Evidence that Sea State Bias is different for ascending and descending tracks

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Abstract

Jason-1 and TOPEX/POSEIDON (T/P) measured sea-surface heights (SSHs) are compared for five regions during the verification tandem phase. The five regions are of similar latitude, spatial extent, and include the Gulf of Mexico, Arabian Sea, Bay of Bengal, and locations in the Pacific and Atlantic Oceans away from land. In all five regions a bias, defined as Jason SSH – TOPEX-B SSH, exists that is different for ascending and descending tracks. For example, in the Gulf of Mexico the bias for ascending tracks was –0.13 cm and the bias for descending tracks was 2.19 cm. In the Arabian Sea the bias for ascending tracks was –2.45 cm and the bias for descending tracks was –1.31 cm. The bias was found to depend on track orientation and significant wave height (SWH), indicating an error in the sea state bias (SSB) model for one or both altimeters. The bias in all five regions can be significantly reduced by calculating separate corrections for ascending and descending tracks in each region as a function of SWH. The correction is calculated by fitting a second-order polynomial to the bias as a function of SWH separately for ascending and descending tracks. An additional constraint is required to properly apply the correction and we chose to minimize the sum of the TOPEX-B and Jason-1 root-mean-square (rms) crossover differences to be consistent with present SSB models. Application of this constraint shows that the correction, though consistent within each region, is different for each region and that each satellite contributes to the bias. One potential source that may account for a portion of the difference in bias is the leakage in the wave forms in TOPEX-B due to differing altitude rates for ascending and descending tracks. Global SSB models could be improved by separating the tracks into ascenders and descenders and calculating a separate SSB model for each track.

Keywords: TOPEX/POSEIDON, Jason, Sea State Bias, Altimetry

1 Introduction

During the first eight months after its launch, Jason-1 was in a verification phase where its orbit was positioned to sample the ocean within 1 km of the nominal mission ground track at the equator and 72 s ahead of the T/P satellite (Ménard et al., 2003). After the verification tandem phase, T/P was repositioned into a ground track interleaved with the Jason-1 orbit to begin the scientific tandem phase. The verification phase allows direct comparison of the data collected by the two satellite systems, because the state of the ocean is expected to change very little over the short time between sampling by the two satellites. Therefore, any differences between the data collected by the two systems can be attributed to differences in sensor performance, orbital corrections, and the data processing methods used.

One important application of satellite altimeter data is the estimation of the zonal and meridional components of the geostrophic velocity fields. Prior to the beginning of the scientific tandem phase, the crossover method (Parke et al, 1987) was the primary way to estimate geostrophic velocities from exact-repeat orbit satellite measurements at the intersections of ascending and descending tracks. There are several sources of error in the crossover method because the ascending and descending tracks pass over the crossover points at different times and the velocity components must be obtained from a geometrical transformation of nonorthoganal estimates of cross track speeds. The combination of error and the coarse spatial resolution of the crossover points makes these velocities of limited use when used in conjunction with a regional field experiment.

The beginning of the scientific tandem phase, during which Jason-1 and T/P have coordinated orbits with half the spacing of the original T/P mission, prompted development of the parallel-track method (Stammer and Dietrich, 1999). The parallel-track method estimates the geostrophic velocity components from between-track differences of SSH, from a tandem altimeter mission. The parallel-track method will be particularly sensitive to systematic biases between the two satellites, since it estimates the velocities as a difference in SSH between the two altimeter measurements. For example, a 5 cm bias between parallel tracks at 25°N with a 150 km track spacing would result in the magnitude of both components of geostrophic velocity being about 4 cm s^{-1} too large, and the magnitude of the total velocity would be about 6 cm s^{-1} too large.

In preparation for a field study in the Gulf of Mexico, in which T/P and Jason-1 data are expected to supplement the field measurements, the bias between Jason-1 and T/P SSH was intensely scrutinized. The bias, defined as

$$\Delta(x,y,t) = SSH_J(x,y,t) - SSH_T(x,y,t),$$

was found to be 1.03 cm for the entire Gulf of Mexico, however, the bias for ascending tracks was found to be –0.13 cm and the bias for descending tracks 2.19 cm. The possible sources for a different bias between ascending and descending tracks were thought to be due to orbit deviation from the nominal ground track and a poor cross-track gradient estimate or SSB error. An investigation of satellite orbit deviations from the nominal ground track revealed that the orbits were always within the specified ±1 km and that there was no relation between the bias and the deviation, thus leaving SSB error the most likely source of the bias.

The SSB, which is a correction made to account for differences in the reflection of the radar pulse due to surface waves, is the largest error affecting the range measurements of Jason-1 and T/P (Vincent et al., 2003). The SSB is typically estimated empirically by fitting data to a relationship between SSB, SWH, and wind speed (Gaspar et al, 1994; Chambers et al., 2003) or through nonparametric methods (Gaspar and Florens, 1998; Gaspar et al., 2001). In either case, the SSB is a global estimate that implicitly assumes no spatial or directional dependence, which raises two important questions: (1) does the SSB vary regionally, and (2) does SSB vary for ascending and descending tracks. The answer to the second question was clearly yes in the Gulf of Mexico. To answer the first question and confirm the second question, the bias was investigated in four other regions of similar latitude and spatial extent, including the Arabian Sea, Bay of Bengal, and locations in the Pacific and Atlantic Oceans away from land (Figure 1). The answer to the first question is yes, because the bias was found to exist in all five regions. The bias is related to track orientation and significant wave height (SWH) and both altimeters were found to contribute to the bias in varying amounts, depending on the region. A separate bias correction for ascending and descending tracks in each region as function of SWH was found to nearly eliminate the bias while simultaneously reducing the rms of each satellite's crossover differences.

2 Jason-1 and T/P Data Sets and Data Processing

The T/P data used in this study are the merged Geophysical Data Records (GDRs) produced by the Jet Propulsion Laboratory for T/P Cycles 346–360 and 362–364, which covers January through August, 2002. The Poseidon-2 radar altimeter onboard the T/P satellite was turned on during Cycle 361 and was not used. Jason-1 Cycles 1 and 2 (T/P Cycles 344 and 345) were considered unreliable and were excluded. The Jason-1 data used were the interim GDRs for the same cycles used for the T/P data. All standard environmental corrections are applied from the GDRs. The corrections are examined along track and bad values are flagged as outliers. The height data are interpolated to reference ground tracks, and errors during interpolation are reduced through the use of a geoid gradient correction. Next, ocean tides are removed and orbital corrections are calculated by fitting a once per revolution sinusoid to the demeaned and deseasoned SSH data along each track, after which the mean SSH and seasonal signal are restored. Finally, the mean SSH calculated at each reference ground point over the full ten years of the T/P mission is removed to produce the SSH anomalies. To ensure consistency, the same tidal and inverse barometer correction were applied to both data sets. For a detailed description of the data sets and initial processing used see Whitmer and Jacobs (this issue).

