MANTRA-O18: An Extended Version of SUTRA Modified to Simulate Salt and δ^{18}O Transport amid Water Uptake by Plants

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ABSTRACT

Sea level rise and the increasing landward intrusion of storm surges pose the threat of replacement of salinity-intolerant vegetation of important coastal habitats by salinity-tolerant vegetation. Therefore, a means is needed to better understand the processes that influence this vegetation shift and to aid in the management of coastal resources. For this purpose, a hydrology–salinity–vegetation model known as MANTRA was developed by coupling a spatially explicit model (MANHAM) for simulation of vegetation community dynamics along coastal salinity gradients with SUTRA, a USGS groundwater flow and transport model. MANTRA has been used to project possible future changes in Coot Bay Hammock in southern Florida under conditions of gradually rising sea level and storm surges. The simulation study concluded that feasibility exists of a regime shift from hardwood hammocks to mangroves subject to a few conditions, namely severe damage to the existing hammock after a storm surge and a sufficiently persistent high salinity condition and high input of mangrove seedlings. Early detection of salinity stress in vegetation may facilitate sustainable conservation measures being applied. It has been shown that the δ^{18}O value of water in the xylem of trees can be used as a surrogate for salinity in the rooting zone of plants, which is difficult to measure directly. Hence, the model MANTRA is revised into MANTRA-O18 by including the δ^{18}O of the tree xylem dynamics. A simulation study by MANTRA-O18 shows that effects of increasing salinization can be detected many years before the salinity-intolerant trees are threatened with replacement.

INTRODUCTION

Climate change and resulting sea level rise (SLR) will inflict changes that may be irreversible in coastal ecosystems, particularly those of low lying landscapes and atoll islands. Sustained by a fragile balance of freshwater and seawater interactions, the Everglades ecosystem is especially susceptible to sea level rise as documented in Ross et al. (2000, 2009). Along coastal southern Florida, the freshwater marsh has been observed to be replaced by mangroves (Gleason et al. 1974; Willard et al. 1999; Williams et al. 1999). Many such shifts from salinity-intolerant vegetation to salinity-tolerant vegetation have been attributed to sea level rise (Alexander and Crook 1974; Lara et al. 2002; Kirwan and Megonigal, 2013). The pace of such shifts may be affected positively or negatively by the self-reinforcing positive feedback between the vegetation and salinity (Passioura et al. 1992; Sternberg et al. 2007), as well as the frequent and intensified salinity pulses associated with the increasing impact of storm surges as a consequence of sea level rise (Scheffer et al. 2001; Teh et al. 2008). There is a need to understand, predict, and prepare for the consequences of climate change-related impacts, in particular the effects of SLR and storm surges on both the short-term dynamics of salinity in the soil and groundwater and the long-term effects on vegetation. For this purpose, a hydrology–salinity–vegetation model known as MANTRA (Teh et al. 2013) was developed by coupling a spatially explicit model (MANHAM) for simulation of vegetation community dynamics along coastal salinity gradients with SUTRA, a USGS's groundwater flow and transport model. MANTRA has been applied to a Coot Bay Hammock along the southwestern coast of Everglades National Park to project the possible future changes in such coastal hammocks under sea level rise and storm surges (Teh et al. 2015). This simulation study underscores that three conditions are necessary for a hardwood hammock to undergo a regime shift leading to a mangrove community; sufficiently severe damage to the existing hammock to open a gap to allow growth of invading propagules, a large input of salinity persisting for a long enough period of time to favor growth of mangrove propagules in competition with remaining freshwater vegetation, and an input of enough mangrove propagules to allow mangroves to be present in sufficient number to influence the future soil salinity. It is desirable to have an early indicator of impending shifts in vegetation due to salinity stress. Water salinity of the vadose zone, salinity of xylem water and predawn water potential are some of the potential indicators of critical transition from salinity-intolerant vegetation to salinity-tolerant vegetation but there are uncertainties and limitations in the measurements of these indicators (Zhai et al. 2016). It has been shown that the oxygen isotope composition (δ^{18}O value) of plant stem water may be an indicator of salinity stress (Vendramini and Sternberg 2007). Hence, the model MANTRA is revised into MANTRA-O18 by including the δ^{18}O of the tree xylem dynamics. A brief overview of MANTRA-O18 is given in the following section.

