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Sedimentation, elevation and marsh evolution in a southeastern Australian estuary during changing climatic conditions

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Abstract

Mangrove and salt marsh vertical accretion and surface elevation change was measured at Kooragang Island within the Ramsar-listed Lower Hunter estuarine wetlands in New South Wales, Australia, using surface elevation tables and marker horizons over a ten-year period. We surveyed mangrove, salt marsh and a zone of mangrove encroachment into salt marsh. The period of analysis was dominated by El Niño (drought) climatic conditions, though included a series of east coast low pressure systems and associated storms over the central coast of NSW in June 2007. The storms may have initially caused scouring of sediments in the mangrove zone, followed by significant accretion within both the mangrove and salt marsh during the six months following the storms, with most of this accretion corresponding to spring tides several months after the storms. These accretion events were not accompanied by an equivalent elevation change, and robust elevation trends over the study period in mangrove and salt marsh indicate that the storms may have had little impact on the longer-term elevation dynamics within both the mangrove and salt marsh at Kooragang Island. Elevation dynamics in these zones appear to be regulated by vertical accretion over longer time periods and modulated by hydrology at shorter temporal scales. Elevation declined in the mangrove encroachment zone despite continued vertical accretion and we propose that this discrepancy may be associated with expansion of tidal creeks near the zone of mangrove encroachment or loss of salt marsh vegetation. This pattern of encroachment is consistent with observations from sites throughout the region and may be related to climatic perturbations (El Niño Southern Oscillation) rather than directly attributed to the storms.

Keywords

sedimentation, conditions, elevation, marsh, evolution, southeastern, australian, estuary, during, changing, climatic

Disciplines

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Sedimentation, Elevation and Marsh Evolution in a southeastern Australian Estuary during Changing Climatic Conditions

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ABSTRACT

Mangrove and salt marsh vertical accretion and surface elevation change was measured at Kooragang Island within the Ramsar-listed Lower Hunter estuarine wetlands in New South Wales, Australia, using surface elevation tables and marker horizons over a ten-year period. We surveyed mangrove, salt marsh and a zone of mangrove encroachment into salt marsh. The period of analysis was dominated by El Niño (drought) climatic conditions, though included a series of east coast low pressure systems and associated storms over the central coast of NSW in June 2007. The storms may have initially caused scouring of sediments in the mangrove zone, followed by significant accretion within both the mangrove and salt marsh during the six months following the storms, with most of this accretion corresponding to spring tides several months after the storms. These accretion events were not accompanied by an equivalent elevation change, and robust elevation trends over the study period in mangrove and salt marsh indicate that the storms may have had little impact on the longer-term elevation dynamics within both the mangrove and salt marsh at Kooragang Island. Elevation dynamics in these zones appear to be regulated by vertical accretion over longer time periods and modulated by hydrology at shorter temporal scales. Elevation declined in the mangrove encroachment zone despite continued vertical accretion and we propose that this discrepancy may be associated with expansion of tidal creeks near the zone of mangrove encroachment or loss of salt marsh vegetation. This pattern of encroachment is consistent with observations from sites throughout the region and may be related to climatic perturbations (El Niño Southern Oscillation) rather than directly attributed to the storms.

KEYWORDS

storms, mangrove, salt marsh, surface elevation, vertical accretion, sea-level rise

1. INTRODUCTION

Coastal wetlands in southeastern Australia are in a state of flux due to the widespread encroachment of salt marsh by mangrove noted in many studies (Saintilan and Williams, 1999; Rogers et al., 2006; Oliver et al., 2012); a pattern that is increasingly observed in concomitant mangrove and salt marsh communities globally (Saintilan et al., in press). In Australia, this encroachment pattern has been attributed to rainfall in recent Queensland studies (Eslami-Andargoli et al., 2009; Eslami-Andargoli et al., 2010), and sea-level rise in the southern states of New South Wales and Victoria (Rogers et al., 2006). That was the case in the Hunter estuary of New South Wales, where 67% of salt marsh was lost over three decades to 2000 (Williams et al., 1999). As part of the present study, a series of surface elevation tables and marker horizons (SET-MH) (Cahoon et al., 2002) were deployed on Kooragang Island of the Hunter estuary in 2001 within salt marsh, mangrove and mangrove encroachment zones to determine patterns of sedimentation and vertical accretion with respect to water level trends associated with mangrove encroachment.

Under prevailing conditions in southeastern Australia, tidal waters that flood coastal wetlands are typically turbid (Adam, 1990) and flow velocity of tides is reduced as they move over mangrove and salt marsh vegetation, enabling sediments and organic material to settle on the marsh surface (Adam, 1990; Mazda et al., 1997; Saenger, 2002). Where sediment contribution to a coastal wetland is derived from tidal incursions rather than terrigenous processes, vertical accretion is typically proportional to the volume of water inundating the marsh surface (Rogers et al., 2006), which is consistent with trends found elsewhere (Kirwan and Guntenspergen, 2010). Vertical accretion is also typically greater in mangrove forests than in salt marsh, even though the density of vegetation is less, as they are located lower in the tidal frame and are inundated more frequently and to a greater depth than salt marshes (Adam, 1990; Rogers et al., 2006; Saintilan et al., 2009). Processes of subsidence and accretion may be influenced by episodic prolonged drought and/or major floods of long return period (Rogers et al., 2005; Rogers et al., 2006; Rogers and Saintilan, 2009).

Relationships between tidal flow, vertical accretion and marsh elevation have been recognised for some time and marshes have been found to accumulate sediment and organic material at rates equal to historic rates of sea-level rise (Bricker-Urso et al., 1989; DeLaune et al., 1989; Lynch et al., 1989; Woodroffe, 1990; Reed and Cahoon, 1993; Roman et al., 1997; Friedrichs and Perry, 2001). Vertical accretion is well recognised as an important influence on wetland stability, and research is now focussing on wetland resilience and factors limiting their capacity to build elevation at rates equivalent to sea-level rise (Kirwan et al., 2010; Stralberg et al., 2011; Rogers et al., 2013).

