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Global coastal wetland change under sea-level rise and related stresses: The DIVA Wetland Change Model

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ABSTRACT

The Dynamic Interactive Vulnerability Assessment Wetland Change Model (DIVA_WCM) comprises a dataset of contemporary global coastal wetland stocks (estimated at 756 × 10^3 km^2 (in 2011)), mapped to a one-dimensional global database, and a model of the macro-scale controls on wetland response to sea-level rise. Three key drivers of wetland response to sea-level rise are considered: 1) rate of sea-level rise relative to tidal range; 2) lateral accommodation space; and 3) sediment supply. The model is tuned by expert knowledge, parameterised with quantitative data where possible, and validated against mapping associated with two large-scale mangrove and saltmarsh vulnerability studies. It is applied across 12,148 coastal segments (mean length 85 km) to the year 2100. The model provides better-informed macro-scale projections of likely patterns of future coastal wetland losses across a range of sea-level rise scenarios and varying assumptions about the construction of coastal dikes to prevent sea flooding (as dikes limit lateral accommodation space and cause coastal squeeze). With 50 cm of sea-level rise by 2100, the model predicts a loss of 46–59% of global coastal wetland stocks. A global coastal wetland loss of 78% is estimated under high sea-level rise (110 cm by 2100) accompanied by maximum dike construction. The primary driver for high vulnerability of coastal wetlands to sea-level rise is coastal squeeze, a consequence of long-term coastal protection strategies. Under low sea-level rise (29 cm by 2100) losses do not exceed ca. 50% of the total stock, even for the same adverse dike construction assumptions. The model results confirm that the widespread paradigm that wetlands subject to a micro-tidal regime are likely to be more vulnerable to loss than macro-tidal environments. Countering these potential losses will require both climate mitigation (a global response) to minimise sea-level rise and maximisation of accommodation space and sediment supply (a regional response) on low-lying coasts.

1. Introduction

Millennial, centennial and decadal records of changing patterns of coastal wetlands, including mangrove forests, saltmarshes, mudflats and associated habitats, show that they are particularly sensitive to environmental change (e.g. Morris et al., 2002; French, 2006; Mudd et al., 2009). More recent system changes also reflect the impacts of human activities superimposed on these natural dynamics, such as drainage and conversion to agriculture (e.g. Gedan et al., 2009) and aquaculture (e.g. Murdiyarso et al., 2015). There is concern, therefore, as to how near-future global environmental change will further modify these systems (e.g. Alongi, 2008; Kirwan et al., 2010; Fagherazzi et al., 2012).

On contemporary timescales, tidal wetlands are biologically productive ecosystems of high biodiversity supplying multiple ecosystem services. At the same time they are subject to significant, and accelerating, rates of global coastal wetland loss due to natural and anthropogenic drivers (e.g. Adam, 2002; Millennium Ecosystem Assessment, 2005; Barbier et al., 2011; Nicholls et al., 2011). Davidson (2014) estimates that natural coastal wetlands have declined by 46–50% since the beginning of the 18th century and by 62–63% over the course of the 20th century and Leadley et al.'s (2014) Wetland Global Extent Index estimates an almost 50% decline between 1970 and 2008.

Ecosystem services and loss rates have become linked over the last decade with the recognition of the role of low-lying wetlands in natural coastal protection (e.g. Shepard et al., 2012), following the interactions between mangrove ecosystems and the wave fields of the 2004 Asian tsunami (e.g. McIvor et al., 2012) and between coastal marshes and 2005 Hurricanes Katrina and Rita on the Gulf Coast, USA (e.g. Barbier

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et al., 2013) amongst others. Much remains to be done, however, on identifying the exact linkages between mosaics of coastal habitat area and habitat fragmentation and the maintenance of a coastal protection function (e.g. Barbier et al., 2008; Koch et al., 2009; Loder et al., 2009; Gedan et al., 2011). Furthermore, these debates are embedded in a context where the knowledge of the general spatial distribution of coastal wetland ecosystems is currently poor, particularly for saltmarshes (e.g. Rebelo et al., 2009; Saintilan et al., 2009; Chmura, 2011). There are serious gaps in the information base and much of the data that has been collected has come from different sources and different time periods and at a range of scales (Friess and Webb, 2014). Indeed, Friess et al. (2012) goes as far as to argue that the under-reporting of saltmarsh from the tropics underpins the presumption that mangrove replaces saltmarsh in the tropical intertidal zone. These shortcomings have hampered the assessment of the extent and condition of wetlands and proper estimations of the rate of loss. Thus one review concludes ‘a number of prognostications have been made regarding the future of the world's mangrove forests in the face of climate change with local, regional, and global forecasts ranging from extinction to no or little change in areal coverage’ (Alongi, 2008, 8).

Accelerated sea-level rise is a major threat to wetland futures at regional to global scales. However, most detailed studies on wetland vulnerability to accelerated sea-level rise have been over small spatial scales and short timescales and most concentrate on the likelihood of vertical drowning (Webb et al., 2013), when sediment accumulation on the platform cannot keep vertical pace with sea-level rise. There has been less emphasis on rates of horizontal retreat, associated with wave-induced marsh boundary erosion (Mariotti and Carr, 2014). Thus, for example, the Surface Elevation Table — Marker Horizon (SET-MH) methodology has the necessary precision to allow annual surface elevation change to be related to annual rates of sea level change (Cahoon et al., 2002) although inter-site and inter-annual variations in surface response characteristics are high (Cahoon et al., 2006). Historically, the SET-MH global network of sites has been patchy and not focussed on those areas where wetland loss rates are thought to be particularly high (Webb et al., 2013). However, there has been an expansion of sites globally in the last few years and it is becoming possible to use this network to model larger scale patterns in wetland vulnerability, as has been shown for Indo-Pacific mangrove SET sites (Lovelock et al., 2015). Furthermore, SET datasets have been used as calibration datasets in other models of wetland change, most notably the SLAMM model; we return to this usage below.

