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The magnitude and nature of 'noise' in world sea-level records

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Abstract
While average world sea-level is rising at a uniform rate of 1-1.5 mm yr-1, regional rates can vary by an order of magnitude. Over time scales of several years these rates can be 10-100 times greater because sea-level is affected at this scale by highly changeable meteorological and oceanographic variables. The inherent "noise" level in world sea-level records is 35 mm. Much of this is expressed as fluctuations on the order of 20-100 mm with a frequency of 3-5 years. This latter "noise" is highly coherent at tide gauges around the globe and appears unrelated to resonance or wave excitation in oceans. It is suggested that this variability reflects changes in the world hydrological budget linked to the Southern Oscillation. This latter phenomenon relates to the strength of trade winds in the tropical Pacific Ocean and can generate significant drying followed by flooding over continental landmasses.

Keywords
sea-level, world, noise, coherence, climate effect

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The magnitude and nature of `noise' in world sea-level records

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ABSTRACT: While average world sea-level is rising at a uniform rate of 1-1.5 mm yr^{-1}, regional rates can vary by an order of magnitude. Over time scales of several years these rates can be 10-100 times greater because sea-level is affected at this scale by highly changeable meteorological and oceanographic variables. The inherent "noise" level in world sea-level records is 35 mm. Much of this is expressed as fluctuations on the order of 20-100 mm with a frequency of 3-5 years. This latter "noise" is highly coherent at tide gauges around the globe and appears unrelated to resonance or wave excitation in oceans. It is suggested that this variability reflects changes in the world hydrological budget linked to the Southern Oscillation. This latter phenomenon relates to the strength of trade winds in the tropical Pacific Ocean and can generate significant drying followed by flooding over continental landmasses.

1 INTRODUCTION

The outcome of the present debate on global sea-level in a greenhouse-warmed world is dependent upon not only the magnitude of future warming but also the nature of global sea-level behaviour. To date, that debate has often naively assumed that any sea-level response will be of equal magnitude globally and that it will reflect melting of ice-caps and thermal expansion of the upper layers of the ocean (Titus, 1986). Our present knowledge of sea-level behaviour based upon long term historic records from various parts of the globe is however at odds with this view (Emery and Aubrey, 1991). Analysis of long-term historic records from various parts of the globe has found that regional climatic change in precipitation, barometric pressure and temperature induce quite divergent responses in sea-level (Bryant, 1988). A fundamental characteristic of global sea-level is its large spatial and temporal variability over distances as little as 200-300 km and timescales as short as a few days. This brings into question the appropriateness of the currently perceived global rise in sea-level of 1.0-1.5 mm yr^{-1} (Barnett, 1983; Gornitz and Lebedeff, 1987). It also indicates that the likely outcome of any climatic change, of which greenhouse-induced warming is but one part, will be regional discrepancies in the magnitude of sea-level rises and falls.

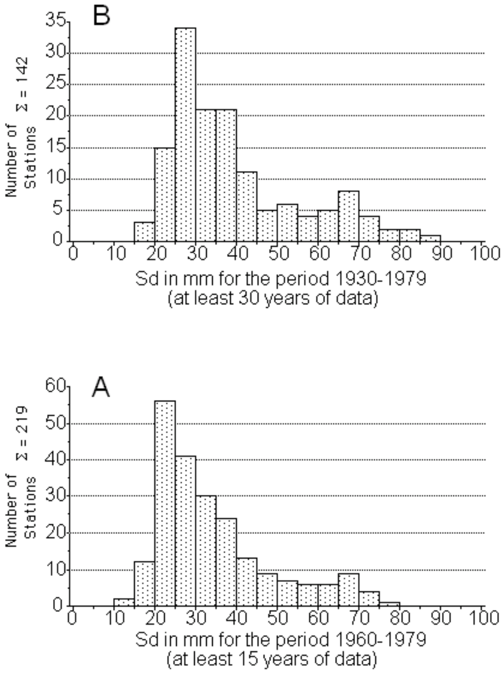

Figure 1 Histograms of the standard deviation of sea-level records a) 1960-79 b) 1930-1979

There are other aspects about the nature of sea-level that have been poorly considered both in terms of studies on sea-level and future projections. While the variation in sea-level appears to be climatically induced, the timing and magnitude of fluctuations in sea-level records appears to be coherent over great distances. The aim of this paper is to examine a) the magnitude and distribution of the background variability present in world sea-level records, b) the role of climate in producing this variability, c) the degree of coherence globally present in this background "noise" and d) the likely causes of this coherence, in particular the role of the global hydrological cycle. This latter information is necessary if engineers need to evaluate the effectiveness of large engineering projects proposed to mitigate future global sea-level rise.

