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Surface Flow Structure of the Gulf Stream From Composite Imagery and Satellite-Tracked Drifters

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Surface flow structure of the Gulf Stream from composite imagery and satellite-tracked drifters

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Abstract. A unique set of contemporaneous satellite-tracked drifters and five-day composite Advanced Very High Resolution Radiometer (AVHRR) satellite imagery of the North Atlantic has been analyzed to examine the surface flow structure of the Gulf Stream. The study region was divided into two sections, greater than 37°N and less than 37°N, in order to answer the question of geographic variability. Fractal and spectral analyses methods were applied to the data. Fractal analysis of the Lagrangian trajectories showed a fractal dimension of 1.21± 0.02 with a scaling range of 83 - 343 km. The fractal dimension of the temperature fronts of the composite imagery is similar for the two regions with D = 1.11± 0.01 over a scaling range of 4 - 44 km. Spectral analysis also reports a fairly consistent value for the spectral slope and its scaling range. Therefore, we conclude there is no geographic variability in the data set.

A suitable scaling range for this contemporaneous data set is 80 - 200 km which is consistent with the expected physical conditions in the region. Finally, we address the idea of using five-day composite imagery to infer the surface flow of the Gulf Stream. Close analyses of the composite thermal fronts and the Lagrangian drifter trajectories show that the former is not a good indicator of the latter.

1 Introduction

The Gulf Stream has been the topic of an enormous amount of research over the past decades, particularly meanders, eddies, and the velocity distribution within the Stream. The emphasis has ranged from quantitative analyses of the kinematics and dynamics of the Stream to a more qualitative description of the hydrography. In the past, surface drifters or sequential satellite images were used to determine the surface flow of the Gulf Stream. Unfortunately, these studies only focused on obtaining the flow kinematics information from small-scale features in sequential images, feature-tracking.

Feature tracking is an operator-dependent process where an image surface feature is chosen and tracked subjectively from one sequential image to the next. Sea surface velocities are then calculated from the image to image displacement of the feature and the time elapsed between the images. LaViolette (1984) estimated surface velocities around the Alboran Sea gyre by tracking features in sequential Advanced Very High Resolution Radiometer (AVHRR) and Coastal Zone Color Scanner (CZCS) imagery. Vastano and Borders (1984) used this method with an interactive algorithm to track submesoscale features in the western North Pacific. A verification study of this procedure was undertaken along the California coast by Svejkovsky (1988). By using CZCS, AVHRR and surface drifter data, Svejkovsky determined that the calculated surface velocities from the images differed by a rms of 0.06 $m\ s^{-1}$ from the drifter velocities (Svejkovsky, 1988).

Although feature tracking has provided important contributions, there are several problems with this procedure. The main one is that the variability in cloud cover and thermal contrasts between images sometimes prevents the tracking of the most prominent and interesting surface feature. Thus, a new approach to the study of surface flow is desirable. One such possibility for inferring the surface flow structure of the Gulf Stream is composite imagery. A composite is a "weighted average" of a sequence of images. Compositing of the images produces higher quality pictures and decreases the number of images to analyze.

The goal of this study is to relate some quantifiable features of the composite images to the Gulf Stream. To do this the drifter and image data must be linked so as to infer near-surface flow kinematics of the Gulf Stream. This was done by comparing the sea surface temperature (SST) features from satellite composites with contemporaneous drifter trajectories in order to determine

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if there is a good correlation between the two data sets. The comparisons were made by applying statistical and fractal analyses methods to the data.

To answer the question of whether it is possible to infer the surface flow structure of the Gulf Stream from the relationship of this data, four topics must be addressed. Some recent studies have concentrated on the use of multifractals to observe temperature and drifter data. Multifractal properties display different fractal dimensions at different scales. However, reliable estimates of multifractal properties require large accurate data sets. As this is not the case here, a different approach in analyzing our data by dividing it into two geographic regions has been chosen. This approach is used to answer the question: Is there geographic variability in the contemporaneous data set that multifractal analysis may obscure? The point of this study is to determine whether the geographic location of the data set effects the fractal nature of the space curve. Multifractal analysis would not make it possible to determine this independence or dependence on geographic location. Spectral and fractal analyses are used to determine the suitable scaling range for the data. Another question to answer is whether the fractal dimension is a good indicator of the spectral slope. Lastly, the use of five-day composite imagery, as opposed to sequential imagery, is explored. In summary, the following four questions are addressed in this paper. Is there geographic variability? What is a suitable scaling range? Is the fractal dimension a reliable indicator of the spectral slope? Is a five-day composite image a good indicator of the trajectory data?

In the following section the contemporaneous data set is described. The fractal and spectral analyses methods are discussed in Sects. 3 and 4, respectively. Finally, in Sect. 5 the conclusions of the research are presented.

2 Data

The surface drifter data used in this research was deployed as part of the Florida Atlantic Coast Transport Study (FACTS) in 1984. The drifters were composed of a 10 cm diameter PVC pipe approximately 3 m in length with a dampener at the bottom. A 50 cm protrusion above the sea surface enabled the drifters to be easily tracked by Service ARGOS using the TIROS/NOAA random access receivers. A detailed description of the satellite-tracked buoys is discussed in Maul (1985). Complete discussion of the FACTS surface drifter paths can be found in FACTS study (1986).

