RAIN AND ICE FLAGGING OF ENVISAT ALTIMETER AND MWR DATA

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ABSTRACT

Altimetry range, wave height, and wind speed measurements are often corrupted by two effects over the ocean: rain and sea-ice. Radiometer measurements, which provide the altimetric wet troposphere correction, are similarly corrupted by the presence of rain or sea-ice in the instrument's footprint. To avoid contamination of sea surface height measurements, it is imperative that data influenced by either of these effects be edited out. The waveform "peakiness" parameter, available on the GDR data sets is effective at identifying sea-ice returns when stringent thresholds are applied. The mean relationship between backscatter (σ^0) at the two altimeter frequencies allows one to flag data impacted by both rain and sea-ice. We present here a new method for flagging rain or sea-ice contaminated data, based on two-dimensional histograms of σ^0.

1. INTRODUCTION

The three fundamental measurements from radar altimetry: range, significant wave height (SWH), and wind speed, are computed from the radar's return echo (waveform) assuming incoherent scattering by capillary waves on the ocean surface [1]. In the presence of rain the altimetric signal is attenuated and the waveform's shape is distorted, resulting in errors in all three parameters. Similarly, radar returns from floating sea-ice do not resemble normal ocean echoes and lead to erroneous estimates of range, SWH and wind speed. We seek here to develop an algorithm based on backscatter measurements (σ^0) from the dual-frequency RA-2 altimeter on Envisat which will eliminate both rain and sea-ice contaminated data.

Previous studies on the impact of rain on altimetry data [2], [3] suggested that the difference in signal attenuation at the two radar frequencies (Ku- and C-band for TOPEX and Jason-1; Ku- and S-band for Envisat) could be exploited for rain detection and editing. The mean relationship between the backscatter at the two frequencies, σ^0_{Ku} and σ^0_S (or σ^0_C), was computed as a function of backscatter and a rain-flagging edit criterion was based on a threshold below the mean relationship. In general, the higher frequency Ku-band backscatter is attenuated more than the C- or S-band data in the presence of rain. Hence a threshold of –0.5 dB [2] or two standard deviations below the mean relationship [3] indicates data likely to be contaminated by rain. These relationships are the basis of setting a rain-flag on the TOPEX and Jason altimetry products.

Envisat altimetry data corrupted by sea-ice are routinely flagged based on the waveform's "peakiness". Peakiness is calculated from the ratio of the maximum power found in any of the waveform bins divided by the total power in all 128 waveform bins, Eq. 1. The factor of 82 reflects the number of bins to the right of the RA-2 track point. The nominal track point is 18 bins to the left of the middle 64th bin [M. Roca & S. Laxon, pers. comm.]. This relationship is analogous to the algorithm originally developed for ERS-1 [4].

$$Peakiness = \frac{82 \times \max(P_i)_{i=0}^{127}}{\sum_{i=0}^{127} P_i} \tag{1}$$

Normal ocean returns are expected to have peakiness values in the range of 1.5-1.8. Higher peakiness values from specular returns are typically found in sea-ice and lower values arise from data over land and other non-ocean surfaces. This edit criterion is useful for flagging sea-ice, though it does detect some data associated with rainy tropical regions.

2. THE 2-D BACKSCATTER HISTOGRAM

The methodology derived here relies on the full distribution of backscatter at the two altimeter frequencies, rather than on the mean relationship between them. No assumption is made that the Ku-band is attenuated more than the S-band, as one would expect in true rain conditions. Our aim is to flag *all* suspicious data whose σ^0_{Ku}/σ^0_S relationship have a low probability, i.e. they are outliers.

2.1 Creating the rain-free distribution

As in previous studies, we want to create a "rain-free" distribution using data that are stringently screened

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before deriving the backscatter relationship. Data from Envisat cycles 15-29 (9 April 2003 to 31 July 2004) were analyzed for this study, and 1-second averaged records passing all of the following tests were included:

50°S < Latitude < 50°N
1.5 < Peakiness < 1.8
Attitude < 0.2° (based on waveforms)
Liquid Water Content < 0.6 kg/m^3 (from radiometer)
GDR flags: nominal (ignoring rain-flag); ocean only

These edit criteria eliminate the majority of records affected by sea ice (the latitude and peakiness limits) as well as those likely to be influenced by rain. Note that we ignore the original rain-flag present in the GDRs in order to create our new rain-free distribution.

