Policy Impact Program: Driving UAE's Strategic Visions

A Tale of Sea Level Dynamics in the Arabian Gulf

(Executive Summary)

Muhammad Usman

College of Natural and Health Sciences, Zayed University, Dubai, UAE
Muhammad.usman@zu.ac.ae

1. Introduction

The present-day configuration of the Arabian Peninsula results from its Eocene to Oligocene separation from the Horn of Africa. As a result, the west and northwest part of the Arabian Peninsula has the Red Sea and mountains respectively whereas the land slopes on the eastern side move towards the Arabian Gulf and end up against the Iranian Zagros mountains. From the climatic perspective, the Arabian Gulf is influenced by the Mediterranean Sea and the Arabian Sea in the northern part of the Indian Ocean. It mostly lacks the intense storms of the Mediterranean and the Indian Ocean. This proves to be advantageous from a climatological perspective that the "noise" of the daily and seasonal fluctuation does not entirely mask the potential long-term trends.

The economic interest in this area has resulted in several studies that employ both observation and simulation. The meteorological observations were utilized to calculate the climate variability of the Shamal wind across the Gulf and found that the frequency of Shamal episodes has increased recently. By using the low-resolution SWAN model outputs coupled with typical coarse-resolution global reanalysis winds previous studies investigated the basin-wide wave climate and trends in the Gulf. A series of studies conducted at the regional level have offered targeted perspectives on particular parts of the basin. One study reported the wave dissipation at the Hendijan mud coast, while other studies evaluated the amount of available wave energy along coastlines. Another study reported the bathymetry effects and wind variability for wave prediction near Doha. So far, the impact of Shamal winds on the wave characteristics along Qatar's northern shore has been also studied in detail. Previously, a high-resolution and accurate hindcast of the

Gulf wind and wave conditions has been analyzed. Furthermore, the latest study provided a comprehensive overview of the climate mean-state and variability across the Arabian Gulf and Oman Region using satellite-derived sea surface temperature (SST), surface wind, and Chlorophyll-a concentration (Chl-a) datasets.

As several major settlements are located in the coastal areas of the Arabian Gulf so understanding the sea level variability both on seasonal and long-term scales carries huge socioeconomic significance. So far detailed spatiotemporal maps that indicate the sea level variability along the entire length of the sea level variability along the entire Arabian Gulf are missing from the literature. In this research, I conduct a detailed space-time analysis of the sea level variability along a profile that covers the entire Arabian and Oman Gulf using all the available satellite altimetry data from 1993 to March 2023. To ensure stationarity I decompose the space-time data into seasonal and trend components using the Hodrick-Prescot (HP) filter and then model seasonality using first-order Fourier series and a simple sin function and compare the two seasonal models. Furthermore, to explore the possible association between the Arabian and Oman Gulfs I calculate and compare the amplitude and phases.

2. Research Question(s)

i. Can the seasonal rise and fall of the sea level in the Arabian Gulf be explained by considering the Arabian Gulf as a closed system or does the Arabian Gulf sea level rise correlate with Oman Gulf's level variability?

ii. Which model explains the seasonal variability in the best possible way (firstorder Fourier series or simple sin function)?

iii. Find out the phase lag and amplitude differentials between the Arabian and Oman Gulfs

3. Research Methods

The satellite altimetry and wind velocity data have been accessed from the European Centre for Medium-Range Weather Forecasts (https://www.ecmwf.int/). Equation (1) shows the raw time series data.

$$y_t = \tau_t + c_t + \varepsilon_t \text{ ---(1)}$$

In equation (1), the yt is the original time series, τt is the trend component, c_t is the cyclic component and ε_t is the error.

To ensure stationarity in each component and to eliminate the chances of bias associated with cyclic (when modeling the long-period component) and long-period (when modeling the cyclic component) components, I have used the Hodrick–Prescott filter (Hodrick and Prescot, 1997).

$$\underset{\tau}{min}\left(\sum_{t=1}^{T}(y_t - \tau_t)^2 + \lambda\sum_{t=2}^{T-1}[(y_{t+1} - \tau_t) - (\tau_t - \tau_{t-1})]^2\right) \text{ --- (2)}$$

In equation (2) the first term is the cyclic component the second term is the trend component and λ is the smoothing parameter. For monthly data, the value of λ was set at 129,600.

To model the seasonal component, it is important to "denoise" the data. So here I use convolution

$$(f * g)(x) = \int_{-\infty}^{\infty} f(\tau)g(x-\tau)d\tau \text{ --- } (3)$$

In the above equation, $(f * g)(x)$ shows functions that are being convoluted, τ indicates the real number variable of functions f and g. $g(\tau)$ represents the convolution of the function $f(x)$.

