

ON THE RELIANCE ON MODELLED WAVE DATA IN THE ARABIAN GULF FOR COASTAL AND PORT ENGINEERING DESIGN

James Walker, Enda Murphy, Francesco Ciardulli¹ and Luc Hamm²

Despite intense maritime activities in the Arabian Gulf, there is a general lack of long-term in-situ wave measurements to inform engineering design. Consequently, there is a very strong reliance on numerical modelling tools to help define extreme design parameters. Wave hindcast models often use satellite altimeter data (in the absence of in-situ measurements) for calibration and validation. The temporal and spatial resolution of altimeter data relative to the scale of the Arabian Gulf limits its application in this region. Notwithstanding these limitations, the satellite altimeter data remains the primary data source for model verification. In this paper wave data from five satellite missions is compared with a numerical metocean hindcast study. A method to assess the uncertainty of the satellite records is discussed.

Keywords: altimetry data; satellite; waves; Arabian Gulf

INTRODUCTION

The Middle East contains more than half of the proven world oil reserves. Access to the oil provides huge investment and wealth opportunities in the region with the present economies of many Gulf nations almost solely reliant on the petroleum industry. The Arabian Gulf includes the world's largest offshore oil field (Safaniya) and the largest offshore gas field (South Pars/North Dome). Recently, construction of islands to replace platforms has commenced in the Zakum offshore oil field (fourth largest in the world) to increase production. Onshore, there is a very high demand for land adjacent to the coastline for the development of private, public and commercial infrastructure (Figure 1).



Figure 1. Artists image of Bluewater Island, Dubai. Featuring the world's largest Ferris Wheel (presently under construction).

Despite the intense development activities both offshore and along the coastline, there is a general lack of long-term in-situ measurements of waves in the Arabian Gulf. Consequently, there is a very

¹ Artelia Gulf, P.O.Box 18271, Dubai, United Arab Emirates

² Artelia, 6 rue de Lorraine 38130 Echirolles

strong reliance on numerical wave hindcast models to help define extreme wave design parameters. In the absence of in-situ wave measurements, the wave hindcast models are generally calibrated and validated using satellite altimeter data.

In this paper, altimetry data from five satellite missions is compared with a numerical wave hindcast study developed for the Arabian Gulf. The application and reliability of the altimetry data as a substitute for in-situ wave data in the confined seas of the Arabian Gulf is investigated. This includes developing quality control procedures or “filtering rules” to apply to the raw altimetry datasets.

METOCEAN CONDITIONS

The Arabian Gulf is a semi enclosed water body centered in the Middle East. The shoreline forms international borders with Oman, United Arab Emirates, Qatar, Bahrain, Saudi Arabia, Kuwait, Iraq and Iran. Water depths are in excess of 100m at the entrance to the Arabian Gulf, but are typically less than 50m over the majority of the water body (Figure 2).

