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Assigning a Rain Flag to NSCAT Observations Using SSM/I Rain Maps

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1. Introduction

This Technical Memorandum discusses the problem of assigning a rain flag to NSCAT observations using rain maps derived from the microwave radiometer SSM/I. The major problem in assigning a rain flag is the fact that SSM/I and NSCAT fly on different satellites, and hence simultaneous observations are not available. SSM/I is aboard the DMSP polar orbiters, and NSCAT will be aboard the Japanese ADEOS-1. The lack of simultaneous observations is a severe limitation on any rain flagging technique because rain fields are highly variable in both space and time. However, since there is no microwave radiometer on ADEOS-1, using SSM/I rain maps is one of the few remaining options for NSCAT.

Parenthetically, there is also the possibility of using the ADEOS-1 OCTS infrared observations to measure the cloud top temperatures, thereby inferring the location of rain cells. The drawback to using OCTS is that there is not a direct relationship between cloud top temperatures and rain. Also, a considerable investment of time and resources would be required to do the necessary OCTS-NSCAT data merging and collocation, and a reliable OCTS rain algorithm would need to be developed. However, considering the limitations of using SSM/I rain maps, which will be discussed herein, the OCTS option should possibly be reconsidered as a future research activity.

To investigate the feasibility of using SSM/I for NSCAT rain flagging, we simulate the rain flagging process by using two SSM/I's: one flying on the DMSP F10 satellite and the other flying on the F11 satellite. In the simulations, the F11 rain observations are used to flag the F10 observations, i.e., the F10 SSM/I plays the role of NSCAT. Since both SSM/I's can detect rain, the simulations show how well various rain flagging techniques work.

We use SSM/I observations taken during the year 1992, when the descending node times for F10 and F11 are 8:30 AM and 5:00 AM respectively. Thus there is a 3.5 hour time difference between F10 and F11 observations. When ADEOS-1 is launched in August 1996, the SSM/I on F13 will still be in operation (unless some unforeseen failure occurs). The descending node time for ADEOS-1 is 10:30 AM, and the descending node time for F13 is 6:00 AM. Thus the observation time difference for F10 and F11 is very similar to that for NSCAT and F13. This similarity gives credibility to the simulation.

The SSM/I all-weather ocean algorithm developed by *Wentz* [1995] and *Wentz and Spencer* [1996] is used to compute rain rate from the SSM/I observations. We consider this algorithm to be the state-of-the-art. An analysis of the retrieved rain rates on a multi-year global basis shows that 86% of the SSM/I observations are free of rain, 8% of the observations contain very light rain that is less than 0.2 mm/hr (when averaged over 30 km), and 6% of the observations have a rain rate greater than 0.2 mm/hr. For the most part, we expect that the 'very-light-rain' observations will not significantly degrade the NSCAT wind retrieval and hence should not be flagged as rain. In fact, some of the 'very-light-rain' observations are actually heavy, non-raining clouds. Thus for the purpose of flagging NSCAT observations, we classify an SSM/I observation as rain only when the retrieved rain rate is greater than 0.2 mm/hr.

We consider four time scales: 'daily', 'weekly', monthly, and monthly climate. For the daily time scale, we use the F11 SSM/I morning (evening) orbit segments to flag the F10 SSM/I morning (evening) observations. Thus the daily time scale is actually of the order of 3 to 4 hours. For the weekly time scale, a 6-day global map (a short week) of F11 SSM/I rain observations is first compiled, and then this map is used to flag the F10 observations for that week. Similarly, for the monthly time scale, a monthly global map of F11 SSM/I rain observations is first compiled, and then this map is used to flag the F10 observations for that month. The monthly climate case is the same as the monthly case, except that the rain flagging is based on a monthly rain map that is an average of 4 years (1992 to 1995).

The same spatial scale is used for all cases. This spatial scale is 1° in latitude by 1° in longitude. That is to say, the daily, weekly, monthly, and monthly climate rain maps are all at a 1° latitude-longitude resolution. For each 1° cell, the rain maps give the percentage of SSM/I observations that detected rain for the specified time period. The 1° spatial scale, which is about 100 km, corresponds to a time scale of about 3 hours. Thus the spatial scale is commensurate with the finest time scale being used.