All drifters were deployed 70 nm southeast of Cape Canaveral at 28 ° N latitude and 80 ° W longitude. They were positioned at the 75 m isobath. A single undrogued buoy was released each month from April 1984 to March 1985. This set of drifter data was chosen for the study because their time period coincides with infrared satellite images.

The infrared satellite imagery was collected by the advanced very high resolution radiometer aboard the NOAA-9 satellite. This polar-orbiting satellite flies over the east coast of the United Sates twice a day. Because the NOAA-9 AVHRR system has three infrared channels, one short and two long, sea surface temperatures can be determined for both the night and day passes.

The AVHRR data was received and processed by the Rosenstiel School of Marine and Atmospheric Science (RSMAS) of the University of Miami. Many steps were undertaken to process the data. The AVHRR image was subsampled so that every fourth pixel in every fourth array was kept, giving a spatial resolution of about 4 km. The SST is determined by measuring the infrared radiation from the ocean. In order to obtain an accurate temperature measurement, atmospheric corrections were done. Because the view from the satellite changes with each orbit, the images were remapped to an area between 85 - 62 ° W longitude and 22 - 42 ° N latitude. Cloud screening was applied to the remapped SST images to reduce the amount of cloud cover.

The next major processing step was to produce 5-day composites for a set of individual images. A composite is a weighted average of a sequence of images. For each pixel of the five sequential images, the warmest SST was kept, thus decreasing the cloud cover. It is reasonable to create SST composite images because the surface temperature does not change that drastically within five days for the oceanographic space scales researched. A second cloud screening was performed on the composites. Finally, the SST fields were smoothed for each composite by applying a 3-by-3 pixel median filter. A more detailed description of the image data processing is discussed in Brown (1986).

The AVHRR data from NOAA-9 overlaps the FACTS drifter data by one year: 1985-1986. Figure 1 shows a 5-day composite image with several FACTS drifters superposed on the image. For this study only images corresponding to the dates March 26 through April 1 1985 (image 85), April 2 through 5 (image 92), and April 6 through 10 (image 96) were analyzed. These composite images were divided into two geographic regions, greater than 37°N and less than 37°N, as shown in Fig. 2.

3 Fractal Analysis

A fractal is any "geometric object whose shape is irregular and/or fragmented at all scales" (Osborne, et al., 1989). In other words, the object is self-similar at different length scales. Self-similarity is a quality of a structure where the geometry on one length scale corresponds to the geometry at another (Moon, 1987).

The fractal dimension is the measure of the dimension of the fractal, which can be a non-integer. A fractal curve is irregular at all length scales, exhibiting small or large scale wiggles at any length (Osborne, et al., 1989)

