The Feasibility of Estimating Ocean Surface Currents on an Operational Basis Using Satellite Feature Tracking Methods

L. C. Breaker,*
V. M. Krasnopolsky,+
D. B. Rao,*
and X.-H. Yan**

Abstract

The feasibility of using a relatively new technique, often referred to as satellite feature tracking, for estimating ocean surface currents is described. Sequential satellite imagery is used to determine the displacements of selected ocean features over the time intervals between successive images. Both thermal infrared (IR) imagery from the Advanced Very High Resolution Radiometer (AVHRR) and ocean color imagery have been used to conduct feature tracking. Both subjective and objective techniques related to feature tracking exist to estimate surface flow fields. Because of the requirement for accurate earth location and coregistration of the imagery used in feature tracking, the technique has been primarily restricted to coastal regions where landmarks are available to renavigate the satellite data. The technique is identical in concept to the approach that has been used in meteorology for the past 25 years to estimate low-level winds from geostationary satellite data.

Initially, a description of the feature tracking technique is given, followed by the history of satellite feature tracking in oceanography. Next, the limitations associated with this technique are discussed. Also, only a few validation studies have been conducted to verify the results of satellite feature tracking. These studies are summarized together with some new results. Although this technique produces surface flow patterns that generally agree with the expected patterns of flow, discrepancies in speed and direction are often found when detailed comparisons with in situ observations are made. With respect to current speeds in particular, serious underestimates have occasionally been observed. A case study is given illustrating the technique for the slope water region off the U.S. East Coast. Finally, an example of a surface current analysis that is being produced experimentally for one region off the East Coast is presented.

In spite of certain limitations, this technique offers the potential for acquiring synoptic-scale coverage of the surface circulation in coastal areas on a quasi-continuous basis. Such information will be vital in supporting hydrodynamic circulation models that are currently being developed for U.S. coastal waters.

*NOAA, National Meteorological Center, Washington, D.C.
+General Sciences Corporation, Laurel, Maryland.
**University of Delaware, Newark, Delaware.
Corresponding author address: Laurence C. Breaker, National Oceanic and Atmospheric Administration, National Meteorological Center, Washington, DC 20233.
In final form 5 May 1994.

1. Introduction

Surface currents play an important role in a number of ocean-related activities such as search and rescue missions, containment of oil and toxic chemical spills, optimal ship routing, and the management and exploitation of living and nonliving resources. The measurement of surface currents, however, has been a continuing problem in oceanography since the time observations of ship drift were first recorded. Eulerian measurement techniques, when applied to the upper surface layer of the ocean, have encountered problems due to mooring and instrument motions from surface waves. Lagrangian measurements using drifters also present problems for estimating surface flows. Such observations are not usually acquired at the surface but at some depth below the surface. Also, the logistics and cost of deploying drifters make them a poor choice for attempting to obtain synoptic coverage on an operational basis. Because of the inherent limitations in estimating surface currents using conventional measurement techniques, remote sensing techniques, such as satellite feature tracking, are being used more extensively to obtain information on the surface circulation of selected ocean areas.

Satellite feature tracking is accomplished by measuring the displacements of selected thermal or ocean color features (or patterns) between successive satellite images (usually ~12 or ~24 h apart) that have been spatially aligned or coregistered. The technique has been used to estimate the surface circulation in such regions as the California Current, the Gulf Stream, in and around the Kuroshio Current, the Gulf of Mexico, the English Channel, off the west coast of Ireland, and over the Chatham Rise off New Zealand.

There has been no detailed report summarizing the essential elements of the feature tracking approach, its limitations, and the possibility of producing satellite-derived surface current analyses on a regular basis. Consequently, this report explains the technique (including a short history of its development), outlines the major problems associated with it, presents a case study, and, finally, offers prospects for the future, including a brief description of an experimental surface current analysis that is currently being produced and could lead to the generation of a fully operational product in the future.

2. Satellite feature tracking

The concept of feature tracking is based on elementary kinematics where the displacement of a unique feature (thermal or ocean color) at the ocean surface, which can be identified in two successive satellite images, is measured and then divided by the time interval between the images to obtain the corresponding velocity. Consider Fig. 1: if (x_1, y_1) are the coordinates of a particular feature at time t_1, and (x_2, y_2) are the coordinates of the feature at time t_2, then the displacement of the feature can be expressed in standard Cartesian coordinates approximately[1] as

$$\mathbf{D} = (x_2 - x_1)\mathbf{i} + (y_2 - y_1)\mathbf{j}, \qquad (1)$$

[1]To be more precise, **D** should be calculated as the great circle distance over the surface of the earth, but for the small displacements that are usually encountered in practice, **D** calculated according to (1) is very close to the great circle distance.

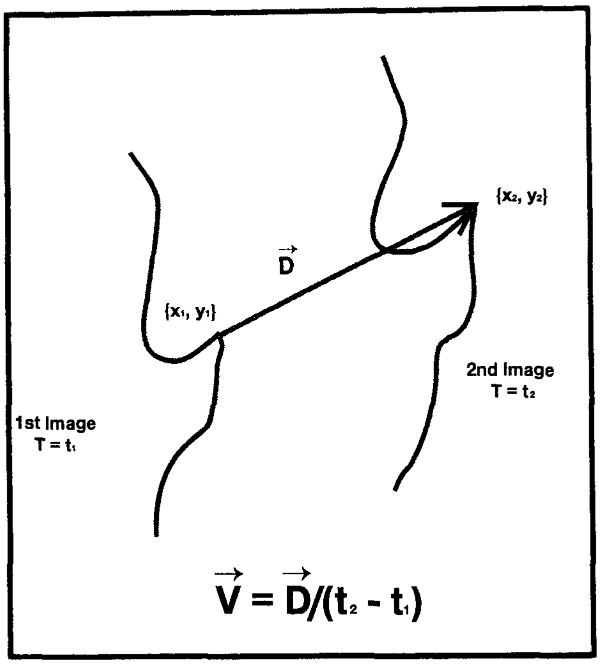

FIG. 1. A sketch of the basic kinematics involved in satellite feature tracking.

and for the time interval $\Delta t = t_2 - t_1$, the corresponding velocity is

$$\mathbf{V} = \mathbf{D}/\Delta t. \qquad (2)$$

In practice, feature tracking is accomplished using an image display system where successive images can be coregistered and compared. By flickering back and forth between the images, the movement of selected features can be tracked from one image to the next. To measure the feature displacements, the earth locations (i.e., coordinates) of the features in each image must be known or determined. Two images approximately 24 h apart are shown in Fig. 2 (10 and 11 May 1993), and the corresponding surface current vectors obtained from feature tracking are shown in Fig. 3. Although these images appear to be quite similar, it is the subtle changes that occur in the locations of the features, between the images, that provide the basis for inferring the field of motion. Also, to clearly identify and track the movement of the various features portrayed, it was necessary to greatly increase the grayshade contrast in these images.[2] According to Fig. 3, vigorous flow to the northeast (>50 cm s^{-1}) is associated with the Gulf Stream, whereas weaker but well-organized flow to the southwest is indicated in the slope water region located between the Gulf Stream and the continental shelf. Flow into Delaware Bay is also apparent.

