Modeling the Effects of Storm Surges

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ABSTRACT
We use a multi-faceted approach to attempt to estimate possible consequences of sea level rise in general and storm surges in particular to low-elevation coastal areas. Our current modeling effort is focused on the Gulf Coast of southern Florida, but this will be extended to areas of Southeast Asia. The main components of the project are as follows. (1) We are compiling an historical record of major storms (hurricanes) that have affected southern Florida, including their windfields and impacts. (2) We are improving a landscape hydrology model of freshwater overland and estuarine flows in southern Florida to take into account effects of sea level rise on coastal hydrology and salinity. (3) We are improving on models of major vegetation types that may be affected by sea level rise and storm surges. (4) We will model the inland movement of water and salinity from storm surges. The current status of these tasks will be described here; in particular, modeling storm surge effects on vegetation. A possible consequence of sea level rise will be a 'regime shift' in coastal vegetation due to inland intrusion of high-salinity water, both from average rise in sea level itself and storm surges. We have developed a vegetation model (Teh et al. 2008), that simulates the transition zone between mangrove and tropical hardwood vegetation. The model supports the hypothesis that a major storm surge, carrying salinity inland, could cause a 'regime shift' of vegetation cover from hardwood hammock to mangrove over large areas.

Keywords: vegetation regime shift, sea level rise, hydrologic modeling, sedimentation

1. INTRODUCTION

Sea Level Rise (SLR) is one of the most significant predicted consequences of global climate change and has the potential to affect coastal ecosystems worldwide. In Florida, SL has increased more than 20cm in less than a century. Rapid SLR in this low elevation area is thought to be responsible for destabilizing coastal wetlands leading to a loss in area (Wanless et al., 1994). Wanless and Vlaswinkel (2005) reported on the transition of vegetation on Cape Sable in extreme southwestern Florida. The freshwater marsh on Cape Sable has changed into a shallow marine lagoon over a period of a few decades, while the marl ridge that was once farmed is now flooded by tides 80 times a year. Ross et al. (2008) noted the loss of pine forest in the Florida Keys. These changes may be the result not only of sea level rise itself, but of storm surges that created 'regime shifts' ("a relatively sharp change from one regime to a contrasting one, where a regime is a dynamic 'state' of a system," Scheffer 2009). Further shifts may occur in the ecotones between freshwater and brackish or saline vegetation types in coastal areas as SLR increases. Wetland ecotones will shift with SLR as one vegetation community is converted into a different vegetation association (or to open water), both from average rise in sea level itself and exposure to storm surges. Ecotones have been shown to shift quickly during periods of rapid, abrupt climate change, with measurable movement occurring on the order of mere decades (Peteet, 2000; Olf et al., 1988; Donnelly et al., 2001). Consequently habitat suitability will change for faunal species affecting abundance and distribution and community structure and ecology.

This is more than simply a regional problem restricted to southern Florida. Extensive, low-lying coastal wetlands are found throughout the USA and indeed the world. Examples include the Chesapeake Bay and Louisiana in the US, and coastal areas in Belize, northeast Brazil, Surinam, Venezuela, the Irrawaddy, Ganges and Niger River deltas (Myanmar, Bangladesh and Nigeria), and Gulf of Carpentaria (Australia) to name a few. A major region of interest for extension of the modeling will be Southeast Asia. Here we describe work being conducted by the U. S. Geological Survey in southern Florida to forecast effects of SLR. Figure 1 shows the current geographic area being studied and some of the components of the project. Our description of the project below is necessarily abbreviated due to space limitation, so we attempt only to give a quick overview.