Short-term perturbations, such as storms and droughts, may substantially influence the relationship between tidal flow, vertical accretion and marsh elevation (Reed, 1989; Rogers and Saintilan, 2009); consequently these perturbations have been postulated to influence the long-term resilience of marshes (Cahoon and Reed, 1995; Cahoon et al., 1995a; Day et al., 1995; Friedrichs and Perry, 2001; Reed, 2002). Storm impacts can be substantial and cause significant geomorphic change in coastal wetlands (Nyman et al., 1995; Cahoon, 2003; Cahoon et al., 2003; Davis et al., 2004; Cahoon, 2006; Smith et al., 2009), and surface elevation tables and marker horizons have been used to explore accretion and elevation changes in coastal wetlands following hurricanes in the Gulf of Mexico and Honduras (Cahoon et al., 2003; McKee and Cherry, 2009; Whelan et al., 2009) and a storm event in southern California (Cahoon et al., 1996). Turbidity within estuaries fluctuates in response to storms, flood events and prolonged drought, and may result in substantial storm deposits and/or redistribution of sediments (Nyman et al., 1995; Cahoon et al., 1996; McKee and Cherry, 2009; Whelan et al., 2009). Alternatively, the increased flow velocities and raindrop impact associated with storms may remove sediments from coastal wetlands (Pethick, 1991; Cahoon et al., 1995a; Guntenspergen et al., 1995). Cahoon (2006) reviewed the elevation response of coastal wetlands to storms and found that many studies reported elevation changes equivalent to the degree of accretion or erosion attributed to the storm; however, in some cases, subsurface processes influenced the elevation response. Six subsurface processes were identified to influence the relationship between accretion/erosion following a storm and elevation change: compaction, shrinkage, root decomposition, root growth, swelling and lateral folding.

Research on the relationship between short term perturbations, such as storms, and marsh geomorphology is in its infancy; the role of storms in regulating the function and structure of estuaries or their vegetation communities is not well understood (Day et al., 1997; Davis et al., 2004) and the longer term signature of extreme events is a considerable knowledge gap. In addition, studies of the response of coastal wetlands in Australia to storms are lacking, with storm response research focussing on estuarine hydrodynamics (Wolanski, 1977; Eyre, 1998; Moore et al., 2006; Drewry et al., 2009). Climate change and sea-level rise in the 21st

century will add pressure on coastal wetlands (Bernstein et al., 2007; Rahmstorf et al., 2007; Horton et al., 2008; Vermeer and Rahmstorf, 2009; Jevrejeva et al., 2010), including increased frequency and intensity of short-term perturbations (Webster et al., 2005), and so it is timely to consider the role of storms in long-term wetland resilience.

One characteristic limitation of short time-series observations of surface elevation, even encompassing a decade or more, is that the observation period may not include extreme events that might profoundly influence longer-term trends. This limitation is noted by Webb et al. (2013) who recommend a minimum 5 to 10 year data set for comparison with local relative sea-level rise. Our study period encompassed the extremes of a prolonged El Niño drought (2001-2006), and an exceptional series of storms and flooding events in 2007, with a return to neutral climatic conditions in the following five years (2008-2012). Using SET-MH data (reanalysed from Howe et al., 2009; Rogers et al., 2012) we investigated accretion and elevation changes occurring in mangrove and salt marsh at Kooragang Island over a 10.5-year period, which encompassed the range of processes likely to influence sedimentation and surface elevation in the longer-term. Specifically, we explored two hypotheses: H1) extreme storm events; characterised by high intensity rainfall, extreme flooding and associated catchment sediment yield; have a long-term effect on rates of estuarine wetland accretion and surface elevation change; and H2) mangrove encroachment is driven by an elevation deficit within the salt marsh and mangrove encroachment zone. This paper contributes to knowledge gaps about the long-term geomorphic influence of extreme storms on estuarine wetlands and the influence of extreme storms on the structure and function of vegetation communities.

2. STUDY SITE

Kooragang Island (151° 48’E, 32° 55’S), located approximately 10 km from the mouth of the Hunter River in southeastern Australia, was formed from fluvial deposition of sediments at the mouth of the river that resulted in the development of a series of deltaic islands and channels (Figure 1). The Hunter River has a length of approximately 300 km and drains a relatively large catchment area of 22 000 km^2. The Hunter River forms a barrier estuary with a semi-diurnal tidal regime and a tidal range of 1.9 m at the river mouth. In geomorphic terms, the Hunter estuary is mature with well-developed mangrove and salt marsh communities and extensive alluvial plains (Roy et al., 2001). Water levels within the Hunter estuary increased at a rate of 1.1 mm y^{-1} between 1966 and 2010 (based on mean annual water level at Newcastle Harbour, BOM, 2012b). Over the study period water levels increased by 14.6 mm y^{-1} at the Ironbark Creek water level gauge (MHL, 2012b) located approximately 1 km downstream from the mangrove study site and 7.3 mm y^{-1} at the Hexham Bridge water level gauge located approximately 4 km upstream from the study site (MHL, 2012a). Discharge within the Hunter River reflects the influence of the El Niño Southern Oscillation on rainfall within the catchment over the study period (Figure 2).

Figure 1: Location of study site. (a-b) Kooragang Island. (c) SET-MH on Kooragang Island. Basemap sources: Esri, DigitalGlobe, GeoEye, i-cubed, USDA, USGS, AEX, Getmapping, Aerogrid, IGN, IGP, swisstopo, and the GIS User Community.