Feature tracking relies on the subjective identification and tracking of individual ocean surface features. Related pattern matching techniques are also used to estimate surface flows objectively and automatically. Some of the advantages and disadvantages of pattern matching techniques are discussed in the following section. Most of the software and hardware required to conduct feature tracking is available commercially. Currently-available workstation technology is especially well suited to this task.[3]

3. The application of satellite feature tracking to the problem of estimating ocean surface currents

a. History

Satellite feature tracking is related to change detection analysis, a field that has a long history in military

[2]Often edge enhancement techniques are applied to further clarify the features of interest.

[3]A dedicated feature tracking system is being used at the National Oceanic and Atmospheric Administration's (NOAA's) National Meteorological Center that incorporates a VAX/VMS 4000 workstation together with Interactive Data Language (IDL)-based software.

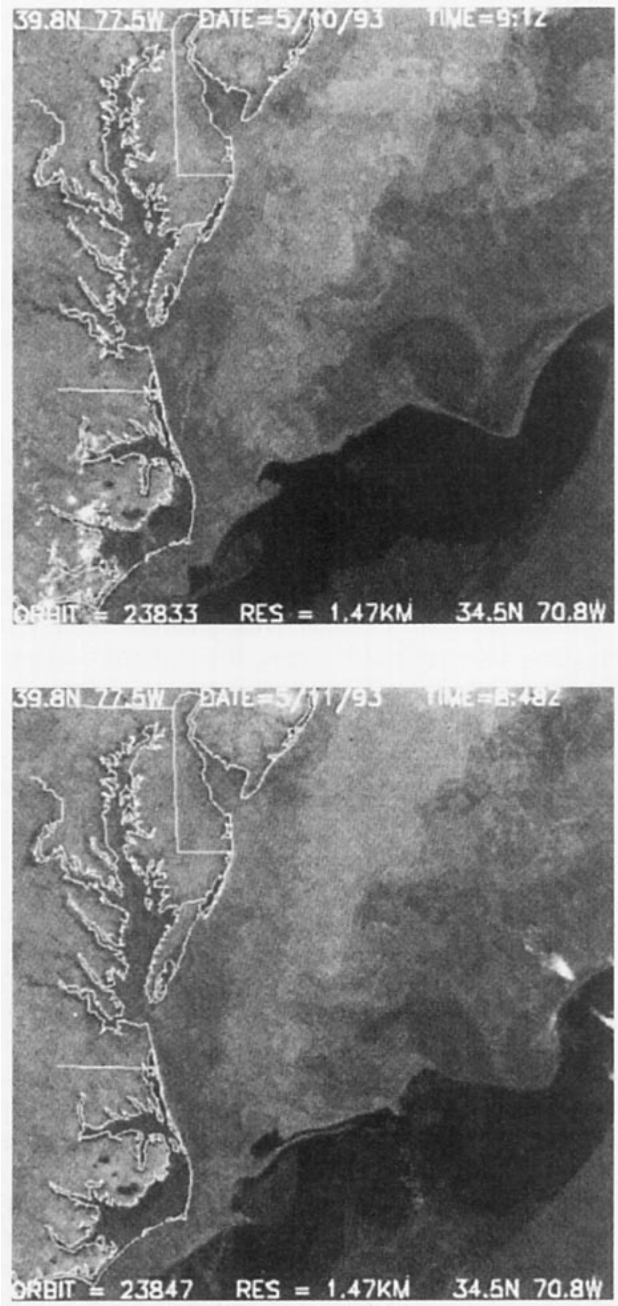

FIG. 2. Two AVHRR satellite SST images for the region 34.5°–39.8°N and 70.8°W to the coast. The top image was acquired at 0910 UTC 10 May 1993 and the lower image at 0848 UTC 11 May 1993. The resolution in each case is 1.47 km per pixel.

reconnaissance (e.g., Doty 1958). Feature tracking has been used by meteorologists for the past 25 years or so to estimate low-level winds by tracking the displacements of selected cloud elements in sequential imagery from geostationary satellites (e.g., Hubert and Whitney 1971). Sea-ice motion has been estimated from sequential satellite imagery since the mid-1970s using visual, IR, and synthetic aperture radar satellite data.

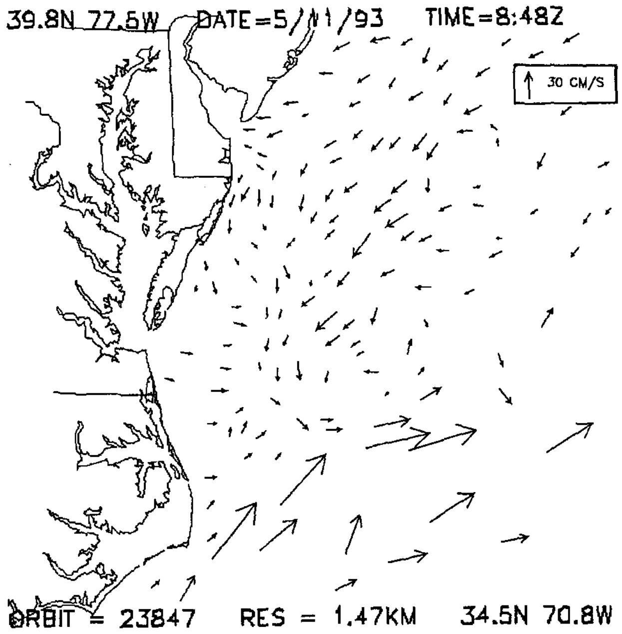

FIG. 3. Ocean surface currents obtained from the images shown in Fig. 2 using satellite feature tracking. The velocity vectors are plotted at the midpoints between the locations of the features in the two successive images.