The optimal filter developed by Powell and Leben (2004) was designed to minimize the error associated with white noise when calculating SSH slope, and thus, geostrophic velocity. The filter can also be modified and applied directly to the heights, which we have done since we are investigating height biases. The width of the filter is selected based on the dominant scale of interest, and is typically chosen so the filter half-power wavelength most closely exceeds twice the first baroclinic Rossby radius of deformation, which is related to the dominant length scale of mesoscale variability (Chelton et al., 1998). In the Gulf of Mexico the deformation radius is near 40 km, thus we chose to employ a filter width of 13 points which when applied to the 1 Hz SSH data has a window width of 92.9 km. When applying the filter, only segments longer than 13 points without any missing data are allowed, thereby eliminating any enhanced error caused by using shorter filter lengths or interpolation. Thus, the filter half-width (6 points) is lost from the beginning and ending of each segment of data. It has been shown that shorter velocity scales do not effect standard altimetric corrections (Leeuwenburgh and Stammer, 2002), thus, filtering them out will not effect the bias calculations. The same filter was applied to all of the Jason1 and T/P height data.

An example of the application of the filter to Track 102, T/P Cycle 346, Jason-1 Cycle 3 (Jason-1 cycle numbers equal T/P cycle numbers–343) in the Gulf of Mexico can be seen in Figure 2. The estimated noise levels for this track and cycle are 2.90 cm for Jason-1 and 1.87 cm for T/P, which is nearly the same as the total noise level of all the tracks in the Gulf of Mexico. The increased noise level in Jason-1 is clearly evident in the Jason-1 unfiltered data (black curve) when compared to the T/P unfiltered data (blue curve). In each case, the filtered curve captures the underlying structure while strongly reducing the white noise levels. The filter also removes short wavelength real signal along with the noise. However, the scale of these features is much less than the Rossby radius of deformation and their removal is considered acceptable because short wavelength features should not affect the long wavelength bias of a large region.

The SSB models used to correct the data are the preliminary nonparametric model for Jason-1 and the updated SSB model for TOPEX-B developed by Chambers et al. (2003). The preliminary SSB model used for Jason-1 is known to require adjustment, however, since the correction is applied globally to all tracks it is unlikely that it would cause the difference in bias between ascending and descending tracks. We also examined the bias using the standard SSB model for T/P as well as the updated version of Chambers et al. (2003) and found no fundamental change in our results. Thus, the difference in bias between ascending and descending tracks can not be accounted for using a single SSB model.

3 Regional SSH Bias Comparisons and Corrections

Comparisons of SSH bias was done regionally on a track by track basis by calculating the mean bias of each track over all cycles available during the verification phase. Four of the five regions investigated display a persistent bias that is different for ascending and descending tracks (Figure 3). The bias in the Gulf of Mexico has the largest mean difference between ascending and descending tracks at 2.32 cm, followed by the Bay of Bengal at 1.63 cm, the Arabian Sea at 1.15 cm, the Atlantic Ocean box at 0.87 cm, and finally the Pacific Ocean box at 0.10 cm. Figure 4 shows the average bias for 12 tracks in the Gulf of Mexico. Clearly, the descending tracks are positively biased while the ascending tracks show a slightly negative bias. The short wavelength nature of the bias in the Gulf of Mexico indicates orbit deviations are not the likely cause, because orbit deviations are long wavelength features (Colombo, 1989). In order to fully rule out orbit deviations as the source of the bias difference, the bias was investigated as a function of orbit deviation from the nominal ground track and no relation was found, hence, the SSB models used for T/P and Jason-1 are the likely source of the bias difference between ascending and descending tracks.

The SSB is typically found as a function of SWH and wind speed for both parametric and nonparametric models with a typically larger dependence on SWH (Chambers et al., 2003: Gaspar et al., 1994). With this in mind, the average T/P measured SWH in the Gulf of Mexico for twelve tracks is plotted in Figure 5 in a manner similar to Figure 4. Use of the Jason-1 measured SWH renders the same basic results with slight variations, therefore, similar results are attainable using either SWH data set. We use the T/P SWH measurements throughout. The same short wavelength structure seen in the height biases is clearly evident in SWH, indicating there is a relation between bias and SWH. Similar results occur in the other four regions investigated (not shown), including the Pacific Ocean box. This suggests that the different biases seen in the ascending and descending tracks can be corrected by calculating a different correction in each region for ascending and descending tracks as a function of SWH.

The mean biases of ascending and descending tracks are different for each region (Figure 3). The mean biases in the Atlantic and Gulf of Mexico regions show Jason-1 consistently measures a higher SSH value than T/P for descending tracks, and a slightly lower SSH value is measured for ascending tracks. The mean biases in the Arabian Sea and Bay of Bengal regions show that Jason-1 measures a lower SSH value than T/P for both ascending and descending tracks. The mean biases in the Pacific Ocean region show that Jason-1 measures a slightly higher SSH than T/P for both ascending and descending tracks.

The bias corrections in each region are determined by least squares fitting a second order polynomial to the bias as a function of SWH separately for ascending and descending tracks. To begin, a range of SWH is selected based on a histogram of SWH in each region (Figure 6, top panel). Then a second order polynomial is least squares fit to the bias as a function of the selected SWH range for ascending and descending tracks (Figure 6, lower 2 panels). Prior to least squares fitting, the SWH was filtered in the same manner as the heights using the Powell and Leben (2004) filter to optimally reduce the white noise of the measurements and render a robust fit. Other methods of smoothing SWH were tried, including running averages and low-pass filtering, with similar results, however, the filter of Powell and Leben was used for consistency with the SSH processing. Once the necessary corrections are calculated, it must be determined how to best apply the corrections to the T/P and Jason-1 data, because it is not clear which satellite is biased (i.e., is Jason-1 too high or is T/P too low). The constraint requires the sum of the rms differences of the crossover points for T/P and Jason-1 to be minimized. Figure 7 shows the sum of the T/P and Jason-1 rms differences of the crossover points for the Bay of Bengal region. The abscissa shows what percentage of the correction must be added to the T/P descending tracks and the ordinate shows what percentage must be added to the T/P ascending tracks. The percentage of the corrections to be subtracted form the Jason-1 descending and ascending tracks is simply 100 minus the percentage of the T/P correction. For this case, in order to minimize the rms difference of the crossover points, 0% (from Figure 7) must be added to the T/P descending tracks and 100% must be subtracted from the Jason-1 descending tracks. Similarly, 42% must be added to the T/P ascending tracks and 58% subtracted from the Jason-1 ascending tracks . The percentage of the corrections to apply to T/P and Jason-1 for the five regions are given in Table 1. In all five regions the rms difference for the crossover points remains the same or is reduced for both T/P and Jason-1 SSH measurements after application of the correction (Table 2).

