Abstract

Tides at High Latitudes

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One misconception about tidal sedimentation is that, at high latitudes, tides are always negligible. If this was the case, all high-latitude coastal sedimentation would be either wave or river dominated, with waves commonly being reduced by the presence of sea ice, leading to a preponderance of river-dominated sedimentation. An examination of tidal theory and a review of modern coastal tidal data and modeling results demonstrates that this "myth" is not true universally and that latitude does not exert a strong control on the tides. Instead, the amplitude of the tide is controlled by the degree of connection with the global ocean and local bathymetric and coastal morphology. Even in polar regions, conditions sometimes favor the generation of high tidal ranges and strong tidal currents (Figure 1) that can contribute significantly to sedimentation. This "myth" that tides can always be ignored in high latitude seas may be the result of two factors.

Firstly, there may have been undue reliance on the use of equilibrium theory to explain tides on the Earth. Equilibrium tidal theory imagines an Earth completely covered by a uniform-depth ocean, in which lunar gravitational attraction generates two bulges of water, one beneath the Moon and the other on the opposite side of the Earth. These bulges then migrate around the world as the Earth rotates (Kvale, 2006; Dalrymple, 2010). In this model, the bulges have their maximum height, and thus the maximum tidal range, near the equator, with the peak of the bulges oscillating between ~28^{o} north and south of the equator as the Moon's declination changes on a 27.3-day period. At the poles, the amplitude of the tidal bulge is small, so the tidal range would be nearly zero, and the remaining tide should be predominantly diurnal. While equilibrium tidal theory provides a simple first-order explanation for many aspects of tidal dynamics, it ignores the presence of continents that constrain the movement of the tidal bulges, and also ignores the influence of the Coriolis effect, which causes the direction of tidal-wave progression to deviate from a straight line. Real tides on Earth are, instead, described better by the dynamic tidal theory which takes these factors into consideration. Because of the presence of the continents, the tidal bulges must take a circuitous path around the Earth (Allen, 1997) and cannot reach all parts of the ocean with equal intensity because the tide's forward motion is blocked or impeded by constrictions and/or because some of the tidal energy is dissipated by bottom friction and form drag over large-scale topographic irregularities. The Coriolis effect causes the tidal wave to bank up against one side of the water body through which it is passing, generating higher tidal ranges on the right-hand side (relative to the direction of wave motion) of the basin in the northern hemisphere and on the left-hand side in the southern hemisphere (Allen, 1997). The Coriolis effect is also responsible for the generation of amphidromic points, about which the tidal wave rotates, with zero amplitude at the center and increasingly larger amplitudes farther outward. In addition, the tidal wave interacts with the geometry of the basin as a whole, and with individual smaller parts of the basin, to either amplify or diminish the tidal amplitude. Amplification of tidal ranges occurs wherever the energy of the wave is compressed into a smaller cross-sectional area (either because of rapid shallowing or a narrowing of the

basin), or where the natural period of the area approximates one of the astronomically determined tidal periods (i.e., there is an approach to resonant conditions).

