# DEVELOPING GLOBAL LONG-TERM ALTIMETER DATASETS AND CLIMATOLOGIES OF OCEAN WAVE MEASUREMENTS

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## 1. INTRODUCTION

Our objective is to build long-term climatologies of ocean significant wave height and wave period based on satellite altimeter data. The motivation is to validate operational wave forecasting systems; to improve our understanding of the role of waves in atmosphere-ocean dynamics, ocean surface transport and mixing; and to facilitate the detection and measurement of global climate change as revealed in ocean wave parameters. Other applications include better estimation of ocean-based renewable energy resources and of extreme sea states.

## 2. CALIBRATING ALTIMETER WAVE MEASUREMENTS

The methodology involves the calibration of altimeter-derived significant wave height ($H_s$) and zero-crossing wave period, $T_z$, against a network of *in situ* buoys. Here we use buoy data from the National Data Buoy Center (NDBC) database, freely available from the US National Oceanic and Atmospheric Administration (http://www.ndbc.noaa.gov).

Altimeter $H_s$ and radar backscatter coefficient, $\sigma_o$, are extracted for the whole duration of the altimeter mission. We have focused initially on the dual-frequency altimeters, TOPEX, ENVISAT and JASON-1. For illustrative purposes, we present TOPEX results only here. Collocation of altimeter and buoy data is done for a maximum time separation of 30 minutes (buoy data are hourly) and a spatial separation of up to 100 km; these are standard choices. The altimeter data are obtained via the Radar Altimeter Database System (RADS) at Delft University of Technology (http://rads.tudelft.nl/rads/rads.shtml). $H_s$ is measured directly by the altimeter and the wave period is calculated from $H_s$ and $\sigma_o$ via the algorithm of [1].

Using orthogonal distance regression (ODR; [2]), we derive best linear fits between buoy and collocated altimeter estimates of $H_s$ and $T_z$. We can do this once for the whole duration of the collocated dataset (i.e. the whole satellite mission) or for a chosen time interval (see below). The slope and intercept of the best fit provides a calibration for the altimeter estimate of the desired wave parameter. While the buoy data are taken to represent 'ground truth', the ODR technique does allow for the accounting of some buoy measurement error. Specifically, the method assumes that the error variances in the altimeter and buoy measurement are the same.

Figure 1 shows the relation between TOPEX-derived $T_z$ and buoy-measured $T_z$ for the duration of the satellite mission. The method also yields the altimeter-buoy bias (in seconds) and the root-mean-square error (rmse) of the calibration, together with the correlation coefficient, as estimated over the whole dataset. The best fit through the raw dataset is derived first. Outliers beyond 3*rmse from the best fit are then rejected, and a new best fit is made through the filtered data.

## 3. TIME-VARYING CALIBRATION

An important consideration when dealing with long-term datasets is the development of a robust technique to perform the calibration in time. In particular, how do the best-fit parameters change in time, and what is the dependence on the duration of the collocated dataset for the ODR results?

Our investigations show that, for example, ten days of data provide too few measurements for a reliable calibration. Conversely, although performing the calibration over a year (or longer) typically provides tens of thousands of altimeter-buoy data pairs, leading to a high-precision calibration, it smoothes over potentially significant intra-annual variability. We found that a sliding three-month window, incremented by one month, gives a good compromise between statistical robustness (several hundred collocated data pairs in the case of TOPEX) and capturing temporal variability in $H_s$ and $T_z$. Figure 2 shows the time series of the slope of the best fit regression for TOPEX $T_z$ against buoy $T_z$ for such a three-month sliding window.

## 4. SEASONAL VARIABILITY IN ALTIMETER WAVE DATA

The following observations can be made on the basis of plots, such as that shown in Figure 2, of TOPEX, ENVISAT and JASON data:

- The time series of regression parameters for the altimeters display seasonal variations.

- TOPEX has a seasonal cycle in wave period bias which peaks in summer, although the 'peak' value is actually close to zero.
- ENVISAT and JASON wave period biases are in phase with that of TOPEX, also peaking in summer, but with largest non-zero values then.
- TOPEX-buoy $H_s$ bias peaks in winter 1997. There is no clear seasonal cycle, in contrast to rms error.
- ENVISAT-buoy $H_s$ bias has a seasonal 'cycle' which has a peak in summer and a low plateau (rather than distinct trough) in winter/spring. JASON is similar.