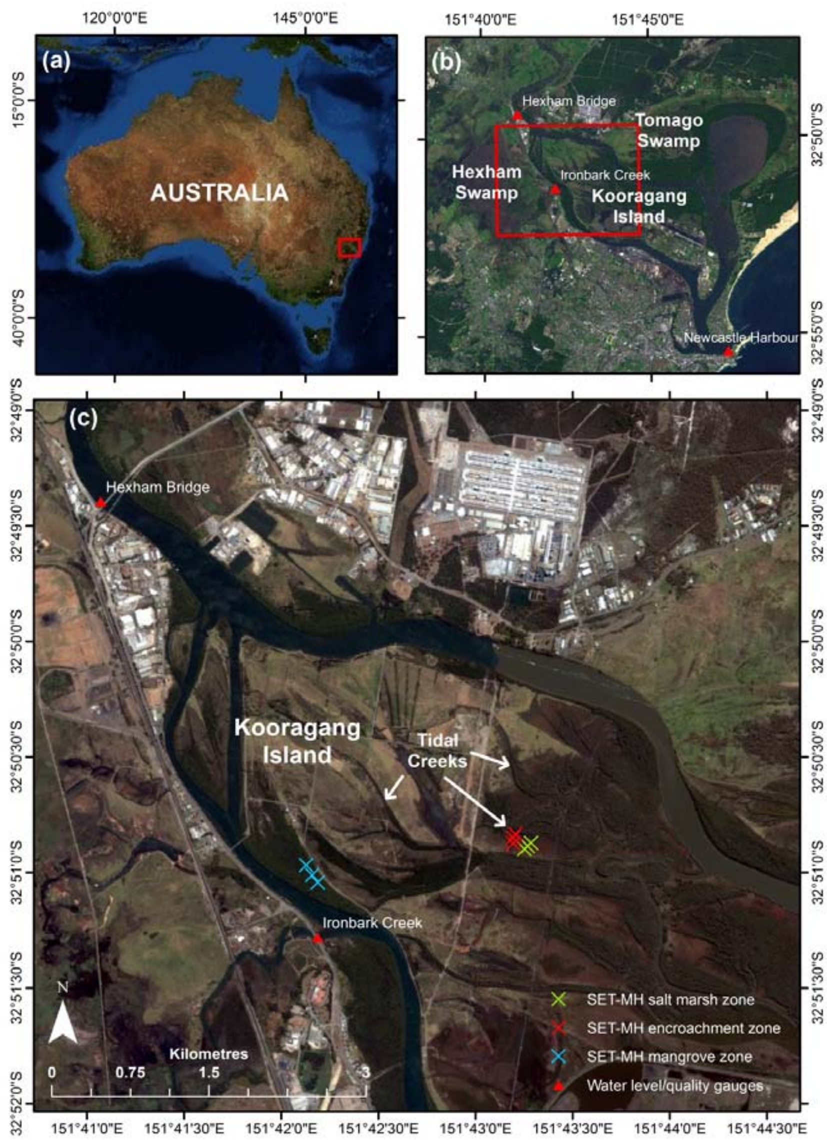
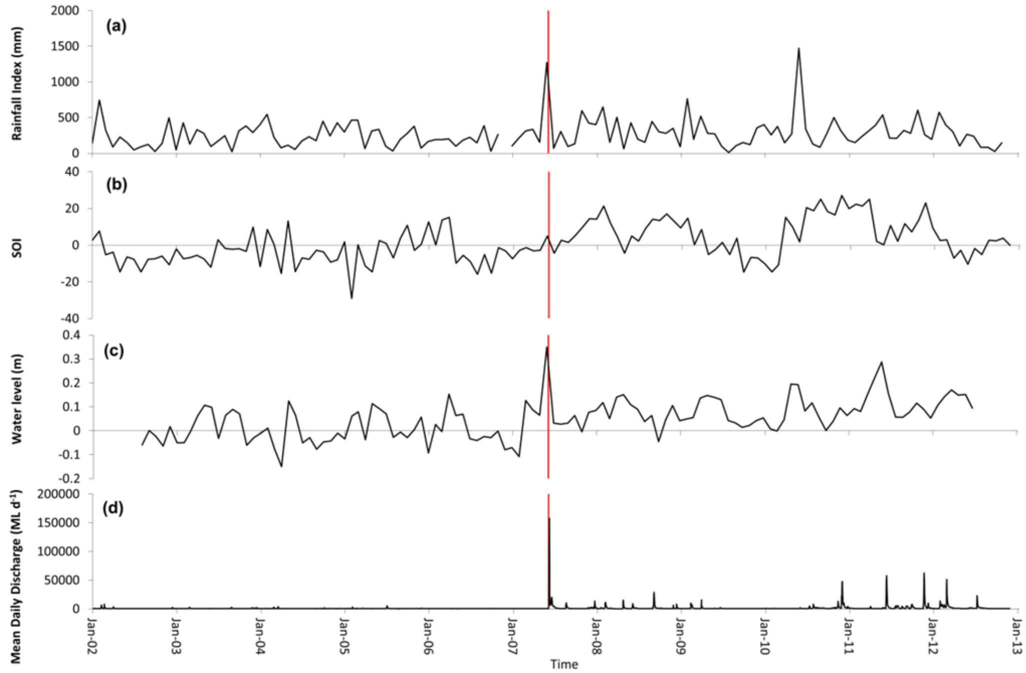


Figure 2: Climatic and hydrological parameters within the Hunter River catchment over the study period (January 2002 to August 2009). (a) Index of catchment rainfall, based on the combined rainfall at the Cessnock Airport (32°47’19”S, 151°20’16”E), Williamtown RAAF (32°47’36”S, 151°50’9”E), Jerry’s Plain Post Office (32°29’50”S, 150°54’35”E) and Scone Airport (32°2’1”S, 150°49’35”E) gauges. (b) Southern Oscillation Index. (c) Mean monthly water level, as measured at the Ironbark Creek water level gauge (MHL, 2012b). (d) Daily total discharge (ML), as measured at the Singleton water flow gauge (NOW, 2012). The storm event is indicated by a red vertical line in (a)-(d).



The Hunter estuary contains approximately 2500 ha of saline coastal wetlands, of which 1711 ha was identified as mangrove communities and 705 ha as salt marsh (Williams et al., 1999). Between 1954 and 1994, the area occupied by salt marsh has declined, primarily due to industrial development, drainage works and landward migration of mangrove into areas occupied by salt marsh. More specifically, salt marsh has declined by 55% at Kooragang Island from 930 ha in 1954 to 422 ha in 1994, while mangrove area has increased by 20% from 532 ha in 1954 to 636 ha in 1994 (Williams et al., 1999).