4 Discussion

The different bias seen between ascending and descending tracks cannot be caused by the present SSB models used on the T/P and Jason-1 data due to their global consistency. The evidence for this is threefold: (1) The difference between the corrections for descending and ascending tracks is distinct for each of the five regions (Figure 8), (2) the constraint that the sum of the rms differences be minimized by the correction does not exhibit a consistent pattern as to which satellite's SSB model is causing the bias (Table 1), and (3) the mean SWH for all tracks in all regions is similar (Figure 8). Since the present SSB models, both parametric and nonparametric, determine a single SSB model to be applied to all tracks for the entire globe, ascending and descending tracks with similar mean SWH are hypothesized to have the same bias, regardless of region or SSB model employed. However, this is not the case. Thus, the present SSB models do not cause the different bias between ascending and descending tracks.

One possible source that may account for a portion of the different bias between ascending and descending tracks is the altitude rate (Phil Callahan, personal communication). The altitude rate, which is different for ascending and descending tracks, causes leakage in the wave forms in TOPEX-B that are different for ascending and descending tracks. The magnitude of the bias caused by this is 0.5 to 1 cm in the five regions examined. The magnitude of the bias caused by the different altitude rates in the Gulf of Mexico is around 0.5 cm, but the difference in the corrections between

between descending and ascending tracks in the Gulf of Mexico is generally greater than 2 cm, thus, the bias generated by altitude rates accounts for less than 25% of the bias seen in the Gulf of Mexico. Furthermore, application of the correction in the Gulf of Mexico constrained by the minimization of the sum of the rms crossover differences indicates that the full correction must be subtracted from Jason-1 ascending tracks and that 62% must be subtracted from Jason-1 descending tracks (Table 1). This suggests that the Jason-1 data is the primary source of the bias in the Gulf of Mexico, even though the Jason-1 does not suffer the same wave form leakages (Phil Callahan, personal communication). In fact, none of the five regions requires the correction to be applied only to T/P, suggesting that SSB is still the likely source of the bias in all five regions.

The corrections determined on a regional basis, while significantly reducing the bias of most tracks, cause several individual tracks to slightly increase in bias (Figure 8). This indicates that, in general, a regional correction could be improved upon by calculating corrections on a track by track basis. Corrections for track 8, which ascends through the Gulf of Mexico and descends through the Arabian Sea (Figure 1), were calculated separately for its ascending and descending portions. The difference in the correction between ascending and descending tracks is significant and ranges from minimum a of –2.0 cm at 0.25 m SWH to a maximum of 0.46 at 3.5 m SWH (Figure 9). The regional correction for track 8 (ascending in the Gulf of Mexico) actually increases the mean bias of the track form 0.46 cm to 0.81 cm, but the single track correction reduces the mean bias of the track to 0.06 cm. Similarly, the regional correction for track 8 (descending in the Arabian Sea) reduces the the mean bias of the track from –2.09 cm to –0.81 cm, but the single track correction reduces the mean bias of the track to –0.25 cm. Similar results hold for other tracks (not shown). This indicates that, although an improvement, a regional correction can be further improved upon by calculating separate corrections for the ascending and descending portions of individual tracks.

5 Conclusions

A difference in bias between ascending and descending tracks was shown to exist between Jason-1 and T/P. A possible source of a portion of this bias may be due to wave form leakage in TOPEX-B caused by differing altitude rates for ascending and descending tracks. An examination of the bias indicates that both Jason-1 and T/P contribute to the bias in differing amounts depending on the region, showing that the bias caused by differing altitude rates cannot account fully for the biases seen here (otherwise the corrections would have to be applied fully to T/P in all regions, because Jason-1 does not suffer the same wave form leakage). It was also shown that the bias is not caused by the present SSB models. Furthermore, the bias cannot be corrected by the present method of calculating a single, global SSB model for each satellite without separate consideration of individual ascending and descending tracks. A simple correction based on a second order polynomial between the bias and a least square fit applied to T/P SWH separately for ascending and descending tracks on a regional basis significantly reduces the bias in each region, but may increase the bias on individual tracks. Calculation of corrections for the ascending and descending portions of an individual track can further reduce the bias. Although we only examined the dependence of the bias on SWH, our results suggest that the SSB models for both T/P and Jason-1 should be constructed separately for the ascending and descending portions of each track. These results may be universal, that is, the same conclusions drawn here for T/P and Jason-1 may be true for other satellite systems as well. This study presented evidence that the biases in ascending and descending tracks are different, and suggested a simple method to remove it, further work is required to fully isolate the cause of the bias and optimally remove it.

Acknowledgments

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Table 1

Region	T/P asc	T/P dsc	Jason-1 asc	Jason-1 dsc
ARAB	100	0	0	100
BENG	45	0	55	100
GOM	0	28	100	62
ATL	100	0	0	100
PAC	53	44	47	56

Table 1: Column 1: Percentage of correction to apply to T/P ascending tracks. Column 2: Percentage of correction to apply to T/P descending tracks. Column 3: Percentage of correction to apply to Jason-1 ascending tracks. Column 4: Percentage of correction to apply to Jason-1 descending tracks.

Table 2

Region	T/P orig	T/P corr	Jason-1 orig	Jason-1 corr
ARAB	5.66	4.74	4.88	4.47
BENG	4.92	4.81	5.12	5.02
GOM	7.38	7.31	7.33	7.14
ATL	4.18	4.15	3.82	3.82
PAC	3.35	3.34	3.35	3.34

Table 2: Column 1: rms difference of T/P crossover points before correction. Column 2: rms difference of T/P crossover points after correction. Column 3: rms difference of Jason-1 crossover points before correction. Column 4: rms difference of Jason-1 crossover points after correction.

