VOLUME 4 2013

The International Journal of

Climate Change: Impacts and Responses

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THE INTERNATIONAL JOURNAL OF CLIMATE CHANGE: IMPACTS AND RESPONSES
http://on-climate.com/

First published in 2013 in Champaign, Illinois, USA
by Common Ground Publishing
University of Illinois Research Park
2001 South First St, Suite 202
Champaign, IL 61820 USA

www.CommonGroundPublishing.com

ISSN: 1835-7156

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Storm Surges and Climate Change Implications for Tidal Marshes: Insight from the San Francisco Bay Estuary, California, USA

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Abstract: Tidal marshes are dynamic ecosystems that are influenced by oceanic and freshwater processes and daily changes in sea level. Projected sea-level rise and changes in storm frequency and intensity will affect tidal marshes by altering suspended sediment supply, plant and wildlife communities, and the inundation duration and depth of the marsh platform. The objective of this research was to evaluate how regional weather conditions resulting in low-pressure storms changed tidal conditions locally within three tidal marshes. We hypothesized that regional storms will increase sea level heights locally, resulting in increased inundation of the tidal marsh platform and plant communities. Using site-level measurements of elevation, plant communities, and water levels, we present results from two storm events in 2010 and 2011 from the San Francisco Bay Estuary (SFBE), California, USA. The January 2010 storm had the lowest recorded sea level pressure in the last 30 years for this region. During the storm episodes, the duration of tidal marsh inundation was 1.8 and 3.1 times greater than average for that time of year in 2010 and 2011, respectively. At peak storm surges, over 65% in 2010 and 93% in 2011 of the plant community was under water. We also discuss the implications of these types of storms and projected sea-level rise on the structure and function of tidal marshes and how that may affect the hydro-geomorphic processes and marsh biotic communities. This type of information is useful to managers for incorporating local climate change into developing their monitoring, management, and adaptation strategies.

Keywords: climate change; ENSO; storm; salt marsh; sea-level rise; San Francisco Bay; tide

Introduction

Climate change impacts on the coastal zone include sea-level rise (Holgate and Woodworth 2004; Rahmstorf *et al.* 2007; Kemp *et al.* 2011), changes in precipitation and ocean sea surface temperature (Hamlet and Lettenmaier 2007; Bengtsson *et al.* 2009), and changes in the frequency and intensity of storms (Graham and Diaz 2001; Emanuel 2005; Webster *et al.* 2005; IPCC 2007). The Pacific Decadal Oscillation (PDO), a larger and slower cycling ocean pattern, is related to sea surface temperatures and sea-level pressure and has implications for local storm activity (Bond and Harrison 2000). In addition, other climate oscillations such as the El Niño Southern Oscillation (ENSO) vary every 3 to 7 years and exert control on the severity and frequency of storms throughout the North American Pacific coast (Abeysirigunawardena and Walker 2008; Hopkinson *et al.* 2008). At the local scale, El Niño can result in an increase in rain and stormy weather (Myoung and Deng 2009). However, there is a considerable degree of uncertainty around the patterns of El Niño and the potential for El Niño-like conditions to increase with projected warming of sea surface temperatures from global warming (Cobb *et al.* 2003). Yet, warmer sea surface temperatures have been related to an increase in the annual number and proportion of category 4-5 hurricanes since 1970 (Emanuel 2005; Webster *et al.* 2005). Along the northern Pacific coast of North America, an intensification of winter precipitation (Salathé 2006), will pose significant threats to coastal areas from storm surges and sustained winds (Mousavi *et al.* 2011). Sea-level rise and storm frequency and/or intensity are the greatest threat to the near-term sustainability of coastal ecosystems (Cayan *et al.* 2008, Nicholls and Cazenava 2010).

Coastal tidal marshes are found within the intertidal zone of temperate estuaries, along low-energy coastlines of mid to high latitudes at the ecotone between terrestrial and marine systems

The International Journal of Climate Change: Impacts and Responses
Volume 4, 2013, on-climate.com, ISSN: 1835-7156
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(Archibold 1995; Mitsch and Gosselink 2000). They are dynamic, highly productive ecosystems that support species adapted to living in physiologically challenging conditions. Tidal marsh platforms flood during high water and are drained by first or second-order tidal channels (or creeks). Tidal marshes are dominated by halophytic plants that have varying tolerances to inundation and salinity, resulting in strong ecological zonation across the elevation gradient (Mancera *et al.* 2005).

The combination of organic matter and mineral sediment deposition can allow tidal marshes to build their platform elevation to offset changes in local sea level (DeLaune *et al.* 1990; Watson 2008; Gedan *et al*. 2011). The magnitude of mineral sediment accretion is a function of suspended sediment concentration and inundation time, which is assumed to be related with surface elevation (Krone 1987; French 1993; Callaway *et al*. 1996; Kirwan *et al*. 2010). Delivery of suspended sediment can occur during storm surges (Zedler *et al.* 1986). However, inadequate sediment supply from local land use change may limit the ability of tidal marshes to keep pace with future sea-level rise (Syvhski *et al*. 2009; Kirwan *et al*. 2010). Vegetation plays an important role in the accretion process by trapping sediment and contributing organic matter to the subsurface peat layer (Morris *et al.* 2002). However, it is unknown whether tidal marshes will be able to keep pace with current accelerated rates of sea-level rise and how storms may change the relationship between accretion rate and sea level (Rybczyk and Cahoon 2002; Pont *et al*. 2002; Orr *et al.* 2003).