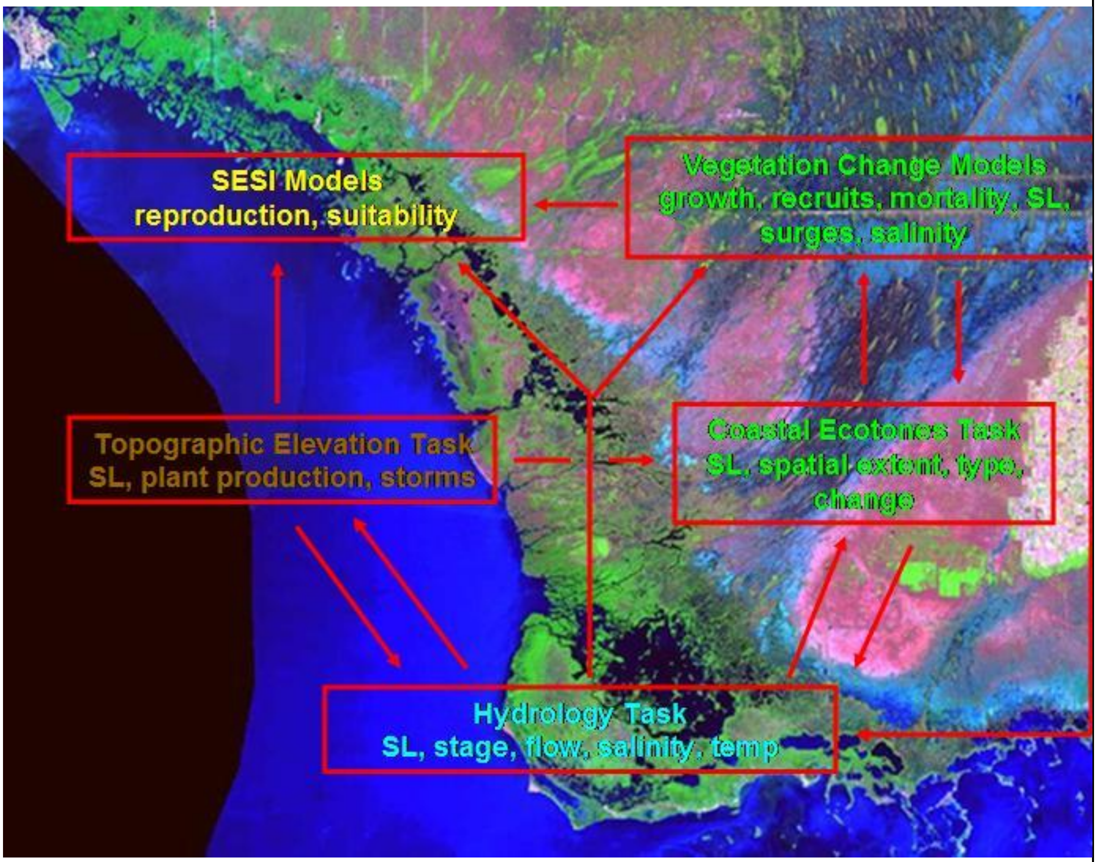

Figure 1. Project diagram showing relationships among major model components. Shown is a 134 x 97 km area. Components of the current work are listed.

2. UNDERSTANDING AND FORECASTING EFFECTS OF SEA LEVEL RISE

To develop a realistic suite of ecological models to predict effects of SLR and storm surges in the coastal Greater Everglades, we will address the following technical needs: (1) Enhance an existing hydrologic model to reliably hind-cast multi-decadal observed SLR with a time-series of documented changes in coastal marsh, mangroves, and open tidal flats. (2) Add a landscape topographic change component to the hydrologic model, which incorporates feedbacks between hydrology forcing parameters and vegetation dynamics to describe land elevation changes concomitant with SLR. (3) Develop mechanistic models of coastal vegetation change, which describe how hydrologic change associated with SLR induces vegetation regime change. Incorporate episodic disturbance events, particularly extreme storms, and their impact on the 3 modeling efforts listed above. (4) Integrate vegetation and hydrologic models to provide output to assess habitat suitability for selected species using what we call 'spatially explicit species index (SESI)' models (Curnutt et al. 2000). (5) Develop a predictive capability for the integrated biologic-hydrologic models, which incorporates comparative assessments of effects to vegetation and species under various restoration or management scenarios and SLR scenarios.

2.1 Hydrology Models to Quantify the Effects of Rising Sea Level and Storm Surge Events.

An existing hydrology model, Flow and Transport in a Linked Overland/Aquifer Density-Dependent System (FTLOADDS) (Swain et al., 2003), is being extended to address SLR. It simulates two-dimensional hydrodynamic surface water and three-dimensional ground water with complete mathematical description of all the significant forcing factors and relevant transport quantities. FTLOADDS covers the entire southern Florida coast and has been used to develop understanding of coastal flow and salinity regime, inland wetland dynamics, and the effects of ground water. In addition to simulating SLR, the model is being modified to take into account effects of increased air and sea temperature on coastal water and evapotranspiration, general changes in precipitation patterns, and the effects of increased storm event frequency and intensity. One consequence of sea level rise will be regime changes in coastal vegetation due to inland intrusion of high-salinity water, both from the average rise in sea level itself and from storm surges. We will use computer simulation models linking landscape hydrology with vegetation dynamics in order to study scenarios related to sea-level rise and storm surges. Algorithms for simulating sediment transport will be integrated into the flow model to determine changes in elevation for long term estimates (Ganju et al., 2006). Net gain and loss of sediment can be determined at locations along the coast for a typical year and also for specific events such as hurricanes. Event simulation will rely on existing data collected during recent hurricanes to synthesize wind and storm-surge levels for historic storms. The net effect of the yearly cycle and specific events will be tabulated to determine longer-term deposition and accretion in the coastal area.