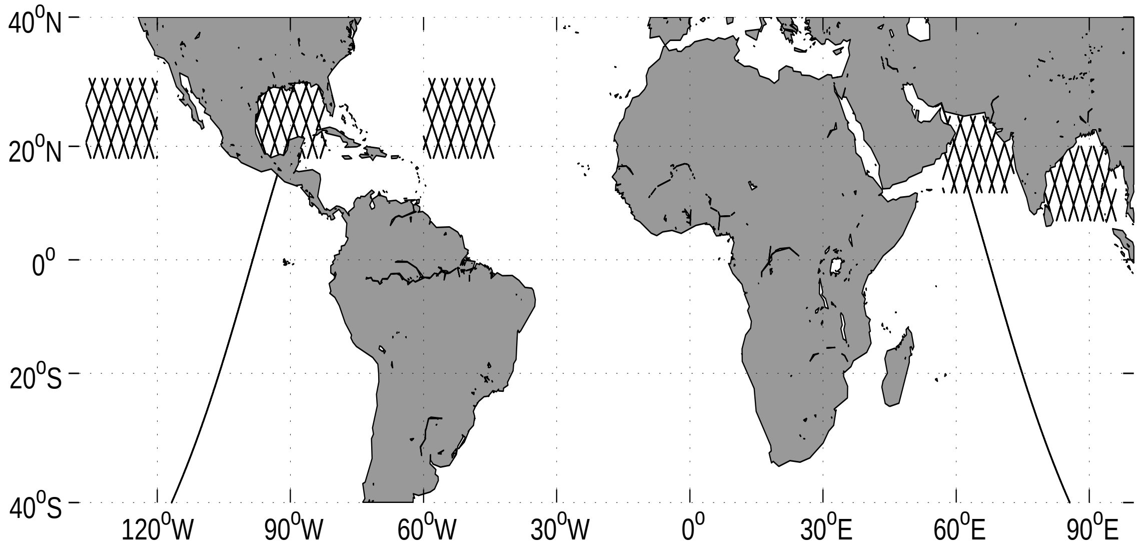

Figure 1: Map showing the locations of the five regions where the bias is examined. They are, from left to right: Pacific Ocean, Gulf of Mexico, Atlantic Ocean, Arabian Sea, and Bay of Bengal. The thin lines represent the ground track of the satellite paths. The two long lines extending from the Gulf of Mexico and The Arabian Sea are track 8.

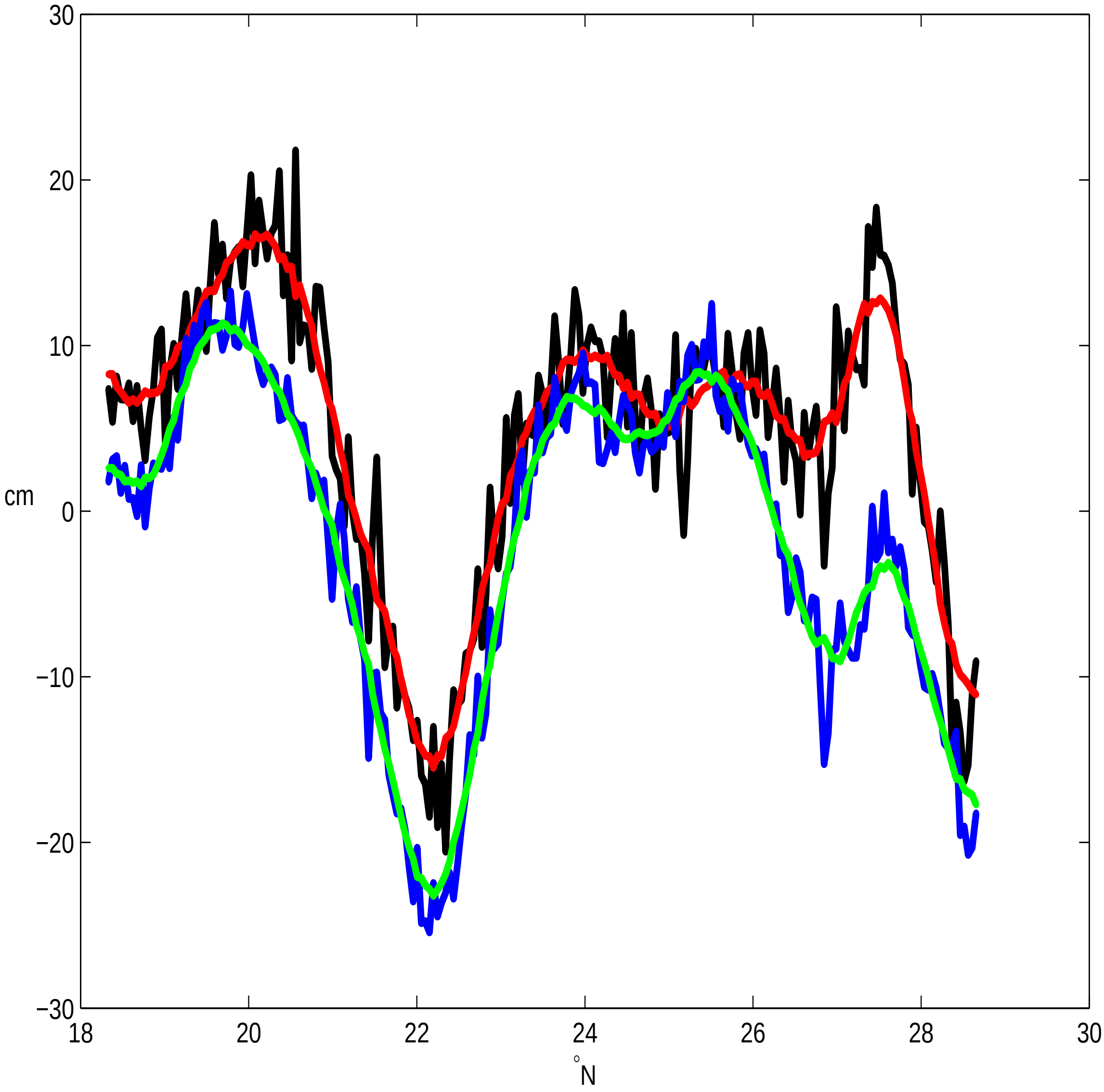

Figure 2: Plot showing the raw and filtered Jason-1 and T/P SSH data for Track 102, T/P Cycle 343, Jason-1 Cycle 3. Black curve: raw Jason-1 SSH. Red curve: filtered Jason-1 SSH. Blue curve: raw T/P SSH. Green curve: filtered T/P SSH. The filter removes the short wavelength white noise while retaining the mesoscale wavelength structure.

