APPENDIX 12.H. POTENTIAL EFFECTS OF RIVERINE FLOW REDUCTION ON THE FISHERIES OCEANOGRAPHY OF THE SOUTH ATLANTIC BIGHT

The St. Johns River interacts with the continental shelf in the south Atlantic bight (SAB). In this dynamic, sub-tropical system, processes act at a range of spatial and temporal scales, with the predominant spatial scales being the inner, mid and outer regions of the SAB and the predominant temporal scales being shorter than the summer–winter seasonal cycle that dominates in the more temperate mid-Atlantic bight (Atkinson and Menzel 1985; Menzel et al. 1993).

In terms of supporting fish and fisheries production, two functional elements play key roles — hydrodynamics and trophic webs. The patterns and variation exhibited by these elements determine if the various life history stages of fish can “find” the right combination of environmental conditions, food and refuge to support their survival and growth. Given their vulnerability to starvation and predation and their limited mobility, fish larvae and early juveniles represent critical life history stages and the focus here.

The SAB runs from West Palm Beach to Cape Hatteras (Menzel et al. 1993). The region is characterized by a fairly broad continental shelf that narrows at the northern and southern ends of the bight. The shelf is broadest, 120 km (75 mi), off Georgia and South Carolina, and it extends approximately 90 km (56mi) off Jacksonville. Generally, the shelf in the SAB slopes gently to about 75 m (246 ft), with no large topographic features found off Jacksonville and the St. Johns River. In addition to the St. Johns River, nine other rivers provide the bulk of the freshwater input into the SAB. At the edge of the continental shelf, the Gulf Stream marks the offshore boundary of the SAB.

Differences in the dominant drivers of circulation and trophic webs (i.e., nutrient inputs) divide the SAB into three regions running from inshore to offshore (Atkinson et al. 1983; Blanton et al. 2003). The inner shelf extends to the 20 m (66 ft) isobath, with circulation driven by wind, tides, and density gradients established when freshwater is discharged from rivers. Along much of the coast of the SAB, tidal currents are dissipated when they flow into and out of estuaries and tidal inlets (Pietrafesa et al. 1985; Blanton et al. 2004). In this region, nutrients enter primarily as organic material being exported from estuaries and tidal marshes. The mid shelf experiences less influence from riverine inputs, with circulation driven by wind and tides, along with meanders, eddies and other intrusions of the Gulf Stream that occur on 2–14 d cycles (Atkinson et al. 1984; Pietrafesa et al. 1985). Nutrients in the mid shelf can come from the inner shelf if cross-shelf currents are established, but Gulf Stream intrusions with upwelled water introduce considerable amounts of “new” nitrogen (Atkinson 1985). Off Georgia and South Carolina, such intrusions reach the mid shelf less often because the Gulf Stream is further offshore. The outer shelf is similar to the mid shelf, with more frequent and extensive influences from the Gulf Stream. Temperatures and salinities typically exhibit a gradient from inshore to offshore. Inshore temperatures can fall to 10°C in winter, but the average range is 12 to 28°C. Upwelling can raise water colder than 28°C onto the outer shelf, and circulation driven by winds or density gradients may carry it shoreward. Inner shelf waters are approximately isothermal in the fall and winter, but they stratify in the summer. Salinity also varies primarily along an inshore to offshore gradient, with a halocline evident on the inner shelf in spring and summer and relatively little variation alongshore even in regions between river mouths. During periods of high discharge, inshore salinities may fall below 30‰.

Winds in the SAB ultimately arise from interactions among three principal centers of action — the Azores high, the Ohio Valley high and the Icelandic low (Blanton et al. 1985; Menzel et al. 1993). The interactions generate patterns on 2–14 d cycles that become conflated with the influences of the Gulf Stream. At the scale of months, five regimes have been identified (Weber and Blanton 1980; Blanton et al. 1985). The winter pattern (November–February) is characterized by cold fronts on 2–10 d cycles and southerly winds along Florida's north coast. Winds off northern Florida in the spring transition period (March–May) shift from east–northeast to westerly, with winds over much of the SAB being variable. In the summer (June and July) off north Florida, winds become northerly until they become disorganized in fall (August). Strong south–southwest winds blow during Mariner's fall (September and October).

