SEA COAST AND SEA LEVEL TRENDS

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Coastal residents know that the sea is never still. We witness the daily rise and fall of the tide against our shores, covering and uncovering the *intertidal zone*. We watch the water's edge rise higher still during a 'northeaster' as *storm surge* adds to the tide. These events occur and reoccur in cycles and each time a degree of normalcy returns before a new cycle begins. What we don't see with our own eyes is the slow change in water level that keeps on going – a very long cycle or *sea level trend*.

That trend - up or down - has gotten the attention of coastal scientists and engineers for some time now. They 'see' it through carefully maintained instruments called *tide gauges* that track sea level *relative to the land* over long periods of time – up to a hundred years or more. Marine geologists, who regard that as a mere speck on the unending time scale of earth history, have devised other means such as carbon-14 dating of oyster shells and peat deposits, to discover where the sea has been in ages past. They know, for example, that sea level has risen over a hundred meters (328 feet) from where it stood off the US east coast during our last *ice age* some 15,000 years ago. Locking water up in polar ice caps and continental glaciers leaves less of it in the world's oceans and seas causing sea level to go down. Sea level of course goes the other way when the ice melts, a trend continuing at present and aided, we suspect, by *global warming* and *thermal expansion* of the huge volumes of seawater in the oceans.

Meanwhile the earth itself is not still. The earth's outer shell – the *lithosphere* - consists of a series of moving *tectonic plates* on which both ocean basins and continents ride. New plates are born of volcanic intrusions at mid-ocean ridge systems and tend to sink into an underlying hot plastic layer called the *asthenosphere* as they diverge and move away from the central ridge, cooling and becoming denser over thousands of years. Where plates converge at so-called *active continental margins,* large landmasses are thrown upward to form mountain belts such as the Alps and the Andes. This is the global view - what we'd call the 'big picture'; locally we have other, *isostatic* processes at work rebalancing the earth's crustal load though regional uplift or subsidence. These processes include collection of sediments in river deltas and flood plains, removal of water from underground aquifers, and rebounding of areas formerly covered by ice sheets to name a few.

All the above means that there are two basic types of sea level change to keep in mind: 1) *eustatic* or world-wide change in sea level due primarily to increasing or decreasing ocean volumes and 2) *local apparent change* in sea level due to the vertical movement of land. Satellite altimetry and global positioning systems (GPS) are now measuring both with considerable accuracy around the world. These techniques are new, of course, and haven't produced long records as tide gauges have. Tide gauge records, on the other hand, show only the net result of both kinds of change going on at once: the combined vertical movement of land and sea.

But if you are concerned with the here and now of coastal planning – storm tides and flood risk management in particular – there's absolutely no need to separate 'sea coast' from 'sea level'. The only sea level change we care about in that case is the one relative to the land. In all but one of the following examples, we will make use of data available from the U.S. National Oceanic and Atmospheric Administration (NOAA) and one of its branches, the National Ocean Service (NOS).

