Sea-state effects on Satellite Altimetry – Overview of established models and recent developments

Nelson PIRES[1*], Joana FERNANDES[1], Christine GOMMENGINGER[2] e Remko SCHARROO[3]

[1] DGAOT, Faculdade de Ciências, Universidade do Porto
[2] National Oceanography Centre (Southampton, UK)
[3] EUMETSAT (Darmstadt, Germany)

(nelson.pires@fc.up.pt; mjfernan@fc.up.pt)

Keywords: Satellite Altimetry, Sea State Bias, Ocean surface waves, Statistical models

Abstract: Sea-state effects are an intrinsic property of the large footprint of the measurements made by the radar altimeter, since the surface scattering elements do not contribute equally to the radar return. Ocean wave troughs are inherently more likely to contribute to the return radar signal, as they scatter back towards the satellite, whereas wave crests scatter away from the satellite. This centimeter-scale measurement bias, induced by ocean surface waves, is referred to as the altimeter Sea State Bias (SSB) and needs to be modeled and corrected to retrieve precise ocean dynamic topography for each along-track observation. The current estimates of SSB are obtained using empirical models computed by bilinear interpolation on a table of Sea Surface Height (SSH) variability versus the Significant Wave Height (SWH) and Wind Speed (U10) retrieved from the altimetric signal, and is based on empirical fits for each sensor using different approaches such as parametric and nonparametric statistical methods. Recent work suggests that these methods based solely on wave and wind information from the altimeter, may be improved with additional surface gravity wave information that became available. This work presents an overview of the current models and a global comparison of those against a new SSB model developed at the University of Porto, a global, multi-mission model, based on 3 parameters, solely derived from altimetric data.

1. Introduction

The sea state bias (SSB) is a geophysical altimetric correction caused by the influence of local sea-state in the altimetric radar pulse and is still one of the largest terms in satellite altimetry error budget. Research on the understanding the SSB and on the improvement of SSB retrieval methods is an up-to-date topic, crucial to the full exploitation of altimeter measurements made both in the conventional Low Resolution Mode (LRM) and the new Synthetic Aperture Radar (SAR) mode.

Since ocean wave troughs are inherently more likely to contribute to the return radar signal, as they scatter back towards the satellite, whereas wave crests scatter away from the satellite, thus the centroid of the mean reflecting surface is shifted away from the mean sea level towards the troughs of the waves. This bias, known as the electromagnetic bias (EM), means the range tends to be overestimated relative to the mean surface position. In addition, a skewness bias also exists from the assumption in the onboard algorithms that the probability density function of heights is symmetric, while in reality it is skewed. Finally, there is a tracker bias, which is a purely instrumental effect, instrument dependent. The sum of EM bias, skewness bias and tracker bias is called Sea State bias (SSB) [Chelton et al., 2001]. This centimetre-scale measurement bias remains as one of the largest source of uncertainty connected with the altimetric signal.

Until recently, SSB operational models were developed using empirical relationships between altimeter range bias, wind speed, and significant wave height estimates [Gaspar et al., 1994, Gaspar and Florens, 1998, Gaspar et al., 2002, Labroue et al., 2004] and with backscatter coefficient ($\sigma 0$) instead of wind speed [Melville et al., 1991, Scharroo and Lillibridge, 2005], but [Glazman et al., 1994,Kumar et al., 2003] suggested that this two-parameter SSB models may not entirely parameterize range bias variability attributed to regional complexities in the ocean wave regimes. [Tran et al., 2006] used additional information from wave field statistics generated from the NOAA's WAVEWATCH III (WW3) numerical ocean wave model to develop several sea state bias correction models. An enhanced three-dimensional SSB model was derived from U10, SWH and estimates of mean wave period (Tm) retrieved from the numerical ocean wave model [Tran et al., 2010]. This three-dimensional SSB correction model reduces sea surface height variance both at global and regional scale, but it has the inconvenience of requiring external information to altimetric data, which may lead to conclusions that may not be directly related with the altimetric signal.