The two-dimensional scattergram of σ^0_S vs. σ^0_{Ku} for all data passing these tests for a single 35-day cycle is shown in Fig. 1. The encircled population of points at high σ^0_S is due to the so-called "S-band anomalies".

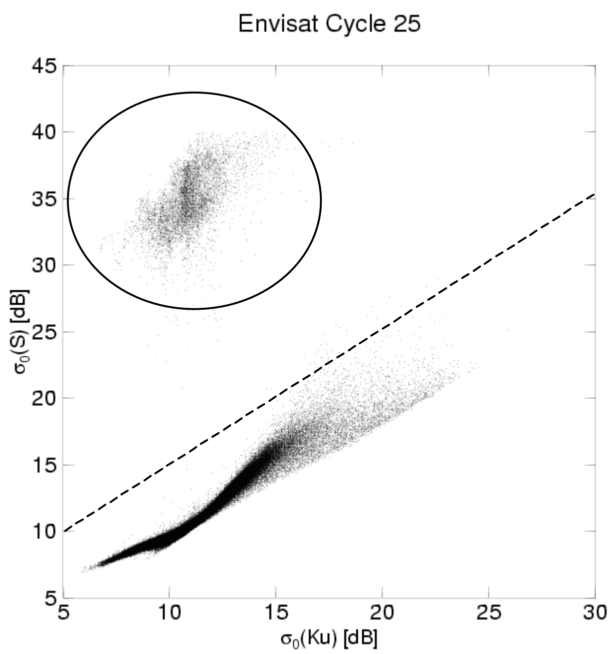

Fig. 1 Scattergram of Ku and S-band backscatter

An as yet unresolved hardware issue with the RA-2 altimeter, affecting roughly 5% of the data, causes abnormal S-band waveforms which continuously accumulate energy, rather than properly resetting between 18 Hz samples. An example of a typical S-band anomaly is shown in Fig. 2. A descending pass from Cycle 11 traverses S. America (going from right to left in the figure) and the S-band backscatter values jump above 20 dB relative to the Ku-band values. The decaying oscillatory nature of this phenomenon is typical. It is caused by the power values in each waveform bin overflowing the 16-bit integer limit of on-board storage, and as time goes on the overflow in different waveform bins gets out of phase and destructively interfere.

The end result is the unrealistically high values of S-band backscatter seen in Fig. 1. Fortunately these data are far enough removed from the true relationship to be easily edited: we reject any data where σ^0_S - σ^0_{Ku} > 5 dB, *i.e.* any data above the dashed line in Fig. 1.

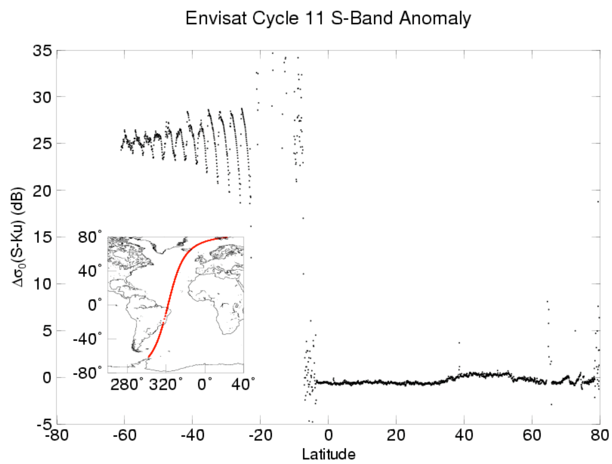

Fig. 2. Example S-band anomaly

2.2 Creating the 2-D histogram

To create a two-dimensional cumulative histogram of the backscatter relationship illustrated in Fig. 1 the following steps are performed:

1. Remove the liquid-water atmospheric attenuation correction supplied by the radiometer from both the σ^0_S and σ^0_{Ku} values.

2. Bin the σ^0 values into 0.05 dB bins for both Ku- and S-band, over the range of 0-40 dB.

3. Rank the bins according to the number of points falling in each bin, from bins with zero points to the bin with the maximum number of points:

$$j(i): C_j > C_{j-1} \quad \forall\; i, j = 1, M \qquad (2)$$

where the index i denotes the unsorted array of bins, j denotes the index for the array sorted by counts per bin C, and M is the total number of bins: $(40/0.05)^2$=640,000.

