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Letter

Influence of the 18.6-year lunar nodal tidal cycle on tidal flats: Mont-Saint-Michel Bay, France

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ABSTRACT

The influence of the 18.6-year nodal tidal cycle on estuarine accretion, and indirectly on channel migration patterns, in Mont-Saint-Michel Bay, a UNESCO World Heritage Site famous for its monastery, is explored over three tidal cycles from a 68-year dataset that combines aerial photographs (1947–2007), one DGPS survey (1997), and nine LiDAR Digital Elevation Models (2002–2015). Sand-flat elevation and sediment-budget changes in this megatidal environment were further determined over the last nodal cycle using DGPS and LiDAR surveys. We infer that the changes observed are linked to variations in tidal prism and current velocities in this shallow, large tide-range setting. Increasing (rising tidal range) or decreasing (falling tidal range) flood-dominated asymmetry are deemed to lead, respectively, to waxing and waning of sediment import, in the form of large sand banks, into the bay over the 18.6-year nodal tidal cycle that, in turn, force channel migration. Coriolis acceleration and centrifugal forces are also considered to contribute to the observed channel migration.

1. Introduction

The influence of the 18.6-year nodal lunar tidal cycle on coastal sedimentation has been highlighted by several studies. Examples include enhanced erosion or sedimentation on the mud-bank-influenced Guianas coasts (Wells and Coleman, 1981; Gratiot et al., 2008), shoreline changes in the islands of the Wadden Sea (Oost et al., 1993), and varved sedimentation in the Santa Barbara Basin (Berger et al., 2004), even though, as Mazumder and Arima (2005) have claimed, ancient sediments rarely record the imprint of lunar nodal cycles, because of the requirement of having at least nearly two decades of uninterrupted sedimentation preserved.

Allen (1990) considered the influence of the nodal cycle in a computational model on saltmarsh growth, but French (2006) showed, also from a modelling perspective, significant variability in marsh sedimentation associated with this cycle. Based on field observations and using a semi-empirical model, Jeuken et al. (2003), Townend et al. (2007) and Wang and Townend (2012) showed that the long-term large-scale sediment budget changes in the Westerschelde Estuary in the Netherlands and in the Humber Estuary in England were controlled by the nodal tide variation. Dronkers (2005) analysed a long dataset of net sediment accretion and erosion in the Wadden Sea and found a correlation with the 18.6-year lunar nodal cycle and no correlation with meteorological influences. However, with the exception of these previous studies, field evidence of the effects of this tidal cycle on the morphology of tidal flats is relatively rare.

Wang and Townend (2012) stressed the fact that even though the nodal cycle induces only a small variation in tidal amplitude (typically only about 4% of the tidal range), the impact on water volume in an estuary can be significant. The impact can be even more substantial for sediment transport because of the nonlinear relationship between tidal range and current strength. The tidal prism being proportional to the cross-sectional area of a tidal basin or estuary, each potential water volume change can influence the topography and morphology of the latter. However, as far as the 18.6-year tidal lunar cycle is concerned, short-term morphological changes in tidal flats are difficult to isolate from those associated with other forcing factors, such as long term storminess. Notwithstanding this difficulty, water volume changes would be expected to be particularly important in the networks of tidal channels that form pathways of water and sediment flux in tidal flats over much of a semi-diurnal tidal cycle. Coco et al. (2013) underscored the point that the morphodynamics of such networks are

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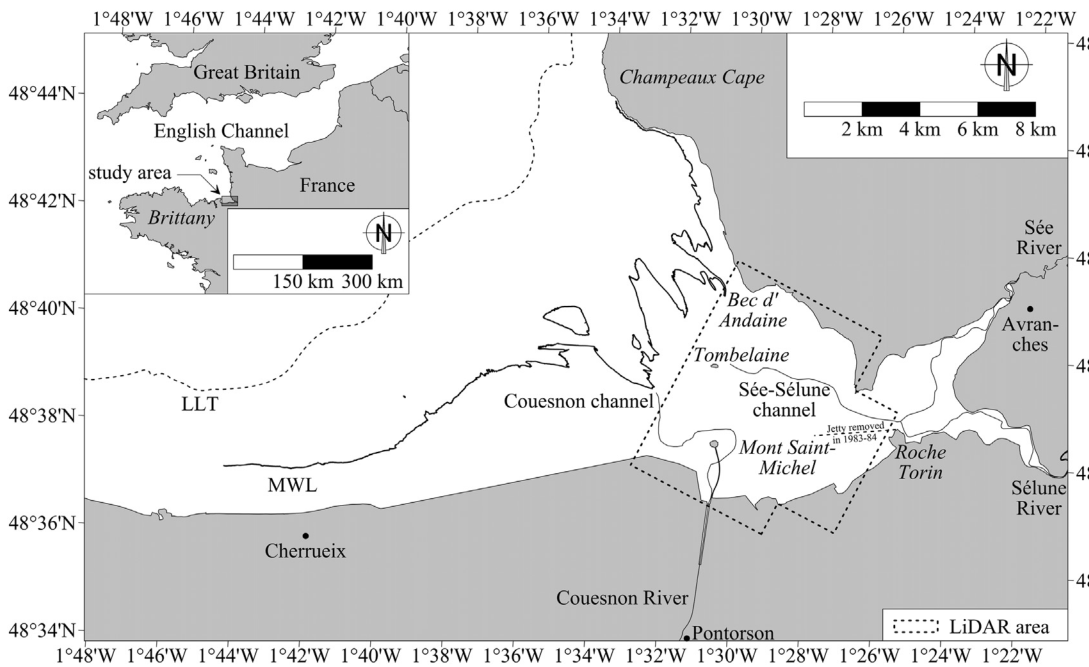