MANTRA-O18

MANTRA-O18 is an extended version of SUTRA (Voss and Provost 2002) that is capable of simulating (i) vegetation community dynamics and (ii) variable-density flow and transport of two solutes; i.e., salt and ^{18}O, through variably to fully saturated porous media. So this extended version named MANTRA-O18 is:

(a) An improvement of SUTRA in that the U.S. Geological Survey's spatially explicit model of vegetation community dynamics along coastal salinity gradients (MANHAM) is integrated, and,
(b) A simplified version of SUTRA-MS (Hughes and Sanford, 2015) in that the number of solutes is limited to two with one solute (salt) effecting fluid density and the other solute (^{18}O isotope) not affecting fluid density.

In MANTRA-O18, the water uptake rates of hammock and mangrove are determined based on the solute (salt) concentration S calculated by the SUTRA module. The total water uptake by plants then affects the fluid density and fluid pressure, which consequently change the salinity.

Further details regarding MANHAM and MANTRA can be found in Teh et al. (2008) and Teh et al. (2013). Changes were made to the fluid and solute mass balance equations so that the pure water fluid uptake by the salinity-excluding plants is properly accounted for, including the incorporation of a second solute mass balance equation for ^{18}O isotope; hence the name MANTRA-O18. Internally in MANTRA-O18, the proportion of ^{18}O isotope (^{18}O/^{16}O) is tracked numerically and then converted to δ^{18}O for a resulting output using

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$\delta^{18}\mathrm{O} = \left[{}^{18}\mathrm{O} / {}^{18}\mathrm{O}_{\text{standard}} - 1 \right] \times 1000$ with ${}^{18}\mathrm{O}_{\text{standard}}$ as the standard mean ocean water (SMOW).

TEST CASE: PURE FLUID OUTFLOW

To illustrate the effect of pure fluid outflow on salinity and ${}^{18}\mathrm{O}$ isotope, a domain as illustrated in Figure 1 used. It should be noted that domain setup and the parameter values are used for testing purposes so their scale and magnitude may not be realistic. The saline seawater is marked with $\delta^{18}\mathrm{O}$ value of +4‰ while the fresh pure water is marked with $\delta^{18}\mathrm{O}$ value of –3‰.

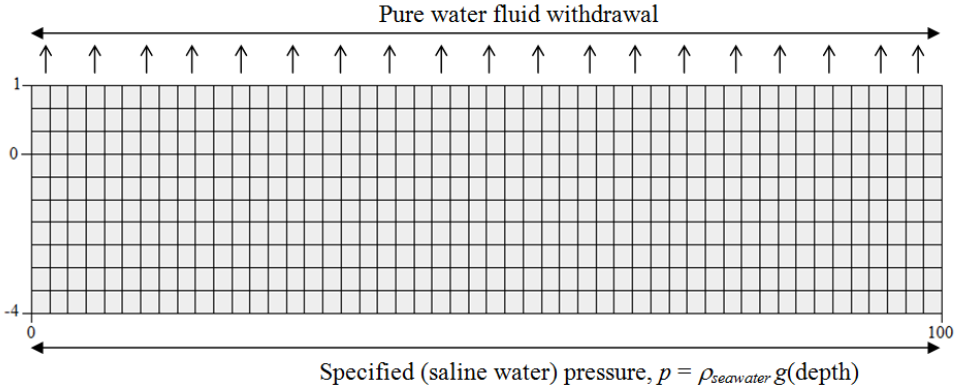
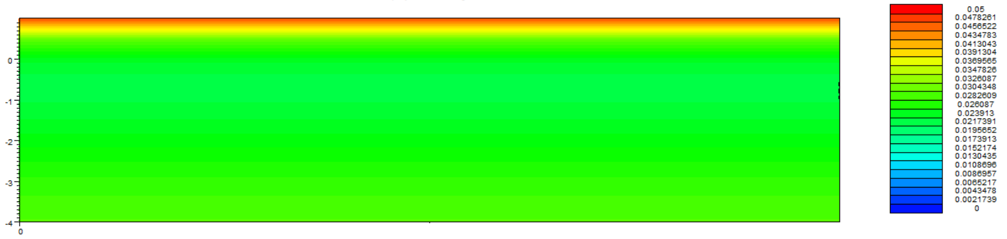


Figure 1. Domain setup of simple fluid outflow case.

