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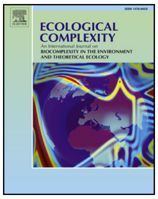

Identifying process scales in the Indian river lagoon, Florida using wavelet transform analysis of dissolved oxygen

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ABSTRACT

The Indian River Lagoon (IRL) estuary in Florida is experiencing emergent "super" algal blooms in the northern reaches, a complex process occurring within a highly interconnected and complex system. This study describes the spatio-temporal structure of dissolved oxygen observations within the estuary to assist in identification of causes for these emergent conditions. Exploratory data analysis describes the data. Wavelet transform computations describe patterns of stable processes and discontinuities in the expected seasonality of the observations. Dissimilarity analysis describes spatial clusters based on these temporal characteristics. These clusters allow for comparison of the results at multiple spatial scales related to external socio-economic processes. Combined, the results provide multiple, highly localized scale domains and thresholds. This space-time localization allows for synthesis with unexamined variables of similar or different data types to assist in identification of functional relationships or causal mechanisms. The expected spatial relatedness between sampled locations is not present, indicating difficulties for management of the estuary. Our conclusions suggest a shift in focus from restoration of historic waterscapes to restoration of the expected seasonality of dissolved oxygen.

1. Introduction

The greater Indian River Lagoon (IRL) System is a biologically diverse estuarine system that stretches 155 miles along Florida's central east coast. The estuary is of aesthetic, social, and economic value to both the region and the state of Florida, providing major economic benefits through commercial and recreational fisheries, serving as a popular tourist attraction (Humphreys et al., 1993) and the production of fresh citrus.

Estuaries are some of the most productive environments on earth, rich in organic matter and nutrients. Estuaries provide safe haven for species versus the open sea for breeding, spawning, and as nursery grounds, buffer coasts from storms or flood, filter water for sediments or pollutants, and record history as it happens through sediment erosion and deposition. In 2010, an unprecedented (Daytona Beach News-Journal, 2013) "super" algal bloom led to the loss of 50,000 acres of sea grass in the Northern IRL. In August 2014, St. Johns River Water Management District (SJR WMD) scientists reported that three algal blooms were present in the Northern IRL, two near State Road 50 in Titusville and one located south of the NASA Causeway. In the central lagoon near Cocoa, Florida, an algal bloom first observed in early July 2014 was still present during routine water sampling on August 6, 2014. These events are occurring despite decades of research, management, and restoration activity. There is a clear need to define and describe the dynamic estuarine processes in the IRL, both for understanding present or future impacts from changing climate and human socioeconomic activity (Burkett et al., 2001).

Research needs identified by the Millennium Ecosystem Assessment (MA) emphasize the need to consider the social with the physical; account for dynamism and change; account for complexity; address issues of scale; and focus on ecosystem structure and process. The estuary is a complex system directly connected to other complex systems, including associated processes in land, ocean and atmosphere. Cause is understood to also be complex and contingent (Byrne, 2005). Methods are needed that enable us to delve into complex causal processes (Byrne, 2005) where the recommendation is to harness complexity (Ostrom, 2009), not eliminate it. Yet there is no clear disciplinary framework in which to engage with complexity in a coherent way (Cilliers et al., 2013).

The inception of algal blooms is an indicator of water quality issues. The challenge in water quality monitoring is to not only elucidate the dominant climatic, hydrological and biogeochemical processes occurring at different temporal scales (Milne et al., 2009) but also in terms of space. Water quality time series are typically non-stationary and

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represent the aggregation of many complex processes driven by external factors and occurring at different scales (Milne et al., 2009) that are difficult to separate and identify. Yet most research related to water quality analysis focuses on single direct drivers, such as land use change or invasive species.

Results of analyses are also dependent on the boundaries chosen in space and time, the scale or 'frame' imposed on the study area and the observation intervals (Cao and Lam, 1997). Any change in these will provide different results (Cilliers, 2005; O'Neill and King, 1998; Wiens, 1989). The problem of imposing boundaries in space and time, the Modifiable Areal Unit Problem (MAUP), is well known (Gehlke and Biehl, 1934).

While the use of multi-scale analytical techniques to address issues of the MAUP are well documented, the problem of bounding the data itself is generally unrecognized. Relational variability in space and time compounds the problem of data selection for analysis. The traditional approach to understanding impacts chooses a subset of all possible variables for analysis, where choices are made based on previous studies, known physical relationships in other systems, or convenience/availability of data. This is done despite the understanding that algal blooms result from interactions between many possible variables, some of which may not be known or are related only at certain scales. This relatedness may also vary over space and time.

The traditional, empirical approach to understanding ecosystem impacts is then to test relationships between two or more measurable properties. While this approach can quantify relationships between the chosen variables, any understanding in relation to variables not chosen remains unknown. The strength of the correlation found is relative to the variables examined, the chosen dependent variable, and the selected spatial or temporal boundaries. A different variable, a different boundary will provide different results. Such results are repeatable but not necessarily comparable, synthesizable, or translatable to similar environments.

