

## Comment on "Seasonal Variation in Wind Speed and Sea State From Global Satellite Measurements" by D. Sandwell and R. Agreen

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In a recent paper, *Sandwell and Agreen* [1984; hereafter SA] presented figures of global seasonal wind speed and sea state as measured by the GEOS 3 satellite altimeter. Since that time, *Chelton and McCabe* [1985; hereafter CM] have found that problems exist in the algorithms used to retrieve wind speed from altimeter measurements of radar backscatter. These problems were discovered too late to be of use in the analysis of SA. However, because they have a significant impact on the accuracy of wind speed estimation from altimeters, it is important that they be pointed out now so that the results of SA are not misused. Although the results presented here do not alter many of the conclusions of SA in a qualitative sense, they do become important for any quantitative interpretation of the seasonal winds presented by SA. In addition, the data distribution maps presented here (Figures 3a-3f) are useful for pointing out limitations in other applications of GEOS 3 data (e.g., use of the altimeter sea level measurements to study surface geostrophic currents).

A detailed description of sea surface wind speed estimation from radar altimeters is given in CM. Briefly, wind speed retrieval is a two-step procedure. In the first step, the power of microwave radiation backscattered from the sea surface is determined from parameters measured by the altimeter receiver. To account for variations in transmitted power, the return power is normalized by the transmitted power. This normalized radar cross section is usually referred to as  $\sigma^{\circ}$ . The  $\sigma^{\circ}$  measurements must be corrected for variations in the attitude angle of the satellite and variations in the height of the satellite above the sea surface.

The second step in wind speed retrieval is to estimate wind speed from  $\sigma^{\circ}$ . This estimation is based on the principle that the roughness of the sea surface increases with increasing wind speed. The backscattered power measured by the altimeter receiver consists of microwave radiation reflected specularly from the sea surface over an approximate 10-km footprint directly beneath the satellite. As the sea surface roughens, much of the transmitted radiation is specularly scattered away from the radar antenna. Thus wind speed is inversely related to  $\sigma^{\circ}$ . The algorithms used to estimate wind speed from  $\sigma^{\circ}$  are purely empirical, based on comparisons with coincident measurements from buoys.

In a detailed investigation of the performance of wind speed estimation from the Seasat altimeter, CM identified problems with both steps of the procedure for wind speed retrieval. For Seasat, the power received by the altimeter antenna was converted to a constant output level for other receiver stages using a digital step attenuator automatic gain control (AGC). Thus  $\sigma^{\circ}$  can be computed directly from AGC (with the aforementioned satellite attitude angle and height corrections). CM found that the tables used to compute  $\sigma^{\circ}$  resulted in a dis-

continuous dependence on AGC. This algorithm was incapable of producing  $\sigma^{\circ}$  values in the range from 11.2 to 12.0 dB, which corresponds to wind speeds from about 5 to 7  $\text{ms}^{-1}$ . This error is clearly serious for wind speed estimation, since this wind speed range is very near the peak in a distribution of global wind speeds.

After correcting for the error in the Seasat  $\sigma^{\circ}$  algorithm, CM still found peculiarities in the estimated wind speeds. These peculiarities were traced to discontinuities in the slope of the model function used to estimate wind speed from  $\sigma^{\circ}$ . For Seasat, wind speeds were computed from  $\sigma^{\circ}$  using a three-branch logarithmic model function developed by *Brown et al.* [1981]. The change in the slope of the model function at the two branch points (10.12 and 10.9 dB values of  $\sigma^{\circ}$ ) resulted in abrupt changes in the distribution of wind speeds computed from  $\sigma^{\circ}$ . CM proposed a new single-branch model function which is very nearly the same as the Brown et al. model function for wind speeds less than 11  $\text{ms}^{-1}$  (corresponding to the two lower branches of the three-branch algorithm). For higher wind speeds, the two model functions diverge rapidly.

Wind speed retrieval from the GEOS 3 ALT differed from the Seasat ALT both in the hardware configuration and in the algorithm used to estimate wind speed from  $\sigma^{\circ}$ . On GEOS 3, the backscatter was measured directly using an analog receiver. (This was changed on Seasat to a digital system because of calibration problems inherent in analog systems.) Since  $\sigma^{\circ}$  was measured using an analog system, wind retrieval from GEOS 3 should be immune from errors of the type found in the Seasat  $\sigma^{\circ}$  algorithm (aside from calibration problems with the analog system).

However, the nature of the algorithm used to compute wind speed from GEOS 3 measurements of  $\sigma^{\circ}$  does introduce errors in the wind speed. Wind speed estimation was based on a two-branch algorithm proposed by *Brown* [1979] which had the form

$$\sigma^{\circ}(\text{dB}) = -2.1 - 10 \log_{10} (a \ln u_{10} + b)$$

where  $\sigma^{\circ}$  is measured in dB and  $u_{10}$  is the wind speed at 10 m above the sea surface. The parameters  $a$  and  $b$  were evaluated by least squares analysis of a very limited ship and buoy data base. The result was a two-branch algorithm with a branch point at 9.2  $\text{ms}^{-1}$ . For the lower wind speed branch,  $a = 0.02098$  and  $b = 0.01075$ . For the upper wind speed branch,  $a = 0.08289$  and  $b = -0.12664$ .