Feature tracking methods in oceanography were originally applied to aerial photography to estimate the circulation in coastal regions (e.g., Burgess and James 1971). Dye markers were often used to establish a basis for tracking the movement of surface waters (e.g., James 1972). Spence and Legeckis (1981) and Koblinsky et al. (1984) estimated eddy-related velocities for a Gulf Stream cyclonic eddy and eddies in the California Current, respectively, using feature tracking applied to Advanced Very High Resolution Radiometer (AVHRR) satellite data. Vastano and Bernstein (1984) and Vastano and Borders (1984) estimated surface velocities in and around the Oyashio Front off Hokkaido, Japan, using feature tracking applied to AVHRR satellite data. Using the results of feature tracking from the Oyashio region, Vastano and Reid (1985) derived a streamfunction expansion for the surface flow field from which they estimated the sea surface topography.

Emery et al. (1986) adapted an objective technique for automating the feature tracking approach that had previously been accomplished subjectively by an analyst. The method employs pattern or template matching between two images and is referred to as the maximum cross-correlation (MCC) method.[4] Surface currents in the English Channel were estimated using

[4]Essentially the same technique has been used by meteorologists for about 20 years to estimate low-level winds (Leese et al. 1971).

the MCC method applied to ocean color satellite data from the Coastal Zone Color Scanner (CZCS) (Garcia and Robinson 1989).

Kelly (1989) presented an inverse model to infer surface flow fields using the nondiffusive temperature conservation equation applied to successive AVHRR-derived maps of SST. To produce realistic flow fields, the divergence, energy, and vorticity were minimized. For a series of AVHRR images off northern California, results obtained using this inverse technique compared favorably with simultaneous in situ Doppler acoustic log measurements acquired in an area where the SST gradients were strong. This approach, although not a feature tracking technique per se, produces results that are comparable to those obtained using automated feature tracking (Kelly and Strub 1992).

Wahl and Simpson (1990) examined the physical processes that influence the velocities obtained using the MCC method. The effects of both diffusion and air–sea heat exchange were considered. Surface velocities in and around the Gulf Stream obtained using the MCC method were compared with simulated surface currents from a numerical model for this region (Emery et al. 1992). For model-generated realizations less than 12 h apart, excellent agreement was found between the model-generated flows and those obtained using the MCC method.

b. Limitations

A number of problems exist in the application of the feature tracking technique for estimating ocean surface currents. It is assumed that sea surface temperature (for IR satellite data) or surface chlorophyll concentration, or other derived parameters from ocean color, serve as conservative passive tracers of the flow. Further, the motion is assumed to be solely advective. Local thermodynamic processes, however, can produce changes in the surface temperature field that may be interpreted as advective when, in fact, they were due to surface heat exchange or diffusion (Wahl and Simpson 1990). Nonconservative effects can lead to local changes in SST that will be interpreted as advective in the case of feature tracking and thus could lead to serious errors in estimating surface velocities. Ocean color may likewise be affected by nonconservative effects due to local changes in biological productivity. Also, confusion may arise between propagating wave and advective motions in regions where both types of motion occur. Propagating waves move with phase speeds that often greatly exceed the speeds associated with advective motions. Propagating waves, for example, occur along the northern boundary or north wall of the Gulf Stream, and care must be taken to avoid tracking the nonadvective motions that occur in such regions.

The extent to which feature tracking captures the total flow field, rather than the along-isotherm or cross-isotherm components for SST, is a question that often arises in evaluating surface velocities obtained using the feature tracking technique. A range of possibilities exists; in some cases the cross-isotherm component of the flow may be the only contribution to the flow field that is detectable from the SST gradient structure. In other situations, detectable features may be transported primarily by the along-isotherm component of the flow. The extent to which feature tracking captures the total flow will vary depending on the features that can be detected and the type(s) of flow that occur.

The time separation between the images used in feature tracking is an important consideration. If the time separation is too short (several hours or less), then the feature displacements may be so small (several kilometers or less) that any errors in earth location, for example, make it difficult to estimate the corresponding velocities with reasonable accuracy. If the time separation is too long, the features begin to lose their identity, making it difficult to track them. In practice, time separations between images of 12–24 h appear to work well for AVHRR data (Svejkovsky 1988), although Tokmakian et al. (1990) found that the greatest accuracies in estimating surface velocities were achieved when the interval between the images was minimized.

The motion between images is generally assumed to be rectilinear when, in fact, it may contain rotational components. The problem of possible unresolved rotational motion generally arises for both feature tracking and pattern matching techniques. This problem, however, whether interactive or automated techniques are used to estimate the flow, is minimized by keeping the time separation between the images as short as possible.

Finally, two of the most important (and obvious) limitations of feature tracking are 1) cloud cover and 2) the lack of features, or gradient structure, in the SST or ocean color fields. For example, in the Gulf of Mexico during the summer, the surface mixed layer becomes essentially isothermal and, as a result, it becomes difficult or impossible to apply feature tracking in this region using IR imagery.

c. Earth location accuracy

Another problem associated with satellite feature tracking is earth location accuracy. Errors in earth location can translate directly into errors in the calculated surface velocities and, in fact, can be amplified because the feature tracking process essentially requires a differencing of the images involved. In some cases, certain navigation errors may be common to the images used in the feature tracking and, as a result, may be compensatory. Such compensatory effects cannot be relied upon, however, and so the absolute accuracy in earth locating the satellite data is critical. Absolute errors in navigation of up to 15 km for AVHRR satellite data have been observed (e.g., Krasnopolsky and Breaker 1994). Since errors of this magnitude are often of the same order as the actual feature displacements, clearly, such errors must be taken into account. The cover figure shows surface flow vectors in the Gulf Stream area off North Carolina obtained using feature tracking applied to an AVHRR image pair acquired on 31 January 1993, approximately 12 h apart. At a number of locations, velocities with (white) and without (black) navigation corrections are shown. The corrections for navigation error alter the apparent speed and direction of flow significantly, particularly in cases where the flows are relatively weak. The mean difference in current speed between the original and the corrected fields is 27 cm s^{-1} and the mean difference in direction is 34°.

Landmarks are often used to improve the navigation for images acquired over coastal areas. As geographic anchor points, they serve as the basis for stretching or warping the image to achieve alignment with an earth-oriented coordinate system. The mathematical procedures that are employed determine, in part, how well this stretching or remapping process is accomplished. Also, very small errors in the corrections that are generated over land where landmarks are available can grow rapidly when they are extrapolated over the ocean. The process of extrapolating navigation corrections away from landmarks is particularly sensitive to the distribution of landmarks, the uncertainty in their location, and the mathematical expansions that are used to represent the corrections (Krasnopolsky and Breaker 1994).