Tidal marsh terrestrial wildlife are well adapted to their dynamic environments and many are found exclusively in this coastal zone (Basham and Mewaldt 1987; Bias and Morrison 2006; Spautz *et al.* 2006; Rush *et al.* 2009; Tsao *et al*. 2009). Wildlife have been negatively affected by habitat degradation and loss (Nichols *et al*. 1986; Greenberg *et al.* 2006; Schwarzbach *et al.* 2006; Takekawa *et al.* 2006; Brusati and Grosholz 2009), and several are now listed as endangered or as species of special concern (USFWS 1984; USFWS 1985). Examples of species at risk include the endemic and federally endangered California clapper rail (*Rallus longirostris obsoletus*) (Fig. 1), salt marsh harvest mouse (*Reithrodontomys raviventris*), Suisun song sparrow (*Melospiza melodia maxillaris)*, San Pablo song sparrow (*M. m. samuelis),* and salt marsh common yellowthroat (*Geothlypis trichas sinuosa*; Takekawa *et. al.* 2011). These five species nest and seek shelter in high marsh vegetation in San Francisco Bay that provides protection from predators; however, high tide refugia are limited to narrow strips along levees, exposing wildlife to predators (Albertson 1995). Other examples of species of concern include the light-footed clapper rail (*Rallus longirostris levipes*), which prefer the low intertidal zone dominated by cordgrass (*Spartina spp.)* for feeding and nesting sites (Foin *et al.* 1997), and the Florida salt marsh vole (*Microtus pennsylvanicus dukecampbelli*) which has decreased substantially in abundance as a result of habitat loss (Woods *et al*. 1992; USFWS 1997). Coastal storm surges negatively impact terrestrial wildlife through decreases in fecundity and survival (Milton *et al.* 1994; Van de Pol *et al.* 2010).

Figure 1. a) The U.S. Federally endangered California clapper rail (Rallus longirostris obsoletus) spends most of its time using salt marsh channels (creeks) for feeding, especially during low tides. b) The same channel at mean higher high water (MHHW) is inaccessible to terrestrial wildlife forcing animals into the marsh platform vegetation. If sea level heights increase from sea-level rise, storm events or a synergy of both, wildlife are at higher risk from drowning and predation.

Our objective was to evaluate how regional low-pressure storms changed local tidal conditions. We hypothesized that regional weather conditions will increase sea level heights locally, resulting in increased inundation of the tidal marsh platform and plant communities. Storm events may impact the hydro-geomorphic processes and the biotic communities of coastal tidal marshes, and thus are important to evaluate in light of projected climate change. Here, we present results from two storm events at three tidal marshes in the semi-enclosed San Francisco Bay Estuary (SFBE), California, USA.

Methodology

Study Area

The SFBE supports the largest extent of tidal marsh in California. In 1850, tidal marsh covered an estimated 2,200 km^2 (Atwater *et al*. 1979), but fragmentation and modification through large scale land use changes resulted in loss of >80% of historic tidal marshes (Goals Project 1999). SFBE currently supports 162 km^2 (40,000 acres) of fragmented tidal marshes (Goals Project 1999) with recent restoration efforts underway to reverse this loss (Kershner 2010). Suspended sediment availability varies within SFBE but may be reduced from historic levels due to dam construction, bank protection, and the decrease in the sediment pulse from hydraulic mining (1880s), all of which have resulted in a ~50% reduction in suspended sediment discharge in the Sacramento River from 1957-2001 (Wright and Schoellhamer 2004; Schoellhamer 2011).

The tidal regime of the SFBE is mixed semi-diurnal and has an average diurnal range of 1.78 m (Golden Gate tide gage). Tide range varies seasonally with highest astronomical tides occurring in the winter and the summer. SFBE has a Mediterranean climate with cool, wet winters when storms with low atmospheric pressure produce high rainfall and strong winds. In California, Atmospheric Rivers (ARs) play an important role in storms and floods and have caused the largest historical storms in this region (Dettinger 2011). SFBE also lies within the California Current system where PDO and ENSO events contribute to regional climatic variation. For example, El Niño conditions affect local weather and can increase sea level height (SLH; +15-30 cm; Takekawa *et al.* 2006) typically in the winter months from December through March (Wilkerson *et al.* 2002). In addition, southerly winds are more likely during El Niño (Ryan *et al.* 1999), which can

contribute to SLH variation. However, within SFBE, storm surges generally do not exceed 0.7 m (Cayan *et al.* 2008). Future mean sea-level rise projections for California range from 44 to 166 cm by 2100, which may exacerbate storm SLHs (National Research Council 2012).

San Pablo Bay, located in the upper reach of SFBE is largely protected from wind and wave energy from the Pacific Ocean (Fig. 2). Local SLH is influenced by ocean tides, freshwater input from local creeks and rivers, and freshwater inflow from the Sierra Nevada through the Sacramento – San Joaquin Delta (Delta) via Suisun Bay and the Carquinez Strait. The bay is shallow with most areas less than 2 m below mean lower low water (MLLW; Jaffe et al. 2007). At the watershed scale, the suspended sediment supply is dominated by discharge from the Delta and augmented by river discharge from low elevation watersheds (Goman and Wells 2000).

Nearly 85% of San Pablo Bay tidal marshes have been altered by human activities such as diking, mining, salt pond development, and farming. The remaining tidal marshes are dominated by halophytic plants such as common pickleweed (*Sarcocornia pacifica*), pacific cordgrass (*Spartina foliosa*), bulrush (*Bolboschoenus maritimus*), and *Scirpus* species. They are generally located at high elevations within the marsh platform at mean high water (MHW).

Site-level measurements at three tidal marshes were used to evaluate how weather conditions during storms changed local SLHs compared to non-storm times within the marsh (Fig. 2). These sites are located in San Pablo Bay: a portion of the San Pablo Bay National Wildlife Refuge, hereafter SPB [38° 08’ N, 122° 24’ W], Coon Island [38° 11’ N, 122° 19’ W], and Petaluma Marsh [38° 11’ N, 122° 33’ W]. Coon Island and Petaluma Marsh are brackish tidal marshes located along the Napa and Petaluma Rivers, respectively. Both sites receive freshwater input from upstream sources and are influenced by tides from San Pablo Bay. SPB is located along the northwestern edge of San Pablo Bay and is influenced by tidal action and freshwater input via the Carquinez Strait and other local watersheds, including the Napa and Petaluma Rivers.