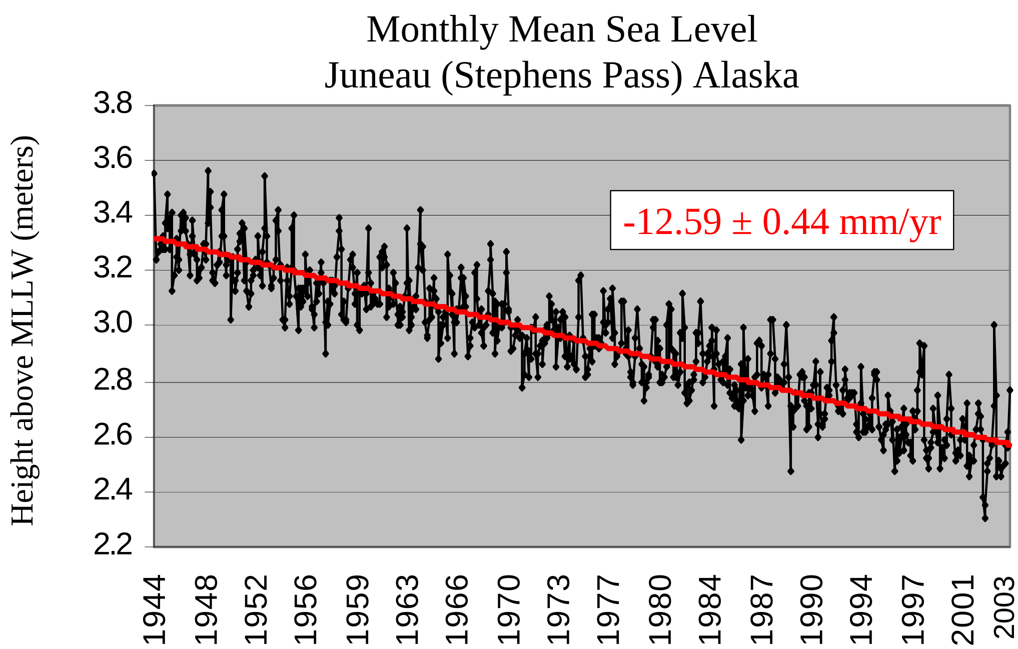
Tide gauges are instruments that record water level above a fixed point on land where the instrumentation comprising the *tide station* is installed. This initial point is called the *station datum* (NOAA/NOS symbol: STND). It's completely arbitrary, usually marking the position of *tide staff* 'zero', the vertical reference on a graduated scale (the tide staff) with which gauge readings are made to agree. Although the staff and its zero are rigidly fixed to a firm object such as a pier, engineers take no chances on the permanency of the station datum: a series of bench marks are always installed on land adjacent to the station and connected to it by leveling surveys. These surveys are repeated at regular intervals to verify the stability of the station datum.

With the passage of time and successful collection of water level readings measured above station datum, a new vertical reference can be calculated called a *tidal datum*. In the U.S. there are quite a variety of these with names like Mean Higher High Water (MHHW), Mean Lower Low Water (MLLW) and Mean Sea Level (MSL). Basically they are all average water levels that have one thing in common: they require 19 years of data to determine. Not just any 19 years but a specific 19-year period defined by NOAA/NOS and referred to as the *National Tidal Datum Epoch* (NTDE). For an explanation of specific tidal datums and how they are defined, see my online tides and currents tutorial at www.vims.edu/physical/research/TCTutorial/TCT.htm. Here the central point to keep in mind is this: tidal datums are an attempt to keep up with changing sea level relative to the land. We can use any one we choose – or the station datum itself – for the job of finding out what those changes actually look like measured continuously over long periods of time.

So exactly how do we go about determining sea level trends at tide stations? In the past this was usually done using plots of *yearly mean sea level* (YMSL), the arithmetic average of all the hourly height readings during a given year. By averaging over a year, we effectively remove those 'visible' cycles mentioned earlier, including the *astronomical tide* caused by the gravitational interactions between the earth, moon, and sun. More recently, NOS and others construct plots of *monthly mean sea level* (MMSL) by using monthly averages in place of annual ones. Monthly averaging removes most of the tidal oscillations leaving the non-tidal sea level change for us to examine. The exceptions are the so-called seasonal tides, which oscillate at periods of one year and one-half a year. Although there is an astronomical contribution to the seasonal tides, most of their water level variation is due to thermal expansion of seawater induced by annual cycles of atmospheric heating and cooling. If we avoid using a fraction of a year in our trend analyses, these too will average out. And when assessing flood-risk, there's good reason to use MMSL as is: it contains a broad sub-tidal spectrum of meteorological surge (set up and set down) in addition to the seasonal tide.

Fortunately, NOAA/NOS makes it extremely easy. Their web site, http://co-ops.nos.noaa.gov/, offers a huge supply of water level data for a considerable number of tide stations. Opening the *Water Level Observations* menu, a subsequent menu under *Verified/Historical Water Level Data* contains compilations of monthly means. In addition to place and time, our choices include several reference datums. To avoid negative numbers, I prefer to use the current MLLW datum based on the 1983-2001 NTDE. Let's look at some examples.

