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Continuous monitoring of coastline dynamics in western Florida with a 30-year time series of Landsat imagery

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ABSTRACT

Continuous monitoring of coastline dynamics is of crucial importance to the understanding of relative contributions of various potential driving factors behind the long-term coastline change. While a large number of efforts have been made to extract coastline and detect coastline change with remotely sensed data, the temporal frequency and spatial resolution of coastline datasets obtained are generally not fine enough to reflect the detailed process of coastline retreat and/or advance, particularly in coastlines with subtle variability. To overcome these limitations, we developed a method to continuously monitor the dynamics of a muddy coastline with subtle variability in western Florida at annual and subpixel scales using time-series Landsat data (1984–2013). First, robust indicators were used to indicate the annual "average" location of the dynamic coastline. Due to the complexity of muddy-coast morphology, the annual average location is represented not by the coast "line", but by the fractional inundated "area" of coastline pixels (pixels where the coastline is located), namely annually inundated area. Second, the annually inundated area of coastline pixels was estimated with a model proposed in this study, and the uncertainty was estimated with the Monte Carlo method. The retrievals were validated at 10 sites with aerial imagery, and the overall RMSE (root mean square error) is 11.48%. Third, the long-term trend for the time series of annually inundated area was derived with a statistical model. The results indicate that the muddy coast in western Florida continues to shrink with an average rate of 0.42 ± 0.05 km^2/year during the three decades. This study demonstrates the feasibility of time-series Landsat data in continuous monitoring of coastline dynamics.

1. Introduction

Global mean sea level has risen through the 20th century, and it is expected to rise in an accelerated manner in this century due to ice melt and thermal expansion (Nicholls & Cazenave, 2010; Webb et al., 2013; Yang et al., 2013), which constitutes a serious threat to stability of coastal ecosystem and property of millions of people (Arkema et al., 2013; Kirwan & Megonigal, 2013). To cope with these problems, monitoring coastline dynamics is of crucial importance, since it provides essential information for understanding the coastal response to contemporary climate change and human impacts (Jones et al., 2009).

Compared with conventional survey methods, remote sensing has the advantage of monitoring of coastline dynamics over a variety of spatio-temporal scales. However, the choice of remotely sensed data for large-scale coastline observation is often a compromise between temporal frequency and spatial resolution. The coastline data derived from aerial imagery (Ford, 2013; Jones et al., 2009; Morton, Miller, & Moore, 2004), airborne Lidar (Light Detection and Ranging) (White & Wang, 2003; Shrestha, Carter, Sartori, Luzum, & Slatton, 2005) or SAR (synthetic aperture radar) (Lee & Jurkevich, 1990; Mason & Davenport, 1996) has fine spatial resolution, but the cost is prohibitively high for frequent observation over large areas. Satellite imagery obtained from Advanced Very High Resolution Radiometers (AVHRR) or Moderate Resolution Imaging Spectrometer (MODIS) has high temporal frequency and global-scale coverage, and was successfully applied to assessing the drastic shoreline change of Poyang Lake at a monthly scale (Feng et al., 2012), but its spatial resolution is too coarse to track the subtle variability of coastlines. In this context, Landsat imagery with moderate frequency (16 days) and medium resolution (30 m) is potentially more useful than other data sources for monitoring coastline dynamics at large scales.

To date, a large number of efforts have been conducted to extract coastlines and estimate the change rate using Landsat imagery, but there are several recurring limitations in these previous studies. First, the time interval used in the monitoring of coastline dynamics is often greater than ten years due to limited data availability or relatively coarse spatial resolution of Landsat imagery (Ekercin, 2007; Murray, Clemens, Phinn, Possingham, & Fuller, 2014; Rahman, Dragoni, & El-Masri, 2011), so the coastline data obtained at such a time scale can only be used to roughly estimate the change rate, not reflecting the detailed process of coastline retreat and advance during the study period. However, monitoring this non-linear dynamics with higher temporal

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frequency is essential to improving our understandings on the relative contribution of each driving factor (Le Cozannet, Garcin, Yates, Idier, & Meyssignac, 2014). For example, Gratiot et al. (2008) extracted the coastlines of French Guiana from 1986 to 2006 at the annual scale and found that the dominant control of the coastline fluctuation was the 18.6 year nodal tidal cycle. Second, the spatial resolution of Landsat imagery is not fine enough to detect most coastline changes around the world within the time scale required for coastal management (Le Cozannet et al., 2014; Pardo-Pascual, Almonacid-Caballer, Ruiz, & Palomar-Vázquez, 2012), except for places affected by human activities or strong hydrodynamics such as deltas (White & El Asmar, 1999; Rahman et al., 2011; Yu, Hu, Muller-Karger, Lu, & Soto, 2011). Therefore, new algorithms have been developed to extract coastline at the subpixel level of Landsat imagery (Foody, Muslim, & Atkinson, 2005; Muslim, Foody, & Atkinson, 2006; Pardo-Pascual et al., 2012). The accuracy of sub-pixel methods (RMSE is about 3 m) is better than that of pixel-level methods (RMSE > 15 m), but until recently, little further research has been proposed to detect coastline changes using successive coastline data obtained at the subpixel level. Third, the proxy for coastline location, or coastline indicator, generally used in Landsat imagery is waterline (the instant boundary of water and land at the time of satellite observation) (Murray et al., 2014; Pardo-Pascual et al., 2012; Rahman et al., 2011), but it is not an ideal indicator for tidal area because of the distinct variations in horizontal positions of waterline due to tidal fluctuation, especially for coasts with gentle slopes.