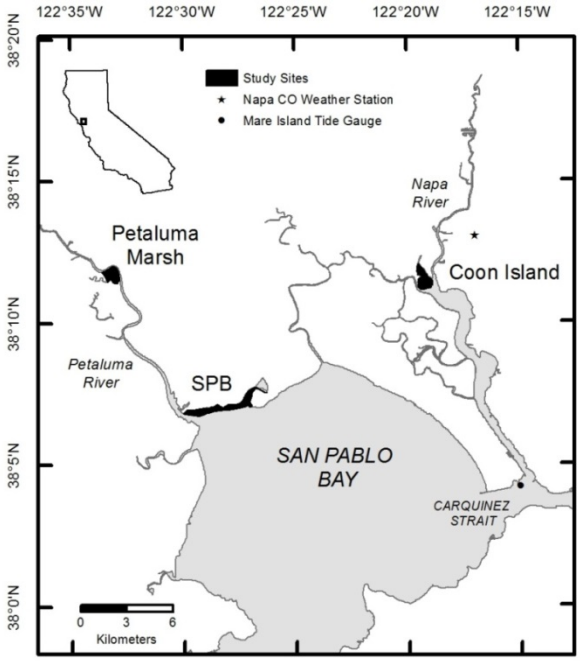

Figure 2. Data was collected at three tidal marshes in San Pablo Bay, California, USA, located in the northern reach of the San Francisco Bay Estuary. Here the tidal marsh platforms are inundated infrequently due to their high elevations.

Site Characterization

Survey-grade elevation surveys were performed in 2009-2010 at all study sites using a Leica RX1200 Real Time Kinematic (RTK) Global Positioning System (GPS) rover (± 1 cm x,y, ± 2 cm z accuracy; Leica Geosystems Inc., Norcross, GA). The rover positions were received from the Leica Smartnet system (www.leica-geosystems.com) and referenced to a National Geodetic Survey benchmark (X 552 1956 Mare Island). The average measured vertical error for the benchmark was ± 2.5 cm which is near the stated error of the RTK rover. Elevation data was surveyed in transect lines perpendicular to the bay edge; a survey point was taken every 25 m and 50 m separated transect lines. The Geoid03 model was used in calculating elevations (NAVD88; North American Vertical Datum of 1988) and all points were projected to NAD83 UTM zone 10. In addition, plant species richness and abundance were recorded concurrently at 50% of the elevation points. Plant species were identified within a 0.25 m^2 quadrat, and height (mean, maximum, measured within 0.05 m) and percent cover were estimated for each species.

Tidal marsh digital elevation models for all sites were created using the exponential model for Ordinary Kriging in ArcMAP (ArcGIS 9.3, ERSI 2009, Redlands, CA). Model parameters were adjusted to minimize the mean-root-square error (RMS), an internal measure of model performance. Lag size and number of lags were optimized for each site (lag size x lag number < ½ maximum distance among points, ERSI), and anisotropy was used because of the assumed linear trend in elevation. Resultant models were cross-validated by comparing models created with 70% of the data and tested with the remaining 30% of the data.

Weather

Storm events were characterized by low sea level pressure (SLP), high wind speeds, and substantial rainfall, with SLP being the most reliable metric of storm intensity (Bromirski *et al*. 2003). Hourly weather data for 2010 to 2011 was obtained from the National Climatic Data Center (NCDC; www.ncdc.noaa.gov) for the Napa County airport (38° 12’ N, 122° 16’ W), the nearest weather station to our field sites (Fig. 2). Two storms were selected for analysis based on their low SLP (daily minimum SLP below 1008.6 mb, the 2nd percentile level for San Francisco 1948-99, Bromirski *et al*. 2003), which was used as a metric for storm intensity. Days were categorized as either storm or non-storm based on the 2nd percentile level of SLP. Long-term weather data recorded at the San Francisco Airport was obtained from the NCDC for 1980-2011.

Inundation

Water level data loggers (Model 3001, 0.01% FS resolution, Solinst Canada Ltd., Georgetown, Ontario) were deployed at all three sites at the mouth of a second order channel (tidal creek) to capture inundation frequency and depth. Data was collected continuously every six minutes from January 2010 through May 2011. Water level logger units were surveyed with the Leica RTK GPS at the time of deployment and during data downloads to correct for any movement of the logger. Water levels were compensated for local barometric pressure with data from nearby independent loggers (Model 3001, 0.05% FS accuracy, Solinst Canada Ltd., Georgetown, Ontario). Mean high water (MHW) and mean higher high water (MHHW) were calculated by averaging 2010 high water peaks for each site. Tidal datums were adjusted to account for the 19-year lunar cycle from which NOAA calculates tidal epochs by comparing 2010 MHW and MHHW from four long-term tide stations around SFBE to the current NOAA tidal epoch. Observed and predicted local tides were calculated using sea level data from the Mare Island tide gage (38° 4.2’ N, 122° 15’ W; NOAA; www.tidesandcurrents.noaa.gov). The differences between predicted and observed SLHs were used to compare storm versus non-storm times. Non-storm was defined as the period within the same month when the storm did not occur. The weather conditions during the non-storm period were assumed to be typical for that time of year. To determine the amount of water on the marsh platform throughout the storm episodes the depth of site water level, D, was defined by (a) and the inundation index, I^*, was defined by (b):

$$(a)\ D = W - E$$

$$(b)\ \ I^* = \int_0^{D_{max}} T\ \partial\ D$$

where, W is observed water level, E is mean elevation of the marsh platform, and T is cumulative time as a percent. The inundation index (b) was used to compare periods of storm and non-storm episodes for all sites. Inundation was quantified by calculating the area under the curve (AUC) of depth vs. percent cumulative time and calculated for D from 0 to the maximum observed depth. To determine whether the variation in inundation was significant between storm and non-storm periods, the difference between AUC values was tested with a one-way t-test compared with zero.