2. Rain Flagging on a Daily Basis

The advantage of rain flagging on a daily basis is that the time difference between the SSM/I and NSCAT observations is as small as possible. Thus the error due to the temporal variability of rain is minimized. The major disadvantage is that there will be large portions of the NSCAT swath for which no rain flag is available. We will first discuss the problem of 'holes' (i.e., missing data) in the daily rain maps and then discuss how well the rain flagging can be done in those regions where the rain flag is available.

The problem of holes in the daily rain maps is clearly shown in Figures 1 through 5. These figures show the overlap of F10 and F11 SSM/I observations for the morning orbit segments and for the evening orbit segments. The five figures correspond to January 1 through 5, 1992, respectively. In these figures, the gray areas shows ocean regions where there is no F10-F11 overlap. For some days, such as January 2, the overlap is very good, with the F10 SSM/I flying over the same ocean areas that were viewed by F11 3.5 hours earlier. However for other days, such as January 5, the F10 and F11 swaths are 'out of phase' and the overlap area is very small. In these non-overlap gray areas, no rain flag is available. Note that the largest gray areas in these figures are due to gaps in the F10 and F11 data streams.

Possibly, one could interpolate in time and space to assign a rain flag to these areas. We did not investigate this alternative but note that a time-space interpolation will degrade the time scale for the rain flag. We expect the results from such interpolations will lie somewhere between the results for the daily time scale and those for the weekly time scale.

This effect of the F10 and F11 swaths phasing in and out is easily explained by a simple model. For an Earth orbiting satellite, the longitude of the ascending node for the N^{th} orbit is

$$\phi_N = \phi_1 - 0.004167\,(N - 1)\,P \qquad (1)$$

where 0.004167 degrees/second is the Earth's rotation rate, ϕ_1 is the longitude (degrees) of the ascending node for the first orbit, and P is the orbital period (seconds). Let the F10 and F11 swaths begin with perfect overlap, i.e., ϕ_1 is the same for both satellites. Then after N orbits, the difference in between the F11 and F10 longitudes at the equator crossing is

$$\Delta\phi = 0.004167(N - 1)(P_{F11} - P_{F10}) \qquad (2)$$

where P_{F10} and P_{F11} are the orbital periods for F10 and F11, respectively. In January 1992, P_{F10} = 6039 sec and P_{F11} = 6117 sec. Thus the swath phasing varies as

$$\Delta\phi = 0.325(N - 1) \tag{3}$$

There are about 14 orbits each day, and hence each day at the equator the F10 swath moves about 500 km relative to the F11 swath. It is easy to show that the cycle time Λ of the swath phasing is given by

$$\Lambda = \frac{P_{10}P_{11}}{P_{11} - P_{10}} \tag{4}$$

For the F10 and F11 SSM/I's, Λ = 5.5 days. Thus every 5 to 6 days, the F10 and F11 swaths go through one complete cycle of being nearly coincident to being interlaced with little overlap. The F13 SSM/I period is about the same as F11, and the ADEOS-1 period is about 6060 sec. Thus for F13 and NSCAT, the swath phasing cycle Λ is about 7.5 days.

We now turn to those regions where there is overlap and assess the performance of the daily rain flag. For each 1° cell, we compute a rain flag based on the number of F11 rain observations for the cell. For example, for the daily swath maps (i.e., Figure 1 through 5) there are typically 4 to 6 SSM/I observations for each 1° cell. We compute the percent of these observations for which rain is detected. Figures 1 through 6 shows this percentage of rain observations, with the color purple indicating 0% and red indicating 100%. We denote this percentage by ρ and call it the 'rain likelihood indicator' (RLI).