4. Assign a cumulative percentile value to each bin:

$$S_j = \frac{100 \times \sum_{i=1}^{j} C_i}{N} \quad \forall\ j = 1, M \qquad (3)$$

where S_j is the cumulative sum of counts for the current bin j and all bins with a lower count value, expressed as a percentage of the total number of measurements N from all bins. The resulting values of S range from 0 (bins with no data) to S_M = 100% (the bin holding the largest number of points). The range of percentile values will always be 0-100%, regardless of the number of records going into the analysis. The two-dimensional cumulative σ^0 histogram, computed for Envisat cycles 15-29, is presented in Fig. 3.

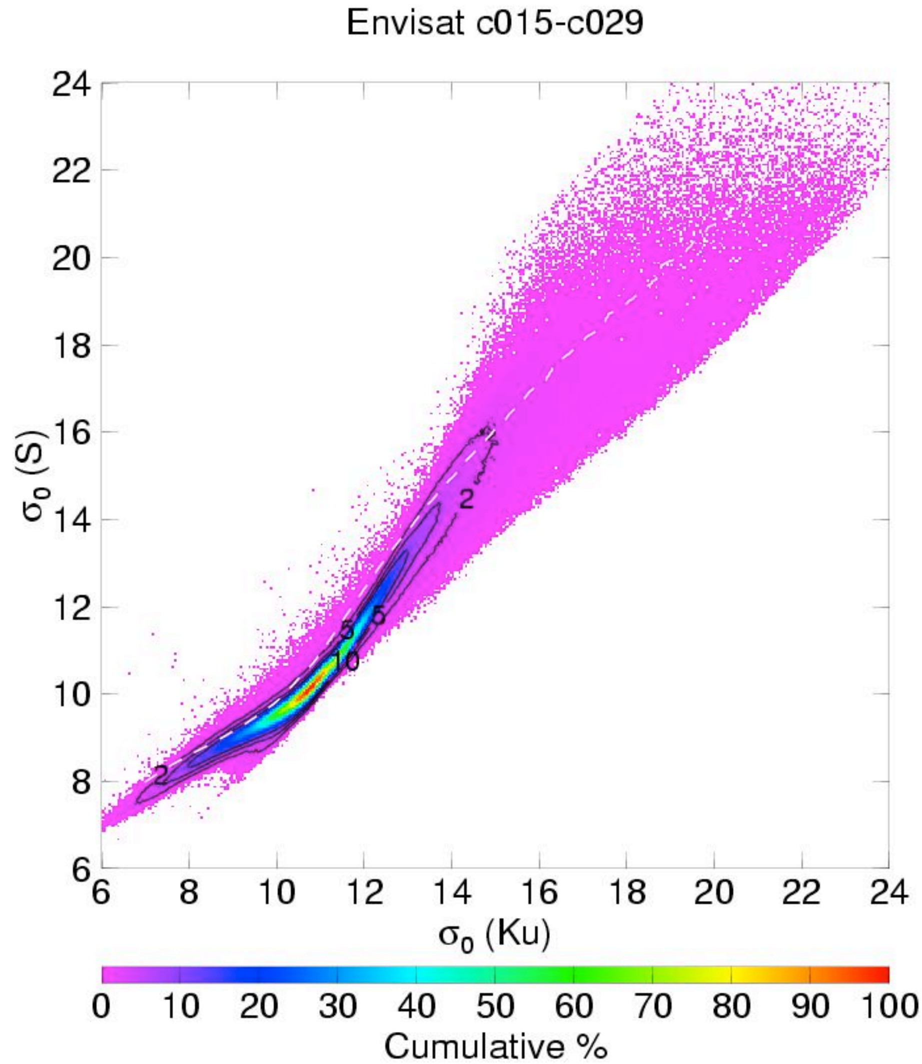

Fig. 3. Cumulative 2-D histogram of $\boldsymbol{\sigma^0}$ for cycles 15-29
Contours of the 2%, 5% and 10% percentile level are emphasized

A subset of the full grid (0-40 dB) is shown in Fig. 3 to focus on the shape of the histogram in the region where the majority of the data reside. Each grid point is color coded by its cumulative percentile value, from very small non-zero values in purple to the 100% bin, in red at σ^0_{Ku}=10.775, σ^0_S=10.125 dB. In the data-rich region the contours of percentile values, in black, are closed and rise smoothly towards the maximum. The white-dashed line illustrates the current rain-flag algorithm used for Envisat, based on a 0.5 dB offset from the mean relationship between backscatter values.

