Predicted Changes in Interannual Water-Level Fluctuations Due to Climate Change and Its Implications for the Vegetation of the Florida Everglades

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Abstract The number of dominant vegetation types (wet prairies, sawgrass flats, ridges and sloughs, sloughs, and tree islands) historically and currently found in the Everglades, FL, USA, as with other wetlands with standing water, appears to be primarily a function of the magnitude of interannual water-level fluctuations. Analyses of 40 years of water-depth data were used to estimate the magnitude of contemporary (baseline) water-level fluctuations in undisturbed ridge and slough landscapes. Baseline interannual water-level fluctuations above the soil surface were at least 1.5 m. Predicted changes in interannual water-level fluctuations in 2060 were examined for seven climate change scenarios. When rainfall is predicted to increase by 10 %, the wettest scenario, the interannual range of water-level fluctuation increases to 1.8 m above the soil surface in sloughs. When rainfall is predicted to decrease by 10 % and temperatures to increase by 1.5 °C, the driest scenario, the range of interannual range of water-level fluctuations is predicted to decrease to 1.2 m above the soil surface in sloughs. A change of 25–30 cm in interannual water-level fluctuations is needed to change the number of vegetation types in a wetland. This suggests that the two most extreme climate change scenarios could have a significant impact on the overall structure of wetland vegetation, i.e., the number of vegetation types or zones, found in the Everglades.

Introduction

In wetlands worldwide, annual and interannual water-level fluctuations are the main drivers that control the composition of plant and animal communities/assemblages, the distribution and abundance of individual plant and animal species, and the development of landscape features (Keddy 1991; Richter et al. 1997; Middleton 2002; Leira and Cantonati 2008; Wantzen et al. 2008). Like other wetlands, the Everglades, FL, USA, has both annual and interannual water-level fluctuations (McVoy et al. 2011). The former are caused by seasonal precipitation patterns and the latter by interannual precipitation cycles lasting one or more decades. During an interannual cycle, there are years with below normal precipitation, followed by years of above normal precipitation. A change in the range of water levels during an interannual cycle, if not caused by various local anthropogenic disturbances like drainage or land-use change, can potentially be used as an indicator of climate change for wetlands. If climate change significantly decreases or increases the range of interannual water-level fluctuations, the overall vegetation of a wetland (i.e., the number of vegetation types it has) could be altered.

Keddy and Fraser (2000) in a paper on the management and conservation of wetlands along the shores of lakes noted that the amplitude of long-term water-level fluctuations determined the number of vegetation zones in lakeshore wetlands. Keddy (1991) and Keddy and Fraser

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(2000) suggest that water-level fluctuations of between 1 and 4 m over a 10-year period are needed to support the maximum number of plant communities in wetlands associated with lakes. The higher interannual water levels (4 m) are associated with very large lakes and reservoirs. For most lakeshore wetlands, interannual water-level fluctuations that maximize vegetation diversity are in the 1–2 m range, and within this range 4 or 5 vegetation types can be supported. If interannual water levels are constricted, the number of vegetation types will decrease (Keddy 1991; Keddy and Fraser 2000). If interannual range of water-level fluctuations, however, become too large, wetland vegetation may be eliminated completely. Similar observations have been made for other kinds of wetland with standing water. For example, for prairie potholes, if the interannual range in water-level fluctuations is small (<50 cm), only one or two vegetation types will be found, whereas if it is large (>100 cm) four or five vegetation types will be found (see Stewart and Kantrud 1971).

These and other field observations (van der Valk, unpublished) suggest that for approximately every 25–30 cm increase or decrease in the range of interannual water-level fluctuation, another vegetation type can either be supported or an existing one will be lost. Unfortunately, there is no experimental evidence to confirm that a long-term change in the amplitude on interannual water-level fluctuations of 25–30 cm will result in the gain or loss of a vegetation zone in a wetland. Such a study is badly needed. It is also uncertain if this change in magnitude of long-term water-level fluctuations is similar for all types of wetlands. This is unlikely. The change required is undoubtedly a function of the magnitude of interannual water-level fluctuations normally experienced by a wetland (see Keddy and Fraser 2000). It should be noted that only surface water fluctuations considered. In this paper, we will restrict ourselves to water-level changes above the soil surface for two main reasons: (1) the existing conceptual model only deals with water-level fluctuations above the wetland surface; and (2) the responses to water levels dropping below the surface of a wetland are poorly understood. The impacts of the drop of water levels below the surface of a wetland, i.e., a drawdown, have been studied in a variety of wetlands. When this happens it can result in increased fires, establishment of many species from the seed bank, vegetative spread of emergents, and temporary loss of submersed species, etc., Field and experimental studies of drawdowns, however, suggest that they do not have an impact on the number of vegetation zones found in a wetland (see van der Valk 2000, 2007). However, drawdowns are important for the re-establishment of vegetation types that may have been eliminated during high water events (van der Valk 2000, 2007; Keddy and Fraser 2000). In short, for wetlands with standing water, the range in