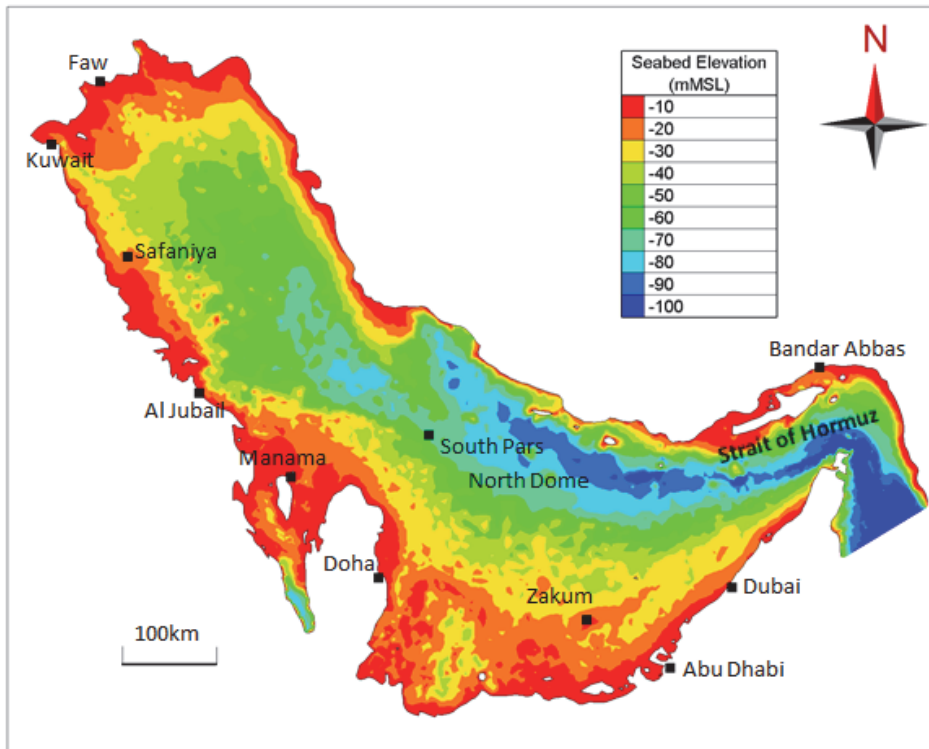


Figure 2. Arabian Gulf seabed elevations (relative to mean sea level, MSL).

The Arabian Gulf is approximately 800km long, 200km wide and reduces to a width of 39km at the entrance (Strait of Hormuz). Waves from the Indian Ocean do not contribute to the sea state in the Arabian Gulf, except in close proximity to the Strait of Hormuz. Therefore, all waves are generated by local wind fields.

Winds in the Arabian Gulf are dominated by Shamals. Shamals originate in the mountains of Turkey and Iraq and the high plains of Saudi Arabia. The winds sweep across the Arabian Gulf from the north-west and are typically strongest during the summer months. Whilst these winds can be persistent, they are not overly strong with 1 in 100 year return period wind speeds typically not exceeding 25m/s across the water body.

The dominant north-westerly wind direction (Figure 3) is aligned with the longest fetch in the Arabian Gulf. Based on several metocean studies for the region, the 1 in 1 year and 1 in 100 year return period *Significant Wave Heights* (H_s) in the south-east of the Arabian Gulf are typically 3.0-3.5m and 5.0-5.5m respectively. The 1 in 100 year return period *Significant Wave Height* in the north-west of the Arabian Gulf is lower and is typically around 4.5m. Waves are generally short crested due to the limited fetches.

The 1 in 100 year return period *Peak Wave Period Wave* (T_p) used in design is typically in the range of 8 to 11s.

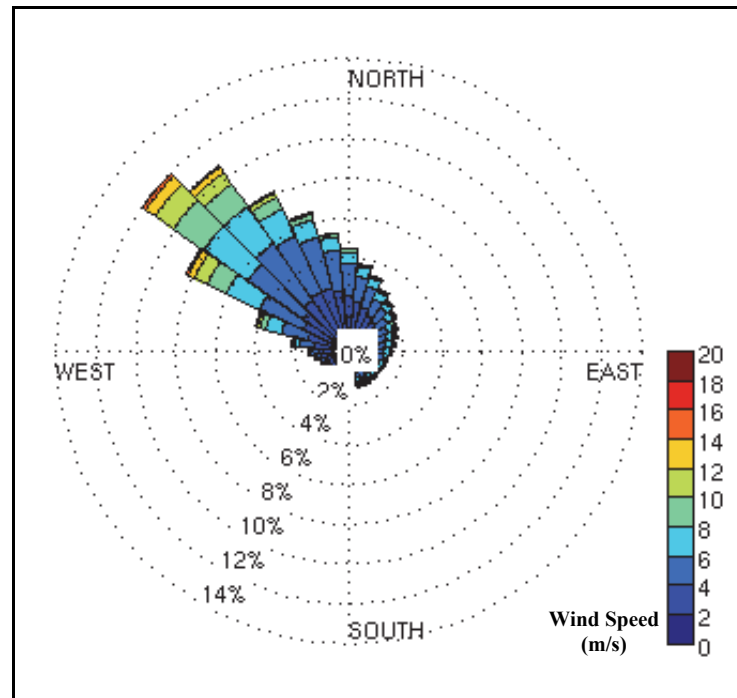


Figure 3. Wind rose near Abu Dhabi (based on 51 years of 6 hour interval data, 10 minute average wind speed at 10m above MSL).

WAVE HINDCAST MODELS

Two metocean studies have recently been completed for a location at 25.4°N and 53.5°E in a water depth of approximately 26m (Point P, Figure 4). These will subsequently be referred to as Study A and Study B. Study A provides output on a model grid with 0.2° by 0.2° (22km x 22km) resolution and spans a 51 year period from 1958 to 2008. Study B provides output on a model grid with 0.0625° by 0.0625° (7km by 7km) resolution and spans a 49 year period from 1961 to 2009. Both studies were reportedly calibrated and validated against in-situ wave measurements and satellite altimetry data. However, it is noted that the in-situ wave measurements are from short term data sets and consequently do not contain records for severe storm events.