Fig. 1. Map of Mont-Saint-Michel Bay showing the location of the two main channels and the area covered by LiDAR surveys. LLT: Lowest Low Tide level, MWL: Mean Water Level.

strongly enmeshed with those of the ambient tidal flats and saltmarshes.

The aim of this study was to explore the influence of the lunar tidal cycle on the morphology and channels of tidal flats in Mont-Saint-Michel Bay (France) using a 68-year span of data drawn from a combination of vertical aerial photographs and satellite images, DGPS surveys and LiDAR. In particular, patterns of channel mobility were used as a proxy for highlighting the influence of changes in tidal range associated with the nodal cycle. Accretion/erosion patterns and sediment budget variations over the last two decades (1997–2015) were further combined with channel mobility to explore the morphodynamic implications of variations in tidal range related to the nodal tidal cycle.

2. Study site

Mont-Saint-Michel Bay is located on the northwest coast of France in the English Channel and at the entrance of the Normandy-Brittany Gulf (Fig. 1). The regional setting is a megatidal environment characterized by the second highest tidal range in Europe with a mean of 12 m and up to 15 m during very large spring tides (Levoy et al., 2000). The bay is under the influence of the semi-diurnal tidal regime of the English Channel with a slight diurnal inequality, and is characterized by a large sand flat comprising lower and mid-intertidal zones of about 500 km^2, and exhibiting mobile sand banks, backed by upper-intertidal zone saltmarshes dissected by tidal channels. The bay is world famous for its monastery constructed during the Middle Ages on a 92 m-high circular granite outcrop (the Mont), and it obtained the status of a UNESCO World heritage site in 1979. The bay also shows a relatively diverse morphology and substrate sedimentology as a result of variations in exposure to waves, tidal currents, winds, and sand-bank and tidal-channel mobility.

The saltmarshes front polders constructed over the last two centuries. The spatial distribution of the sediment cover over the intertidal area shows a decrease in grain size from the lower part of the tidal flat to the upper part, reflecting the progressive reduction in energy affecting the bed. The lower and mid-intertidal zones mainly comprise medium and fine sand and the upper intertidal zone very fine bioclastic sand with 2–5% of clay (Desguée et al., 2011). The areas closest to the saltmarshes have an overall mud content (silt and clay) of 20–25%, locally termed “tangue”. Three small rivers (the Sée and Sélune, which have a common estuarine channel, and the Couesnon; (Fig. 1) with mean water discharges of 8 to 15 m^3 s^{-1} flow into the eastern part of the bay. Their annual sediment inputs are considered as negligible (Larsonneur, 1994).

Currents are relatively strong in this megatidal bay. On the flats, maximum velocities are reached at the beginning and end of the flood limb. Minimum velocities occur at high tide (Desguée et al., 2011). Velocities range from 1.35 to 1.6 m s^{-1} during mean spring tides, but they are enhanced in the estuarine channels of the three rivers where they can exceed 2.2 m s^{-1}. A tidal bore less than 1 m-high is observed during spring tides in both estuary channels. Flood currents are, on average, 1.5 to 2 times stronger than ebb currents, thus reflecting flood-dominated asymmetry. This inequality is also marked by the ebb duration which is, on average, 2 to 3 times longer than that of the flood (Migniot, 1997).

The bay is exposed to short-fetch waves from the English Channel. Wave propagation is rendered complicated by the shoreface bathymetry, the Channel Islands, and the presence of numerous shoals and inlets, all of which cause a decrease in wave heights over the shoreface (Levoy et al., 2000). Consequently, much of the bay is a low wave-energy zone, but Desguée et al. (2011) showed that waves can generate active sediment transport during storms.

