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Decadal-Scale Changes in West Coast Shelf Internal Tides (The Tides, They are a Changin')

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Abstract

The National Science Foundation (NSF) Co-OP (Coastal Ocean Program) Project RISE (River-Influenced Shelf Ecosystems) seeks to understand how primary and secondary productivity are enhanced by large river plumes in upwelling regions, using the Columbia River plume as a case study. Columbia River plume waters are rich in silicate and iron, but relatively depleted in nitrate. Mixing of nitrate-rich upwelled water with the plume is, therefore, important to plume primary production. Large internal tidal currents cause part of the necessary mixing. Accordingly, any long-term changes in these internal tides could impact productivity. Because no decadal-scale current observations are available to evaluate changes in internal tides, an indirect approach is needed -- we examine long-term changes in the surface tide (which is affected by internal tides) relative to the astronomical tidal potential. Of course, observed tides are affected by human manipulation of coastal environments as well as by changes in internal tides. Thus, four methods were used to separate estuarine human and coastal effects on observed surface tides:

- Examination of historical changes in tidal admittance along the West Coast using long-term tide stations between 16° and 60.5° N; 14 million hourly tidal heights for 1854 to 2004 were analyzed. These stations show a broad range of human impacts, but most show increasing tides.
- Use of tidal constituent ratios to diagnose processes; e.g., a channelization-induced reduction in estuarine friction affects the S_2/M_2 ratio, while a decrease in K_1/M_2 may indicate the changing influence of internal tides, at least north of 30° N.
- Examination of the spatial pattern of tidal properties in the three major West Coast shallow estuaries for which multiple stations with long records are available (San Diego and San Francisco Bays and the Columbia).
- Analysis of seasonal patterns in tidal admittance relative to river flow and sea level in the Columbia, to separate fluvial and shelf processes.

Conclusions

- Surface M_2 amplitude is increasing at most West Coast stations, suggesting that the energy partition between the surface and internal tides is undergoing change. Human alterations of harbors and secular trends in tidal potential do cannot account for these changes.
- K_1 is also increasing for reasons that are unclear; changed shelf wave activity and human alteration of harbors may both be involved.
- Increases in tidal range may cause coastal erosion to accelerate; tsunami hazard zones may move landward.
- These long-term changes in processes may be related to changes in coastal stratification and global climate change.
- A rapid increase in tidal amplitude within the Columbia Estuary has been caused both by human factors (decreased river flow and bed friction, and increased channelization/funneling of the tide) and shelf processes.
- Seasonal changes in Astoria M_2 amplitude are correlated with sealevel (MSL, a surrogate for changes in shelf stratification) and river flow, but MSL and river flow are not correlated with each other. Thus, changes in Columbia tides may be related to both shelf and local processes.
- A better measure of shelf stratification is needed in order to quantify changes in internal tides and their energetics in the plume area.

Why Do Coastal Tides Change??

- Changes in amplitude or phase of shelf internal tides, altering suface tides: This may occur because of warming at the surface or at depth, increasing or decreasing stratification. Reduced freshwater discharge may also decrease stratification; the 19th Century was a very wet period along the West Coast, and flow diversion from rivers has increased drastically since 1900.
- Changes in estuarine processes: Decreased bed friction (due to reduced river flow and sediment transport), channelization (reducing friction), and shoreline alteration (which usually reduces area and volume and funnels the tidal wave) may increases tidal amplitudes. Sealevel rise and tectonic changes may also alter tides.

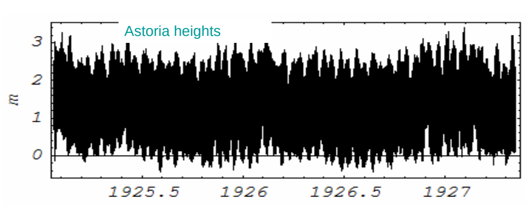
Because human engineering of harbors is ubiquitous, a tide gauge in an estuary is an imperfect tidal instrument! Still Flick et al. (2003) show increases in range at 6 of 12 "open-coast" stations along the West Coast, with decreases at only 3. Because this work is based on compiled tidal ranges, it is difficult to discern causal mechanisms from it. An analysis based on tidal constituents is provided here.