Both studies use 6-hourly time step wind fields to force spectral wave models. Study A uses wind data obtained from the European Centre for Medium-Range Weather Forecasts (ECMWF) and defines the winds as 10-minute averages at 10m above mean sea level (MSL). Study B defines the winds as 1-hourly averages at 10m above MSL. Omni directional statistical extreme *Significant Wave Heights* from the two studies are summarised in Table 1.

Table 1. Extreme <i>Significant Wave Heights</i> at 25.4°N and 53.5°E in a water depth of approximately 26m.		
Return Period	Study A	Study B
1 in 1 year	3.8m	3.5m
1 in 5 years	4.8m	4.4m
1 in 100 years	5.2m	5.8m

For the two studies, there is a difference between the reported wave heights of approximately ±10%. The differences between the two independent studies are relatively small considering that they apply modelled wind fields to generate a modelled sea-state from which the statistical Peak Over Threshold (POT) method is then applied to derive the extreme wave heights.

Time series (3 hourly) wave data is available from Study A and is used for comparison in subsequent sections of this paper.

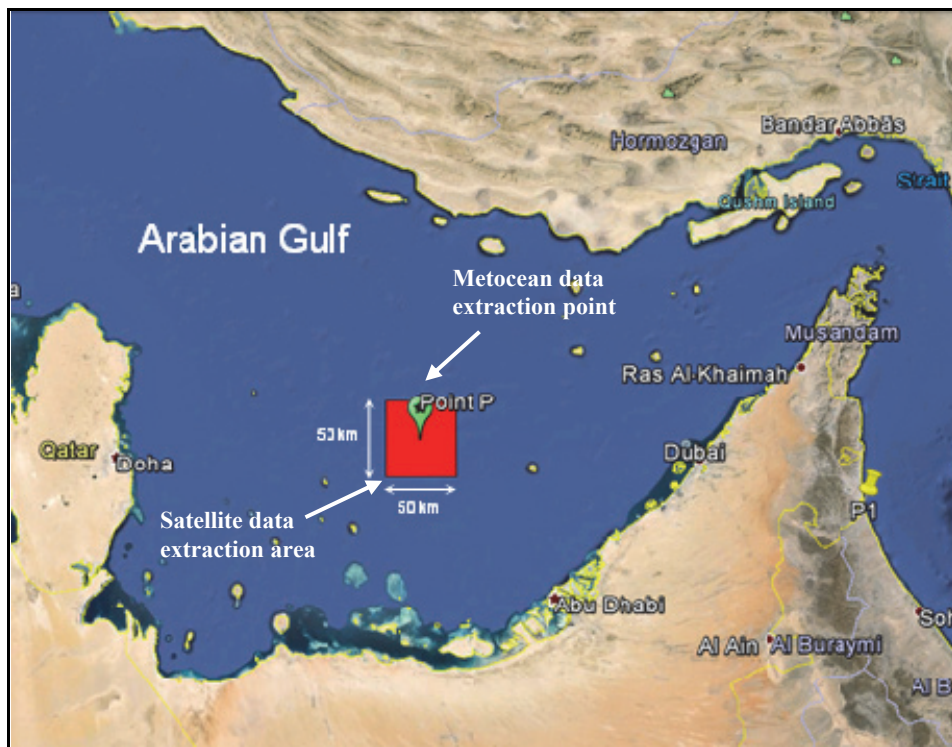


Figure 4. Data extraction location for metocean and satellite data.

ALTIMETRY SATELLITES

Altimetry data from numerous satellites (both operative and decommissioned) are used for calibration and validation of Arabian Gulf wave hindcast models. These data extend from 1991 to the present day. A brief summary of these satellites is as follows:

- ERS-1 (European Remote Sensing Satellite) was launched in July 1991. Repeat orbit cycles of 3, 35 and 168 days. Radar Altimeter (RA) operating in C band to measure waves and a Synthetic Aperture Radar (SAR) to measure winds. End of mission March 2000.
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- Envisat (Successor to ERS-2) was launched in March 2002. Orbit cycle 35 days. Dual frequency RA (K_u and S bands) and Advanced SAR (ASAR). End of mission May 2012.
- TOPEX/Poseidon launched in August 1992. Dual frequency RA (K_u and C bands). End of mission January 2006.
- Jason-1 (Successor to TOPEX/Poseidon) was launched in December 2001. Dual frequency RA (K_u and C bands). End of mission July 2013.