The bay is infilling (Larsonneur, 1994) from sediment inputs from the English Channel composed of about 50% bioclastic and 50% minerogenic sand and silt and the rest from in situ bioclastic production. The main identified sediment transport pathway into the bay is located on the northern fringes and in the central part (Migniot, 1997). A secondary pathway occurs probably sporadically on the western side in front of the saltmarshes near the monument (Gluard, 2012). This infilling occurs essentially through sand banks migrating into the bay. High channel mobility in the bay is favoured by the particular characteristics of the prevailing sediment, which is typically fine-grained but hardly cohesive.

3. Datasets and methods

In order to estimate elevation changes over the tidal flats in the course of at least one nodal tidal cycle, the first high-resolution topographic survey of the bay carried out using photogrammetry and DGPS in 1997 provided an initial state that was compared with a 2015

Table 1
Data sources used in the study of channel and sand flat evolutions.

Years	Type of data	Source
1947, 1952, 1955, 1960, 1961, 1965, 1966, 1969, 1970, 1972, 1973, 1977, 1978, 1979, 1980, 1984, 1986, 1989, 1991, 1992, 1996, 1997, 2000, 2002	Aerial photographs	IGN géoportail: http://www.geoportail.gouv.fr/accueil
2002, 2007, 2009, 2010, 2011, 2012, 2013, 2014, 2015	LiDAR	Syndicat Mixte Mont-Saint-Michel and Clarec project: http://www.unicaen.fr/dataclarec/home/

LiDAR coverage. This period covered falling (1997–2007) and rising (2007–2015) limbs of the nodal tidal cycle. In addition to delineating areas of erosion and accretion, the elevation differential also provided an estimation of sediment budget change over this period. These results concern a large area of the bay and must be considered as orders of magnitude because of the difference in resolution between the two types of surveys, LiDAR yielding much higher-resolution data than those of the 1997 field survey. The saltmarshes were excluded from this comparison because LiDAR data give a poor description of the micro-topography of salt marshes, especially when these are dense (Chassereau et al., 2011), which is the case in Mont-Saint-Michel Bay.

Twenty-four vertical aerial photographs of the intertidal area of Mont-Saint-Michel Bay taken at low tide (Table 1), and spanning the period from 1947 to 2002, were used to analyze changes in the tide-influenced channel network formed by the Sée-Sélune and Couesnon rivers (Fig. 1). The locations of the channels were manually extracted from the aerial photographs following geometrical corrections, and integrated into a GIS database. ~~Eight~~ Nine LiDAR datasets (coverage area shown in Fig. 1) were obtained at low tide during spring tides between 2002 and 2015. The LiDAR datasets were provided directly in Digital Elevation Model format with a mesh size of 1 m. A simple technique was used to extract tidal channel networks from the LiDAR intensity data. For each survey, an image of intensity values of the studied area was used to locate the main channels. The contrast in reflectance intensity between tidal flat and channels allowed delineation of the channels by a human operator. Channel mobility patterns were thus monitored over a period of 68 years, fully covering 3 nodal tidal cycles of 18.6 years. The bay forms a large triangle-shaped open area oriented west-north-west. A bisecting line is used to separate the northern and southern sectors and the percentage of See-Sélune channel locations within each sector calculated for all dates. The line is slightly different before and after 1984, the date corresponding to removal of the Roche Torin Dike (Fig. 1).

The nodal tidal oscillations were determined from numerical modelling of tidal levels derived from SHOM (National hydrographic office) data.

4. Results

4.1. Intertidal sand flat changes and the sediment budget at a timescale of one nodal tidal cycle

Fig. 2a and b shows the main elevation changes during the last lunar cycle between 1997 and 2007 (decreasing M2 tidal range) and between 2007 and 2015 (an increasing M2 tidal range). These changes tend to depict a quasi-opposite behavior in the various parts of the bay. From 1997 to 2007 (Fig. 3a), the main erosion areas were in the northern part of the bay where sand flat elevation changes exceeded 2.5 m. Accretion mainly occurred in the centre of the bay. Between 2007 and 2015 (Fig. 2b), a dominant erosion zone is found in the southern part of the bay in front of the saltmarshes west and east of the monastery. A second erosion area is identified in the northwest confines of the bay. Accretion occurred in front of the northern saltmarshes, around Tombelaine Island, and southward towards “Pointe du Grouin”, exactly where erosion was observed in the course of the previous period. Areas where similar elevation changes were observed during the two phases of the nodal cycle are small. Between 1997 and 2007, the sediment budget is slightly positive with a gain of only 18,800 m^3 over the intertidal area, whereas a net accretion of 1 Mm^3 is observed with the phase of increasing M2 tidal range. Over the entire cycle, these estimates show a gain of sediment close to 1 Mm^3, confirming the long-term infilling of the bay, while highlighting large variability in the sediment budget depending on the considered timescale. This infill occurs through the formation and bay-ward migration of large sand banks.

