved, but fundamentally, it is still challenging to confirm which nutrients are most important to blooms
- New and evolving models can help explore questions related to best management practices across bloom stages (and potentially life history stages)
  - If certain nutrients were removed at beginning, middle, end of a bloom – would blooms not reach as high density? Would severity decrease over time?
  - How can we do a better job of tracking key nutrients as they move through complex ecosystems?

IMAGE BY NOAA-NCCOS

FURTHER REFLECTION(S)

- What clear messages to do we want to convey to the public and other researchers about what we are doing, where there are gaps, and how we deal with uncertainty?

- Can we ID gaps in knowledge going forward?
  - To what end are measurements being made?
  - Where do we need consistent data? What data? Implications for models?

- Is *K. brevis*’s fundamental niche (from literature) still true?
  - Do we need to update rate measurements and N budget(s)?
  - How do multi-stressors impact rate measurements and budgets?
  - Do we need to rethink lab experiments?

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IMAGE BY NOAA-NCCOS

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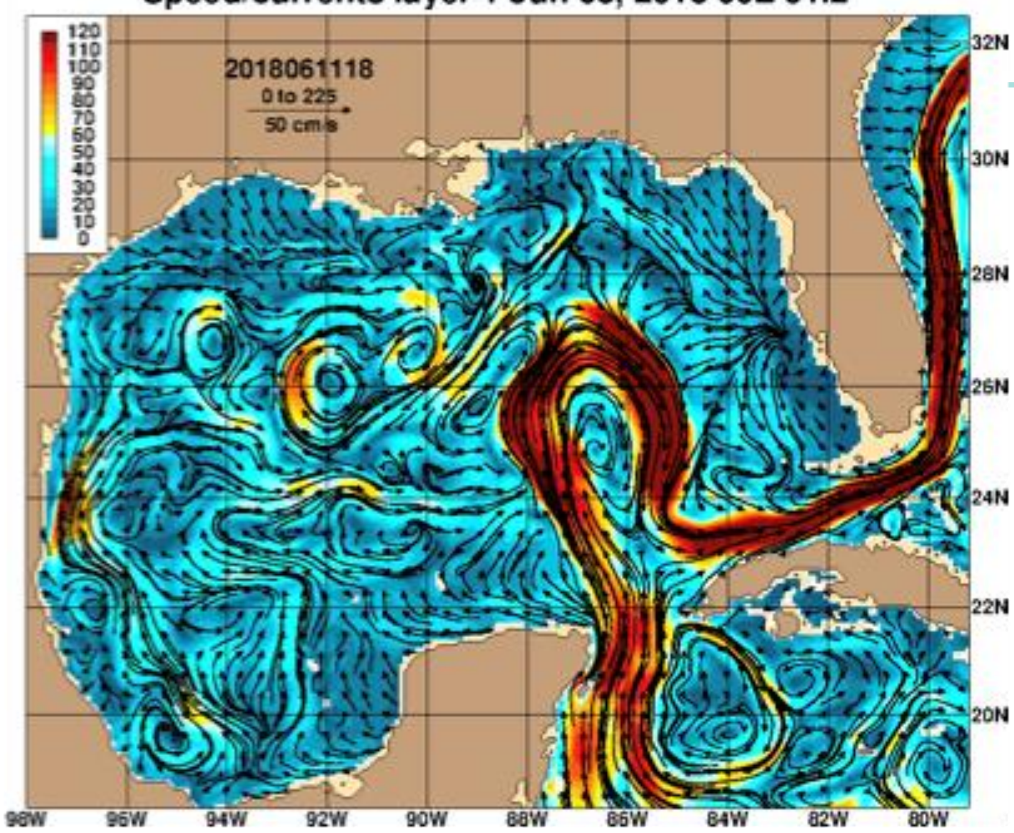
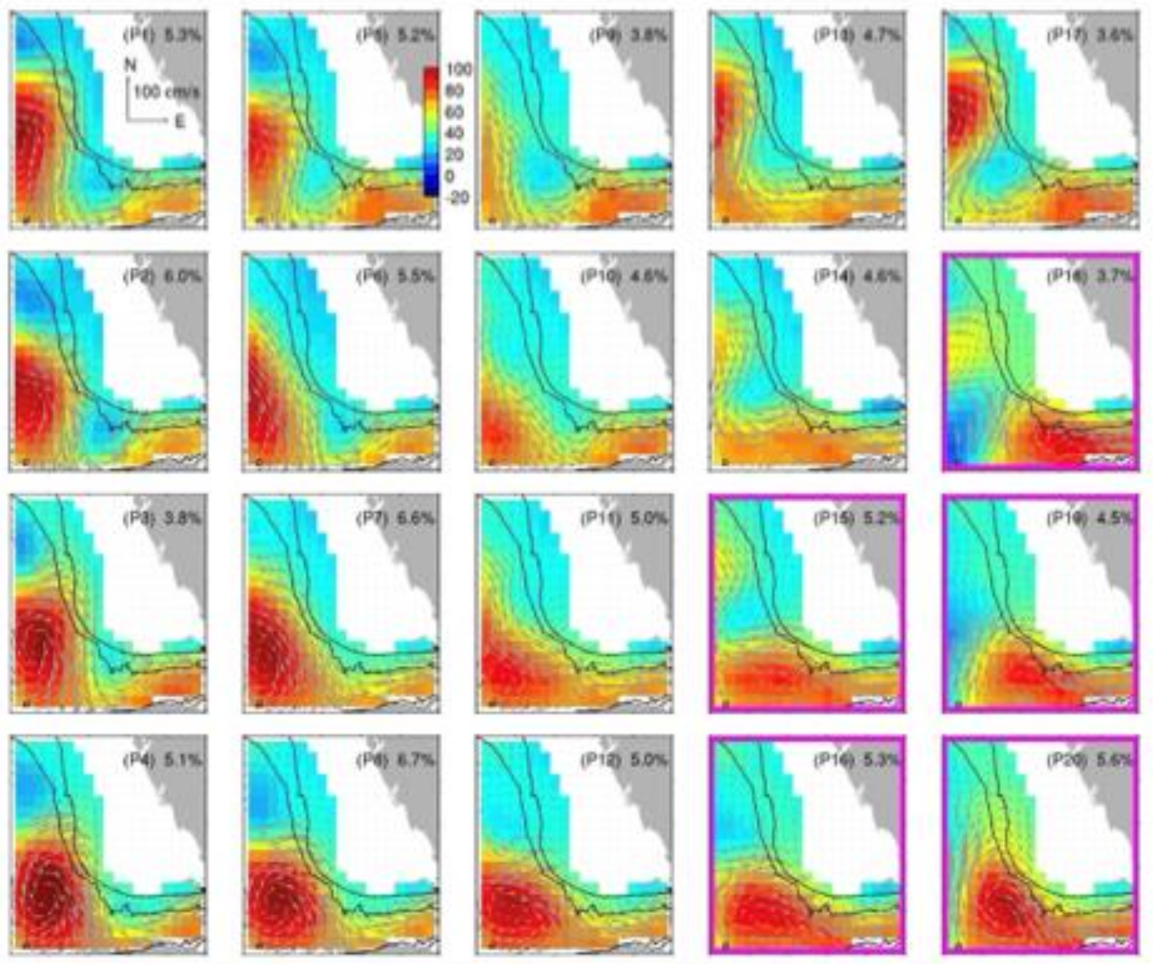
IMAGE BY NOAA-NCCOS