Several sources of navigation error exist. Timing errors due to clock drift aboard the spacecraft, and departures in the satellite orbit from ephemeris model predictions, for example, may cause relatively large errors in navigating AVHRR satellite data. However, these errors can usually be corrected by applying a simple realignment of the images with respect to the underlying geography because the resulting error fields are spatially uniform. Of greater concern are situations where the navigation errors are not spatially uniform (i.e., over distances of ~1000 km or less). Rapid variations in the navigation error field often reflect variations in spacecraft attitude due to roll, pitch, and yaw. For nonuniform navigation errors, constant corrections over an entire scene may be unsatisfactory; instead, linear or even nonlinear corrections may be required. As the navigation corrections become more complicated, however, the potential for errors in these corrections to become large over the ocean increases. The rapid variations in navigation error described above can be reduced by including information on roll, pitch, and yaw in ephemeris models that provide global navigation for polar-orbiting satellite data. Procedures such as those developed by Krasnopolsky and Breaker (1994) typically reduce errors in earth location by at least a factor of 4, and under favorable conditions rms errors of 1–2 pixels can be achieved.

d. Objective versus subjective techniques

It is clearly desirable to employ an objective basis for estimating surface flows in order to eliminate the need to select features subjectively. Also, objective techniques may be successful in resolving the flow in areas where distinct features are difficult to find when feature tracking is conducted subjectively. Results obtained subjectively naturally depend in part on the analyst involved. The standard technique for objectively estimating surface flows using sequential imagery is the MCC method mentioned earlier. It relies on pattern matching between coregistered images to obtain the translational motion for predefined subregions within an image. The pattern matching is conducted using two-dimensional cross correlation. The location of the maximum cross correlation defines a displacement and a direction from which a unique surface flow vector can be obtained that corresponds to the subregion being analyzed.

Certain problems arise in the use of the MCC technique. It takes into account only translational motion. Rotational and deformational motions cannot be determined using this approach. Kamachi (1989) modified the MCC technique to include the effects of rotation by using a rotational registration. By including rotation, longer time intervals between images could be employed. Kuo and Yan (1993) used an automated shape matching technique to calculate surface flows from AVHRR imagery and found that the effects of rotation and scale changes, as well as translation, could be taken into account. In a case study conducted in the slope water region off the East Coast, Kuo and Yan estimated the rotational contribution to the flow and found it to be important. The MCC method is also computationally intensive. Wu et al. (1992) used a modified form of the MCC method to calculate advective surface flows that included the application of a statistical test to determine the relative significance levels of the calculated velocities. The test was useful in identifying areas where the MCC method was ineffective.

Objective techniques for estimating surface velocities usually suffer from several deficiencies. First, when the calculations involve cross correlation, the result is a statistic that has a significance level associated with it. Establishing this confidence level and interpreting the result are often difficult. Such problems can arise in areas where the property gradients are weak or ill defined. A second problem relates to spatial resolution. The size of the subregion that is used to conduct the pattern matching must be specified. If the size of the subregion is too large, then important structure in the flow may be lost. If the subregion is too small, confidence in the calculated result may be small. Third, in areas of concentrated, intense flows, the MCC method has been shown to produce large underestimates of the actual flow speeds (e.g., Kelly and Strub 1992).

New pattern recognition techniques are also being developed to estimate surface velocities using sequential satellite imagery. Wu and Pairman (1991) developed a new approach to calculate surface advective velocities using AVHRR imagery. The method relies on pattern matching, but unlike the MCC approach, it performs the matching by establishing feature point correspondences between the images. Yan and Breaker (1993) applied two pattern recognition techniques to AVHRR imagery to obtain estimates of surface flow in the slope water region off the East Coast. The first technique employed 1) pattern selection, 2) pattern recognition, and 3) a set of geometrical calculations to determine both the cross- and the along-isotherm displacements (Pitas and Venetsanopoulos 1986). The second method involves the use of line correspondences and is based on the kinematical equations of motion (see Arce et al. 1987 for greater detail). This technique was used to compute the 11 velocity vectors shown in black in Fig. 4 (and are shown together with 11 flow vectors obtained interactively in the same area).

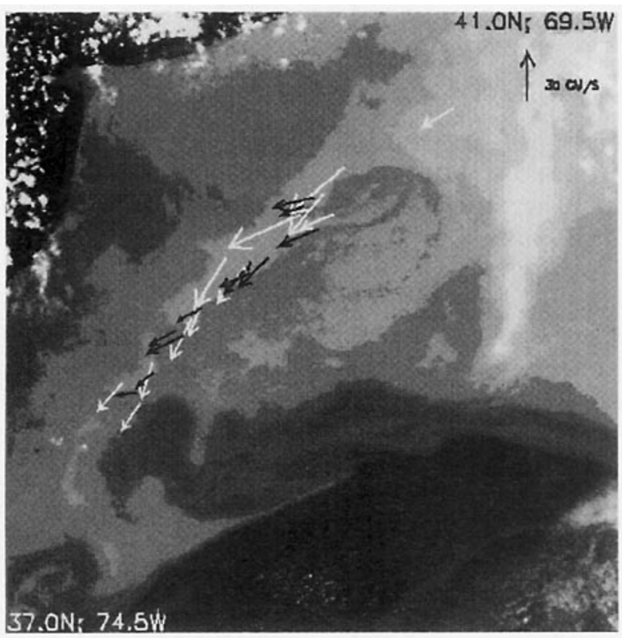

FIG. 4. Two AVHRR satellite images approximately 12 h apart acquired on 24 June 1991 were used to produce the flow vectors shown. The second image, acquired at 1900 UTC 24 June, provides the image background. The area shown (37°–41°N, 70°–74°W) encompasses both shelf and slope waters plus a portion of the Gulf Stream in the lower right-hand corner. Two sets of surface flow vectors for this approximately 12-h interval on 24 June 1991 have been included using 1) the interactive approach (in white), and 2) an objective approach based on pattern recognition (in black)—see text for details.