Mangrove communities on Kooragang Island are located at lower tidal elevations and are dominated by the grey mangrove, *Avicennia marina*, which grows to heights in excess of 15 m. The river mangrove, *Aegiceras corniculatum*, may be located beneath the *A. marina* canopy. Salt marsh areas are typically located landward of mangrove forests and are dominated by *Sporobolus virginicus* and *Sarcocornia quinqueflora*, with extensive areas of *Juncus kraussii* and *Baumea juncea*. An intermediate zone where mangroves are actively encroaching into salt marsh is evident at Kooragang Island; and this process has been identified as a driver of salt marsh decline in southeastern Australia (Saintilan and Williams, 1999). Permanent tidal pools and small salt pans are characteristic features of the salt marshes of Kooragang Island. Tidal waters are delivered to upper intertidal areas by tidal creeks or from adjacent mangrove that align tidal creeks.

2.1 CLIMATIC CONDITIONS

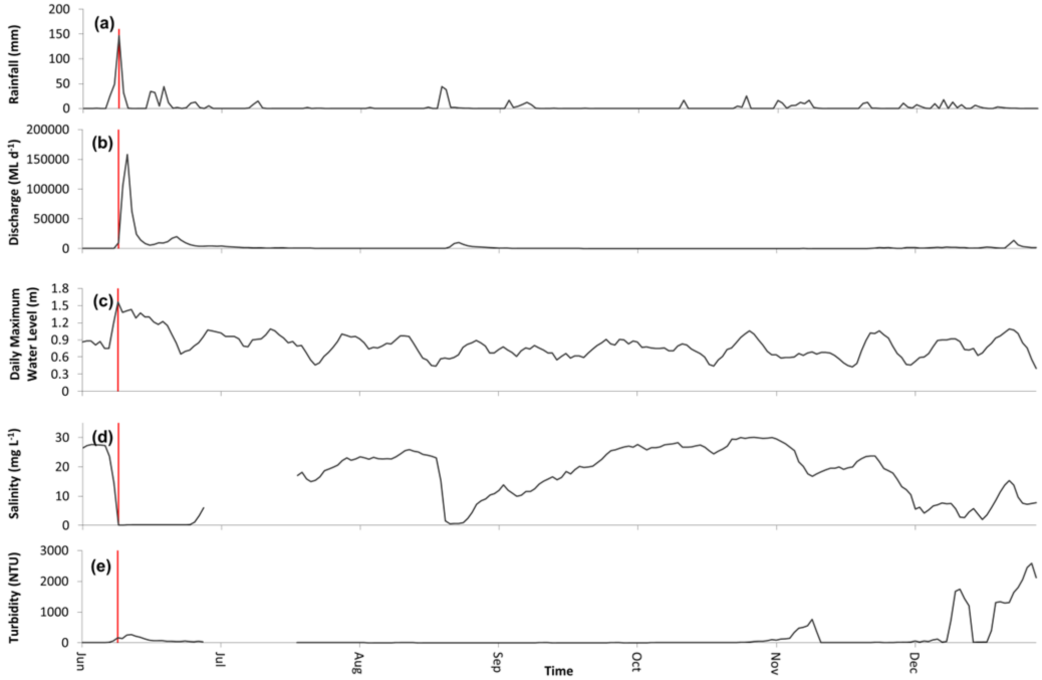
The study period extended across a period of below-average rainfall associated with prevailing El Niño conditions (Figure 2). This pattern was broken in 2007 by a series of low pressure systems and associated storms described below. Following this event, the Southern Oscillation Index was positive and fluvial discharge increased, with a consequent increase in mean water level within the estuary.

In June 2007, five low pressure systems, known as east coast lows (ECL; Hopkins and Holland, 1997), developed along the east coast of Australia. While the development of five ECL in one month is not unprecedented, with similar events occurring in 1950 and 1974, the impacts of the 2007 ECL were significant for the Hunter area of New South Wales. Storm force winds in excess of 120 km h^{-1} pushed the bulk-ore carrier Pasha Bulker onto Nobby's Beach, located at the mouth of the Hunter River. Significant flooding, described as the worst in 52 years in the Hunter Valley, resulted in deaths and property damage (BOM, 2012c).

The most significant ECL for mainland NSW occurred 8-9 June 2007 and caused widespread damage to the Hunter Valley, Central Coast and Sydney Metropolitan regions. Daily rainfall, measured at Williamstown (32°47'S, 151°50'E) (Figure 1), peaked on 9 June at 147 mm (Figure 3a) exceeding the long-term monthly average (Figure 2a, BOM, 2012a). Storm surges, based on wave heights of 14.1 m recorded at the Sydney Waverider Buoy (33°47'S, 151°25'E, BOM 2009b), and flooding reduced tidal amplitude within the Hunter estuary and caused a peak in water levels of 1.56 mAHD (metres above Australian Height Datum) at 4:00 am on 9 June, measured at Hexham Bridge (32°49'S, 151°41'E), 0.72 m higher than the peak recorded the day before (Figure 3c, MHL, 2012a). Water levels returned to a more typical pattern by the end of June.

Figure 3: Climatic and hydrological parameters at or near Kooragang Island between June and December 2007. (a) Daily total rainfall (mm), as measured at the Williamstown weather station (BOM, 2012a). (b) Daily total discharge (ML), as measured at the Singleton water flow gauge (NOW, 2012). (c) Daily maximum water level (m), as measured at the Hexham

Bridge water level gauge (MHL, 2012a). (d) Daily mean salinity (mg L^{-1}), as measured at the Ironbark Creek water quality gauge (MHL, 2012b). (e) Daily mean turbidity (NTU), as measured at the Ironbark Creek water quality gauge (MHL, 2012b). The storm event is indicated by a red vertical line in (a)-(e).



The storms of 8-9 June 2007 were marked by a sharp increase in fluvial discharge, as evident at the Hunter River water flow gauge at Singleton (32°34'S, 15°11'E), which peaked at 95 032 ML day^{-1} on 9 June 2007 (Figure 3b, DWE, 2009). The substantial freshwater contributions caused a sharp decrease in salinity (Figure 3d) and increase in turbidity (Figure 3e), as measured by the Ironbark Creek water quality data logger (32°51'S, 151°42'E, MHL 2009) (Figure 1, MHL, 2009).