One of the advantages of the 2-D histogram method is that a continuous edit criterion is achieved, rather than a binary on/off flag. The user specifies a percentile cutoff value, which is roughly the amount of *additional* data that will be edited above and beyond the normal editing applied to achieve this relationship. For example: using a 2% cutoff (which lies close to the traditional edit flag shown in Fig. 3) a record whose [σ^0_{Ku},σ^0_S] values fall in a bin outside the 2% contour will be flagged as bad. Unlike the traditional method, which only flags data where the Ku-band is attenuated relative to S-band, our histogram technique will flag all outliers lying outside the chosen percentile cutoff level.

Since the percentile contours are closed, choosing a cutoff value naturally implies a limit on the ranges of acceptable σ^0_{Ku} and σ^0_S values. A 2% cutoff limits the acceptable backscatter values to a range of about [6.8-15.1 dB, 7.5-16.1 dB] in Ku- and S-band, respectively.

3. USING THE HISTOGRAM ICE/RAIN FLAG

The cumulative histogram illustrated in Fig. 3 is stored as a lookup table. As GDR data records are processed, the values of σ^0_{Ku} and σ^0_S are used to determine the proper location in the lookup table, which supplies the histogram percentile value for that record. If the percentile value is lower than the user's specified cutoff (*e.g.* 2%) then that record is flagged as bad.

Fig. 4 and Fig. 5 compare the geographical distribution of points flagged by the original rain flag on the GDR with those flagged by our new histogram flag using a 2% cutoff value. In general the locations of flagged values are similar and are associated with regions of high precipitation in the Indian Ocean, along the equatorial ITCZ (Inter-Tropical Convergence Zone), and in the South-Pacific Convergence Zone extending on a line southeast from Indonesia to S. America. Both flags pick up sea-ice contaminated data at the edges of the polar regions which were not already removed by the peakiness limit of 1.5-1.8.

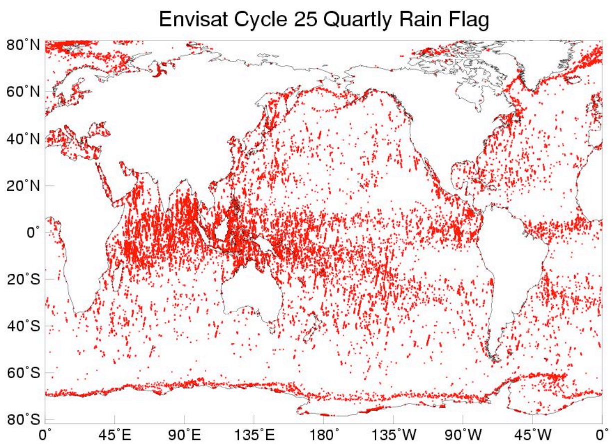

Fig. 4. Points flagged by original rain flag - Cycle 25

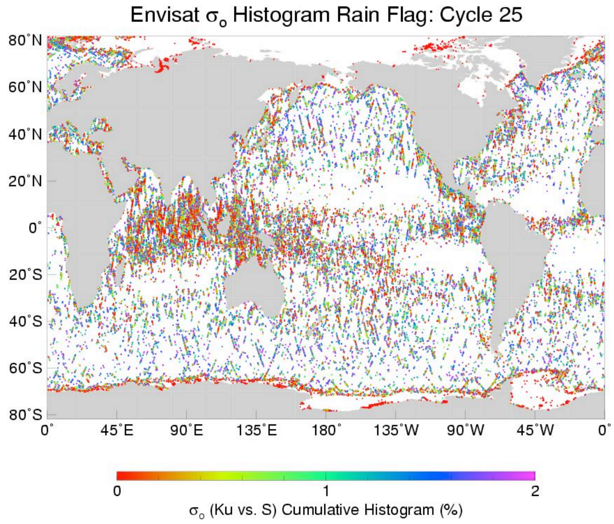

Fig. 5. Points flagged by 2% histogram flag - Cycle 25

The data flagged in the subtropics are likely to exhibit "reverse-attenuation" where S-band backscatter is less than that at Ku-band. This phenomenon was examined in [2], but the traditional rain-flag, expecting attenuation of Ku relative to S-band, will not remove these data. Finally, some of the outliers seen in Fig. 5 are due to "σ^0 blooms" where very high values in backscatter, in either Ku or S-band, place them outside the limits associated with the 2% cutoff, as discussed earlier. These blooms are most likely associated with very low wind conditions or surface slicks, which cause unusually high backscatter returns [5].