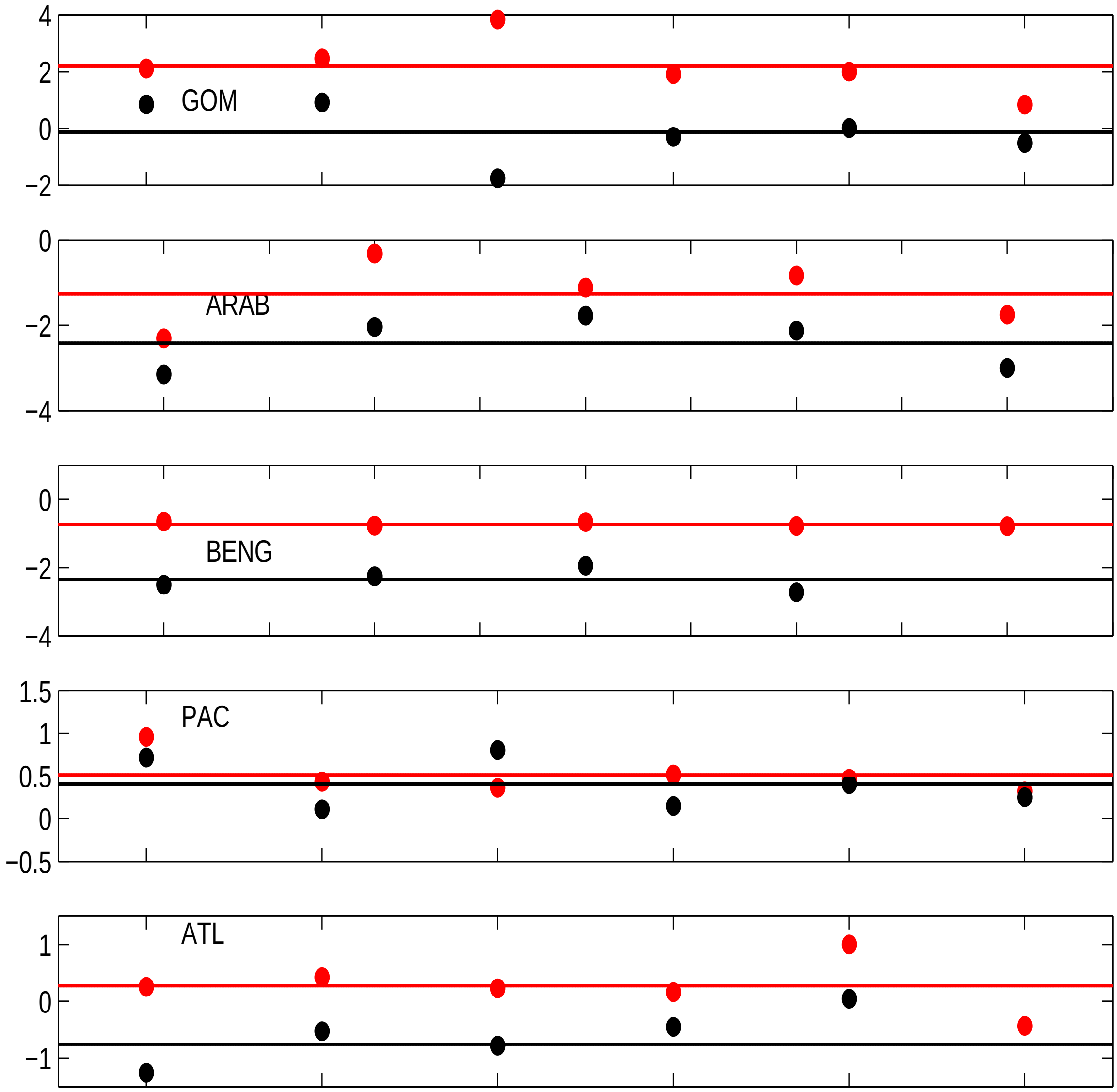

Figure 3: Plots showing the mean bias for ascending (black circles) and descending (red circles) tracks in each region. The mean bias for all ascenders and descenders for each region is marked by black and red lines, respectively.

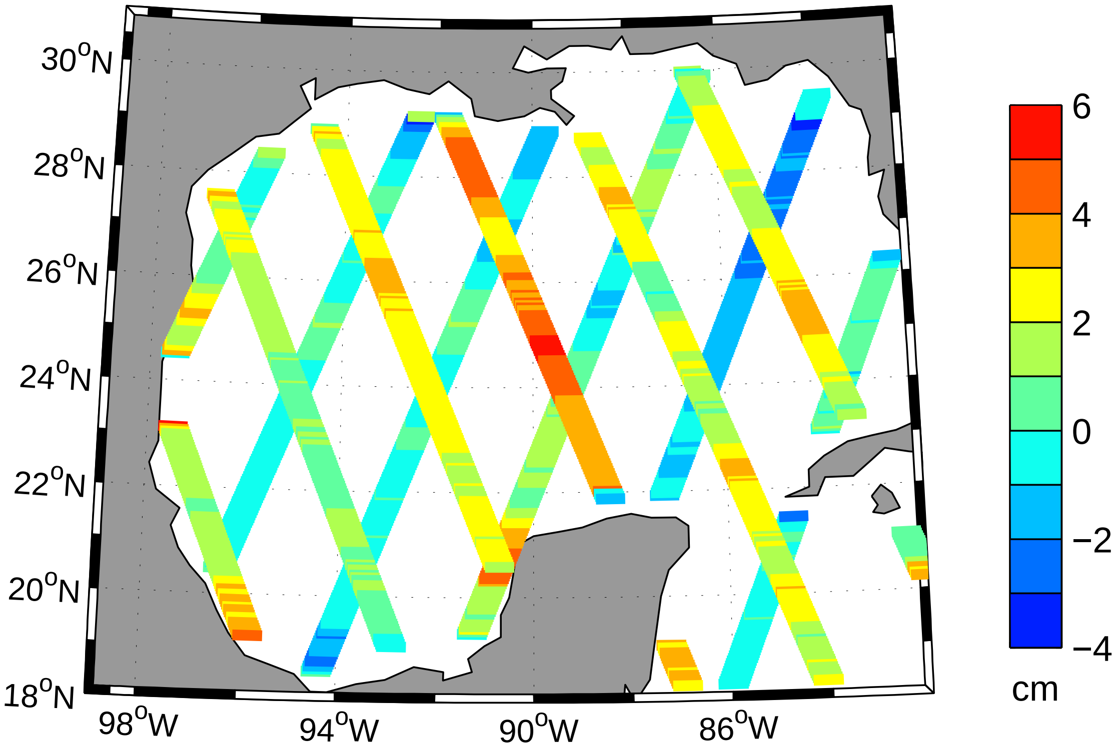

Figure 4: Geographic distribution of SSH bias of Jason-1 relative to T/P in the Gulf of Mexico. Descending tracks (sloping down from left to right) show a clear positive bias while ascending tracks (sloping up from left to right) show a slight negative bias. All tracks show short wavelength features.