To parameterize and test the model, it is essential to understand how coastlines have changed in the past due to the effects of sea level rise. Using historical charts aerial photographs, the rate of ecotone movement is being traced. This will allow estimation of biologic feedback mechanisms that may be operating in allowing the wetland to maintain itself in the face of SLR. Accurate charts of coastal waters were being produced by the U.S. Coast Survey (now NOAA) by the mid-1800s. Often coastal wetlands, and most importantly, differences in vegetation types, are depicted in great detail (Smith et al., 2002). Charts from the 1920s for ENP have been geo-referenced and published online as part of an earlier project by the PIs (Smith et al., 2002). By measuring the rates of ecotonal movement since ≈1920 we will develop parameters for use in predictive landscape models.

2.2 Landscape Elevation Change Concomitant with SLR.

It is possible that coastal wetlands will not be able to keep up with the rapid future rate of SLR (Morris et al., 2002). A habitat can "keep up" with SLR rise in two ways: 1) move upslope (Spackman et al., 1966: Ramcharan, 2004); 2) and, trap and bind sediments and build peat and thus increase elevation (Cohen and Spackman, 1977: Cahoon and Lynch, 1997). The former is represented by an ecotone moving across the landscape over time. The latter can be measured as sediment accumulation over time. Sediment accumulation and vertical accretion represent an important biological feedback in the coastal Everglades. Some mangrove forests in the Everglades have accumulated >6 m of peat in the past 3,000 yrs (Cohen and Spackman, 1977). A single storm event can cause both erosion as well as large sediment deposition, depending on the storm track (Smith et al., 2007). We hypothesize that sediment accumulation and wetland elevation change across the coastal Everglades will vary by wetland type. Long-term estimates (past millennium) of sediment accretion for the coastal Everglades will be gathered from the literature (e.g. Spackman et al., 1996). Impacts of recent episodic events will be taken from our research (Smith et al., 2007) augmented by literature reports (e.g., Kang and Trefry, 2003). High resolution (quarterly – yearly) measurements of wetland surface elevation and sediment accretion are available from a network of surface elevation tables (SETs) and feldspar marker horizons that have been operated since 1998 (Smith, 2003: Whelan et al., 2005). We will use these data to develop a simulation of sediment accumulation (or loss) dynamics across our study area based on published methodologies (e.g. Chmura et al., 1992; Reyes et al., 2000). The model will be linked to both our hydrodynamic model and models of vegetation regime shifts (see below).

2.3 Mechanistic models of vegetation regime change

Mechanisms have been identified underlying stability of ecotones between coastal vegetation communities in southern Florida; in particular, mangrove, hardwood hammock, and freshwater marsh ecosystems, which occupy overlapping geographical areas. For example, regarding the hammock and mangrove vegetation; both mangroves and hammock species obtain their water from the unsaturated soil layer (vadose zone). The vadose zone is underlain by brackish ground water, so that evapotranspiration, by depleting water in the vadose zone during the dry season, can lead to infiltration by more saline ground water. Although hardwood hammock trees tend to decrease their evapotranspiration when vadose zone salinities begin to increase, thus limiting the salinization of the vadose zone, mangroves can continue to transpire at relatively high salinities. Thus, each vegetation type tends to promote local salinity conditions that favor itself in competition, which helps explain the stability of sharp boundaries between the types (Sternberg et al., 2007). However, if the rate of change of SRL is fast enough, or the salinity pulse from a storm surge large enough, stabilizing feedback loops can be overcome and positive feedback can then drive rapid large scale vegetation change. A sharp upward salinity perturbation of an area initially dominated by hardwood hammock, by reducing hardwood tree growth and favoring invasion by a few mangroves, may lead to a positive feedback cycle of increasing salinity and increasing mangrove invasion. This could lead to rapid large scale shifts in vegetation. Increase in salinities of the vadose zone induced by these events might eradicate the salinity intolerant hardwood hammocks at higher elevations and promote rapid landward migration of mangroves (Teh et al., 2008).