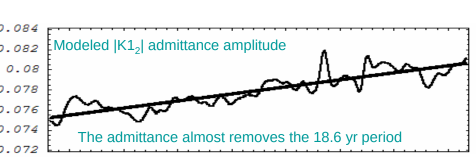
Methods

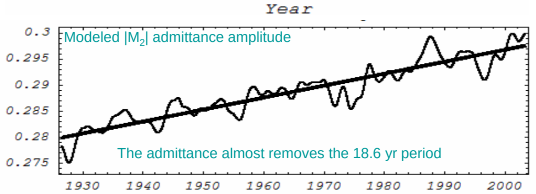
Two kinds of tidal analysis were used to determine tidal properties and their changes: harmonic analysis or HA (the t_tide program of Pawlowicz et al., 2002), and complex demodulation (or CD). The two give similar results but have complementary strengths and weakness. HA is faster when extraction of a large number of constituents is needed, CD is more useful when admittance calculations (also used by Colosi and Munk, 2004) are needed.

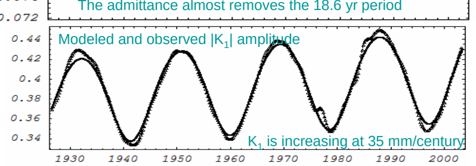
Calculation of a complex admittance (a complex ratio of tidal response to astronomical forcing, resolved into an amplitude ratio and phase difference) is useful, because detection of long-term trends in HA results is complicated by pronounced 18.6 yr nodal cycles in both amplitude and phase, especially for K_1. The admittance calculation largely eliminates the nodal signal, because it is present in both the tides and the potential. The determination of trends in tidal properties is illustrated in the following figures. The steps are:

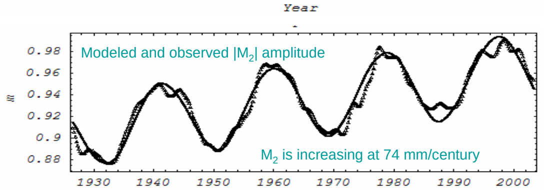
1) Assemble a multi-decadal time series with a common time base and datum level – for many stations this is the rate-limiting step!
2) Calculate the tidal potential for period of record, based on t_tide routines t_astron.m and t_equilib.m
3) Extract K_1, M_2, and S_2 from the tidal data and the potential by complex demodulation via a 26013 hr complex Kaiser filter; a weighting scheme handles gaps.
4) Determine the admittance amplitude & phase difference.
5) Fit a linear trend to admittance amplitude and phase difference, using yearly data points.
6) Invert the linear models to determine trends in the tidal constituent amplitude and phase.