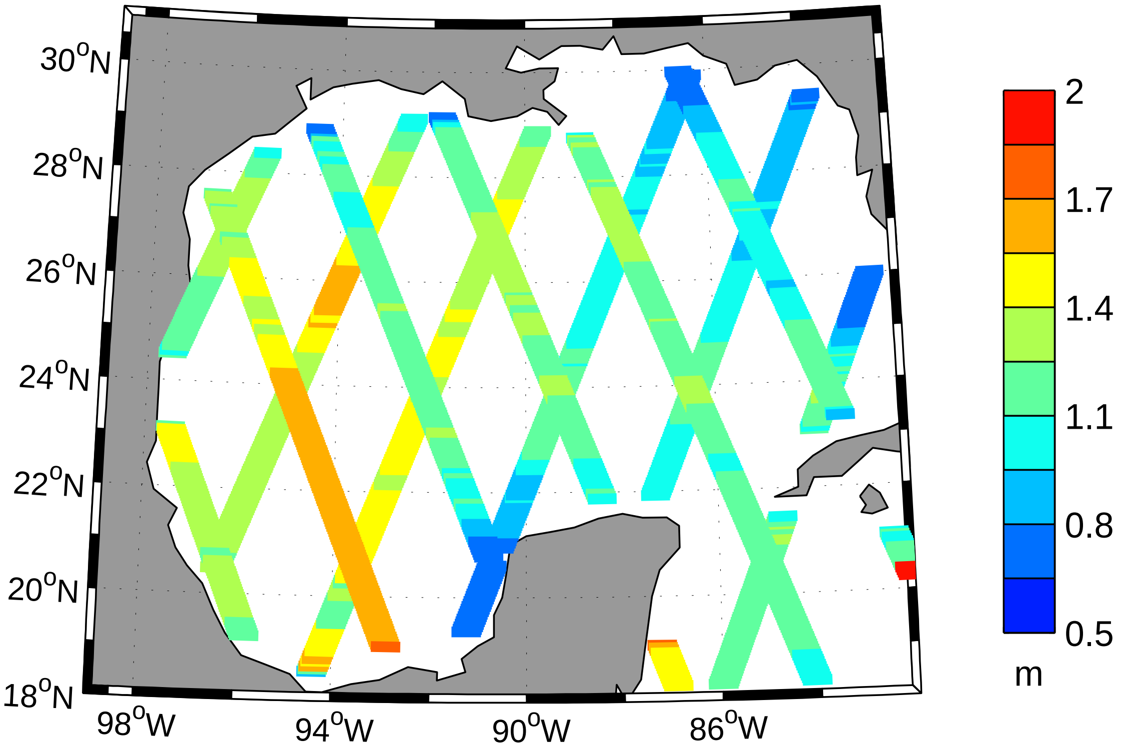

Figure 5: Geographic distribution of SWH in the Gulf of Mexico. Short wavelength features similar to those of the bias in Figure 4 are evident.

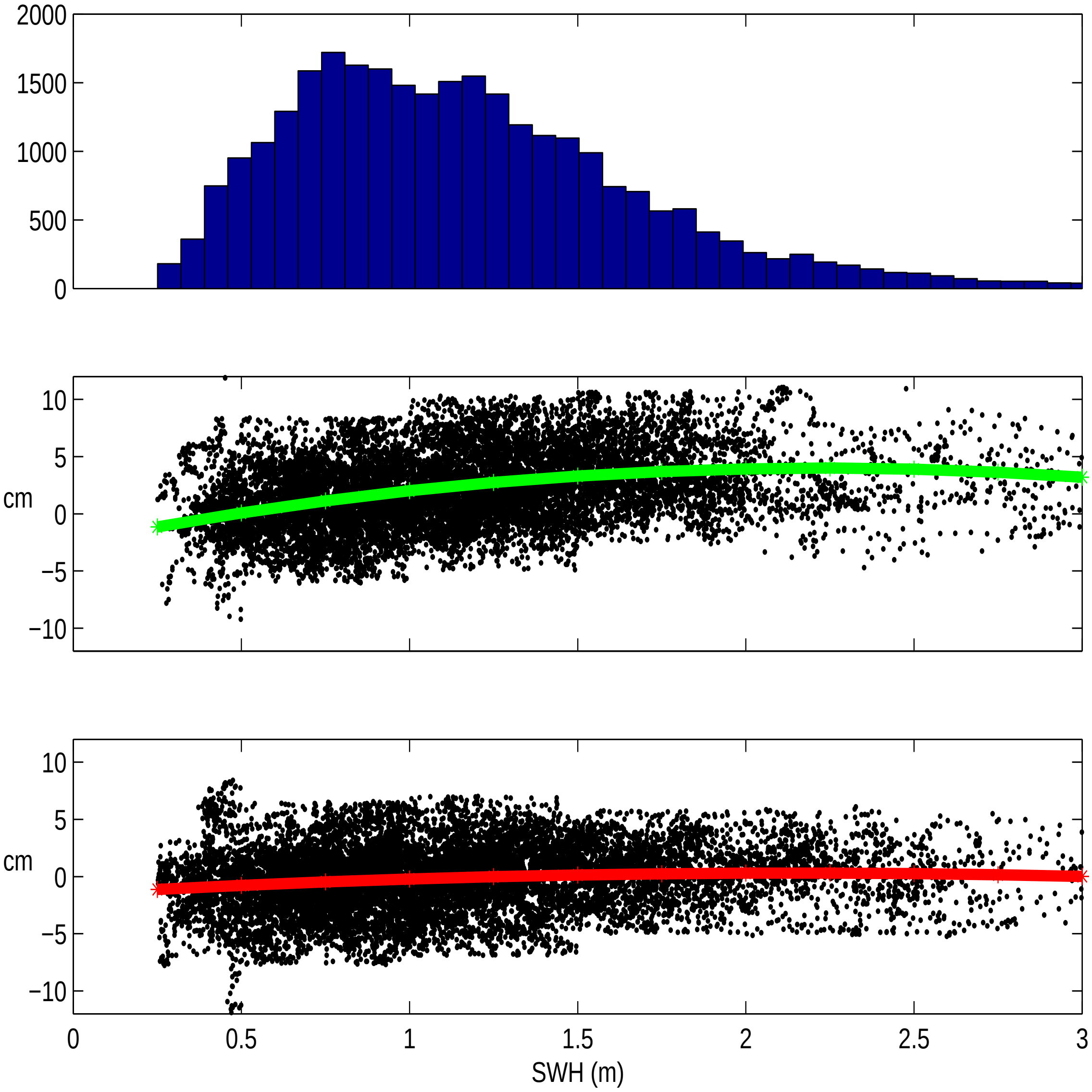

Figure 6: Top panel: Histogram of SWH in the Gulf of Mexico. Middle panel: Bias as a function of SWH (black dots) for descending tracks. The green curve represents the least squares fit of a second order polynomial to the bias as a function of SWH. Bottom panel: Bias as a function of SWH (black dots) for ascending tracks. The red curve represents the least squares fit of a second order polynomial to the bias as a function of SWH.