Results from of a quantitative model simulation (Sternberg et al., 2007; Teh et al., 2008) illustrate how this can occur. The model simulates mangrove and hardwood hammock trees on a 10- x 100 grid of 1 x 1 m pixels (for a conceptual view of the spatial model, see Figure 2). Competition of mangroves and hardwood hammock trees are modeled, with abiotic conditions of tides, precipitation, evaporation, and movement of water in the vadose zone. Figure 3 shows a cross-section along an elevational gradient of 100 meters from sea level (far left) to one meter above sea level (far right). A sharp vegetation ecotone from mangrove to hammock vegetation type initially occurs from about the locations of cells 13 to 15 along the elevation gradient (see Figure 3), or 39 to 45 meters horizontal distance. This ecotone corresponds roughly to the maximum tidal height. All cells to the left of the ecotone are occupied purely by mangroves and all cells to the right are occupied by hardwood hammock trees exclusively. The salinity gradient is correspondingly sharp (Figure 4). However, on day 1 of the simulation the entire area is assumed flooded by marine water due to a storm surge event, raising salinity to 30 ppt across the entire modeled area (see plot of day 1 in Figure 4). One day after the heavy surge, the salinity in the vadose zone remained at about 30 ppt throughout the entire study domain. After 0.25 year, the relatively reduced evapotranspiration associated with the high fraction of hardwood hammocks biomass in the cells coupled with precipitation significantly reduced the salinity. After an initial period of decrease, the salinity started to creep back up around 5 years after the storm surge. Initially, hardwood hammocks dominated the cells at higher elevation (higher height class). After the storm surge, because the salinity reduces the competitive ability of the hammock species, mangroves started to invade the higher elevation regions, resulting in a lower percentage of cells dominated by hardwood hammocks in higher height class (Figure 3). Salinity slowly increases across the upper part of the elevation gradient.

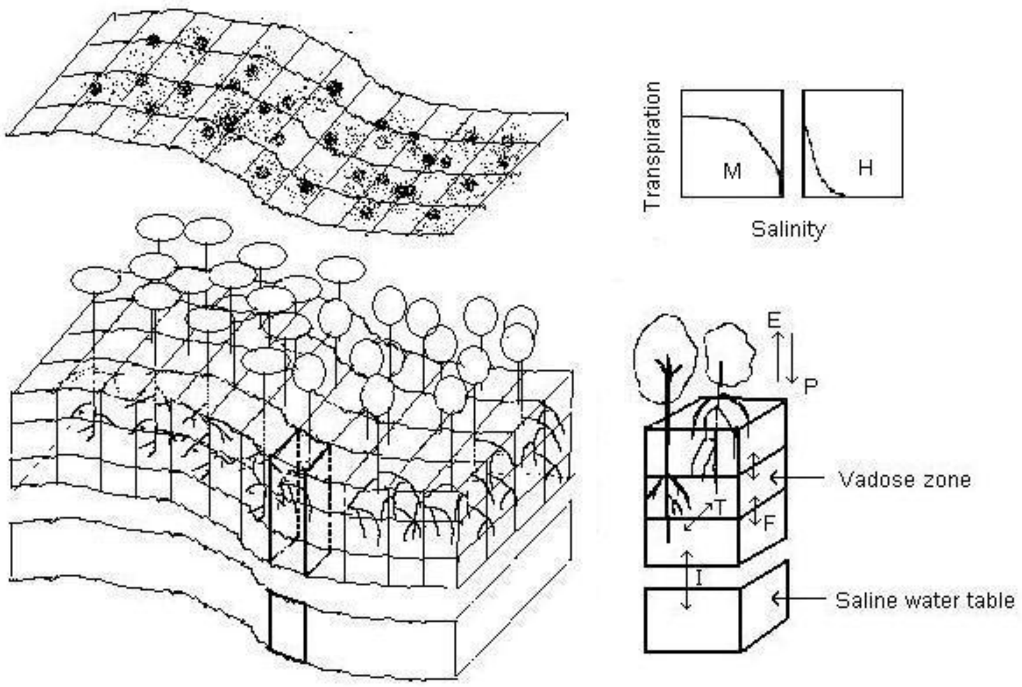

Fig 2. Bottom left: grid-based three dimension hammock/mangrove community, elevation decrease toward right side (seaward). Top left: two-dimensional continuous surface occupied by individual trees, dots show zone of influence (ZOI). Top right: transpiration of mangrove (M) and hammock (H) as a function of vadose zone water salinity. Bottom right: interaction between infiltration (I), plant water uptake (T), evaporation (E), precipitation (P), and flux between vertical layers (F).