4.2. Time-space variations in migration of the Sée-Sélune and Couesnon channels

The successive northward and southward locations of the Sée-Sélune in the bay are depicted in Fig. 3a. The channel moved from the central axis of the bay northward and then swung back southward in a typical seesaw movement. The channel was located along the northern flanks of the bay in 1947, 1969–70, 1991–92, 2007–2010 and the southern flanks in 1960–1966, 1977–1980, 1996–2000, 2012–2015 (Fig. 3a). Over the same time, the Couesnon also migrated over a large swathe, moving from west to east, and suddenly back to west. Clearly, the pattern appears to be cyclic with a period of 15–20 years.

The extreme (south and north) positions of the Sée-Sélune channel show a strong positive relationship with the low and high water levels induced by the 18.6-year nodal lunar cycle (Fig. 3b), suggesting a relationship between channel positions and this cycle. The Couesnon channel, in front of the monastery, has regularly maintained an easterly position in the course of phases of increasing M2 tidal range, and especially close to the peaks of this increase (1961, 1979–1980, 1995, 2012), whereas the most westward locations are observed during periods of decreasing M2 influence (1970–1971, 1989–1990; 2001–2004). An exception to this is the present location (2015) which is clearly out of phase. The possible reasons for this divergence are discussed later.

5. Discussion

Although the sediment-budget data for Mont-Saint-Michel Bay covers only the period 1997–2015, it is hypothesized here that the see-saw pattern, over a period of 68 years, of tidal channel mobility, in close agreement with swings in the 18.6-year nodal tidal cycle, is indirectly influenced by sediment import into or export from the bay, as has been suggested for the Wadden Sea (Jeuken et al., 2003; Dronkers, 2005). The primary mechanism through which this is likely to occur is correlative changes in tidal prism and current velocities in this shallow, large tide-range bay that are matched by increasing or decreasing flood-dominated asymmetry during the 18.6-year nodal tidal cycle. Tidal asymmetry is a non-linear effect which increases with increasing relative tidal amplitude (ratio of tidal amplitude to depth). Even for relatively small tidal amplitudes the tidal wave is distorted when propagating into Mont-Saint-Michel Bay. Net tidally induced sediment import into the bay thus should occur for almost every tide, although large amplitudes contribute much more than low amplitudes. Large tidal amplitudes induce strong tidal distortion in the shallow Mont-Saint-Michel Bay, resulting finally in a tidal bore during a short flood period with high current velocities, compared to a long ebb period with low velocities.