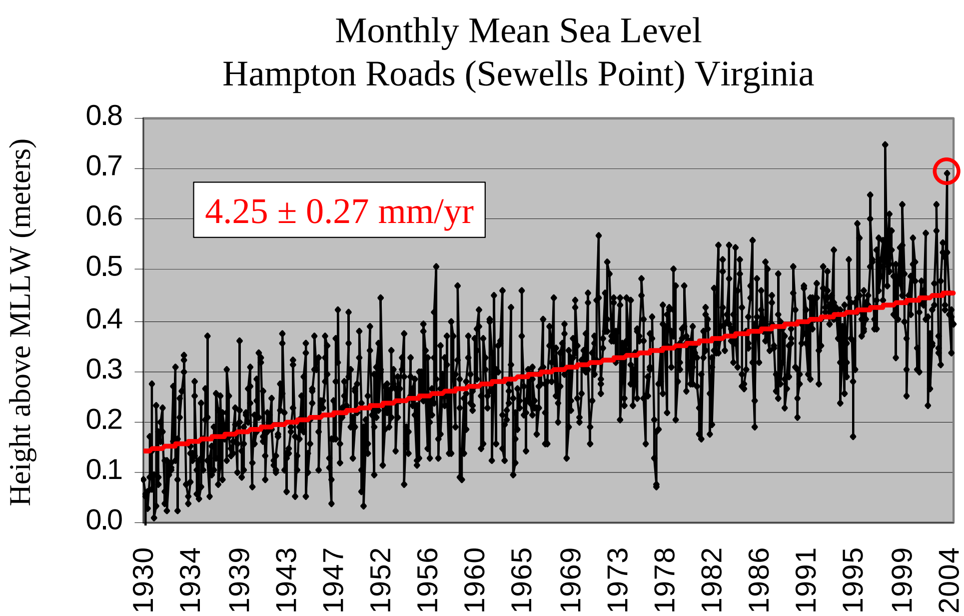
Juneau, Alaska lies right in the middle of an active continental margin. If we didn't already know that, our first clue might well be a plot like the one shown below. The '+' symbols connected by the black lines in the graph are the MMSL elevations (in meters above 1983-2001 MLLW) from 1944 through 2003. The red line is the line of best fit obtained from least squares regression (regressing MMSL elevation on time in years). Its slope gives an estimate of the sea level trend at Juneau: a whopping minus 12.59 mm per year! If continued, this trend would result in a mean sea level fall relative to the land of 1.26 meters (4.13 feet) over the next century. But the MMSL data points show quite a bit of scatter about the trend line. How certain can we be that this trend will hold up? We have already used statistical inference to estimate the slope of the regression line or the trend. Assuming the processes at work are steady and their effects random normally distributed, a second statistical number is available based on the standard error of the trend estimate. In the 59-year record at hand, the standard error or *confidence interval* amounts to ± 0.44 mm per year at the 95% level of confidence (5% chance of the real trend being outside this interval). As we will see in some other examples, our confidence lessens by quite a bit when we are forced to deal with shorter records.