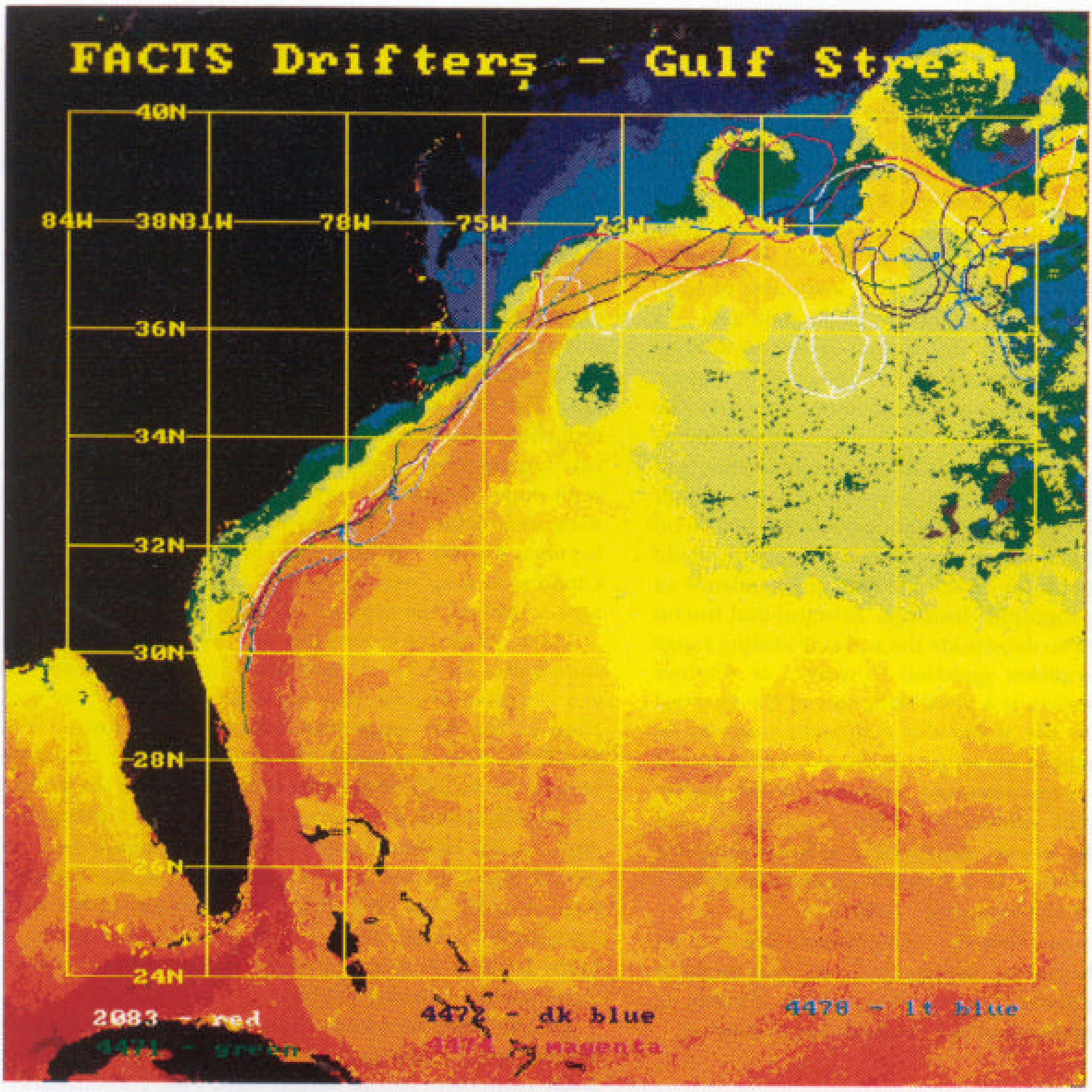


Fig. 1. Five-day composite imagery for the period March 26 through April 1, 1985 showing the geographic regions.

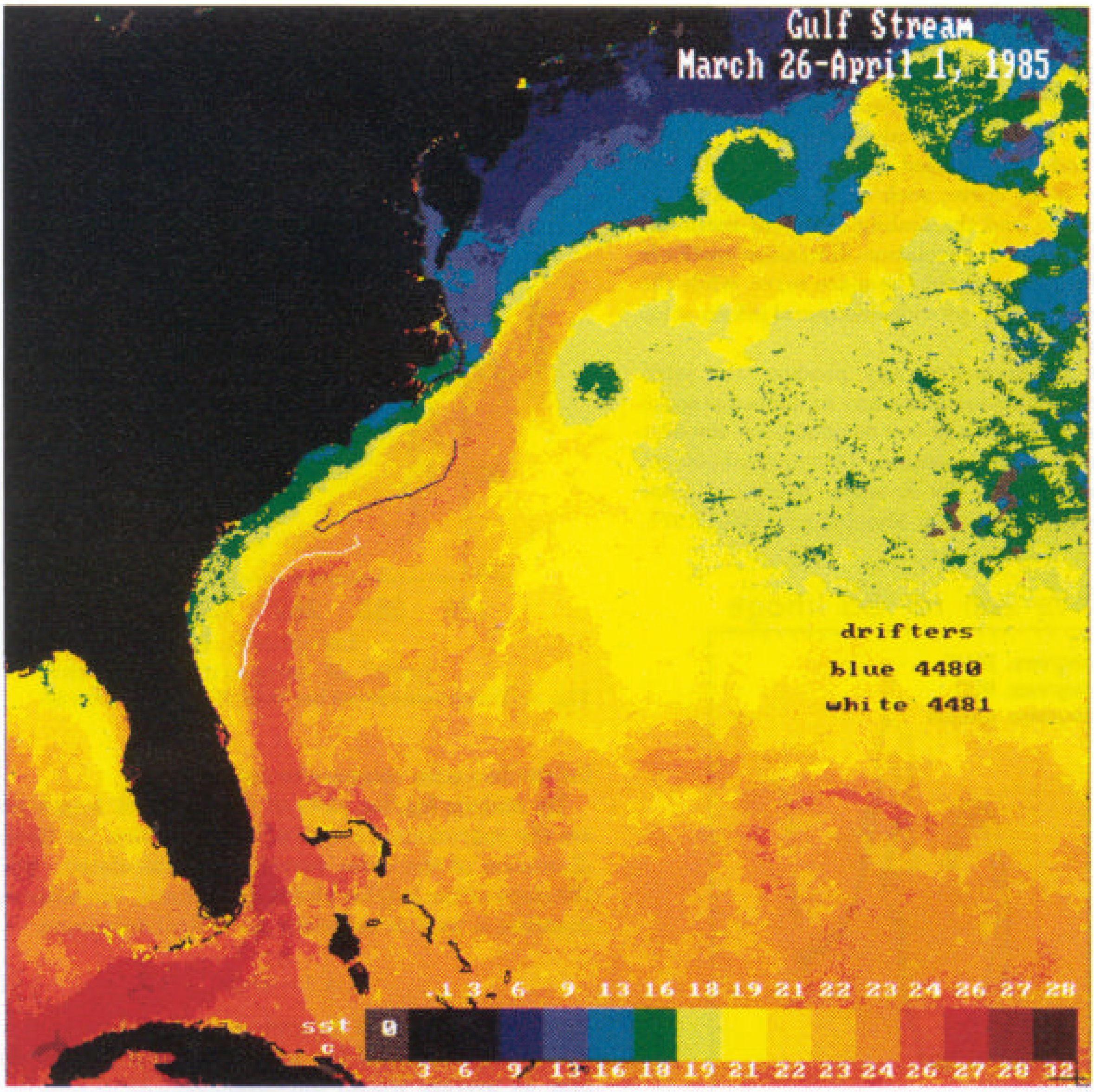
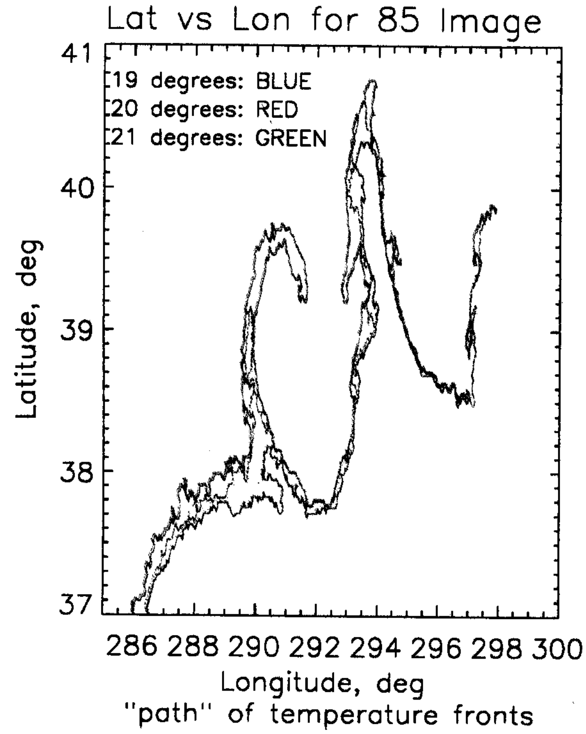