Because the satellites measure water surface elevation they have the dual function of being capable of measuring both sea level elevation and wave height. It is interesting to note that the TOPEX/Poseidon satellite measured an average Global Mean Sea Level (GMSL) rise of 3.1mm/year, Jason-1 is measuring 2.3mm/year and the Envisat satellite measured only 0.5mm/year. The authors understand that this inconsistency is still to be understood and resolved.

The satellite measurements provide instantaneous measurements of the *Significant Wave Height*. The satellites do not presently have the capability to measure other wave parameters such as maximum wave height, wave period, wave steepness, wave direction or storm duration. These are all important parameters in coastal engineering design and are subsequently derived or inferred from the numerical models. The satellite coverage of wave measurements in the Arabian Gulf is shown in Figure 5. The yellow tracks indicate the paths of the ERS-1, ERS-2 and the Envisat satellites. The red tracks indicate the paths of the TOPEX/Poseidon and Jason-1 satellites.

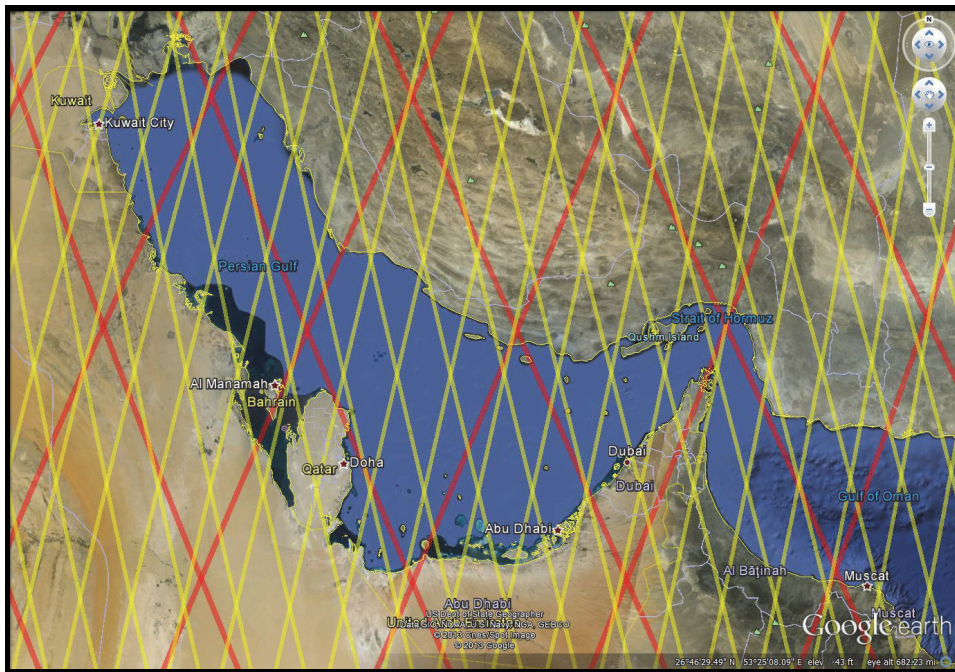


Figure 5. Satellite tracks over the Arabian Gulf

ALTIMETRY DATA

A review of more than 20 years of satellite wave altimeter data in the Arabian Gulf has been undertaken. The data is extracted for the entire region with a detailed assessment undertaken over a 50km x 50km collocation area centered on Point P (Figure 4) as outlined by Durrant et al. 2009. Many of the analysed satellite passes contained high variability along each track (Figure 6).