In order to compute wind speed, this algorithm must be inverted, which gives

$$u_{10} = \exp [(S - b)/a]$$

where

$$S = 10^{-[\sigma^{\circ}(\text{dB}) + 2.1]/10}$$

This model function for wind speed is shown graphically in Figure 1. Note the discontinuous slope of the model function

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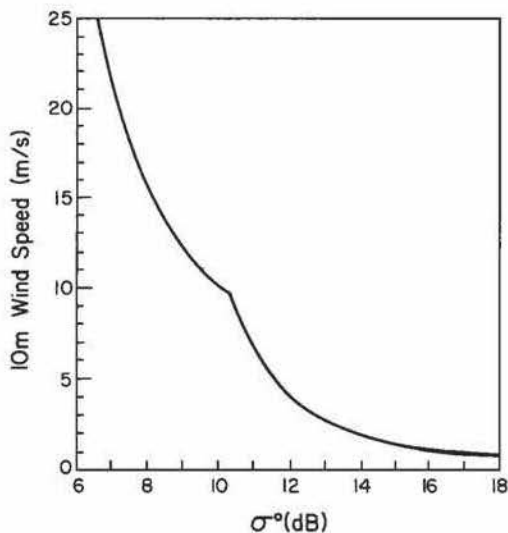


Fig. 1. The *Brown* [1979] two-branch wind speed model function implemented in geophysical processing of GEOS 3 ALT data.

at the branch point at  $9.2 \text{ ms}^{-1}$  (corresponding to a  $\sigma^\circ$  value of 10.3 dB).

(Note: *Brown et al.* [1981] later developed a three-branch algorithm for computing wind speed from  $\sigma^\circ$  for the GEOS 3 ALT. This algorithm had exactly the same form as that given above (with branch points at 7.87 and 10.03  $\text{ms}^{-1}$ ) and was based on an expanded data base consisting of high-quality measurements from National Data Buoy Office buoys. The three-branch algorithm was implemented in geophysical processing of the Seasat ALT data but was not used in the final geophysical processing of GEOS 3 ALT data.)

Problems with the *Brown* [1979] two-branch wind speed model function are easily identified with a simple histogram of wind speeds from the GEOS 3 ALT (Figure 2). There is an abrupt change at  $9.2 \text{ ms}^{-1}$  in the global distribution of wind speeds. Based on the results of CM, this abrupt change is due to the discontinuous slope at the  $9.2 \text{ ms}^{-1}$  branch point. The approximate factor of 2 change in slope at  $9.2 \text{ ms}^{-1}$  results in a factor of 2 increase in the number of wind speeds observed in the  $9.2\text{--}9.4 \text{ ms}^{-1}$  bin over the  $9.0\text{--}9.2 \text{ ms}^{-1}$  bin.

Thus as noted in CM, it is essential that any model function used to compute wind speed from  $\sigma^\circ$  be continuously differentiable. Clearly, the GEOS 3 ALT data must be reprocessed using a new model function for wind speed in order to obtain reliable estimates of global winds. A form for the new model function is proposed in CM.

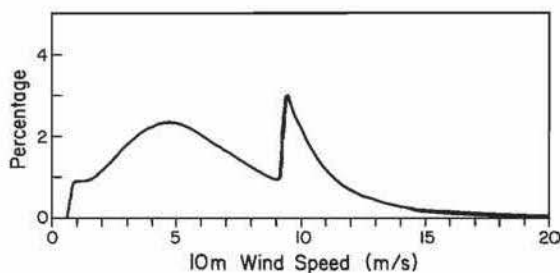


Fig. 2. Histogram of 10-m wind speeds computed from approximately 3.3 million observations during the full  $3\frac{1}{2}$  year GEOS 3 mission using the *Brown* [1979] two-branch wind speed model function. Wind speed measurements less than  $0.01 \text{ ms}^{-1}$  have been excluded. Bin size is  $0.2 \text{ ms}^{-1}$ .

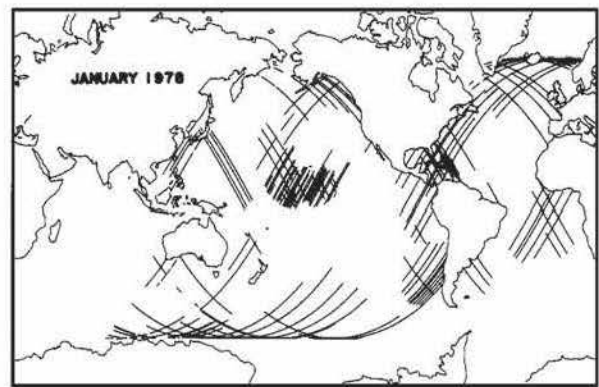
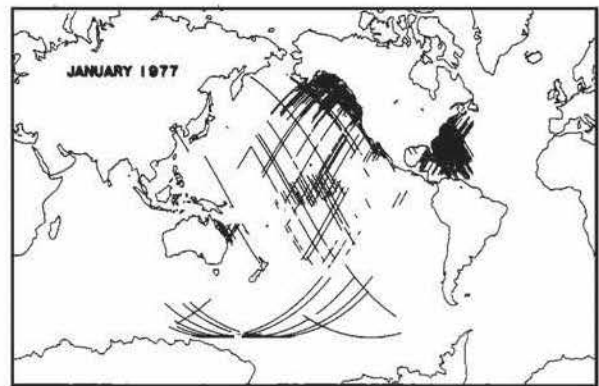
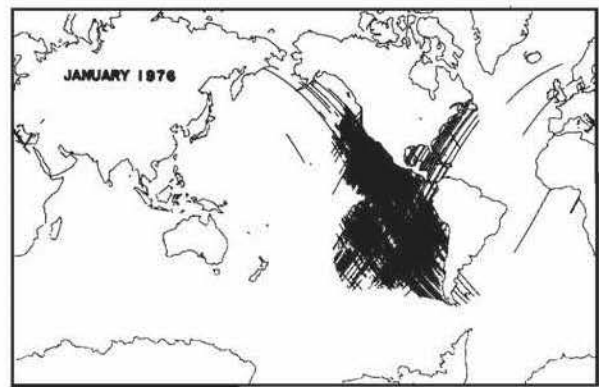


Fig. 3a. GEOS 3 ground tracks during all times when the ALT was turned on during January.