3. METHODS

Numerous studies have indicated that vertical accretion may not accurately indicate changes in marsh surface elevation (Reed and Cahoon, 1993; Cahoon and Lynch, 1997; Cahoon et al., 1999; Cahoon et al., 2002). For this reason, elevation dynamics were disaggregated into changes in elevation and vertical accretion according to the method of Cahoon et al. (2002). Marsh surface dynamics were determined using a network of surface elevation tables (SETs) to determine relative changes in the marsh surface elevation and feldspar marker horizons (MH) to estimate vertical accretion.

3.1 SURFACE ELEVATION AND VERTICAL ACCRETION

SETs (version IV, Cahoon et al., 2002) were used to investigate surface elevation dynamics. SETs enable detection of changes in surface elevation in intertidal and shallow sub-tidal environments and have a confidence interval of 1.4 mm. SETs were installed according to the techniques of Boumans and Day (1993). Nine SET monitoring stations were established at Kooragang Island, with three located within a stable mangrove forest on the southern side of Kooragang Island, three within a stable salt marsh community, and three within an ecotone mangrove/salt marsh community (Figure 1). Initial measurements were taken on 29 January 2002 and subsequent measures were taken at irregular intervals on 4 March 2003, 18 November 2003, 8 March 2005, 30 August 2005, 21 December 2005, 18 April 2006, 7 February 2007, 12 July 2007, 22 September 2007, 3 December 2007, 2 February 2008, 1 April 2008, 11 June 2008, 3 August 2009, 17 May 2010 and 16 August 2012.

Vertical accretion was determined in conjunction with each SET monitoring station. Three MH were established on the marsh surface at the perimeter of each SET monitoring station at the time of the initial SET measurements (i.e. 29 January 2002). MH serve as a marker against which vertical accumulation of sediment and organic matter can be determined. Accretion was determined by the distance between the marsh surface and the feldspar horizon within a mini core extracted from the MH. Three replicate mini cores were taken from each MH in conjunction with SET measures except for 8 March 2005 and 21 December 2005. Marker horizons were reapplied over the study period due to dispersion or bioturbation and were not detected by 16 August 2012.

3.2 STATISTICAL ANALYSES

SET values that were not within two standard deviations of the mean for a sample were regarded as outliers and excluded from statistical analyses. These outliers may occur when SET pins are located on an obstruction, such as a pneumatophore stick or crab burrow. The corrected data set was then used to generate accumulative mean surface elevation change values for each zone. Similarly, accumulative mean vertical accretion for each zone was generated from replicated MH measures. Rates of vertical accretion and surface elevation change over the study period were calculated using a linear trend analysis.

To test the influence of the storm event on accretion and elevation trends over time (i.e. H1) change in surface elevation and vertical accretion between sampling periods were standardized by conversion to annual rates of surface elevation change and vertical accretion (mm y^{-1}). Multivariate repeated measures analysis of variance was used to identify statistical differences between rates of vertical accretion and rates of surface elevation change within zones and over time using a threshold p-value of 0.10. Assumptions of normality, homogeneity and sphericity were found to be true.

To test the influence of elevation deficits on mangrove encroachment (i.e. H2), rates of surface elevation change for each SET arm direction were generated using linear elevation trends. Where rates of surface elevation change were normally distributed, one-sample t tests were applied to rates of surface elevation change within each zone using a threshold p-value of 0.10 to establish whether the mean rate of surface elevation change within each zone was equal to or greater than water level changes. For non-parametric distributions, Wilcoxon rank test was applied in a similar manner. Comparison rates of water level change were generated to represent long-term water level trends and water level trends over the study period. Water level trends were generated from water levels at Newcastle Harbour ocean tide gauge between 1966 and 2010 (i.e. 1.1 mm y^{-1}, BOM, 2012b) and water levels at the Hexham Bridge water level gauge over the study period (i.e. 7.3 mm y^{-1}, MHL, 2012a).

4. RESULTS

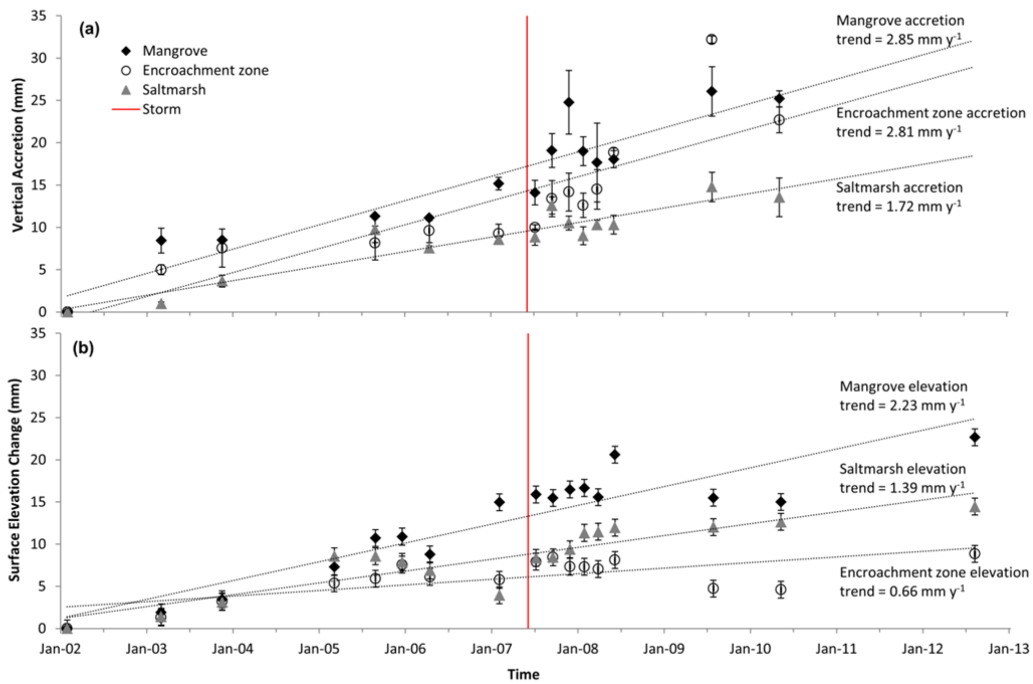
4.1 Influence of storm event on rates of accretion and surface elevation change

Multivariate repeated measures ANOVA indicated that there was no significant difference between the degree of accretion and surface elevation change (p=0.5252). However there was a significant difference over time (p=0.0003) and an interaction effect between accretion, surface elevation and time (p=0.0009) (Table 1: Model a). While significant differences were not detected between zones (p=0.2916), differences were detected between zones over time (p=0.0265) and between accretion and elevation change within zones over time (p=0.0014). This was largely driven by significant differences in the degree of accretion and surface elevation change within the mangrove encroachment zone (p=0.0633; Table 1: Model b), rather than the mangrove zone (p=0.9939; Table 1: Model c) and the salt marsh zone (p=0.4002; Table 1: Model d).