To overcome these limitations, we developed a method for continuous monitoring of the dynamics of a coastline with subtle variability at finer temporal and spatial scales using all available Landsat imagery. Since the coastline continues to change through time, more robust indicators, which indicate the "average" location of the dynamic coastline at a certain time scale (Boak & Turner, 2005), were used to replace the instant waterline. The time scale used in this study was set to one year, so that coastline fluctuation can be further linked with annual climate records to reveal the relative contribution of each driving factor. The effectiveness of this method was demonstrated for detecting coastline change in a typical muddy coast of western Florida, whose coastline change is at the subpixel level of Landsat imagery during the study period (1984–2013) (<30 m) (Morton et al., 2004). Due to the complexity of coastal morphology, it is difficult to precisely delineate a contour around the muddy coast at the subpixel level with previous methods. Hence, the annual average location of the dynamic coastline is represented not by the "line", but by the fractional inundated "area" of coastline pixels corresponding to the indicator, namely annually inundated area.

The main objectives of this study are to: 1) find more robust coastline indicators to represent the annual average location of the dynamic coastline in the muddy coast, 2) develop a method to estimate the annually inundated area of coastline pixels at the subpixel level of Landsat imagery, and 3) derive the long-term trend of annually inundated area.

2. Study area and coastline indicator

2.1. Study area

In the Gulf of Mexico, the erosion or accretion rate of sandy coast was provided in the National Assessment of Shoreline Change report (Morton et al., 2004), but for now, there has been little research on quantifying the long-term change rate for the muddy portion occupying nearly 42% of the Gulf shore. Therefore, this study was applied to a representative muddy coast in western Florida, which is dominated by extensive salt marshes and to less extent mangroves. The study area (Landsat scene, path 17 row 40) (Fig. 1) entirely covers the Waccasassa Bay Preserve State Park, and the coastline is about 130 km long, extending from Cedar Key to Homosassa Bay. Except for the portion around Cedar Key, the coast in this region has rarely been affected by human activities such as fishing or timber harvesting, and also has little alteration in physical or hydrologic conditions (Geselbracht, Freeman, Kelly, Gordon, & Putz, 2011), which constitutes a natural site for studying the impact of sea-level rise on coastline dynamics. Tidal condition varies across the region, the north of the Crystal Bay is mainly tidal (the tidal range is <1.5 m), but the south is mostly micro-tidal (little variations in horizontal positions of waterline). During the past several decades, the coast suffered continuous erosion, but the magnitude of the erosion is <30 m due to weak hydrodynamics (Morton et al., 2004), indicating that it is essential to undertake change detection at the subpixel level of Landsat imagery. Since we were primarily concerned with coastline changes, small river banks in the inland area were not included in this study.

2.2. Coastline indicators for the muddy coast

In this study, coastline indicators for the muddy coast, which represent the annual average location of the dynamic coastline, were selected based on coastline type (covered by vegetation or not) and tidal condition (tidal or micro-tidal).

For the muddy coastline covered by no or sparse vegetation in tidal area, selecting a suitable indicator is relatively complicated due to tidal fluctuation. However, during a tidal cycle, since the remnant surface water of mudflat can remain for a long time (Ryu, Won, & Min, 2002), the wet/dry line (namely high-water line, HWL, Fig. 2a) between tidal flat and land is nearly static. Thus, the HWL is considered as a stable indictor to the inundation extent of a tidal cycle, and then the annual mean HWL can be used to represent the annual average location of the dynamic coastline. According to the water level model proposed by Moore, Ruggiero, and List (2006), the location of the HWL is determined by the actual water level at high tide on the beach (the sum of high-tide height and wave runup) (Fig. 2b). In the muddy coast, due to weak wave condition, the effect of wave runup can be ignored, so the annual mean HWL is mainly determined by the annual mean high-tide height (namely mean high water, MHW).

In the tidal coast dominated by dense salt marsh, the steep cliff between tidal flat and marsh platform, which is formed from a series of complex physical and biological processes (Mariotti & Fagherazzi, 2010), makes the canopy of salt marsh hardly submerged. Thus, the edge of salt marsh is nearly static within a year, and is considered as a robust indicator to the marsh coastline. For the tidal coast covered by mangrove, since the undisturbed mangrove forest does not go underwater, the edge of mangrove forest is used as a coastline indicator. For micro-tidal coastlines either covered by vegetation or not, the waterline is a suitable indicator at the annual scale.

3. Data

3.1. Landsat imagery

All available Landsat TM (Thematic Mapper) and ETM+ (Enhanced Thematic Mapper Plus) imagery (path 17 row 40) from 1984 to 2013 with cloud cover <30% were downloaded from United States Geological Survey Center for Earth Resources Observation and Science (USGS/EROS). A total of 473 standard Level 1 Terrain-corrected (L1T) products were obtained for the scene (Fig. 3). For L1T products, systematic geometric errors have already been corrected with ground control points and a digital elevation model (DEM), and the geolocation accuracy is better than 0.4 pixels. The at-sensor radiance (digital number, DN) was converted to surface reflectance to reduce atmospheric effects such as Rayleigh scattering, aerosol scattering and gaseous absorption, which was achieved with the Landsat Ecosystem Disturbance Adaptive Processing System (LEDAPS) atmosphere correction tool (Masek et al., 2006; Vermote et al., 1997). Bad-quality observations including clouds, cloud shadows and SLC-off gaps were also identified since they are noise for change detection. Clouds and cloud shadows were screened with a recently developed algorithm named Fmask (Function of mask) (Zhu