In order to take into account the effect of non-uniformities in the vadose zone, this zone is modeled as divided into 5 vertical layers, to take into account the development of vertical heterogeneity and the vertical distribution of plant roots. Figure 5 shows the sharp gradation from the high salinity (mangrove) and low salinity (hammock) zone. There is a vertical pattern in this gradient. The boundary moves landward with depth in the subsurface. This is probably due to percolation of water, carrying salt downward. The boundaries for the dry season and wet season are similar with the exception that the boundary of the surface layer during the wet season moves landward compared with the dry season. This is probably due to higher tides during the wet season, bringing sea water farther inland. When averaged over the whole vadose zone, the dry season has higher salinity than the wet season, because of less wash out of salinity by precipitation.

2.4. Development of models for effects of sea level change on species populations

The projected changes in habitat due to sea level rise may have strong effects on some of the native species of southern Florida. Estuarine and coastal aquatic species at the freshwater/marine interface will be among the first impacted. To assess the effects of changes in salinity, water temperature, and depth, the biologic-hydrologic model simulations will be used as input to models called Spatially Explicit Species Index (SESI) and Habitat Suitability Index (HSI) models (DeAngelis et al. 2000). As a first application we are developing models for the endangered Florida manatee and the fresh and marine submerged aquatic vegetation (SAV) on which it feeds.

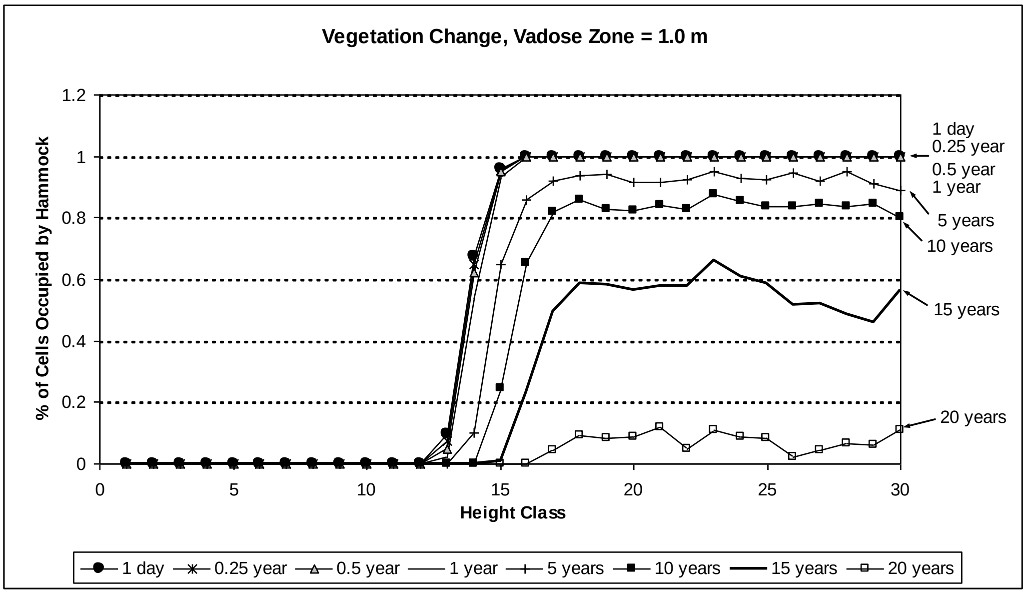

Figure 3: Elevation profile showing the fraction of cells occupied by hammocks when a storm surge is assumed to occur at day 1. The term 'height class' refers to the identification number of the spatial cell along the elevation gradient. Elevation above sea-level increases from left to right.