Since a large number of individual wind speed estimates are averaged in each  $2^\circ$  square in the maps presented by SA, a histogram of the average wind speeds will of course not exhibit the abrupt change at  $9.2 \text{ ms}^{-1}$ . Indeed, according to the Central Limit Theorem, a histogram of averaged winds must be very nearly Gaussian. However, the peak in this distribution will be biased toward a lower wind speed than for averages of individual winds computed using a more accurate model function. (This is not in general true but is true for the case considered here.) Therefore the seasonal wind speeds presented by SA are generally lower than would be obtained if a more accurate model function were used (see Figures 4 and 16 of CM).

Before any steps are taken to reprocess the data, it is useful to examine the spatial and temporal distribution of the GEOS

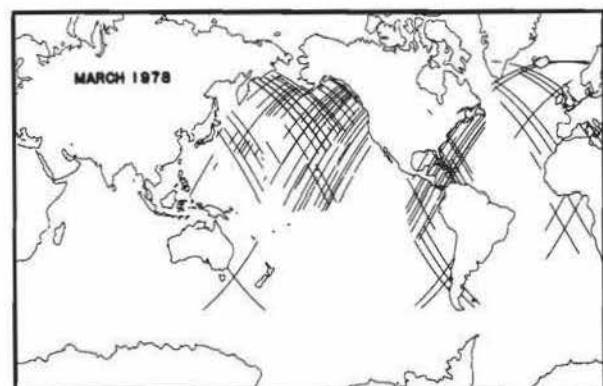
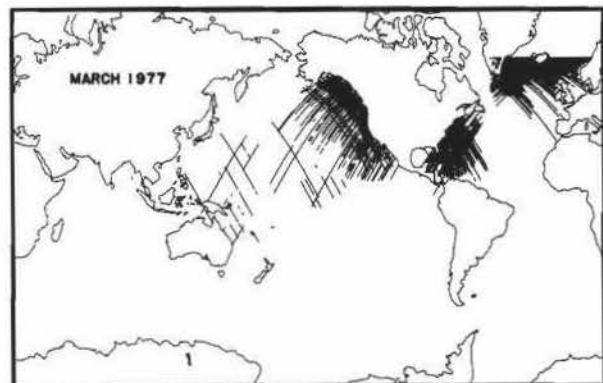
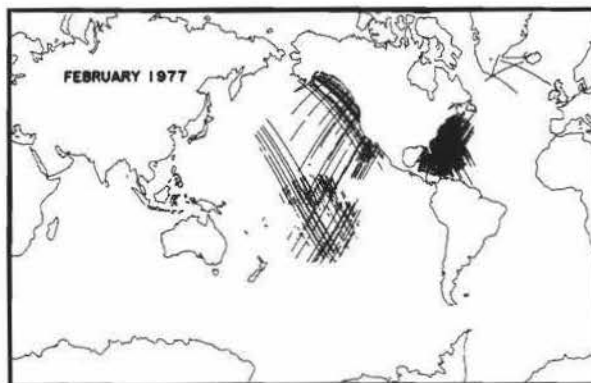
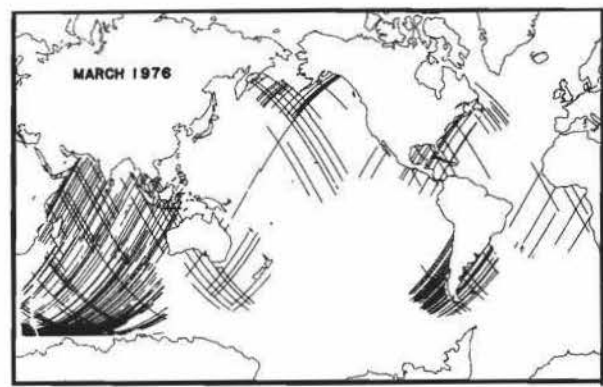
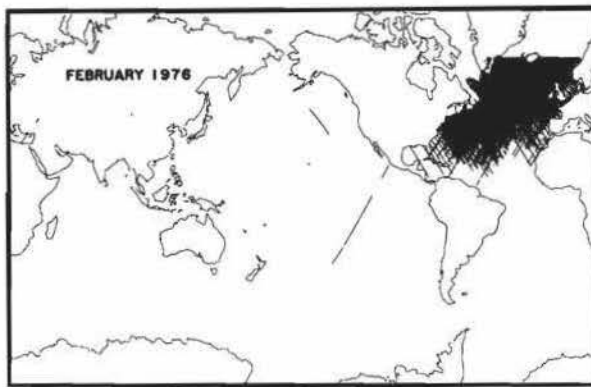


Fig. 3b. As in Figure 3a except for February.

Fig. 3c. As in Figure 3a except for March.

3 ALT  $\sigma^{\circ}$  measurements in some detail. This information is given to a very limited degree by SA in their global summaries of the number of observations by  $2^{\circ}$  latitude and longitude regions. They show the total number of boreal winter (which they define to be December, January, February, and March) and summer (defined as June, July, August, and September) observations over the  $3\frac{1}{2}$  year GEOS 3 mission (April 1975 to November 1978). A more detailed examination reveals serious limitations in the seasonal wind speed data provided by SA. The GEOS 3 ground tracks during all times when the ALT was turned on are shown in Figure 3 for each individual month during the  $3\frac{1}{2}$  year mission.

Some of the salient features of the boreal winter (December, January, February, and March) sampling by the GEOS 3 ALT are:

1. Only the western North Atlantic and eastern North Pa-

cific oceans were sampled every month during the  $3\frac{1}{2}$  year GEOS 3 mission.

2. There were very few measurements south of  $30^{\circ}\text{S}$  during any month.

3. The entire Indian Ocean was sampled only during the month of March 1976.

4. The western North Pacific Ocean was sampled by only a very small number of ground tracks in January, February, and March of 1978.