surface water level over an interannual cycle appears to determine the overall structure of the wetland's vegetation, i.e., the number of vegetation types or zones (submerged, floating-leaved, emergent, wet meadow, etc.).

Interannual fluctuations of water levels typically have periods of one or more decades. South Florida (Fig. 1) undergoes such interannual fluctuations in annual precipitation over a period of between 10 and 20 years (Duever et al. 1994; McVoy et al. 2011). Although there have been no experimental studies of the impacts of a change in the magnitude of wet-dry cycles on the vegetation of the Everglades, there are relevant observational studies. Bernhardt and Willard (2009), who investigated historic changes in the ridge and slough landscape, were able to detect the impact on the pollen abundance of ridge and slough taxa (see their Fig. 10) associated with the North Atlantic Oscillation (NAO) during the late nineteenth and twentieth century. During periods of positive NAO, higher winter precipitation is predicted in South Florida, and this corresponded with pollen of more aquatic taxa in sloughs. Likewise, Beckage et al. (2003) found a relationship between a decrease in dry-season rainfall and fires in Everglades National Park that appears to be linked to the El Nino Southern Oscillation (ENSO). Although they vary in detail, like apparent periodicity and putative cause, there are multiple sources of evidence for interannual cycles of precipitation, and hence water-level fluctuations, impacting the plants and animals of the Everglades. Each year in the Everglades, plant and animal populations fluctuate in size and adjust their distributions in response to changes in annual and interannual water levels, and numerous studies have observed these seasonal and in some cases interannual shifts. Data on the impacts of interannual water-level fluctuations on plant and animal assemblages in the Everglades were reviewed and synthesized by Bedford et al. (2012). They concluded that some species and species assemblages are most abundant and widespread during wet years while others are most abundant and widespread during dry years but that none would be eliminated over a cycle. Field observations indicate that vegetation responses to water-depth changes in the Everglades can occur in only a few year. Zweig and Kitchens (2008) reported that slough communities were invaded by sawgrass when there was a minimum water level beneath the peat surface for three consecutive dry years. During wet years, however, sawgrass stands fragmented after several years of wet weather when water depths greater than 60 cm above the ridge surface. Likewise, Armentano et al. (2006) found that slough species replaced sawgrass after an increase in mean water level of 30–40 cm in Taylor Slough between 1980 and 1990: sawgrass coverage increased after water levels dropped. Even tree islands can be gained or lost due over relatively short periods, i.e., decades, due to changes in

Fig. 1 Deviations from mean annual precipitation in South Florida from 1887 to 1997. The *dark solid line* is the 5 year running average. From McVoy et al. (2011)
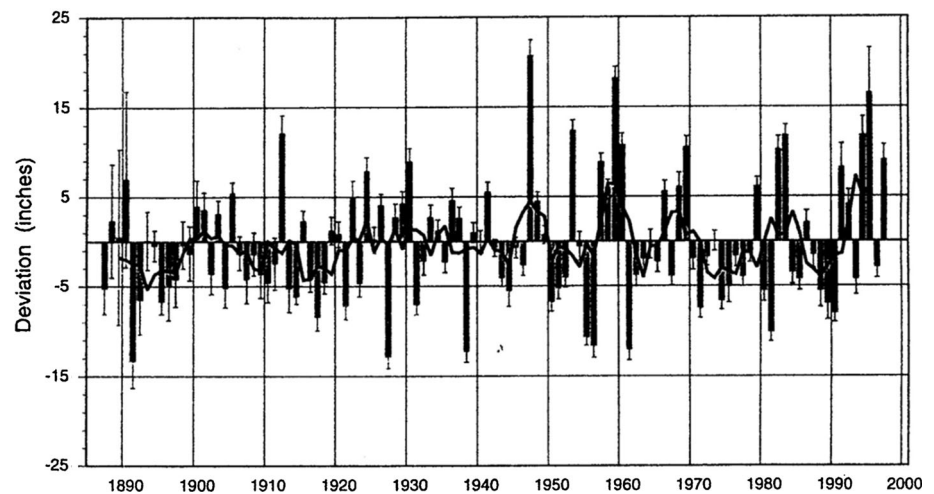
hydrology (Sklar and van der Valk 2002). Table 1 summarizes the observed responses of plant assemblages to interannual water-level fluctuations in the Everglades.