Moreover, in another field of study, some models have been proposed to retrieve wave period information (Tm, Tz) exclusively from the radar altimeter signal, combining both significant wave height (SWH) and radar backscatter cross-section measurements ($\sigma 0$) fitted with buoys measurements. To date, there is a number of algorithms proposed in this topic by [Davies et al., 1997, Gommenginger et al., 2003, Quilfen et al., 2004] each one with their advantages and drawbacks.

2. Modelling SSB

Over the past years, different approaches have been adopted in the modeling of the SSB, leading to progressively improved predictions, better explaining the remaining SSH variability. Parametric formulations were carried out by [Gaspar et al., 1994, Chelton, 1994] where the SSB is estimated from a multiple linear regression approach on the basis of two predictor variables, significant wave height (SWH) and wind speed (U10). More recently, improved estimates were obtained from nonparametric regression methods based on kernel smoothing approaches [Gaspar and Florens, 1998], local linear kernel [Gaspar et al., 2002,Labroue et al., 2004], and smoothing splines [Feng et al., 2010] using the same two predictors only, or with an additional third predictor [Tran et al., 2010b]. A new SSB model has been developed at University of Porto in the sense of being a global multi-mission model, based on 3 parameters, solely derived from altimetric data (SWH, U10 and Tz). Equation (1) represents the SSB UPT using the three predictors derived from altimetric data.

$$SSB_y = \beta_0 + f_1(SWH_y) + f_2(U10_y) + f_3(Tz_y) \tag{1}$$

The chosen approach for this SSB modeling was the smoothing spline method embedded in a general framework provided by Generalized Additive Models (GAMs). As previously described above, this paper presents an overview of the established SSB models (SSB Tran, SSB CLS) and a global comparison of those against the new model developed (SSB UPT).

3. Results

This work concerns the entire phase A of Jason-1 mission, from cycle 001 to 260. The main reasons for this choice were the fact that we are dealing with one of the longest altimetric missions with a time span from 2002 to 2010 and because the two most used and widely accepted SSB models, the CLS nonparametric sea state bias (SSB CLS) from [Gaspar et al., 2002] and the nonparametric sea state bias combined with wave model (SSB Tran) from [Tran et al., 2010b] are available for this mission. The method implemented for model comparison, is based on average binning of SSB corrections against the altimeter SWH and U10 for all measures. Once the corrections are closely linked to its predictors, this procedure allows to make a clear analysis of the SSB behavior for the SWH-U10 domain. Figure 1 shows this results.

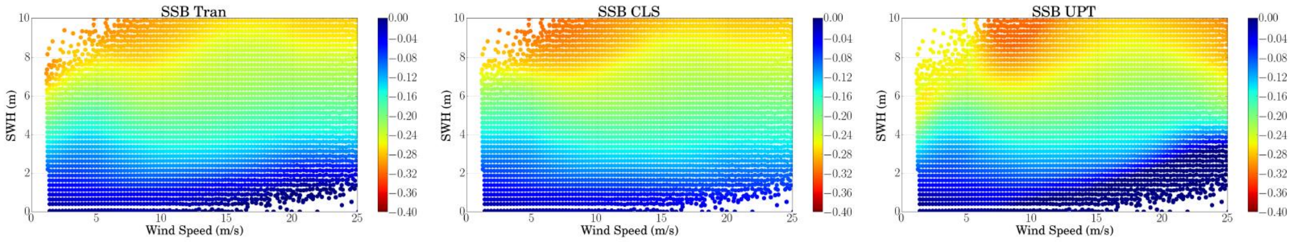

Figure 1 – Left and middle plots represent the bin-averaged SSB Tran and SSB CLS computed for the first 260 cycles of Jason. Right plot shows the resulting model SSB UPT binned for the same domain.

Table 1 – Summary statistics of the three models considered.