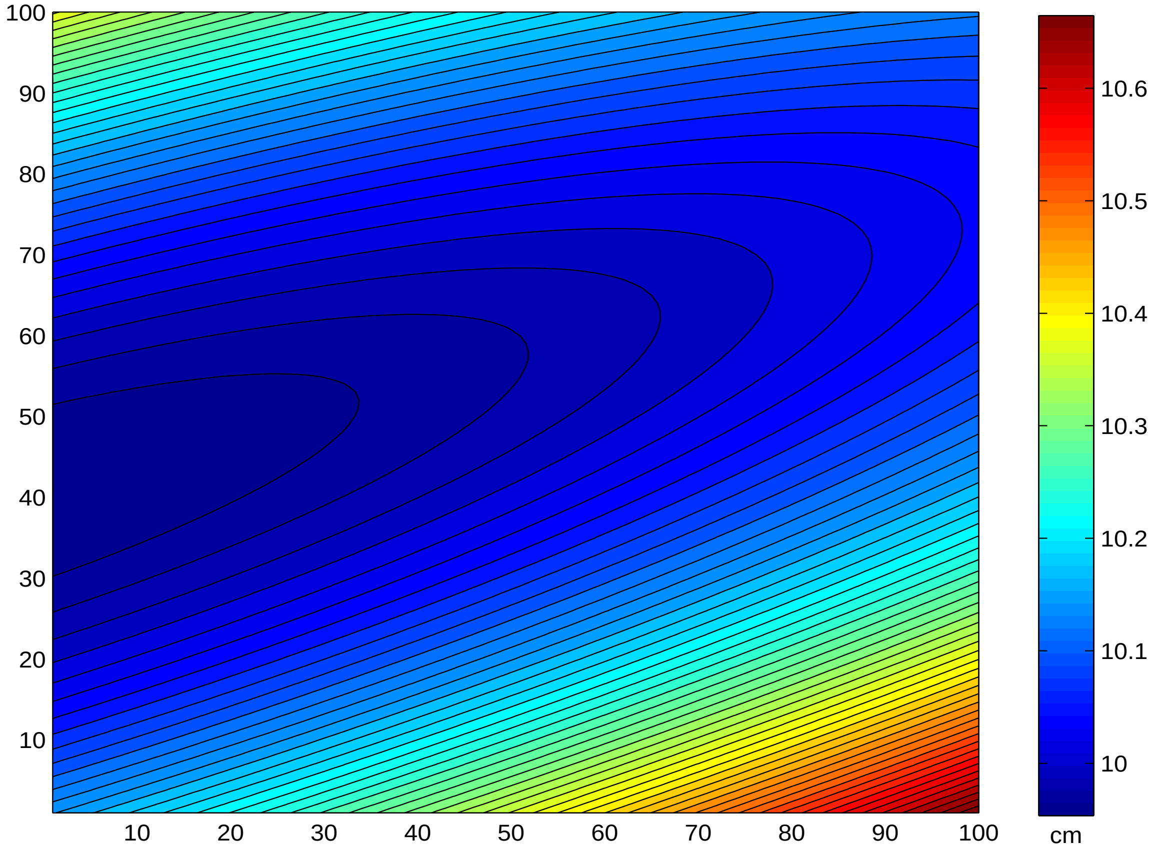

Figure 7: The sum of the rms difference of T/P and Jason-1 crossover points in the Bay of Bengal. The abscissa shows what percentage of the correction must be added to the T/P descending tracks and the ordinate shows what percentage must be added to the T/P ascending tracks to minimize the rms difference.