Now, to model the denoised time series I use first-order Fourier series (4) and simple sin function (5)

$$G_{seasonal} = a + bt + \alpha \sin(\omega t + \theta) + \beta \cos(\omega t + \varphi) \text{ --- } (4)$$

$$G_{seasonal} = a + bt + \alpha \sin(\omega t + \theta) \text{ --- } (5)$$

As we have monthly data the assumption that I make is that the occurrence of seasonal processes is the same i.e. $\omega = 2pi/12$

For the modeling fitting I use scipy.optimize.curve_fit library of Python which uses the Levenberg-Marquardt algorithm and is utilized to solve nonlinear least-square fit problems.

It combines both Gaussian Newton Algorithm and gradient descend methods.

The wind data is provided in u and v components. The magnitude can be calculated using equation 6 and the direction can be calculated considering the different scenarios mentioned in equations 7, 8, 9, and 10.

$$W_{magnitude} = \sqrt{(u^2 + v^2)} \text{--- } (6)$$

When both u and v are positive.

$$W_{direction(deg)} = \tan^{-1}(u/v) \text{---}(7)$$

When u is positive and v is negative.

$$W_{direction(deg)} = 90 + \tan^{-1}(|v|/u) \text{ --- } (8)$$

When both u and v are negative.

$$W_{direction(deg)} = 180 + \tan^{-1}(|v|/|u|) \text{---}(9)$$

When u is negative and v is positive.

$$W_{direction(deg)} = 270 + \tan^{-1}(v/|u|) \text{---}(10)$$

4. Key Findings

Figure 1 indicates the study area and the white line indicates the profile along which the data has been extracted. Figure 2a displays the extracted raw data, Figure 2b shows the extracted trend component and Figure 2c delineates the seasonal component along the profile of ~1570 km length i.e. Arabian-Oman Gulfs Transect. Figure 3 has been created using all the available monthly data (both altimetry and ERA-Reanalysis wind data) and each month has been stacked and the average has been calculated and is displayed in each panel. Figure 4 shows the wind rose diagram that shows the direction and percentage of wind magnitudes that blow at the selected points (a) and (b) indicated in the inset. At the selected points (indicated in the inset of Figure 4), the extracted seasonal component is first "denoised" using convolution, and then I apply two models (First Order Fourier Series and Sine Function) to figure out the magnitude and phase of seasonal components. In Figure 6a, I compare the calculated signals at the two points, and in Figure 6b I calculate the phase lag by moving one signal against the other with a lag of one month. The place where two signals overlay constructively has the maximum correlation coefficient value (i.e. phase lag of 180 degrees or 6 months in this case).

Figure 2 exhibits sea level variability during the entire study period from 1993 to 2023. Though the spatial variability in trend is not clear in the raw data i.e. Figure 2b, the extracted trend component indicates that long-term variability has started in the southern part of the Arabian Gulf (i.e. between 500km and 100km region) before any other area along the profile. Furthermore, the amplitude of the seasonal component stays uniform for the entire range of ~1200 km i.e. predominantly in the Arabian Gulf. After 1200 km there is a clear change in phase and the seasonal peak comes mainly in the summer rather than the winter time as observed along the length from 0 to 1200 km.

Figure 3 shows that peaks of sea level arrive by the start of the winter season (October-November) in the Arabian Gulf and by the start of summer (April-May) in the Oman Gulf. Also, one can observe that with the reversal of wind velocity direction over the Oman Gulf, sometime in June, the sea level in the Oman Gulf starts to fall while the sea level in the Arabian Gulf starts to rise, as soon as the wind velocity becomes somewhat unidirectional i.e. around December the level of the Arabian Gulf starts to fall while the level of Oman Gulf starts to rise. Sea level rise with the seasonal wind velocity reversal is well established and has been observed in the Red Sea, and the oceanic part of northern Australia. Figure 4 further elaborates on the wind velocities. One can observe that in the Arabian Gulf, the wind velocity is mostly unidirectional and mostly in the southeastern direction (Figure 4a). While in the Oman Gulf, the wind direction and magnitudes are variable, however, the northwestern component dominates which is nearly opposite to the wind direction observed in the Arabian Gulf.