SSB Model	mean (m)	std (m)	min (m)	max (m)
SSB Tran	-0.1069	0.0046	-0.309	0.037
SSB CLS	-0.1115	0.0047	-0.321	-0.004
SSB UPT	-0.1038	0.0050	-0.324	-0.001

The summary statistics of Table 1 calculated for all the three models shows a slight underestimation of SSB UPT with respect to variability, all the three models have low standard deviations, however, SSB UPT predictions are a little bit smoother than the other two. This results could be explained by different modelling approaches, where SSB Tran and SSB CLS estimates are obtained from nonparametric regression methods based on kernel smoothing approaches, and SSB UPT estimates are calculated with smoothing spline methods. Section 3.1 and 3.2 presents the results for a comparative study of sea level anomalies (SLA) with respect to the three models.

3.1 Sea Level Anomalies analysis by satellite cycle number and latitude

Regarding SLA analysis, the selected approach was based on collinear track analysis based on their time with respect to the equator passages. The metrics used to evaluate the models performances were based on temporal and spatial analysis of SLA variances and their differences. Figure 2 shows two plots with SLA variance differences per cycle estimated with SSB Tran, SSB CLS and SSB UPT. For a better comparison, both plots have represented (in yellow) the observed variance differences from SLA estimated with SSB Tran and SSB CLS models.

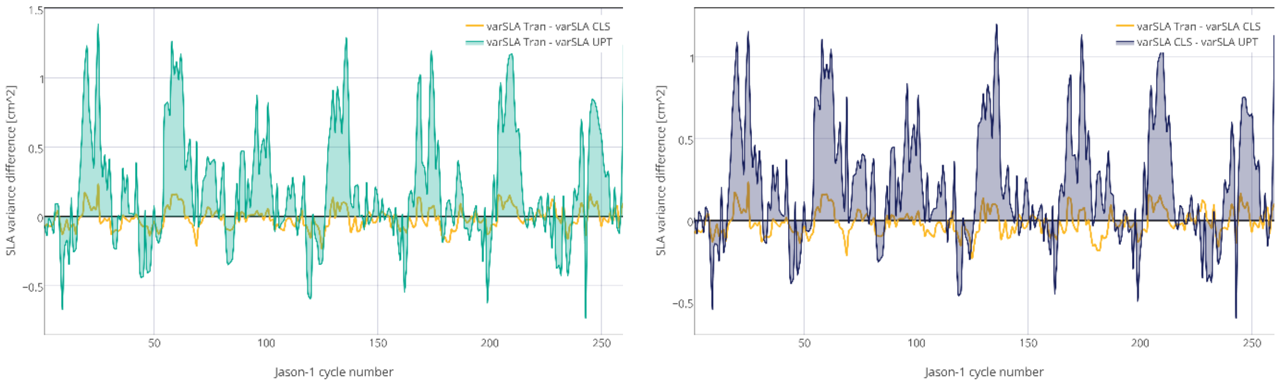

Figure 2 – Differences of SLA variance estimated with the three SSB models for each Jason-1 cycle. Left plot shows in green the SLA variance differences between SSB Tran and SSB UPT. Right plot shows the same metric in blue for SLAs computed with SSB CLS and SSB UPT respectively.

From Figure 2 it can be observed a variance reduction of SLA for the most of Jason-1 cycles when using the SSB UPT model, where the difference range doesn't exceed the absolute value of 2 cm^2. Both plots show close results due to the similarity between SSB Tran and SSB CLS models. A similar analysis was performed for latitude values. Figure 3 shows how the differences of SLA variances behave along latitudes between -60 and 60 degrees, the range latitudes of Jason-1.