3.1 Verification of the Ice/Rain Flag

Independent estimates of rain-rate distributions can be used to verify the spatial patterns observed in Fig. 4 and Fig. **5**. The SSM/I passive microwave radiometer on board the Defense Meteorological Satellite Program (DMSP) spacecraft provide global monthly rain-rate estimates. Fig. 6 presents the March 2004 monthly average rain-rate from the F13 DMSP satellite, which corresponds to the time period of the rain flagging in Cycle 25 shown above. The regions of high precipitation along the ITCZ, SPCZ and Indian Ocean confirm the validity of the rain flags. The extremely dry regions just west of North and South America are also evident. The flagging seems to be picking up significantly more data in the Indian Ocean compared to the rain-rate distribution there. This could be due to low-wind (high σ^0) conditions in this region, rather than true rain events.

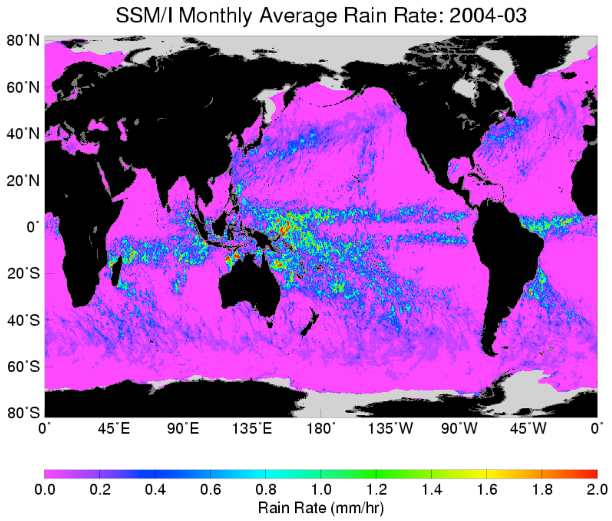

Fig. 6. SSM/I Rain-rate for March, 2004

The efficacy of the histogram rain flag can be assessed by looking at the reduction in variability of both range and significant wave height. Fig. 7 shows the distribution of the 1-second averaged sea surface height (SSH) variability, σ_{SSH}, as a function of the histogram flag cutoff value. The region of highest data density is around 8-10 cm, with a large increase in outliers of σ_{SSH} below 5%. This confirms that a choice in the neighborhood of 2% will reduce the number of points with high σ_{SSH}, which is often used as an edit criterion itself. Similarly, Fig. 8 shows the distribution of wave height variability, σ_{SWH}, vs. histogram flag value. Again the region where the most outliers occur is found below a 5% cutoff, with typical values of σ_{SWH} around 50 cm.