Accretion rates were found to vary between zones (p=0.0055) and was consistently greater within the mangrove zone than the salt marsh zone and reflects their respective positions within the tidal frame (Figure 4a). Accretion rates did vary significantly over time (p=0.0317) and there was a significant interaction between time and zone (p=0.0032; Table 1: Model e).

Post-hoc analyses indicate that these temporal differences were primarily driven by a peak in accretion between July and December 2007, and subsequent erosion between December 2007 and April 2008. This peak in accretion rate was most prominent within the mangrove zone where soil material accumulated at a rate of 27 mm y^{-1} between July and December 2007 (when sediment accretion peaked) and then eroded or compacted at a rate of 40 mm y^{-1} between December 2007 and April 2008. Increased accretion was not detected immediately following the storms of June 2007; rather, the storm event appears to have partially eroded sediments (or reduced the soil volume above the marker horizons) within the mangrove zone and had little impact on accretion within the salt marsh zone. Despite the temporal variability, accretion rates at Kooragang Island exhibit an upward trajectory over the study period in the mangrove and salt marsh zones. Soil is accumulating at a rate of 2.9 mm y^{-1} within the mangrove zone and 1.7 mm y^{-1} within the salt marsh zone.

Figure 4: Accretion and elevation trends for mangrove, salt marsh and mangrove encroachment zones at Kooragang Island. (a) Vertical accretion, and (b) surface elevation change. The storm event is indicated by a red vertical line in (a) and (b).



Surface elevation increased at a rate of 2.2 mm y^{-1} within the mangrove zone and 1.4 mm y^{-1} within the salt marsh zone between January 2002 and August 2012. Rates of surface elevation change varied significantly between zones ($p=0.0064$) and over time ($p<0.0001$), though there was an interaction effect between zones and time ($p<0.0001$; Table 1: Model f). The mangrove zone exhibited a rapid increase in surface elevation between April and June

2008, estimated at 5.05 mm. Surface elevation gain on June 2008 exceeded vertical accretion by 32%. Decreases in surface elevation in April 2006 and April 2008 were contrary to the upward surface elevation trajectory. The salt marsh zone exhibited a similar decrease in surface elevation in April 2006 but continued decreasing until February 2007 when elevation and accretion reached equilibrium. A rapid increase in elevation evident in July 2007 exceeded accretion by 3.73 mm.

Trends in the mangrove encroachment zone were complex. Accretion increased at 2.8 mm y^{-1} and corresponded to the intertidal position of this zone between mangrove and salt marsh (Figure 4). This was not accompanied by an equivalent increase in surface elevation, which increased at 0.7 mm y^{-1} over the study period. Rates of surface elevation change and vertical accretion varied significantly in this zone ($p=0.0633$, Table 1: model b) and the discrepancy between accretion and surface elevation became increasingly evident following the storms of June 2007.

4.2 Influence of elevation deficits on mangrove encroachment

Statistical analyses indicated that rates of surface elevation change within the encroachment zone were not normally distributed ($p=0.049$, Table 2). Tests of significance between rates of surface elevation change and long-term water level trends indicated that rates of surface elevation change in the mangrove zone have exceeded the long-term water-level trend, though the difference between water level and rates of surface elevation change in the encroachment and salt marsh zones were not significantly different (Table 2). Rates of water level change over the study period markedly exceeded the long-term trend, and in all zones rates of surface elevation change did not exceed water level trends and an elevation deficit was apparent.

5. DISCUSSION

5.1 Influence of storm event on rates of accretion and surface elevation change

Rates of surface elevation gain and accretion at Kooragang Island varied significantly throughout the 10.5 year study period (Table 1: Model a), though these changes were not consistent between vegetation zones. With regards to Hypothesis 1, we detected no change in rates of accretion and surface elevation over time within the mangrove zone (Table 1: Model c), significant differences were detected over time within the salt marsh zone (Table 1: Model d), and significant differences were detected between rates of surface elevation change and accretion within the mangrove encroachment zone (Table 1: Model b). These differences are largely attributed to variable accretion and estuarine hydrodynamics.

Table 1: Multivariate repeated measures analysis of variance results indicating significant differences between rates of surface elevation change and vertical accretion within mangrove, salt marsh and the zone of mangrove encroachment at Kooragang Island, Hunter River. Significant values ($p<0.10$) indicated in **bold**.

Model	Variables		Significance			
	Dependent	Effects	Whole Model	Effects	Time	Time x Effects
a	Change in all zones	Effect 1: Measure (surface elevation, accretion) Effect 2: Zone (mangrove, salt marsh, encroachment)	P=0.0137	Effect 1: P=0.5252 Effect 2: P=0.2916 Effect 1 x Effect 2: P=0.1327	**P=0.0003**	Effect 1: **P=0.0009** Effect 2: **P=0.0265** Effect 1 x Effect 2: **P=0.0014**
b	Change in mangrove encroachment zone	Measure (surface elevation, accretion)		**P=0.0633**	P=0.4148	P=0.2285
c	Change in mangrove zone	Measure (surface elevation, accretion)		P=0.9939	P=0.2567	P=0.7001
d	Change in salt marsh zone	Measure (surface elevation, accretion)		P=0.4002	**P=0.0015**	**P=0.0003**
e	Change in accretion	Zone (mangrove, salt marsh, encroachment)		**P=0.0055**	**P<0.0001**	**P<0.0001**
f	Change in surface elevation	Zone (mangrove, salt marsh, encroachment)		**P=0.0064**	**P<0.0001**	**P<0.0001**