Fig. 2. Five-day composite imagery for the period March 26 through April 1, 1985 showing the geographic regions.

Thus, one can determine the fractal dimension of any fractal curve. The data available for this research represents spatial curves which are most probably fractal curves. Therefore, their geometric properties may be determined from any fractal analyses method.

Several methods can be used to calculate the fractal dimension of a space curve, such as the correlation dimension, yardstick, and the scaling exponent methods. Both the yardstick and correlation dimension methods give spatial information about the space curve, while the scaling exponent method provides temporal information (Osborne, et al., 1989).

These three methods generally produce the same value for the fractal dimension for any monofractal space curve. The yardstick method was deemed to be the best approach in finding the dimension. This method gets its name from the length of the division, 'yardstick', used to follow the space curve (see Mandelbrot, 1967, 1977, 1983).



For this study, the space curve analyzed was the temperature front gradient 'line' on the coastal side of the Gulf Stream. As an example, the 'line' outlining only this side of the 20 ° C water was labeled the 20 ° C temperature front. This was done for all temperature divisions. Figures 3 and 4 display the temperature fronts for image 85 broken up into their respective geographic regions. Once these temperature space curves were produced, fractal analysis was undertaken. In the future, it would be interesting to apply these same techniques to the temperature front 'line' along the ocean side of the Gulf Stream to see how closely the fractal dimensions for the two sides compare to one another.

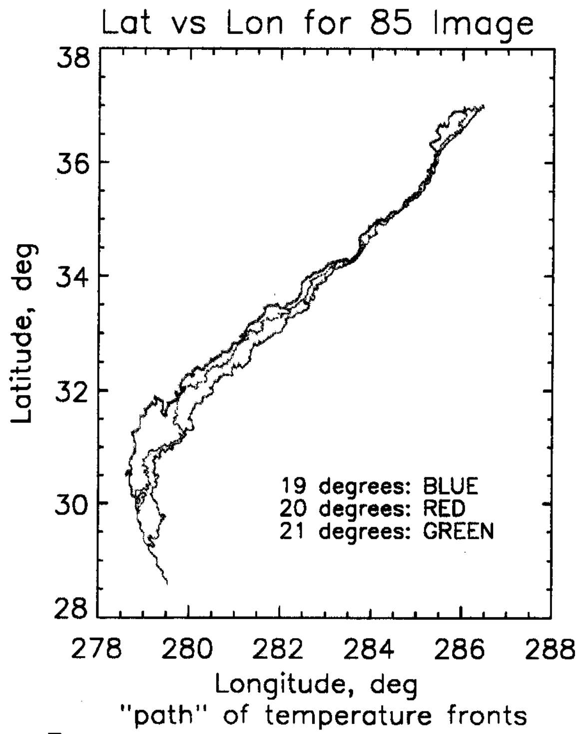


Fig. 4. Temperature fronts less than 37 deg. for image 85.

By making log/log plots of the yardstick length versus the approximate length of the trajectory, the fractal dimension of the space curve can be calculated. Once the slope of the log/log plot is determined, the following equation is used to calculate the fractal dimension:

$$D = 1 - slope, \tag{1}$$

where D is the fractal dimension.

The trajectories of the satellite-tracked drifters display an average fractal dimension of 1.21 ± 0.02 over a scaling range of 83 - 343 km. This average value is generally consistent with previous studies. Osborne, et al. (1989) applied three different fractal analyses methods on three drifters deployed in the Kuroshio extension in 1977. The yardstick method was one of the methods used to determine the fractal dimension of the drifter trajectories. The average fractal dimension for the drifters was $D = 1.23 \pm 0.06$ on the scaling range of 20 to 100 km (Osborne, et al., 1989). Also using the yardstick method, Sanderson and Booth (1991) calculated the average fractal dimension of ten drifters released in the NE Atlantic over the Rockall Trough in 1983. They determined that $D = 1.28 \pm 0.08$ over the space scales extending from 5 to 100 km (Sanderson and Booth, 1991). Previous studies and the present study show that the drifter trajectories are fractal.