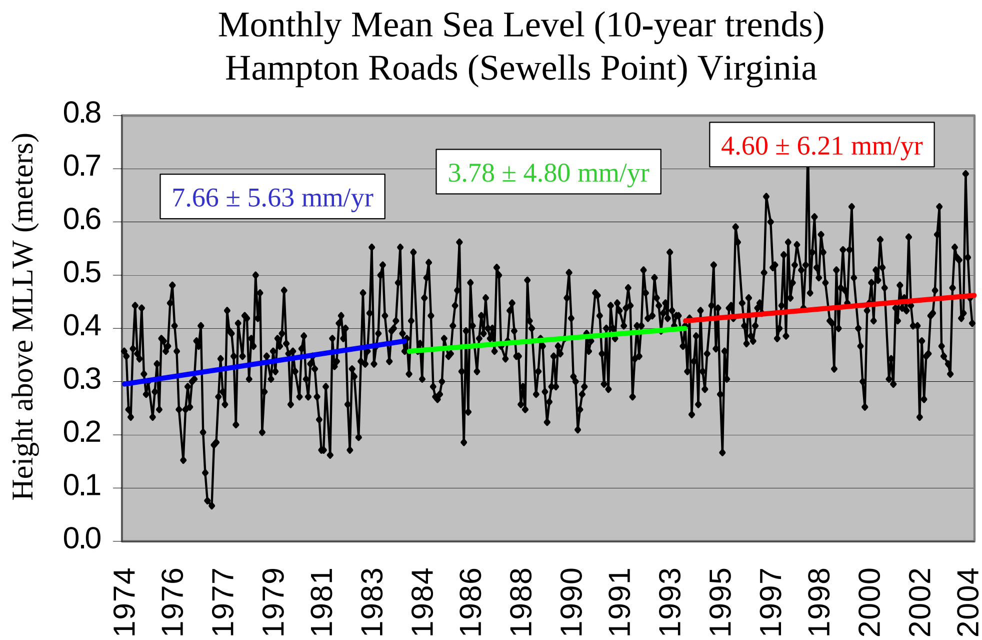
I always like to bring forth an Alaskan sea level trend when I hear the words 'sea level rise' and 'sea level trend' being used interchangeably as though they were one and the same. Obviously if eustatic sea level is rising here (the current world estimate is around 2 mm per year), parts of the coastal zone in Alaska are rising much faster in the active convergence zone between the Pacific plate and the North American plate. Even where there are no recorded water levels available, one may still see other signs of emergent coasts. On the island of Curaçao in the Netherlands Antilles the clues take the form of geologically recent coral reef structures exposed in wave-cut terraces lying well above present sea level (Curaçao lies at the boundary between the Caribbean plate and the South American plate).

Hampton Roads, Virginia lies on a passive or 'trailing edge' continental margin - the tectonic opposite of the Alaskan example. Normally land rises on active margins and sinks on passive ones. So at Hampton Roads we have an example of rising sea level relative to the land that typifies most of the U.S. east coast. The trend at Hampton Roads is a positive 4.25 mm per year based on the 73-year record between 1930 and 2004. The confidence interval of 0.27 mm per year is again calculated at the 95% level of confidence. Now we'll ask what this has to do with flood risk assessment. Just this: You may have heard the term '100 year storm' applied to a hurricane like the one that struck Hampton Roads in August 1933 or even Hurricane Isabel, a storm that struck here in September 2003 (see www.vims.edu/physical/research/isabel/). Roughly speaking, the term refers to a *storm tide* (combined storm surge, astronomical tide maximum) that has a 1-in-100 chance of occurring in any given year. As a matter of probability, we can only say that the *average* interval between successive events is 100 years – not that such events will re-occur precisely every 100 years. The question is, what is sea level likely to do in the meantime?

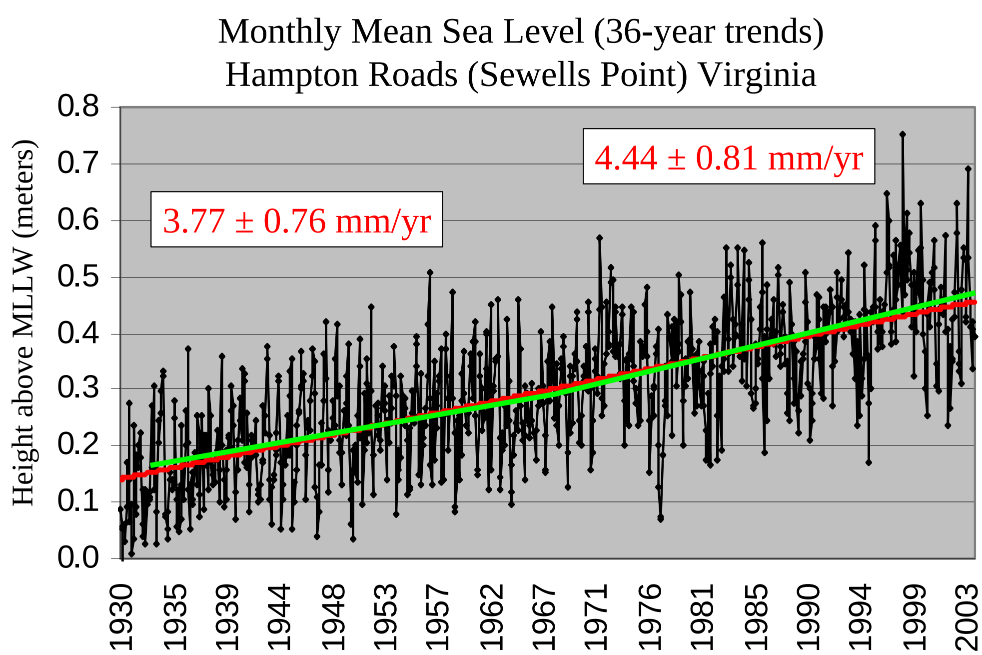
If the answer to the above question in fact turns out to be an increase of 0.425 meters (1.4 feet) in the base level that the next 100-year storm tide actually starts from, we're beginning to get the idea that sea level change matters at these time scales. But that's only part of the risk story. Notice the individual MMSL elevations deviate substantially from the red line representing the long-term trend. In the short term, these deviations from trend can add – or subtract – substantially to the final mean sea level for the monthly bin into which the next major storm happens to fall. The red circle in the graphic below highlights the MMSL that presented itself to Hurricane Isabel in September 2003.