If the interannual range of water level is the major driver of a wetland's vegetation structure as proposed by Keddy (1991), the potential impact of climate change on the range of interannual water levels can be used to predict if climate change will have an effect on its overall vegetation. This presupposes that the historic, and, if different, contemporary interannual range of water levels is adequately documented. This unfortunately is rarely the case for wetlands, but fortunately it is the case for the Everglades. The objective of this study is to examine if the predicted changes in the hydrology of the Everglades due to climate change (Obeysekera 2014) are potentially large enough that they could alter the overall vegetation of the Everglades. We did this by quantifying the contemporary annual and interannual range hydroperiods of the ridge and slough landscapes of the Everglades and then to predict the range of water-level fluctuations during interannual cycles under 7 different climate change scenarios. Our criterion

for a significant change is that it has to differ by 25–30 cm or more from the contemporary range of interannual water-level fluctuations. This threshold is consistent with that observed in the field or proposed by Armentano et al. (2006), Givnish et al. (2008), Zweig and Kitchens (2008) for community change to occur in the Everglades. In this paper, an increase or decrease in the interannual range of 25–30 cm in surface water levels is assumed to be enough to cause the gain or loss of a vegetation type and thus significantly change the overall characteristics of the Everglades. Nevertheless, that this is a realistic threshold level for the Everglades needs to be verified. We will first, however, briefly describe how annual and interannual water-level fluctuations are characterized.

Harmonic Analysis

Annual and interannual water-level fluctuations can be described using harmonic analysis (*see* Nuttle 1997a, b). Harmonic analysis is used to describe time series data as the mean plus the sum of a finite number of sinusoidal

Table 1 Responses of selected plant assemblages (along a hydrologic from wettest to driest) when subjected to annual water-level fluctuations during wet, normal, and dry years over a wet-dry cycle (see Fig. 4)

Assemblage	Wet year	Normal year	Dry year
Slough species	Positive	Neutral	Negative[a]
Sawgrass (*Cladium jamaicense*)	Negative	Neutral	Positive[b]
Flood tolerant shrub and tree species	Neutral	Neutral	Positive[b]
Flood intolerant tree and shrub species	Negative	Neutral	Positive[b]
Wet prairie species	Positive	Neutral	Negative[a]

Positive, range/area of assemblage increases; Neutral, little impact on range/area; and Negative, range/area decreases. Adapted from Bedford et al. (2012)

[a] Positive with respect to recruitment

[b] Negative with respect to increased fire damage

functions that vary over time. Each sinusoidal function or harmonic describes an oscillation or fluctuation over some time scale. For each harmonic in a hydrological time series that describes water levels or flows at a point, the mean water level or flow, its amplitude, and its phase angle, where in the cycle $t = 0$, is used to characterize it (Fig. 2). There is often more than one harmonic. For most wetlands, there is an annual harmonic and an interannual harmonic. This general approach to describing water-level fluctuations or hydroperiods has also been advocated by Richter et al. (1997), Nestler and Long (1997), and van der Valk (2005), among others. Specifically, both the primary (annual) and secondary (interannual) harmonics of water-level fluctuations can be quantified using (1) the mean water depth around which water levels fluctuate, (2) the amplitude (A) or range (R, $R = 2A$) of water-level fluctuation(s) over a cycle, and (3) periodicity (length) of a cycle (Nuttle 1997a). Nuttle (1997a) has used harmonic analysis to characterize the first harmonic (annual fluctuations) at a gaging station (P33) in Everglades National Park in order to investigate changes to annual hydroperiods over time on the nesting success of wood storks in the Park. Interannual harmonics, however, were not investigated, but can be inferred from the annual variation on water-level fluctuations observed. As already noted, Beckage et al. (2003) used water-level data from the same gage to investigate the impacts of ENSO on fires in the Everglades National Park, and they detected an interannual harmonic.

