A Hybrid Method of Direct Estimation Sea State Bias Models

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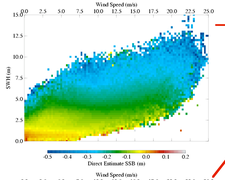
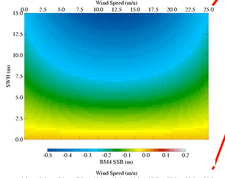
ABSTRACT The sea-state bias (SSB) correction to sea surface height is an important error source in satellite altimetry. We have developed a "hybrid" method for estimating SSB error models that blends the direct estimation approach of Vandemark, et al., 2002, with a smoothing and extrapolation by a best-fit parametric function. Our approach does not enforce any smoothness or parameterization in data-rich zones of the Wind Speed (U) and Wave Height (SWH) space: we retain the full detail of the directly estimated SSB correction there, in order to gain insight into the structure of the correction and reveal instrumental effects. In data poor zones of the U-SWH plane, where the direct method yields sparse and noisy estimates, our method smoothly extends the trend defined by the data rich region. This approach is readily implemented in a practical algorithm. We have applied it to ERS-1, ERS-2, TOPEX, Poseidon, Jason-1, and GFO. We observe remarkable similarities in the structure of the SSB models between the various altimeters, particularly those with a common heritage such as Jason-1 and Poseidon. We form sea surface height residuals relative to the GSFC00.1 mean sea surface, applying all standard geophysical corrections except SSB. These residuals are averaged in wind/wave bins to generate the directly estimated values. Inspection of these values shows the importance of proper data editing: we find that editing based on flag bits alone is often insufficient, but editing on Δ_{ssh} or Δ_{swh} effectively removes measurements contaminated by sea ice or rain cells. The structure of the SSB model is revealed after averaging data over intervals as short as a few months, so long as the bins contain large numbers of observations. We fit a low-order polynomial to the binned data, weighted by the standard errors in each bin. Our hybrid model is generated by blending this polynomial with the direct estimation values, using a weighting scheme based on the number of observations in each bin: well-sampled bins retain directly estimated values while the polynomial surface extends the analysis to regions of the wind/wave domain poorly resolved by the data.

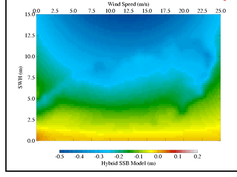
The Hybrid Model Formulation: A Jason-1 Case Study



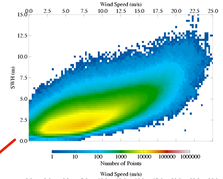
- **Form Direct Estimate of SSB from Height Residuals**
  - Apply all geophysical corrections *except* SSB
  - Compute height residuals relative to GSFC00.1 MSS
  - Average residuals in 0.25 m/s by 0.25 m wind/wave bins
  - Height residual field shows the true underlying SSB (note that height bias has been removed)

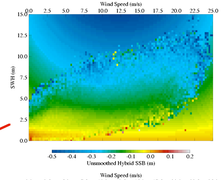


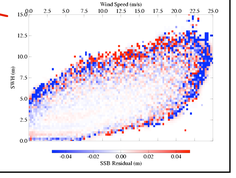
- **Evaluate Parametric Fit to Direct Estimates**
  - Estimate BM4 coefficients (see table below): SSB = [a0] + SWH ⋅ (a1 + a2 ⋅ U + a3 ⋅ U² + a4 ⋅ SWH)
  - Weight residuals by RMS and # points in bin when fitting
  - Bias coefficient, a0, is *not* restituted in final model
  - Polynomial function now satisfies SSB=0 when SWH=0



- **Blend Direct & Parametric Fields to Form Hybrid Model**
  - Remove BM4 from direct estimate to form SSB residuals
  - Assign zero residual value to bins with low number of points (ie fringe values set to parametric fit)
  - Smooth SSB residuals, weighting by RMS and # points
  - Blending unsmoothed residuals with BM4 shows 'fringe'
  - Final hybrid model is sum of BM4 and smoothed residuals
  - Direct & Hybrid model differences small in data rich regime



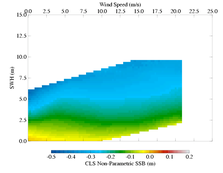




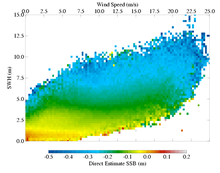
BM4 Coefficients for Recent Altimetric Data

BM4 Coeff	ERS-1	ERS-2	GFO	Jason-1	Poseidon	TOPEX-A	TOPEX-B
a0	0.063765	0.127760	0.118507	0.114762	0.030627	0.037366	0.048123
a1	-0.065759	-0.068381	-0.053259	-0.022284	-0.058005	-0.027380	-0.031656
a2	0.000513	0.001319	0.003090	0.000261	0.001496	0.002798	0.003355
a3	-0.002586	-0.002052	-0.00398	-0.002473	-0.001484	-0.003119	-0.002859
a4	0.000155	0.000117	0.000150	0.000101	0.000065	0.000123	0.000095