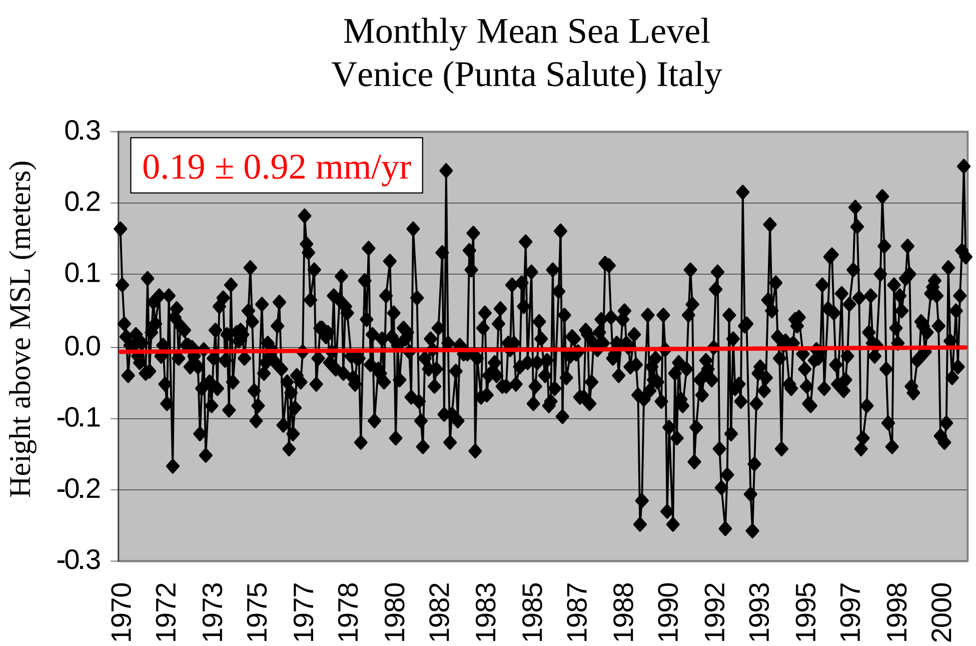
While longer and longer water level series are desirable in order to 'nail down' a trend by reducing the confidence interval around it, we are all aware of the possibility that trends can change, that sea level rise (or fall) might actually accelerate with time. From our personal perspective as coastal-dwelling human beings, we're more concerned with where sea level is going than where it has been. In the face of this concern, our desire to tease out the latest trend from within the most recent data is understandable. How about a 10-year record then; will that yield anything useful? Take a look at the graph below of the three most recent 10-year trends at Hampton Roads and I think you'll agree that the answer is no. Not only do the trends vary inconsistently from one period to the next, the confidence intervals exceed the expected trend in two out of three cases. We're unable to draw an inference even about whether the trend is up or down!