In practice, an objectively produced first-guess field of surface flow vectors compared against, and then selectively combined with, results obtained interactively may be a reasonable approach for developing an operational product.

e. Validation

Few comparisons have been made between satellite-inferred surface flows and in situ observations in order to determine the accuracy of the satellite-based measurements. This is not surprising in view of the difficulties involved in attempting to acquire simultaneous satellite and in situ data.

Svejkovsky (1988) compared surface flow estimates obtained from AVHRR and CZCS satellite data interactively with surface flows obtained from surface drifters (0.5-m depth) along the California coast. The satellite-derived flows had an rms error of about 6 cm s^{-1} compared to the drifter-derived flows; there was a tendency for the satellite-obtained values to underestimate the in situ values, particularly at speeds greater than 40 cm s^{-1}.

Tokmakian et al. (1990) compared satellite-derived surface flows (AVHRR and CZCS) with in situ Acoustic Doppler Current Profiler (ADCP) and hydrographic data and found rms errors of 14 cm s^{-1} for image separations of 6 h, and 25 cm s^{-1} for image separations of 18 h or greater. Tokmakian et al. attributed these relatively large errors in part to the use of the MCC approach.

Holland and Yan (1992) compared satellite-derived surface currents using an automated feature tracking approach based on pattern recognition with in situ currents (5–10-m depth) acquired from 17 moored buoys in the Delaware coastal region. Both the buoy and the satellite observations were averaged and then correlated for the cases where they could be compared directly. Overall, for all of the 17 buoys taken together, 1) correlation for direction was 0.83 and for speed it was 0.96, and 2) the mean speeds obtained from the buoys were approximately 8 cm s^{-1} higher than those obtained using the automated feature tracking approach of Holland and Yan, where individual buoy mean values ranged from 10.5 to 112.8 cm s^{-1}.

Kelly and Strub (1992) conducted a comprehensive comparison of surface flow fields obtained using two methods applied to AVHRR data, with in situ flow fields obtained from ADCP and near-surface drifter measurements, and with Geosat altimeter data. The methods of estimating surface velocities using the AVHRR satellite data were 1) automated feature tracking (MCC method), and 2) inversion of the heat equation (Kelly 1989). To conduct these comparisons, extensive reprocessing of their data was required. These comparisons were made in the coastal transition zone off northern California over a period of several days in July 1988. The two AVHRR-related methods yielded similar results but differed significantly with the in situ data both in speed and direction. The AVHRR-derived speeds were 30%–50% lower than the in situ data, and the rms differences in direction were approximately 60°. The differences in direction, however, were of the same order as the differences in direction between the two types of in situ data themselves. In the vicinity of locally intense flows, or jets, the AVHRR-derived flows underestimated the geostrophic velocities obtained from the altimeter by 50%–100%. Kelly and Strub found that significantly higher velocities could be obtained using the AVHRR data by subjectively tracking the features, particularly in the regions where the jets occurred. They concluded that the AVHRR-derived flow fields were useful in characterizing the patterns of circulation that occurred and that with additional information, such as altimeter or surface drifter data, the AVHRR-derived flows could be constrained to produce better overall estimates of the speed. Although these results bring into question the utility of the AVHRR-derived estimates of surface flow in this case, it must be emphasized that their results apply only to one relatively small region along the U.S. West Coast where the flow regime is known to be spatially complex and rapidly varying in time. The few similar studies that have been conducted elsewhere, however, have generally shown better agreement between the AVHRR-derived surface flows and in situ data.

We have compared feature tracking results using AVHRR imagery for the Gulf of Maine with the corresponding seasonal flow for this region (Fig. 5). Our synoptic view of the surface circulation was obtained from images acquired on 22 and 23 August 1993 (i.e., approximately 24 h apart). This field has been smoothed slightly in order to suppress the noiselike influence of the semidiurnal tide that cannot be adequately resolved with the satellite observations. Also, we have deleted a small number of the original observations that did not exceed a specified lower threshold for speed (Fig. 5b). This threshold (γ) is a function of the spatial resolution of the satellite imagery used in the feature tracking analysis and the time separation between the images, and is given by

$$\gamma = \frac{k \cdot r}{\Delta t},$$

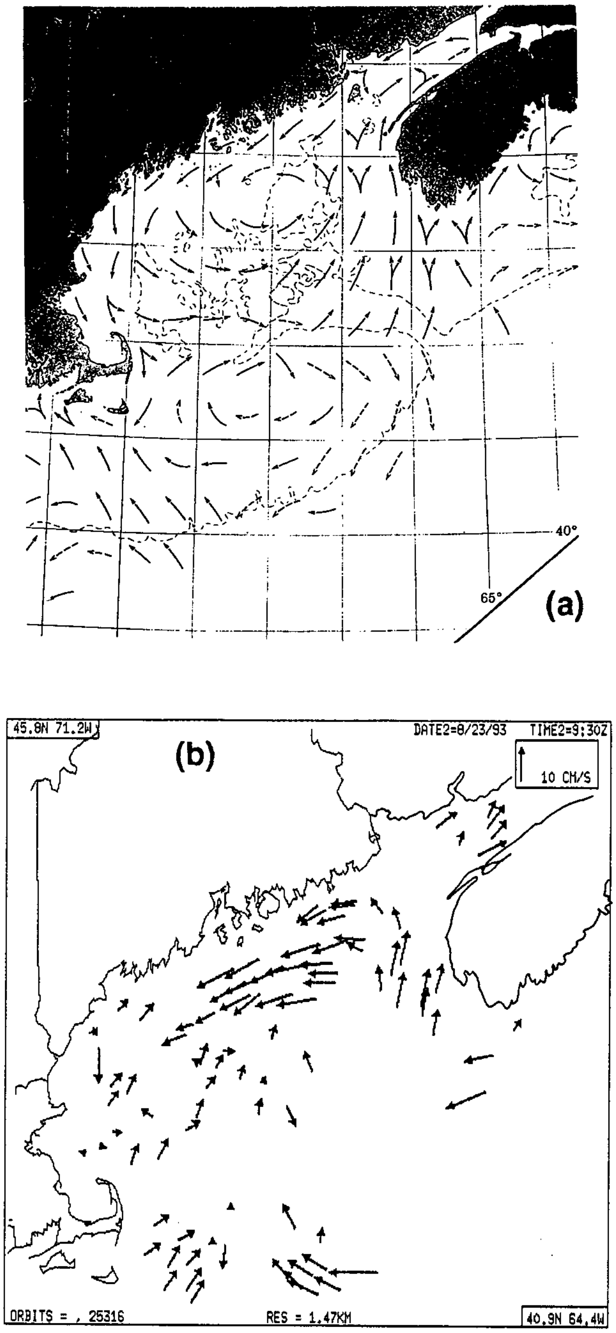

FIG. 5. Panel (a) shows the climatological pattern of surface circulation in the Gulf of Maine during summer and autumn (Bumpus and Lauzier 1965). Panel (b) shows a "snapshot" of the surface circulation in the Gulf of Maine obtained from AVHRR satellite imagery acquired approximately 24 h apart on 22 and 23 August 1993.

where r is the image resolution (1.47 km in our case), Δt is 24 h, and k is a constant (27.8) that converts the results to centimeters per second. Thus, in the present case a threshold of 2 cm s^{-1} was applied.