2 THE MAGNITUDE AND DISTRIBUTION OF "NOISE" IN SEA-LEVEL TRENDS

The present eustatic rate of sea-level rise ranges from 1.0-1.5 mm yr^{-1} (Barnett, 1983; Gornitz and Lebedeff, 1987). These values suffer from a number of limitations including high spatial and temporal variability and gaps in world coverage, especially in the centre of oceans and in the southern hemisphere (Bryant, 1988). More seriously, such values have not been evaluated relative to the base level of variability inherent in world sea-level records. Such a determination is crucial, because rates of sea-level rise can only be judged as significant when they exceed this base level. In order to determine the global variability in annual sea-level records, 219 stations with ≥15 years of measurement between 1969 and 1979 were extracted from sea-level records compiled by the Permanent Service for Mean Sea Level, Bidston Observatory, UK. A linear trend calculated using Pearson product moment regression analysis was subtracted from each record and the standard deviation of residuals calculated for each record. A histogram of these standard deviations is presented in Figure la, while a progressive record of these values eastwards around the globe are plotted in Figure 2.

The first standard deviation generally characterises the

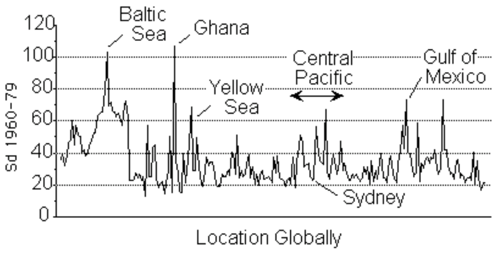

Figure 2 Standard deviations of sea-level records with at least 15 years data 1660-1979 plotted eastwards around the globe beginning in Scandinavia

magnitude of variability within any time series. For sea-levels this value ranges from 13.0 to 93.8 mm with a mean of 35.0 mm equivalent to a variance in global sea-level of 1225 mm^2. Figure 2 illustrates that there are preferred regions where the inter-annual variability in sea-level records is exceptionally high. Generally most sea-level records have standard deviations between 20 and 40 mm. The Baltic and Yellow Seas, central Pacific and Gulf of Mexico contain a high proportion of stations where standard deviations exceed 50 mm. These regions are ones where climatically induced sea-level fluctuations such as storm surges or seiching are prominent. The high values in the central Pacific region are mainly due to changes induced by fluctuations in the Southern Oscillation characterised by changes in the intensity of trade winds.

The value 35.0 mm defines globally the average variability against which annual increments in eustatic sea-level rise must be referenced before any sea-level rise can be judged as significant. For instance, presently accepted rates of sea-level rise of 1.0-1.5 mm yr^{-1} (Barnett, 1983; Gornitz and Lebedeff, 1987) must be measured for periods of 23-35 years before they can be considered as trends and not part of the underlying variability in sea-level. Enhanced rates of sea-level rise of 20-30 cm in the next 50 years can only be credibly defined on a global scale with at least a decade of data. Trends for individual stations may require even longer periods of measurement before they can be dubbed as significant. There are two caveats that must be put on a base level of 35 mm. Firstly, it is doubtful if the stations used in this analysis are completely representative of the globe. The data set excludes about 60% of the world's coastline and includes only a few values from the centres of oceans. Secondly, this value may not be representative of long-term variability in sea-level records. An analysis of 142 stations extracted from the same data base for a longer period, 1930-1979, produced an average standard deviation of 39.3 mm (Figure lb). The concept of a eustatic rise in sea-level induced by Greenhouse warming must incorporate the possibility that the inherent variability in global sea-level can also change.