We will use the range of surface water-level fluctuations above the soil surface in sloughs in ridge and slough areas to estimate the range in interannual water-level fluctuations in the Everglades. Sloughs in ridge and slough areas have the largest interannual range in water levels and all other vegetation types have smaller ranges because they occur at higher elevations. In practice, this means the difference between the highest water level in the wettest year of a cycle and the lowest water level in the driest year in sloughs in the ridge and slough areas is used to estimate the range of water levels during an interannual cycle. Figure 3
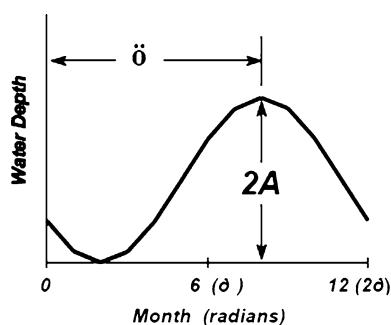

Fig. 2 Characterizing one period of a hydroperiod by amplitude (A) and phase angle (ö). *Note* $2A = R$, the maximum range in water depth over a cycle. From Nuttle (1997b)

presents idealized annual water-level fluctuations in a wet, normal, and dry year. The annual range in water levels is 1.2, 0.6, and 0.5 m for the wet, normal, and dry years, respectively. The interannual range is 1.5 m. If during driest year, the water level falls below the surface of the slough, the lowest water level is considered to be 0. In other words, the range in interannual water-level fluctuation that we are using is for standing water only. The effects of high water events have a greater impact and last much longer than those of low water events (van der Valk 1981; van der Valk and Davis 1978). Even submersed plants can survive periods without surface water.

Study Area: The Everglades Ridge-Slough Landscape

The Everglades are composed of a number of distinct landscapes (Ogden 2005; McVoy et al. 2011; Aumen et al. this issue). Areas with ridge and slough topography occupy the deepest part of the Everglades and thus are the best areas in which to examine the maximum range of water levels during an interannual cycle. This landscape has a striking pattern of teardrop-shaped tree islands embedded in a regular, striped background of ridges and sloughs oriented in the direction of water flow (Browder and Ogden 1999; David 1996; Kushlan 1990). It was also the most widespread of its landscapes, and it once occupied much of the central Everglades as well as Shark River Slough (Sklar and van der Valk 2002; Givnish et al. 2008; McVoy et al. 2011). Of the 1,105,000 ha (2,730,000 acres) of the pre-drainage Everglades, ridge and slough topography was estimated to have occupied 607,000 ha (1,500,000 acres) or 55 % (McVoy et al. 2011). Much of the historic ridge-slough landscape has been severely disrupted by drainage over the last century. Today, the ridge and slough landscape covers only about 271,000 ha (670,000 acres) or 45 % of the remaining Everglades (McVoy et al. 2011). One of the least disturbed areas of ridge and slough landscape is found in the central part of Water Conservation Area 3A. It is this area that is the focus of our study. Because it is the deepest part of the Everglades, the range of water-level fluctuations during an interannual cycle in this area provides the best estimate of the range of interannual surface-water fluctuations for the entire Everglades. Unfortunately, drainage canals and dikes have so altered the hydrology of much of the remaining Everglades that it will, in reality, be difficult to distinguish climate change impacts on hydrology from those caused by local anthropogenic disturbances.

Methods

We used a water-level gaging station (3A-4) found in the ridge- and slough-dominated central part of Water

Fig. 3 Idealized annual hydroperiods during wet, normal, and dry years over an interannual cycle in the ridge and slough landscape of the Everglades. Over the entire interannual cycle, the range of water level is about 1.5 m as measured from the soil surface in a slough