Figure 5 illustrates the fractal dimension for the two geographic regions of the satellite images, as well as the entire temperature front of the image. The average fractal dimension for both regions is approximately 1.11 ±

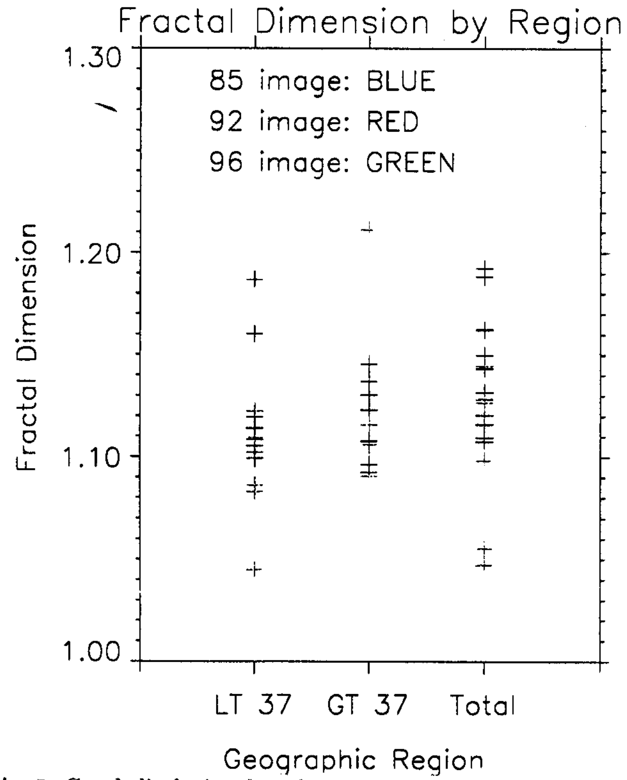


Fig. 5. Graph displaying the value of the fractal dimension for the different geographic regions. LT 37: less than 37 degree region, GT 37: greater than 37 degree region.

0.01. Comparisons between the two geographic sections show that there is no variability in the fractal dimension. Thus, it suggests that there is no dependence on the location of the temperature front and its value of D. Table 1 shows that the fractal dimension and scaling range is internally consistent for the image temperature fronts. The values of the fractal dimension confirm that the contemporaneous data set is weakly fractal at best.

Table 1. Fractal Dimension Values for Temperature Fronts and FACTS drifters

- Drifters: ave D = 1.21 ± 0.02, scaling range= 83 - 343 km
- Temp. Fronts, < 37: ave D = 1.11 ± 0.01 scaling range = 4 - 43 km
- Temp. Fronts, > 37: ave D = 1.12 ± 0.01 scaling range = 4 - 44 km
- Entire Temp. Front: ave D = 1.11 ± 0.01 scaling range = 6 - 39 km

4 Spectral Analysis

There is a close relationship between the fractal character of a signal and its power spectrum, provided that the spectrum has a pure power law, $f^{-\alpha}$, and the Fourier phases are uniformly distributed random numbers. Osborne, et al. (1989) show that the spectral slopes of the

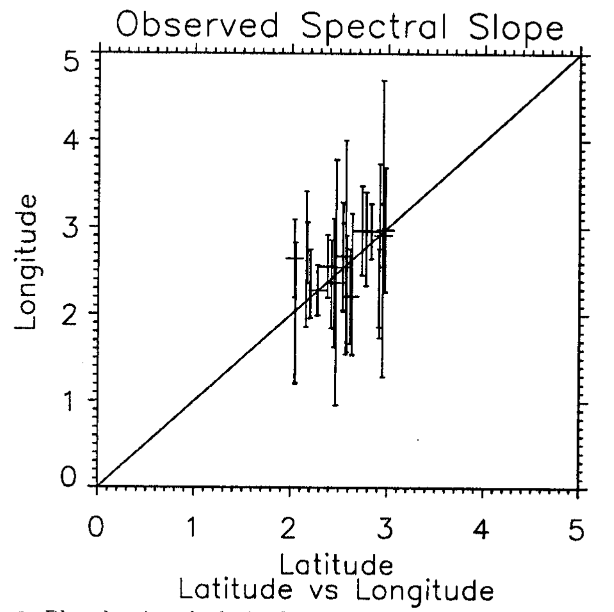


Fig. 6. Plot showing the latitude versus longitude displacements for the Observed spectral slope for both geographic regions. Error bars are included.

latitude and longitude components of the data can be related to its fractal dimension by the following equation:

$$D = min[2/(\alpha - 1), N], \tag{2}$$

where D is the fractal dimension, α is the slope of the spectrum and N is the space dimension. The fractal dimension of a space curve implies a power-law dependence of its power spectrum. In contrast, the power-law dependence does not necessarily imply fractal behavior because the spectrum may not be purely power law and the phases may not be perfectly random. However, it can be used as an indicator of possible fractal behavior.

Power spectral analysis was applied to the latitude and longitude displacement data for the two data sets. Power-law spectral plots were graphed where the best fit line of the least squares fit method was used to determine the slope of the power-law spectrum. Slope values were obtained from the unfiltered spectra. Estimates of the spectral slope using Eq. 2 were also calculated. Henceforth, these spectral slope values will be called observed spectral slope and calculated spectral slope for the former and latter, respectively.