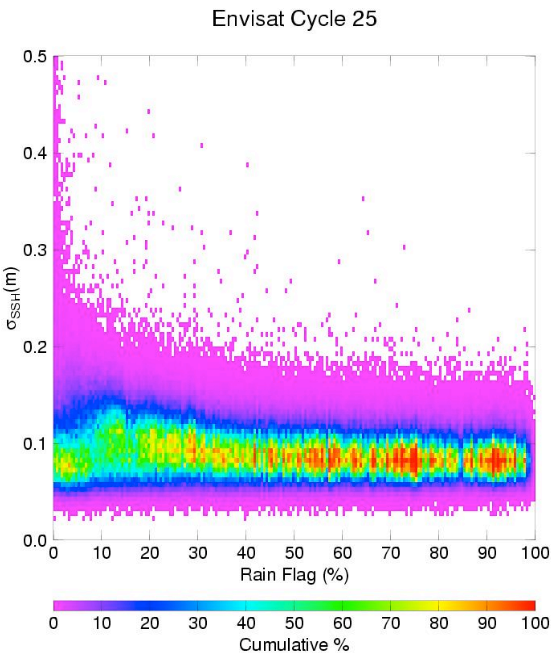

Fig. 7. SSH variability as a function of rain flag cutoff

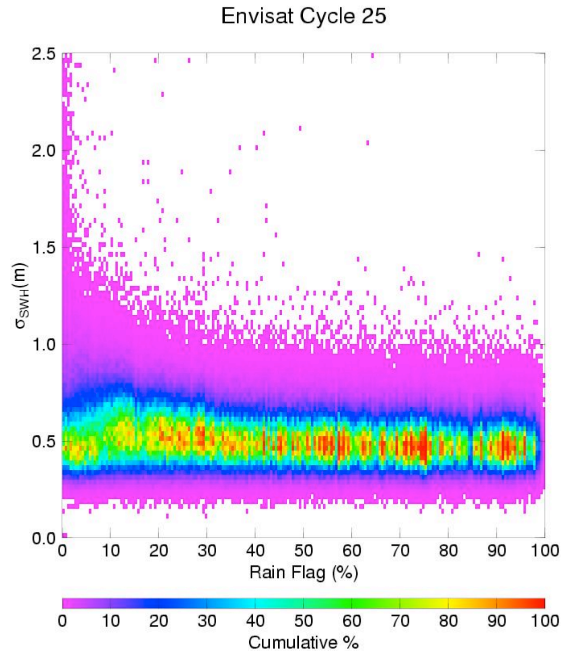

Fig. 8. SWH variability as a function of rain flag cutoff

3.2 Improved Sea Surface Height Statistics

If the histogram flag is effectively removing suspect data, we should observe a decrease in sea surface height variability in regions affected by rain or sea-ice. The geographical distribution of SSH variability for cycles 15-29, is shown in Fig. 9, after applying a 2% edit criterion. For this and subsequent plots the data were binned into 2°x2° regions before computing the statistics. The height variability seen in Fig. 9 is as we would expect from a clean altimetric dataset, with RMS values exceeding 32 cm in the major oceanic current systems, and variability below the 5 cm level in the quiescent regions of the ocean such as the subtropical S. Pacific. This is an indication of the overall high quality of the Envisat RA-2 data, since no explicit orbit-error removal has been applied to the data.

The difference in SSH variability between the case of 2% editing vs. no editing with the rain flag (*i.e.* a 0% cutoff) is shown in Fig. 10. Regions in red indicate a reduction in RMS variability of up to 2 cm. Regions in blue, primarily limited to the Arctic sea-ice edge, indicate increased SSH variability as a result of editing. As expected, the improvement in SSH variability statistics occurs along the ITCZ and SPCZ, as well as along the edge of the Antarctic ice edge.