Annual Hydroperiod			
Mean	0.9 m	0.6 m	0.25 m
Range	1.2 m	0.6 m	0.50 m
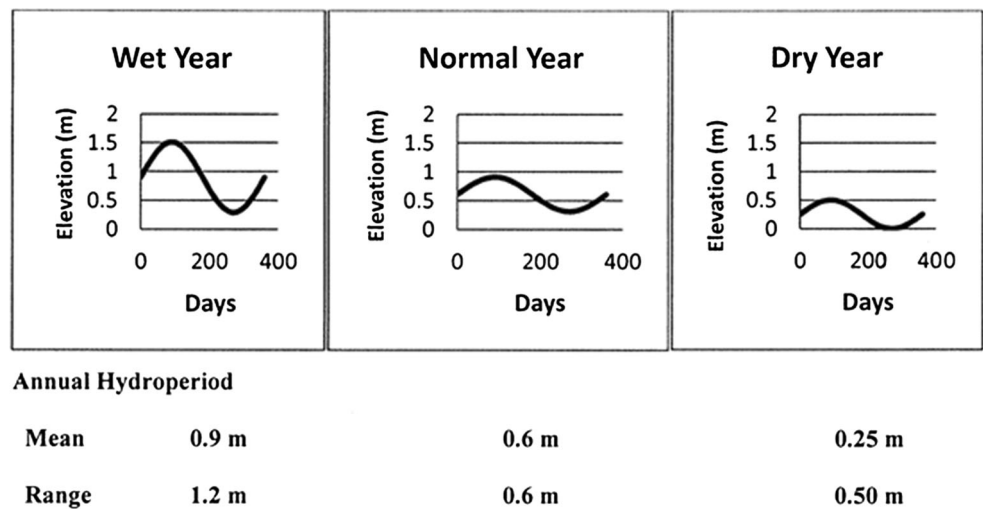
Conservation Area 3A to establish the current range of interannual water-level fluctuations based on water-level measurements from 1965 to 2005, the baseline years. The range in interannual water-level fluctuations that we used is the difference between the maximum water level in the wettest year and the minimum water level in the driest year during the baseline period, with water levels below the soil surface ignored, i.e., the minimum is considered to be 0 when there is no surface water. The year 1995 was the wet year and 1974 was the dry year. These same years were used to calculate the interannual hydroperiod for each future scenario that was analyzed.

Seven climate change scenarios were examined to see how they would affect the water levels at this gaging station using the South Florida Water Management Model (SFWMM). Temperature increases were incorporated into the model by estimating the increased evapotranspiration (ET) using a temperature-based method for computing ET (Obeysekera 2014). Rainfall data were uniformly increased or decreased by 10 % over the entire year. Once climate change adjusted Rainfall (RF) and ET data sets were created for each of the baseline years, they were used as input to the SFWMM to predict water-level changes at gage 3A-4. For a complete description of all seven climate change scenarios, see Obeysekera (2014).

Hydrographs of these seven scenarios at Gage 3A-4 (Fig. 4) indicated that of the seven scenarios, the scenario that increased annual rainfall 10 % resulted in the most frequent high water levels. A decrease in rainfall and an increase in evapotranspiration was the scenario with the most frequent lowest water levels. Having canals in the model did not make any difference at this gage location. Only the baseline scenario and the two extreme scenarios, a 10 % increase in rainfall and a 10 % decrease in rainfall and an increase in evapotranspiration, will be considered from hereon. For a discussion of the selection of these
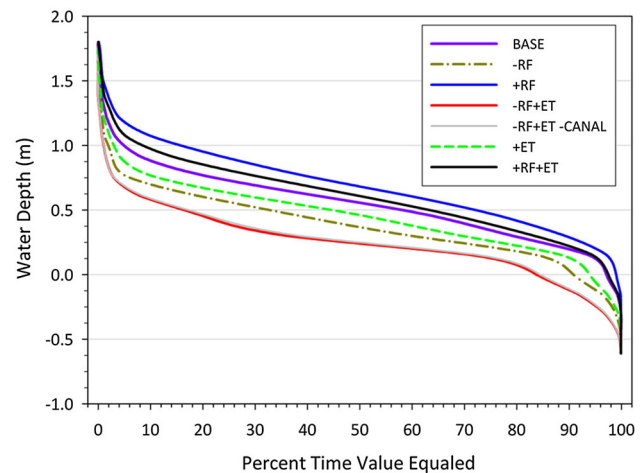

Fig. 4 Hydroperiod graphs of the baseline and six possible future climate scenarios. BASE = Baseline data 1965–2005, $-$RF = decrease in rainfall 10 %, $+$RF = increase in rainfall 10 %, $-$RF $+$ ET = decrease in rainfall 10 % and increase in evapotranspiration with canals modeled, $-$RF $+$ ET = decrease in rainfall 10 % and increase in evapotranspiration without canals modeled, $+$ET = increase in evapotranspiration, and $+$RF $+$ ET = increase in rainfall 10 % and increase in evapotranspiration. Only BASE, $+$RF, and $-$RF $+$ ET scenarios were considered for further analyses

seven scenarios and the how the climate changes scenarios were applied to the baseline data to predict the impacts on climate change in the hydrology of the Everglades, see Aumen et al. (2014) and Obeysekera (2014).