5. The eastern North Atlantic Ocean was sampled by only a very small number of ground tracks in February 1976, December 1977, and February and March 1978.

6. The entire South Atlantic Ocean was essentially unsampled. (SA block out much of this region in their figures, but the reliability of the seasonal mean in regions not blocked out remains questionable.)

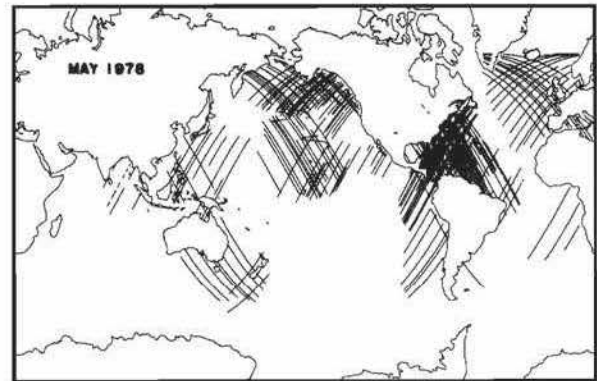
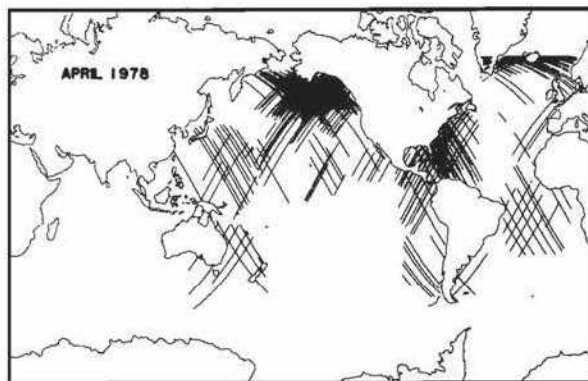
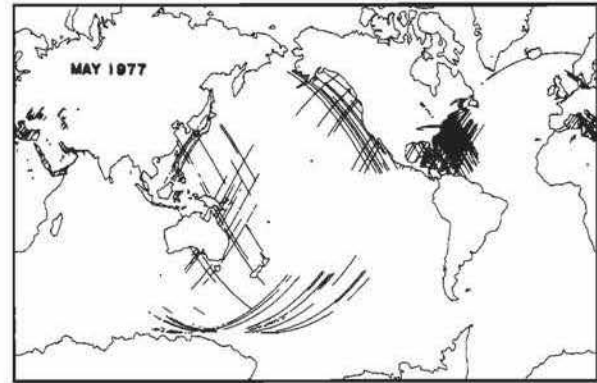
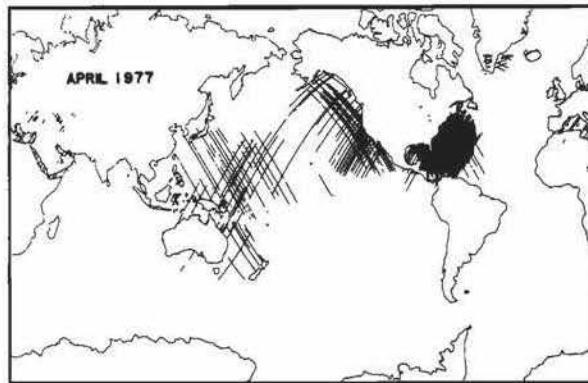
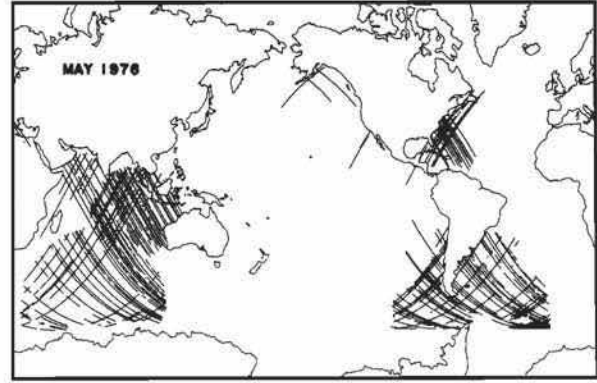
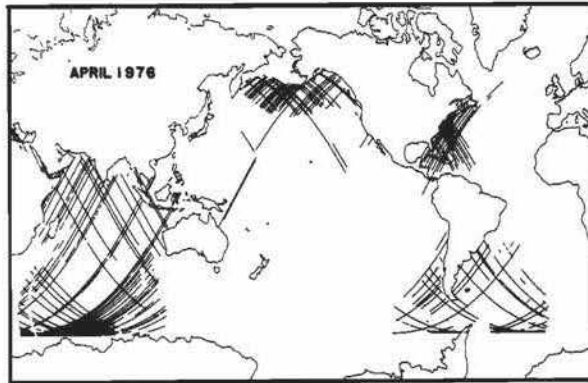
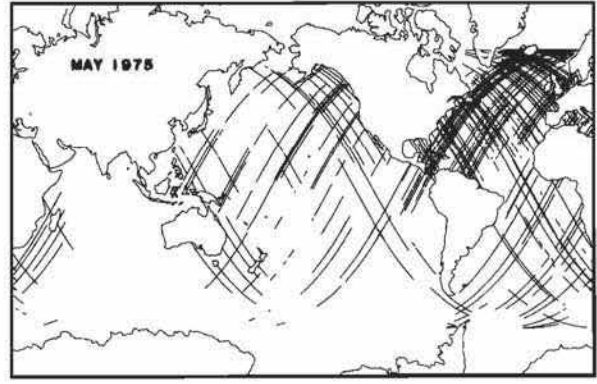
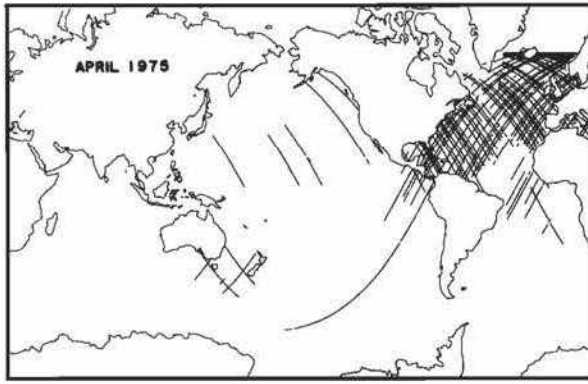


Fig. 3d. As in Figure 3a except for April.