We investigated the seasonal variations in regression gradient further. Recall that the altimeter-derived $T_z$ is a function of $H_s$ and $\sigma_o$. If the altimeter overestimates low values of $H_s$ (smaller wave heights are more prevalent in summer), and underestimates high values of $H_s$ (larger wave heights are more prevalent in winter), then this would introduce an artificial seasonal bias. So we first derived a bias correction for $H_s$ from the complete extracted TOPEX dataset (September 25, 1992 – October 9, 2005); i.e. we performed a one-time global calibration on $H_s$. Then we determined the effect this had on the derived values of $H_s$ and $T_z$. We found that this makes virtually no difference to the strong seasonal variability in the ODR parameters of best-fit gradient and intercept. While the bias in $H_s$ decreased by typically 5-10 cm (i.e. bias reduced towards zero), the bias in $T_z$ actually increased by ~0.25 s. Note, of course, that the Mackay algorithm was developed on uncalibrated altimeter data. Thus, while the calibration improves (i.e. reduces) the bias in $H_s$, as it should, the bias in $T_z$ increases. In conclusion, the seasonal variation in altimeter-buoy calibration is genuine ocean wave variability. We therefore do not apply the one-time global calibration on $H_s$ first; but instead separately calibrate altimeter measurements of $H_s$ and $T_z$ against the buoy network using time-varying calibration coefficients.

## 5. GLOBAL CALIBRATED WAVE PRODUCTS

Next, the three-month sliding window calibration, sequentially incremented by one month, is applied to each dataset of along-track altimeter measurements (1Hz), yielding along-track global estimates of $H_s$ and $T_z$ for each altimeter mission. These along-track data are then gridded to a regular temporal (monthly) and spatial grid ($2^o$x$2^o$) over the global ocean (within the latitude range covered by each satellite altimeter). Gridding is performed using a two-dimensional Gaussian function with a search radius and full-width half-maximum both equal to 300 km. This gives a reasonable compromise between smoothing and resolution, although there is still evident altimeter 'trackiness' in the maps (not shown here).

## 6. FUTURE WORK

Continuation of the work will include the investigation of other collocation techniques, such as the triple collocation between three independent datasets, which leads to estimate of errors on all data sources [3]. Additional altimeter datasets, from past and emerging missions, will be incorporated in the study, including data from ERS-2, Geosat Follow-On, JASON-2 and the future Cryosat-2 and Sentinel-3 altimeters.

In order to better understand the underlying physical processes, the wave climatologies will be analysed in terms of their spatio-temporal characteristics using a combination of Empirical Orthogonal Function analysis (including complex EOFs to detect and estimate any phase changes, possibly indicating propagating physical features such as eddies, fronts or planetary waves), and wavelet analysis (analogous to time-dependent Fourier analysis). These characteristics will be related to possible forcing mechanisms such as changes in wind strength (e.g. as measured by satellite scatterometers), and to climate indices such as El-Niño Southern Oscillation, the North Atlantic Oscillation and the East Atlantic Pattern. Relationships between wave climate and climate indices (e.g. the NAO) have previously been suggested and these more comprehensive datasets should enable a more detailed assessment of these relations.

## 7. CONCLUDING REMARKS

The development of robust long-term climatologies of ocean significant wave height and wave period is an important contribution to climate research and operational wave forecasting systems.

We have calibrated satellite altimeter measurements of significant wave height, $H_s$, and zero-crossing wave period, $T_z$, over the global ocean. $T_z$ is calculated from $H_s$ and $\sigma_o$ using the algorithm of Mackay *et al.* (2008).

We used orthogonal distance regression to determine best linear fits of altimeter-buoy measurements of $H_s$ and $T_z$ using buoy data from the US National Data Buoy Center. A sliding three-month calibration window achieved a good compromise between a well-determined calibration and capture of intra-annual ocean wave variability. Calibrations have been applied to global along-track altimeter measurements of $H_s$ and $T_z$ for a number of satellite missions. We presented examples above from the TOPEX mission.

The NOC-calibrated global gridded datasets of altimeter wave measurements will be made available freely for

Internet download in the near future. Sample NetCDF files of global along-track TOPEX altimeter data (1Hz), and movies of global gridded TOPEX wave period and significant wave height, can be accessed here: http://www.noc.soton.ac.uk/ooc/SURFACE/SATELLITE_WAVES/waves.php