For comparison, we consider the climatological summer/autumn surface flow for the Gulf of Maine (Fig. 5a) (Bumpus and Lauzier 1965). Both fields clearly show the prevailing cyclonic circulation that occurs in the Gulf of Maine (Bumpus 1973), although the satellite data are too sparse to resolve this eddylike pattern along its southern flank. The satellite observations also reflect to some extent the anticyclonic circulation that is often observed over Georges Bank, just south of the Gulf of Maine.

According to Bumpus, surface currents in the Gulf of Maine are relatively weak, with speeds on the continental shelf varying between about 2 and 6 n mi day^{-1} (4.3–12.9 cm s^{-1}). Table 1 stratifies our results according to speed and shows that 65% of our satellite-derived speeds fall between the specified limits and that 94% fall between the slightly wider limits of 1–7 n mi day^{-1} (2.2–15.0 cm s^{-1}). Although the results of our comparison are not conclusive, the satellite observations and the climatology appear to be in reasonable agreement.

The few studies that have been conducted to validate the feature tracking approach suggest that there is a tendency for feature tracking methods to underestimate the true speeds. Our own work also supports this conclusion. The assumption of rectilinear motion between satellite fixes undoubtedly contributes to this bias. In at least one case, the underestimates of speed were in the range 30%–50%, indicating that a serious problem exists in this area. According to Kelly and Strub (1992), the tendency for AVHRR data to underestimate the speed, particularly in areas where intense flows occur, may represent an inherent limitation in the data rather than a limitation in the method(s).

One of the primary goals in conducting future validation studies should be to obtain sufficient comparison data so that representative error statistics can be generated. These statistics can then be used to calculate confidence limits for the satellite-derived velocity estimates. Once confidence limits can be produced, the utility of these observations will be greatly enhanced.

Table 1. Distribution of surface current speeds in the Gulf of Maine (Bumpus 1973).

Speed interval n mi day^{-1}	Percent of values contained within interval
2.0–6.0	65%
1.8–6.2	70%
1.5–6.5	85%
1.0–7.0	94%

4. A case study: Application to the slope water region off the East Coast

To illustrate the feature tracking technique, a case study is presented where we apply feature tracking to a portion of the slope water (SW) region off the East Coast. This region spans the area between the continental shelf and the Gulf Stream. The circulation in the SW region is dominated by alongshore, southwestward flow from the Labrador Current. Surface currents in this region tend to be weak (of the order of 10 cm s^{-1}) and are generally parallel to the bathymetric contours. The circulation is often disturbed by warm-core rings that entrain waters from the Gulf Stream and the Sargasso Sea. Another prominent feature in the SW region is the shelf/slope front that overlies the continental shelf break. This frontal regime separates shelf water near the coast from slope water farther offshore. Both the shelf/slope front and an eddy centered at 39.5°N, 71.3°W (just to the northeast of the center of the image) are apparent in the AVHRR satellite image shown in Fig. 4.

In the following analyses, three AVHRR IR images, acquired on 24 and 25 June 1991, were employed. The time interval between the first and second images was approximately 12 h, whereas the time interval between the second and third images was approximately 24 h. By selecting a sequence of three cloud-free images closely spaced in time, we were able to examine the continuity of the flow over the entire 36-h period.

Corrections for errors in earth location were initially applied using landmarks to renavigate the images. The analysis was conducted subjectively. A description of the analysis system that was used to conduct the feature tracking is contained in Breaker et al. (1992).

The surface flow vectors that were extracted are shown in Fig. 6a. Twenty-nine velocity vectors were calculated for each of the two adjacent time periods (~12-h interval followed by an ~24-h interval). Overall, the velocities ranged from about 5 to 40 cm s^{-1} and differed significantly for the two adjacent time periods. In many cases there is a significant veering or turning to the right indicated. The dramatic changes in flow direction, which are even more apparent in the streamline analysis shown in Fig. 7b, may have been due to inertial oscillations in the surface mixed layer that

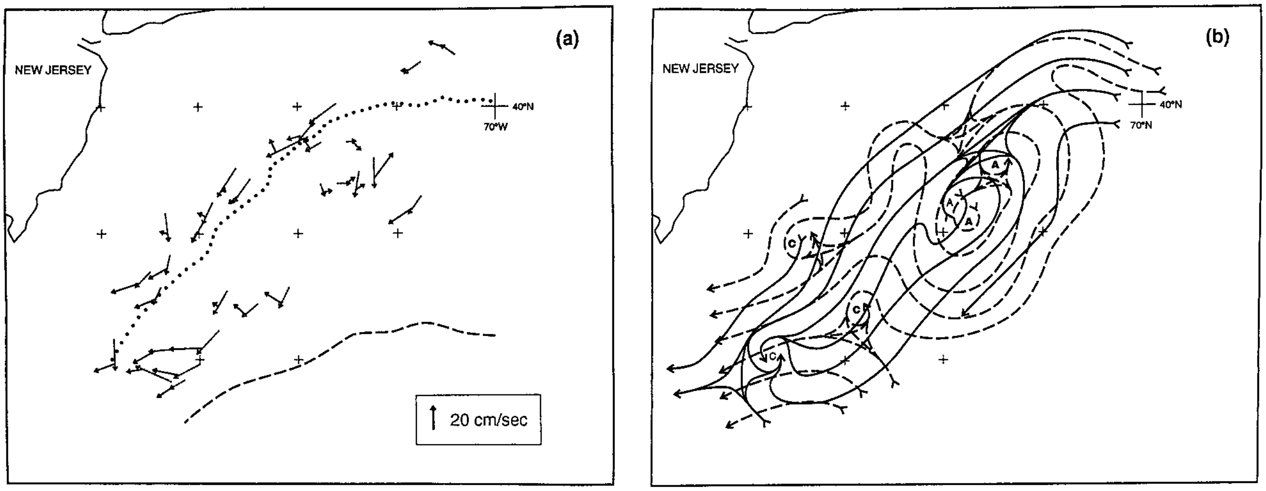

FIG. 6. Panel (a) shows surface flow vectors for two adjacent intervals on 24 and 25 June 1991. (The image from 24 June is shown in Fig. 4.) The first interval was approximately 12 h (solid) followed by an approximately 24-h interval (dashed). The dots indicate the location of the continental margin, and the dashed line indicates the location of the north wall of the Gulf Stream. Panel (b) shows corresponding streamline analyses for each period (first period—solid contours; second period—dashed contours).

resulted from a brief, but intense, wind event on 23 June, a day prior to the start of the satellite sequence.