A value for ρ is computed for each daily 1° cell observed by F11. A rain flag I is then assigned to each cell based on the value of ρ:

$$I = 0 \quad \text{when } \rho \le \rho' \tag{5a}$$

$$I = 1 \quad \text{when } \rho > \rho' \tag{5b}$$

where ρ′ is some RLI threshold value. As ρ′ increases, the number of cells flagged as rain decreases. For the extreme case of ρ′ = 0%, all cells which contain at least one rain observation are assigned a rain flag. For the other extreme case of ρ′ = 99.9%, only those cells for which all observations are rain (i.e., ρ = 100%) are assigned a rain flag. (Note that ρ′ = 100% is a degenerate case in which no rain flag is assigned, and hence we limit ρ′ to a maximum value of 99.9%.)

The rain flag I derived from the F11 observations is then applied to the F10 observations. For example, if I = 1 for a particular 1° cell on the morning of January 1, 1992, then all F10 observations falling within that cell on the morning of January 1, 1992, are assigned a rain flag. For the period from January 1 through February 29, 1992, we computed the following statistics for the F10-F11 overlap regions:

$$F = 100\,(N_3/N_1) \tag{6}$$

$$S = 100\,(N_4/N_2) \tag{7}$$

N_1 = total number of F10 observations that detected no rain
N_2 = total number of F10 observations that detected rain
N_3 = total number of F10 observations that detected no rain but were flagged as rain
N_4 = total number of F10 observations that detected rain and were flagged as rain

The value F is the percent of no-rain observations that were incorrectly flagged as rain, and the value S is the percent of rain observations that were correctly flagged as rain. Thus, F is a measured of False alarms, and S is a measure of the Skill of the rain flagging.

Figure 6 shows the false alarm rate F plotted versus the skill factor S. The purple curve at the bottom shows the results of using the daily F11 rain map to flag the F10 observations. This curve is generated by varying the parameter ρ' from 0% to 99.9%. The left end of the curve corresponds to ρ' = 99.9%, for which a rain flag is assigned only when all observations in the 1° cell are rain. The right end of the curve corresponds to ρ' = 0%, for which a rain flag is assigned when at least one observation in the 1° cell is rain. For the most aggressive rain flagging (i.e., ρ' = 0%), 62% of the F10 rain observations are being correctly flagged, while 12% of the F10 no-rain observations are being misclassified as rain. For the most timid rain flagging (i.e., ρ' = 99.9%), only 14% of the rain observations are being correctly flagged, but the false alarm rate is very low, being about 1%. Thus the F versus S curve provides the means to do a tradeoff analysis between correctly flagging rain observations and incorrectly flagging no-rain observations.

The other curves in Figure 6 show the results for different time scales. All these curves are generated by varying the parameter ρ' from 0% to 99.9%. A comparison of the curves shows the effect of the time scale on the rain flagging. Clearly, the shorter time scales provide better rain flagging. The results for the weekly, monthly, and monthly climate time scales will now be discussed.

3. Rain Flagging on a Weekly Basis

The problem of holes in the daily rain maps is remedied when the observations are averaged over a week (actually 6 days). Figure 7 shows two weekly rain maps for January 1 through 6, 1992, and for January 7 through 12, 1992. The figure shows the percent of F11 SSM/I observations that detected rain over the 6-day period. Some of the daily features shown in Figures 1 through 6 are still apparent in the weekly composite. For example, the storm tracks in the North Pacific are quite distinct in the weekly image. The weekly rain maps derived from F11 cover all ocean areas, and hence a rain flag can be assigned to all F10 observations.

The turquoise curve in Figure 6 shows the tradeoff between F and S for the weekly time scale. In generating this curve, the observations for the entire year of 1992 are used. Clearly the weekly results are not as good as those for the daily time scale. For example, if one wants to have a skill factor S of 50% (i.e., correctly flag 50% of the rain observations), then the cost will be a false alarm rate F of 19% for the weekly maps as compared to 6% for the daily maps. The turquoise curve also shows that to obtain the maximum skill factor of S = 85%, one must tolerate a false alarm rate of F = 54%. A value of F = 54% means that over half of all NSCAT observations would be assigned a rain flag and presumably discarded! Throwing away half of the NSCAT observations to avoid rain is too extreme, and one must settle for a lower skill factor.