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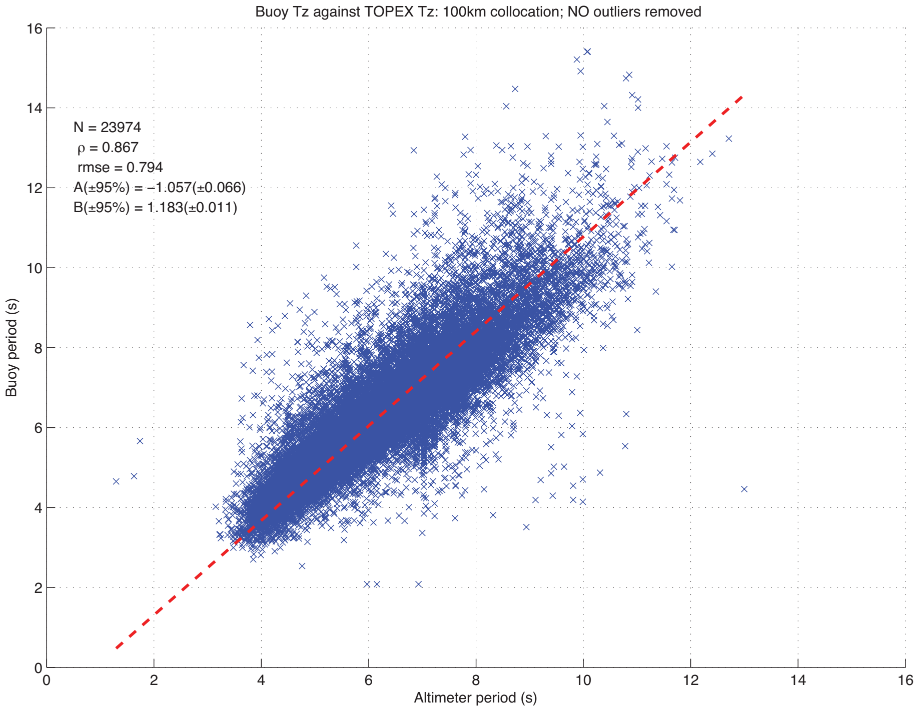


*Figure 1. Orthogonal distance regression of buoy and TOPEX measurements of zero-crossing period, $T_z$, for the complete TOPEX mission. The slope of the best-fit regression, B, and the intercept, A, are shown with the 95% confidence limits. The cross-correlation coefficient, ρ, is 0.867. After rejection of 3*rmse outliers, ρ improves to 0.901.*

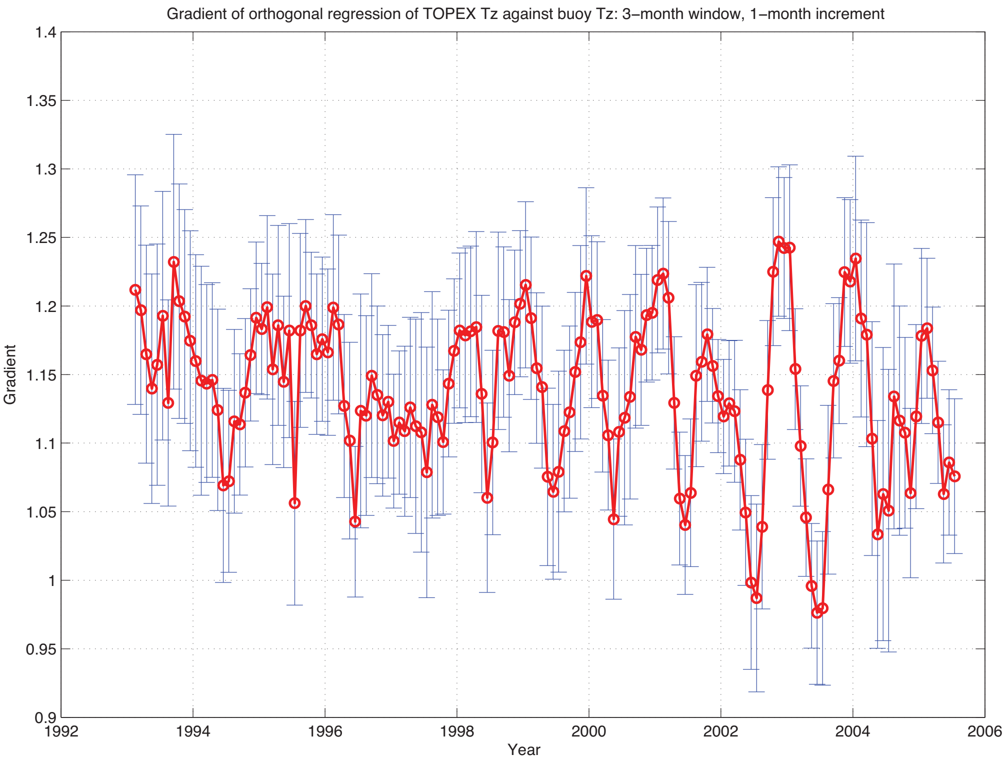


*Figure 2. Time series (red) of the regression gradient, together with 95% confidence limits (blue), for buoy $T_z$ against TOPEX $T_z$. Note the increase in the amplitude of the time variation in the gradient during 2002-2004.*