Consistent with storms of this magnitude, fluvial indicators highlight the energetic state of the Hunter River immediately following the storms of June 2007. River discharge (Figure 3b) peaked at 95 032 ML d^{-1} at Singleton on 9 June 2007 and corresponding to the observed accretion and high discharge was high turbidity, as recorded at the Ironbark Creek water quality data logger, for a number of weeks following the storms of 8-9 June (Figure 3e). Salinity at Ironbark Creek indicates that flows in the Hunter River were dominated by fluvial inputs immediately following the storm event. Sediments transported by these flows were likely to have been deposited in the estuary or transported offshore through the river entrance. The freshwater plume extending through the estuary appears to dissipate approximately 18 days after the storms of 8-9 June and is marked by an increase in salinity (Figure 3d) and a reduction in turbidity (Figure 3e). Scouring was evident immediately following the storms within the mangrove zone, with a deficit of 1 mm between February 2007 and July 2007, though this change is within the error margin of the SET technique. As accretion within the salt marsh immediately following the storms increases at a similar rate to that immediately prior to the storm event, it is evident that scouring was absent or minimal within the salt marsh zone. This is consistent with the reduced depth and velocity of flow and higher vegetation cover in the salt marsh than in the adjacent mangrove (Mazda et al., 1997; Saintilan et al., 2009).

In the months following the storms, accretion within both the mangrove and salt marsh zones accelerated. This was particularly evident in the mangrove zone where deposits of 10.67 mm were evident by December 2007. A moderately high rainfall event in August and associated moderate discharge event caused some freshening of the Hunter estuary at this time (Figure 3a, b, d). Apart from this event, rapid deposition following the storms of June 2007 occurred during a period of normal river flow activity. However, this period was marked by extremely high turbidity in mid-November and mid-December (Figure 3e). Unlike the previous turbidity peak following the storms of June 2007, these peaks were not associated with large storm or flood events (Figure 3a, 3b). Rather, they were measured approximately 15 days following high water solstice spring water levels (Figure 3c). We propose that increased tidal velocities associated with the high water solstice spring water event caused the remobilisation of sediments deposited within the body of the estuary and facilitated their transport into the fluvial delta of the Hunter estuary, where the SET and MH are established. Due to the high water levels associated with this event, these remobilised sediments were readily deposited within both the mangrove and salt marsh of Kooragang Island. While variation in rates of accretion (Table 1: Model e) and elevation change (Table 1: model f) was detected over time, comparison with accretion trends indicate that extreme event discharge and subsequent sedimentation spikes had little overall impact on the trend within the mangrove and salt marsh at Kooragang Island (Figure 4); nor did they appreciably influence longer-term elevation trends.

While studies of storm impacts on coastal wetlands tend to focus on storm deposits (Reed, 1989; Nyman et al., 1995; Cahoon et al., 1996; McKee and Cherry, 2009), scouring, as observed immediately following the storms of June 2007, is not unprecedented (Pethick, 1991; Cahoon et al., 1995a; Guntenspergen et al., 1995). The pattern of erosion and deposition observed in this study was explained by estuarine hydrodynamics; however, it also fits the classic beach theory model presented by Pethick (1991), whereby erosion acts to flatten the marsh profile and dissipate wave energy, with subsequent deposition occurring during calm periods. In particular, the lack of erosion within the salt marsh after the storm event may indicate that the velocity of fluvial flows was insufficient to erode salt marsh substrate and that the dense salt marsh vegetation cover limited erosion from raindrop impact. The subsequent increase in estuary sediment budget appears to have delivered an increased sediment supply to the salt marsh, particularly during the king tides of the summer of 2007-08.

Based on results from this study site and others in southeastern Australia, Rogers et al. (2006) proposed that during drought dominated climates, when fluvial inputs are limited, wetland surface elevations are largely influenced by vertical accretion and shallow compaction. This has been reported elsewhere (Cahoon et al., 2011) and explains differences observed within the salt marsh zone over time (Table 1: model d) where surface elevation fluctuations prior to the 2007 storms were attributed to shrinkage of salt marsh soils. Conversely, results from this study indicate that elevated water levels associated with wetter climatic conditions and increased fluvial inputs may cause wetland surfaces to swell and return to consistent rates of elevation gain. In addition, increased fluvial inputs provide more opportunities for sediment to be delivered to both mangrove and salt marsh areas. Further monitoring throughout subsequent El Niño and La Niña cycles will provide insight into this hypothesis.

These trends contrasted with the zone within which mangroves were encroaching on salt marsh, which has not built elevation since the 2007 storm event and overall elevation gain in the encroachment zone was less than 0.7 mm y^{-1}. This occurred in spite of continuing vertical accretion. Numerous mechanisms for the departure of elevation trends from vertical accretion trends following storms have been proposed by Cahoon (2006) with studies citing compaction, soil shrinkage or peat/root decomposition (Cahoon et al., 1995b; Cahoon et al., 1999; Cahoon et al., 2003). Since similar trends were not observed in the adjacent mangrove and salt marsh zones it is unlikely that these are the cause of the discrepancy. Rather, we propose two additional mechanisms in this case. First, the discrepancy may be attributed to the loss of salt marsh vegetation as the zone is encroached by mangrove. In this case, the 2007 storms mark the shift from an El Niño dominated climate to La Niña dominated climate (Figure 2b), and was associated with an increase in water levels within the estuary (Figure 2c), which may limit salt marsh growth in the encroachment zone. While Rogers et al. (2005) observed expansion of the root zone and a corresponding elevation increase as mangrove re-established in salt marsh at Homebush Bay, Australia, we have observed loss of salt marsh vegetation from the encroachment zone at Kooragang Island as mangrove seedlings establish and prior to their rapid growth. This may be facilitated by shading of vegetation by mangrove seedlings. However, loss of salt marsh root volume might be expected to be replaced by encroaching mangrove root systems. Second, expansion and incision of tidal creeks in this zone, as discussed below, may be drawing water from sediments in the immediate vicinity causing shrinkage of the surface elevation. Continued monitoring of vegetation changes, tidal creek expansion and accretion and elevation trends in this zone will aid identification of the processes driving mangrove encroachment of salt marsh.