The aquifer is assumed to sit on top of saline groundwater so a constant specified pressure is defined at the bottom boundary. At the top boundary, a constant outflow of pure water fluid is imposed. Note that there is no recharge of freshwater so the continuous uptake of water will unreasonably cause a severe build-up of salt. This is certainly not a realistic setup but the objective of this set up is to demonstrate the build-up of salt and transport of ${}^{18}\mathrm{O}$ isotope in MANTRA-O18 so the results will be illustrated at a fixed time at $t = 100$ day. Figure 2(a) illustrates the build-up of salt in the presence of pure water fluid outflow from the surface cells. The corresponding simulated $\delta^{18}\mathrm{O}$ concentration is shown in Figure 2(b), showing no build-up of $\delta^{18}\mathrm{O}$, as the $\delta^{18}\mathrm{O}$ isotope is withdrawn together with the pure water fluid. As the fresh water fluid ($\delta^{18}\mathrm{O}$ = –3‰) available in the domain is being continually withdrawn by the plants, the saline groundwater ($\delta^{18}\mathrm{O}$ = +4‰) at the bottom boundary gradually infiltrates into the upper layers and mixes with the fresh water fluid. The infiltration of saline groundwater from the bottom boundary and the withdrawal of $\delta^{18}\mathrm{O}$ isotope by the plants causes the $\delta^{18}\mathrm{O}$ isotope concentration to decrease from the bottom to the top of the domain.

SLR SIMULATION

The simulation results of MANTRA-O18 for a coastal transect subjected to SLR rate of 3 mm/year are illustrated here. Figure 3 shows the steady-state hammock and mangrove biomass, salinity and $\delta^{18}\mathrm{O}$ isotope profiles simulated by means of MANTRA-O18 before the SLR event. The changes in hammock and mangrove distribution, as well as salinity and $\delta^{18}\mathrm{O}$ isotope profiles for 100 years after SLR, are shown in Figure 4.


(a) Salinity with outflow of fluid

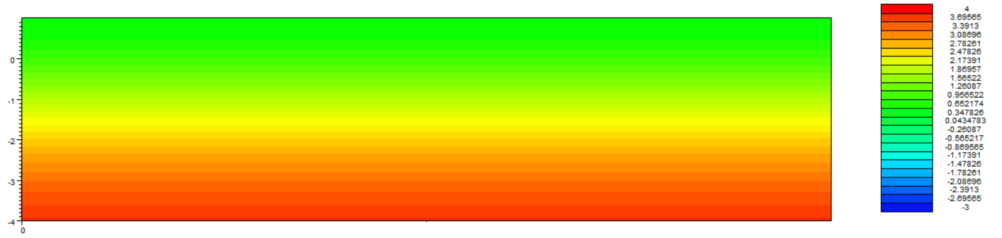

(b) d18O concentration with outflow of fluid

Figure 2. Simulated (a) salinity and (b) δ^{18}O concentration with outflow of fluid.

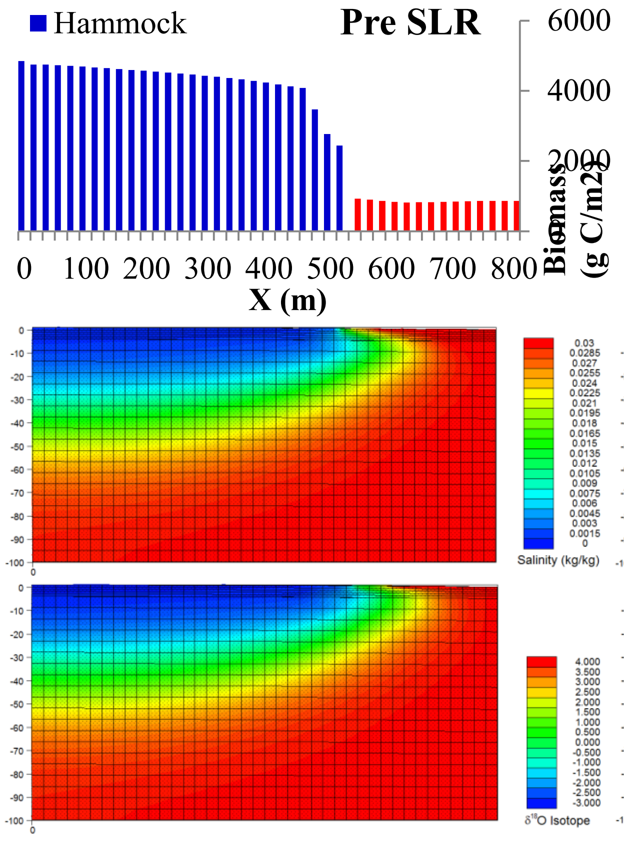


Figure 3. Simulated hammock and mangrove biomass (top), salinity (middle) and δ^{18}O isotope (bottom) profiles without sea level rise (SLR).