Fig. 3e. As in Figure 3a except for May.



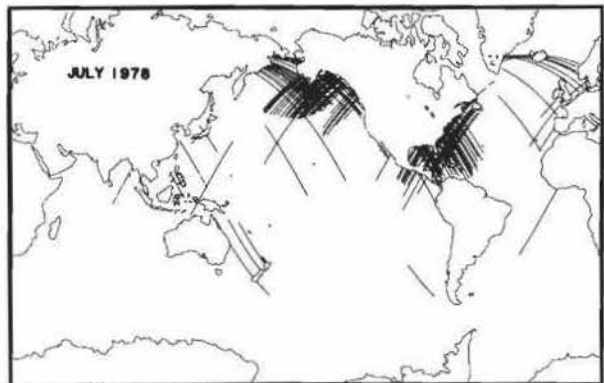
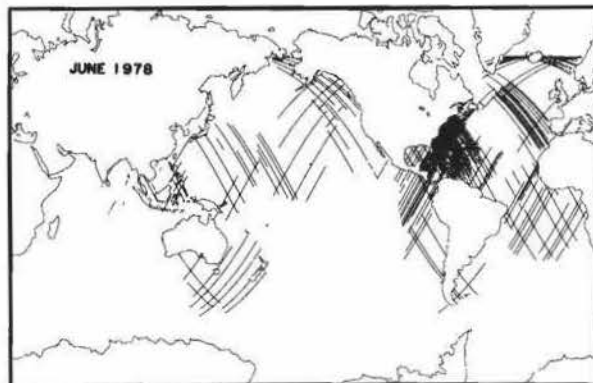
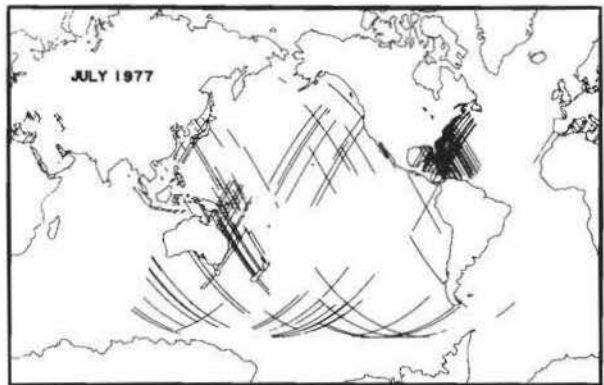
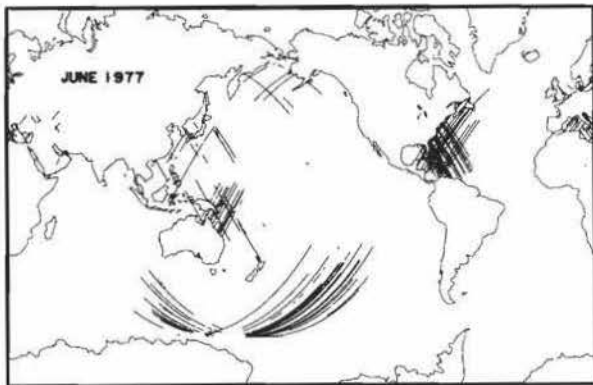
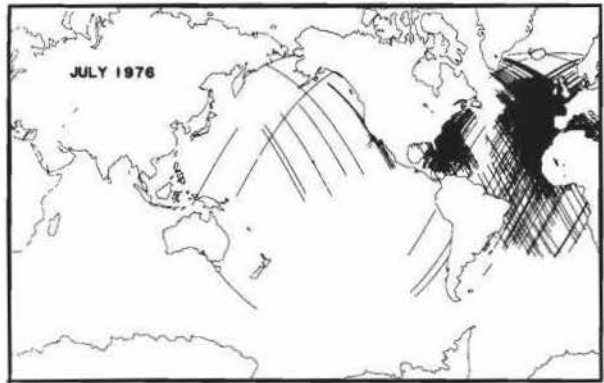
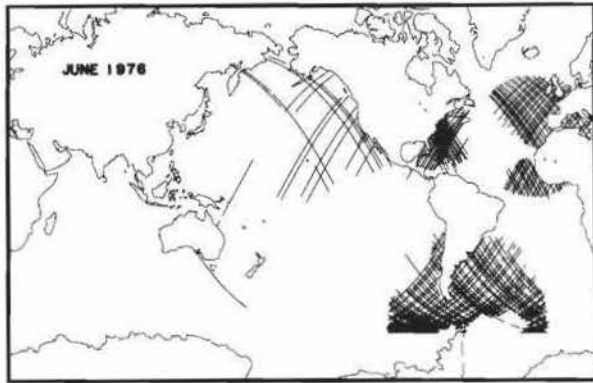
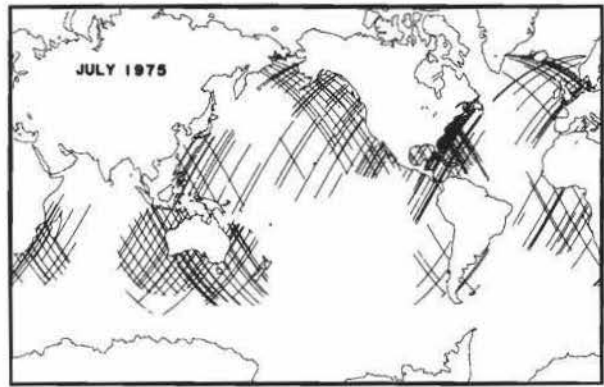
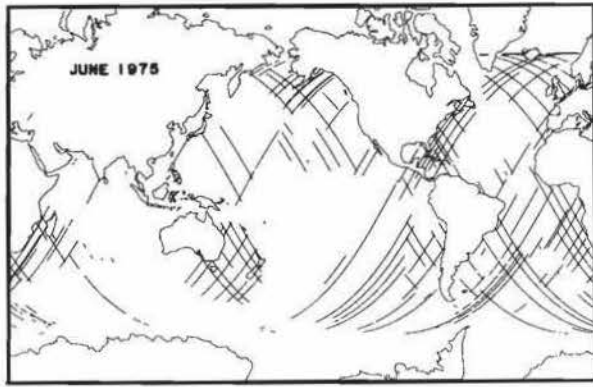