4. Rain Flagging on a Monthly Basis

In this section we discuss the results obtained when the rain map is averaged over a one-month period. We consider two cases: (1) a contemporaneous monthly rain map is made for each month during the NSCAT mission, and (2) monthly rain maps that come from a climatology. The advantage of using a climate monthly map is that a fixed rain flag table can be implemented before NSCAT is launched and no updating is required. The disadvantage is that interannual variations will make the climate monthly rain map less reliable than a monthly rain map computed for the particular month in question.

Figure 8 shows two monthly rain maps, one for January 1992 and the other for July 1992. Figure 9 is the same as Figure 8, except that the January and July maps represent an average over 4 years from 1992 thorough 1995. Also, Figure 9 shows the F10, rather than F11, rain observations because our existing climatology rain data base just includes F10 observations. There is a good deal of similarity between the 1992 monthly averages and the 1992-1995 monthly averages, although the 4-year averages are considerably smoother.

The green and red curves in Figure 6 shows the F versus S tradeoff for the monthly time scale and the monthly climate time scale, respectively. In generating these curves, the observations for the entire year of 1992 are used. Somewhat surprisingly, the two curves are not that different. The monthly rain flag performs slightly better than the climate rain flag. However, neither rain flag is very reliable. For example, to obtain a skill factor S = 50%, the false alarm rate is 24% for the monthly map and 27% for the climate map. In other words, approximately one quarter of the NSCAT observations would need to be discarded in order to correctly flag one half the rain cells.

5. Choosing the Appropriate Rain Flag

Thus far we have just considered a binary rain flag I that is either 0 or 1. There are other possible ways to specify the rain flag. A 2-bit rain flag can be defined as follows:

$$I = 0 \quad \text{when } \rho \le \rho'_1 \tag{8a}$$

$$I = 1 \quad \text{when } \rho'_2 \ge \rho > \rho'_1 \tag{8b}$$

$$I = 2 \quad \text{when } \rho'_3 \ge \rho > \rho'_2 \tag{8c}$$

$$I = 3 \quad \text{when } \rho > \rho'_3 \tag{8d}$$

where ρ is the RLI (i.e., the percent of rain observations in a given 1° cell), and ρ'_1, ρ'_2, and ρ'_3 are increasing RLI threshold values ($\rho'_3 > \rho'_2 > \rho'_1$). Another alternative is to simply let the value of ρ be the rain flag. This allows the User complete flexibility in flagging rain. However, with any flagging scheme, ultimately the User must make the binary decision of whether or not to used the NSCAT observation.

The value of providing the User with more than a binary rain flag is that the rain flagging can be tailored to the particular User application. For example, when conducting a calibration-validation (cal/val) activity for NSCAT, the User may elect to use an aggressive rain flag (i.e., a small ρ threshold) to ensure that the cal/val data set is of the highest quality. However, when making daily wind vector maps, an aggressive rain flag will result in persistent large holes in the wind field, and hence a more conservative flag can be chosen.

In choosing the appropriate value for the RLI threshold, the User can refer to Figure 6 and select the desired tradeoff between correctly flagging rain observations versus incorrectly flagging good observations. Figure 10 can then be used to find the corresponding RLI threshold value. Figure 10 is the same as Figure 6, except that the RLI threshold value ρ' is plotted versus the skill factor S, rather than F versus S. Figure 10 shows how the value of ρ' goes from 99.9% to 0% as the skill factor S increases from it minimum value to its maximum value.