In Figure 5, the extracted time series data at the two points indicates that inter-annual seasonal variability is not uniform with jumps during different epochs. To, estimate the seasonal component, it is essential to remove bias coming from the short-term signals. To "denoise" the data, I applied convolution and then modeled the time series data using the first-order Fourier series and simple sine function. One can see that both models explain the seasonal component nearly in the same way. By the principle of parsimony, one can conclude that simple sine function modeling is enough in the study region to estimate the seasonal component.

Figure 6, depicts the phase and amplitude (calculated from sine function) both for the Arabian and Oman Gulfs. One can see that seasonal oscillations in the Oman Gulf are greater as compared to the Arabian Gulf also there is a strong inverse phase relationship i.e. correlation coefficient has a value of -0.985. Furthermore, when examined for the correlation value with an increasing phase of one month, one can observe that the relation becomes strongly positive i.e. correlation coefficient has the value of 0.96 after an interval of 6 months. This proves that there is a phase difference of 6 months between the peaks of the Arabian and Oman Gulfs.

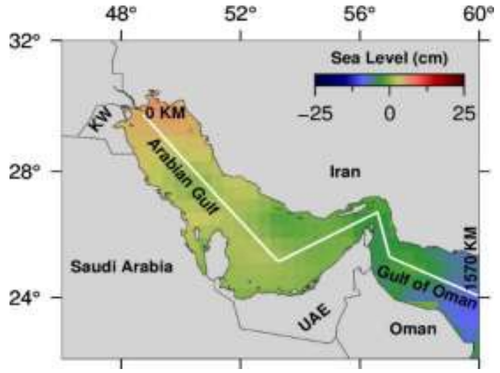

Figure 1. Location map of the Arabian and Oman Gulfs. The colors indicate the sea level change during the August month. The white line indicates the profile (Arabian Oman Gulf Transect) where data has been extracted and plotted in Figure 2.

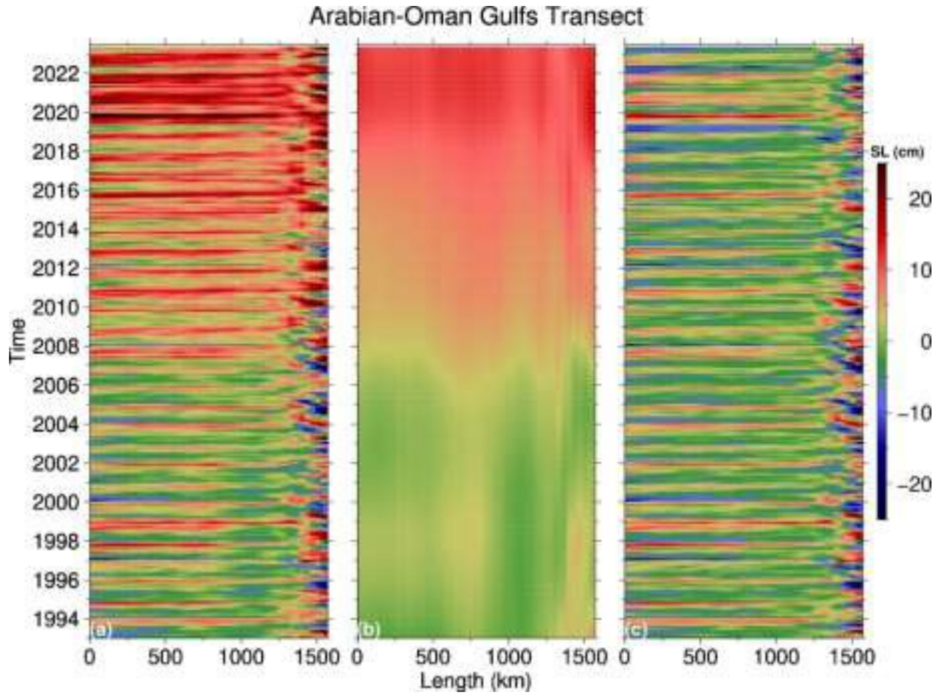

Figure 2. Spatiotemporal map of all the available satellite altimetry data (1993 to 2023). The vertical axes indicate the time while the horizontal axes show the length. (a) Raw data (b) extracted trend component using HP filter and (c) extracted seasonal component using HP filter.