Extended periods of inundation can lead to compaction of the organic peat layer from the weight of large volumes of water, potentially offsetting marsh accretion gain from storm sediment deposition (e.g., Cahoon 2006). To assess the potential for marsh compaction during storms, MHHW volume above elevation of the marsh platform was calculated using marsh area, mean elevation, and the water level logger data, and then compared to maximum storm water volume.

We developed *K* (c) as a comparison metric to standardize for area between sites.

$$(c)\quad K = \frac{(Max\ SLH - Mean\ Elevation) * Area}{(MHHW - Mean\ Elevation) * Area}$$

For example, *K* = 2 would indicate water volume on the marsh platform is twice the observed average volume at MHHW. A one-sample t-test was used to determine whether *K* was significantly different from one.

The amount of vertical vegetation exposed at extreme SLHs during storm episodes is an important yet underappreciated variable in the survival of tidal marsh terrestrial wildlife. Rates of wildlife predation and drowning are believed to be greater during high marsh platform inundation levels, as animals are forced to move out of the habitat to adjacent uplands (Albertson 1995). To assess storm impacts on tidal marsh habitats, we calculated the amount of available vegetation during storm and non-storm MHHW as well as at maximum SLH during the storm. Mean height of dominant vegetation, based on percent cover, was used in conjunction with the elevation model to calculate the percent of vertical vegetation structure inundated by high water. Paired t-tests were used to determine significance of differences between storm and non-storm periods across study sites. All statistical analysis was completed using R (www.cran.r-project.org).

Results

Marsh Characterization

Across the three study sites, 88% of the elevation survey points fell within 1.5-2.0 m, NAVD88 (Table 1). The low slope elevation is characteristic of tidal marshes (Archibold 1995) and a critical geomorphic feature when considering marsh platform flooding. Residual model error (RMS) was low (mean error across all sites = 0.083 m), representing 3.5% of the elevation range. Pickleweed (S. *pacifica*, SAPA) was the most prevalent species across sites (90.8% survey points).

Other common tidal marsh species were found in lower abundance, including bulrush (B. maritimus, BOMA, 15.3%), Grindelia stricta (GRST, 7.5%), Frankenia salina (FRSA, 7.4%), and Spartina spp. (SPFO, 3.2%) with average heights (cm) of 45 (SAPA), 92 (BOMA), 68 (GRST), 27

(FRSA), and 77 (SPFO); these plant percent cover and heights were incorporated into the vegetation inundation modeling

Table 1: Study site characteristics and study survey data summary, elevation in NAVD88 and tidal range data modified from NOAA. Coon Island and Petaluma Marsh are similar in size and tidal range; however, SPB is double in area and sits at a lower tidal range. (n) represents the number of survey points.

	Area (km^2)	Mean Elevation (m)	Elevation Range (m)	Tidal Range (m)	Elevation Survey (n)	Vegetation Survey (n)
Coon Island	987	1.83	1.25	1.48	799	364
Petaluma Marsh	806	1.87	1.41	1.49	655	356
SPB	1802	1.76	1.49	1.39	950	513