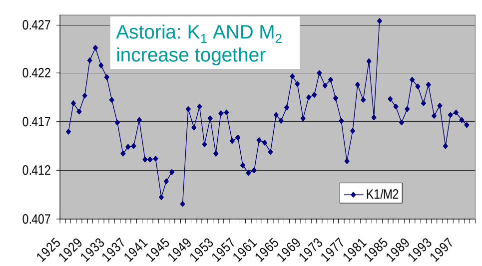


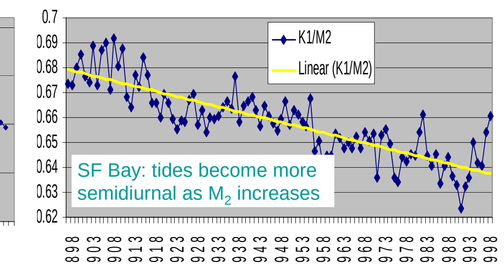


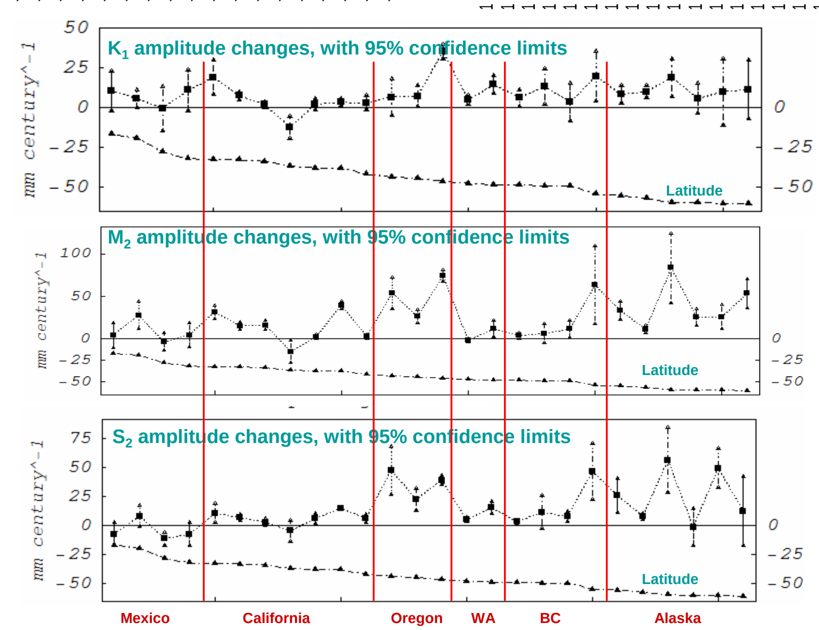
Long-Term Changes in West Coast Tides – The Big Picture

Analysis of 1.4×10^7 tidal height observations show that tidal amplitudes for the K_1, M_2 and S_2 constituents are increasing at most stations north of 37° N; K_1 and M_2 are increasing at most stations from 16° to 60.5° N. K_1 is increasing despite the fact that linear internal tides do not exist north of the turning latitude of ~30° N. S_2 changes are generally smaller than those for M_2, but at a few stations (e.g., Acapulco and Guaymas) S_2 changes are opposite in sign to those for M_2. While some stations (like San Diego and Astoria) are strongly affected by estuarine alteration (diking, jetties and channelization), many of the stations are in relatively deep water and are little affected by human alterations. Increases in M2 are strongest locally around San Francisco, off Oregon, and in Northern British Columbia and Alaska.

San Francisco and Astoria provide an interesting contrast. K_1 is increasing only slowly at San Francisco, even though M_2 is increasing fairly rapidly, so the tide has become more semidiurnal over the last century. Early observations between 1854 and 1877 (not shown here) suggest that this increase in M_2 and the M_2/K_1 ratio has been occurring for at least 150 years. At Astoria, both K_1 and M_2 are increasing at about the same rate, so that the M_2/K_1 ratio is fairly stable, as is the character. Also, decreased river flow has decreased bed friction and slightly increased Astoria tides, but no river-flow correlation has been found for San Francisco. Because the San Francisco gauge is at the mouth, changes in resonance internal to the estuary are unlikely to have affected this gauge; changes in the coastal internal tidal regime are a likely cause. As shown below, the Astoria gauge shows both local and coastal influences.







The Data

The analysis approach employed requires nearly continuous for a period of >19 yrs; two nodal cycles (37.2 yrs) is preferable. While limited checking for spikes, changes in datum and timing errors was carried out, we relied heavily on the error checking by the University of Hawaii Sealevel Center in construction of its "research-grade" data set. Two stations (Toke Pt, WA and Cabo San Lucas, Mexico) were rejected *in toto*, because of large, irregular variations in tidal properties. Neah Bay before 1942, San Francisco before 1898, San Diego before 1963, and Los Angeles before 1960 were not used in the regression analyses. Discontinuous data segments <10 years long for several stations were neglected.