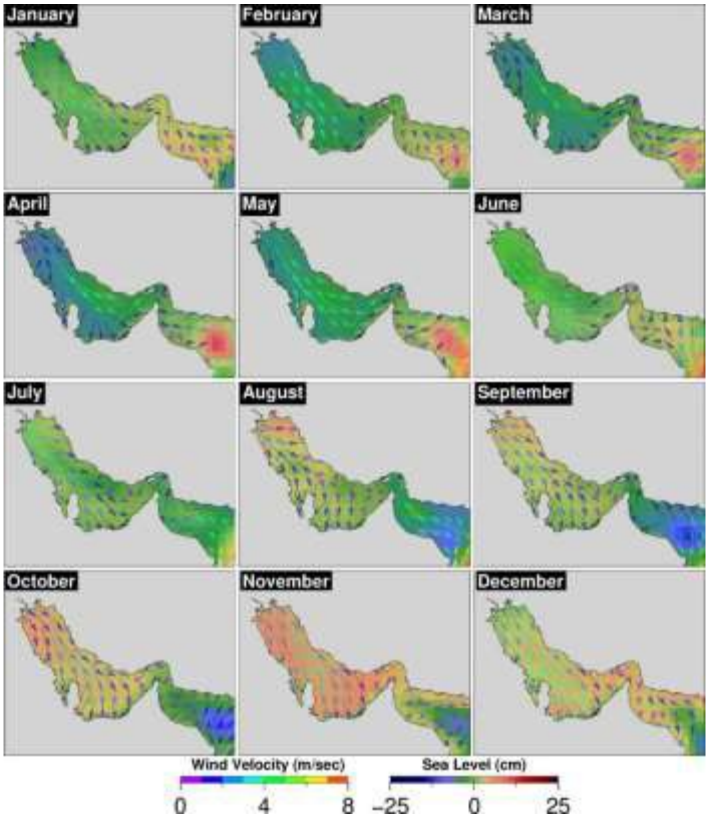

Figure 3. Monthly snapshots of satellite altimetry data overlaid with wind velocity reanalysis data. Each map depicts the average of the entire 30 years i.e. each month's data has been stacked and overage was calculated.

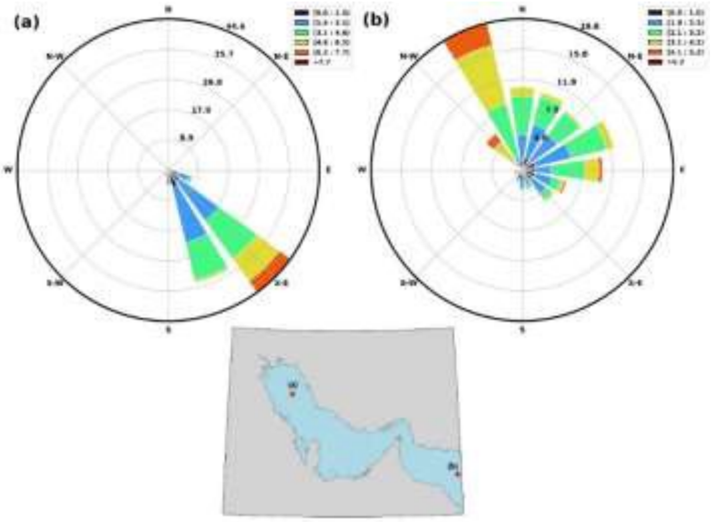

Figure 4. The rose wind velocity maps at the two selected points (a) in the Arabian Gulf and (b) in the Oman Gulf. The position of the columns indicates direction while the color indicates the percentage of wind speed as indicated in the given legend.