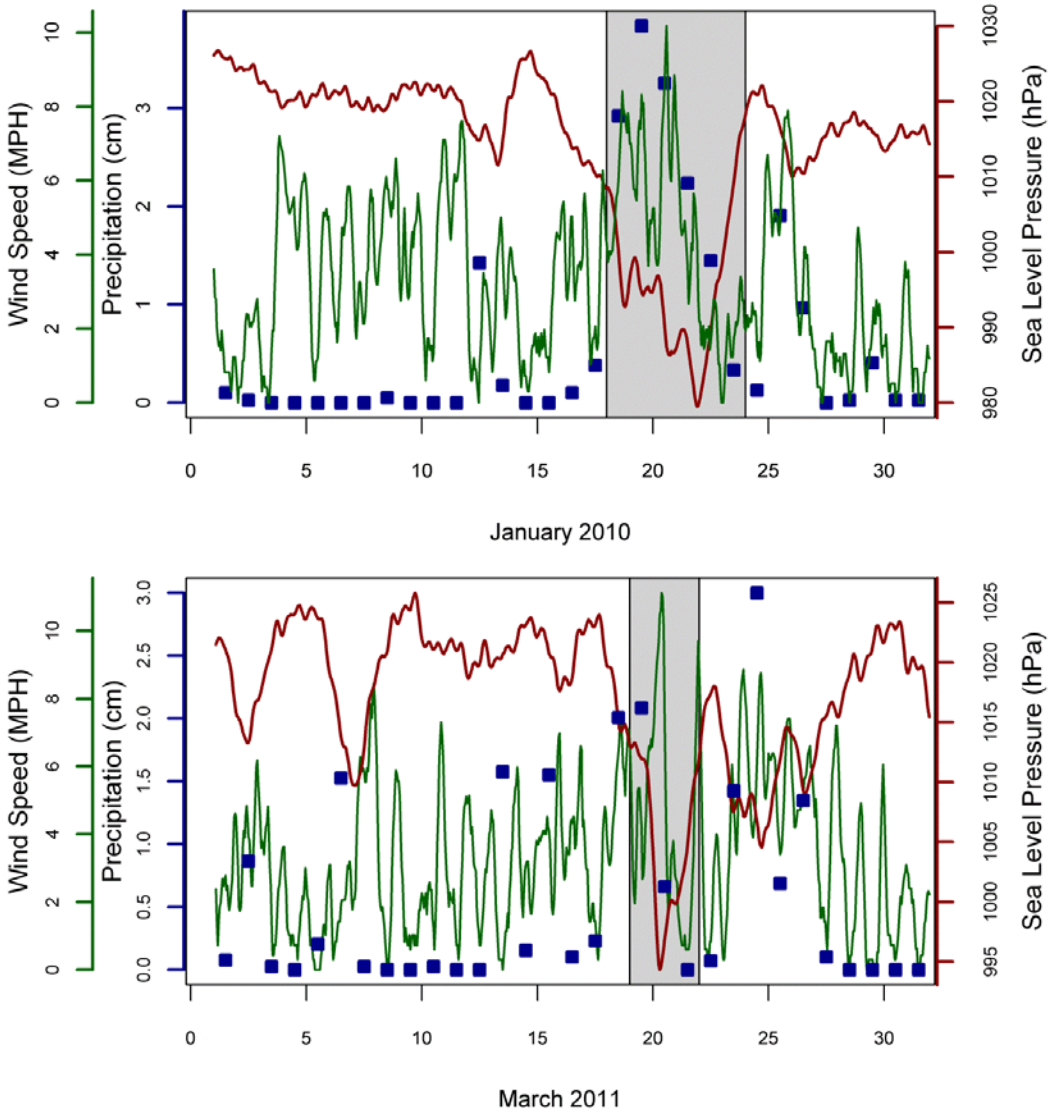

Figure 3. The shaded storm periods showed higher than normal mean daily wind speed (green, MPH), higher daily total precipitation (blue, cm), and lower hourly sea level pressure (red, hPa) for both January 2010 and March 2011 (Napa county airport).

Storms

The two storm episodes occurred on 18-23 January 2010 and 19-21 March 2011. Air pressure at sea level (SLP), was significantly lower during the storm episodes than during the non-storm periods each month (January: $t_{29} = 8.62$, $p < 0.0001$; March: $t_{29} = 4.48$, $p = 0.0001$; Fig. 3). This resulted in a difference between measured observed tidal level and predicted tidal level (Fig. 4). Minimum SLP was 979 mb and 993 mb for the January 2010 and March 2011 storms, respectively; the January 2010 storm had the lowest SLP recorded in the estuary since at least 1980. Mean daily

wind speed and precipitation was higher (Fig. 3) during the January 2010 storm when compared to non-storm periods, although only the precipitation increase was significant (wind speed—January: $t_{29} = 1.97$, $p = 0.06$; March: $t_{29} = 1.62$, $p = 0.12$; precipitation—January: $t_{29} = 6.70$, $p = 0.0001$; March: $t_{29} = 0.72$, $p = 0.47$).

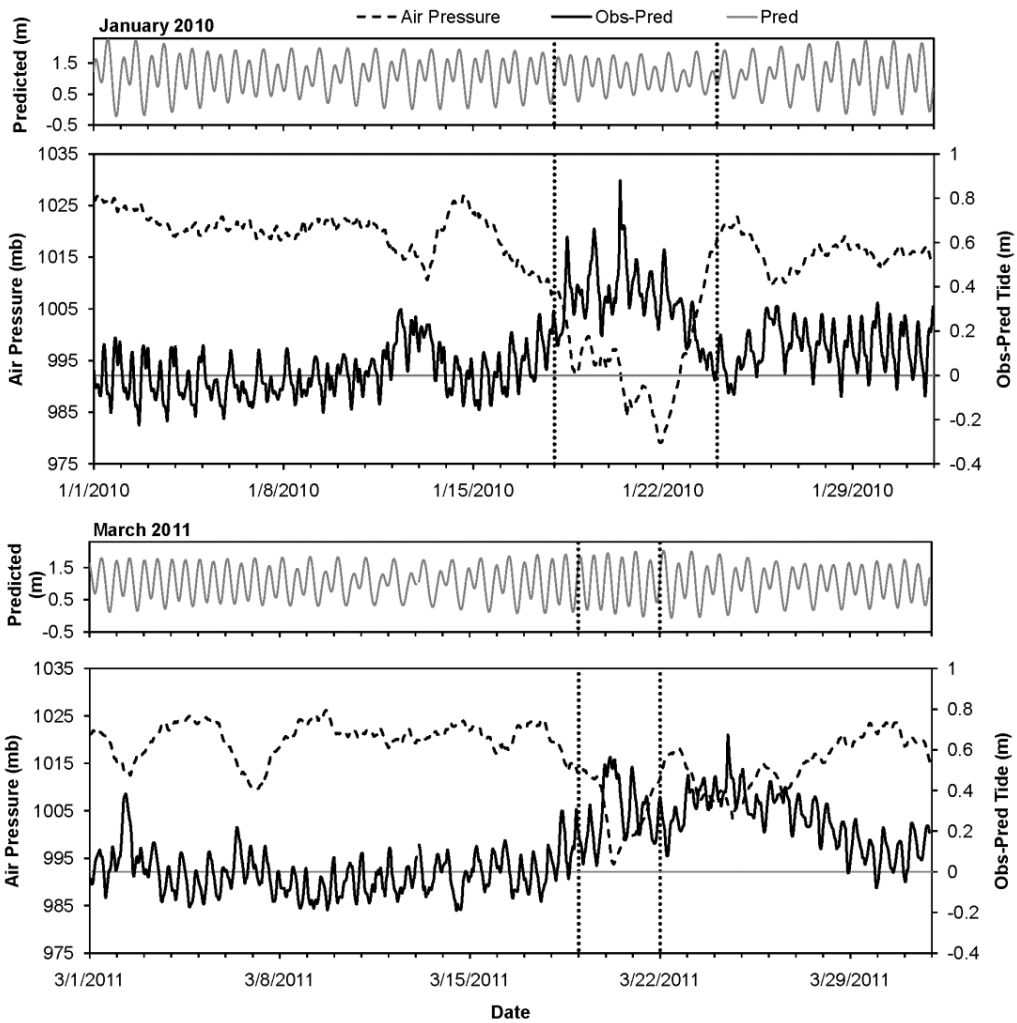

Figure 4. The difference in observed and predicted sea levels (m) in relation to air pressure (mb) and predicted tides (m, NAVD88) was substantial for both storm episodes. Storm episodes showed a drop in air pressure and a large difference between the observed sea levels compared to the astronomical predicted sea levels (modified from National Climatic Data Center for the Mare Island tide gage and Napa County airport).