Tidal Data Records

Station	Latitude	Dates	Data Sources
Acapulco	16.8°	1952-1995	UHSLC[1]
Manzanillo	19.05°	1953-2001	UHSLC
Guaymas	27.95	1953-1986	UHSLC
Ensenada	31.85	1956-1991	UHSLC
San Diego	32.7	1906-2002	UHSLC, NOAA[2]
La Jolla	32.8	1924-2004	NOAA
Los Angeles	33.7	1923-2004	UHSLC, NOAA
Monterey	36.6	1973-2004	UHSLC, NOAA
San Francisco	37.8	1898-2004	Scripps[3], NOAA
Alameda	37.8	1933-2002	NOAA
Crescent City	41.75	1933-2004	UHSLC, NOAA
Charleston	43.34	1978-2004	UHSLC, NOAA
Newport	44.6	1942-2004	UHSLC, NOAA
Astoria	46.17	1925-2004	USGS[4], NOAA
Seattle	47.6	1903-2004	NOAA
Neah Bay	48.35	1942-2004	UHSLC, NOAA
Victoria	48.43	1909-2003	IOS[5]
Friday Harbor	48.55	1932-2002	NOAA
Pt Atkinson	49.15	1914-2003	IOS
Tofino	49.33	1964-2003	IOS
Prince Rupert	54.32	1963-2003	IOS
Ketchikan	55.2	1949-2003	UHSLC, NOAA
Sitka	57.03	1950-2002	UHSLC, NOAA
Seldovia	59.46	1979-2004	UHSLC, NOAA
Yakutat	59.54	1961-2004	UHSLC, NOAA
Seward	60.12	1967-2004	UHSLC, NOAA
Cordovia	60.56	1964-2004	UHSLC, NOAA

1=UHSLC = U. Hawaii Sealevel Center, 2= Dr. C. Zarvas, NOAA

3 = Dr. R. Flick, Scripps, 4 = Dr. A Gibbs, USGS, 5 = Dr. R. Thomson, IOS

Acknowledgements and Data Sources

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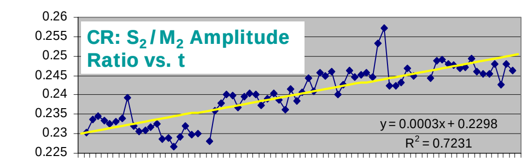
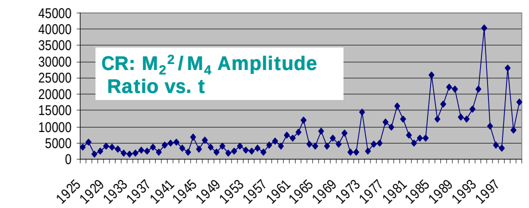
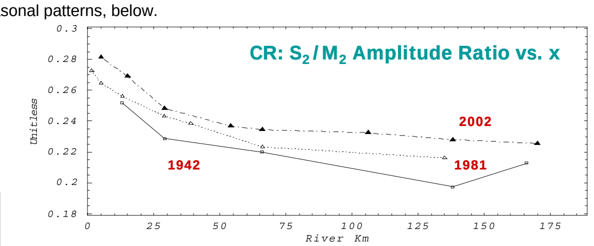
Astoria: Distinguishing Local and Coastal Influences

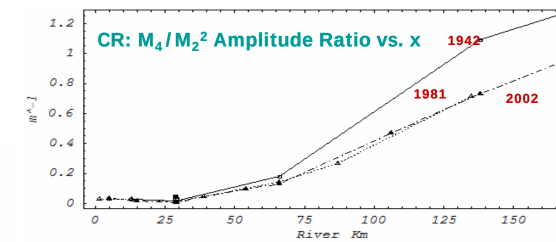
A. Spatial Patterns in Constituent Ratios