Fig. 3f. As in Figure 3a except for June.

Fig. 3g. As in Figure 3a except for July.

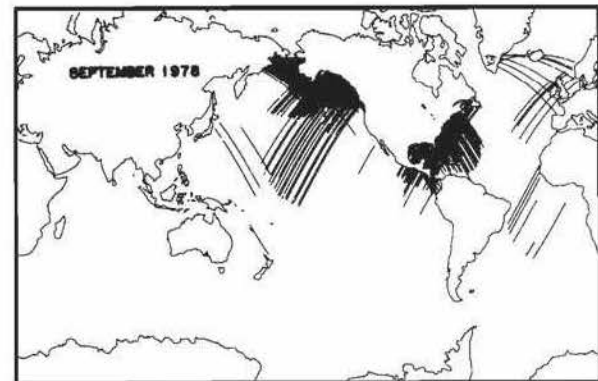
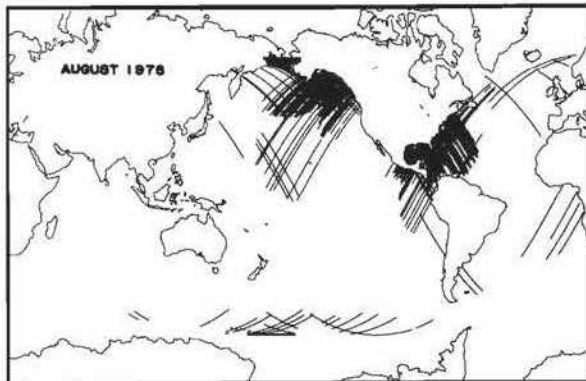
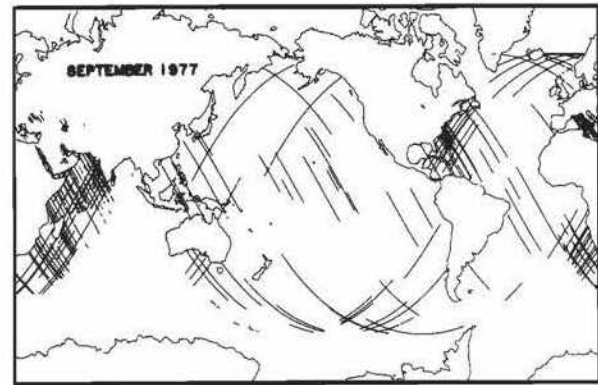
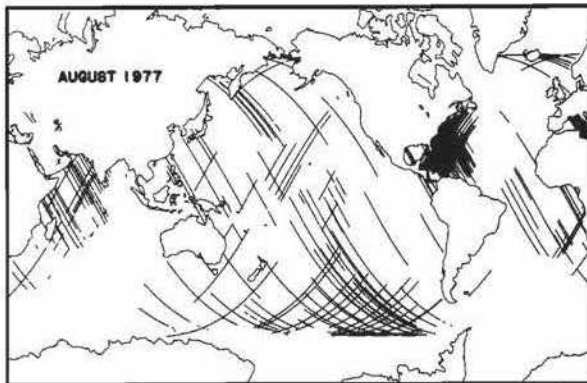
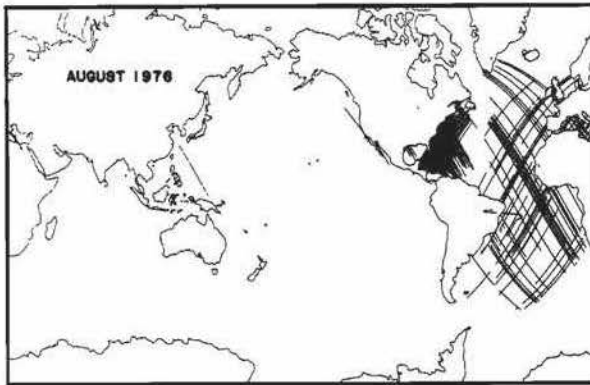
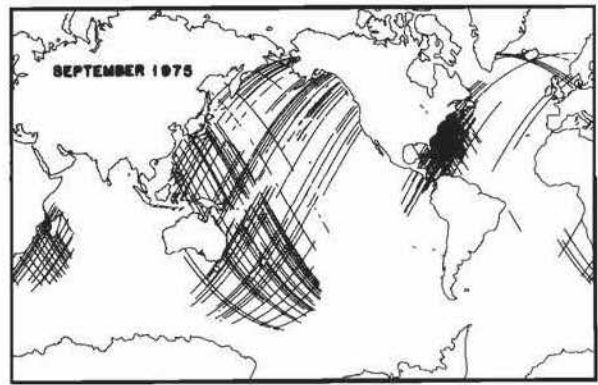
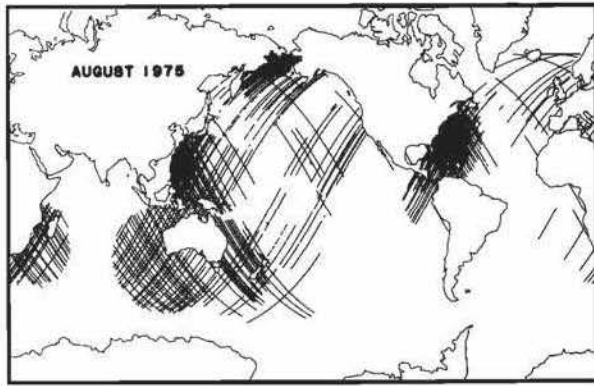