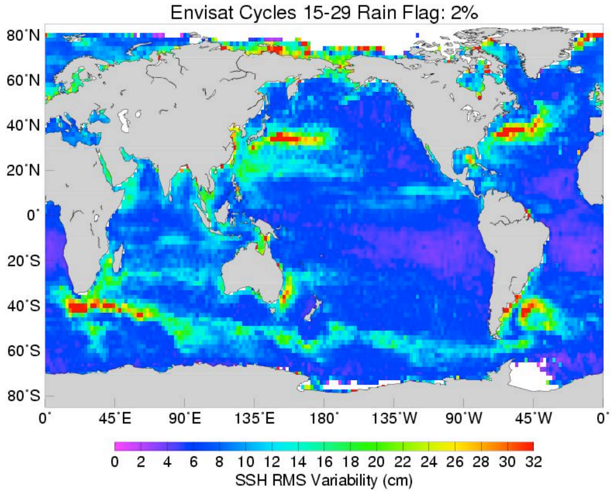

Fig. 9. SSH Variability after 2% rain flag editing

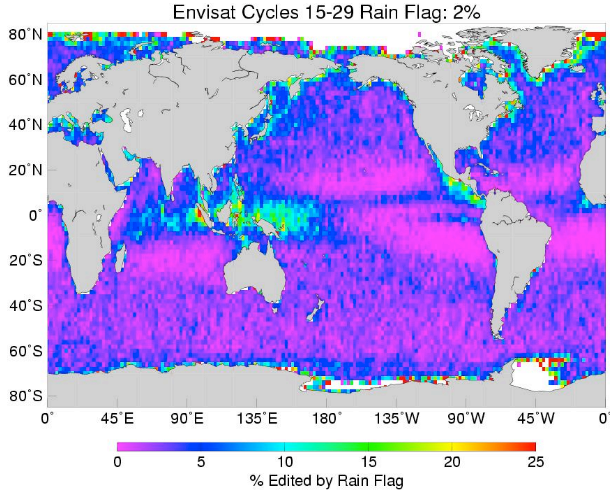

Fig. 11. Percentage of data edited in 2°x2° regions: 2%

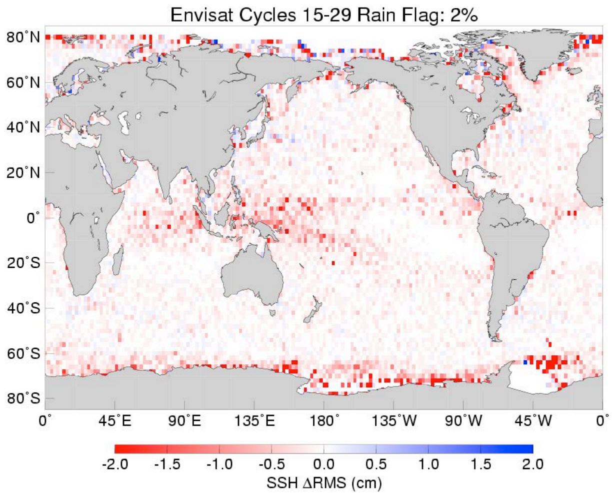

Fig. 10. Reduction in SSH variability: 2% editing

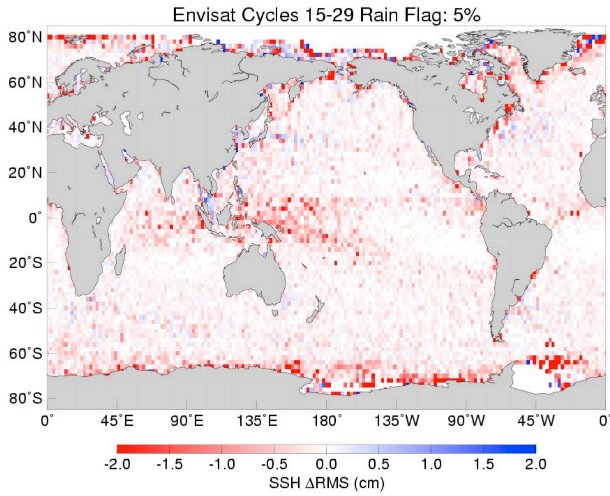

Fig. 12. Reduction in SSH variability: 5% editing

One concern about the histogram flag editing is that the implicit limiting of σ^0 may remove excessive amounts of data in low wind (high σ^0) regions. To assess this we generate statistics on the percent of data removed in each 2° square with a 2% cutoff limit, Fig. 11. The amount of data edited out (above and beyond the routine editing already applied) is highest in the region around Indonesia and the Indian Ocean, reaching nearly 20% in some locations. However, there is no indication that the "Doldrums", with low mean wind speeds, have excessive amounts of data removed. This gives us confidence that data being impacted by rain are properly edited with this technique.

Fig. 12 and Fig. 13 provide similar statistics on the reduction in sea surface height variability and percent of data edited, but now using an edit cutoff value of 5%. Fig. 14 and Fig. 15 show the results after applying a 10% cutoff value.