Relationships between components and observations made are also relative to the observer or what is observed. Examination of any single component of an ecosystem in relation to 'everything else' allows relationships between elements to arise through analysis. Doing so addresses issues where "the experimental practices themselves determine the character of what they make visible" (Bird, 1987, pp. 256). Analysis from a single perspective at multiple scales avoids reducing any part of the system through generalization or aggregation, avoids selection of a subset of elements and any bias inherent in such choice, and allows for consideration of the target variable as both potential driver and potential response.

Process scale matters for complex systems analysis (Forbes, 2017). Consideration of process allows for unification of the two "sides" of complexity (Capra and Luisi, 2014): Prigogine's focus on the transfer of material, energy or 'information' between system elements (Prigogine and Stengers, 1984) with the relational approach to complexity (Maturana and Varela, 1980). In landscape ecology, these two "sides" of complexity refer to landscape function and structure. Structure refers to the spatial and temporal relationships between elements within a landscape, and function refers to the spatial and temporal flows of energy, material, or 'information' between elements (Walsh et al., 2004). Structure described at scale in terms of space and time essentially allows for connection of the results to other ecological processes (Forbes, 2014).

Scale is defined here as the physical dimension of a thing with measurements expressed in standardized units (O' Neill and King, 1998). To understand causal factors related to an emergent condition requires understanding which elements are related (structure), how they are related (function), and at what scale. It is desired to identify and describe scales of process (Sayre, 2005) and therefore, illustrate the production of scale over time (Marston, 2000; Sayre, 2009; Swyngedouw, 1997).

Scale identification techniques such as wavelet transforms describe scale domains (Wiens, 1989), those scales where processes are consistent, homogeneous, or persist (Meentemeyer, 1989; Stallins,2006). Scale domains are similar to patches in landscape ecology, except the emphasis is on homogeneity of process over homogeneity of characteristics or constituents. The identification of a scale domain naturally leads to identification of edges, discontinuities, thresholds, or breakpoints between scale domains (Gunderson et al., 2007). Thresholds may indicate a shift to a new domain or reflect a temporary change (Wu and Li, 2006).

The aim of this paper is then to demonstrate structural analysis of a single variable: dissolved oxygen (DO). Dissolved oxygen (DO) is one of the most important factors in an aquatic environment, and is accepted as a measure of the general health of an estuary. Dissolved oxygen measurements constitute a 'water quality time series' that are typically non-stationary and result from many complex processes driven by factors that may occur at different temporal scales (Milne et al., 2009). Levels of DO can be impacted from both social and physical processes. This study therefore seeks to describe the space–time structure of DO observations across the Northern IRL. Analysis at multiple scales addresses the ecosystem research needs identified by the MA. Understanding the structural health of the estuary may then inform mitigation efforts to ensure a relatively stable, healthy, resilient estuarine system within the context of changing climate and changing socioeconomic conditions.

Our objectives in this study were to: (1) describe a 20-year set of monthly DO observations using exploratory data analysis and descriptive statistical techniques; (2) describe the spatio-temporal structure of the observations using wavelet transforms to examine process scales; and (3) cluster individual wavelet transforms using dissimilarity analysis. The expectation prior to EDA is that the data is statistically 'out of control', which is usually the case for ecological data. We expected that the dominant process scale for DO in a Florida estuary would be the 12-month scale based on seasonal temperature changes, where colder temperatures lead to increased levels of DO in winter and warmer temperatures lead to decreased levels of DO in summer. We also expected that clustering the wavelet results will reveal similarities between nearest neighbor stations, in accordance with spatial autocorrelation of ecological data.

2. Study area

The greater IRL system lies on the east coast of Florida between latitudes 26°57′N and 29°03′N and between longitudes 80°05′W and 80°55′W (Woodward-Clyde Consultants, 1994). The greater IRL system extends 155 miles through six coastal counties, from Ponce de Leon Inlet in Volusia County in the north, to Jupiter Inlet in Palm Beach County in the south (Fig. 1). The System includes three interconnected estuaries: Mosquito Lagoon, Indian River Lagoon and the Banana River Lagoon, as well as portions south of the St. Lucie Inlet known as Hobe Sound and Jupiter Inlet.

The lagoons are surrounded by upland areas, both mainland and barrier islands. Watershed boundaries divide and define the drainage areas. Major physiographic features include coastal hills and lagoons, barrier islands, natural and man-made inlets, the Intracoastal Waterway, mosquito impoundments and drainage canals (Woodward-Clyde Consultants, 1994). The lagoons themselves are long, narrow and relatively shallow (Fig. 1), with an "average depth of four feet and a width that varies from a half mile to five and a half miles" (Steward et al., 1994, B-1).

Rainfall averages about 50 inches annually over the region (Steward et al., 1994). Major inputs to the Lagoon are direct rainfall on the Lagoon surface, direct surface water runoff, overland runoff, stream and canal flow, groundwater seepage, and discharges from wastewater treatment plants (Steward et al., 1994; Woodward-Clyde Consultants, 1994). Hydrological outputs from the System are evaporation, and discharge through the inlets to the ocean (Woodward-Clyde Consultants, 1994).