Upwelling predicts blooms at seasonal to event time scales



http://ocgweb.marine.usf.edu/

1997-2015 Most common patterns in the loop current (based on Sea Surface Height)



Liu et al. 2016

Physical model advances:
PCMHAB, State, IOOS funding

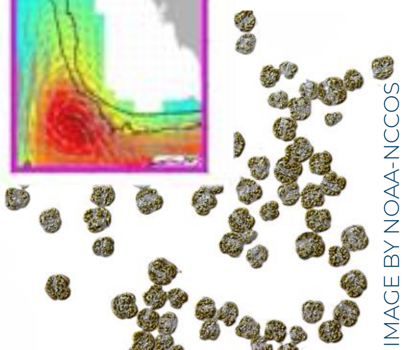


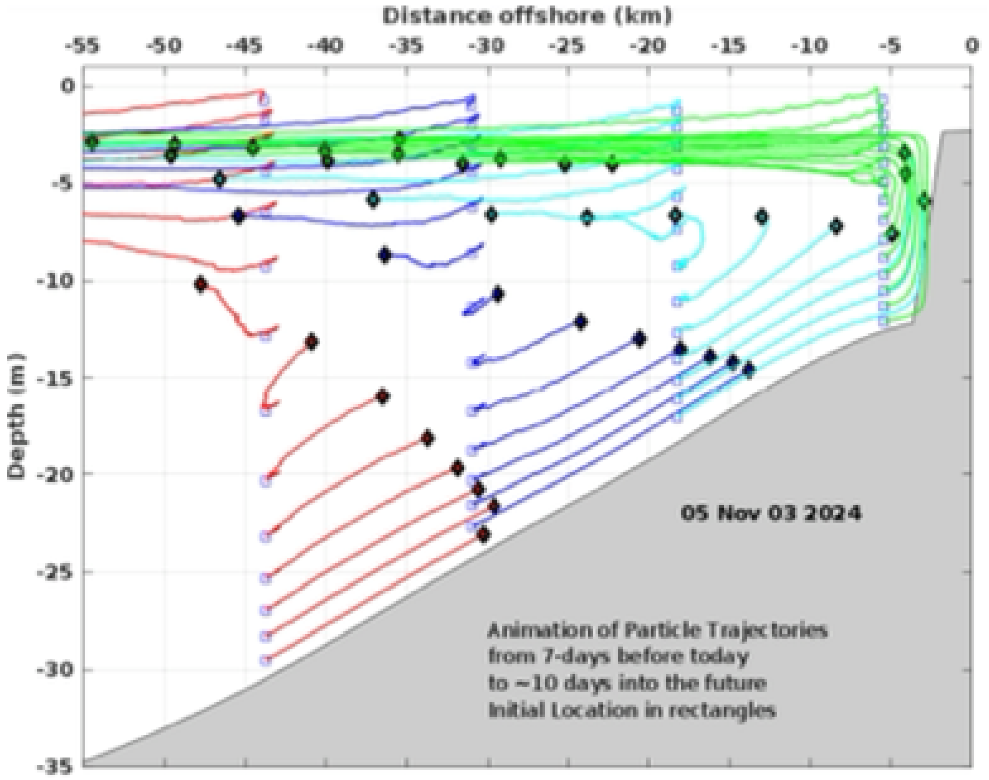
IMAGE BY NOAA-NCCOS