The second possible cause of the myth may be that, in the modern world, most of the Arctic Ocean and the coast of Antarctica do, in fact, have very small tidal ranges (i.e., most of these shorelines are microtidal (i.e., < 2 m range); King et al., 2005; Kowalik and Proshutinsky (1994); Padman et al. (2002); Padman and Erofeeva (2004)). This is consistent with the prediction of equilibrium tidal theory that tides at high latitudes are always small and so can be ignored in modeling of coastal systems and their deposits. However, the small tides in the Arctic Ocean are fundamentally the result of its semi-enclosed geometry and the rather limited connection with the global ocean, much like the Mediterranean Sea. In addition, the Arctic basin is not resonant with any of the dominant tidal frequencies, so basin-scale amplification does not occur. The small tides along most Antarctic coasts are the result of the fact that most of the continental margin has a narrow continental shelf (typically < 150-200 km wide), which does not allow significant amplification of the oceanic tide. As a result, the general tidal range is small. In both areas, the influence of sea ice (typically less than 2 m thick) on tidal dynamics is minimal. Floating ice moves up and down freely with the tide. Where it is also free to move laterally, its influence is small; if lateral motion of the ice is inhibited, the additional friction along the base of the ice apparently reduces tidal amplitudes by only 5-10% (Murty, 1985; Prinsenberg, 1988). However, around Antarctica, the coastal ocean is locally covered by ice shelves comprised of glacial ice that is 100-2000 m thick. Although these ice shelves float freely on the ocean, they decrease the water depth, which can have a large impact on tidal dynamics, with the potential for dramatic increases in tidal range because of the compression of the tidal-wave's energy into a smaller cross-sectional area. For example, some of the largest tidal ranges in Antarctica (ca. 6 m; Doake, 1992) have been recorded near the grounding line of the Rutford Ice Stream in the southern part of the Ronne Ice Shelf. Of course grounded ice, including shore-fast ice that is frozen to the sea bed, blocks the landward passage of the tidal wave.

At all latitudes, including those near the poles, the largest coastal tidal ranges occur in the inner part of funnel-shaped embayments, in which convergence and an approach to resonance generate significant tidal amplification. For example, an examination of the 13 modern hypertidal areas (i.e., areas where tidal ranges during spring tides are more than 6 m) recognized by Archer (2013) shows that 10 of them occur at relatively high latitudes (i.e., > 45^{o} N or S): the Gulf of Mezan (Murmansk), Russia (65^{o} N); Sea of Okhotsk, Russia (62^{o} N); Ungava Bay, northern Quebec (59^{o} N); Turnagain Arm, Cook Inlet, Alaska (61^{o} N); Liverpool Bay, England (53^{o} 30' N); several estuaries in Patagonia, Argentina (52^{o} S); the Severn River, England (51-52^{o} N); the English Channel (51^{o} N); Mont Saint Michel Bay, France (49^{o} N) and the inner Bay of Fundy, Canada (45-46^{o} N). Indeed, only 2 of the 13 hypertidal sites, the Gulf of Cambay, India (22^{o} N) and NW Australia (16^{o} S), occur at an equatorial latitude (i.e., within 25^{o} of the equator), despite the fact that the tide-generating force is greatest near the equator.

The bottom line is that significant tidal action can occur at any latitude if the (paleo-)geography is appropriate: equatorial areas need not have higher tidal ranges than all areas near the poles. At any latitude, to get large tides the basin must have a free connection with the global ocean, must not have a geometry that damps the incoming tidal wave by destructive interference between the incoming and outgoing waves, and must have a local coastal geometry that compresses the tidal wave into a landward-tapering cross-sectional area. At locations where such geometric constraints do not exist, tidal ranges will remain microtidal as they are in the open ocean. It must be remembered, however, that a large tidal range is not required to cause significant tidal influence or even tidal dominance (Dalrymple, 2010). Instead, it is the tidal prism (i.e., the volume of water flowing through a particular cross section during each tide) that determines the strength of the currents and the degree of tidal influence (cf. Figure 1). Consequently, large rivers that flow across low-gradient coastal plains can be strongly tide-influenced to tide-dominated even if the tidal ranges is only moderate. The requisite paleo-geographic situation for at least local tidal dominance must have existed during deposition of the tide-dominated incised-valley deposits in the Eocene succession of Spitzbergen (Plink-Björklund and Steel, 2006), which was at nearly its current latitude at that time (78° N. Thus, the same rules govern the occurrence of tidal deposits in polar areas as apply elsewhere on the Earth. [For more information on polar-ocean tides, visit http://www.esr.org/ptm_index.html].