Wind stress combines with set up and set down of sea level and buoyant freshwater discharged by rivers to drive circulation over the inner shelf (Bumpus 1973). Inside the 15 m isobaths, low density water tends to flow southward at < 5 cm s^{-1} (2.0 in s^{-1}) creating a relatively stable, isolated and retentive coastal frontal zone (CFZ; Kourafalou et al. 1996; Edwards et al. 2006, 2007, 2008; Li et al. 2006; Martins and Pelegri 2006). Northerly wind stress can reverse the flow, spread the CFZ seaward and create vertical salinity gradients that are stronger than horizontal gradients (Chen 2000; Gutierrez et al. 2006; Li et al. 2006). Southerly winds force a narrowing of the CFZ along the coast and mixing that breaks down vertical gradients (Gutierrez et al. 2006). Switches between the two circulation patterns can take place in 6–12 h (Pomerory et al. 1983). In addition, northerly and easterly winds favor upwelling (relatively common in spring and summer) and southerly and southwesterly winds favor downwelling (Kourafalou et al. 1996). Stratification promotes a flow pattern typical of estuaries, with offshore flow at the surface and inshore flow near the bottom. Furthermore, stratification can generate fronts that concentrate fish larvae and their prey (Grimes and Kingsford 1996) and interact with tides to generate internal waves capable of transporting material shoreward across the shelf (Shanks 1988; Ryan and Yoder 1996).

The mid and outer shelf waters exhibit less consistent circulation with wind, tides and the Gulf Stream interacting to provide forcing (Lee et al. 1985; Verity et al. 1993). Winds generate along-shelf circulation, with the direction varying according to the five, seasonal wind patterns. Wind can also affect set up and set down of water along the coast to generate cross-shelf circulation (Chen 2000). Such effects are less significant off north Florida because the changes in water level are less amplified across the narrower continental shelf. Semidiurnal tides generate cross-shelf circulation, and the Gulf Stream generates significant along-shelf circulation. Off northern Florida, the predominant along-shelf circulation is to the north, although meanders, eddies and other intrusions of the Gulf Stream may establish other patterns on 2–14 d cycles.

Productivity in the SAB averages approximately 35.0×10^{12} g carbon yr^{-1} (7.7×10^{10} lbs y^{-1}) (Menzel et al. 1993). On average, productivity decreases offshore (inner shelf = 17.9×10^{12} g carbon yr^{-1} (3.7×10^{10} lbs yr^{-1}) , mid shelf = 11.2×10^{12} g carbon yr^{-1} (2.5×10^{10} lbs yr^{-1}), outer shelf = 5.9×10^{12} g carbon yr^{-1} (1.3×10^{10} lbs yr^{-1}). Given the more stable, subtropical temperatures, productivity in the SAB does not exhibit the strong seasonal signal seen in the mid-Atlantic bight.

Over the inner shelf, nutrients are supplied mainly as organic compounds formed following rapid uptake and recycling of inorganic nutrients in estuaries and tidal marshes (Yoder 1985; Pomeroy et al. 1993). Bacterial remineralization supplies nutrients to phytoplankton. Biomass as measured by chlorophyll concentrations tend to decrease offshore, with a relatively sharp drop at the edge of the CFZ, which moves in response to rain-driven discharge from rivers. Such discharge also generates alongshore gradients, with higher chlorophyll near the mouths of rivers and estuaries. The distribution of production also varies with mixing and stratification. Low flow during summer promotes stratification and higher production, whereas high flow in spring mixes and spreads the CFZ over a larger area but production per unit area falls. A potential incongruity in the existing literature is a focus on spring inputs of freshwater and nutrients, which is not accurate for the St. Johns River due to significant discharge in the late summer. For example, high concentrations of chlorophyll *a* off north Florida in August were attributed to upwelling (Bontempi and Yoder 2004), but riverine discharge may have contributed.

Secondary productivity in the inner shelf region involves two main genera of copepods, *Oithona* and *Paracalanus*, with occasional injections of *Oncaea* from offshore and *Acartia* from inshore (Pomeroy et al. 1993). Both *Oithona* and *Paracalanus* tolerate low concentrations of food, and *Oithona* can form relatively dense aggregations probably because it suffers less predation pressure. Overall abundances shift due to the influences of stratification, upwelling, and the expansion and contraction of the CFZ caused by salinity changes, but it appears that secondary production is sufficient to support recorded densities of larval fish and other secondary consumers.

Production in the mid and outer shelf waters is more heavily influenced by upwelling induced by Gulf Stream intrusions (Yoder 1985; Verity et al. 1993). Such intrusions can inject up to 25% of the nitrogen required to support primary production, and phytoplankton biomass can increase from < 5 mg chlorophyll *a* m^{-2} to > 50 mg chlorophyll *a* m^{-2} (Atkinson et al. 1984; Ryan and Yoder 1996). Thus, the outer regions of the SAB are not simply seaward extensions of “diluted” conditions from the inner shelf or landward extensions of oligotrophic, oceanic conditions characterized by extensive recycling of nutrients. Overall production in these regions varies according to the number, spatial extent and level of production in Gulf Stream intrusions, with this variability affecting trophic webs. Key primary consumers include copepods in the genus *Temora*, which are found in upwelled water around the world (Paffenhöfer 1985; Verity et al. 1993).