Table 2. Inundation index (I*), as calculated by the area under the curve (AUC), for both storm events across all three salt marsh sites. Sites showed similar trends between storms, and the marsh platform was inundated longer and deeper during the storm episodes compared to the rest of the month

	January 2010		March 2011	
	Storm	Non-Storm	Storm	Non-Storm
Coon Island	5.29	2.74	9.28	1.52
Petaluma Marsh	4.72	2.25	9.51	1.12
SPB	7.97	3.46	11.85	2.03

Strong southerly winds in the first three days of the January 2010 storm forced water onto the marsh platform, increasing the observed storm surge. The March 2011 storm also produced winds from the south but only for one day. Marsh platform inundation during the January 2010 and March 2011 storm episodes was significantly greater than during non-storm periods across each of our three sites based on AUC values ($t_2 = 4.77$, $p = 0.04$, $t_2 = 14.25$, $p = 0.005$, respectively; Table 2). Across study sites, the mean ratio of *I** (±SE) of storm:non-storm, was 2.11±0.11 for January 2010 and 6.81±0.83 for March 2011 (Fig. 5).

Water level loggers placed in channels captured the upper 66% of the full tide range during both storms. We were unable to calculate mean sea level (MSL) *in situ* because the sensor did not provide readings during low tides when water drained from the channels; however, the high elevation of the studied marshes captured the biologically and geomorphically meaningful portion of the tidal cycle that inundated the marsh platform. The MHW and MHHW (North American Vertical Datum 1988) for Petaluma Marsh were 1.76 m and 1.91 m; for Coon Island 1.77 m and 1.93 m; and for SPB 1.68 m and 1.85 m, respectively.

At all sites, the amount of time the marsh platform was inundated was significantly longer during storm events than non-storm periods; the January 2010 storm inundated the marsh platform an average of 6.7 h/d compared with 3.8 h/d during non-storm periods ($t_2 = 15.87$, $p = 0.004$). At all sites during the March 2011 storm, marsh platforms were inundated even longer, an average of 8.3 h/d compared with 2.7 h/d during non-storm periods ($t_2 = 43.56$, $p = 0.0005$, Table 3).

K was 5.13 for the peak flood in the January 2010 storm and significantly different from 1.0 ($t_2 = 4.46$, $p = 0.047$; at all sites). *K* was marginally insignificant for March 2011 because of increased variation around the mean at 10.69 ($t_2 = 4.07$, $p = 0.055$; Table 4). Across all sites, *K* was higher during March 2011 than January 2010, and Petaluma Marsh had the highest value for both storm episodes because of its relatively high elevation and low MHHW volume during non-storms.

The percent of vertical vegetation inundated during the January 2010 storm episode was significantly greater for the maximum SLH ($t_2 = 6.14$, $p = 0.026$), and greater but not significant during MHHW ($t_2 = 3.67$, $p = 0.067$) when compared to non-storm periods. In contrast, the percent of vertical vegetation inundated in the March 2011 storm was significantly greater than non-storm periods in the same month for MHHW ($t_2 = 23.03$, $p = 0.002$) and maximum SLH ($t_2 = 19.65$, $p = 0.003$, Table 5).

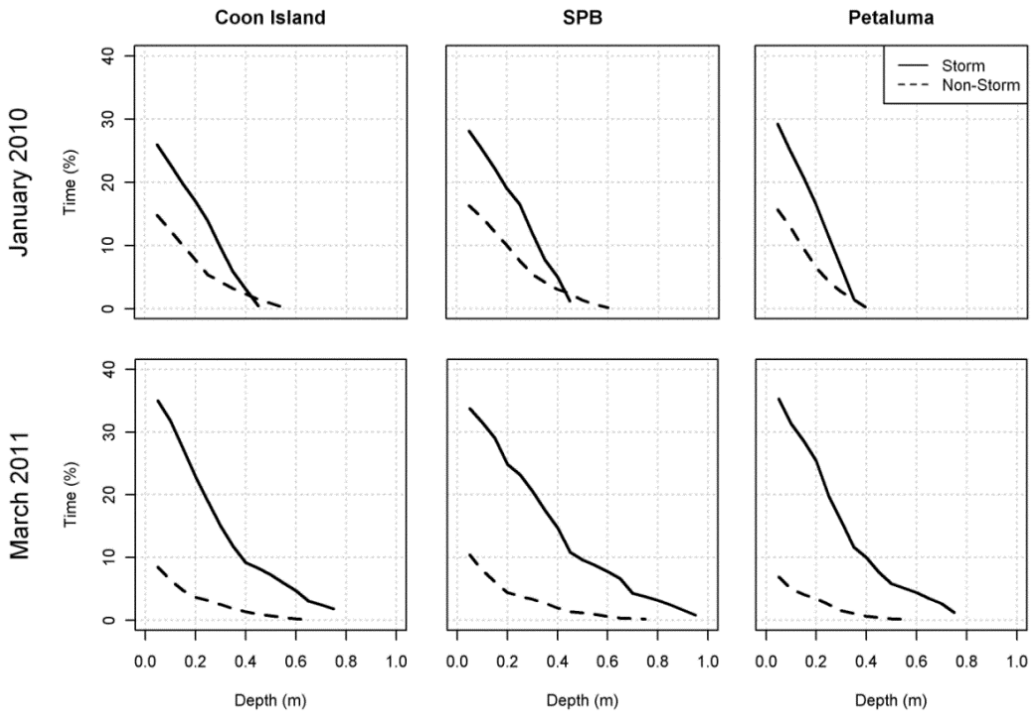

Figure 5. During both storm episodes the percentage of time the tidal marshes were inundated was greater than during non-storm days in the same month for all study sites. Depths were similar, with March 2011 showing slightly higher depths of water during the storm. For Coon Island and SPB the non-storm period of the month had deeper water levels due to the high astronomical tides in January 2010; however, the storm episode had water resting on the marsh platform longer.

Table 3. Hours per day the tidal marsh platform at mean elevation was inundated during the two storm episodes. This was calculated using deployed water level loggers at six-minute resolution at all sites. Non-storm time was considered all other days of the month minus storm days. The January 2010 storm had double the inundation time compared to non-storm days of the same month. However, the time of inundation almost tripled during March 2011.