3 CLIMATIC REASONS FOR SEA-LEVEL VARIABILITY

Tectonic factors cannot be used to account for the spatial variation evident in Figure 2 because the scale over which this forcing operates is generally much longer. Climatic factors, especially atmospheric oceanographic coupling, offer much wider scope for explaining this noise in sea-level records and have been applied to this end quite satisfactorily over timescales ranging from days to decades (Barnett, 1984; Bryant, 1988). Regionally these climatically induced changes can exceed the 1-1.5 mm yr^{-1} eustatic rate by a factor of 10-100 times. On annual timescales river discharge is important in the East China Sea and accounts for 7-21 per cent of the variance in sea-level along the eastern United States coastline (Meade and Emery, 1971; Emery and Aubrey, 1991). More significant are the persistent inter-annual fluctuations in sea-level associated with El Nino-Southern Oscillation (ENSO) events in the equatorial Pacific region (Wyrtki, 1982). Generally tropical air movement in the Pacific is dominated by strong easterlies which blow warm surface water towards the western side of the Pacific, piling it up to heights of 20 cm or more. The easterlies oscillate (the Southern Oscillation) in strength every three to five years. Their failure leads to an El Nino-Southern Oscillation event that causes the propagation of a Kelvin wave eastwards across the Pacific in the space of two months. During the 1982/83 event, sea-levels fluctuated between 30 and 40 cm across the equatorial Pacific (Harrison and Cane, 1984). These sea-level fluctuations are not restricted to the tropics. They can spread along the west coast of the Americas over several months (Enfield and Allen, 1980). The 1982/83 El Nino-Southern Oscillation event raised sea-levels 35 cm above average as far north as the Oregon coast (Komar, 1986). Long term fluctuations in sea-level can also reflect changes in the intensity of winds, shifts in the location and intensity of pressure cells or long term changes in rainfall over the coastal sector of an ocean (Bryant, 1991). Finally a study of monthly sea-level, atmospheric pressure, temperature and precipitation at 91 stations around the world for the period 1933-1980 found that 50%, 60%, 24% and 34% of the variance respectively in these variables was inter-related (Bryant, 1988).

4 THE NATURE OF COHERENCE

The above observations imply a degree of coherence in not only the behaviour of sea-level globally but also in the behaviour of the climatic forcing variables. This coherence has been recognised previously. For instance Hamon et al. (1975) identified a strong spatial coherence in sea-level at most stations along the east coast of Australia. Across the Pacific Ocean sea-levels generally are inversely correlated in response to the Southern Oscillation (Wyrtki, 1982). Pariwono et al. (1986) extended this further and showed excellent correspondence between sea-levels in South Australia with those in Southern California. Thus while sea-level records evidence a high degree of noise, it appears that this noise is synchronous over long distances. As an illustration of this, annual sea-level records for the period 1930-1974 for London, Trieste (Venice), New York, Tokyo (Aburatsubo) and Sydney, were plotted (Figure 3) and analysed statistically to determine the degree of cross-correlation. The stations represent both northern and southern hemispheres. They also represent open ocean and enclosed sea environments which are not in resonance with each other. On a gross scale it is evident that some of the major fluctuations in these sea-level records occur contemporaneously. For instance, there is a prominent dip in all records around 1949-50 and a peak around 1952-53. Many of the fluctuations in the figure also correspond to those appearing in a composite of South Australian and southern Californian records (Pariwono et al., 1986).

The records were first detrended using Pearson product moment regression analysis. Cross-correlation was then performed at yearly lags to discern any precession in the peaks of fluctuations. This analysis tended to indicate that fluctuations in the Sydney record preceded ones in the London and Venice records by 1 year which themselves preceded those in New York and Tokyo by an additional year. It should be pointed out that these are the best fit lags and that

Table 1. Principal Component Analysis of lagged sea-level records of 5 major tide gauges 1930-1974

City	lag in years	% Variance in Group 1	% Variance in Group 2
New York	1	16.4	64.5
Tokyo	1	45.4	12.3
Sydney	-1	45.2	28.4
London	0	57.5	0.4
Venice	0	31.3	7.7
All gauges		39.1	22.6

there are times when fluctuations in sea-level appear contemporaneously between records. The time series were then shifted to reflect these best fit lags and analysed using Principal Component Analysis (PCA). PCA has the capacity to extract the structure of coherence from data sets by grouping together similar variables (in this case residuals of lagged sea-level records) into groups or components (Ebdon, 1985). The magnitude of this coherence for variance groupings of records can then be assessed by calculating factor scores. Two coherent groupings are evident above the noise level of the data. The factor scores for each grouping together with the percentage of the variance explained for each city are presented in Table 1. The largest grouping accounts for 39.1% of the total variance in the 5 detrended sea-level records. This group includes all records except New York. It indicates that 45% of the interannual variability in the Tokyo and Sydney records and 57.5% of that in the London record are coherent when lagged slightly relative to each other. The second grouping indicates 28.4% of the variability in the Sydney record is correlated with 64.5% of that in New York. Allowing for the fact that the records have been shifted relative to each other, this result implies that sea-level at New York rises after it does at Sydney.