For comparison with 11 of the subjectively determined surface flow vectors obtained along the shelf/slope front for the initial 12-h period, 11 surface flow vectors were calculated using a fully automated objective approach (Fig. 4). The method relies on pattern recognition and involves the use of line correspondences (see previous section for references). Because this technique includes rotation as well as translation, it has the potential for providing a more accurate description of the surface flow than the MCC method that includes translation only. The surface flow vectors obtained using the objective approach (shown in black) correspond closely to the surface flow vectors obtained using the subjective feature tracking approach (shown in white).

5. Concluding remarks

Feature tracking techniques have reached a state of development where their use should be considered within an operational framework.[5] Feature tracking is now being used in the Gulf of Mexico as part of Texas A&M's Texas Flow Experiment (TEXFLEX) program (Fortnightly LA·TEX 1992) to predict the movement of oil spills that occur in the region. With the availability of real-time AVHRR satellite data [and Sea-Viewing, Wide Field-of-View Sensor (SeaWiFS) ocean color satellite data in the near future[6]] plus recent advances in workstation technology, the production of surface current analyses for U.S. coastal waters on an operational basis is clearly achievable. Although problems still exist in using AVHRR satellite data to estimate surface currents, particularly the speeds, it may be possible to develop methods of correction that will enhance their utility, and efforts should be directed in this area. Also, the possibility of including altimeter data from the *ERS-1* and *ERS-2* satellites is now being examined.

A surface current analysis is being produced by NOAA's Ocean Product Center on an experimental basis using feature tracking applied to AVHRR satellite imagery. This analysis covers the North Carolina coastal region and has been produced weekly since September 1993 (Fig. 7). At this time, the product can be obtained through NOAA's National Climatic Data Center in Asheville, North Carolina.[7]

Since about 1975, at least 25 studies have appeared in the ocean-related literature concerning feature tracking and automated versions thereof. There was a surge of interest in demonstrating the application of these techniques during the mid-1980s. Since then, fewer, but more in-depth, studies have continued to appear.

---

[5]The Japan Meteorological Agency produces the only operational surface current analysis based on observations at the present time. This analysis covers the western Pacific (25°–45°N, 123°–150°E) but includes only GEK, drifter, ship drift, and ADCP observations.
[6]Ocean color data from the SeaWiFS sensor will provide a new and important source of satellite data for feature tracking.
[7]In the near future, it will also be available over a direct dial-in telephone facsimile network.

The problem of satellite data navigation has not received the attention it deserves, particularly with respect to corrections for navigation that are extrapolated over oceanic regions far removed from landmarks. Also, more validation studies are needed to establish a firm observational basis for the feature tracking methodology.

Recent developments related to feature tracking include the use of mathematical inversion methods (e.g., Kelly 1989) and pattern recognition techniques to estimate surface flow fields. Such developments may help to stimulate greater interest in, and use of, feature tracking techniques in the future.

In addition to the important role that satellite-derived surface currents could play in the various applications mentioned earlier, they also would constitute an important source of data for initializing and validating hydrodynamic coastal circulation models. Consequently, there is a real need to implement a system for producing synoptic ocean surface current analyses on an operational basis; the data and the technology are now available to accomplish this goal.

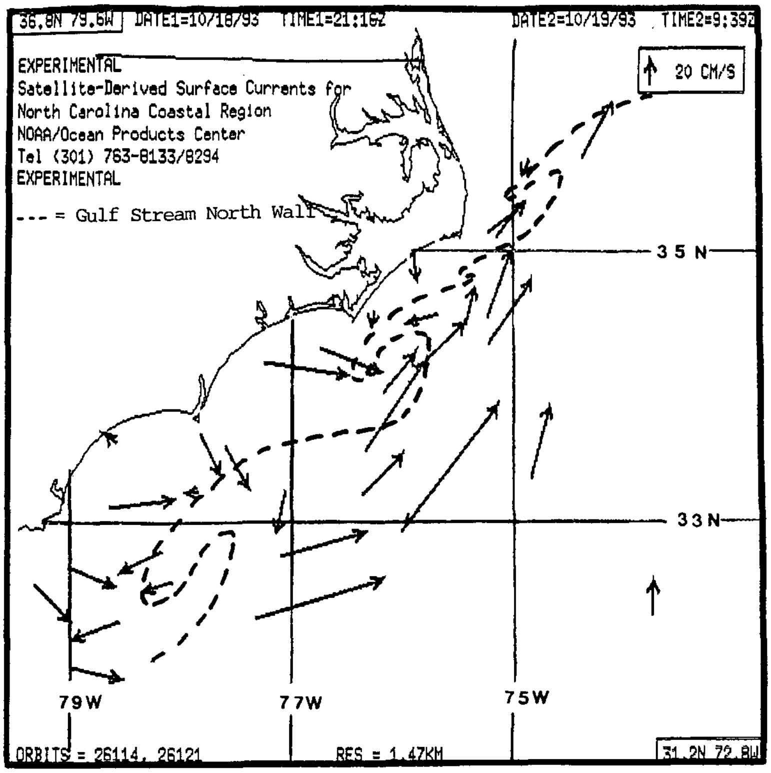

FIG. 7. Experimental surface current analysis for the North Carolina coastal region. This analysis was produced from two AVHRR images acquired approximately 24 h apart on 18 and 19 October 1993.

Acknowledgments. The authors would like to thank Drs. W. Campbell, M. Waters, and E. Kalnay, and Ms. J. Clark for their continued interest and participation in this work. We also thank Dr. Frank Aikman for a thorough review of the manuscript. We acknowledge support from COASTWATCH, a project of NOAA's Coastal Ocean Program. XHY specifically acknowledges support from NOAA/SEA GRANT through Grant NA16RG0162-03. This paper is OPC Contribution No. 93.