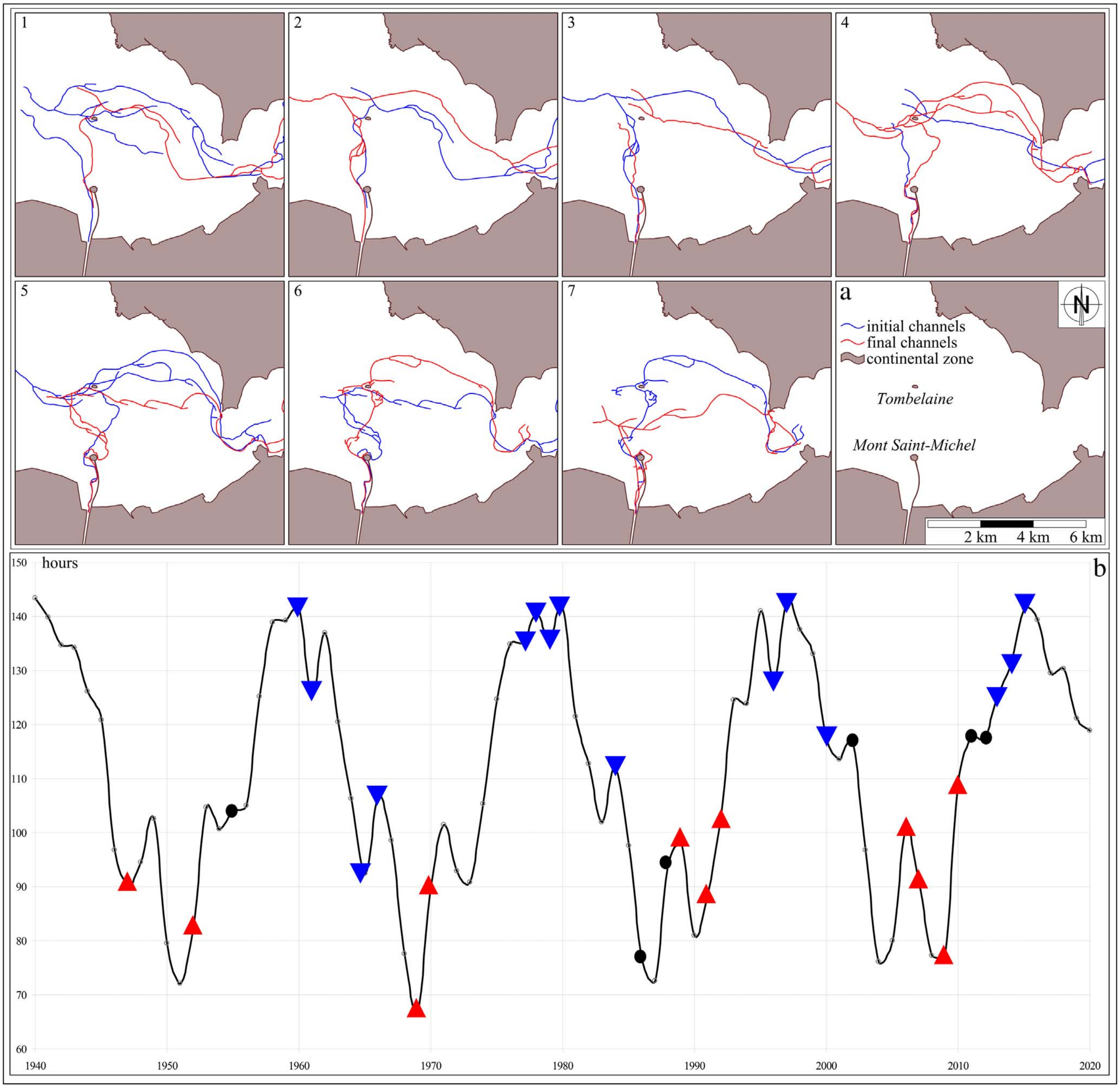

Fig. 2. (a) Migration of the Sée-Sélune and Couesnon channel over the following periods: (1) 1947–1961, (2) 1961–1969, (3) 1969–1979, (4) 1979–1992, (5) 1992–1997, (6) 1997–2007, (7) 2007–2015; (b) time above the Mean Spring High tide level since 1940 and locations of the Sée-Sélune tidal channel: red triangles indicate a northern location, blue triangles a southern location, and black circles intermediate locations. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

This reinforced flood-dominated asymmetry is deemed to generate enhanced sediment import with preferential accretion of the intertidal flats. During phases of tidal range decrease, the flood-dominated asymmetry diminishes, and weaker tidal currents result in a more balanced bay sediment budget, and even in mild erosion or accretion. Accretion of the bay should thus be enhanced during phases of the lunar nodal cycle with high astronomical tides. Other processes also influence net sediment import or export. Sedimentation and erosion time lags favour net sediment import to tidal flats, whereas wave stirring favours (generally) net sediment export. These two processes also depend in some way on the tidal amplitude, but are probably less influential than tidal asymmetry.

The response of tidal embayments to tidal lunar forcing depends also on the morphological timescale which can vary with the length of the embayment (Jeuken et al., 2003; Wang and Townend, 2012). A morphological timescale related to achieving (dynamic) equilibrium is probably much larger than the nodal cycle, at least for large estuaries. The morphological timescale in Mont-Saint-Michel Bay cannot be determined from the available data. These data only show that the sediment volume in this bay hardly increased in the period from 1997 (close to highest astronomical tides) to 2007 (lowest astronomical tides in 2006), whereas the sediment volume in 2015 (highest astronomical tides) is considerably higher than in 2007. There are no precise data on the tidal phases corresponding to the largest increase in sediment volume. It is possible, for instance, that the fastest increase in sediment volume occurred in time intervals around 1997 and 2015 - as should be expected if tidal asymmetry is the major driving factor.