There is another consideration when choosing the appropriate RLI threshold that relates to the accuracy of the rain flag. Figure 11 shows the percent of flagged observations that are actually rain versus the skill factor S. For example, when $\rho' = 99.9\%$ for the daily time scale, only 14% of the global rain observations are being flagged, but of those 14%, 52% are being properly identified as rain, as shown by Figure 11. Thus only a few observations are being flagged, but the rain flagging accuracy is relatively high. Figure 11 shows that the accuracy of the rain flag increases as ρ' increases, as to be expected. This accuracy statistic is defined by

$$A = (100\ N_4)/(N_3 + N_4) \qquad (9)$$

where N_3 and N_4 are defined above. In choosing the best RLI threshold, the User should consider the accuracy statistic A along with the skill factor S and the false alarm rate F.

6. Conclusions

The F13 SSM/I can be used to assign a rain flag to the NSCAT observations. However, the tradeoff between correctly identifying rain versus discarding good (i.e., no rain) observations is not very attractive. Table 1 shows the percent of no rain observations that will be mistakenly flagged as rain if one wants to obtain a rain flag skill factor of 50%. A skill factor of 50% corresponds to correctly flagging half the NSCAT rain observations, while having the other 50% of the rain observations go undetected. The values in Table 1 come from Figure 6.

As is to be expected, better rain flagging results are obtained for the short time scales. The daily time scale does a reasonably good job of flagging rain observations. However as discussed in Section 2, there will be holes in the daily rain maps for which a rain flag is not

Table 1. The false alarm rate for a rain flag with a skill factor of 50%.

Time Scale	Percent of good NSCAT observations mistakenly flagged as rain
Daily	6%
Weekly	19%
Monthly	24%
Monthly Climate	27%

available. One possible option is to use a space-time interpolation to fill in the holes. For this option, the performance of the rain flag will lie somewhere between that for the daily time scale and that for the weekly time scale. The time-scale results also indicate that not much is gained by using a monthly contemporaneous rain map as compared to using a monthly climate rain map.

Figure 6 shows that a 50% to 60% skill factor is probably the best that can be obtained. The cost of trying to achieve a higher skill factor is too great in terms of the number of good observations that would be discarded. Thus even in the best case scenario, about half of the NSCAT rain observations will go undetected, unless one is willing to discard a large portion of the NSCAT observations.

7. Recommendations

1. The NSCAT rain flag should be in terms of the rain likelihood indicator ρ (RLI), which is the percent of rain observations detected by SSM/I in a 1° cell. This gives the User complete flexibility in choosing the appropriate ρ threshold flagging value for his/her application.
2. Monthly climatology RLI maps should be generated from the 1988-1995 SSM/I observations. The climatology RLI should be included in the NSCAT Level-1 data record and the NSCAT Level-2 data record. However, it must be emphasized that the climatology RLI has limited utility. It will probably be most useful in identifying certain ocean areas that are void of rain, such as the subtropical highs in the Southeast Pacific and Southeast Atlantic, and certain other areas that have persistent rain, such as the intertropical convergence zone (see Figure 9).
3. We should consider producing daily SSM/I RLI maps for NSCAT rain flagging. Figure 6 and Figure 11 clearly show that rain flagging on a daily time scale is significantly better than rain flagging on a weekly or monthly time scale. A space-time interpolation method needs to be developed to fill in the holes in the daily rain maps. With respect to implementation of the daily RLI maps, we suggest that in the Level-2 NSCAT data record one byte be reserved for the daily RLI. During the routine Level-2 processing, this byte is set to 255, indicating no daily RLI is available. (There will be another byte that contains the climate RLI.) When the daily RLI maps are ready, the daily RLI byte can be put into the data record. We suggest that Remote Sensing Systems (RSS) produce the maps and then FTP the maps to JPL. RSS will be processing all the SSM/I data through the year 2000. Due to the extensive quality control and other factors, the delivery of the daily RLI maps will probably lag about 2 months. This is to say, the daily maps for January would be delivered in March. If needed, the delivery time can be speeded up, but this will require additional resources and may somewhat compromise the data quality.
4. Rain flagging on weekly and monthly time scales should not be done. The results for these time scales are significantly worse than the daily time scale. In fact, the monthly time scale rain flag is not much better than the climate rain flag. If RLI maps are to be made from contemporaneous SSM/I observations, then daily maps should be used.

8. References

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