Rather than 10 years, we might choose to examine a pair of 36-year intervals by splitting the Hampton Roads record roughly in two. The resulting trends shown in the figure below are slightly different; the rise of 4.44 mm per year from 1968 through 2003 is greater than the rise of 3.77 mm per year from 1932 through 1967. Accelerated sea level rise? It's impossible to say from these estimates - the 95% confidence intervals are large enough in each case to explain the difference.



Venice, Italy is a bit different from the previous examples. Although this ancient city lies not far from the emergent foothills of the Italian Alps (along the boundary between the African and Eurasian plates), a broad coastal plain intervenes with a long history of sediment accumulation. Yet another factor affecting the local sea level trend was added in recent times: large amounts of ground water were pumped from deep aquifers under the Venice Lagoon for industrial use. According to the Tide Forecasting Centre of the Venice Municipality, relative sea level at Venice rose by about 23 cm (0.75 feet) between 1920 and 1970, mostly due to land subsidence while ground water removal was underway. Because of the obvious threat to the city and the surrounding islands, the practice was halted in 1970. To see what has happened since, I analyzed data from 1970 through the year 2000 for the Punta Salute tide station in Venice (data kindly made available by the Tide Forecasting Centre). Here are the results:



Is Venice still sinking? If it is, it's not by much. The 31 years of record from 1970 through 2000 are insufficient to make a long-term statistical prediction – up or down – with any degree of confidence. The main reason for the uncertainty is the high level of variance about the trend line. Frequent Meteorological surge and *seiche* events in the northern Adriatic Sea are responsible for these deviations from the norm and the resultant flooding now seen in Venice (the city was flooded more than 100 times in 1997). The trend itself may warrant a 'good-thus-far' attitude and a resolve not to remove any more ground water.

STATISTICAL METHODS

The calculation of sea level trend and confidence intervals was done using linear regression methods. If x is the time in years and y is the sea level height in meters, the regression equation that yields the trend (as a slope m) is

$$y = mx + b + \varepsilon$$

where m is the slope and b is the y-axis intercept of the regression line that best fits the x,y data in the least squares sense. The symbol ε represents an error term. In using a regression equation, we are assuming that y is a function of x. That is, if given a precise value of x, then $\hat{y} = mx + b$ is an estimate of y and $\varepsilon = y - \hat{y}$. The 'fit' is achieved by making the sum of squares of ε as small as possible. The following steps are recommended to obtain the set of regression parameters, m and b, that accomplish this for a sample data set of size n:

1. Calculate the data means, $\bar{x} = \Sigma x / n$ and $\bar{y} = \Sigma y / n$
2. Remove the means from the data to obtain $X = x - \bar{x}$ and $Y = y - \bar{y}$
3. Calculate the regression coefficient: $m = \Sigma XY / \Sigma X^2$
4. Calculate the y-axis intercept: $b = \bar{y} - m\bar{x}$

Confidence intervals are obtained from the following calculations:

1. Sum of squares of deviation from regression: $\Sigma d^2 = \Sigma Y^2 - (\Sigma XY)^2 / \Sigma X^2$
2. Mean square deviation from regression: $s^2 = \Sigma d^2 / (n-2)$
3. Sample standard error of the regression coefficient: $s_m = s / \sqrt{n \Sigma X^2}$
4. Confidence interval about the regression coefficient: $CI = s_m t_{.05}$ where $t_{.05}$ is the t-distribution at p = 0.05 ($t_{.05} \cong$ 1.97 for n >120).

<u>MMSL or YMSL?</u> A reduction in sea level variance is achieved by taking annual averages rather than monthly averages of hourly heights. Although time series plots of YMSL values appear smoother than corresponding plots of MMSL over the same time period, there are twelve times as many data points in the latter case. Greater n value produces a smaller sample standard error of the regression coefficient, offsetting any statistical advantage gained in deriving confidence intervals about the sea level trend with YMSL as opposed to MMSL values. Once again, the MMSL values are useful in assessing the flooding risk presented by enhanced sea level during months in which hurricanes and tropical storms occur.