Direct Estimate vs. CLS Non-Parametric

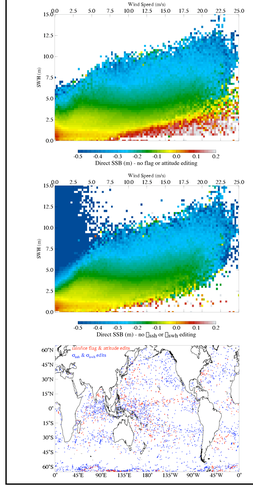


- Similar structure across data rich region
- Shift in distribution of ~ 1 m in SWH
- Differences due to SSB=0 @ SWH=0 and overall bias constraints



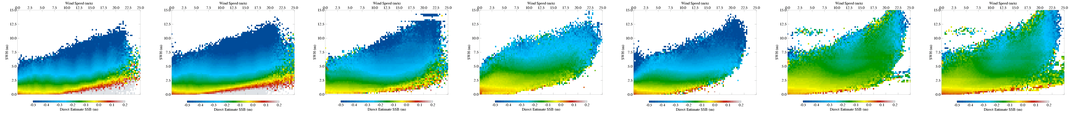
Editing Non-Ocean Radar Returns

- Altimeter/Radiometer quality flags with reasonable attitude limits remove high wind / low wave regime
- Limits on Δ_{ssh} and Δ_{swh} remove low wind / high wave regime
- Spatial distribution of edited values indicates combination of sea ice & rain
- For Jason-1: replace Δ_{ice} by Δ_{swh}

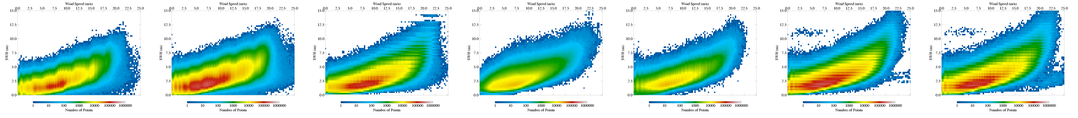


ERS-1 Phase C - OPR V6 / ERS-2 Cycles 0 - 42 / GFO Cycles 37 - 93 / Jason-1 Cycles 2 - 22 / Poseidon Cycles 11 - 307 / TOPEX Side-A Cycles 11 - 153 / TOPEX Side-B Cycles 236-346

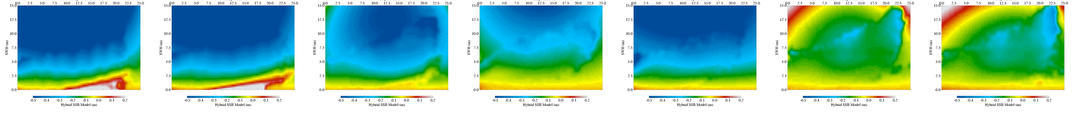
Direct Estimate



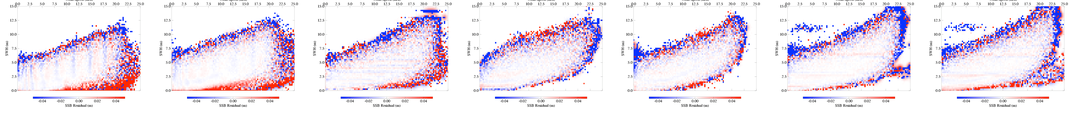
Number of Points



Hybrid Model



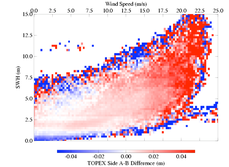
Direct - Hybrid Residuals



Hybrid Model Results for Modern Altimetry Missions

- All data sets edited similarly: deep sea (depth > 1000 m); +/- 65° latitude; Δ_{ssh}, Δ_{swh}, attitude limits; flag editing as equivalent as possible
- Quantization effects for some missions: SWH for GFO and TOPEX; wind 'ripples' in ERS-1 and to a lesser extent ERS-2
- Undeveloped sea regime (moderate to high wind / low wave) prominent in ERS-1 & -2 and somewhat in GFO; perhaps insufficient editing
- Standard editing criteria applied to TOPEX data fails to remove all outliers
- TOPEX Side-A (prior to degradation) and TOPEX Side-B models similar, except at high wind, but differ markedly from other altimeters

TOPEX Side A-B Differences



Conclusions and Outlook

- Direct estimate of SSB from relative sea heights can be done with limited amount of data, quickly, and spanning data-poor regions of wind/wave space.
- To avoid introduction of extra noise and to extend the model throughout wind/wave space, a hybrid technique was developed, taking the best of both parametric and non-parametric modeling.
- All altimeters, except TOPEX, show similar structure. There is no reason to believe that the TOPEX SSB is free of tracker bias.
- The advantage of the hybrid SSB model over established parametric models, in terms of crossover height differences, is small, except for the "recent" GFO and Jason-1 missions.
- Issues of quantization, both in wind and wave direction, requires more study.
- Due to the correlation between geographical location and wind/wave values, small changes may be seen in crossover statistics, even when significant changes are made to the SSB model. This makes the construction and validation of SSB models difficult.

RMS Crossover Differences (cm)

[Δt < 5 days; SWH < 8 m]

Satellite	BM3/BM4	Hybrid
ERS-1	7.22	7.15
ERS-2	6.48	6.48
GFO	9.11	8.96
Jason-1	6.46	6.25
Poseidon	6.40	6.40
TOPEX-A	6.17	6.14
TOPEX-B	5.68	5.62