During phases of tidal range increase, maximum tidal currents become stronger and tidal asymmetry is enhanced, especially in the shallow landward part of the basin. The channel volume (depth, width)

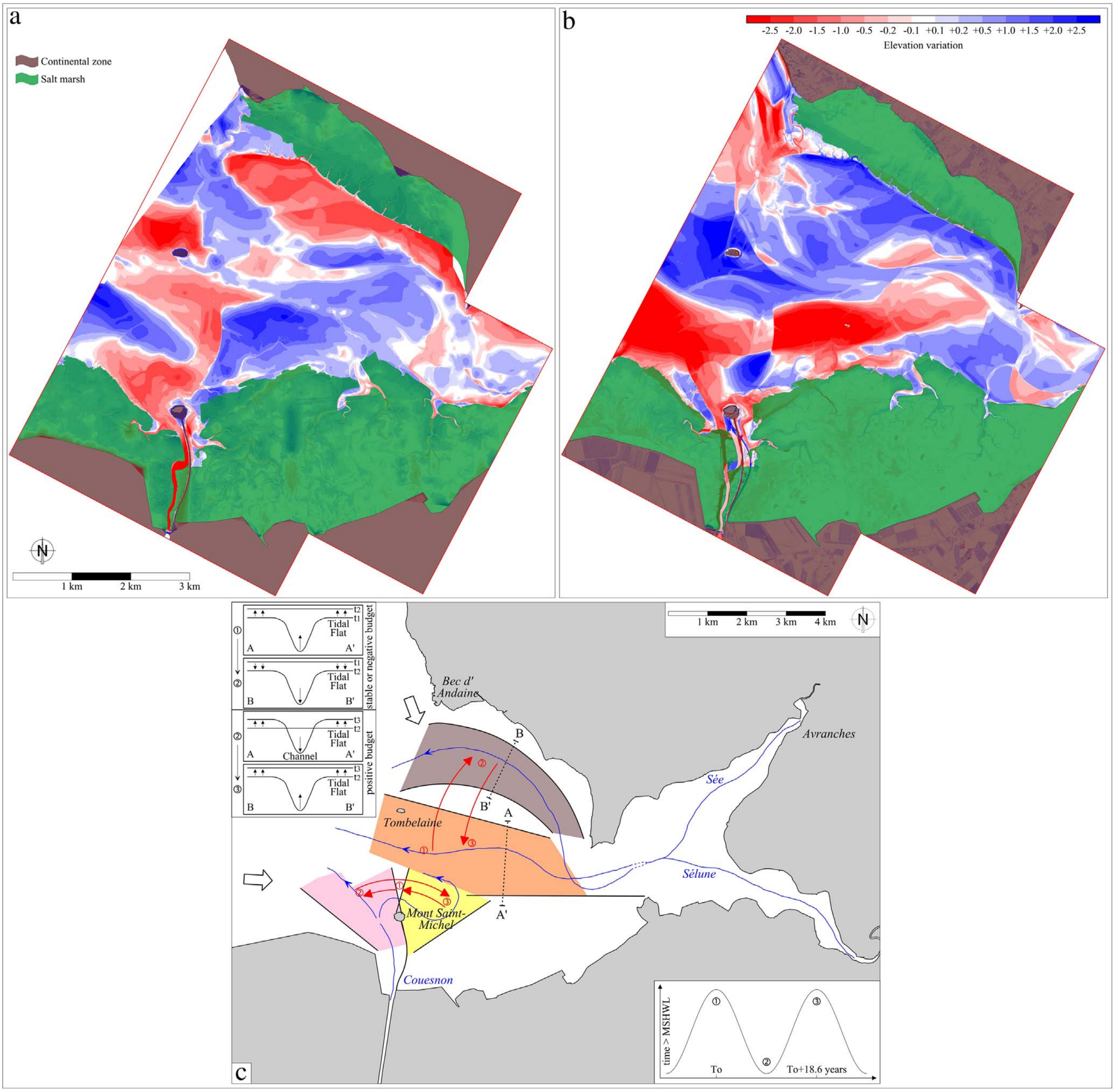

Fig. 3. Sand flat elevation changes in Mont-Saint-Michel Bay (a) during a phase of increasing tidal range linked to the nodal lunar cycle (July 1997–July 2007) and (b) during a phase of decreasing of tidal range (July 2007–June 2015), (c): conceptual model of main channel migration and sand flat behavior at a timescale of a nodal lunar cycle.