The generic problems of large-scale analysis have been addressed in part by the development of macro-scale landscape models. These models vary in structure, complexity and the ease with which they can be applied. The more sophisticated landscape models use geomorphic and hydrologic sub-models to distribute fluxes of water, sediments and nutrients across a raster grid (e.g. CELSS model: Sklar et al., 1985) to calculate likely changes in wetland type extent. However, the data and computational requirements of such an approach largely preclude its application as a broad-scale tool for wetland analysis (Martin et al., 2002; Reyes, 2009; Couvillion and Beck, 2013). Simpler models, such as cellular automata (Ross et al., 2009), capture the key characteristics of wetland dynamics empirically, require fewer data, and are easily applied, but the ability to deal with low frequency, high magnitude impacts and the recognition of the interaction and feedback of geo-morphological and ecological processes are missing (Kirwan and Guntenspergen, 2009). Nevertheless, these approaches are useful for calibration purposes, as we demonstrate below. Of this suite of large-scale models, the one that has been most widely applied is the ‘Sea Level Affecting Marshes Model’ (SLAMM) (Clough et al., 2010). SLAMM is open source and has a user-friendly interface for implementation; is based on empirical calculations so that computation times are substantially less than those required for complex numerical models; and implementation has low data demands.

The pioneering Global Vulnerability Assessment (GVA), and its subsequent revision, is a macro-scale model which provided the first worldwide estimates of the impacts of accelerated sea-level rise on coastal systems (Hoozemans et al., 1993; Nicholls et al., 1999). This included a first-order perspective on coastal wetland loss. Subsequently, the data on coastal wetland stocks has improved (e.g. Vafeidis et al., 2008; Spalding et al., 2010; Giri et al., 2011), and the understanding of the main drivers of change, including sea-level rise, has increased (Nicholls, 2004; McFadden et al., 2007; Nicholls et al., 2007). Hence, a re-evaluation of these earlier assessments of wetland vulnerability is timely. This paper discusses the further development and application of a broad-scale wetland change model: the Dynamic Interactive Vulnerability Assessment Wetland Change Model (DIVA_WCM), originally developed within, and subsequently to, the European Community DINAS-COAST Project. In this paper we show how a newly constituted database of contemporary global coastal wetland extent can be linked to a revised conceptual model of the controls on wetland health and resilience. In comparison to its previous version (McFadden et al., 2007), the revised model has been parameterised with quantitative data where possible, calibrated by SLAMM and other model outputs and validated by expert knowledge, including map-based approaches. Thus, in its current form the model provides better-informed macro-scale projections of likely future wetland extents than have been available previously.

2. Methods

2.1. The DIVA modelling framework

DIVA is an integrated, global modelling framework of coastal systems that assesses biophysical and socio-economic consequences of sea-level rise and socio-economic development, taking into account coastal erosion, coastal flooding, wetland change and salinity intrusion (http://www.diva-model.net; Hinkel, 2005; Hinkel and Klein, 2009; Hinkel et al., 2010, 2013, 2014). The DIVA data modelling framework divides the world's coast (excluding Antarctica) into 12,148 variable length coastal segments (mean length: 85 km; range: 0.009 km to 5213 km) and associates up to 100 data values with each segment (Vafeidis et al., 2008). Each segment represents a relatively homogenous unit based on geomorphology, population density and administrative boundaries; there are a greater number of segments in the more populated areas. Only the DIVA data associated with wetland change are considered in this paper.

DIVA is driven by climate and socio-economic scenarios. Using the HadGEM2-ES Earth System model from Phase 5 of the Coupled Model Intercomparison Project (CMIP5), three sea-level rise scenarios have been investigated in this paper, representing a subset of the scenarios described by Hinkel et al. (2014). These scenarios consider three Representative Concentration Pathways (RCP) — RCP2.6, RCP4.5, and RCP8.5. The RCPs correspond to different levels of greenhouse gas concentration trajectories, ranging from a world of strong climate mitigation to one of increasing emissions. A major uncertainty in projecting future sea-level rise is the contribution of land-based ice. In Hinkel et al. (2014), each RCP scenario is associated with three levels of ice melt (low, median and high) to create a ‘very likely’ range. The scenarios represent patterns of change (representing thermal expansion and changes in ocean circulation, plus gravitational changes from ice sheets (the contribution from ice caps is assumed to be uniform)) where some parts of the world have higher or lower sea-level rise compared with the global mean. Projected global mean sea-level rise to the year 2100 with respect to 1995 (mean sea level during 1985–2005 baseline period) for each of the scenarios is given in Table 1 (median values, with 5% and 95% quantiles in parentheses; after Hinkel et al., 2014). In this demonstration paper, we cover the widest range of sea-level rise scenarios, from the lowest (5%) quantile of RCP2.6 (29 cm by 2100), through the median rate of sea-level rise for RCP4.5 (50 cm), to the 95% quantile of RCP8.5 (110 cm). Finally, the