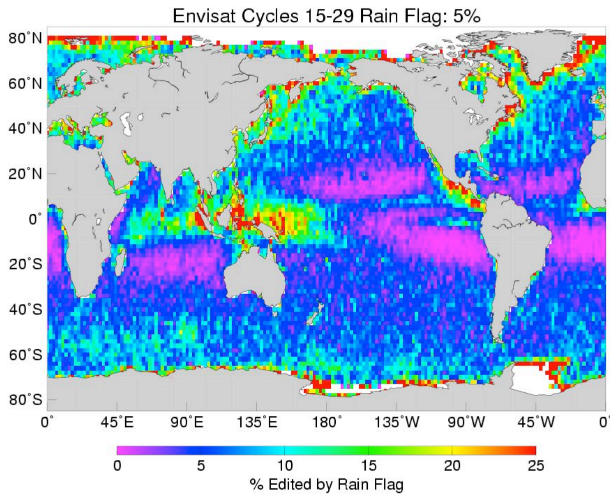

Fig. 13. Percentage of data edited in 2°x2° regions: 5%

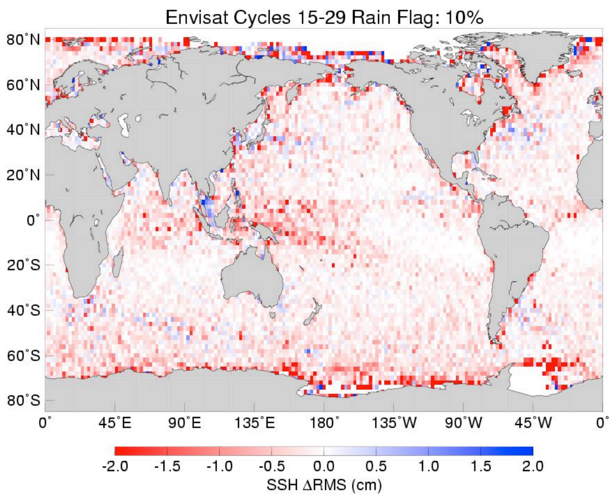

Fig. 14. Reduction in SSH variability: 10% editing

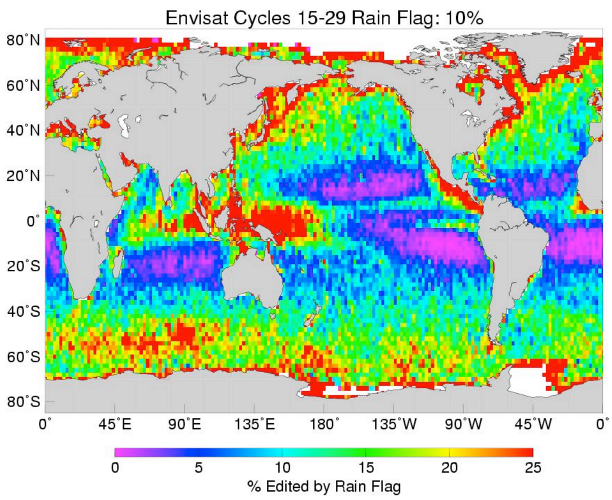

Fig. 15. Percentage of data edited in 2°x2° regions: 10%

It is apparent from this series of plots that an edit criterion of 10% or more removes excessive amounts of data, and that regions where RMS height variability actually increases (shown in blue, indicating degraded performance) become more common. As our previous results showed, a good compromise between data loss and improvement in SSH statistics can be achieved in with a cutoff of about 2-5%.

The globally averaged statistics of SSH variability and amount of data edited, as a function of the imposed edit flag value, are presented in Table 1. Although the RMS values for height variability continue to decrease with more stringent editing, the largest reduction occurs within the first 1-2%. The amount of data lost, however, increases directly as the edit criterion is raised. The actual amount of data removed globally is somewhat larger than the flag value itself, most likely from sea-ice affected regions above ±50° latitude, the limit used to construct the 2-D histogram on which the flag is based.

Table 1. SSH Variability and Percent of Data Edited vs. Edit Flag Cutoff Value

Edit Criterion	Global RMS SSH (cm)	% Edited by Ice/Rain Flag
0 %	10.05	0 %
1 %	9.94	1.56 %
2 %	9.92	2.79 %
5 %	9.85	6.59 %
10 %	9.75	12.79 %

4. CONCLUSIONS

We have developed a new method to flag altimetry data that are corrupted by rain and sea-ice. It is similar to traditional methods, being based on the relationship between backscatter at the two radar frequencies. Unlike previous methods, however, the editing is not restricted to the case of attenuation of the primary Ku-band backscatter relative to the secondary S-band backscatter. A cumulative two-dimensional histogram is created in the primary vs. secondary backscatter space, providing a continuous ice/rain flag based on percentile cutoff values from the data distribution.

A 2% histogram flag cutoff value agrees well with the traditional rain flag for the case of Ku-band attenuation while additionally removing data with “reverse attenuation” where the S-band is attenuated more than Ku-band. Given the closed contours of the histogram percentile values, an implicit limit on backscatter is applied by our method, thereby removing data affected by “σ^0 blooms” at either frequency.

The relationship between other edit criteria, namely the 1-second averaged sea surface height and significant wave height standard deviations, shows that a 2-5% edit criterion removes the majority of outliers in those parameters. A reduction in sea surface height variability of up to 2 cm is achieved in regions adversely affected by rain, along the ITCZ and SPCZ convergence zones. Applying more stringent edit criteria removes excessive amounts of data without greatly improving the global statistics of sea surface height variability.

This method is appropriate for removing suspect data to provide the best estimates of sea level for long-term climate studies. It is less well suited for rain studies *per se*, as it removes data affected by a variety of causes, not just rain. Nonetheless, the distribution of flagged data in rainy regions agrees well with independent estimates from the SSM/I sensor.

Finally, the issue of S-band anomalies remains, though a 5 dB cutoff in the difference between Ku and S-band σ^0 can effectively remove the data. Other studies [6] have shown that ~5% of the data are impacted by this hardware anomaly. We are investigating methods that undo the linear accumulation of power to restore the original S-band waveforms, allowing the majority of the over-ocean data to be recovered..

5. REFERENCES

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6. ACKNOWLEDGEMENT AND DISCLAIMER

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