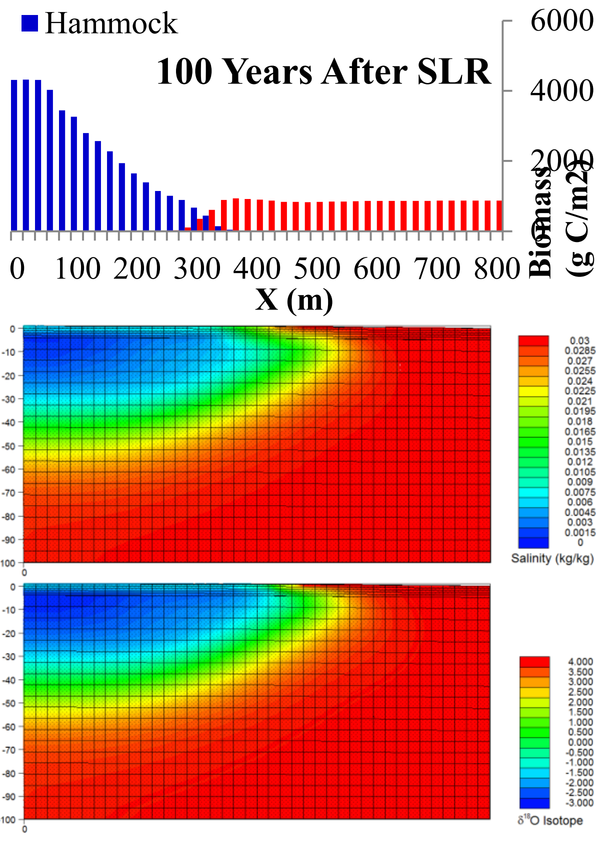


Figure 4. Simulated hammock and mangrove biomass (top), salinity (middle) and δ^{18}O isotope (bottom) profiles 100 years after SLR begins.

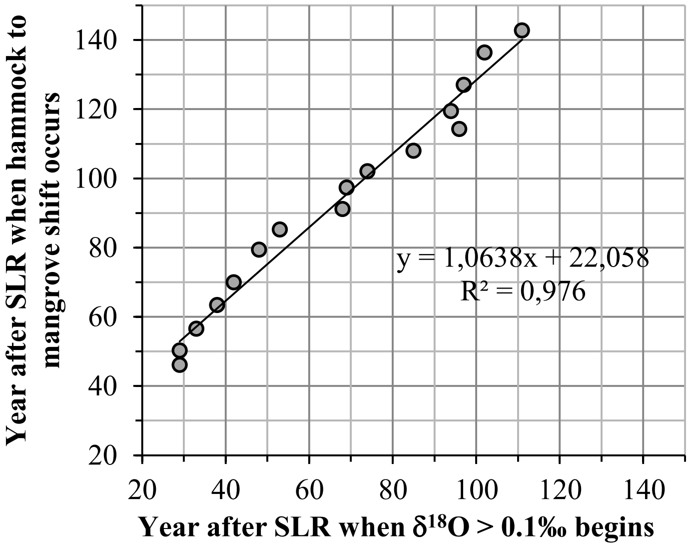


Figure 5. Number of years after SLR initiation when hammock to mangrove shift occurs plotted against the number of years after SLR initiation, when δ^{18}O value of these cells exhibit a difference of greater than 0.1‰.

DISCUSSION AND CONCLUSION

This paper introduces the model MANTRA-O18 in which δ^{18}O of the tree xylem is coupled with the modeling of hydrology, salinity, and the responses of both salinity-intolerant and their competing salinity-tolerant trees. The results of a test case are presented to illustrate the features of the simulated salinity and δ^{18}O. MANTRA-O18 has also been used to assess the potential of tracking the yearly δ^{18}O of plant stem water to predict the shifting of vegetation as a result of SLR. As shown in Figure 5, simulation results by MANTRA-O18 on a test case indicate a linear relation between the year when the shift from hammock to mangrove occurs and the year when the δ^{18}O difference is greater than 0.1‰ (the current precision of measurement of the isotopic composition of stem water). This suggests that for this test case of SLR, the annually-averaged δ^{18}O could start to exhibit values greater than 0.1‰ at least 20 years (mean ≈ 26 years, standard deviation ≈ 5 years, min ≈ 17 years, max ≈ 35 years) before the hammock to mangrove shift occurs. The correlation obtained here is for this particular problem setup, so the value could be different for other setups. However, the notion that the δ^{18}O difference substantially precedes the shift in vegetation is likely transferrable to other situations.

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