Table 2: T-test and Wilcoxon rank test results for differences between rates of surface elevation change over the study period and water level changes. Comparisons were made with long-term rates of water level change and rates of water level change over the study period. Significant values ($p<0.10$) indicated in **bold**.

Zone	Normal Distribution	Surface Elevation (SE) and Long-term Water Level (WL) Trend			Surface Elevation (SE) and Study Period Water Level (WL) Trend		
		ΔSE>ΔWL	ΔSE=ΔWL	ΔSE<ΔWL	ΔSE>ΔWL	ΔSE=ΔWL	ΔSE<ΔWL
Mangrove	P=0.3418	**P<0.0001**	**P<0.0001**	P=1.0000	P=1.0000	**P<0.0001**	**P<0.0001**
Encroachment	P=0.0490	P=0.6411	P=0.7178	P=0.3589	P=0.9998	**P=0.0005**	**P=0.0002**
Salt marsh	P=0.6607	P=0.1155	P=0.2311	P=0.8845	P=1.0000	**P<0.0001**	**P<0.0001**

5.2 Influence of elevation deficits on mangrove encroachment

An increase in relative water level, identified elsewhere as an elevation deficit, (the difference between wetland surface elevation and the estuary water level trend, based on long-term water level trends at Newcastle Harbour) was evident within the mangrove encroachment zone (-0.4 mm y^{-1}) while a decrease was evident in the mangrove zone (1.1 mm y^{-1}) and salt marsh zone (0.3 mm yr^{-1}). Analyses highlighted that elevation changes within the mangrove zone significantly exceeded long-term water levels trends; the same relationship was not identified within the salt marsh and mangrove encroachment zones. Comparisons with water level changes over the study period indicated a strong probability of a deficit between elevation gain and water level changes within all zones (Table 2), however, given the variability in water level trend over the study period it may be more appropriate to establish elevation deficits on the basis of long-term water level trends, which are less prone to fluctuations associated with climatic perturbations.

Historical aerial photography demonstrates a history of mangrove encroachment at the margins of salt marsh dating to the 1950s, and our own vegetation observations shows a thickening of mangrove vegetation and ongoing recruitment of juveniles over the study period. Our interpretation is that higher water levels following the storms (Figure 2c) and associated increase in tidal prism has reactivated the tidal creek along which mangrove encroachment is occurring. The increase in tidal prism may be limiting salt marsh growth or causing tidal creek incision of the floodplain, draining nearby soils and depressing surface elevations immediately adjacent to the creek, where our SETs are situated. We also note that this and other factors may facilitate mangrove colonization in the encroachment zone including shading of salt marsh vegetation by mangrove juveniles and increased exposure to erosion from rainfall due to low vegetation cover. The salt marsh zone has resisted mangrove encroachment, in spite of a period of prolonged freshening during the recruitment season in 2007, consistent with strong vertical accretion and fairly consistent elevation gain.

Our observations on the Hunter estuary are consistent with the pattern of mangrove recruitment throughout Australia, in which mangroves extend into salt marsh and freshwater wetlands along tidal channels. Adam (1997) notes the comparative rarity of tidal creeks in Australian salt marshes, and this may be a consequence of relatively stable sea-level conditions in the region over the latter Holocene (Thom and Roy, 1985). Increased water level within estuaries has the effect of increasing the discharge of tidal creeks, increasing their capacity and promoting lateral extension (Friedrichs and Perry, 2001). The gradual increase in sea-level during the past few decades has reactivated tidal creeks in the tropical north (Knighton et al., 1991; Winn et al., 2006), and several NSW and Victorian sites, where rapid mangrove expansion has followed tidal creek channel networks (Saintilan and Hashimoto, 1999) and the reactivation of palaeo-channels (e.g. the Currambene system studied by Saintilan and Wilton, 2001).

6. CONCLUSIONS AND IMPLICATIONS FOR MARSH STABILITY

Propositions that storm events may be critical to the maintenance of wetland elevations are typically associated with events where storm sediment deposits are accompanied by an equivalent (or greater) degree of elevation increase. In this paper we have demonstrated that low frequency, high magnitude storm events may have a variable impact on wetlands within the same system, depending upon vegetation type and dominant processes influencing their distribution. The storm event that occurred in the Hunter Valley on 8-9 June 2007 appears to have had little impact on surface elevation trends on the mangrove and salt marsh at Kooragang Island, with elevation dynamics largely influenced by longer-term accretion rates and shrink-swell of sediments associated with drought, large fluvial flows and elevated estuarine water levels. Short-term deviations from longer-term accretion trends were evident and were attributed to the influence of the June 2007 storms and subsequent high spring tides on estuarine hydrology and sediment dynamics. These were short-lived, with the new material quickly eroded and/or autocompacted. This contrasts with trends in the encroachment zone, where the return to wetter conditions heralded by the 2007 flood does seem to have reinvigorated tidal creeks, which we suggest as the primary vector for mangrove encroachment on Kooragang Island. Within this zone, elevation decreased despite continued vertical accretion. We propose that this discrepancy is driven by loss of salt marsh biomass in this zone or draining soils in association with tidal creek expansion and incision; a hypothesis supported by observations of the pattern of encroachment across multiple systems.

This research implies that increasing frequency and/or intensity of storms in the future, as projected for the 21st century, may influence estuarine wetlands that are undergoing transition, while relatively stable sites may be better equipped to adjust to perturbations. Specifically, we found that the mangrove encroachment zone was unable to build elevations at rates equivalent to water level changes following the storm event, while the mangrove and salt marsh zones were able to build elevation at rates exceeding sea-level rise. As the 2007 storms coincided with the shift from an El Niño dominated climate to a La Niña dominated climate the driver of the discrepancy between accretion and elevation may be related to longer-term climatic perturbations (El Niño Southern Oscillation) rather than directly attributed to individual storms events.

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