Spatial patterns of constituent ratios provide, with tidal theory (Jay, 1991), a means to detect the mechanisms of changes in tidal properties. In particular, we seek to distinguish the effects of: a) reduced river flow, b) more channelized topography, and c) altered shelf tides. Reduced flow and channelization both decrease friction, but river flow exhibits a seasonal cycle, whereas bathymetric changes occur on decadal scales. The S_2/M_2 amplitude ratio reflects the strength of friction on the semidiurnal tide as it varies over the tidal month; the influence of river flow is secondary; the influence of both the nodal cycle and river flow can be eliminated by a careful choice of years. S_2/M_2 shows a marked and ongoing increase at Astoria and throughout the system. Clearly, a hydraulically more efficient channel is one major influence on Astoria tides. Tidal theory shows that the M_2^2/M_4 amplitude ratio is a sensitive indicator of river flow. In fact, this ratio can be used to hindcast river flow from tidal observations (Jay and Kukulka, 2003). The changing M_2^2/M_4 ratio reflects the impacts of flow regulation and diversion, which have been increasingly effective since the onset of the managed flow regime ca. 1970. Comparison of the M_2^2/M_4 vs river flow relationship for 1940-42 with that since 1980, also shows the impact of increased hydraulic efficiency. Given the large changes in hydraulics and flow in the Columbia, can we still see any impact of changes in shelf tides? Yes! The evidence comes from observations near the mouth in 1940-43 and 1981-89, where the M_2 amplitude has increased ~20 mm over two nodal cycles (comparing years matched for nodal phase and flow). These changes are unlikely to stem from changes in friction or residence inside the estuary, because the boundary condition on a resonant wave is that the entrance amplitude is set by the ocean; only the amplitude inside the estuary changes. Also, the reflected wave (which might show the impacts of conditions at more landward points) is small in convergent, strongly frictional systems like the Columbia. This conclusion is reinforced by consideration of seasonal patterns, below.

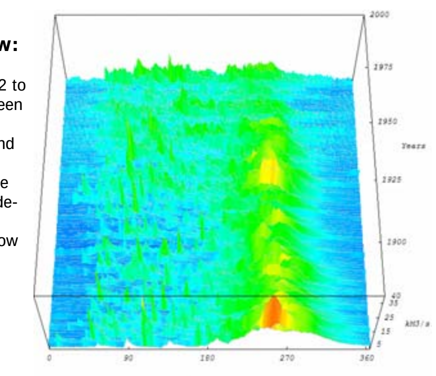


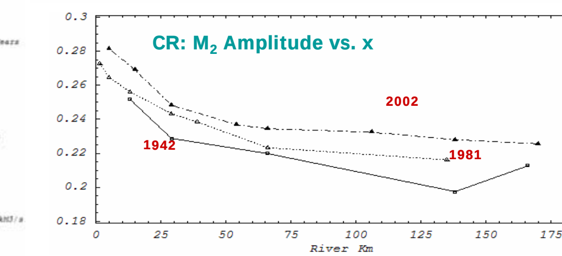






Columbia River Flow: The daily observed flow at Beaver (km-85) for 1892 to 1999. Spring flows have been reduced ~45% by flow regulation and diversion and a drier climate. Spring freshets are earlier because of warmer temperatures, de-forestation and irrigation depletion. The changing flow cycle affects tides, habitat and possibly plume productivity.





B. Seasonal Patterns in Tidal Processes

Seasonal patterns in the M_2 tidal admittance at Astoria are related to both river flow and coastal processes. We use mean sealevel (MSL) as a surrogate for coastal stratification, with high MSL corresponding to weakly stratified conditions during winter storms, which are known to decrease internal tidal activity in the Columbia Plume. Low MSL during upwelling conditions would then correspond to periods of high stratification and, presumably, increased internal tides. This approach is imperfect, because it does not distinguish winter conditions with high MSL due to storms (which weaken stratification) from those where high MSL is caused by high winter flows. We note, however, that MSL and river flow at Astoria have different spectral signatures and are not well correlated at periods less than ~6 mo. A regression model that includes river flow Q_R and MSL explains ~70% of M_2 admittance amplitude (or phase) variations. Use of either Q_R and MSL alone is much less successful. In contrast, only about 30% of K_1 variance can be explained by fluctuations in Q_R and MSL. This may indicate that changes in stratification affect M_2 more than K_1, because linear K_1 internal tides do not exist at 46° N. A better measure of coastal stratification is needed to analyze this problem further.