The definition of self-similarity states that the geometric shape of any space curve is identical at all scaling ranges (Moon, 1987). Thus, there is no preferred length scale for such space curves. Figure 6 shows a test for self-similarity for the spectral slopes of the composite image temperature fronts. The solid line is a line of slope equal to one. If the data set were self-similar, we would expect the observed spectral slope values for the longitude and latitude components to be the same. As shown by Fig. 6, there is a wide range of scatter around the 45° line, indicating that the space curves are not self-similar. The amount of scatter about this line is not dependent on the geographic location of the temperature front data. This suggests that geographic location does not play a part in the self-similarity and fractal nature of the space curve. The error bars displayed in Fig. 6 represent the statistical limits of the least squares fit method.

True fractals should exhibit a spectral slope commensurate with the fractal dimension (Osborne, et al., 1989). If our data set is fractal, we would expect a strong correlation between the observed and calculated spectral slopes. Thus, it is necessary to determine whether the fractal dimension agrees with the spectral slope values. However, determining spectral slopes is not always a straight forward matter. Slope characteristics often are dependent upon the degree of spectral smoothing and the a-priori selected scaling range. This is illustrated in Fig. 7, which is a comparison of slopes determined from raw spectra for a scaling range of about 60 to 250 km with the slopes inferred from the fractal dimension. There is considerable scatter in this plot. This can be reduced by smoothing the spectra and/or restricting the scaling range.

The lack of a strong correlation between the observed and calculated spectral slope values would suggest to some that the composite image temperature front data is fractal but that the spectra may not be perfect power laws and the phases may not be purely random. However, for the reasons given above this is not necessarily true. Further analysis is required to resolve this issue.

A comparison between the degree of error displayed in Fig. 6 and Fig. 7 shows that the large uncertainty in the observed spectral slope may disguise the amount of correlation between the observed and calculated spectral slopes. Because of the large difference in error for the two sets of spectral slope values, it appears that the filtering/biasing which occurs in each analyses method effects the estimates differently.

The scaling ranges and observed spectral slope values for geographic regions of the three composite images are given in Table 2. The greater than 37°N region has a higher scaling range than the less than 37°N. Observed spectral slope values in the greater than 37°N are fairly consistent with an average of 2.61 ± 0.11 over an average scaling range of 63 - 250 km. The less than 37°N region has inconsistent observed spectral slope values. These values also scale over a smaller length scale range.

5 Conclusions

We have studied a contemporaneous data set of satellite-tracked drifter buoys and AVHRR composite satellite imagery by fractal and spectral analyses. Comparisons were made to determine whether or not there was a strong link between the two data sets. Detailed analyses shows that there is not a strong tie between the composite temperature fronts and the trajectories of the surface drifters.

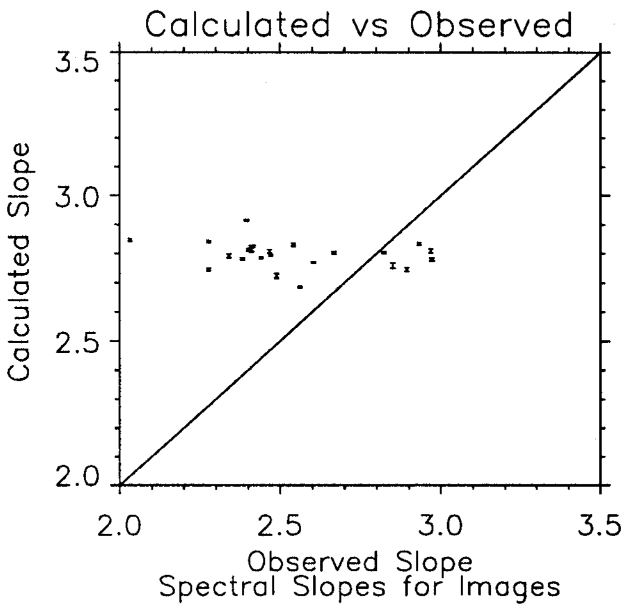


Fig. 7. Plot of the Observed spectral slope versus the Calculated spectral slope for both geographic regions. The solid line represents the 1:1 line. Error bars are included.

The composite image data was divided into two regions: greater than 37°N and less than 37°N, in order to determine whether the location of the temperature front affects the values calculated for the spectral slope and fractal dimensions. Results show that the spectral slope and fractal dimension of the different regions, as well as the corresponding scaling range, are consistent. Thus, there is no geographic variability to the contemporaneous data set. The fractal dimension also suggests that the contemporaneous data set is not fractal.

The observed spectral slope scaling range for the composite imagery is different for the two regions. The temperature front spectral slope for the greater than 37°N scales over the range 63 - 249 km, whereas the other

Table 2. Observed spectral slope values and scaling ranges

Scaling Range: Entire Front		
IMAGE	SPECTRAL SLOPE	RANGE
85	2.66 ± 0.16	71 - 159 km
92	2.68 ± 0.04	81 - 191 km
96	2.81 ± 0.12	96 - 240 km
Scaling Range: > 37 deg		
IMAGE	SPECTRAL SLOPE	RANGE
85	2.66 ± 0.12	113 - 423 km
92	2.66 ± 0.06	55 - 134 km
96	2.52 ± 0.14	22 - 190 km
Scaling Range: < 37 deg.		
IMAGE	SPECTRAL SLOPE	RANGE
85	2.73 ± 0.10	29 - 53 km
92	2.35 ± 0.10	79 - 266 km
96	2.47 ± 0.12	40 - 76 km

region has a scaling range of 49 - 132 km. A suitable scaling range for the contemporaneous data set is approximately 80 - 200 km.