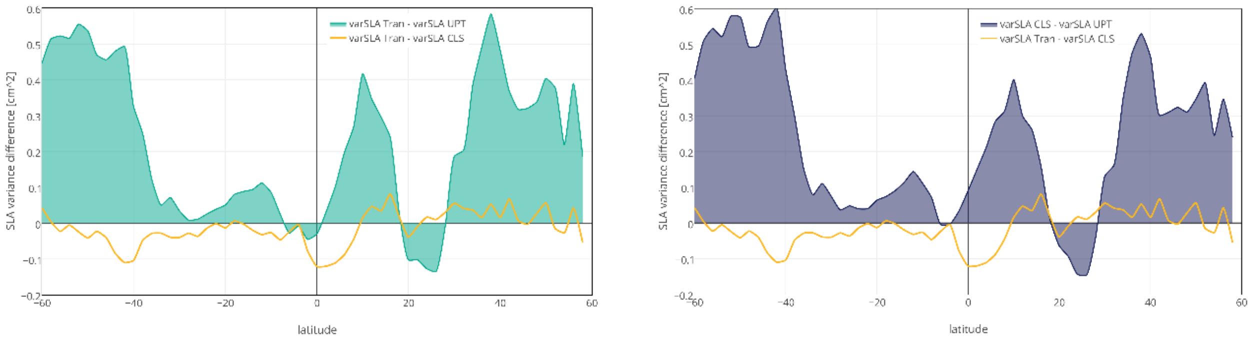

Figure 3 – Differences of SLA variance estimated with the three SSB models for Jason-1 latitudes. Left plot shows in green the SLA variance differences between SSB Tran and SSB UPT. Right plot shows the same metric in blue for SLAs computed with SSB CLS and SSB UPT respectively.

Figure 3 shows a reduction of SLA variance for almost all latitude range when computed with SSB UPT. The exception to this result is shown only for latitudes between 20 and 30 degrees, and it could be explained by the higher density of coastal areas, which may affect the correction behavior. To better understand this differences, a spatial analysis was also performed for the three models.

3.1 Spatial analysis of SLA differences

Figure 4 from next page shows how the SLA variances between models differ globally. To perform a spatial analysis of SLA variances, the collinear tracks were binned in lat-lon squares of 4º, and as expected, there are no big differences between SLA variances when estimated with SSB Tran and SSB CLS, since the two models are fairly close. In relation to SSB UPT, it was also expected a similar behavior when compared with each of the previous models, but it is clear to observe a SLA variance reduction mainly in swell regions, denoting a slight correlation between these results and the Tz algorithm used for SSB UPT modelling. From Figure 4 it is also observed an increase of SLA variance when estimated with SSB UPT for some coastal regions which was already pointed from the analysis of Figure 3.