	January 2010		March 2011	
	Storm	Non-Storm	Storm	Non-Storm
Coon Island	6.23	3.59	8.40	2.94
Petaluma Marsh	7.02	3.76	8.47	2.57
SPB	6.75	3.92	8.10	2.50

Table 4. K value, a comparison metric, was developed to standardize the study sites by area. K is defined by the amount of water as a multiple of MHHW volume on the marsh platform at maximum sea level height (SLH, m), for the two storm events. Here, MHHW is used as an indicator of 'normal' high water volume on the marsh platform in a year, whereas K is the magnitude more than the average volume.

	January 2010 (*K*)	Max SLH (m)	March 2011 (*K*)	Max SLH (m)	MHHW Volume (km3)
Coon Island	3.86	2.24	7.00	2.57	103.88
Petaluma Marsh	6.93	2.20	15.14	2.58	38.05
SPB	4.60	2.19	9.94	2.68	167.63

Table 5. Percent of vertical vegetative habitat inundated during both storm episodes across all sites. The March 2011 storm had 80-90% of the available habitat inundated and therefore functionally unavailable for wildlife. The maximum sea-level height (Max SLH) was highest at Petaluma Marsh during both storm episodes. MHHW and Max SLH were determined from water level loggers deployed in 2nd order channels.

	January 2010			March 2011		
	MHHW Non-Storm	MHHW Storm	Max SLH Storm	MHHW Non-Storm	MHHW Storm	Max SLH Storm
Coon Island	40.88	55.95	65.41	7.46	80.94	93.59
Petaluma Marsh	46.58	73.90	78.52	15.55	92.85	97.78
SPB	54.27	65.46	72.23	23.45	90.00	95.85

Discussion

Extreme SLHs were modulated predominately through the inverse barometer effect (Chelton and Davis 1982), where a 1 hPa drop in air pressure results in a ~1.65 cm increase in sea level (Bromirski *et al.* 2003). We found that the storm episodes of January 2010 and March 2011 produced extreme local SLHs and resulted in tidal marsh platform inundation ~1.8 and 3.1 times greater, than during non-storm periods within the same month (Fig. 4). The largest astronomical tide of 2010 occurred just after the January 2010 storm event, which contributed to the overlap of inundation curves between storm and non-storm periods (Fig. 5). The March 2011 storm coincided with the highest predicted tide of the month. This produced conditions with greater depth and duration of inundation and higher K and I^* values, than the January 2010 storm (Tables 2-4).

Substantial differences in the non-storm periods between January 2010 and March 2011 contributed to the relatively higher storm indices for March 2011. The higher astronomical tides in January 2010 compared with March 2011 increased inundation time but not depth during the non-storm periods. The January 2010 storm resulted in a 2-fold increase in the amount of time water remained on the tidal marsh platform and a similar increase in K. The March 2011 storm had a 3-fold increase in both K and duration of water on the tidal marsh platform. The volume of water sitting on the marsh platform surface can increase peat compaction; however, the amount of compaction depends on the percentage of subsurface organic matter (Cahoon *et al.* 2006; Cahoon 2006). The development of a tidal marsh compaction model that accounts for the percent of organic matter in the soil, sediment type, and platform inundation (e.g., I^*) would improve our understanding of how extreme SLHs affect marsh elevation.

While we did not measure *in situ* sediment deposition rates during storms, based on previous observations (e.g., Stumpf 1983; Cahoon *et al*. 1996) we can infer that an increase in turbidity and duration of inundation increases sediment deposition on the marsh platform. Each storm produced spikes in suspended sediment coming into San Pablo Bay with turbidity 21 times greater than the monthly average in January 2010 and 22 times greater in March 2011 (G. Shellenbarger, USGS, personal communication, 9 June 2011). Turbidity peaked ~3 days after the end of the January 2010 storm, whereas it peaked <12 hrs after the Marsh 2011 episode (G. Shellenbarger personal

communication, 9 June 2011). Non-storm tidal action may be insufficient for long-term persistence of tidal marsh elevation, and episodic storms may contribute significantly to annual accretion rates with 1-2 events capable of delivering enough sediment to maintain marsh platforms (Stumpf 1983; Reed 1989; Cahoon *et al.* 1996; Roman *et al.* 1997; Ward *et al.* 2003; Callaway and Zedler 2004). Monitoring suspended sediment concentrations, deposition rates, and marsh compaction during and after storms are important to understanding tidal marsh elevation changes.

During periods of average MHHW the amount of vegetation submerged was 7-55% at the study sites, which varied by season (Takekawa *et al.* 2013). In contrast, during the peak storm times we found that 65-98% of the vegetation was under water across all sites (Table 5). During the March 2011 storm, there was a 7-fold increase in the amount of vegetation under water compared with the average non-storm period. Many tidal marsh wildlife species have developed breeding strategies to avoid predation and nest drowning from high tides and seasonal storms (Takekawa *et al.* 2011). For example, the March 2011 storm episode occurred during the reproductive season (March-April) for the California black rail (*Laterallus jamaicensis coturniculus:* Takekawa *et al*. 2006; Tsao *et al*. 2009), where we observed 80-90% of the vegetation was submerged at all sites. Extreme SLHs that increase the volume and duration of water on the marsh platform and results in vegetation submergence are likely to reduce fecundity of tidal marsh wildlife (Massey *et al.* 1984; Takekawa *et al.* 2006).

Conclusion

The objective of our research was to evaluate how regional low-pressure storms changed tidal conditions locally. Storm surges that drive water farther onshore can result in erosion, compaction, saltwater intrusion, and increased sediment deposition that threaten plant and wildlife communities (Wiley and Wunderle 1993; Milton *et al.* 1994; Cahoon *et al.* 1996; Michener *et al.* 1997; Culberson *et al.* 2004; Temmerman *et al*. 2004; Cahoon 2006). We hypothesized that regional weather conditions will increase SLH locally, resulting in increased inundation of the tidal marsh platform and plant communities. Storm events are important to evaluate in light of projected climate change and sea-level rise.