Results and Discussion

Contemporary and predicted overall interannual water-level fluctuations for the wettest, normal, and driest year are presented in Fig. 5. An analyses of the predicted changes in water levels under all seven scenarios indicated

that the range of water levels changed significantly over an interannual cycle when compared to the baseline years for only a couple of them. Consequently, we present data from only these two most extreme climate change scenarios: an increase in rainfall of 10 % and a 10 % decrease in rainfall and 1.5 °C increase in temperature. The latter is the worst case scenario for drier conditions because of both decreased rainfall (−RF) and an increased evapotranspiration (−RF + ET).

Increasing rainfall by 10 % did not alter the overall range of water-level fluctuations (200 cm) when compared to the baseline period (Fig. 5). When adjusted to eliminate water levels below the surface of the soil, however, the interannual surface water range is 180 vs. 150–160 cm for the baseline years. Since this is a predicted increase of about 25–30 cm in the range of interannual surface water levels, under this scenario it is possible that that the Everglades could support an additional vegetation type or see a great increase in slough vegetation (see Givnish et al. 2008; Zweig and Kitchens 2008; Bernhardt and Willard 2009). Decreasing rainfall by 10 % and increasing the mean temperature by 1.5 °C, also did not change the overall range of water-level fluctuations over an interannual cycle (200 cm). However, when adjusted to remove water levels below the soil surface, the interannual surface water level range is only 120 cm. This is about 25–30 cm

Fig. 5 Contemporary (1965–2005) and predicted under two climate change scenarios (10 % increase in rainfall (Increase RF) and 10 % decrease in rainfall plus in 1.5 °C increase in temperature (*Decrease RF*, *Increase ET*)) seasonal changes in water depths during dry, normal, and wet years during an interannual cycle at gage 3A-4 in the ridge and slough areas of Water Conservation Area 3A
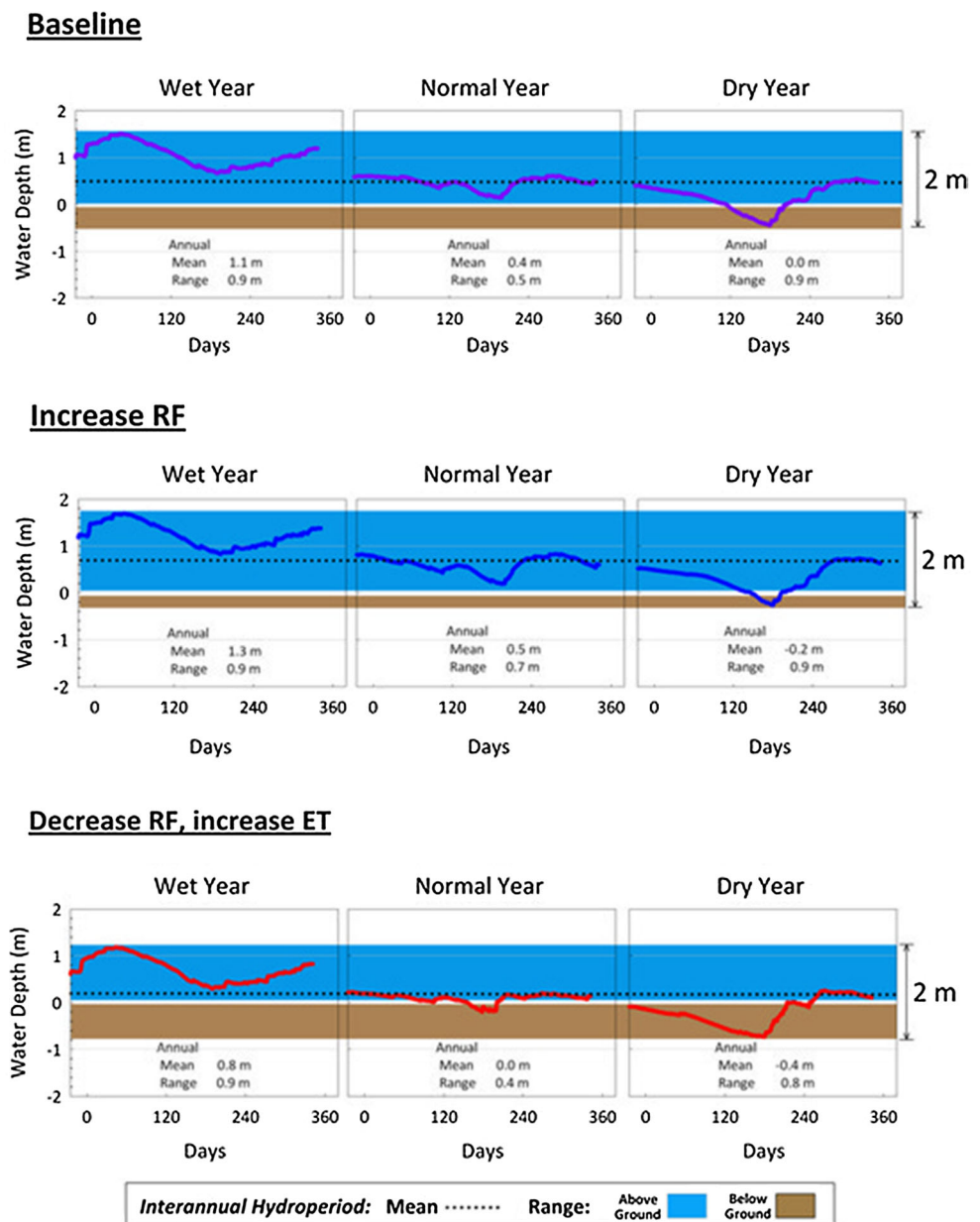
less than during the baseline years. Thus, under this scenario, the Everglades are predicted to lose a vegetation type. This is consistent with what has been observed in the Everglades already, a degradation of the ridge and slough landscape as sloughs are replaced with sawgrass in areas that have become drier (Givnish et al. 2008; Bernhardt and Willard 2009).