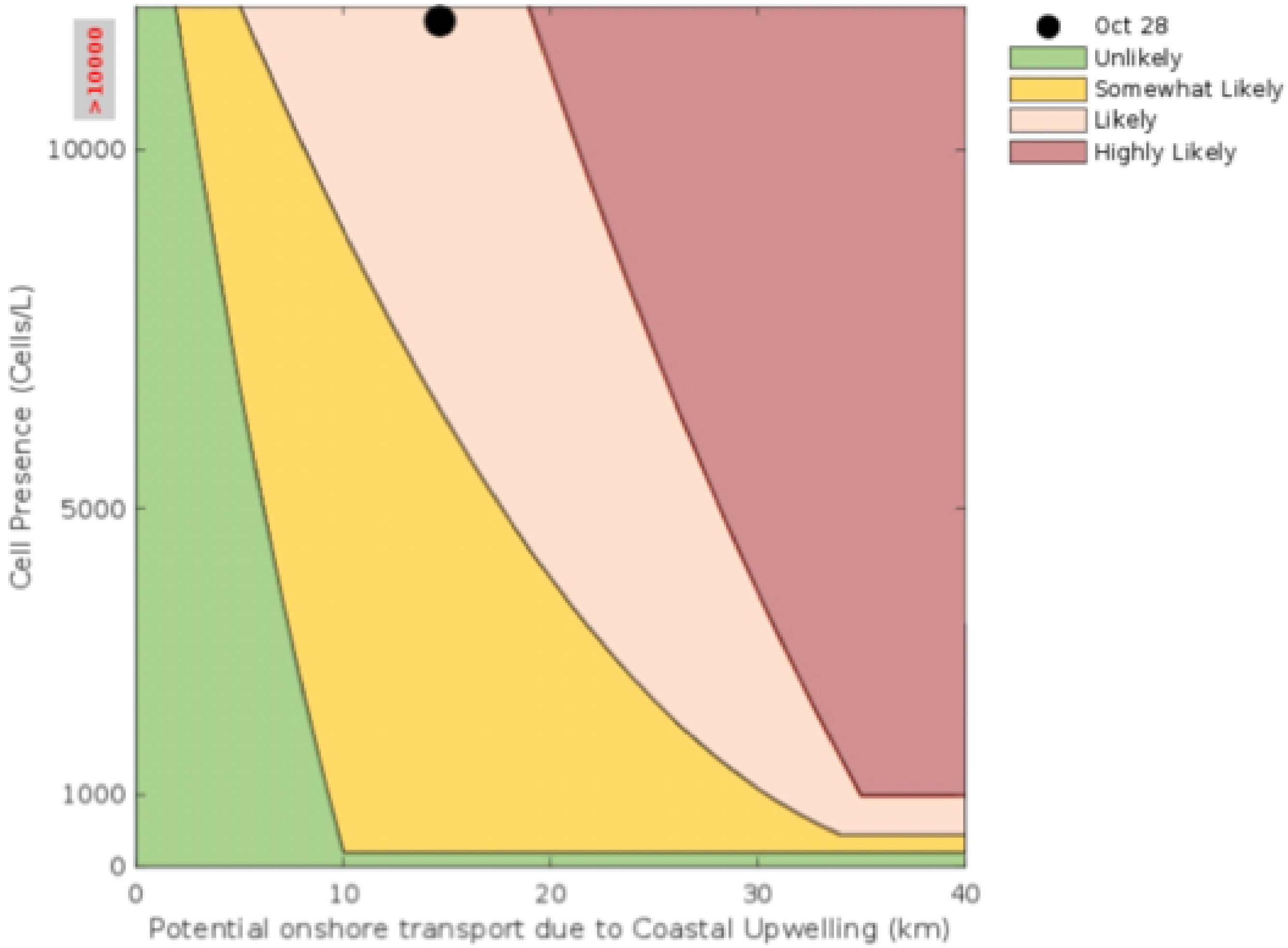
Forecasting initiation/manifestation

need to update

(not shown – USF seasonal forecast based on Loop Current position and strength – Liu et al. 2016)

NOAA NCCOS Bloom Intensification Model





https://coastalscience.noaa.gov/science-areas/habs/hab-forecasts/gulf-of-mexico/florida-intensification-forecast/

IMAGE BY NOAA-NCCOS