Late stage larvae and juveniles of two major groups of fish use the estuaries and coastal waters of the SAB — inshore spawners that return to the mouths of estuaries to spawn (e.g., potentially croaker, Lassuy 1983; red drum, Reagan 1985; spotted sea trout, Johnson and Seaman 1986; bay anchovy, Morton 1989) and offshore spawners that release eggs at various locations in the mid and outer shelf (e.g., menhaden, Rogers and Van Den Avyle 1983; probably white and striped mullet, Collins 1985a, 1985b, Collins and Stender 1989; spot, Hales and Van Den Avyle 1989; bluefish, Oliver 1989; potentially croaker, Schaffler et al. 2009). Offshore spawners have evolved to spawn at places and times that allow larvae to exploit mean conditions (e.g., circulation and productivity) that will support their growth, survival and transport to inshore regions, with behaviors such as vertical migration keeping larvae in suitable water masses (Boehlert and Mundy 1988; Cowen et al 1993; Forward et al. 1996, 1999a; Hare and Cowen 1996; Quinlan et al. 1999; Strydom 2002; Pittman and McAlpine 2003). At potentially varying distances from estuaries, probably determined by their size, sensory capabilities and swimming abilities, larvae of various species use cues (e.g., gradients or changes in salinity, temperature or concentrations of chemicals, including amino acids) to locate the mouths of estuaries (Dittman and Quinn 1996; Forward et al. 1996, 1999a; Kingsford et al. 2002). Once within range, fish may exhibit selective tidal stream transport, in which cues (e.g., changes in salinity, depth, turbulence and light) stimulate changes in activity or vertical distribution. In general, larvae remain in inflowing water and avoid outflowing water, with the relevant currents established by tides and density gradients (Boehlert and Mundy 1988; Hales and Van Den Avyle 1989; Forward et al. 1996, 1999a, b; Werner et al. 1997; Schaffler et al. 2009; Blanton et al. 1999; Churchill et al. 1999; Trancart et al. 2004; Hare and Govoni 2005; Braverman et al. 2009). Inshore spawners also rely on cues to find estuaries and selective tidal stream transport to move upstream or maintain their position (Reagan 1985; Rowe and Epifanio 1994; but see Schultz et al. 2000). Inshore spawners may exhibit adaptations to mean conditions, with some evidence that larvae of certain species get transported south and eventually offshore in the persistent, low salinity surface current of the CFZ; enter the northward flowing countercurrent in the mid shelf region; and get returned inshore as seasonal wind shifts or fronts establish onshore currents (Hare et al. 1999; Epifanio and Garvine 2001).

Larvae of both groups will not survive if there is a mismatch between their trophic or environmental needs and their location (Hjort 1914; Cushing 1972; Legett and DeBlois 1994; Crowder and Hoss 1999; Govoni and Spach 1999; Quinlan and Crowder 1999; Govoni 2005). For example, Gulf Stream intrusions, which are not predictable at the evolutionary time scale, can advect larvae of offshore spawners away from the coast (Govoni and Spach 1999; Hare et al. 1999; Quattrini et al. 2005), and storms resulting in increased discharge can sweep larvae of inshore spawners out of estuaries (Schultz et al. 2000). In the match–mismatch and member–vagrant models (Cushing 1972; Sinclair 1988; Leggett and DeBlois 1994), losses of larvae result from a spatial mismatch (incorrect environmental conditions) or an energetic mismatch (insufficient food or predation). In both cases, access to a sufficiently large zone of suitable environmental conditions, refuge and food represents a key driver of successful growth, recruitment and reproduction, as per a model proposing overlap between passive and active habitats as the key to growth, survival and reproduction (Browder and Moore 1981).

Changes in flow from rivers, including the St. Johns River, can affect conditions experienced by larval fish in the SAB. Altered flow can affect the mean oceanographic conditions of the SAB by changing the extent, vertical structure and horizontal structure of the CFZ, with the relative dominance of wind and the Gulf Stream lessening the importance of such effects for early larval stages of offshore spawners. Changes in flow that alter levels of primary production would affect larvae by increasing bottom-up and top-down energetic losses due to starvation or slower growth that increases predation pressure. Larvae of inshore spawners and later larval stages of offshore spawners will be affected by changes in the extent and strength of cues from estuaries and potentially a change in the effectiveness of selective tidal stream transport (Strydom and Whitfield 2000). Management of activities that will reduce flow would be improved by access to production functions relating changes in fish growth, survival and reproduction to changes in flow, salinity, access to suitable habitat and other related factors. Such modeling has been attempted for crabs and shrimp (see invertebrate chapter), but the models would need to be tailored to the St. Johns River and targeted species of fish. Examination of such models will highlight both key gaps in knowledge that should be filled as part of planning activities that will alter flow and key parameters to monitor as part of ongoing adaptive management of such activities.

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