If the wettest scenario should actually occur, upland areas on the periphery of the Everglades that historically were never or rarely flooded will become flooded during wet years of interannual cycles and will be converted to dry-end wetlands such as wet prairies. (In reality because much of the Everglades is in diked impoundments, very little new wetland could develop along the periphery because the Everglades has nowhere to expand upslope.) Sloughs in the lowest areas would lose all their emergent and floating-leaved species because prolonged deeper water depths during wet years will eliminate these species. If the driest scenarios should actually occur, there would be a significant loss of sloughs because the sloughs in the ridge and slough areas would become invaded by sawgrass. In short, during the wettest scenario, the existing vegetation is expected to move upslope creating a new deep water zone in the deepest areas so that the Everglades might be able to have six vegetation types. During the driest scenario, the vegetation would move downslope with the elimination of the sloughs so that the Everglades would now have only four vegetation types. In reality, the actual responses of the vegetation to these two extreme climate change scenarios would vary significantly across the Everglades because of local topographic differences and how water levels would be managed in different areas. Our results suggest that climate change could have a significant impact on the overall vegetation of the Everglades, but determining exactly how the vegetation might respond will require a detailed analysis of the topography and hydrologic management of each if the Water Conservation Areas and various sections of Everglades National Park. Other factors linked to hydrology would also have to be considered, such as fire frequency, the spread of invasive species, peat accumulation rates, and sea level rise. See Zweig and Kitchens (2008) for a detailed account of short-term vegetation changes in Water Conservation Area 3 due to water level changes and Wetzel et al. (2011) for a general review of factors responsible for vegetation changes in the Everglades.

In summary, our results suggest that the most extreme climate change scenarios could significantly alter the range of interannual water-level fluctuations in the Everglades, and that this could alter the number of vegetation types that can be supported. Under these extreme scenarios, climate change would have an impact on the distribution and composition of vegetation types in the Everglades with an increase in the range of interannual fluctuations potentially benefitting the Everglades by increasing vegetation

diversity and a decrease reducing vegetation diversity. Our results suggest that a significant increase or decrease in the predicted interannual range of water-level fluctuations could be used as an indicator that climate change could alter the overall vegetation of a wetland.

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