We observed both an increase in water depth and duration during both storm events, which resulted in an increase of vegetation submergence at all sites. Changes in inundation regimes can alter the biological zonation of plant communities due to inundation and salinity tolerance limitations (Foin *et al.* 1997; Mendelssohn and McKee 1988; Day *et al.* 2008; Zedler 2010). In addition, during large storms vegetation may be buried or covered with silt which can reduce primary productivity or cause dieback (Callaway and Zedler 2004). In contrast, storm flushing and sediment influx can increase delivery of nutrients and reduce soil salinity, which are necessary to promote vegetative growth (Zedler *et al.* 1986; Zedler 2010). However, torrential rains create runoff with high sediment loads that can increase deposition and bury vegetation (Day *et al* 2007; Zedler 2010). Locally, water discharge can lag behind during heavy rainfall, which may lead to high SLHs for several days after a storm (Bromirski and Flick 2008). The high elevation marsh platform characteristic of our study sites is usually flooded infrequently and thus contains hypersaline soils and salt-tolerant species (e.g., *S. pacifica*). After periods of extended inundation from storms, Zedler *et al.* (1986) reported unusually low *S. pacifica* ground cover at a California salt marsh. In contrast, extensive periods of flooding can create anoxic conditions that reduce vegetative vigor and may cause diebacks (Mendelssohn and McKee 1988; Cahoon *et al.* 1996; Day *et al.* 2008). Important knowledge gaps exist about the effects of storms on vegetation and ecosystem response (Zedler 2010). Monitoring of tidal marsh vegetation response to increased flooding from storms would improve our understanding and provide insight into forecasting changes due to sea-level rise and storms.

Marsh wildlife species are accustomed to living in a dynamic system and have physiological and behavioral adaptations that allow their persistence (Greenberg *et al.* 2006). At our study sites

during the March 2011 storm, there was a 7-fold increase in the amount of inundated vegetated habitat. During storms wildlife with limited dispersal abilities are forced to adjacent upland areas or levees (Hulst *et al*. 2000). Predation from feral cats (*Felis catus*) and red foxes (*Vulpes vulpes regalis*), have been shown to have a large impact on California clapper rail populations during high water events (Foin *et al.* 1997; Harding *et al*. 2001). In addition, the salt marsh harvest mouse has also been shown to move to dense upland vegetation during high water (Bias and Morrison 2006; Hulst *et al*. 2000), presumably to avoid exposure from predators and drowning. However, if storms increase in frequency or severity with climate change, this will decrease the amount of available habitat and will displace wildlife from their current range and expose them to competition and predation as forced dispersal occurs (Zedler *et al.* 1986). In addition, storms during the breeding season, like the extreme event in March 2011, can overtop nests and cause egg failure, reducing fecundity of marsh wildlife (Massey *et al.* 1984; Takekawa *et al.* 2006). For example, nests built in marshes are positioned low enough in the vegetation to avoid predation, but high enough to avoid flooding risk (Massey *et al*. 1984; Schwarzbach *et al.* 2006); however, many species may be maladapted to an increase in the frequency of storms during spring breading seasons.

Climate Change

Sea-level rise and an increase in coastal storms could negatively affect tidal marshes. Global climate models (GCMs) have yet to converge on future scenarios for storms (Bengtsson *et al.* 2009; Stephens 2011); however, Pacific coast storms have increased in frequency and intensity (Graham and Diaz 2001). SLH extremes have increased 20-fold in SFBE since 1915 (Cayan *et al.* 2008). More frequent and intense El Niño events, as a result of warming in the central Pacific Ocean (Lee and McPhaden 2010), will bring more storm episodes to the SFBE as El Niño tends to shift storm tracks south from the Washington and Oregon coasts. In addition to changes in storm frequency, ongoing sea-level rise will create more SLHs extremes (Cayan *et al.* 2008), like those observed in January 2010 and March 2011.

During the 2009-2010 El Niño, 20 days were recorded with SLP below the local threshold for intense storms for SFBE (Bromirski *et al.* 2003). The thermal expansion of seawater and prevailing winds during El Niño raised sea levels in the eastern part of the Pacific, and effectively reduced the difference between non-storm and storm conditions during January 2010. 2011 was a La Niña year (www.elnino.noaa.gov), which also factored into the differences between the March 2011 and January 2010 storm SLHs. The timing of astronomical tides and ENSO are important factors when evaluating storm-elevated SLHs.

Because the high tidal marsh platforms of our study were inundated infrequently by tides during non-storm periods, a change in sea-level and storm frequency or intensity could substantially alter the inundation frequency-duration of the marsh platform. The increased depth and duration of flooding during the January 2010 and March 2011 storm events combined with relatively high sediment delivery from the local turbidity record indicated that storms may provide local suspended sediment to build marsh elevation relative to sea-level rise. Wind-driven re-suspension of sediment in the spring resulted in the highest annual suspended sediment concentrations in SFBE (Schoellhamer 2002). Therefore, while storms are potentially detrimental to existing plant and wildlife communities, they may be important for long-term tidal marsh stability with sea-level rise.

Acknowledgments

The authors would like to thank the U.S. Geological Survey (USGS), Western Ecological Research Center, the USGS National Climate Change and Wildlife Science Center for funding support, and the U.S. Fish and Wildlife Service California Landscape Conservation Cooperative and Region 8 Inventory and Monitoring Program for recent program contributions. In addition, we would like to thank the USGS California Water Science Center (G. Shellenbarger, J. Drexler, D. Schoellhamer) and the University of California, Davis, Geography Graduate Group for assistance (D.Elliott-Fisk, S. Ustin). The authors would like to thank K. Spragens for study design support, and P. Elsen, T. Henner, T. Bui for project assistance. Helpful review comments were provided by J. Albertson, S. Jones, and L. Smith. Any use of trade, product, or firm names in this publication is for descriptive purposes only and does not imply endorsement by the U.S. government.

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ISSN 1835-7156