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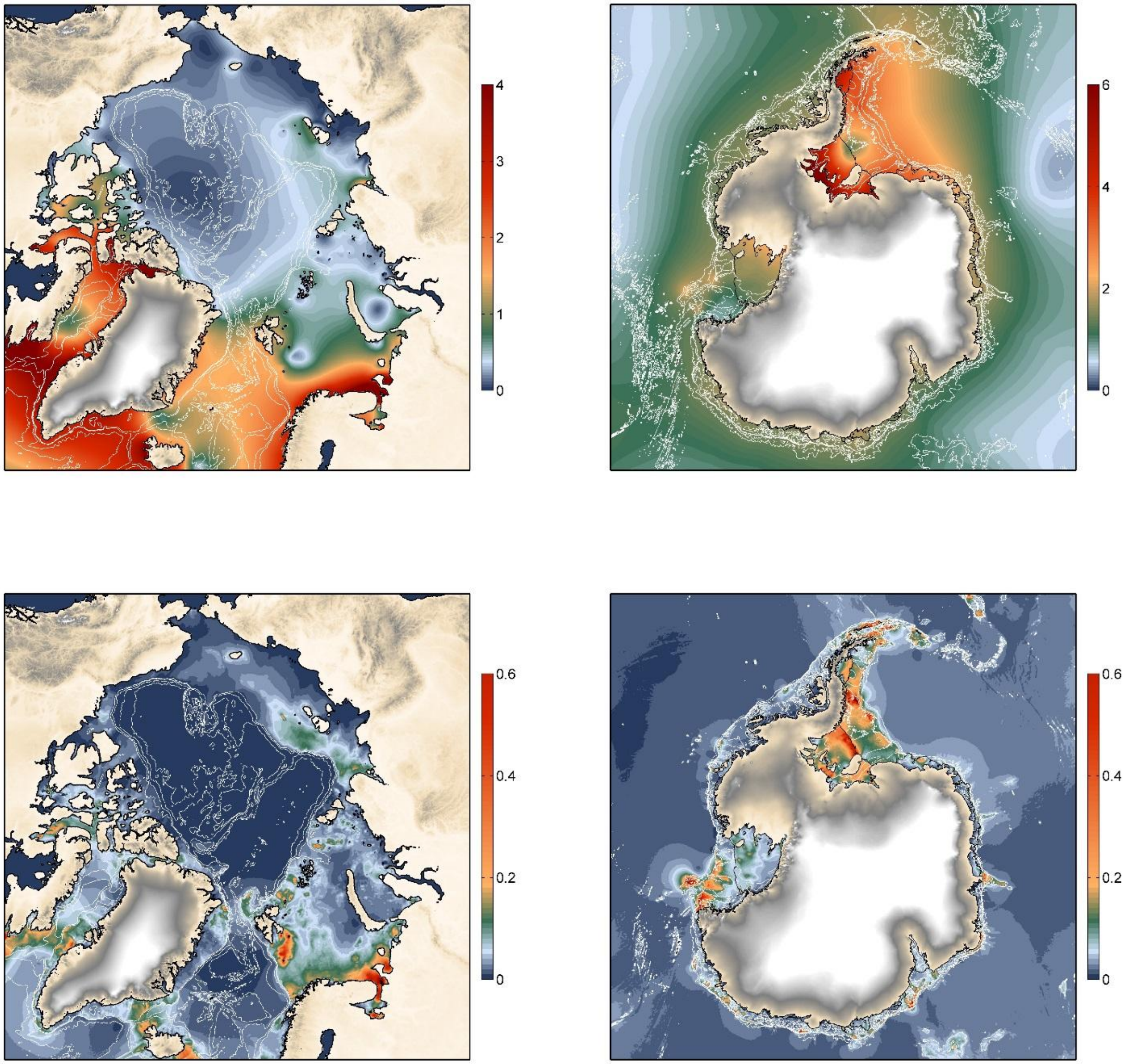

Figure 1: Tide characteristics from high-resolution polar tide models. Left panels: Arctic Ocean tidal range (m: top) and mean tidal-current speed (m s^{-1}; bottom) from Padman and Erofeeva (2004). Right panels: Same,for Antarctica, from Padman et al. (2002).