Fig. 3h. As in Figure 3a except for August.

Fig. 3i. As in Figure 3a except for September.

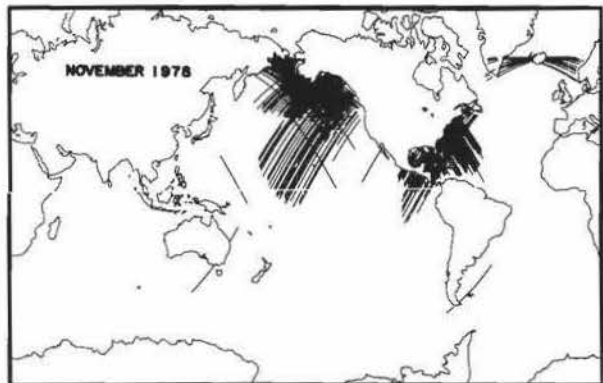
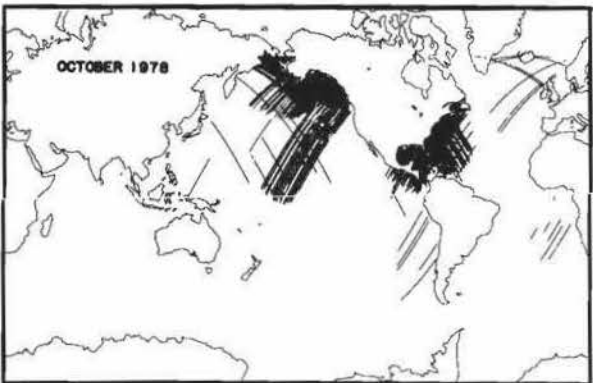
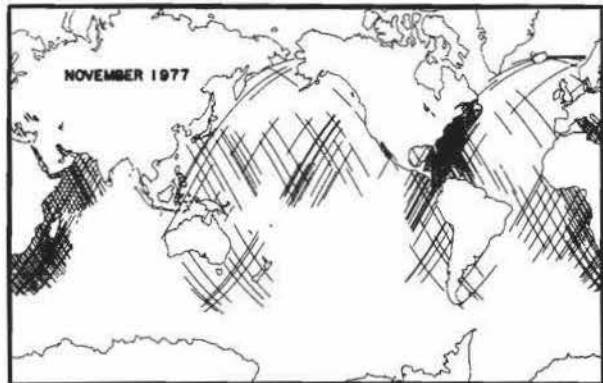
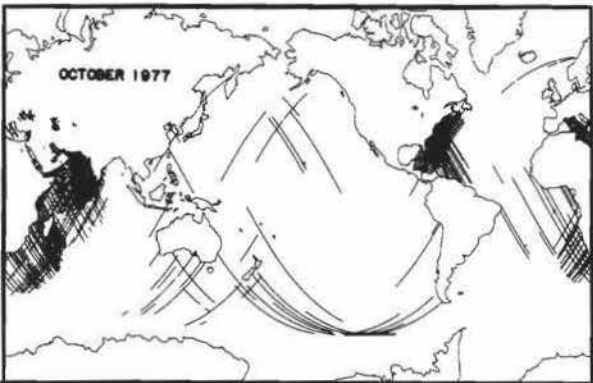
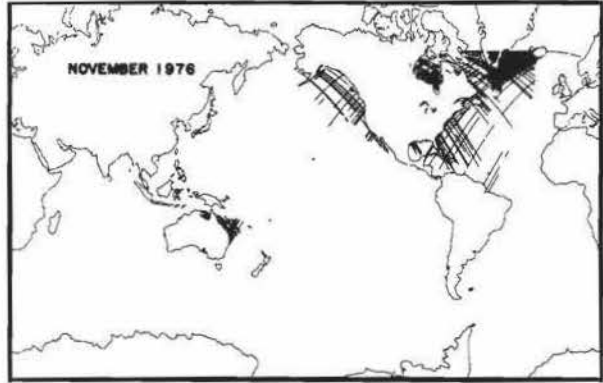
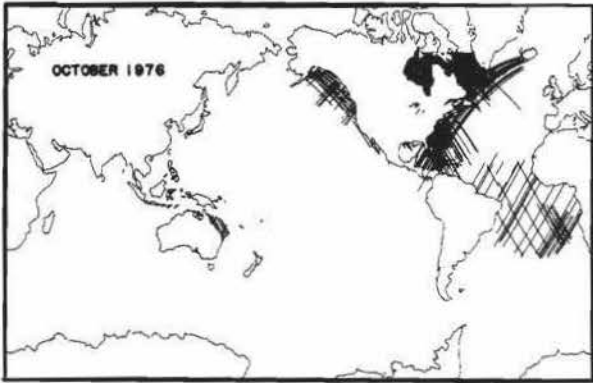
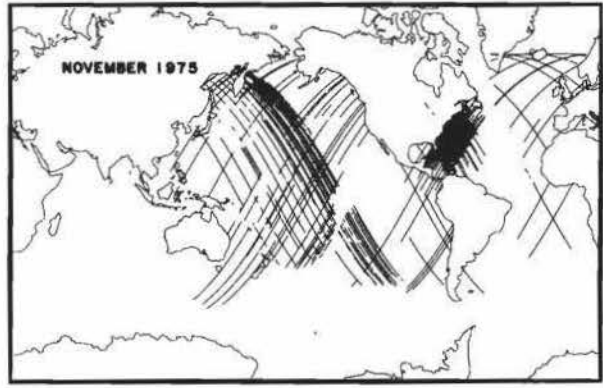
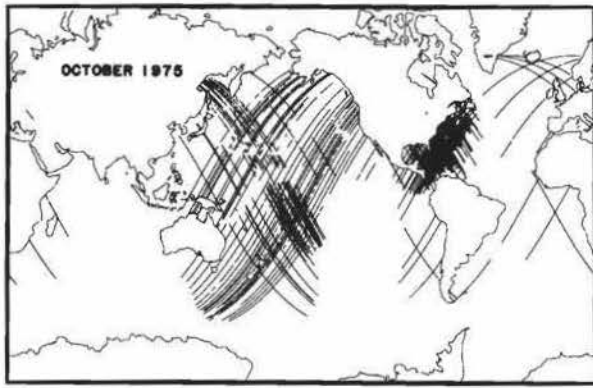