References

Arce, G. R., W. E. Wonchoba, and E. R. Malaret, 1987: Estimating the three-dimensional motion of a rigid planar patch in Hough parameterspace. *SPIE Conf. on Advances in Intelligent Robots and Computer Vision,* Vol. 848, Cambridge, MA, Int. Soc. for Optical Engineering, 454–461.

Breaker, L. C., L. D. Burroughs, T. B. Stanley, and W. B. Campbell, 1992: Estimating surface currents in the slope water region between 37° and 41°N using satellite feature tracking. OPC Contribution No. 48, National Meteorological Center, Washington, DC, 47 pp.

Bumpus, D. F., 1973: A description of the circulation on the continental shelf of the east coast of the United States. *Progress in Oceanography,* Vol. 6, Pergamon Press, 111–157.

——, and L. M. Lauzier, 1965: Surface circulation on the continental shelf off eastern North America between Newfoundland and Florida. *Serial Atlas of the Marine Environment,* American Geographical Society, Folio 7, Plate 8, 4 pp.

Burgess, F. J., and W. P. James, 1971: Airphoto analysis of ocean outfall dispersion. Federal Water Quality Office, EPA, Water Pollution Control Research Services 16070 ENS, 290 pp.

Doty, R., 1958: Aloft with balloon and camera. *J. Photographs and Motion Pictures of George Eastman House,* **7,** 197–209.

Emery, W. J., A. C. Thomas, M. J. Collins, W. R. Crawford, and D. L. Mackas, 1986: An objective method for computing advective surface velocities from sequential infrared satellite images. *J. Geophys. Res.,* **91,** 12 865–12 878.

——, C. Fowler, and C. A. Clayson, 1992: Satellite-image-derived Gulf Stream currents compared with numerical model results. *J. Atmos. Oceanic Technol.,* **9,** 286–304.

Garcia, C. A. E., and I. S. Robinson, 1989: Sea surface velocities in shallow seas extracted from sequential Coastal Zone Color Scanner Satellite data. *J. Geophys. Res.,* **94,** 12 681–12 691.

Holland, J. A., and X.-H. Yan, 1992: Ocean thermal feature recognition, discrimination, and tracking using infrared satellite imagery. *IEEE Trans. on Geosci. Remote Sens.,* **30,** 1046–1053.

Hubert, L. F., and L. F. Whitney Jr., 1971: Wind estimation from geostationary satellite pictures. *Mon. Wea. Rev.,* **99,** 665–672.

James, W. P., 1972: Diffusion coefficients and current velocities in coastal waters by remote sensing techniques. *Remote Sens. Environ.,* **3,** 352–361.

Kamachi, M., 1989: Advective surface velocities derived from sequential images for rotational flow field: Limitations and applications of maximum cross-correlation method with rotational registration. *J. Geophys. Res.,* **94,** 18 227–18 233.

Kelly, K. A., 1989: An inverse model for near-surface velocity from infrared images. *J. Phys. Oceanogr.,* **19,** 1845–1864.

——, and P. T. Strub, 1992: Comparison of velocity estimates from

Advanced Very High Resolution Radiometer in the coastal transition zone. *J. Geophys. Res.,* **97,** 9653–9668.
Koblinsky, C. J., J. J. Simpson, and T. D. Dickey, 1984: An offshore eddy in the California Current system. *Progr. Oceanogr.,* **13,** 51–69.
Krasnopolsky, V. M., and L. C. Breaker, 1994: The problem of AVHRR image navigation revisited. *Int. J. Remote Sens.,* **15,** 979–1008.
Kuo, N. J., and X. H. Yan, 1993: Using the shape-matching method to compute sea surface velocities from AVHRR satellite images. *IEEE Trans. Geosci. Remote Sens.,* in press.
LATEX Data Office, 1992: TEXFLEX and TEXFLOW: Texas A&M programs complement LATEX. *Fortnightly LA·TEX,* Vol. 2, No. 1, Texas A&M University, 2 pp.
Leese, J. A., C. S. Novak, and B. B. Clark, 1971: An automated technique for obtaining cloud motion from geosynchronous satellite data using cross-correlation. *J. Appl. Meteor.,* **10,** 118–132.
Pitas, I., and A. N. Venetsanopoulos, 1986: Nonlinear order statistic filters for image filtering and edge detection. *Signal Processing,* **10,** 395–413.
Spence, T. W., and R. Legeckis, 1981: Satellite and hydrographic observations of low-frequency wave motions associated with a cold core Gulf Stream ring. *J. Geophys. Res.,* **86,** 1945–1953.
Svejkovsky, J., 1988: 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.
Tokmakian, R., P. T. Strub, and J. McLean-Padman, 1990: Evaluation of the maximum cross-correlation method of estimating sea surface velocities from sequential satellite images. *J. Atmos. Oceanic Technol.,* **7,** 852–865.
Vastano, A. C., and R. L. Bernstein, 1984: Mesoscale features along the First Oyashio Intrusion. *J. Geophys. Res.,* **89,** 587–596.
——, and S. E. Borders, 1984: Sea surface motion over an anticyclonic eddy on the Oyashio Front. *Remote Sens. Environ.,* **16,** 87–90.
——, and R. O. Reid, 1985: Sea surface topography estimation with infrared satellite imagery. *J. Atmos. Oceanic Technol.,* **2,** 393–400.
Wahl, D. D., and J. J. Simpson, 1990: Physical processes affecting the objective determination of near-surface velocity from satellite data. *J. Geophys. Res.,* **95,** 13 511–13 528.
Wu, Q. X., and D. Pairman, 1991: Computing sea surface velocities from sea surface temperature—A relaxation labeling approach. *IGARSS'91 Remote Sensing: Global Monitoring for Earth Management. 1991 Int. Geoscience and Remote Sensing Symposium,* Helsinki, Finland, The Institute of Electrical and Electronic Engineers, 157–161.
——, ——, S. J. McNeill, and E. J. Barnes, 1992: Computing advective velocities from satellite images of sea surface temperature. *IEEE Trans. Geosci. Remote Sens.,* **30,** 166–176.
Yan, X.-H., and L. C. Breaker, 1993: Surface circulation estimation using image processing and computer vision methods applied to sequential satellite imagery. *Photogramm. Eng. Remote Sens.,* **59,** 407–413.