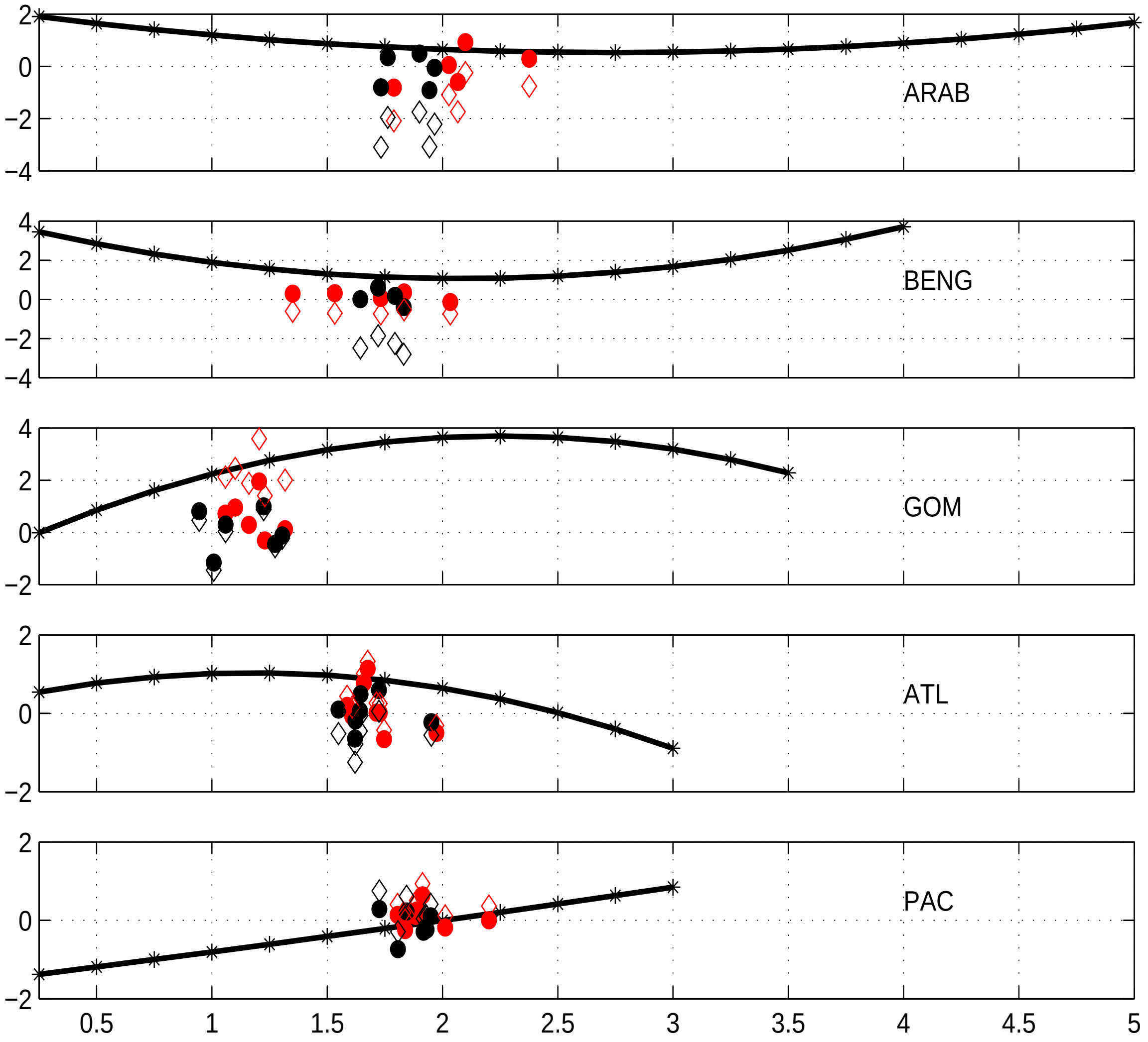

Figure 8: The difference between the corrections for descending and ascending tracks in each region (black lines with asterisks, i.e., the green curve minus the red curve from the second and third panels of Figure 6) as a function of SWH. The black and red diamonds represent the original mean bias of the ascending and descending tracks, respectively. The red and black circles represent the mean bias after the regional corrections have been applied. Each circle and diamond is plotted at the mean SWH of its respective track (calculated over all available cycles).

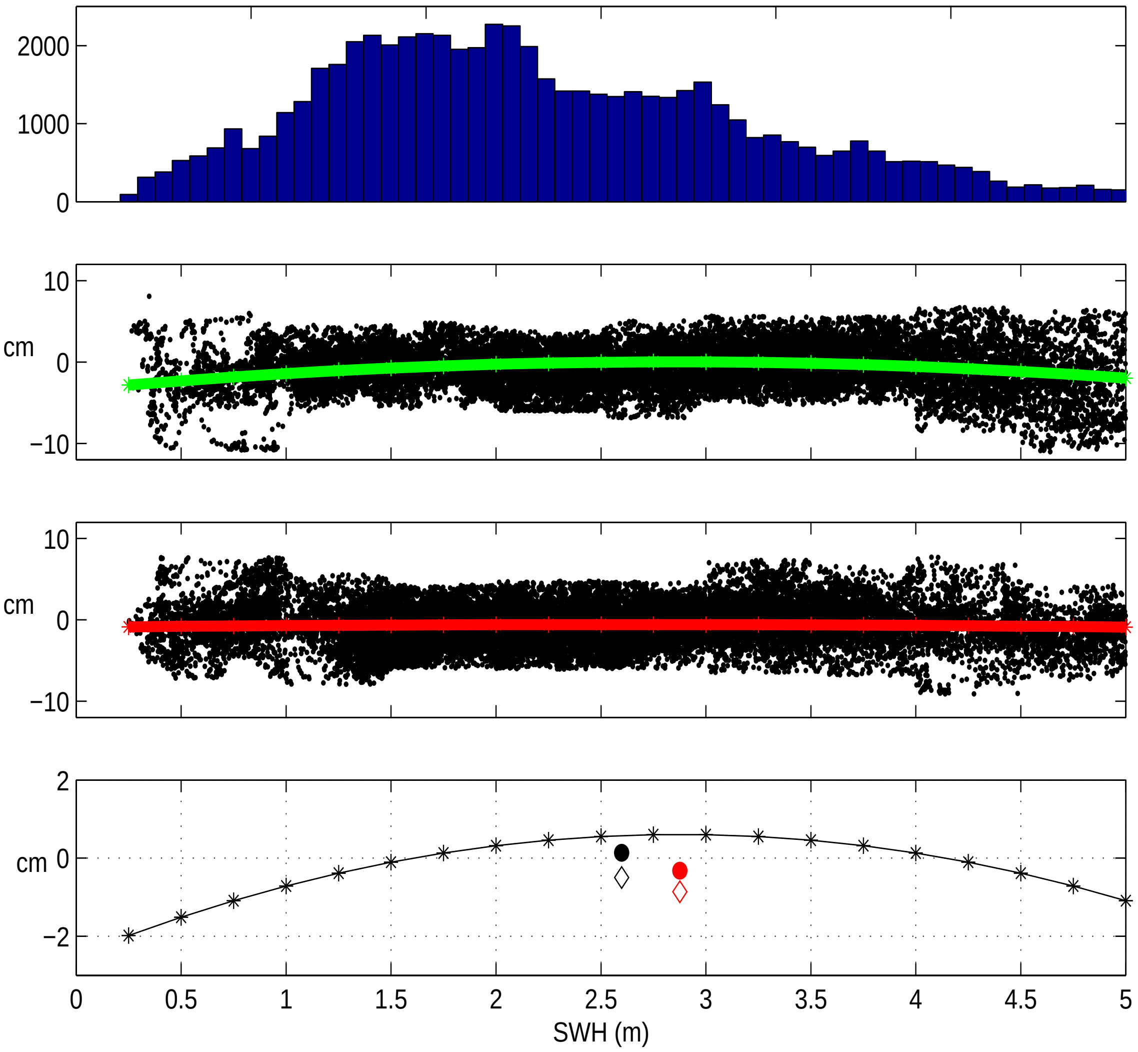

Figure 9: First panel: histogram of the SWH for track 8. Second panel: Bias as a function of SWH (black dots) for the descending portion of track 8. The green curve represents the least squares fit of a second order polynomial to the bias as a function of SWH. Third panel: Bias as a function of SWH (black dots) for the ascending portion of track 8. The red curve represents the least squares fit of a second order polynomial to the bias as a function of SWH. Fourth Panel: The difference between the correction for the descending and ascending portions of track 8 (black line with

asterisks) as a function of SWH. The black and red diamonds represent the original mean biases of the ascending and descending portions of track 8, respectively. The black and red circles represent the mean biases after application of the correction. The circle and diamond are plotted at the mean SWH of its respective portion of the track.