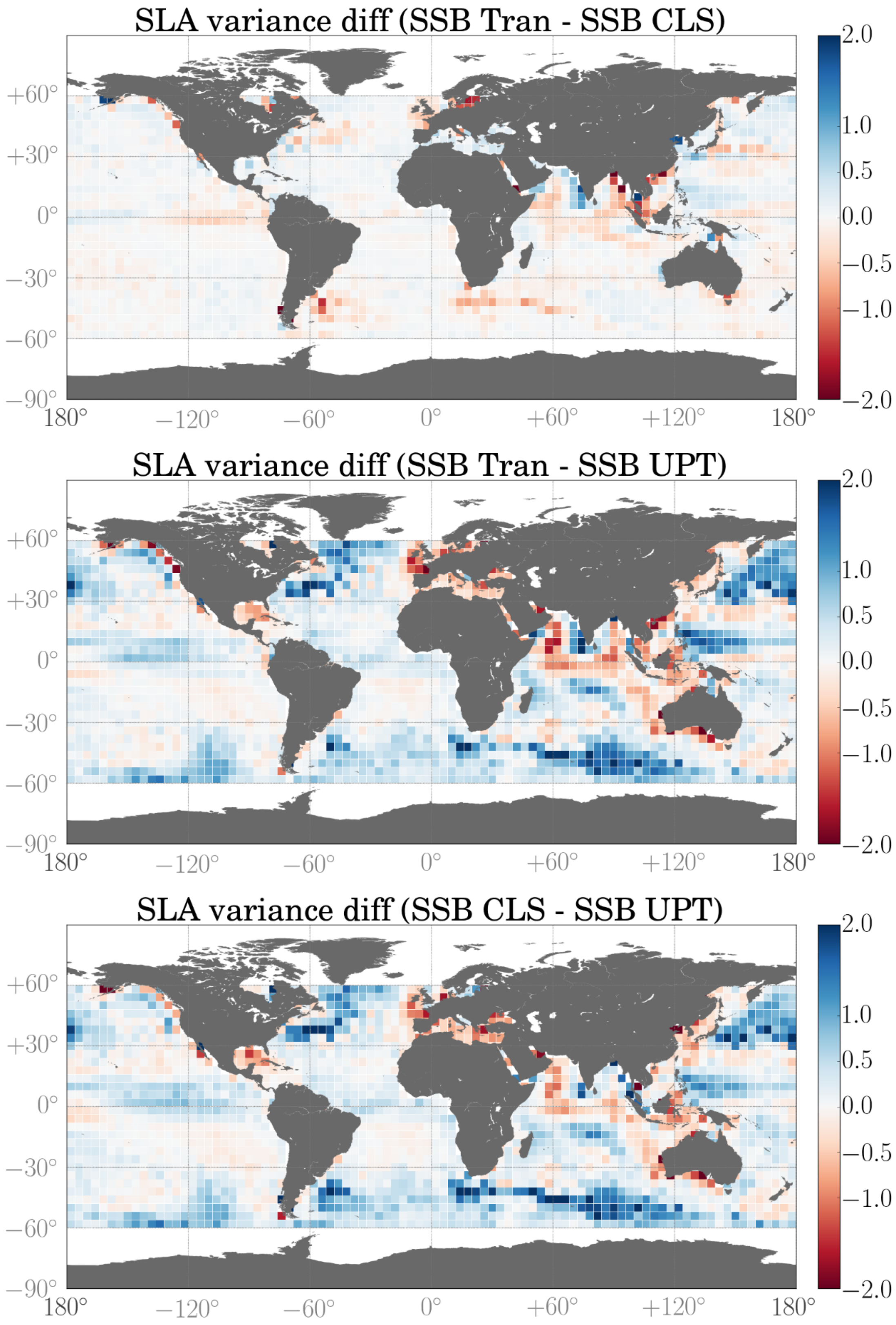

Figure 4 – Spatial analysis of differences in SLA variance estimated for SSB Tran, SSB CLS and SSB UPT.

Analyzing the variance differences of SLA estimated using each of the three SSB models, a variance reduction was verified in some geographical regions with the SLA computed with SSB UPT, comparing with SLA computed with the standard SSB models. As exposed before, SSB UPT is using a third predictor not implemented in SSB Tran and SSB CLS, which could explain a better sea state characterization, and consequently, a better correction prediction. But these results could be also explained by a different approach of regression modeling, since the standard models use kernel smoothing methods, a different statistic technique from smoothing splines.

4. Conclusions

As exposed in the introduction section, this work presents an overview of the current SSB models available for the altimetric mission Jason-1, and a global comparison of those against a new SSB model developed at the University of Porto. The new model was designed to be a global, multi-mission model based on 3 parameters, solely derived from altimetric data.

This comparison study was focused on two methodologies, a direct comparison of the three SSB models (SSB Tran, SSB CLS and SSB UPT) based on average binning against the altimeter Significant Wave Height and Wind Speed for all Jason-1 measures, and where it was observed a slight underestimation of SSB UPT with respect to variability and smoother predictions as well. The second methodology used for comparison, was based on Sea Level Anomalies analysis and variance differences by satellite cycle number, latitude and geographic regions between SLAs computed for each SSB model. The results obtained show a variance reduction for most of the cycles and latitudes considered using the SLA computed SSB UPT. The same results were found for global spatial analysis where it can be observed a SLA variance reduction when computed with SSB UPT mainly in the swell regions, South Pacific and North Atlantic sea state regimes.

For future work, it is intended to continue with the development of SSB models in order to implement it for different altimetric missions and different sensor types, expecting to cover all the past missions since TOPEX/Poseidon until CryoSat-2 mission and the future Sentinel-3 as well.

References

[Chelton, 1994] Chelton, D. (1994). The sea state bias in altimeter estimates of sea level from collinear analysis of TOPEX data. Journal of Geophysical Research, 99:24995-25008.