As stated earlier, a direct relationship can be made between the fractal dimension of the space curve and its spectral slope. This relationship can be used to possibly determine whether a data set is fractal or not. This analyses was done in order to determine whether the fractal dimension was a reliable indicator of the spectral slope. The results indicate that this is not a straight forward issue and that previously reported analyses may not be consistent. Resolution of this issue is being pursued separately.

For this research effort we have restricted our studies to 5-day composite imagery. Analyses suggests that the 5-day composite is not a good indicator of the fractal character of drifter trajectories. The temperature front fractal dimension, scaling range and spectral slope values are substantially different from the drifter data. More research is needed to see if 10-day or 15-day composite images are reliable indicators of the fractal properties of the drifter paths.

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References

Brown, O.B. and G.P. Podesta, Satellite sea surface temperature (SST) climatology development for fisheries. Final Report, Contract NA 85-WC-77-06134, submitted to US National Oceanic and Atmospheric Administration. Univ. of Miami, 1989.

Sanderson, B. G., and D. A. Booth, The fractal dimension of drifter trajectories and estimates of horizontal eddy-diffusivity, *Tellus*, *43A*, 334 – 349, 1991.

Svejkovsky, J., Sea surface flow estimation from advanced very high resolution radiometer and coastal zone color scanner satellite imagery: A verification study, *J. Geophys. Res.*, *93*, 6735 – 6743, 1988.

Vastano, A. C., and S. E. Borders, Short communication: Sea surface motion over an anticyclonic eddy on the Oyashio Front, *Rem. Sens. Envi.*, *16*, 87 – 90, 1984.

La Violette, P. E., Advection of submesoscale thermal features in the Alboran Sea gyre, *J. Geophys. Res.*, *14*, 550 – 565, 1984.

Mandelbrot, B. B., How long is the coast of Britain? Statistical self-similarity and fractional dimension, *Science*, *155*, 636 – 638, 1967.

Mandelbrot, B. B., *Fractals: form, chance and dimension*, Freeman, 1977.

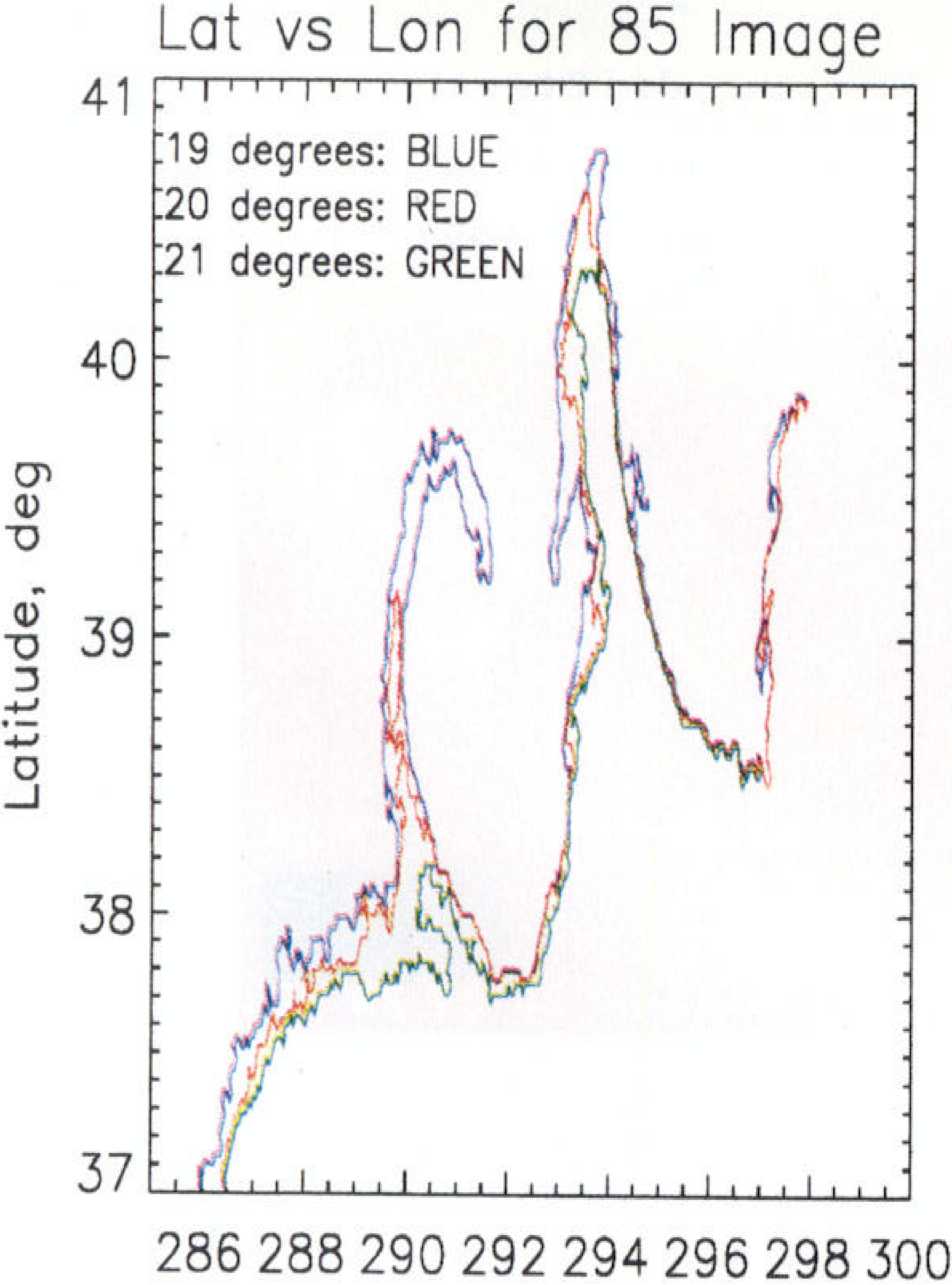
Mandelbrot, B. B., *The fractal geometry of nature*, Freeman, 1983.