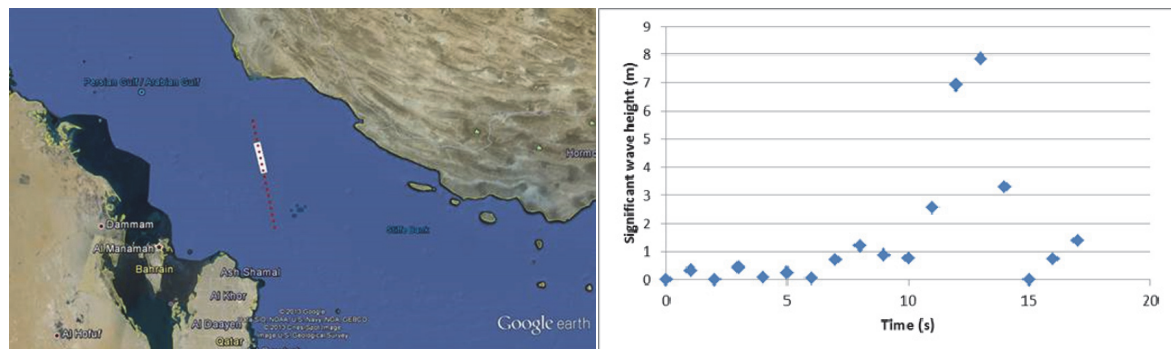


Figure 5. Wave height variability along a satellite track

The satellite altimeter data has previously been shown to provide reasonable estimates of extreme wave conditions (H_s) on global oceanic scales (e.g. Carter et al. 1992). However, the temporal and spatial resolution of altimeter data and the close proximity to land limits its application in the confined seas of the Arabian Gulf. Quality control of the data is therefore a vital step in the development of numerical wave hindcast models, since this data provides the main basis for calibration and validation. The main objective of the quality control process is to identify and reject observations that are obviously in error, as well as the more difficult process of identifying measurements that fall within valid and reasonable ranges, but nevertheless are erroneous.

A common approach is to reject any collocated data in a satellite pass which falls outside two or three standard deviations of the mean value (Durrant et al. 2009; Rousseeuw and Croux 1993). However, many satellite passes contained so much variability along each track that it was still difficult

to identify which data points were erroneous outliers. A new set of 4 filtering criteria were imposed based on a trial-and-error approach:

1. Data points falling outside 2 median absolute deviations from the median were rejected (outliers).
2. Passes where the median absolute deviation was higher than 50% of the median value were excluded (meaning there was so much scatter that outliers could not be reliably determined).
3. Passes containing less than 4 non-zero significant wave height observations were excluded (on the basis that there were not enough data points to reliably differentiate between valid data and outliers).
4. Passes where less than 50% of the data points were non-zero were rejected.

A time series of the unfiltered and filtered data is presented in Figure 6. The filtering removes all altimeter data greater than $H_s > 3\text{m}$.

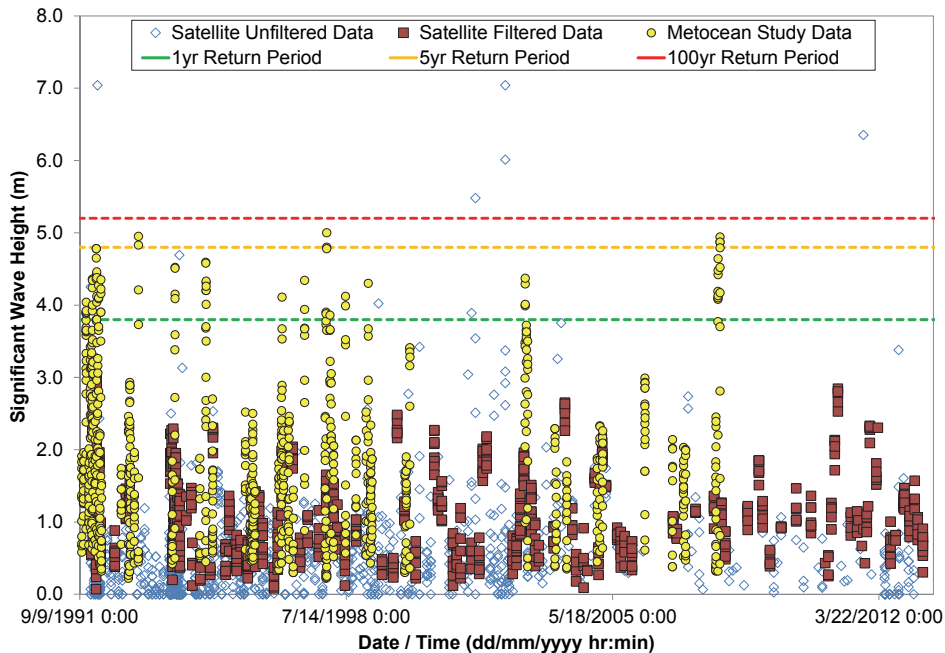


Figure 6. Time series of metocean data and satellite altimetry data (filtered and unfiltered).