[Chelton et al., 2001] Chelton, D. B., Ries, J. C., Haines, B. J., Fu, L. L., and Callahan, P. S. (2001). Satellite altimetry, in Satellite Altimetry and Earth Sciences edited by L. Fu and A. Cazenave. International Geophysics Series, 69:1-31.

[Davies et al., 1997] Davies, C. G., Challenor, P. G., and Cotton, P. D. (1997). Measurement of wave period from radar altimeters. Ocean wave measurement and analysis – American Society for Civil Engineering, pages 819-826.

[Feng et al., 2010] Feng, H., Yao, S., Li, L., Tran, N., Vandemark, D., and Labroue, S. (2010). Spline-Based Nonparametric Estimation of the Altimeter Sea-State Bias Correction. IEEE Geoscience and Remote Sensing Letters, 7(3):577-581.

[Gaspar and Florens, 1998] Gaspar, P. and Florens, J. (1998). Estimation of the sea state bias in radar altimeter measurements of sea level: Results from a new nonparametric method. Journal of Geophysical Research, 103(98):803-814.

[Gaspar et al., 1994] Gaspar, P., Le Traon, P., and Zanife, O. (1994). Estimating the sea state bias of the TOPEX and POSEIDON altimeters from crossover differences. Journal of Geophysical Research, 99(12):24981-24994.

[Gaspar et al., 2002] Gaspar, P., Labroue, S., and Ogor, F. (2002). Improving Nonparametric Estimates of the Sea State Bias in Radar Altimeter Measurements of Sea Level. Journal of Atmospheric and Oceanic Technology, 19:1690-1707.

[Glazman et al., 1994] Glazman, R. E., Greysukh, A., and Zlotnicki, V. (1994). Evaluating models of sea state bias in satellite altimetry. Journal of Geophysical Research, 99(C6):12581-12591.

[Gommenginger et al., 2003] Gommenginger, C. P., Srokosz, M., Challenor, P., and Cotton, D. (2003). Measuring ocean wave period with satellite altimeters: A simple empirical model. Geophysical Research Letters, 30(22):2150.

[Kumar et al., 2003] Kumar, R., Stammer, D., Melville, W. K., and Janssen, P. (2003). Electromagnetic bias estimates based on TOPEX, buoy, and wave model data. Journal of Geophysical Research, 108(C11):3351.

[Labroue et al., 2004] Labroue, S., Gaspar, P., Dorandeu, J., Zanif_e, O., Mertz, F., Vincent, P., and Choquet, D. (2004). Nonparametric Estimates of the Sea State Bias for the Jason-1 Radar Altimeter. Marine Geodesy, 27:453-481.

[Melville et al., 1991] Melville, W. K., Stewart, R. H., Keller, W. C., Kong, J. A., Arnold, D. V., Jessup, a. T., Loewen, M. R., and Slinn, a. M. (1991). Measurements of electromagnetic bias in radar altimetry. Journal of Geophysical Research, 96(C3):4915.

[Quilfen et al., 2004] Quilfen, Y., Chapron, B., Collard, F., and Serre, M. (2004). Calibration/Validation of an Altimeter Wave Period Model and Application to TOPEX/Poseidon and Jason-1 Altimeters. Marine Geodesy, 27:535-549.

[Scharroo and Lillibridge, 2005] Scharroo, R. and Lillibridge, J. (2005). Non-ParametricSea-State Bias models and their relevance to sea level change studies. In Proceedings of the 2004 Envisat & ERS Symposium, volume 2004.

[Tran et al., 2006] Tran, N., Vandemark, D., Chapron, B., Labroue, S., Feng, H., Beckley, B., and Vincent, P. (2006). New models for satellite altimeter sea state bias correction developed using global wave model data. Journal of Geophysical Research, 111.

[Tran et al., 2010] Tran, N., Vandemark, D., Labroue, S., Feng, H., Chapron, B., Tolman, H. L., Lambin, J., and Picot, N. (2010). Sea state bias in altimeter sea level estimates determined by combining wave model and satellite data. Journal of Geophysical Research, 115:1-7.