Maul, G.A., FACTS: The Florida Atlantic Coastal Transport Study, *EOS*,*66*, *(19)*, 434 -435, 1985.

Moon, F. C., *Chaotic Vibrations: An introduction for applied scientists and engineers*, John Wiley & Sons, 1987.

Osborne, A. R. et al., Fractal drifter trajectories in the Kuroshio Extension, *Tellus*, *41A*, 416 – 435, 1989.

Physical Oceanographic Study of Florida's Atlantic Coast Region - Florida Atlantic Coast Transport Study (FACTS), 2-Tech Report, Florida Institute of Technology, 1986.



"path" of temperature fronts

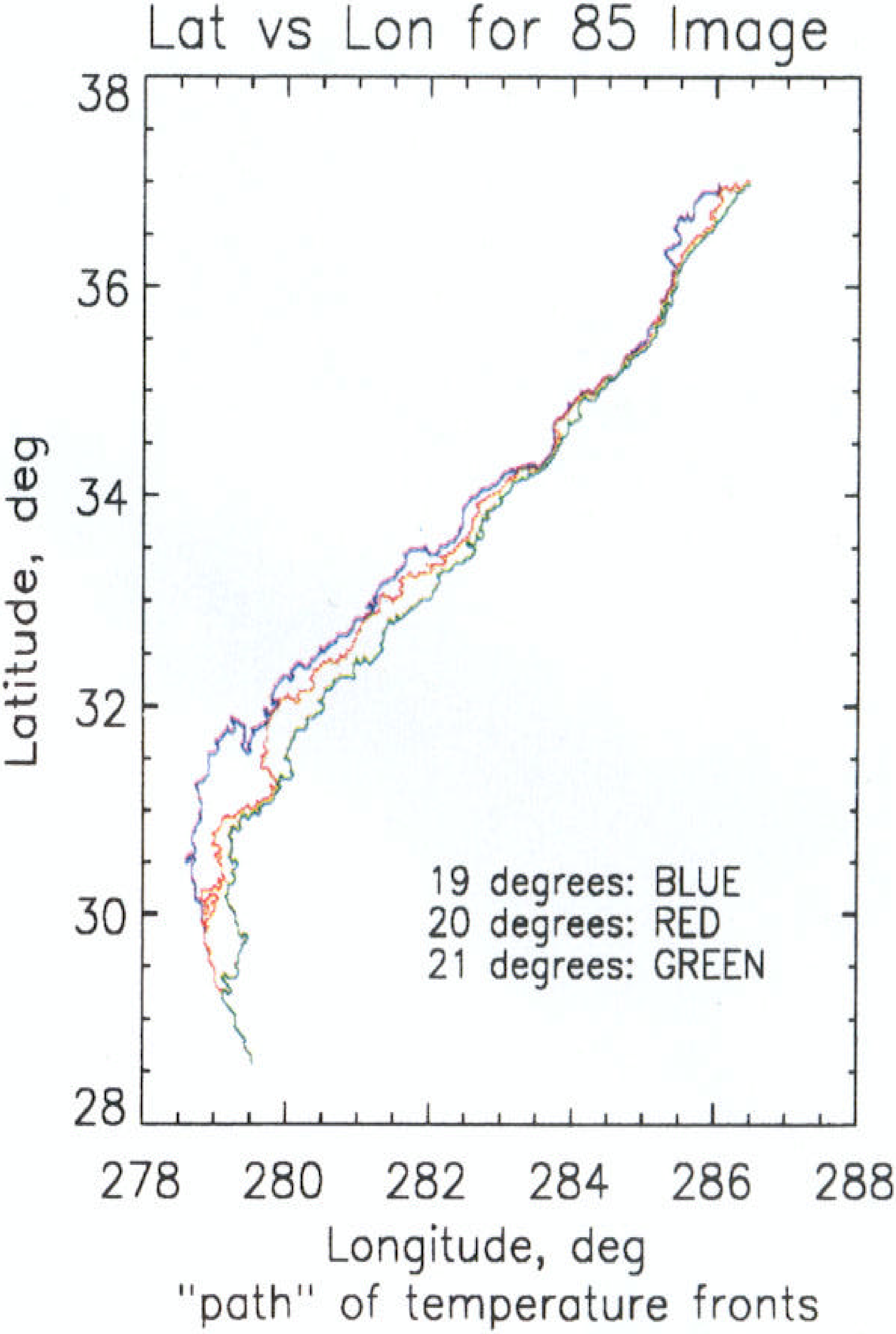


Fig. 4. Temperature fronts less than 37 deg. for image 85.