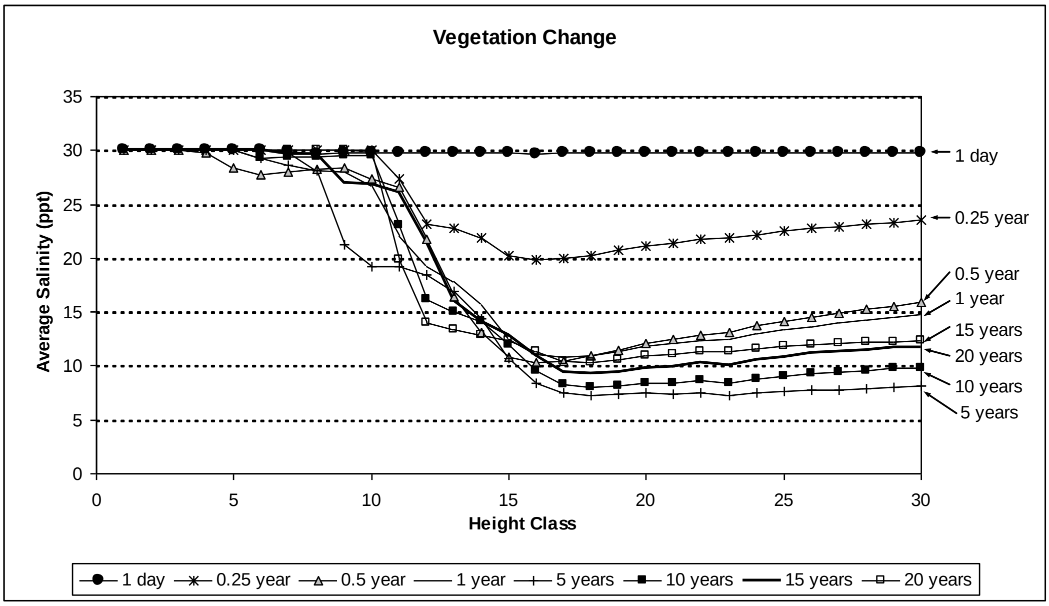

Figure 4: Average salinity (ppt) profiles along the elevation gradient at eight times starting from one day following the storm inundation, for the scenario in which vegetation was allowed to undergo successional changes. The term 'height class' is defined in Figure 3.

2.5. Development of predictive capabilities

The major objective is the development of the forecasting model; to apply the landscape modeling to prediction. This will utilize a range of sea-level rise scenarios as postulated by the IPCC and other sources and include storm surges. Predictions will first be superimposed on existing conditions and changes in coastal habitats for the representative 10-year period.

The model also includes the increased sea and air temperatures and subsequent effects on coastal temperature and evapotranspiration rates. The water-level, salinity regime, and hydro-period data produced will then be applied to the landscape relationships developed in the hind-cast analysis to predict future vegetation and habitat configurations. A process-based model of vegetation will exert feedback on the vadose zone salinity.

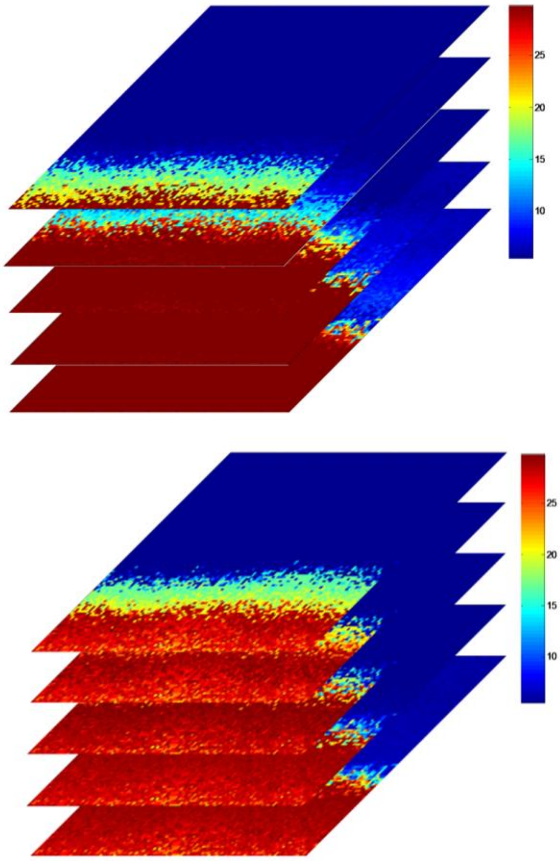

Fig 5. Salinity gradient along the elevation gradient of vadose zone at each vertical vadose zone layer for the dry season (top) and wet season (bottom). The color bar refers to salinity concentrations, with red being highest.

3. ACKNOWLEDGMENTS

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