increases, whereas tidal flats accrete – a process that has been well documented for the Eastern Scheldt (Louters et al., 1998). Our data provide clues, however, for processes that might be responsible for the shifts in the positions of the Sée, Sélune and Couesnon, and suggest that these are not a direct outcome of the nodal tidal cycle but of levels of accretion associated with changes in tidal asymmetry related to this cycle. It seems, in particular, that bayward migration and growth of sand banks force a change of direction of the tidal channels. We attribute this landward migration and growth of sand banks to enhanced sediment import in periods of high tidal amplitudes. The channels seem to be "forced", respectively southeastward for the Sée-Sélune and eastward for the Couesnon, away from the main sediment transport pathways into the bay. As tidal amplitude and resulting tidal asymmetry attain their maximum, it may be expected that sediment import becomes maximum. Accretion is the integral of sediment import. Maximum accretion is thus shifted a quarter nodal cycle relative to the tidal amplitude. Because of this, channel migration is not necessarily in phase with accretion. Being a local short-term phenomenon in Mont-Saint-Michel Bay, channel migration is probably more closely in phase with the tidal amplitude (and with tidal current strength and tidal asymmetry) than with accretion (this would be the case, for example, if Coriolis plays an important role – as discussed later). At the peak of the rising limb of the nodal cycle (blue triangles in Fig. 2b), the Sée-Sélune attains a southern location, sometimes close to the central axis of the bay. This phase corresponds to a stronger channel bed slope that could be favourable to the initiation of export of sediments towards the lower part of the bay and/or towards the offshore zone. During phases of decreasing tidal range, the corresponding decrease in flood and ebb currents, albeit with flood-dominant asymmetry still prevailing, is, as stated above, presumed to result in a net decrease in sediment import into the bay, and even possibly, sediment export if tide-induced accretion is overruled by wave-induced erosion of tidal flats. However, we hypothesize that the progressive northward swing of the channel is forced by sand choking. In periods of the lunar nodal cycle with relatively small tides, channel shifts can be triggered by infill of previously enlarged channels with sediment derived from previously accreted sand banks and this could explain channel migration from the central axis towards the north of the bay.

The Couesnon channel shows a distinct migration from west to east, which seems generally in phase with the movements of Sée-Sélune channel which swings from south to north and then north to south within a single nodal cycle. The Couesnon channel just in the front of the monastery, is located westward when the amplitude of the tidal range of the lunar cycle is weak and eastward when it is high. However, in contrast to the Sée-Sélune channel, the westward migration of the Couesnon during decreasing tidal ranges can be extremely rapid, as observed during winter 2000–2001 and in May 2012, characterized by meander cutoffs operating over only a few days. The Couesnon is also subject to a degree of anthropogenic control related mainly to the construction of dikes in the bay and a dam up-channel. The 'out-of-phase' May 2012–2015 location of the Couesnon corresponds to active water releases from this dam built in 2009. Fig. 3c shows a conceptual model of main channel migration and sand flat behavior at a timescale of a nodal lunar cycle.

From a theoretical viewpoint, centrifugal (inertial) effects and Coriolis acceleration may play a role as well in the migration of the Mont-Saint-Michel Bay channels, as demonstrated by van Veen (1950) for the WesternScheldt Estuary, and by the Li et al. (2011) for the Changjiang (Yangtze) Estuary. For a current of 1 m s^{-1}, the Coriolis effect has similar magnitude as the centrifuge effect in a meander with a radius of 10 km. Meanders associated with the bay channels have a radius of 2 to 5 km. The Coriolis acceleration is thus 2 to 5 times weaker than the centrifugal acceleration. Centrifugal effects strengthen channel meandering and meander migration and thus promote shifts in channel position. Earth rotation tends to concentrate flood flow and ebb flow at opposite channel banks, thus shifting flood-dominated and ebb-dominated channels in opposite directions (as observed also in other estuaries). Both effects are strongest when tidal amplitudes are large. Flood-dominant channels should therefore be more active in the southern part of the bay and ebb-dominant ones in the northern part (for a more detailed discussion, see Dronkers, 2016, p. 295). During phases of rising tidal range, flood-dominant channels are expected to migrate towards the south.

6. Conclusions

The results of this study provide a rare example of remote sensing-based experimental work highlighting the potential effects of the 18.6-year nodal tidal cycle in temporal variations in the sediment budget of a large, shallow megatidal embayment that influence, in turn, tidal channel mobility patterns. The pattern of increased sedimentation observed during the half-cycle limb of rising tidal range illustrates the importance of changes in tidal prism and attendant flood-dominant tidal asymmetry. On a more local scale, the study strongly suggests considering the influence of this cycle in the infill of Mont-Saint-Michel Bay, which is assured by sediment import from the English Channel and in situ biogenic inputs. The bay is an important World Heritage site that attracts millions of tourists every year. This attraction is assured by the insular character of the monastery, which is increasingly threatened by bay infill. A large-scale sediment management project costing millions of euros has been implemented as part of the solution to preserve the insular character of the monument. Our study provides a framework for considering the role of the 18.6-year nodal tidal cycle in generating decadal to bi-decadal-scale sediment budget fluctuations in Mont-Saint-Michel Bay that need to be considered in long-term sediment budget perspectives and in forecasting changes in the locations of the channels debouching in the bay.