A final consistency check was implemented by considering physical constraints on *Significant Wave Heights*. Because the Arabian Gulf is a semi-enclosed sea with relatively short fetches, wind sea conditions prevail (i.e. there is limited or no swell). Consequently, a strong correlation between wind speed and *Significant Wave Height* is expected. The relationship between collocated significant wave heights (altimeter-derived) and the wind speed (U_{10}) from Study A was evaluated and compared to several empirical relationships [SMB, Wilson, and Kahma & Calkoen – as cited in CIRIA/CUR (2007)], for both the filtered and unfiltered altimetry database (Figure 7), using a maximum fetch length along the Arabian Gulf. As discussed in CIRIA/CUR (2007), the Kahma & Calkoen formula for unstable air-sea interface conditions provides a conservative estimate of the *Significant Wave Height* and can therefore be thought of as an upper bound. It is clear that the filtering procedure described above removes the vast majority of data points where *Significant Wave Heights* exceed the theoretical limits (based on the associated wind speed).

This analysis indicates that the filtered altimeter-derived *Significant Wave Heights* for the period 1991-2008 are broadly consistent with the physics of fetch-limited wind wave generation. It is therefore inferred that the filtering procedure is effective in removing erroneous data for the entire (1991-2013) altimeter database.

Having applied the filter criteria to remove all the corrupt altimeter data, the key finding is that no severe storm events ($H_s > 3\text{m}$) have been correctly measured or detected by the satellites.

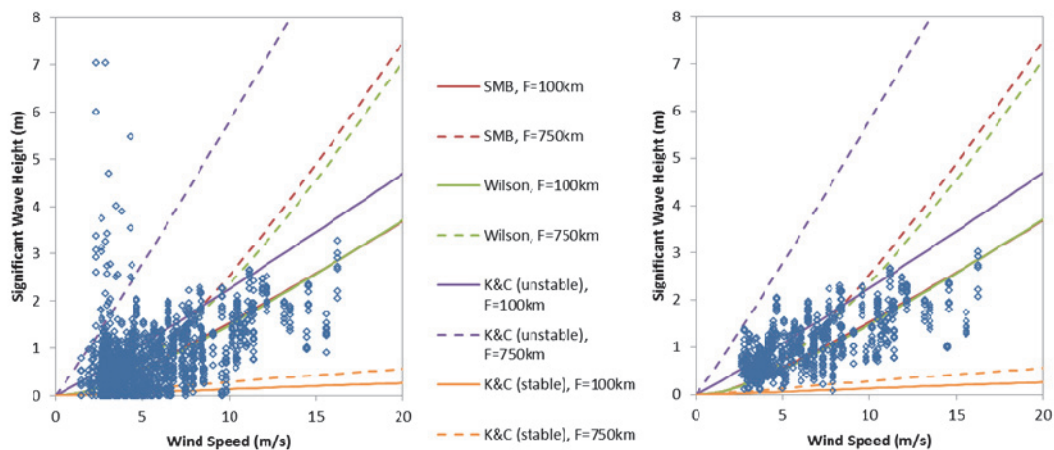


Figure 7. Wind speed vs. Significant Wave Height (unfiltered in left plate, filtered in right plate).

DISCUSSION AND CONCLUSIONS

There is a general lack of long-term in-situ measurements of waves in the Arabian Gulf. Consequently, there is a very strong reliance on numerical wave hindcast models to help define extreme wave design parameters. In the absence of in-situ wave measurements, the wave hindcast models are generally calibrated and validated using satellite altimeter data.

Between 1991 and 2008 twelve storm events exceeding the 1 in 1 year threshold are contained within the model hindcast data set (Figure 6). Four of these events exceed the 1 in 5 year threshold. For the same period, the filtered altimeter *Significant Wave Height* data does not exceed 3m, well below the 1 in 1 year wave height threshold. Thus, numerical wave models for the Arabian Gulf are typically calibrated and validated using minor and frequent storm events. The uncertainty of the numerical wave model results for more severe storm events is therefore not easily quantified.

The temporal and spatial resolution of altimeter data and the close proximity to land limits its application in the confined seas of the Arabian Gulf. Rigorous quality control criteria need to be applied to the satellite measurements due to the high variability in measurements. The satellite measurements provide instantaneous measurements of the *Significant Wave Height*. The satellites do not presently have the capability to measure other wave parameters such as maximum wave height, wave period, wave steepness, wave direction or storm duration. These are all important parameters in coastal engineering design and are subsequently derived or inferred from the numerical models.

Until satellite altimetry measurements develop more sophisticated capabilities, the implementation of long-term in-situ measurements of waves at strategic locations in the Arabian Gulf would be highly beneficial. In the United Arab Emirates, Dubai Municipality has recently implemented a near shore wave monitoring program, however a more extensive networks of in-situ instruments is required to support marine engineering design activities in other countries bordering the Arabian Gulf.

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