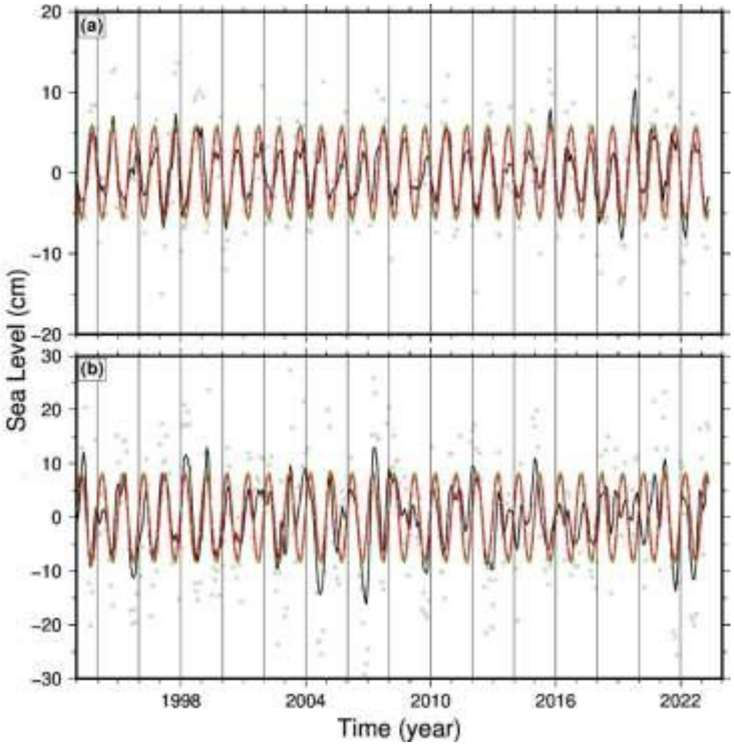

Figure 5. The sea level change at two points indicated in the inset of Figure 4. (a) Arabian Gulf and (b) Oman Gulf. The vertical lines show the year start at every two years interval. The light grey dots indicate data points, black line shows a "denoised" time series after applying convolution. The red line shows the model calculated by applying first-order Fourier series and the green dots show the model calculated by applying the simple sine function.

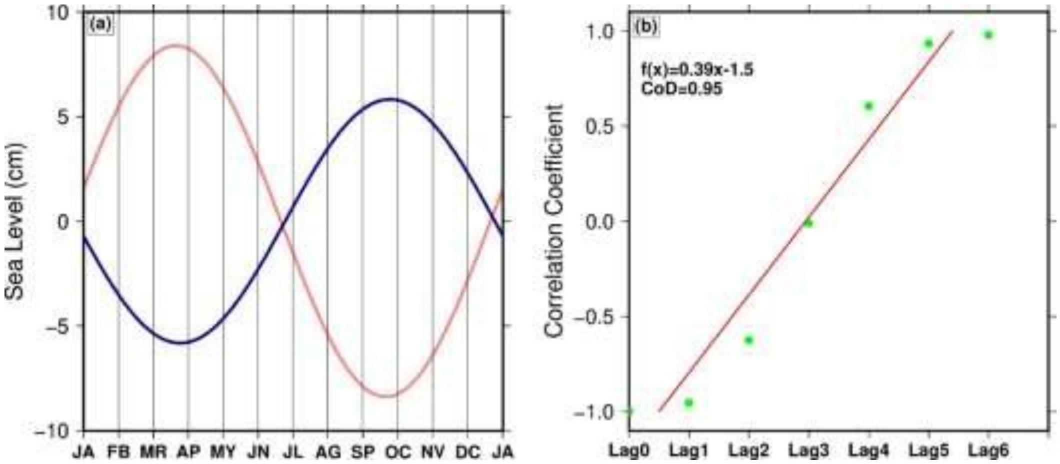

Figure 6. Phase and amplitude comparison of the two water bodies (calculated from sine function). (a) red color shows Oman Gulf and blue color depicts Arabian Gulf. (b) Phase calculation by increasing the lag between Arabian and Oman Gulf signals.

5. Implications

- Arabian Gulf's seasonal sea level is possibly influenced by the sea level variability of Oman Gulf. It indicates that along with the local atmospheric conditions, regional seasonal conditions also play an important role.
- Secular (long-term) sea level rise varies in space which suggests that along with regional processes, the local phenomena significantly influence the sea level variability along the entire length of the Arabian Gulf.
- In summary, for the planning and management, understanding both seasonal and long-term components is important, and a precise ocean-level change model can be developed by incorporating both local and regional phenomena rather than treating the Arabian Gulf as an isolated closed system.

6. Conclusion

In this research, satellite altimetry data has been utilized and sea level variability along a profile that covers both the Arabian Gulf and Oman Gulf has been examined. To ensure stationarity the raw data has been decomposed using an HP filter. To suppress the noises in the seasonal component, I use the convolution technique and model the seasonal component using first-order Fourier series and sine function. It is found that both models work fairly well and by following the principle of parsimony, one can rely on the sine function to model the seasonal component. An inverse correlation between the Arabian and Oman Gulf's sea level rise has been found that has a phase lag of 6 months and it is possibly driven by wind velocity reversals, indicating that Arabian Gulf dynamics cannot be explained by treating the Arabian Gulf as an isolated closed system. Furthermore, in the Arabian Gulf wind velocity is mostly unidirectional while in the Oman Gulf, there are various components of wind velocity with a dominance by the NW component.

Future Research:

- Satellite altimetry data contains total sea level rise signal (mass addition+ thermal expansion), while satellite gravimetry data measures sea level rise only through mass addition. In the future, to estimate the thermal expansion component, I will subtract satellite altimetry data from satellite gravity data. It will assist in understanding the contribution of sea temperature variability to the sea level change.
- I will also incorporate the local tide gauge data and will validate both satellite altimetry and satellite gravimetry data.