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References

Allen, J.R.L., 1990. Salt-marsh growth and stratification: a numerical model with special reference to the Severn Estuary, southwest Britain. Mar. Geol. 95, 77–96.
Berger, W.H., Schimmelmann, A., Lange, C.B., 2004. Tidal cycles in the sediments of Santa Barbara Basin. Geology 32, 329–332.
Chassereau, J.E., Bell, J.M., Torres, R., 2011. A comparison of GPS and lidar salt marsh DEMs. Earth Surf. Process. Landf. 36, 1770–1775.
Coco, G., Zhou, Z., van Maanen, B., Olabarrieta, M., Tinoco, R., Townend, I., 2013. Morphodynamics of tidal networks: advances and challenges. Mar. Geol. 346, 1–16.
Desguée, R., Robin, N., Gluard, L., Monfort, O., Anthony, E.J., Levoy, F., 2011. Contribution of hydrodynamic conditions during shallow water stages to the sediment balance on a tidal flat: Mont-Saint-Michel bay, Normandy, France. Estuar. Coast. Shelf Sci. 94, 343–354.
Dronkers, J., 2005. Natural and Human Impacts on Sedimentation in the Wadden Sea: An Analysis of Historical Data. National Institute for Coastal and Marine Management/RIKZpp. 47.
Dronkers, J., 2016. Dynamics of Coastal Systems, second ed. World Scientific Publ. Co.pp. 750.
French, J., 2006. Tidal marsh sedimentation and resilience to environmental change: exploratory modelling of tidal, sea-level and sediment supply forcing in predominantly allochthonous systems. Mar. Geol. 235, 119–136.
Gluard, L., 2012. Evolution des Fonds Sédimentaires Sous L'influence de la Divagation des Chenaux Aux Abords du Mont-Saint-Michel. PhD University of Caenpp. 300.
Gratiot, N., Anthony, E.J., Gardel, A., Gaucherel, C., Proisy, C., Wells, J.T., 2008. Significant contribution of the 18.6 year tidal cycle to regional coastal changes. Nat. Geosci. 1, 169–172.
Jeuken, M.C.J.L., Wang, Z.B., Keiller, D., Townend, I.H., Liek, G.A., 2003. Morphological Response of Estuaries to Nodal Tide Variation. Int. Conf. Estuaries & Coasts (ICEC-2003)pp. 167–173.
Larsonneur, C., 1994. The Bay of Mont-Saint-Michel: a sedimentation model in a temperate macrotidal environment. Senckenberg. Marit. 24 (1/6), 3–63.
Levoy, F., Anthony, E.J., Monfort, O., Larsonneur, C., 2000. The morphodynamics of megatidal beaches in Normandy, France. Mar. Geol. 171, 39–59.
Li, M.T., Chen, Z.Y., Yin, D.W., Chen, J., Wang, Z.H., Sun, Q.L., 2011. Morphodynamic characteristics of the dextral diversion of the Yangtze River mouth, China: tidal and the Coriolis force controls. Earth Surf. Process. Landf. 36, 641–650.
Louters, T., Van den Berg, J.H., Mulder, J.P.M., 1998. Geomorphological changes of the Oosterschelde tidal system during and after the implementation of the Delta project. J. Coast. Res. 14, 1134–1151.
Mazumder, R., Arima, M., 2005. Tidal rhythmites and their implications. Earth Sci. Rev. 69, 79–85.
Migniot, C., 1997. Synthèse Générale des Connaissances sur les Problèmes Hydro-sédimentaires. Mission Mont-Saint-Michel, Rétablissement du caractère maritime du Mont-Saint-Michel. pp. 89.
Oost, A.P., de Haas, H., Ijensen, F., van den Boogert, J.M., de Boer, P.L., 1993. The 18.6 yr nodal cycle and its impact on tidal sedimentation. Sediment. Geol. 87, 1–11.
Townend, I.H., Wang, Z.B., Rees, J.G., 2007. Millennial to annual volume changes in the Humber Estuary. Proceedings of the Royal Society A 463, 837–854.
Van Veen, J., 1950. Eb- en Vloedschaar Systemen in de Nederlandse Getijwateren. Tijdschrift Koninklijk Nederlansch Aardrijkskundig Ggenootschap Vol. 67. pp. 303–325 (English translation and annotations by Van de Spek, A., Stive, M. and Zitman, T. 2001. Publ. Delft University, Symposium for the retirement of prof. K. d'Angremond).
Wang, Z.B., Townend, I.H., 2012. Influence of the nodal tide on the morphological response of estuaries. Mar. Geol. 291–294, 73–82.
Wells, J., Coleman, J., 1981. Physical processes and fine-grained sediment dynamics, coast of Surinam, South-America. J. Sediment. Res. 51, 1053–1068.