5 REASONS FOR THIS COHERENCE

Pariwono et al. (1986) attributed this high coherence in sea-level to pressure patterns associated with the Southern Oscillation; however a more fundamental factor must be involved because the results include two European gauges not normally evidencing pressure responses to the Southern Oscillation. If atmospheric pressure is not implicated, then this coherence must relate to changes in either temperature or rainfall. There is little doubt that both air and sea surface temperature fluctuations over 2-3 year periods are coherent globally (Folland et al., 1984). However the magnitude of these oscillations (0.5-1.0° C) appears unlikely to be sufficient to affect sea-levels through thermal expansion to the degree observed in Figure 3. Rainfall is the more plausible cause; yet this factor cannot operate solely at the local level to produce such a coherent signature globally. Rainfall can only be invoked at this broad scale as part of the global hydrological cycle. The Southern Oscillation has a major effect on the global hydrological cycle because it is associated with widespread, alternating droughts and floods over Africa, Australia, India and southeast Asia (Bryant, 1991). Oscillations between drought and flood occur at intervals of 3-5 years, the same cycle as fluctuations in sea-level. During its dry phase (El Nino-Southern Oscillation events) when trade winds in the tropical Pacific Ocean are reduced, sea-levels drop in the west Pacific and rise in the east. At the same time drought dominates land masses with water draining from continents and accumulating in the oceans. During wet phases (La Nina events) the trade winds strengthen leading to enhanced monsoonal rainfall conditions in Australia, India, southeast Asia and Africa. Rain

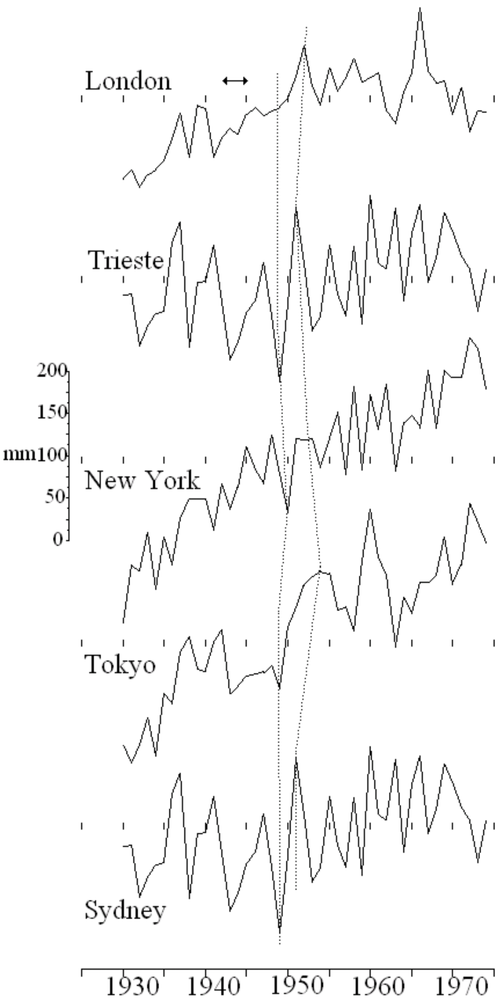

Figure 3 Annual sea-level records between 1930 and 1974 for five major tide gauges

accumulates over these continental land masses in drainage systems, lakes or watertables. During these periods evaporation from oceans supplying this rainfall lowers global sea-levels. The area of landmass involved is on the order of 16 x 10^6 km^2, equivalent to 10-11 % of the surface area of the oceans. Typical rainfall amounts to 200-400 mm in the transition from a dry ENSO phase to a wet La Nina phase over the space of 2-3 months. This volume of rainfall averaged over the oceans represents a change in sea-level of 22-45 mm. This approximates the standard deviation inherent in global sea-levels and begins to equal the magnitude of many of the inter-annual variations evident in Figure 3. While the Southern Oscillation may be responsible for these rainfall variations, the delays in the exchange of water between continents and oceans results in coherent but lagged changes in sea-level measured at tide gauges distributed around the globe.

6 CONCLUSIONS

The inherent variability in world sea-level records is around 35 mm. This value must be exceeded before rises in average global sea-level can be viewed as representing a significant trend. If the sparse coverage of tide gauges is symbolic of world sea-level, then the sea-level rise of 100-150 mm over the past century is meaningful. Much of the variability in tide gauge records regionally is due to climatic-oceanographic forcing; however a significant percentage of this "noise" at inter-annual timespans is coherent across the globe. Because many places globally are affected by drought at the same time, water drains from the continents and accumulates in the oceans forcing world sea-level up. Heavy rainfall also tends to occur at the same time in many places. Water is then taken from the oceans and temporarily stored in lakes, rivers and watertables on continents. As a consequence world sea-level drops. This exchange has implications for large scale projects designed by engineers to mitigate against future sea-level rises. For instance a shift to more frequent ENSO events leading to droughts over Africa, India, Southeast Asia and Australia will not only exacerbate these rises, but will also require longer time periods for the diversion of water from oceans to continents to be effective.

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