Fig. 3j. As in Figure 3a except for October.

Fig. 3k. As in Figure 3a except for November.

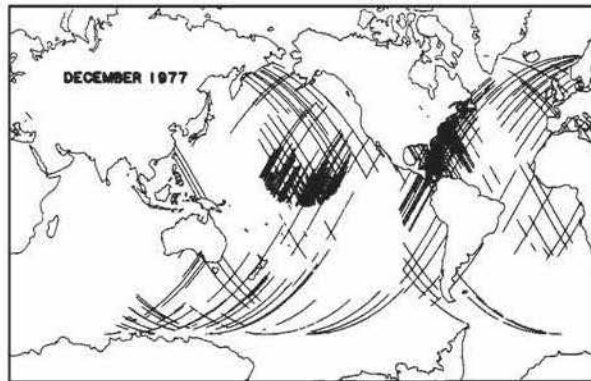
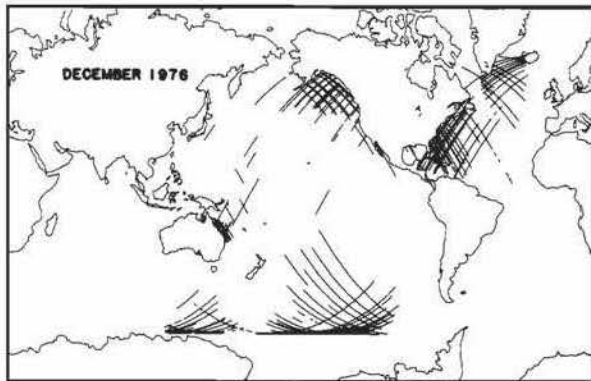
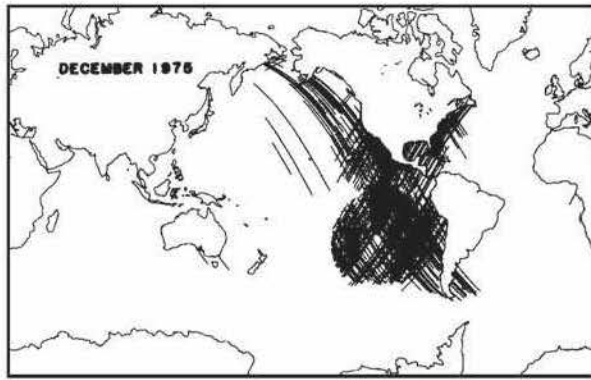


Fig. 3f. As in Figure 3a except for December.

Some of the salient features of boreal summer (June, July, August, and September) sampling by the GEOS 3 ALT are:

1. The western North Atlantic and eastern North Pacific Oceans were sampled nearly every month during the GEOS 3 mission.
2. Again, the number of observations south of 30°S was relatively small.
3. The central and South Indian Ocean was never sam-

pled. (SA block out the southern Indian Ocean but show contours in the central Indian Ocean.)

4. The eastern half of the equatorial Pacific Ocean was essentially unsampled (except for a few ground tracks in August and September 1977).

5. Sampling of the South Pacific Ocean was essentially limited to August 1977 (with a very few ground tracks in June, July, and September 1977).

6. The western South Atlantic Ocean was sampled only in June 1976 (with a few ground tracks in August 1976).

From these figures, it is clear that, except for the western North Atlantic and eastern North Pacific Oceans, the temporal and spatial sampling of the global Ocean by the GEOS 3 ALT was very irregular. In many areas, the seasonal mean values presented by SA are based on measurements taken in different years. Since it is known that there is strong interannual variability in global winds, the representativeness of the seasonal winds in SA is questionable. This is true even in a relative sense where winds in one geographical region are compared with those in another (since the winds in different regions may have been sampled by GEOS 3 in different years).

The conclusion is that patterns of winds presented by SA are, at best, only qualitatively correct because of weaknesses in the two-branch model function for wind speed and irregular temporal and spatial sampling by GEOS 3. It is questionable whether reprocessing GEOS 3 ALT data for wind speed would be useful scientifically for more quantitative examination of global wind speeds. The maps in Figure 3 help identify geographic regions where the mean wind speeds presented by SA are least trustworthy. Although reliable statistics on seasonal winds could probably be computed from GEOS 3 data in a few selected regions (using a corrected single-branch wind speed model function), statistics on global winds would probably not be very meaningful.

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